Towards fault tolerant quantum photonics circuits

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Abstract— **We report our latest progress in integrated quantum photonics within Silica-on-Silicon waveguide chips: a unit visibility Hong Ou Mandel Dip and CNOT truth table, with single photons from a two photon Spontaneous Parametric Down Conversion (SPDC) Source. The increase in performance, compared to previous results, is due to polarisation and spectral fine tuning of the SPDC source, and the stability inherent in silica waveguide devices.**

I. INTRODUCTION

Quantum information science promises profound new technologies in communication [1], information processing [2,3], and ultra-precise measurement [4]. However, these quantum technologies must be robust to imperfections in their components and to the effects of environmental noise. Encoding quantum information in photons is promising for fast transmission and low noise [5, 6]. Integrated photonics holds great promise for miniaturizing and scaling quantum logic circuits [7], and high fidelity single qubit operations have been demonstrated [8]. We report integrated photonic devices that exhibit near-unit fidelity quantum interference and two-photon entangling logic operation. This high fidelity operation relied on a spectrally tuned photon source producing near-identical photons. These results show that photonic quantum circuits can perform at the high fidelities required for quantum technologies.

II. EXPERIMENTAL SETUP

A. Introduction and Setup

In the last two years we have developed silica-on-silcon waveguides quantum circuits that can process individual photons and reduce the limitations in scalability and stability of previous large-scale (bulk) systems [9]. Quantum phase stability and generation of entanglement within a chip, together with high-fidelity two-photon entangling gates have been demonstrated [7].

The CNOT gate shown in Fig. 1A shows a schematic of an integrated controlled-NOT (CNOT) gate. The silica –on-silicon waveguides guide photons via total internal reflection in much the same way as single mode optical fibres. Waveguides are brought into proximity (several μm) to realize directional couplers whose reflectivity η is controlled via the length of the coupling region. The major factors determining the performance of such devices are photon loss (typically approx. 0.1dB/cm); the quality of single photon interference [10] at directional couplers; and the quality of multiphoton interference in interferometers formed by two or more directional couplers.

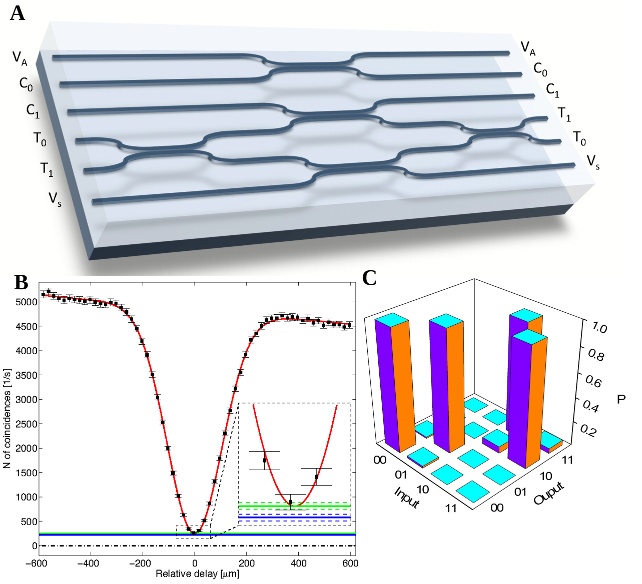

Figure 1. High-fidelity of photonic quantum circuits. (A) Achematic of a waveguide CNOT gate. (B) High visibility quantum interference in a waveguide directional coupler. (C) Experimentally measured 'truth table' for a CNOT gate circuit.

B. Results

We measured the rate of detecting a single photon in each output of an $\eta = 0.5267 \pm 0.0004$ directional coupler as a function of the arrival time of the photons. The measured rate of detecting photons from different pairs is plotted in Fig. 1B (blue line).The single photon interference visibility taking this rate into account is $V_{meas} = 0.995 \pm 0.004$ which corresponds to a relative visibility of $V_{rel} \equiv V_{meas}/V_{ideal} = 1.001 \pm 0.004\%$. The green line shows the expected level of the minimum for an $\eta = 0.5267$ coupler. These data correspond to perfect single photon interference, within error bars.

