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Roadmap on 5D Photonics for nano and beyond

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Abstract:

As photonic systems grow more complex, it becomes increasingly difficult to capture their behavior within the conventional four dimensions of space and time, particularly for systems operating at the nanometer scale, where strong confinement effects, near-field interactions, and subwavelength structuring introduce additional layers of complexity.The concept of 5D photonics reflects this shift by incorporating additional physical, material, computational, adaptive, and quantum degrees of freedom as active components in design, control, and function. Rather than defining a single extra coordinate, higher-dimensional photonics is about operating photonic systems within expanded, dynamically accessible state spaces where multiple dimensions can interact and evolve together. This roadmap brings together perspectives ranging from modeling and design concepts to experimental platforms, materials, components, and system-level implementations. It covers a wide spectrum of synthetic and structured dimensions, nonlinear and strong-field regimes, adaptive and reconfigurable architectures, cyber-physical and engineering approaches, as well as inherently high-dimensional quantum and excitonic systems. Across all these areas, higher-dimensional thinking emerges not as an abstract construct but as a practical tool for enabling new functionalities, overcoming conventional design limitations, and bridging physical systems with digital and AI-driven layers.

By framing these diverse developments within a shared higher-dimensional perspective, the roadmap aims to provide orientation in a rapidly expanding field, reveal conceptual connections between traditionally separate areas of photonics, and highlight common challenges and opportunities. In doing so, it positions higher-dimensional photonics as a central paradigm for developing future photonic technologies that are increasingly adaptive, intelligent, and integrated across physical and virtual domains.

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Introduction

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At first glance, 5D photonics sounds provocative and catches the attention – but its meaning remains unclear. The first four dimensions are clearly defined: three dimensions in space and the fourth dimension in time. Translated into modern photonics, this corresponds to three-dimensional nanostructured optical systems that can be modified over time and become dynamic via externally applied adaptive components. 4D photonics is widely accepted and has become indispensable in a wide range of applications. The fifth dimension is not so clearly defined, and this article aims to highlight how differently this fifth dimension is viewed by experts in their respective fields. It also examines whether a consensus can be reached on its significance in photonics research and illustrates what advantages such an additional degree of freedom may offer, including the possibility of overcoming limitations inherent to conventional four-dimensional descriptions.

We, the initiators of this article, draw on conceptual work currently being developed within the Cluster of Excellence PhoenixD in Hanover, where optical systems are increasingly considered in conjunction with digital models. In this context, we explore a viewpoint in which the fifth dimension is associated with an additional, digitally mediated layer that complements the progression from static one-, two-, and three-dimensional optical structures to dynamically reconfigurable four-dimensional systems. This step introduces hybrid physical–digital degrees of freedom that allow system behaviours inaccessible within a conventional four-dimensional description. By coupling optical architectures with responsive computational environments, fundamentally new functionalities become achievable. Such an intelligent dimension may be implemented through full-fledged simulations, trained neural networks, interacting digital twins (“Digital Family”), dedicated interaction layers, or sensor-feedback mechanisms that actively steer the photonic system. A central challenge lies in achieving real-time interaction between digital and photonic domains, ideally approaching zero latency relative to the intrinsic timescale of the system.

However, the hybridization of physical-digital degrees of freedom with increasing of intellectual dimension is closely linked to the continuous development and rapid growth of physical capabilities and technologies in modern photonics. This means that discussions of the prospects of 5D photonics must inevitably include and these aspects.

Therefore, the broader concept of 5D photonics extends far beyond the only digital view and encompasses a wide range of alternative approaches. Higher-dimensional descriptions play a central role in modern optics, most prominently in phase-space formalisms that pair spatial coordinates with their corresponding wave-vector components. Such representations extend photonic modelling beyond the conventional four dimensions and offer a natural starting point for incorporating additional physical, material, or algorithmic parameters into a unified coordinate space. Within this emerging perspective, 5D photonics is not characterised by a single, universally adopted definition but rather by a spectrum of conceptual frameworks that expand the ways in which optical systems can be described, controlled, or optimized. The

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diversity of these viewpoints reflects the rapidly evolving landscape of the field, and it is precisely this variety of approaches that forms the basis of the contributions presented in the next section.

From this broader perspective, the contributions compiled in this roadmap demonstrate how various research approaches provide a practical interpretation of higher-dimensional photonics. Conceptual and modelling studies shed light on how temporal evolution, nonlinear wave dynamics and thermodynamic principles can lead to behaviour that effectively transcends conventional four-dimensional formalisms [Demircan, Biancalana, Mei, Lalanne]. Structured fields and engineered resonances demonstrate how synthetic dimensions can emerge from the modal, geometric or dispersive structure of light and matter [Sedeh; Vaičaitis; Takayama; Wetzel; Tuz]. Strong-field interactions and ultrafast material responses demonstrate how dimensionality can dynamically arise when the medium evolves under intense excitation or rapid state transitions [Husakou; Bergé; Vábek, Polynkin]. Additional degrees of freedom, which are rooted in vectorial and chiral light–matter interactions, extend this landscape into regimes where polarisation and symmetry define accessible photonic states [Sergeyev; Menshikov; Gorkunov]. Computational and virtual frameworks create expanded design spaces in which parameters, models and digital twins act as operational dimensions for optimisation and control [Beuchler, Binkowski, Mahlau and Wohletz]. Several contributions demonstrate how these dimensions manifest in adaptive, integrated and context-aware architectures that exploit them directly in devices and platforms [Karabchevsky; Stiller; Zheng; Zayats; Babicheva; Hinkelmann]. Furthermore, cyber-physical environments extend photonic systems into real-time feedback and co-design spaces, linking physical behaviour with engineering-scale digital layers [Fütterer; Schlein]. Quantum and excitonic phenomena finally show that higher-dimensional state spaces are intrinsic to coherent many-body systems, offering natural pathways for ultrafast, multi-timescale, and emergent photonic behaviour [Rübeling; Malomed; Chichkov; Wegener; Athanasiou]. Taken together, these perspectives outline a field that is no longer confined to a single interpretation of a ‘fifth dimension,’ but instead converges toward a multifaceted and interconnected view in which physical, material, computational, adaptive, engineering, and quantum coordinates jointly define the future of photonics.

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Section 1.1 – Dynamical adaptive photonics

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Status

Exploring controllable dynamical optical systems opens new and versatile possibilities for manipulating light. A prime example is photonics with time-varying materials [1], a field widely regarded as a paradigm shift in the control of light and optical technologies [2]. Based on the inherent duality of space and time in Maxwell's equations, this emerging area manipulates optical pulses via temporal modulation rather than spatial structuring [3,4]. This approach enables entirely new avenues for light–matter interaction, pushing the limits of traditional optics [5]. The central concept lies in transferring spatial optical effects into the temporal domain. A temporal mirror, for instance, acts as time analogue of a spatial reflector: when an electromagnetic wave encounters a sudden change of material properties in time, it is reflected in frequency rather than in space, leading to color shifts and reversal of propagation direction. A crucial requirement is the ability to rapidly and reversibly modify material parameters such as permittivity or permeability [2].

An alternative route draws inspiration from nonlinear fiber optics [6], where high intensities accumulate over extended propagation lengths. In this context, temporal reflection has been demonstrated both theoretically [7] and experimentally [8,9], revealing that optical pulses can be efficiently controlled via time-dependent refractive-index changes [10,11]. The all-optical reflection process itself has been known in different contexts and has been described under various names, including the optical push-broom [12], event-horizon analogue [13], and optical diametric drive acceleration [14]. Figure 1 illustrates the temporal reflection of a quasi–group-velocity-matched dispersive wave at a soliton in a nonlinear fiber, using the setup presented in Ref. [11]. The unique nature of this manipulation becomes immediately apparent: the reflection is intrinsically linked to a frequency shift, which can occur toward both higher (blue) and lower (red) frequencies. This property makes the effect particularly appealing for single-photon applications, which are highly challenging but strongly demanded.

The role of time can be exploited in two complementary ways: it acts both as a controllable material parameter and as a resource for realizing distinct optical functionalities in successive temporal sequences. The concept of temporal adaptivity is therefore central. We have shown that temporally cascaded adjustability can substantially enhance system performance [15]. It denotes a conceptual framework that enables a more efficient use and enhancement of underlying linear and nonlinear optical processes. In such schemes, each temporal window defines an individual operational regime with tailored conditions, while subsequent sequences build upon the evolving system state. This approach extends the accessible parameter space of a static system but effectively also introduces additional operational dimensions (5D Photonics).

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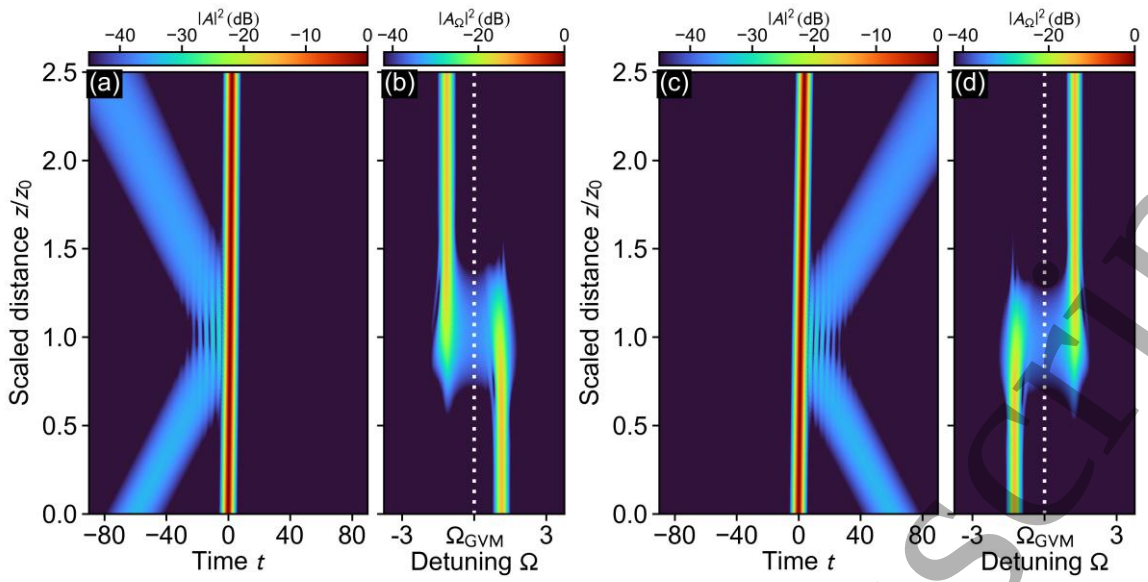


Figure 1 (a) Reflection of a weak dispersive wave (DW) off the leading edge of a soliton. Propagation distance is scaled by the distance it takes for the DW to reach the soliton. (b) Frequency downshift of the DW, corresponding to the reflection process in the frequency domain. Vertical dashed line indicates the frequency detuning group-velocity matched to the soliton. (c) Reflection of a DW off the trailing edge of a soliton. (d) Corresponding frequency upshift of the DW in the frequency domain.

Current and future challenges

Theoretical studies in time-varying materials predict phenomena such as non-reciprocity [16] and time crystals [17], yet experimental verification still simply not exist. The main challenge lies in achieving sufficiently fast and strong refractive-index changes without exceeding material damage thresholds. Fiber-based systems offer a particularly promising platform. Their long interaction lengths enable the accumulation of nonlinear effects at comparatively low peak intensities, making temporal modulation phenomena experimentally accessible. Realizing these effects, however, requires carefully engineered dispersion profiles and synchronized pulses with incommensurate frequencies to drive the desired temporal modulation with high fidelity. Beyond their practical advantages, fiber systems also offer a conceptual bridge toward temporal analogues of quantum-mechanical systems. Owing to the formal analogy between the governing propagation equation and the Schrödinger equation, one can shape temporal potentials—time-domain equivalents of spatial potentials in quantum mechanics. These enable incoherent attractive interactions and give rise to bound states of light in time and resonant coupling between optical modes. Recent theoretical studies suggest that such temporal potentials can give rise to optical molecules [18,19], meta-atoms with discrete eigenstates [20], and even photonic solids—temporal counterparts of spatially periodic structures. Figure 2 shows an example of a photonic meta-atom with three trapped states. To further advance this principle, dispersion engineering plays a crucial role. Suitable dispersion properties are required to stabilize temporal bound states and to control their coupling dynamics. Promising candidates for such implementations include diamond- and silicon-based waveguides, which combine high nonlinearity with excellent optical transparency and damage resistance. A remarkable feature of temporal analogue systems is that the eigenstates of such meta-atoms are not defined by their energy, as in conventional spatial systems, but by their wavenumber. This fundamental distinction enable applications in single-photon manipulation within dynamically varying photonic environments.

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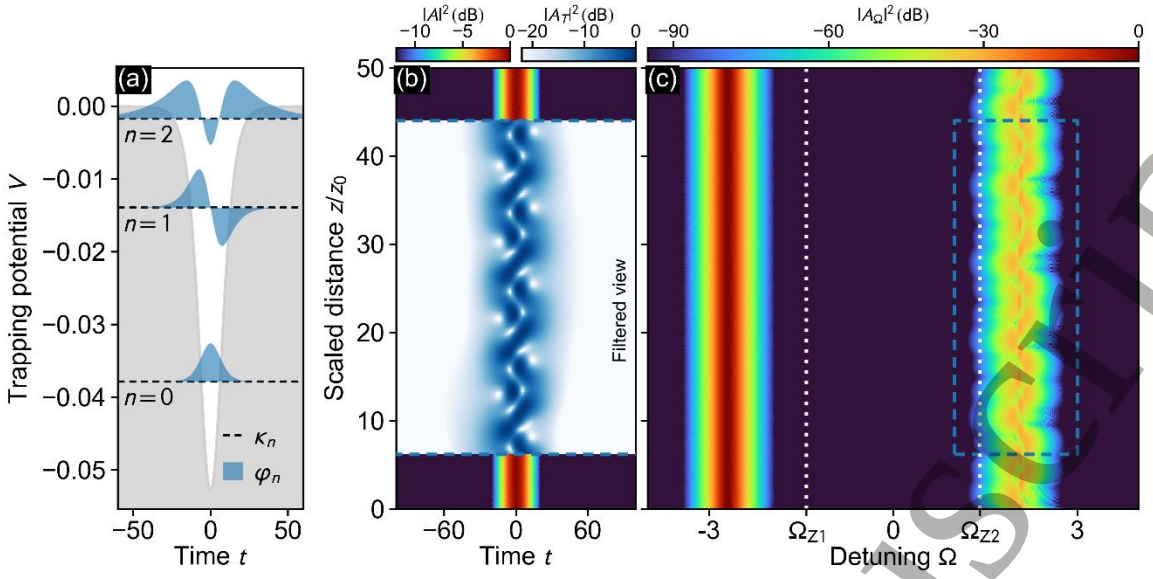


Figure 2. (a) Soliton induced potential well V_T with three trapped states at eigenvalues κ_n and waveshapes φ_n (n=0,1,2). (b) Propagation dynamics of the soliton in presence of weak trapped states. The propagation distance is scaled by the soliton period. (c) Corresponding spectrum. Vertical dotted lines indicate zero-dispersion points. An inverse Fourier transform of the spectral range enclosed by a dashed box in panel (c) is shown in the box in panel (b).

Advances in science and technology to meet challenges

Progress in dynamical adaptive photonics relies on adjustable materials whose optical parameters can be modulated rapidly, strongly, and uniformly in time. Space–time-engineered metamaterials and metasurfaces are particularly promising: their subwavelength resonators enable strong field enhancement and programmable dispersion, translating modest control signals into large effective temporal modulations. Among material platforms, epsilon-near-zero (ENZ) media stand out. Their unusual dispersion permits large index perturbations for relatively small excitation energies, and recent work has shown sub-picosecond, all-optical control of nonlinear coefficients and carrier dynamics—key ingredients for high-speed temporal modulation.

Waveguide-based architectures provide another versatile route, offering long interaction lengths and precise dispersion control within compact geometries. Implementing robust temporal effects requires synchronized multi-pulse schemes, involving incommensurate frequencies and well-defined induced refractive-index changes. For integrated implementations, as mentioned, diamond and silicon platforms represent leading candidates: diamond combines broad transparency and high thermal conductivity with outstanding damage tolerance, while silicon photonics provides mature fabrication and strong Kerr nonlinearity. Controlling two-photon absorption and free-carrier effects remains essential to achieve high-contrast temporal modulation.

The rapid evolution of ultrashort-pulse sources provides the technological foundation for dynamical adaptive photonics. Few-cycle and CEP-stable laser systems now deliver femtosecond-scale temporal precision and broad spectral bandwidths, enabling dynamic modulation at optical frequencies. Together, adaptive metamaterials, engineered fibers, and integrated diamond or silicon platforms—powered by modern ultrafast sources—define the technological path toward experimentally realizing fast, strong, and low-loss temporal control.

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A particularly promising direction builds upon the concept of temporally cascaded adjustability introduced earlier. By extending this principle through computationally assisted adaptivity, it becomes possible to access entirely new parameter spaces and effectively introduce virtual dimensions into photonic systems. In this framework, specific functionalities can be activated during defined temporal windows, allowing each stage of an optical process to build upon the dynamically adjusted conditions of the previous one. For example, in the pulse compression scheme presented in Ref. [7,11], soliton dispersive wave collisions already result in a threefold compression after nine repetitions, without adaptive control. However, by adapting the wavelength and intensity of a control pulse to the evolving spectral and temporal properties of the signal pulse, a substantial further improvement can be expected. Each temporal window thereby refines the desired effect, while subsequent stages operate under optimized conditions derived from the preceding state. Such computer-assisted optimization enables pre-calculated, cascaded schemes—or even closed-loop implementations—in which feedback dynamically adjusts control parameters in real time.

Concluding remarks

Dynamical adaptive photonics is still in its infancy, with only a few experimental demonstrations so far—mostly in fibre-based systems. Yet theory already reveals a wealth of unexpected temporal effects and a rapidly expanding range of possibilities. As similar as these concepts appear to their spatial counterparts, the underlying mechanisms differ fundamentally. Consequently, their limitations are also distinct—for instance, a bandwidth limit for a temporal cavity would not apply in the same way as in a spatial resonator. These differences point toward a genuine paradigm shift in optical technology, where time itself becomes a functional design dimension. Moreover, such temporally controlled optical systems can be further extended and integrated with other adaptive approaches.

The emerging ability to assign specific optical functionalities to distinct temporal windows defines a new design paradigm. Each temporal sequence can explore its own multidimensional parameter space, where dispersion, nonlinearity, and spectral response are dynamically reconfigured. Looking ahead, computational control, real-time optimisation, and machine-learning-based strategies will make it possible to orchestrate these temporal and multidimensional degrees of freedom with high precision. Such systems could combine optical adaptivity with computational intelligence—paving the way toward self-optimising photonic architectures that also expand the frontiers of optical computing and AI-driven information processing.

Acknowledgements

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Section 1.2 – Linear and Nonlinear Time-Varying Refractive Index Media

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Status

Time-varying refractive index (TVRI) media are optical materials whose refractive index changes as a function of time. The theoretical investigation on this topic started in 1958 [1], with very few subsequent landmark papers mostly focusing on wave amplification and moving plasma fronts [2][3][4]. Unlike ordinary static materials, these dynamic media break time-translation symmetry, giving rise to novel phenomena with no analogue in static optics. This enables temporal refraction and reflection at "time interfaces," where frequency is shifted while wavenumber is conserved, the temporal dual of spatial refraction and reflection [5]. Single temporal interfaces have been implemented with pump-probe experiments using transparent conducting oxides (TCOs) such as AZO and ITO [6], epsilon-near-zero (ENZ) materials showing large refractive-index modulation and ultrafast nonlinear response on sub-ps scales [7].

A periodic variation of the refractive index (or a periodic arrangement of time interfaces) yields *photonic time crystals* (PTCs): homogeneous media that exhibit Floquet band structures featuring the crucial concept of forbidden momentum gaps (*k*-gaps, first described in [8] and observed in [9]), rather than frequency gaps (see Fig. 1). This distinction is more than formal: unlike spatial photonic crystals, which suppress propagation in selected frequency bands, PTCs can also exchange energy directly with the external modulation, enabling exponential amplification, broadband frequency conversion and unusual spontaneous-emission control [10]. Experiments demonstrating linear time interfaces and repeated time-boundary physics have very recently been successfully performed in the microwave regime [11-12], although these should be regarded as microwave analogues or precursor platforms rather than fully optical PTCs.

Nonlinearity adds another layer of richness to TVRI media. For instance, when second-order harmonics are tuned inside a *k*-gap, they can get parametrically amplified, theoretically leading to a massive cascade of higher-order harmonics [13]. More importantly, PTCs unlock gap-soliton families (first introduced in [14]) that self-trap within *k*-gaps and, in theory, can display a wide variety of interesting phenomena [15]. A successful implementation of a fully nonlinear PTC has not yet been achieved at the time of writing; such a device would open new vistas on many fronts, such as the construction of completely new types of lasers and tunable optical sources. At present, the clearest direct realisations of repeated time-boundary physics are in the RF/microwave domain, while optical experiments have established ultrafast time-refraction and reflection and frequency translation in ENZ media, but not yet a many-cycle optical PTC.

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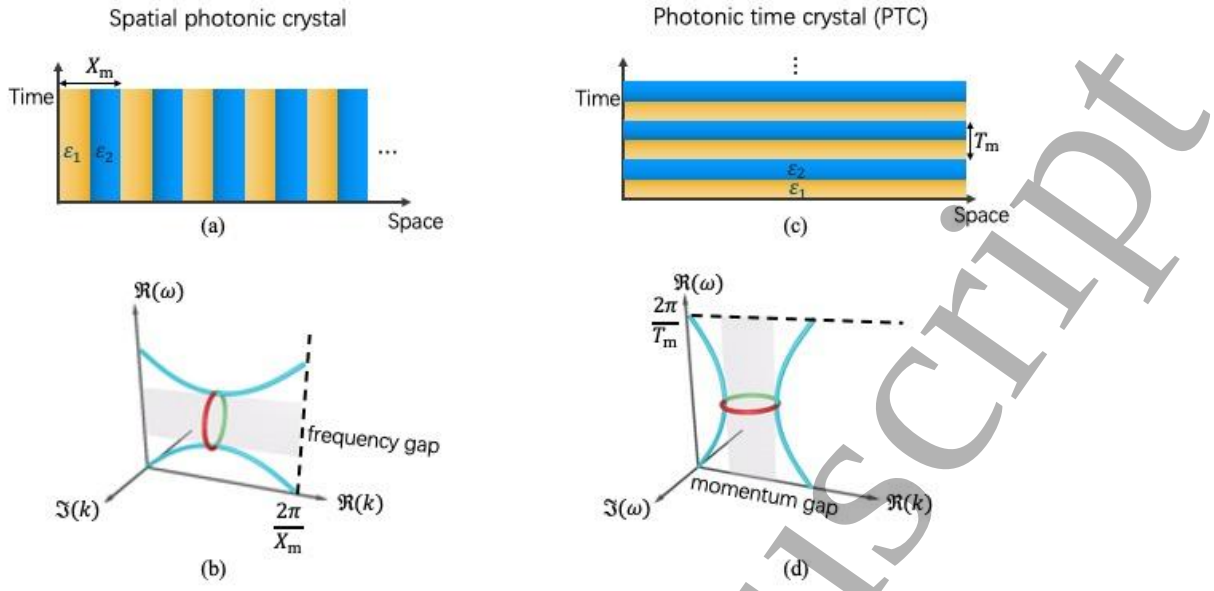


Figure 1. (a) Conventional spatial photonic crystal and (b) its frequency gap. (c) Photonic-time crystal (PTC), a homogeneous and isotropic medium with a temporal periodic variation of the refractive index, and (d) its momentum gap, where temporal *k*-gap solitons [13] can be excited when nonlinearity is present. [Figure kindly provided by Prof C. Rockstuhl, Karlsruhe Institute of Technology, Germany; produced by Dr Xuchen Wang (Harbin Engineering University, Qingdao, China). See the comprehensive review article [10] for a full explanation of this figure].

Current and future challenges

Realizing a nonlinear PTC requires overcoming tightly coupled constraints in speed, loss, uniformity, and control. Optical-frequency PTCs demand large real-index excursions on the fs scale. While ENZ oxides (ITO/AZO) provide sizable index modulation with ultrafast response, achieving modulation on (or near) a single optical cycle with low added absorption remains difficult; multi-cycle operation exacerbates dissipation and thermal load, risking the quench of the desired *k*-gap amplification. Strong, fast modulation in ENZ films typically introduces free-carrier absorption and heating; in many-cycle sequences these losses accumulate and can overwhelm parametric gain unless actively managed or compensated. Quantitatively separating the useful real modulation from the concomitant losses, while keeping the relevant figure of merit high, is therefore a central future materials challenge. Nonlinear PTC physics is also sensitive to the duty cycle, harmonic content, and phase of $\boldsymbol{n}(\boldsymbol{t})$. In finite films, temporal boundary conditions at interfaces contribute comparably to bulk modulation and can even oppose it depending on angle and polarization, complicating the effective temporal lattice seen by pulses. Ensuring spatially uniform time interfaces, where the change of refractive index occurs homogeneously with sub-cycle variation is therefore critical.

Experiments have convincingly realized single time interfaces and even sequential time reflections in the RF/microwave domain; however, scaling to dozens or hundreds of cycles with stable phase and controlled gain/loss to directly observe *k*-gap dispersion and exponential growth remain an open challenge. Synthetic-time photonic lattices partly bridge this gap but introduce their own calibration and synchronization burdens. The predicted *k*-gap solitons require deep, fast modulation and an interplay between Floquet band curvature and effective nonlinearities. Operating points that support solitons must also remain stable against

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noise amplification inherent to parametric gain; practical devices will presumably need seeded start-up and feedback to avoid chaotic growth. Quantitative targets are therefore needed: in the near IR, one optical cycle is only a few femtoseconds, whereas in microwave platforms picosecond switching is already sufficiently abrupt with respect to the carrier period to emulate time boundaries and repeated Floquet modulation [11].

Direct, phase-sensitive mapping of Floquet bands and *k*-gap gain is still scarce. Experiments require time-resolved spectral-phase diagnostics and angle/mode-resolved detection to decouple bulk versus boundary contributions and to quantify growth rates per period. Predictive multi-physics models that couple Maxwell dynamics with carriers, heat, and realistic pumps are essential to guide the design and to extract the Floquet exponents from the measured transients. Collectively, these issues define the near-term roadmap: reducing dissipation at fixed modulation depth, synthesizing uniform and phase-stable $\boldsymbol{n}(\boldsymbol{t})$ over many periods, detecting Floquet observables directly, and validating the nonlinear operation in intermediate platforms before attempting fully optical implementations.

Advances in science and technology to meet challenges

Progress toward a working nonlinear PTC in the optical regime hinges on coordinated advances in different areas: material science and dissipation control; resonant architectures that relax speed and amplitude requirements; and deterministic temporal waveform synthesis with spatial uniformity. An ENZ material such as AZO can produce large relative changes in $\boldsymbol{n}$, leading to strong optical nonlinearities, but at the cost of generating carrier absorption and heating that can hinder the build-up of the multiple time-reflections and time-refractions required for many-cycle PTC operation. One of the advantages of TCOs is that the absorption wavelength range is moderately separated from the ENZ range, allowing a certain freedom to engineer meaningful experiments on a single time refraction/reflection event [7]. For an infrared pulse of about 1.3 $\boldsymbol{\mu}$m, the single-cycle time is about 5 fs. In the seminal ENZ-AZO switching paper [16], the authors show excitation and recombination times below 1 ps near the ENZ band, with large reflectance changes at telecom wavelengths. Their work explicitly notes that the process is "in principle limited by the material absorption time (~10 fs) and recombination time," highlighting 10 fs as a theoretical lower bound rather than a demonstrated device recovery time. This indicates that improved TCO and ENZ materials remain a central priority. Advances are needed in the control of oxygen vacancies, dopant density, grain structure, defect states, and multilayer heat extraction, so that useful refractive index changes can be decoupled as much as possible from dissipative losses [17]. This must be complemented by more advanced theoretical investigations of TCO-like media: classical or semiclassical models such as the ones proposed in [18] fit data well but remain semi-phenomenological; more predictive, composition-aware theories are needed to guide materials discovery.

A second, and probably more realistic, route is to relax the raw switching requirement by using resonant architectures. Structured resonant media, metasurfaces, and microcavities can transform modest material modulation into a large effective temporal detuning through field concentration and narrow linewidth. In this sense, resonant enhancement may circumvent the need for truly bulk few-femtosecond switching, because the relevant quantity becomes the effective modulation of the device transfer function rather than the absolute value of the material index swing. Recent work on ENZ-based structured platforms [7] and on resonantly enlarged momentum gaps [19] suggests that this route is one of the most credible bridges between current ultrafast materials and future optical PTCs.

A promising near-term direction for nonlinear PTCs is the RF/microwave regime [11]. To realize nonlinear PTCs on a transmission line, the propagation constant $\boldsymbol{\beta}(\boldsymbol{t})$ must be modulated deeply and coherently with low loss. A proposed practical route is to retain the loaded microstrip as the synchronization backbone—optical fan-out, picosecond switching, and uniform time interfaces—and augment each unit cell with a

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parallel reactive nonlinear branch so the RF/microwave signal self-modulates its propagation constant $\boldsymbol{\beta}(\boldsymbol{\omega},\boldsymbol{t}) \approx \boldsymbol{\omega}\sqrt{\boldsymbol{L}'(\boldsymbol{I},\boldsymbol{t})\boldsymbol{C}'(\boldsymbol{V},\boldsymbol{t})}$, where $\boldsymbol{L}'$ and $\boldsymbol{C}'$ are the series inductance and shunt capacitance per unit length, respectively, and nonlinearity enters via current and voltage dependence. A sensible option would be to use an anti-series varactor stack as the shunt element [20]: the intrinsic $\boldsymbol{C}'(\boldsymbol{V})$ nonlinearity yields a Kerr-like response while suppressing even-order distortions and improving power handling; a comb-locked electrical or optical drive can preserve the lattice phase. Other possibilities include nonlinear series inductance, $\boldsymbol{L}'(\boldsymbol{I})$, via compact magnetic or semiconductor saturable inductors at room temperature. In all cases, the existing optical trigger maintains homogeneous, phase-locked many-cycle time boundaries, while the added branch supplies the self-action needed for *k*-gap gain and temporal gap-soliton formation. In this sense, microwave PTCs are not merely substitutes for optical ones, but a natural proving ground for the nonlinear Floquet physics that optical platforms will ultimately need to reproduce.

Concluding remarks

TVRI media elevate time to a full design dimension, enabling temporal refraction/reflection, *k*-gap physics, parametric gain and amplification, and new types of nonlinear wave excitations. With few-interface demonstrations now spanning water waves to RF/microwaves and ENZ-assisted optics, the pivotal task is scaling to many-cycle, low-loss, programmable PTCs. Progress will hinge on low-loss ultrafast materials, resonant enhancement, precise waveform control, robust metrology, and co-integration. If achieved, TVRI media platforms could deliver a new generation of lasers, compact parametric amplifiers, temporal filters and isolators, broadband frequency shifters, topologically robust time-boundary states, and completely new types of quantum-information components — transforming photonics much more than spatial photonic crystals did a generation ago.

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Section 1.3 – Hidden Dimensions in Optical Thermodynamics

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Status

Research in nonlinear fiber optics traditionally focused on single-mode fiber geometries. Recently, optical multimode fibers have been shown to exhibit several intriguing nonlinear phenomena, such as spatiotemporal mode-locking [1] and beam self-cleaning [2]. At low input powers, perfectly spatially coherent input beams dephase due to intermodal dispersion, leading to an incoherent speckle pattern at the fiber output. This dephasing effect appears strongly mitigated at elevated input powers, i.e., energy localizes in the fundamental mode of the multimode fiber, and the output coherence is substantially increased. Two different lines of thought have developed to explain beam self-cleaning. On the one hand, an increased coherence can be understood by the formation of a spatial soliton [3]. Propagation in the fiber is described by the (3D+1)- dimensional Nonlinear Schrödinger Equation (NLSE), which features an eigenvalue solution, known as the Townes soliton. On the other hand, it has been argued that accurate modeling of the NLSE for an N-modal system leads to an overwhelming number of nonlinear mixing terms $\sim N^3$. Consequently, a statistical description of the multimode system emerged, which is known as optical thermodynamics [4]. This novel theory successfully describes thermalization processes [5]: an initial excitation of higher-order modes converges toward thermal equilibrium, which can then be described by Rayleigh-Jeans or Bose-Einstein statistics. However, optical thermodynamics encounters a serious challenge when describing beam self-cleaning or spatial mode-locking. During either of these processes, the occupation in the fundamental mode p_0 increases at the expense of higher-order mode occupation $p_i>0$; i.e., entropy $S=-\Sigma\ p_i \ln p_i$ decreases as coherence improves. Moreover, as the number of modes of a typical multimode fiber is limited to $N\sim100$ and dissipative effects can be neglected, such a decrease of entropy would obviously violate the second law of thermodynamics, which demands that entropy in a closed system never decreases. This dilemma can only be cured when hidden dimensions exist that serve to absorb the apparent loss of entropy. Consequently, while the theory of optical thermodynamics appears highly promising for a deeper understanding of nonlinear multimode systems, clarification of the apparent entropy leak is mandatory to justify its use beyond convergence toward thermal equilibrium.

Current and future challenges

To trace the possible origin of the entropy leak, we conducted a series of beam self-cleaning experiments [Fig. 1(b-e)] with additional control of the polarization state of the input as well as polarimetric and spectral analysis of the output beam. As this analysis was conducted in the anomalous dispersion regime of the fiber

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at 1560 nm, we observe the formation of a temporal soliton, which subsequently undergoes a Raman self-frequency shift of up to 150 nm upon further nonlinear propagation [6], as shown in Fig. 1(a). Widely independent of the input polarization, nonlinear propagation in the multimode fiber is accompanied by a reduction of the degree of polarization (DOP), which is already strongly reduced after only 0.5 m of nonlinear propagation and virtually vanishes after 10 m [Fig. 1(g)], i.e., the self-cleaned beam profile appears nearly completely unpolarized like a thermal light source. This depolarization effect appears correlated with the Raman shift, i.e., the beam becomes virtually unpolarized after it experiences a Raman shift [7] of more than 100 nm or 12 THz, which corresponds to the maximum of the Raman gain in silica fibers. Given the strong correlation of the DOP with the Raman shift, we identify inelastic scattering as the possible origin of the observed depolarization. As any information originally encoded in the input polarization is lost in this process, the associated polarization entropy automatically maximizes [see Fig. 1(f)]. In other words, the apparent increase in the spatial coherence is intimately connected to a concomitant reduction of the DOP. This finding clarifies the mysterious loss of entropy in beam self-cleaning experiments as a transfer of entropy from the (3D+1)-dimensional phase space of the NLSE into a fifth dimension, namely, polarization. While this explanation relies on the Raman scattering as the underlying mechanism for depolarization, the Raman self-frequency shift requires the formation of solitons, which can only form in the anomalous dispersion regime. Consequently, seeking a similar entropy transfer mechanism remains a challenge for future investigation. One potential mechanism may be the emergence of a complex temporal shape or spectral profile, i.e., along the fourth rather than the fifth dimension. In any case, we are confident that higher-dimensional analysis beyond two-dimensional beam profiles will ultimately resolve the apparent entropy loss in beam self-cleaning.

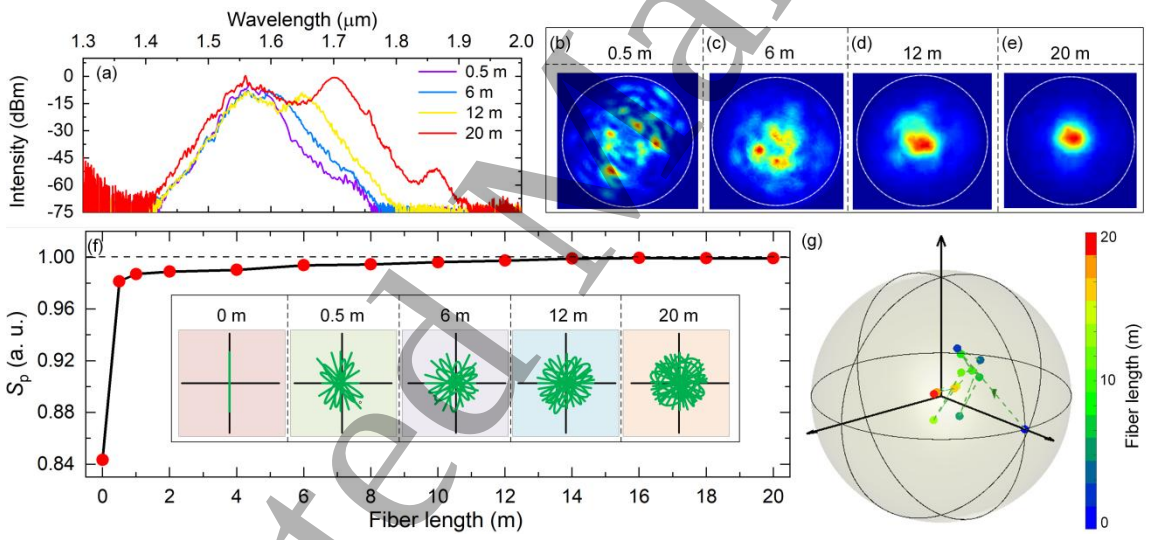


Figure 1. (a) Output spectra from a 0.5 m (purple), 6 m (blue), 12 m (yellow) and 20 m long (red) GRIN multimode fiber when the input beam is linearly polarized. Corresponding output beam profiles of the (b) 0.5 m, (c) 6 m, (d) 12 m, and (e) 20 m long fibers. (f) Calculated polarization entropy S_p for different fiber lengths. Insets are conceptual diagrams to viualize the evolution from a perfectly polarized to an unpolarized state. (g) After calculating the Stokes parameters, a Poincaré sphere representation is used to illustrate how the polarization state changes with the fiber length. While both the spectrum and the beam profile show signs of some ordered evolution, the polarization evolves towards disorder.

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Advances in science and technology to meet challenges

We explain the apparent entropy loss during Raman beam cleanup as an entropy exchange between different degrees of freedom in the thermodynamic system. Given the near-complete loss of information encoded in the initial polarization and the maximization of polarization entropy, there is no apparent breach of the second law in a more complete view of the closed thermodynamic system. However, a quantitative analysis by numerical simulation requires substantial amendments to existing codes. In particular, while a vector theory of Raman amplification [8] exists, this formalism only accounts for polarization manipulation on the surface of the Poincaré sphere; that is, it does not allow for modeling depolarization effects. The propagation of partially polarized light has only scarcely been treated in literature [9], and depolarization effects in liquids and gases have been mostly addressed in the physical chemistry literature [10]. Finally, formalisms based on a partial differential equation, such as the NLSE, make it hard to realistically incorporate inelastic random scattering into this fully deterministic framework. Moreover, given that inclusion of polarization effects will increase the number of modes by a factor 2, which, in turn, increases the number of nonlinear mixing terms in the NLSE by another factor 2^3=8, a statistical approach appears more sensible. To this end, careful polarimetry experiments on the beam self-cleaning phenomenon across different wavelength regimes and pulse durations appear necessary to understand how the depolarization effect scales with pulse and fiber parameters. Finally, in addition to applications of beam self-cleaning, Raman-based polarization modification also appears to be an intriguing new means of generating completely depolarized light with high brilliance.

In conclusion, we have shown that a thermodynamic model of the beam self-cleaning phenomenon may violate the second law of thermodynamics if the statistical description of the occupation is limited to two spatial dimensions. Such a description, therefore, appears incomplete. To maintain and extend the validity of optical thermodynamics, it appears mandatory to expand the system into additional dimensions. Our experiments indicate that entropy may be transferred from the spatial domain into an additional polarization domain. The Raman self-frequency shift mediates this depolarization effect and maximizes polarization entropy concomitantly with the decrease of spatial entropy of the beam profile during self-cleaning. This finding finally explains the apparent entropy leak that was observed in many previous beam self-cleaning experiments.

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Section 1.4 – The hidden dimension in nanophotonics design: understanding

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Status

In many engineering and scientific domains, e.g. fluid dynamics, mechanics, or photonics (our focus here), the discretization of the governing differential equations results in billions of unknowns for accuracy, particularly in industrial settings, where complex, large-scale systems are commonplace. The inverse problem—designing the optimal structure—is even more challenging (See Section 5.3). Further complexity enters in "multi-physics" scenarios in which different governing equations (wave equation, heat equation, etc.) are coupled.

Despite this apparent complexity, many systems of practical interest exhibit behaviour that depends on only a small number of latent (reduced-order) parameters. Such parameters can often be uncovered through simplified models, which temporarily suppress fine-scale details and enable the formulation of more universal physical laws. A well-known example in nanophotonics is coupled mode theory 0, which assumes that a small number of modes, connected through fitted coupling coefficients, can adequately capture the system's behaviour.

At the same time, advances in computing power, hardware architectures, and numerical algorithms have driven an increasing reliance on large-scale full-wave simulations, typically based on finite-difference or finite-element methods. In parallel, inverse problems are now frequently addressed using adjoint-based optimization or neural-network-driven approaches.

These developments give rise to a paradox in modern computational science. Although simplified, interpretable representations of physical systems are often available, there is a growing shift toward "black-box" methods and what might be termed blind simulation. This shift is likely to accelerate in the near future.

This Section does not argue against the value of full-wave simulation—on the contrary, its potential is undeniable. Rather, it raises a fundamental question: what is lost in the transition toward increasingly opaque computational methods? And, if such losses are significant, how might they be mitigated? We advocate for complementing black-box simulation and design with an equally important objective: understanding.

Current and future challenges:
The opacity of modern computational design

In recent years, an increasing number of high-impact studies have reported near-optimal designs obtained through high-dimensional optimization driven by opaque, black-box neural networks—often referred to as

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foundation models—coupled with equally opaque simulation tools. This emerging approach may be described as a *black-squared* (b^2) paradigm. When pushed to the geometric extreme, yielding fully freeform structures (Figure 1), these designs often exhibit intricate and mysterious patterns 0. Such structures

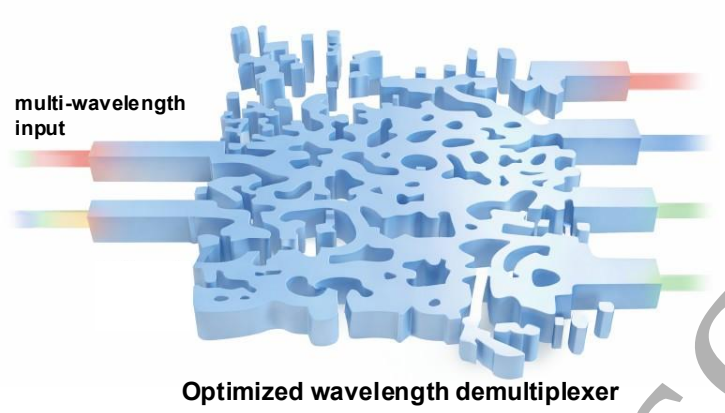


Figure 1. AI-driven freeform optimization in nanophotonics often yields complex *Swiss-cheese* patterns—powerful, if mysterious. Comprehension lags behind: Are the design tolerant to imperfection? Governed by multiple scattering? How close are they from upper bound physical limits, and how does that limit scale with footprint? (Figure inspired by 0).

appear to lie far beyond human intuition, fostering the impression that machines have surpassed human designers.

In a deep neural network, the layers are designed to transform raw input data (such as images, signals) with millions of variables into progressively more abstract and high-level features. Each layer operates on the output of the previous layer, which means that the deeper layers learn increasingly complex representations of the input data. This hierarchical learning process mimics human perception—starting with basic features and moving to more abstract representations.

Deep networks are often said to learn latent representations of the complex world. These latent representations are the results of non-linear combinations of features or interactions between the many design variables, which might not be easily discovered by human experts, though they may hold key insights into how the design works. However, these latent representations are not directly interpretable. The neural network does not "tell us" what the latent information represents, nor does it necessarily align with physical models that we can understand..

One parallel might be the “shut up and calculate” paradigm in quantum physics—should we not just accept the power of these tools, even if we do not understand fundamental reasons for the predicted performance? Yet we believe the complexity of these designs does not rival philosophical interpretations of quantum mechanics; we *should* aim to understand how they “truly” work. Such understanding might be exemplified by whether we can answer: what are the fundamental limits to the performance we are optimizing for? Why?

Advances in science and technology to meet challenges:
Intelligent simulation and rational design

Physically grounded, interpretable approaches can reveal *why* a design works and *how* it can be improved. Between brute-force simulations involving billions of variables and overly simplistic models that, while

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insightful, lack predictive power, there exists an intermediate paradigm we call *intelligent simulation*. This approach seeks to combine the strengths of both extremes. Ideally, an intelligent simulation identifies a small number of key latent parameters, relates them to physically meaningful quantities for direct interpretability, and still leverages the high dimensionality of the underlying system to achieve accurate predictions. We illustrate its power through three examples.

The first example concerns the development of grating theory in the 1970s. At that time, limited computational resources necessitated the design of highly efficient simulation methods, often grounded in sophisticated mathematical formulations with rapidly converging expansions. For instance, Rayleigh expansions were systematically employed in both the substrate and superstrate to enforce outgoing wave conditions, enabling a clear analytical distinction between propagating and evanescent waves. By contrast, most modern simulations that rely on finite-difference time-domain or finite-element methods, typically enforce these conditions with perfectly matched layers. While powerful and general, these layers tend to obscure physical interpretation and are often computationally demanding.

Furthermore, key physical quantities—such as the poles and zeros of the scattering operator—were frequently computed explicitly. Dispersion relations of bound states in the continuum were explicitly characterized, either as complex-valued frequencies as functions of the real part of the wavevector, or conversely as complex wavevectors as functions of the real frequency. Zeros, in particular, were often exploited to design unitary scattering efficiencies in selected diffraction orders, see, e.g., 0. Today, such explicit characterization is seldom carried out, even though the set of poles—the spectrum of the associated non-Hermitian operator—encodes the most fundamental information about the system.

The second example is more recent and dates from a period when finite-difference time-domain and finite-element methods began to dominate computational electromagnetism. It concerns high-Q photonic-crystal cavities formed by introducing defects (i.e., missing holes) in dielectric slabs. In the race towards high-Q, it was rapidly realized that cavity Q's could be significantly enhanced by adjusting the position and size of the holes surrounding the defect. An emblematic illustration is the tenfold Q-enhancement with a three-hole defect cavity, achieved by shifting the two holes at the cavity extremities 0 (see Fig. 2).

The cavity mode can be understood primarily as a standing wave resulting from the interference of counterpropagating guided modes of a photonic-crystal waveguide with a single missing row. As such, it contains in-plane spatial frequency components exceeding the free-space wavenumber in the surrounding air cladding. Based on this observation, the authors of 0 introduced the concept of *gentle confinement*, whereby the cavity boundaries are engineered to avoid abrupt spatial variations of the mode profile. Instead, a gradual transition is imposed, ensuring that the mode remains predominantly composed of in-plane wavevectors lying below the air light line, thereby reducing radiation losses. While this concept was validated through "black-box" FDTD simulations, it does not directly reveal the physical mechanisms responsible for the observed enhancement: high-Q cavities have all a reduced weight of wavevectors above the air light line and vice versa.

A complementary, more "modal" approach provides clearer physical insight. By modelling the cavity as a Fabry–Pérot resonator and using dedicated Bloch-mode numerical tools, the tenfold Q-enhancement is traced back to two key effects 0. First, the group velocity of the photonic-crystal-waveguide guided mode is reduced by approximately a factor of two, effectively doubling the energy storage time within the cavity. Second, the shifted holes act as an impedance-matching section, adiabatically transforming the propagating Bloch mode of the waveguide into the evanescent Bloch mode of the surrounding photonic-crystal mirrors (Fig. 1) and effectively reducing out-of-plane scattering losses at the waveguide terminations.

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Identifying these mechanisms provides valuable and transferable design principles. For instance, Q-factor enhancement through mode slowdown can be systematically exploited in a variety of geometries, including ring resonators and plasmonic nanoresonators. Similarly, impedance matching via gradual Bloch-mode tapering can be exploited across a wide range of photonic structures, including nanobeam cavities, micropillar Bragg cavities, and double-heterostructure PhC cavities 0.

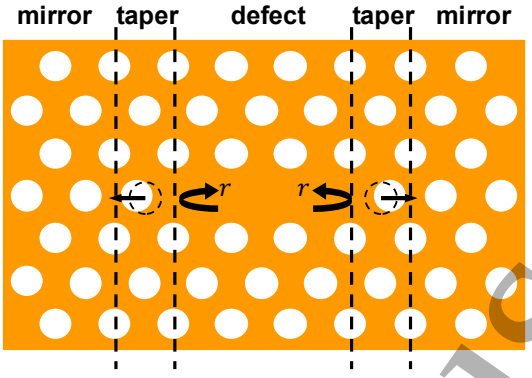


Figure 2. With a modal interpretation of gentle confinement with shifted holes, the Q-factor enhancement results from the slowdown of the guided Bloch mode in the cavity defect and its progressive impedance adaptation to the evanescent Bloch modes of the mirrors.

A third example arose recently in the design of a scattering device for augmented-reality applications [7]. Ideally, the device scatters strongly around a single wavelength (e.g., the source wavelength in the display), for many angles, while otherwise transparent across a wide range of frequencies and angles (e.g., radiation from the outside world, passing through the device). In a first attempt, the authors applied topology optimization to pixelated metasurfaces. They found designs that could concentrate their scattering within a relative bandwidth of $\Delta\omega/\omega = 1/30$ (far narrower than plasmonic approaches), but only for a small range of incoming angles, $\Delta\theta = \pm 12°$. The authors then tried a rational design, inspired by the flat bands of Moiré systems, and discovered simple two-parameter structures with guided-mode resonances that fit within the same $1/30$ bandwidth but with a much broader angular range of $\pm 45°$.

Could such simple designs really outwit computational inverse design? Not strictly: the background scattering in the latter designs was increased significantly. As measured by the numerical objective used in the optimization, the latter designs are worse. However, rational analysis revealed that the background scattering for these structures appear Fabry-Perot-like, motivating the introduction of an additional thin-film layer separately optimized as an anti-reflection coating for these structures. With this coating, the rational designs outperform the computationally optimized structures on every dimension. Physical insight reshaped the design "architecture" in a critically important way.

These examples illustrate a common pattern: understanding the latent physics of a problem—whether through modal decomposition, spectral characterization, or symmetry-inspired design—yields not only better-performing devices but also transferable principles applicable across geometries and physical systems. More generally, photonic design problems typically involve a multitude of hyperparameters that influence their "optimal" solutions, which are difficult to identify without physical insight. A natural question then arises: can these low-dimensional descriptors be discovered automatically, and can neural networks be trained to express their knowledge in physically interpretable form?

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Conclusions

Foundation models are not the culmination of AI, but merely its first operational layer. A second layer, called wrappers is now emerging to mediate, extend, and increasingly control the use of these models. In nanophotonics, this evolution is already visible in the rise of agentic frameworks [8-9]. These systems exhibit autonomy, retain memory, generate code, embed numerical Maxwell solvers, and orchestrate complex, multi-step workflows. Rather than simply executing tasks, they decompose problems, construct plans, and iteratively refine solutions—blurring the boundary between tool and collaborator. Yet, despite these advances, the collaboration remains fundamentally superficial. Today's systems excel at optimization but fall short at understanding. Their internal reasoning is largely inaccessible, leaving users to trust outputs without insight.

If AI is to become a true scientific partner, it must move beyond performance and toward interpretability. This requires shedding light on the *latent knowledge* encoded in hidden layers by making explicit which features drive decisions and why [10]. More radically, it calls for training neural networks to compress their knowledge into a small number of physically meaningful, low-dimensional parameters that can be directly understood by scientists. Without this step, AI risks remaining a powerful but opaque optimizer—efficient, yet epistemically limited. Similarly, this is a call to researchers: make the effort to understand your design. Ask your neural network to explain it, and strive for real insight. Only then will a genuine dialogue emerge between you and the neural network, which may lead to discover unexpected phenomena, such as a thin metal film acting as a lens with super-resolution capabilities.

Looking further ahead, digital scientists may recursively take over each step of this hierarchy, proposing and carry out their own research agenda, promising to drive an exponential acceleration in the growth of knowledge. Following Geoffrey Hinton's suggestion in his Nobel Prize remarks, "AI will enable us to create highly intelligent and knowledgeable assistants who will increase productivity in almost all industries."

However, it is not yet today that humanoid researchers orchestrate several b^n digital scientists for a flurry or new discoveries. We can turn to chess for a relevant analogy. Even after "Deep Blue" defeated Gary Kasparov, the greatest "chess player" in the world was not in fact a computer program. For the next ten or fifteen years, the best chess was played by humans working in tandem with computers, each leveraging its own advantages. We might anticipate similar progress in fields such as photonics: leveraging cutting-edge computational tools while providing our own human advantages ("understanding," "intuition," etc.) may yield the greatest return. At least for a few years.

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Section 2.1 – Multidimensional Structuring of Light and Matter

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Status

Advances in photonics have shown that light is not limited to three-dimensional space. Instead, it possesses a multidimensional nature in which space, time, and frequency are closely connected and should be considered together [1]. In particular, early studies of vector beams and those carrying orbital angular momentum revealed that optical fields can sustain complex spatial and polarization patterns, which later enabled the realization of other exotic topological structures such as optical skyrmions [2], Möbius strips [3], and optical knots [4]. However, beyond spatial shaping, exploring the spectral properties of light has been equally important. In particular, the frequency content of light not only carries information but also determines how optical fields propagate, interfere, and interact with matter in space and time. With the emergence of lasers, light reached intensities high enough to reveal nonlinear interactions with matter. Nonlinear interactions between structured light and matter enable applications in ultrafast optics [5], quantum optics [6], optical signal processing [7], and advanced microscopy [8]. As nonlinear optics advanced, the focus shifted to multidimensional optical structures in which the spatial, temporal, spectral, topological, and polarization properties of light are closely connected.

Current and future challenges

Optical wavefront-shaping devices, including spatial light modulators (SLMs) and digital micromirror devices, have long provided precise control over the spatial topology of optical fields through programmable phase and amplitude modulation [1]. However, their macroscopic, pixelated design and often limited optical power handling restrict resolution, speed, and robustness, making them unsuitable for regimes where light must actively reshape itself through nonlinear interactions with matter. Spectral control, in contrast, has been achieved through bulk nonlinear crystals such as periodically poled lithium niobate and potassium titanyl phosphate [9], which offer efficient frequency conversion but require long interaction lengths, stringent phase matching, and thermal stabilization. Consequently, although SLM-based systems allow flexible spatial modulation and nonlinear crystals enable efficient spectral conversion, they remain separate bulk-optics technologies. Integrating these approaches to generate and control truly multidimensional light fields remains a significant challenge.

One possible route to integrating spatial shaping and nonlinear frequency conversion on a single platform is to engineer the nonlinear interaction so that the upconverted field is produced with the desired spatial and topological characteristics. This approach, known as nonlinear holography, operates by translating an optical interference pattern into a spatial modulation of the second-order susceptibility within ferroelectric crystals such as lithium niobate and potassium titanyl phosphate. This patterned nonlinearity enables processes like second-harmonic generation to produce light fields with controlled wavefront, amplitude, and phase at new frequencies [10]. However, current implementations remain limited to one or two spatial dimensions, leading to an inherent trade-off between structural complexity and conversion efficiency. Although three-dimensional nonlinear volume holograms could, in principle, be designed to preserve phase matching while reconstructing arbitrary field distributions at new frequencies, such systems are difficult to realize and often inefficient due to their limited interaction volumes. Therefore, despite significant advances in structured light and nonlinear optics, achieving simultaneous and efficient control of spatial, temporal, and spectral degrees

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of freedom within a single compact platform remains a key challenge in the pursuit of truly multidimensional photonics.

Advances in science and technology to meet challenges

The development of photonic metamaterials and metasurfaces has opened new possibilities for controlling light at the nanoscale [11]. Composed of periodic arrays of subwavelength meta-atoms, these engineered structures provide a versatile platform for sculpting the amplitude, phase, and polarization of optical fields in space and time across both linear and nonlinear regimes. Although the subwavelength thickness of optical metasurfaces may appear unsuitable for nonlinear optics, where long interaction lengths are typically required for efficient frequency conversion, this limitation is overcome by their ability to achieve strong field localization and enhancement through optical resonances [11]. From localized Mie-like modes confined within individual meta-atoms [12] to nonlocal quasi–bound states in the continuum (QBIC) [13], these resonant modes confine light to deeply subwavelength scales, enhancing light–matter interactions and uniquely relaxing the conventional phase-matching constraints that limit bulk nonlinear processes.

In our recent work, we demonstrated that such meta-structures could generate and preserve complex three-dimensional optical topologies through the concept of topology imprinting [14], where the fundamental and third-harmonic fields share identical spatial and topological characteristics, as illustrated in Figure 1(a). To implement this concept, we designed a phase-only hologram that simultaneously controls both the amplitude and phase of the generated harmonic fields. The holographic function combines a diffraction grating and a desired phase profile (e.g., OAM or optical knot), $\varphi(x,y)$, imprinting the desired topology directly into the nonlinear response. While in conventional metasurfaces the optical response is governed only by spatial modulation of the linear susceptibility, in our case, the metasurface acts as an engineered nonlinear medium, where the effective nonlinear third-order susceptibility $\chi^{(3)}_{\text{eff}}(x,y)$ is precisely controlled through the geometry and spatial arrangement of the meta-atoms. When excited by a fundamental field $E_{FF}(x,y)$, the generated third-harmonic field can be expressed as $E_{TH} \propto \chi^{(3)}_{\text{eff}}(x,y)E^3_{FF}(x,y)$. As a result, the generated far-field third-harmonic pattern is determined by the Fourier transform of the metasurface's spatially varying nonlinear susceptibility. Essentially, the spatial distribution of meta-atoms across the surface dictates the local modulation of the effective optical susceptibility, such that the overall susceptibility can be expressed as $\chi^{(3)}_{\text{eff}}(x,y) \propto \sum_m a_m \exp\left\{im\left[\frac{2\pi(x+y)}{\Lambda} + \varphi(x,y)\right]\right\}$, where a_m is the m-th Fourier amplitude determined by the local field enhancement due to the meta-atom-determined phase and amplitude modulation, and Λ denotes the grating period [14]. Therefore, the resulting TH field,

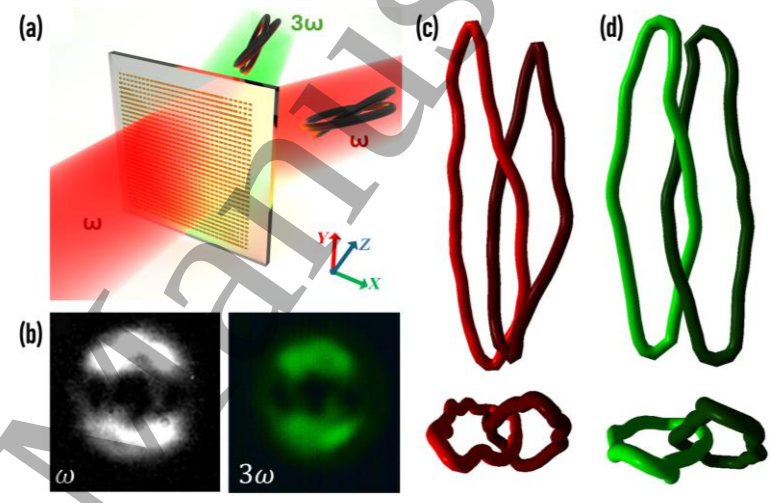


Figure 1. Concept and experimental realization of topology imprinting in nonlinear metasurfaces. (a) Schematic illustration of a metasurface engineered to spatially modulate the effective nonlinear susceptibility, enabling identical wavefronts at both fundamental and harmonic frequencies. (b) Measured intensity Hopf links near the z = 0 plane at fundamental and third harmonic waves. (c–d) Three-dimensional reconstruction of vorticity lines showing Hopf-linked topologies in the fundamental and third harmonic wavelength, respectively.

