Quantum Random Walks Circuits with Photonic Waveguides

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Abstract—**Arrays of 21 evanescently coupled waveguides are fabricated to implement quantum random walks and a generalized form of two-photon non-classical interference, which was observed via two photon correlation.**

Keywords-component; quantum optics; waveguides; quantum computing; quantum random walks.

I. INTRODUCTION

Quantum random walks, the quantum analogue of statistical random walks, have great potential for designing a new generation of quantum algorithms and can be regarded as a primitive for universal quantum computation. Derived from Richard Feynman's original proposal in the 1960s, physical observation of random walks based upon quantum mechanical behaviour has been an important pursuit in modern quantum physics. Demonstrations of discrete time quantum walks have so far included Nuclear Magnetic Resonance [1], the phase space of trapped ions [2], the position space of trapped ions [3], and the path of a single photon in a network of (bulk) linear optics [4].

Continuous time quantum walks (CTQW) have been demonstrated using NMR [5] and in a so called ``optical version of Galton's board" in the optical frequency space of an optical resonator [6] and in the tunnelling of light in coupled arrays of integrated waveguide structures [7].

The effective de-coherence free properties of photons make them an attractive test-bed for realizing quantum walks (as well as many other quantum mechanical behaviour). Quantum circuits are typically a series of nested interferometers (including [4]), which due to the nature of interferometry realized with bulk optics, is severely limited in size and complexity.

One of the most promising architectures for realizing CTQW is based on inherently stable integrated waveguide structures, already demonstrated in realizing optical circuits for quantum application [8-12].

For any circuit that would realize a quantum walk based on linear optics using an n-mode unitary, one could construct the circuit as a decomposition of 2-mode unitaries [13]. Decomposing circuits in this manner is, however, costly with respect to repeated bending circuitry into and out of interferometers. Instead, observation of larger CTQW (currently of the order 20-30 vertices) can be achieved using the direct tunnelling of light between coupled, ordered waveguide on a single array [7] (Fig. 1). By using this same architecture, the effects of Anderson localization on propagating quantum information [14] has been experimentally simulated using coherent light [15].

The statistics from measuring CTQW can be also predicted with a classical treatment. This provides motivation for the theoretical study into the distinctly non-classical effects of interfering more than one identical photon in an array of coupled waveguides [16]. This generalization of Hong-Ou-Mandel interference leads to various patterns of correlated statistics dependent upon the input state. While part of the model can be verified with classical correlation statistics (as they do in [16]), no experiment to date has been reported using quantum states of single photons to reproduce the full quantum correlation behaviour.
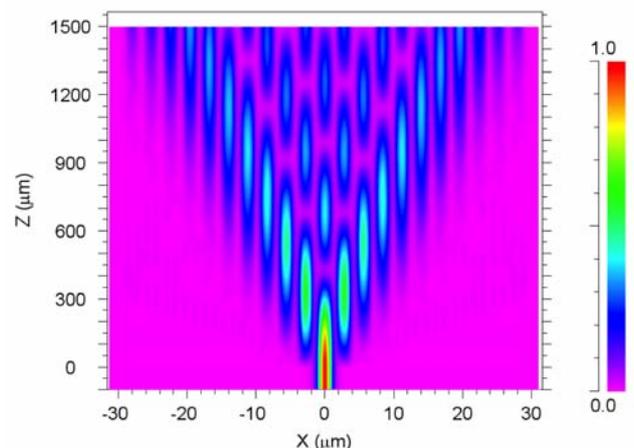

Figure 1. A BPM simulation of the light propagation along the waveguides array when the light is injected into the central waveguide.
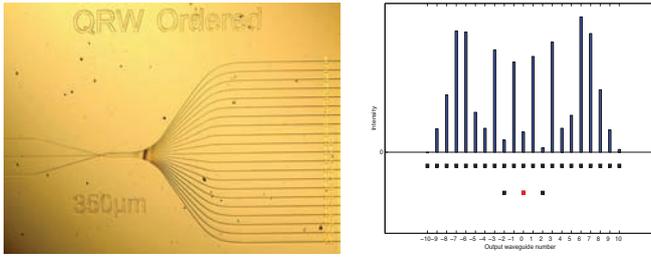
Figure 2 Left: An optical micrograph of a 21 waveguide quantum random walk device. Three input waveguides, initially separated by 250 micron, fan in to the 350 micron long coupling region, and 21 waveguides fan out to a 125 micron spacing. Right: Single photon quantum random walk data.

