Quantum Walk in Integrated Photonics

(for Quantum Computation and Simulation)

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Quantum Computation and Information

Richard Feynman - 1982

“Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy”


Trapped Ions  Solid State  Photons
Integrated Photonics

Compacting bulk optical tables into small chips.

Femtosecond laser written is a novel technique which allows:

- 3D structures
- polarization insensitive waveguides
- fast prototyping

Directional Couplers

Phase Control
Quantum Walk

Classical Random Walk:

Quantum Walk:
What are the questions?

Further advancement in femtosecond laser written photonic platform, studying more complex structures: larger number of waveguides, operation in different wavelengths, reconfigurability of the phase shifters.

Experiments in quantum information and simulation of quantum systems with increasing complexity.

Develop a state-of-the-art system for photonic quantum simulation with generation, control and detection of quantum light.
Reconfigurable Integrated Photonic Chip at Telecom Wavelengths - I

Femtosecond laser written Mach-Zehnder interferometer operating at telecom wavelength (1550nm).

Generation of pairs of single photon by Spontaneous Parametric Down Conversion (SPDC) using a Bismuth Borate crystal (BiBO).

Hong Ou Mandel interference dip visibility

$$V = 0.981 \pm 0.007$$
Reconfigurable Integrated Photonic Chip at Telecom Wavelengths - II

Thermally reconfigurable photonic device allows to control the phase of the photon in waveguide.

\[ \phi = \varphi_1 - \varphi_2 = \Phi_0 + \sum_i \alpha_i P_i \]

The temperature gradient due the heating of the waveguide creates a “bend” on the waveguide.
Reconfigurable Integrated Photonic Chip at Telecom Wavelengths - III

Measurements were done with classical light, single photon and two photon interference.

\[ b_i^\dagger = \sum_j U_{ij}^{\text{theo}} a_j^\dagger \quad U^{\text{theo}} = \begin{pmatrix} \sin \phi & \cos \phi \\ \cos \phi & -\sin \phi \end{pmatrix} \]

The results show the correct functioning of the device both classically and at a quantum level.

A tomography of the device shows an average gate fidelity of:

\[ \mathcal{F} = 0.998 \pm 0.001 \]
Photonic Simulation of Entanglement Generation and Transfer in a Spin Chain - I

Simulation of spin chain dynamics and generation of entanglement using a photonic platform.

Bosonic statistics: \( |\Psi^+ \rangle = \frac{|HV \rangle + |VH \rangle}{\sqrt{2}} \) \(\text{Symmetric}\)

Fermionic statistics: \( |\Psi^- \rangle = \frac{|HV \rangle - |VH \rangle}{\sqrt{2}} \) \(\text{Anti-Symmetric}\)

SPDC photon generation \(\beta\)-Barium Borate crystal (BBO)

392.5nm \(\rightarrow\) BBO

785nm

785nm

\(\text{p polarization analysis}\)

IF

HWP

1/2 BBO

PC

delay lines
Photonic Simulation of Entanglement Generation and Transfer in a Spin Chain - II

Quantum transport for boson and fermion in a 1D chain.

Quantum transport in a spin chain

Simulation with a $M$ step discrete-time quantum walk

Entanglement generation at half dynamic

Encoding

1 2 3 4 5

$H, t^*$

$t = 0$

$t = t^*/2$

$t = t^*$

Néel state: $\downarrow\uparrow\downarrow\uparrow\downarrow$

Entanglement generation at half dynamic

$|\psi^+_{1p}\rangle_{15}$

$|\psi^+_{1p}\rangle_{24}$
Photonic Simulation of Entanglement Generation and Transfer in a Spin Chain - III

Symmetric Input state

Strong contribution on the diagonal term of the matrix.

Bosonic Coalescence

Anti-Symmetric Input state

Strong contribution on the off-diagonal term of the matrix.

Pauli Exclusion Principle
Photonic Simulation of Entanglement Generation and Transfer in a Spin Chain - IV

Resulting state in a perfect Néel state transfer: $|\psi_{\text{out}} \rangle = |\psi_{1p}^+ >_{15} |\psi_{1p}^+ >_{24} |0_{1p} >_3$
Photonic Simulation of Entanglement Generation and Transfer in a Spin Chain - V

Entanglement certification of the one-photon path-encoded Bell state

\[ |\psi_{out} \rangle = (\alpha|10 >_{15} + \beta|01 >_{15})(\gamma|10 >_{15} + \delta|01 >_{15})|0 >_{3} \]

1) Check of coherence between states (15) and (24).

\[ V_{S1} = 0.51 \pm 0.05 \quad V_{S5} = 0.40 \pm 0.03 \]
\[ V_{S2} = 0.74 \pm 0.03 \quad V_{S4} = 0.82 \pm 0.03 \]

2) Entanglement fraction with respect to the ideal one-photon Bell state

\[ \epsilon_{ij} = \langle \psi_{1p}^{+}|\rho_{ij}|\psi_{1p}^{+} \rangle \]

\[ \epsilon_{15} = 0.66 \pm 0.03 \quad \epsilon_{24} = 0.74 \pm 0.03 \]
Superconducting Single Photon Detectors

Superconducting detectors operating at low temperatures (~4K).

Photon absorption breaks Cooper pairs, so there is a local brake of superconductivity.

High detection efficiency: ~ 70% (possibility to go even higher).

Operating at high efficiency at free running mode.

Dark counts of the order of few hundreds (Low).

Short detector dead time.
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