Quantum walk with integrated photonics

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http:\\quantumoptics.phys.uniroma1.it
"Information is physical”
R. Landauer

The processing of information is governed by the laws of physics.
Quantum information

**Challenges: from basic sciences** to emerging quantum technologies

- **Fundamental physics:**
  - Test of non-locality, quantum contextuality
  - Shed light on the boundary between classical and quantum world
  - Exploiting quantum parallelism
to simulate quantum many-body systems
- **New cryptographic protocols**
- **Quantum sensing:** imaging, metrology
- **Quantum computing**
  - quantum simulation
How to encode qubit with light?
Suitable hardware for quantum communication

Photon: quantum of the electromagnetic field
Photoelectric effect – Einstein (1905)

Qubit encoded into photon's degrees of freedom

Examples:
- Single photon polarization
- Spatial mode
- Time bin
- …
Quantum information
Polarization of light

Poincaré sphere

Qubit

\[ \alpha |0\rangle + \beta |1\rangle \]

Polarization of a single photon

\[ \alpha |H\rangle + \beta |V\rangle \]

H: horizontal
V: vertical
Quantum Optics for Quantum Information Processing

- Qubit state: \( \alpha |0\rangle + \beta |1\rangle \) \( \longleftrightarrow \) \( \alpha |H\rangle + \beta |V\rangle \)

Polarization of a single photon:
- H: horizontal polarization
- V: vertical polarization

Mode of the electromagnetic field (k, wavelength)

- Logic gate acting on a single qubit
- Rotation of the polarization: waveplates

- Measurement of the qubit:
  - polarizing beam splitter
  - Single photon detectors
Generation of entangled states

Non-linear crystal

Pumping laser

For more details: next talk by Harald Weinfurter

\[ |\psi^-\rangle = \frac{1}{\sqrt{2}} \left( |H\rangle|V\rangle - |V\rangle|H\rangle \right) \]
Quantum information
Implementation via path encoding

Qubit realization with photons

<table>
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<tr>
<th>POLARIZATION qubit</th>
<th>PATH qubit</th>
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<tbody>
<tr>
<td>$</td>
<td>H\rangle \equiv</td>
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<td>V\rangle \equiv</td>
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Manipulation: beamsplitters and phase-shifters

Problem!

Phase-stability of the interferometer...
Photonic quantum technologies: a promising experimental platform for quantum information processing

SETUP: COMPLEX OPTICAL INTERFEROMETERS

- Large physical size
- Low stability
- Difficulty to move forward applications outside laboratory
Integrated photonics: Bulk optics limitations

The main limitations of experiments realized with bulk optics are:

- Large physical size
- Low stability
- Difficulty to move forward applications outside laboratory

Possible solutions? Integrated waveguide technology
Integrated quantum photonics

Preparation

Manipulation

Detection
Integrated quantum photonics

Preparation

Manipulation

Detection
Summary

I) Laser writing techniques
   First step: beamsplitters

II) Quantum walk

III) Simulation of disordered systems
Femtosecond pulse tightly focused in a glass

Combination of multiphoton absorption and avalanche ionization induces permanent and localized refractive index increase in transparent materials

Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity with respect to the laser beam, along the desired path.

What about polarization encoding?

Laser writing technique for devices able to transmit polarization qubits

- Femtosecond pulse tightly focused in a glass

- Combination of multiphoton absorption and avalanche ionization induces permanent and localized refractive index increase in transparent materials

- Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity with respect to the laser beam, along the desired path.
How to guide light on a chip?

Fiber optics: guiding of light

Total internal reflection:
- Cladding with refraction index $n_1$
- Core with refraction index $n_2 > n_1$

Diameter few microns
Integrated photonic quantum circuits

In collaboration with Politecnico di Milano and Istituto di Fotonica e Nanotecnologie - CNR

L. Sansoni
N. Spagnolo
C. Vitelli
P. Mataloni
F. Sciarrino

A. Crespi
R. Ramponi
R. Osellame
Femtosecond laser writing

Characteristics:
- Rapid device prototyping: writing speed = 4 cm/s
- Propagation of circular gaussian modes
- Circular waveguide transverse profile
- 3-dimensional capabilities
- Low birefringence
- Suitable to support any polarization state
Substrate of borosilicate glass
(no birefringence observed)

Femtosecond infrared laser: $\lambda=1030\text{nm}$
Pulses: $300\text{fs}$, $1\text{W}$
Repetition rate $1\text{ MHz}$

L: interaction region

Note: the coupling of the modes occurs also in the curved parts of the two waveguides

Polarization entanglement on a chip

\[ V_{\psi^-} = 0.930 \pm 0.005 \]
\[ V_{\text{Tripl}} = 0.928 \pm 0.007 \]


QUANTUM SIMULATION
VIA QUANTUM WALKS

R. Feynman:
“To exploit quantum hardware
to simulate quantum systems”

Realization of quantum simulation
via quantum walks

Classical random walk:
A walker must make a choice (randomly) of moving either left or right at each step.

