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Development of mesoscale photonics and plasmonics: a tribute to the jubilee of Professors Igor V. Minin and Oleg V. Minin

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ABSTRACT

This March 2020, Professors Igor V. Minin and Oleg V. Minin, Doctors of Physics, correspondent members of Russian Academy of Metrology, outstanding scientists in the field of diffractive optics, terahertz photonics and calculation experiment technology, has marked their 60-th anniversary. This article gives a brief review of their life-time achievements in science and education. We briefly analyze the jubilee's contribution to the development of photonics, diffractive optics, shock waves, cumulative jets, field localization by mesoscale particles, and acoustic.

Keywords: diffractive optics; nanophotonics; subwavelength focusing; optical forces, terajet; acoustic jet; photonic hook, hypercumulation.

1. INTRODUCTION

On March 22, 2020, we will be celebrating 60th birthday of outstanding scientists, teachers, twins and friends, doctors of Technics, of the professors, corresponding members of the Russian Academy of Metrology Igor Vladilenovich Minin and Oleg Vladilenovich Minin (Figure 1).

This article is about the life and scientific results of the jubilees, analyzing I.V.Minin's and O.V.Minin's contribution to the creation of new directions in science – 3D diffraction optics of millimeter and THz waves, hypercumulations, subwavelength structured light - photonic hook, acoustic jet.

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Figure 1. Professors Igor V. Minin (left) and Oleg V. Minin (right)

2. MILESTONES

Igor and Oleg Minin graduated in 1976 with honors from high school and enrolled at the Physical Department of the Novosibirsk State University. They graduated from Novosibirsk State University in 1982. I.V.Minin defended his thesis for the degree of candidate of physics and mathematics on radiophysics, including quantum physics at St. Petersburg Electrotechnical Institute in 1986. O.V.Minin defended his thesis for the degree of candidate of physics and mathematics on radiophysics, including quantum physics in Tomsk Institute of Atmospheric Optics, in 1987. At the same time, from 1981 to 1982 they part-time worked as the laboratory assistants at the Institute of Applied Physics (IAP, Novosibirsk). The results of the thesis in 1982, 1988, 1991 formed the basis of the monographs (in Russian), later also translated to English[1-3]. These works were awarded by the Minister of Defense of the Russian Federation (for the best scientific work during 1997-2000). As up to date, I.V.Minin and O.V.Minin have 450 joint research publications, including 22 monographs (12 in Russian, 9 in English and 1 in Chines) and more than 100 author's certificates and patents.

After defending their theses, I.V.Minin and O.V.Minin worked in IAP as assistants and senior researchers. In 1991, they received a certificate of associate professors. In March 2004, I.V.Minin and O.V.Minin defended their doctoral thesis at the Novosibirsk State Technical University (on the same day) and received degrees of Doctor of Technical Sciences. In addition, they are members of the several editorial boards of scientific journals, experts of the Russian Science Foundation, Federal experts in scientific fields, experts of the COST 284 "Innovative Antennas for Emerging Terrestrial & Space-based Applications", IASTED, and awarded with medals named after V.I. Vernadsky and A. Nobel. The biographical data of Profs. I.V.Minin and O.V.Minin were included in Marquis Who's Who in the World.

3. SCIENTIFIC DIRECTIONS

I.V. Minin and O.V.Minin have established strong research foundations in different fields of physics having a global priority including 3D diffraction optics of millimeter and THz waves, hypercumulations, terajet, subwavelength structured light - photonic hook, acoustic jet. They have been awarded a lectureship in different physical area at DaimlerChrysler AG, Doiche Aerospace, Technische Universitat Munchen (Germany), Harbin Institute of Technology, MMW State Key Lab, Nanjing, Beijing Institute of Technology, Capital Normal

University (China), Samsung Electronics (Korea), National University of Singapore, Universidad Technica Federico Santa Maria (Chile), and many institutes as invited professors.