II. Methods

For the device fabrication silicon oxynitride (SiON) layers are grown on thermally oxidized (8μm) Si <100> wafers (Fig. 2). The deposition is carried out in an Oxford parallel plate PECVD reactor utilizing SiH_4 and N_2O precursors. After annealing the channel waveguides are obtained by standard lithography and reactive ion etching in CHF_3 / O_2 chemistry. The channel structures are covered by a PECVD silicon oxide (SiO_2) cladding layer.

We coupled single photon pairs into the waveguides arrays and detected with silicon avalanche single photon detectors. To generate the single photon pairs a type I spontaneous parametric downconversion process was used. This is a $\chi^{(2)}$ nonlinear process where a bismuth borate BiB2O6 crystal is pumped by a 402 nm wavelength, 60 mW laser. The single photons are collected with polarization mantaining fibre arrays and injected into the waveguides. At the output a single mode fibre array was used to connect each waveguide to each detector.

The characterization of the QRW arrays has been done by measuring the single photon distribution (Fig. 2 left).

III. Results and Concluding Remarks

Fig. 2 left reports the output intensity when a single photon is injected into the central input waveguide.

When two photons are coupled into the waveguides, two photon correlation can be measured and the results are shown in Fig. 3. Remarkably the general behaviour of the quantum walks is demonstrated for the first time and it is in accordance with the predictions (Fig. 4). These results represent a first step highlighting the quality of these structures and their potential for quantum computing applications.
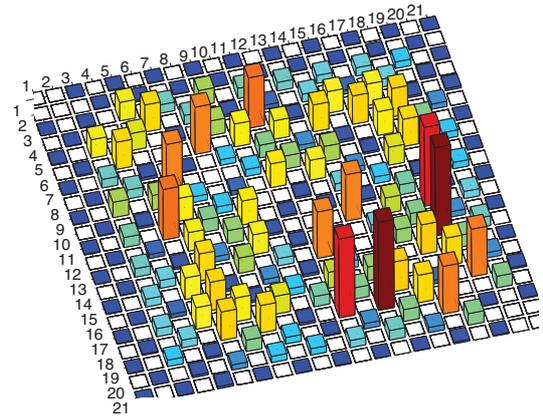

Figure 3. Measured 2-photons quantum correlation matrix when the photons are coupled to two adjacent waveguides.
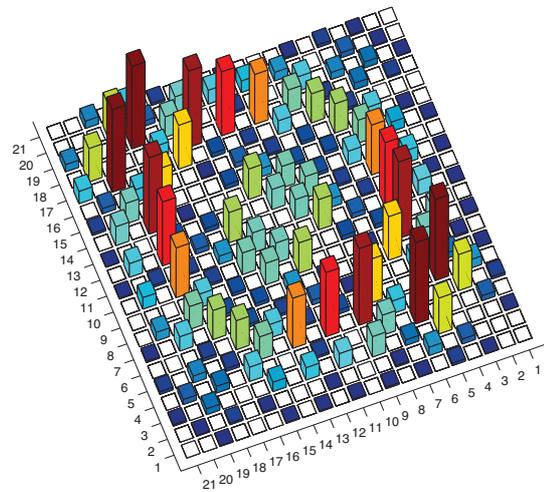

Figure 4. Simulation of the 2-photons quantum correlations when the photons are couple to adjacent waveguides.

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