Quantum Photonic Processor based on Silicon Nitride Waveguides

Student Paper

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ABSTRACT

Stoichiometric high-index-contrast silicon nitride waveguides can accomplish some of the important needs of photonic quantum information processing, such as high complexity and low loss. We demonstrate a versatile linear optical photonic processor for quantum information processing based on stoichiometric silicon nitride waveguides. The photonic processor is fully programmable and remotely controllable. The 8×8 unitary network is the largest fully programmable universal quantum photonic processor, based on silicon nitride waveguides realized so far. Demonstrating its versatile functionality we observe on-chip two-photon interference of high visibility, i.e., about 80%, with less than 10% variation in visibility between various nodes, i.e., beam splitters, of the photonic processor. Our findings show that stoichiometric silicon nitride is a promising platform for integrated, programmable quantum information processing.

Keywords: quantum information processing, linear optical processor, stoichiometric silicon nitride, two-photon interference.

1. INTRODUCTION

Integrated linear optical processors have become, in the recent past years, instrumental in the development and success of quantum information processing (QIP), enabling the realization of compact and stable quantum gates [1] and showing great potential for the study of quantum walks [2] and quantum key distribution [3]. The development of integrated quantum optics applications requires a significant increase of the circuit functionality, which is only possible with a dense concentration of long and complex pathways on the same photonic chip. However, at the same time, the overall optical chip size is limited due to fabrication constrains while waveguide platforms with insufficient index contrast or low optical transparency threaten to wash out quantum interference via curvature and propagation loss. These limitations highlight the need of a low-loss high-index-contrast material platform.

Stoichiometric silicon nitride ($\mathrm{Si_3N_4}$) grown with low-pressure chemical vapor deposition (LPCVD), different from other types of silicon nitride [4], offers the unique combination of high index contrast ($\Delta n \sim 25\%$), ultralow straight-propagation loss (0.0004 dB/cm [5]), low insertion loss (<0.5 dB [6]), and spectrally wide transparency (from 400 nm to 2.5 µm).

Here, we present a universal linear optical photonic processor for QIP which is the largest so far realized in $\mathrm{Si_3N_4}$ with low propagation losses and a high component density, on par with the state of the art [1]. The photonic processor is a fully tunable, reprogrammable and remotely controllable optical 8×8 Blass matrix [7], which implements an 8×8 universal unitary network. We demonstrate the proper functioning of the photonic processor for QIP via observing on-chip two-photon quantum interference with high visibility, programmable towards multiple nodes within the matrix.

2. QUANTUM PHOTONIC PROCESSOR

The architecture of the quantum photonic processor is given in Fig. 1. It is a realization of an optical 8×8 Blass matrix and comprises 64 unit cells each of which are composed of a phase shifter (in red) and a tunable beam splitter (in blue), enabling thus any 8×8 unitary transformation. The 128 tunable elements (64 tunable beam splitters and 64 phase shifters) enable each a 0-to-2π phase shift, i.e., ideally a 0-to-100% splitting ratio for the beam splitter. Due to technical reasons (enabling microwave-photonic applications as well) only the waveguides at the bottom were directly accessible. Nevertheless, the full 8×8 matrix, i.e., the whole depth of the circuit, can be accessed by routing the light from the bottom inputs to all the beam splitters.

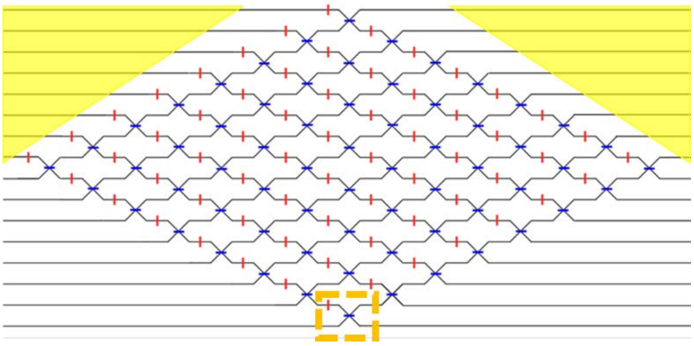

Figure 1 Schematic of the optical 8×8 Blass matrix. The orange box indicates one of the 64 unit cells: a phase shifter (red vertical line) and a tunable beam splitter (blue horizontal line). Although the top waveguides are not accessible (yellow triangles), the top part of the chip can be exploited by routing light from below.

To ensure propagation losses as low as 0.2 dB/cm and single-mode propagation at telecom C-band wavelengths (around 1550 nm) a double-stripe waveguide cross section is chosen [8]. The total on-chip propagation losses are bounded to less than 35%, a value that corresponds to the longest-possible on-chip geometrical path length (about 10 cm). A polarization maintaining fiber array is bonded to the chip to give access to the waveguides. The processor is overall temperature-stabilized by a Peltier element and an independent tuning of the 128 phase shifters is accomplished thermally via USB controlled drivers. The entire assembly comprising the chip, fiber array and electronics is packaged into a single portable box with a USB and power socket at its back, and with 16 standard fiber sockets at the front panel. After transportation of the box from Twente to the single-photon source in Oxford, there was no need for recalibrating the tuning elements on chip. After plugging in the single-photon source, the experiments were carried out straightforwardly via computer control of the USB input.

