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Twisted waveguides as arbitrary unitary gates in polarization-encoded quantum information processing circuits

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Abstract: Integrated photonics is a remarkable platform for the realization of quantum computations due to its flexibility and scalability. Here we propose a novel paradigm exploiting twisted waveguides as a building block for polarization-encoded quantum photonic computations on a chip. We unveil a transformation (gate) matrix in the closed form and demonstrate that twisted waveguides can implement arbitrary Bloch sphere rotations. The outcomes of this research may open a new direction in the development of quantum computing architectures on a chip.

To encode information in a single photon one must use its physical degrees of freedom such as path, momentum, angular momentum, and polarization. For reaching a higher information processing capability per chip footprint it is desirable to make use of the maximum possible number of them. Photon polarization is an always-available natural degree of freedom and is thus among the most widely used encoding mechanisms. To benefit from using an integrated platform it is crucial to perform most or ideally all light manipulations on a chip as most losses occur at a stage of coupling light into a chip or from a chip. However, despite the recognized strength of integrated photonics in controlling light, manipulation of polarization on a chip yet remains elusive.

Although integrated photonic polarization-encoded CNOT gate has been demonstrated in laser-written chips, the polarization manipulation in the reported works [1]–[3] was performed using either bulk or fiber optics. On-chip polarization manipulation schemes based on tilted basis waveguides are typically used serving as waveplates [4], [5] where the waveguide symmetry axis is the optical axis. Such schemes, however, suffer from a number of drawbacks: they are extremely sensitive to fabrication intolerances and due to the cross-section mismatch with normal waveguides exhibit significant coupling losses [6].

Here we report general polarization transformation with twisted waveguides. We note that twisted waveguides are capable not only to rotate the linear polarization but also to cause the polarization transformation due to their structural elliptical birefringence. Therefore, twisted waveguides can be suggested as arbitrary unitary gates in polarization-encoded quantum information processing circuits.

Results

Using modal expansion in helical reference frame and perturbation theory we have obtained an analytical expression for the transmission matrix of a twisted waveguide which is a general Bloch sphere rotation [7]. The main conclusion is that twisted waveguides can approximate arbitrary unitary operations with arbitrary precision and reasonable design constraints. Our results pave the way to robust yet simple building block for integrated photonic polarization-encoded quantum information processing with twisted waveguide architectures. Figure 1 summarizes the results of the investigation.

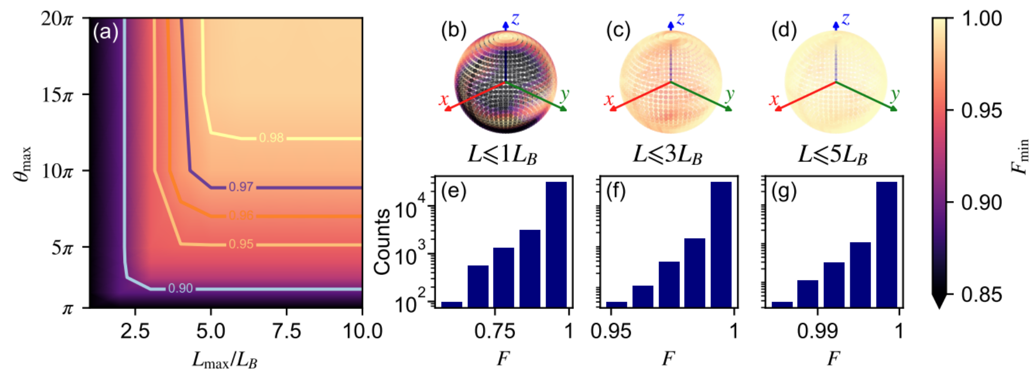

Figure 1. Twisted waveguide approximation of arbitrary single-qubit gates. (a) shows worst fidelity $F_{\min}$ over all single qubit gates as a function of twisted waveguide design constraints, where $\theta_{\max}$ is the maximum twist angle, $L_{\max}$ is the maximum twist length measured in terms of linear beat lengths L_B. (b-d) show the worst fidelity over rotations around a given axis with $\theta_{\max} = 20\pi$ and three different $L_{\max}$ constraints, histograms (e-g) below the spheres visualize the distribution of approximation fidelities. *Cited from* [7].

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