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$E_{TH} \propto E_{FF}^3(x,y)\sum_m a_m \exp\left\{im\left[\frac{2\pi(x+y)}{\Lambda}+\varphi(x,y)\right]\right\}$, consists of a superposition of multiple diffraction orders, each carrying a phase term of $m\varphi(x,y)$, and an intensity proportional to $|a_m|^2$. The diffraction grating can be optimized to maximize the amplitude of the field in the desired diffraction order. To demonstrate this concept, we applied the topology-imprinting approach to both two- and three-dimensional light topologies, such as OAM beams and Hopf links. Figure 1(b) shows the measured intensity distributions of the generated beam near the $z = 0$ plane, at both fundamental and TH wavelengths. To reconstruct the complete three-dimensional topology, we recorded interference patterns across fifty axial planes at different propagation distances. By tracing the phase singularities within these slices, we reconstructed the continuous singularity lines that define the topological structure of the structured light beam. The resulting three-dimensional mapping of these singularity lines reveals the formation of a Hopf-linked topology, shown in Figures 1(c) and 1(d) for the fundamental and third harmonic wavelengths, respectively. Their corresponding top views are shown at the bottom of each panel. We note that the primary objective of this work was to demonstrate the concept of topology imprinting in nonlinear metasurfaces rather than to optimize nonlinear conversion efficiency. Therefore, in the present design, the metasurface was not engineered as a high-quality factor resonant structure capable of simultaneously providing full 2π phase coverage and strong local field enhancement. As a result, the local field intensity inside each meta-atom remains relatively low, and therefore high nonlinear conversion efficiency was not expected to be the primary performance metric in our study. Nevertheless, to provide a reference for the generated signals, we evaluated the relative conversion efficiency between different diffraction orders of the third-harmonic signal and found that the first-order TH intensity is approximately 9% of the zeroth-order TH intensity. Although the absolute conversion efficiency is low, the structured harmonic signals remain clearly detectable and sufficient to validate the topology-imprinting concept. The topology-imprinting approach, in which identical wavefronts emerge simultaneously at the fundamental and harmonic frequencies, is poised to integrate structured matter and structured light within a compact, multidimensional photonic platform. With these developments, extending the topology-imprinting approach to include the temporal and polarization domains is a natural next step, combining spatial, temporal, and polarization control to achieve multidimensional manipulation of light in integrated photonic platforms.

Concluding remarks

In conclusion, the convergence of structured matter and multidimensional structured light represents a significant step toward realizing multidimensional photonics. In the context of topology-imprinting metasurfaces, the concept of 5D photonics can be understood in terms of simultaneously engineered and coupled degrees of freedom in the light–matter interaction. In our platform, these five degrees of freedom are: (i) the spatial distribution of the optical field, (ii) its topological structure, (iii) the spectral degree of freedom associated with nonlinear frequency conversion, (iv) the transverse momentum defined by diffraction orders, and (v) the spatially engineered nonlinear susceptibility of the metasurface. The generated harmonic field is determined by the interplay of these coupled parameters. The metasurface therefore performs a multidimensional transformation in which spatial, topological, spectral, momentum, and material degrees of freedom are intrinsically linked within a single device. In this perspective, topology imprinting does not simply represent spatial wavefront shaping at a new frequency, but rather a multidimensional structuring process in which both light and the nonlinear material response are co-designed. This simultaneous control over multiple coupled degrees of freedom provides a concrete physical implementation of higher-dimensional photonics and illustrates how metasurfaces can operate as platforms for multidimensional light-matter interactions beyond the conventional four-dimensional framework of space and time. Although the proposed topology-imprinting concept has so far been implemented using a static metasurface, several realistic pathways exist toward reconfigurable implementations. Since the generated harmonic field is governed by the spatial distribution of the effective nonlinear susceptibility and the local optical response of the meta-atoms, dynamic control can be achieved by actively modifying these quantities at the meta-atom level, thereby enabling real-time control over the imprinted topology of the harmonic field.

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One approach involves incorporating tunable materials whose refractive index can be modified by external stimuli, such as phase-change materials, carrier-injection semiconductors, electro-optic materials, and two-dimensional materials [15],[16]. This enables dynamic tuning of the local resonant response and control over the amplitude and phase of the generated harmonic field. A second approach involves mechanically reconfigurable or MEMS-actuated metasurfaces, where adjusting the relative position or spacing of meta-atoms modifies the nonlinear holographic response and reconfigures the topology and diffraction pattern of the generated harmonic field [17]. A third approach is based on spatiotemporal modulation, where the metasurface response is modulated in time using electrical or optical control signals, enabling real-time control over harmonic generation and topology switching [18]. These approaches would transform topology-imprinting metasurfaces from static nonlinear holograms into dynamically reconfigurable platforms in which multiple coupled degrees of freedom including spatial, spectral, momentum, material, and temporal can be actively controlled, providing a pathway toward adaptive and multidimensional photonic systems. Additionally, it is noteworthy that existing designs rely on local Mie-type resonances, which, while enabling wavefront manipulation, inherently suffer from low harmonic conversion efficiency [12]. To overcome this limitation, we recently proposed a hybrid approach that combines the Pancharatnam–Berry phase with nonlocal QBICs, integrating broadband phase control with strong field confinement to realize efficient nonlinear holography [19]. Incorporating this approach with topology imprinting could enable high-performance platforms capable of generating structured light with high efficiency across a broad frequency range. With these recent advances, the emerging field of spatiotemporal light structuring, encompassing skyrmionic and other topological field states, is poised to transform our understanding of light–matter interactions and redefine the field of structured light and its applications for the next-generation photonic technologies.

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Section 2.2 – Nonlinear frequency conversion of structured light

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Status

Following the Franken and his colleagues' groundbreaking experiment on second harmonic generation in 1961 [1], the nonlinear optics quickly became a widely used tool in many fields of science and technology. Though its methods are currently used in many applications, such as microscopy and spectroscopy, communications and computing, etc., [2] the nonlinear optical phenomena are most widely used for the nonlinear frequency conversion and the development of new sources of coherent radiation in the frequency ranges where the direct laser sources are unavailable. Thus, the second and third harmonic generation, sum and difference frequency mixing, stimulated Raman scattering, supercontinuum and parametric light generation among other processes, can cover virtually all spectral ranges including the visible, far infrared, terahertz (THz), vacuum ultraviolet (VUV), and even X-ray frequencies [2-4]. However, apart from the intuitive requirement that the materials used for the nonlinear frequency conversion be transparent to the pump and generated radiations, the efficiency of any nonlinear process is additionally restricted by phase-matching conditions requiring that the velocity of the pump wave(s) or driving polarization be equal to the phase velocity of the newly generated radiation. Initially, birefringent phase matching was used for perpendicular polarizations of the pump and generated waves, which allows to tune the refractive indices (and velocities) of the involved waves by properly orienting the nonlinear crystal [4]. Together with the transparency requirement of the materials, this phase-matching strongly reduces the available materials and spectral ranges for efficient frequency conversion. To overcome this problem, quasi-phase matching (QPM) was soon proposed. In this method, nonlinear materials can be engineered (periodically poled) so that, during propagation, the relative phase between the pump and generated waves shifts periodically to ensure maximum generation efficiency [4, 5]. Although this method is more universal, the available materials are basically limited to ferroelectrics, where simple and efficient periodic poling is possible. Note that in contrast to the Gaussian beams typically used in nonlinear optics, the structured light has many more freely tunable parameters. Thus, it is more flexible and can be used in a wide variety of nonlinear optical applications, including Bessel beam-pumped second harmonic generation, parametric light generation, stimulated Raman scattering, and four-wave mixing. The spatial parameters (i.e., angular spectrum pattern shape) of the emitted radiation can be modified and controlled by varying the cone angle of the Bessel beam, as demonstrated in references [6-10]. Additionally, it is worth mentioning the generation of terahertz radiation by optical rectification using tilted pulse fronts, which has become a well-established technique for the efficient THz radiation generation [11]. Thus, in comparison to regular pump pulses, the use of the tilted front ones allows to increase the THz generation efficiency in the same materials by several orders [12].

Current and future challenges

Note that the use of structured light for nonlinear frequency conversion has generally been quite limited because, in most previous experiments, structured beams had to be produced using inflexible optical elements such as axicons, axicon-lens combinations, phase plates or photographically produced holograms.

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However, the situation has changed dramatically over the last decade with the rapid development of spatial light modulators (SLMs) [13], which are essentially two-dimensional planar devices capable of controlling beam intensity, polarization, phase or a few of these parameters at the same time [14-16]. Therefore, SLMs have become powerful and simple tools for creating complex and flexible structured light beams. Specifically, a variety of Bessel and Airy beams, which are important in nonlinear optics, can be easily produced using a computer-controlled SLM [16-18]. Thus, it was recently demonstrated that the generation efficiency of THz radiation in air increased by more than fivefold using abruptly autofocusing Airy beams [18]. It is worth noting that the increase in generation efficiency in this experiment was primarily the result of modifying the nonlinear medium, specifically by adjusting the length and density of the laser-created air plasma. In another experiment [19], the spectral control of supercontinuum generation by an Airy beam pump in a highly nonlinear optical fiber was observed. However, most of the successful frequency conversion experiments with structured light pump beams were demonstrated during THz radiation generation, while the other spectral ranges were left unexplored. This can be explained by the fact that THz radiation generation is a specific phenomenon, where due to longer wavelengths of generated radiation the modification of the pump beams with SLMs is easier and more advantageous than in the case of visible or UV radiation generation. Nevertheless, the flexibility of structural light suggests that in principle structural light beams can help to solve the problem of phase matching for virtually any nonlinear process by engineering the light phase along the optical axis in proper way. However, in many cases of nonlinear frequency conversion, it is necessary for the intensity of the light to be as high as possible, in addition to the required phase dependence. Matching these two requirements is not simple, though a few sophisticated methods have been proposed to solve this problem [13-15]. This may be the main reason why universal nonlinear frequency converters based on SLM-created structural light beams suitable for arbitrarily chosen nonlinear media and spectral ranges have not yet been demonstrated or proposed.

Advances in science and technology to meet challenges

Apparently, two approaches could be used to overcome the phase-matching problem using SLMs. The first method involves artificially creating an intense, structured beam in which the velocity of the light along the optical axis is equal to the speed of the generated light. In principle, this is possible [13], but it is not a trivial task, since in most cases nonlinear optical applications require maintaining high light intensity along the entire length of the intended interaction, in addition to the engineered light speed. However, note that phase matching in normally dispersive media requires subluminal pump speeds, while in most cases the simple structured beams (e.g., Bessel and Bessel-Gaussian beams) have superluminal light velocities [20]. On the other hand, Bessel-like beams seem to be the most promising candidates since they can possess a prolonged central high-intensity region (see Fig. 1) where the light velocity can be easily variable [17, 20].

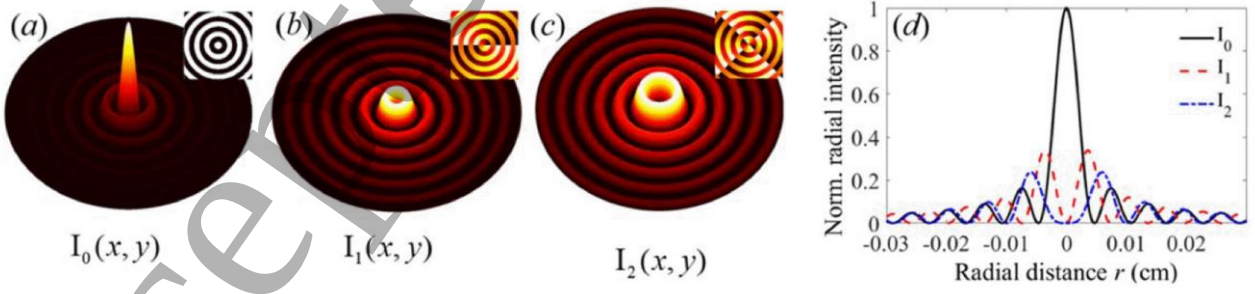


Figure 1. The intensity distribution in the transverse cross-section of the ideal Bessel beam: (a) 0th order, (b) 1st order, and (c) 2nd order Bessel beams. The transverse phase distributions are shown in the insets. (d) Line profile of Bessel beams (intensities are normalized with the peak intensity of 0th order Bessel beam). Reprinted from [17].

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The second approach is analogous to quasi-phase matching in crystals. It involves periodically alternating phase of the pump beam along the optical axis to ensure optimal phase relations between the pump and generated waves. However, this approach faces serious challenges because the spatial period of periodically poled nonlinear materials is typically a few micrometers. Thus, the light phase must be modulated with the same periodicity. Though SLMs currently offer high spatial modulation efficiency with micrometer resolutions (with a pitch of less than 4 μm [21]), the straightforward approach of transmitting directly the transverse beam phase modulation to the longitudinal one could hardly be possible. Therefore, more sophisticated methods must be proposed to solve this problem. In addition, it is well-known that in the case of QPM with the small poling period (of the order of a few micrometers) imperfections of created structures could strongly reduce the efficiency of the frequency conversion [5]. Thus, to ensure the efficient light generation with structured light beams, the phase jumps should be as steep as possible.

As an alternative, a simplified option would be to modulate the light intensity or polarization from maximum to zero with the same periodicity instead of phase modulation. This approach could also result in some quasi-phase matched frequency conversion, though with lower efficiency than with periodic phase alternation. However, the requirement for steep light intensity and/or polarization modulation should still be considered, which could again be a difficult task.

Concluding remarks

The rapid development of SLMs has opened new perspectives for the flexible and complete control of the spatial and polarization degrees of freedom on light, which has enabled the creation of structured light beams suitable for nonlinear optical frequency conversion. However, achieving high conversion efficiency generally requires these beams to possess a few distinctive features, such as a prolonged high-intensity region with a tailored phase dependence or a modified light speed along the optical axis. This remains a complex and challenging problem that requires further technological progress and theoretical analysis. This could explain why structured light beams are not yet widely used for nonlinear optical applications. However, implementing such techniques could significantly impact nonlinear optics and many related fields of science and industry. Note that, depending on the nonlinear process, the use of structured light instead of regular Gaussian beams for nonlinear frequency conversion apart from enhancing generation efficiency could provide improved, well-controlled other parameters of the generated light, such as an extended wavelength tuning range, divergence and other spatial, spectral and even temporal characteristics of the emissions. Note that at the moment the most feasible approach seems to be the use of Bessel-like beams for the difference frequency generation in nonresonant gases, such as air, where due to the low media dispersion coherence lengths of the nonlinear processes usually are quite large [22].

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Section 2.3 – Edge bound states in the continuum for on-chip applications

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Status

In the last decade, research on photonic bound state in the continuum (BIC), an optical mode having very high-quality factor (Q-factor), has been flourishing [1,2]. A BIC is a highly confined trapped mode, and it exists in a nanostructured host medium at a certain special point of leaky spectral region of dispersion above the light line. It experiences low radiation loss without leakage due to the suppression of radiative modes by destructive interference in the system [1], as illustrated in figure 1(a). As a result, a BIC exhibits a theoretically infinite Q-factor, in the case of an ideal structure with no absorption or scattering loss.

BIC modes have been observed in various nanostructured systems including gratings [3,4], metasurfaces [5-9] and photonic crystals (PhCs) [1,10,11]. In the case of PhCs there are two types of BICs: symmetry-protected and accidental. A symmetry-protected BIC is supported at the Γ point of the dispersion diagram with no parallel wavevector component in the lattice plane. Accidental BICs, which are also known as Fredrich-Wintgen BICs [1], propagate in the structure with a finite parallel wavevector component. In the case of a real system with a finite number of periodic elements, surface roughness due to fabrication imperfection, and material loss, the ideal BIC cannot be obtained thus the real-world mode is generally called quasi-BIC. In this case the Q-factor can be quite large, but not infinite. High Q-factors and tightly confined electric fields of the BIC modes trapped in the structure are attractive for boosting the light-matter interaction. Therefore, BIC modes have been studied for numerous potential applications, such as lasing [5], enhancement of light emission [9], wavelength conversion by nonlinear optical process [8], light signal modulation [10], and biochemical sensing [4-6] (figure 1(d)-1(f)).

Most of the BIC modes are excited by off-plane incident light in the free-space configuration. The optical response is also detected in transmission or reflection in the off-plane geometry, as illustrated in figure 1(b). Meanwhile, the majority of the BIC modes propagate in plane. In order to take advantage of high Q-factor BIC modes for on-chip applications, it is desirable to excite BIC modes in the plane of the photonic crystal lattice via waveguides and extract the outcome, for instance, a switched, modulated, or emitted optical signal, by waveguides for further processing directly on chip (figure 1(c)).

Current and future challenges

A photonic crystal is a periodic arrangement of dielectric or metallic elements (the equivalent of atoms in a real crystal), whose unit cell size is typically smaller than the wavelength of light. PhCs exhibit a photonic bandgap, a wavelength region where the propagation of light is prohibited.

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It is known that a truncated photonic crystal supports a surface wave or an edge state that exists below the light line and is able to propagate without leakage [12]. Such surface waves are Bloch surface-localized eigenstates, discrete states supported at the edge of periodic structures. By modifying the geometry of the terminating row, this edge state becomes an edge propagating BIC mode above the light line. Although predicted more than a decade ago [13,14], it is only recently that this unique type of BIC was observed [15]. This edge bound state in the continuum, *edge BIC* for short, propagates in the vicinity of the terminating dielectric pillars with intense electric field concentration around the pillars and a high Q-factor (figure 2). This distinguishes edge BIC modes from other types of bulk BIC that are supported in the middle of nanostructures, such as photonic crystals, gratings, and metasurfaces.

The observed edge BIC was supported on a silicon pillar photonic crystals fabricated on a silicon-on-insulator (SOI) wafer with a footprint of 20 μm by 10 μm. In this case, there were extra difficulties due to the presence of a silica substrate. Indeed, the substrate induced a supplementary leakage loss channel leading to extremely low transmittivity of the resonance wavelength. We minimised this loss by using a double pillar, where the top part was the Si of the photonic crystal while the bottom was made of silica. Moreover, experimental Q-factors were moderate (~400) due to the imperfection of Si pillars resulting in scattering loss, and due to the finite length of the photonic crystal. This contrasts to large Q-factors (1,000 – 1,000,000) of experimentally observed BIC modes for telecom wavelengths excited from free space with normal or close to normal incidence [16].

Edge BIC showed a potential for biosensing reacting on the presence of dielectric nanocoating (1-5 nm), by a clearly detectable shift of resonance wavelength. This edge BIC mode is sensitive to minute changes of the dielectric environment, therefore it may have on-chip applications in switching or modulation of optical telecommunication signal [17], since such minute changes can be induced by optical pumps with low fluence. Its high Q-factor and tight confinment makes the edge BIC a potential tool for any application where slight changes in the environment need measuring, including for example, Raman spectroscopy but also more fundamental studies on light-matter interaction.

Advances in science and technology to meet challenges

In order to adopt edge BIC modes for on-chip applications, we need to address several challenges, both in design and nanofabrication of the structures: (1) design alternative 2DPhC platforms, (2) minimise the nanofabrication imperfections to reduce scattering loss, (3) integrate photonic circuits elements supporting edge BICs on-chip.

(1) The Q-factor scales with the number of periods [18]. However, a larger number of periods increases the radiation loss through the substrate and scattering loss due to imperfect fabrication. The right compromise between the high Q-factor and radiation loss depends on specific application and design.

Suppression of leakage from the substrate is a critical issue [15] that can be mitigated by using a free-standing membrane-based 2DPhC composed of holes array in a dielectric slab. This type of structure is a common design of 2DPhCs [1,11]. However, edge BICs have not yet been predicted for air hole array 2DPhC. Designing an edge BIC on this type of 2DPhC will allow obtaining a membrane structure, thus eliminating the need for a substrate and, as such a major loss channel. These membrane-type photonic crystals have been developed for various functionalities, such as laser, filters, waveguides [19] and would be attractive alternative design for PICs.

(2) From the nanofabrication aspect, there are two main directions where advances are required. On one side, the etching of the structures is important such that to minimise the sidewall roughness and reduce the

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scattering loss. As well, the control of the sidewall angle is necessary to control the resonance quality. From the lithography part, a more accurate and precise control of the structure dimensions is paramount to obtain the resonance at the correct wavelength. These improvements can be obtained by, for example, using specific masks during etching and optimising the lithography process parameters.

(3) Apart from the edge BIC, other types of BIC modes can be observed on an SOI platform. Coupling a quasi-transverse electric mode of a Si slab waveguide with a quasi-transverse magnetic mode of a ridge waveguide generates BIC modes [20]. Therefore, there is a rich variety of possible BIC modes (edge and conventional) to be used in integrated photonic circuitry. BICs can be supported by ridge waveguides, 2DPhCs and other elements of photonic circuits. The bottleneck is the effective universal coupling solutions of different types of modes.

Concluding remarks

BIC modes have been studied intensively in last decade thanks to the prospect of getting limitless high Q-factors. A photonic platform could include BICs modes for enhancing light-matter interactions. The BIC solutions typically belong to modes confined in the guiding layers. However, any photonic element has an edge. These terminations of the photonic integrated circuits so far are mostly ignored. In this roadmap, we discuss another high Q propagating modes - edge BICs supported on truncated 2DPhCs and terminations of other structures. The edge BIC can be excited by conventional ridge waveguides in the plane of the substrate, making them accessable for on-chip applications. The presence of surface modes residing on the side walls of photonic elements might increase the nomenclature of solutions used either in photonic circuitry or in sensing. There exist technical challenges to realize photonic crystal structures supporting edge propagating BICs and integrate them with other circuit elements. We expect that development of nanofabrication processes and suitable design of nanostructures for Si or III-V semiconductor-based platform can bring edge BIC directly to potential applications.

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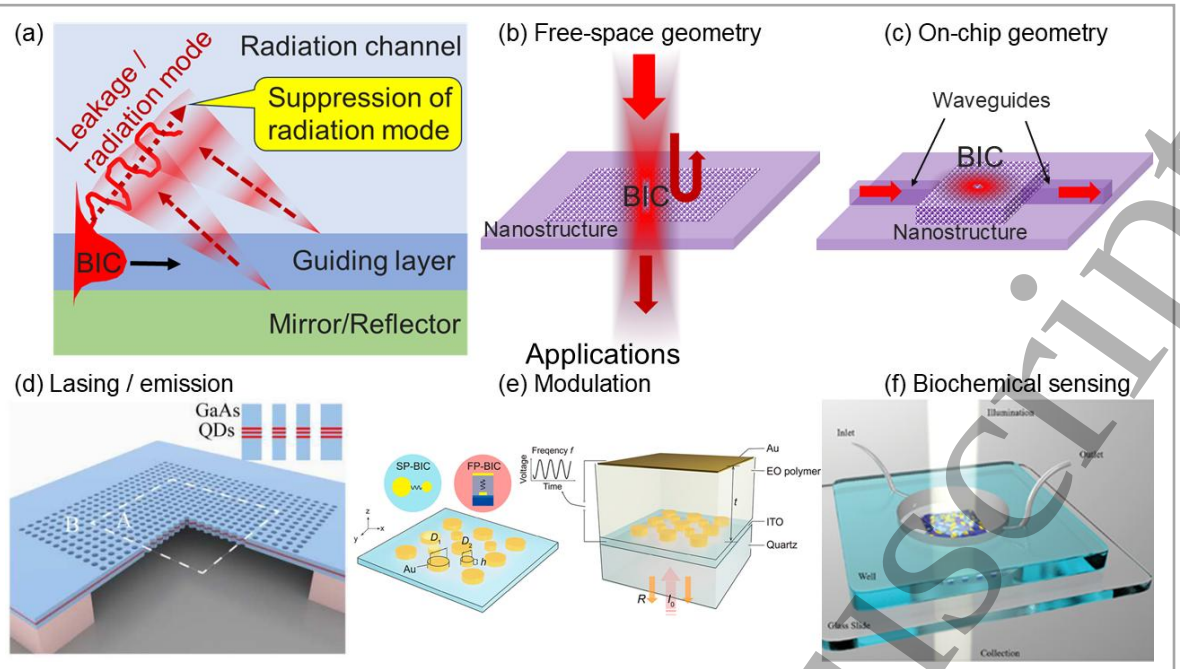


Figure 1. (a) Conceptual illustration of photonic bound states in the continuum in (b) free-space (out-of plane) and (c) on-chip (in-plane) geometries. Applications of BICs in free-space system for (d) lasers and emitters whose emission by optical pump is enhanced by intense electric fields of BIC mode (adapted from [5]. CC BY.), (e) modulation of optical signal in reflection by applied voltage between Au reflector and ITO film (adapted from [10]. Copyright © 2022 American Chemical Society.) and (f) biochemical sensing by detecting the spectral shift of BIC resonance induced by the local change of refractive index due to the presence of biomarkers (adapted from [6]. CC BY 4.0.).

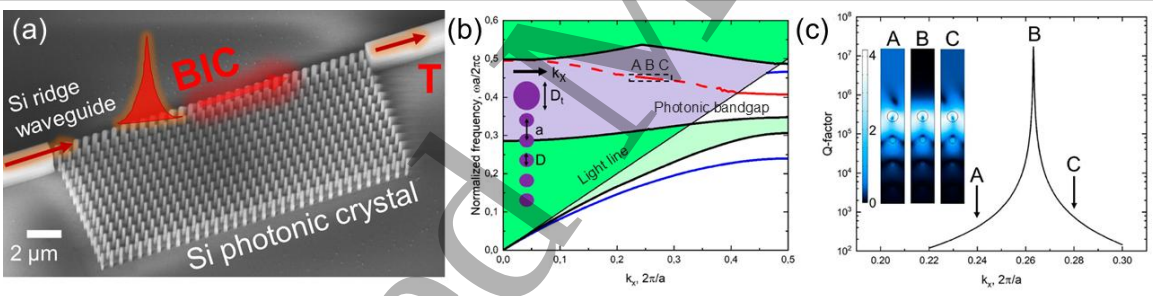


Figure 2. (a) Scanning electron microscope (SEM) image of Si pillar PhC and ridge waveguides. (b) Simulated dispersion for the PhC with the terminating row of pillars with diameter D_t = 270 nm in air with the light line. The dashed red line shows the dispersion of the leaky mode with edge BIC. The inset shows the unit cell of the truncated photonic crystal with the pillar diameters of terminating row D_t and the rest of photonic crystal D, respectively and the lattice constant a, as well as the wavevector k_x. (c) Simulated quality factor of the leaky surface waves at point A, B, and C along the dashed red line inside of black dashed box in (b). The inset shows the electric field profile of propagating mode (electric field parallel to Si pillars) around the terminating raw of Si pillar photonic crystal. Adapted from [15]. CC BY-NC-ND 4.0.

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Section 2.4 – Nonlinear photonics with multiple degrees of freedoms – Smart and multidimensional control

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Status

Properly defining 5D photonics remains a difficult task, as the term appears across many research areas, each tied to specific optical concepts. While a universal framework is still lacking, 5D photonics can be broadly regarded as light–matter interactions expanded into a higher-dimensional space, exploiting multiple degrees of freedom. In practice, whether specific descriptions of light in terms of e.g. polarization, beam orbital angular momentum (in free space optics), or beam modal decomposition (in guided photonics), a simple and widely applicable view considers 3D spatial properties combined with spectral features, and temporal dynamics. This standpoint, that we adopt here, is intrinsic to many photonic platforms, from fiber systems to integrated photonic circuits, and underpins applications ranging from ultrafast laser processing and nonlinear optics to hyperspectral imaging and quantum information.

Historically, nonlinear optics has always been multidimensional, with early demonstrations reported in bulk crystals and multimode fibers [1]. Yet, the need for physical insight and improved light confinement progressively favored the use of single-mode waveguides, where lower dimensionality drastically simplifies modeling. In most linear photonic systems, spatial, spectral, and temporal components are approximately separable, enabling analytical descriptions and efficient simulations. Nonlinear interactions, however, fundamentally alter this ideal representation: previously independent degrees of freedom become coupled, producing fully multidimensional dynamics in which spatial, spectral and temporal components evolve conjointly.

For instance, in ultrafast guided pulse propagation, the recent advent of ultrashort laser pulses prevents a simple and low dimensionality description: temporal pulse evolution cannot be decoupled from nonlinear spectral broadening. While these phenomena have been extensively studied over the years in numerous scenarios [2], extending them to a higher dimensionality introduces additional complexity, but also unlocks new physical regimes and dynamics [3].

A clear example is the resurgence of multimode fibers (MMFs), where nonlinear intermodal interactions give rise to rich spatiotemporal behavior |4]. Phenomena such as multicolor nonlinear spiral-shaped beams (see Fig. 1), spatiotemporal solitons, multimode instabilities, frequency–space coupling and nonlinear energy transfer between modes illustrate how light propagation becomes effectively 5D, with sophisticated coherent 2D spatial structures, featuring large spectro-temporal deformations across different polarization states, emerging from the interplay of all these degrees of freedom.

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However, fully harnessing this potential requires suitable multidimensional characterization and processing tools to channel the inherent complexity of 5D photonic architectures. Below, we discuss several challenges in advanced multidimensional wavepacket control, and specific approaches we are currently investigating.

Current and future challenges

Recent advances in ultrafast sources, multimode waveguides, spatio-temporal modulation, as well as spectral–temporal and polarization shaping are progressively pushing photonics into inherently (5D) multidimensional regimes. This trend aligns with the rapid expansion of tools that enable high-resolution access to, and control of, multiple degrees of freedom, ideally adjustable simultaneously. In this view, we have recently worked at the forefront of several key aspects targeting both the control and the characterization of these different degrees of freedom:

In the spatial domain, we demonstrated controllable self-organization in MMFs, tuning modal population and polarization dependent nonlinear spatial reshaping by adjusting initial conditions [5]. Through power adjustment, selective nonlinear coherent focusing and coherent spiraling in crystals can also be leveraged [6-7] (see Fig. 1b-c). These approaches can further exploit multi-wavelength pumping for multidimensional spatial reshaping and can be harnessed for advanced nonlinear microscopy, illustrating the inherent connection between different degrees of freedom in multidimensional wave propagation [7-8].

In single-mode waveguides, multi-wavelength pumping with suitable pulse synchronization provides a high degree of reconfigurability in the phenomena underlying nonlinear spectral broadening [9]. Alternatively, coherent optical seeding, obtained through selective spectral tailoring of ultrashort pulses, can be used to control otherwise spectral broadening [10-11].

Beyond standard telecom approaches (e.g. waveshapers, electro-optic modulators), we also reported the use of programmable photonic integrated circuits (PICs) for tailoring temporal wavepacket properties. Used as on-chip reconfigurable delay lines, such PICs enable advanced and scalable temporal pulse patterns on flexible timescales, from femtosecond to nanosecond domains. This approach, somewhat analogous to a synthetic temporal dimension, was demonstrated for autonomous picosecond pulse shaping [12], high-dimensional quantum-key distribution [13], and reconfigurable spectral broadening [14-16].

Altogether, these recent examples from our group illustrate the diversity of mechanisms now available to regulate 5D dynamics across multiple regimes and architectures. They enable structured light fields, multimode propagation, and high-dimensional optical transformations to be controlled with high precision. However, this multidimensional coupling introduces major challenges. Nonlinear simulations quickly become computationally prohibitive as the parameter space scales with dimensionality, while nonlinear effects can induce sensitive dynamics that hinder both practical optimization and experimental stability [2,4,11].

As applications become more demanding, existing tools remain useful, but are not designed for fully integrated multidimensional control. A seamless continuum is still needed between active control, accurate characterization, and real-time adjustment of the underlying dynamics. Machine-learning strategies are key to exploring and exploiting complexity [17-18], yet they require suitable control schemes and advanced multidimensional diagnostics to operate effectively.

Advances in science and technology to meet challenges

Progress in 5D photonics relies on the convergence of multidimensional shaping techniques, advanced monitoring tools, and suitable control strategies. These developments offer unprecedented flexibility in

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preparing and manipulating complex wavepackets, yet they also make control fundamentally more demanding. The resulting complexity naturally motivates the integration of machine learning (ML) and AI approaches [17], which provide scalable means to explore high-dimensional parameter spaces, identify optimal operating points, and stabilize sensitive nonlinear dynamics [18].

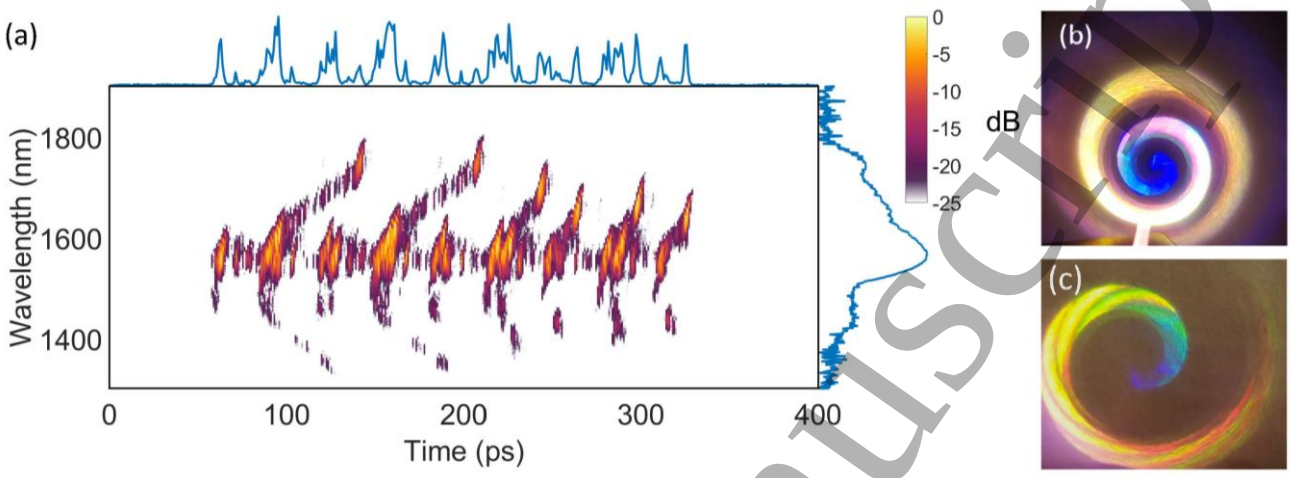


Figure 1. (a) Experimental spectrogram of a tailored supercontinuum generated in a nonlinear fiber. The spectrogram is recorded using asynchronous nonlinear sampling based on an X-FROG (cross-correlated frequency-resolved optical gating) measurement via sum-frequency generation. Reconfigurable input temporal patterns (analogous to a synthetic temporal dimension) enable multiple and complex interactions during nonlinear propagation, illustrating indirect spectro-temporal coupling. The X-FROG provides a temporal resolution of 922 fs, achieved through asynchronous sampling (acquisition time: 10 s). (b) Nonlinear multicolor spiral beam induced by a self-focusing solitary wave in a cubic crystal. (c) Coherent superposition of two nonlinear spiral beams created by the same laser source, and involving 5D (2D spatial, spectral, temporal, polarization state).

However, AI-driven optimization imposes its own constraints. ML strategies require large, high-quality datasets, and fast repeated measurements of the full multidimensional state of light. Techniques such as spatially resolved spectral interferometry, time-stretch dispersive Fourier transform, multimode frequency-resolved optical gating, and ultrafast tomographic reconstruction are becoming essential [19]. These diagnostics must simultaneously capture the spatial distribution, modal content, spectral features, and temporal evolution of complex fields. Yet, they also require probing and exploring the (input) parameter space sufficiently well for AI architectures to extract relevant information that conditions such multidimensional wavepacket dynamics. Notably, sampling the parameter space scales with the power of the dimensions involved, and can clearly become extremely time-consuming when dealing with 5D photonics: efficient and fast diagnostic tools are therefore required.

Asynchronous X-FROG (Fig. 1a), exemplifies this class of tools. In the version we recently developed, it enables spectro-temporal wavepacket characterization with sub-picosecond resolution and refresh rates approaching the Hertz regime [16]. Such capabilities can feed online optimization loops, reinforcement-learning, and the acquisition of large datasets for training neural networks or other predictive models (i.e. typically several thousands of reconfigurable wavepackets acquired in a matter of few hours). As

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dimensionality increases, monitoring becomes as critical as shaping. Fully exploiting 5D wavepacket control requires diagnostic frameworks that resolve all relevant observables preferably within a single measurement architecture. Traditional characterization tools face inherent trade-offs between resolution, refresh rate, and sensitivity, which limit their suitability for real-time or AI-driven optimization. Importantly, systems such as X-FROG can incorporate spatially resolved measurements via spatial-division multiplexing or scanning, yet fully probing all dimensions remains inherently time-consuming. In multidimensional systems, the optical energy is distributed across many degrees of freedom, thus reducing the signal available per observable. This places stringent demands on detection sensitivity and noise performance, which are particularly critical for ML-based optimization methods, and must therefore iterate rapidly and reliably.

Concluding remarks

Looking ahead, next-generation 5D photonics will require characterization tools able to capture weak, incoherent, and non-repetitive signals fluctuating across multiple degrees of freedom [20]. In parallel, advances in structuring propagation media beyond conventional multimode-fiber shaping are in position to be transformative. Longitudinally and transversally engineered, active, or programmable single mode/multimode waveguides, enabled for instance by tailored rare-earth doping or liquid/gas-filled fibers, will unlock new avenues for controlling complex fields. Such engineered platforms will enhance applications like advanced imaging while positioning 5D photonics as a foundation for emerging optical-computing paradigms. Together, multidimensional shaping of several type of nonlinear materials, fast and energy-efficient monitoring, multiple (synthetic) scales, nonlocality and multiphysics processes, as well as AI-driven optimization define a natural pathway for unlocking the full potential of 5D photonics. The convergence of major advances in artificial intelligence, ultrafast metrology, and complex-systems science, each distinguished by recent Nobel Prizes in Physics, highlights the opportunities currently opening. As these technological developments mature, 5D photonics will likely become a merging platform where complexity is not a challenge, but rather a powerful resource for improved performance and advanced functionalities.

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Section 2.5 – Spatiotemporal Dynamics in Metasurfaces Intended for Lasing Systems

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Status

Remarkable advances in fabrication methods have sparked widespread interest in nano- and microstructures, engaging a broad spectrum of scientific disciplines. These developments have led to the emergence of numerous exciting concepts and promising technologies across diverse fields such as information technology, energy, high-density data storage, life sciences, and security. In the realms of plasmonics and photonics, research has progressed beyond passive optical components like mirrors and lenses, toward the development of optically active systems. These include ultrafast optical switches with high on/off contrast [1], dynamically reconfigurable nanoantennas [2], and nanolasers [3]. Innovations such as 5D photonics, which harness spatial, spectral, and polarization degrees of freedom for optical property modulation, are further pushing the boundaries of modern technologies. Such dynamic structures become possible by integrating nanostructures with materials whose properties can be dynamically modulated, enabling enhanced nonlinear optical effects with ultrafast response times [4, 5].

In particular, complex laser systems possess numerous spatial degrees of freedom and display diverse and rich behaviours. In recent years, laser systems built on the principle of hybridization of optically active inclusions (quantum dots) and ensembles of particles (nanostructures) have been of considerable interest since they are promising for designing of nanoscale systems with specified characteristics [6,7]. Such hybrid structures serve as a basis for the subwavelength coherent sources of plasmons (spasers [8]) and photons (nanolasers [9]). This is possible because correctly ordered systems of metallic or dielectric nanoparticles allows one to realize the necessary degree of localization of the electromagnetic field and its spatial distribution (such systems are typically considered in the framework of the theory of metamaterials and metasurfaces). The field localization is provided by electromagnetic coupling between the particles forming the arrays resulting in appearance of the ultra-narrowband resonances in the spectra which are highly desirable for achieving coherence in laser systems. These resonances are often associated with the structural asymmetry of the building blocks of the structure, providing access to trapped (dark) modes [10, 11] (the term 'trapped mode' is traditionally used in describing electromagnetic modes which are weakly coupled to free space [12]; in recent years, these modes are often referred to bound states in the continuum, BICs [13]). A vast majority of the theoretical models of such structures describe only their stationary states. On the other hand, lasers operate in transient regimes, which require special consideration. Therefore, establishing

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control over both spatial and transient processes (spatiotemporal dynamics) in optically active structures is of paramount importance.

Current and future challenges

Limitations in single-particle nanolasers and spasers stem largely from their intrinsic design, particularly their dependence on a single feedback mechanism, which restricts the resonator's quality factor and overall performance. This design constraint leads to challenges such as high radiative losses, limited directionality, and reduced emission efficiency. To overcome these shortcomings, researchers have investigated arrays of plasmonic or dielectric resonators and proposed the use of metasurfaces [10], which are engineered, periodic arrays of subwavelength resonators (see, Fig. 1a). These structures enable strong near-field interactions between individual elements, leading to the formation of collective coherent modes [14, 15] that enhance light confinement and feedback. A key advancement in metasurface design involves introducing spatial asymmetry into unit cells, which allows the system to support trapped modes. These modes significantly improve the resonant behaviour by reducing radiative losses and enabling sharper spectral features. Furthermore, the strong near-field localization associated with trapped modes increases the overlap between the electromagnetic field and the gain medium, thereby boosting modal gain and energy conversion efficiency. As a result, metasurface lasers operating in trapped-mode regimes are expected to exhibit lower thresholds, narrower linewidths, and improved directionality compared to conventional resonators.

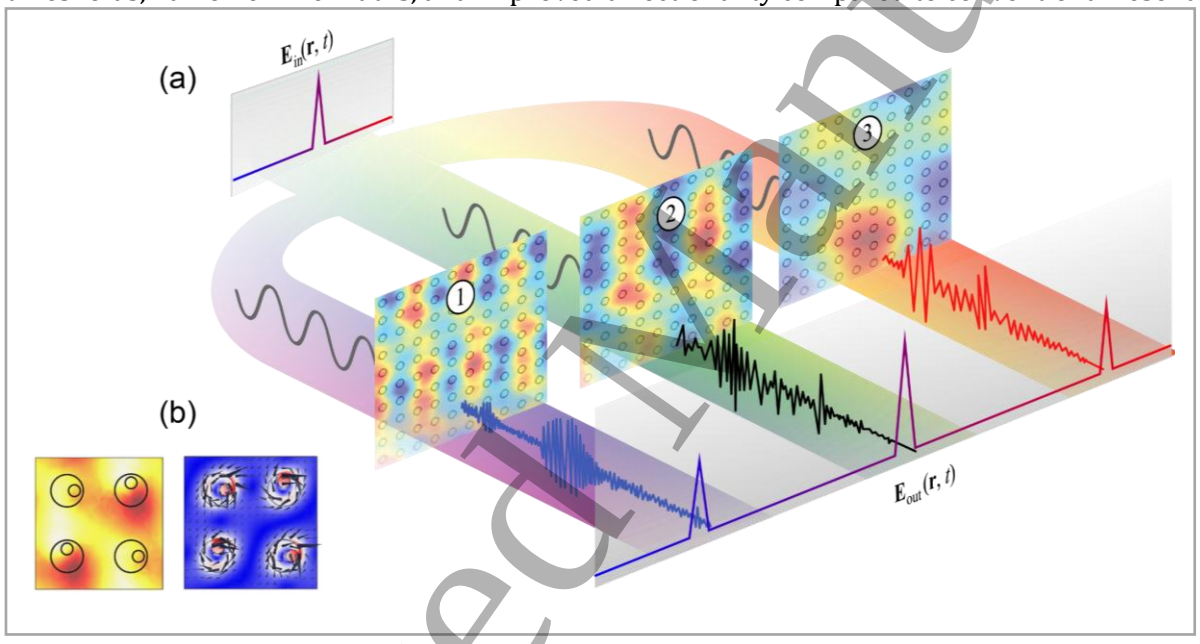


Figure 1. (a) Schematic of the spatiotemporal pulse generator, with a dielectric metasurface covered by an inhomogeneous optically active (QDs) superstrate. Superstrate characteristics (e.g., degree of inhomogeneity and gain) may change over time as shown in panels 1–3. (b) Magnitude distribution and vector flow of the electric field of the trapped mode in a unit cell of a cluster-based metasurface.

Dynamic control over the resonance spectrum is especially important for tailoring and manipulating light propagation at the nanoscale. Active nanophotonic devices, capable of tuning their optical response in real time, are considered vital for the integration of optical and electronic components on a single chip. In particular, devices that can produce coherent light pulses at ultra-high repetition rates are of great interest. However, the implementation of such systems based on plasmonics is hindered by strong optical losses in metals, especially at visible and near-infrared frequencies. To mitigate this, researchers have proposed combining low-loss dielectric resonators with optical gain media, such as dye molecules [16], to achieve loss compensation, signal amplification, and light generation.

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Nevertheless, there is a notable difference between plasmonic and dielectric systems that lies in field localization behavior. In plasmonic structures, the electric field is concentrated outside the particle, enhancing interaction with the gain medium. Dielectric structures, by contrast, confine the field internally. Fortunately, cluster-based dielectric metasurfaces can be engineered to resolve this issue and produce external 'hot spots' [17], enabling dielectric analogs of spasers with improved energy efficiency and field accessibility (see, Fig. 1b).

Theoretical modeling of such advanced lasing systems demands a hybrid approach, blending classical electromagnetic theory with quantum optics. While steady-state models like rate equations are useful, they often fail to capture transient dynamics, which are critical for pulsed or fast-switching applications. Systems featuring loss compensation and parity-time (PT) symmetry require rigorous analysis, particularly under non-steady-state conditions [18]. Therefore, there is a need in an electromagnetic framework for the designing lasing systems composed of resonant dielectric metasurfaces with optically active inclusions as well as studying their non-steady-state operation conditions.

Advances in science and technology to meet challenges

A comprehensive understanding of light interaction with linear and nonlinear two-dimensional periodic structures, which comprise both active and passive elements, requires not only frequency-domain analysis but also advanced time-domain modelling. Pulsed excitation of such structures demands time-resolved algorithms capable of capturing transient dynamics, especially for systems supporting trapped modes in low-loss, nonlinear dielectric metasurfaces. These metasurfaces provide a powerful platform for enhanced light–matter interaction and ultrafast optical control.

Key scientific challenges include:

(i) Frequency-domain studies of local field distributions in varying geometries, exploring the dependence of field enhancement on inter-element spacing and excitation frequency. This includes optimizing shapes and materials to maximize *Q*-factors, enhance field confinement, and understand luminescence and gain mechanisms.

(ii) Time-domain analysis of nonlinear metasurfaces operating near trapped-mode resonances, focusing on threshold nonlinearity coefficients for optimal response and the emergence of spatial or temporal instabilities.

Modelling such complex, open optical systems is computationally demanding. While finite-difference time-domain (FDTD) methods [19] are widely used for their simplicity, they often require significant resources to minimize boundary-related artifacts. Analytical methods [20], though insightful, are limited to idealized geometries and lack flexibility for realistic designs. A rigorous time-resolved description of active metasurfaces requires the Maxwell-Bloch formalism [21], as simplified rate-equation models fail to capture coherent light-matter interaction, phase dynamics, and ultrafast transient processes. The Maxwell-Bloch system self-consistently describes the evolution of the electromagnetic field, medium polarization, and population inversion, enabling accurate modelling of pulse formation, gain saturation, and mode competition in nanolaser systems. This approach combines Maxwell's equations for electromagnetic wave propagation with Bloch equations describing quantum dynamics in active media such as atoms, molecules, or quantum dots (QDs). Unlike simplified rate-equation models that assume steady-state behaviour, the Maxwell–Bloch framework captures ultrafast dynamics, gain saturation, mode competition, and coherent pulse formation. It is especially effective for simulating nanoscale lasers, spasers, VCSELs, and similar systems where quantum coherence and field localization are critical.

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The Maxwell-Bloch equations form a nonlinear and coupled system, with feedback between the light field and the quantum system. Nonlinearity arises from the dependence of the medium's polarization on the electric field via the Bloch dynamics. This model can be generalized to include multiple energy levels, inhomogeneous broadening, spatial effects (full 3D Maxwell's equations), carrier dynamics (e.g., in semiconductors), and gain and saturation (e.g., in lasers or spasers). By using this formalism, one can design nanostructures of increasing complexity from canonical geometries to arbitrary shapes, arranged individually or as periodic arrays. This enables the identification of high-Q metasurfaces capable of strong field localization via coupling between resonators, resulting in ultra-narrowband resonances which are essential for coherent light generation.

In the context of 5D photonics, the governing Maxwell-Bloch equations do not imply an actual increase in dimensionality. Rather, the term refers to the simultaneous control of multiple degrees of freedom of light (spatial, spectral, polarization, temporal, and phase) within a unified physical platform. Accordingly, the Maxwell-Bloch framework remains three-dimensional in space, while being extended to account for vectorial fields, multimode interactions, and time-dependent material responses, thereby enabling access to these additional functional dimensions.

Ultimately, controlling both spatial and transient processes through spatiotemporal dynamics in nonlinear metasurfaces opens a pathway to novel, actively tuneable light sources. These systems will be central to future advances in ultrafast photonics, 5D data encoding, and integrated quantum technologies.

Concluding remarks

The overarching goal is to develop and experimentally validate a novel modeling approach for spasers and nanolasers. The aim is to advance understanding of lasing dynamics, stability, saturation, and intermode interactions using hybrid, time-domain methods. These combine efficient linear techniques adapted to include time-varying media with nonlinear density matrix formalisms. Periodically arranged, optically coupled nanoresonators are of particular interest due to their ability to produce exceptional reflection, transmission, emission, and near-field enhancement. We call for a focus on the study of the transient dynamics of nanolasers, especially those generating stimulated emission via trapped modes with strong near-field localization. While wave propagation in infinite arrays of passive nanoresonators is well studied, the behavior of active structures remains insufficiently explored. A key objective is to investigate how propagating light pulses can be coherently transformed into stationary excitations retained within the structure through dynamic modulation. We also propose to explore how periodic nanoresonator arrays embedded in time-varying media can manipulate light with subwavelength precision. This will support advanced functionalities such as 5D photonics, where spatial, spectral, polarization, temporal, and phase degrees of freedom are harnessed for ultrahigh-density information processing and storage while pushing control well beyond the diffraction limit.

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Section 3.1 – Femtosecond-scale strong-field metallization in nanostructures and related applications

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Status

In the recent decades, advances in the laser optics provided sub-10-femtosecond pulses with sufficient intensity to rapidly transfer the electrons in dielectric to the conduction zone[1]. This can result in a drastic transition of the dielectric function from positive to negative values (so-called metallization[2]) and corresponding rapid growth of the conductivity. This time-domain transition leads to creation and modification of the plasmonic resonances of the nanostructrures[3] in the frequency domain. As a phenomenon which manifests itself both in time and frequency domain, it contributes to 5D plasmonics effects which are intrinsic for nanoparticles and nanostructures. The phenomena which are related to this dynamics encompass both matter modification (such as formation of laser-induced periodic surface structures[4]) and light modification (such as pulse compression[5] and short pulse emission [6] and are therefore highly relevant for the contemporary plasmonics, photonic and signal processing[7,8].

Among the effects and techniques which can lead to the change of the conduction zone population and/or to the metallization, we mention, on one hand, electronic (directly transferring electrons to a nanoparticle[9]) approaches and, on the other hand, strong-field-induced population of the conduction zone which can be virtual[2] or real[1,2,10], as illustrated in Fig. 1(a). While the former group of techniques is characterized by long response times, the latter one happens on the scale of a few femtoseconds.

As a result of the abovementioned dynamics, the conductivity of the nanoparticle grows dramatically, often accompanied by the drop of dielectric function from positive to negative values, as shown schematically in Fig. 1(b). This leads to qualitative femtosecond-scale change of the electromagnetic properties of the material. The most relevant of these changes include the appearance[11] and shift[6] of the plasmonics resonance, arising possibility of the surface-localized[12] and bulk-localized[13] excitation of plasmonic resonances, as well as a change of the reflectance of the nanostructure. The latter effect can manifest itself as an oscillating mirror[14] as well as the recently predicted motion of the mirror in the multiplayer Bragg structure[5], as illustrated in Fig. 1(c).

Current and future challenges

Despite a wide range of applications as depicted in Fig. 1(d) which include pulse compression, material modification[4], high-harmonic emission, and short pulse emission, the field of femtosecond-scale strong-field modification of nanostructure dielectric function meets challenges associated with both practical issues of damage and search for the suitable materials as well as shortcomings of the available theoretical-numerical approaches. Especially in the regime of multi-pulse excitation, optical damage of the sample is

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often the limiting factor which forces the use of low-repetition-rate or even single-shot setups. Simultaneously, the systematic numerical investigations are hindered by the fact that the available methods are either quite simplistic (such as simple analytical ionization rates and semiclassical models for the electron motion) or require prohibiting numerical efforts (such as time-dependent density-function theory or even time-dependent Schrödinger equation [15] approaches).

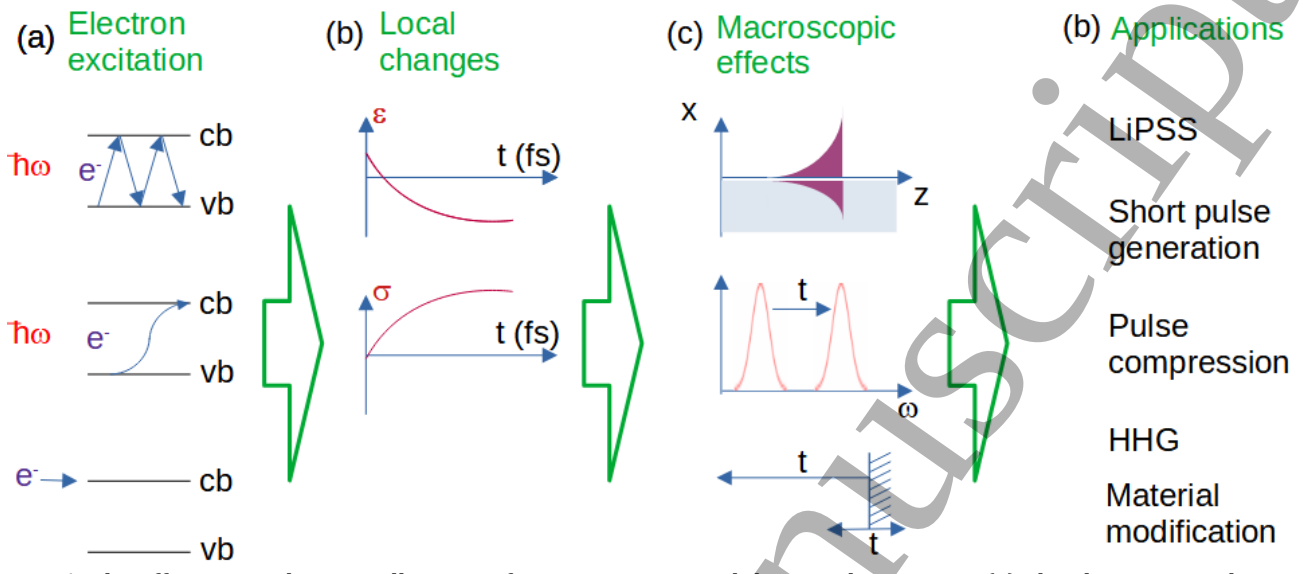


Figure 1. The effects providing metallization of nanostructures and their applications. In (a), the electron population of the conduction band is provided by (from top to bottom) virtual transitions to the conduction band, strong-pulse photoexcitation, and direct electron transfer. In (b) the transition of the dielectric function from positive (dielectric) to negative (metal) values is illustrated (from top to bottom), associated with significant increase of the conductivity. In (c), the related physical effects are depicted: (from top to bottom) formation of surface plasmons, creating and shift of the plasmonic resonances, as well as motion and oscillations of plasma mirrors. In (d), the relevant application areas are listed.

Advances in science and technology to meet challenges

To advance the field, it would be of key importance to search for the materials[16] which have large damage thresholds by composition optimization and material strcturing[17,18] while having a potential of significant modification of the dielectric function and/or conductivity. Simultaneously, the designs and geometries which facilitate fast heat evacuation can be favorable. From the point of view of the simulations, numerical approaches which are both accurate and time-efficient need to be developed. This can include e.g. refinement of the ionization models [19] which utilize a limited number of parameters which characterize the ionizing pulse and medium to calculate the ionization rate or optimized formulations of the TDDFT [10] which still produce semi-qunatitative accuracy sufficient for the practical calculations. While TDDFT is more accurate than analytical models, it will be important to find a middle way providing both reliable and fast simulation, which might also include e.g. TDSE with reduced dimensionality.

Concluding remarks

Femtosecond-scale strong-field metallization of nanostructures is a rapidly evolving field which encompasses various areas of optics and physics in general. Up to now, the interconnection of the research efforts and their synergy remains underdeveloped. Beyond the above-described technological and numerical challenges, growth of interdisciplinary research is therefore of particular importance. It has a potential to uncover novel investigation techniques and numerical-theoretical approaches and further advance the fascinating field of nanostructure metallization.

Acknowledgements

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Section 3.2 – Laser-plasma terahertz sources: Intensity as 5th dimension

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Status

Terahertz (THz) science has surged in importance in recent decades, due to its transformative potential across many fields, including molecular spectroscopy, condensed matter physics, medical imaging, security and cultural heritage [1,2]. THz radiation, which refers to electromagnetic pulses in the $0.1-100$ THz frequency range (with oscillation timescales from tens of femtoseconds to tens of picoseconds), uniquely interacts with matter: it excites free carriers, optical phonons and molecular transitions, and can penetrate several millimeters into nonconductive materials. However, strong attenuation by water limits its atmospheric and long-range applications, driving the need for intense THz sources.

Strong THz fields operating close to the GV/m range are also needed for emerging applications such as particle acceleration [3], ultrafast phase transitions in solids [2], atom probe tomography [4], THz-induced electron field emission [5], or selective catalysis in chemical reactions [6]. Some cutting-edge research even anticipates fields exceeding 10 GV/m, which could enable unprecedented control over charged particles and structural properties of matter [7].

Most existing THz sources rely on spectral down-conversion through nonlinear optical processes. For example, optical rectification of femtosecond laser pulses in anisotropic crystals [8] can generate mJ-level THz energies and field amplitudes larger than 0.1 GV/m. Yet this technique is limited by narrow spectral bandwidths and laser-induced damage to solid-state emitters.

Laser-plasma interactions offer a compelling alternative for producing intense, broadband THz radiation. Key mechanisms in gases include, among others [5], plasma-induced photocurrents [9] and ponderomotively driven plasma wakefields [10], the occurrence and amplitude of which depend critically on the laser intensity (I_L) – a defining parameter than can be considered the 5th dimension of the system. I_L is basically the time-averaged norm of the Poynting vector, common to both conventional nonlinear optics and plasma physics.

At moderate intensities ($10^{13}-10^{14}$ W/cm^2), photoionization events in gases created by two-color optical pulses with asymmetric temporal profiles occur at instants of stepwise increase in the electron density coupled with nonzero values of the laser vector potential [9]. This results, for near-infrared pump pulses, in residual low-frequency electron currents, which in turn emit broadband THz fields (> 30 THz) with ~ 0.1 GV/m amplitudes and μJ-level pulse energies, but with relatively low ($\sim 10^{-4}$) conversion efficiency.

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At higher intensities ($10^{15} - 10^{17}$ W/cm^2), the Lorentz force exerted by the laser field pushes plasma electrons, generating longitudinal wakefields that oscillate at the electron plasma frequency – falling within the THz range [10]. These wakefields can reach $1 - 10$ GV/m amplitudes, but they remain mostly confined within the plasma [see Figs. 1(a,b)]. To achieve remote, high-field (>1 GV/m) THz emission, researchers are now turning to relativistic processes driven by ultrahigh-intensity (UHI, $> 10^{18}$ W/cm^2) lasers, which promise to unlock new possibilities in THz science and technology.

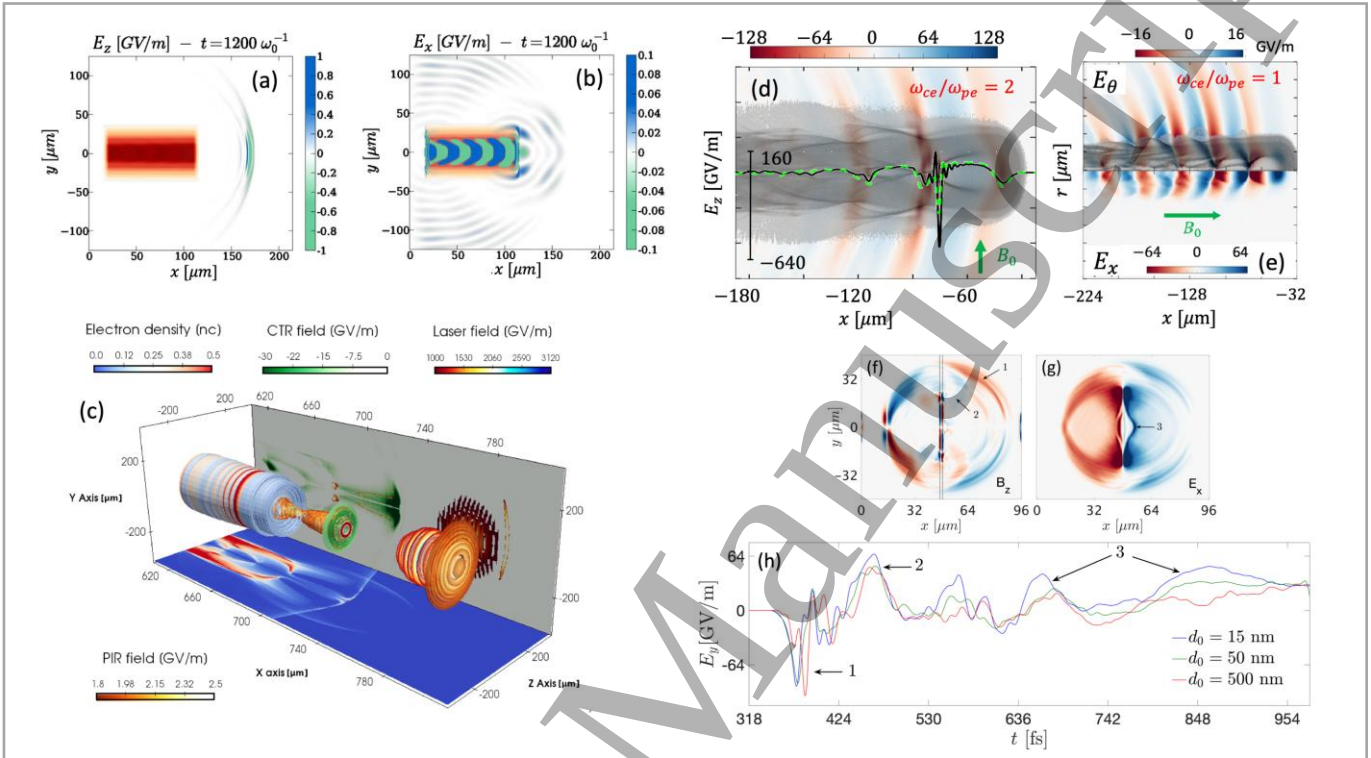


Figure 1. (a) Transverse and (b) longitudinal field components generated inside an argon plasma channel and transmitted into vacuum, using a moderately intense (5×10^{16} W/cm^2), two-color Gaussian pulse with 35 fs duration and 20 μm diameter simulated with the particle-in-cell CALDER code ($\omega_0^{-1} = 0.53$ fs) [10]. The photocurrent-induced THz field, polarized along the laser field's direction (E_z), maintains an amplitude close to the GV/m level outside the plasma, whereas the longitudinal field (E_x) rapidly decays. The emitted spectrum extends to 90 THz. Stronger THz emissions require alternative mechanisms in the UHI range: (c) Radially polarized THz field (green lobe, 160 μJ energy) produced by coherent transition radiation (CTR) following ionization of a helium gas target by a two-color 2.2×10^{19} W/cm^2 pump pulse [11]. The orange lobe shows the photocurrent-induced THz radiation (PIR, 1.3 μJ energy). Accelerating plasma cavities are visualized in the $x - z$ plane. (d,e) THz fields from a helium plasma created by a single-color pulse at the same intensity, with an applied magnetic field of (d) 572 T and (e) 286 T, respectively orthogonal [19] and parallel [20] to the wakefield direction. Plasma electron density profiles are shown as gray areas. (f) Transverse and (g) longitudinal THz electric fields from the interaction of a 1.4×10^{20} W/cm^2 , 30 fs laser pulse with a thin (500 nm) CH_2 foil [14]. (h) THz waveforms recorded at a probe point outside the plasma for varying target thicknesses; waveform features (1, 2, 3) are discussed in the text.

Current and future challenges

The UHI regime is characterized by laser-driven electrons oscillating at relativistic energies, which occurs when $I_L \lambda_L^2 \geq 10^{18}$ Wμm^2/cm^2, with λ_L being the laser wavelength. The laser fields are then strong enough to accelerate – directly or indirectly via induced plasma waves – electron beams to energies ranging from a few

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MeV to a few GeV, depending on whether the target is solid or gaseous. This relativistic acceleration leads to the generation of unprecedented THz pulse energies (exceeding 10s of mJ) over compact spatiotemporal scales. In this regime, the primary THz conversion mechanism is coherent transition radiation (CTR), emitted as the fastest electrons cross the plasma-vacuum interfaces [12]. In laser-solid interactions, this mechanism is supplemented by radiation from the slower plasma expansion, which takes place over several picoseconds [13]. Additional radiative processes – e.g. antenna radiation at target edges [14] or synchrotron emission from less energetic electrons [15,16] – can further contribute to the overall THz yield.

Exploring UHI interactions demands access to facilities capable of delivering laser pulses with multi-terawatt to petawatt peak powers, $\sim 0.8-1\ \mu$m wavelengths, $\sim 10^{19-22}$ W/cm^2 intensities and ~ 20 fs $-$ 1 ps pulse durations. Such facilities are becoming increasingly widespread in academic and national laboratories worldwide, especially those producing relatively low-energy (1-10 J), ultrashort (<100 fs) pulses.

On the simulation side, understanding the collective dynamics of relativistic plasmas necessitates an *ab initio* kinetic approach. Particle-in-cell (PIC) codes are currently the most efficient tools for modeling these systems self-consistently, by combining a Lagrangian description for charged particles with an Eulerian description for electromagnetic fields. The plasma is represented as a collection of macroparticles governed by the relativistic Newton equation, where the Lorentz force is computed from the fields known at the surrounding grid nodes. Current densities resulting from particle motions are then projected onto the grid to advance the fields via Maxwell's equations.

Figure 1 illustrates PIC simulations of THz generation using the CALDER code [17] for various interaction setups. Based on a hybrid MPI/OpenMP parallelization, CALDER can run on tens of thousands of Tier-0 supercomputer cores and describe a broad range of physical processes – Coulomb collisions, field and impact ionization, emission of X-ray and gamma-ray photons, generation of electron-positron pairs, etc. Key numerical challenges include extending current 2D simulations of solid-density plasmas over picosecond timescales and, ultimately, scaling up 3D simulations to experimentally relevant spatial scales ($>100^3\ \mu$m^3). Achieving these goals will require algorithmic improvements such as enhancing the scalability of PIC codes and possibly adapting them for GPU acceleration.

Advances in science and technology to meet challenges

Recent advances in UHI lasers and PIC numerical simulations have spurred tremendous progress in THz science.

In dilute (10^{18-19}cm^{-3}) gases exposed to laser pulses shorter than, or comparable with, the plasma wavelength $\lambda_p = 2\pi c/\omega_{pe}$ (c is the light speed and ω_{pe} the electron plasma frequency), longitudinal wakefields can accelerate electrons to ultrarelativistic energies ($0.1-1$ GeV) along the ionized channel, resulting in intense THz emissions via CTR [11, 12]. For example, 3D PIC simulations of ~ 4 J, 35 fs, two-color pulses – combining a 1-μm fundamental wavelength and its second harmonic – interacting with a helium gas predict CTR-based generation of THz pulses with $15-100$ GV/m amplitude and energies up to ~ 10 mJ depending on the gas density – far exceeding the μJ emission from photocurrents [Fig. 1(c)].

Recent research has explored magnetized gas plasmas, where electron plasma (ω_{pe}) and cyclotron (ω_{ce}) frequencies are comparable and both lie in the THz domain. For $\sim 10^{18}$cm^{-3} electron densities, this condition requires an external magnetic field exceeding 100 T, at the limit of state-of-the-art pulsed magnet technology [18]. When this field is applied perpendicular to the laser path, the wakefield is an extraordinary mode oscillating at near ω_{pe}, with a transverse component approximately scaling as ω_{ce}/ω_{pe}. This component can

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be transmitted, and even amplified, into vacuum when $\omega_{ce}/\omega_{pe} > 1$ [19], potentially generating $>$ 100 GV/m THz fields with $\sim 10^{-3}$ conversion efficiency according to simulations [Fig. 1(d)]. Strong ($>$ 30 GV/m) THz emissions with a dominant azimuthal component are also expected from plasmas embedded in parallel, $\sim$ 500 T magnetic fields [20], see Fig. 1(e).

In solid targets, the laser pulse interacts only with a very thin ($\sim \lambda_p \ll \lambda_L$) surface plasma layer, producing moderately relativistic ($\sim 1-10$ MeV) electrons, but with high number ($> 10^{20}$ cm^{-3}) and current ($> 10^{15}$A/m^2) densities. THz emission mainly arises from the interplay of CTR from target-escaping electrons, coherent synchrotron radiation from space-charge-reflected electrons, and dipole-type radiation from the slower-expanding plasma [7,13,15,16].

Simulations disclosed additional THz mechanisms in ultrathin ($< 1\ \mu$m), finite-width (50 μm) solid foils driven by 10^{20} W/cm^2 ultrashort pulses [14]. Besides CTR [burst '1' in Figs. 1(f,h)], emissions stem from surface electron currents interacting with the target's transverse edges [burst '2' in Figs. 1(f,h)] and deformed surfaces due to ion expansion [sheath field '3' in Fig. 1(g)]. These contributions, reaching $\sim$ 80 GV/m, accumulate to form a picosecond-long THz waveform [Fig. 1(h)], with amplitude increasing as the target is made thinner.

Concluding remarks

The THz physics community has made groundbreaking progress by leveraging UHI laser-plasma interactions to produce unprecedentedly strong THz sources. Recent experiments using high-energy ($>$ 100 J), 0.7 ps laser pulses with microchannel targets have achieved record-high joule-class THz yields [7]. Meanwhile, PIC simulations suggest that even millijoule-class THz pulses can be generated with widely available, joule-class, few-femtosecond lasers, revealing multiple conversion mechanisms depending on laser parameters and target type (solid or gas). Notably, magnetized gas plasmas offer the potential to control THz polarization by adjusting the direction of the applied magnetic field [19,20].

Harnessing these high-power laser resources and advanced PIC modeling opens new avenues for high-field THz science, particularly in condensed matter physics. As shown in Table 1, laser intensity emerges as a critical parameter for optimizing laser-to-THz conversion efficiency, representing a pivotal dimension in extreme 5D photonics, promising new physics and disruptive innovations to come.

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Table 1. Conversion efficiencies and related mechanisms in laser-plasma interaction in the moderate intensity and UHI regimes. The input laser beam is assumed linearly polarized. Angular emissions are just indicative.

Laser Intensity	$\mathbf{10^{13-14}\ W/cm^2}$	$\mathbf{10^{15-17}\ W/cm^2}$	$\mathbf{10^{18-19}\ W/cm^2}$	$\mathbf{> 10^{20}\ W/cm^2}$
Conversion mechanism	Photocurrents (2C*)	Photocurrents (2C*) or magnetized wakefields (1C)	CTR or magnetized wakefields (1C)	CTR (1C)
Laser-to-THz conversion efficiency	0.01%	0.06%	$0.15 - 0.5\%$	$\sim 1\%$
Peak THz amplitude (GV/m)	0.1	1-10	15-100	80
Electron density (cm^{-3})	10^{16-17}	10^{17-18}	10^{18-19}	10^{22-24}
Angular emission	Narrow (< 5-10°)	Weak (< 45°)	Weak (< 45°)	Broad (> 45°)
THz polarization states	Linear, parallel to laser direction	Parallel to laser or orthogonal to magnetic field	Radial or orthogonal to magnetic field	Radial

[a] 2C = two-color pump, 1C = single-color pump.

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Section 3.3 – 5D+ Multiscale Modelling of High-Harmonic Generation in Gases

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Status

High harmonic generation (HHG) in gases is a well-established tabletop source of coherent extreme ultraviolet (XUV) radiation, which is used in various research domains [1,2]. The fundamental microscopic mechanism is explained by the so-called three-step model [3]: (1) an intense laser ionises an atom, (2) the freed electron is accelerated by the laser field and (3) can recombine with the parent ion, releasing the excess energy as XUV photons as depicted in Fig. 1. A quantitative description requires solving the time-dependent Schrödinger equation (TDSE). Beyond this microscopic picture, the macroscopic propagation of the driving laser field must also be considered, particularly the phase matching between the infrared (IR) driving pulse and the generated harmonics, which critically determines the XUV signal strength [4]. Capturing the intricate coupling between the microscopic and macroscopic scales remains a formidable challenge, as the laser pulse undergoes substantial temporal and spatial reshaping due to nonlinear propagation effects.

Realistic modelling of HHG experiments therefore demands an accurate description of the infrared (IR) laser propagation *and* the interaction of the laser with the quantum system (atom). Because these two problems involve different scaling both in space and time, a multiscale approach is required — though at the cost of high dimensionality. A recent attempt to address this issue is the modular multiscale approach (MMA) [5], which couples the unidirectional pulse propagation equation (UPPE) [6] with the TDSE. Figure 1 shows the schematics of the MMA in its least expensive but physically meaningful configuration. The macroscopic nonlinear propagation of the driving laser is treated in cylindrical coordinates $r_\perp, z$, that is, asymmetric beam shapes are excluded, but otherwise the temporal and spatial reshaping, e.g., due to plasma effects, is fully taken into account in this 3D $(r_\perp, t, z)$ description [7]. The coupling to the microscopic system is taken as a one-way road: The time-dependent laser field obtained from the UPPE is used to solve a TDSE at each macroscopic position, however, the impact of the XUV generation on the driving laser is neglected. Moreover, only one-dimensional atoms are considered, making the microscopic problem 2D (x', t'). Thus, the complete description spans (at least) 5D. Finally, the XUV signal can be retrieved by integrating the source terms obtained from the TDSE in the whole interaction volume. Describing beams with complex polarisations or orbital angular momentum [8], IR fields in guided geometries [9], or quantum phenomena as entanglements and non-classical aspects of light [10,11] increases the dimensionality of the MMA framework.

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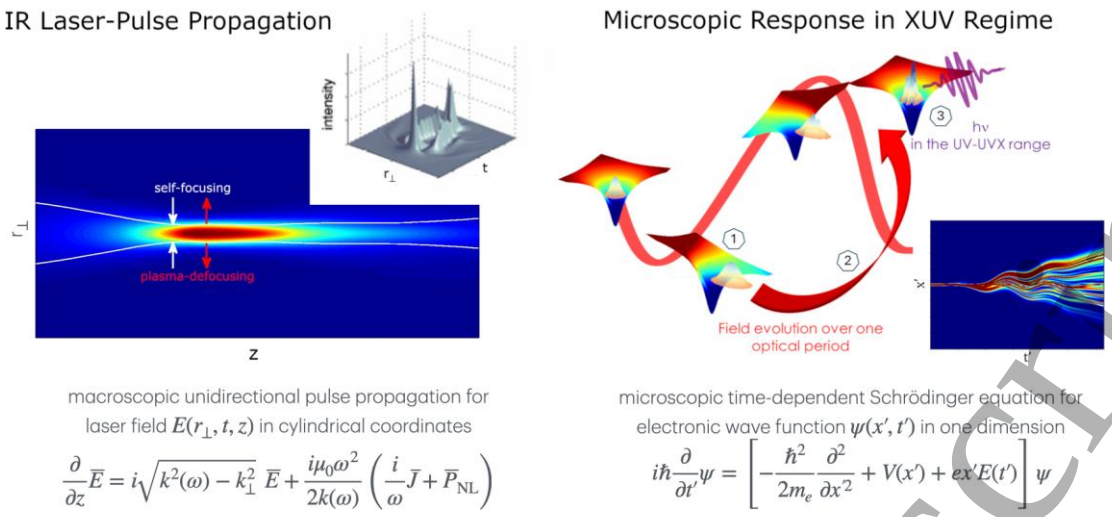


Figure 1. The Multiscale Modular Approach (MMA) for the modelling of high-harmonic generation in gases. *Left*: Macroscopic description of the IR pulse in cylindrical coordinates, yielding the laser field $E(r_\perp, t, z)$ which is strongly affected by nonlinear propagation effects such as self-focusing and plasma-defocusing, to name a few. *Right*: Microscopic quantum-mechanical description of the atomic system coupled to the laser field. The microscopic response is solved for fixed spatial macroscopic coordinates $r_\perp, z$, where the electronic wave function $\psi(x', t')$ depends on the microscopic spatial variable x' and the (much faster) microscopic time t'. Thus, the problem to solve is (at least) 5D.

Current and future challenges

The current implementation of the MMA framework is capable of predicting the HHG spectra emitted from extended gas targets and achieves agreement with the corresponding experimental measurements. MMA has been benchmarked against experimental data and the results are highly encouraging. In particular, MMA was recently used to design and test a high-harmonic generation (HHG) scheme with enhanced phase matching based on controlled pre-ionization of the gas [12]. Moreover, several ongoing collaborations with experimental teams aim to further refine the MMA model and establish it as a reliable tool for design and interpretation of experiments. However, to cover (a) a wider range of phenomena and (b) reinforce the predictive capability while keeping computational costs reasonable, several complementary challenges must be addressed. To this end, the MMA framework is modular in design, and a shared interface interconnects all modules to make the code user-friendly and exploitable also for non-experts in computational physics.

Microscopic modules extending the TDSE to 3D-atoms (or even to molecules) will target both (a) and (b), and with a vectorial IR field description in UPPE [13] it will be possible to simulate more advanced HHG setups involving, e.g., polarisation gating [14]. On the other hand, there are questions that require the execution of many simulations to investigate a large multiparametric space, e.g., when variations in the gas density profile or in the macroscopic laser spatiotemporal profile are considered. Therefore, it is also desirable to include simplified models such as the strong-field approximation (SFA) [15], or even refine the current 1D-TDSE effective potential [16]. Macroscopic modules may account for the vectorial IR field, as already mentioned, tailor beam shapes for specific applications [17], or account for guided IR propagation in, e.g., capillaries — enabling deep-ultraviolet pulse generation [9]. Finally, HHG in solids [18] could also be attainable in a further extension to cover an even wider class of strong-field phenomena. Moreover, a detailed characterisation of the XUV field within the target during the interaction is necessary to obtain full spatio-

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temporally resolved XUV fields. In particular, the spatial information contained in the XUV signal is crucial for the accurate interpretation of the experimental measurements [19].

A whole range of further challenges arises from quantum phenomena such as entanglements and non-classical states of light (e.g. squeezed or cat states). The direct approach that replaces wavefunctions by density matrices will tremendously increase the dimensionality of the problem, and similarly for composing the quantum states of light. Another challenge is the potentially very large input-parameter space, which may require the use of advanced machine-learning techniques, such as neural networks [20]. The respective modules then need to be designed to be easily interfaced for such applications.

Advances in science and technology to meet challenges

Further development of the modular multiscale approach (MMA) is essential to address the challenges outlined above. Such progress will inevitably entail a substantial increase in the dimensionality of the problem — for example, when the microscopic model is extended to three-dimensional atoms or more complex systems. In its most complete configuration, each of the three core components of the MMA is fully resolved in both space and time, yielding an overall twelve-dimensional (12D) problem. Consequently, the numerical solution of such an extended MMA becomes more and more computationally demanding. To give an example for the scaling of the computational costs, passing from cylindrical to full 3D description of the pump laser propagation increases these costs by roughly the number of discretization points in one transverse spatial dimension, i.e., typically by three orders of magnitude. However, these efforts are justified because the extended MMA framework offers exciting opportunities to explore new regimes of light–matter interaction. One promising direction involves adopting a quantum treatment of both driving infrared (IR) and emitted XUV fields [10,11], an emerging field that has attracted increasing attention for its potential to generate nonclassical light, including squeezed states. Another particularly active line of research concerns soliton dynamics in guided geometries, which can lead to deep-ultraviolet (DUV) pulse generation [9]. This area is rapidly expanding due to its ability to produce short, intense pulses in the UV–DUV spectral range. The MMA framework, with its capacity to self-consistently link microscopic and macroscopic scales, is ideally positioned to address these fundamental interplays of microscopic and macroscopic effects.

Crucially, recent advances in computing technology are transforming what is computationally feasible. Over the past three decades, the available computing power has increased exponentially — by roughly an order of magnitude every five years — turning problems once deemed intractable into solvable ones. This evolution enables the MMA to simulate complete HHG experiments with increasing realism. However, this potential can only be fully realised if numerical algorithms continue to evolve in parallel with emerging hardware architectures. In particular, graphics processing units (GPUs) — originally designed for computer graphics but now widely used in scientific computing — offer massive parallelisation capabilities that are ideally suited to the most computationally intensive task of MMA: performing tens of thousands of TDSE simulations concurrently. Since this step constitutes an *embarrassingly parallel* problem, it maps efficiently onto GPU-based architectures. Given that there are no indications of a slowdown in the exponential growth of computational resources, it is reasonable to anticipate that the modular open-source MMA framework will soon expand well beyond its current five-dimensional configuration, paving the way toward quantitatively predictive, high-dimensional simulations of strong-field and attosecond phenomena.

Concluding remarks

In conclusion, we have reviewed the current status and future prospects of the modular multiscale approach (MMA) for modelling high-harmonic generation (HHG) in gases. In its present form, the MMA is capable of predicting HHG spectra from extended gas targets with good qualitative agreement with experimental

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observations. The modular open-source MMA software suite is publicly available at https://mma-hhg.github.io, where ongoing developments and updates can be found. Looking ahead, extending the current five-dimensional configuration toward a fully resolved twelve-dimensional framework will enable a more comprehensive and quantitative description of HHG, encompassing both microscopic and macroscopic dynamics. Achieving this goal requires advances in both physical modelling and computational strategies. In particular, the remarkable growth in available computing power — driven by modern high-performance architectures such as GPUs — is a key enabling technology for the next generation of multiscale simulations.

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Section 3.4 – Extreme nonlinear optics with structured light

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Status

Extreme nonlinear optics operates at laser intensities above the ionization threshold of all materials – liquids, solids, gases, and, perhaps one day, even the vacuum itself. Its applications are numerous, spanning fields as diverse as micromachining, spectroscopy, directed energy, nuclear fusion, and fundamental science. Many of these fields benefit from techniques that cause light to deviate from its usual behavior, namely from propagating along straight paths at the speed of light. Such techniques rely on the judicious shaping of the available degrees of freedom – the spatial and temporal profile, topology, and polarization. However, the nonlinear nature of laser pulse propagation and the often complex response of the medium to intense fields make the design and implementation of tailored spatiotemporal structures challenging. Here, we describe two approaches that enable new functionalities of intense laser pulses: lightwave structures that propagate along curved trajectories and at arbitrary speeds.

Our first example involves an intense, ultrashort optical pulse with a bottle-like beam shape used to guide another laser beam along an extended curved path in ambient air. It has been shown that intense, ultrashort laser pulses propagating in air leave behind air-density perturbations with millisecond-scale lifetimes [1,2]. By pre-shaping the beam, an air waveguide can be created for another, either pulsed or continuous-wave laser beam that follows [3,4]. Air waveguides demonstrated so far have been straight. In a separate development, a beam-shaping strategy has been devised to force a laser beam to follow an arbitrary path in a linear transparent medium [5]. The generalization of this approach to doughnut-shaped beams has been demonstrated in the context of optical trapping and manipulation of microscopic particles in a liquid [6].

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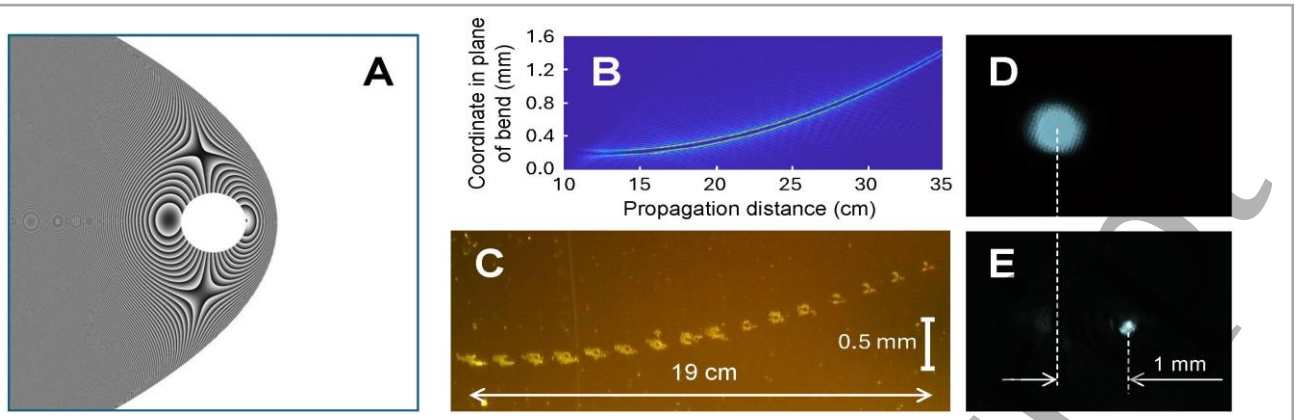


Figure 1. Phase pattern of the mask which, in combination with a 175° base-angle axicon lens, is used to generate a bottle beam following a parabolic trajectory (A). Intensity slice in the curvature plane, computed assuming linear beam propagation, i.e., neglecting air nonlinearity and ionization (B). Single-shot burns produced by the beam on a gold-coated silicon wafer along the propagation path (C). Probe-beam intensity patterns imaged at the exit of the curved air waveguide on a CCD camera with the waveguiding beam off (D) and on (E).

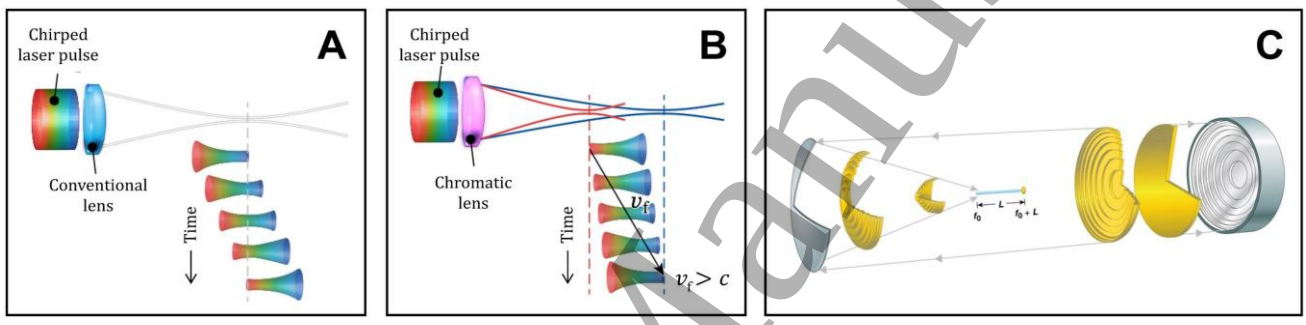


Figure 2. In conventional focusing of a chirped pulse (A), a lens brings all frequencies to the same focal point, producing a stationary focus. In flying focus (B), a chromatic lens maps different frequencies to different axial positions, creating a moving focal point. In the example shown, the focus moves superluminally. By adjusting the chirp or chromatic dispersion, the focal point can be programmed to follow arbitrary trajectories over distances far exceeding the Rayleigh range. In the "ultrashort" flying focus (C), a radially stepped echelon introduces a spatially varying group delay, while an axiparabola maps different radial segments of the beam to different longitudinal positions. This scheme enables control over the time-dependent trajectory of the focal point. (Adapted with permission from [7] © Optica Publishing Group.)

Here, we present recent results demonstrating this beam-shaping strategy with ultraintense, ultrashort laser pulses in air, enabling waveguiding along a parabolic trajectory. The results of our proof-of-principle experiment are summarized in Fig. 1. The waveguide-generating Ti:sapphire laser system emits 50-fs pulses with 30 mJ energy at a repetition rate of 10 Hz. The beam is shaped according to the method outlined in [6], producing a bottle-like ionization pattern that follows a parabolic trajectory, deviating from a straight line by approximately 1 mm over a ~20 cm propagation distance. The energy deposited into the air drives an axially imploding shockwave that reaches the center of the doughnut-shaped beam pattern approximately 50 ns after the pulse has passed. At that time, a weaker, 6-ns probe pulse at 532 nm is coupled into the generated air waveguide. The exiting probe beam is imaged on a CCD camera for analysis, revealing clear guidance along the curved trajectory, as shown in Fig. 1(D,E). Potential applications of these curved air waveguides include charged particle acceleration, remote sensing, and directed energy.

The second example of advanced spatiotemporal shaping is the so-called *flying focus*. Spatiotemporal control of laser intensity has emerged as a powerful paradigm for tailoring light–matter interactions [7]. These

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methods deliberately couple spatial and temporal degrees of freedom to create pulses with dynamic structures. The peak intensity of such pulses can move independently of the group velocity – forward, backward, or transverse to the propagation direction – at arbitrary speeds, even exceeding the speed of light in vacuum [8–10]. This flexibility enables new regimes of light–matter interaction, with potential impact on nonlinear optics [11,12], plasma-based applications [10,13], and strong-field quantum electrodynamics [14]. Representative implementations are illustrated in Fig. 2.

The first experimental realization of a flying focus employed a chromatic diffractive lens to focus a chirped laser pulse [15]. The lens maps each wavelength to a distinct longitudinal position, while the chirp sets the arrival time at that location. As a result, the intensity peak moves between the focal points of the minimum and maximum wavelengths at a constant, tunable velocity set by the chirp. More complex spectral phases can generate tailored focal trajectories. However, this *chromatic flying focus* limits the bandwidth available at each focal position, imposing a lower bound on the duration of the moving intensity peak and restricting its utility in applications that rely on ultrafast interactions.

The recently demonstrated *ultrashort flying focus* overcomes this limitation by replacing chromatic aberration with spherical and higher-order geometric aberrations [10]. In this approach, an axilens maps different annuli in the near field to distinct axial positions in the far field, while a radially stepped echelon controls their relative timing. When designed for near-luminal motion, the resulting intensity peak has a duration close to that of the initial pulse. Its main limitations are reduced tunability of the far-field transverse profile and variation of the spot size along the extended focal region due to the applied geometric aberration.

Trade-offs in the achievable pulse structures of both chromatic and ultrashort flying focus techniques have motivated the development of alternative approaches such as the *self-flying focus* and *flying focus X* that exploit optical nonlinearities in the near field and far field, respectively [15].

Current and future challenges

Two major challenges in generating and applying intense laser pulses with tailored profiles are: (i) the complexity of designing spatiotemporal structures that achieve the desired propagation in the presence of a nonlinear medium response, and (ii) limitations imposed by optical damage to beam- and pulse-shaping components. The structured beams discussed above were designed and implemented using linear analysis, assuming that the nonlinear response of the medium does not dominate pulse propagation – an assumption that may break down at ultrahigh intensities.

For the curved air waveguide, optical damage to the polymer-based, 1-inch-aperture phase mask (~10 mJ/cm^2 under multi-pulse operation) limited the pulse energy to 30 mJ, restricting the waveguiding length to ~20 cm. In the case of the chromatic flying focus, the highest demonstrated intensity to date is 3.5×10^{17} W/cm^2, limited by damage to transmissive optical elements. Recent experiments at the Laboratory for Laser Energetics at the University of Rochester employed a reflective axiparabola and a reflective radial echelon, achieving an ultrafast flying focus beam with a vacuum intensity of 1.2×10^{19} W/cm^2.

Advances in science and technology to meet challenges

Plasma optics can withstand intensities orders of magnitude higher than conventional optics, enabling spatiotemporal control of high-intensity laser pulses [16]. Because the refractive index of plasma depends on electron density and laser frequency, controlled density variations can emulate a wide range of optical elements. For example, a plasma channel can function as a chromatic lens, replacing the solid-state lens used

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in the chromatic flying focus. Plasma-based optics can mitigate optical damage limitations in conventional beam-shaping systems and offer, in principle, dynamically reconfigurable pulse shaping.

The flying focus pulses described above have found utility in a wide range of applications through a forward-design approach, where their known properties are assessed for their ability to achieve a desired outcome [10,11-14]. Adaptive optics and gradient-based machine learning enable a more versatile inverse design approach, in which the full spatiotemporal structure of a pulse is optimized for a desired outcome. This enables refinement of existing flying-focus configurations, discovery of hybrid schemes, and generation of entirely new pulse structures. The use of adaptive optics has been experimentally demonstrated in a configuration that replaces the echelon in the ultrashort flying focus with a spatial light modulator and a deformable mirror [17], while recent simulations have shown that gradient-based machine learning can identify novel spatiotemporal structures tailored to nonlinear optical and plasma-based applications [18]. Together, these methods enable rapid, automated control of the lightwave structure, expanding flying-focus functionality.

Concluding remarks

As demonstrated by the two examples above, the implementation of tailored optical waveforms with ultrahigh-intensity laser pulses enables unusual propagation dynamics with potential utility for applications. Looking ahead, control of the polarization degree of freedom offers a route to further expand the functionality of intense optical waveforms and overcome limitations of existing spatiotemporal shaping approaches [19,20]. Realizing this potential will require the development of polarization-shaping hardware capable of operating at ultrahigh intensities, enabling full control of the lightwave structure across all degrees of freedom.

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Section 4. 1 – From Hidden to Harnessed: Polarisation Dynamics in Mode-Locked Fiber Lasers

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Status:

Polarisation Dynamics Control in Mode-Locked Fiber Lasers

Mode-locked fibre lasers (MLFLs), which generate trains of ultrashort optical pulses, are key enabling platforms for applications in metrology, high-resolution spectroscopy, and optical communications [1–18]. The polarisation dynamics that underpin MLFL performance were, until recently, regarded as an uncontrolled "hidden variable." Over the past decade, however, polarisation has been reframed as a controllable degree of freedom that can be exploited to stabilise, scale, and functionalise ultrafast laser sources [1–18]. The development of rapid, high-resolution polarimetry has enabled real-time tracking of the state-of-polarisation (SOP) evolution on timescales down to individual cavity round trips. Since the SOP can remain locked or evolve over multiple temporal scales, polarisation stability has become a critical requirement for advanced applications in metrology [8,14], spectroscopy [12–15], and high-speed fibre-optic communications [12]. Beyond these, dynamic SOP control offers opportunities in areas such as optical trapping and manipulation of atoms and nanoparticles, and in photonic control of magnetisation (see Refs. in [1]). Uncontrolled SOP evolution can induce timing jitter through energy redistribution among longitudinal modes, and can trigger transitions between the fundamental soliton, multi-pulsing, soliton-molecule, and noise-like pulse regimes [1,11]. In nonlinear-polarisation-rotation (NPR)-based mode-locked lasers, slow drift in fibre birefringence can cause sudden loss of mode-locking or cyclic switching between pulse regimes unless actively stabilised [1,4,6]. For advanced applications such as optical frequency comb generation, dual-comb spectroscopy, and precision metrology, fine control of the repetition rate, centre wavelength, and comb spacing is often achieved through precise SOP management [8,13–15]. Control over SOP evolution also enables the generation of vector solitons and structured light pulses ("vector waveforms"), opening new avenues in nonlinear optics and supporting applications such as multi-channel telecommunications, quantum information processing, and ultrafast metrology [1–18]. State-of-the-art systems can now manipulate vector soliton molecules, compound pulse complexes, and bound dark–bright soliton pairs by tuning the cavity's linear and circular birefringence, anisotropy, and pump power, and through injected optical signals. Recent progress integrating AI and machine-learning-based feedback control has further enhanced active polarisation stabilisation and intelligent regime control in MLFLs [16–18].

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Current and Future Challenges:

Control Mechanisms for Polarisation Management

Polarisation control in mode-locked fibre lasers (MLFLs) encompasses a spectrum of techniques ranging from fixed passive configurations to dynamic, algorithm-driven active systems. Passive approaches include polarisation-maintaining (PM) fibre cavities, saturable-absorber-based mode locking (such as SESAMs and low-dimensional materials), and nonlinear polarisation rotation (NPR), which may operate in passive or quasi-passive regimes [1–18]. PM-fibre-based MLFL cavities remain the benchmark for achieving high polarisation extinction ratios (PER) over 20 dB, sub-100 fs relative timing jitter and strong immunity to environmental perturbations [15], making them well suited to applications such as precision metrology and optical telecommunications [8,9,15]. However, PM fibres also present challenges, including reduced nonlinear thresholds for effects such as stimulated Raman and Brillouin scattering, and a tendency to exhibit transverse mode instability (TMI) at lower powers compared to non-PM fibres. These effects can degrade PER and complicate power scaling. Semiconductor saturable absorber mirrors (SESAMs) and emerging low-dimensional materials (e.g. graphene, carbon nanotubes, black phosphorus, and transition-metal dichalcogenides) are widely used as passive mode-locking elements. These materials act as saturable absorbers and, with the help of in-cavity polarisation controllers, often offer high polarisation stability in terms of the degree of polarisation (DOP) over 90 % and broadband operation but are limited by their damage thresholds, device-to-device variability, and fabrication reproducibility [1–3,5,8,12–14].

Nonlinear polarisation rotation (NPR), arising from the optical Kerr effect, induces intensity-dependent changes in SOP in a non-PM fibre. NPR-based mode-locking enables spectral shaping and pulse-duration control [4,6–9,11], and, with the application of a polarisation-sensitive component, a 45°-tilted fibre Bragg grating (TFG), supports a high PER of 33 dB [6]. However, NPR systems are inherently sensitive to environmental drift due to fluctuating fibre birefringence and therefore require frequent manual adjustment when no adaptive stabilisation is present. While passive polarisation-control techniques provide good baseline stability and simple implementation, they cannot dynamically compensate for environmental variations or operational changes. As such, their use is most effective in tightly controlled environments or in systems with modest performance requirements.

Motivated by the need for robust, tunable, and self-healing operation, recent efforts have focused on integrating AI and machine-learning-based algorithms into active polarisation feedback systems. Reported strategies include: (i) deep Q-learning, reinforcement-learning, and human-in-the-loop optimisation for self-tuning mode-locking and rapid recovery from detuning or environmental disturbances; and (ii) physics-informed neural networks for predictive modelling and real-time optimisation of complex vector polarisation dynamics [16–18]. Although these algorithm-driven solutions offer enhanced adaptability and resilience, they introduce trade-offs in terms of speed, stability, computational overhead, and system complexity [16–18].

Advances in science and technology to meet challenges:

Polarisation dynamics control

The last years have seen intense research activity and substantive progress in both the methodology and hardware for polarisation dynamics control in MLFLs. Using advanced polarisation management within the cavity, research teams have advanced the real-time observation and AI-driven control of dissipative soliton molecule formation and dissociation, even in the normal dispersion regime. It has been made possible by the precise tuning of polarisation transmission functions, polarisation controller settings, and time-stretch dispersive Fourier transform (TS-DFT) detection, which captures the nuanced behaviours of repulsion, attraction, and transient annihilation among multicomponent solitons [1-3, 6-15]. Additionally, it has recently been demonstrated that an injected signal with a rotating state of polarisation enables the manipulation of the MLFL's output polarisation dynamics (Fig. 1 a-i). The injected signal with periodically evolving orthogonal linear states of polarisation with amplitudes E_x and E_y takes the following form [4, 5]:

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$$E_x = a \cdot cos(\Omega t + \phi_0), E_y = a \cdot sin(\Omega t + \phi_0) \cdot exp(i \cdot \Delta\varphi). \quad (1)$$

Here time is normalised to the roundtrip time, a is the amplitude of the injected signal normalised to the amplitude of the lasing signal, Ω is the frequency of oscillations normalised to the fundamental frequency of MLFL, and ϕ_0 is the initial phase, $\Delta\varphi$ is the phase difference between the orthogonal SOPs. Synchronisation of the injected optical signal shown in Eq. (1) with internal polarisation oscillations of MLFL results in the vector harmonic entrainment (VSHE), resulting in the train of ultrashort pulses modulated by a slowly varying envelope and cyclic trajectories on the Poincaré sphere (Fig.1 a, d, g and b, e, h [4]). As shown in Fig. 1c and 1f, the VSHE occurs through the overlapping and synchronisation of the low-frequency injected signal and the sidebands around the high-frequency component of the internal oscillations. With further increased amplitude of the injected signal (see Fig. 1 g, h, i), the strong coupling between high- and low-frequency components leads to frequency locking at low frequency. The obtained results can pave the way for a new generation of photonic spike processors (PSPs [19]) that explore the winnerless competition (WLC) approach [20]. The PSPs mimic the event-driven signalling of biological neurons, encoding information as discrete optical pulses ("spikes") rather than continuous voltages [19].

Recent studies have shown dual-comb fibre lasers employing PM cavities, spontaneous bidirectional mode-locking, and tunable repetition rates by adjusting cavity length for one direction while keeping the other fixed. The maximum tuning range in recent experiments has reached nearly 1 MHz, and high mutual coherence between the two combs is realised due to the polarisation-multiplexed cavity design [15]. These results open the door for next-generation self-referenced, adaptive, and highly coherent comb sources [13-15]. It is especially of interest for developing a new Mueller matrix polarimetric dual-comb approach for simultaneous measurement of the Fibre Bragg Grating (FBG) sensor's strain and torsion [13].

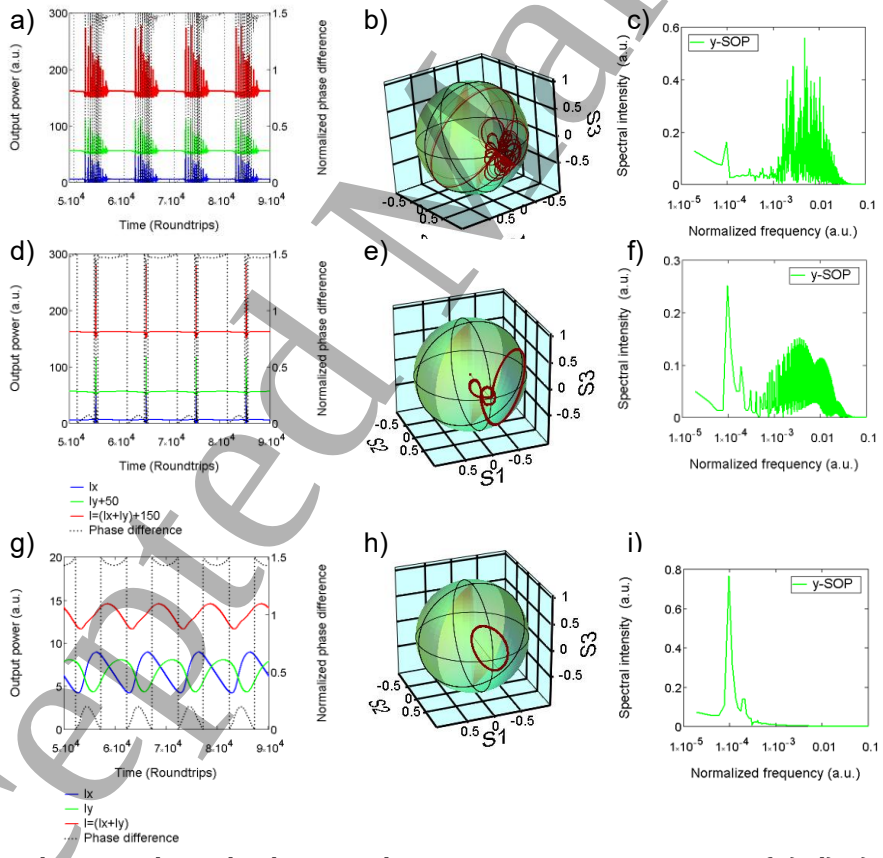


Figure 1. Polarisation dynamics driven by the vector harmonic entrainment in terms of a), d), g): powers of individual polarisation components I_x (blue) and I_y (green), the total output power I (red) and the normalised phase differences between orthogonally polarized SOPs (black dot); b), e), h): trajectories on Poincaré sphere; c) f), i) Fast Fourier transform spectrum of the y SOPs' power dynamics with frequencies normalized to the fundamental frequency (green).

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Parameters: a), b), c) a=0.19; d), e), f) a=0.25; g), h), i) a=1. The other parameters: a) - i) $\Omega = 0.00005\pi$, $\phi_0 = 0, \Delta\varphi = -\pi/4$ (Adapted from [4]).

Concluding remarks

Polarisation dynamics control in mode-locked fibre lasers is a rapidly advancing and increasingly central area of ultrafast photonics research and applications. Recent progress has shown that the convergence of high-power, scalable laser hardware, predictive and adaptive machine-learning algorithms, and high-precision diagnostics has significantly advanced polarisation control techniques, enabling exceptional pulse quality, stability, and reliability even under demanding operating conditions.

AI-driven optimisation of the injected pulse's state of polarisation (SOP) offers new opportunities to harness and manipulate the dynamic evolution of multi-pulsing waveforms—including pulse assembly, dissociation, and oscillatory (breathing) behaviours. This capability is critical for ultrafast pulse shaping and rapid waveform control and opens pathways for encoding information in non-binary formats via wavelength-to-launch-condition-driven polarisation switching processes.

Further advances in polarimetric dual-output frequency combs could enable the use of a single FBG for simultaneous measurements of strain and torsion, paving the way for cost-effective and compact shape-sensing technologies. Such developments are highly relevant for structural health monitoring across aerospace, marine, and renewable-energy infrastructure, where early-stage fault detection and real-time condition monitoring are essential for preventing catastrophic failures (see Ref. [13]).

Acknowledgements

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Section 4.2 – Nonlinear metasurfaces for near-infrared polarimetric imaging

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Status

Light is not just intensity, it is a multidimensional carrier of information. At every point in space, an electromagnetic wave has four degrees of freedom: amplitude, phase, polarization orientation, and ellipticity [1]. Among these, polarization plays a unique role in revealing material properties, biological structures, and even astronomical phenomena. The State of Polarization (SoP) describes how the electric field oscillates and is fundamental for applications ranging from remote sensing and biomedical imaging to quantum optics and astronomy [2, 3]. Moreover, adding spectral and spatial freedom will support even advanced functionalities such as 5D photonics, where spatial, spectral, polarization, and phase degrees of freedom are harnessed for ultrahigh-density information processing and storage.

To analyze SoP across extended scenes, we can resort to imaging polarimetry, which maps polarization pixel by pixel. This technique enables insights into surface geometry, texture, and optical activity. Among conventional approaches, the traditional one allows the full-polarimetric assessment through consecutive light-intensity measurements obtained by rotating optical elements [4]. The bulky nature of the required setup prevents an efficient system miniaturization. As an alternative, polarization cameras, operating within the spatial division measurement approach in linear regime, are based on a set of linear gratings integrated with the camera sensor [5]. Although the absence of moving parts, such devices are insensitive to the circular polarization component, thus preventing full polarimetry. More recently, such limitation has been only partially overcome by the integration of circular polarization filters, such as liquid crystal polymers [6], whose efficient application still needs to face limitations related to material compatibility or environmental stability.

In the last decade, metasurfaces (flat optical elements composed of nanoscale scatterers) have transformed light manipulation. They allow unprecedented control over amplitude, phase, and polarization in ultrathin devices. Metasurface-based polarimeters have demonstrated compactness and integration potential, but challenges remain: limited sensitivity to circular polarization, narrow operational bandwidth, and high fabrication costs, especially in the near-infrared (NIR) range. These limitations motivate the search for new paradigms that combine simplicity, speed, and broadband performance [7, 8, 9].

Current and future challenges

One very challanging goal is real-time, full-Stokes polarimetric imaging without moving parts or complex electronics. Existing solutions often require multiple detectors or sequential acquisitions, which hinder speed and scalability. Sensitivity to circular polarization, a key parameter for detecting chirality in biological samples or advanced materials, remains weak in most linear metasurface designs [8].

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Another challenge is integration with NIR systems, critical for medical diagnostics and fiber-optic communications. Devices must be compact, cost-effective, and compatible with large-area fabrication. Achieving this while maintaining high efficiency and low noise is nontrivial. Furthermore, as optical systems evolve toward multifunctionality, polarimeters must coexist with imaging, sensing, and even computational tasks in a single platform.

Finally, the field faces a trade-off between complexity and performance. High-end metasurfaces offer exquisite control but demand nanofabrication facilities and expensive materials. Bridging this gap requires innovative approaches that exploit also intrinsic material properties and not only intricate geometries.

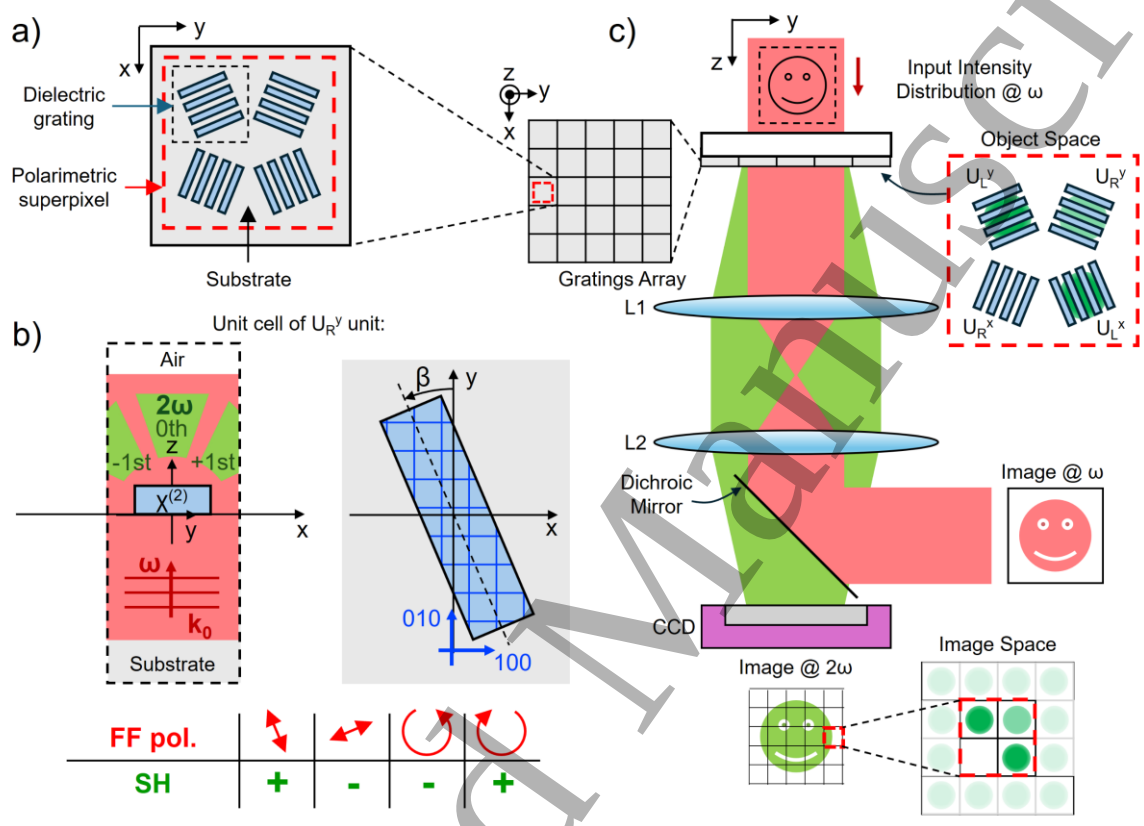


Figure 1. Visualization of the nonlinear polarimetric device. (a) Polarimetric super-pixel consists of four all-dielectric gratings. (b) Under illumination by a pump irradiation, the fundamental field generates a second harmonic signal in the layer, which is most prominent for right (or left) circular polarization (RCP or LCP) or linear input collinear to the grating grooves, and negligible for the LCP (RCP) or linear polarization orthogonal to the grooves. (c) second harmonic response from the polarimetric units arranged in an array of super-pixels is relayed by the telescope on the CCD, allowing for the imaging polarimetry.

Advances in science and technology to meet challenges

A promising route lies in nonlinear optics [10, 11], specifically second harmonic generation (SHG). When light interacts with a nonlinear medium, it can produce radiation at twice the input frequency. If this process depends on polarization, the generated signal becomes a direct fingerprint of the SoP. This concept enables polarimetry without conventional analyzers or multiple measurements [12, 13].

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Recent studies [14] show that AlGaAs gratings, rotated at specific angles (β) with respect to the crystalline lattice, exhibit strong polarization-dependent SHG, including sensitivity to circular components. By arranging four such gratings into a super-pixel, each optimized for a different polarization basis, it is possible to reconstruct all Stokes parameters from a single image capture. This design eliminates moving parts, reduces cost, and operates efficiently in the NIR.

Beyond theory, simulations confirm that these structures achieve near-unity second-harmonic circular dichroism (SH-CD) at telecom wavelengths, ensuring robust discrimination between left- and right-handed polarization. Although the geometry of the structure is optimized to exhibit near-unity SH-CD at specific wavelength, a broad operational bandwidth (~200 nm) is also achieved. Among the geometrical parameters involved in the structure, the one most subject to variation in value, due to the manufacturing procedure used, is the width of the bar. In this regard, a variation in the value of the geometrical parameter (within fabrication tolerances) determines two effects: (i) a reduction of the maximum SH-CD value and (ii) a variation of the wavelength value at which the maximum SH-CD occurs. All things considered, combined with scalable fabrication and passive operation, this approach promises fast, broadband, and compact polarimetric imaging, opening doors to 5D photonics devices, where spatial, spectral, polarization, and phase degrees of freedom are harnessed for information processing and storage.

Concluding remarks

Nonlinear metasurfaces redefine polarimetry by merging simplicity with functionality. Leveraging SHG in engineered AlGaAs structures, they enable full-Stokes imaging in a single shot, without mechanical complexity or costly detectors. This technology could revolutionize fields where polarization is a hidden but critical parameter, from detecting cancer biomarkers to enhancing machine vision and quantum communication. As research advances, nonlinear metasurfaces may become the cornerstone of next-generation optical systems, combining speed, accuracy, and integration in ways previously unimaginable.

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Section 4.3 – Maximum chirality with metaphotonics

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Status

Along the lines of this Roadmap article, among all degrees of freedom extending photonics into multidimensional spaces, helicity of light stands out as a basic intrinsic property quantifying its chirality, i.e., dissymmetry with respect to mirror reflections. Chiral forms of light, circularly polarized waves, serve as access points through which photonics encounters chirality in a much broader context as a category ubiquitous in science and life. Metaphotonic structures such as metasurfaces allow us to sense, quantify and even control chirality of diverse forms of matter.

Long ahead of the introduction of the term "chirality" [1], peculiar left-right dissymmetry of light-matter interactions attracted attention of legendary 19th century scientists [2,3]. Left and right circularly polarized (LCP and RCP, respectively) light waves appeared as tools accessing natural molecular-scale chirality. In spite of the subtleness of chiral optical effects in nature, photonic instruments have been continuously improved to tackle chirality-related problems all over the modern scientific landscape spanning from virus detection and drug design to extraterrestrial life search [4].

Artificial materials with strongly chiral electromagnetic response have evolved from upscale models built to unveil the origin of natural optical chirality (5,6) to the true backbone of future chiral optical instrumentation. As the demand for sources, detectors, filters, and sensors of chiral light is growing, photonic systems with chiral functionalities require compact chiral elements. Recent rise of worldwide interest in the design and study of chiral metasurfaces is driven by their unprecedented strong and versatile optical chirality.