Quantum walk:
The walker uses a ‘quantum coin’ mechanism that allows it to move in a superposition of both left and right.
IMPLEMENTATION OF QUANTUM WALKS: OPTICAL SYSTEMS

Quantum walks: photons propagating along an array of beam splitters and phase shifters.
Photonic implementation of quantum walks

- Single photons
- Beam splitters
- Phase shifters
- Photodetectors

Table showing steps and sites:

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QW SITES

STEPS
Beamsplitter arrays

- 16 3D-beamsplitters with balanced reflectivities $R_H = R_V = 49\%$ able to support any polarization state

- Control path lengths up to few nanometers:
  all interferometers with phase difference between the two arms set equal to 0

- Stable operation of the BS arrays: length 32 mm, width about 1 mm

Quantum walk with two particles..

If two simultaneous quantum walkers travel their symmetry must influence the output probability distribution.

**GOAL:** to exploit the polarization degree of freedom in order to inject different entangled states of two photons.

By changing the symmetry of entanglement we can simulate the quantum dynamics of the walks of two particles with bosonic or fermionic statistic.

\[ |\Psi^\phi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A|V\rangle_B + e^{i\phi} |V\rangle_A|H\rangle_B) \]

*For Bosons* \( \phi = 0 \)

*For Fermions* \( \phi = \pi \)
Two-particles quantum walk: experimental setup

Generation of two-photon entangled states with different symmetries

\[ |\Psi^\phi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |V\rangle_B + e^{i\phi} |V\rangle_A |H\rangle_B) \]

BS array on a chip

Eight output modes:

Measurement of coincidences between modes i and j
Two-particles quantum walk: results

Similarities between theory and experiment

\[ S = 0.982 \pm 0.002 \quad S = 0.973 \pm 0.002 \quad S = 0.987 \pm 0.002 \]


See also: continuous quantum walk by J. Mathews, et al., arXiv: 1106.1166
Simulation of disordered systems
Simulation of disordered systems

**Beam-splitter**  **Phase shift**

Input

Propagation

Output modes

**Phase shifting by geometrical deformation**

**POLARIZATION INDEPENDENT**

.... FIRST EXPERIMENTS....

To simulate different types of disorders:
Simulation of static disorder

Disorder depends:
- from location
- but NOT from time

Andersen localication....

64 Beam splitters
64 phase-shifters
Polarization independent
Simulation of disordered systems: Single particle quantum walk

Ordered system

Disordered system
Simulation of disordered systems: Single particle quantum walk

Ordered system

Disordered system


Two-particle quantum walk with disordered systems: … experiments missing so far...

Ordered VS Static Quantum Walk: Experimental results

**ORDERED**

**BOSONS**

4 steps

**FERMIONS**

6 steps

**SINGLE**

8 steps
Integrated quantum simulations...

**Adding the Third Dimension...**

**Tritter**

![Diagram of Tritter]

Hong-Ou-Mandel coalescence of three photons

**Tetrater**

![Diagram of Tetrater]

**Simulating bosons, fermions...**

\[
|\Psi^\phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)
\]

- **Bosons**
  - \(\phi = 0\)
- **Fermions**
  - \(\phi = \pi\)

Fermionic behaviour with multi-chip approach

**Higher dimensionality for quantum walk...**

![Diagram of quantum walk]

**Adding interaction...**

ancillary photons and modes
The tritter: a three-mode splitter

Three-dimensional femtosecond laser-writing extension to three modes of a beam-splitter

Simple integrated structure
Simultaneous interference of the three modes
Exploring three-photon interference

INPUT:

OUTPUT:

$k_1, k_2, k_3$
The tritter: a three-mode splitter

Tritter by femtosecond laser-writing

Experiment

Characterization of the tritter by single photon and two photon measurements

Theory

High correspondence between the ideal and the reconstructed device

$S = 0.973 \pm 0.001$
Photonic coalescence of 3 photons

Experimental three-photon bosonic coalescence

Three-photon input state: $|1, 1, 1\rangle$

Model taking into account the reconstructed tritter matrix and photon distinguishability

Visibilities outperform the classical bound for coherent state inputs

N. Spagnolo, C. Vitelli, L. Aparo, P. Mataloni, F. Sciarrino, A. Crespi, R. Ramponi, R. Osellame, 
*Three-photon bosonic coalescence in an integrated tritter*, [arXiv:1210.6935]
propagation on the chip with \( m \) modes

Input: \( n \) photons

Output: \( n \)-photon state

Can a classical computer efficiently simulate these experiments?
propagation on the chip with \( m \) modes

Input: \( n \) photons

Output: \( n \)-photon state

Can a classical computer efficiently simulate our experiments?

**Answer: NO!!**

**WHY:** the permanents of \( n \times n \) matrices must be calculated

Permanent of a matrix: hard to calculate with a classical computer

\[
\text{per}(A) = \sum_{\sigma \in S_n} \prod_{i=1}^{n} a_{i,\sigma(i)}
\]

\[
\text{det}(A) = \sum_{\sigma \in S_n} \text{sgn}(\sigma) \prod_{i=1}^{n} a_{i,\sigma(i)}
\]

Conclusions and perspectives

- Beamsplitter able to support polarization encoded qubit
- Polarization sensitive devices
- Quantum walk with two-particles in different entangled states: simulation of Anderson localization

Circuits with 3-dimensional geometries


Quantum walk: