Integrated photonic technologies for quantum information processing

SAPIENZA
UNIVERSITÀ DI ROMA

Fabio Sciarrino

Dipartimento di Fisica,
"Sapienza" Università di Roma

evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

"Information is physical"

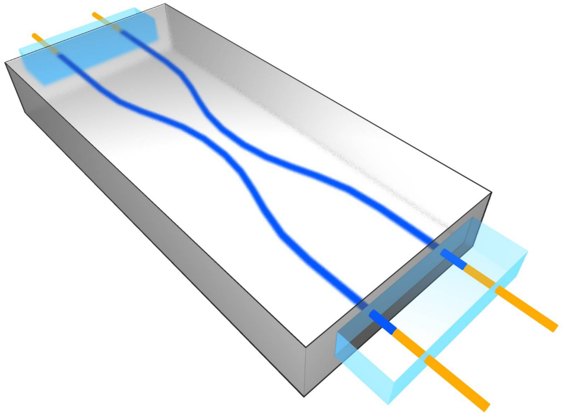
R. Landauer

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

Outline

I) Elements of quantum information

II) Integrated photonic quantum circuits



Quantum information

Challenges: from basic sciences to emerging quantum technolo

- Fundamental physics:

  Test of non-locality, quantum contextuality

  Shed light on the boundary between classical and quantum world

  Exploiting quantum parallelism

  to simulate quantum random many-body systems

- New cryptographic protocols
- Quantum sensing: imaging,metrology
- Quantum computing, quantum simulation

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Entanglement: new resource to elaborate information

Entanglement:

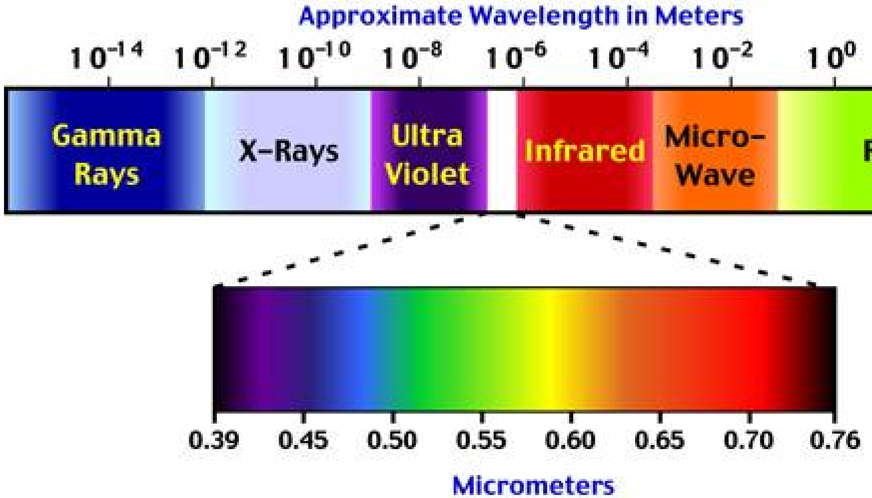
ristic trait

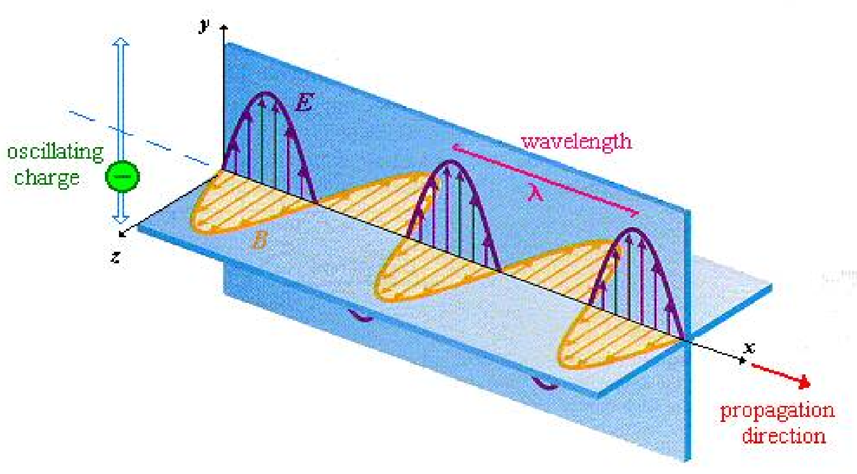
echanics

E. Schrödinger

Optics for Quantum Information

Suitable hardware for quantum communication



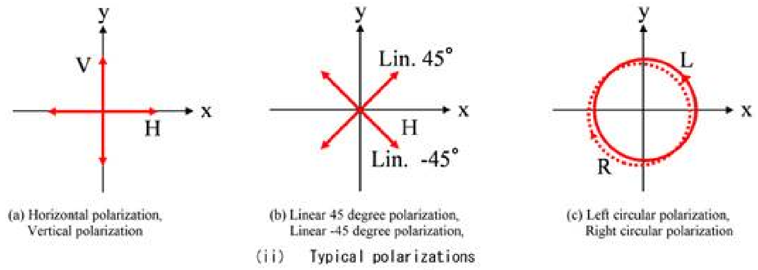


Photon: quantum of the electromagnetic field

Photoelectric effect – Einstein (1905)

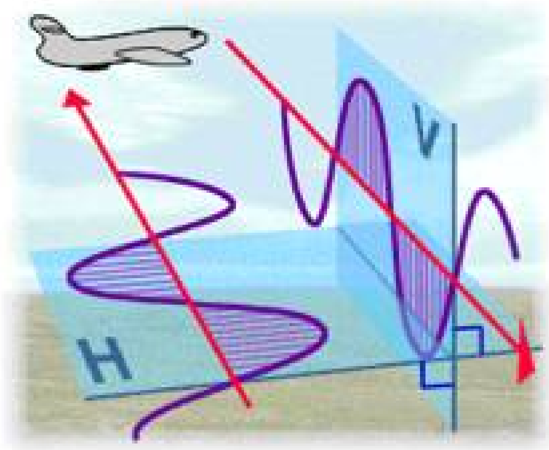
Qubit encoded into photon's degrees of freedom

Examples:
- Single photon polarization
- Spatial mode
- Time bin
-...



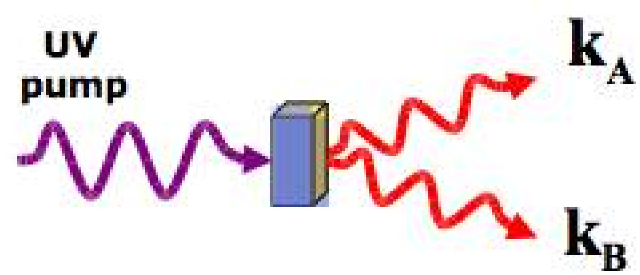
Polarization encoding of qubit

Polarization:
direction of oscillation
of the e.m. field

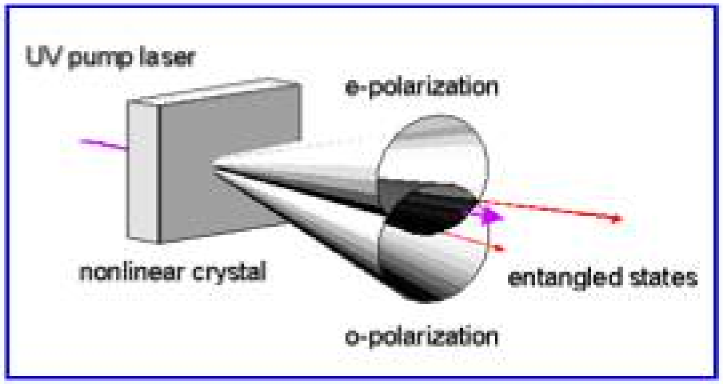


$$\alpha|0\rangle+\beta|1\rangle \longleftrightarrow \alpha|H\rangle+\beta|V\rangle$$

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



- Many applications:
  - Quantum non-locality tests
  - Quantum cryptography
  - Quantum teleportation
  - Quantum metrology
  - Quantum computation
  - Simulation



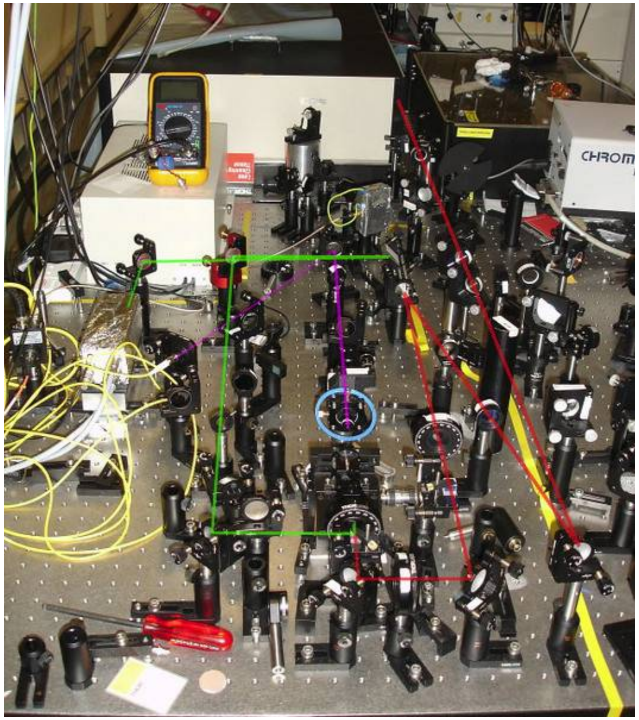
$$|\psi^-\rangle = \frac{2}{\sqrt{2}}(|H\rangle|V\rangle - |V\rangle|H\rangle)$$

Integrated photonics: Bulk optics limitations

Photonic quantum technologies:
a promising experimental platform for quantum information processing

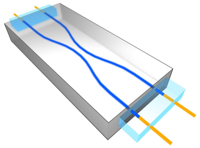
SETUP: COMPLEX OPTICAL INTERFEROMETERS

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



Possible solutions?

Integrated waveguide technology

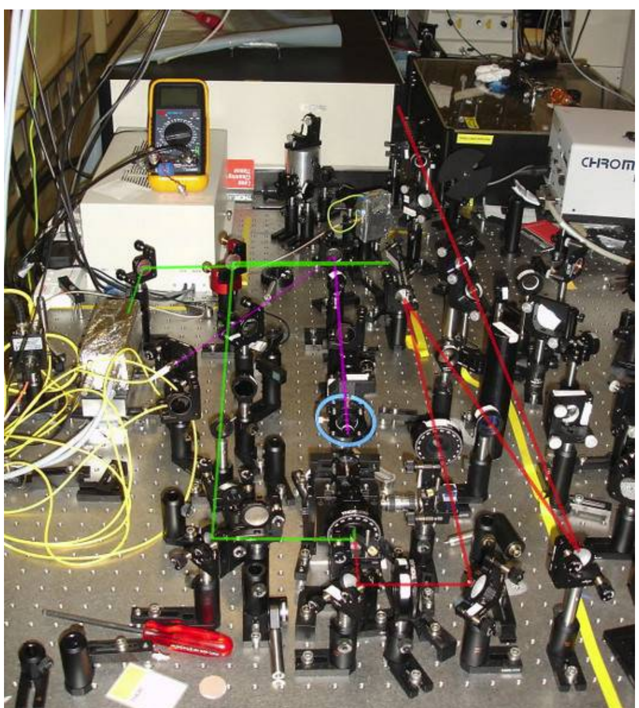


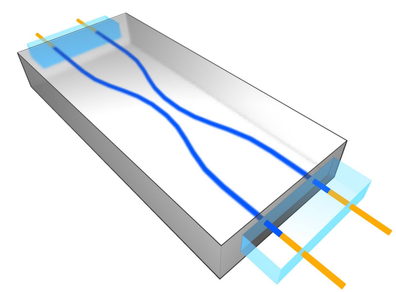
Integrated photonics: Bulk optics limitations

The main limitations of experiments realized with bulk optics are:

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

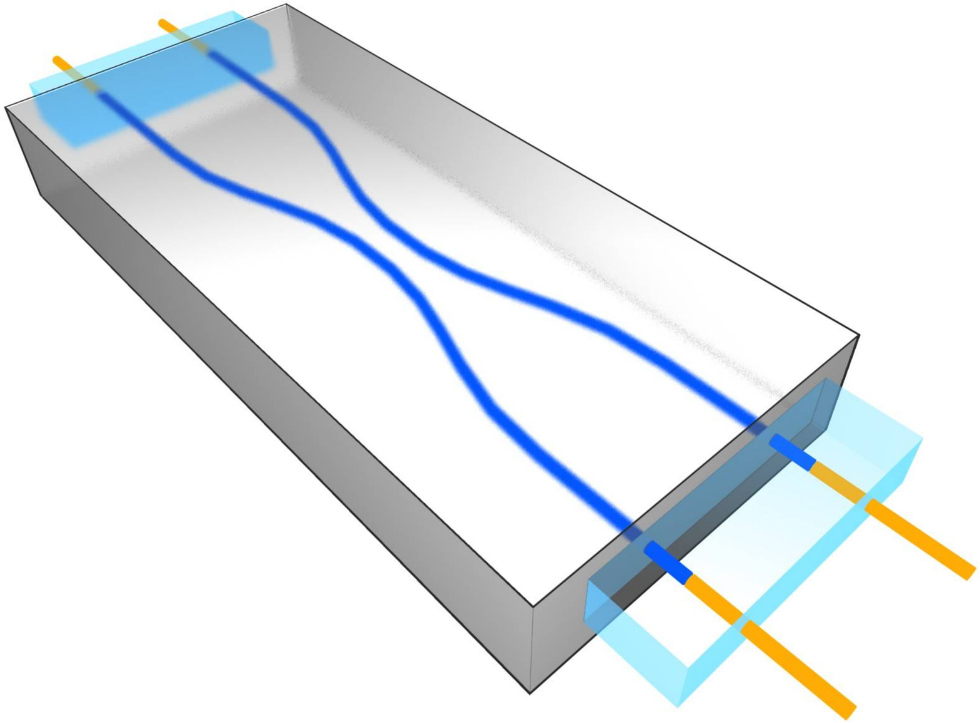
Possible solutions? Integrated waveguide technology





II) Integrated photonic quantum circuits

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



L. Sansoni
I. Bongioanni
G. Vallone
F. Sciarrino
P. Mataloni

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NAZIONALE DI
OTTICA

POLITECNICO
MILANO

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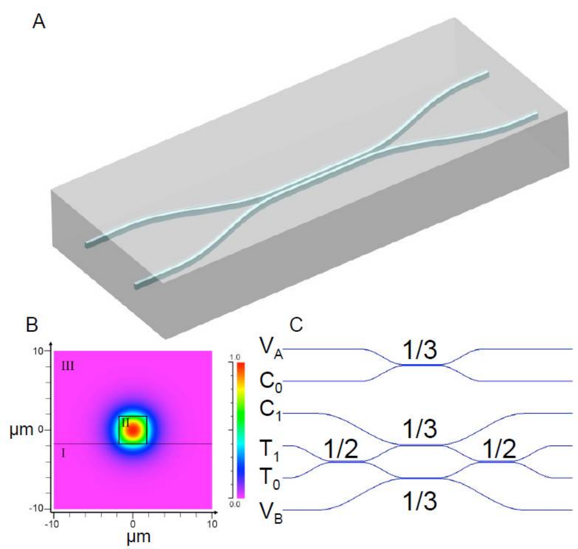
A. Crespi
R. Ramponi
R. Osellame

Integrated photonics: First experiments....

The main limitations of experiments realized with bulk optics are:

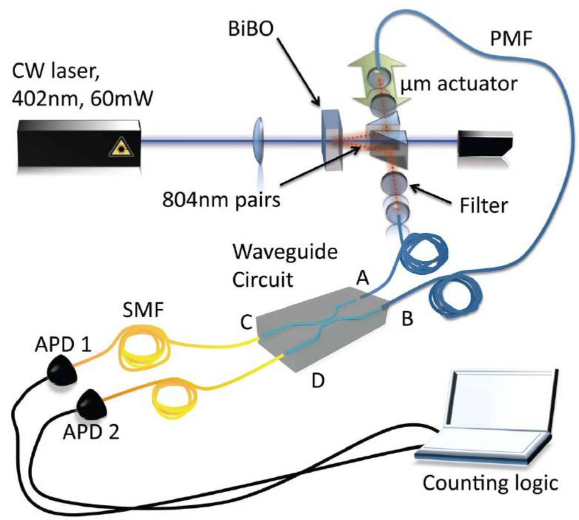
- ✓ Large physical size
- ✓ Low stability
- ✓ Difficulty to move forward applications outside laboratory

Possible solutions? **Integrated waveguide technology**



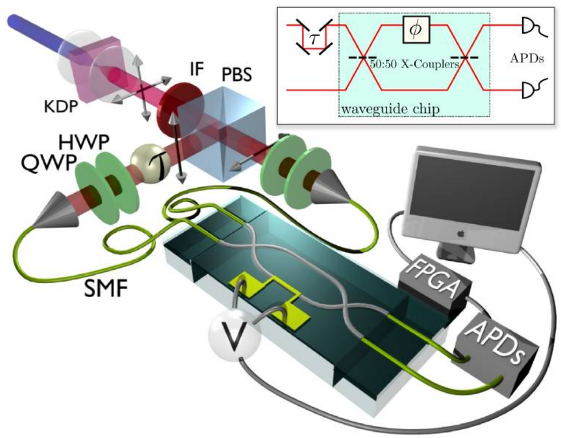
CNOT gate

Politi *et al*. Science (2008)



HOM effect

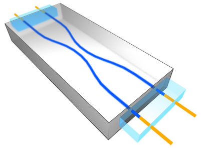
Marshall *et al*. Optics Express (2009)



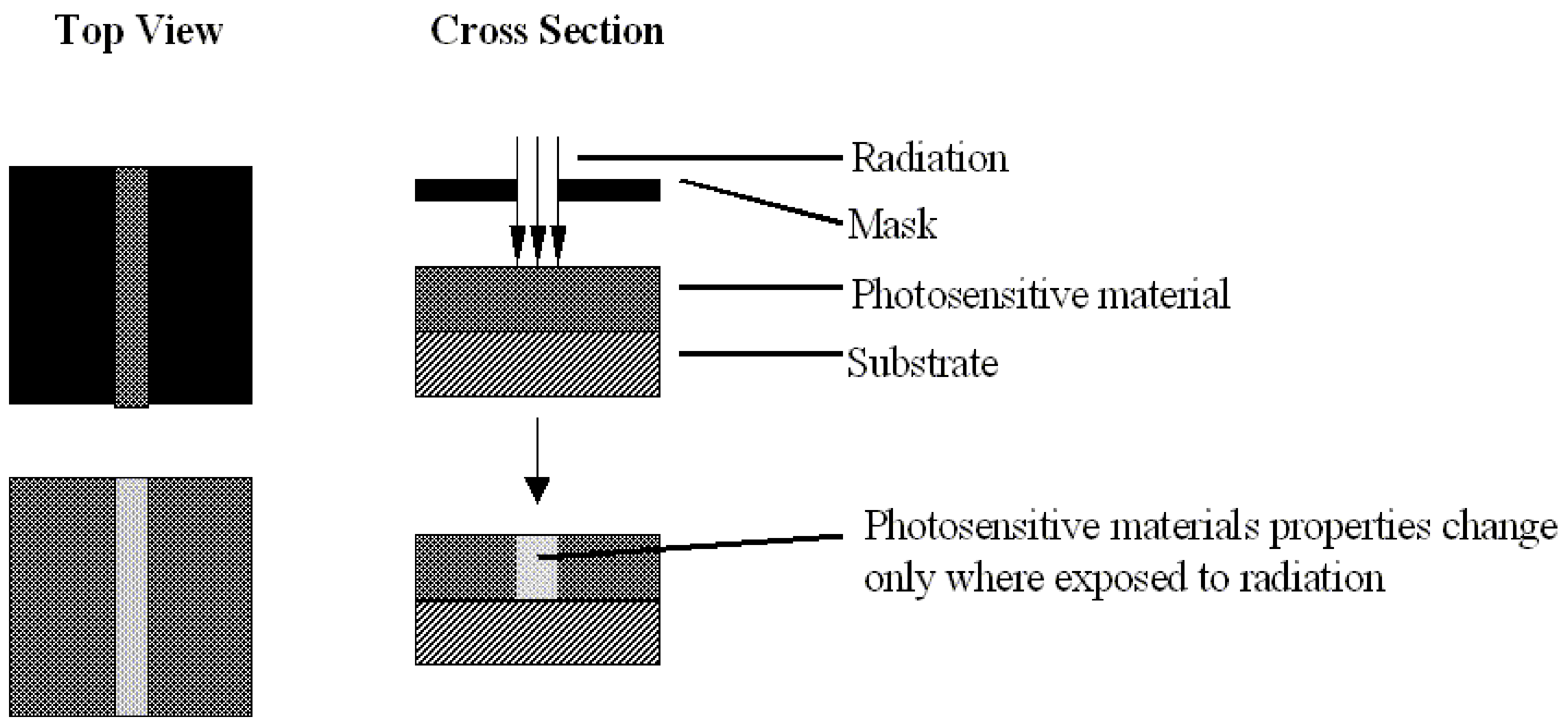
Phase control

Smith *et al*. Optics Express (2009)

So far, all experiments realized with path encoded qubits

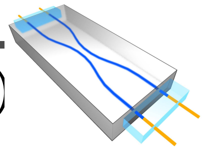


Lithography



- 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*

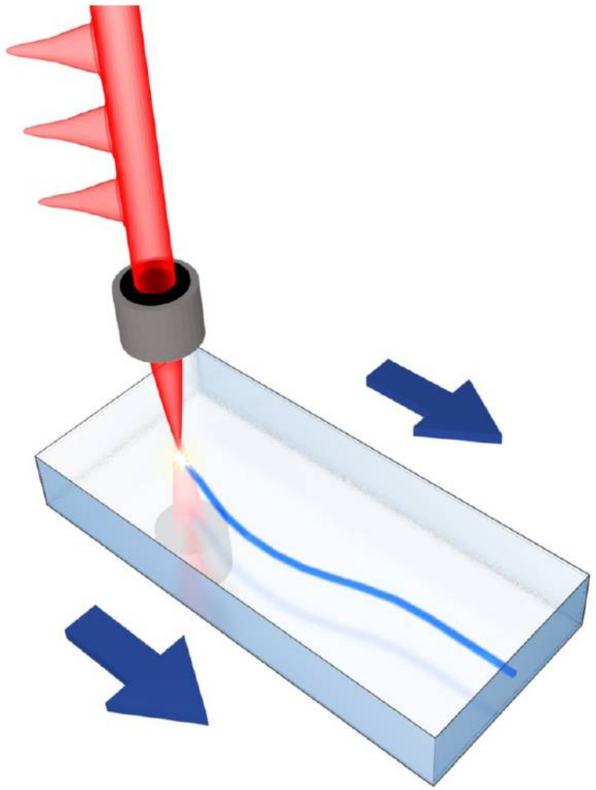


A. Politi et al. *Science* **320**, 646 (2008); J. C. F. Matthews et al. *Nature Photonics* **3**, 346 (2009)
A. Politi et al. *Science* **325**, 1221 (2009).

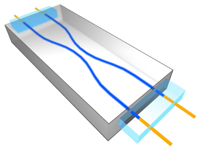
Femtosecond laser writing

What about polarization encoding?

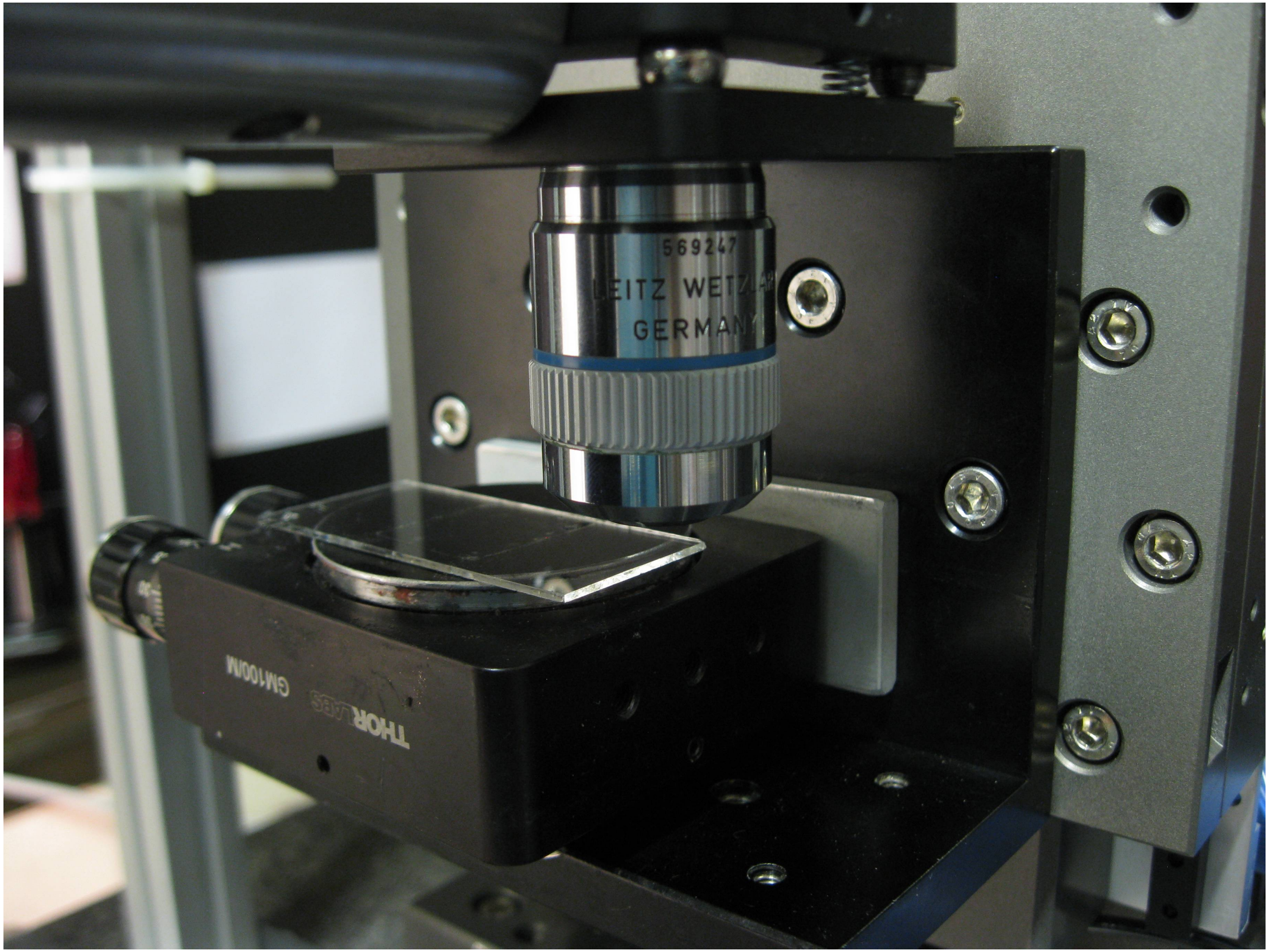
Laser writing technique for devices able to transmit polarization qubits



- 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



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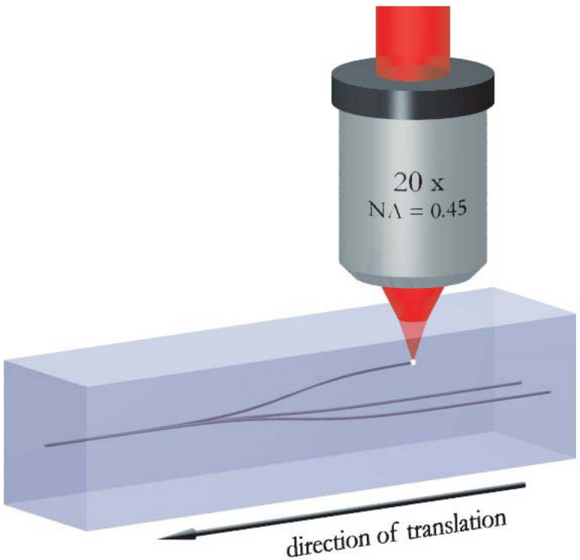
Femtosecond laser writing

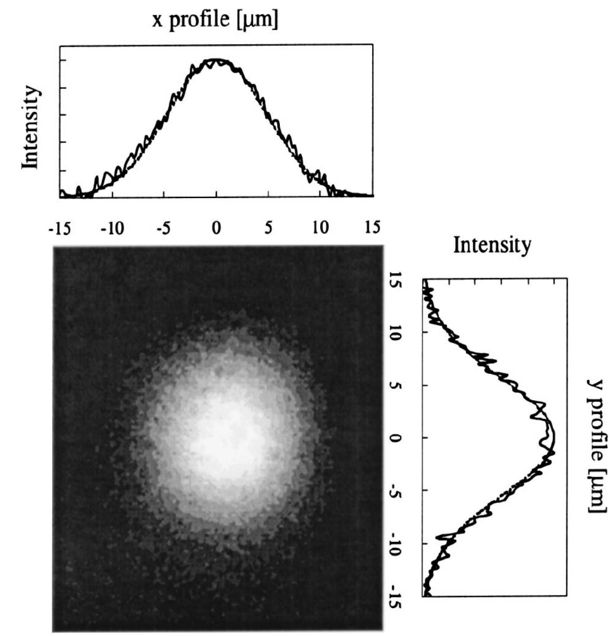
3-dimensional capabilities

Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

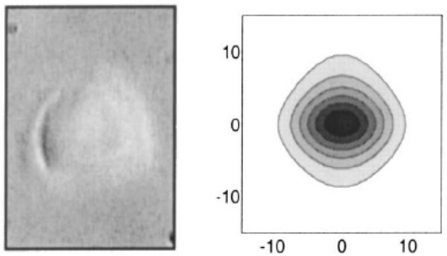


Characteristics:

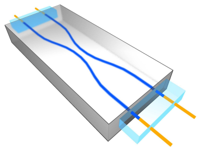


Circular waveguide transverse profile

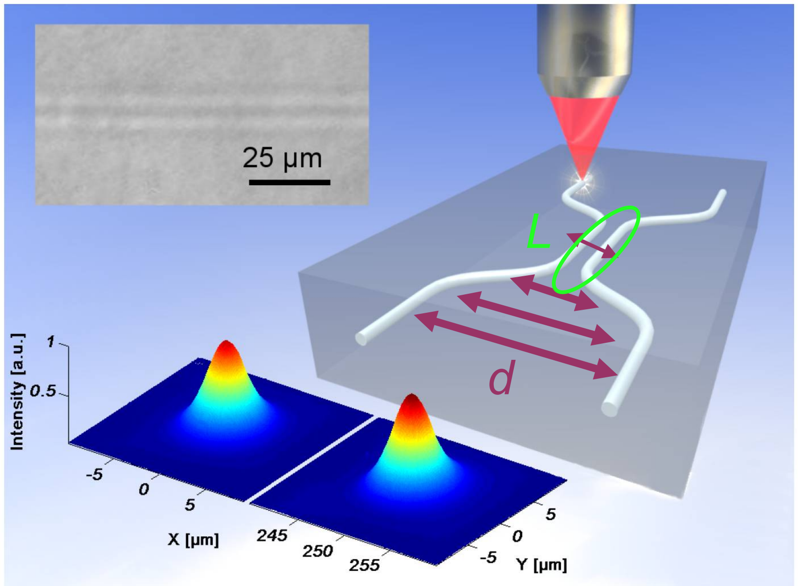
Low birefringence



SUITABLE TO SUPPORT ANY POLARIZATION STATE



Integrated beam splitter



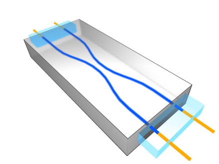
Substrate of borosilicate glass
(no birefringence observed)

Femtosecond infrared laser*:* λ*=1030nm*
Pulses: τ *=300fs,* 1W
Repetition rate 1 MHz

L: interaction region

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

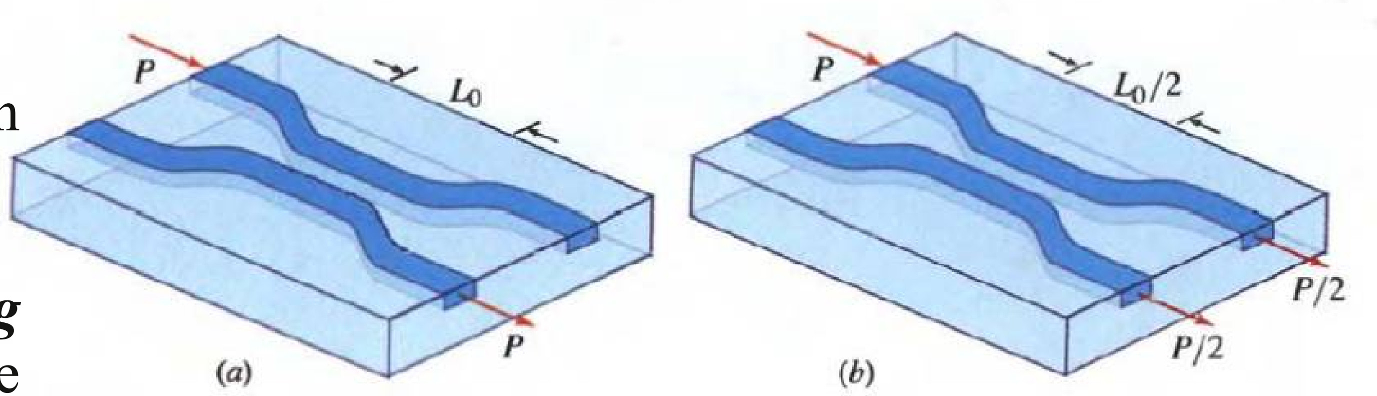
Propagation losses
~0.5dB/cm
Bending losses
<0.3dB/cm



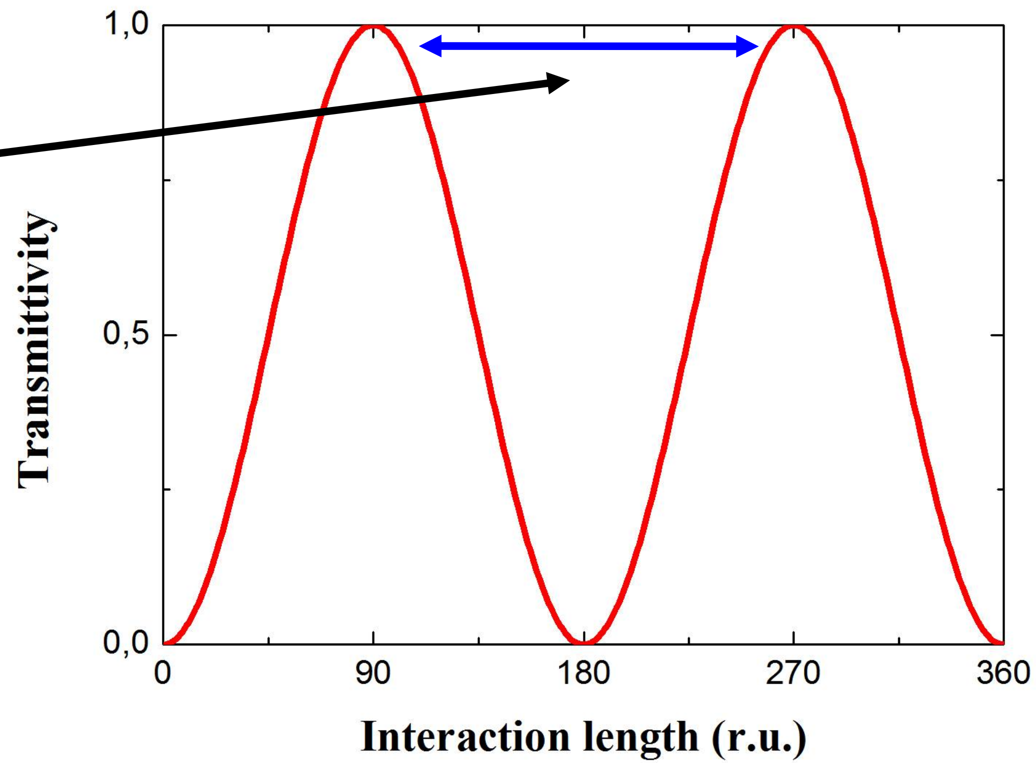
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

Tunability of the direction coupler transmission

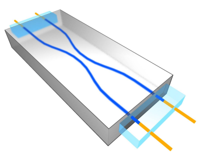
Optical power transfer follows a sinusoidal law with the interaction length.



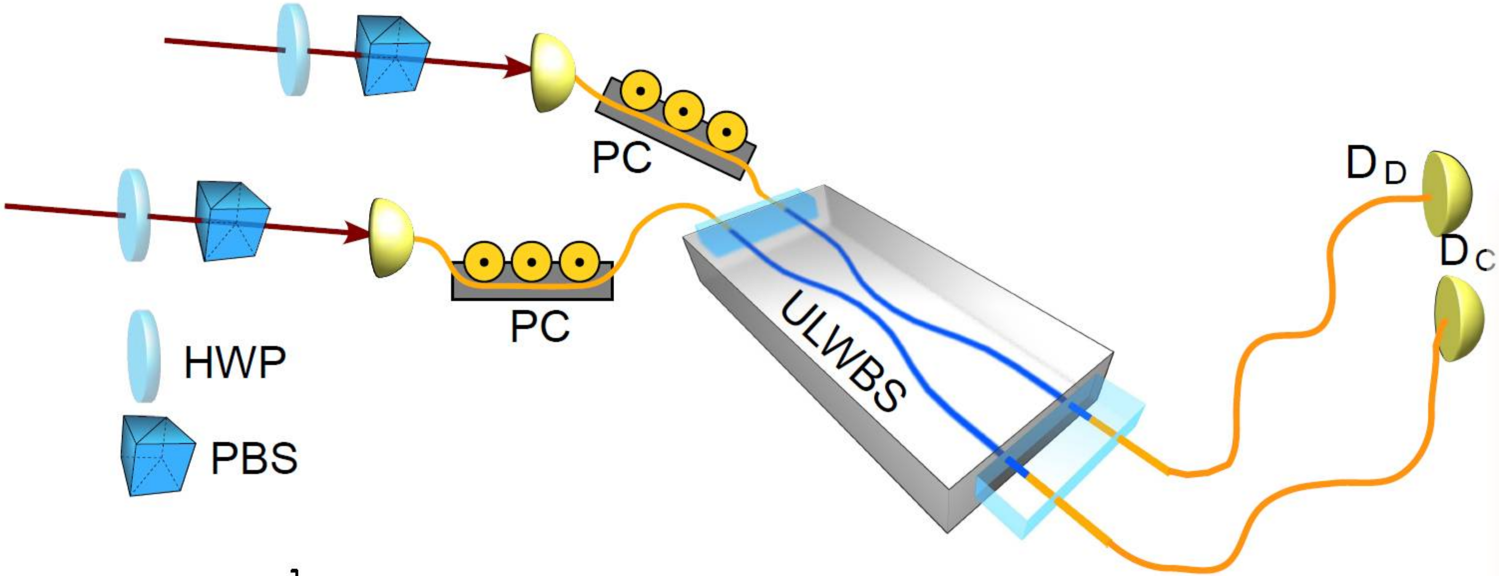
Oscillation period (***beating period***) depends upon the coupling coefficient of the two guided modes.



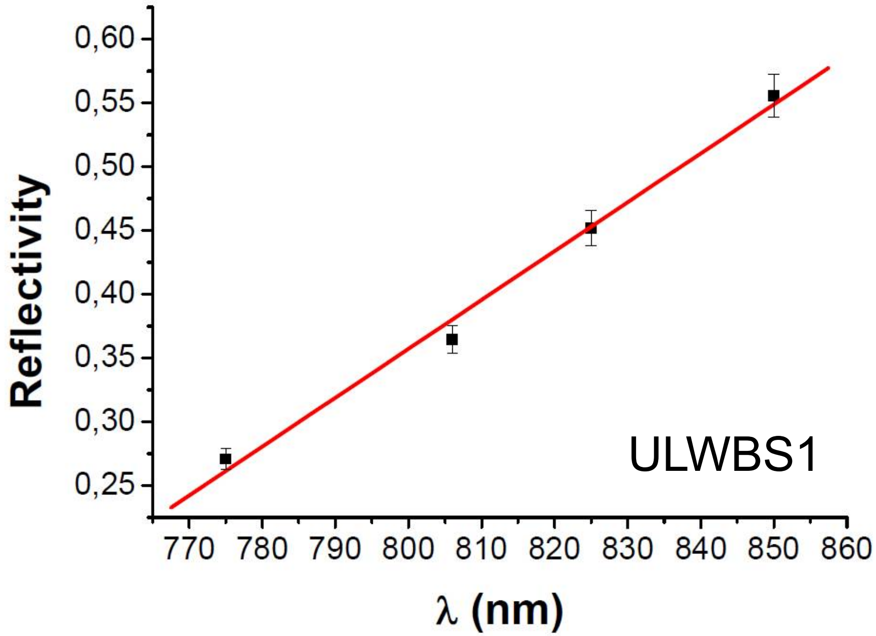
Periodicity of the transmission depends from the *Effective index of refraction*



Results: classical light

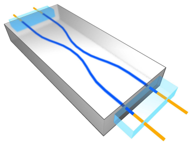


Polarization degree G>99.8%



$$R_H = 0.492 \pm 0.002$$

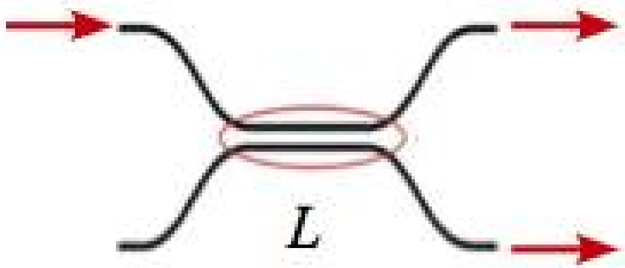
$$R_V = 0.581 \pm 0.002$$

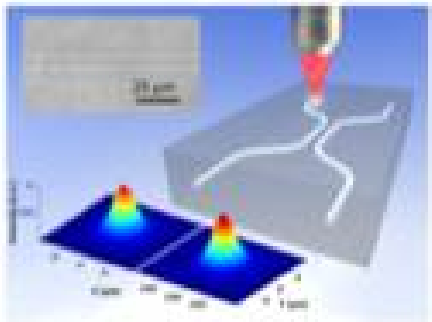


Directional coupler as beam splitter

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

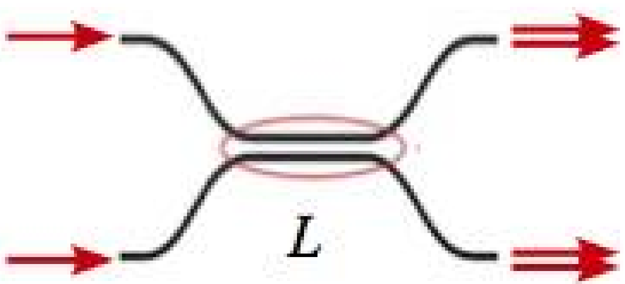
Single photons

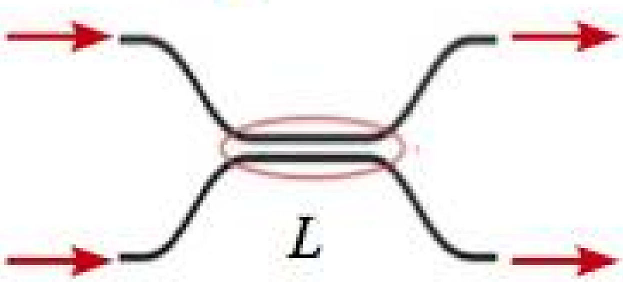




Two-photon states

Identical separable states





Symmetric states: Triplet

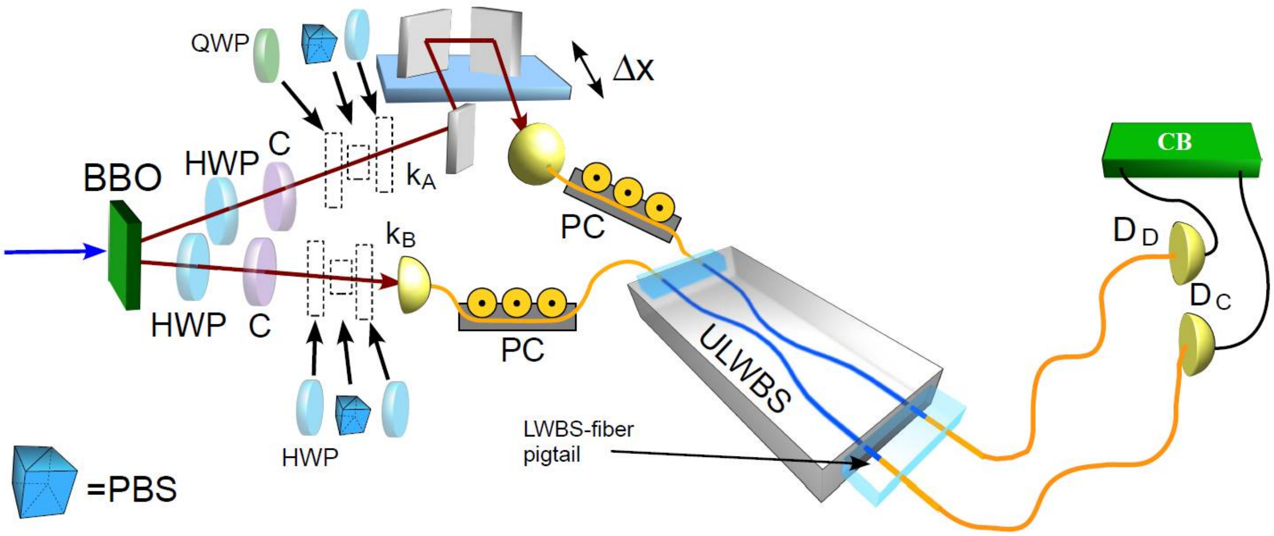
Antisymmetric state: Singlet

Entangled states

$|\Psi^-\rangle$

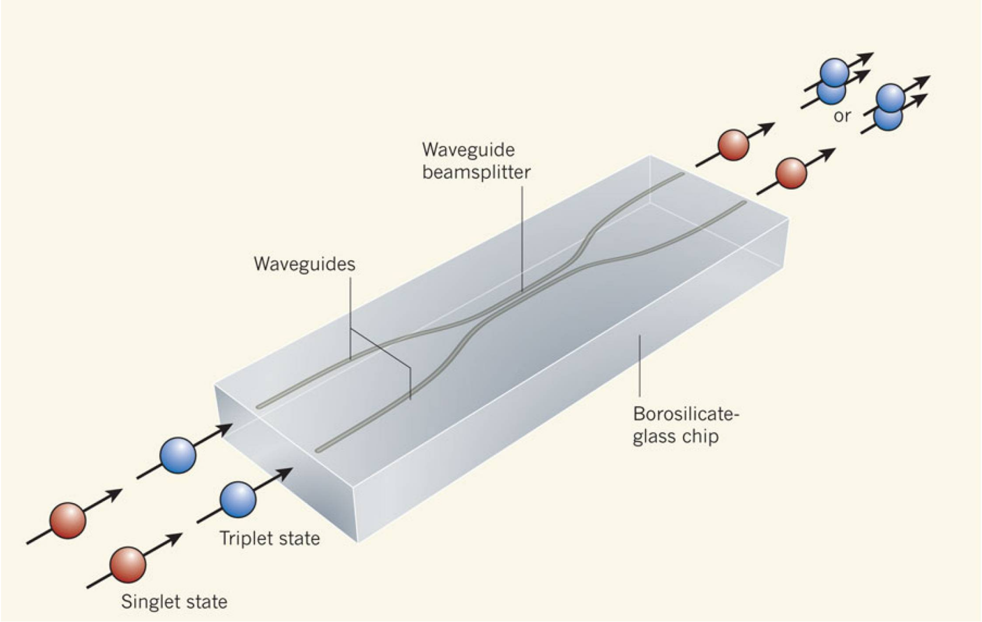
$\left\{|\Psi^+\rangle, |\Phi^-\rangle, |\Phi^+\rangle\right\}$

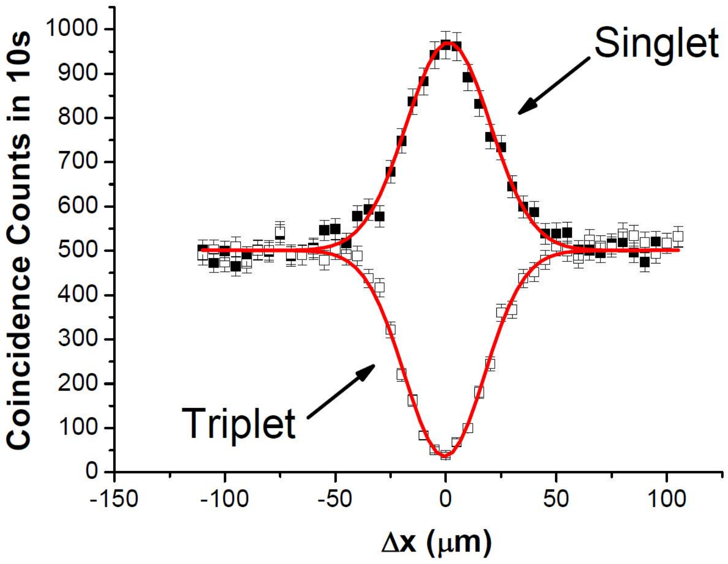
Polarization entanglement on a chip



$$V_{|\Psi-\rangle} = 0.930 \pm 0.005$$

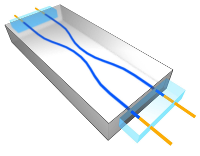
$$V_{|Tripl\rangle} = 0.928 \pm 0.007$$



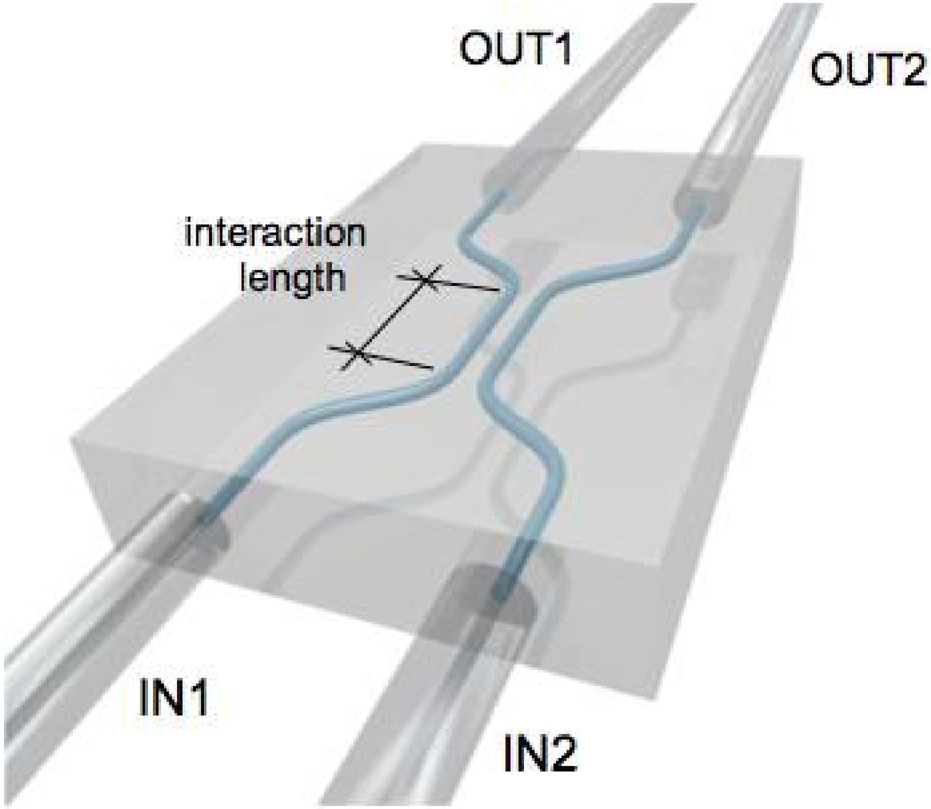


M. Lobino & J.L. O'Brien *News & Views* Nature (2011)

L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

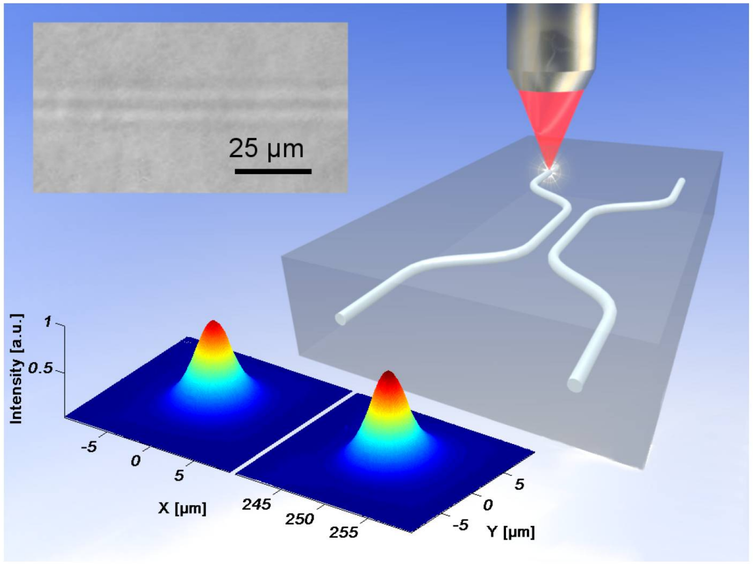


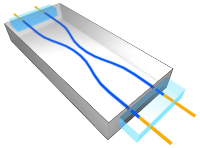
How can we realize polarization dependent devices ?



I) Transmission depends from the interaction length

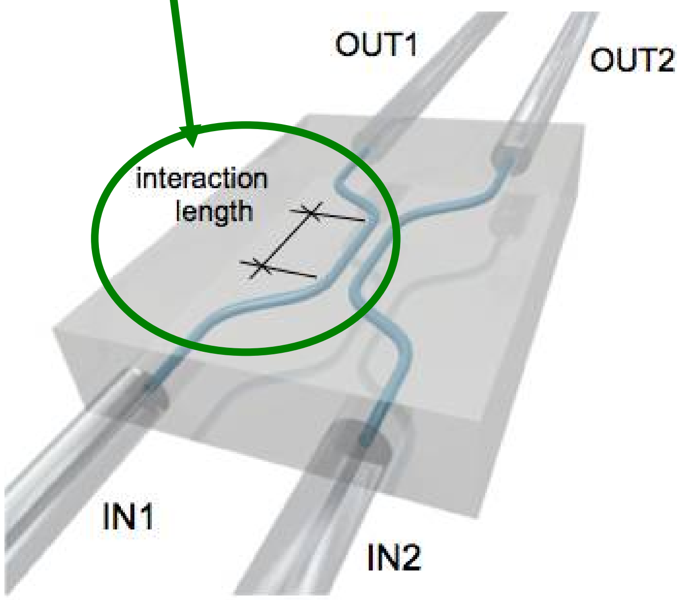
II) Small anisotropy behaviour due to residual asymmetry of the waveguide:
Different periodicities

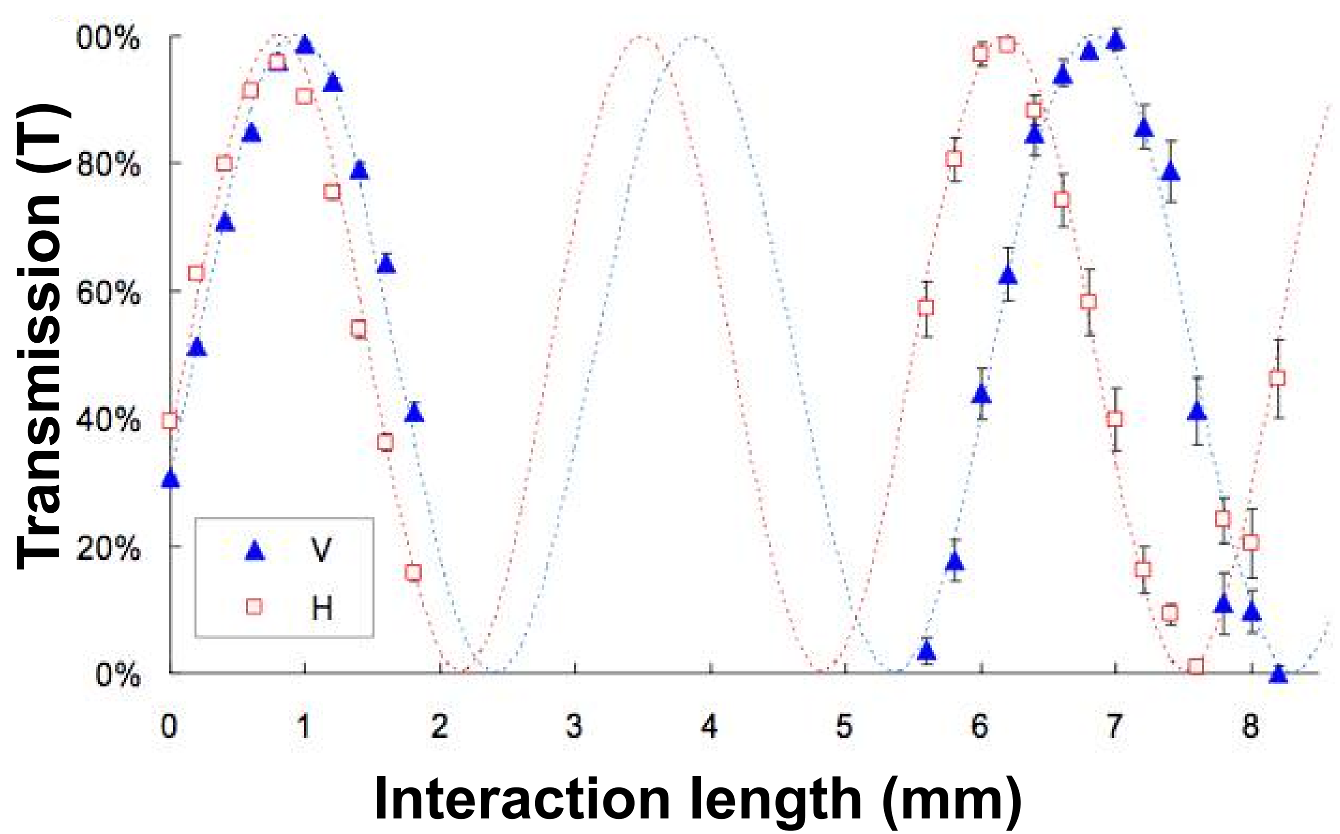




Partially Polarizing Directional Couplers (PPDC)

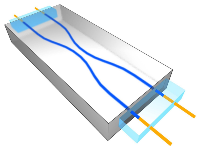
Interaction length



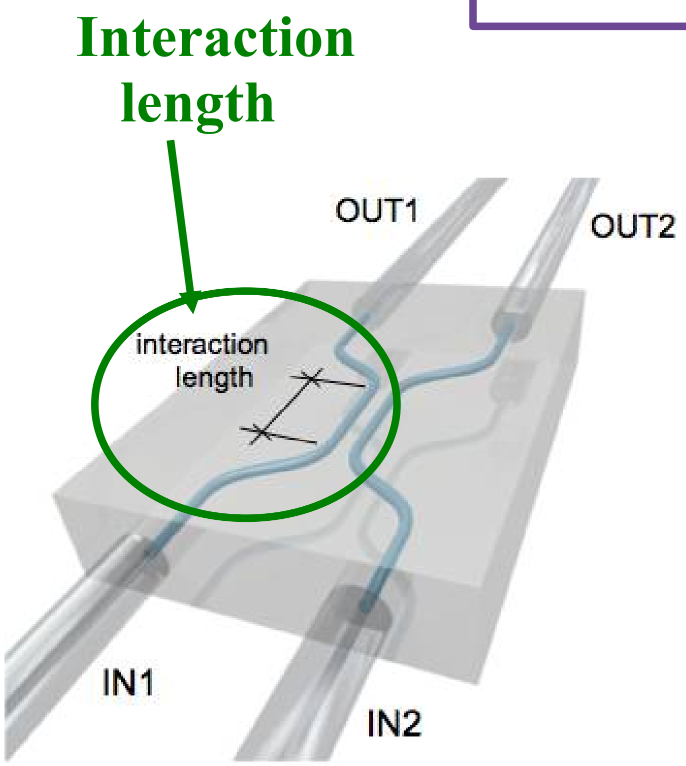


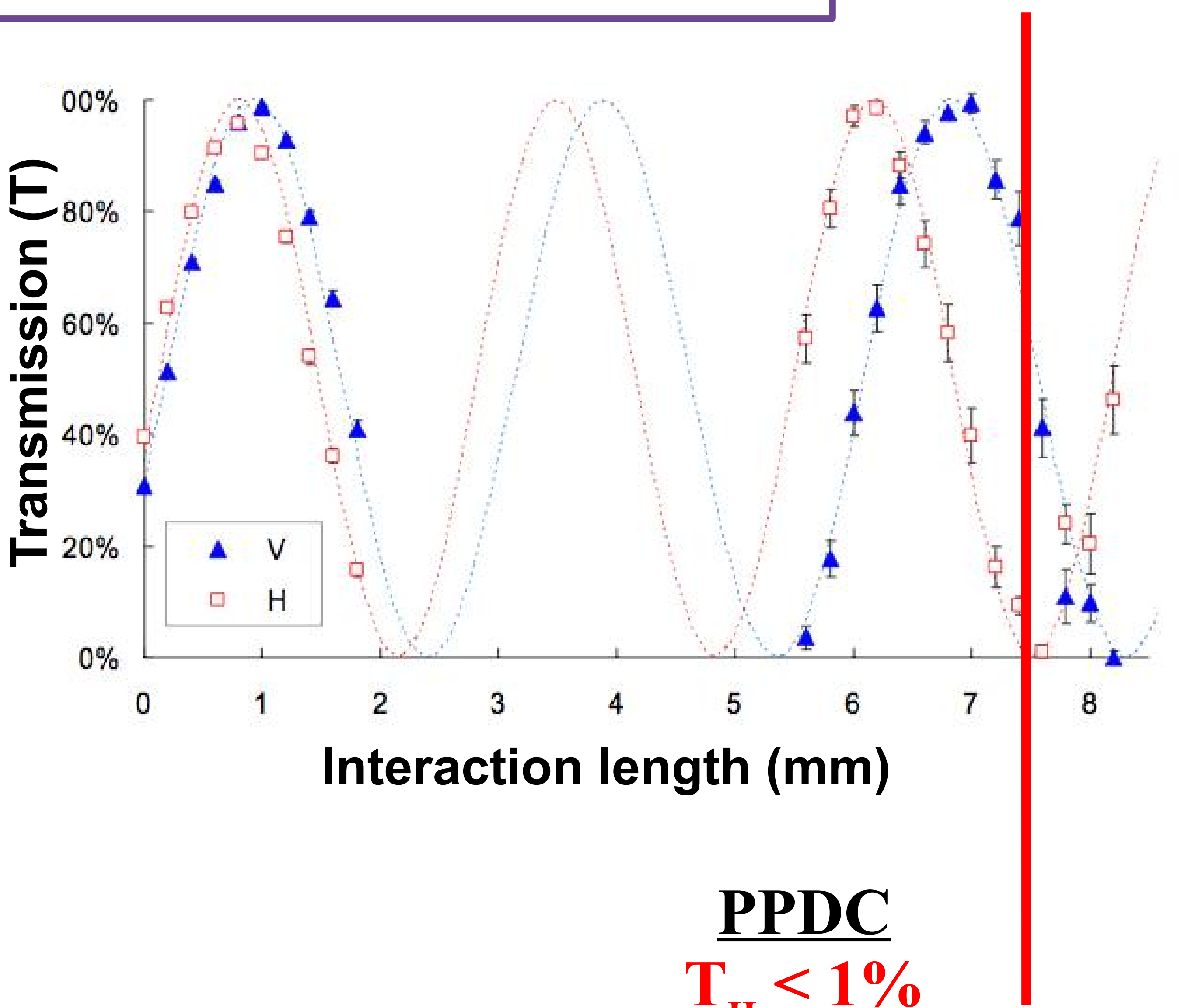
Interaction length → **Transmission for horizontal polarization (T_H)**

Transmission for vertical polarization (T_V)



Partially Polarizing Directional Couplers (PPDC)

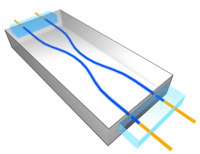




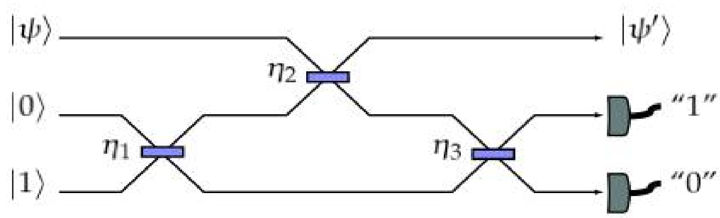
PPDC

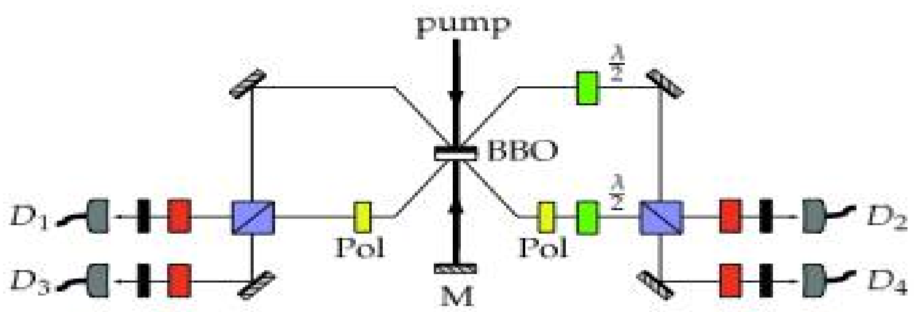
$T_H < 1\%$

$T_V = 64\%$



Linear optical quantum computing



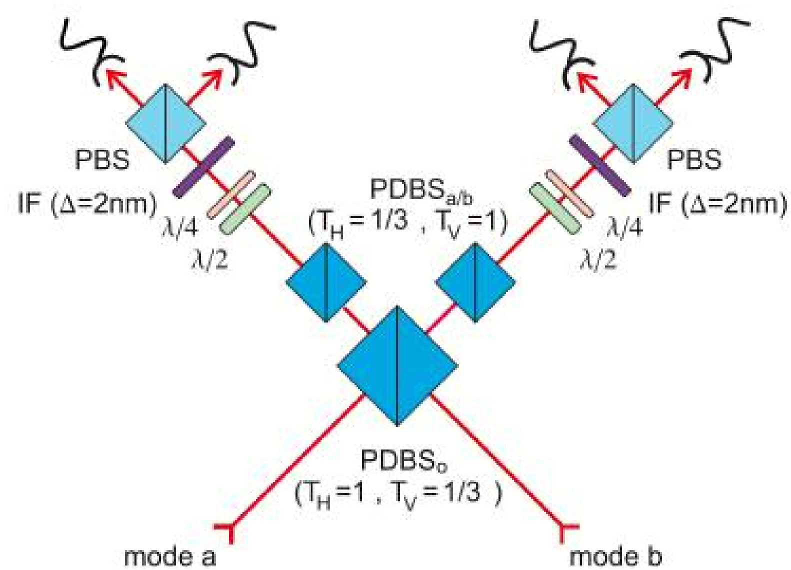


Knill et al., *Nature* **409**, 46 (2001).
Kok et al. *Rev. Mod. Phys.* **79**, 135 (2007)

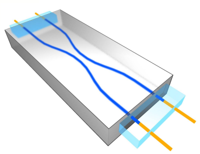
CNOT gate for polarization qubit

$$\{|0\rangle_C, |1\rangle_C\} \equiv \{|H\rangle, |V\rangle\}$$
$$\{|0\rangle_T, |1\rangle_T\} \equiv \{|D\rangle, |A\rangle\}$$

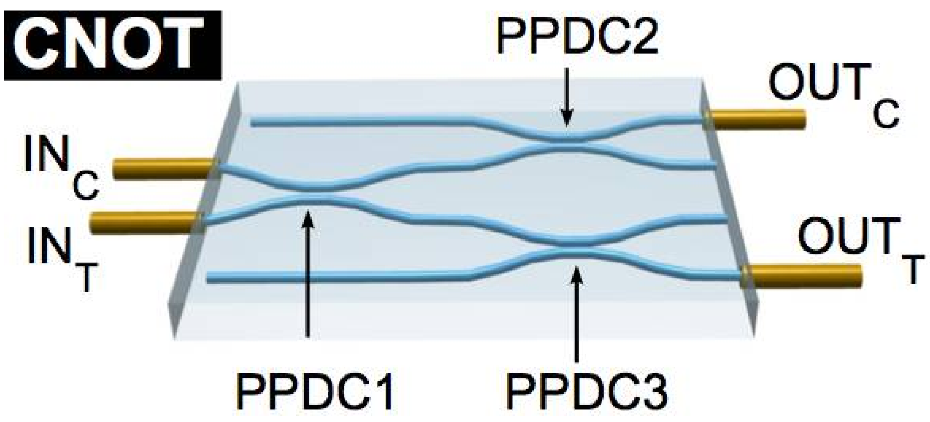
- partial polarizing beam splitters
- post-selection
- success probability (p=1/9)

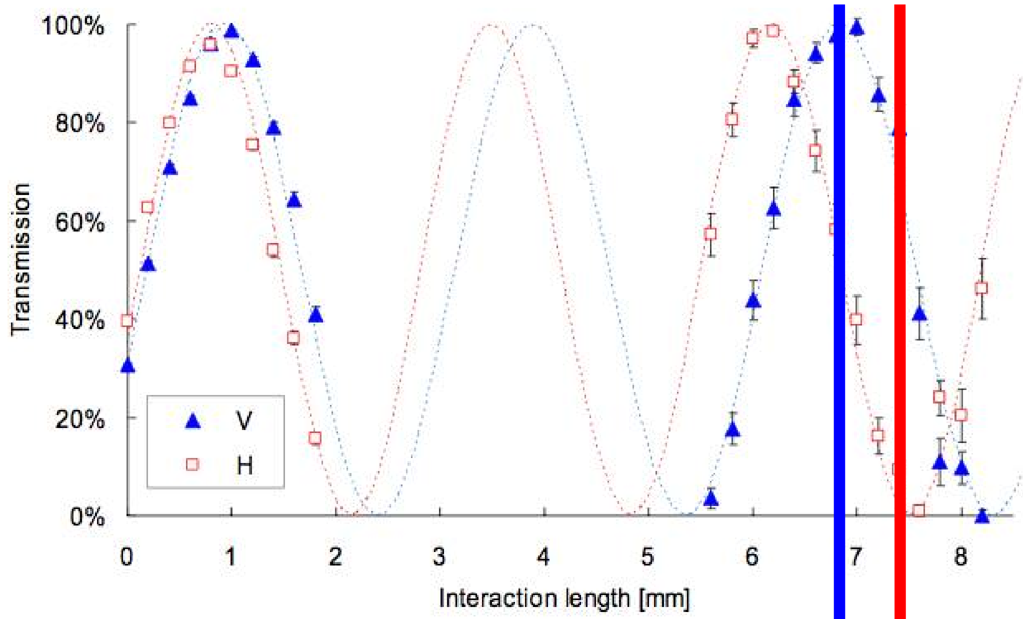


Kiesel, et al, *Phys. Rev. Lett.* **95**, 210505 (2005).
Okamoto, et al, *Phys. Rev. Lett.* **95**, 210506 (2005).
Langford, et al, *Phys. Rev. Lett.* **95**, 210504 (2005).



CNOT gate for polarization qubit





PPDC1

$T_H = 0$

$T_V = 2/3$

PPDC2 - PPDC3

$T_H = 1/3$

$T_V = 1$

PPDC2 - PPDC3

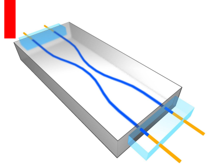
$T_H = 43\%, 27\%$

$T_V = 98\%, 93\%$

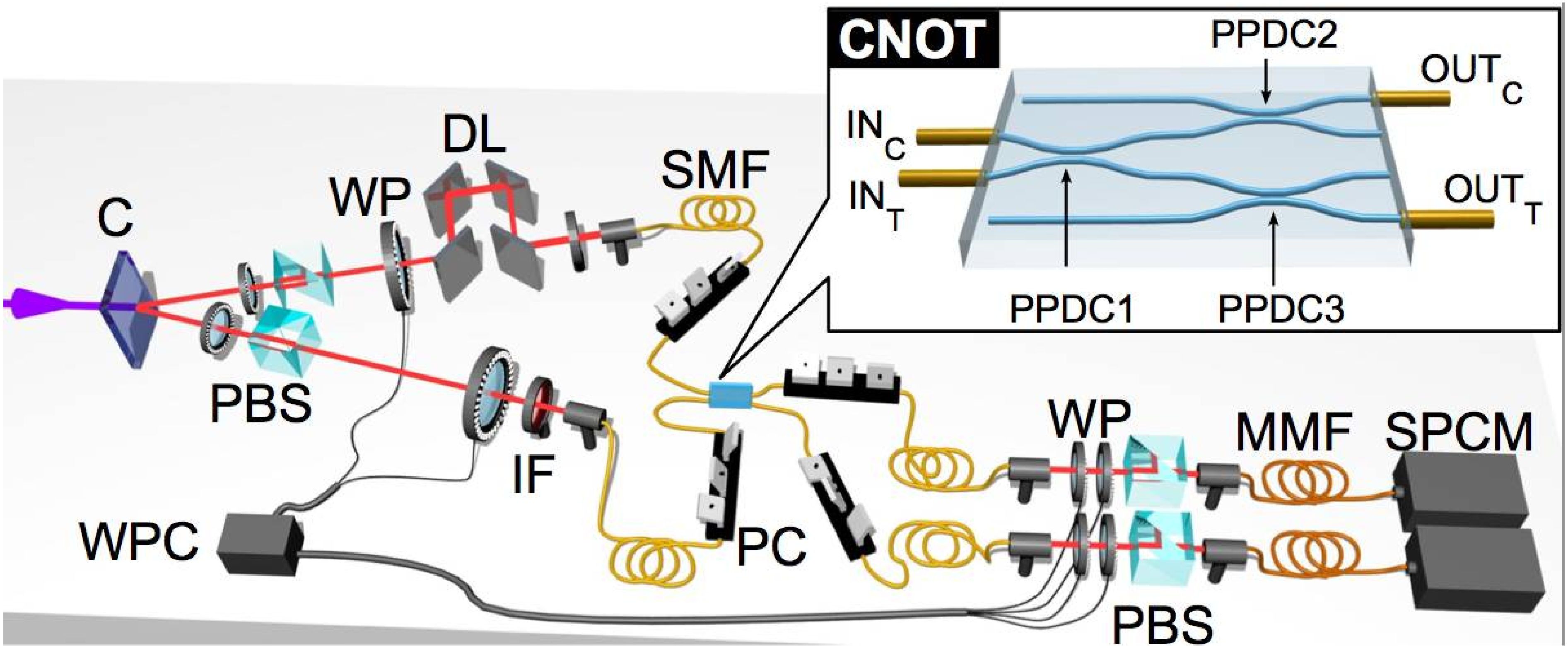
PPDC1

$T_H < 1\%$

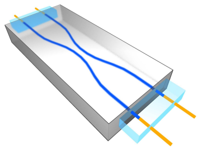
$T_V = 64\%$



CNOT gate for polarization qubit



Polarization: degree of freedom of light suitable for interface with other systems



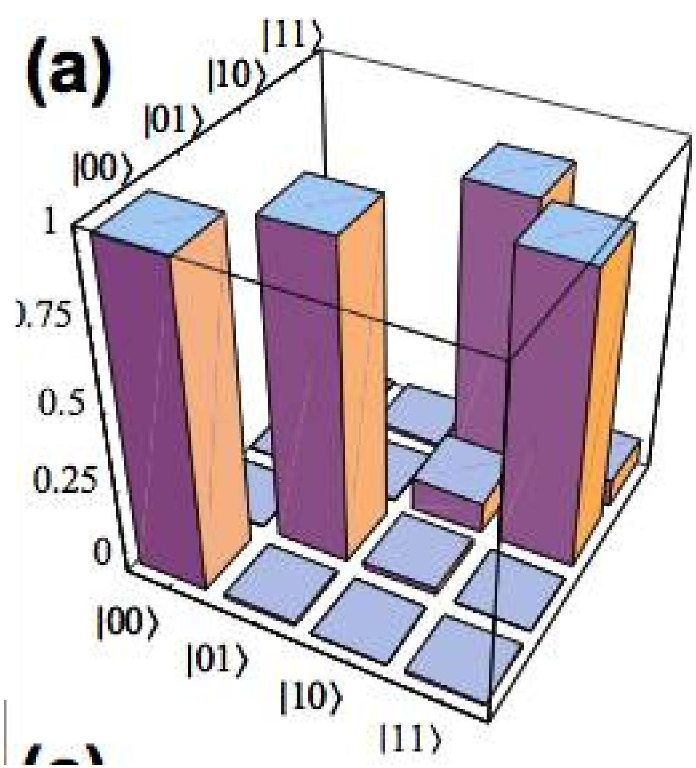
Truth table of the CNOT

Two-qubit gate

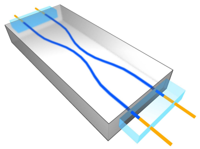
C_{in}	T_{in}	C_{out}	T_{out}
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

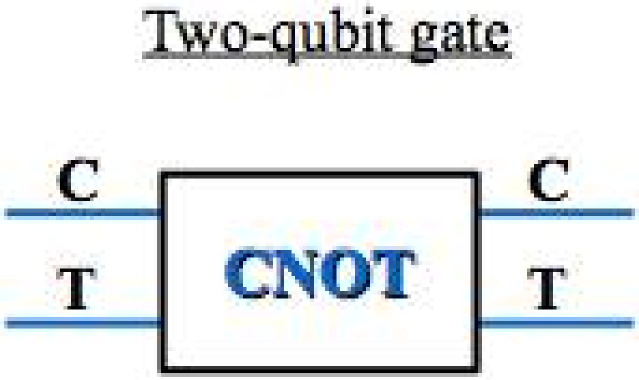
Experimental data:



$$F_{measured} = 0.940 \pm 0.004.$$



Generation and discrimination of entangled states



CNOT gate transforms entangled state into separable one and viceversa

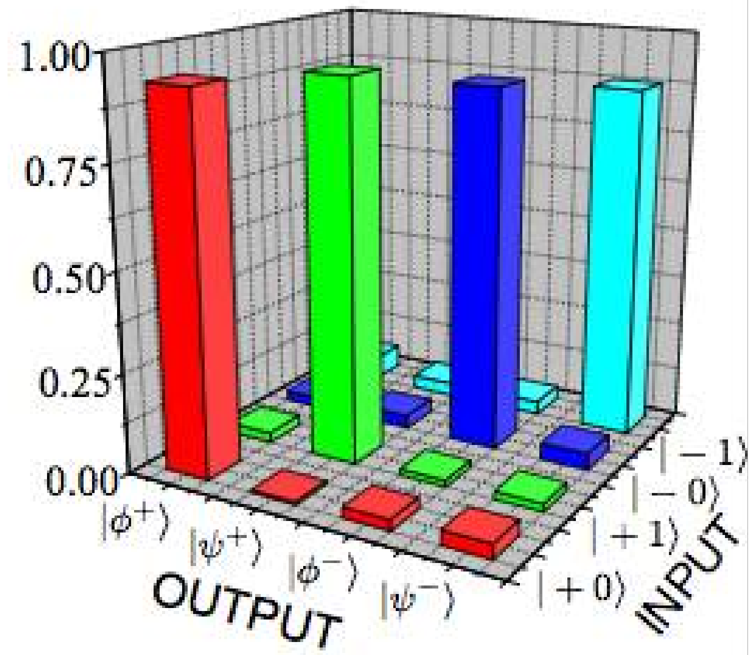
$$|+\rangle_C|0\rangle_T \rightleftharpoons |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_T + |1\rangle_C|1\rangle_T)$$

$$|+\rangle_C|1\rangle_T \rightleftharpoons |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|1\rangle_T + |1\rangle_C|0\rangle_T)$$

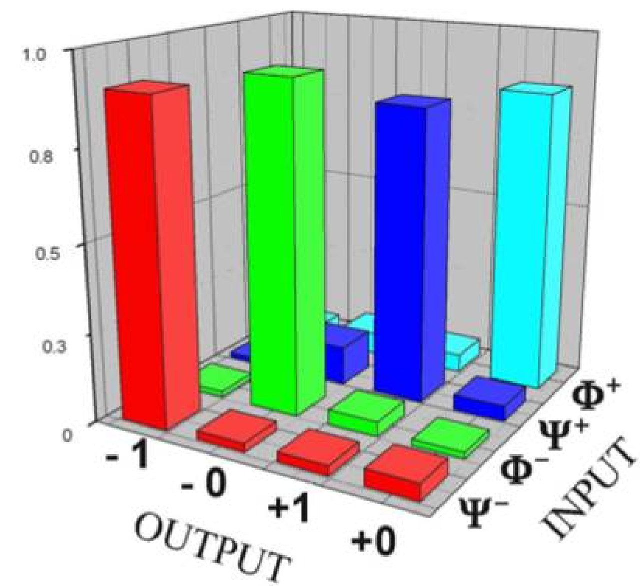
$$|-\rangle_C|0\rangle_T \rightleftharpoons |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|1\rangle_T - |1\rangle_C|0\rangle_T)$$

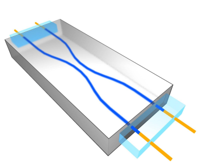
$$|-\rangle_C|1\rangle_T \rightleftharpoons |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_T - |1\rangle_C|1\rangle_T)$$

A. Crespi, *et al.*, quant-ph 1105.1454

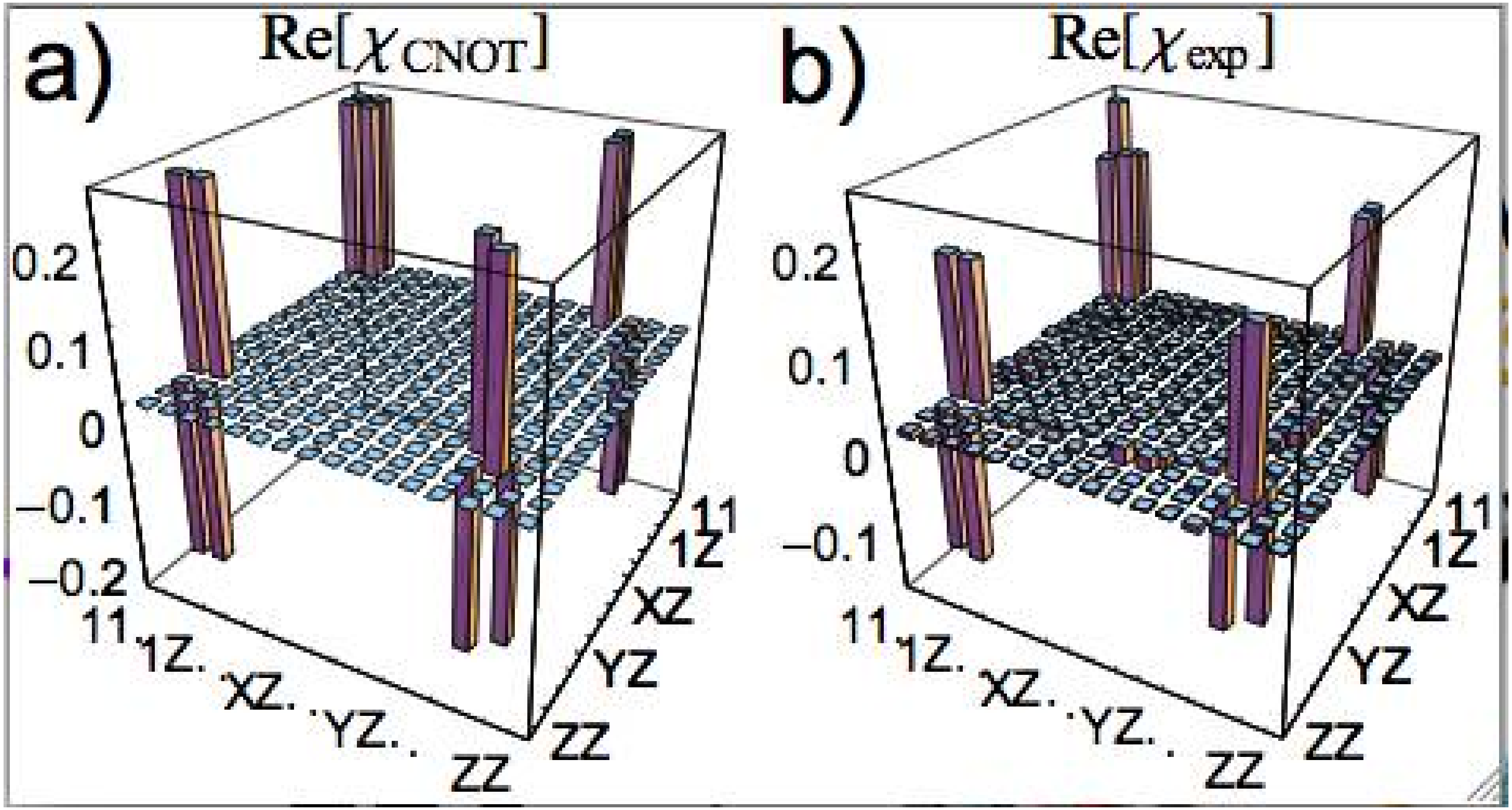


F = 0.912 ± 0.004





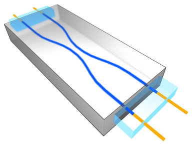
Quantum process tomography of the CNOT gate



$$F_{\text{measured}} = 0.906 \pm 0.003$$

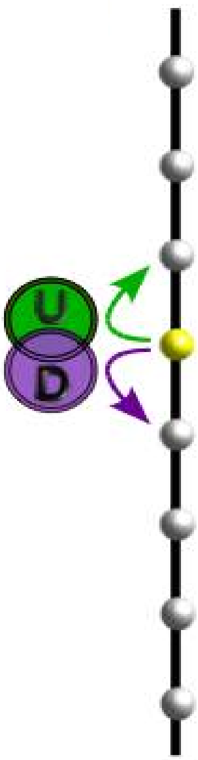
partial distinguishability of the two photons

$$F_{\text{estimated}} = 0.943 \pm 0.006$$



First applications: Quantum walk

Quantum walk: extension of the classical random walk:
a walker on a lattice “jumping” between different sites with given probability



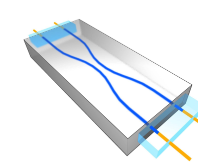
In discrete quantum walk one or more quantum particles evolve on a graph, with their evolution governed by their internal quantum coin (QC) states

The walker in the position j is described by the quantum state |j>.

The particle shifts up or down depending on the internal QC state |U> or |D>

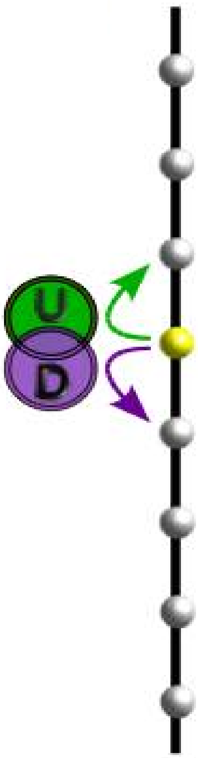
Evolution of the walk described by the following step operator

$$E = \sum_j |j-1\rangle\langle j| \otimes |U\rangle\langle U| + |j+1\rangle\langle j| \otimes |D\rangle\langle D|$$



Single particle: Quantum Walk

Differences between classical and quantum: interference



classic

position

$N \backslash i$	-5	-4	-3	-2	-1	0	1	2	3	4	5
0						1					
1					$\frac{1}{2}$		$\frac{1}{2}$				
2				$\frac{1}{4}$		$\frac{1}{2}$		$\frac{1}{4}$			
3			$\frac{1}{8}$		$\frac{3}{8}$		$\frac{3}{8}$		$\frac{1}{8}$		

\# of steps

sum of probabilities
for each path

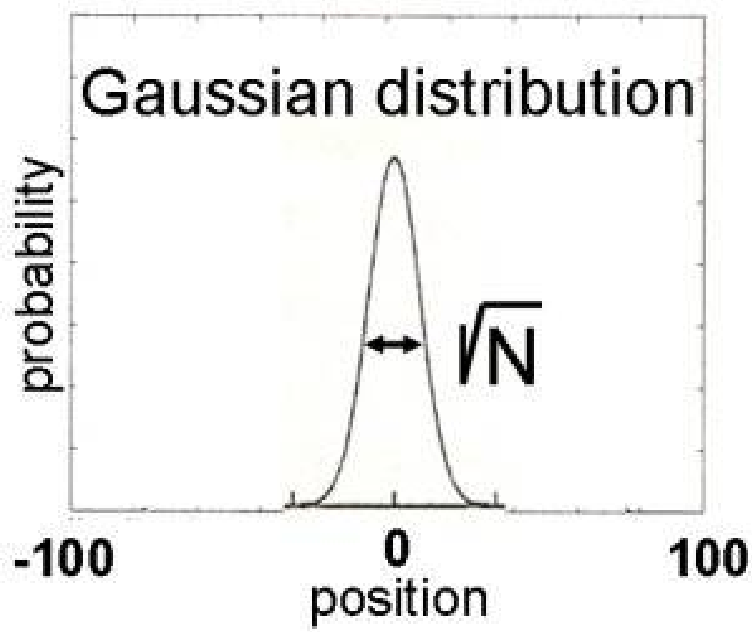
QM

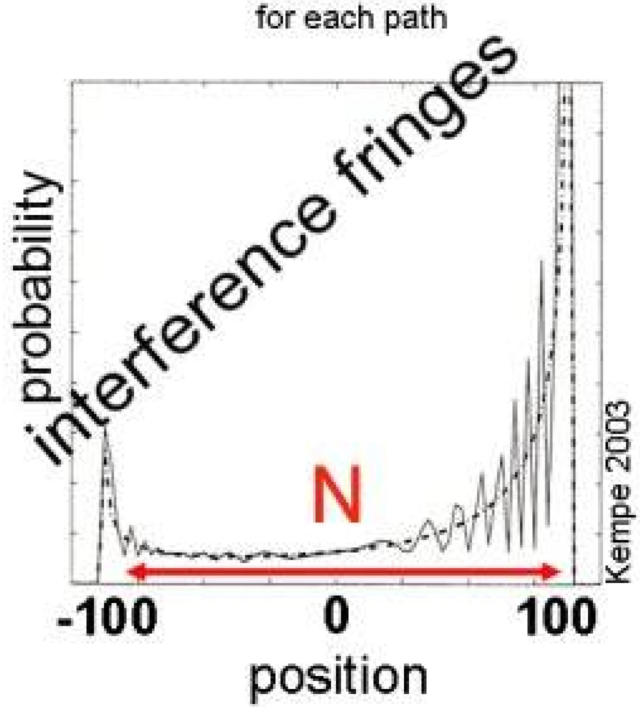
position

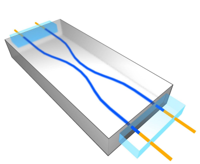
$T \backslash i$	-5	-4	-3	-2	-1	0	1	2	3	4	5
0						1					
1					$\frac{1}{2}$		$\frac{1}{2}$				
2				$\frac{1}{4}$		$\frac{1}{2}$		$\frac{1}{4}$			
3			$\frac{1}{8}$		$\frac{1}{8}$		$\frac{5}{8}$		$\frac{1}{8}$		

\# of steps

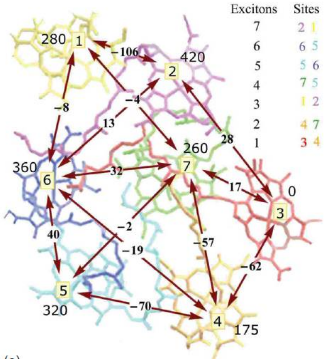
coherent sum of probability amplitudes
for each path





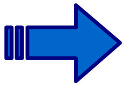


Why Quantum Walk ?

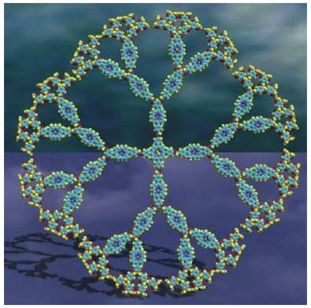


Energy transfer: within photosynthetic systems can display quantum effects such as delocalized excitonic transport which can be simulated by QW.

Controlled transition from Classical to Quantum:
QW can be employed for testing the transition from the quantum to the classical world by applying a controlled degree of decoherence.

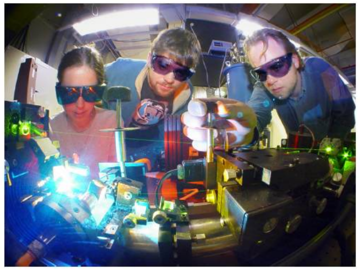


QW?



Light-harvesting molecule is efficient at concentrating light at its center as quantum walk reaches the target vertex exponentially faster than a classical walk: because of destructive interference between the paths that point backward, toward the leaves.

Faster quantum Computation:
It has been theoretically proven that QWs allow the speed-up of search algorithms

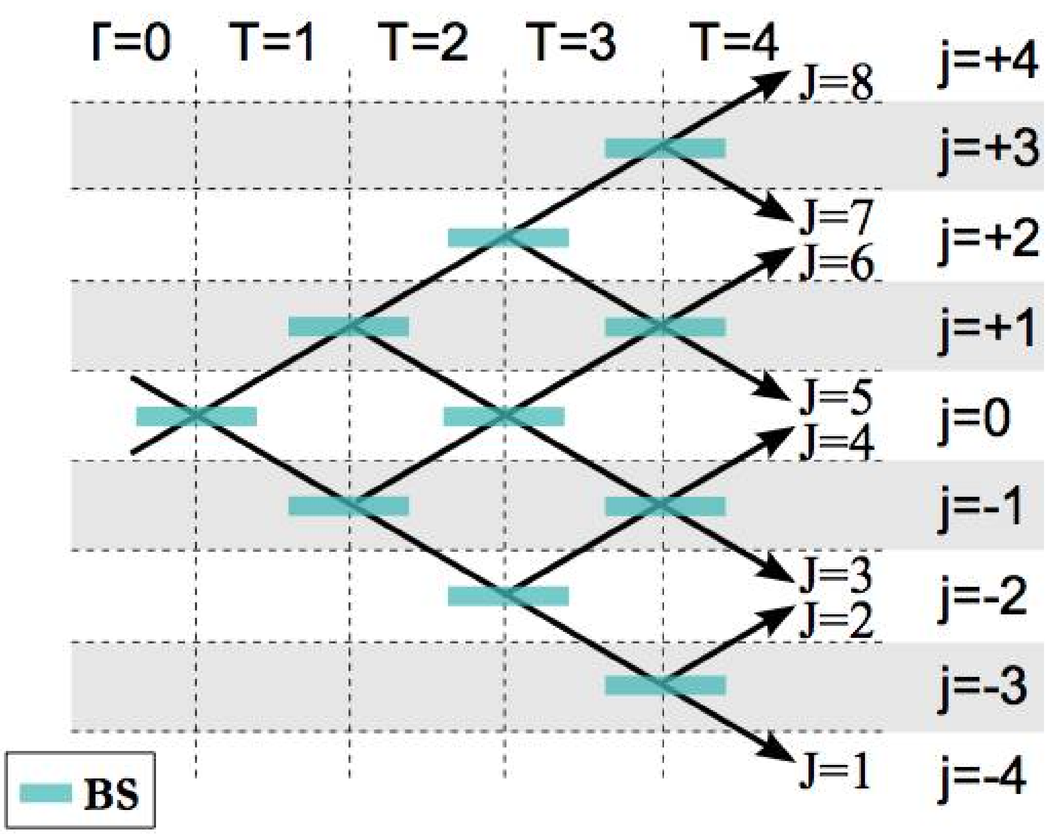


Photonic implementation of quantum walks

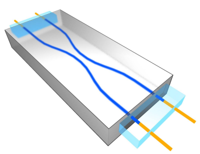
The simulation of quantum walks on a line can be implemented using single photon states, beam splitters, phase shifters, and photodetectors.

I) Each vertical line of beam splitters representing a step of the quantum walk.

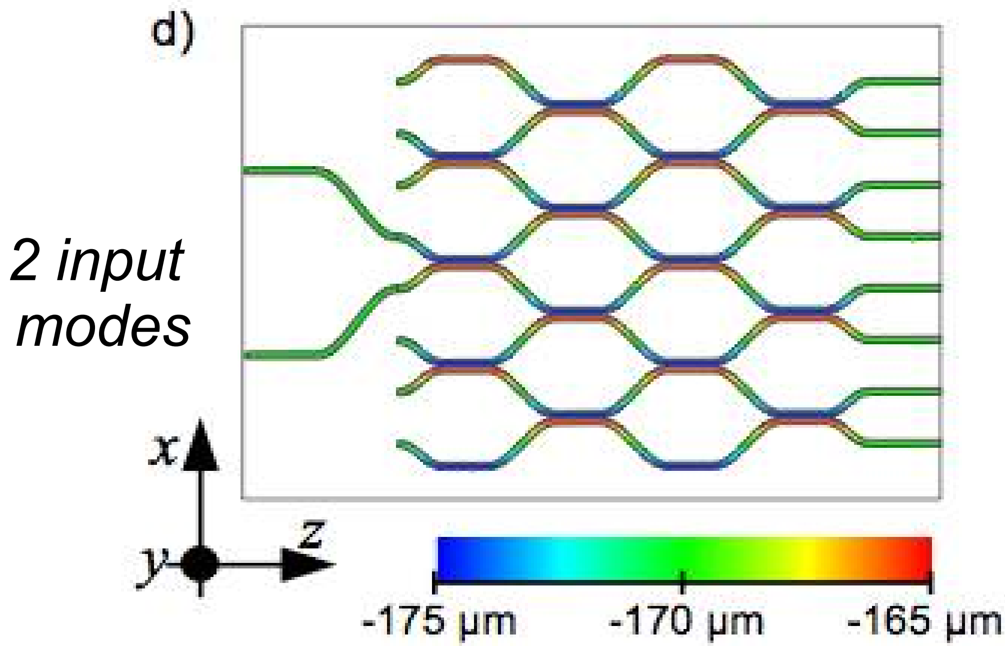
II) Horizontal strips represent the position |j> of the walker.



The walker position j is related to the ouptut odes J of the array



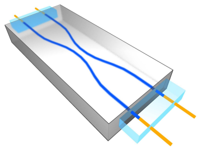
Beamsplitter arrays via 3D chip



- 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 betwen the two arms set equal to 0

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

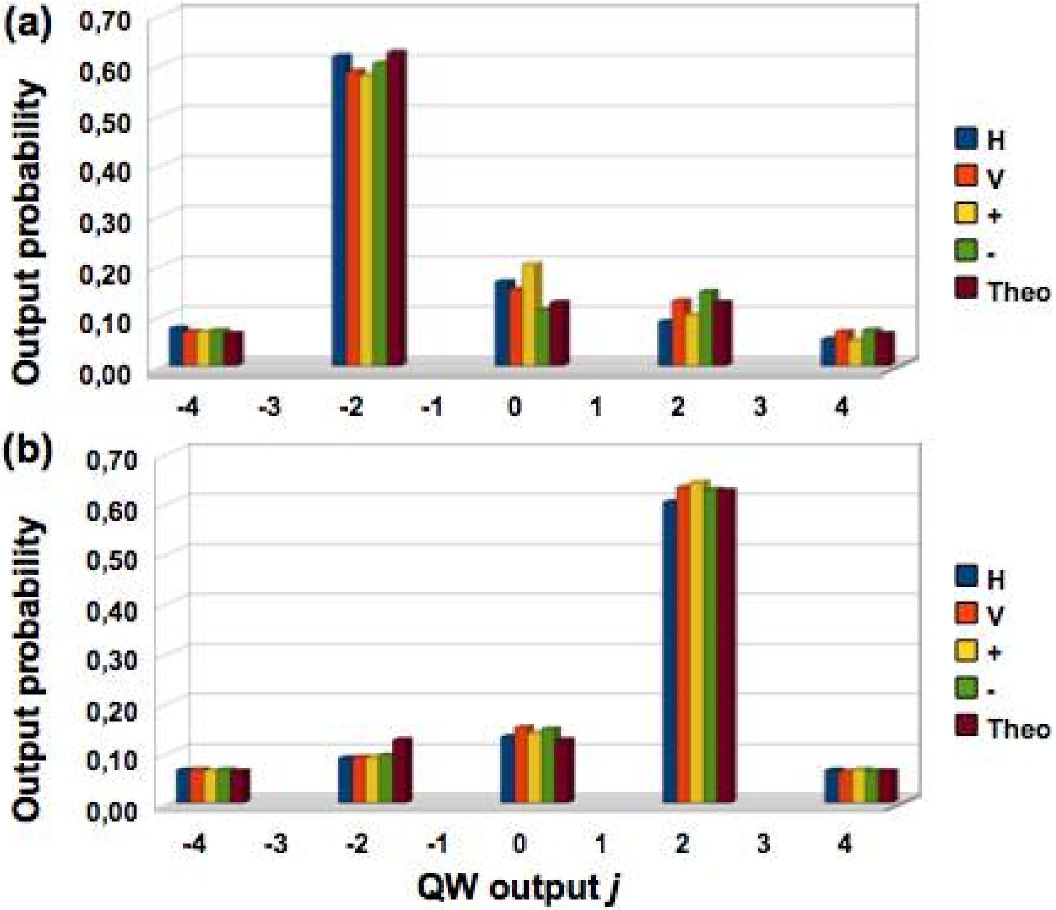


L. Sansoni, *et al.*, quant-ph 1106.5713

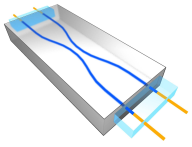
Single-particle quantum walk

We inject a single photon
in the BS array

We observe the same quantum walk
independently of the polarization state



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



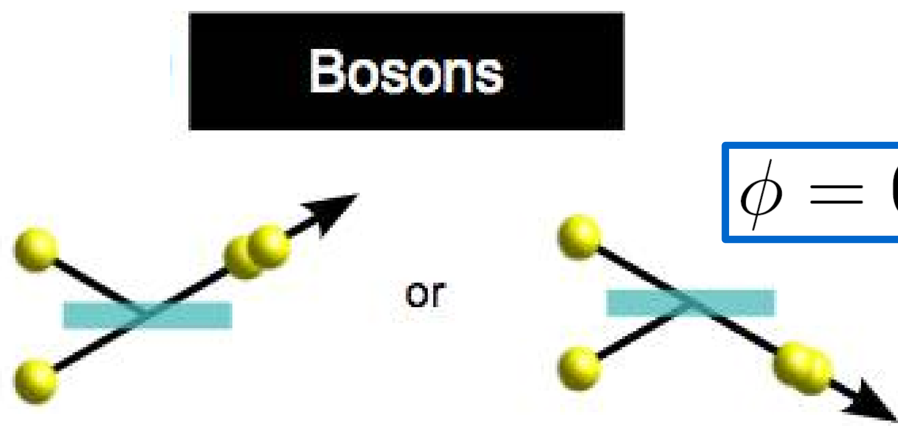
Quantum walk with two particles..

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

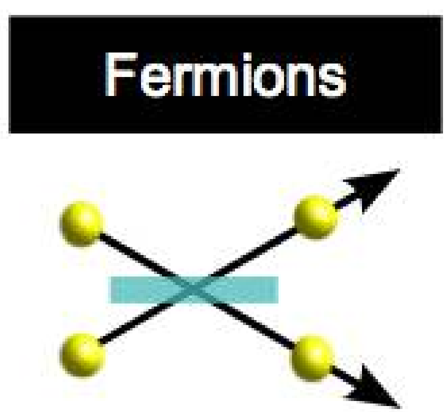
***GOAL**: to exploit the polarization degree of freedom in order to inject different entangled states of two photons*

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

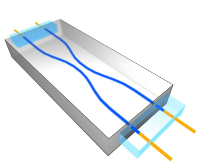
$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$



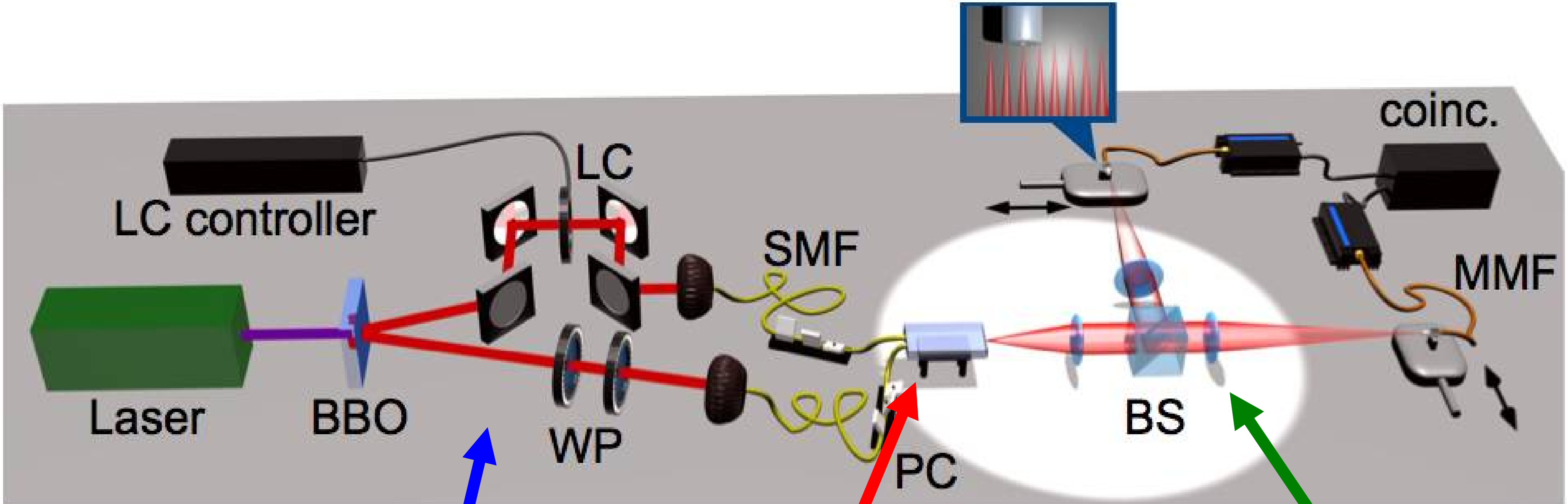
$\phi = 0$



$\phi = \pi$



Two-particles quantum walk: experimental setup



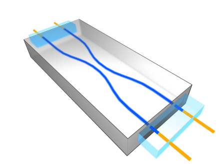
BS array on a chip

Eight output modes:

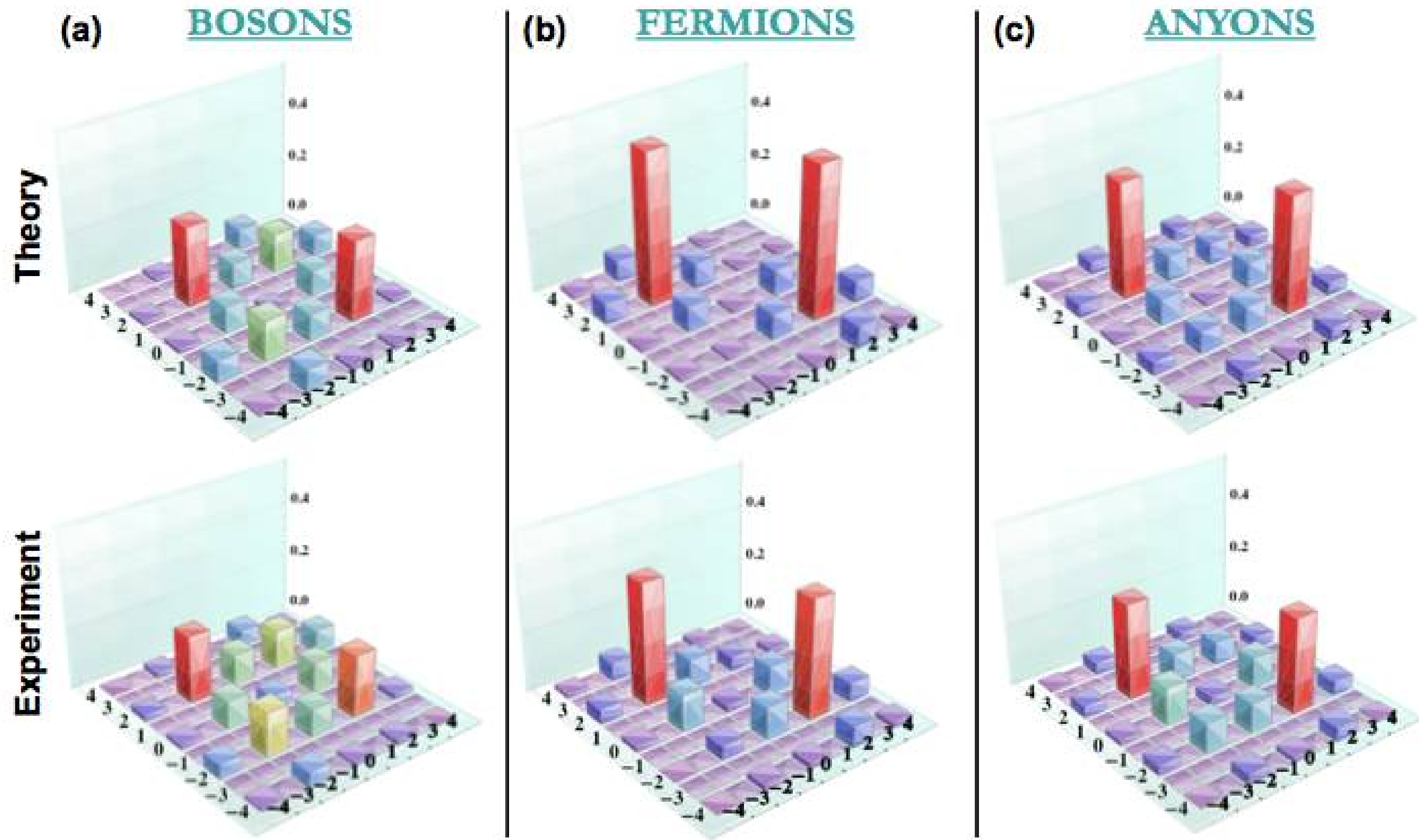
Measurement of coincidences between modes i and j

Generation of two-photon entangled states with different symmetries

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

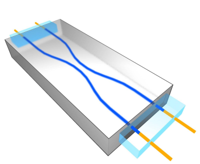


Two-particles quantum walk: results



Similarities between theory and experiment

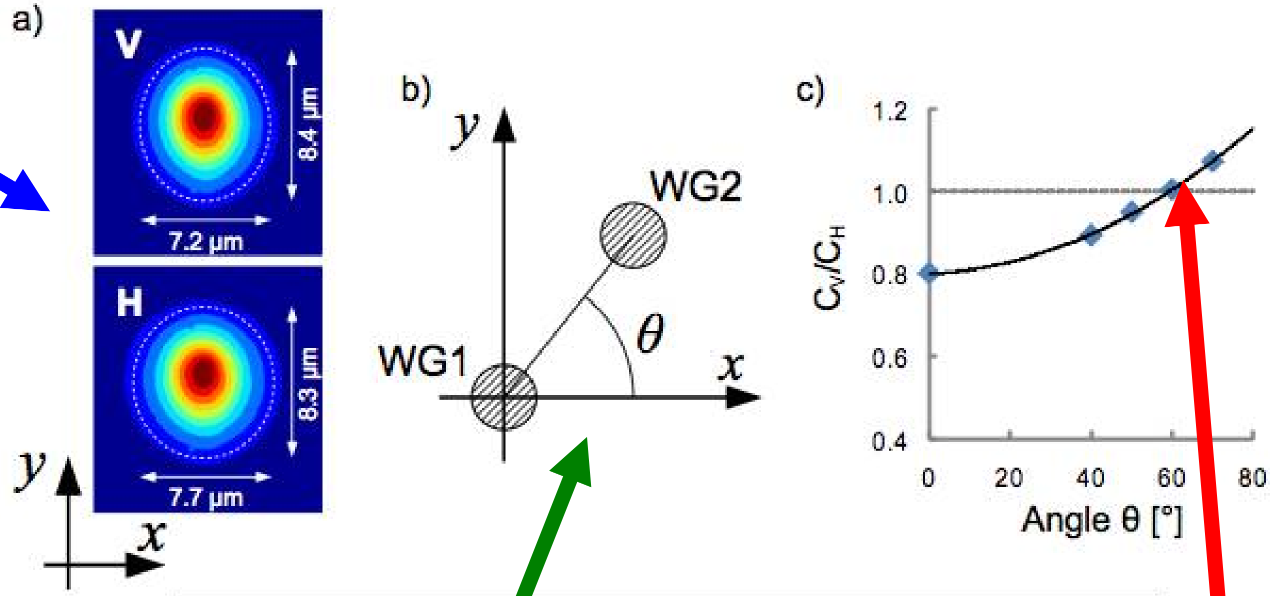
S = 0.982 ± 0.002 **S = 0.973 ± 0.002** **S = 0.987 ± 0.002**



L. Sansoni, *et al.*, quant-ph 1106.5713

Improving the on-chip devices: 3D architecture

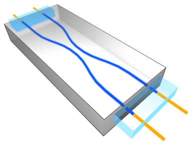
- Previous results: $R_H = 0.49$, $R_V = 0.58$
  along the y axis the V polarized mode slightly greater than the H polarized one



- Tight control on the reflectivities for the two polarizations:
  3 D architecture:
  Depending on the angle of the geometry, different coupling for the polarization H and V

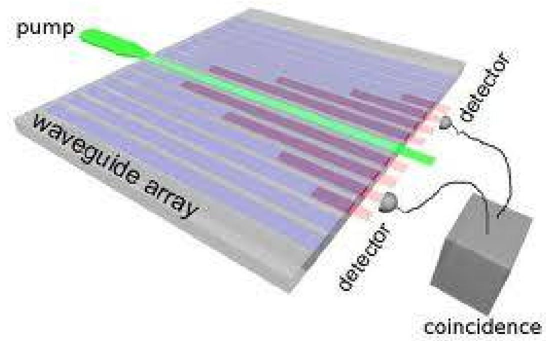
$R_H = R_V$

- **High-balancement between the different polarizations**



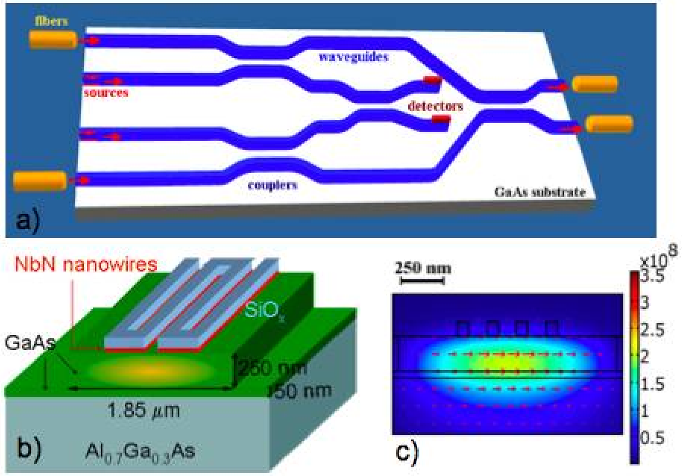
Perspectives.....

- Integrate quantum sources



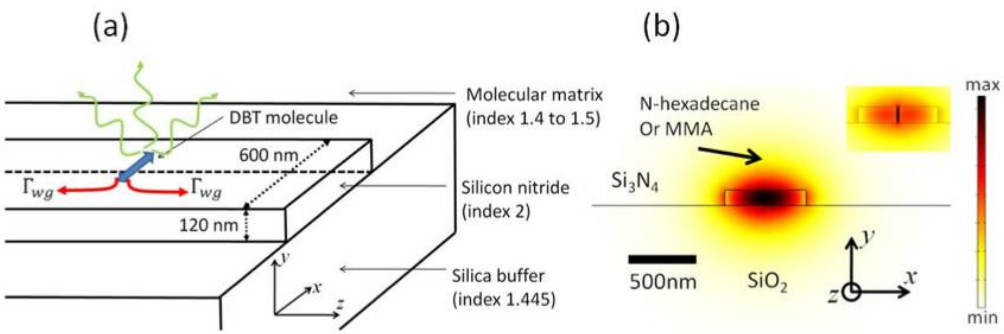
Solntsev, et al., arXiv:1108.6116

- Integrate detectors



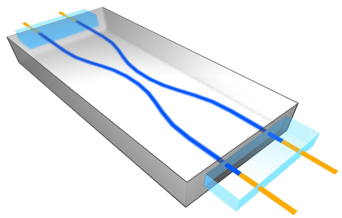
arXiv:1108.5107

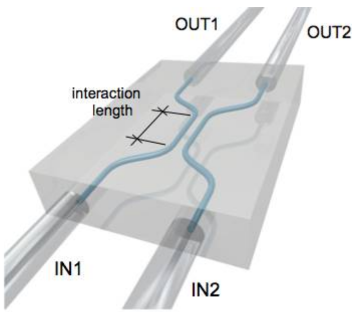
- Introduce non-linearities on chip

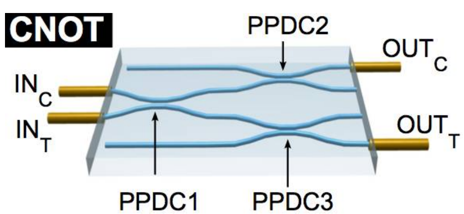


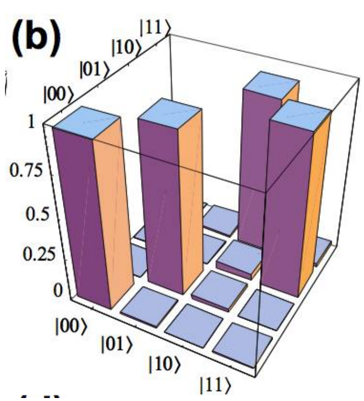
J. Hwang and E. Hinds, New J. Phys. 13, 085009 (2011)

Conclusions and perspectives









- Beamsplitter able to suport polarization encoded qubit
- Polarization sensitive devices
- Integrated CNOT for polarization qubit
- Quantum walk with two-particles in different entangled states

- *NEXT STEPS:*
- Tunable integrated waveplates
- Hybrid manipulation of path and polarization for quantum information processing and non-locality tests

L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

CNOT gate: A. Crespi, *et al,* Nature Communication (in press)

Quantum walk: L. Sansoni, *et al.*, quant-ph 1106.5713

SEVENTH FRAMEWORK PROGRAMME

SAPIENZA UNIVERSITÀ DI ROMA

FUTURO IN RICERCA