QUCHIP
Quantum Simulation on a Photonic Chip

Quantum simulation with integrated photonics

PICQUE

MARIE CURIE ACTIONS

erc

HORIZON 2020

3D-QUEST

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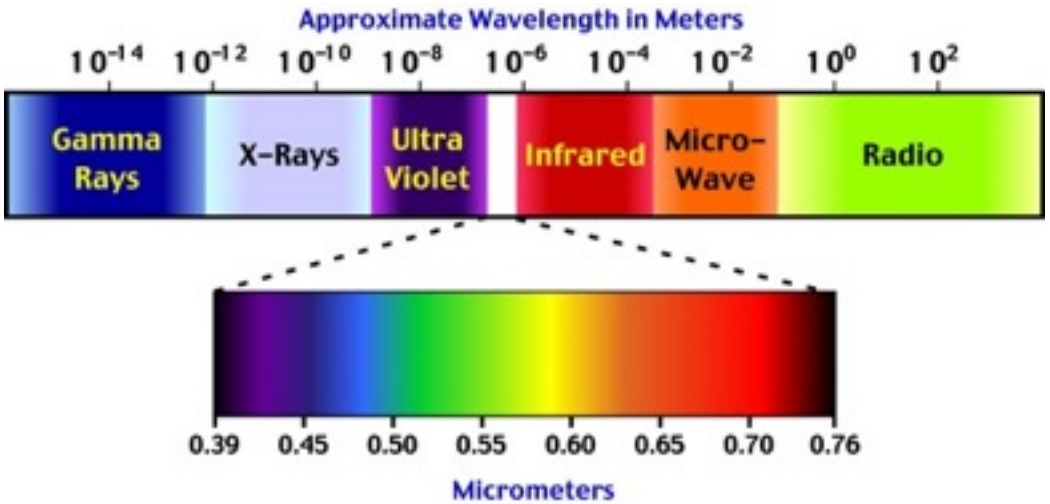
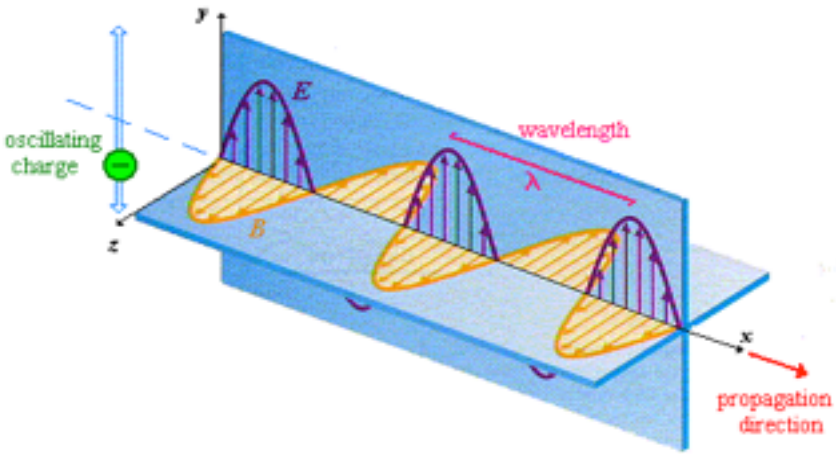
www.quantumlab.it

Optics for Quantum Information

Suitable hardware for quantum communication

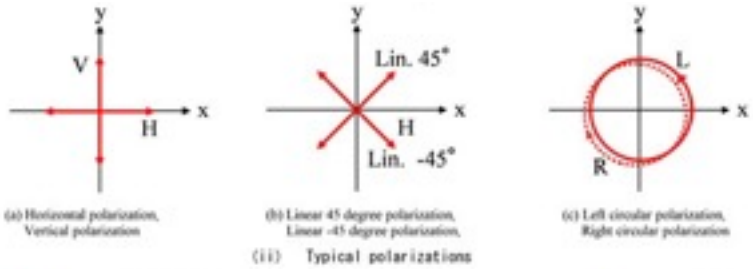




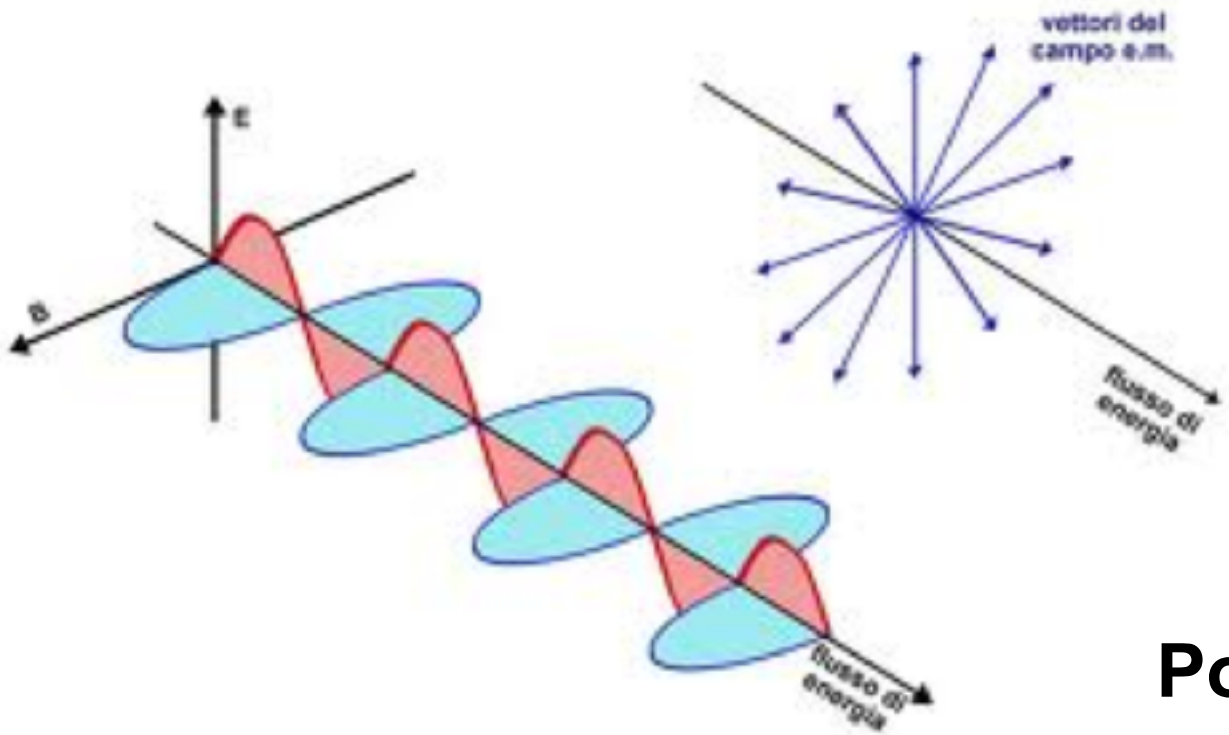
Photon: quantum of the electromagnetic field
Photoelectric effect – Einstein (1905)

Qubit encoded into photon's degrees of freedom

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



Polarization of light



Qubit → **Polarization of a single photon**

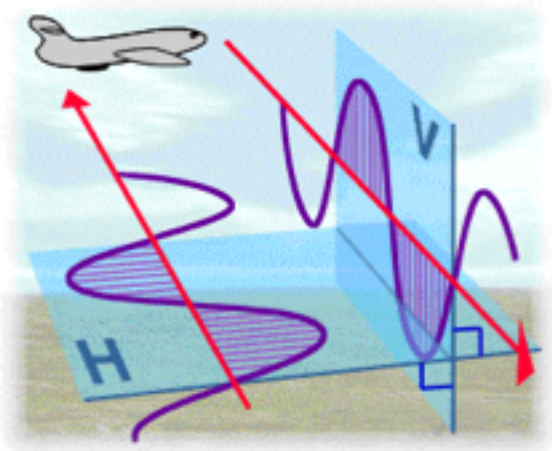
$$\alpha|0\rangle + \beta|1\rangle$$

$$\alpha|H\rangle + \beta|V\rangle$$

H: horizontal
V: vertical

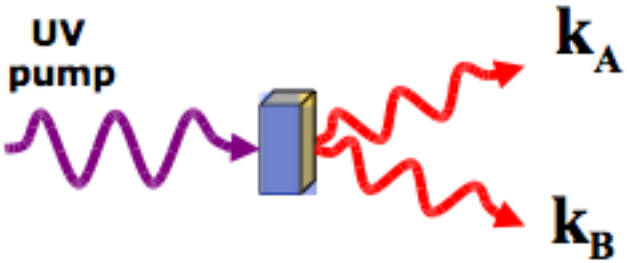
Polarization encoding of qubit

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



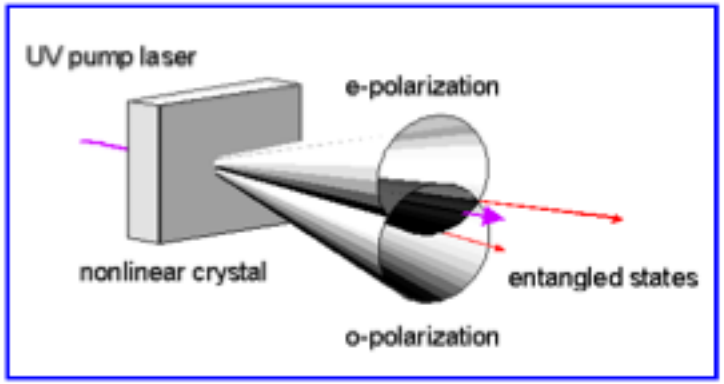
$$\alpha|0\rangle+\beta|1\rangle \longleftrightarrow \alpha|H\rangle+\beta|V\rangle$$

- 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



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

Quantum Optics for Quantum Information Processing

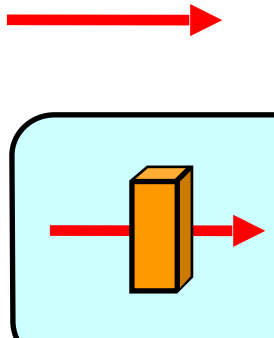
- Qubit state

  Polarization of a single photon:

  H: horizontal polarization

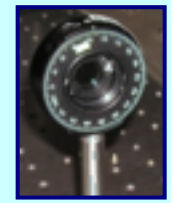
  V: vertical polarization

  Mode of the electromagnetic field (k,wavelength)



- Logic gate acting on a single qubit

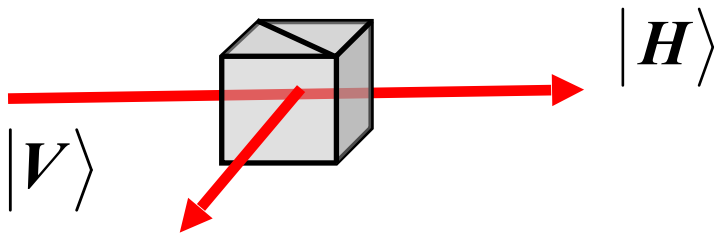
  Rotation of the polarization: waveplates

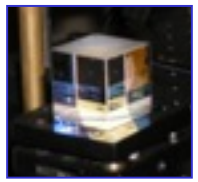


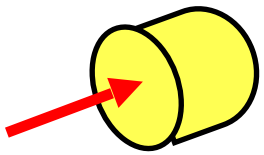
- Measurement of the qubit:

  polarizing beam splitter

  Single photon detectors







Quantum Optics for Quantum Information Processing

- Two qubit logica gate (CNOT gate)

"Interaction" between two photons

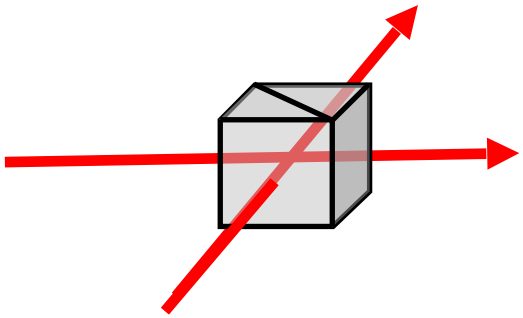
  – **Linear**

  Polarizing beam-splitter

  Beam-splitter

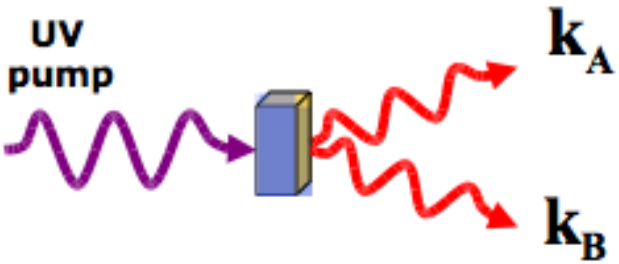
  Measurement process

Beamsplitter

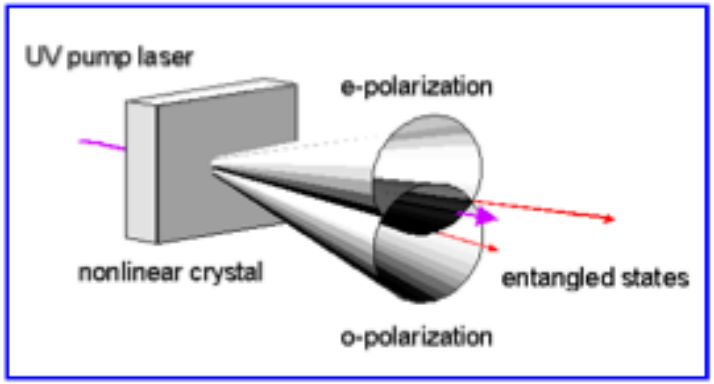


  – **Non-linear**

  Interaction with atoms



- Generation of entangled states
  – Spontaneous parametric down conversion

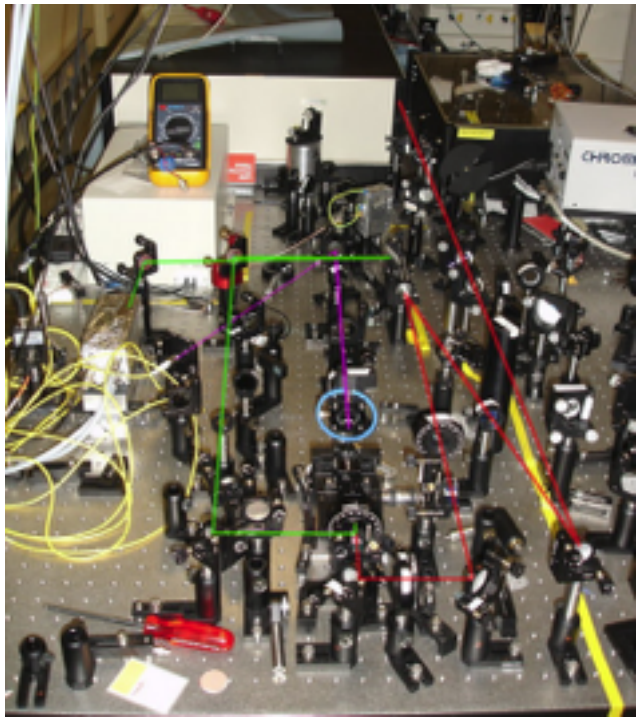


Integrated photonics: Bulk optics limitations

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

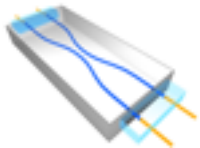
SETUP: COMPLEX OPTICAL INTERFEROMETERS

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



Possible solutions?

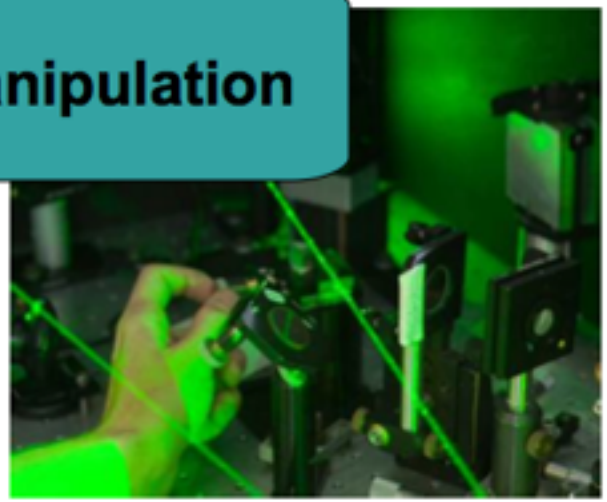
Integrated waveguide technology



Integrated quantum photonics

Preparation

Manipulation

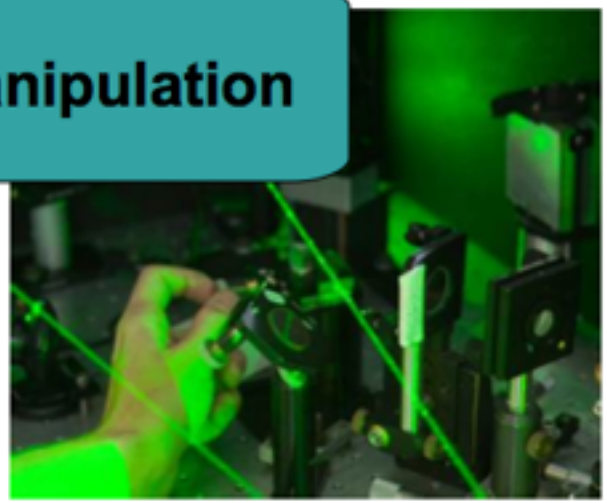


Detection

Integrated quantum photonics

Preparation

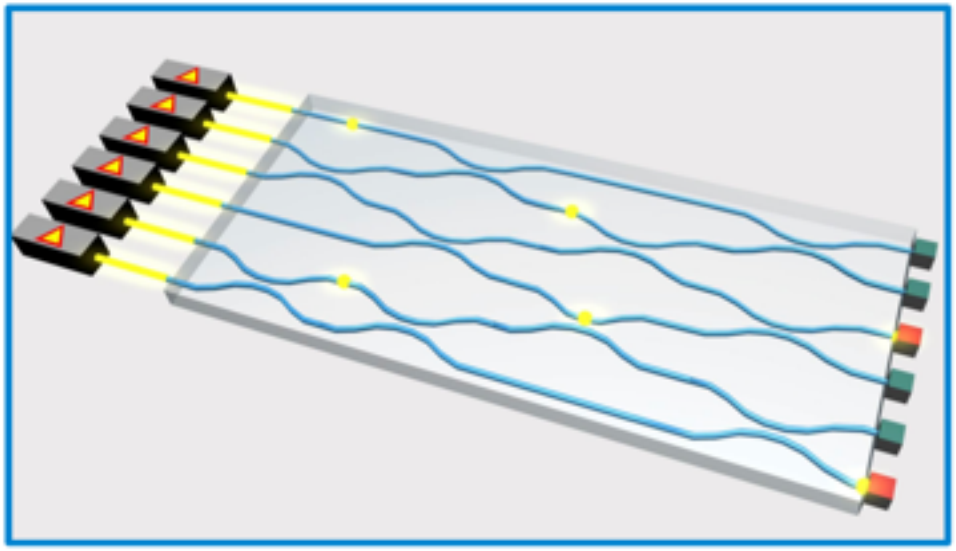
Manipulation



Detection

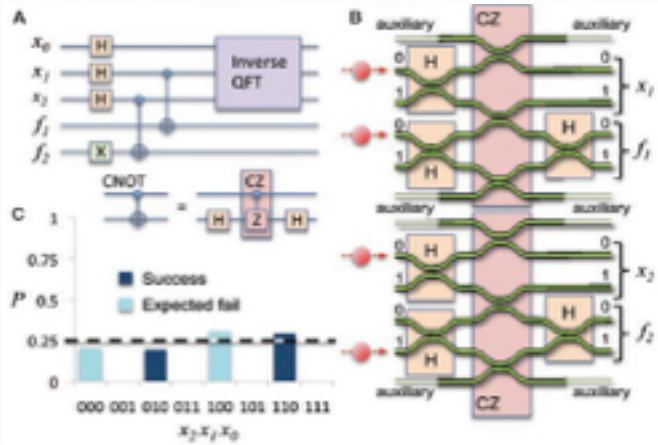
- Single photon sources
- Manipulation
- Single photon detectors

ON THE SAME CHIP

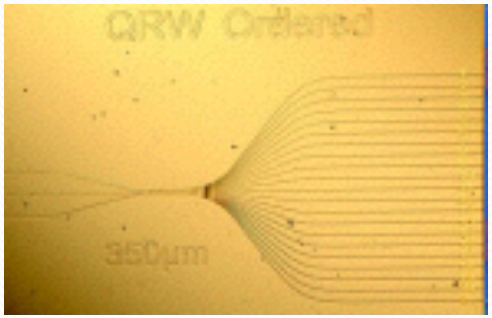


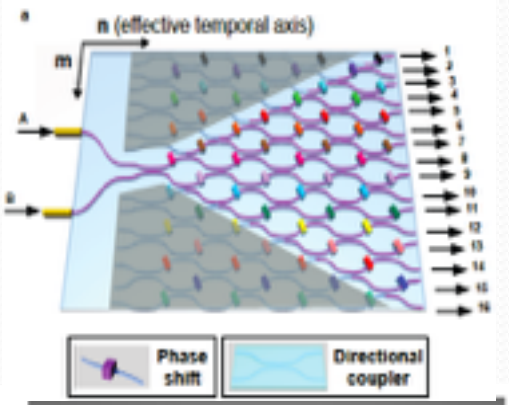
Integrated quantum photonics: new opportunities..

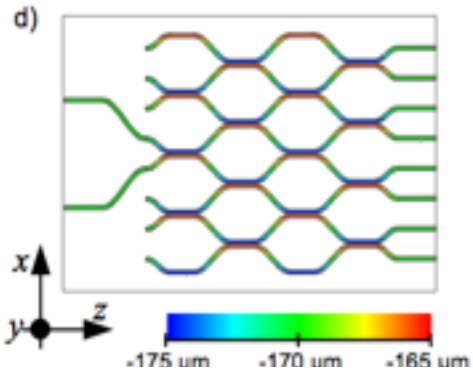
Quantum factoring algorithm on a chip

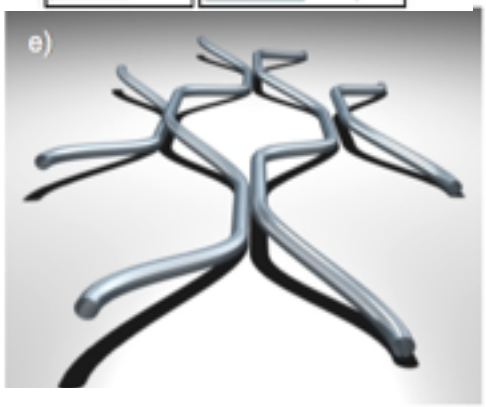


Integrated quantum walks

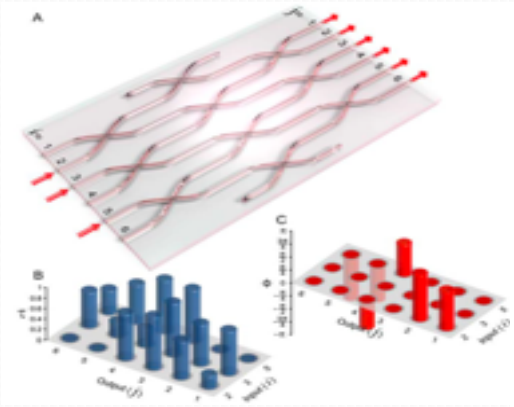


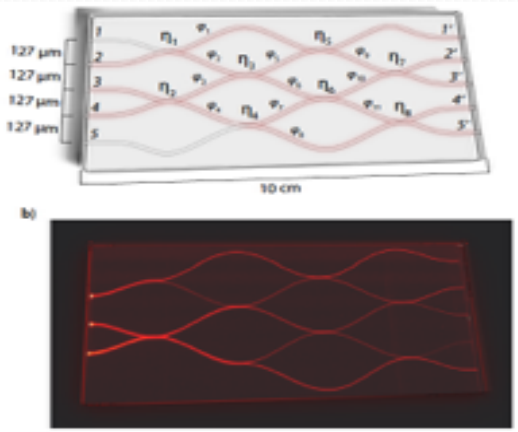


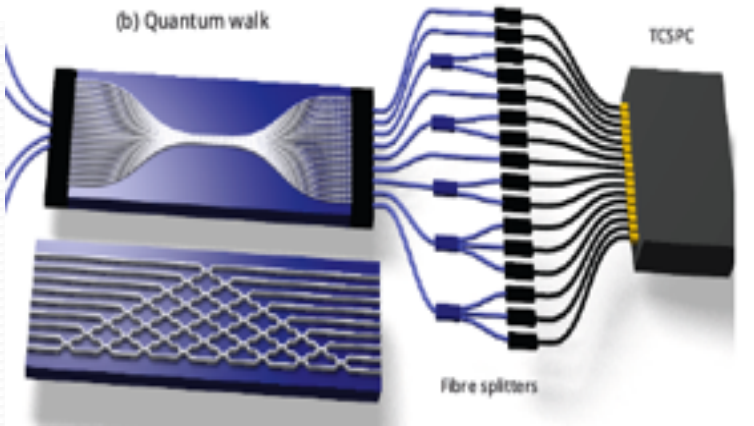




Boson Sampling in an integrated chip

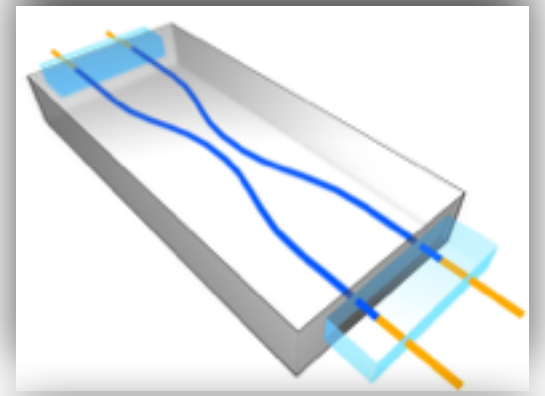




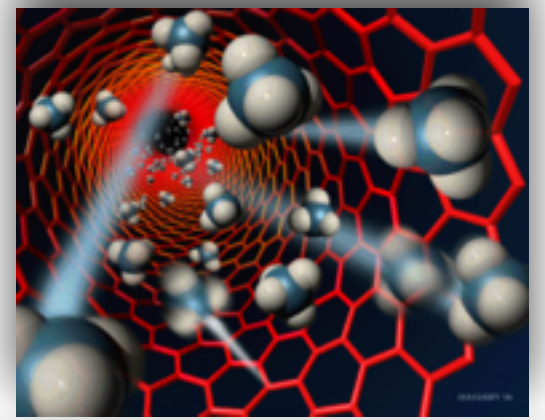


Outline

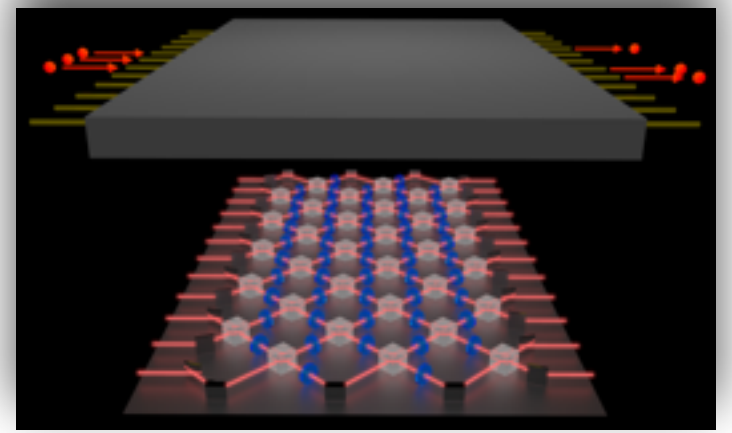
Lecture 1 - Integrated quantum circuits



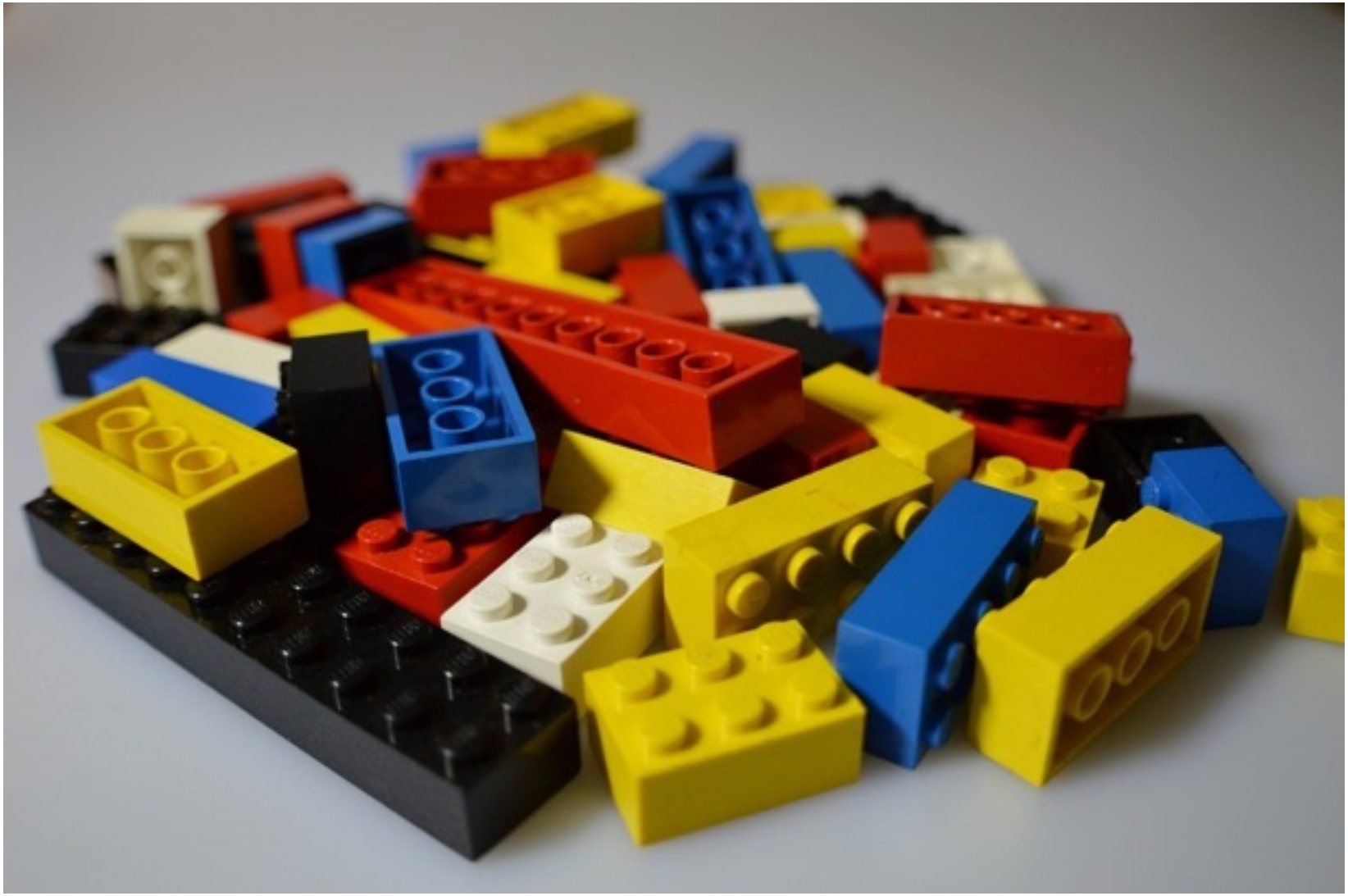
Lecture II - Quantum simulation via quantum walk



Lecture III - Boson sampling



Building blocks…



Lecture 1: Integrated quantum photonics

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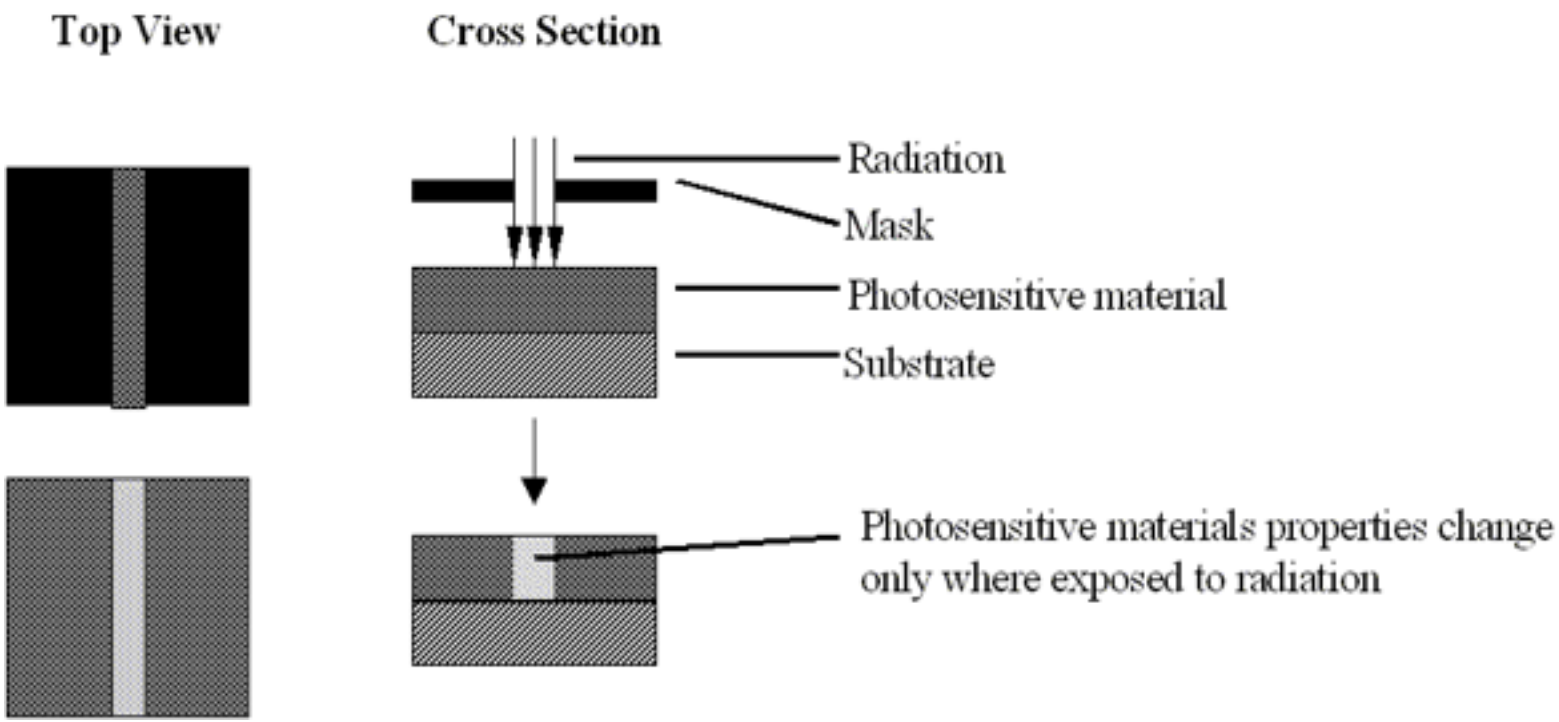
Lithography



- 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*

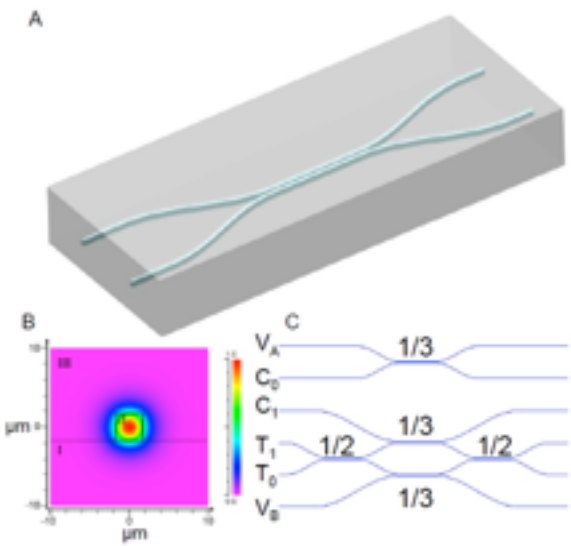
A. Politi et al. *Science* **320**, 646 (2008); J. C. F. Matthews et al. *Nature Photonics* **3**, 346 (2009)
A. Politi et al. *Science* **325,** 1221 (2009).

Integrated photonics: First experiments....

The main limitations of experiments realized with bulk optics are:

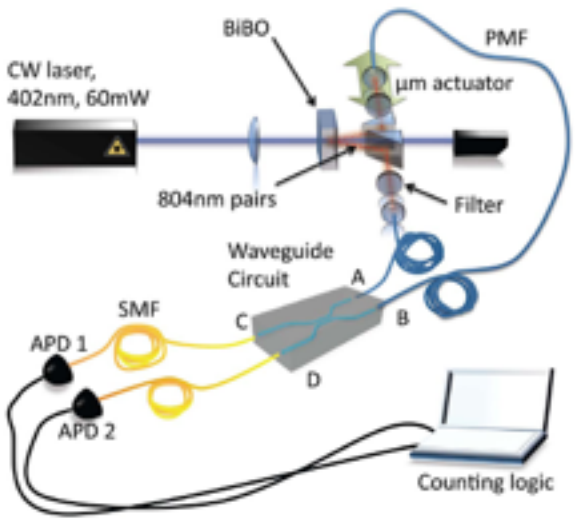
- ✓ Large physical size
- ✓ Low stability
- ✓ Difficulty to move forward applications outside laboratory

Possible solutions? Integrated waveguide technology



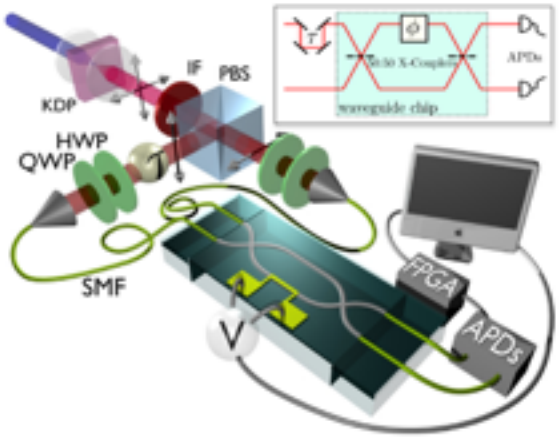
CNOT gate

Politi *et al.* Science (2008)



HOM effect

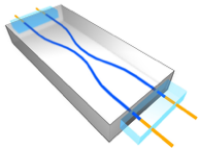
Marshall *et al.* Optics Express (2009)



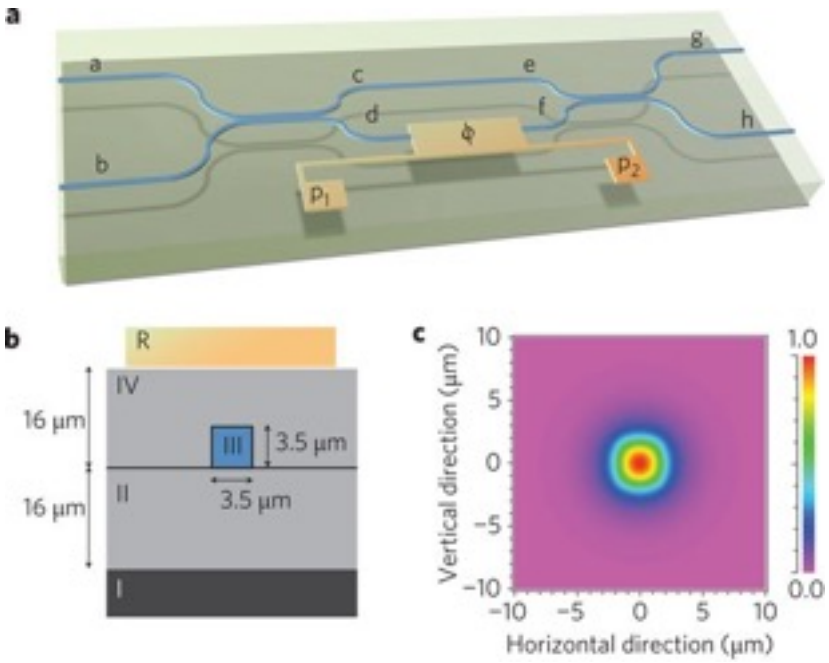
Phase control

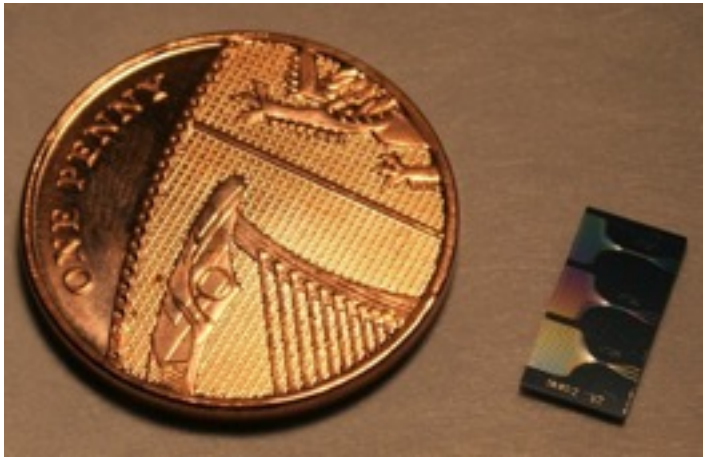
Smith *et al.* Optics Express (2009)

All experiments realized with path encoded qubits



Integrated photonics: First experiments....





A. Politi et al. *Science* **320**, 646 (2008);
J. C. F. Matthews et al. *Nature Photonics* **3**, 346 (2009)
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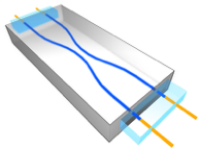
- ✓ *Shor's algorithm*

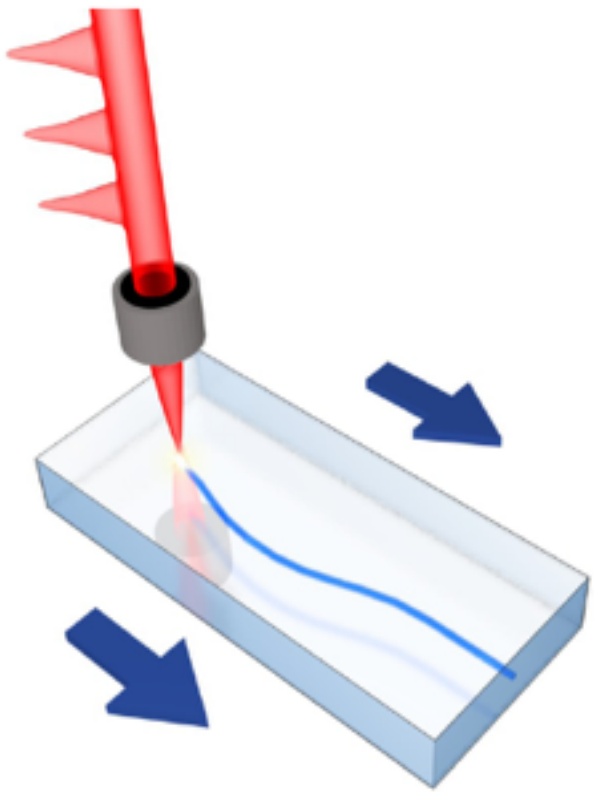
All experiments realized with path encoded qubits



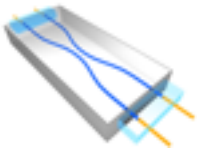
Femtosecond laser writing

What about polarization encoding?

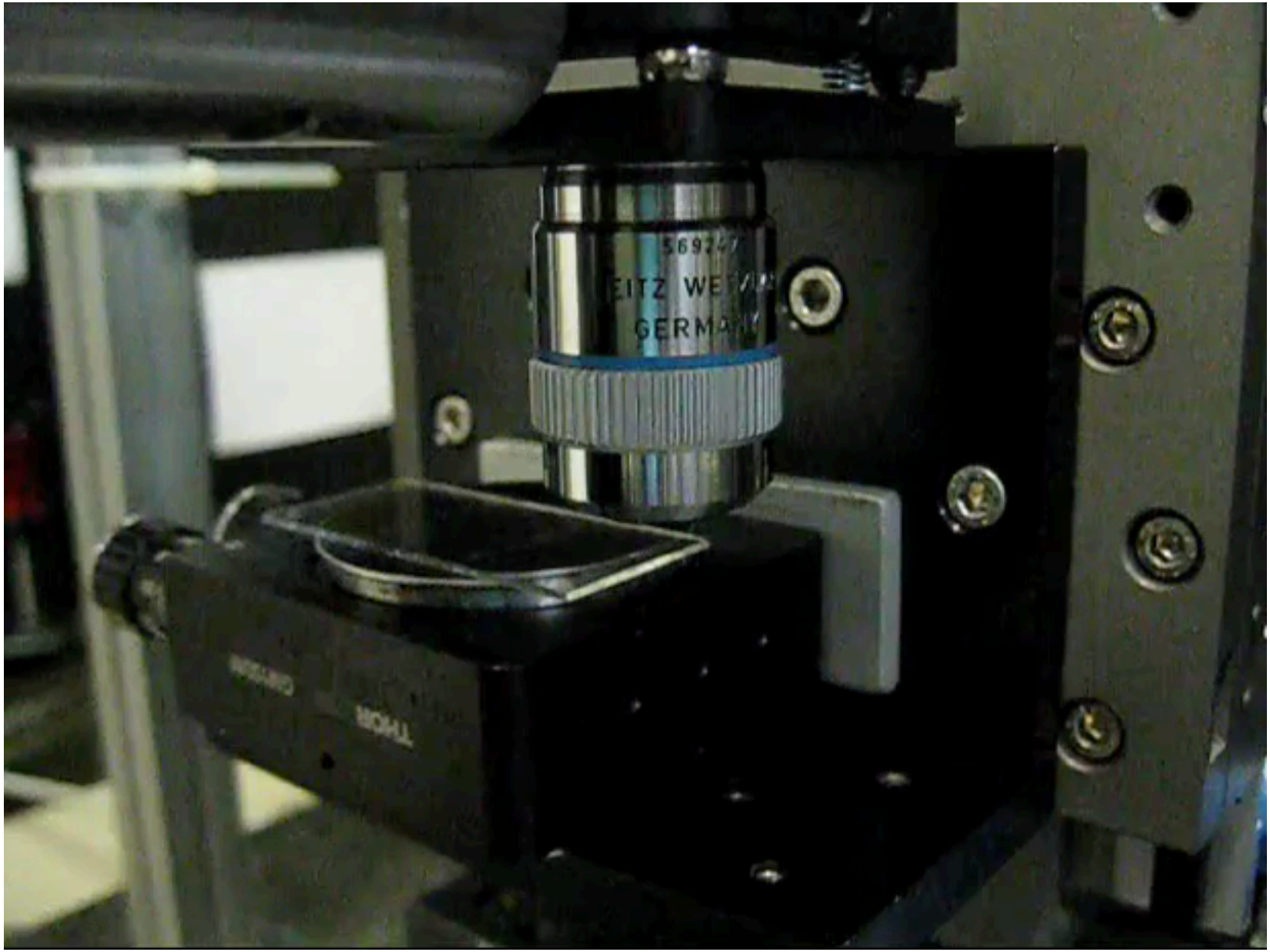
Laser writing technique for devices able to transmit polarization qubits



- 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

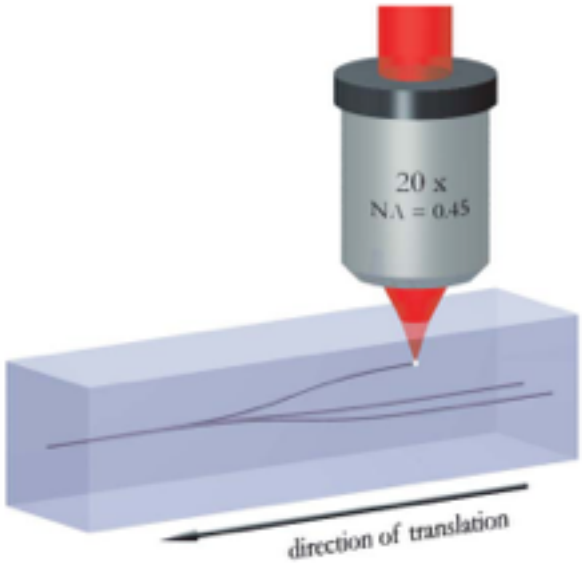


Femtosecond laser writing

3-dimensional capabilities

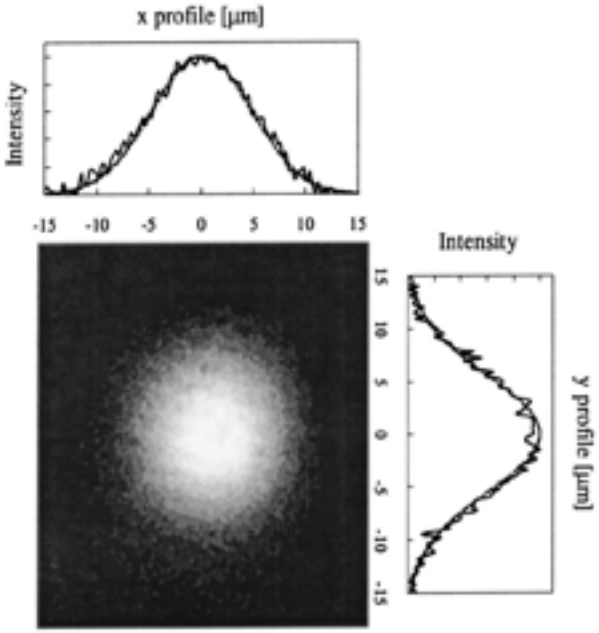
Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

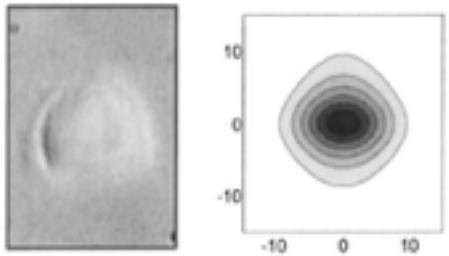


Characteristics:

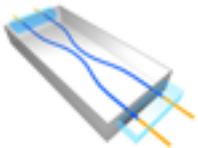
Circular waveguide transverse profile



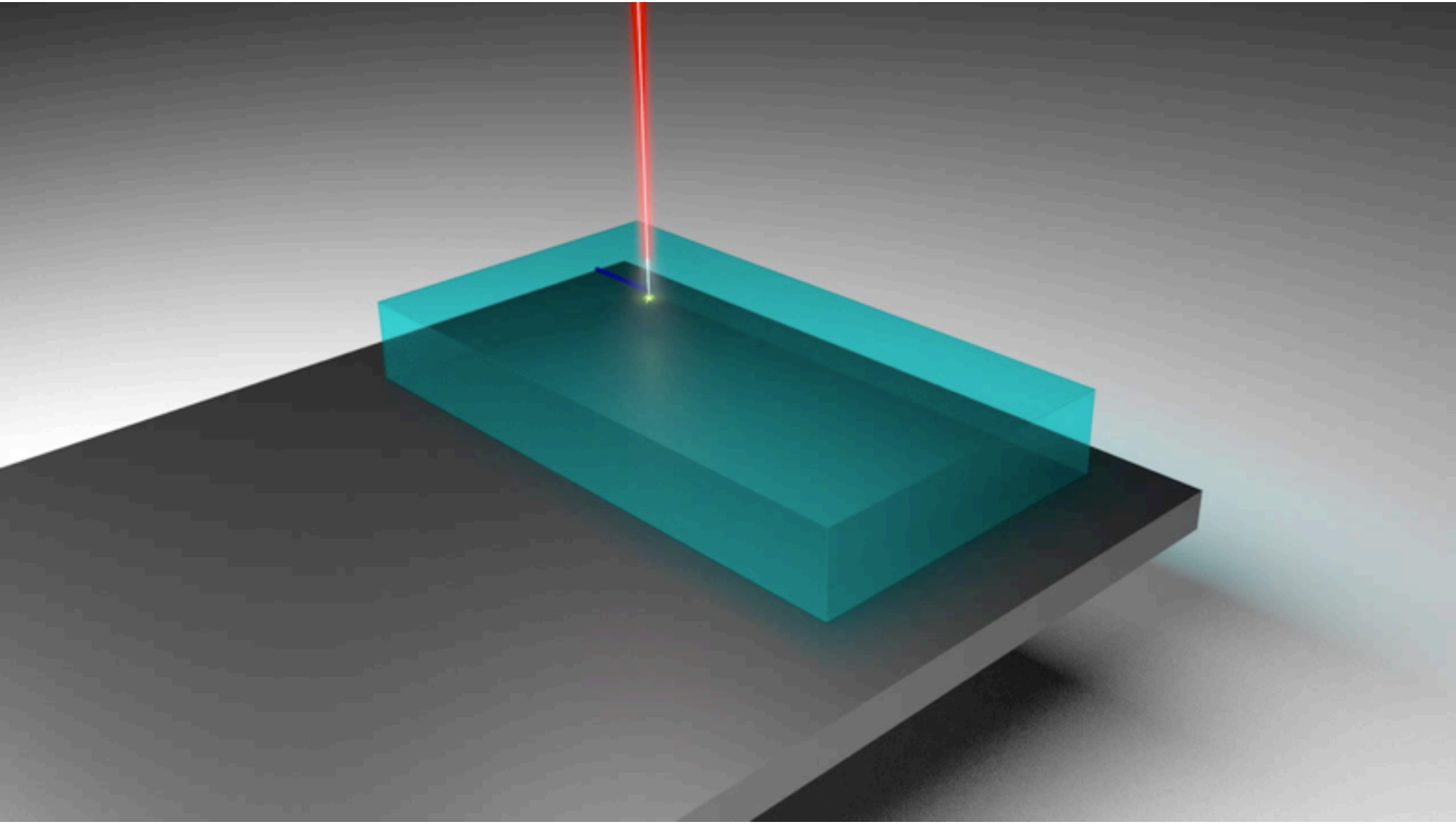
Low birefringence



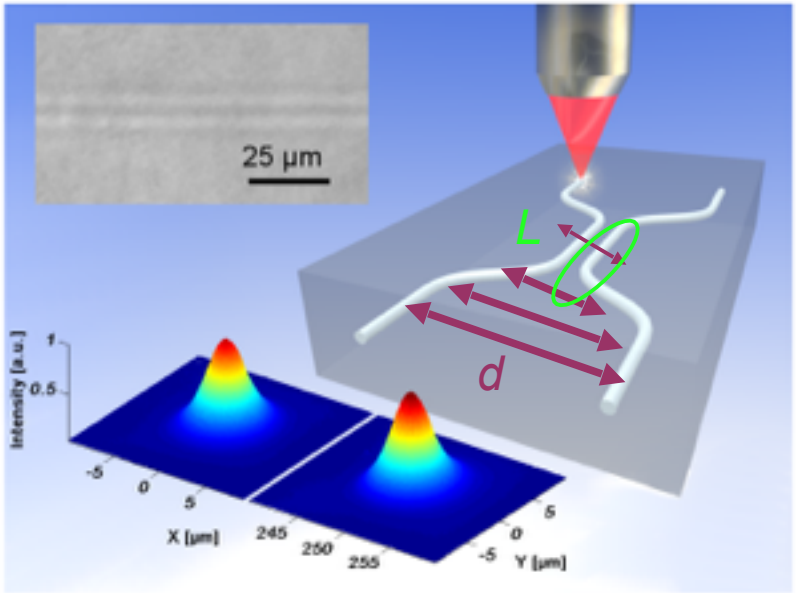
SUITABLE TO SUPPORT ANY POLARIZATION STATE



Femtosecond laser writing



Integrated beam splitter



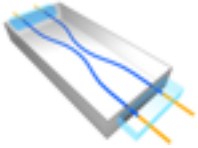
Substrate of borosilicate glass
(no birefringence observed)

Femtosecond infrared laser: λ=*1030nm*
Pulses duration :=*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

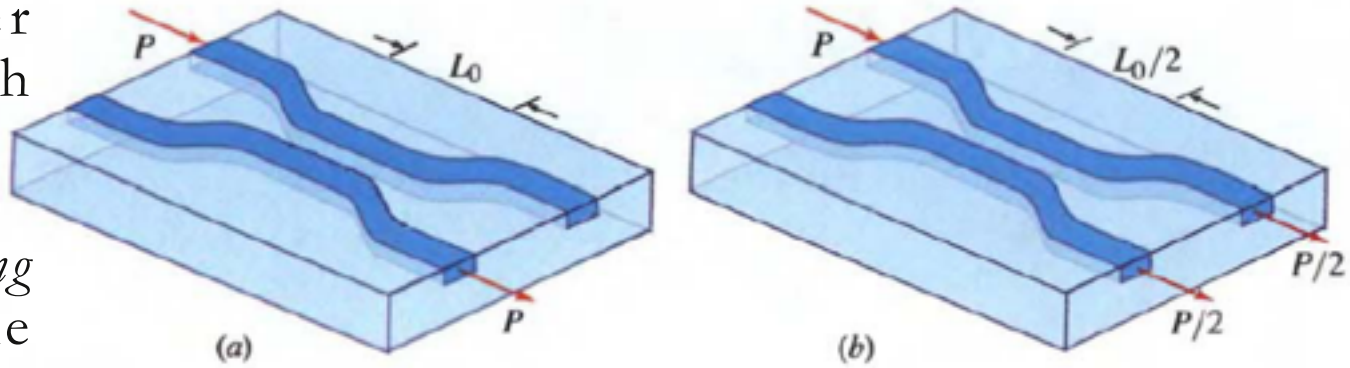


L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

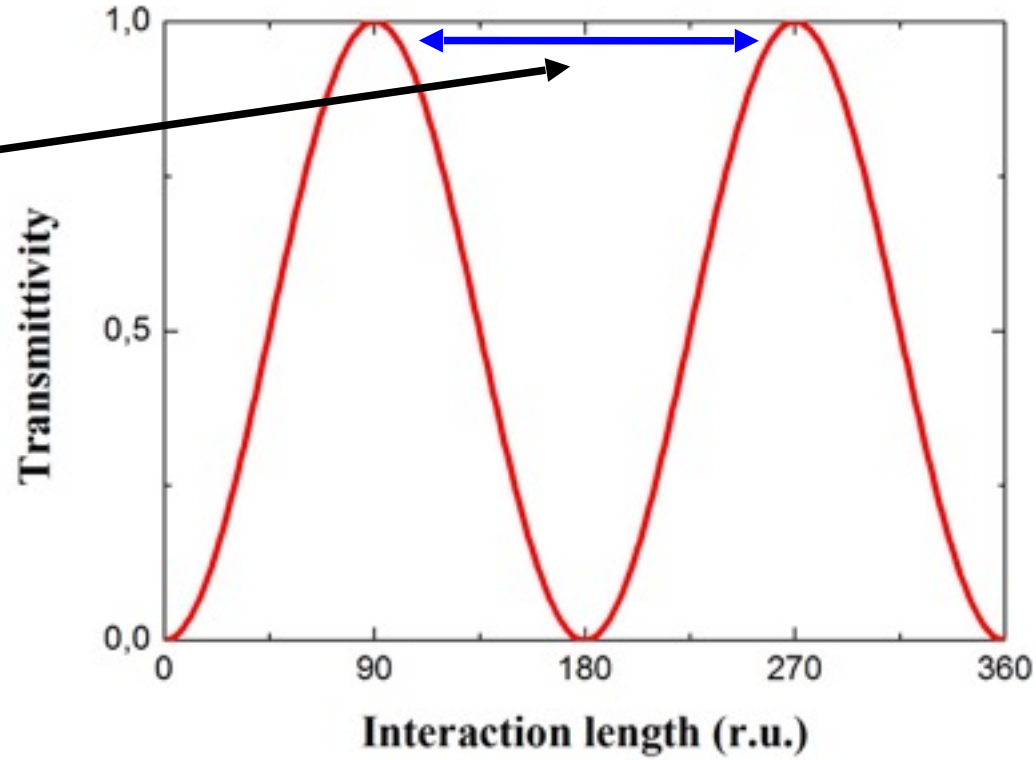
Tunability of the direction coupler transmission

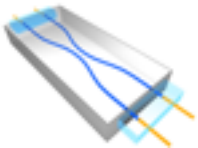
Optical power transfer follows a sinusoidal law with the interaction length.

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

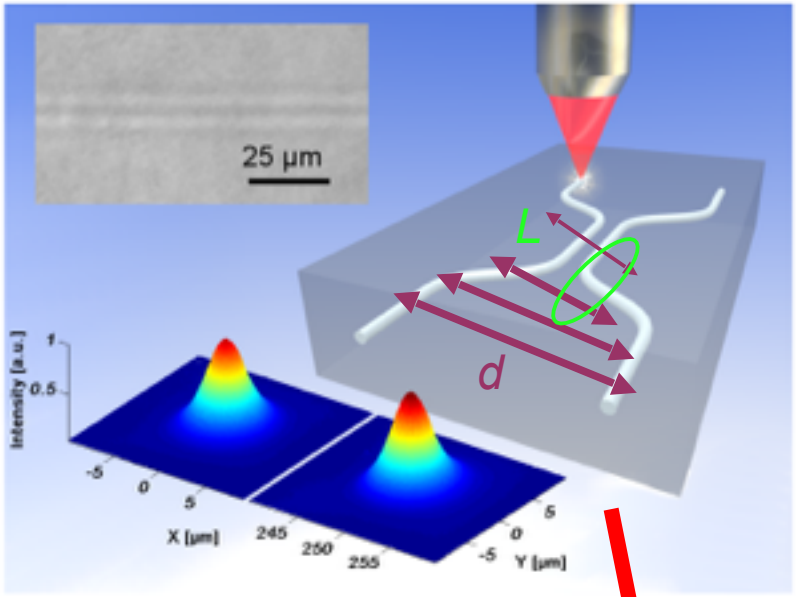


Periodicity of the transmission depends from the *Effective index of refraction*

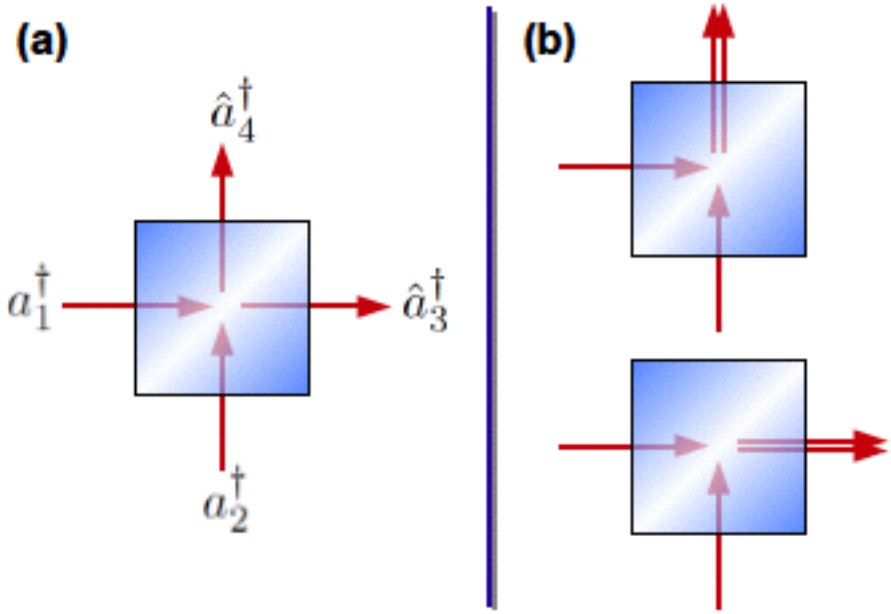


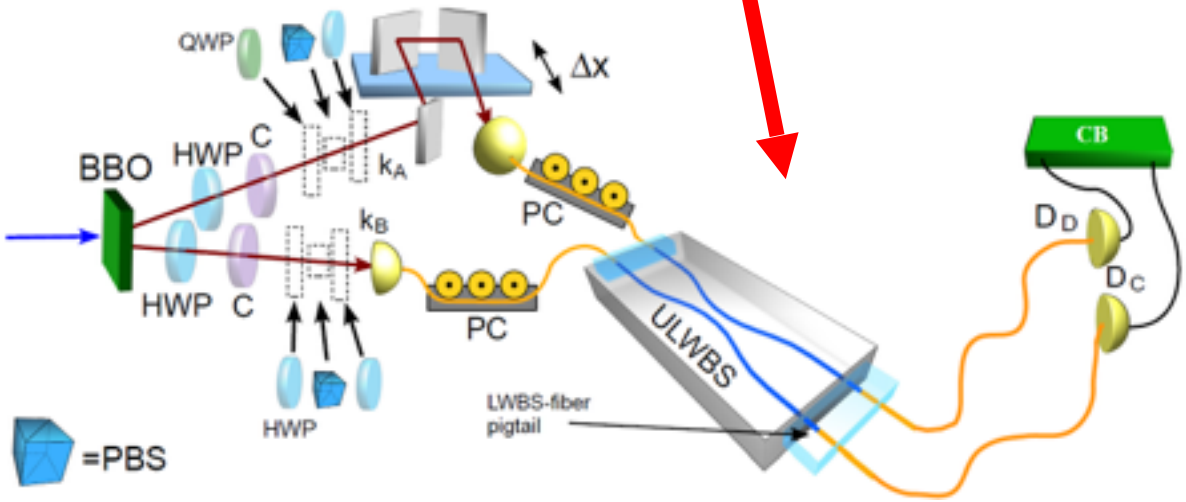


Integrated beam splitter



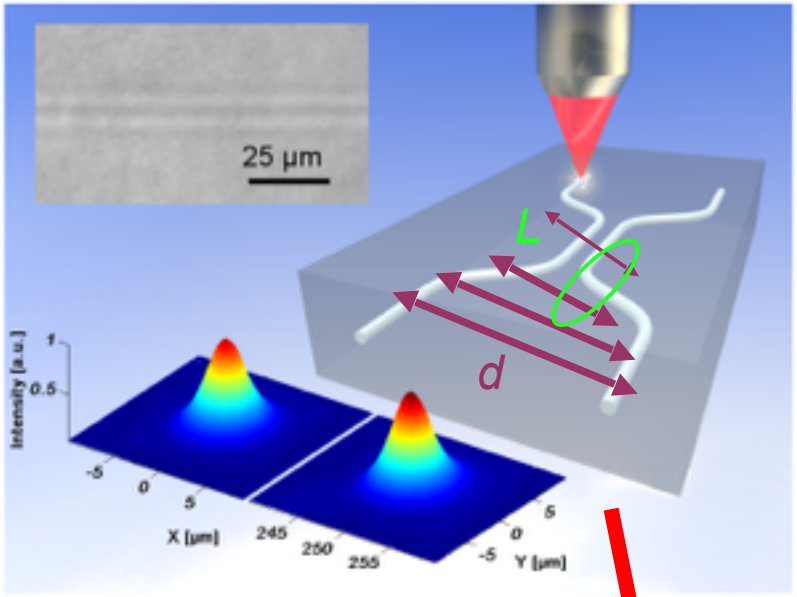
Indistinguishable photons: Bosonic coalescence

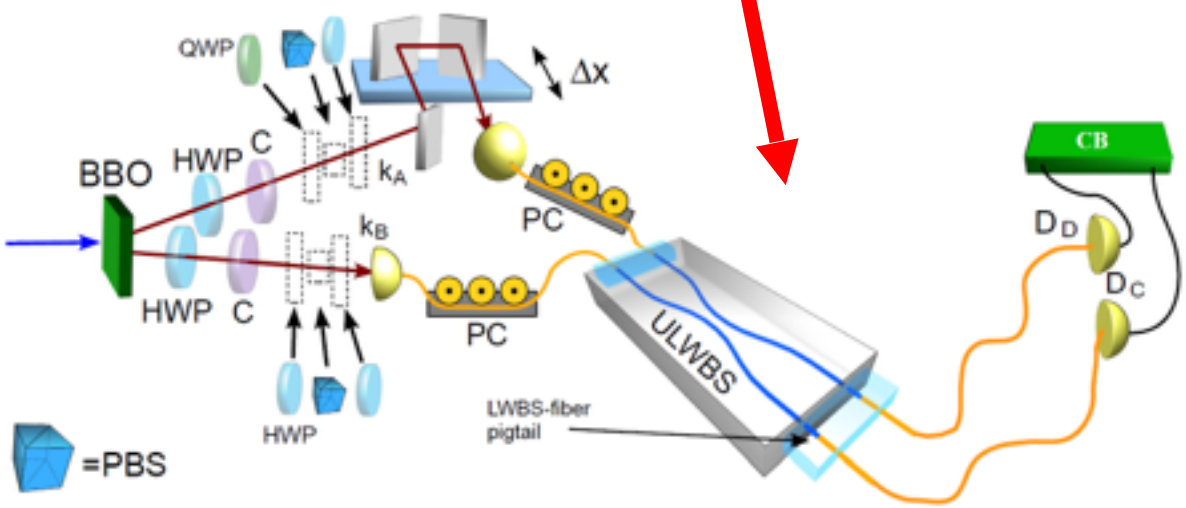


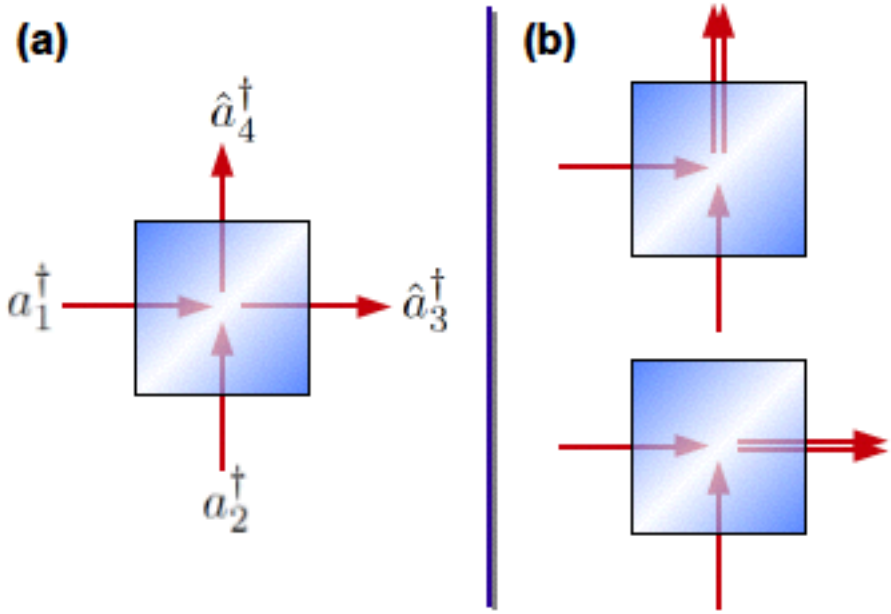


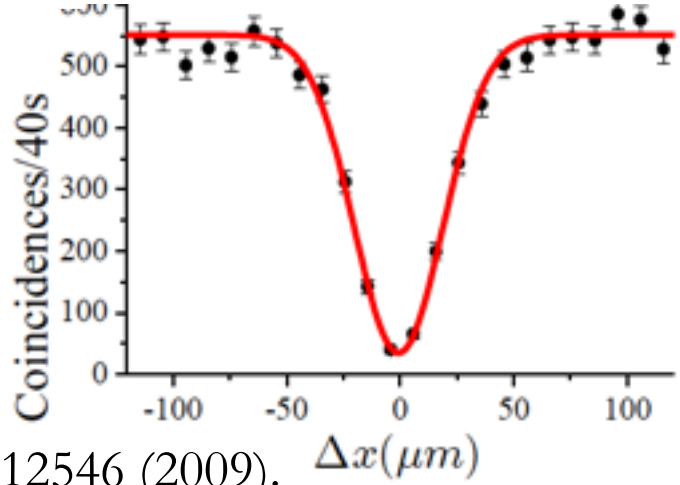
Integrated beam splitter

Indistinguishable photons: Bosonic coalescence







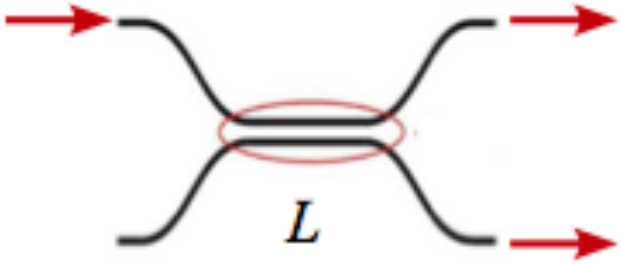


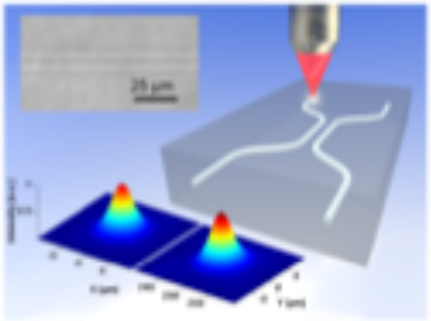
G. D. Marshall et al., *Opt. Express* **17**, 12546 (2009).
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

Directional coupler as beam splitter

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

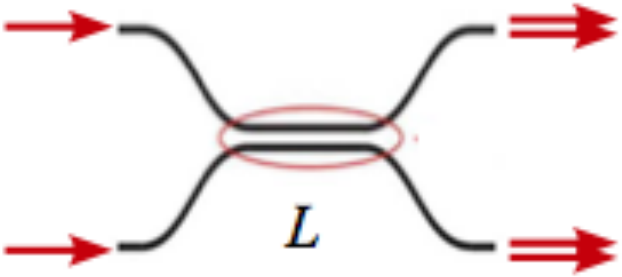
Single photons

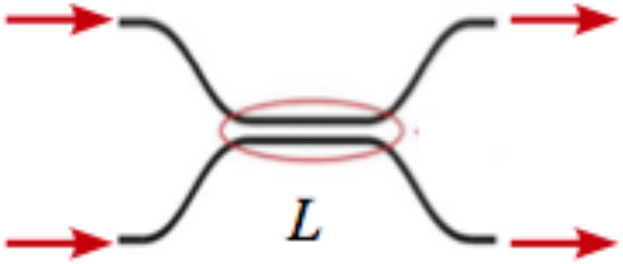




Two-photon states

Identical separable states





Symmetric states: Triplet

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

Antisymmetric state: Singlet

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

Two-photon entangled state on a beamsplitter...

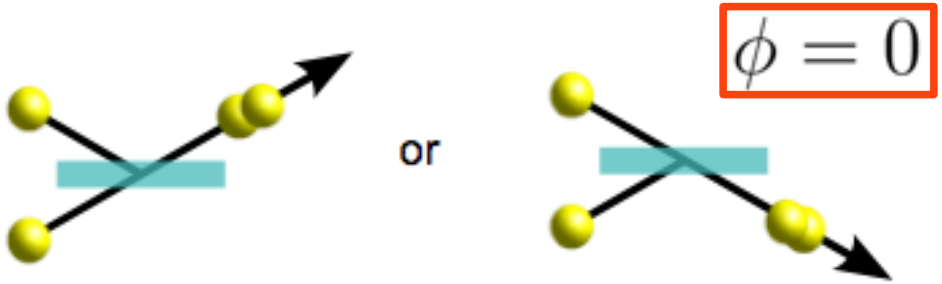
The symmetry of two particles influences the output probability distribution

Polarization independent integrated beam splitter

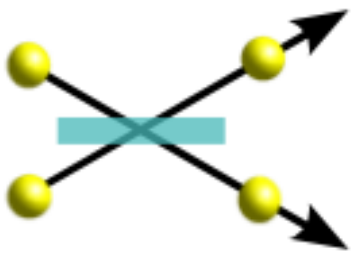
Exploit <u>polarization entanglement</u> to simulate other particle statistics

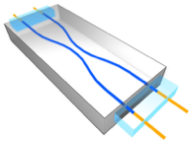
$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$

Bosons

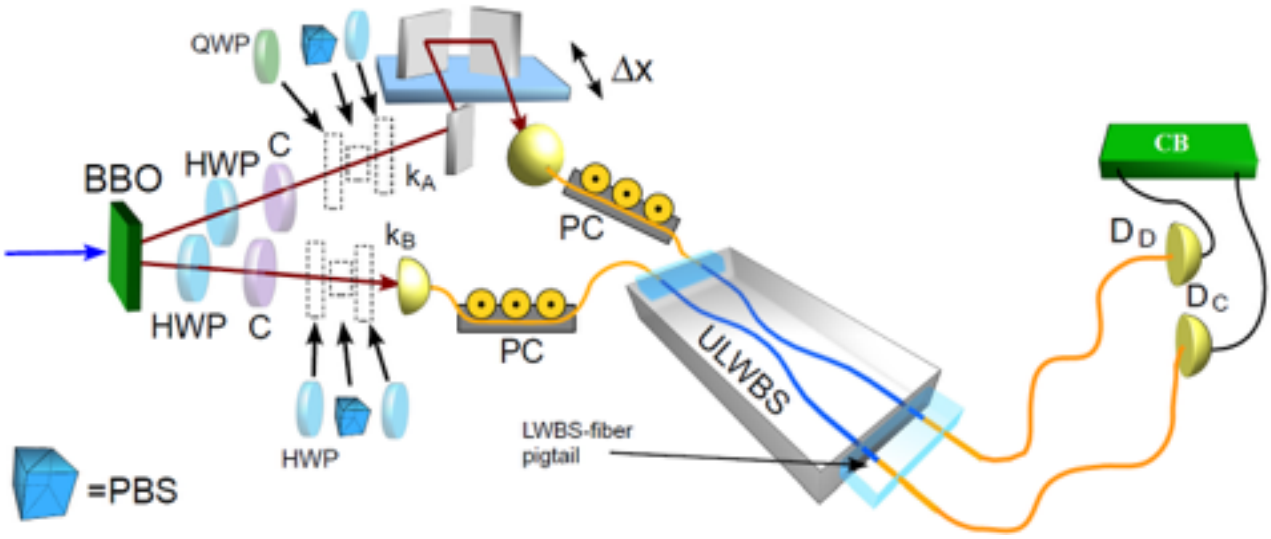


Fermions



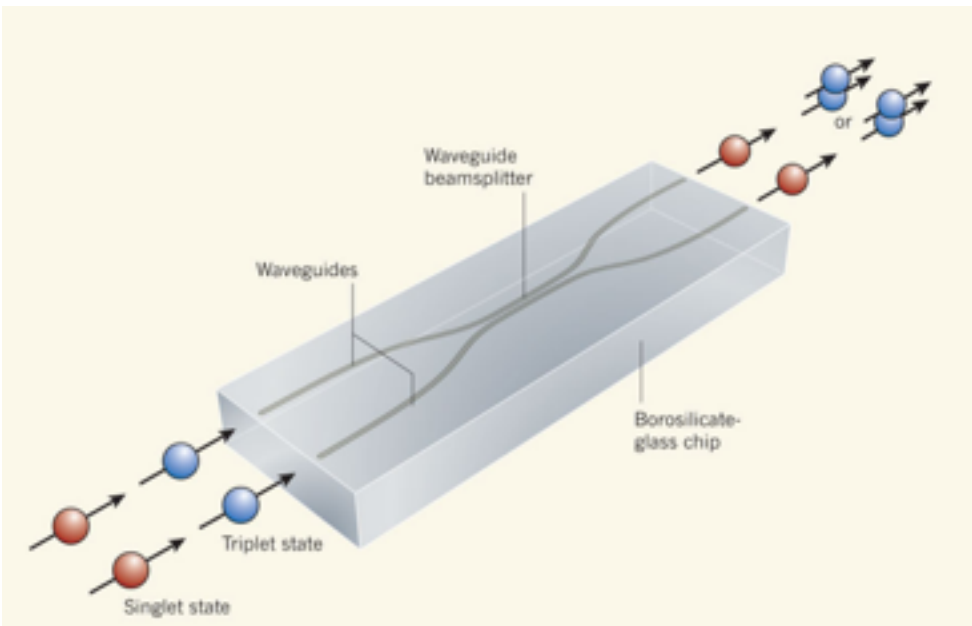


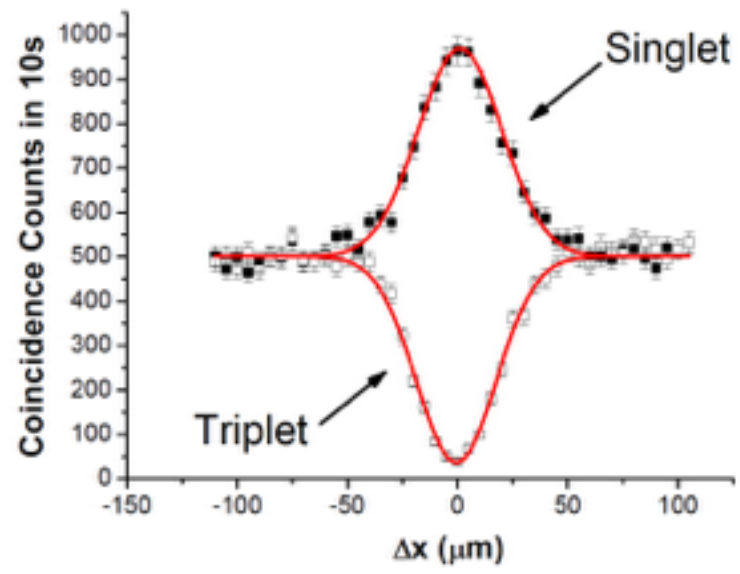
Polarization entanglement on a chip



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

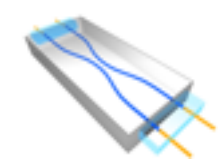
$$V_{|Tripl\rangle} = 0.928 \pm 0.007$$





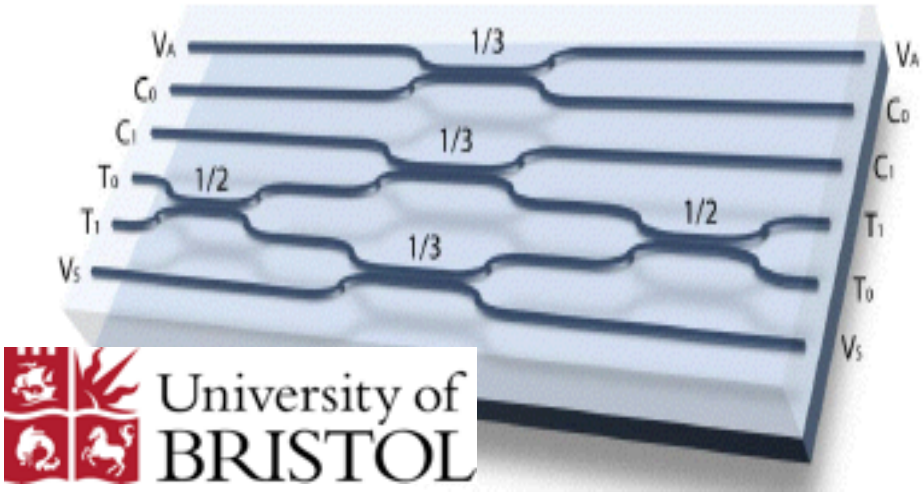
M. Lobino & J.L. O'Brien *News &Views* Nature (2011)