Earlier approaches to the design of chiral metasurfaces were based on complex-shaped twisted, screw-like and helical metallic elements [7–10]. Recent achievements rely on meta-atoms of much easier in fabrication shapes made of high refractive index transparent materials. The key to achieve strong chirality is the use of high-quality factor (high-Q) resonances underpinned by specific photonic eigenmodes – quasi bound states in the continuum (quasi-BICs). One can maximize their optical chirality and turn a BIC into a chiral quasi-BIC isolated from waves of a particular circular polarization. Then the metasurface remains transparent to such waves and interacts resonantly with those of the opposite helicity [11,12]. Moreover, one can employ pairs of specifically aligned quasi-degenerate modes and realize maximum selective chiral mirrors made as planar photonic crystal slabs [13,14]. Since such geometry is optimal for one step lithography, it is truly remarkable that such slabs can become strongly optically chiral while remaining flat. Their environment symmetry can be broken by substrates [15] or additional layers [16], and then the quasi-degenerate states hybridize into strongly chiral pairs.

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To embrace the full variety of possible types of maximally chiral transmission and reflection by metasurfaces, we take for

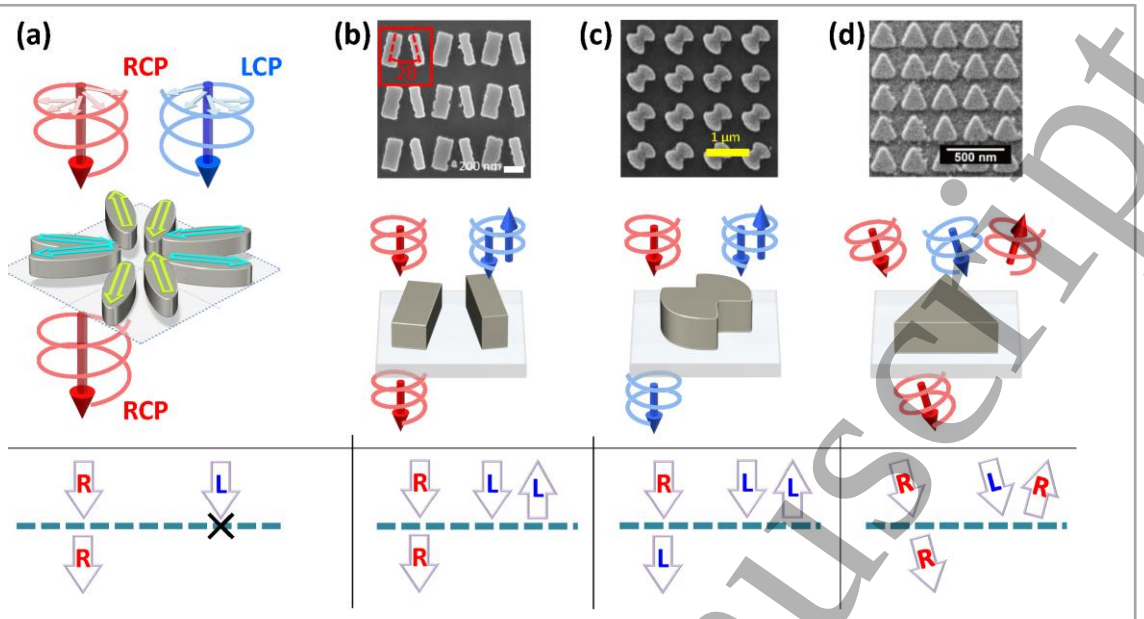


Figure 1. Regimes of maximum chiral selectivity of transmission and reflection of metasurfaces classified by the point symmetry and illustrated by recent optical structures made as arrays of silicon particles (electron microscopy images shown on the top). (a) C4-rotationally symmetric arrangement of silicon rods transparent for RCP waves and resonantly absorbing LCP waves [11]. (b) Asymmetric [17], (c) mirror symmetric [18] and (d) extrinsically chiral [19] silicon metasurfaces selectively interacting with LCP and RCP waves. Simplified schematics on the bottom visualize qualitative differences between all four regimes.

guidance their point symmetry and show in Fig. 1 the four qualitatively different cases:

Rotation-symmetric chiral absorber. Rotation axes of the order 3 and higher forbid conversion of circular polarizations in transmission and prescribe their full conversion in reflection. Combined with reciprocity requirements, this means that optical chirality is manifested as a difference in RCP/LCP absorption. The particular realization depicted in Fig. 1(a) relies on the excitation of electric dipoles oscillating in anti-phase in adjacent silicon rods. The vertical offset in each pair of rods ensures their cancellation along the RCP polarization helix [11].

Single-mode fully asymmetric chiral filter. Restrictions on reflection can be lifted if a metasurface lacks point symmetry elements. Then it can reflect, instead of absorbing, the waves of blocked circular polarization. First practical realizations are based on pairs of dielectric rods, see Fig. 1(b), having different heights and a small opening angle [12,17].

Chiral flat mirror. In spite of the lack of geometric chirality, metastructures fabricated from planar layers by cutting vertical holes or slits can maximum selectively interact with circularly polarized waves. Here the transmitted wave helicity is bound to invert. Very different realizations include a silicon nitride photonic crystal slab [13] as well as silicon particles of broken in-plane symmetry [18] shown in Fig. 1(c).

Extrinsic-chiral mirror. Even for metasurfaces possessing multiple orthogonal mirror symmetry planes, the so-called extrinsic optical chirality [20] for obliquely incident waves remains allowed. In Fig. 1(d), we sketch such a structure using the example of recent metasurface composed of triangular prisms [19].

By comparing the allowed types of maximum-selective interactions with RCP/LCP light at the bottom of Fig. 1, one recognizes their qualitative differences. One also notices that the case in Fig. 1(a) actually depicts the

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conventionally expected limit of the natural molecular optical chirality. Reaching such limit, however, requires macroscopic quantities of natural chiral substances. For hundred nanometre thick chiral metasurfaces, not only this but also other types of maximum-chiral optical phenomena are feasible. Chiral metasurfaces from the available versatile toolbox allow tackling problems in very different fields of photonics, enriching them with chiral effects, functions and applications.

Current and future challenges

Practical advances of metasurfaces with high-Q chiral resonances critically depend on the capabilities and precision of available fabrication techniques. For intrinsically chiral designs as in Fig. 1(a,b), usual quasi-BIC metasurface challenges, such as very low absorption loss and exceptional accuracy, are aggravated by the necessity to break the mirror symmetry of meta-atoms which, even in the simplest cases, have to be precisely elevated [11] or tilted [21] or be different in height [12,17,23]. Fabrication of planar mirror-symmteric variants [13-16,18] as in Fig. 1(c) can be performed with conventional lithographic techniques. As their optical chirality relies on accurate spectral matching of quasi-degenerate photonic eigenstates, the precision requirements are higher than usual and often dozens of samples with slightly different parameters are to be created for only a couple of optimally functioning ones to be selected in the end. Extrinsic chiral designs as the one in Fig. 1(d) are the least demanding in fabrication, For them, however, more challenges appear in optical experiments set for the non-standard off-axis performance.

Upon all technical problems resolved, metasurfaces with high-Q eigenstates selectively coupled to circularly polarized light are efficient optical cavities facilitating chiral lasing [21]. Combining metasurfaces with mirrors, one can built ultra-compact optical resonators performing low-voltage chiral electroluminescence [19]. Further improvement of such and similar chiral light sources faces technological challenges: one has to learn how to integrate efficient optoelectronic materials with dielectric metasurfaces without compromising the long-term stability of emission and high finesse of metasurface eigenmodes.

Expanding the library of materials brings us into the actively emerging field of chiral polaritonics. Integrating layers of excitonic van der Waals materials into resonant metasurfaces [22] or fabricating chiral quasi-BIC metasurfaces entirely from such materials [23] grants exciton-polaritons with remarkably strong chiral dissymmetry manifested in both linear and nonlinear optics. Introducing chiral quasi-BIC adds a degree of freedom: strong light-matter interaction defining the polariton formation occurs only for photons of a desired helicity. Further advances require merging of optical and condensed matter theoretical frameworks and, again, mastering of the corresponding nanoscale processing techniques.

Reports of intriguing chiral phenomena arriving from nonlinear metaphotonics demonstrate that chiral metasurfaces have unlocked a new dimension there. Previously, the transition from bulky nonlinear crystals to ultrathin resonant metasurfaces allowed lifting phase-matching conditions restricting nonlinear optical interactions. Now, by engineering chiral quasi-BICs, one can aim at optimizing these interactions for particular combinations of circularly polarized input and output waves. Unexpectedly for some, problematic in fabrication metastructures of complex geometric-chiral shapes are not always required here. Arrays of basic cylindrical particles are capable of strong dichroism of harmonic generation [24]. Moreover, even achiral metasurfaces pumped by achiral linearly polarized light can generate circularly polarized harmonics by virtue of peculiar interplay of contributions of several achiral eigenmodes [25]. Current achievements rely on quasi-BICs resonating either at the pump or at the higher harmonic frequency. Truly full control of the polarization degree of freedom will be achieved in metasurfaces hosting a set of chiral quasi-BICs resonating at all interacting wave frequencies. As the latter differ by several times, the problem still awaits a general solution.

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Reverse nonlinear process of spontaneous parametric frequency down-conversion is widely used for generation of pairs of entangled photons – the fuel of emerging quantum telecommunications. So far, it has received less attention in chiral metaphotonics for two possible reasons. For one, the corresponding experiments are more sophisticated, and, for the other, metasurfaces generally provide much lower generation rates compared to nonlinear crystal-based sources. It is logical to expect that, instead of competing with the latter, quantum metasurfaces will rather supplement them with unique degrees of freedom. It is unclear how chirality can be turned into an entangled quantity, or whether eventually, chiral symmetry can be spontaneously broken in the process of photon pair generation.

High-quality factor metasurface eigenmodes can also be the key to the hard long-standing problem of enhanced molecular chirality sensing. Chiroptical sensor devices are strongly restricted by the available amounts of analytes – drugs, biomolecules, or disease biomarkers. For fast and reliable diagnostics, one has to register weak optical fingerprints of molecular chirality. With the general theoretical background readily formulated (26), first theoretical estimates are now appearing of chiral sensor performance boosted with quasi-BICs (27). Being yet relatively far from experimental realization, this line of thought, if properly followed, will result in brightest practical achievements of chiral metaphotonics.

Advances in science and technology to meet challenges

Current strategies of the metasurface design primarily rely on the coupled-mode concepts supplemented by parameter optimization with extensive numerical modelling. Straightforward progress here can be achieved by employing inverse design algorithms. As in every modern field, high hopes are pinned on the deep learning approach. Real breakthroughs will occur when AI will be employed to design chiral photonic eigenmodes.

The future progress in chiral polaritonics will definitely require advanced theoretical frameworks unifying photonic eigenmode analysis with the quantum condensed matter theory. Even though the first steps could rely on simplified incorporation of excitons as specific permittivity poles, further developments have to include much more detailed knowledge of the exciton behaviour. For example, great variety of very peculiar effects comes to mind when one combines exciton dispersion in the electronic 3D k-space with the metasurface eigenmode branching in its 2D k-space. The direct product of the two spaces is 5D, and one has to operate in it to reveal the true potential of chiral polaritons. On the practical side, one can expect chiral room temperature polariton condensates storing chiral quantum information and performing polaritonic chiral lasing.

For all great expectation to be fulfilled, one has to substantially advance in nanoscale processing of emerging photonic materials. These include already mentioned van der Waals materials either integrated as layers or shaped into bulk nanostructures. Among many others, metal halide perovskite semiconductors are very attractive for mass production as they combine simple synthesis with impressive optoelectronic properties. Their general instability, however, implies severe problems for perovskite integration in metasurfaces. One has to specifically adapt every technological step to preserve the composition and crystalline structure, avoiding defects of any kind. Similarly challenging are topological insulators which promise to be a new platform where plasmonic field enhancement, dielectric confinement, and topologically protected transport coexist. Their insulating bulk and metallic surface states enable spin-polarized, low-loss, and dynamically tunable chiral resonances.

For the consumer electronics market, metaphotonic elements with the options of active control and external chirality tuning will be of advantage. Very different switchable light/voltage/temperature/stress driven devices will appear using dielectric metastructures hybridized with phase-change and liquid-crystal

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materials. One can exploit intrinsic semiconductor nonlinearities for all-optical chirality control. Practical progress in any of these directions has the potential to extend the powerful ideas to more previously inaccessible applications and more complex geometries.

Optical enantiomer-selective detection of molecules is highly desired by biology and pharmacology industries to accelerate the search for new predictive biomarkers and for effective screening of physiologically active molecules. The corresponding devices are bound to combine metaphotonic, microfluidic and biosensor components on one chip. Advancing point-of-care biosensors and lab-on-a-chip devices will represent a significant step toward the next-generation healthcare solutions.

Concluding remarks

Contemporary hundred-nanometer-thick chiral optical metasurfaces not only immensely exceed natural materials in efficiency, but critically enrich the pallette of available chiral optical phenomena. To date, this has been repeatedly verified in chiral linear optics. Recent developments in chiral metaphotonics promise to uncover the fundamental properties of chiral light-matter interactions in structured photonic media for important applications in chiral biosensing, nonlinear and quantum photonics, and polaritonics. The emerging platform of chiral resonant photonics has the potential for practical realizations in many applications, such as chiral sensing, by reducing the size of the corresponding components facilitating their on-chip integration in portable devices such as smartphones.

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Section 5.1 – A 5D concept for space-time optimal control problems with application to simplified optical laser induced Carreau flow

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Status

Advances in modern laser technology push light–matter interaction into multiscale regimes that require a fully coupled multiphysics description [6, 13]. In more detail, the laser material processing includes the propagation of the laser beam, the interaction of the laser beam with the surrounding material, heat conduction, and phase transitions when solid materials become molten. The latter requires to model fluid flows with the incompressible Stokes or Navier-Stokes equations. An overall derivation of the resulting physical framework was done in [14]. In prior work, different modules of that system with state-of-the-art numerical discretizations and solvers have been developed, e.g., laser-beam using time-harmonic Maxwell's equations[3], and coupled flow-temperature models[2]. We take first steps toward a more accurate representation of laser-induced fluid dynamics, which has so far been addressed only in limited form. Using new scientific computing techniques in optimal control, we optimize non-Newtonian fluid flows by solving the corresponding parameter-dependent space–time optimality system in a single unified step. A 5D photonic formulation, in which spatial, temporal, material, optical, and control parameters act as coordinated dimensions, provides a coherent framework for representing and optimizing such laser-driven flow phenomena. One model for non-Newtonian fluids is the Carreau model [1,12], where we use a simplified version. Optimal control problems were already discussed in [4,8], whereas partial differential equations in a space-time setting are presented in [9,10]. We consider the optimal control problem: Find the state $y_\rho \in Y$ and the control $u_\rho \in U$ minimizing some cost functional

$$J_\rho(y,u)$$

subject to a simplified Carreau flow model

$$\partial_t y - \nabla_x \cdot ((1+c|\nabla_x y|^2)^{\frac{n-1}{2}} \nabla_x y) = f + u \ \text{ in } Q = \Omega \times (0,T) \subset \mathbb{R}^4,$$
$$y = 0 \ \text{ on } \partial\Omega \times (0,T), \qquad y(0,\cdot) = y_0 = 0 \ \text{ in } \overline{\Omega}$$

serves as state equation, where $\Omega \subset \mathbb{R}^3$ is a bounded polyhedral domain in space, $(0,T)$ denotes the time interval, Y and U are appropriate spaces for the state and the control. We refer to [9,10] for the variational formulation of the state equation as well as existence, uniqueness and regularity results together with the corresponding references. The cost functional $J_\rho: Y \times U \mapsto \mathbb{R}$ depends on a regularization resp. cost parameter ρ that allows us to control the energy cost $\| u \|_U^2$ of the control. The constants n and c are positive material parameters. In [11], this was achieved for a non-simplified Carreau model on a 2D domain. The concept of this work consists in a full space-time setting with optimization, and then the extension of the work to more sophisticated models. The 5D concept is structured as follows: three dimensions for space, one for time, and one for the optimization including ρ.

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Current and future challenges

Current challenges of the corresponding topic are the complexity due to nonlinearities, the optimization and the high number of unknowns arising during the simulation. A high number of unknowns increases the accuracy of the approximate solution but also comes along with an increased computational cost. Using the cost functional and the state equation, we can derive the first-order optimality system also called Karush-Kuhn-Tucker (KKT) system; see [15]. The KKT system reads as follows: Find the state $y_\rho \in Y$, the control $u_\rho \in U$, and the adjoint $p_\rho \in P$ such that

$$\mathcal{L}'(y_\rho, u_\rho, p_\rho)(y, u, p) = 0, \ \forall (y, u, p) \in Y \times U \times P$$

with the Lagrangian $\mathcal{L}(y, u, p) := J_\rho(y, u) - A(y, u)(p)$, where $A(\cdot,\cdot)(\cdot)$ is defined by

$$A(y, u)(p) := (\partial_t y, p)_{L^2(Q)} + ((1 + c|\nabla y|^2)^{\frac{n-1}{2}} \nabla_x y, \nabla_x p)_{L^2(Q)} - (f + u, p)_{L^2(Q)},$$

and derived from the variational formulation of the state equation; also see [9,10]. In practice, we look for an approximate solution of the KKT system obtained by some discretization. We use space-time P_1 finite elements. More precisely, we decompose the 4D space-time cylinder $Q = \Omega \times (0, T)$ into pentatopes (4-simplices). An example for a cost functional is the so-called tracking type functional given by

$$J_\rho(y, u) = \frac{1}{2} \int_0^T \| y_d(t) - y(t) \|^2_{L^2(\Omega)} \, dt + \frac{\rho}{2} \| u \|^2_{L^2(Q)},$$

where y_d is the given desired state (target), and ρ denotes the regularization/cost parameter. In our numerical experiment, we use the desired state

$$y_d(x, t) = \exp(-100 \| x - (0.25 * \sin(t\pi), 0.25 * \cos(t\pi), t) \|_2^2),$$

motivated by a laser point and the source term $f \equiv 0$.

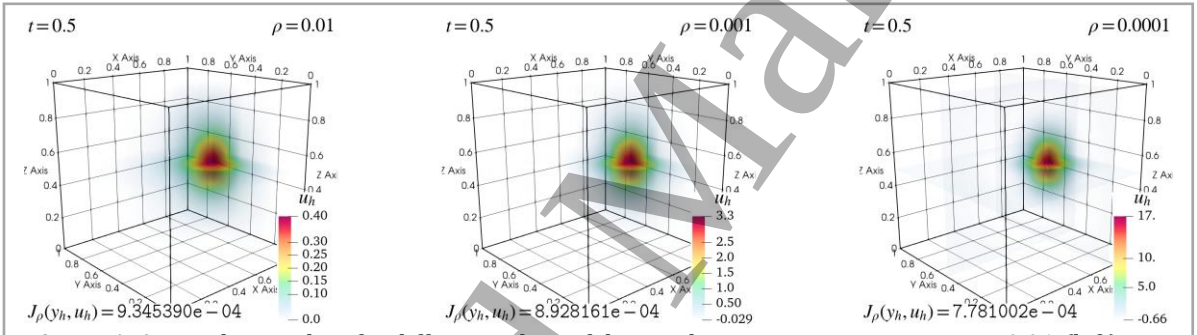


Figure 1. *Optimal control u_h for different values of the regularization parameter ρ: $\rho = 0.01$ (left); $\rho = 0.001$ (middle); $\rho = 0.0001$ (right).*

In Figure 1, we present a density plot of the control u_h over the spatial domain Ω at a fixed time $t = 0.5$, and for three points in the 5-th dimension, the regularization parameter ρ, i.e. $\rho \in \{0.01, 0.001, 0.0001\}$. We observe a strong influence of ρ on the magnitude of the control u_h. For instance, in the leftmost plot, we observe a maximal value of 0.33 of the control u_h, whereas on the rightmost plot, the maximal value of u_h has increased to 17. Note that the control itself has the same shape for all ρ, as the target function y_d is the same for all ρ. The simulation producing the plot in Figure 1 was done on a regular pentatopal grid with $\sim 480 \times 10^6$ mesh elements, resulting in approximately 31×10^6 degrees of freedom (dofs) for the state as well as the costate, respectively. This choice corresponds to a global discretization parameter (mesh size) $h \sim 1/24$. Future challenges include an increasing number of dofs which enhances the accuracy.-To effectively tackle these challenges, it is crucial to develop and implement parallel algorithms capable of solving these demanding problems efficiently. Another way to improve the efficiency is adaptive mesh refinement. However, here a particular challenge is to combine it with parallel implementation, since this is not available for 4D problems until now. Another future challenge is to use a more realistic flow model. However, this yields even more complex nonlinearities. Additionally, limited control problems can also be considered, where the control is only applied to specific parts of the domain, such as the boundary. These

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practical requirements would increase the complexity of the optimization. Moreover, additional (box) constraints imposed on the control or/and the state are of practical interest in many applications; see [15].

Advances in science and technology to meet challenges

As computational power increases, more complex models and higher number of degrees become more viable. The fidelity of the model can be improved through dialogue across multiple disciplines. By including experts from various fields the model can be adapted accordingly to better capture laser material processing. Due to nonlinearities, special numerical solvers as discussed in [5,7] might be required. Additionally, the parallel implementation of algorithms can significantly improve the efficiency and scalability of simulations.

Concluding remarks

This work presents a 5D concept to optimizing non-Newtonian fluid flows through a simplified Carreau flow model. We solve the optimization problem by approximating the solution of the KKT System with fully space-time finite element methods instead of the more traditional time-stepping technique. Therein, the finite element method is formulated in 3D in space, 1D in time, and 1D in the optimization loop, yielding a 5D overall framework.

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Section 5.2 – Emerging tools in design optimization for resonant 5D photonic devices

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Status:

Design of Resonant Nanophotonic Devices

The emerging field of 5D photonics investigates systems where, in addition to the three spatial coordinates and time dimension, one or more system parameters represent extra dimensions. Prominent examples are photonic time crystals, which have recently been demonstrated experimentally [1]. System parameters include, e.g., geometric parameters of the nanostructures and material parameters. In the design optimization of nanophotonic devices, such parameters are determined to achieve specific device functionalities [2].

Resonances, also called quasinormal modes, are crucial for the improved functionality of nanophotonic devices, as they enable strong electromagnetic field enhancement and precise control of light–matter interaction [3]. For the optimization and fundamental understanding of resonant nanophotonic devices, state-of-the-art eigensolvers are employed to compute the resonance frequencies and modes [4,5]. A standard approach is to solve the source-free Maxwell's equation in the frequency domain, with a time-harmonic dependency of the electromagnetic field. The Arnoldi algorithm [6] is the most prominent numerical approach for eigenproblems in software packages in computational photonics.

By systematically varying the system parameters, one can explore how geometric or material modifications affect the system response. Design optimization enables to reach device performance goals and novel functionalities in photonic applications [7,8]. Knowledge of the sensitivities of the resonance frequencies and modes with respect to the system parameters is crucial for optimization algorithms [9,10]. In this setting, 5D nanophotonic applications involve the system parameters as well as the sensitivities of the electromagnetic field with respect to the system parameters.

Recently, numerical tools based on rational approximation of optical response functions have been developed to compute resonance frequencies and modes. Riesz projection [11,12] is based on contour integration of the response function for obtaining a rational approximation, and the AAA algorithm [13-16] exploits adaptive sampling of the response function combined with solving a least squares problem. These methods can overcome key challenges, as they are based on a fundamentally different formulation of Maxwell's equation that explicitly includes source terms.

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Current and future challenges:

Numerical performance and sensitivities

Material dispersion, which is ubiquitous in nanophotonic applications, leads to the fact that the eigenproblems defining the resonance frequencies and modes are nonlinear eigenproblems. When solving the source-free Maxwell's equation, linearization is typically required, which significantly increases the degrees of freedom in the numerical implementation [4,6]. Moreover, standard approaches often involve computing a dense spectrum of resonance frequencies and performing mode filtering a-posteriori, which can substantially increase the computational effort [17]. The sensitivities of resonance frequencies and modes with respect to the system parameters are usually evaluated using finite differences. This further adds to the computational effort, as it requires solving additional resonance problems for each of the parameters [10].

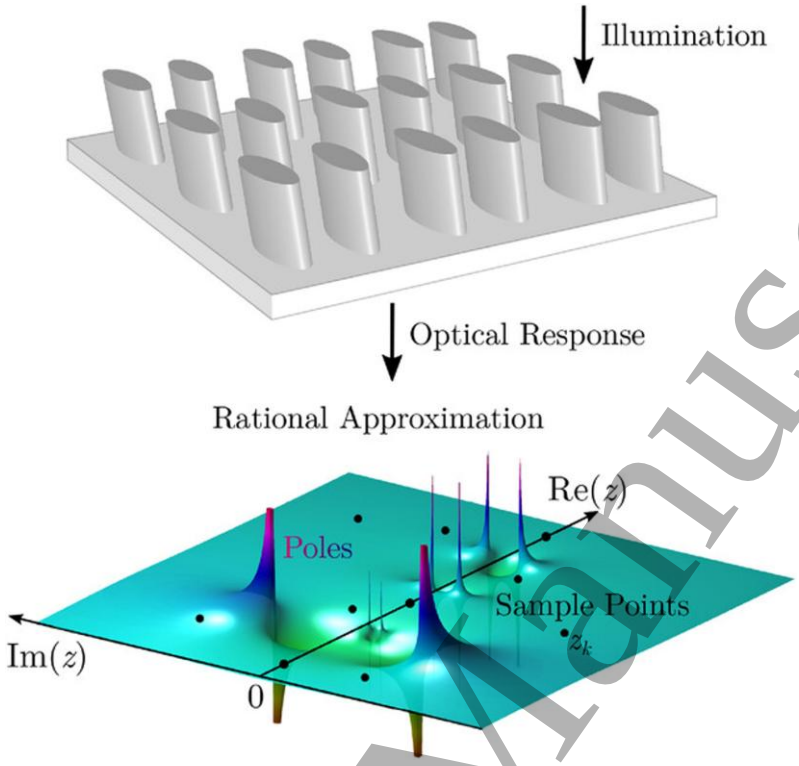


Figure 1. Rational approximation of the optical response of a metasurface. The poles of the rational approximation are located in the complex frequency plane, and they are associated to the resonance frequencies of the metasurface. The poles can be used to compute the resonance modes of the system.
Reproduced under terms of the CC-BY-NC-ND 4.0 license; Fridtjof Betz, Martin Hammerschmidt, Lin Zschiedrich, Sven Burger, and Felix Binkowski. Efficient Rational Approximation of Optical Response Functions with the AAA Algorithm. Laser Photonics Rev. 18, 2400584 (2024).

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Advances in science and technology to meet challenges:

Adaptions of AAA rational approximation for resonance problems

Tools from complex analysis can be employed to address the challenge of the computation of solutions to resonance problems. Instead of solving Maxwell's equation without a source term, Maxwell's equation with a specific light source,

$$\boldsymbol{\nabla} \times \boldsymbol{\mu}_\mathbf{0}^{-\mathbf{1}} \boldsymbol{\nabla} \times \mathbf{E}(\mathbf{r}, \boldsymbol{\omega}) - \boldsymbol{\omega}^\mathbf{2} \boldsymbol{\epsilon}(\mathbf{r}, \boldsymbol{\omega}) \mathbf{E}(\mathbf{r}, \boldsymbol{\omega}) = \boldsymbol{i\omega} \mathbf{J}(\mathbf{r}),$$

is considered. The solution of this equation is given by the scattered electric field $\mathbf{E}(\mathbf{r}, \boldsymbol{\omega}) \in \mathbb{C}^\mathbf{3}$, which arises due to the source term $\mathbf{J}(\mathbf{r}) \in \mathbb{C}^\mathbf{3}$, where $\boldsymbol{\omega} \in \mathbb{C}$ is the angular frequency and $\mathbf{r} \in \mathbb{R}^\mathbf{3}$ is the spatial position. The spatial distribution of material and the material dispersion are described by the permittivity $\boldsymbol{\epsilon}(\mathbf{r}, \boldsymbol{\omega}) = \boldsymbol{\epsilon}_r(\mathbf{r}, \boldsymbol{\omega}) \boldsymbol{\epsilon}_\mathbf{0}$, where $\boldsymbol{\epsilon}_r(\mathbf{r}, \boldsymbol{\omega})$ is the relative permittivity and $\boldsymbol{\epsilon}_\mathbf{0}$ is the vacuum permittivity. For optical frequencies, the permeability typically equals the vacuum permeability $\boldsymbol{\mu}_\mathbf{0}$. Sources at sampling points $\boldsymbol{\omega} \in \mathbb{C}$ in the complex frequency plane are taken into account, which enables the construction of a rational approximation of the optical response function of interest. The response of an illuminated metasurface is a prominent example where rational approximation can be used for the investigation of the system; see Figure 1. Contour integral methods can be applied for obtaining such a rational approximation [12]. Key figures of the response function, such as poles and zeros, are directly available by applying Cauchy's residue theorem.

The AAA algorithm is a further powerful tool for rational approximation [13,14]. A scalar-valued function $\boldsymbol{f}(\boldsymbol{z})$ is approximated by a rational function $\boldsymbol{r}(\boldsymbol{z})$ in a barycentric representation, based on a number $\boldsymbol{M}$ of sampling points $\boldsymbol{z_k} \in \boldsymbol{Z} \subseteq \mathbb{C}$, together with the function values $\boldsymbol{f_k} = \boldsymbol{f}(\boldsymbol{z_k})$. The algorithm greedily adds sampling points $\hat{\boldsymbol{z}}_\boldsymbol{j}$ to a subset $\widehat{\boldsymbol{Z}} \subset \boldsymbol{Z}$, and also the corresponding function values $\hat{\boldsymbol{f}}_\boldsymbol{j}$, and performs iterations where each iteration yields a rational approximation $\boldsymbol{r}(\boldsymbol{z})$ of order $\boldsymbol{m - 1}$,

$$\boldsymbol{r}(\boldsymbol{z}) = \frac{\boldsymbol{n}(\mathbf{z})}{\boldsymbol{d}(\boldsymbol{z})} = \frac{\sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} \frac{\widehat{\boldsymbol{w}}_\mathrm{j} \hat{\boldsymbol{f}}_\mathrm{j}}{\boldsymbol{z} - \hat{\boldsymbol{z}}_\mathrm{j}}}{\sum_{\boldsymbol{j=1}}^{\boldsymbol{m}} \frac{\widehat{\boldsymbol{w}}_\mathrm{j}}{\boldsymbol{z} - \hat{\boldsymbol{z}}_\mathrm{j}}},$$

where the weights $\widehat{\boldsymbol{w}}_\boldsymbol{j}$ minimize the error with respect to the least squares problem

$$\sum_{\boldsymbol{z_k} \in \boldsymbol{Z} \setminus \widehat{\boldsymbol{Z}}} |\boldsymbol{f_k} \boldsymbol{d}(\boldsymbol{z_k}) - \boldsymbol{n}(\boldsymbol{z_k})|^\mathbf{2} .$$

The AAA algorithm also provides the poles and zeros of the response function of interest. Recently, the AAA algorithm has been directly used to compute the resonance modes corresponding to the underlying poles [15-17], and for the investigation of hidden poles in systems with scattering thresholds [18].

The main computational effort when applying the AAA algorithm in nanophotonics is solving Maxwell's equations at the sampling points. In Ref. [16], sampling in the complex frequency plane near the resonance frequencies of a metasurface is employed. This strategy is compared to an equidistant sampling strategy along the real frequency axis. Sampling near the resonance frequencies significantly increases the accuracy of the obtained rational approximations. This accuracy is directly related to the error of the computed resonance modes and frequencies.

Methods based on rational approximation for computing resonance frequencies and modes offer several advantages: (i) Linearization of the nonlinear eigenproblems is not required since the material models are

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evaluated at the given sampling frequency points. This can significantly reduce computational costs when the material models are characterized by many poles. (ii) Domain decomposition approaches can be implemented. This enables the treatment of systems with multiple scattering [19]. (iii) Solving Maxwell's equation at the different sampling points can be performed in parallel, which can reduce the total computation time. (iv) By selecting specific light sources, only the physically relevant solutions are computed. A-posteriori mode filtering is not necessary. However, this also implies that the accuracy of computed resonance modes and frequencies depends on the choice of the source. When the source term does couple sufficiently to the mode of interest, then the accuracy will be sufficient. (v) Sensitivities can be computed with negligible computational cost, since algorithmic differentiation is available for solving Maxwell's equation with a source term [10,20].

The last point is particularly important for the design of 5D nanophotonic devices. The optimization of such systems requires electromagnetic field solutions for multiple parameter combinations, and the availability of sensitivities can significantly accelerate this process.

Concluding remarks

Methods based on rational approximation of optical response functions are promising tools for the design of 5D nanophotonic devices. Key figures, such as poles, zeros, and residues for modal expansion, are directly accessible, and sensitivities obtained via algorithmic differentiation can be incorporated to enable efficient and accurate optimization of the systems.

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Section 5.3 – Inverse Design of Photonic Components for Real-World Applications

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Status

Inverse design is an algorithm for determining the optimal structure of an optical component, where the desired functional properties serve as an objective. This represents a paradigm shift as the algorithm does not rely on human intuition. Consequently, it allows for exploration of large design spaces that would be intractable to navigate manually. In other words, the simulation and optimization of three spatial and one temporal dimension opens a fifth dimension through a digital twin of the real-world. By simulating and optimizing in this fifth dimensions, new discoveries are possible that would not be feasible through physical experiments alone. This is especially true for nonlinear and time-varying systems described in the previous sections.

The interest in inverse design is fueled by the rapid growth of photonic integrated circuits (PICs) and their potential to overcome bottlenecks in modern computing and communications. As transistor scaling approaches physical limits, photonics offers an alternative to classical computing via optical or quantum computing [8, 17]. In these applications, photonics offers advantages regarding speed and energy consumption. Beyond computing, inverse-designed components are being investigated for sensing, augmented reality displays and telecommunication via on-chip optical interconnects [18]. These diverse applications demand a wide range of compact, efficient, and often highly specialized building blocks, which is a perfect fit for inverse design.

Currently, most inverse design approaches rely on electromagnetic solvers using the finite-difference time-domain (FDTD) method with gradient computation through adjoint sensitivity analysis [2]. Design geometries are represented using shape-based parameterizations, discretized material grids, or level-set formulations [19]. The optimization difficulty mainly depends on the number of parameters given by the representation type and geometry size, as well as the complexity of the fabrication constraints. Utilizing the gradient computed through adjoint analysis, the parameters of the design representation can be updated using the Adam optimizer [20]. These iterative updates increase the functionality in small steps until a simulation budget is reached or the optimization process converges to either a local or global optimum.

In recent years, inverse-designed components have been fabricated and validated on the silicon-on-insulator (SOI) platform for a number of applications. This includes ultra-compact wavelength demultiplexers, mode converters, and lenses that outperform their traditionally designed counterparts in terms of footprint, efficiency, or bandwidth [18]. These successes demonstrate that inverse design can produce non-intuitive

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geometries exploiting complex interference effects, which would be impossible to conceive through conventional design approaches.

Current and future challenges

Despite theoretical advances [2, 4], the practical application of inverse design methods in photonic component development remains limited. This limited adoption can be attributed to several key challenges impeding the implementation of inverse design techniques in industrial settings.

Firstly, the inverse design process requires many iterative simulations to achieve optimal performance [1-4]. Since each simulation entails computational resources and time, inverse design leads to a high cost factor. Consequently, simulation speed and sample efficiency are key challenges that need to be addressed, particularly for complex photonic structures from nonlinear and time-varying materials requiring accurate modeling.

Additionally, optimization algorithms face challenges in accommodating the different fabrication constraints imposed by various manufacturing techniques. These constraints vary substantially between fabrication methods, such as silicon photonics [5] and two-photon polymerization (2PP) [7], each imposing different geometric limitations within the design parameterization. These constraints are exemplified in Figure 1. Developing optimization algorithms that generalize across a range of fabrication requirements remains a challenge. Moreover, design constraints lead to numerous local optima in the optimization landscape. Optimization algorithms like gradient descent are susceptible to convergence to these local optima rather than a global optimum [1].

Lastly, a critical limitation of current inverse design approaches is the sensitivity of optimized designs to fabrication tolerances, especially in silicon photonics [6]. Many generated structures show substantial performance degradation when subjected to minor deviations from their intended specifications during manufacturing. This problem is amplified in silicon photonics due to the high refractive index contrast between design and background material. The evaluation of tolerance sensitivity through simulation presents additional computational challenges. Since many design features may vary during fabrication, the computational cost of a full tolerance analysis scales exponentially with the number of design parameters. This renders a complete tolerance analysis impractical and even approximations are costly.

Consequently, further research needs to be conducted to lower the barrier of adopting inverse design algorithms in real-world applications.

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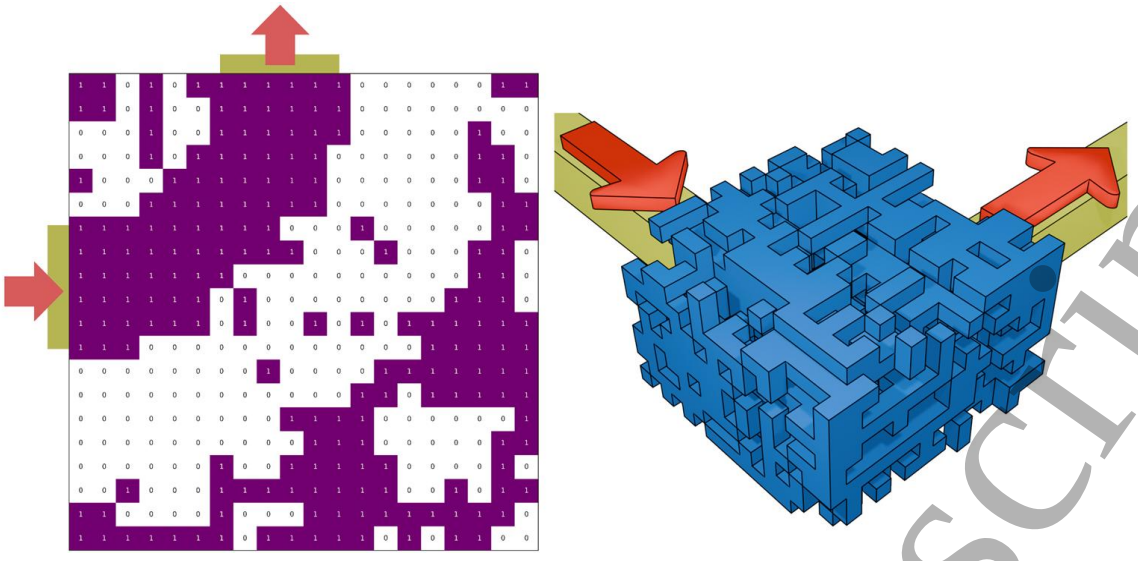


Figure 1. Visualization of a waveguide corner design in silicon photonics (left) and polymer (right). The two-dimensional silicon photonic design has a fabrication constraint regarding the minimum feature size, which is inherently enforced with the discretization in square pixels of appropriate size. The three-dimensional polymer design has additional fabrication constraints: All design voxels need to be connected to the ground and no fully enclosed air cavities may exist. The constraints increase the difficulty drastically. Adapted with permission from [1].

Advances in science and technology to meet challenges

Addressing the computational bottleneck that limits inverse design adoption requires fundamental improvements in electromagnetic simulation infrastructure. One advancement in this area is the open-source framework FDTDX [2, 3] for high-performance FDTD simulations. Unlike CPU-limited alternatives such as Meep, FDTDX enables simulations on various hardware accelerators like graphics-processing units (GPU) or tensor-processing units (TPU). This allows for large-scale simulations and optimizations with billions of grid cells in minutes rather than hours or days. The high memory requirements of the adjoint method for gradient computation in time-domain simulations can be alleviated through automatic differentiation. FDTDX provides a memory-efficient implementation of automatic differentiation leveraging the time reversibility of Maxwell's equations [2]. These speed and memory improvements directly address the challenge of sample efficiency by reducing per-simulation costs and making iterative optimization accessible to the broader research community.

Additionally, new gradient-free optimization algorithms based on multi-agent reinforcement learning have shown promising results in topology optimization [1]. This gradient-free approach completely removes the need for costly gradient computation and is more robust to the challenge of local optima. Another gradient-free global-optimization approach for automatic design is Bayesian Optimization (BO; sometimes also known as Kriging). It is known for its sample efficiency in evaluating expensive black-box functions, for example the simulation of photonic components. By using a probabilistic surrogate model (e.g., a Gaussian Process) of the underlying unknown optimization approach, it can efficiently interpolate between different designs. This allows for an optimal trade-off between exploration of new designs versus exploitation of similar designs already showing promising characteristics. The commonly known limitation of BO to low-dimensional problems with less than 20 dimensions was recently challenged by several publications [13-16]. In the past,

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BO has only been applied to high-dimensional problems if additivity of the underlying problem was given (i.e., subsets of the dimensions could be optimized independently from each other) [11] or if there was a low-dimensional effective subspace [10]. By now, there is evidence that BO can also be applied to problems with thousands of dimensions if the maximum likelihood estimation of BO is initialized in a good way [9]. Further techniques like multi-fidelity optimization for cheap approximations of the underlying problem (e.g., saving simulation time) or multi-objective optimization for finding optimal trade-offs of different objective measures show the versatile potential of BO [12].

Concluding remarks

The field of inverse design for photonic components stands at a juncture where theoretical advances must translate into practical industrial adoption to fulfill its promise as a useful fifth dimension of nanophotonic. Although significant advancements have been made in computational frameworks and inverse design of components on silicon-on-insulator platforms, key barriers remain. The computational burden of iterative simulations, sensitivity to fabrication tolerances, and convergence to local optima continue to limit widespread implementation. However, emerging solutions show promise. High-performance GPU/TPU-accelerated simulations dramatically reduce the simulation cost of photonic components. Additionally, gradient-free approaches like multi-agent reinforcement learning offer robustness against local optima, and advances in high-dimensional Bayesian optimization provide sample-efficient global optimization strategies. In combination with the growing demands for specialized components in photonics applications, inverse design is positioned to become an indispensable tool for next-generation PICs. Success in overcoming current limitations will unlock the full potential of complex, high-performance photonic designs, surpassing conventional approaches.

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Section 5.4 – 4D Spatio-Temporal Photonic Materials

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Status

In nanophotonics, we seek to control light: the way it propagates through space and how it interacts with matter. A canonical approach is to spatially structure materials on a length scale comparable to or less than the wavelength of light. Through such structuring, we can, for example, change the local refractive index to steer light in any direction, or impose strong diffraction toward a particular order, or forbid propagation altogether. The constituting materials can be diverse, e.g., metals, dielectrics, magnetics, two-dimensional materials, and many more, and the structuring can be localized, periodic, disordered, or random. Yet, while extremely versatile, spatial structure suffers from two limitations.

Firstly, the properties of these photonic structures are static and fixed upon fabrication. Modifying them, as is often required to adjust the functionality over time, is exceptionally challenging. Secondly, and perhaps more fundamentally, in the realm of a linear response, a beam of light can only be shaped through carefully absorbing or redirecting parts of the wave. Through this process, it is not possible to radically change the spectrum of the beam, such as converting a visible beam of light to an infrared one.

To tackle these challenges, time-varying materials have recently been proposed, characterized by a temporal change in material properties on time scales as short as, or even shorter than, the oscillation period of the incident light [1]. Such materials can enact a sudden change in the wave impedance, thus constituting the temporal equivalent of a spatial interface [2]. At such a time interface, an unusual analogue of reflection occurs, whereby a broadband pulse is partly time-reversed [3]. Sequences of temporal interfaces form temporal slabs and multilayers, and continuous modulations can form temporal tapers [4]. Moreover, periodic variations produce photonic time crystals, characterized by instabilities that occur at the temporal analogue of a band gap [5].

Just as a sequence of spatial interfaces allows us to tailor the propagation and directional spread of electromagnetic waves within an optical field, photonic time-varying media also allow us to control the frequency content and the temporal characteristics of light. Understanding the interface conditions, dispersion relations, and band structure provides insights that guide current experimental efforts [6, 7]. In

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particular, linearized models enable the use and generalization of a host of powerful theoretical tools, such as photonic band structures, to understand the properties of time-varying media in a regime where nonlinear effects caused by probe light are negligible.

Experiments at radio frequencies, along with other wave-based physical systems, such as those using water, sound, or pressure waves, have demonstrated multiple aspects of photonic time-varying media [8, 9]. Even at optical frequencies, where the modulation timescales of the material parameters need to be extremely short, a large temporal change in material properties can be induced by exciting free carriers on the timescale of a few femtoseconds [10-12]. Nevertheless, several challenges must be overcome if photonic time-varying media are to be used in future devices.

Current and future challenges

To ultimately deliver the promise of comprehensive control over light in both spatial/momentum space and temporal/frequency space, we need to work toward 4D photonic materials, structured on spatial and temporal scales comparable to the wavelength and oscillation period of the electromagnetic field [13]. A carefully engineered spatial structure can significantly enhance or even enable the observation of time-varying effects. By leveraging spatial structuring, one can harness slow-light phenomena, confine probe fields with high precision, and amplify pump fields, thereby unlocking the full potential of time-varying media. This combined structuring across spatial and temporal length scales can occur via different means, as illustrated in Fig. 1. Although early work has primarily focused on theoretical and computational grounds, multiple experimental platforms have recently demonstrated the viability of single-cycle and potentially sub-cycle modulation timescales. However, further opportunities are yet to be explored, both in terms of pump compression, in the design of nanostructures that optimize pump-probe interactions, and in the search and modeling of low-loss, highly nonlinear materials with ultrashort response times, the primary challenges inherent to 4D photonic materials.

High modulation amplitude and frequency requirement: We need to achieve a significant change in material properties when modulated over time. To create a momentum band gap, a hallmark of a photonic time crystal, with a magnitude of about 5%, a relative modulation of the refractive index of around 20% is required [14]. Additionally, the materials should experience minimal losses so that, when light is parametrically amplified, any intrinsic absorption does not impede net amplification. However, achieving such a substantial modulation remains difficult when a fast response is necessary. Therefore, a primary challenge is to identify photonic materials that provide both fast and large modulation of their material properties. Currently, epsilon-near-zero (ENZ) materials and semiconductors are being actively investigated for this purpose, as listed in Table 1 [16]. This task is a fundamental science challenge, as a deeper understanding of the underlying processes is essential, along with developing ways to enhance modulation strengths and shrink the associated timescale.

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Table 1. Specific properties of selected ENZ materials and semiconductors relevant for attaining a time-varying permittivity. Here, we assume third-order nonlinearity as the source of time modulation.

Material	Modulation amplitude [%]	Modulation frequency [2πTHz]	Pump intensity [GWcm^{-2}]	$\chi^{(3)}$ [10^{-18}m^{2}V^{-2}]	Im(ε)
Indium titanium oxide (ITO)	1.65	484	5.5	1.60	0.352
Aluminum zinc oxide (AZO)	0.13	442	13	0.35	0.2
Germanium	0.01	130	0.7	1.92	0
Silicon	0.001	180	0.7	0.262	0

Spatiotemporal control of light: We must create dedicated experimental platforms with integrated capabilities for both spatial and temporal control. These platforms should enable precise synchronization between structural dynamics and optical excitation, enhance light-matter interactions for pump light, and efficiently trap probe light as it undergoes spatiotemporal modulations. This setup will enable phenomena such as nonreciprocal light propagation, dynamic bandgap engineering, and ultrafast optical switching in space/momentum and time/frequency. Additionally, scalable and reproducible fabrication methods and reliable control schemes will be essential for moving from proof-of-concept demonstrations to functional devices. Ultimately, the merging of material science, nanofabrication, and ultrafast optics will determine how quickly 4D photonic materials transition from a conceptual idea to a transformative technology for next-generation photonic systems.

Advances in science and technology to meet challenges

Combining spatial and temporal periodicities: To address the challenges, we must develop a fundamental understanding of the interplay between spatial structuring and temporal modulation [15]. In particular, slow-light effects can significantly enhance the interaction of light with time-varying materials, thereby amplifying the impact of temporal modulation. But these effects are delicate and difficult to achieve experimentally. Resonances, either localized at nanoparticles or delocalized on metasurfaces, can boost both spatial and temporal modulations but require complex nanofabrication and excitation. Such explorations require purposeful leveraging of the nanophotonic toolbox. Achieving this goal calls for (1) advanced numerical methods capable of accurately and efficiently exploring the complex coupling between spatially structured devices and temporal dynamics across temporal and spatial scales and (2) efficient experimental spatio-temporal excitation and hyperspectral detection schemes.

Ensuring thermal robustness: While bulk or thin-film materials can be strongly pumped to achieve temporal modulation of their properties, introducing spatial structuring often creates material defects that significantly lower the thermal damage threshold. This limitation currently prevents the effective combination of spatial structuring with substantial temporal modulation. Therefore, beyond developing materials that sustain significant property modulations, it is crucial to ensure that these materials maintain their robustness after being spatially structured, continuing to support high modulation amplitudes without degradation.

Distinguishing time-varying and nonlinear optics: It is scientifically crucial to explore and clearly distinguish the differences and possible similarities between phenomena enabled by temporal modulation

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and those related to established nonlinear optical effects [16]. Although both involve dynamic changes in material properties and can lead to frequency conversion, amplification, or nonreciprocal behavior, their underlying mechanisms and physical interpretations vary. Understanding these differences is not just about classification; it is vital for identifying the unique benefits of time-varying photonic systems. Most novel effects in time-varying systems are beyond the perturbative limit of conventional nonlinear optics, and are therefore better described with a Floquet picture.

For instance, there is a significant difference in the phase-matching condition for parametric amplification in conventional nonlinear systems and time-varying systems. While conventional nonlinear systems require phase matching to be satisfied in space, time-varying systems require it in time. As a result, the amplified field grows as a function of time in PTCs as compared to that in space in conventional nonlinear parametric amplifiers [16]. Furthermore, temporal modulation can generate synthetic dimensions and motion [17], Floquet band structures, and momentum band gaps, providing new ways to control light that can be understood and efficiently modeled via clear analytical and phenomenological frameworks. At the same time, temporal modulation at optical frequencies inherently requires harnessing the nonlinearities of the underlying medium. Therefore, a thorough assessment will help clarify where established nonlinear frameworks still apply and where entirely new theoretical tools are needed. This effort will ultimately expand our understanding of light–matter interactions in dynamic media and help develop new functionalities beyond the capabilities of traditional photonics in the linear, nonlinear, nonlocal, and quantum regimes [18-20].

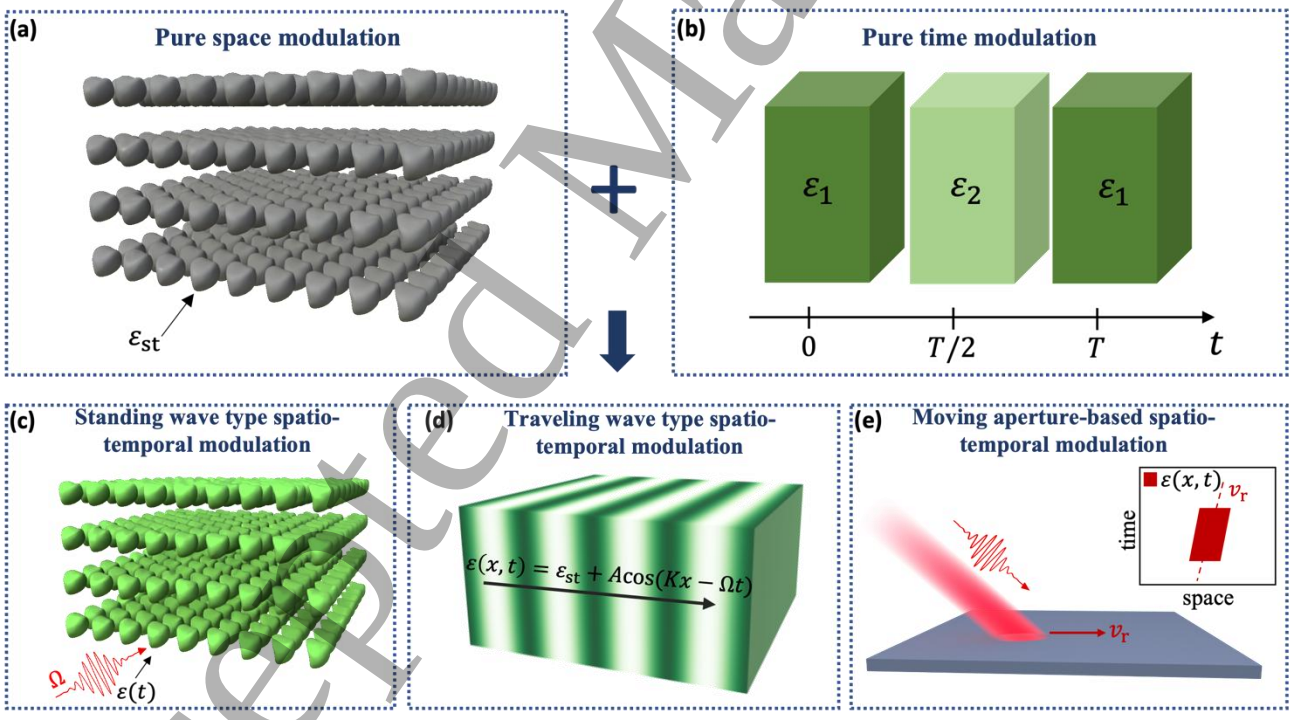


Figure 1. (a) A purely spatial metamaterial made from a periodic arrangement of static meta-atoms in 3D. The permittivity of each meta-atom is ε_{st}. (b) A strictly temporal metamaterial (also known as a photonic time crystal).

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Here, the considered system is an infinite spatially homogeneous medium whose permittivity oscillates periodically between the values ε_1 and ε_2 with the time-period T. These two examples are classical 3D and 1D photonic systems, respectively. (c-e) Various realizations of 4D photonic materials include (c) spatio-temporal photonic metamaterials made from periodic arrangements of time-varying meta-atoms; (d) spatio-temporal photonic material whose permittivity is represented by a traveling wave $\varepsilon(x,t) = \varepsilon_{\mathrm{st}} + A\cos(Kx - \Omega t)$, where K is the modulation wavevector (pointing here, arbitrarily, into the x-direction so that it appears as a scalar), Ω is the modulation frequency, and A is the amplitude of the traveling wave, which moves synthetically with speed $v = \Omega/K$; (e) spatio-temporal photonic material based on synthetically moving apertures. The modulation is created by an obliquely incident pump laser on a thin film. Here, the pump modulates the permittivity of the thin film as $\varepsilon(x,t)$, and the modulated permittivity pattern (aperture) moves on the surface of the film with the velocity v_{r}.

Concluding remarks

The emergence of photonic time-varying media represents a paradigm shift in our ability to control light, extending the traditional spatial manipulation of nanophotonics into the frequency domain. Realizing the full potential of 4D photonic materials requires overcoming significant challenges. Key among these is developing materials capable of sustaining large, fast modulations while maintaining low losses and high damage thresholds after spatial structuring. Dedicated experimental platforms with precise spatio-temporal control are essential for translating theoretical predictions into scalable, functional devices. Additionally, distinguishing the unique phenomena enabled by temporal modulation from established nonlinear optical effects will deepen our understanding and reveal novel functionalities inaccessible through conventional photonics.

4D photonic materials stand at the frontier of nanophotonics, promising transformative capabilities for optical communication, computing, and sensing. The path forward demands interdisciplinary collaboration across material science, nanofabrication, ultrafast optics, and theoretical physics. As we address current challenges and leverage the synergies between spatial and temporal control, photonic time-varying media will evolve from a conceptual framework into a cornerstone technology, fundamentally reshaping how we harness and manipulate light.

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Section 6.1 – The Road Ahead for 5D Photonic Integration on a Chip

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Status

The rapid acceleration of photonic technologies has created an urgent need for platforms that surpass the limitations of traditional 2D and quasi-3D integrated photonic circuits[1]. Current chips—whether silicon photonics, silicon nitride, lithium-niobate-on-insulator, or III–V hybrids—excel in compactness and scalability but remain fundamentally constrained by planar architectures, static geometries, and limited reconfigurability. As applications such as neuromorphic computing, quantum information processing, ultra-high-capacity communications, and distributed sensing continue to expand, photonic systems must evolve beyond conventional design rules and dimensional boundaries.

This need has catalyzed the emergence of 5D photonics, an integrative framework where photonic chips exploit three spatial dimensions, time, and a programmable material dimension to achieve unprecedented functionality. Already, several enabling threads are converging to support this paradigm. Advances in femtosecond laser direct writing now allow volumetric structuring of transparent substrates, producing true 3D waveguide architectures[2], photonic crystals[3], and on-chip delay networks. Parallel progress in inverse design and topology optimization has demonstrated that algorithmically engineered structures can outperform human-designed devices by orders of magnitude in bandwidth, mode control, and functional density.

On the materials front, emerging classes such as MXenes[4], phase-change materials[5], chalcogenides[6], and electro-optic polymers[7] are introducing dynamic, nonlinear, and reconfigurable behaviours that constitute the “fifth dimension” of photonics. These materials support ultrafast tuning of refractive index, strong χ^3 nonlinearities, and multi-state optical memory, enabling devices that learn, adapt, and respond to their environment. Recent demonstrations of MXene-based nonlinear activators on silicon waveguides, programmable metasurfaces, and hybrid volumetric–planar structures underscore the feasibility of embedding functional degrees of freedom directly into photonic chips.

Meanwhile, temporal photonics—including integrated optical true time delay lines[8], photonic memories[9], and dispersion-engineered structures[10]—is becoming a central component of next-generation architectures. These capabilities are foundational for neuromorphic processing, reservoir computing, temporal-mode quantum encoding, and ultrafast AI accelerators.

Despite these advances, the field remains fragmented. Existing systems typically integrate only one or two of the “dimensions” of 5D photonics, and no platform yet unifies volumetric structuring, nonlinear material programmability, and deterministic temporal control in a single photonic chip. The next major step is therefore coherent integration—merging 3D geometry, time, and material state into unified architectures

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capable of dense, multifunctional, and adaptive photonic processing. Achieving this will define the next era of photonic technology and reshape how light-based systems compute, store, and manipulate information.

Current and future challenges

Despite remarkable progress across materials science, inverse design, and integrated photonics, the transition from conventional planar systems to fully functional 5D photonic chips faces significant scientific and engineering challenges. Overcoming these obstacles will require coordinated advances in fabrication, materials integration, multidimensional design frameworks, and scalable packaging strategies.

A fundamental challenge lies in volumetric fabrication. While femtosecond laser direct writing and multilayer lithography have demonstrated promising capabilities, they still lack the resolution, repeatability, and large-area uniformity required for densely integrated 3D photonic architectures. Creating arbitrary refractive-index landscapes with nanoscale precision throughout a bulk substrate remains beyond current manufacturing capabilities. Developing hybrid approaches—combining laser writing, additive manufacturing, and inverse-designed preforms—will be crucial to achieving functional 3D complexity at scale.

Equally significant are challenges in materials integration. The fifth dimension of photonics—dynamic, state-dependent material behaviour—relies on integrating highly nonlinear, tunable, or phase-programmable materials such as MXenes, chalcogenides, and electro-optic polymers. These materials introduce compatibility issues with CMOS processes, thermal budgets, long-term stability, and interfacial losses. Co-designing photonic structures and active materials, while ensuring environmental robustness and low optical loss, remains an open research frontier.

From a theoretical perspective, implementing 5D photonic architectures demands new computational design paradigms. Existing inverse-design tools are computationally intensive and typically limited to small, planar regions. Extending them to three dimensions, time-dependent dynamics, and multi-state materials requires high-performance computing, reduced-order models, and machine-learning-accelerated solvers. Achieving deterministic optimization in such a vast design space is a central challenge for the field.

In the device domain, temporal photonics introduces its own complexities. Integrated optical true time delay, photonic memory elements, and temporal-mode manipulation require simultaneously controlling group velocity, dispersion, and nonlinear interactions. Ensuring stability and precision at the femtosecond-to-nanosecond scale is nontrivial, particularly in multi-material systems with varying thermal and mechanical responses.

Another major challenge is scalability and system-level integration. Even as individual components—3D waveguides, nonlinear activators, or programmable metasurfaces—demonstrate strong performance, integrating hundreds or thousands of such units into a unified chip without crosstalk, thermal drift, or fabrication-induced variability remains an unsolved problem. Packaging and interfacing multi-dimensional photonic chips with fiber networks, electronic controllers, and quantum or AI systems adds further complexity.

Looking forward, transformative breakthroughs will be required in multi-material fabrication illustratively proposed in Figure 1, inverse-designed 3D architectures, ultralow-loss nonlinear materials, and coherent integration across spatial, temporal, and functional dimensions. Successfully addressing these

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challenges will unlock the full promise of 5D photonics, enabling adaptive, multifunctional photonic processors that far surpass the capabilities of today's integrated photonic platforms.

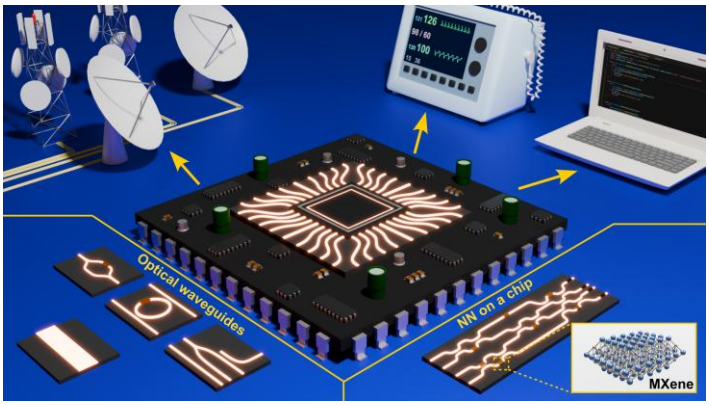


Figure 1. Vision of a 5D photonic chip unifying volumetric waveguide architectures, programmable material states, and temporal control within a single platform. This paradigm enables reconfigurable, nonlinear, and intelligently controlled photonic systems capable of adaptive, multifunctional processing for next-generation computing, quantum technologies, sensing, and communication technologies.

Advances in science and technology to meet challenges

Addressing the challenges inherent in realizing 5D photonic chips will require coordinated breakthroughs across materials science, computational photonics, fabrication technologies, and system-level integration. These advances must extend well beyond incremental improvements, establishing a new technological foundation capable of supporting multidimensional, adaptive, and densely integrated photonic systems.

A central scientific need is the development of next-generation volumetric fabrication techniques. Femtosecond laser direct writing must evolve toward higher resolution, deterministic control of refractive index, and multi-material compatibility. Emerging approaches-such as ultrafast Bessel beam structuring, adaptive optics–corrected laser writing, and two-photon/additive nano-fabrication-offer promising pathways to achieve deep-volume patterning with sub-micron precision. Equally important is the integration of inverse-designed preforms and structured fiber draws, which could enable scalable production of 3D optical architectures impossible to lithographically pattern.

On the materials front, progress will hinge on programmable and multifunctional photonic materials. MXenes, chalcogenides, 2D heterostructures, and hybrid electro-optic polymers must be engineered for lower loss, improved thermal stability, and controlled nonlinearities. Advances in surface chemistry, defect engineering, and atomic-level epitaxy will be critical to producing materials that can switch, modulate, and store photonic information on ultrafast timescales. Integrating these materials into 3D platforms will require novel adhesion layers, low-temperature bonding strategies, and interface-passivation techniques.

Major scientific advances are also needed in 5D computational design frameworks. New algorithms-combining adjoint optimization, physics-informed neural networks, and multi-objective reinforcement learning-must be capable of exploring vast design spaces encompassing spatial geometry, temporal dynamics, dispersion profiles, and nonlinear states. Accelerating these algorithms through GPU/TPU clusters and reduced-order modelling will make full-chip 3D + time optimization feasible for the first time.

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In the domain of temporal photonics, advances are required to master on-chip optical memory, true time delay, and dispersion engineering. This includes developing photonic UltraRAM-like structures, integrating slow-light waveguides, and creating coherent temporal-mode converters capable of shaping light in multidimensional Hilbert spaces. Such devices will underpin neuromorphic, quantum, and secure communication architectures.

Finally, fully realizing 5D photonic chips will require disruptive progress in integration and packaging. This includes photonic–fiber fusion interfaces with 3D mode matching, heterogeneous integration of multiple nonlinear materials, and self-aligned assembly of volumetric photonic modules. Long-term reliability will depend on breakthroughs in thermal management, encapsulation, and automated calibration of devices whose behaviours evolve across multiple dimensions.

Together, these scientific and technological advances will transform 5D photonics from an emerging concept into a robust platform for next-generation computing, communication, and quantum technologies.

Concluding remarks

The emergence of 5D photonics marks a transformative shift in how photonic systems are conceived, designed, and implemented. By uniting volumetric architectures, temporal control, and programmable material states, this framework transcends the fundamental limitations of planar integrated photonics and opens a pathway toward unprecedented functional density and adaptability. Realizing this vision will require coordinated advances across materials science, inverse-design algorithms, nonlinear photonic engineering, and scalable 3D fabrication-but the potential impact is profound. Functional photonic chips operating across five degrees of freedom will enable ultrafast neuromorphic processors, reconfigurable quantum photonic platforms, intelligent sensor networks, and distributed computing systems embedded directly in optical fibers and transparent substrates[11,12]. As these technologies mature, 5D photonics is poised not merely to extend current capabilities, but to redefine the technological landscape-ushering in a new era where light-driven computation, memory, and communication merge seamlessly into integrated, multidimensional photonic intelligence.

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Section 6.2 – Towards programmable gas-phase sonophotonics

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Status

Today, the vast majority of optical elements are solid-state-based and static. They allow us to shape the spatial properties of laser beams including position, direction and divergence (e.g. mirrors, lenses, waveguides) as well as temporal and spectral properties (e.g. filters, gratings, modulators). Typically, these optical elements serve a single purpose and offer limited reconfigurability. Solid-state-based optical elements which enable dynamic properties include, for example, electro- and acousto-optical systems and spatial light modulators. A recent effort takes a fresh look at reconfigurable optical systems while moving away from solid-state-based light control, introducing gas-phase sonophotonics [1].

The approach underlying gas-based sonophotonics relies on intense ultrasonic sound fields that act on an optical beam via pressure-induced spatially controlled refractive index modulation in gases such as ambient air. The underlying principle is well-established in the solid-state-phase and e.g. used in acousto-optical modulators: the acoustically controlled refractive index modulations cause phase retardations, which lead to diffraction and refraction, effectively controlling light wave propagation. Acousto-optic modulators are widely used not only to control optical intensity, but additional characteristics of laser pulses including carrier-envelope phase and spectral properties [2-4]. Harnessing the inherent spatio-temporal dynamics of sound waves, gas-based sonophotonic approaches reach far beyond acousto-optic modulation, opening multidimensional light control. Building on previous works [5, 6], a major step in this direction was taken recently. Using highly intense ultrasound waves and long interaction length in ambient air, intense laser pulses could be deflected directly in air [1]. This new approach shows great promise: While supporting good diffraction efficiency [7] and excellent beam quality conservation [1], this work drastically expands the parameter range of acousto-optical modulators, supporting three orders of magnitude higher peak power (in the 10 GW range) and an expected wide spectral coverage.

In this roadmap, we outline the challenges and opportunities that lie ahead as gas-based sonophotonics matures from proof-of-principle demonstrations targeting simple laser beam deflection towards practical, programmable optical systems capable of manipulating extreme optical fields, representing a 5D photonics platform, composed of the four spatio-temporal dimensions and the programmable control space, enabled via the ultrasound-induced refractive index field.

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Current and future challenges

While a conventional acousto-optic modulator requires only a near-planar acoustic wave, sonophotonics leverages engineered 3D sound fields to sculpt spatio-temporal refractive-index landscapes. A promising route to achieve this is the usage of ultrasound transducer arrays, leveraging 3D sound field shaping via amplitude and phase control of individual transducers. This adds degrees of freedom promising control beyond simple power and phase modulation: by programming the acoustic field, a single platform may enable steering, focusing, shaping wave fronts, and imprinting spatio-temporal and spectral structure, i.e. multi-dimensional photonic control. A particularly promising implementation scheme is the gas-phase sonophotonic waveguide [8, 9].

A sonophotonic waveguide can be shaped via an optical refractive index distribution which supports optical waveguiding e.g. in a gas, mediated by intense ultrasound waves. In a cylindrically symmetric ultrasound resonator, radially propagating intense ultrasound waves can form a standing acoustic field if resonator diameter and ultrasound wavelength are selected to support resonant field enhancement [10]. The resonant ultrasound field raises the optical refractive index on the resonator symmetry axis every sound field cycle T_{ac} (e.g. $T_{ac} = 1/f_{ac} \approx 3.3$ µs at at ultrasound frequency of $f_{ac} = 300$ kHz), enabling optical guiding along the symmetry axis for repetitive optical laser pulses which are synchronized in time to the acoustic wave. Fig. 1(a, b) illustrates this concept: A cylindrically symmetric standing-wave produces a Bessel-like (J_0) sound pressure profile (blue) which corresponds to an optical refractive index profile n(r). During each acoustic half-cycle when the refractive index reaches a maximum at the center, the local index profile mimics the index profile of a graded-index fiber. Using the beam propagation method [8], we numerically determine the corresponding guided fundamental optical mode (Fig 1(b), red). For the presented simulation data set, we consider a cylindrical sound-hard tube with four ultrasonic transducers per longitudinal tube segment, all emitting 300 kHz ultrasound waves into ambient air, resulting in a peak sound pressure of +367 Pa and -143 Pa and a fundamental optical mode field diameter of 280 µm for an optical wavelength of 1 µm [8, 9].

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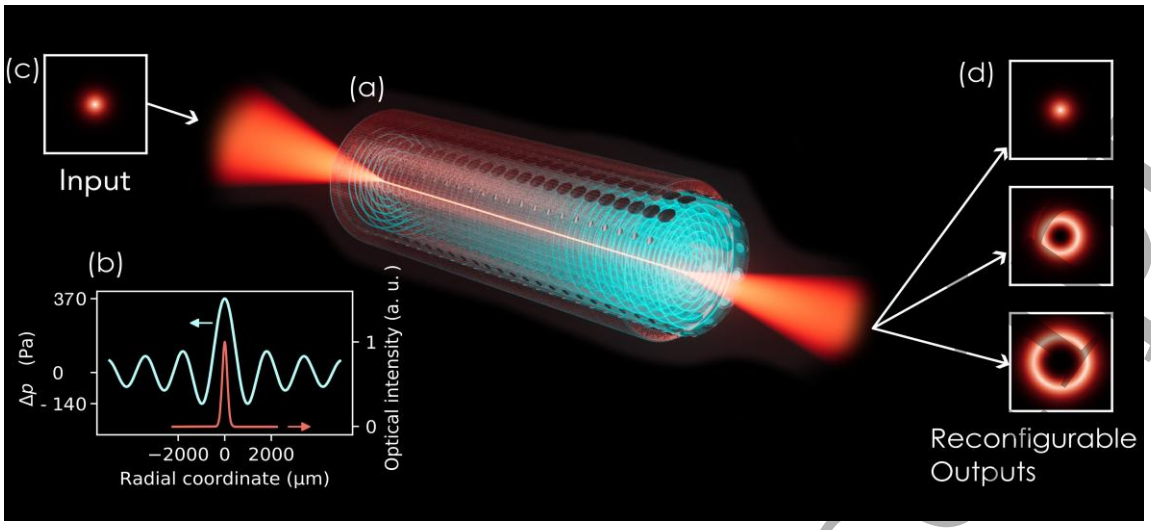


Figure 1. A sonophotonic waveguide and mode shaper. (a) Artistic depiction showing a tube with arrays of ultrasound sources placed at the tube wall, emitting 300 kHz sound waves radially towards the tube center. Blue: the emerging standing sound field inside the tube with a pressure maximum on the central symmetry axis. Red: the guided laser beam. (b) Calculated emerging radial pressure distribution (blue) and the resulting radial optical power distribution of the fundamental guided mode. (c) Spatial input beam profile of the beam shown in (a). (d) Exmple range of optical modes supported by the sonophotonic waveguide.

In a gas-based sonophotonic waveguide, the refractive index profile n(r) can be adjusted via acoustic amplitude and phase. This radically new approach allows for novel applications, promising e.g. programmable mode shaping (Fig. 1(c, d)), mode conversion, focusing and beam steering.

While the sonophotonic waveguiding concept promises intriguing characteristics, it comes with multiple implementation challenges. First, the high sound pressure level required to achieve a refractive index modulation contrast Δn supporting waveguiding ($\Delta n \approx 10^{-6}$ at 367 Pa in air) sets severe demands on the transducer technology. This is in particular challenging, as small transducer apertures and gas-coupled transducers do not favor high sound-pressure levels. At 367 Pa, the optical refractive index reaches $\Delta n \approx 10^{-6}$ in ambient air [11]. Gas-phase sonophotonic waveguides will therefore be weakly guiding, supporting a large mode field diameter and favoring long propagation lengths. Importantly, a sonophotonic control system must be adapted to the wave nature of acoustic pressure fields, including the temporal dynamics. This offers control opportunities for pulsed lasers, including access to pulse-to-pulse dynamics without additional optical components. The temporal domain represents the fourth dimension of the platform. Combined with the programmable fifth dimension, it offers spatio-temporal pulse control beyond what is possible in static waveguides. Second, the weak guiding conditions demand longitudinally homogeneous or only slowly changing refractive index profiles. Practical waveguides must therefore support smooth transverse acoustic field profiles, suppressing higher-order acoustic resonances which can introduce undesired optical scattering and longitudinal uniformity, mitigating boundary effects, optical modal beating, and phase slippage that may translate into pointing errors and mode impurity. In addition, acoustic attenuation, boundary-layer losses, and acoustic streaming can heat the gas and distort the refractive index profile, setting parameter scaling limits. A third and key challenges arises due to the highly multi-dimensional, multi-objective optimization demands if a large number of ultrasound transducers need to be controlled. To achieve configurability, the signals driving the individual transducers must be actively controlled to create a sound field that in turn provides the desired optical properties, representing a challenging inverse design

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problem. Progress will depend on systematic, multi-physics-aware optimization workflows—possibly combining inverse design of the acoustic/optical structure with digital-twin co-simulation, integrated diagnostics, and closed-loop control strategies to achieve application-grade performance.

Advances in science and technology to meet challenges

The rapid evolution of machine learning provides us with robust frameworks for navigating problems characterized by many degrees of freedom. Programmable sonophotonic elements span a large control parameter space, forming great challenges where machine learning methods can unlock their full potential. If several individually controlled ultrasonic transducers create a complex spatio-temporal sound field, three main challenges arise.

(i) Inverse design: Typically, when designing an optical element, the design process is inverse, starting with desired optical properties of the envisioned device, the device geometry needs to be derived. In the specific case of a sonophotonic device, the forward direction is simple: We can simulate the emerging sound field and then subsequently propagate a laser beam through it, obtaining output beam/ pulse characteristics. The inverse question, i.e., how to drive the individual transducers to drive a sound field that has the desired effect on a given optical input, is hard. To address similar challenges, machine learning-based approaches have worked very well [13]. The design challenge scales with the degrees of freedom, and for a sonophotonic device, this number can be large. Considering single-frequency ultrasonic transducers in a four-transducers-per-segment array forming a sonophotonic waveguide with 200 segments, 1,600 degrees of freedom emerge if amplitude and phase control are considered. While this poses severe challenges for traditional optimization like Bayesian optimization [14], deep learning methods such as gradient-descent approaches thrive in this regime [15-17], making supervised mode-target matching a near-term tractable goal for moderate transducer counts. Optimization across the full 1,600-dimensional space with real-time updates within a single acoustic cycle (≈3.3 μs) set a longer-term challenge.

(ii) A second challenge lies in verification and measurement: to assess the performance of an optical element, one needs to accurately and quantitatively determine the spatio-temporal refractive index modulation. For static 2D or 3D phase samples, this is a well-known challenge [18, 19] while in a multidimensional and optionally time-dependent case with a weak optical index contrast, standard methods cannot easily be applied. Here, emerging methods using machine learning approaches show great potential [20-22], using multimodal measurement-driven physics-informed or -augmented neural networks. Direct application to a confined standing-wave geometry with $\Delta n \approx 10^{-6}$ has, however, not yet been demonstrated and remains an open research problem.

(iii) Finally, in order to design and optimize a sonophotonic device such as a sonophotonic waveguide, advanced adaptive control mechanisms are needed. Such a control mechanism must map the predicted control signal to a real physical device and deal with model inaccuracy, thus addressing the so-called simulation-to-reality or sim-to-real gap. This is also an active field in machine learning and recent algorithms based on reinforcement learning succeed in training models to handle this challenge, e.g., using formal methods [23] or model predictive control approaches [24]. Near-term implementations can realistically leverage offline-trained models with periodic updates on timescales much longer than the acoustic period ($T_{ac} \approx 3.3$ μs). Fully closed-loop real-time control operating within a single acoustic cycle remains a longer-term objective, contingent on advances in latency-optimized inference hardware.

Concluding remarks

We have introduced gas-based sonophotonics as an emerging platform for 5D—and potentially higher dimensional—photonics. Within the D5 scope of the roadmap, the three spatial dimensions of the gas volume and time constitute the conventional four dimensions; the fifth is defined by the programmable acoustic control space, each point of which sets a distinct refractive-index landscape $\Delta n(r, t)$ imprinted in the gas on

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microsecond timescales without any permanent material modification. While earlier work has already shown that gas-based sonophotonics can disrupt conventional photonic components by vastly expanding the acousto-optically addressable parameter space of laser sources [1], our contribution extends this paradigm to configurations employing multiple ultrasound sources and to a gas-based sonophotonic waveguide concept. These multi source architectures provide additional degrees of freedom, enabling reconfigurable control over an extended set of optical output dimensions. As a result, sonophotonics offers a clear pathway toward future high-dimensional light control across large spectral and optical power ranges.

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Section 6.3 – Acoustic waves to capture context and enable recurrent optical neural networks

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Status

Photonic machine learning promises energy efficient computing and high-capacity and high-speed signal processing. Optics has the potential to fulfill the requirements, but it mostly relies on the ability of upscaling the different concepts and providing in-situ learning mechanism. There has been a plethora of proposed approaches, ranging from Mach-Zehnder meshes on a chip [1], diffractive networks [2], VCSELs [3] and recently optical-fiber-based and nonlinear photonics approaches [4-13]. The latter carry optical information over long lengths and are able to transmit information with low loss and at a high bandwidth. Several approaches use nonlinear fiber optics for processing information, for example supercontinuum generation as a reservoir [8]. One novel way of adding new functionalities is through the nonlinear optical effect of stimulated Brillouin-Mandelstam scattering (SBS) [10-13]. SBS couples an optical pump wave, a counterpropagating optical Stokes wave and a traveling acoustic wave together [14] – an interaction which can even reach the strong coupling regime [15] and can be used for entanglement generation [16]. SBS was exploited for optical sensing, microwave photonics, narrow-linewidth lasers and Brillouin microscopy and was experimentally investigated in photonic integrated chips as well as optical fibers [17-23].

The fact that SBS involves acoustic waves makes the approach interesting in terms of time scales and new functionalities. For example, acoustic waves remain much longer in the transmission medium than light waves, which enables access to past computational steps. The interaction is also inherently nonlinear, which can be used for deep learning. The interaction of optical and acoustic waves can be controlled by external optical pulses which makes it a powerful tool for different photonic systems and neural network structures. Very recently, optoacoustic signal processing has therefore been demonstrated for the use in photonic neuromorphic computation [10-13,24-26].

An all-optical nonlinear activation function has been demonstrated based on traveling sound waves [13]. It has a programmable nonlinearity, low optical losses, is frequency selective, coherent and compatible with integrated photonic chip approaches (Figure 1). Different activation functions such as a LEAKYRELU or SIGMOID shape were shown by only altering external optical parameters (control pulses). As SBS can amplify the signal, this type of nonlinear activation can also compensate for insertion loss providing optical gain as high as 20 dB. This important when projecting towards deep optical neural networks where each layer adds additional losses.

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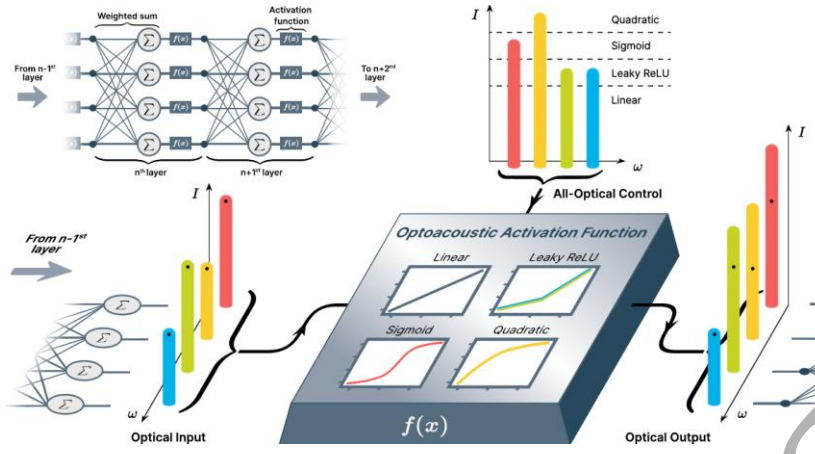


Figure 1. Concept of inserting an optoacoustic activation function (controlled all-optically and being able to compensate optical losses) into a generic optical neural network [14]. Such an activation function can be implemented in the synthetic domain, in Mach-Zehnder configurations and others which are based on waveguides or optical fibers. Figure by Grigorii Slinkov.

Photonic memory was studied as volatile and non-volatile approaches [27]. Acoustic waves can serve with their much slower speed as versatile and flexible memory, particularly as high-speed and coherent random-access memory. Via the effect of SBS, the photonic-phononic memory coherently transfers optical information to traveling acoustic waves, that propagate at 5 orders of magnitude lower speed [10,11,24-26,28,29]. The Brilloulin-based memory addresses key requirements for an optical high-performance random-access memory due to its coherence [11,29], on-chip compatibility [29], frequency selectivity [25] and high bandwidth [24]. The memory was also proven to be quick-access [24], can be operated flexibly at several positions on a photonic chip. This type of photonic memory is nonreciprocal because of the directionality of the acoustic waves, which is an advantage as data is not impacted by simultaneously counterpropagating optical data pulses [31].

Because the acoustic waves stay longer in the medium, they are also perfect candidates for recurrent optical networks. Usually, these networks are implemented as fabricated structures or delay lines, which limits the bandwidth, multifrequency operations in the synthetic domain and requires slow tuning of the parameters. Acoustic waves can be generated at the nanosecond scale. Using acoustic waves, the recurrent functionality can be implemented in a versatile manner in a transmission waveguide itself. The optoacoustic recurrent operator (OREO) was experimentally demonstrated in Ref. [12] to process contextual information such as time series signals. OREO links information of an optical pulse train via interaction acoustic waves and therefore, the information of one optical computation step is linked via acoustic waves to the next one. Similarly to the photonic-phononic memory, OREO is controlled via external optical pulses, therefore no actuators are needed. The interaction between the different data pulses can be repeated and the processing steps are linked over several layers as long as the acoustic wave has not decayed. OREO can be introduced as a bi-directional perceptron for new classes of optical neural networks.

Current and future challenges and advances in science and technology to meet challenges

As acoustic waves can add tunable delay in information processing as well as nonlinearity for artificial neural networks and sensitivity to the environment, they bridge several time scales, can act as detectors and sensors and are reconfigurable. This new dimension can therefore lead to a new class of application and computing architectures.

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Several challenges of the approach are as follows. One prominent limitation is the short acoustic lifetime—only a few nanoseconds—caused by damping of the acoustic waves, which leads to short times for memory and signal processing. However, several approaches have been shown to overcome this limitation. An optical 'refresh' schemes that reinforces the existing acoustic waves by transferring energy to them without rewriting the stored data, has been experimentally proven. Another approach uses different polarizations where the incoming data and outcoming data is traveling in different optical modes and are additionally delayed by an acoustic wave [38]. Yet another way is to cool the system to about 4 K, extending signal retrieval to around 140 ns—more than an order of magnitude longer than at room temperature [10]. This increased lifetime could benefit more advanced signal-processing architectures by supporting higher data throughput. Note that a storage time of around 140ns additionally to a short optical pulse time of around 100 ps results in a delay of 14000 pulse widths which is unachieved in most other schemes. Another challenge is the intrinsically narrow Brillouin resonance linewidth, which can hinder signal processing with short pulse. In glass fibers, fused silica, the 30 MHz linewidth limits optical pulse durations to a few nanoseconds. Recent studies, however, show that using sufficiently high gain can offset this constraint, enabling operation with much shorter pulses [24]. A further challenge is increasing the information capacity, which can be pursued through coherent encoding schemes. Recently, researchers have demonstrated the storage of quadrature-phase-shift-keyed (QPSK) signals at both room and cryogenic temperatures [11]. The next major step will be scaling this capability to support higher-order QAM formats. Besides the classical domain, one can also imagine the processing of quantum information. In recent works, SBS interactions have been experimentally investigated towards the quantum domain [32-38]. One challenge and prospect is therefore to treat quantum information instead of classical information which brings other requirements to noise, stability and fidelity of the processes. Upscaling this type of systems can either be done at the level of the input: taking into account the phase space with potentially up to 10bits information capacity per pulse, 100 frequency channels and a 100 pulse long pulse train, one can reach 10^5 bits [11] without taking into account different polarization states [39] and higher order spatial modes. With recently achieved record optoacoustic gain factors [40] and by using many neural network layers [12], upscaling is within reach.

An important challenge for neuromorphic systems is the in-situ training – a challenge which holds for most of the optical neural networks approaches . Here, the 5D approach represents the immediate feedback while training the physical systems and potentially self-learning systems as going forward. So far, many optical approaches for computing use the approach to train the system digitally off-line and use the optical neural network for inference with very low losses, high speed and large information throughput. However, training a neural network takes up a lot of energy, often more than is actually used for inference. Therefore, we consider the two biggest challenges in optical neural networks the upscaling to large systems and the in-situ training of the physical systems themselves.

In optoacoustic systems, there are different options for training, for instance the manipulation of the optical phase by detuning off-resonance [11]. As depicted in Fig. 2, the optical phase can either be retrieved as originally encoded or manipulated while in the acoustic domain by different optical control pulses, demonstrating a spiral of possible phase read-outs.

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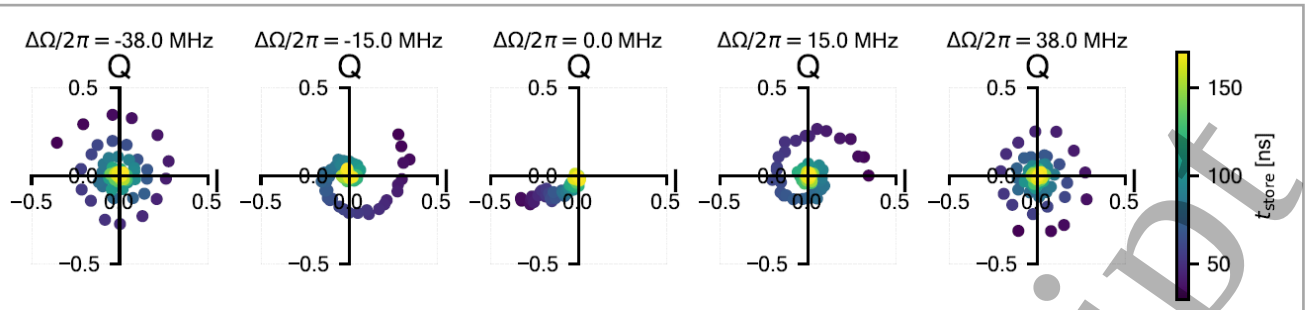


Figure 2. Phase-phase diagram of coherent optical data that has been stored in acoustic waves and retrieved under different conditions [12]. The phase information can either be read-out or manipulated in the acoustic domain such that the phase can be used a training parameter for the optoacoustic system. Figure by Olivia Saffer and Jesus Marines Cabello.

In this chapter, the focus is on optoacoustic signal processing, but there is a real plethora of promising approaches in the community, a small subset of them is mentioned in the table below:

Table 1. Novel functions enabled by a selection of photonic machine learning approaches.

New Functions and degree of freedom	Applications
Frequency combs for computing: synthethic domain	Energy-efficient signal processing in the synthetic domain, beneficial for telecom networks.
Deep diffractive neural networks: 3D computing	Spectral and spatial pattern recognition, classification of optical signals.
Micro-LED arrays: Reconfigurable in the time domain	Reconfigurable and modular general purpose optical deep neural network.
Optoacoustic signal manipulation: Acoustic domain, additional time dimension	Flexible and reconfigurable neural networks, language recognition and image classification.

Concluding remarks

Photonic machine learning will contribute to efficient signal processing in many applications despite the grand challenges. In-situ training of optical neural networks will here be of utmost importance because it allows these systems to learn directly within the photonic hardware, avoiding the costly back-and-forth transfer of data between optical and electronic domains and fully exploiting the speed, parallelism, and energy efficiency of light-based computation. The acoustic domain will add another dimension to enable reconfigurable, fabrication-less and trainable networks that carry information in the optical domain. It can add memory, access to the environment, processing in the optical frequency domain and even nonlinearity. This additional dimension might make systems faster as the recurrency can be implemented in the transmission lines themselves, substituting complicated feedback-structures that induce losses.

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Section 6.4 – Adaptive photonic measurement systems – novel tools for sensing and imaging in life sciences

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Status

Optics and photonics currently provide viable solutions for versatile applications in medicine and the life sciences owing to the distinctive interaction between electromagnetic radiation and biological matter. A broad spectrum of optical techniques, ranging from incoherent and coherent imaging over linear and nonlinear spectroscopy to spatially and temporally resolved light-matter interrogation has found its way into a multitude of use cases in medical diagnostics, therapy, environmental and process monitoring or biochemical analytics. Typical examples are label-free and miniaturized optical systems for sensing of hazardous substances or detection of pathogenic microorganisms [1], disease diagnostics [2] and health monitoring [3].

A state-of-the-art integrated optical bio-sensing system is shown in Figure 1. Using surface plasmon resonance (**Error! Reference source not found.**) detection, which is label-free and requires minimal sample preparation, reliable detection of individual biomolecules (C-reactive protein, CRP) in liquid environment was achieved **Error! Reference source not found.**. For high specificity, aptamer-functionalisation was implemented. Target-induced dissociation (**Error! Reference source not found.**) and aptamer-functionalised gold-nanoparticle (**Error! Reference source not found.**)-enhanced assays enable limits of detection (LoD) in the nanomolar range. This allows for sensitivities comparable to medical-grade laboratories. The miniaturised system was operated by a smartphone, also showing that optical sensing and

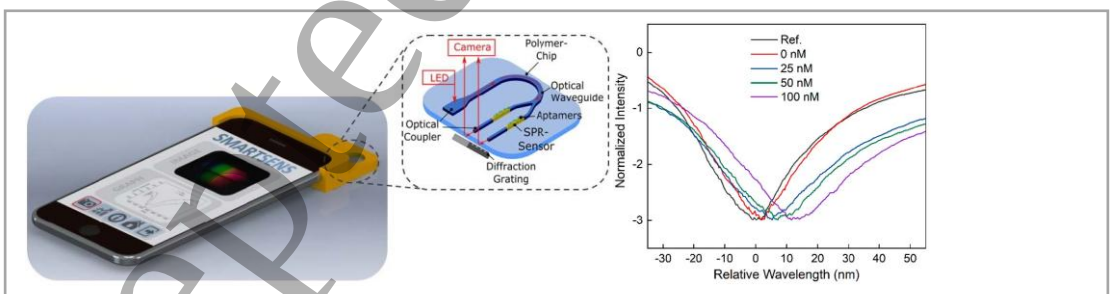


Figure 1. Left: Developed **Error! Reference source not found.** sensor. Microfluidic and optical sensor chip embedded into 3D printed housing (yellow element) attached to and operated by a smartphone. Right: Measured **Error! Reference source not found.**

microfluidics can be realized by cost-efficient scalable fabrication **Error! Reference source not found.**.

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In another example, a high-speed ellipsometer was developed for the study of biological interaction, surface chemistry, and thin-film characterization **Error! Reference source not found.**. The novel phase modulator spectroscopic ellipsometer (**Error! Reference source not found.**) approach does not require movable parts and was used to detect E.*coli* bacteria with a LoD of 10^{-2} **Error! Reference source not found.**/ml. Still, adaption to different use cases is not possible so far.

Current and future challenges

Many of the optical measurement systems available today represent individual solutions for specific use cases. Most of them are not yet broadly available and manufacturing cannot easily be scaled up. A photonic platform which is adaptable on demand to different use cases would represent a major advancement offering the possibility to realize sustainable, resource-efficient and reconfigurable systems, e.g., for automated high-throughput diagnostics or distributed sensing networks in bio-analytics, with highest sensitivity and specificity. Functional micro- and nano-optics consisting of stimuli-responsive, phase-change or active materials which can be tuned by electrical or magnetic fields, temperature, or light could form the basis for a more advanced future platform, however, material compatibility and on-chip integration as well as calibration are still challenging. Furthermore, rapid switching between functionalities as well as easy and on-the-spot analysis of the measurement would be beneficial. To realize this, a combination of real components and their virtual representation on the same physical platform which is at the core of 5D photonics needs to be implemented. For fast analysis, artificial intelligence (AI)-based data processing and/or photonic computing networks co-integrated on the same chip are required which are also not available at large. Ultimately, the challenge is to realize miniaturised and environmentally robust devices that can function in harsh in-field conditions, making realtime applications and adaption feasible.

Advances in science and technology to meet challenges

Future versions of such devices will strongly benefit from 5D photonic concepts, e.g., be capable to perform fully automated, high-throughput, quantitative screening and diagnostics, adaptable to different sensing and imaging applications by using external stimuli. For example, nanophotonic elements such as diffractive optics or metasurfaces can be employed to tailor the far-field spatial and spectral properties or the polarization of the light used for sample interrogation or to adjust the spectral bandwidth and resolution of spectrometers, yet ensuring high measurement speed and robust operation for all functionalities. This can be achieved, e.g., by tuning of the properties of the system components, e.g. the refractive index, nonlinear coefficients or the shape of the structures both locally or globally. Manipulation of the near-field properties of nanophotonic elements can be exploited for superresolution microscopy, in particular in connection with micro- and nano-light emitting diode (LED) arrays [7]. On-demand reconfiguration of the systems by minuscule changes of optical or structural properties will further enhance the application range. Also, the on-chip co-integration of real and virtual system will enable automated calibration reducing the need for re-calibration and service throughout the whole life time of the devices. The vision to reduce the size of expensive laboratory-scale biosafety laboratories to table-size dimensions providing unique opportunities for distributed analytics can become reality. Consequently, currently unmet demands for multiplex detection of a large variety of substances, e.g., bacteria, viruses or toxins from liquid biopsies or gas-phase, essentially in realtime, will be possible. With that, early diagnostics of diseases such as cancer, inflammation or viral and chronic infections appear feasible, at reduced costs and personnel expense. To be competitive, future 5D photonic systems need to reach sensitivity levels comparable to those of current state-of-the-art (laboratory) systems, i.e. in the nanomolar or picomolar range, preferably at lower cost and smaller footprint. Also, high-volume production suitability of the systems would be advantageous.

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Approaches towards the realization of adaptive integrated photonic systems rely on the capabilities of modern manufacturing technologies for micro- and nano-optics. Prominent examples for such technologies are electron beam lithography, stereo-lithography or single and multi-photon polymerization which have demonstrated their potential to enable functional photonics at those scales. Such elements bridge the size gap between the wavelength of the light (several 100 nm) and the dimension of typical biomolecules (nm-range) and enable the creation of resonant structures with high quality factors, ultimately increasing the interaction between target molecules and sensing area. An example of a manufactured metasurface with narrow resonances forming bound states in the continuum (BIC) suited for biomolecule detection can be found in [8, 9], see Figure 3, demonstrating the feasibility of such approaches. By changing the geometry, shape or orientation of the structures fabricated by semiconductor structuring technology through external action different spectral bands could be addressed.

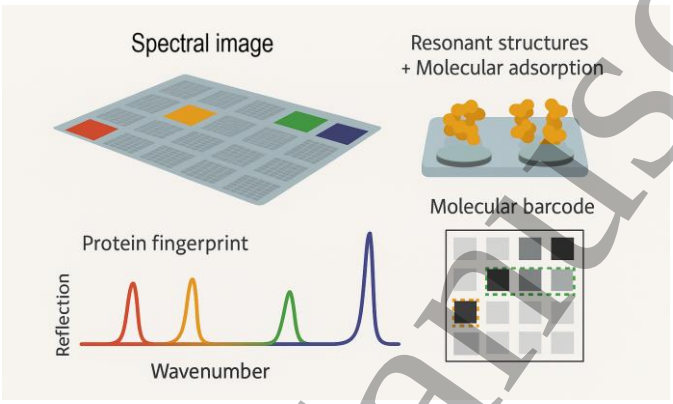


Figure 2. Concept for biochemical detection relying on dielectric metasurfaces. (a) Structured dielectric surfaces consisting of resonant structures ensure high quality factors and high vibrational band amplification of adsorbed molecules. (b) If the resonance wavelengths of individual pixels (color-coded areas) are tuned to molecular-specific bands, spatial encoding of spectrally resolved molecular signatures is possible. (c) Read-out of the encoded information creates barcode spectra suited to analyse the chemical fingerprint of complex biosamples. Redrawn from [8].

The 5D photonics concept takes such approaches one decisive step further, by envisioning tuning of such resonances in a fast and reproducible way, efficiently and at the micro- and nanoscale, on the basis of external stimuli, e.g. by using phase-change materials or switchable polymers, see Sections 5.4 and 6.6 for suitable concepts. Interesting materials and structures for such purposes could be (i) thermoresponsive hydrogels, e.g. poly(N-isopropylacrylamide) (PNIPAm), or soft-responsive liquid crystalline networks (LCNs), (ii) azobenzene photoswitches, (iii) chalcogenide phase-change materials, e.g. $Ge_2Sb_2Te_5$ (germanium-antimony-tellurium, GST), and (iv) nanostructured all-polymer metasurfaces based on polymethylmethacrylate (PMMA) films or silicon-based dielectrics, to name just a few, compare also [9-12]. Ideally, the tuning of the material properties and the reconfiguration of the system functionality is to be achieved optically, as light-induced stimulation is fast, energy-efficient and enables a high degree of spatial and temporal control. Also, Fano, plasmonic, or scattering resonances might be exploited as foundation for future 5D photonics systems [13-16].

Overall, such a measurement platform could be adapted to different target substances and ideally to multiplexed species detection on the same chip with clinical-grade sensitivity and robust operation on the spot, e.g. for point-of-care testing (POCT) [5], tumour imaging [17, 18] or distributed and remote sensing [19]. More advanced measurement concepts employing the orbital angular momentum (OAM) of light or

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quantum optics-based approaches relying on chip-integrated single photon or entangled photon pair sources might increase the sensitivity by orders of magnitude, thus, leading to the next generation in integrated optical instruments in life sciences [20]. Table 1 shows some examples of the novel functionalities which can be realized in future together with the potential application areas.

Table 1. Novel functions enabled by adaptive photonics for applications in life sciences.

New Functions	Applications
Automated diagnostics: Analysis of complex biosamples.	Biosafety-level high-throughput laboratory at table-size scales.
Mobile and wearable biosensing: Integrated photonics for multiplexed biomolecule detection	Affordable point-of-care testing with high sensitivity and specificity.
Tissue-optical interfaces: Enhanced efficiency of optical tissue stimulation at cell-level.	Optical control of cell-based processes. Tissue and neuronal stimulation.
Lensless imaging: Micro-LED arrays for super-resolution imaging of biological samples.	High-resolution smart microscopes for analysis of biosamples.
Metasurface-functionalised optical fibers: tailored light generation.	In vivo endoscopic **Error! Reference source not found.**, Raman spectroscopy, in-fibre analytics, and 3D-controlled light-delivery.
Multi-functional imaging: micro- and nanooptics for polarization-sensitive cameras	Low-footprint optical systems for live cell imaging and biofilm analysis

Concluding remarks

The vision of integrated optical systems with control of functionality requires the realization of custom-designed micro- and nano-optics from stimuli-responsive materials and the combination of the physical system with its virtual counterpart on the same platform. This might find versatile applications which are not accessible so far using static systems. The miniaturisation of components and the spatial and temporal tuning of their properties, e.g. refractive index, non-linear coefficients, polarization or beam shape, lend themselves for the realization of such systems, for multiplexed biosensing, linear and non-linear imaging spectroscopy, or high-throughput screening, among others. Medical diagnostics and therapy can benefit from the envisioned developments, i.e., for endoscopic optical coherence tomography (OCT) for cancer screening or chip-based dual frequency comb spectroscopy for breath gas analysis. To achieve these goals, research on (multi-)responsive materials which can be processed using modern manufacturing technology, efficient optics design approaches, e.g. based on inverse design, or resonant and tunable metasurfaces in the visible and infrared wavelength range is required. It would also be beneficial to realize the systems by manufacturing technology beyond lithography, e.g., by single or multi-photon polymerisation or microscope projection photolithography [21], as these can process low-cost and flexible polymer materials [22-24]. Also, the use of ceramic, glass-based, conductive and biodegradable materials will be beneficial. The transfer of 5D photonics to the life sciences can thus represent a major step towards resource-efficient and yet highly functional measurement devices based on optical principles, suited for precision medicine, realtime analysis or in vivo imaging, in particular when combined with deep learning/AI concepts. When implemented on photonics networks, the latter can even be made much more energy-efficient compared to state-of-the-art. Finally, quantum optics concepts can be employed to enhance the functionality of the measurement systems or enable completely new devices with significantly increased sensitivity, also for in vivo applications. All

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this might ultimately pave the way for the democratization of 5D photonics in medicine, the life sciences and society as a whole.

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Section 6.5 – Metafibres: an advanced solution for optical communications by using metasurfaces on the tip of optical fibers

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Status

Optical communications, the backbone of modern global communication systems, require effective fiber-to-fiber and fiber-to-chip interfacing. While the former is routinely done with end-fire coupling, the latter require some nontrivial coupling solution using gratings, and adiabatic couplers. However, as the nomenclature of optical fibers significantly expands, finding effective fiber-to-fiber coupling solutions in the case of multimode and multicore fibers is no longer trivial. One potential solution to this problem is to employ metasurfaces. A metasurface is a periodic nanostructure with in-plane dimensions a lot smaller than the wavelength of light under consideration and can be designed to manipulate the phase front of light for focusing, steering, beam shaping etc. However, to fully benefit from the compactness of the metasurface, it would be ideal if it is placed directly on the fiber tip. Research regarding integrating metasurfaces at the tip of optical fibers, so-called *metatips* or *metafibers*, is currently expanding. [1-3].

Metafibers have been developed initially for biosensing applications [4-8], but currently they are developed towards applications in optical telecommunication, for example to sort optical signals from one multicore fiber to the other, convert different modes from a multimode fiber and couple them into another multimode or a multicore fiber, to focus or steer light signals [9-16].

Nowadays, there are two main approaches for obtaining a metasurface, or metasurface-like structures directly on the tip of a fiber. One option is to fabricate the metasurface on the tip of the fiber using 2-photon polymerization (2PP). [16] A higher resolution way of doing direct fabrication is to use focused ion beam (FIB) [6, 7] or electron beam lithography (EBL). [4]

The other option is to fabricate the metasurface separately and then transfer it to the fiber. In this case, the two possibilities are either by using microtransfer printing [17], or using the so-called punch-through technique. [9]

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Initial proof of principle demonstrations of the possibilities of using one or another technique were made. However, a quantitative comparison between the various options is not yet possible due to the non-standardized way of measuring the various coupling efficiency or insertion loss data in these cases.

Current and future challenges

One of the main challenges in using metafibers for optical communications is in the design of the metasurfaces. For example, when designing a metasurface at the tip of a multimode fiber, optimizing the design for maximum transmission of each converted mode while minimizing mode crosstalk is non-trivial and has yet to be fully solved.

The current trend of increasing data transmission rates in fiber is to use multicore fibres (1000-core fibres are available now [18]) and/or including another degree of freedom, for example, vortex beams of different orders specified by high-order modes, or the optical angular momentum parameter *l.* [19] When applying these solutions, the efficient multiplexing-demultiplexing of modes becomes an issue, especially when handling many modes. In laboratory conditions, the free space setups successfully address this challenge. However, they cannot be straightforwardly transferred to commercial networks, as difficulties arise in system alignment, in spatial positioning of elements and nonuniversality of each particular solution in presence or expanding nomenclature of the fiber modes. In contrast, metatips can be directly adjusted for any type of mode conversion/selection avoiding alignment problems in most cases. Additionally, mechanical stiffness and resilience of the direct fabrication of metasurfaces on the fibers also works for such approach.

From a fabrication perspective, each of the current techniques has advantages and disadvantages. In the case of 2PP techniques, while successful, it lacks the needed resolution and, as such, the metasurface is sometimes not placed directly on the fiber tip but a specific distance away by using polymer spacing. [10] Moreover, most of the 2PP techniques use polymers and thus the refractive index is small, leading to the need for tall structures to obtain the required phase contrast. Both these factors lead to very fragile structures, thus difficulty in handling the metafibers.

In the case of direct fabrication on the tip of the fiber using FIB or EBL techniques, the needed resolution can be achieved. In addition, there is more flexibility in choosing fabrication materials with high refractive index or even metals. However, the FIB techniques are slow, can easily damage the fiber itself and generally have low sidewall angles and high roughness, while the EBL ones are difficult to implement.

When transferring ready-made metasurfaces, one can obtain high-index membranes, and the patterning is relatively easy using well-developed techniques. However, the alignment of the metasurface to the fiber, as well as the adhesion between the two can be challenging.

Advances in science and technology to meet challenges

As the nomenclature of modes available for optical communications is expanding, there is a need to prepare a library of designs of metasurfaces for specific mode conversions, e.g. vortex beam to gaussian, gaussian to high-order fiber mode, etc. Such a library will provide a standardization of the needed metasurfaces, from which automatic design tools will pick up the initial intelligent guesses for further optimization in the frames of the formulated requirements. These final designs can be obtained through inverse design techniques, where iterations of intuitive structures are optimized, using machine learning algorithms, topology optimization packages or artificial intelligence approaches. However, thorough numerical validation of

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extended multilayer designs is still based on direct Maxwell's solvers thus it constitutes a bottleneck in the design procedure.

The biggest challenge so far as seen from the current state of nanofabrication is the metafibers production. Most of the current techniques are not scalable, thus reaching large scale production of metafibers is a direction of research.

Fabricating metasurfaces directly on the tip of the fiber is still far from the large-scale production capability it should have. If this technology proves itself to be reliable for proof-of-concept demonstrations, specific lithography machines that can handle exposure on the fiber tip with the needed resolution need to be developed.

Currently, micro-transfer printing is a technique with the greatest potential for scalability. In recent years, the angular and lateral resolution of this technique advanced greatly and, with the improvement of designing alignment-tolerant metasurfaces, it reached a level where one can envisage using it to medium and large-scale production of metafibers. One aspect to be still investigated relates to the adhesion of the metasurface onto the tip of the fiber, but techniques like alumina-alumina bonding [20] can be of help here.
In both these nanofabrication cases, we are lacking certain technological advances to obtain reproducible, large-scale production of the metafibers but the advancements in micro-transfer printing technique position this approach as the most reliable for large-scale production.

Looking further, reconfigurability of metafibers may be needed for certain applications. Neither of the existing solutions nowadays are built with reconfigurability in mind. One possible solution could be a hybrid approach, where tuning is electrical, but having electrodes and metal contacts on the tip of the fiber is not straightforward. Optical reconfigurability might be another possible solution, where one mode of a multimode fiber can be used for tuning.

Concluding remarks

Nowadays, metasurfaces are the most advanced compact structures to control beam propagation while optical fibers are the backbone of internet technology. Combining these two research fields will lead to new, more effective and reliable procedures for transmitting long-distance signals and interfacing long-distance and short-distance optical communications. However, it is highly challenging both from the scientific and technological point of view to merge these research fields.

This hybridization will not only bring new possibilities for optical communications and interfacing various fibers but will advance our knowledge on the possibilities of metasurfaces and, possibly, allow for new applications of these structures. To achieve this hybridization there is a clear need for a further dimension. This dimension may reside in the use of advanced neural networks for designing these surfaces, but also in the development of the fabrication techniques needed for reaching the desired functionality. The 5D metafibers achieved will allow for easier, faster and more reliable integration of optical systems, from high-capacity data transmission to IOT devices and advanced sensors.

Research into the possibility of obtaining reconfigurability of metafibers will also lead to better reconfigurable metasurfaces overall and allow for quick interfacing of different types of fibers, when necessary.

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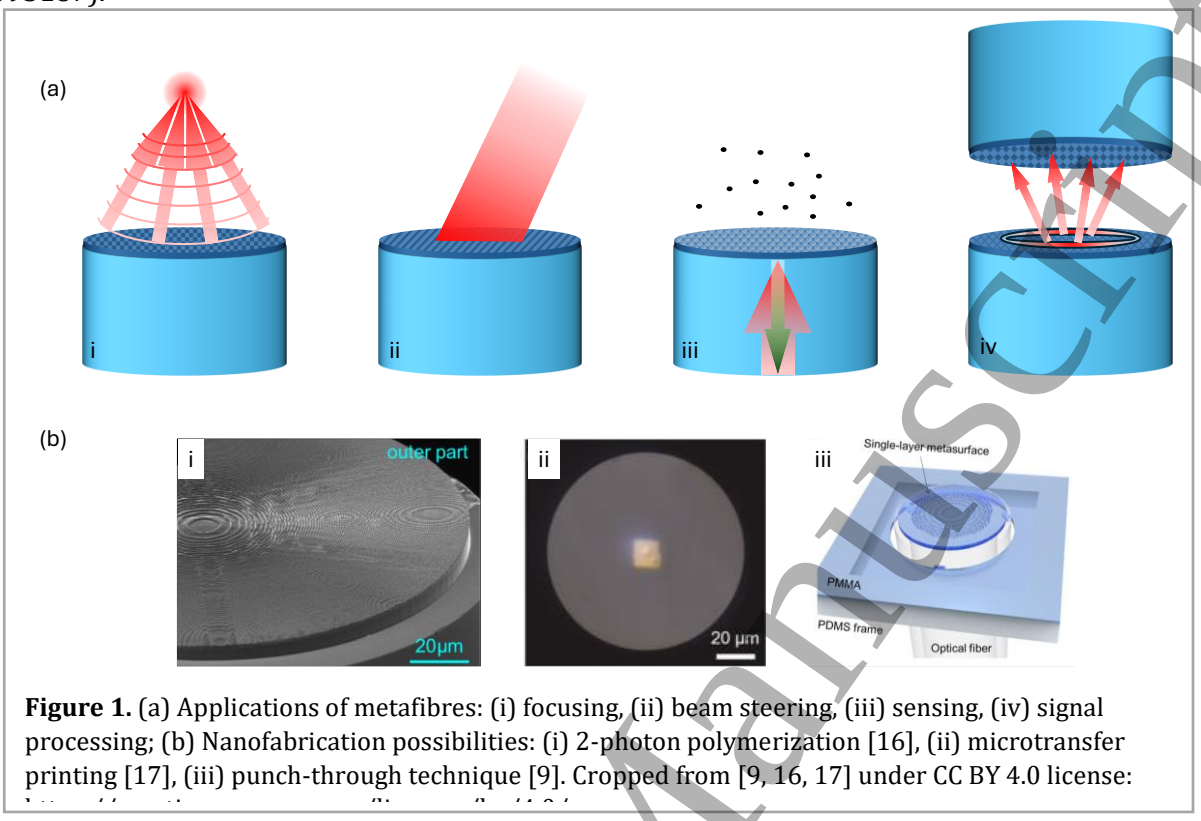


Figure 1. (a) Applications of metafibres: (i) focusing, (ii) beam steering, (iii) sensing, (iv) signal processing; (b) Nanofabrication possibilities: (i) 2-photon polymerization [16], (ii) microtransfer printing [17], (iii) punch-through technique [9]. Cropped from [9, 16, 17] under CC BY 4.0 license:

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Section 6.6 – Material and design challenges in active nanophotonic devices and metasurfaces

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Status

Over the past two decades, metasurfaces and nanophotonic structures have revolutionized light manipulation at subwavelength scales, transitioning from fixed diffractive elements to multifunctional and reconfigurable platforms. Early demonstrations were primarily focused on the static control of phase and amplitude using dielectric or plasmonic nanoantennas. However, the introduction of active and hybrid materials, such as electro-optic compounds, phase-change materials (PCMs), and transparent conducting oxides (TCOs), has transformed metasurfaces into dynamic and programmable systems capable of modulating light across multiple dimensions [1], thereby laying the foundation for high-dimensional multifunctional photonic platforms. The emerging field of 5D photonics, encompassing wavelength, polarization, spatial position, phase (or amplitude), and temporal tunability, can revolutionize photonic devices, unlocking new functionalities and superior performance, provided that continued advances in nanophotonic architectures, materials science, and dynamic optical control are sustained.

Today, the field of 5D photonics is rapidly progressing toward compact, integrable, and energy-efficient devices that outperform conventional bulk optics. Metasurfaces with electrically tunable materials, such as $LiNbO_3$, and other emerging ferroelectric oxides ($BaTiO_3$ and $BiFeO_3$), enable fast and reversible modulation of the refractive index for high-speed beam steering [2]. PCMs such as vanadium dioxide (VO_2) are promising materials because their metal-insulator transition enables fast, reversible, and large optical modulation [3-5]. In addition, other PCMs, such as $Ge_2Sb_2Te_5$ and Sb_2S_3, offer non-volatile switching and multi-level memory states, enabling optical data storage, reconfigurable filters, and neuromorphic photonics. TCO materials, such as indium tin oxide (ITO), aluminum-doped zinc oxide (AZO), and lanthanum-doped barium stannate (LBSO), have epsilon-near-zero (ENZ) properties and extend dynamic control to the infrared spectrum, achieving sub-picosecond modulation through carrier-density tuning [6,7]. Integration of these materials into metasurfaces allows simultaneous control of multiple degrees of freedom, realizing the full potential of "5D" manipulation.

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Despite these advances, challenges persist in achieving low-loss, broadband, and energy-efficient tunability, as well as scalable CMOS-compatible fabrication. Addressing these challenges is crucial because controlling all “five dimensions” of light enables the production of compact, chip-scale devices, which could fundamentally reshape imaging, communication, and sensing applications. Further progress will yield transformative gains: ultrafast reconfigurable optical networks, intelligent photonic processors that mimic biological perception, adaptive holography, and compact LiDAR systems. Although metasurfaces and nanophotonic structures enable effective "5D" light manipulation, achieving fast dynamic control remains limited by material performance and fabrication constraints. Continued exploration of hybrid active materials and multiphysics modelling will bridge the gap between static nanophotonics and provide real-time optical control, ultimately establishing 5D photonics as the cornerstone of future quantum information technologies.

Current and future challenges

Realizing the full potential of 5D photonics demands overcoming formidable fundamental and engineering challenges across materials, device architectures, and system-level integration. For example, high-speed electro-optical modulation requires thick materials. Meaningful phase shifts can be achieved by applying large voltages. Scaling such devices without sacrificing efficiency or bandwidth remains an unresolved problem. Furthermore, incorporating ferroelectric or electro-optic oxides onto silicon platforms introduces lattice-mismatch, thermal-stress, and interface-degradation issues that affect long-term stability. These materials and fabrication challenges can be mitigated by synthesizing new materials, such as low-dimensional semiconductors, and further tuning material dimensions and compositions (e.g., 2D/3D heterostructures and hybrid architectures).

PCMs offer an alternative route toward nonvolatile reconfigurability, yet they face their own limitations. The high optical loss and the thermal energy required for switching in compounds such as $Ge_2Sb_2Te_5$ impede low-power and high-speed operation. Achieving reversible, multi-state phase transitions with minimal absorption in the visible and near-infrared spectral regions remains a key challenge. Research into alternative PCMs, such as Sb_2Se_3, GeSe, or chalcogenide-based alloys with engineered bandgaps, may enable lower-loss tunability suitable for optical computing and programmable metasurfaces. However, integrating these materials into nanoscale architectures requires reliable patterning, robust encapsulation, and endurance over many switching cycles.

TCOs, including ITO, AZO, and LBSO, enable ultrafast refractive index modulation via carrier-density tuning; however, they suffer from narrow spectral windows where ENZ behavior can be efficiently exploited. Achieving high optical confinement, modulation depth, and energy efficiency while maintaining transparency across the visible-to-infrared range presents a significant research challenge. Currently, most TCO-based electro-optic and carrier-driven modulators exhibit modulation speeds limited to the few tens of gigahertz, far below the terahertz range required for ultrafast communication and signal processing [22].

Beyond material-specific challenges [8], the integration of active metasurfaces into complex systems introduces new demands for accurate modelling, multiphysics optimization, and scalable nanofabrication. Coupling multiple control dimensions, such as simultaneous amplitude, phase, and polarization modulation [9], requires precise calibration and integration with electronic and photonic circuitry. Overcoming these obstacles will pave the way toward fully reconfigurable, low-loss, and high-speed 5D photonic platforms capable of transforming optical communication, adaptive imaging, and on-chip signal processing.

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Different active material platforms offer complementary advantages in dynamic nanophotonic devices, balancing switching speed, modulation strength, and operational endurance while enabling multifunctional control of optical fields across several degrees of freedom (Table 1). Advances in materials synthesis, nanofabrication, device engineering, and computational design allow the realization of 5D photonics [10]. New materials, such as chalcophosphates, exhibit tunable optical properties and hold promise for low-loss, broadband modulation in dynamic nanophotonic structures [11]. Van der Waals materials are highly attractive for metasurfaces because their atomically thin layers enable strong light–matter interaction, tunable optical responses, and seamless integration with diverse substrates [13,14]. Silicon carbide is a promising material due to its wide bandgap, excellent thermal stability, and strong electro-optic response, making it well-suited for high-power, high-speed nanophotonic and metasurface applications [15-18]. Being CMOS-compatible and mechanically/thermally robust, with a variety of interesting optical and electrical properties, silicon carbide can be a very useful complementary platform for the next generation of these advanced photonic devices. Progress in this field will rely on improved high-throughput, high-resolution fabrication [19], including refined electron-beam and focused-ion-beam lithography, precise thin-film growth, and controlled doping. Process control will critically depend on surface characterization, including advanced near-field optical microscopy and spectroscopy techniques capable of directly mapping field localization and nanoscale electro-optic responses, complemented by ellipsometry and multimodal electron microscopy.

Table 1. Comparison of material platforms for dynamic nanophotonics and metasurfaces, highlighting representative examples, functional capabilities, switching speeds, modulation strength, endurance, and their potential roles in multidimensional light control [3-7, 11, 15-18, 21-24].

Material class	PCMs	TCOs	2D and layered van der Waals materials	Electro-optic materials
Representative examples	VO_2, germanium antimony telluride, antimony sulfide	ITO, AZO, LBSO	Graphene, transition metal dichalcogenides, hexagonal boron nitride, and black phosphorus	$LiNbO_3$, barium titanate, silicon carbide, ferroelectric oxides
Additional functionality	Nonvolatile phase switching with large refractive index contrast and multilevel programmability	Carrier-density tuning and ENZ optical response enabling strong electro-optic modulation	Atomically thin layers with gate-tunable optical conductivity, strong light–matter interaction and optical confinement, enhanced nonlinearity, quantum effects	Field-driven refractive index modulation with low optical loss and strong electro-optic response
Typical switching speed	ns to μs, depending on the excitation	fs to ps	fs to ps	ps to ns
Modulation depth / optical tunability	Very large index change enabling strong amplitude and phase control	Large refractive index variation near the ENZ regime	Moderate modulation, typically enhanced by resonant nanostructures	Moderate to strong phase modulation with low absorption
Endurance / cycling	Typically 10^6–10^9 switching cycles, depending on material and thermal conditions	Very high for carrier-driven electrical modulation	High for electrically gated operation	Extremely high for electric-field-driven operation
Potential applications in 5D photonics	Reconfigurable metasurfaces, programmable optical filters, adaptive holography, optical memory	Ultrafast modulation, dynamic beam steering, wavelength-selective devices, integrated nanophotonics	Hybrid metasurfaces, ultrafast modulation, polarization-sensitive devices, quantum information processing	High-speed beam steering, tunable lenses, polarization control, and wavefront shaping

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Engineered structures with PCM show enhanced field confinement and tunable light–matter interaction, achieving controlled amplitude, phase, and polarization even under varying excitation conditions (Fig. 1). Resolving integration challenges between these materials and established photonic fabrication platforms is essential for scalable active nanophotonic devices. In particular, VO_2 requires effective control of stoichiometry, crystallinity, and film thickness to preserve a sharp and repeatable insulator–metal transition [3-5]. Advances in deposition methods such as atomic-layer deposition, pulsed-laser deposition, and reactive sputtering can enable uniform, wafer-scale VO_2 films compatible with silicon photonics. Additional progress in interface engineering, thermal management, and encapsulation will be necessary to prevent degradation and ensure reliable switching [23]. Developing fabrication flows that integrate VO_2 with nanostructures and standard lithographic processes will allow reproducible metasurface performance and facilitate large-scale device manufacturing. In addition, novel ferroelectric heterostructures and epitaxial integration on silicon or III–V substrates will combine high-speed tunability with CMOS compatibility.

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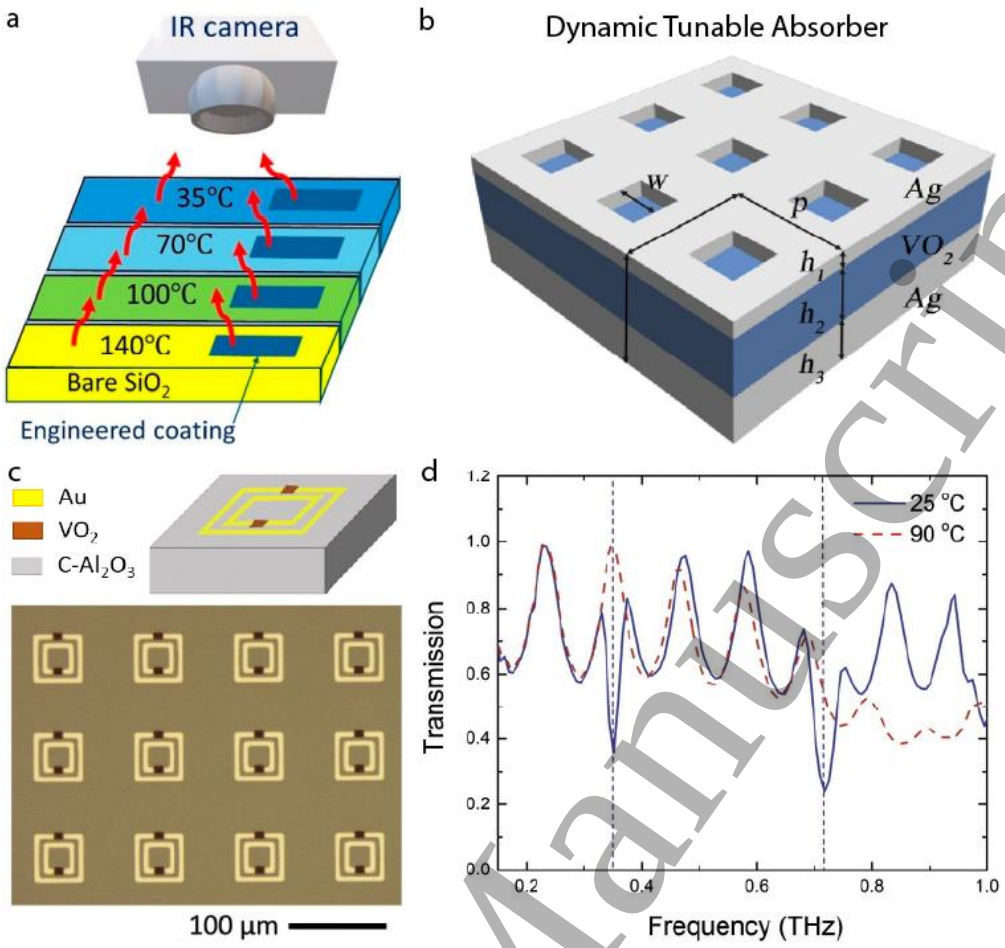


Figure 1. Integration of PCMs in metasurfaces: The case of VO_2. **a** Schematic of the dynamic modulation of a metasurface incorporating PCM. The unmodulated structure exhibits standard optical response across wavelengths and angles. In contrast, the engineered metasurface with PCM shows enhanced field confinement and tunable light–matter interaction, achieving controlled amplitude, phase, and polarization even under varying excitation conditions. **b** 3D view of a dynamic tunable absorber based on VO_2 sandwiched between metal layers. PCM allows for switching functionality of the metasurface absorber across the entire visible band. **c** Schematic of hybrid split-ring resonator (SRR) metasurface based on patterned VO_2 on Al_2O_3 (top) and optical microscope image of arrays of SRR structure and patterned VO_2 (bottom). A modulation efficiency of over 50% can be achieved at the resonant frequencies of this hybrid SRR–VO_2 metasurface device. **d** Comparison of measured transmission spectra of hybrid SRR-patterned VO_2 device at 25°C and 90°C. By changing the conductivity of VO_2 via temperature, the behavior of the SRR gap was adjusted from capacitive to resistive in order to modulate the THz beam transmission at their resonance frequencies (0.3 THz and 0.7 THz) in this hybrid SRR–VO_2 device. a Reproduced from [4], b from [20], and c,d from [21].

Advances in the synthesis and fabrication of TCOs aim to improve carrier mobility, achieve tunable carrier concentration, and reduce damping to extend the tunability range [6,24]. For example, the ENZ wavelength, optical loss, and thickness of the AZO thin film are effectively controlled by the appropriate selection of dopant ratio, deposition temperature, and the number of macrocycles during deposition (Fig. 2). Substantial progress is being made toward integrating TCOs with standard photonic fabrication platforms. Widely used materials, such as ITO and AZO, are increasingly compatible with established thin-film deposition and patterning processes, enabling reliable incorporation into nanophotonic devices. Advances in controlled deposition and post-deposition annealing have improved film quality, carrier mobility, and interface

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stability. At the same time, emerging oxides, such as LBSO, are attracting attention due to their high mobility, and continued refinement of growth conditions, doping control, and integration with nanostructures is enabling scalable fabrication of actively tunable TCO-based photonic components.

From a technological standpoint, realizing multidimensional control calls for the scalable fabrication of hybrid metasurfaces with precise nanoscale patterning. Advances in metasurface design, including optimized nanoantenna geometries and novel unit-cell configurations, enable stronger optical field confinement and enhanced light–matter interaction, paving the way for more efficient, compact, and multifunctional nanophotonic devices [12]. Plasmonic nanostructures offer a pathway to enhanced light–matter interaction, enabling hot electron generation that can drive ultrafast modulation and energy-efficient switching in active metasurfaces and nanophotonic devices [25]. Complementary to these approaches, the observation of a Drude-like optical response and suppressed metal–insulator transition in titanium oxide thin films highlights the role of free-carrier dynamics and broadband optical constants in governing light–matter interaction, providing additional pathways for tunable photonic functionality [26]. Integration with machine-learning-based inverse design tools and multiphysics simulations will accelerate the optimization of metasurface responses across all degrees of freedom. Collectively, these developments will drive 5D photonics toward real-time, multifunctional platforms that unify material agility with system-level intelligence.

Concluding remarks

In summary, the leap from static nanophotonics to fully dynamic 5D photonic platforms marks a decisive frontier pushing light control into a new multidimensional regime. The simultaneous control of wavelength, polarization, spatial field distribution, phase, and temporal response will enable highly efficient, powerful devices that are compact, adaptive, and capable of real-time operation. Continued innovation in electro-optic, phase-change, and transparent conducting materials, combined with hybrid integration and data-driven design methodologies, will be critical to overcoming current limitations in speed, efficiency, and scalability. There is no single material solution to address the challenges of 5D photonics. Progress will depend on the skillful development of non-traditional materials and/or their integration into multi-material systems, combined with novel nanostructure design and fabrication. As material performance advances, metasurfaces and nanophotonic structures will evolve into programmable optical systems with unprecedented functionality and performance. These capabilities will not only transform classical applications in imaging, communication, and sensing but also open pathways toward intelligent, reconfigurable photonic architectures essential for next-generation information processing and quantum technologies. Future advances will likely depend on hybrid approaches that combine multiple tunable materials and leverage machine learning or inverse design to optimize device functionality across all five dimensions.

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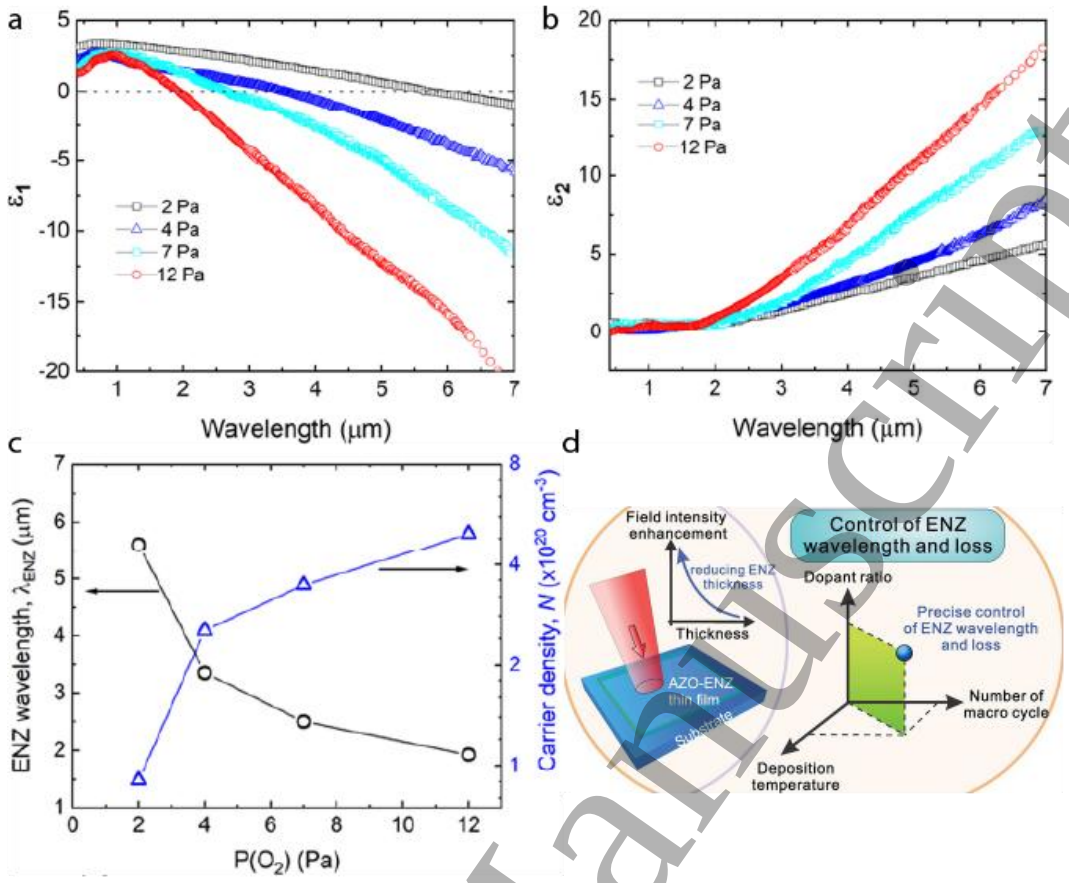


Figure 2. TCO tunability. **a** Real ε_1 and **b** imaginary ε_2 parts of permittivity of LBSO films deposited on MgO at four different oxygen pressures (2, 4, 7, and 12 Pa). **c** ENZ wavelength λ_{ENZ} and carrier density N for LBSO films deposited on MgO at different oxygen pressures. **d** Control of ENZ wavelength of Al-doped zinc oxide AZO with atomic layer deposition process. ENZ wavelength, loss, and thickness of the AZO thin film are effectively controlled by the appropriate selection of dopant ratio, deposition temperature, and the number of macrocycles during the deposition process. The excitation of the ENZ mode and the field intensity enhancement within the AZO-ENZ thin films are controlled by the loss and thickness of the AZO nanolayers. a-c Reproduced with permissions from [6] and d from [7].

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Section 6.7 – Coherent thermal emission with nonlocal metasurfaces

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Status

The concept of 5D photonics includes another degree of freedom that can take different realizations. Thermal properties of light do not add literally a new dimension, but they just move the concept of light into new reality. Usually, thermal radiation from conventional objects is considered as broadband and unpolarized emissions being described by the Planck law. This incoherent nature originates from a stochastic distribution of thermal fluctuations, microscopically described as an ensemble of two-level systems with random orientations and transition momenta. Fundamentally, the Planckian limit arises from the product of the Bose-Einstein statistics and the Local Density of States (LDOS) of free space [1]. To transcend these limitations, nanophotonics [2] offers a pathway to engineer the LDOS using high-Q resonators, thereby reshaping the spectrum, directionality, and polarization of thermal emission. However, relying on isolated optical nanoantennas typically results in extremely low thermal emissivity. Since thermal emission arises from the coupling of microscopic thermal dipoles into optical modes, isolated subwavelength structures suffer from a limited interaction volume, resulting in negligible output power compared to spatially extended sources. To achieve substantial output power and high directionality, it is essential to couple an ensemble of thermally excited emitters to a spatially extended (nonlocal) mode. Since the seminal work [3], which demonstrated coherent thermal emission using surface phonon polaritons on corrugated surfaces (Fig. 1(c)), intensive research has been sparked [4] into engineering temporal and spatial coherence in the far field. Recently, nonlocal metasurfaces [5] shaped a new discipline of "thermal metasurfaces"[6], enabling compact, coherent mid-infrared (MIR) sources with tailored emission, bypassing bulky external optics. The integration of these platforms into the 5D photonics landscape is driven by their unique ability to bridge microscopic structural design with macroscopic light-field manipulation. By engineering resonances in momentum space, nonlocal metasurfaces allow for the simultaneous coordination of frequency, spatial wavevector, and polarization state. This multi-variable coupling transforms thermal emission into a deterministic, wavefront-shaped coherent source, embodying the essence of 5D photonics.

The realization of temporally coherent thermal emission is conceptually straightforward. It necessitates manipulating the interplay between absorptive and radiative losses to simultaneously achieve a high total Q-factor and a balance between these two channels. According to temporal coupled mode theory, maximum absorptivity (and thus emissivity) is attained when the radiative loss rate equals to the intrinsic absorption rate, a state known as the critical coupling condition. In this context, all-dielectric metasurfaces [7] (often on a metallic reflector) offer a superior platform compared to their metallic counterparts. While metallic metamaterial absorbers have been explored for spectrally selective thermal emission [8], their achievable temporal coherence is inherently limited by significant Ohmic dissipation. Conversely, by exploiting mechanisms to realize high-Q resonances in all-dielectric nonlocal metasurfaces—such as bound states in

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the continuum (BICs)[9] and quasi-guided modes (QGM)[10]—highly coherent thermal emissions have been proposed [11]. Experimental demonstrations have showcased emission bandwidths as narrow as ~20 nm in the MIR using a metagrating structure (Fig. 1(b), left panel) [12]. However, a defining characteristic of nonlocal optical modes is their strong spatial dispersion. Since thermal fluctuations provide broadband excitation (dictated by Planck's law), all optical states along the dispersion band are populated, giving rise to emissions at different frequencies for different output angles. This phenomenon, often referred to as the rainbow effect, is a typical behavior with nonlocal optical modes[3,12] and it can lead to detrimental effect in practice. Given that thermal signals are generally weak, large-area metasurfaces are preferred to ensure a high signal-to-noise ratio for sensing applications. Furthermore, MIR objectives with large numerical apertures (NA) are required to maximize signal collection over a wide range of output angles. Consequently, the existence of the rainbow effect leads to the simultaneous collection of spectrally shifted resonances within the NA, causing spectral broadening due to an overlap of these spectral components and thereby deteriorating the temporal coherence. To address this issue, high-Q flatband designs have been realized to pin thermal emissions to a constant wavelength across different output angles. A notable design involves harnessing the band-folding mechanism by introducing a period-doubling perturbation into a 2D metasurface (Fig. 1(b), middle panel) to induce coupling of QGMs and the originally existing guided mode resonances (GMRs)[13]. This approach successfully demonstrated thermal emission at 5.144 mm with a linewidth of 23 nm over a wide range of output angles, exhibiting significantly higher flexibility when the thermal emitter is integrated with high-NA MIR optics.

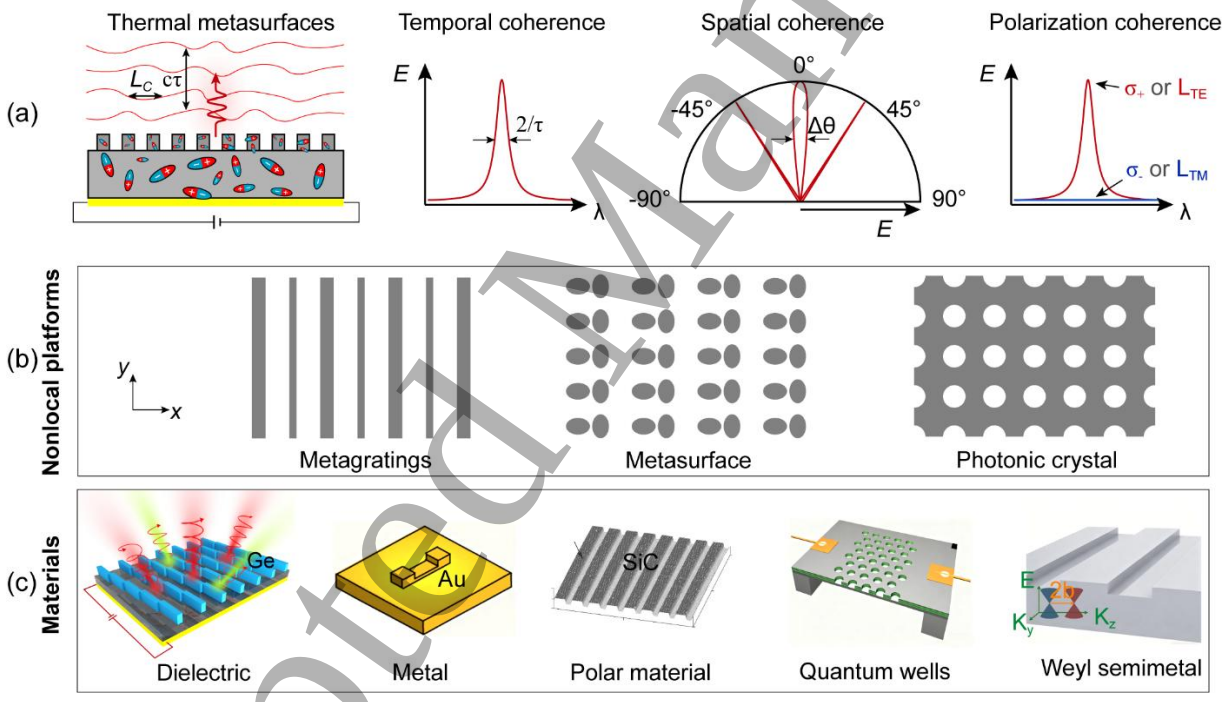


Figure. 1 Coherent thermal sources enabled by nonlocal metasurfaces. (a) Illustrative coherence properties of thermal metasurfaces; (b) Metasurface platforms supporting optical resonances; (c) Representative systems employed in designs. Panels in (c) are adapted from [16] under the CC BY-NC license; and with permission from [20], copyright 2024, American Physical Society; [3], copyright 2002, Springer Nature; [18], copyright 2012, Springer Nature; and [22], copyright 2020, American Chemical Society.

The spatial coherence of thermal emission manifests as the angular directionality (see Fig. 1(a)), which is fundamentally determined by the range of spatial/Fourier components involved at a given frequency. For most applications, highly directional thermal emission normal to the metasurface is preferred. While period-

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doubling perturbations can successfully facilitate the generation of high-Q QGMs, this mechanism involves folding the band-edge states from the boundary of the first Brillouin zone to the Γ point. Since these states typically exhibit a flat dispersion, they span a large range of wavevectors, leading to a broad angular distribution (low spatial coherence) in the far field. To overcome this limitation, period-tripling perturbations have been leveraged to fold the steeper part of the original dispersion band to the Γ point, thereby significantly restricting the number of Fourier components involved in the normal direction [14]. By this means, thermal emissions that simultaneously exhibit high temporal coherence (controllable by the magnitude of the perturbation) and enhanced spatial coherence have been proposed and reported.

Most coherent thermal emissions reported to date exhibit linear polarization, primarily because the underlying high-Q nonlocal optical modes originate from linearly polarized guided modes. Achieving full polarization control—specifically combined with high temporal coherence— remains a significant frontier. A robust strategy is to manipulate the global lattice symmetry rather than relying solely on the local symmetry of meta-atoms[15]. For example, by employing periodically shifted waveguide segments in an array placed on a metallic reflector (Fig.1(c)), nonlocal metasurfaces with monoclinic lattices that break mirror symmetry have been successfully harnessed to realize circularly polarized thermal emission [16].

Current and future challenges

Despite tremedous progress in realizing spatiotemporal coherent thermal emissions via nonlocal metasurfaces, a fundamental bottleneck remains in material quality. Most reported devices rely on evaporated high-index materials (e.g., amorphous Ge), which suffer from high intrinsic absorption losses compared to their crystalline counterparts. Consequently, experimental emission bandwidths in the MIR are currently limited to ~ 20nm. In principle, transitioning to lower-loss crystalline materials could unlock significantly higher Q-factors and temporal coherence. While current bandwidths suffice for static gas sensing, emerging applications like free-space optical telecommunications demand stricter performance metrics. Although recent work has demonstrated emissivity modulation speeds up to 20 MHz by combining nanoscale heaters with nanophotonic resonances [17], future telecom protocols will require significantly faster modulation rates alongside narrower linewidths to maximize channel capacity. For sensing applications, precise spectral alignment with molecular absorption fingerprints is critical. However, achieving exact matching via static geometric design is challenging due to inevitable fabrication tolerances. Developing mechanisms for active spectral tunability and polarization reconfiguration is therefore essential to compensate for manufacturing errors. Furthermore, a persistent challenge lies in background suppression. Since metasurfaces are periodic, higher-order diffraction modes or secondary dispersion bands can enhance "parasitic" thermal emission at unwanted frequencies within the broadband blackbody background. Eliminating these spurious signals to ensure a high signal-to-noise ratio (SNR)—enabling the use of simple point detectors instead of spectrometers—remains a formidable hurdle.

Furthermore, most current designs for coherent thermal emissions still exhibit the rainbow effect. A grand challenge is to engineer thermal emitters that achieve simultaneous high temporal and spatial coherence. An even further step is to realize coherent thermal emissions with arbitrary emission patterns, similar to those demonstrated with conventional metasurfaces. The prerequisite is that the emissions must maintain their high temporal coherence within the framework of nonlocal metasurfaces.

Advances in science and technology to meet challenges

To address the challenges outlined above, future research must converge on advanced material platforms, novel structural designs, and frontier physics concepts. First and foremost, intrinsic material dissipation must be minimized. Advanced growth techniques, including Molecular Beam Epitaxy and Metal-Organic

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Chemical Vapor Deposition, should be explored to produce single-crystalline materials with superior optical quality compared to evaporated films. Furthermore, integrating semiconductor quantum well (QW) structures offers a strategic pathway to suppress background radiation. By engineering QWs to exhibit a high refractive index (required for mode confinement) while featuring narrowband intersubband absorption aligned solely with the target wavelength[18], the emissivity at off-resonant frequencies is naturally suppressed. This significantly enhances the SNR, which is critical for sensing applications. Current designs predominantly incorporate metallic reflectors, which introduce parasitic Ohmic losses. Moving towards metal-less all-dielectric architectures is highly promising. Such designs, where absorption occurs exclusively within the dielectric layer, not only reduce loss but also offer new degrees of freedom—for instance, enabling unidirectional guided resonances without back-reflectors [19]. Additionally, the scope of nonlocal physics is expanding beyond dielectrics. Recent investigations indicate that Surface Plasmon Polaritons (SPPs) can be engineered to operate in the nonlocal regime [20]. High-Q plasmonic thermal emission with high temporal coherence can be envisioned, analogous to mechanisms realized with SPhPs [3], provided that the geometry is carefully optimized for full polarization control.

To realize thermal emission with simultaneous temporal and spatial coherence, precise engineering of the Q-factors in momentum space is required. The design goal is to ensure that the radiative Q-factor is high only at a specific frequency and wavevector, and exhibits a steep dependence on the wavevector [21]. Consequently, the critical coupling condition—which dictates maximum emissivity—is satisfied only at this specific momentum state, effectively filtering out the "rainbow" background. Such distinct Q-dependence can be engineered by leveraging Non-Hermitian physics, specifically by coupling optical resonances with distinct loss properties within the same structure.

The tunability of coherent thermal emissions can be achieved via electro-optic, thermo-optic, or acousto-optic effects driven by external stimuli. For instance, electrical injection in semiconductors or magnetic fields in Weyl semimetals [22] can actively modulate optical properties. Given that heating is intrinsic to thermal emission, harnessing temperature-dependent effects for self-adaptive spectral or polarization control is particularly interesting. To overcome the slow thermal inertia limiting modulation speeds, novel mechanisms involving fast thermal processes—such as hot-electron dynamics[23] in plasmonic or dielectric metasurfaces—should be exploited.

Finally, realizing coherent thermal emitters with arbitrary radiation patterns requires integrating wavefront shaping mechanisms, such as the Pancharatnam-Berry phase. The primary challenge lies in applying geometric rotations to individual unit cells without disrupting the collective nature of the nonlocal modes. Specifically, one must ensure that the resonance frequency remains invariant under rotation to preserve the delicate high-Q properties across the entire device[24]. Alternatively, topological metasurfaces[25] offer a robust paradigm shift. By exploiting topologically protected states, it becomes possible to generate structured thermal light that is inherently immune to structural disorder and fabrication imperfections.

Concluding remarks

We have provided an overview of thermal emitters based on metasurfaces, highlighting strategies to harness key physical phenomena in nonlocal photonics to address practical challenges—specifically, employing high-Q flatband physics to enable the collection of thermal signals from large-area metasurfaces using high-NA objectives without deteriorating temporal coherence, and utilizing intrinsic chiral responses for precise polarization control. *To benchmark the performance of nonlocal metasurface-based thermal emitters, it is instructive to compare them with existing mid-infrared (MIR) technologies[26]. Traditional gas lasers, while highly coherent, are typically bulky and lack spectral tunability. Quantum cascade lasers (QCLs) provide high performance but require complex epitaxial growth and sophisticated driving electronics, leading to high costs. In contrast, filtered blackbody sources suffer from low energy efficiency as out-of-band energy is wasted as heat.*

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Nonlocal metasurfaces represent a compelling alternative for integrated sensing; they provide the narrow linewidths required for molecular fingerprinting while allowing the central emission wavelength to be arbitrarily tuned across the MIR and FIR spectra simply by adjusting structural dimensions, all within a compact and cost-effective footprint. Finally, we have identified remaining challenges and proposed potential research directions and solutions to pave the way toward practical applications of coherent thermal radiation based on nonlocal metasurfaces. While tremendous effort is still required to realize thermal radiation with highly controllable, laser-like characteristics, coherent thermal emissions still represent a promising MIR source which ultimately may provide a cost-effective and compact alternative to QCLs for widespread MIR applications.

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Section 6.8 – Thin-film lithium niobate integrated photonics

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Status

Integrated photonic platforms have become a cornerstone of modern optical technologies. Mature applications require compact, scalable, and energy-efficient manipulation of light on a chip. Silicon supports dense, CMOS-compatible integration but lacks a strong electro-optic effect, with modulation relying on carrier-dispersion mechanisms which introduce absorption loss and bandwidth limits. Silicon nitride provides ultralow-loss passive performance but needs heterogeneous integration for active functions due to weak nonlinearity and lack of electro-optic properties. III–V materials enable optical gain through their direct bandgap, yet struggle with propagation loss, wafer-scale manufacturing, and chip-level integration of active and passive components. In contrast, lithium niobate provides a perfect platform for realizing fast switchable photonic networks, required for future 5D photonics. Lithium niobate ($LiNbO_3$, LN) has evolved from a bulk crystal used in discrete electro-optic and second-order nonlinear optical devices to a leading material for wafer-scale integrated photonics [1]. The introduction of thin-film lithium niobate (TFLN) on insulator has enabled high refractive-index contrast waveguides with strong optical confinement and low propagation loss. The smart-cut technology based on ion-slicing and wafer bonding of Czochralski-grown lithium niobate single crystals on insulator materials such as silicon dioxide [2, 3] now delivers single-crystalline thin films with sub-micrometer thickness and wafer diameters up to 8 inches, supporting large-scale integration. Alternative approaches for manufacturing single crystalline lithium niobate originate in epitaxial growth by various processes such as molecular beam epitaxy [4], liquid phase epitaxy [5], sputtering methods [6], chemical vapour deposition [7], and pulsed laser deposition [8].

TFLN-based optical waveguides are typically made by electron beam lithographic patterning and ion-based dry etching with reported propagation losses in the range of some dB/m at 1.5 μm [9]. Femtosecond laser and photo-lithography-assisted chemo-mechanical etching produce ultra-smooth sidewalls with surface roughness reaching 0.1 nm and sub-dB/m propagation losses [10, 11]. Scaling production toward large wafer sizes up to 8 inches was realized through deep-UV lithography, however, with rather moderate losses of 0.47 dB/cm [12]. An alternative scheme is loading the TFLN with a strip material featuring similar refractive index [13] or a low-index organic polymer [14]. Etchless techniques benefit from mitigating the non-trivial LN etching and, instead, typically relying on mature fabrication of the loading material. Just recently, additive methods, such as multiphoton lithography, have been demonstrated, which allow flexible and sustainable prototyping by adding or erasing photonic structures on reusable substrates [15].

The device landscape has matured rapidly. High-speed TFLN modulators feature sub-volt half-wave voltage V_π with electro-optic bandwidths in the order of 100 GHz [16-19], see Table 1. Together with low propagation losses in the range of 1 dB/m, TFLN photonics outperforms other platforms such as silicon and

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indium phosphide. Corresponding microelectrodes are fabricated by either metal lift-off or fs-laser ablation. High-Q microring-resonators [9, 11, 20] enable narrowband filters, frequency combs, and nonlinear converters. Periodically poled structures allow to exploit the highest second-order nonlinear tensor element d_{33} by applying strong electric fields > 20 kV/mm, suitable for both x-cut [21, 22] and z-cut [20, 23] TFLN wafers. They deliver efficient second-harmonic generation [20], quantum frequency conversion, and entangled-photon sources [24]. These developments position TFLN as a universal photonic platform for classical and quantum information technology, such as data communication, microwave photonics, quantum optics, and optical signal processing.

Table 1: Comparison of several performance metrics for different TFLN electro-optic modulators.

Year	$V_\pi \cdot L$ (V·cm)	On-chip insertion loss (dB)	Extinction ratio (dB)	3-dB bandwidth (GHz)	Reference
2018	2.2	< 0.5	30	> 100	[16]
2021	2.7	1 ± 0.5	20	> 50	[18]
2022	2.35	< 0.3	> 20	110	[17]
2025	1.02	2.9	> 20	108	[19]

Current and future challenges

Despite exceptional progress, TFLN integrated photonics faces several challenges, before it can realize large-scale photonic systems. Scalable manufacturing remains a primary limitation. The wider adoption of tightly confining TFLN waveguides is currently impaired by challenges associated with the smart-cut and etching processes. Ion implantation and ion milling introduce crystal damage that reduce yield and optical quality [25, 26]. Reproducibility over large wafers, the high cost, and availability of customizable TFLN substrates constrain commercial uptake. Achieving defect-free bonding and maintaining precise thickness homogeneity over large substrate sizes beyond 8 inches will increase uniformity, repeatability, and reliability of TFLN wafers.

At the device level, production cost and reproducibility of low-loss optical waveguides is another obstacle. Current fabrication involves many single steps and the effort needed for realizing low surface roughness and steep-wall ridge waveguides is high and not yet realized in a standardized commercial process with high yield. Scalability of low-loss waveguide production processes towards large-scale wafers is not straight-forward in most cases due to above-mentioned challenges associated with TFLN wafers and as underlying nanostructuring processes typically rely on ultra-precise field stitching for large-scale PICs. In terms of modulators, optimization of waveguide geometry and electrode design must balance optical confinement with efficient radio-frequency overlap. Present modulators still rely on rather intuitive electrode layouts, and hybrid integration with lasers and detectors adds further thermal and mechanical challenges as well as significant optical coupling losses. In summary, foundry processes for complex and densely packaged TFLN photonic integrated circuits remain rather costly and time-consuming as they are not compatible with mature CMOS or silicon photonics processes, hampering technology transfer into commercial market.

Nonlinear and quantum applications face limits from photorefractive effects and phase-matching tolerances. Large-area periodic poling with sub-micron accuracy remains difficult, and photodamage under high optical power constrains some high-intensity uses such as efficient microwave, mm-wave, or THZ generation. For hybrid platforms, interface losses and thermal mismatch between TFLN and other materials require improved bonding and interposer strategies. In this context, a major challenge is the current lack of low-loss interfaces with standard optical fibers. The current generation of mode-field converters is not yet able to reliably reduce fiber-to-chip coupling losses toward 0.1 dB over a broad spectral range with only very few

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reported designs reaching the sub-decibel level [27]. Besides wafer-scale integration, assembly of discrete micro-optical components can be a solution for off-chip coupling. However, corresponding precision assembly and packaging techniques are inefficient compared to their microelectronics counterparts, rendering them economically impractical.

A deeper challenge arises from the need to embed intelligence throughout the photonic ecosystem. Intelligent control must operate at all stages: fabrication, device calibration, and system operation. Yet data-driven models linking processing parameters to optical performance are still sparse. Integrating real-time sensors in fabrication lines for temperature, strain, or composition monitoring is only beginning. Similarly, implementing adaptive feedback at the device level – such as self-calibrating modulators or resonators – demands robust electronic-photonic co-design.

Advances in science and technology to meet challenges

Overcoming current limitations requires parallel advances in materials, manufacturing, device physics, and intelligent control. The next generation of TFLN integrated photonics will benefit from digitalized, feedback-driven production of TFLN wafers. Epitaxial growth by molecular beam epitaxy and pulse laser deposition techniques are emerging to achieve better thickness control and defect-free layers. Due to its complex phase diagram, one major challenge is stoichiometry, as lithium is among the most reactive elements known whereas niobium forms oxide compounds very slowly [28]. This requires perfect control of evaporation rates, extremely high temperatures (2477°C for niobium), posing major challenges for plant infrastructure, and a reactive oxygen atmosphere at a lattice-matched substrate. Intelligent, sensor-based feedback during layer growth – monitoring e.g. temperature, stoichiometry, or evaporation rates – will improve uniformity and wafer quality. Implementation of external electromagnetic fields during the growth process may facilitate control over crystal properties such as the orientation of the ferroelectric domain or the stoichiometry during the growth process, thereby enabling the production of tailor-made TFLN.

Device performance will advance through disruptive design methodologies, such as inverse [29] or AI-assisted design. Inverse-design tools trained on multiphysics simulations will discover both electronic and photonic component geometries that maximize e.g. electro-optic efficiency while minimizing loss. They will also synthesize non-critical designs, which are more robust with respect to fabrication-related geometric tolerances [30]. Digital twins of modulators and resonators will permit virtual testing and automated tuning after fabrication. Integration of on-chip sensors will allow self-monitoring and self-stabilization under environmental changes, converting static components into adaptive, learning photonic elements. Electro-optic processors based on TFLN could themselves perform these optimization tasks, using photonic computing to deliver feedback at the speed of light – realizing intelligence within the photonic chips.

Scaling for large arrays of densely packaged processing units, preferably in a reconfigurable scheme, will advance classical and quantum applications. Improvements in terms of reliably producing low-loss optical waveguides with propagation losses close to the theoretical material limit of ~0.1 dB/m and foundry processes on large-scale wafers beyond 8 inches is necessary to prevent insertion losses from scaling with increasing number of components. Large-scale reconfigurable all-to-all coupled arrays of photonic components will be crucial for optical neural networks, fully-integrated LiDAR systems, or quantum computing. Recent breakthroughs in

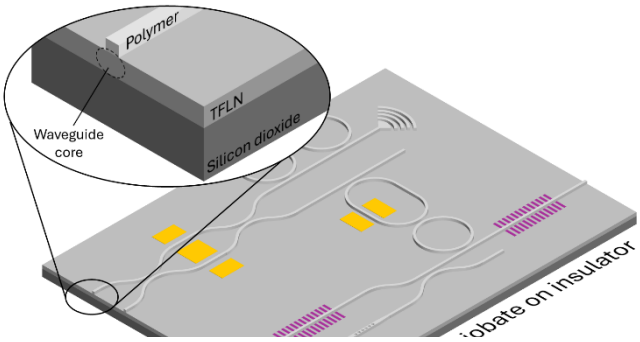


Figure 2. Schematic of a TFLN photonic integrated circuit based on the strip-loaded waveguide concept including optoelectronic and nonlinear optical components.

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Pockels cell cavity lasers by integrating III-V semiconductor gain sections with TFLN-based external cavities offer unrivalled frequency modulation speed and reconfigurability to integrated lasers [31]. High-performance and energy-efficient electro-optic modulators and nonlinear components will pave the way for low-energy cost AI accelerators.

New fabrication techniques are emerging, with additive manufacturing being a promising candidate for significant time-reduction within development cycles of photonic integrated circuits. Recent results based on strip-loaded waveguide concepts are promising not only with respect to design-freedom, but also due to the concept-inherent mitigation of surface roughness-induced optical losses or crystal degradation associated with ion implantation or ionic etching [15]. In general, 3D printing – particularly multiphoton lithography – is a powerful driver of innovation, enabling rapid-iteration prototyping and entirely new fabrication methodologies and design concepts, with the long-term potential to complement or even replace conventional patterning techniques such as electron-beam or UV lithography, which are inherently limited to planar structuring. In this context, increasingly sophisticated photonic integrated circuits based on 3D-printed strip-loaded waveguides may become feasible in the near future, see Fig. 1.

Heterogeneous integration of lasers and detectors through micro-transfer printing of III-V devices on the TFLN platform is emerging, allowing for monolithic integration and, thus, power-efficient and ultra-stable operation of fully chip-integrated photonic processors. Heterogeneous material stacks combining TFLN with InP, AlN, or Si_3N_4 will extend bandwidth and functionality, enabling full photonic-electronic convergence. Furthermore, high-throughput packaging and co-integration with CMOS controllers must be standardized to transition from laboratory devices to reliable photonic circuits. In the long term, vertical architectures of co-packaged optics will facilitate high-bandwidth, low-latency, power-efficient and cost-effective performance.

Concluding remarks

TFLN integrated photonics has matured into one of the most promising platforms for high-speed, low-loss, and multifunctional chip-scale photonic systems. Its combination of strong electro-optic response, large second-order nonlinearity, broad transparency, and compatibility with wafer-scale fabrication positions it at the forefront of both classical and quantum technologies. Yet further transformative potential emerges when placed within the paradigm of 5D photonics, where intelligence becomes an additional dimension alongside space and time.

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Section 6.9 – Toward ultrafast reprogrammable integrated meta-photonics

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Status

Metaphotonics has emerged as a new paradigm to engineer the properties of light beyond what is possible with traditional components. This is based on the control of light-matter interaction at the nanoscale via metallic and/or dielectric nanostructures arranged in 2D or 3D arrays, to form so-called metasurfaces [1] and metamaterials [2], respectively. Metasurfaces offer a versatile platform for electromagnetic wave control, enabling precise manipulation of light properties (e.g., phase, amplitude, wavefront, and polarization) and advanced functionalities, such as achromatic focusing [3], nonlinear generation and structuring [4], polarization conversion and splitting [5], image processing and edge detection [6], and mathematical operations directly in the optical domain [7]. Due to their planar shape and compact size, metasurfaces are compatible with highly miniaturized photonic integrated circuits. We are recently witnessing the merging of waveguide systems typical of silicon photonics and arrays of nanostructures typical of meta-optics, leading to integrated metaphotonics [8]. This includes integrated metasurfaces, meta-waveguides (e.g., metasurfaces fabricated on the top or facet of a waveguide), sub-wavelength nanostructured waveguides, and complex designs found via advanced optimization and inverse design algorithms.

Optical metasurfaces and integrated optical circuits have initially been investigated as passive devices with fixed responses once fabricated. However, their dynamic tuning post-fabrication is of growing interest due to a broad variety of applications, such as beam steering for LiDAR [9], reprogrammable holography for virtual and augmented reality [10], varifocal lensing for imaging and vision technologies [11], colour generation for photorealistic displays [12], and high-speed modulators [13], to name a few. The tunability of the optical response of a metaphotonic system is generally based on perturbing the refractive index of the material itself (e.g., in conductive polymers, where chemical oxidation and reduction can switch the material from dielectric to metallic [14]) or the surrounding medium. This perturbation is most effective when it occurs in regions with a high optical field due to local (e.g., plasmonic or Mie-type resonances) [15] or nonlocal resonances (e.g., collective resonances of the entire metasurface, such as surface lattice resonances and quasi bound states in the continuum) [16]. Reconfigurability in integrated metaphotonics spans a broad spectrum of tuning mechanisms (e.g., thermo-optic, electro-optic, microfluidic, chemical reactions, acousto-mechanical, and nonlinear) and response speeds, from quasi-static mechanisms to ultrafast optical nonlinearities, and research in this area is currently very active [17].

Current and future challenges

Among the electro-optics tuning strategies, liquid crystals (LCs), phase-change materials (PCMs), and carrier refraction hold great potential for application in reprogrammable integrated metaphotonics. LCs offer

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electrically controllable, anisotropic, and spatially reconfigurable refractive index distributions with millisecond-to-microsecond switching, and have been extensively used for on-chip reconfigurability of integrated optics and meta-waveguides [18]. Although typical LCs exhibit relatively slow switching times, recent experiments have shown that ferroelectric nematic LCs can switch on microsecond timescales [19]. Future research is directed at accelerating LC response times to achieve sub-microsecond (and even nanosecond) switching speeds, as well as higher dielectric anisotropy [20]. PCMs such as germanium antimony telluride (GST), its selenium-alloyed variant GSST, and vanadium dioxide (VO_2) are widely used in integrated metaphotonics for their ability to provide reversible and nonvolatile switching between amorphous and crystalline states (or insulating/metallic for VO_2) through thermal, electrical, or optical excitation [21]. These materials provide a large refractive index contrast between states. However, their high absorption in the visible range limits their use. Research efforts are now focused on newer materials, such as $Ge_2Sb_2Se_4Te$ (GSST) that exhibit low absorption and high optical contrast in the visible spectrum, as well as materials with faster switching [22]. In Drude materials, such as doped semiconductors or transparent conducting oxides (TCOs), by modulating the carrier concentration through the accumulation or depletion of charge carriers (akin to the working principles of a MOS capacitor), it is possible to shift the plasma frequency, thus modulating the material's refractive index and absorption properties, for applications in tunable metasurfaces [9], and integrated modulators [23]. Research efforts focus on overcoming several critical challenges in MOS-capacitor–based Drude metaphotonics, such as improving the phase modulation range, modelling the carrier-density perturbation in TCOs [23], reducing optical losses, and increasing the breakdown voltage via high-quality deposition of the oxide layer [24].

The dynamics leading to refractive index changes in LCs, PCMs, and Drude media are much slower than the duration of an optical pulse (i.e., quasi-static), so their refractive index can be considered effectively constant over the pulse timescale. Moving to intrinsic electronic nonlinearities, electro-optic effects (e.g., Pockels, Kerr) and two-dimensional materials (e.g., graphene and transition-metal dichalcogenides) enable sub-nanosecond to picosecond tuning through ultrafast carrier and excitonic dynamics. At the fastest end of the spectrum, ultrafast phenomena span timescales from the duration of a laser pulse to, in some cases, a single optical cycle (femtoseconds to picoseconds), and include processes such as carrier refraction, hot-electron injection, and nonlinear optical effects, including harmonic generation and intensity-dependent refractive index modulation (Kerr effect). These timescales reflect the typical response times of the underlying physical mechanisms and are not directly comparable across platforms.

Among the most transformative frontiers is the emerging field of ultrafast metaphotonics, which aims to realize systems whose optical properties can be switched nearly "instantaneously" in response to external stimuli or control signals based on the use of so-called time-varying materials. In recent years, time-varying materials have been studied for several intriguing applications [25], such as anti-reflection temporal coatings [26], time reflection and time refraction [27], and temporal aiming [28]. A typical assumption in theoretical studies is the possibility of instantaneous switching due to an abrupt refractive index change. While such an assumption is valid in the microwave regime with the availability of several time-varying materials, ultrafast refractive index modulation in the optical regime is of current research interest. This limit is being increasingly approached in TCOs, degenerately doped semiconductors with high free carrier densities, such as indium tin oxide (ITO) and aluminium-doped zinc oxide (AZO) [29]. The ultrafast rise and decay time of TCOs is opening the true realm of optical time-varying materials, with refractive index modulation occurring over a few light cycles or even sub-cycle timescales [30], as also demonstrated in the temporal counterpart of Young's double-slit experiment [31]. When subjected to an optical pump pulse, TCOs show femtosecond response with refractive index changes approaching unity, due to their strong Kerr-like nonlinear response in the spectral range where they exhibit a vanishingly small electric permittivity, known as the epsilon-near-zero (ENZ) regime [32].

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Recent advances illustrate a clear trajectory toward fully reprogrammable on-chip metaphotonic systems in which optical functionality is no longer fixed at fabrication but dynamically defined on demand. A first key direction is optically programmable nonlinear interactions, as demonstrated in Ref. [33], where structured illumination is used to dynamically write the spatial distribution of the effective second-order nonlinearity along a slab waveguide (Figure 1a). By locally modulating the internal electric field through a photoconductive layer modified by the patterned illumination, an electric-field-driven second-order nonlinearity distribution is created (Figure 1b). By projecting different optical patterns, nonlinear signals are processed in the spectral, spatial, and spatio-spectral domains for on-demand functions such as frequency conversion, wavelength routing, and multi-mode nonlinear mixing, all within the same physical chip (Figure 1c). This approach introduces the concept of software-defined nonlinear photonics, particularly when combined with in-situ inverse design algorithms that adaptively optimize the optical programming pattern to realize a target nonlinear response. Complementary to spatial programmability, recent work has shown that time-dependent modulation of material properties can provide a powerful additional degree of freedom. Ref. [35] demonstrates that operating TCOs near their ENZ wavelength enables femtosecond-scale refractive index modulation capable of reshaping the spatio-spectral content of optical pulses. In this regime, time refraction leads to simultaneous frequency and momentum shifts, allowing a single pulse to split into distinct spectral and spatial components. This highlights the potential of time-varying ENZ media for ultrafast switching, beam steering, and signal processing, while also identifying key challenges such as loss reduction, precise pump–probe synchronization, and scalable on-chip integration. Pushing these ideas further, in Ref. [34], ultrafast optical pumping of an ITO film creates a controlled space-time modulation of the refractive index, effectively acting as a synthetic object moving at relativistic or superluminal velocity. The interaction of probe light with this modulation leads to simultaneous diffraction in momentum and frequency. Tunable frequency-momentum diffraction patterns are demonstrated by varying the relative synthetic velocity between the modulation and the probe wave (Figure 1d, e), governed by a super-relativistic Doppler effect. By shaping pump beams in both space and time, this concept can be extended to realize programmable spatio-temporal refractive index dynamic landscapes, enabling ultrafast manipulation of light beyond what is possible with static or purely spatial metasurfaces. Taken together, these works point toward a future generation of integrated metaphotonic platforms that combine spatial programmability, ultrafast temporal control, and nonlinear functionality. By merging optically written material responses with space-time

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modulation and inverse-designed control strategies, reprogrammable metaphotonic circuits could operate as adaptive, software-defined systems capable of real-time reconfiguration across spatial, spectral, and temporal domains, all on a single chip.

Advances in science and technology to meet challenges

The development of integrated metaphotonics faces key challenges related to fabrication accuracy, scalability, optical material properties, multi-material integration, advanced design, and robustness to fabrication imperfections. Advances in materials science may lead to the discovery of new materials with enhanced tunability range, faster switching speed, higher refractive index for mode confinement, and lower optical losses, thus improving efficiency and facilitating thermal management. The latter is a key challenge in integrated metaphotonics, as localized heating can induce refractive index changes, resonance shifts, and thermal cross-talk in dense device arrays. Addressing these effects will require low-loss materials, thermally robust designs, efficient heat dissipation strategies, and the inclusion of thermal constraints in advanced design methodologies and optimization frameworks. The integration of diverse materials into hybrid photonic platforms is a promising area of research. This integration requires advances in nanofabrication techniques to achieve high precision, low defect rates, low optical losses, and consistent tuning across large device arrays, which are essential for scalable production and reliable operations. There is also growing interest in developing integrated photonic hardware that can directly interface with existing electronic systems, creating hybrid photonic-electronic platforms. Such systems could leverage the best of both worlds: the high speed and parallelism of photonics and the mature infrastructure and logic operations of electronics. Research in this direction will focus on developing compatible interconnects, integrated transceivers, and efficient light-to-electronics conversion mechanisms.

While numerical methods are advancing rapidly, providing powerful tools for the optimization and design of complex photonic structures, challenges related to computational complexity, design robustness, and fabrication compatibility remain. For example, the development of closed-loop frameworks that integrate real-time experimental feedback into the design process could significantly accelerate the discovery and optimization of photonic devices. Machine learning and inverse design techniques are expected to play a key

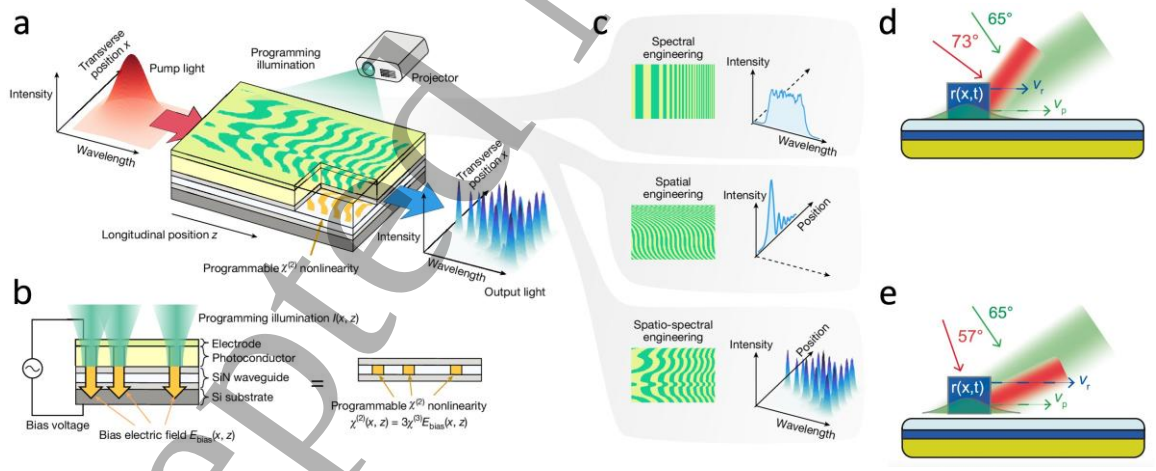


Figure 1. (a) Structured light projected on the surface of a planar waveguide can induce a spatial nonlinear pattern. (b) Structure and physical working mechanism of a programmable waveguide. (c) Varying the longitudinal and transverse structure of the quasi-phase matching gratings enables spectral, spatial, and spatio-spectral engineering of the transmitted signal. (d, e) Space-time diffraction from a synthetically moving refractive index modulation using a pump–probe experiment: the correlation between frequency and momentum depends on the relative speed of probe and modulation. Figures and descriptions adapted from [33, 34].

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role in addressing multi-objective and multi-physics optimization problems in tunable photonic devices, as they enable efficient exploration of the vast parameter spaces inherent to photonic design, leading to improved performance and novel functionalities [36]. Furthermore, substantial advances in both direct solvers and inverse design methodologies are still required to address the computational demands posed by advanced optical materials. In this context, inverse design in the time domain for dispersive and time-varying materials represents an emerging research direction [37, 38]. High-performance computing, including GPU-accelerated and heterogeneous architectures, will be essential to support these developments, enabling the exploration of large-scale design spaces and the discovery of device concepts that remain beyond the reach of conventional approaches.

Concluding remarks

As research continues to advance, the convergence of classical, meta-, and quantum photonics is expected to unlock fundamentally new paradigms in information processing, communication, sensing, and beyond. These developments point toward a future in which metaphotonic chips function as reprogrammable platforms: optical functionalities are dynamically written and erased on ultrafast timescales via pump–probe schemes, creating transient, virtual photonic devices that exist only for the time needed to perform a given operation. In this vision, functionality is no longer hard-wired into the spatial nanostructuring at fabrication but emerges on demand from spatio-temporal control of light–matter interactions, effectively eliminating the need for refabrication and enabling software-defined photonic hardware.

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Section 6.10 – Colloidal 2D Semiconductor Nanocrystals en Route to Photonics

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Status

Colloidal semiconductor nanocrystals (NCs) exhibit dimensions in the range of 10^{-9} m. Excitons in NCs are quantum confined in one dimension at least, which leads to opto-electronic properties (such as the band gap) becoming tunable by the size, shape, surface composition of the NCs. Wet-chemically synthesized zero-dimensional (0D) semiconductor NCs, so-called quantum dots (QDs), have been established as materials of major importance for photonics. They possess high photoluminescence (PL) quantum efficiency and pure color emission, which is used in lighting applications such as lasers and light-emitting diodes, photovoltaics and bioimaging. Their processability is another key advantage, allowing for the use of colloidal NCs directly in solution and for applications via deposition by spin-coating, ink jet printing, spray painting or matrix integration. In 2023, the Chemistry Nobel Prize was awarded to Aleksey Yekimov, Louis E. Brus, and Moungi G. Bawendi for the discovery, synthesis, and demonstration of the optoelectronic properties of NCs.[1, 2] In 2008, the field saw another breakthrough – the discovery of quasi-two-dimensional (2D) NCs, referred to as flat quantum dots (fQDs), nanosheets (NSs) and/or nanoplatelets (NPLs) with strong size quantization determined by the atomic-layer thickness of the systems (see **Figure 1a,b,c** for PbSe fQDs). The strong one-dimensional confinement leads to a decreased dielectric screening, an associated increased binding energy of the generated excitons in the structures and large oscillator strengths. These effects in turn manifest as exceptional opto-electronic properties of 2D NCs, which is surpassing their 0D counterparts, such as emission color purity, suppressed Auger recombination, drastically enhanced light absorption and high emission directionality, as well as reduced thresholds for amplified spontaneous emission and lasing.[3-13] Moreover, the 2D shape of fQDs, NSs and NPLs can be used to organize 2D NCs into stacks and laterally-oriented films to further exploit their anisotropic properties.[7, 14, 15]

Current and future challenges

State-of-the-art 2D semiconductors are generally produced by gas-phase methods or exfoliation techniques. Wet-chemical approaches emerged as a scalable path towards nanomaterials, offering additional advantages such as the possibility to synthesize (lateral) heterostructures and a potentially more versatile integration of the materials. While 2D NPLs composed of cadmium chalcogenides have reached appreciable complexity, both in terms of composition and structure (core-crown, core-shell, core-crown-shell structures), their optical range is limited to UV-Vis wavelengths (see **Figure 1d**). To extend the covered wavelength range further into the infrared, mercury or lead chalcogenides can be prepared either by cation exchange of CdX NPLs or by direct synthesis. For example, lead chalcogenide fQDs and NPLs are synthetically accessible to

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cover industrially relevant telecommunication windows, where optical fibers exhibit low attenuation (see **Figure 1e**).

