Multi-particle Quantum Walks with 2D & 3D Arrayed Waveguides

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***Abstract*—Multi-photon quantum walks on integrated circuits are demonstrated, showing non-classical correlations, in one and two dimensional networks. Time evolution of quantum walks and a scheme for simulating fermionic quantum walks using entanglement are demonstrated.**

Keywords-quantum walk; direct write; integrated waveguides;

I. INTRODUCTION

Quantum walks [1] are the direct quantum-mechanical analogue of classical random walks. They offer the possibility of exploring processes in physical and biological systems, studying large scale quantum interference and provide a route to universal quantum computing.

Continuous-Time Quantum Walks (CTQW) have been realized in different platforms, with single and multiple quantum particles. Single particle CTQW can be described in the context of classical wave theory. Conversely, multi-particle CTQW [2] exhibit truly non-classical behavior and pave the way to new applications in quantum information science.

Integrated circuits provide the ideal platform for implementing large networks of CTQW, due to their inherent interferometric stability and small size. Non-classical interference of single photons has been demonstrated on integrated platforms [3] and is at the heart of emerging quantum technologies [4].

Lithographic fabrication of waveguides is restricted to one dimensional waveguide arrays. The direct-write laser technique for inscribing waveguides in a substrate [5] allows the creation of arrays in three dimensions; hence more complex networks can be fabricated. Coupling between adjacent waveguides can individually be controlled during fabrication and, due to the ability of writing structures in three dimensions, second order coupling for non-adjacent waveguides is present. Here we demonstrate large scale, on chip, non-classical interference and quantum correlations of pairs of indistinguishable photons in the context of CTQW in 1-dimensional and 2-dimensional graph structures.

II. INTEGRATED CONTINUOUS TIME QUANTUM WALKS

A. Method

Photons propagating through a 1-dimensional coupled waveguide array (Fig. 1) are modeled assuming nearest-neighbor coupling with the Hamiltonian for coupled oscillators, setting ħ = 1:

$$\hat{H} = \sum_{j=1}^{N} \left[\beta_j \alpha_j^{\dagger} \alpha_j + C_{j,j-1} \alpha_{j-1}^{\dagger} \alpha_j + C_{j,j+1} \alpha_{j+1}^{\dagger} \alpha_j \right] \quad (1)$$

where the creation and annihilation operators $\alpha_j^{\dagger}$ and α_j acting on waveguide j obey Bose-Einstein statistics, β is the propagation constant of the waveguides and C the coupling between neighbouring waveguides.

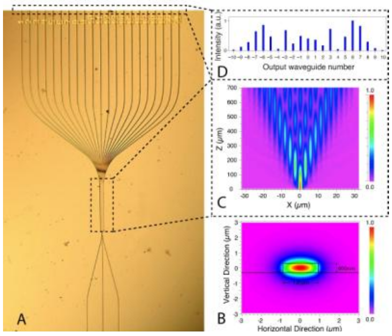

Figure 1. (A) An optical micrograph of a 21 waveguide quantum walk device. (B) Simulation of the transverse profile of the guided mode in the waveguide. (C) Single photon propagation in the array. (D) Output pattern of laser light propagating trough the waveguide array.

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Time evolution is governed by the unitary operator $U(t) = exp(-iHt)$. The probability of a coincidental detection of the two indistinguishable input photons at output waveguides q and r, is given by the correlation function:

$$\Gamma_{q,r}(z) = \frac{1}{1+\delta_{q,r}} \left| U_{q,q'} U_{r,r'} + U_{q,r'} U_{r,q'} \right|^2 \qquad (2)$$

For classical light, including random phase fluctuations that mimic certain properties of quantum light, diagonal correlations $\Gamma_{q,q}$ are related to correlations in the off-diagonal lobes $\Gamma_{q,r}$, $q \neq r$ according to the inequality [6]:

$$V_{q,r} = \frac{2}{3}\sqrt{\Gamma_{q,q}^{(Cl)} \Gamma_{r,r}^{(Cl)}} - \Gamma_{q,r}^{(Cl)} < 0 \qquad (3).$$

This can be violated in the presence of quantum interference.

B. Results [2]

The 1-dimensional CTQW network consists of an array of 21 evanescently coupled silicon-oxy-nitride (SiO_xN_y) waveguides. The measured correlation matrices for adjacent waveguides input photons show the distinct differences between distinguishable and indistinguishable input photons (Fig. 2), demonstrating the non-classical correlations between indistinguishable photons. The vanishing of the off-diagonal lobes indicates a generalised Hong-Ou-Mandel type interference [7] over a large network of 21 modes.

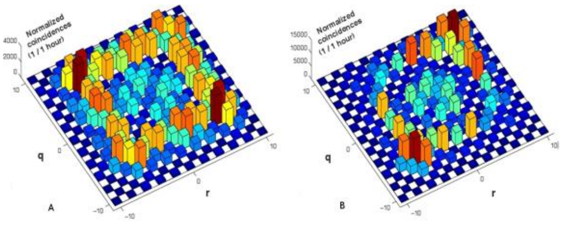

Figure 2. Measured correlation matrices for inputting the photons in adjacent waveguides, when photons are (A) distinguishable and (B) indistinguishable.

The true quantum-mechanical nature of the correlations observed is corroborated by the violations of the inequality Eq. 3 (Fig. 3).

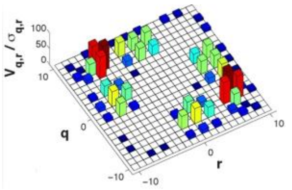

Figure 3. Violations of the inequality Eq. 3, measured for indistinguishable photons, expressed in standard deviations, showing uniquely non-classical behaviour.

III. TIME EVOLUTION

Since the length of the coupling region in the devices measured directly relates to the time of the evolution of the CTQW, by measuring the correlations between indistinguishable photons for different lengths, the coherent evolution of CTQW [8] can be investigated. We experimentally measure three different time steps and confirm the coherent evolution of the input state. The network here has a finite number of waveguides, allowing us to study boundary conditions when photons reach the outermost waveguides.

IV. SIMULATING FERMION CTQW USING ENTANGLEMENT

We show that by using bipartite, two-level entanglement for photon pairs injected in two identical CTQW networks (defined here by the TE and TM modes of the waveguides) and detecting the two-fold coincidences between these two networks, we can simulate the statistics of two non-interacting fermions undergoing a CTQW using photons [9]. Pauli's exclusion principal is observed across many modes, depicted by the vanishing of the diagonal elements of the correlation matrix.

V. 2-DIMENSIONAL QUANTUM WALKS

Three-dimensional waveguide array structures inscribed in a fused silica substrate by the use of a tightly focused femto-second laser have been proposed as a potential convenient platform for manipulating quantum states of light [10]. We experimentally demonstrate the first 2-dimensional CTQW of correlated photons [11] and observe non-classical correlations beyond the classical limit.

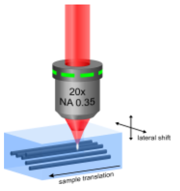

Figure 4. Schematic depicting the direct-write laser technique.

Non-classical interference of photons propagating in orthogonal planes is present, with the output statistics depending on the input state of the photons. Violations are observed across the network showing behavior that cannot be simulated with classical light across a 2-dimensional lattice.

VI. CONCLUDING REMARKS

The inherent stability and small footprint of integrated quantum photonic circuits defines them as an ideal test bed for implementing large, complex networks of CTQW. The direct-write technique opens new, exciting ways for implementing more complex networks, enabling non-trivial coupling between modes of the network.

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