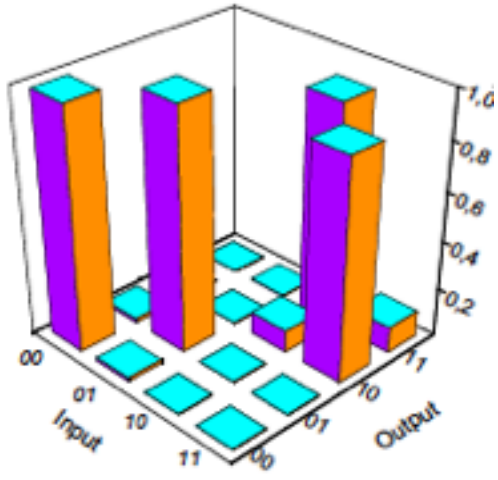
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

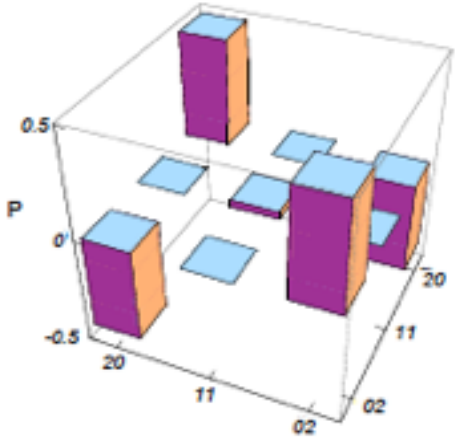


Photonics C-NOT gate

A. Politi et al., Science (2008)

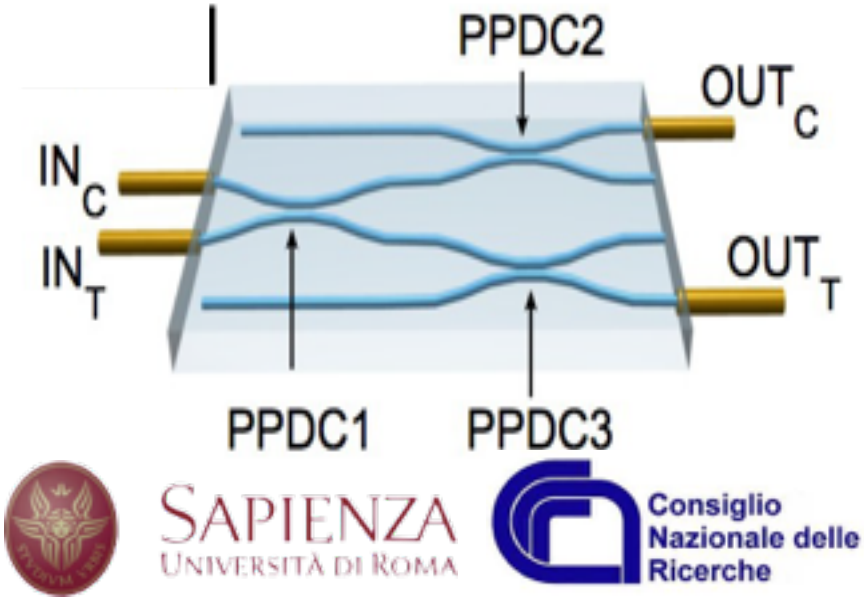


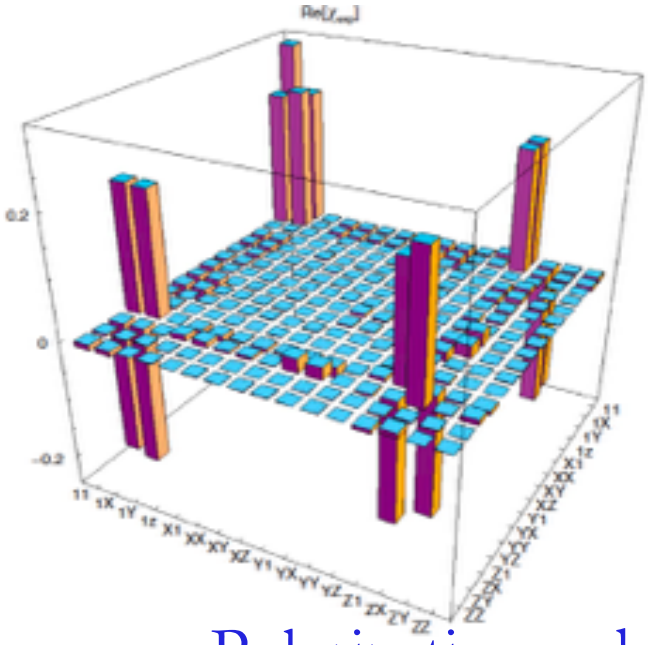




Path qubits V=94.3%

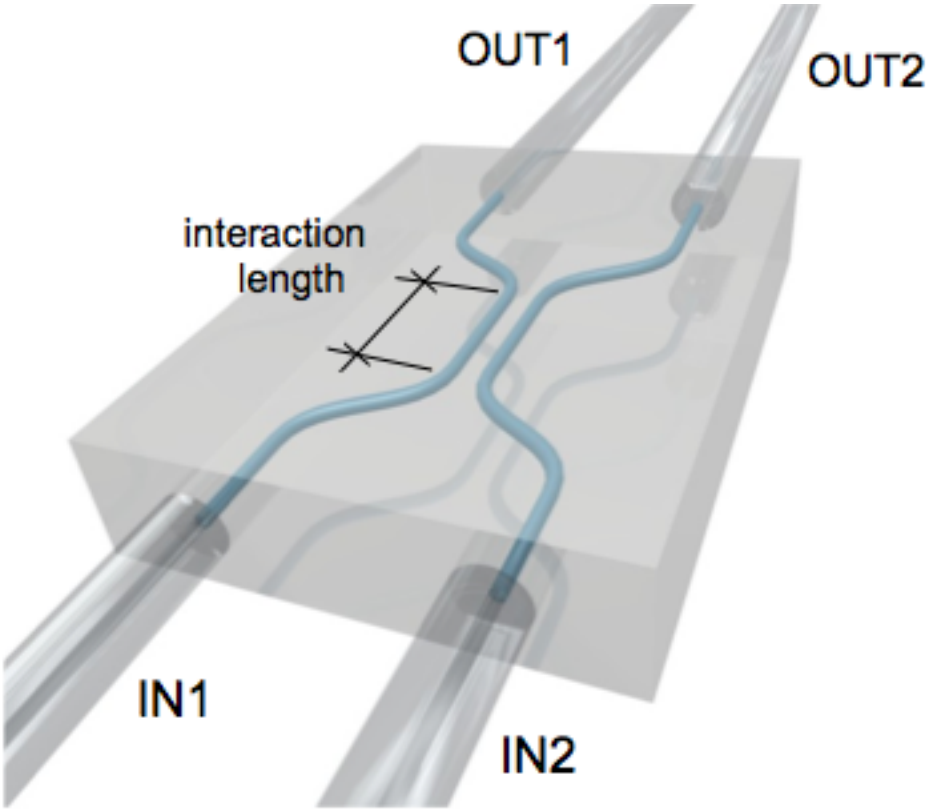
A. Crespi et al., Nat. Comm. (2011)





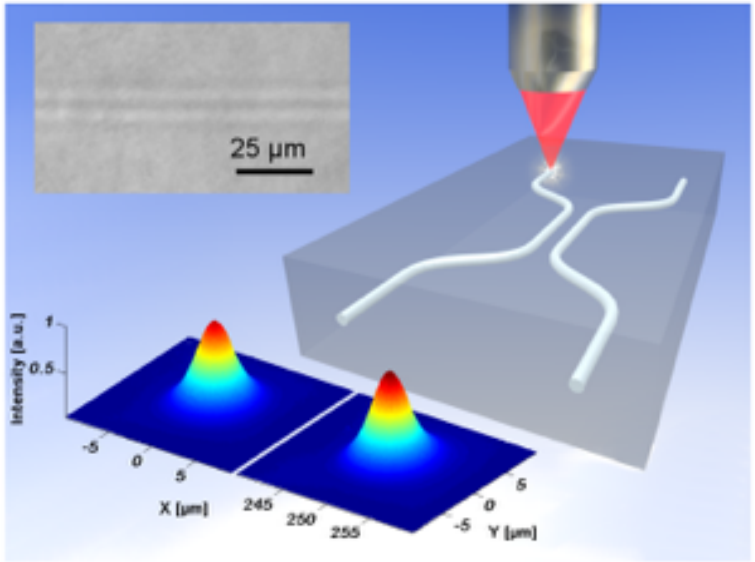
Polarization qubits V=91%

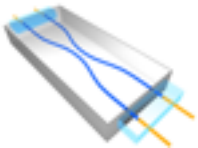
How can we realize polarization dependent devices ?



I) Transmission depends from the interaction length

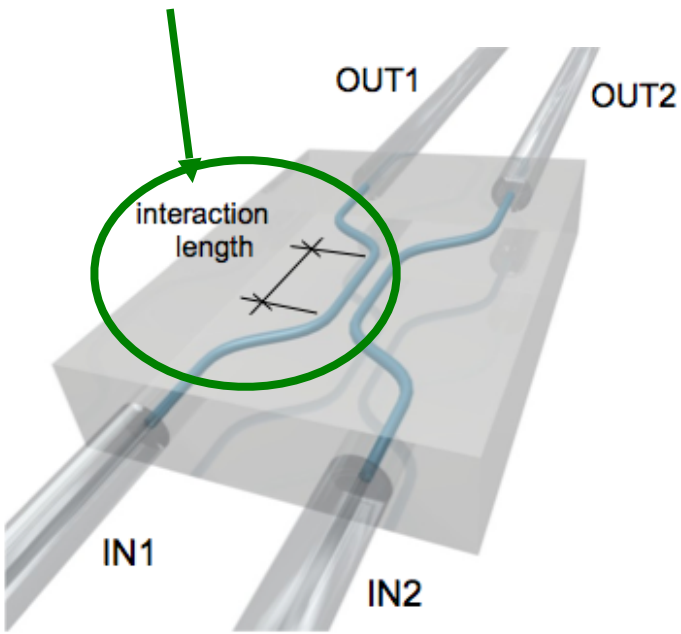
II) Small anisotropy behavior due to residual asymmetry of the waveguide:
Different periodicities

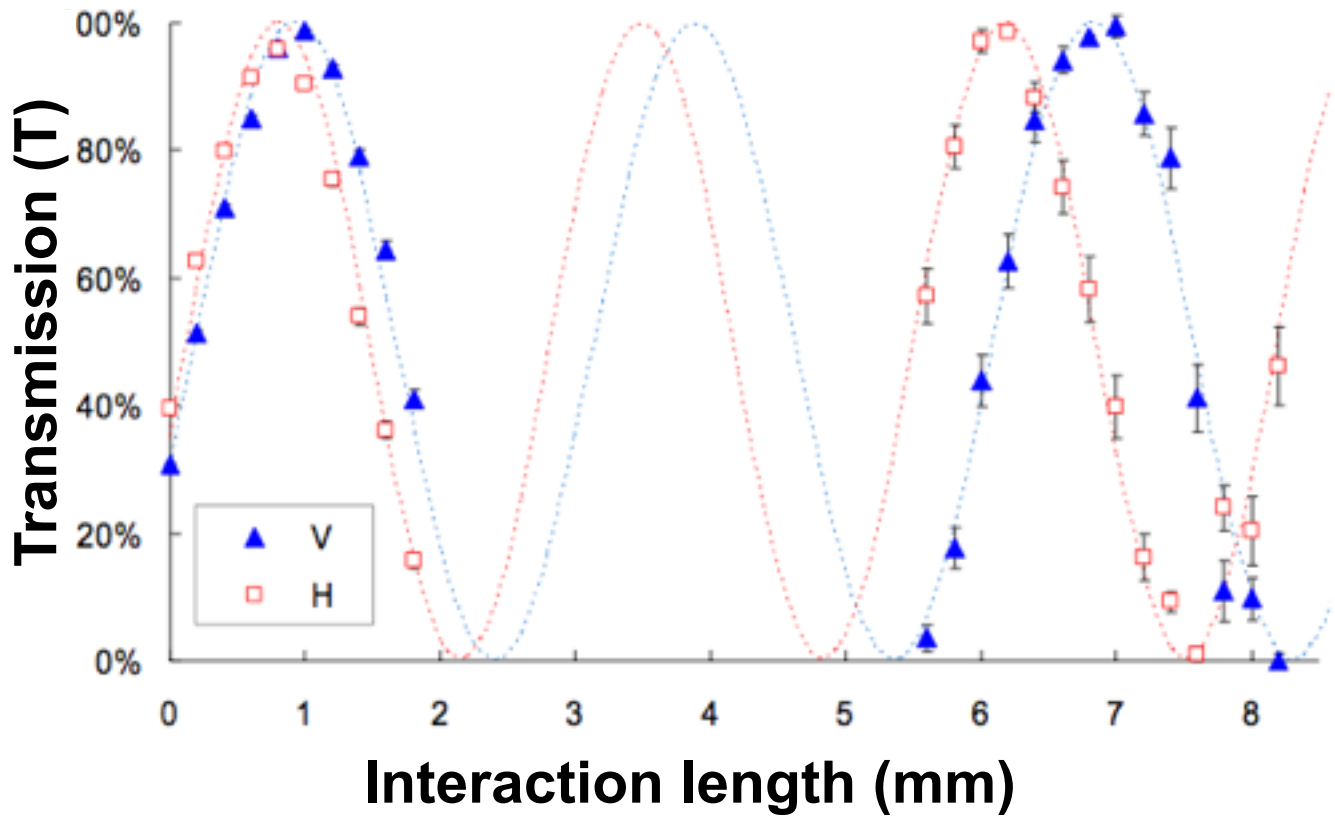




Partially Polarizing Directional Couplers (PPDC)

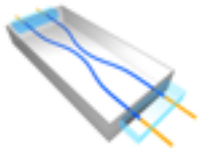
Interaction length



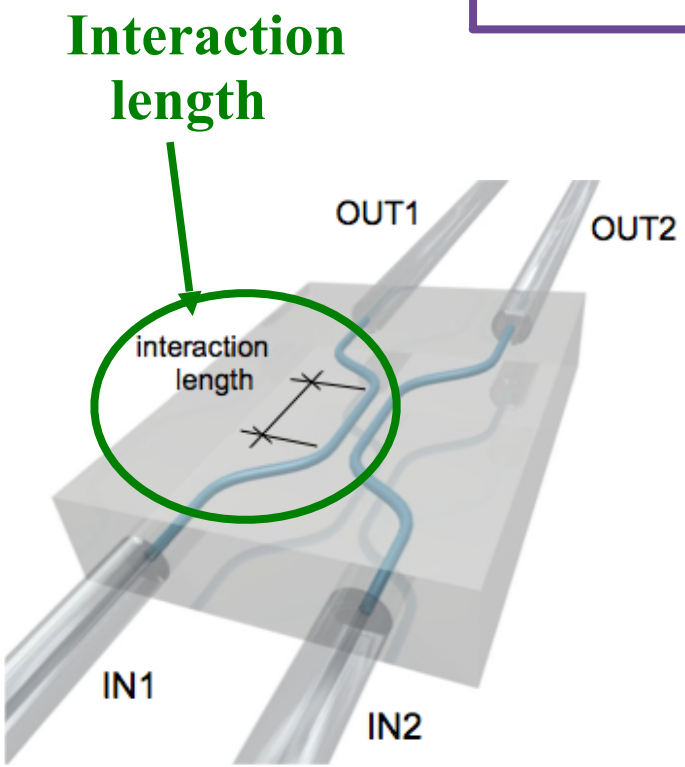


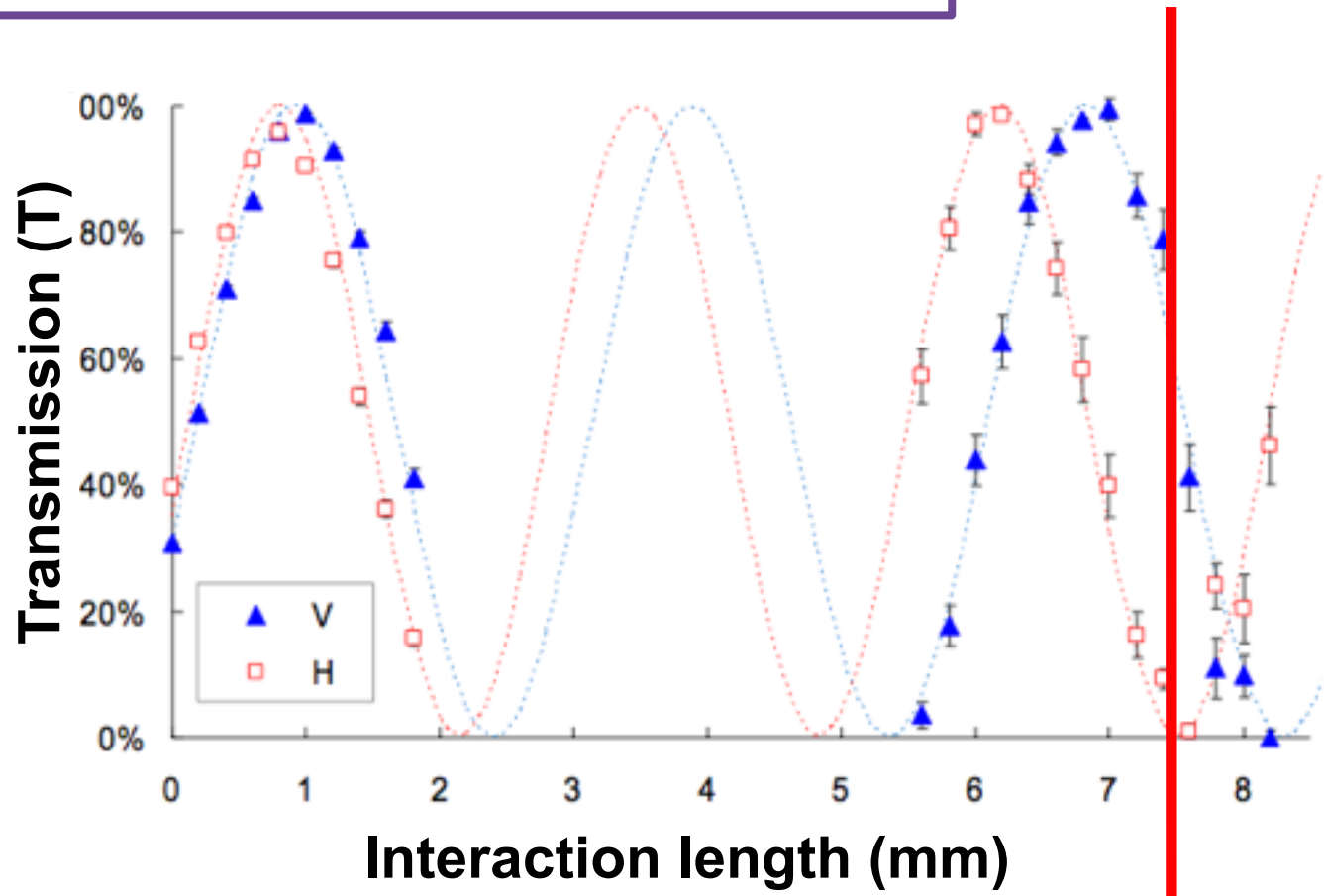
Interaction length → Transmission for horizontal polarization (T_H)

Transmission for vertical polarization (T_V)



Partially Polarizing Directional Couplers (PPDC)

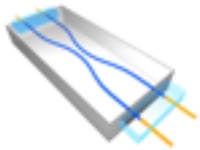




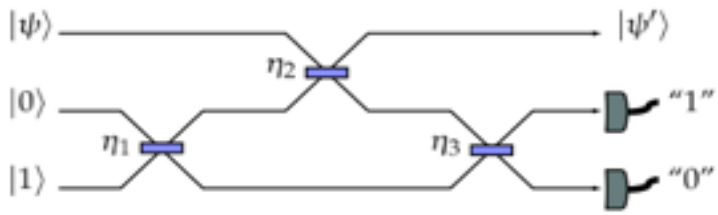
PPDC

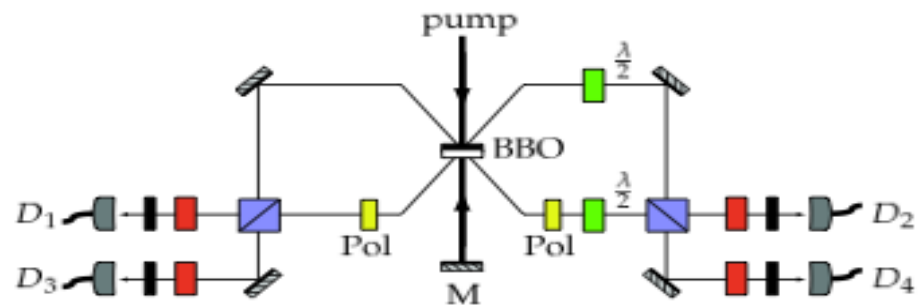
$T_H < 1\%$

$T_V = 64\%$



Linear optical quantum computing



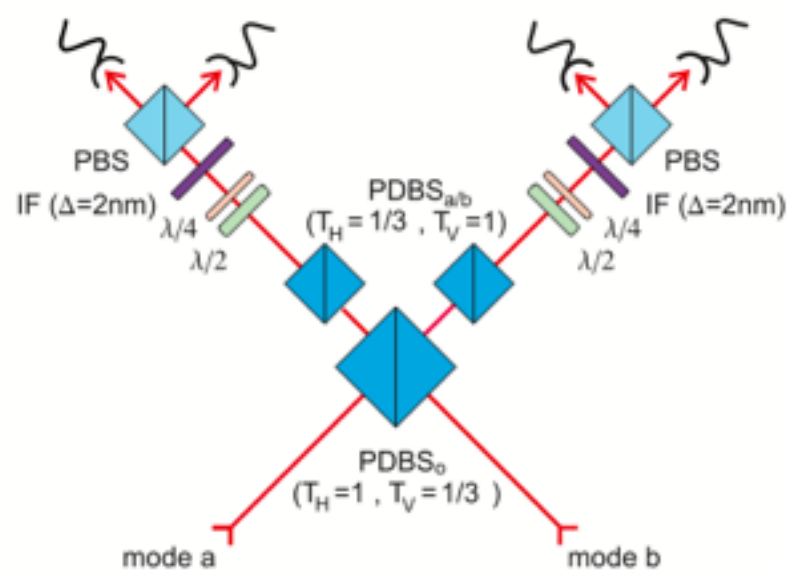


Knill et al., *Nature* **409**, 46 (2001).
Kok et al. *Rev. Mod. Phys.* **79**, 135 (2007)

CNOT gate for polarization qubit

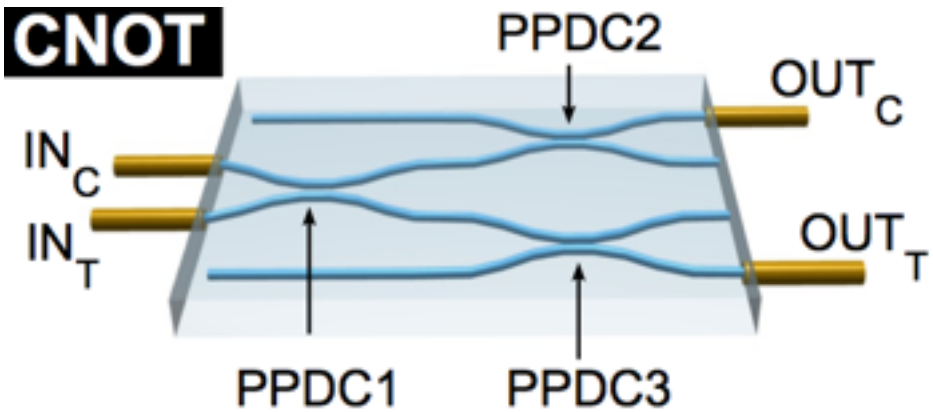
$$\{|0\rangle_C, |1\rangle_C\} \equiv \{|H\rangle, |V\rangle\}$$
$$\{|0\rangle_T, |1\rangle_T\} \equiv \{|D\rangle, |A\rangle\}$$

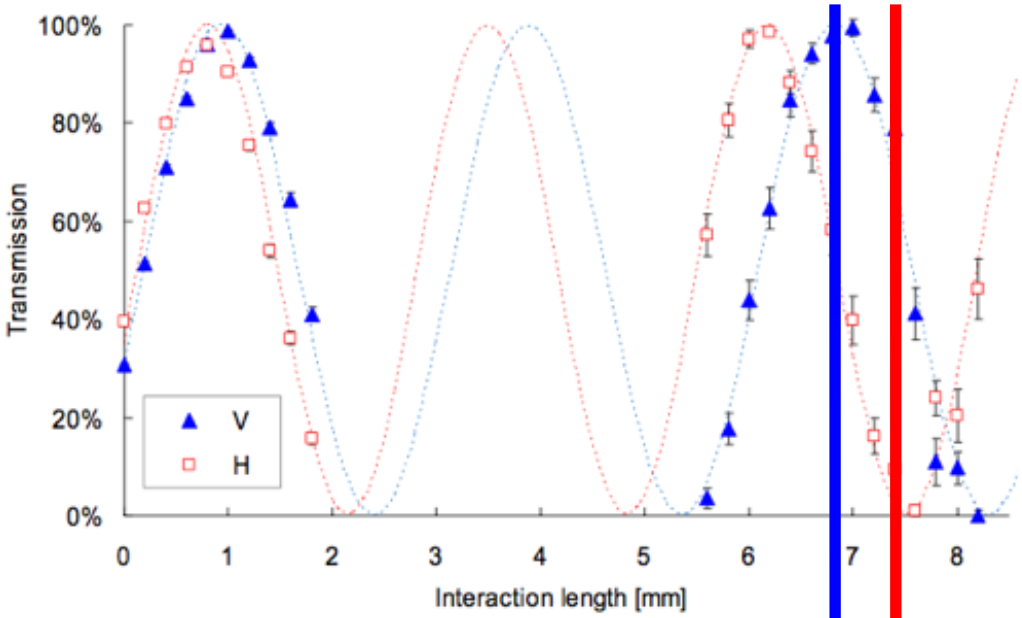
- **partial polarizing beam splitters**
- **post-selection**
- **success probability (p=1/9)**



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



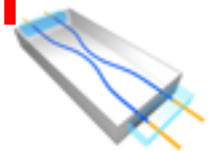


PPDC1
$T_H = 0$
$T_V = 2/3$

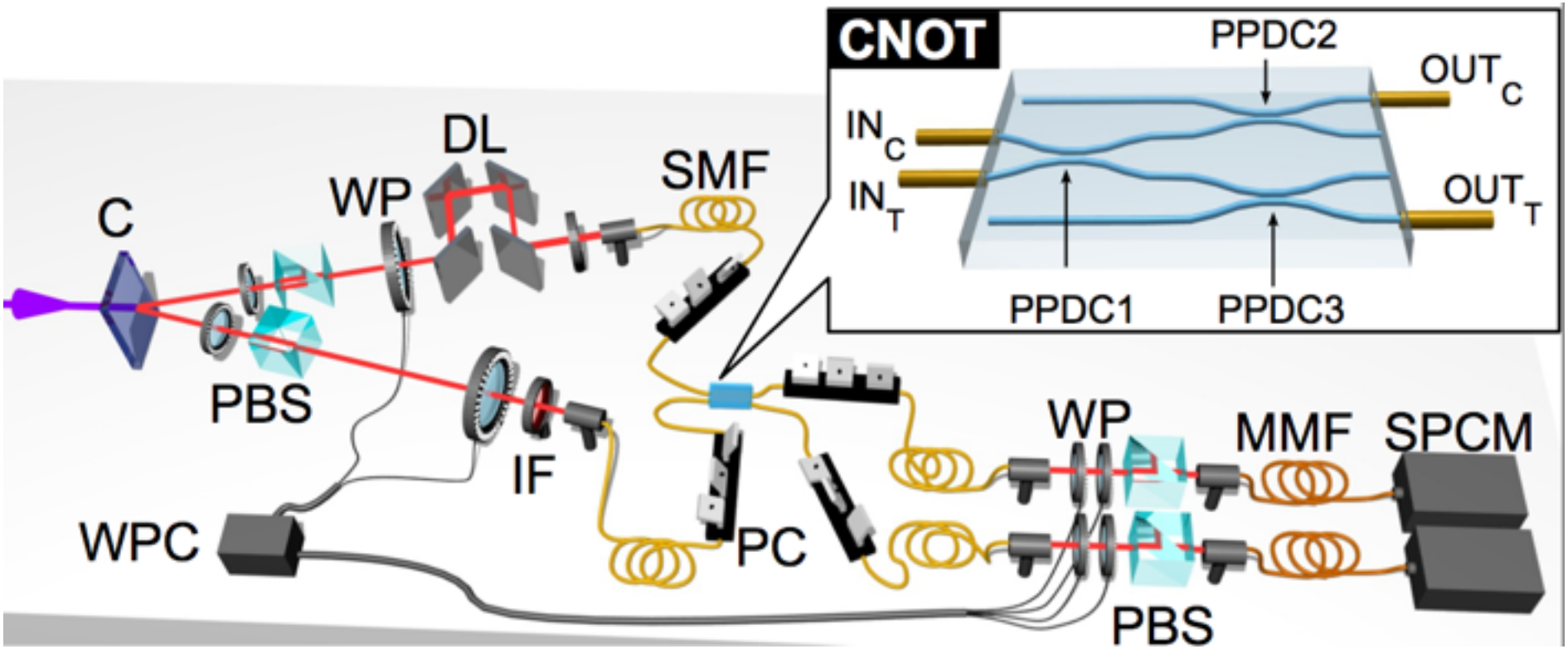
PPDC2 - PPDC3
$T_H = 1/3$
$T_V = 1$

PPDC2 - PPDC3
$T_H = 43\%, 27\%$
$T_V = 98\%, 93\%$

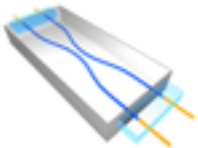
PPDC1
$T_H < 1\%$
$T_V = 64\%$



CNOT gate for polarization qubit



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



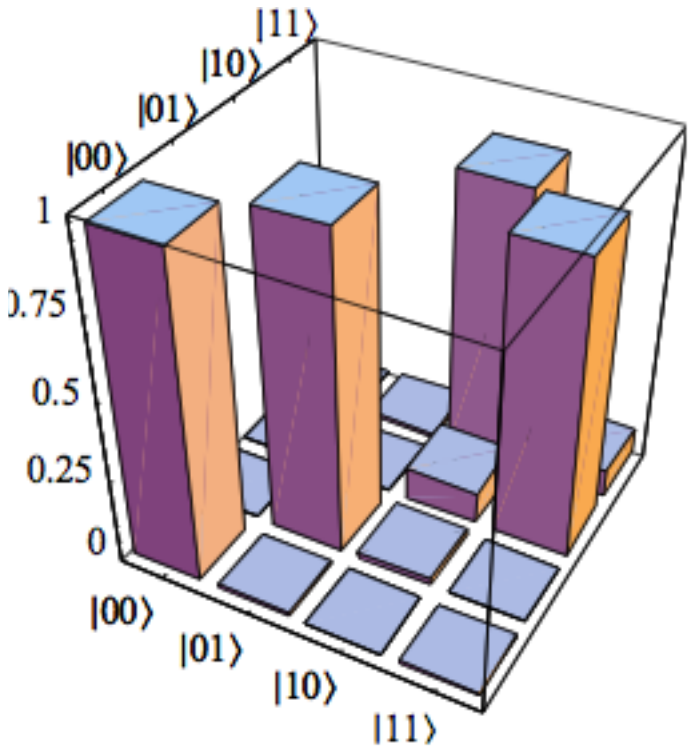
Truth table of the CNOT

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:

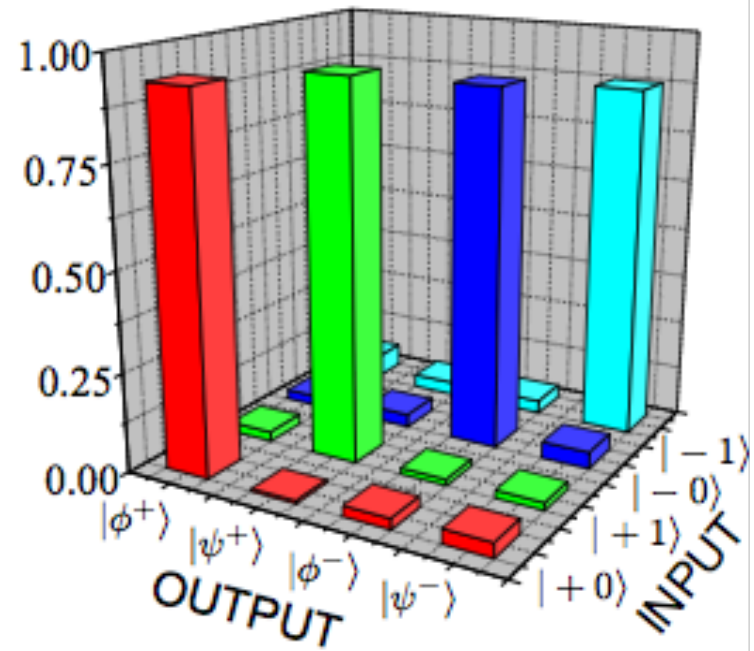


$F_{measured} = 0.940 \pm 0.004$.

Generation and discrimination of entangled states

Two-qubit gate

CNOT gate transforms entangled state into separable one and viceversa



F = 0.912 ± 0.004

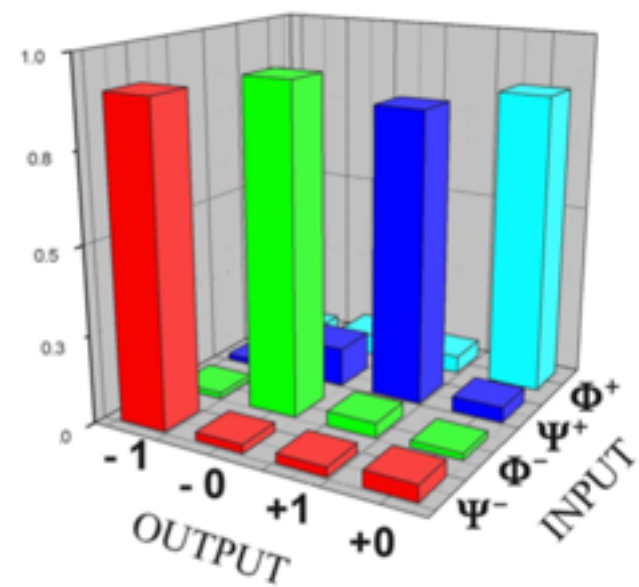
$$|+\rangle_C|0\rangle_T \rightleftharpoons |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|0\rangle_T + |1\rangle_C|1\rangle_T)$$

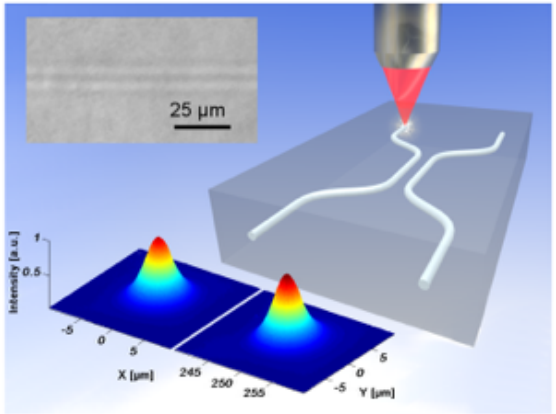
$$|+\rangle_C|1\rangle_T \rightleftharpoons |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_C|1\rangle_T + |1\rangle_C|0\rangle_T)$$

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

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

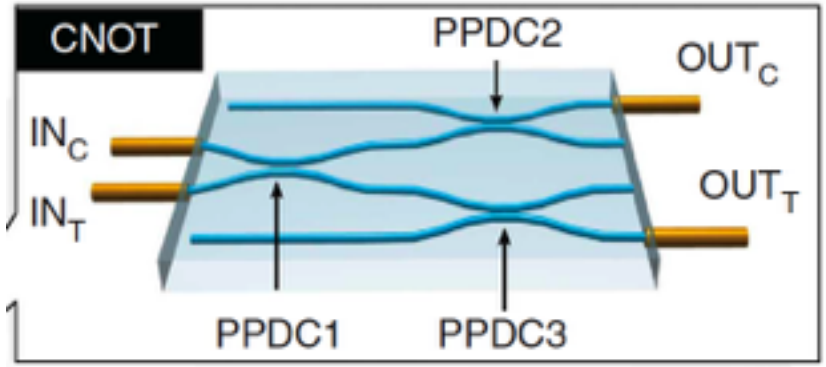
A. Crespi, *et al.*, quant-ph 1105.1454





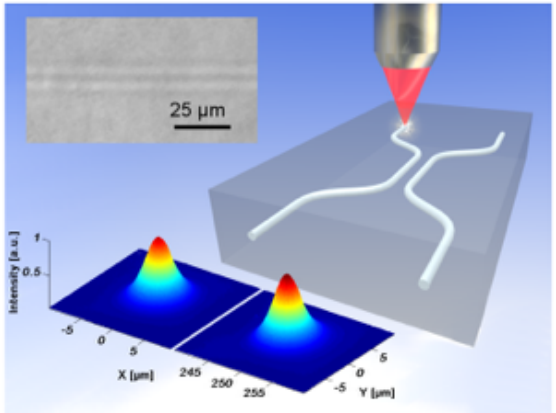
Directional coupler

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



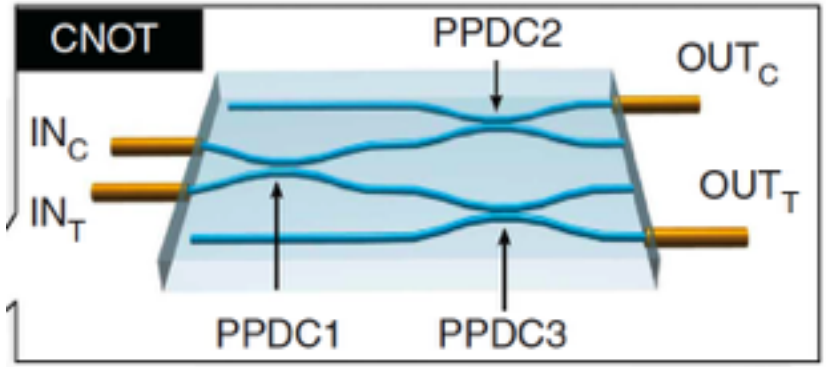
Partially polarizing and logical gate

A. Crespi et al., Nat. Comm. 2, 566 (2011)



Directional coupler

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

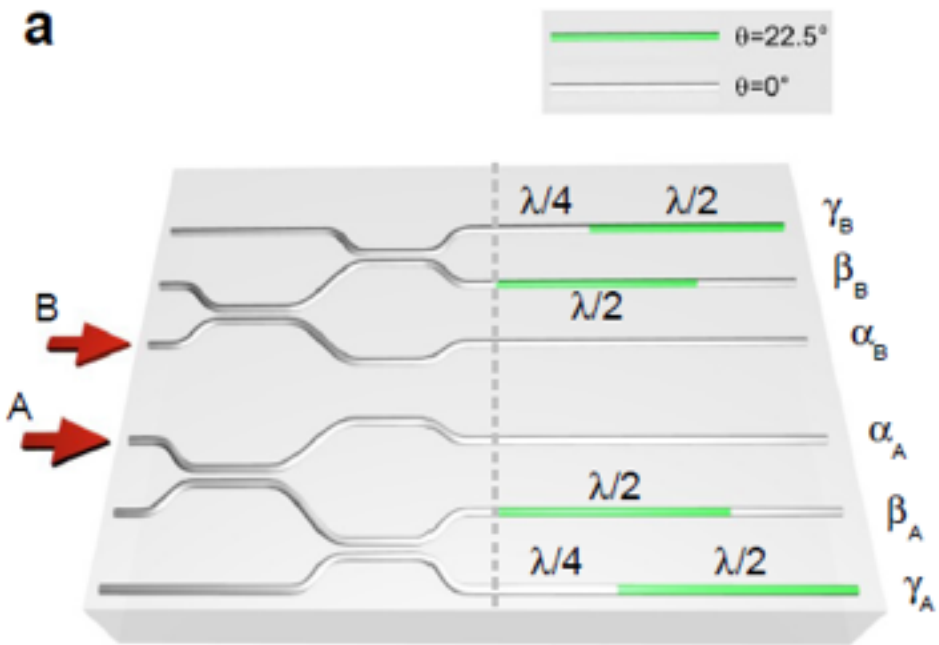


Partially polarizing and logical gate

A. Crespi et al., Nat. Comm. 2, 566 (2011)

Tunable waveplates

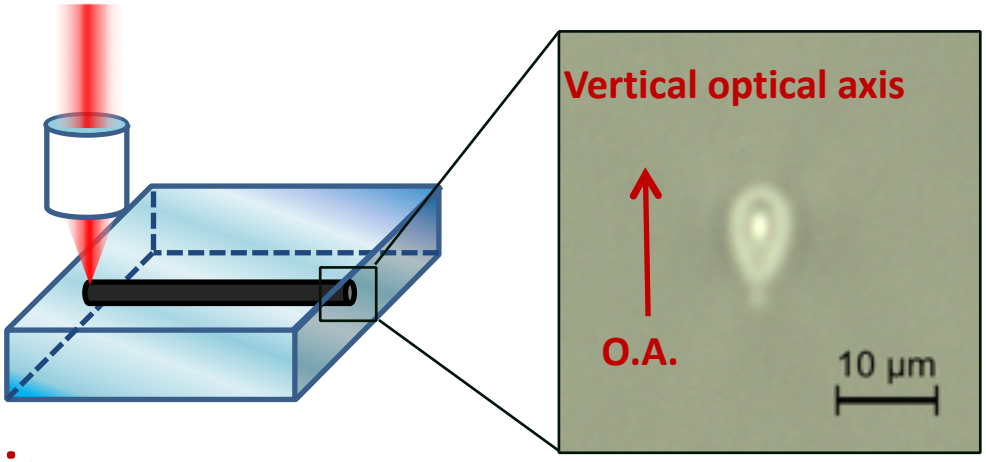
G. Corrielli et al., Nat. Comm. 5, 2549 (2014)



Integrated components for polarization manipulation

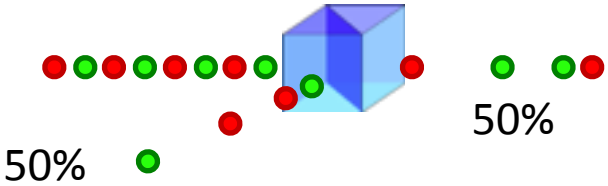
Waveguides fabricated by FLM are birefingent ($b = 10^{-5} \div 10^{-4}$)

- Asymmetric cross section
- Stress field accumulated in the substrate



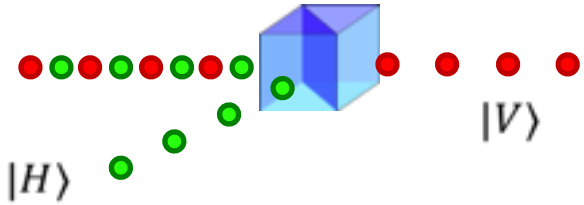
Waveplates... ...with fixed axis

- Beam splitter



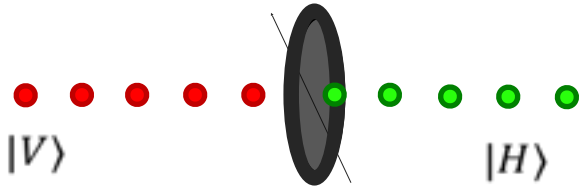
✓ **Demonstrated with laser writing**

- Polarizing Beam Splitter



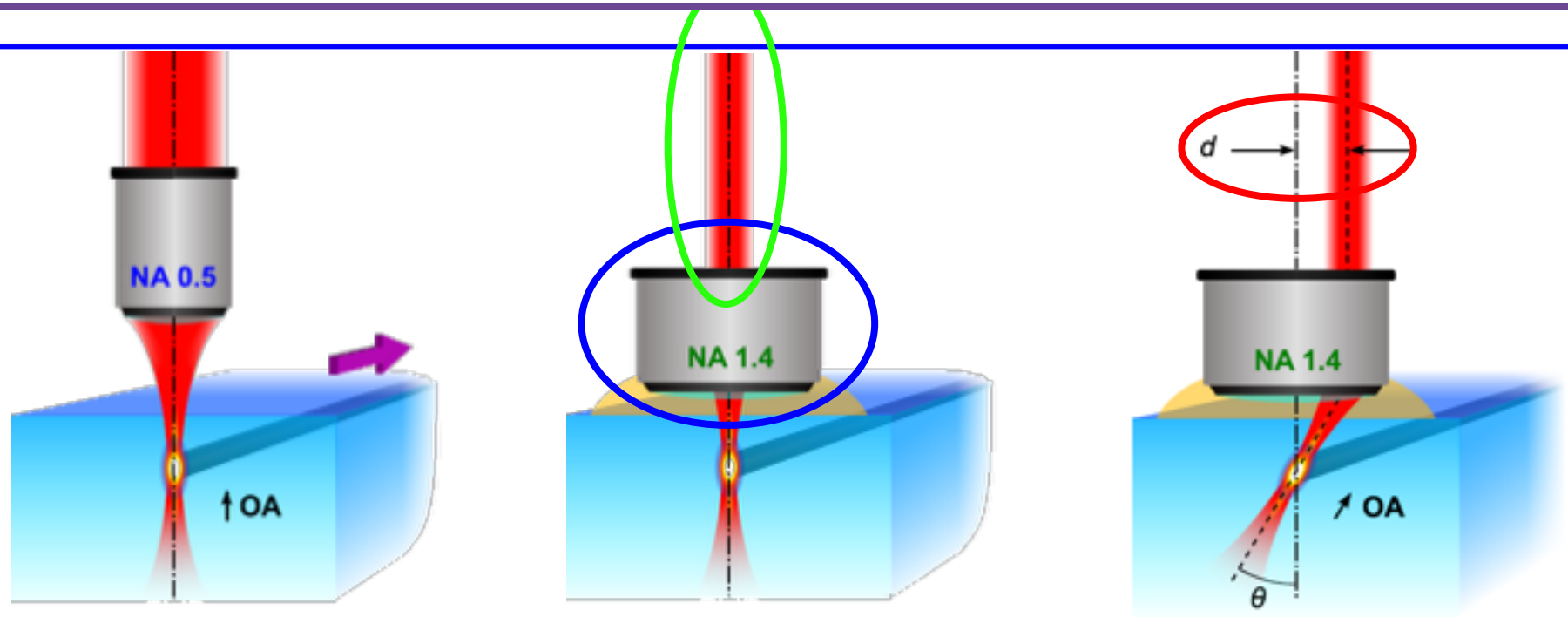
✓ **Demonstrated with laser writing**

- Waveplate with variable axis



✗ **Missing up to 2014**

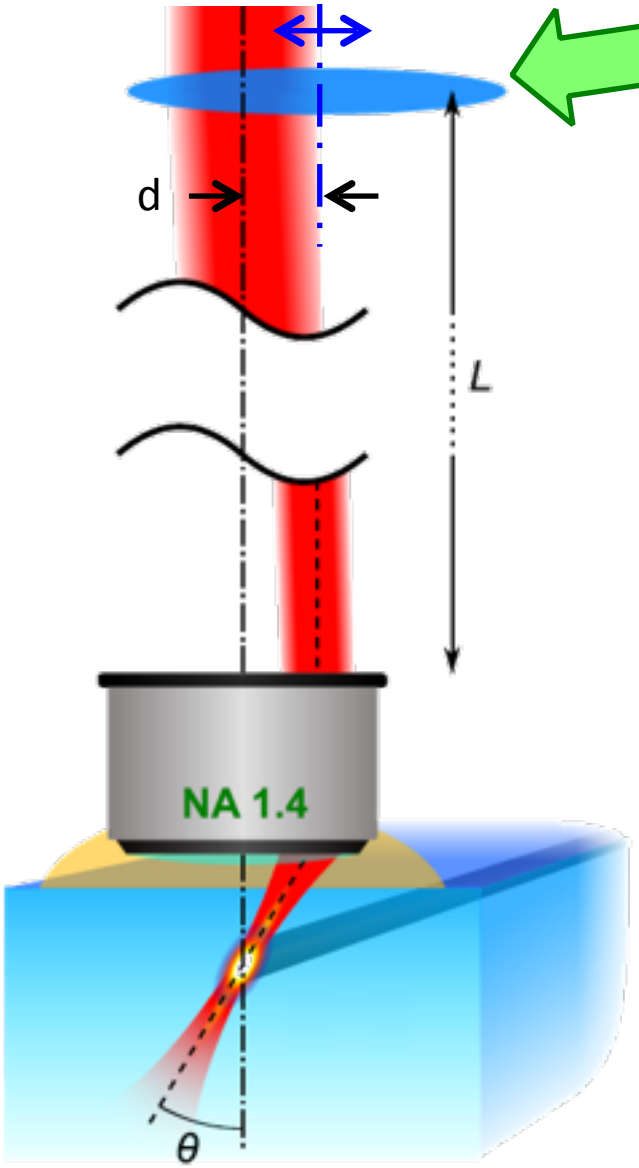
A new fabrication method



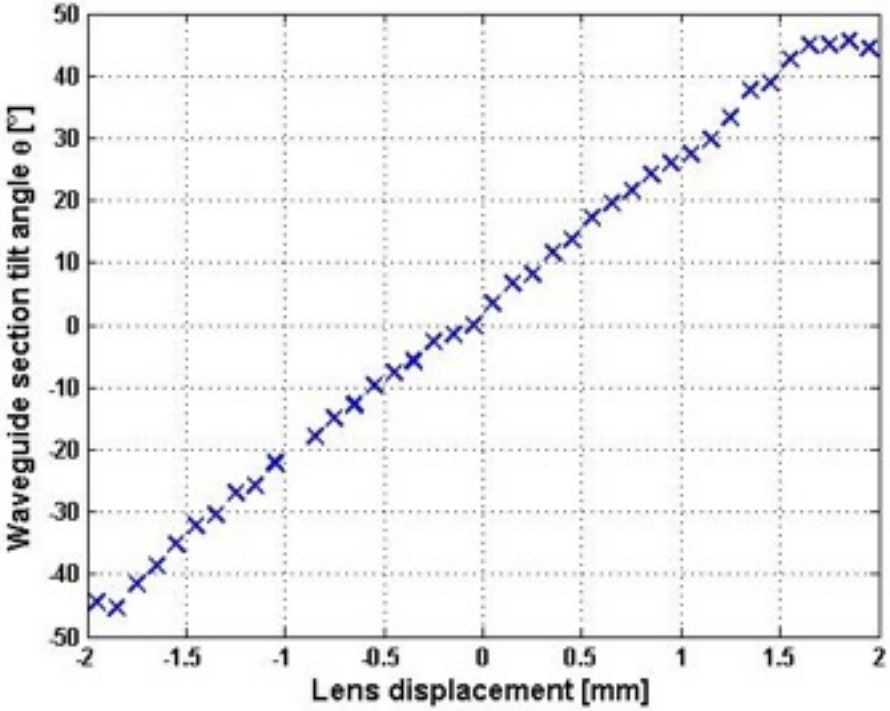
Patent n° MI2013A000631 Pending (2013), G. Corrielli et al, "Metodo di realizzazione di una guida d'onda in un substrato tramite laser a femtosecondi".

- 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.

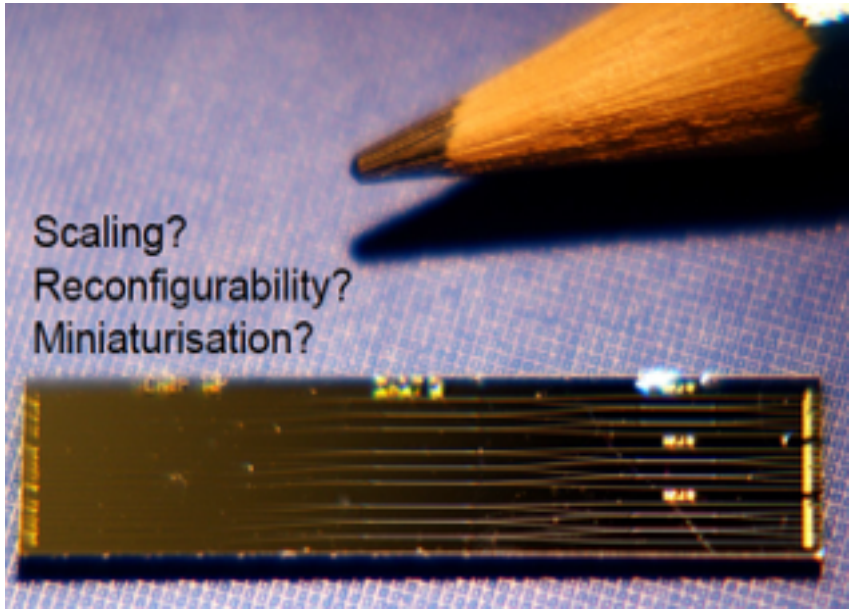
Fabrication of waveguide with tilted cross section

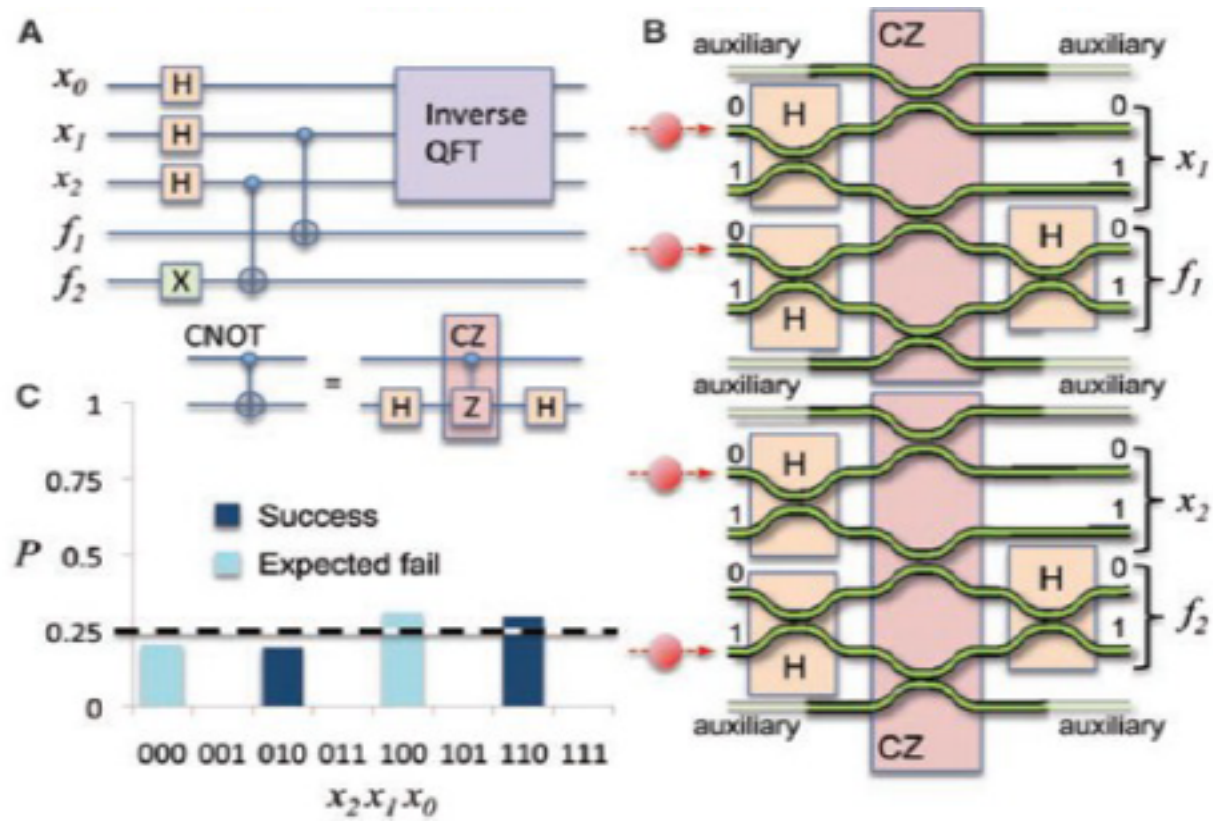


Spheric lens with <u>long focal distance</u>



Quantum factoring algorithm on a chip



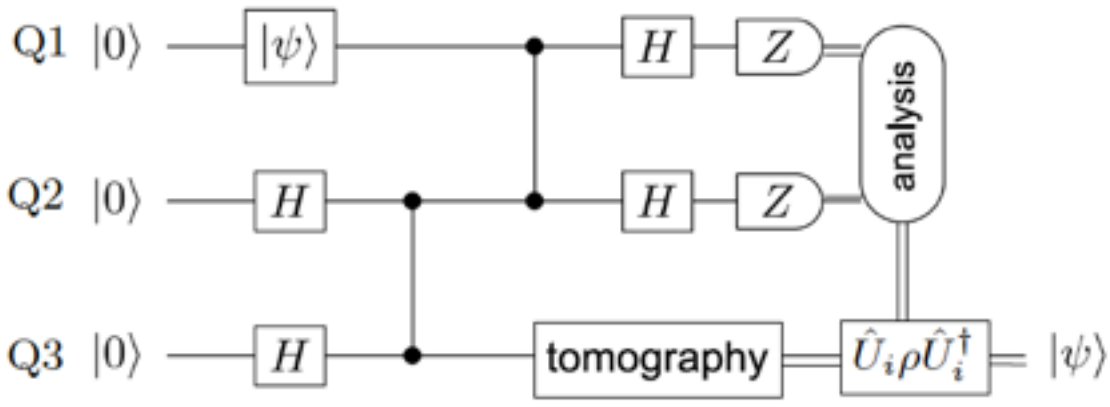


University of BRISTOL

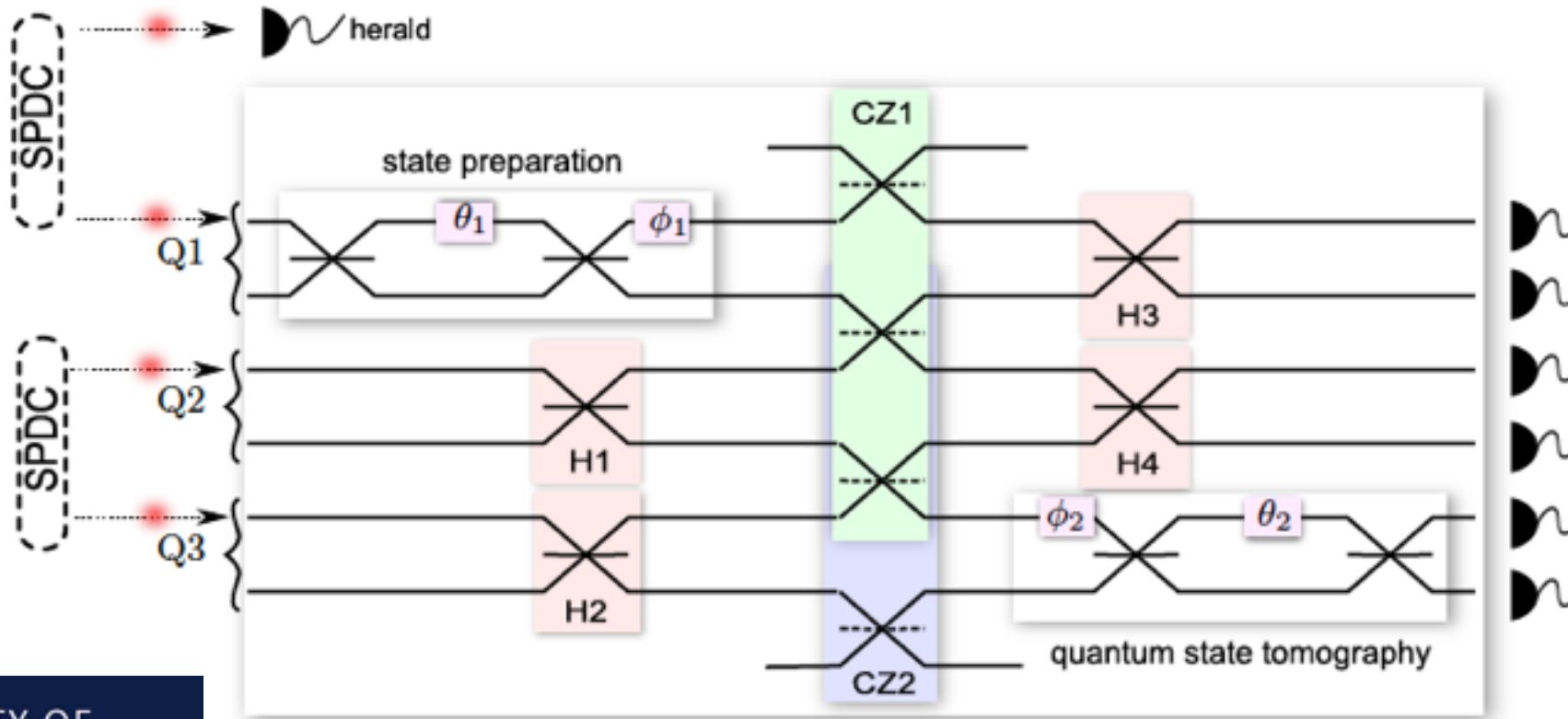
A. Politi et al., Science (2009)

Factoring 15

Quantum teleportation on a chip



2 C-NOT scheme
3 photons

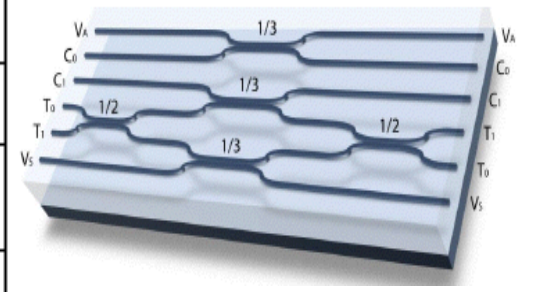


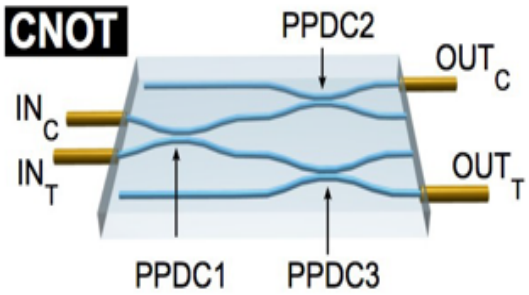
UNIVERSITY OF OXFORD

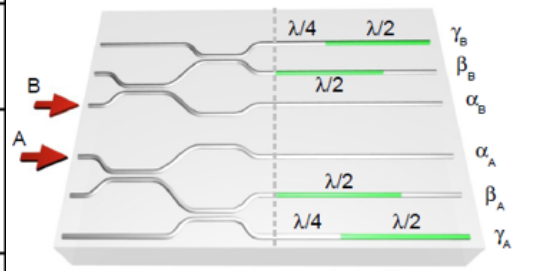
Nature Photonics 8, 770–774 (2014)

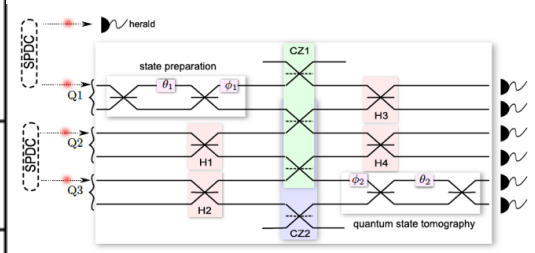
State of the art: linear optical quantum computing on chip

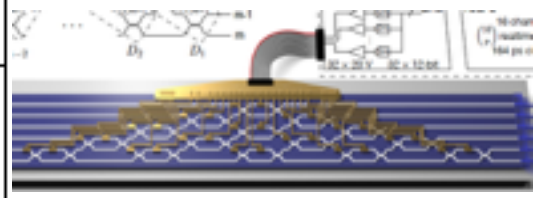
Year	Title	Group	Platform	n	m	Object
2008	Silica-on-silicon waveguide quantum circuits	Bristol	SoS	2	6	CNOT
2009	Shor's quantum factoring algorithm on a photonic chip	Bristol	SoS	2	12	Shor
2010	High-fidelity operation of quantum photonic circuits	Bristol, Queensland	SoS	2	6	CNOT
2011	Integrated photonic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





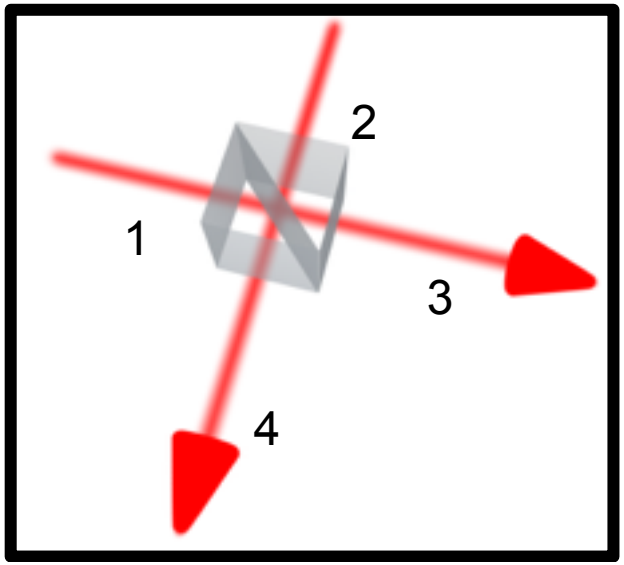




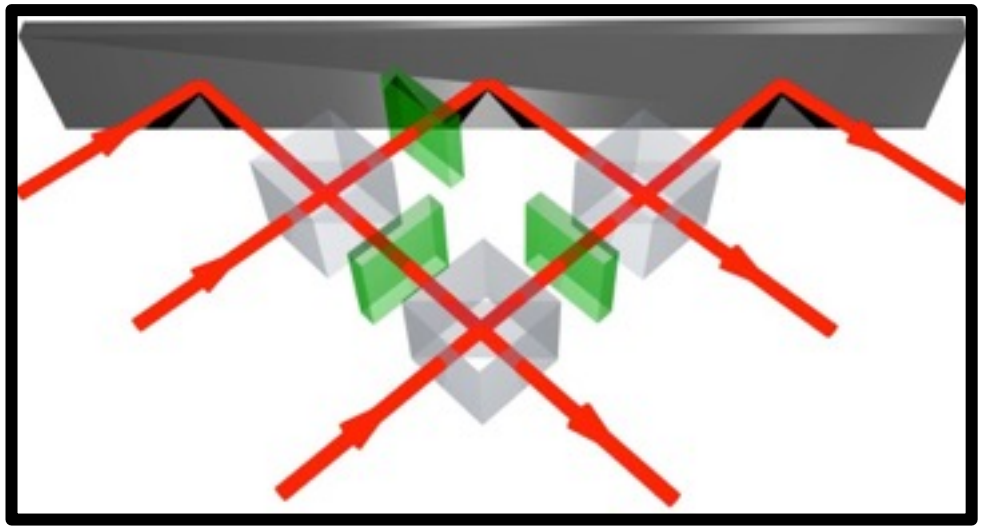


The tritter: a three-mode splitter

Two-mode symmetric interaction



Three-mode symmetric interaction, realized by bulk optics



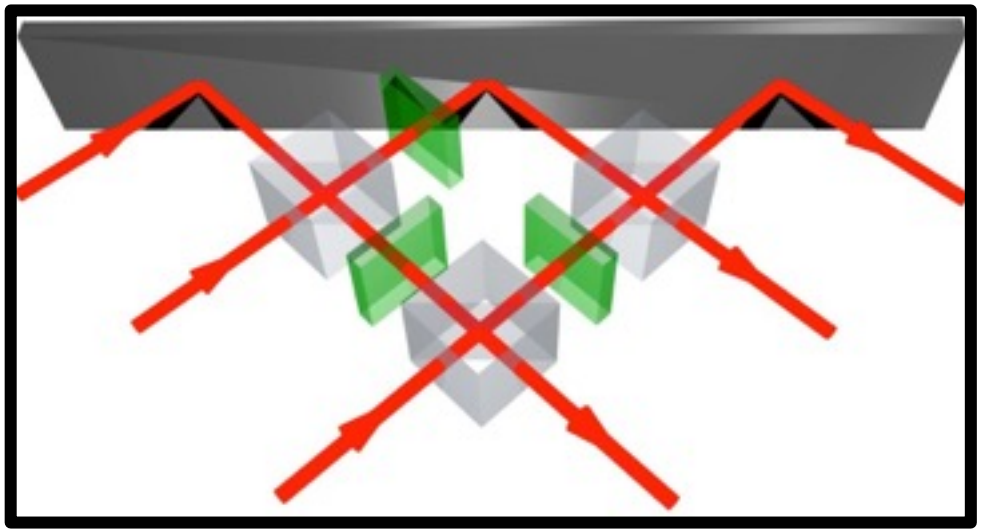
Tritter transfer matrix:

$$U = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & e^{\imath 2\pi/3} & e^{\imath 2\pi/3} \\ e^{\imath 2\pi/3} & 1 & e^{\imath 2\pi/3} \\ e^{\imath 2\pi/3} & e^{\imath 2\pi/3} & 1 \end{pmatrix}$$

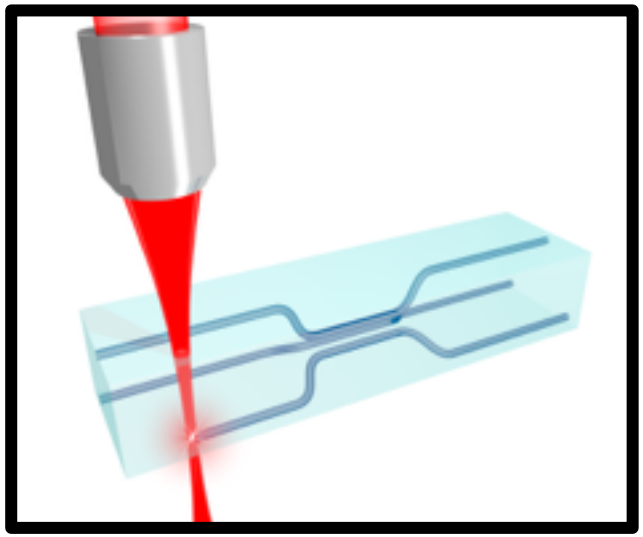
M. Reck, A. Zeillinger, H.J. Bernstein, and P. Bertani, Phys. Rev. Lett. **73**, 58-61 (1994)
M. Zukowski, A. Zeillinger, and A. Horne, Phys. Rev. A 55, 2561 (1997);
R. A. Campos, Phys. Rev. A 62, 013809 (2009).

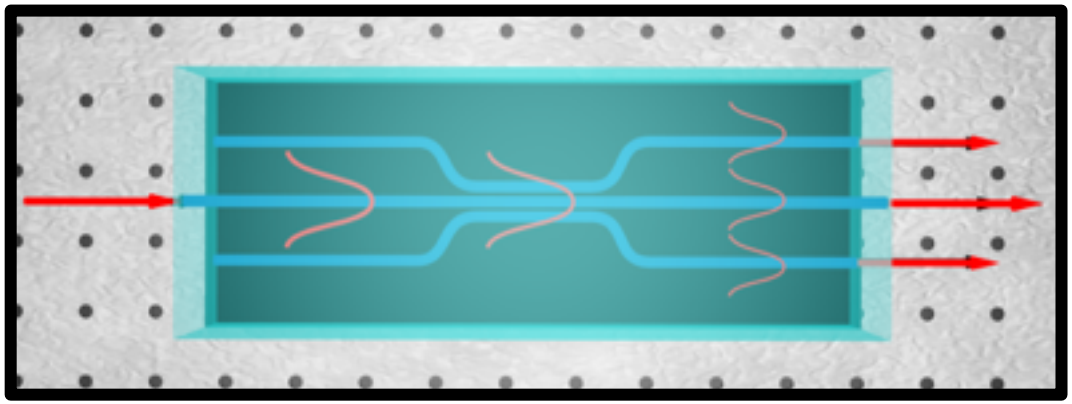
The tritter: a three-mode splitter

Multiport device realized by bulk optics



Femtosecond laser written circuit





A.M. Kowalevicz, V. Sharma, E. P. Ippen, J. G. Fujimoto and K. Minoshima, Optics Letters 30, 1060 (2005).

Interaction lenght:

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

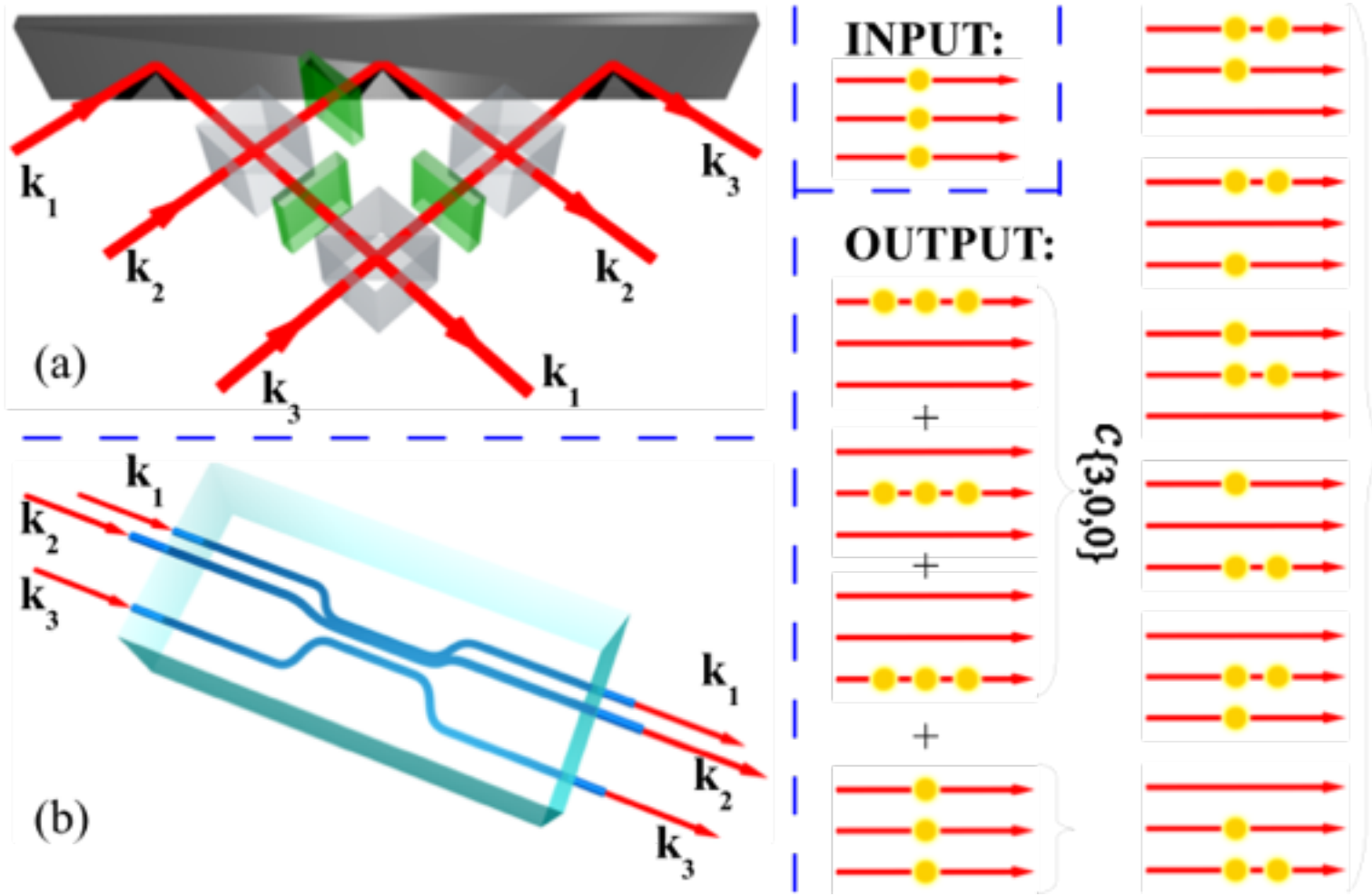
Simple integrated structure

↓

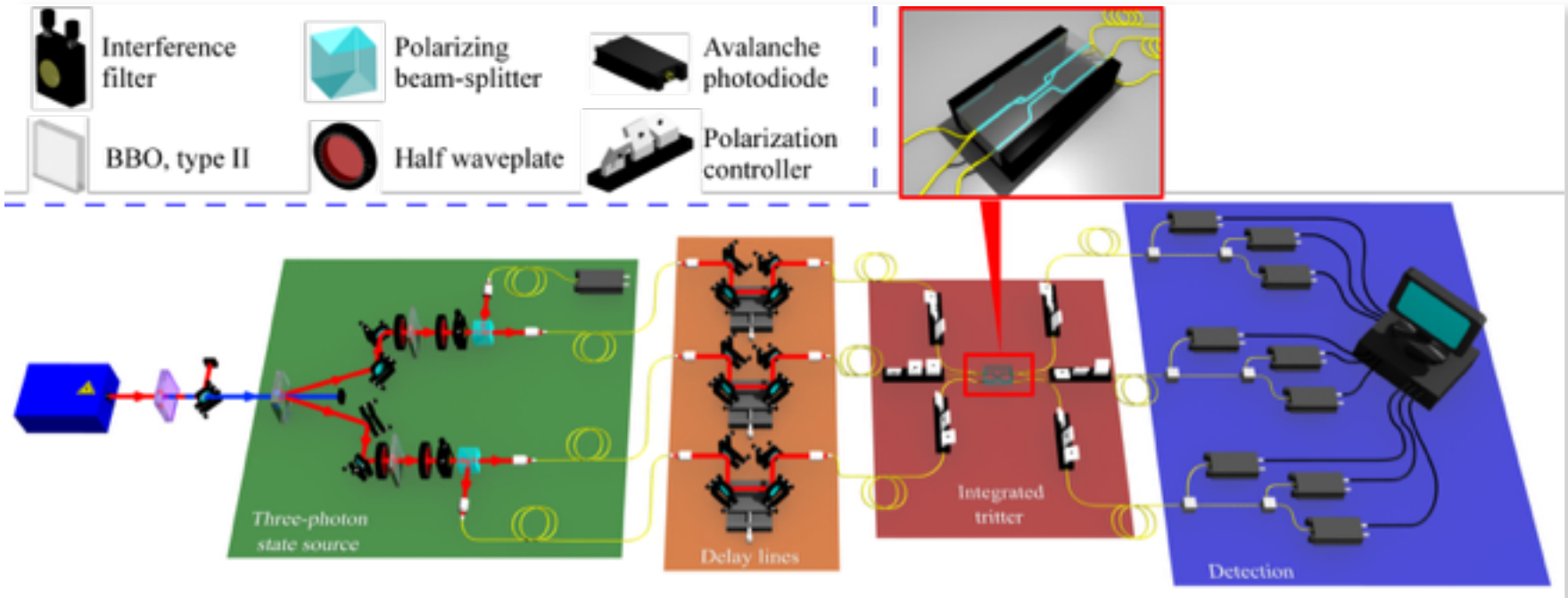
Simultaneous interference of the three modes

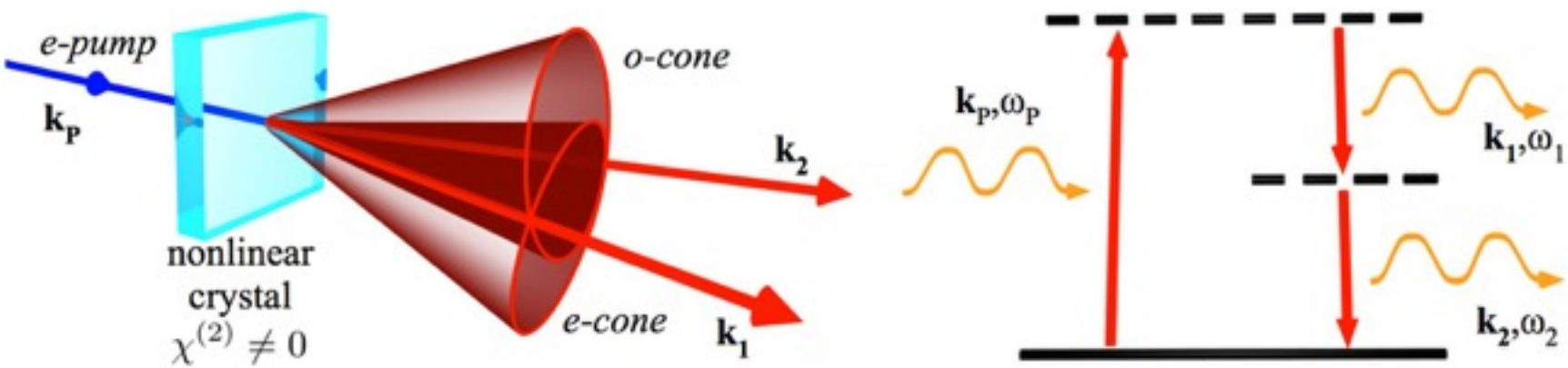
↓

Exploring three-photon interference



The tritter: apparatus





Transfer matrix reconstruction

$$\mathcal{M}_{i,j} = \begin{pmatrix} |\mathcal{M}_{1,1}| & |\mathcal{M}_{1,2}| & |\mathcal{M}_{1,3}| \\ |\mathcal{M}_{2,1}| & |\mathcal{M}_{2,2}|e^{\imath\phi_{2,2}} & |\mathcal{M}_{2,3}|e^{\imath\phi_{2,3}} \\ |\mathcal{M}_{3,1}| & |\mathcal{M}_{3,2}|e^{\imath\phi_{3,2}} & |\mathcal{M}_{3,3}|e^{\imath\phi_{3,3}} \end{pmatrix}$$

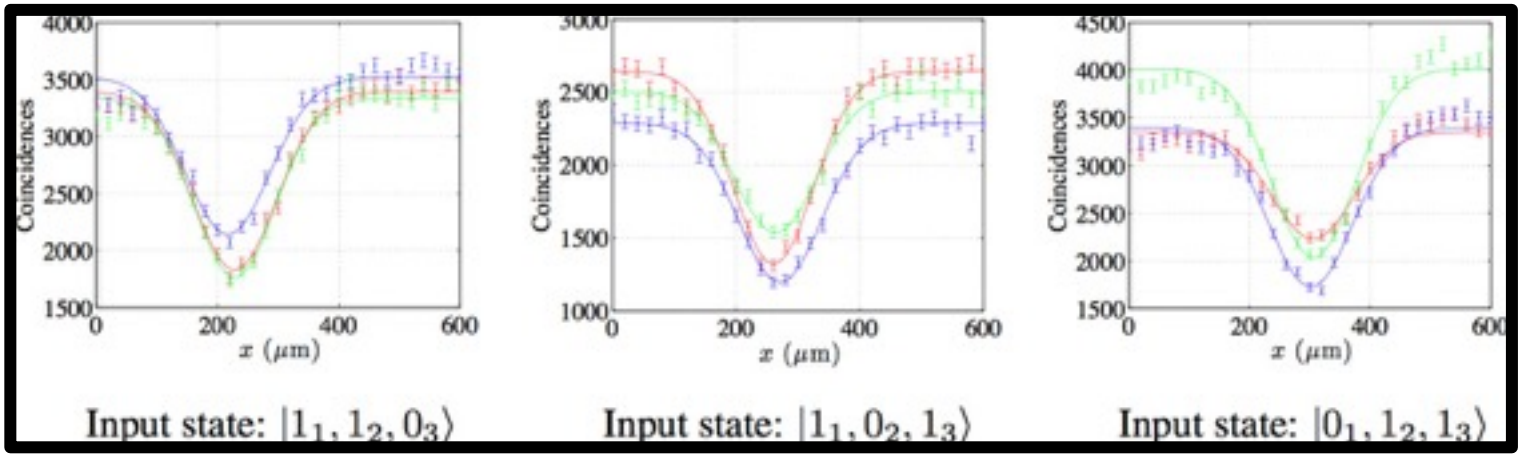
Step 1: Single photon input-output probabilities

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

	Output		
Input	1	2	3
1	0.37	0.34	0.29
2	0.33	0.32	0.37
3	0.28	0.38	0.35

Step 2: Two-photon Hong Ou Mandel interference

$$\mathcal{V}_{i,j;k,l} = \frac{P^{\mathrm{C}}_{i,j;k,l} - P^{\mathrm{Q}}_{i,j;k,l}}{P^{\mathrm{C}}_{i,j;k,l}}$$

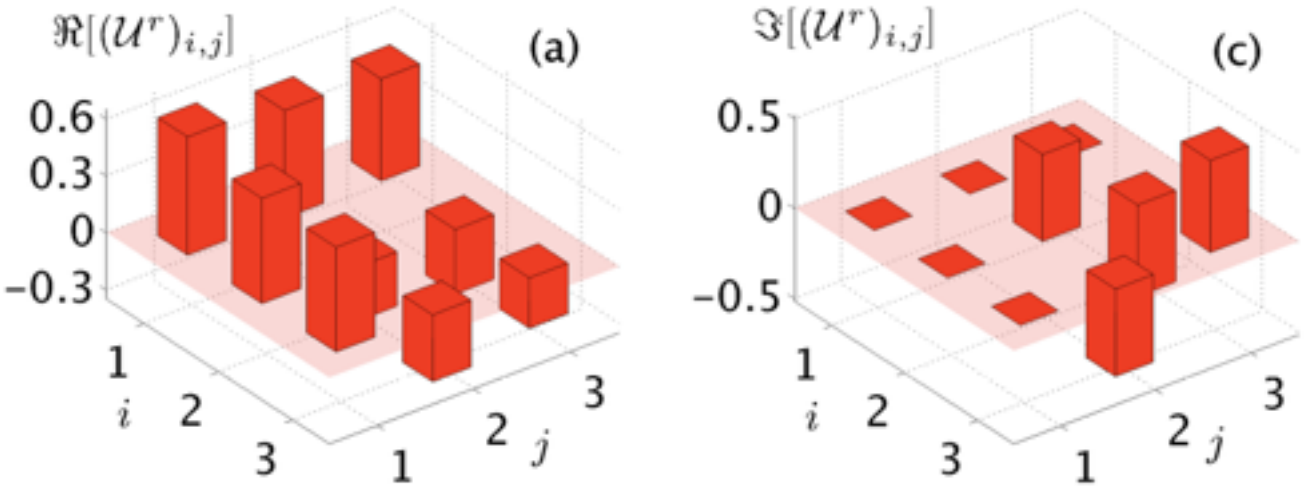


A. Peruzzo, A. Laing, A. Politi, T. Rudolph and J. O'Brien, Nature Communications 2, 349 (2011).
T. Meany, M. Delanty, S. Gross, G.D. Marshall, M. J. Steel and M. J.Withford , Opt. Expr. 20, 26895 (2012).

The tritter: a three-mode splitter

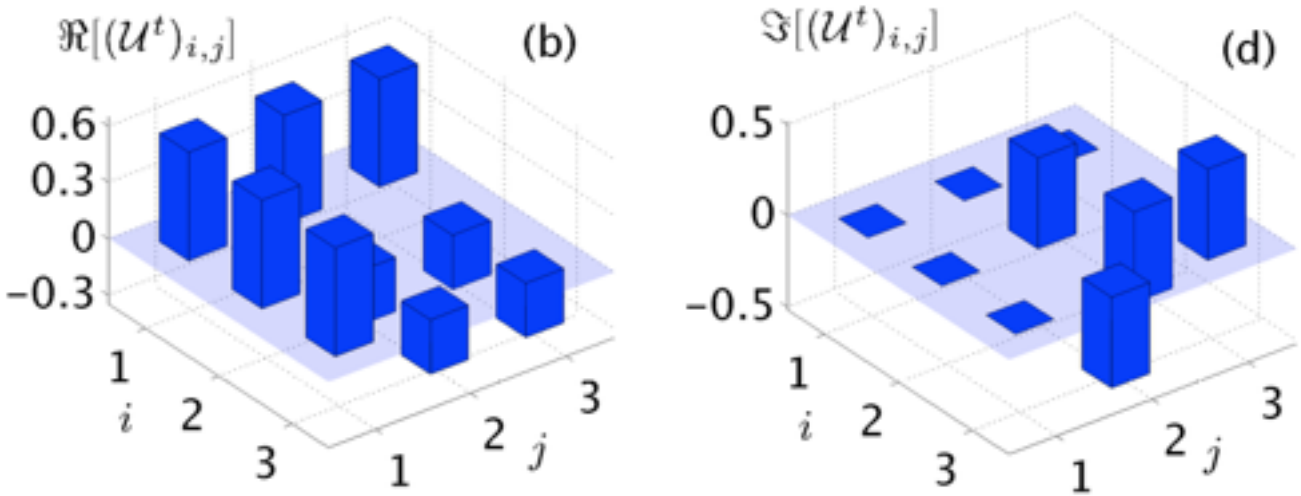
Tritter by femtosecond laser-writing

Experiment



Characterization of the tritter by single photon and two photon measurements

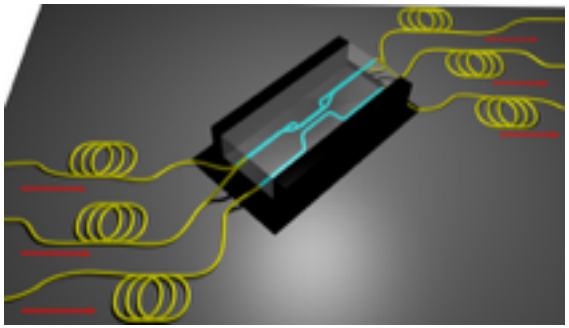
Theory



$$S = 0.973 \pm 0.001$$

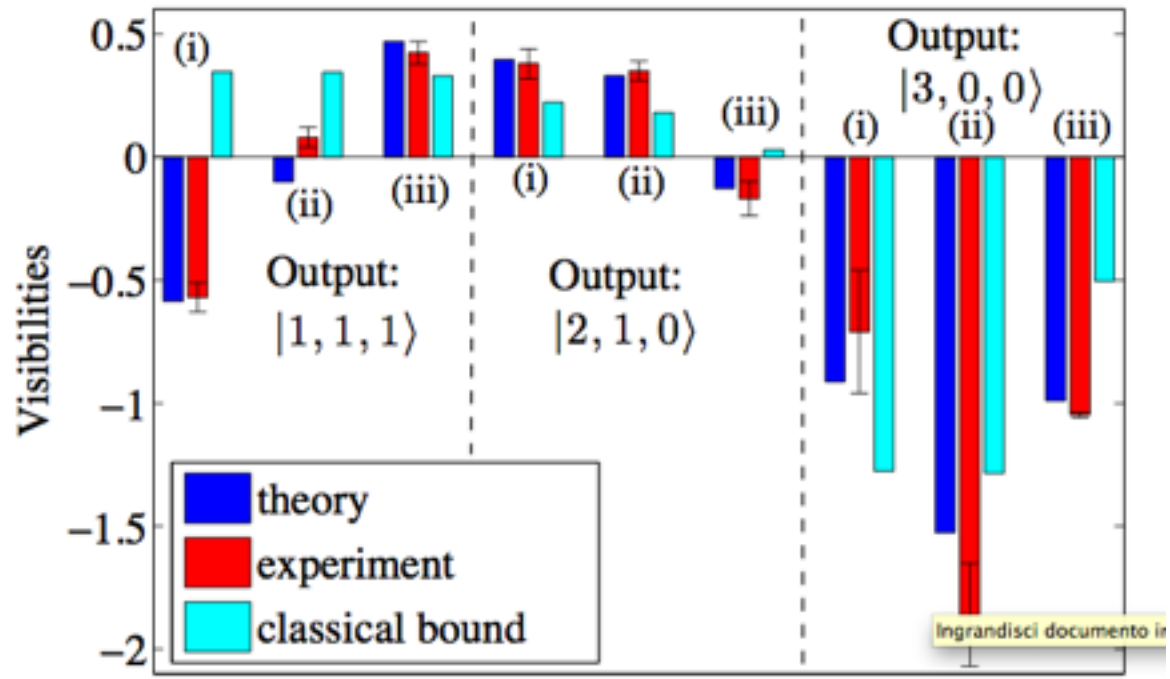
Photonic coalescence of 3 photons

Experimental three-photon bosonic coalescence



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

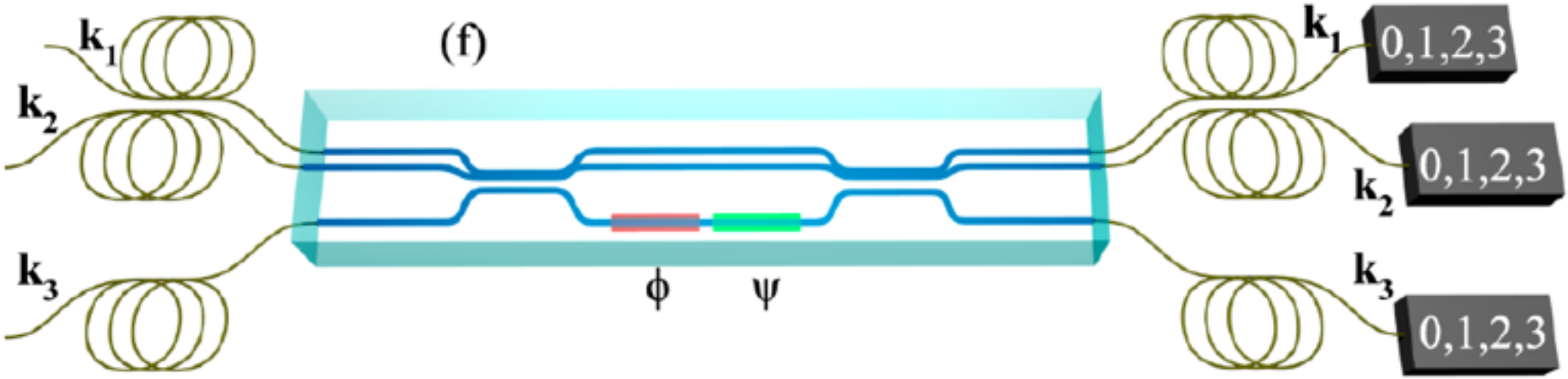
Model taking into account the reconstructed tritter matrix and photon distinguishability



Visibilities outperform the classical bound for coherent state inputs

N. Spagnolo, C. Vitelli, L. Aparo, P. Mataloni, F. Sciarrino, A. Crespi, R. Ramponi, R. Osellame, "Three-photon bosonic coalescence in an integrated tritter", *Nature Communications* **4**, 1606 (2013)

3D Quantum Interferometry

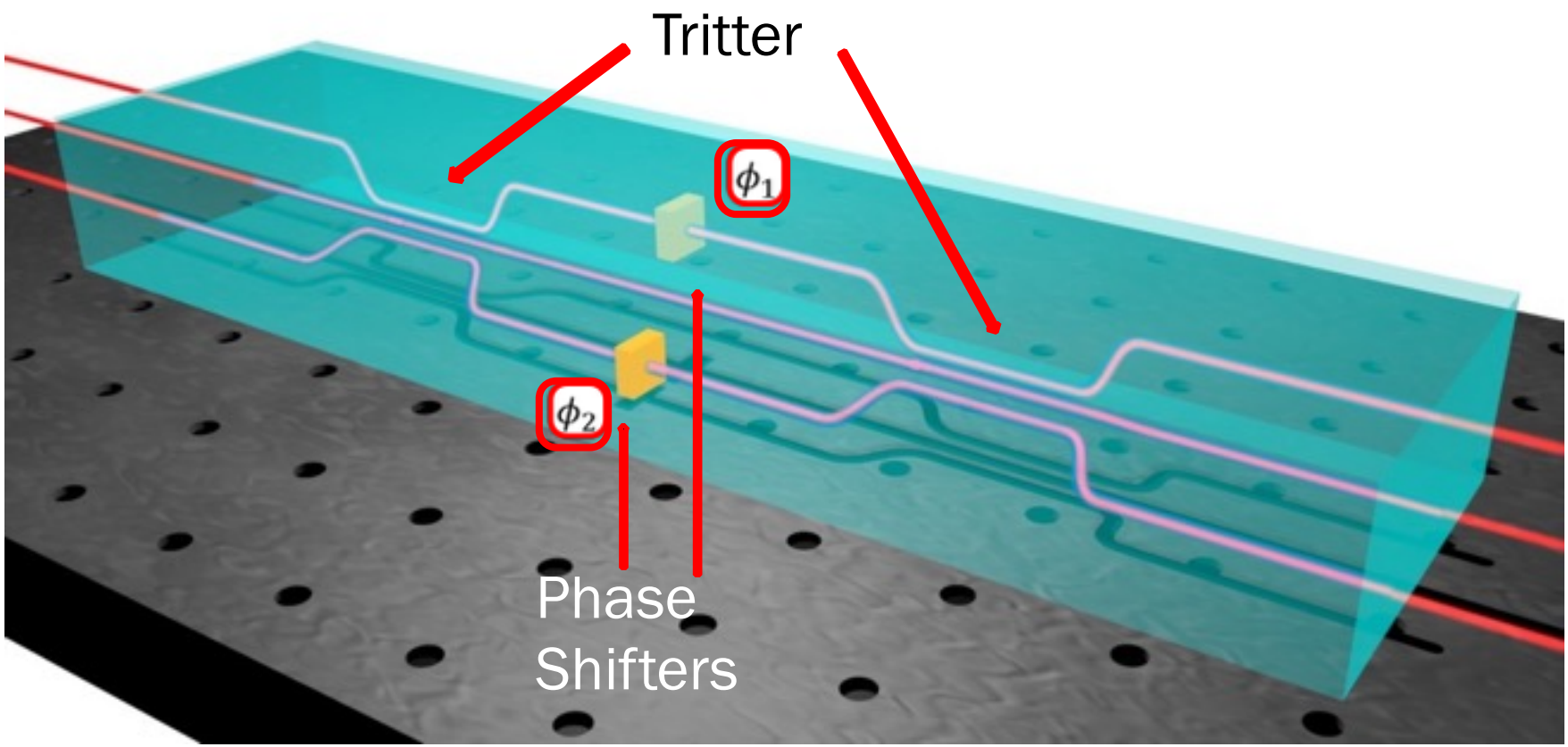


Designing interferometric structures for:

- **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).

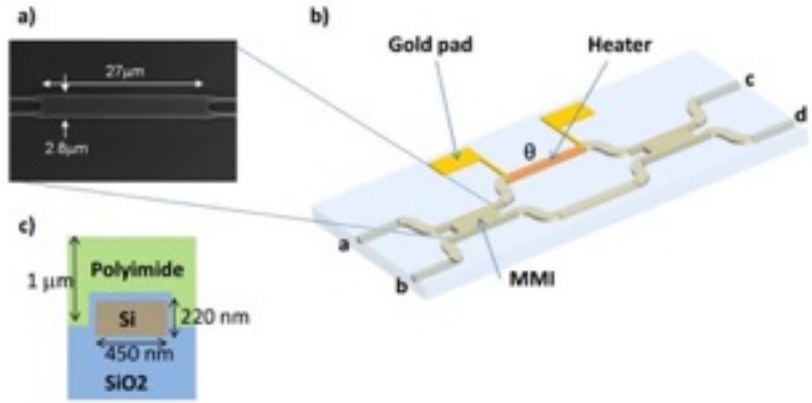
3D Quantum Interferometry: multiparameter estimation



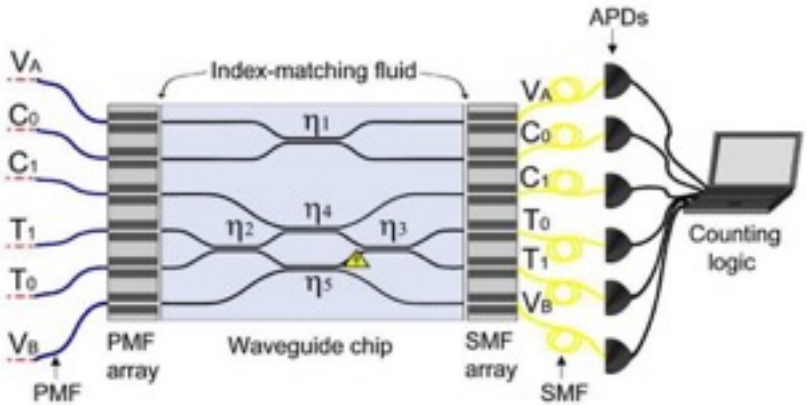
1) What happens if we inject multiple unknown phases inside the interferometer?
2) What are the limits on the simultaneous estimation of multiple parameter?
3) Quantum resources = better estimation?
4) Is there an optimal measurement?

M. A. Ciampini, N. Spagnolo, C. Vitelli, L. Pezzè, A. Smerzi, F. Sciarrino,
"Quantum-enhanced multiparameter estimation in multiarm interferometers", Scientific Reports **6**, 28881 (2015).

