Quantum simulation with integrated photonics

Fabio Sciarrino

Quantum Information Lab
Dipartimento di Fisica
“Sapienza” Università di Roma

http://quantumoptics.phys.uniroma1.it
www.quantumlab.it
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
- …
Polarization of light

Qubit

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

Polarization of a single photon

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

H: horizontal
V: vertical
**Polarization**

direction of oscillation of the e.m. field

\[ \alpha |0\rangle + \beta |1\rangle \leftrightarrow \alpha |H\rangle + \beta |V\rangle \]

- Easy to manipulate: Waveplates and Polarizing Beam Splitters (PBSs)
- Easy to generate entangled states: Nonlinear crystals

- Quantum non-locality tests
- Quantum cryptography
- Quantum teleportation
- Quantum metrology
- Quantum computation
- Simulation

\[ |\psi^-\rangle = \frac{2}{\sqrt{2}} (|H\rangle|V\rangle - |V\rangle|H\rangle) \]
Quantum Optics for Quantum Information Processing

- Qubit state
  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
Quantum Optics for Quantum Information Processing

- **Two qubit logic gate (CNOT gate)**
  “Interaction” between two photons
  - **Linear**
    Polarizing beam-splitter
    Beam-splitter
    Measurement process
  - **Non-linear**
    Interaction with atoms

- **Generation of entangled states**
  - Spontaneous parametric down conversion
Integrated photonics: Bulk optics limitations

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

Possible solutions?
Integrated waveguide technology
Integrated quantum photonics
Integrated quantum photonics

- Single photon sources
- Manipulation
- Single photon detectors
ON THE SAME CHIP
Integrated quantum photonics: new opportunities.

Quantum factoring algorithm on a chip

Integrated quantum walks

Boson Sampling in an integrated chip
Outline

Lecture 1 - Integrated quantum circuits

Lecture II - Quantum simulation via quantum walk

Lecture III - Boson sampling
Building blocks...
Lecture 1: Integrated quantum photonics

Fabio Sciarrino

Dipartimento di Fisica, “Sapienza” Università di Roma

http:∕∕quantumoptics.phys.uniroma1.it
www.3dquest.eu

Bidimensional capabilities;
Squared cross section;
Necessity of masks;
Long time fabrication.

✓ 2- and 4-photon quantum interference, C-not gate realization, path-entangled state of two photons
✓ Shor's algorithm
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

CNOT gate  

HOM effect  

Phase control  
Smith et al. Optics Express (2009)

All experiments realized with path encoded qubits
Integrated photonics: First experiments....


✓ 2- and 4-photon quantum interference, CNOT gate realization, path-entangled state of two photons
✓ Shor's algorithm

All experiments realized with path encoded qubits
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.
Femtosecond laser writing
Femtosecond laser writing

Characteristics:

- Circular waveguide transverse profile
- 3-dimensional capabilities
- Rapid device prototyping: writing speed = 4 cm/s
- Propagation of circular gaussian modes
- Low birefringence

SUITABLE TO SUPPORT ANY POLARIZATION STATE
Femtosecond laser writing
Substrate of borosilicate glass
(no birefringence observed)

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

L: interaction region

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

Propagation losses
\(~0.5\text{dB/cm}\)
Bending losses
\(<0.3\text{dB/cm}\)

Tunability of the direction coupler transmission

Optical power transfer follows a sinusoidal law with the interaction length.

Oscillation period (beating period) depends upon the coupling coefficient of the two guided modes.

Periodicity of the transmission depends from the Effective index of refraction
Integrated beam splitter

Indistinguishable photons: Bosonic coalescence
Indistinguishable photons: Bosonic coalescence

Directional coupler as beam splitter

\[ \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \]

Single photons

Two-photon states

Identical separable states

Symmetric states: Triplet

Entangled states \( \left\{ |\Psi^+\rangle, |\Phi^-\rangle, |\Phi^+\rangle \right\} \)

Antisymmetric state: Singlet

\[ |\psi^-\rangle = \frac{2}{\sqrt{2}} (|H\rangle|V\rangle - |V\rangle|H\rangle) \]
Two-photon entangled state on a beamsplitter...

The symmetry of two particles influences the output probability distribution.

Polarization independent integrated beam splitter

Exploit polarization entanglement to simulate other particle statistics

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

Bosons

\[ \phi = 0 \]

or

Fermions

\[ \phi = \pi \]
Polarization entanglement on a chip


Photonics C-NOT gate


Path qubits V=94.3%

A. Crespi et al., Nat. Comm. (2011)

Polarization qubits V=91%
How can we realize polarization dependent devices?

I) Transmission depends from the interaction length

II) Small anisotropy behavior due to residual asymmetry of the waveguide: Different periodicities
Partially Polarizing Directional Couplers (PPDC)

Interaction length

Transmission for horizontal polarization ($T_H$)
Transmission for vertical polarization ($T_V$)
Partially Polarizing Directional Couplers (PPDC)

Interaction length

Transmission (T)

Interaction length (mm)

\[ \frac{T_H}{T_V} < 1\% \]

\[ T_V = 64\% \]
Linear optical quantum computing


CNOT gate for polarization qubit

\[
\begin{align*}
\langle 0 \rangle_C, \langle 1 \rangle_C & \equiv \{ \langle H \rangle, \langle V \rangle \} \\
\langle 0 \rangle_T, \langle 1 \rangle_T & \equiv \{ \langle D \rangle, \langle A \rangle \}
\end{align*}
\]

- partial polarizing beam splitters
- post-selection
- success probability (p=1/9)

CNOT gate for polarization qubit

\[
\begin{align*}
\text{PPDC1:} & \quad T_H = 0, \quad T_V = 2/3 \\
\text{PPDC2 - PPDC3:} & \quad T_H = 1/3, \quad T_V = 1
\end{align*}
\]

\[
\begin{align*}
\text{PPDC2 - PPDC3:} & \quad T_H = 43\%, 27\% \\
& \quad T_V = 98\%, 93\%
\end{align*}
\]

\[
\begin{align*}
\text{PPDC1:} & \quad T_H < 1\% \\
& \quad T_V = 64\%
\end{align*}
\]
CNOT gate for polarization qubit

Polarization: degree of freedom of light suitable for interface with other systems
Truth table of the CNOT

Truth table:

<table>
<thead>
<tr>
<th>$C_{in}$</th>
<th>$T_{in}$</th>
<th>$C_{out}$</th>
<th>$T_{out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Experimental data:

$$F_{\text{measured}} = 0.940 \pm 0.004.$$
Generation and discrimination of entangled states

CNOT gate transforms entangled state into separable one and vice versa

\[ +_C |0>_T \equiv |\Phi^+> = \frac{1}{\sqrt{2}} (|0>_C |0>_T + |1>_C |1>_T) \]

\[ +_C |1>_T \equiv |\Psi^+> = \frac{1}{\sqrt{2}} (|0>_C |1>_T + |1>_C |0>_T) \]

\[ -_C |0>_T \equiv |\Psi^-> = \frac{1}{\sqrt{2}} (|0>_C |1>_T - |1>_C |0>_T) \]

\[ -_C |1>_T \equiv |\Phi^-> = \frac{1}{\sqrt{2}} (|0>_C |0>_T - |1>_C |1>_T) \]

A. Crespi, et al., quant-ph 1105.1454
Directional coupler

Partially polarizing and logical gate
A. Crespi et al., Nat. Comm. 2, 566 (2011)
Directional coupler

Partially polarizing and logical gate
A. Crespi et al., Nat. Comm. 2, 566 (2011)

Tunable waveplates
G. Corrielli et al., Nat. Comm. 5, 2549 (2014)
Integrated components for polarization manipulation

Waveguides fabricated by FLM are birefringent ($b = 10^{-5} \div 10^{-4}$)

- Asymmetric cross section
- Stress field accumulated in the substrate

→ Waveplates... ...with fixed axis

- Beam splitter

- Polarizing Beam Splitter

- Waveplate with variable axis

✓ Demonstrated with laser writing

✓ Demonstrated with laser writing

✗ Missing up to 2014
Use a microscope objective with very high numerical aperture (e.g. Immersion oil objective, NA 1.4).

Use a reduced laser spot diameter in order to underfill the high NA objective and obtain an effective NA comparable with the standard one.

Displace the beam axis from the center of the objective to produce a rotation in the beam focusing, without changing the focal position.
Fabrication of waveguide with tilted cross section

Spheric lens with long focal distance
Quantum factoring algorithm on a chip

A. Politi et al., Science (2009)
Factoring 15
Quantum teleportation on a chip

2 C-NOT scheme
3 photons

Nature Photonics 8, 770–774 (2014)
# State of the art: linear optical quantum computing on chip

<table>
<thead>
<tr>
<th>Year</th>
<th>Title</th>
<th>Group</th>
<th>Platform</th>
<th>n</th>
<th>m</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Silica-on-silicon waveguide quantum circuits</td>
<td>Bristol</td>
<td>SoS</td>
<td>2</td>
<td>6</td>
<td>CNOT</td>
</tr>
<tr>
<td>2009</td>
<td>Shor’s quantum factoring algorithm on a photonic chip</td>
<td>Bristol</td>
<td>SoS</td>
<td>2</td>
<td>12</td>
<td>Shor</td>
</tr>
<tr>
<td>2010</td>
<td>High-fidelity operation of quantum photonic circuits</td>
<td>Bristol, Queensland</td>
<td>SoS</td>
<td>2</td>
<td>6</td>
<td>CNOT</td>
</tr>
<tr>
<td>2011</td>
<td>Integrated photonic quantum gates for polarization qubits</td>
<td>Milan, Rome</td>
<td>LW</td>
<td>2</td>
<td>4</td>
<td>CNOT</td>
</tr>
<tr>
<td></td>
<td>Generating, manipulating and measuring entanglement and mixture</td>
<td>Bristol</td>
<td>SoS</td>
<td>2</td>
<td>6</td>
<td>CNOT</td>
</tr>
<tr>
<td></td>
<td>with a reconfigurable photonic circuit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Experimental realisation of Shor’s quantum factoring algorithm using</td>
<td>Bristol</td>
<td>SoS</td>
<td>2</td>
<td>6</td>
<td>Shor</td>
</tr>
<tr>
<td></td>
<td>qubit recycling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Integrated optical waveplates for arbitrary operations on</td>
<td>Milan, Rome</td>
<td>LW</td>
<td>2</td>
<td>4</td>
<td>Tomography</td>
</tr>
<tr>
<td></td>
<td>polarization-encoded single-qubits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>polarization qubit</td>
</tr>
<tr>
<td>2014</td>
<td>Arbitrary photonic wave plate operations on chip: realizing</td>
<td>Jena</td>
<td>LW</td>
<td>1</td>
<td>2</td>
<td>Hadamard, Pauli-</td>
</tr>
<tr>
<td></td>
<td>Hadamard, Pauli-X, and rotation gates for polarisation qubits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2014</td>
<td>Quantum teleportation on a chip</td>
<td>Oxford</td>
<td>UV written chip</td>
<td>3</td>
<td>6</td>
<td>Teleportation on a chip</td>
</tr>
<tr>
<td></td>
<td>Universal linear optics</td>
<td>Bristol</td>
<td>SoS</td>
<td>3</td>
<td>6</td>
<td>Hadamard, CNOT,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pauli rotation gates</td>
</tr>
<tr>
<td>2015</td>
<td>Towards high-fidelity quantum computation and simulation on a</td>
<td>Cambridge</td>
<td>SoS</td>
<td>2</td>
<td>6</td>
<td>CNOT</td>
</tr>
<tr>
<td></td>
<td>programmable photonic integrated circuit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CPHASE</td>
</tr>
</tbody>
</table>
The tritter: a three-mode splitter

Two-mode symmetric interaction

Three-mode symmetric interaction, realized by bulk optics

Tritter transfer matrix:

\[
U = \frac{1}{\sqrt{3}} \begin{pmatrix}
1 & e^{i2\pi/3} & e^{i2\pi/3} \\
e^{i2\pi/3} & 1 & e^{i2\pi/3} \\
e^{i2\pi/3} & e^{i2\pi/3} & 1
\end{pmatrix}
\]

M. Zukowski, A. Zeillinger, and A. Horne, Phys. Rev. A 55, 2561 (1997);
The tritter: a three-mode splitter

Multiport device realized by bulk optics

Femtosecond laser written circuit


Interaction length:

Evanescent field coupling between different waveguides
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
The tritter: apparatus
Step 1: Single photon input-output probabilities

\[ |\mathcal{M}_{i,j}|^2 = \frac{n_{i,j}}{\sum_{j=1}^{3} n_{i,j}} \]

Step 2: Two-photon Hong Ou Mandel interference

\[ \mathcal{V}_{i,j;k,l} = \frac{P_{i,j;k,l}^C - P_{i,j;k,l}^Q}{P_{i,j;k,l}^C} \]
The tritter: a three-mode splitter

Tritter by femtosecond laser-writing

Experiment

Characterization of the tritter by single photon and two photon measurements

Theory

$$S = 0.973 \pm 0.001$$
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

3D Quantum Interferometry

Designing interferometric structures for:
- Quantum simulation
- Quantum phase estimation

N. Spagnolo, L. Aparo, C. Vitelli, A. Crespi, R. Ramponi, R. Osellame, P. Mataloni, and F. Sciarrino
Quantum interferometry with three-dimensional geometry, *Scientific Reports* 2, 862 (2012).
1) What happens if we inject multiple unknown phases inside the interferometer?  
2) What are the limits on the simultaneous estimation of multiple parameters?  
3) Quantum resources = better estimation?  
4) Is there an optimal measurement?

Integrated tunable circuits


Integrated tunable circuits


Chip-based QKD. Sibson et al., arXiv 1509.00768 (2015)
Integrated tunable circuits


Reconfigurable MZI Generation

Femtosecond laser writing technique

Integrated tunable circuits
Hong-Ou-Mandel interference in a 50/50 beamsplitter

**CW**

- Power: $P = 800\text{mW}$
- Mandel parameter: $V_{cw} = 0.967 \pm 0.002$

**Pulsed**

- Power: $P = 200\text{mW}$
- Mandel parameter: $V_{p} = 0.923 \pm 0.004$
MZI interference fringes

Classic light

Output 1

0.926 < V < 0.982

Output 2

Single photon

Output 1

V_1 = 0.932 ± 0.008

Output 2

V_2 = 0.981 ± 0.007
NOON effect on a chip

\[ |11\rangle_{12} \]

\[ \frac{1}{\sqrt{2}} (|20\rangle + |02\rangle) \]

\[ \frac{1}{\sqrt{2}} (e^{i2\phi} |20\rangle + |02\rangle) \]

\[ |11\rangle \rightarrow \frac{\sin\phi}{\sqrt{2}} (|20\rangle - |02\rangle) - \cos\phi |11\rangle \]
NOON effect on a chip

\[ |11\rangle \rightarrow \frac{\sin \phi}{\sqrt{2}} (|20\rangle - |02\rangle) - \cos \phi |11\rangle \]