4. MAIN SCIENTIFIC RESULTS

Diffractive optics

In one of their first works[4] they studied the informative properties of a short-focus zone plate in the millimeter band for imaging systems and for the first time proposed a two-component diffractive lens with a wide field of view[5]. They showed that the synthesis task of even the Fresnel zone plate does not have a unique solution and introduced a new free parameter - the reference radius[6,7], which later became known as the reference phase, which allows controlling the quality of focusing[8-15]. Metalenses with a wideband response and low side lobes based on the fishnet metamaterial by combining the zoning, reference phase, and phase reversal techniques were offered and investigated. The metalenses allow reducing chromatic aberrations of the focus. New types of diffraction lenses, antennas and antenna arrays for communication systems for the first time were proposed and investigated[16-27]. In particular: correction of dispersion distortion of femtosecond pulses by using the non-planar surface of diffractive lens[19], an array of hexagonal Fresnel lens antennas[21], zoning rule for designing Square Fresnel zone plate[22], Fresnel zone plate antenna with hexagonal-cut zones[25], a square Fresnel zone plate with zone rotation principle[2,21,22] with chiral sidelobes, etc. To view three-dimensional space in real-time, the frequency properties of diffraction optics were used for the first time - the dependence of the focal length on the wavelength, later called diffraction tomography[18]. Unique methods for suppressing specular reflections and interference noise in real-time three-dimensional image systems were first proposed, developed and investigated[1,18]. The prototype of such a system made it possible to obtain images in the millimeter band with a quality comparable to optical and was awarded LaserFocusWorld Magazine Diploma (2003) for a series of publications in the field of information and communication technologies and the fight against terrorism. In early 1980, under the guidance of professors V.Meriakri (Institute of Radio Engineering and Electronics, Moscow) and V.F. Minin, pioneering studies were begun to construct images of biological objects in the millimeter range and to study the spectral properties of materials, including explosives[28].

I.V.Minin and O.V.Minin were the first to propose a zone plate with a focal length shorter than the wavelength provides superresolution with a minimum size of about a third of the wavelength[29] which was later experimentally confirmed[30]. It has been demonstrated that a similar effect of 3D subwavelength focusing can be achieved using three-dimensional surfaces[31]. To this end, the new flat-ring 3D diffractive lens design was offered which has important constructional and technological advantages. It was shown that it can be easily fabricated at the microwave, higher terahertz and optical frequencies as a planar multilayer package of dielectric rings embedded in a low-permittivity substrate.

It was shown that by choosing free parameters in the synthesis of diffraction lenses based on photonic crystals, their focusing properties can be controlled[32-33]. Moreover, it was demonstrated that a photonic crystal lens with defect provides subwavelength localization of the field up to hundredths of a wavelength[34]. Chiral focus diffraction lenses and phase-only chiral binary square axicon have been also proposed by I.V.Minin and O.V.Minin and investigated[35-36] for optical trapping of nanoparticles and biological object manipulations. Based on these knowledge's they show theoretically and experimentally that only a multilevel angular phase contour in the near-field is needed to create structured orbital angular momentum light in the far-field, exploiting the reciprocal nature of angular momentum and angle[37]. In other words, they showed that it is sufficient to have only three-phase levels instead of a continuous phase variation for the generation of a fundamental OAM mode with a high modal purity[37].

Plasma physics and Shock wave

New effects of plasma properties with condensed dispersion phase initiated in the air by moving hypervelocity body and plasma antenna formed due to chemoionization of combustion products have been discovered[38,39]. Also the pioneering works in hypercumulation effect allowed to develop the concept of acceleration of microparticles to hypervelocity during the ablative acceleration of a metal foil[40,41].

Methods developed by I.V.Minin and O.V. for diffraction optics design made it possible for the first time to focus shock waves in water in an arbitrary region[42-45].

Hypercumulations

The main processes that proceed during the generation of a shaped-charge jet were described by the M.A. Lavrentyev-Birkhoff (the USSR- the USA) theory as a model of plane stationary impingement of incompressible fluid jets at angles less than 180 degrees. It is a well-known fact confirmed by the almost 100-year practice of designing shaped charges. Under the scientific leadership of Prof. Vladilen F. Minin, we have succeeded to create a fundamentally new field of a numerous family of shaped charges with shaped-charge jets as rods having maximum velocities, the same as those related to the classical shaped-charge effect and insignificant slug (if any). An analytical theory of a cumulative jet formation for the regime of forced jet formation was developed. Work on the creation of the scientific foundations of the physics of hypercumulation made a significant contribution to the development of cumulation of energy and cumulative charges. As a result, in such charges, the mass of the formed cumulative jet reaches 80% or more of the mass of the liner. The jet does not look like a thin jet, but already has a 3D shape that can be controlled. It was found that the maximum jet velocity is not limited by the gas-dynamic limit and, for example, for aluminum or copper liners and conventional explosives, can exceed 20 km/s with a material density in the jet of the order of the density of the liner material and under normal conditions, which is not achievable in classical cumulation[46-51]. The results were summarized in the monograph (in Russian[52]) recently translated to Chinese[53]. In astrophysics, highly collimated cumulative jets were also observed to originate from active nuclei galaxies and young stellar objects. These results also give insight into shock physics.

The mechanism for eliminating the instabilities that arise when compressing thin from heavy metals, liners, and the formation of a cumulative jet has been investigated. For the first time, to increase the plastic properties of the material of the cumulative jet, the properties of the crystals of the cladding material were used. Involving the physics of crystals in the physics of cumulation, the creation of anisotropic claddings, can provide an increase in the penetration depth of the barrier, eliminate the strong dependence of the properties of the cumulative jet on the grain size in the cladding[51-53].

Impact craters formed by meteorites were also investigated. It is shown that their formation is described by the hydrodynamic flows of such a collision, taking into account the shape of meteorites and the physical characteristics of meteorites and planetary soil at the point of collision. For the contribution to the theory of hypercumulation, I.V. Minin and O.V. Minin were awarded the medal of the Russian National Committee on Theoretical and Applied Mechanics named after Rakhmatulin in 2013.

Photonics and Plasmonics at the Mesoscale

After the discovery in the late 90s of the effect of subwavelength localization of optical radiation using mesoscale dielectric particles of a cylindrical and spherical shape by B. Lukiyanchuk et al, later called the "photonic nanojet" effect[54], I.V. Minin, and O.V. Minin transferred this effect to the terahertz band[55-58]. They were first able to show that this effect is valid for particles of an arbitrary three-dimensional shape, and not just cylinders or spheres[59-64]. Moreover, for the first time, the possibility of subwavelength localization of radiation was shown not only in the transmission mode but also in the reflection mode[65-66]. These studies, in particular, made it possible to propose a new type of optical traps[67] and waveguides[68]. It was shown for the first time that the simple placement of a mesoscale particle, forming a terajet, at the focus of imaging systems allows one to increase both the resolution of the system and the contrast of the image without changing the radiation frequency used[69].

I.V. Minin and O.V. Minin proposed and investigated various methods for increasing the degree of localization of the field using particle-lenses of different shapes based on pupil mask[70-72], graded-index[73], artificial[74] and nanostructured materials[75]. They discovered and studied the effect of anomalous apodization for particle-lens[70-72]. For the first time, for the purposes of subwavelength localization of radiation, dielectric particles with a refractive index near unity were investigated both in the transmission[76] and reflection[77] modes. It was shown that it is possible to adapt the developed methods for the formation of photonic jets for two-dimensional diffraction gratings[78-80]. The result of these works, in particular, was the development of a terahertz microscope[69,81], the concept of an optical vacuum cleaner and the principle of optomechanical manipulation of nanoparticles[82] and physical principles of development of the State standard of biological cell polarizability[83]. Studies of the characteristics of terajets in the far-field made it possible for the first time to develop a mesoscopic dielectric cuboid antenna at millimeter-wave and THz (5G) band[84].

Recently, a new type of curved light beam beside the Airy type beam, so-called photonic hook, based on mesoscale Janus particles, has discovered by I.V.Minin and O.V.Minin[64]. Photonic hooks are unique, and intriguing phenomena as their radius of curvature is several times smaller than their wavelength[85,86,87]. This is the first time that such a small curvature radius of electromagnetic waves has been recorded. The physical properties of photonic hook show important application prospects in the fields of integrated optics, optical imaging, nonlinear optics, etc. The unique application of generating optical force for transporting nanoparticle along a curvilinear trajectory is especially attractive for subwavelength optical micromanipulation of nanoparticles and cell redistribution[88], and lab-on-a-chip system.

A new physical effect - high order Fano resonances for internal Mie modes in low losses dielectric spheres and “super-resonances” with the ability to create highly localized fields with enhancement values on the level of 10^5, both, inside the particle and outside in the near field region provides magnetic nanojets with giant magnetic fields, and which is attractive for many applications, were also studied[88]. We also discovered an astonishing large ‘heart-like’ multi-time circulation of Poynting vector 3D field-lines with giant angular variation and circulation range[89-90].

The photonic hook phenomenon was further extended to the fields of surface plasmons and acoustic waves[91,92]. The principles of the formation of a photonic jet and terajets were transferred to the field of surface plasmon waves. In particular, the possibility of increasing the propagation length of a surface plasmonic wave by several times was demonstrated[93-94] along with new types of plasmonic lenses[95]. A conical two-dimensional plasmonic-zone plate lens was proposed to realize far-field super-resolution focusing by exciting SPPs and enabling them to couple with radiating propagation modes[96].

Acoustics

O. V. Minin and I. V. Minin are pioneers in the field of the effect of the acoustic jet (acoustojet), which is an acoustic analog of the phenomena of a photonic nanojet and terajet[97-100], as well as acoustic hook[92]. They have also demonstrated the effects of anomalous apodization for acoustic particle lenses[101], as well as the possibility of subwavelength focusing by a cubic lens with a photonic crystal structure[102]. The ability to control the focusing properties of an acoustic zone plate, including the formation of a Bessel beam and reference phase method, has been demonstrated by O. V. Minin and I. V. Minin in[103-105]. New methods for manipulating nanoparticles in droplets have been developed by them as well[106-107].

Conclusion

In conclusion, we wish Igor V. Minin and Oleg V. Minin ongoing scientific endeavors, inexhaustible energy, good health and new creative achievements for the benefit of their country and the international scientific community!

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