Project title: Tunable integrated photonic quantum circuits

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Current state of the art

Quantum information science [1] seeks to illuminate new ways in which non-classical effects can be harnessed for storing, processing and transmitting information encoded in quantum mechanical systems. Giving rise to a wide range of new phenomena, this field of research is deeply rooted in fundamental science, and simultaneously the key to novel functionalities and, ultimately, advanced devices [2]. Among these, perhaps the most profound (and still distant) is the quantum computer, which promises exponentially faster operation for particular tasks such as factorization, efficient search algorithms, and powerful quantum simulations [1]. A promising approach to the miniaturization and scaling of optical quantum circuits is to use on-chip integrated photonic waveguides [3], which will enable significant improvements in performance by virtue of superior stability, low noise and greatly improved spatial mode matching in such architectures – crucial ingredients for for classical as well as quantum interference. In recent years, various breakthroughs were presented, in which the integration of quantum circuits using optical waveguides played an important role.

Our team is among the pioneers of integrated quantum photonic circuitry fabricated by the laser direct-write technique [4]: When ultrashort laser pulses are tightly focused into transparent bulk material, nonlinear absorption takes place leading to optical breakdown and the formation of a micro plasma, which induces a permanent change in the material's molecular structure. In the particular case of fused silica, a densification of the host material yields a permanent increase of the refractive index. The dimensions of these changes are approximately the same as the size of the focal region. By moving the sample transversely with respect to the beam, a continuous modification is obtained and a waveguide can be inscribed (see Fig. 1a). Such guides can be written in almost any arrangements along arbitrary paths, since the only limiting factor in the placement of the focus is the focal length of the writing objective. In one of our latest works, we realized for the first time the so-called "boson sampling" computation [5] in such a glass chip (see Fig. 1b). This implementation directly makes use of the random walk of a few indistinguishable photons in a waveguide network (see Fig. 1c), where the bosonic nature of the photons leads to non-classical interference, producing an output probability distribution for which there is no known efficient classical sampling algorithm (see Fig. 1d).

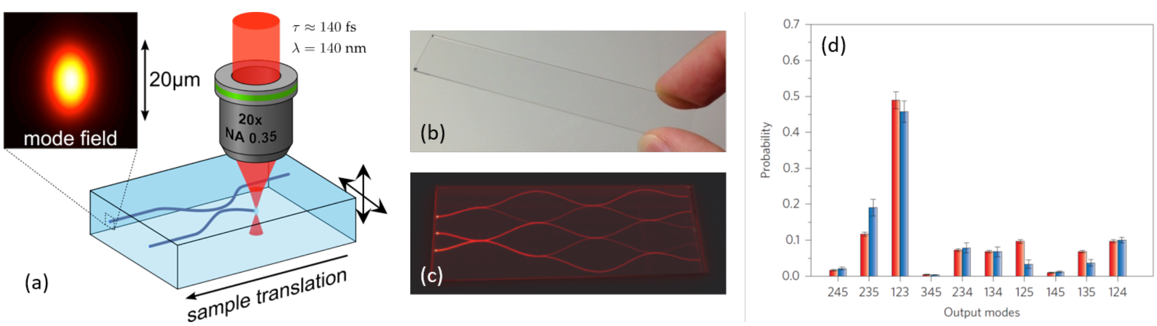

Figure 1: (a) Setup for writing waveguides using ultrashort laser pulses. The inset shows a typical waveguide mode. (b) An optical chip with a waveguide network. Typical lengths are a few centimeter. (c) Fluorescence microscopy image of a waveguide network that was used for the bosonic sampling computation. (d) Results of the bosonic sampling computation. Shown is the probability for all possibilities that the three input photons occupy three different output modes. The red bars indicate the measured probabilities, whereas the blue bars display the output probabilities from the reconstructed unitary transfer matrix.

Research goals and working program

So far, in laser-written waveguide circuits, the integrated structures are static: Once fabricated, they remain as they were created and their functionality can be changed only due to tailoring external parameters, such as the wavelength of the propagating light. However, it would be beneficial to provide a means to actively tune the structure itself. Recent work suggest that local heating of the waveguides locally changes their refractive index, which may be used for switching applications [6]. However, thermal optical effects in glasses are rather slow and allow only very few operations per second. Within this project our group will explore a different approach: **We employ electric-field switching of liquid crystals to provide an accurate and rapid modulation of phase and polarisation of propagating light in laser-written integrated quantum circuits.**

Recently, we were able to fabricate holes through the entire chip height of 1 mm, with cylindrical shape and a width of less than 100 µm [7]. These holes were fabricated by a two-step procedure: First, the bulk material of the chip was preprocessed using ultrashort femtosecond laser pulses. Afterwards, the modifications were etched using with hydrofluoric acid (HF), resulting ion the formation of the holes (see 2, left panel). The idea to be pursued in the context of this PhD thesis project is to infiltrate such structures with electrically tunable liquid crystals. Their narrow confinement will provide a preferred direction of orientation for their constituent molecules. In turn, neighboring holes will serve to place electrodes through which electric fields can be applied to reorient the molecules, allowing for the polarization of guided light to be rapidly switched with minimal thermal load (see 2, right panel).

The doctoral candidate will be responsible for the entire process of fabrication of the samples (in collaboration with our partners who perform the etching process), their characterization, and their introduction into complex quantum circuits.

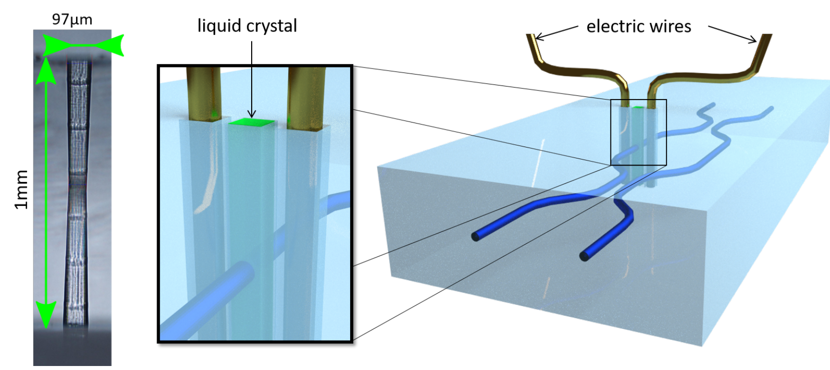

Figure 2: (left) Microscope image of an etched hole through a glass chip. (right) Concept sketch of an integrated polarization switch using liquid crystals.

[1] M. A. Nielsen et al., "Quantum Computation and Quantum Information," Cambridge Univ. Press (2000).

[2] Science 318, 1567 (2007).

[3] Nature Photon. 3, 687 (2009).

[4] Phys. B 43, 163001 (2010).

[5] Nature Photon. 7, 540 (2013).

[6] Light: Science & Applications 4, e354 (2015).

[7] New J. Phys. 23, 093038 (2021)