3. EXPERIMENTAL RESULTS

The single-photon source is composed of two periodically poled $KTiOPO_4$ (PP-KTP) single-mode waveguides (~10 mm long) [9] each pumped with spectrally filtered 1 ps long pulses centered at 775 nm with a repetition rate of 250 kHz from a Ti:Sapphire mode-locked laser providing an average power of 600 mW. In order to simultaneously pump both PP-KTP waveguides, the main beam from the Ti:Sapphire laser is divided into two equally long branches. An adjustable and programmable delay line (≈ 3 cm) is present in one of the two branches in order to enable Hong-Ou-Mandel-type quantum interference experiments [10]. Each PP-KTP waveguide generates, via type II parametric down-conversion, orthogonally-polarized photon pairs at telecom wavelengths (signal and idler at 1553 nm and 1547 nm, respectively) that are separated by polarizers and collected by single-mode fibers. The collection fibers are connected either directly to the detectors (idlers) or after injecting the single photons (signals) through the processor. Single photons leaving the processor were sent to a set of fiber-coupled superconducting single-photon detectors (niobium-based nanowires, efficiency 85%) and the counts were analysed with programmable electronic correlators. A total of four detectors were used: one for each generated photon.

First, we performed a reference Hong-Ou-Mandel (HOM) experiment using a fiber beam splitter with tunable splitting ratio. The signal photons from both waveguide sources are made indistinguishable by setting the delay line to zero. The measured two-photon interference for the reference experiment yields a visibility V_{ref} of about 80%.

Second, on-chip two-photon interference is performed in the form of HOM-type quantum interference. The two signal photons are now coupled into the photonic processor by polarization-maintaining fibers and are let to interfere at the first accessible tunable beam splitter (Fig. 2 (left) green circle). A variable delay is introduced between the signal photons via the aforementioned delay line. The splitting ratio of the tunable beam splitter is optimized to its ideal value, i.e., of 50%, performing a minimization of the coincidence count rate for indistinguishable input photons (i.e., zero delay). The coincidence count rate versus the relative delay of the two single photons is recorded (Fig. 2(right)) showing again a visibility of about 80%, which indicates an excellent fidelity.

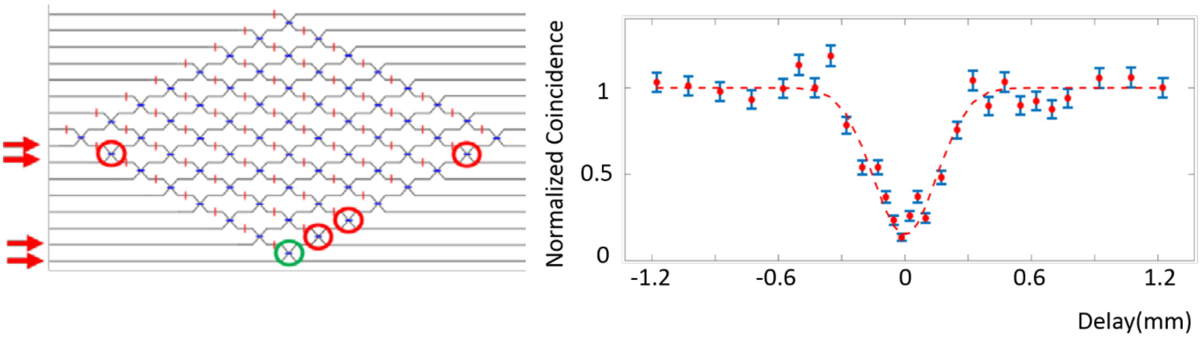

Figure 2 Left: location of various processor nodes (red circles) that where programmed to show two-photon interference, also indicating the used input waveguides (arrows). The green circle indicates the first accessible processor node. Right: two-photon-interference vs delay measured at that node. The dashed curve indicates a Gaussian fit to the data.

To further investigate the flexibility and configurability of our processor, we repeated the experiment of two-photon interference on various on-chip tunable beam splitters (Fig. 2(left) red circles), obtaining similar visibilities. We noticed a variation of the two-photon interference visibility of about ~10% between the first- and last-accessible processor nodes. This variation may have resulted either from slight path length differences between different beam splitters, which can be compensated, or from a deviation of the ideal 50% splitting ratio, which can be optimized.

4. CONCLUSIONS

We have demonstrated two-photon quantum interference on a Si_3N_4 photonic processor with results that compare well with those of an off-chip reference experiment, yielding a visibility of ~80%. The processor provides consistent results, with a variation of 10%, in terms of two-photon quantum interference visibility over its whole extension. Our findings demonstrate the suitability, reliability and, importantly, size-scalability for functionality upscaling at low loss of an integrated linear optical photonic processor based on Si_3N_4 waveguides.

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