A CNOT gate (Fig. 1A) is ideal for testing the performance limits of quantum waveguides circuits, as it contains all of the elements of a general circuit. This CNOT gate works with probability 1/9 – the presence of only one photon in the control and one photon in the target signals success of the gate. We measured the ‘1/3’ coupler in the control part of the circuit (top one of Fig. 1A) to be $\eta = 0.3078 \pm 0.0009$ and assume all 1/3 couplers have this value (due we are not able to measure the other two for being embedded in the circuit). The two ‘1/2’ couplers were measured to be $\eta = 0.442 \pm 0.001$ and $\eta = 0.452 \pm 0.001$. This is a reasonable given previous data on lithographic devices [7]. Fig. 1C shows the measured operation of our device, taking into account the rate of detecting photons form different pairs, as described above. It has a fidelity of $F = 0.969 \pm 0.002$ and a similarity of $S = 0.993 \pm 0.002$ with that expected for the circuit with the measured reflectivities.

III. EXPERIMENTAL DETAILS OF THE PHOTON SOURCE

Fig. 2 shows a schematic of the photon pair source. A 402 nm CW laser was focused to a waist of 40 µm in a 2 mm thick biaxial Type-I BiBO (BiB3O6) crystal. The crystal was cut to generate photon pairs at the degenerate wavelength of 804 nm at an opening half angle of 3 degrees. Due the small spatial spectral spread, we assume that the waist of these ‘daughter’ photons is the same as the waist of the pump beam in the crystal. The daughter photons with the calculated waist at the crystal were then collected into PMF fibres using a single 11 mm aspheric lens, after passing through interference filters with a 2 nm FWHM, centred at 804 nm.

The two main factors in obtaining indistinguishable photon pairs from this source were ensuring that they share the same spectral mode and the same polarisation, both of which should be pure. To ensure that the photons shared the same spectral mode, the spatial collection point and the tilt of the interference filters were matched so that the profile of the transmitted photons had Gaussian shapes that were centred at the same (degenerate) wavelength. To maximise the polarisation purity of the photons collected into PMF fibres, either the slow or fast axis of the fibre must be perfectly parallel (or orthogonal) to the plane formed by the direction of the pump beam and the optic axis of the crystal, since PMFs decohere the polarisation of any photon that projects onto both axes. A polarisation purity test on the photons that exit the PMF confirmed this alignment.

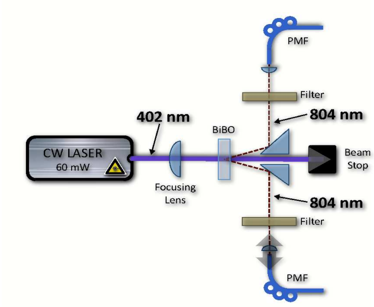

Figure 2. A schematic of the spectrally tuned two photon source. A CW laser was focused to a 40 µm waist at a Type-I BiBO crystal to produce degenerate photon pairs via spontaneous parametric down conversion. The daughter photons were collected into polarisation maintaining fibers (PMFs) after passing through interference filters with a 2 nm FWHM. The source was fine tuned with a spectrometer to ensure fully degenerate photons. The photon pairs were injected into the waveguides from Fig. 1A.

IV. CONCLUSION AND OUTLOOK

We shown the first implementation of optical quantum circuits operating within the limits required for fault tolerant operation needed towards the realization of a quantum computer.

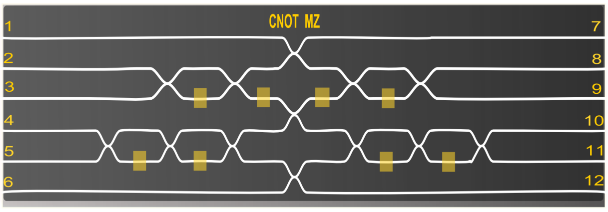

Figure 3. Sketch of an integrated photonic circuit made up of a central CNOT gate and eight phase shifters in integrated interferometers used in order to have a complete characteristion of different quantum dinamical systems.

In order to get a full characterisation of an unknown two qubit process, a new silica-on-silicon waveguide quantum circuit is being tested (Fig. 3) This circuit is made up of a CNOT gate and eight independently controlled phase shifters in integrated interferometers to control two-photon qubit states (Four to control input states and four to act on the output states). We will report on progress and details on this experiment.

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