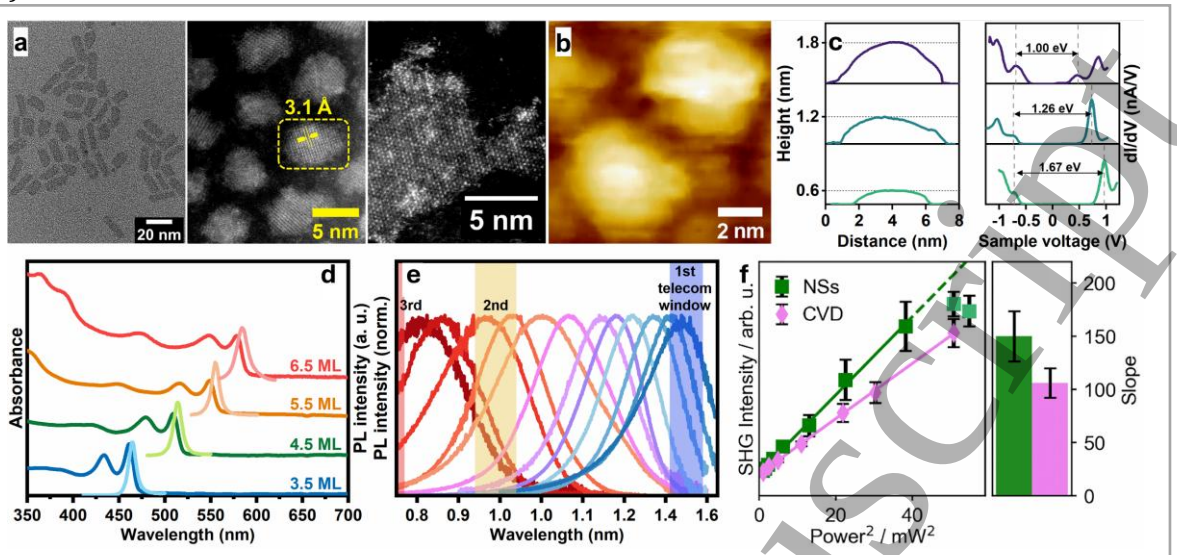


Figure 1. (a)Transmission electron microscopy (TEM) images of ultrathin 2D CdSe NPLs, PbSe fQDs and $Mo_{1-x}W_xS_2$ NSs. (b) Small-scale STM image (V_S = 3 V; I_{set} = 40 pA) of two PbSe fQDs. (c) STM height profiles of PbSe fQDs with thicknesses of 1.8 nm, 1.2 nm and 0.6 nm, representing a mono-, bi-, and trilayer of cubic rock salt PbSe fQDs with representative STS spectra at 77 K (top to bottom; tunneling conditions: V_s =−1 V, I_{set} = 200 pA). (d) Absorption and PL range of CdSe NPLs covering UV-Vis wavelengths and spectral PL tunability of 2D lead chalcogenide (PbX, X = S, Se, Te) fQDs/NPLs spanning the 2nd to 3rd telecommunication window relevant for industry (e). (f) Colloidal WS_2 exhibiting efficient SHG.

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At the same time, the rational design of synthetic protocols requires, *further mechanistic understanding of the formation and growth.* A particular interest lies in *more benign materials* that are free from restricted heavy metals such as cadmium lead or mercury. In this regard, transition metal dichalcogenides (TMDs) are attractive alternatives due to their low toxicity and chemical stability paired with a direct band gap. Although room-temperature PL has been demonstrated for colloidal TMD WS_2 NSs,[16, 17] the PL intensity of colloidal TMD remains low in the ensemble. However, near-unity quantum yield has been achieved in chemically treated and electrically biased exfoliated TMD monolayers. Hence, first steps to a better understanding of the defect types acting as centers for nonradiative recombination, and investigation of their complex interplay with charge carrier dynamics are currently taken. Femtosecond transient absorption spectra of laterally confined TMD NPLs suggest that charge carrier relaxation is dominated by hole capturing through these midgap edge states, whereas larger NSs exhibit an additional slower charge carrier recombination, which ultimately results in μ-PL of colloidal WS_2 NSs.[16, 18, 19] For further advancing colloidal TMDs toward technological maturity, research into the passivation of midgap states and the role of surface ligands is needed. The lack of inversion symmetry, strong exciton binding energies and spin-orbit coupling make TMDs

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exceptional materials for sophisticated photonic applications such as photodetectors, spin-, twist- and valley-tronics, efficient second harmonic generation (SHG) and single-photon emission. For example, colloidal WS_2 NSs show efficient SHG on par and surpassing CVD-grown samples (see **Figure 1f**).[17]

Efficient device integration is as one of the most pressing challenges regarding the near future of NCs. Due to their solution processability colloidal NCs excel in application flexibility and allow coating of variable surfaces or integration into waveguides,[20] sensors,[21] and (optical) fibers (see **Figure 2**).[22-25] However, the interaction between closely packed (f)QDs, NPLs and NSs often leads to nonradiative loss processes, which can significantly decrease the efficiency of devices. Additionally, a "simple" (f)QD/NPL deposition can show poor mechanical stability, and the toxicological properties of colloidal (f)QDs/NPLs are often not well examined. A well-designed integration hence is integral for both, retaining the sought-after qualities of colloidal NCs, and to meet the required characteristics for a given application.

Advances in science and technology to meet challenges

Here, recent integration strategies for colloidal fQDs/NPLs for innovative photonics are presented. **Figure 2a** schematically shows thin films of photoluminescent core-crown CdSe/CdS NPLs encapsulated in the metal-organic framework ZIF-90, and forming an optically sensitive transparent nanocomposite.[21] The zeolitic imidazolate matrix covers the NPLs, prevents PL losses due to extended NPL interaction, and acts as an antireflective coating. Most importantly, in this nanocomposite, the ZIF-90 and the NPLs both act as active layers: the ZIF-90 leads to the adsorption of guest molecules such as water and ethanol, reversibly changing its refractive index. The PL of encapsulated NPLs is sensitive to the gas adsorption under a dynamically altered environment with changes being fast, reproducible and reversible (see **Figure 2b,c**).[21] For making use of the high PL directionality in NPLs, one can alternatively assemble the materials into laterally oriented films by interfacial self-assembly or by layer-by-layer deposition, which provides a protective polyelectrolyte encapsulation as well as the ability to control the interlayer separation distance.[23]

Figure 2d,e,h show the schematic integration of CdSe/CdS core-crown NPLs and PbSe fQDs into (polymer) fibers, which form the foundation of photonic data transmission and communication technologies. Such fibers can be produced by stable-jet electrospinning of Poly(methyl methacrylate, PMMA) nanocomposites, which leads to an efficient polymer encapsulation of the NPLs/fQDs, with their optical properties being retained during the electrospinning process [22, 24, 26] During the electrospinning process, NPLs align perpendicular to the spinning direction, which enables efficient light guiding along the fiber and reduced losses.[22] Alternatively, NPLs can be used directly in colloidal solution, which allows avoiding common disadvantages of polymer composites, such as lower reproducibility and optical losses by scattering due to the local inhomogeneities and aggregation. **Figure 2f,g** illustrates the microfluidic integration of CdSe/CdS NPLs into liquid core optical fibers, which, when combined with a high-refractive solvent, create a suitable photonic environment for low optical gain thresholds (a crucial step toward lasing).[25]

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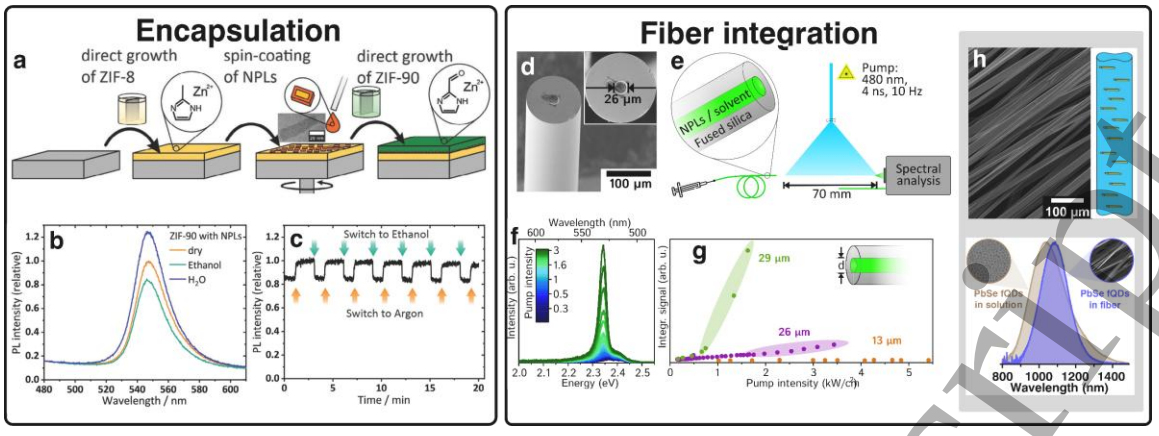


Figure 2. (a) CdSe/CdS NPLs encapsulated by ZIF-90 and acting as optical sensor (b,c), showing changes in the emission of the NPLs when treated with ethanol and water, respectively. (d,e,f,g) Photonic integration of CdSe/CdS NPLs into liquid core fibers, showing low optical gain threshold controllable by the NPL concentration and the fiber diameter. (h) PbSe fQDs integrated into electrospun PMMA fibers, and retaining near-infrared photoluminescence.

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Concluding remarks

The field of colloidal 2D semiconductor nanocrystals exhibits rapid advances being made in synthetic approaches for controlling the opto-electronic properties of an ever-growing material library. Recent data and continued characterization of these flat quantum dots, nanosheets and nanoplatelets not only underpins their exceptional properties compared to solid-state and 0D counterparts arising from their anisotropy, but also provides guidance for their tailoring to address the needs of established and emerging innovative photonics. Here, we give a short overview on how the challenges of retaining the opto-electronic properties of colloidal 2D semiconductor nanocrystals in photonic applications can be tackled. For example, first nanocomposite and fiber optics integration of the materials is demonstrated in highly promising proof-of-concept studies. This progress is only possible by combining chemistry, physics, optics and photonics approaches. Further tuning the stability of the materials by chemical and matrix stabilization, characterizing their excited-state dynamics and forecasting their opto-electronic properties in close collaboration with theory will help to meet the ambitious requirements for 5D photonics.

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Section 7.1 – 5D Photonics enable access to new functionalities in engineering

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Status

Optical technologies are increasingly playing a key role in transforming the field of engineering by overcoming traditional mechanical limitations and unlocking new dimensions and functions in production. One example of this is “on-the-fly bare die bonding”, in which a laser-induced forward transfer (LIFT) ejects dies from a wafer via an ablation-induced release process, rather than using a mechanical actuator. This theoretically increases the bonding assembly speed to up to twice the rate of mechanical detachment, up to 108,000 units per hour [1].

In the ongoing evolution from Industry 4.0 to Industry 5.0 and beyond, the focus of industrial development is shifting from interconnecting systems for smart manufacturing (Industry 4.0) to integrating human-centric aspects such as sustainability and resilience (Industry 5.0) [2]. Within this evolution, the digital twin has emerged as a key paradigm for connecting physical assets and their digital representations, incorporating data, models and simulations. Achieving real-time twinning (synchronization of the states of physical and virtual entities) requires low-latency communication [3]. However, contemporary methodologies are insufficient for establishing a real-time feedback loop that enables direct interaction between virtual and physical systems. This limitation arises from the stringent low-latency requirements for a real-time feedback loop. When the latency within the time domain is shorter than the underlying process dynamics, the time becomes practically irrelevant and negligible, resulting in 'zero latency'.

Compared to traditional electronic interconnects, optical transmission paths offer several advantages, including a significantly higher bandwidth, lower latency, and reduced energy consumption per transmitted bit. Furthermore, the optical transmission paths are resistant to electromagnetic interference and facilitate scalable, high-density connectivity. Consequently, optical technologies are essential for example for high-performance computing and AI systems, which are required for a real-time representation and processing of virtual entities [4]. To address prevailing latency constraints, advanced optical technologies such as 5D photonics must be deployed.

5D photonics are defined as systems that interact with a responsive digital embedding, leading to entirely new functionalities. This involves creating an intelligent overlay of a system's real and virtual worlds. A chronological sequence of processes and simulations within the feedback loop is not strictly necessary. Rather, both worlds should coexist in parallel. Pre-developing the simulation model and continuously aligning it with real-time measurement data during operation significantly reduces computational effort. In this context, reality serves to constantly calibrate the simulation. Consequently, the model does not need to be re-executed in its entirety, requiring only a few cycles for ongoing synchronization. Such a high-efficiency

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approach facilitates achieving 'zero latency', meaning latency periods substantially lower than the system's time constants. This concept is named after its five constituents: the familiar three spatial dimensions, the temporal dimension, and the crucial fifth element the digital or virtual 'dimension' allowing new functionalities.

Current and future challenges

The current and future challenges in 5D photonics center on achieving high-fidelity, real-time control. Ensuring real-time interaction and bidirectional parameter exchange between the digital and virtual layers is crucial. It requires a seamless and harmonious blend of hardware and software elements in order to overcome the bottleneck of latency limits.

Figure 1 shows an example of the interplay between software and hardware. In this scenario, a forklift operator receives an augmented visual overlay that adds a camera-based digital reconstruction of hidden areas to their real view. This provides the operator with the new functionality to see through the lift mast and the transported load. The interaction between the hardware and software components remains reliable, even when the viewing angle changes due to a change in the operator's head position. This is because the real system transmits the operator's current head position to the virtual system, which then adjusts the visualization adaptively to the viewing direction [5]. This system has been demonstrated to work at low vehicle speeds. However, with a maximum measured end-to-end latency of 233.33 ms, it exceeds common standards such as ISO 16,505 for automotive rear-view cameras of 200 ms [6]. Therefore, the latency due to non-optical conventional data transmission concepts is too high for an extension to faster vehicles like cars.

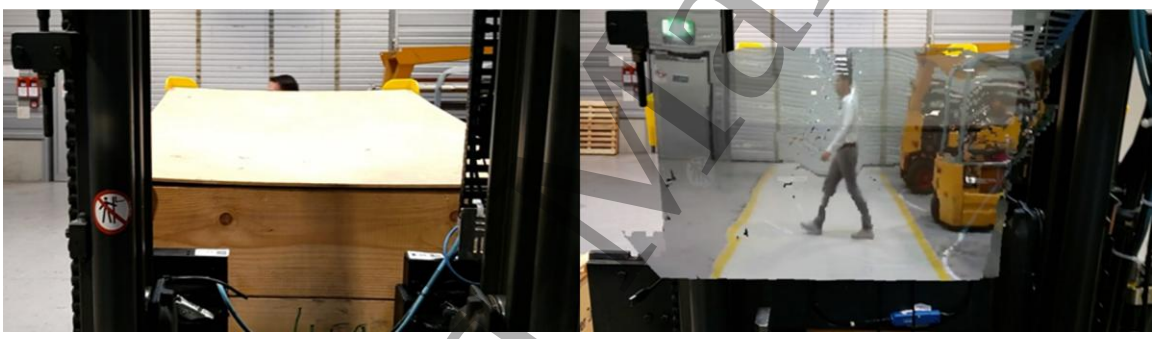


Figure 1. Forklift operator assistance system. Left: driver's view without virtual overlay showing limited visibility. Right: driver's view with virtual overlay and see-through effect. Based on [5]

In order to accelerate data processing in the virtual sphere, it has been demonstrated that AI, deep learning, and machine learning can be successfully employed to reduce simulation times [7,8]. Furthermore, AI-based models can be utilized for control with reduced latency and for predicting properties [9].

In addition to data processing, advances in the corresponding hardware are also necessary. This requires the integration of (non-linear) photonic integrated circuits (PICs) and their packaging. The manufacturing process for PICs must be capable of achieving ultra-high throughput while concurrently meeting the challenge of cost efficiency. This requires the identification and development of new materials to fully exploit the capabilities of adaptive and intelligent photonic systems. Moreover, innovative manufacturing processes are essential to enhance cost efficiency. In the semiconductor industry this trend is also evident in the latest developments of various large companies [10-12].

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Developing software and hardware with faster processing capabilities and higher energy efficiency is essential to supply the virtual environment with in-situ measurement data. This requires multi-parameter acquisition with 'zero latency', enabled by real-time capable sensors.

Furthermore, the feedback loop from data acquisition through processing in the virtual domain back to the real system must also operate in real-time. The integration and implementation of dedicated interaction layers and feedback mechanisms for controlling the photonic system contribute to an additional development challenge.

A generalized comparison between existing computation times and required latencies is precluded by the significant influence of specific hardware and software setups. Instead, accurate assessments necessitate individual benchmarking of the algorithms within their specific operational context.

Advances in science and technology to meet challenges

The full range of potential benefits cannot be fully anticipated, as the symbiosis of physical and virtual domains will enable functionalities that open new parameter rooms. Thus, one selected representative example from material processing is presented to illustrate these emerging capabilities. Figure 2 shows a conceptual scenario of laser direct writing of optical waveguide arrays. The system comprises a physical subsystem, consisting of a laser and a substrate, and a virtual subsystem, illustrated as a yellow cloud with a network-like structure. During the waveguide writing process, multiple optical and non-optical signals are generated but currently remain unused. By acquiring these signals and transferring them to the virtual subsystem, simultaneously processing the data in the virtual sphere and providing adapted laser operating parameters, instantaneous adaption of laser operating parameters will be possible controlling additional new functions: e.g., the damping parameter of a waveguide can be controlled by parameters like pulse shaping, feed rate, pulse duration, pulse energy, and laser polarization in real-time. This necessitates pulse-to-pulse synchronization. Given commercial femtosecond pulsed lasers with a repetition rate of 1 MHz, this implies that a computation time within the nanosecond range is mandatory to satisfy the conditions for 'zero latency' operation. Achieving this enables predefined and previously inaccessible properties to be adjusted directly during processing. This is interesting for quality parameters, which until now have been measured using destructive post-process analysis. Attenuation can be controlled in real-time without the cutback method to determine length-dependent attenuation. Ultimately, this approach supports the realization of a “first-time-right” manufacturing principle.

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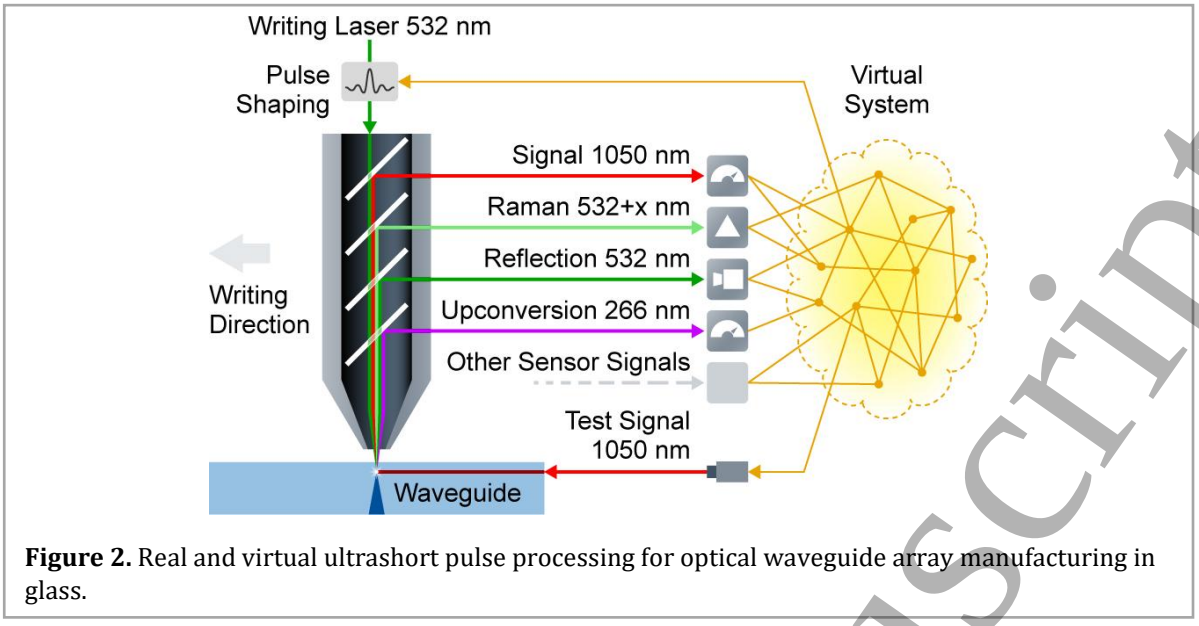


Figure 2. Real and virtual ultrashort pulse processing for optical waveguide array manufacturing in glass.

The concept of 5D photonics can be extended to a wide range of manufacturing processes and other application domains. For example, the principles demonstrated in the forklift operator assistance system could be adapted for medical applications. In such scenarios, multimodal measurement systems, including optical coherence tomography, ultrasound, and spectroscopy, can capture dynamic physiological processes in real-time. This information can then be presented to the surgeon via a digital overlay, enabling enhanced visualization and decision-making during medical procedures.

Concluding remarks

5D photonics is expected to play a key role in future technological developments, as digital overlays or twins introduce a fundamentally new dimension of interaction between physical and virtual domains. This paper has presented several examples in which the 5D concept enhances performance by enabling real-time capabilities, such as the LIFT process and the operator assistance system for forklift drivers. Moreover, new functionalities emerging from this concept are expected to open additional application areas, including the exploration of new parameter spaces for the precise adjustment of product properties.

Realizing such capabilities is challenging and requires seamless interaction between hardware and software components with effectively 'zero latency'. Optical systems for multimodal signal acquisition and data transfer are the key to fulfilling this approach. Therefore, both domains must operate in real time, and further research is necessary to achieve this, as 'zero latency' control is essential to unlocking the full potential of the 5D technology.

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Section 7.2 – Nanocrystal Systems for Reconfigurable Photonics

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Status

The field of laser-based fabrication of semiconductor nanoparticles (NPs) emerged in the early 2000s with pulsed laser ablation (PLA) in liquids, a versatile top-down approach that enables surfactant- and contamination-free synthesis of ultrapure NPs. Pioneering studies first demonstrated the laser-fabrication of metallic NPs [1], followed by semiconductor CdSe quantum dots exhibiting tunable emission [2, 3].

In the last decade, attention has increasingly shifted toward the PLA synthesis of nanostructures from complex, multicomponent crystals, including perovskites. Perovskite-type semiconducting nanocrystals (NCs), such as halide perovskites (ABX_3), gained significant interest since the 2010s due to their exceptional optical tunability, defect tolerance, and compositional flexibility, which make them promising candidates for light-emitters, photovoltaic devices, and quantum optics (fig. 1a). However, perovskite stability strongly depends on composition. Compared to hybrid ABX_3 counterparts, all-inorganic double perovskite systems ($A_2BB'X_6$) generally exhibit higher resistance to moisture, heat, and illumination. Such compositions remain less explored in chemical synthesis due to challenges in controlling multicomponent stoichiometry, whereas PLA offers a direct route to transfer complex target compositions into nanosized form [4].

However, most works related to perovskite NPs utilize chemical synthesis methods, which require organic ligands or surface-capping agents to control nucleation and NCs' growth. These molecules may be essential for stabilizing NCs, but can hinder charge transport and require post-synthetic purification steps, which may affect material quality and reproducibility. In contrast, PLA route for the synthesis of 0D-perovskites avoids the need for stabilizing ligands during formation, enabling direct fabrication of ligand-free NCs and offering greater flexibility for subsequent surface modification with shorter or application-specific molecules. This may improve applicability in optoelectronics, photocatalysis, scintillation, and electrochemical systems [5] (fig. 1b).

Current progress in laser-fabrication of perovskites shows great potential to produce ligand-free NCs with precise size control and high photoluminescence quantum yields (> 70%), avoiding chemical impurities that plague bottom-up routes [7]. Advances include hybrid laser fragmentation for perovskites, enhancing stability against halide migration [8]. In laser-based synthesis, preservation of the initial crystal phase rather than its controlled growth is typically achieved by using short laser pulses to limit thermal decomposition, while the resulting defect density is largely governed by non-equilibrium ablation dynamics.

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The capability of a laser-based approach to generate NCs with clean surfaces is particularly relevant for quantum optics and radiation detection, where surface chemistry critically affects performance. Further advances in this field promise gains in the development of new nanomaterials for modern photonics in the concept of "5D photonics", encompassing multidimensional control of optical, electrochemical, and scintillation properties to create new multifunctional devices [9]. In this framework, perovskite NCs fabricated via PLA may provide tunable emission across the visible to near-infrared range, reasonable radiative efficiency, and access to compositions with improved intrinsic stability for advanced optical, electrochemical, and scintillation devices.

Moreover, laser-controlled modification techniques such as laser patterning and laser printing enable the direct creation of ordered NC arrays and metasurfaces, offering additional control over local resonant and/or nonlinear optical responses [10]. These prospects represent a key step toward on-demand fabrication of reconfigurable photonic materials.

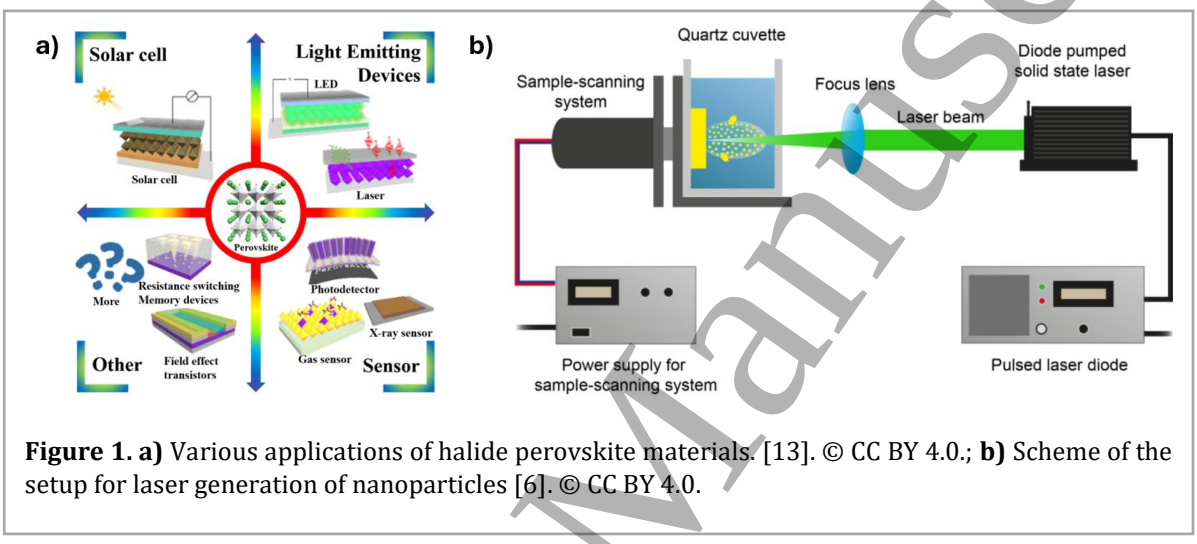


Figure 1. a) Various applications of halide perovskite materials. [13]. © CC BY 4.0.; **b)** Scheme of the setup for laser generation of nanoparticles [6]. © CC BY 4.0.

Current and future challenges

Despite the advantages of the PLA technique, laser-fabrication of perovskite NCs in liquids faces several unresolved challenges. Current challenges include achieving precise size control over morphology, crystallinity, size distribution, and composition, which is largely inherited from the target material. Such polydispersity affects quantum yield and emission tunability, particularly in perovskites, where high temperatures and pressures during ablation can cause phase segregation or higher defect density [3, 5]. Scalability is another major limitation. Current PLA setups have low productivity, limiting gram-scale synthesis for industrial applications, compounded by the need for optimized laser parameters like pulse duration, fluence, and repetition rate to minimize aggregation [2].

For perovskites, inherent instability to moisture, oxygen, and heat exacerbates degradation, necessitating protective shells or media, yet these add complexity to synthesis and applicability [14]. Developing approaches for PLA of various perovskite structures to create stable nanoparticles is essential for advancing their use in functional nanolayers and metamaterials tailored for optical and optoelectronic systems, including 5D photonic architectures. In device-oriented applications, integration of chemically synthesized NPs remains challenging, where poor charge transport and non-radiative recombination reduce efficiency [13, 15]. Laser-fabricated NCs, with their clean surfaces, could overcome these issues, but still need to enhance long-term stability without surfactants and improve biocompatibility for bio-optoelectronics [16].

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Our recent studies demonstrated that femtosecond PLA can preserve complex perovskite compositions, including hybrid and double perovskite systems, in nanocrystalline form [4].

For 5D photonics applications aimed at multidimensional optical data storage and processing using laser-induced nanostructures, challenges include embedding fluorescent perovskite NCs at high density without inducing photobleaching and thermal drift [9]. In electrochemiluminiscent (ECL) sensing, laser-fabricated NCs hold promise as highly sensitive biosensors, but issues like selectivity and NCs' stability in aqueous media continue to hinder clinical translation [11, 12].

Overall, future efforts must address laser-material interactions, hybrid compositing, material durability, and scalability for quantum optics integration, potentially advancing 5D photonics, but requiring NCs with controlled defect density [8, 13, 17]. In addition, interdisciplinary solutions addressing optimized ablation procedures and developing new NC compositions could overcome present limitations, enabling sustainable applications.

Advances in science and technology to meet challenges

To overcome size control and uniformity issues in PLA in liquids for perovskite nanoparticles (NPs), recent innovations include donut-shaped laser beams for precise fragmentation, enabling narrower size distributions and tunable photoluminescence properties in multi-element systems. Scalability is advancing through multi-beam PLA in liquids techniques, which leverage non-equilibrium plasma dynamics to boost productivity toward industrial gram-scale synthesis while minimizing aggregation via optimized fluence and pulse durations [18].

Perovskite instability is primarily addressed through compositional engineering, for example, by using all-inorganic and double perovskite systems with improved intrinsic stability. In this context, laser ablation enables the transfer of such complex compositions into nanocrystalline form, although long-term stability of the resulting nanoparticles remains a challenge. Long-term stability without surfactants benefits from biocompatible hybrid coatings, advancing bio-optoelectronics applications [13, 17].

In ECL sensing, electrode fouling and low aqueous efficiency could be tackled by developing stable perovskite quantum dots, enabling the detection of biologically relevant analytes and long-term emission for clinical biosensors. Advances in coreactant sensing systems and NP-electrode interfaces, such as aqueous-stable emitters, support multiplexed assays [12, 19].

It is important to develop methods for laser ablation of perovskites from many elements in order to form stable nanoparticles of uniform size range and to comprehensively study their electronic and optical properties. Further development of nanolayers and their application in metamaterials will provide practical solutions for various 5D photonics problems.

A relevant and promising direction is the use of nanoparticles as active elements of metasurfaces. The development of research on sustainable laser synthesis technologies of NCs with specific properties, as well as the optimization of their deposition methods on various surfaces, opens up prospects for practical applications, particularly in the field of 5D photonics.

Interdisciplinary approaches, including AI-driven ablation parameter optimization and hybrid composites, promise to resolve many challenges for sustainable, defect-free applications [7, 18, 20].

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Concluding remarks

Laser generation of semiconductor nanoparticles via PLA has evolved from fundamental studies in the early 2000s to a surfactant-free method capable of producing compositionally complex and ligand-free nanocrystals for advanced applications. Current challenges - size polydispersity, limited control over defect density, scalability, intrinsic perovskite instability, and integration into 5D photonics systems - remain significant. While advances in femtosecond laser processing and parameter optimization improve reproducibility and phase preservation, precise control over crystallinity and defect density remains challenging. Further developments will support exploration of perovskite nanomaterials in emerging photonic applications. Addressing these challenges will be essential for establishing laser-synthesized nanoparticles as viable materials for photonics, sensing, and information technologies.

Acknowledgements

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Section 7.3 – Framework for Automated Development and Modeling of Complex Photonic Systems

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Status

With the availability of novel materials 0, processes 0, tools 0, and methods 00 developers find themselves confronted with increasingly complex photonic systems. Additional challenges arise with miniaturization of systems and function integration of components. Automation of product development has seen significant advances, particularly in disciplines such as mechanical design. Artificial intelligence and knowledge-based engineering have progressed from rule-based approaches, relying on explicit expert knowledge, to case-based methods that reuse and adapt prior solutions, and model-based development, which employs analytical and simulation models for systematic optimization 0. These developments have recently converged toward data-driven approaches 0. In contrast, the automation of photonic system development remains underdeveloped, with progress still limited to domain-specific, partially automated design processes. While these efforts represent important progress, they primarily address the design of individual components or subsystems 00. As a result, designs are often biased by the developer's intuition, excluding elements of the solution space without consideration. Therefore, considerable potential remains in extending such methods toward holistic system-level development, where algorithms can explore all possible solutions for simulation and optimization within a unified and automated approach. MacLellan et al. proposed an adaptable framework for the automated inverse design of photonic systems that iteratively optimizes the parameters of each topology, taking the complete solution space into account 0. Wüllner et al. presented a simulation-based development approach containing of an automated CAD-to-ray-tracing workflow for TIR prism rods 0. This workflow for workpieces could be extended to accommodate more complex systems by a constraint-based approach that eliminates designs from solution space that contradict system requirements prior to simulation. To address this, we propose a uniform, generalized, and systematic framework for the development and modeling of photonic systems, restricting the solution space with a constraint-satisfaction problem that links requirements, constraints, and simulation.

The definition of requirements for the intended application forms the essential first step in structuring the design methodology. From these requirements, constraints are formulated and expressed mathematically as constraint functions 0, which establish the boundaries of the simulation. These functions specify value ranges that align with the system requirements, effectively limiting the simulation to designs within the feasible solution space that satisfy all criteria. This approach ensures an unbiased and systematic procedure, optimizing all viable system topologies during simulation. Against the backdrop of ever-increasing system complexity and interdisciplinarity the framework has a holistic approach and is valid across electrical,

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mechanical, and optical domain. The next chapter will specify the framework in more detail and present its main challenges.

Current and future challenges

In order to keep up with advances in product development three challenges remain for the proposed constraint-based framework: deriving requirement constraint interactions, ensuring model integration and interoperability, and implementing robust multi-scale simulation.

The first challenge poses itself in developing a formalized methodology to systematically derive requirements for complex photonic systems. A structured approach to express these requirements using mathematical, logical, or algorithmic models is essential to generalize the design process while exploring the full solution space. The proposed framework allows for defining requirements across all relevant domains, by defining clear rules for requirement derivation, prioritization, and representation. This is implemented using a constraint function.

The second challenge involves the integration and interoperability of models within the framework. Constraints from different domains must be compatible, interconnected, and consistently incorporated into the overall system, a task that becomes more critical as system dimensions shrink. Especially, advances in nanophotonics and metamaterials increase the demand for cross-scale interoperability 00. While prior research has addressed description, simulation, and multiscale integration 0, methodological, computational, and interdisciplinary challenges remain. Formalizing novel materials or optical elements through rigorous mathematical and physical descriptions is necessary before they can be included in constraint functions. Furthermore, representations must be meaningful and comparable across scales, requiring rules for weighting and integrating effects occurring at different levels. With such formalization, the framework supports the development of complex photonic systems spanning multiple dimensions and scales. In Figure 1, a bipartite graph shows exemplary how this approach could be used for the emitting subsystem of a Raman Spectroscope. The mathematical description enables a connection between parameters from different domains like optics, chemistry and microfluidics and the constraints restrict the solution space.

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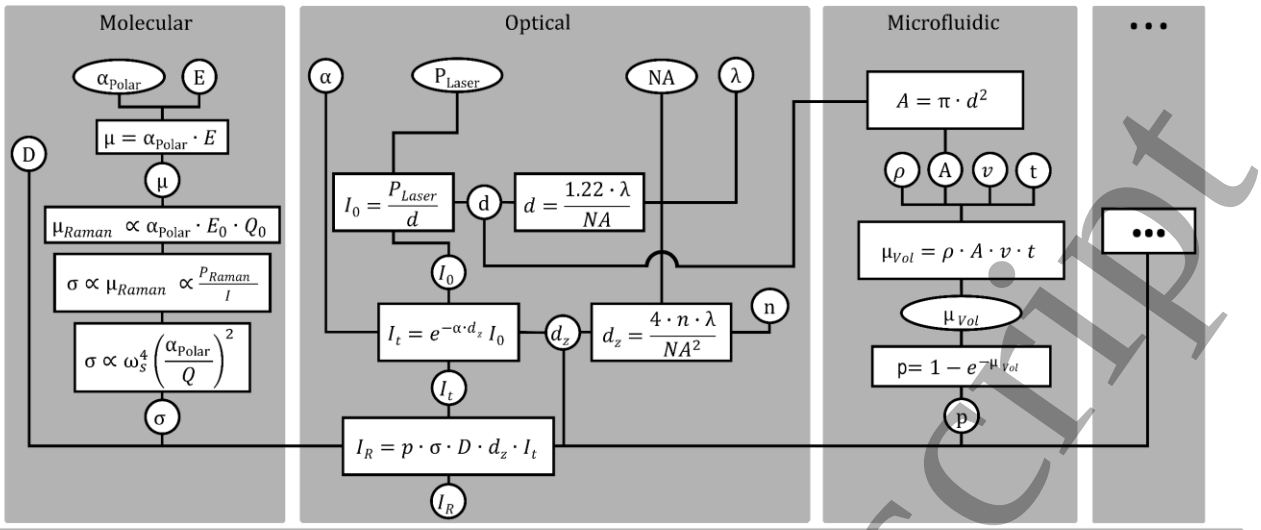


Figure 1. The shown illustration is an example for a constraint-satisfaction problem for an emitting subsystem of a Raman spectrometer for microplastic detection in water. It describes the relationship between representative input parameters and the Raman scattering I_R as the main output parameter. The excitation of a sample consisting of particles dissolved in a liquid is assumed to be carried out using a laser. In the next step, values are assigned to the input variables in order to determine possible solutions to the constraint-satisfaction problem. The equations are provided as examples and are not intended to be exhaustive.

The third challenge lies in implementing multi-scale simulations. Research has largely focused on linking macro- and microscale models, with recent efforts extending to nanoscale phenomena 0. Software tools such as Ansys Lumerical and Zemax or Comsol enable coupling of Maxwell solvers, wave-optical simulations, and ray tracing, which are useful tools for the optimization of existing designs but they lack the ability to generate initial designs and compare the impact of different components under constraints automatically. To ensure an unbiased development, an optimization algorithm for topology and parameters needs to be implemented, comparable to MacLellans approach 0. Additionally, criteria for selecting the final system configuration, for example by comparison via loss functions, must be systematically addressed to ensure efficient development.

Addressing these challenges collectively enables a formalized constraint-satisfaction paradigm capable of developing photonic systems without developers bias across dimensions and across scales.

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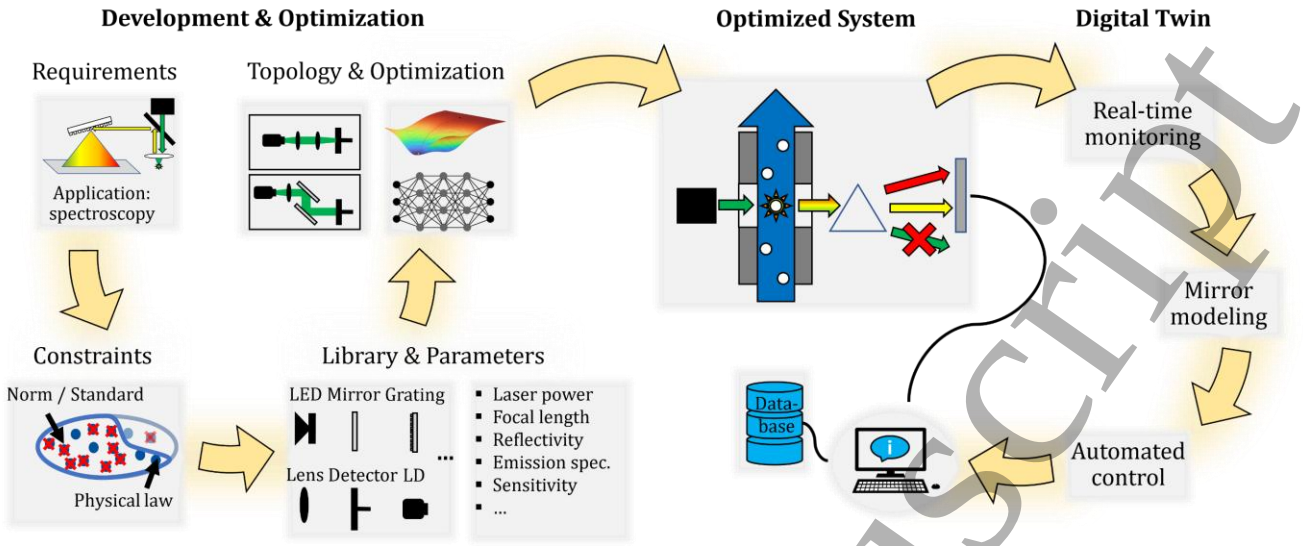


Figure 2. Illustration of the proposed framework: Requirements are derived from the desired application and the constraint function is formulated. The constraint function restricts the solution space for the simulation to designs that satisfy all requirements. Within this solution space all possible system topologies are optimized for their parameters. At the end the final system is chosen by comparing loss functions of all topologies 0. To create a digital twin of the developed system real-time monitoring, mirror modeling, and automated control need to be ensured 0.

Advances in science and technology to meet challenges

To address the growing complexity of systems and accelerate innovation, future development will require the integration of digital models and deep learning-assisted methods. Initial progress in this direction has already been demonstrated through intelligent optical elements, which merge the physical product and its virtual counterpart into a unified representation 0. Within this context, two primary challenges emerge: embedding deep learning-based methods into the framework and incorporating a virtual system model.

Deep learning-based methods evolve the framework from algorithmic supported to artificial intelligence-assisted development. For instance, the knowledge base, represented by a library that contains components for the simulation, can be a large language model that autonomously scans scientific publications and integrates newly identified components. Sullivan et al. introduced a deep learning method that investigates micro structuring of materials and its influence on optical and thermal responses. It consists of a tandem neural network that simulates the optical and thermal output and validated the suggested material and geometry by comparing it to pre-defined constraints 0. Brosowsky et al. developed ConstraintNet, a neural network that considers adjustable constraints for each forward pass 0, demonstrating the usefulness of neural networks for constraint-based simulations. However, further research to extend this approach to system-level applications remains.

Additionally, a digital model of the system, with real-time monitoring, mirror modeling, and automatic control can be embedded 0. For real-time monitoring, interfaces to receive data from components across all domains in the experimental setup are required. This demands considerable effort and therefore concepts to reduce both experimental and computational expenses must be developed. Mirror modeling can be achieved

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by feeding the digital system model with the measured real-time data. This allows for an automatic control by live feedback of data into the system.

For practical implementation, the framework can be embedded in a multi-agent system in which specialized agents oversee individual aspects of the process and negotiate conflicting objectives 0. For the proposed framework possible agents can be requirement definition, constraint formulation, simulation and optimization, knowledge acquisition, and performance evaluation of the final system. Furthermore, an agent controlling tolerance distributions in the system can be employed to achieve robust optical system designs. To achieve this, critical components and component sensitivity needs to be identified and tracked 0. This information is then forwarded, weighed against other parameters and after evaluation considered in the constraint function, which could result in a component replacement. Together, these advances point toward a future in which intelligent, digitally integrated design frameworks enable faster, automated, and more robust development and modeling of complex photonic systems.

Concluding remarks

In this work, an unbiased framework for the development and modeling of complex photonic systems across nano, micro, and macro scales is proposed. To achieve this, requirements must be derived from the intended application and then mathematically described as constraint functions. These constraint functions define boundaries for the simulation and restrict the solution space. This preselection allows for the exploration of every possible design within the restricted solution space, ensuring an unbiased approach to system development. These initial steps are carried out with consideration of the electrical, mechanical, and optical domains. To meet future requirements, this holistic approach can be further developed into an artificial intelligence-assisted multi-agent system with agents representing requirement definition, constraint formulation, simulation and optimization, knowledge acquisition, and performance evaluation of the final system. In this context, digital twins can be integrated as specialized agents within the multi-agent system, enabling real-time monitoring, mirror modeling, and automated control of the physical system. This integration bridges the physical and virtual domains, enhancing collaboration between agents and supporting the efficient development of next-generation photonic products.

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Section 8.1 – Multi-timescale manipulation of quantum light

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Status

Photonic quantum information processing in the spectro-temporal domain promises exceptionally high information bandwidth with access to large Hilbert spaces, both of which are crucial requirements for scalable quantum communication [1] and distributed quantum computing [2]. Exploiting this potential requires precise control over spectro-temporal properties of single photons across a broad range of timescales, from microseconds to picoseconds depending on the application, see Fig. 1. Specifically, three capabilities are essential: First, *adaptive control* enables manipulation of quantum states on microsecond to nanosecond timescales based on past measurement outcomes (feedback), which is required to compensate environmental fluctuations, or by affecting future measurement outcomes (feedforward), essential to implement measurement-based quantum computation [3] and quantum teleportation. Second, *pulse-to-pulse control* allows rapid switching of measurement bases between successive pulses on nanosecond to picosecond timescales, forming the foundation for quantum key distribution [5] and randomized quantum state benchmarking [6]. Third, *single photon pulse shaping* provides deterministic controls of the spectro-temporal structure of single photons on pico- to femtosecond timescales. Tailoring the amplitude, phase and frequency of single photons enables engineered quantum states [7], spectral shearing [8], and efficient interfacing of light-matter systems [9].

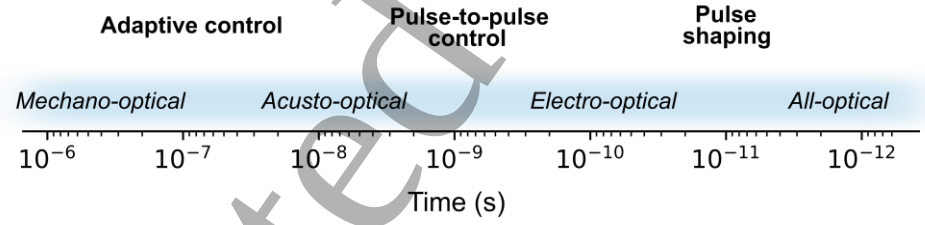


Figure 1: Multi-timescale manipulation of quantum light. Precise and deterministic control across microsecond to picosecond timescales enables three key functionalities: (i) adaptive control for real-time stabilization and measurement-based feed-forward, (ii) pulse-to-pulse control for switching measurement bases and routing quantum information between successive pulses, and (iii) pulse shaping for deterministic engineering of single-photons. The seamless combination of these operations forms the basis for scalable photonic quantum networks.

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Current and future challenges

Recent efforts have started to address scalable multi-timescale quantum photonic systems, especially using fiber-based architectures. In particular, we demonstrated *Chirped Pulse Modulation* enabling *real-time* fourier-domain wave shaping of single as well as entangled photons [10]. Specifically, we used an electro-optic phase modulator (EOPM) placed in between two highly dispersive Chirped Fiber Bragg Gratings (CFBGs) with opposite dispersion, see Fig. 2 (a). In this configuration the CFBGs facilitated dispersive Fourier transformation, which gives access to spectral phase modulation of the input photons via the EOPM, the operating principle is illustrated in Fig. 2(b–d). By rapidly switching the RF modulation frequency (every 10 nanoseconds) among 1.25 GHz, 2.5 GHz, and 3.75 GHz, we realized multi-timescale time-bin superpositions with adjustable spacings of 100 ps, 200 ps, and 300 ps. This provides fully reconfigurable, single-photon pulse shaping on a pulse-by-pulse basis and can feature real-time adaptivity. Furthermore, the system remained robust to photon count-rate fluctuations due to the fast measurement-basis switching and waveform looping on a microsecond timescale. To the best of our knowledge, this is the first demonstration of a compact setup that achieves multi-timescale control functionalities at the single-photon level.

While this system is promising to overcome the limitations of conventional multi-timescale quantum processing schemes such as combining fiber interferometers and switches [11, 12] (e.g., active stabilization, footprint scalability and reconfigurability), there are also challenges associated to this approach. The main challenge is a spectral shift on the output pulses induced by the RF driving field, reducing interference visibility and currently limiting the number of coherently addressable time-bins to a few tens. This spectral shift arises because chirped pulse modulation is not a purely time-domain operation but a joint spectro-temporal transformation. Accordingly, the modulation signal induces a redistribution and shift of spectral components proportional to the modulation frequency. Moreover, due to this shift, currently only time-bin spacings of several hundreds of picoseconds are addressable. By choosing larger frequencies of the RF driving field (e.g., 50 GHz), it would also be possible to superimpose time-bin spacings of up to 4 nanoseconds. Using broadband, sub-picosecond pulses may alleviate this, as their larger bandwidth makes them less sensitive to this spectral walk-off.

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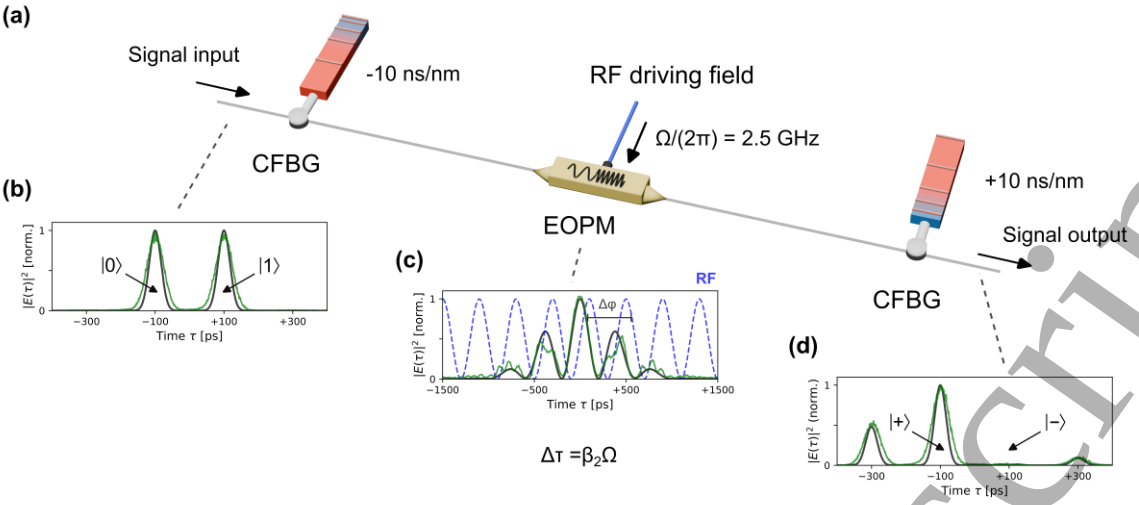


Figure 2: Chirped Pulse Modulation for multi-timescale control of quantum light. (a) Real-time chirped pulse modulation can be realized using an electro-optic phase modulator (EOPM) placed between two oppositely dispersive chirped fiber bragg gratings (CFBGs). (b-d) This enables programmable manipulation of single-photons (here in a superposition of time-bins) across microsecond to picosecond timescales. By changing the frequency of the RF driving field Ω, different temporal spacings of time-bins can be addressed and projective measurements can be implemented. The green curves show experimental data, the black curves show simulation data. The radiofrequency (RF) signal is displayed in blue.

Another challenge of this architecture is its on-chip implementation. In particular, achieving large on-chip dispersion (> 50 ps/nm) and large optical delays (> 1 ns) remain difficult to implement on a nanophotonic chip [13]. To enable the nanphotonic implementation, meta-dispersive structures offer a route to reduce the required dispersion for nanophotonic implementations by engineering a Fresnel-like phase profile rather than relying on uniform delay. In the context of CPM, the periodicity of the RF drive implies that only spectral components within one RF period need to be appropriately repositioned, substantially lowering the absolute dispersion requirement. Integrated pulse shaping has been shown with coupled resonators [14], but faster update rates will require electro-optic phase shifters. Current architectures scale poorly with respect to their footprint, as each mode typically requires a separate resonator or waveguide, highlighting the need for more compact and scalable designs.

Advances in science and technology to meet challenges

Multi-timescale quantum information processing is still an emerging field. While the generation and detection of entangled states are already very advanced [15], efficient control of these degrees of freedom is still challenging. Many tools from optical communications and ultrafast optics have proven useful, but their applicability is limited by insertion losses, bandwidth, and system complexity. As a result, spectro-temporal domain quantum processing currently lags behind other quantum information encodings, such as path encoding, by one to two orders of magnitude in key performance metrics per component [16]. We identify three major challenges that must be addressed to advance multi-timescale manipulation of quantum light:

Conceptual questions remain regarding the scalability and applicability of current architectures for multi-timescale manipulation of quantum light. These challenges concern both the extension to high-dimensional quantum information processing (e.g., qudit dimensions > 100) and the implementation of multi-photon operations. Additionally, bridging different temporal regimes within a unified platform remains non-trivial

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and may require hybrid approaches. To advance the field, existing schemes must be systematically benchmarked, and new architectures explored that integrate spectro-temporal control with other photonic degrees of freedom, such as polarization or spatial modes.

Optical losses remain the primary bottleneck for all photonic quantum technologies. To overcome this limitation, heterogeneous photonic integration combining low-loss, material platforms with different functionalities (e.g. InP, $LiNbO_3$, and Si_3N_4) will be indispensable. Passive components, including waveguides, directional couplers, and microresonators, have achieved exceptional performance over the past decades, with losses below 0.03 dB/cm. In contrast, active components such as electro-optic phase modulators, which are essential for time- and frequency-domain operations, still introduce significant insertion losses and require further improvements. Advancing their integration will be critical to reduce optical losses and manufacturing costs by at least an order of magnitude.

Table 1: Comparison of performance metrics for different architectures for manipulating spectro-temporal modes of quantum light. The listed techniques represent prominent approaches in the field but are not exhaustive. Reported values correspond to estimated upper performance limits achievable in integrated photonic implementations.

Architecture	Domain	Transmission loss	Reconfigurability speed	Modal dimensions	Photonic integration	Major limitation
Delay interferometer [Yu, Hao, et al., Nature Communications 16.1 (2025)]	Time	1.5 – 3.0 dB	~ 0.5 - 10 μs	~ 10	SiPh/SiN	Efficency
Electro-optic modulation [Lu et al., PRL, 125.12 (2020)]	Frequency	3.0 – 5.0 dB	~ 1.0 - 10 ns	~ 100	TFLN/LNOI	RF-Bandwidth
Quantum Pulse Gate [Serino et al., PRX Quantum, 4.2 (2023)]	Time/Frequency	5.0 – 8.0 dB	< 100 ps	~ 100	TFLN/LNOI	Pump shaping
Chirped Pulse Modulation [This work]	Time/Frequency	3.0 – 5.0 dB	~ 1.0 - 10 ns	~ 250	TFLN/LNOI	Dispersion

Integrating photonic and electronic functionalities on a nanophotonic platform will reduce reliance on bulky external microwave drivers by generating and controlling RF driving fields with 25 GHz and beyond directly on-chip. For example, microcombs can serve as local oscillators to synthesize and program radiofrequency signals via their optical beat notes [17] to drive chirped pulse modulation. This step will not only reduce the footprint of devices processing quantum information in the spectro-temporal domain, but also lead to reduced feedback latency (less than a nanosecond) and thus enhance real-time adaptive capabilities. Another path to explore is all-optical spectro-temporal manipulation of single photons on nanophotonic platforms, e.g. via Bragg-scattering four-wave-mixing [18], which could enable unprecedented bandwidths of up to tens of THz providing access to femto-second scale manipulation.

Concluding remarks

Meeting the demands of future quantum photonic hardware and ensuring compatibility with emerging quantum computing and communication platforms will be central challenges for multi-timescale photonic quantum information processing in the coming years. In this perspective, we have emphasized that the ability to manipulate quantum light across (at least) six orders of magnitude in time constitutes a critical milestone

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for advancing quantum science. We have outlined the fundamental challenges, key enabling technologies, and potential integration strategies that could link ultrafast and slower processes in quantum photonic systems. Overcoming these challenges would position photonic quantum information processing—operating seamlessly across multiple timescales—as a cornerstone for scalable, distributed quantum networks. In a broader context, multi-timescale control operationalizes the 5D paradigm by combining digital feedback (time-domain adaptivity) with simultaneous control over multiple photonic degrees of freedom. The hierarchical interplay of slow feedback, fast reconfiguration, and ultrafast pulse shaping links information processing with high-dimensional state control in a unified framework.

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Section 8.2 – Emulating 5D/6D/7D photonics by Bose-Einstein condensates of dipolar particles

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Status

It is commonly known that wave dynamics in photonics can be emulated by matter-wave (MW) dynamics in atomic Bose-Einstein condensates (BECs). The underlying fact is that the basic nonlinear Schrödinger equation (NLSE) in optics is identical to the Gross-Pitaevskii equation (GPE) which governs the MW propagation in BEC, in the mean-field (MF) approximation [1]. Despite the different physical nature of the electromagnetic waves in photonics and MWs in BEC, the similarity in their linear propagation and nonlinear properties (the Kerr effect in optics, and the cubic collisional term in GPE) leads to a remarkable affinity of the respective phenomenologies. A commonly known example is the similarity between solitons in optical fibers [2] and MW solitons in nearly one-dimensional (1D) BEC [3]. In the general case, the spatiotemporal propagation of optical and matter waves is governed by the (3+1)D (alias 4D) NLSE and GPE, respectively. These models give rise to optical/MW multidimensional solitons, truly remarkable ones being those which carry the embedded vorticity (i.e., angular momentum), and still more complex topological modes in the form of *skyrmions* and *hopfions* [4]. However, in stark contrast to 1D solitons, which normally are stable, (2+1)D and (3+1)D solitons are subject to ubiquitous instabilities, which lead, respectively, to the *critical* and *supercritical collapse*, i.e., catastrophic self-compressions of the wave packets (it is classified as critical if it commences when the norm of the localized input exceeds a certain finite critical value, and supercritical if an input with an arbitrarily small norm may initiate the collapse). Still faster growing is the *splitting instability* of multidimensional vortex solitons [4]. Therefore, stabilization of multidimensional solitons in photonics and BEC is a topic which has drawn much interest. In particular, it was predicted that the stabilization may be provided by competing focusing-defocusing nonlinearities in optics [5,6] and a similar mechanism in BEC, provided by the competition of the MF self-attraction and repulsion induced by the Lee-Huang-Yang (LHY) quantum-mechanical correction to MF [7]. In the latter case, the self-trapped states stabilized by the balance of the MF self-attraction and LHY-induced self-repulsion are usually called *quantum droplets* (QDs), as they are actually drops of the quantum superfluid with an extremely low density [7]. These stabilization mechanisms have been demonstrated experimentally for vortex solitons in photonics [8] and fundamental (zero-vorticity) QDs in BEC [9,10]. Stable QDs with embedded vorticity have been predicted in the latter case [11,12]. Another relevant possibility is to stabilize (2+1)D and (3+1)D two-component solitons in the form of *semi-vortices* (with the vorticity carried by a single component) by means of the spin-orbit-coupling (SOC) effect, in BEC [13,14] and photonics [15] alike.

A possibility to create *effectively 6D* states is offered by *dipolar BEC* composed of magnetic atoms [16] or small polar molecules carrying electric dipoles [17]. In this case, two orientational angles of the magnetic/electric moments are added as two effective coordinates to the four spatiotemporal ones, thus

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bringing the total number of coordinates to *six* (often reduced to five, if external conditions fix one angle). Furthermore, the length of *stretchable* electric dipoles may add another artificial degree of freedom, raising the maximum effective dimension to *seven*. The possibility of creating multidimensional QDs in these settings, stabilized by the beyond-MF LHY correction, was cogently demonstrated in direct experiments with the BEC of magnetic atoms [18,19] and polar molecules [20]. While the QDs reported in these works are fundamental (zero-vorticity) ones, the fact that they are composed of atoms or molecules characterized by the *vectorial* magnetic or electric dipole moments makes it very natural to seek solitons that are also characterized by a vectorial order parameter, which may be the angular momentum of vortex solitons.

Current and future challenges

The realization of the effectively 6D/5D realization of the MW dynamics in dipolar BEC is performed by the application of an external spatially uniform dc magnetic or electric field, which polarizes all dipoles in one direction. The respective scaled GPE for the BEC wave function $\boldsymbol{\psi}(\mathbf{r},\boldsymbol{t})$ is [16,18,19]

$$\boldsymbol{i}\frac{\partial\psi}{\partial\boldsymbol{t}} = -\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\nabla}^{\mathbf{2}}\boldsymbol{\psi} + \boldsymbol{g}|\boldsymbol{\psi}|^{\mathbf{2}}\boldsymbol{\psi} + \boldsymbol{\gamma}|\boldsymbol{\psi}|^{\mathbf{3}}\boldsymbol{\psi} + \boldsymbol{\kappa}\boldsymbol{\psi}\int \boldsymbol{U}_{\mathbf{DD}}(\mathbf{r}-\mathbf{r}')\,|\boldsymbol{\psi}(\mathbf{r}')|^{\mathbf{2}}\boldsymbol{d}\mathbf{r}', \qquad (1)$$

where t is time, $\mathbf{r} = (\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ is the set of the spatial coordinates, $\boldsymbol{g}$, $\boldsymbol{\gamma}$ and $\boldsymbol{\kappa}$ are the strengths of the MF local interaction, beyond-MF LHY [7] correction, and dipole-dipole (DD) interactions, with the DD kernel $\boldsymbol{U}_{\mathbf{DD}}(\mathbf{r}-\mathbf{r}') = (\mathbf{1}-\mathbf{3}\boldsymbol{\cos}^{\mathbf{2}}\boldsymbol{\Theta})/|\mathbf{r}-\boldsymbol{r}'|^{\mathbf{3}}$, where $\boldsymbol{\Theta}$, which represents the fifth dimension in the effectively 5D setup, is the angle between vector $(\mathbf{r}-\mathbf{r}')$ and polarizing field $\mathbf{B}$.

The simplest configuration of the vortex soliton in this setup is isotropic, with respect to the field $\mathbf{B}$ (Type 1 in Fig. 1). In this configuration, the vorticity (proportional to the angular momentum), designated by the yellow arrow in Fig. 1, is aligned with $\mathbf{B}$. In this case, the vorticity is represented by an integer value S of the *topological charge*. The respective form of the stationary soliton (QD) solution to Eq. (1) is

$$\boldsymbol{\psi}(\boldsymbol{r},\boldsymbol{t}) = \mathbf{exp}(-\boldsymbol{i}\boldsymbol{\mu}\boldsymbol{t} + \boldsymbol{i}\boldsymbol{S}\boldsymbol{\varphi})\,\boldsymbol{\Psi}(\boldsymbol{\rho},\boldsymbol{z}), \qquad (2)$$

where $\boldsymbol{\mu}$ is a real chemical potential, $(\boldsymbol{\rho},\boldsymbol{\varphi})$ are the polar coordinates in the (y,z) plane, and $\boldsymbol{\Psi}(\boldsymbol{\rho},\boldsymbol{z})$ is a real stationary wave function vanishing at $\boldsymbol{\rho}\to\infty$ and $\boldsymbol{z}\to\pm\infty$. For the vortex state (2), the angular momentum is directed along the z axis, its magnitude being $M = SN$, where the norm of the wave function is $\boldsymbol{N} = \int|\boldsymbol{\psi}(\mathbf{r})|^{\mathbf{2}}\boldsymbol{d}\mathbf{r}$. The meaning of vorticity S as the topological charge (alias *winding number*) is that a round trip circumnavigating the vortex's pivot ($\boldsymbol{\rho}=\mathbf{0}$, in this case) produces a specific value of the change in the phase of the wave function,

$$\boldsymbol{\Delta\Phi} = \mathbf{2}\boldsymbol{\pi}\boldsymbol{S}\,. \qquad (3)$$

However, the relatively simple configuration, represented by Eq. (2), is *always unstable*, as the GPE solution [21]. On the other hand, it was demonstrated in Ref. [22] that a highly nontrivial anisotropic configuration, with the vorticity designated by the vertical brown arrow in Fig. 2, which is oriented *perpendicular* to the polarizing field $\mathbf{B}$ (Type 2 in Fig. 1), gives rise to *stable anisotropic vortex solitons* (QDs), such as the prolate one displayed in the top panel of Fig. 2. Although there is no straightforward ansatz for this solution, similar to Eq. (2), its integer winding number S (the topological charge) is defined by the same universal relation (3). These solitons realize *effectively 5D* stable self-trapped states.

Moreover, Eq. (1) produces *stable* strongly elongated vortex-antivortex-vortex bound states, as shown in the bottom plot of Fig. 2. Another noteworthy possibility, suggested by the prolate shape of the vortex soliton (QD), is to apply a *torque* to it, in the (y,z) plane, *viz.*, $\boldsymbol{\psi}\to\boldsymbol{\psi}\exp\left((iz/z_0)\tanh\left(y/y_0\right)\right)$, aiming to set the soliton in rotation around the x (long) axis. The result is that a weak torque initiates oscillations, while a sufficiently

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strong one indeed makes the vortex soliton a rotating object [22]. On the other hand, simulations of Eq. (1) demonstrate that rotation around short axes in Fig. 2 (x or y) cannot be imposed [22].

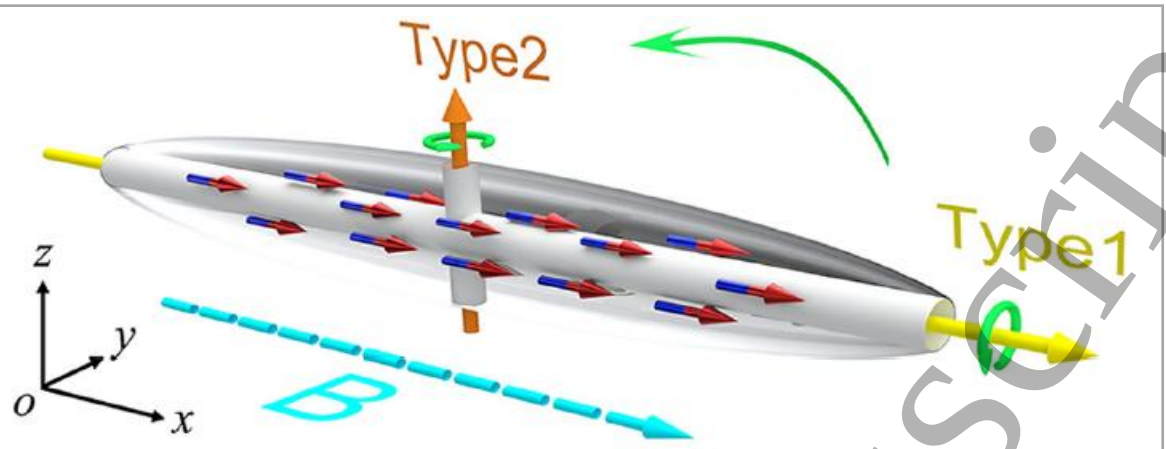


Figure 1. The schematic of the dipolar BEC emulating 5D states, as per Ref. [22], under the action of the polarizing magnetic/electric field **B**. Blue-red arrows designate local magnetic/electric moments of the atoms/polar molecules, while the horizontal yellow (Type 1) or vertical brown (Type 2) arrow represents the vortex' angular momentum (designated by green circular arrows).

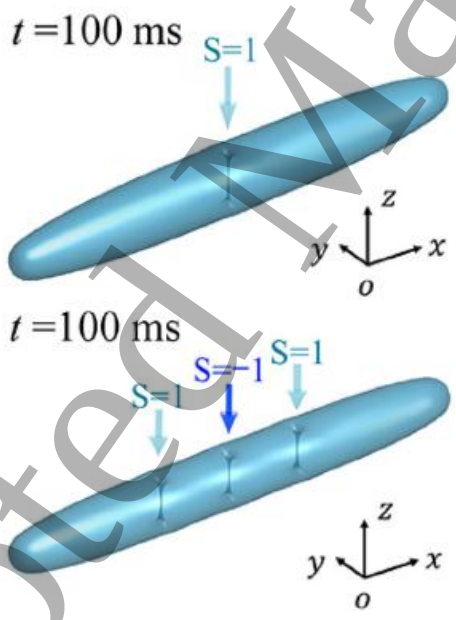


Figure 2. The top plot: an example of a prolate (strongly anisotropic) vortex soliton (QD), generated by Eq. (1), with the vorticity, alias winding number, $S = 1$ (designated by the vertical arrow), which produces the narrow vertical hole at the center of the soliton [22]. The bottom plot displays a vortex-antivortex-vortex bound state generated by the same model. These single-QD and bound states are stable (in particular, at time $t = 100$ ms, in physical units, as indicated in the figure),

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The results summarized above represent the most essential predictions for the dipolar BEC, which may be employed as the simulator of the effectively 6D or 5D nonlinear wave dynamics in photonics, with the directional angles of local dipoles playing the role of two effective coordinates added to the underlying set of four real spatiotemporal ones. A remarkable finding is the existence of the *stable* strongly anisotropic vortex solitons, with the vorticity oriented perpendicular to the direction of the dipoles' polarization, as well as stable vortex-antivortex-vortex complexes, while the obvious isotropic vortex solitons are unstable.

The model suggests a number of new possibilities. A natural, although challenging, generalization of the work is to introduce a BEC mixture of two or several atomic species, described by a system of coupled GPEs. It may produce fascinating states in the form of the above-mentioned *skyrmions* and *hopfions*, which feature two independent topological numbers [4]. In particular, hopfions are, essentially, built as vortex solitons (QDs) with a *twisted* toroidal core, the integer twist representing the second topological number.

Another promising extension is towards the work with *nonstationary* setups, such as the one driven by a *rotating* polarizing magnetic/electric field. One may expect that the prolate vortex soliton may be locked into the rotation mode, provided that the rotation frequency does not exceed a certain critical value, above which the soliton is not able to adiabatically follow the rapid rotation of the governing field. Another relevant option for introducing a nonstationary setup is to apply the polarizing electric field with a fixed orientation, but the strength subject to a time-periodic modulation. This "management" mode may unlock the *seventh* effective coordinate if, as mentioned above, the particles are stretchable polar molecules carrying the electric dipole moment.

It is also relevant to consider interactions between separated vortex solitons (or QDs), as well as collisions between moving ones (the motion is possible as the setup maintains its Galilean invariance). In this context, the long-range microscopic DD interactions between magnetic/electric moments suggest that separated solitons feature effective *macroscopic* DD interactions and, plausibly, formation of bound states in the form of "soliton molecules" (the simplest example is the stable vortex-antivortex-vortex complex is displayed in the bottom panel of Fig. 2), with shapes strongly affected by the anisotropy of the individual vortex solitons (QDs). In particular, it is expected that the "molecules", including ring-shaped chains, may feature robust rotation, thus adding the overall orbital angular momentum to the sum of the spin momenta of individual vortices. Furthermore, a highly challenging subject for the analysis may be looking for complex states in the form of multi-vortex-soliton crystals. Lastly, an interesting possibility is to study the "soliton molecules" and "soliton crystals" in excited states, and thus identify eigenmodes of their internal vibrations.

Concluding remarks

The emulation of the wave dynamics in photonics by means of BEC suggests looking for direct counterparts of the predicted MW (matter-wave) states in optics and photonics. An example is the aforementioned correspondence between SOC-supported solitons in BEC [13,14] and optics [15]. As shown above, the most essential modes predicted in the dipolar BEC are the anisotropic vortex solitons. They may find photonic counterparts in the form of spatiotemporal optical vortices (STOVs) [23], with the optical angular momentum of STOV solitons playing the role of the fifth coordinate added to the spatiotemporal set in the direct realization of the 5D photonics. The stability of these states may be secured in optical media with the above-mentioned competing focusing-defocusing nonlinearity [24]. Another possibility to integrate the multidimensional MW solitons and QDs into optics is to consider the interaction of photonic fields with them, such as the scattering of incident optical waves on the solitons, and optical excitation of their intrinsic modes.

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The above discussion addressed lossless systems. Many types of photonic media, such as laser cavities and exciton-polariton systems, are dissipative, with losses compensated by intrinsic gain or external pump. The respective nonlinear models are based, respectively, on the complex Ginzburg-Landau or Lugiato-Lefever equations. Such models produce diverse multidimensional states, Including stable dissipative solitons with embedded vorticity [4], which may provide the basis for the direct implementation of the effective 5D photonics, similar to the possibilities outlined above for lossless media.

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Section 8.3 – Photonics of the Human Brain

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Status

Speaking about photons in active human brain, we consider them as quanta of electromagnetic radiation representing the entire electromagnetic spectrum. The brain receives and sends electromagnetic signals via nerve cells (neurons), synapses and neurotransmitters. Action potentials in neurons generate low frequency electromagnetic brain waves (delta, theta, alpha, beta, and gamma waves), which are measured by brain electroencephalography (EEG) and magnetoencephalography (MEG). It is also well-known that human brains generate measurable electromagnetic radiation in form of ultraweak photon emission or biophotons, which are by-products of metabolic reactions within cells or can be triggered by neuron currents and neurotransmitters [1-4]. This radiation is not a short wavelength fraction of black body radiation, it has higher intensity and correlates with the brain activity. However, the role of these biophotons in brain functions is still unclear. Biophotons may play a potential role in neural signal transmission and processing [5,6]. Myelin sheath of neurons can serve as dielectric waveguides [7-9]. However, the nature of biophoton signalling remains speculative. According to electromagnetic field theories of consciousness, consciousness may arise from the electromagnetic fields generated by the brain [10]. Effects of electromagnetic radiation on different biological systems and possibilities of non-invasive optical brain imaging and photon transport through the brain are under investigations [11,12]. Recently, it has been shown that cortical and subcortical activity can be understood as a consequence of excitations of fundamental resonance modes of brain geometry [13]. In this paper, we provide a brief discussion of photonics of human brain, emphasizing the quantum nature of all radiation processes. The human brain remains a fascinating object and understanding how it works represents a very important scientific challenge.

Current and future challenges

The theory of black body radiation in vacuum goes back to Planck's formula derived in 1900. Here we consider the thermal black body radiation inside the human brain and its quantum nature. Modern theories completely ignore the role of thermal radiation in brain functions, and the challenge is to understand what photons may be responsible for in the active brain. This radiation is in thermodynamic equilibrium with the brain maintaining a constant body temperature around 36.6°C (97.9°F) through a process called thermoregulation, controlled by the hypothalamus. Energy density of thermal radiation and its spectral characteristics are solely determined by the brain temperature and frequency dependent refractive index. Since the water content of the human brain is in average 73-75 % (for gray matter it is about 80%, while for the more lipid-rich white matter it is about 70%), we can use the refractive index of water.

The time average energy density of the electromagnetic radiation U for black body radiation can be written considering photons with the energy $\hbar\omega$, wave vector $\boldsymbol{k}$, and wavenumber $k = n\omega/c$ in the following form

$$U = \hbar\omega\ \theta_\omega\ \frac{2d^3\boldsymbol{k}}{(2\pi)^3} = \theta_\omega\ \frac{n^3\hbar\omega^3 d\omega d\Omega}{4\pi^3 c^3},$$

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where $\frac{2d^3\boldsymbol{k}}{(2\pi)^3}$ is the number of photon states (modes) per unit volume, $n = n(\omega)$ is the brain refractive index, and $\boldsymbol{\theta_\omega}$ is the number of photons per mode. For isotropic black body radiation

$$U = \theta_\omega \frac{n^3\hbar\omega^3 d\omega}{\pi^2 c^3}, \qquad \theta_\omega = \frac{1}{\exp(\hbar\omega/kT)-1}. \tag{1}$$

This expression defines the radiation energy density in brain in the spectral range $\boldsymbol{d\omega}$ and coincides with the well-known Planck expression for $n = 1$. Radiation power emitted by a unit surface *P/S* of the brain (black body source) is related to the radiation energy density by the following expression

$$P/S = \frac{c}{4}U$$

where the factor ¼ accounts for directional averaging of radiation. According to Wien's displacement law, the radiation power and the radiation energy density have maximum at the same wavelength

$$\lambda_{max} = \frac{b}{T}, \qquad b = 0.29\ \text{cm}\cdot\text{K}.$$

At the normal body temperature, this corresponds to the wavelength $\lambda_{max} = 9.36\ \mu\text{m}$. At this wavelength water is strongly absorbing with the absorption length of the order of 12 $\boldsymbol{\mu}$**m**.

The total energy density and total radiation power (per unit surface) integrated over full spectrum, neglecting the brain refractive index dispersion and considering $\boldsymbol{n}$ as an average value, are given by

$$U_t = \frac{\pi^2 n^3}{15\hbar^3 c^3}(kT)^4 = \alpha n^3 T^4, \quad \alpha = 7.55\times10^{-15}\ \text{erg}\cdot\text{cm}^{-3}\cdot\text{K}^{-4}$$

$$P_t/S = \frac{\pi^2 n^3}{60\hbar^3 c^2}(kT)^4 = \sigma n^3 T^4, \quad \sigma = 5.67\times10^{-12}\ \text{W}\cdot\text{cm}^{-2}\cdot\text{K}^{-4}.$$

The last expression represents the well-known Stefan- Boltzmann law. The average brain surface area due to it very folded structure is approximately 2500 $\mathbf{cm^2}$. To estimate the human brain emitted power to outside world, we can take the total human sculp surface 600 $\mathbf{cm^2}$ divided by 2. This gives for the emitted power $P_t \cong 15\, n^3$ W at the normal body temperature. Note that the total power consumption of brain is usually estimated at the level of 20 W and total human body radiation at the level of 100 W. Since the average brain volume is approximately 1300 $\mathbf{cm^3}$, we can calculate the total radiation energy inside the brain. It is approximately equal to $U_t \cong 0.1 n^3$ erg. In thermal equilibrium the radiated and absorbed energies are equal, therefore the same amount of energy will be stored by water molecules in the brain. What is the role of this thermal radiation and excited water molecules in the brain? Should we feel that as a thermal noise? Would it be responsible for something positive, for example synchronization [14] of neurons and their action potentials? What is the role of ultraweak photon emission or biophotons radiated outside the thermal spectrum is also un-known. The answers to these questions can be given using current progress in the development of *in-vitro* 3D brain models.

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Due to extreme complexity of active human and/or animal brains, it is challenging to make predictive experiments with them. During recent years, we see a rapid development of different *in vitro* 3D brain models (see [15-17] for review). These models represent a paradigm shift and allow to perform much more simple and predictive experiments. Many of these models are based on brain organoids. Brain organoids are simplified, lab-grown models of brain tissue, usually derived from human stem cells or iPSCs. They can mimic certain aspects of early brain development such as cell types, layering, and electrical activity. Recently, a novel concept of Organoid Intelligence (OI) has emerged. OI is aimed at the combination of brain organoids with artificial intelligence systems to generate learning and memory, with the goals of modelling cognition and enabling biological computing applications [18].

In our work [19], we used laser fabricated scaffolds, shown in Fig. 1, for long-term (over 120 days) in vitro development of human iPSC-derived functional neuronal networks. It has been demonstrated that iPSC-derived neuronal progenitors develop into functional neuron–glia networks consisting of different cell types corresponding to their occurrence in the human brain.

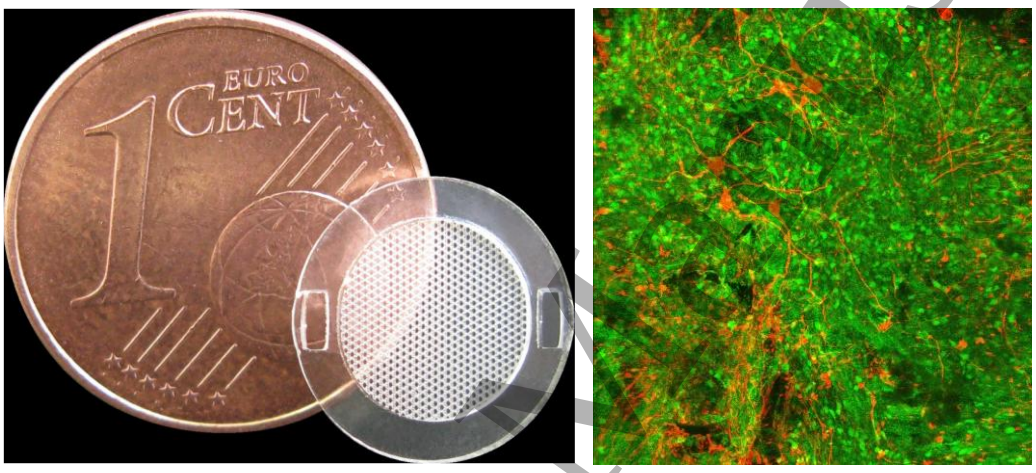


Figure 1. Scaffolds fabricated by two-photon polymerization technique for the development of brain models, commercially available from Laser nanoFab GmbH (left) and functional neurons-glia network developed inside these scaffolds (right).

In the developed brain models one can control the number of different cell types, record action potentials, detect the generated light, and use light and electrical pulses for stimulation. Due to the absence of sculp, these 3D brain models allow performing all possible photonic experiments with them.

In the modern theories of human brain, biological intelligence (BI) and learning occur through the strengthening or weakening of synaptic connections between neurons, a process known as synaptic plasticity. Artificial intelligence (AI) neural networks mirror this process through the adjustment of "weights" — numerical values that determine the strength of connections between artificial neurons. Computer added training and stimulation of functioning 3D brain models could allow to understand how BI and complex brain functions (learning, thinking, consciousness) emerge from 3D network of neurons [20,21].

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Concluding remarks

Human brain remains an astonishing object which attracts attention of many scientists. Physicist Emerson Pugh once said that if the human brain were so simple that we could understand it, we would be so simple that we couldn't. Now the situation is changed due to the development of much more simple and accessible *in vitro* 3D brain models. In this paper, we briefly discussed photonics of human brain and the prospects of using 3D brain models for more controllable research with higher reproducibility and better spatial and temporal resolution. Using microelectrode arrays (MEA), special sequences of electrical signals generated with the help of AI can be used for stimulation and training of 3D brain models, which could lead to understanding of how the human brain works and how BI can emerge in 3D network of neurons.

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Section 8.4 – Excitons instead of Electrons - could Femtosecond Exciton Processing be the Future of Computing?

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Status

Over the past decades, conventional electronic computing—based on electrons as carriers of information—has approached fundamental physical limits. Moore's law no longer applies in its original form [1,2], as further miniaturization is restricted by quantum effects, electrostatic interference between neighbouring circuit elements, and unavoidable energy losses due to heat generation during charge transport [3–5]. Therefore, in the last 10 years the clock speed did not increase significantly and remained at values around a couple of GHz. Even state-of-the-art electronic processors therefore operate on time scales that rarely surpass the order of 200-500 picoseconds [4,5] (Figure 1).

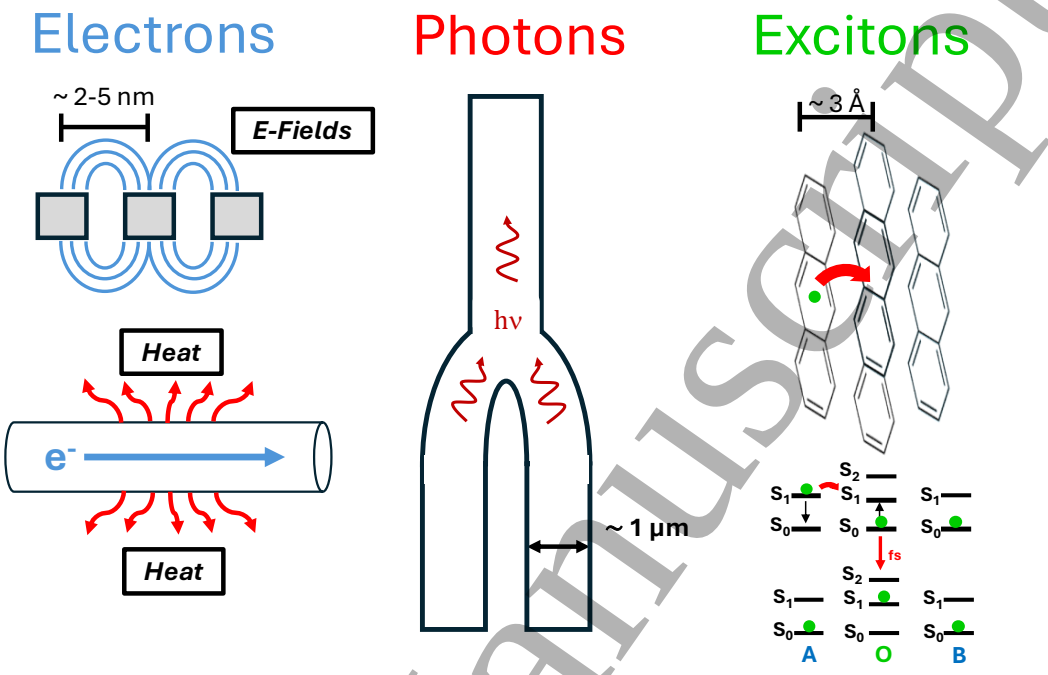
Photonic computing has emerged as an important alternative [6–8]. Photons interact only weakly, propagate at the speed of light, and enable high bandwidths and parallelism through multiplexing of wavelength, polarization, phase, and propagation direction. Several photonic computing concepts have already reached commercial or near-commercial maturity. However, photonic approaches face their own limitations: the diffraction limit constrains miniaturization to the micrometre scale, which restricts dense integration and ultimate parallelization [6,7].

Quantum computing represents another promising alternative, relying on coherent superpositions and entanglement of electronic or spin states in atoms, ions, or solid-state systems [9,10]. While remarkable proof-of-principle demonstrations and first commercial platforms exist, these systems are intrinsically fragile and limited by decoherence, noise, and extreme environmental requirements such as cryogenic temperatures and high vacuum [9-11]. These constraints limit scalability, robustness, and energy efficiency.

However, neutral excitons, i. e. excited, steady states of molecules or other nanobjects, can also be used as information carriers in a digital and stable manner at room temperature within individual quantum systems. As they are "digital" quanta represented by real, robust electronic states of molecules or nanoparticles that can exist at room temperature fixed in solid matrices, decoherence and in principle also noise is no issue. If arranged correctly, entire networks of ultrafast excitonic processors could perform computational tasks at unprecedented speeds on the femtosecond -timescale, with extreme miniaturization and high robustness. The theoretical framework required to realize such systems is well established; however, the primary challenge lies in the generation, synthesis, and interconnection of subunits at precisely defined distances and orientations that enable femtosecond-scale processing. This contribution outlines the fundamental requirements for excitonic computation, illustrate simple molecular arrangements for basic logic operations on the femtosecond timescale, discuss potential strategies to overcome the key obstacles toward realizing a femtosecond excitonic processor, and address considerations of energy consumption. [12] Finally, it will

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provide a brief long-term outlook, including prospects for artificial intelligence based on a femtosecond excitonic "brain."



Timescales	~ 200 - 500 ps	1-100 fs	1 -100 fs
Lengthscales	nm	µm	Å

Figure 1. Characteristic time- and lengthscales of conventional computing with electrons, photonic computing and the proposed femtosecond exciton processing. Only Femtosecond Exciton Processing allows both – ultrafast processing times and lengthscales at molecular dimensions.

Current and future challenges

Ultrafast excitonic computing requires both rapid information transfer and precise spatial control. Exciton migration between individual quantum systems—such as molecules or nanoparticles—can occur via several coupling mechanisms, including Coulombic (dipole–dipole) coupling, exchange interactions, and higher-order multipolar couplings [13,14]. The most widely used theoretical descriptions are Förster resonance energy transfer (FRET), which is dominated by Coulombic interactions [13], and Dexter transfer, which includes exchange contributions [14].

According to Förster theory, the exciton transfer rate between suitable donor and acceptor systems scales with the inverse sixth power of their separation distance [13,14,15]. The corresponding rate constant can be written as

$$k_{ET} = \frac{R_0^6}{\tau_D \cdot r^6} \qquad \text{eq.1}$$

where τ_D is the donor excited-state lifetime in the absence of an acceptor, r is the donor–acceptor separation, and R_0 is the Förster radius, i.e. the distance at which the transfer efficiency is 50%. The Förster radius

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depends on the spectral overlap between donor emission and acceptor absorption, the relative orientation of the transition dipole moments, and the refractive index of the surrounding medium [13,14,15]. As a consequence, femtosecond transfer times require intermolecular distances below a few nanometers—often shorter than the length of several covalent bonds (Figure 2 a). Achieving such distances in a controlled three-dimensional architecture is already a major synthetic challenge but the existence of energy transfer on a femtosecond timescale is well documented in the literature[15].

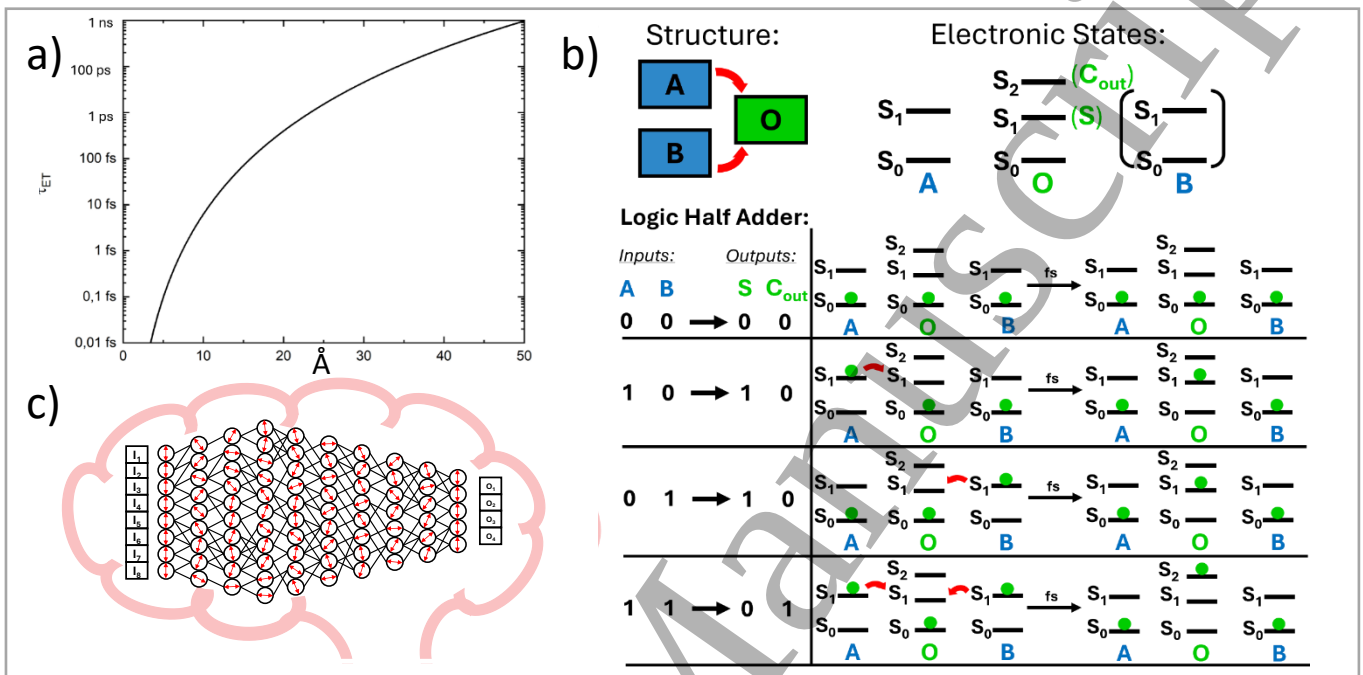


Figure 2. (a) With high Förster radii of R_0=10 nm already distances below 2 nm result in exciton transfer on timescales $\tau_{ET}=1/k_{ET}$ faster than 100 fs. (b) Scheme of a full adder realized with three molecules. Two molecules (A and B) represent the inputs and one molecule (O) represent the output signal (S_1 state of O) and the carry out bit (S_2 state of O). (c) When complex challenges such as the synthesis, arrangement, network nanofabrication and programming of the molecules or nanounits with the right relative orientations, distances and electronic state structure as well as input and output structures are tackled entire „femtosecond excitonic brains“ performing complex tasks such as pattern recognition or AI computing would become feasible at small scales, ambient conditions and unprecedented clock times.

In addition to distance, the relative orientation of transition dipole moments is critical. Förster transfer vanishes for perpendicular dipoles and is maximized for parallel alignment [13,15]. While this directional dependence provides a potential mechanism for routing excitonic information through a logic network, it also imposes stringent constraints on molecular orientation and structural precision in any synthesized network. However, examples such as solid-phase chemistry and modular assembly of artificial DNA-sequences and proteins demonstrates that synthesis of such complex structures is in principle possible.

Another important requirement are suitable electronic properties and state energies of the exciton processor subunits that allow to perform logic operations based on excitonic transfer on the femtosecond timescale. In figure 2 b, a potential electronic and spatial scheme for a molecular exciton full adder is shown. A binary addition of 0 + 1 or 1 + 0 is relatively straightforward: if an exciton is placed on molecule A or B, for example by an initial photon or transfer from neighbouring units, the exciton is transferred downhill to the first

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excited state, S_1, of the output molecule O. This first excited state, S_1, of the output molecule O is then representing the output S = 1.

However, a binary addition of 1 + 1 must result in an output S = 0 and a carry (overflow) C_{out} = 1, i.e. the first excited state, S_1, of the output molecule must not be populated. In principle, this can be achieved when the first exciton from either A or B is transferred to the first excited state S_1 of molecule O, and the second exciton from either A or B induces further energy transfer that promotes the excitation into the second excited state S_2 of the output molecule. According to Förster Theory, this is possible when the density of isoenergetic donor-acceptor transitions for this process is high, which is the case when the *transient absorption* $S_1 \rightarrow S_2$ of the output molecule has a very good spectral overlap with the emission, $S_1 \rightarrow S_0$, of the input molecules A and B. The overflow is then stored in S_2 (C_{out} = 1) for a certain time and can either be transferred to another logic unit nearby – when the corresponding state energies, distances and transition dipole moment orientations are also suitable - or recycled in a cyclic manner within O to the S_1 state for the next computational cycle.

As no electrons are moved around physically, much less heat losses are expected in exciton transfer when the slope of excited state energies is kept at a minimum.

However, although each individual step of such a process has been demonstrated experimentally in related systems [15-20], integrating all components into a single, robust logical femtosecond unit such as a single full adder will be already major challenge albeit possible in the next years. A full implementation of a functional logic network poses extremely demanding challenges for the next decade to come. These include achieving precisely controlled relative distances and orientations in three-dimensional space, as well as selecting quantum systems with appropriate state energies, transition dipole moments—including those of excited-state transitions—and transition densities. Equally important are interfaces that allow optical or near-field excitation and read-out, for example via nano-structured waveguides or near-field fiber optics or nanoelectronics that energize and read out the inputs and the outputs of a potential excitonic network.

Advances in science and technology to meet challenges

Progress toward exciton-based ultrafast processors will require advances across several disciplines. On the materials side, synthetic chemistry and nanofabrication must enable the reproducible creation of quantum units with tailored electronic structures and controlled spatial arrangement at the sub-nanometer scale. Supramolecular chemistry, DNA-based scaffolds, and advanced self-assembly techniques offer promising routes in this direction and have already demonstrated nanometer- and sub-nanometer precision in related contexts. A simple first experimental demonstration could be done by placing two or three molecules, with state energies as described in Figure 2 b and at distances corresponding to transfer rates faster than 100 fs (Figure 2 a) and with corresponding spectral overlaps as described in the above section next to each other. The logic operations can then be performed and read out by pump-probe spectroscopy for a first proof-of-concept. For typical nanoparticles and robust molecules consisting of several condensed aromatic rings the state energies correspond to convenient wavelengths in the visible spectral range. When the molecules have distinct orientations, polarization can be used to specifically populate and read out distinct molecules in the system. Inputs can also be encoded by multiple pump pulse sequences separated on the fs-time scale and read out by multiple probe pulse sequences.

From a theoretical perspective, models are needed to describe exciton dynamics and its timing . Such models will guide the rational design of architectures that balance speed, robustness, and scalability.

On the technological level, novel input and output concepts must be developed to couple excitonic processors efficiently to photonic or electronic systems. Near-field optical techniques, plasmonic antennas, and hybrid photonic–excitonic interfaces are likely to play a central role. An important integration challenge of networks containing exciton computing molecules or nanoparticles will be coupling either light on the µm-scale into

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the Å sized input units or couple nano-electronic input and output devices to the system. However, once these challenges have been tackled, the size of such networks themselves is similarly unlimited as for electronic integrated units.

Finally, concepts are required to program, control, and interconnect multiple excitonic logic units into functional networks capable of complex tasks such as pattern recognition or ultrafast data processing. Optical switchable molecules based on conformational, rotational or intrabond changes or self-learning mechanisms triggered by excitons travelling along switchable molecules at distinct pathways might be one approach to achieve programmability.

Concluding remarks

Exciton-based computing has the potential to be a path toward ultrafast, energy-efficient information processing at room temperature. Existing theories such as the Förster theory along with experimental evidence show that exciton-based computing on an ultrafast timescale is in principle possible but a major challenge will be the suitable arrangement of quantum systems at the right distances, transition dipole moment orientations, electronic state energies as well as transition densities. However, while significant scientific and technological challenges remain, the combination of mature theoretical foundations and rapidly advancing experimental capabilities suggests that the first functional excitonic logic units are within reach. When the first such units have been demonstrated, scalable networks of such units could enable entirely new computing possibilities in the long term, operating on the femtosecond time scales. Once the complex challenges are tackled, entire „femtosecond excitonic brains“ performing complex tasks such as pattern recognition or AI computing would become feasible at small scales, ambient conditions and unprecedented clock times. Since exciton transfer depends critically on the relative orientations of the transition dipole moments, their variation in a three-dimensional network could be one important factor for weight adjustments (amplifying or suppressing the influence between individual nodes) in a neuronal femtosecond exciton network (Figure 2 c).

Acknowledgements

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Section 8.5 – The Prospect of 5D Photonics in Quantum Science

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Status

The integration of adaptivity and intelligence into photonic systems is poised to unlock a vast range of functionalities that were previously difficult, or nearly impossible, to achieve. The concept of 5D photonics serves as a visionary framework to capture this paradigm: it envisions next-generation photonic systems that are both dynamically tunable and enhanced through computational intelligence. In recent years, there has been a growing adoption of such strategies across the photonics community, particularly in the manipulation of classical states of light (Saifullah 2022). Within this context, 5D photonics provides a compelling path forward by merging optical control with adaptive, learning-based feedback mechanisms. While much of the current attention has focused on classical optics, we argue that the same framework can play a transformative role in quantum optics and, by extension, in quantum technologies.

Indeed, photonics lies at the heart of numerous quantum domains, including quantum computation and simulation, quantum communication, quantum metrology and sensing, quantum imaging and the development of advanced photon sources. Each of these areas relies critically on the precise and stable operation of photonic components. For instance, quantum computing platforms, ranging from nitrogen-vacancy centers and superconducting qubits, to trapped ions, neutral atoms, and photonic qubits, all incorporate photonic elements, either as processing tools or as carriers of quantum information (O'Brien 2009). Despite remarkable progress across these platforms, achieving scalable, fault-tolerant quantum systems remains a major challenge. Beyond computation, photonics also underpins quantum communication, promising unparalleled speed and security in information transfer, as well as cavity quantum electrodynamics (QED) approaches that enable novel forms of polaritonic chemistry and control over chemical reactions (Ebbesen 2016). Meanwhile, quantum imaging exploits entangled photon pairs to achieve resolutions and sensitivities beyond classical limits (Moreau 2019).

To fully realize these quantum technologies, photonic systems must operate with unprecedented consistency, accuracy and adaptability. Embedding an intelligent, self-responding agent within such systems introduces a new layer of functionality, enabling them to monitor, process, and respond in real time (feedback), while also refining their future actions from past observations (learning). Together, they form a self-modifying platform capable of predicting, estimating, and proactively correcting errors, thus enabling greater control, robustness, and flexibility in complex quantum operations.

As emphasized in recent works (Reuer 2023), the demand for optimized, real-time feedback will intensify as quantum devices grow in size and complexity. Similar developments are already underway in other fields, where deep learning algorithms have been successfully applied to tasks such as real-time quantum feedback

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control in superconducting qubits (Reuer 2023) and automated tuning of solid-state qubit arrays in high-dimensional parameter spaces (Nguyen 2021). These advances suggest that embedding intelligence into photonic platforms can become a cornerstone for the next generation of adaptive quantum technologies.

Current and future challenges

The proposal of 5D photonics holds strong potential to advance quantum science by addressing key limitations in current quantum optical systems. Indeed, despite rapid progress, major challenges remain that restrict the stability, scalability, and adaptability of quantum photonic platforms.

A first class of problems arises from spectral and temporal instabilities. Quantum light sources often suffer from drifting single-photon wavelengths and intensity fluctuations due to random Stark shifts induced by temperature variations or stray electric fields. These effects undermine the stability and repeatability required for protocols relying on indistinguishable photons (Azzam 2021), such as quantum interference and entanglement generation in computing and communication. In quantum imaging, for instance, preserving the spatial and spectral correlations of entangled photon pairs is essential for maintaining high resolution and contrast (Moreau 2019).

A second class of issues concerns phase coherence and path stability. Optical phase noise – amplified at high optical powers or through environmental perturbations – degrades the generation of structured light fields crucial for quantum information processing (Liu 2025). Similarly, path-dependent losses and phase drifts in interferometric circuits limit the fidelity of on-chip quantum operations. A Mach–Zehnder interferometer, for example, must preserve internal phase stability within a small fraction of a wavelength; even minor temperature changes or vibrations can shift the path length, leading to loss of quantum interference and gate failure (Xavier 2011). Furthermore, temperature fluctuations can induce phase instability, leading to the loss of phase coherence in the light emitted by an atomic ensemble (Gold 2022).

Another challenge lies in limited control and adaptability of light–matter interfaces. Conventional static or closed-cavity designs offer minimal flexibility once fabricated, constraining the tunability of coupling strengths and resonance conditions (Li 2019). This limits the exploration of strong coupling regimes in both quantum chemistry and quantum computing, where dynamic control is critical to optimize interactions or maintain coherence. Additionally, at cryogenic temperatures, this limitation becomes more pronounced, where mechanical vibrations induced by the cryostat can challenge cavity stability and spectral alignment (Vadia 2021).

Finally, the lack of intelligent feedback and adaptive design remains a major obstacle. Current systems often rely on slow, brute-force optimization cycles to maintain alignment, spectral purity, or coupling efficiency. As system complexity grows, this manual tuning becomes impractical, especially for large-scale quantum networks or hybrid photonic architectures. Adaptive and intelligent hardware can replace this trial-and-error approach by monitoring device performance, applying real-time corrections, and maintaining optimal operating conditions autonomously. Beyond stabilization, such systems can also explore large parameter spaces more efficiently than manual methods, identifying configurations that can improve scalability.

In summary, quantum photonic technologies face intertwined challenges of stability, coherence, tunability, and autonomous control. Overcoming these barriers requires integrating sensing, feedback, and learning mechanisms directly into photonic hardware, precisely the goal of the 5D photonics framework.

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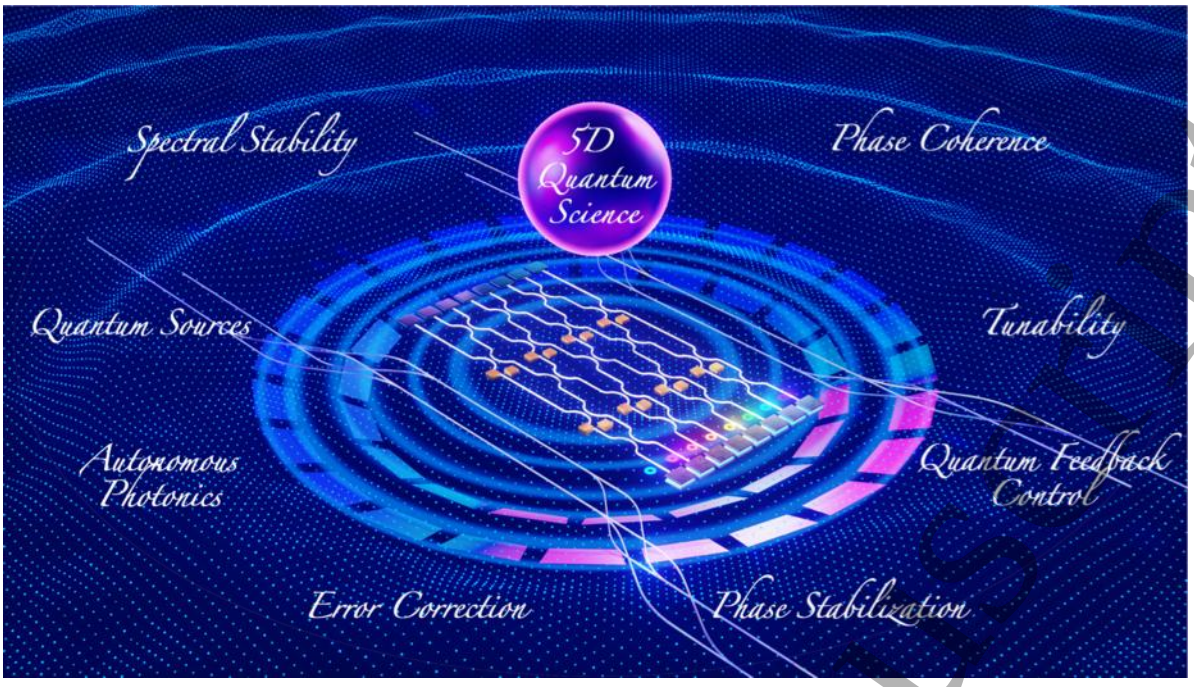


Figure 1. 5D Photonics vision for quantum science. By embedding adaptivity and intelligence within photonic systems, 5D photonics provides a unifying framework to overcome major challenges in quantum photonic technologies – from maintaining spectral and phase coherence to enabling self-optimizing photon sources and dynamically controlled light-matter interfaces.

Advances in science and technology to meet challenges

Recent advances in photonics are beginning to demonstrate how adaptivity and intelligence can transform the control and stability of quantum systems. As mentioned previously, reinforcement learning has been applied to real-time quantum feedback control, with agents capable of interacting with quantum devices on sub-microsecond timescales. More broadly, machine learning techniques are increasingly being employed to enhance various aspects of quantum technologies (Krenn 2023). Such demonstrations mark a key step toward autonomous operation, where systems learn, predict, and self-correct in real time.

One of the central challenges remains the creation of stable and high-quality quantum light sources. Neural-network-based approaches have been successfully used to correct the spatial profiles of distorted Laguerre-Gaussian modes at the single-photon level, ensuring consistent emission and mode purity (Bhusal 2021). Similarly, nonlinear metasurfaces have emerged as compact sources of entangled photon pairs (Fan 2025). Within a 5D photonics framework, these components could evolve into self-optimizing photon sources – adaptive metasurfaces that dynamically lock to peak gain and maintain brightness and indistinguishability without external intervention.

For light–matter interaction, the adoption of open-cavity architectures has provided new degrees of freedom for tuning spectral and spatial resonance conditions, and overall offers greater flexibility compared to closed cavities (Steinmetz 2006). Open cavities already combine mechanical sensing, piezoelectric actuation (Vadia 2021), and photothermal stabilization (Brachmann 2016) to suppress environmental noise, and as such they can provide stability in strong coupling conditions. Incorporating learning algorithms into these architectures could enable predictive stabilization, where cavities anticipate fluctuations and compensate them before coherence is lost. A recent study trained a deep neural network to predict fluctuations in photon

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wavelength (Ramezani 2024). When combined with on-chip adaptive control, such an approach could enable the real-time correction of spectral distortions.

Machine learning has also proven valuable for automated mode-matching and alignment. In one notable study, a reinforcement learning algorithm optimized a free-space resonator's coupling by treating the cavity spectrum as feedback and the mode-matching efficiency as the reward, converging within minutes (Saha 2025). Extending such adaptive optimization to few-photon and cryogenic regimes will directly benefit quantum communication and sensing platforms.

Another compelling case comes from interferometry, where active phase stabilization in integrated interferometers (Di Tria 2025) has achieved hours-long coherence through feedback-controlled architectures. Combining these techniques with lightweight ML algorithms could yield systems that learn the temperature-dependent drift of optical phases and perform corrections, maintaining phase lock under varying conditions.

Concluding remarks

These developments reveal a clear trajectory toward 5D photonics, a framework in which photonic systems are not only tunable and reconfigurable, but also context-aware, self-correcting, and overall "intelligent". This marks a shift from passive optical components to adaptive quantum technologies capable of learning, predicting, and optimizing their own behavior.

Although several promising demonstrations already exist, the field remains largely open, with vast room for exploration. The vision is clear: 5D photonics will enable capabilities that were once viewed as prohibitively difficult, such as autonomous stabilization of quantum systems, self-optimizing photon sources, and dynamically controlled light–matter interfaces.

Rapid progress in nanofabrication, integrated photonics and machine learning is creating the tools needed to realize this vision. As these technologies mature, strategies based on adaptivity and intelligence will increasingly shape not only photonics, but also neighboring domains such as quantum chemistry, sensing, and information processing.

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Section 8.6 – Quantum-mechanical theory of control and manipulation of adaptive optical materials on shortest time scales

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Status

Given the central role that optics and its optoelectronic interfaces have gained in modern time's technology – driven by its speed [1] in computation and communication –, the design of optical materials with specific functionalities is mandatory. For instance, the community seeks materials with high refractive indices or brilliant emitters with reproducible photons for quantum bits [2] – all of them ideally chemically stable, non-toxic, and mass-producible. To increase speed and functionality, adaptive materials, that can be tuned in a time-resolved manner through light–matter interaction are proposed. Such *intelligent optics* will be considered as *four- and five-dimensional* in this roadmap article. The "fifth dimension" is not considered geometric, but rather a digital dimension connected to the system's evolution in order to modify the optical behaviour in real time through software control, feedback, or programmable elements.

For their realisation computer-aided explorations of new materials based on the fundamental theoretical understanding of optical properties are beneficial. Refractive indices originate from the local distortion of the charge distribution of electrons around nuclei, and absorption and emission of optical photons arise from transitions between electronic states at resonance conditions. Such types of photon-electron interplay can be deterministically obtained from electronic structure calculations of the linear and non-linear polarizabilities or the transition densities between the ground and excited states, respectively. State-of-art correlated wave function methods [3] are applied for prediction with density functional theory as a viable alternative. Structural changes or environmental effects on target properties can be considered through multi-scale calculations, e.g., integrated molecular dynamics simulations employing embedding schemes [4]. The significant progress in laser technologies gave access to the femto- and attosecond regime [5],[6], where either static 3D geometries and/or respective electronic configurations undergo light-induced changes, thus granting access to the fourth dimension on the atomic scale: *time*. While femtochemistry has become an established field with broad applications, the observation of pure electron dynamics (attochemistry) is in active progress parallel to the development of new light pulses and sources. For nuclear dynamics calculations, ab-initio molecular dynamics or surface hopping have become well-established techniques to account for combined geometrical and electronic changes [7]. The simulation of the response to attosecond pulses, a timescale on which the heavy nuclei remain immobile, requires an explicitly time-dependent description of the correlated many-electron system within numerous excited states [8],[9],[10],[11], which entails a major effort. Such simulations are in the cost regime of high-level electronic structure methods,

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which are among the most memory- and compute-intensive tasks in quantum chemistry. However, the ultrashort light-mater interactions described using methodologies capable of recording dynamics on the timescale of electronic motion will provide the atomistic understanding needed for the design of smart and adaptive optical mechanisms, thus, marking an important step towards 5D optics.

Current and future challenges

The concept of 5D optics of building dynamically reconfigurable and computationally on-the-fly enhanced optical architectures constitutes a major challenge. To further develop this by employing quantum theory, leads the study of materials properties that can be addressed by light and the search for light-driven control schemes. On the material side, adaptive 5D optics are envisioned as controlled manipulation of physical properties. The idea is that in response to an external stimulus, the material is adapting almost immediately through photo-induced change of properties, e.g., its emission wavelengths, refractive index, or transparency, such that a desired functionality is maximized. This principle is adapted from optoelectronics, where electric currents are interfaced with optical devices (modulators or detectors combined with LEDs or lasers).
Measuring the evolution of an optical excitation can be done by two-pulse techniques, where a first pulse prepares a target state and a second pulse is used for ultrafast probing [12]. Here, the 5D challenge is to direct the outcome of the measurement, instead of its mere detection. Quantum theory can be employed to adjust the external stimulus for the desired outcome. Pulse shaping algorithms exist, but they are based on repeatedly simulating pulse trains and optimising the outcome [8]. Collection of results into databases, machine learning (ML), or even setting up a digital twin of laser pulse driven adaptive optics is a way to speed up feedback even for related tasks.

Adaptive optical materials embed the photoactive chromophores in easy to fabricate host structures, e.g., diamond, lithium niobate, metal-organic frameworks, polymers, or metamaterials [13]. High-level quantum computations of these are significantly demanding even if reducing the simulation to the optically responsive part in multi-scale or embedding approaches. Besides the well-known difficulties of calculating stationary energetics for such large systems, capturing the evolution during and after light-matter interactions poses great challenges. The stability of optically excited states is subject to diverse decay channels like chemical fragmentation or physical dissipation effects due to coupling to internal vibrations or to an environment. Each of these channels will lead to de-excitation on various time scales from atto- up to nanoseconds or even longer. Thus, a dynamical formulation of the multiscale ansatz – a description that incorporates these diverse temporal ranges – is posing the greatest challenge for an explicit time-dependent treatment. Algorithm developments are necessary to further explore the usage of exascale, GPU, or quantum computers in order to speed up calculations.

Advances in science and technology to meet challenges

For time-dependent simulations two major challenges were identified. Firstly, the means for pulse shaping for feedback control. Scientific progress of the 21st century has already evolved from the analytic formulation of models and theories to data-driven discoveries and understandings [14]. ML is nowadays widely used to predict chemical properties - such as absorption spectra - and to interpret their origin based on explainability techniques [15]. Moreover, frameworks are being developed that target the temporal evolution. Data from explicitly time-dependent simulations can be used to train neural networks [16],[17]. These ML-dynamics computations are presently only possible for a very small number of geometrical dimensions, but physics-informed neural networks direct towards treating even large-scale systems. Such “educated” ML algorithms in combination to a digital twin also have the potential to be employed for the 5D control that is necessary for intelligent, adjustable 5D materials.

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Secondly, there is a necessity for a multi-time scale description of dynamics. Dynamical approaches to include couplings to nuclear vibrations or a bath are the propagation of the density matrix [8] or ultimately through an explicit treatment of the coupled electron-nuclear quantum dynamics [18]. Up to date, the latter seems to be out of reach for poly-atomic many-electron systems unless the invention of stable quantum computers and respective software. Algorithms that are based on tensor networks have shown to enable efficient solutions to the many-body Schrödinger equation by compactly representing high-dimensional wavefunctions. This approach not only accelerates classical, CPU-based quantum chemistry calculations but also provides a promising framework for implementing quantum chemical methods on emerging quantum computing architectures. An example are solvers for partial differential equations which were employed for electron dynamics simulation [19]. They promise a polynomial scaling even when electrons are fully correlated. In following up on the advancements of electronic structure quantum computations (3D) on quantum annealers and NISQ devices [20], the realization of explicitly time-dependent calculations on real quantum computers is on the horizon.

Concluding remarks

In the emerging field of light-driven electron dynamics, theoretical foundations are developing in parallel with the invention of new sources and light pulses. Light as external stimulus can address adaptive optical materials and lead to a time-dependent response of their electronic structure, which can be intelligently optimized. For the simulation of such 5D material optical processes an explicit treatment of the time dependence of the electronic structure is mandatory, both experimentally and in the herein discussed simulations.

The corresponding quantum mechanical simulations entail the calculation of multiple excited states on fixed or moving nuclear geometries. Multiple time scales are required: attoseconds for the description of the electronic process itself and longer ones for environment-related de-excitation or relaxation processes. To achieve realism as well as immediate feedback, computer techniques are under development. Among them are namely quantum computing techniques, accounting for the important electron correlation in excited states, and time-dependent, physics-informed ML models, representing a promising avenue for the real-time control of optical properties.

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