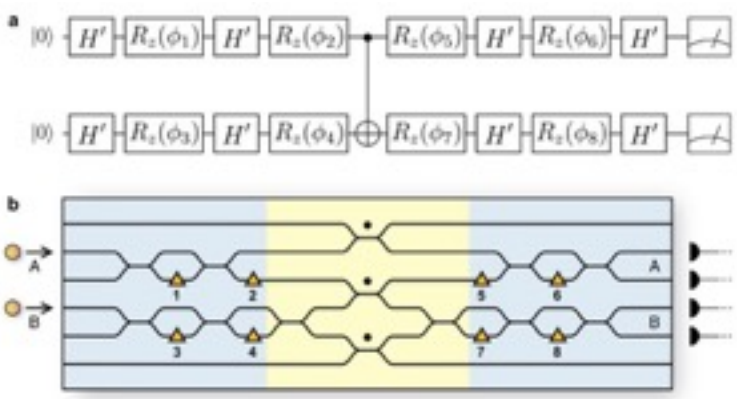
Integrated tunable circuits



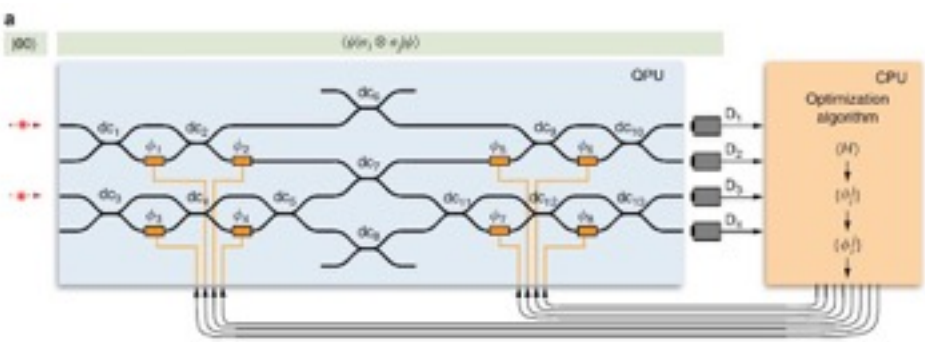
Multimode interference coupler and MZ interferometer. Bonneau et al. *NJP*, 14(4) (2012)



Reconfigurable controlled 2-qubit gate. Li et al. New Journal of Physics, (13) 115009, (2011)

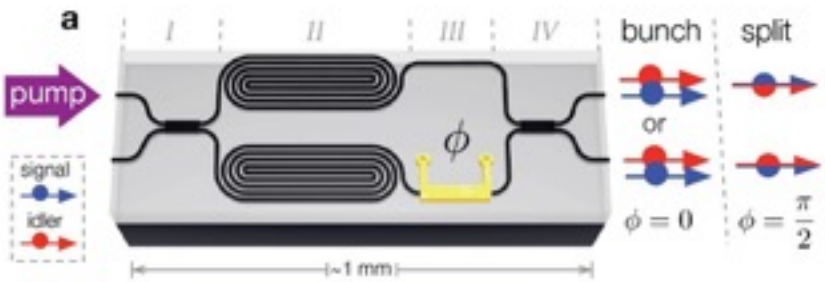


Generation, manipulation and measurement of entanglement. Shadbolt et al. *Nature Photonics 6, 45-49 (2012)*

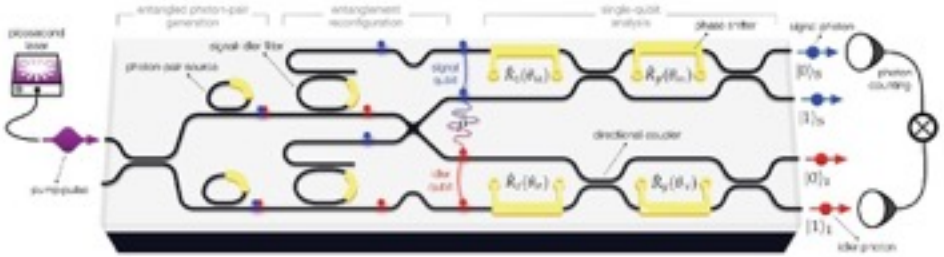


Eigenvalue solver. Peruzzo et al. *Nature Communications 5, 4213 (2013)*

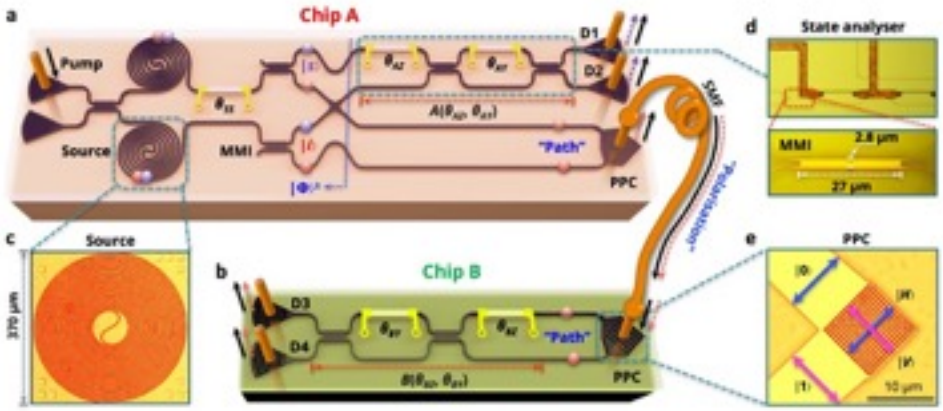
Integrated tunable circuits



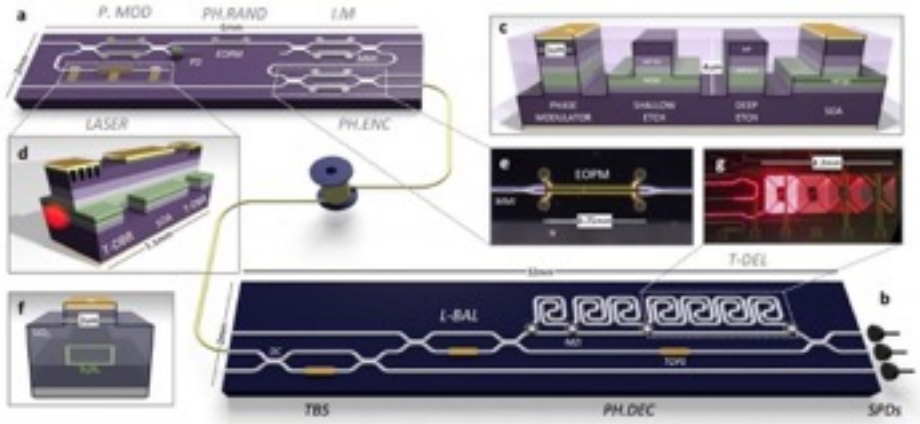
On-chip photon generation and interference. Silverstone et al. *Nature Photonics 6, 104-108 (2014)*



Generation and analysis of path-entangled two-qubit states. Silverstone et al. *Nature Communications 6, 7948 (2015)*

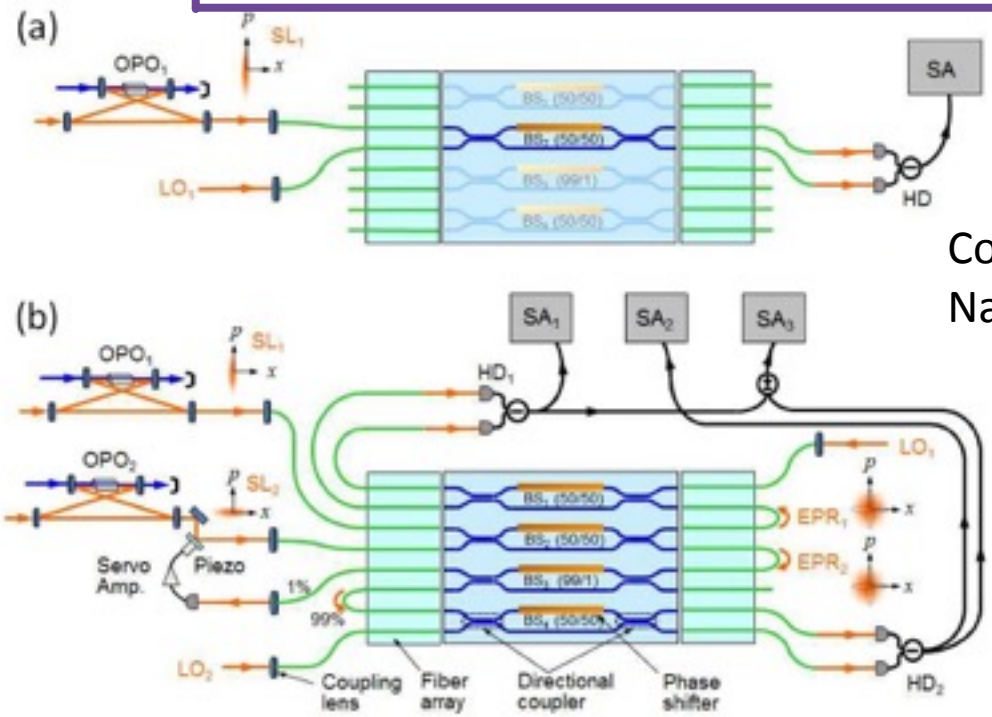


Interconnection and entanglement distribution between distant chips. Wang et al. *Optica 3(4), 7948 (2016)*

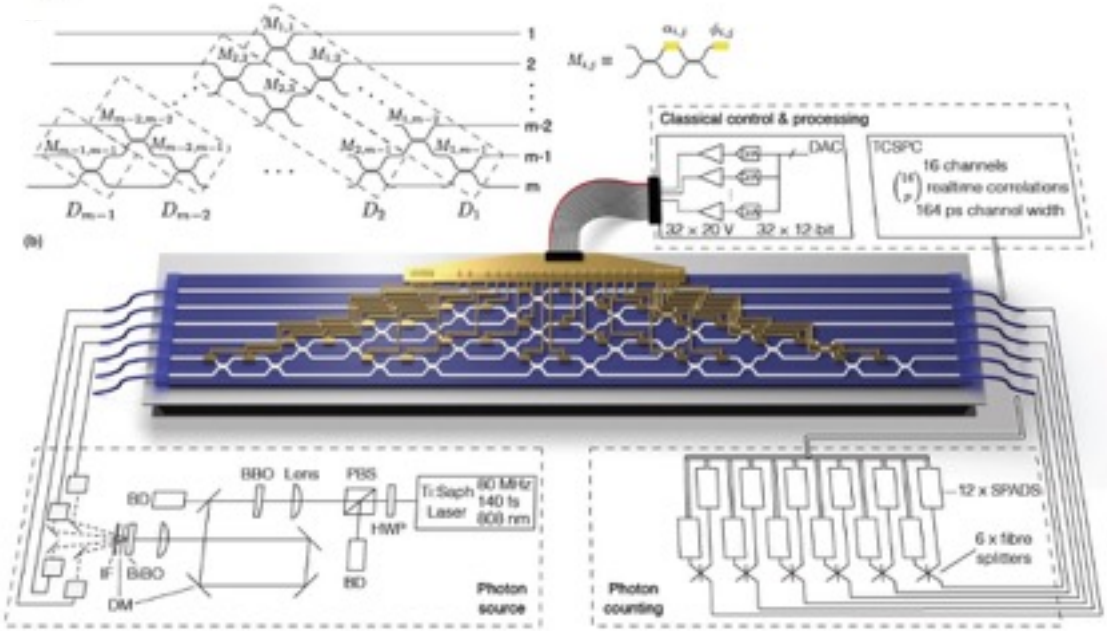


Chip-based QKD. Sibson et al., arXiv 1509.00768 *(2015)*

Integrated tunable circuits

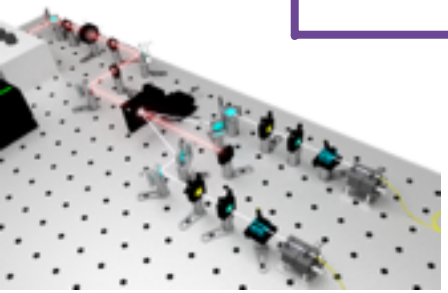


Continuous variable entanglement. Masada et al., Nature Photonics 9, 316-319 *(2015)*

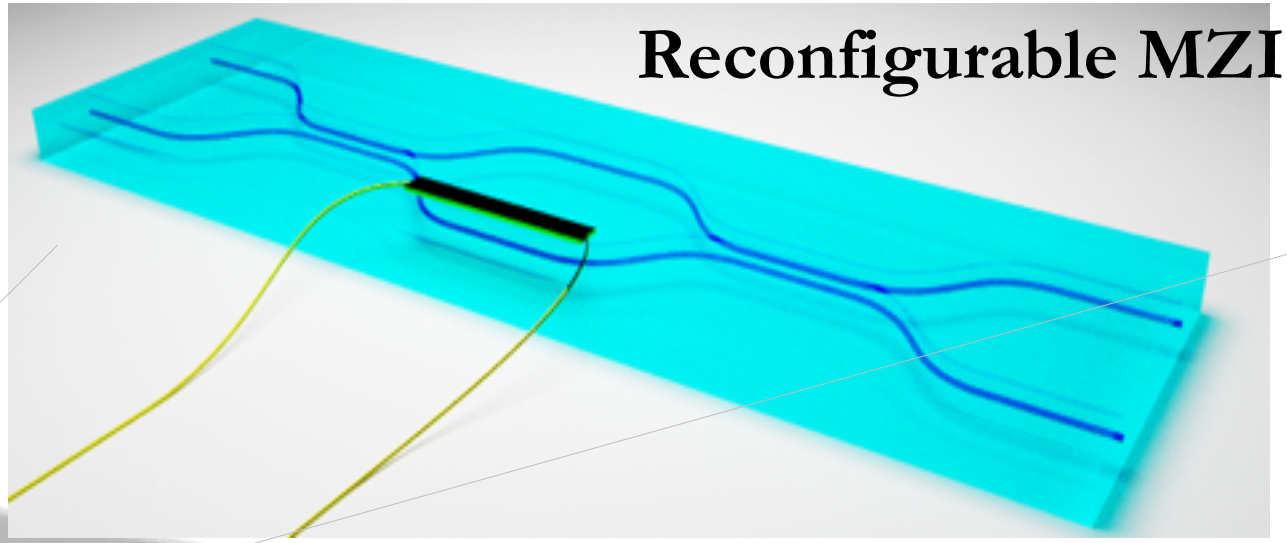


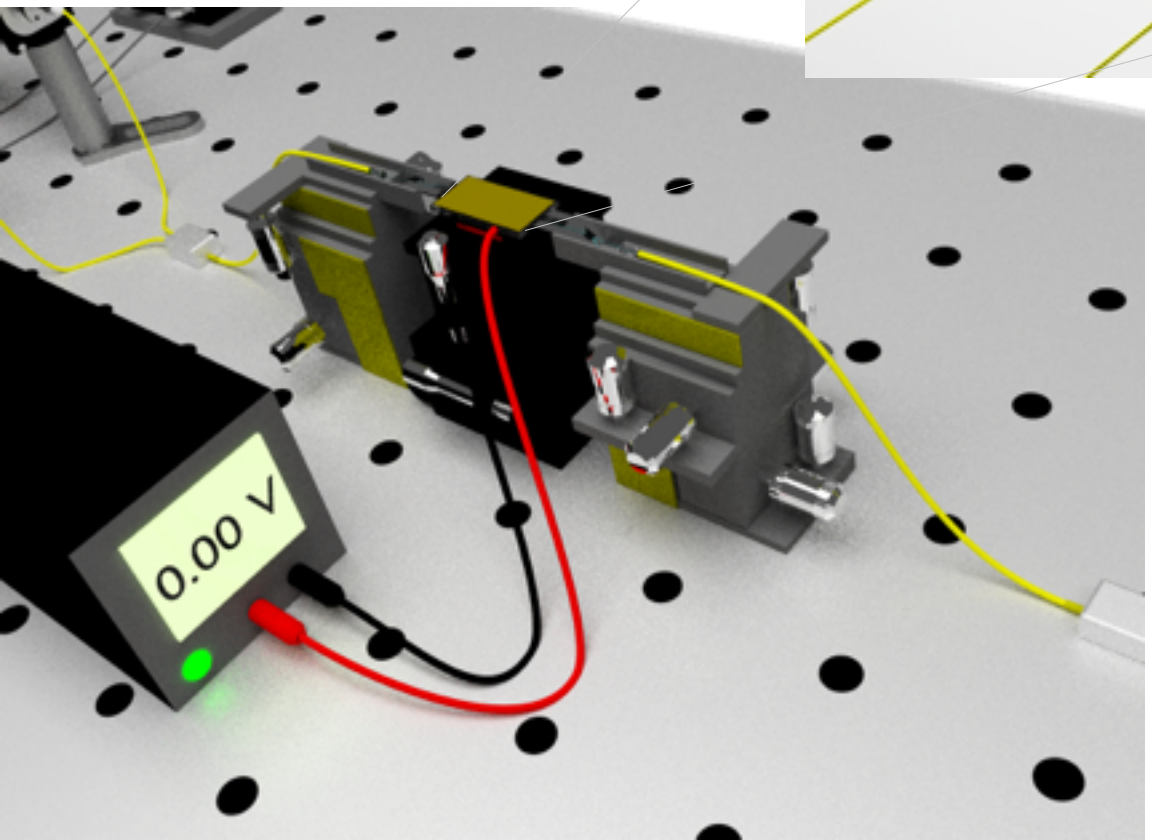
Universal 6-mode chip. Carolan et al., Science 349, 6249 *(2015)*

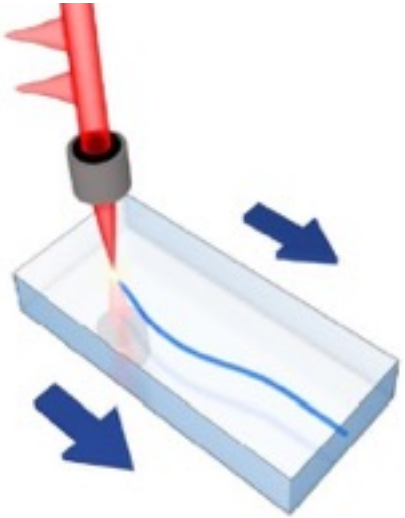
Integrated tunable circuits



Generation



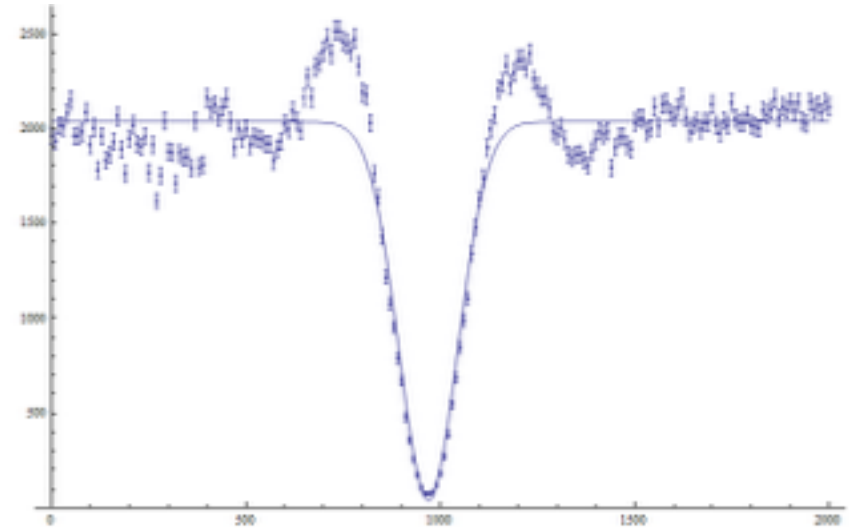




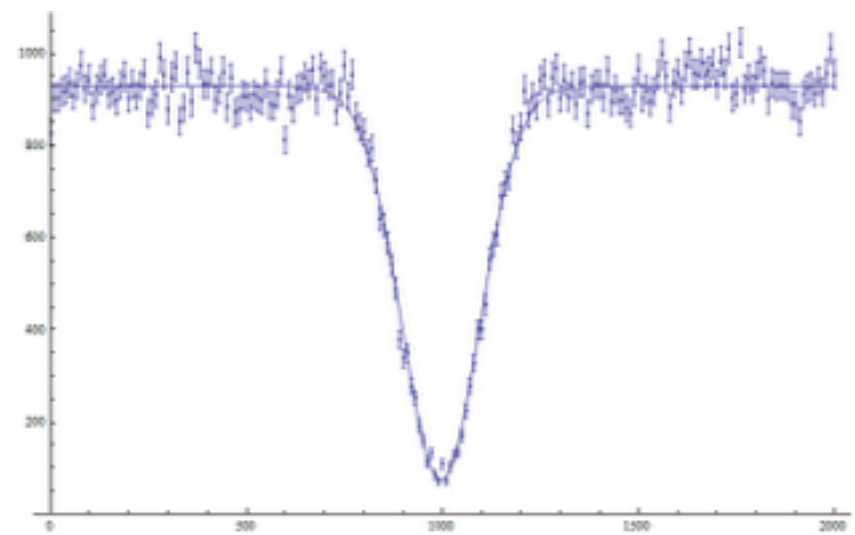
Femtosecond
laser writing technique

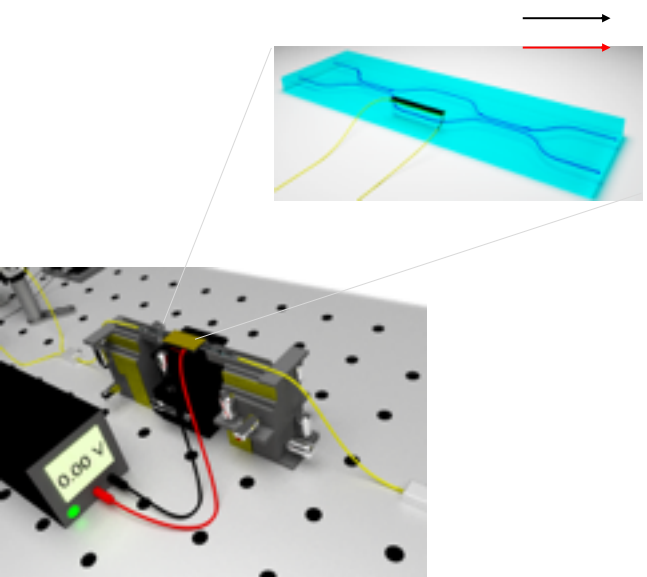
Hong-Ou-Mandel interference in a 50/50 beamsplitter

CW P = 800mW $V_{CW} = 0.967 \pm 0.002$



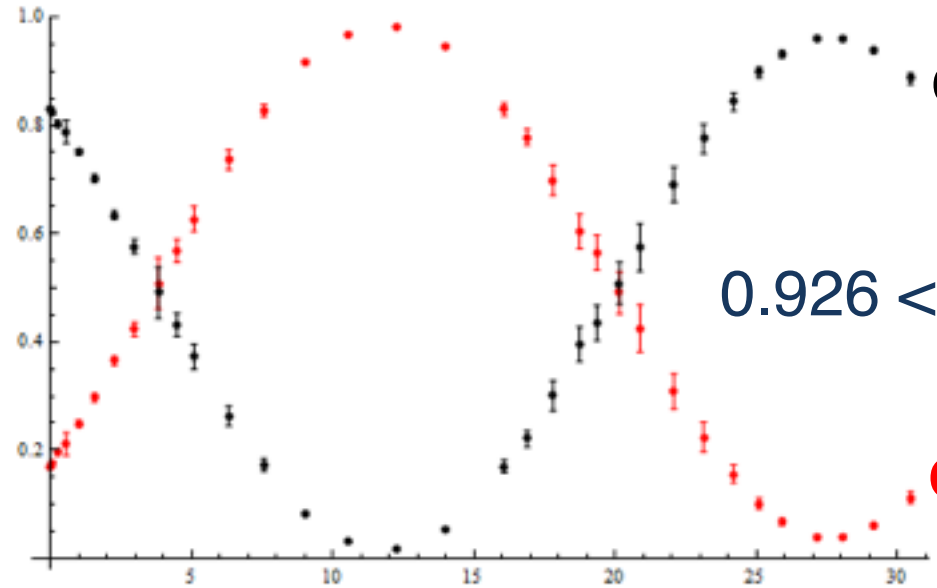
Pulsed P = 200mW $_PV = 0.923 \pm 0.00$





MZI interference fringes

Classic light

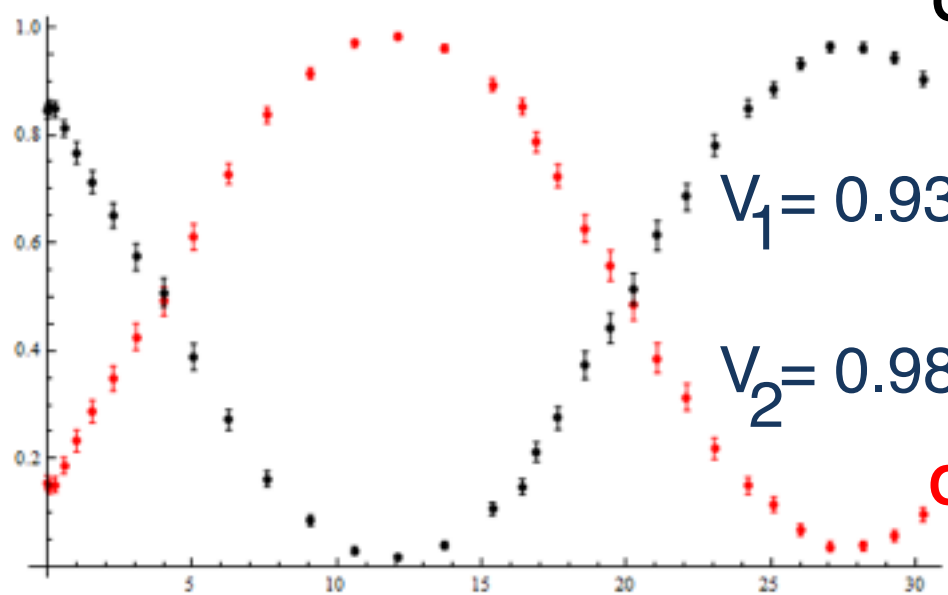


Output 1

$0.926 < V < 0.982$

Output 2

Single photon

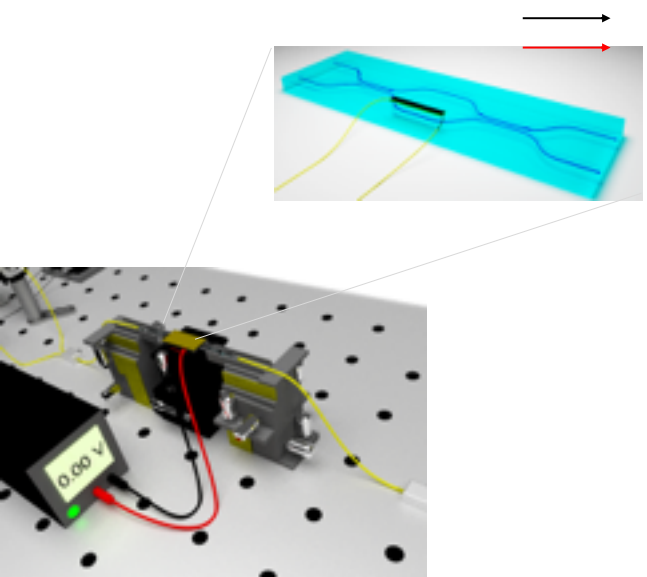


Output 1

$V_1 = 0.932 \pm 0.008$

$V_2 = 0.981 \pm 0.007$

Output 2



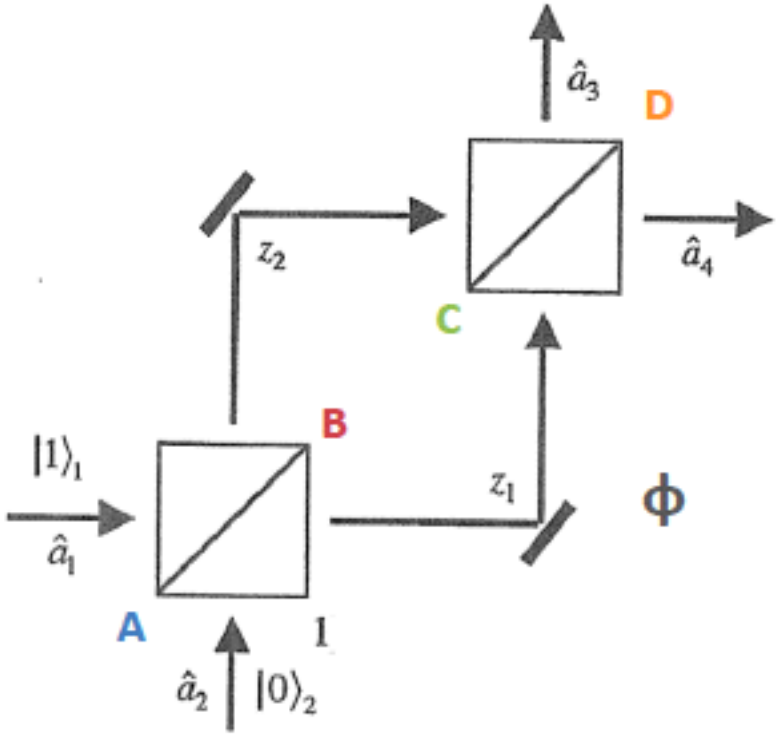
NOON effect on a chip

A $|11\rangle_{12}$

B $\frac{1}{\sqrt{2}}\left(|20\rangle + |02\rangle\right)$

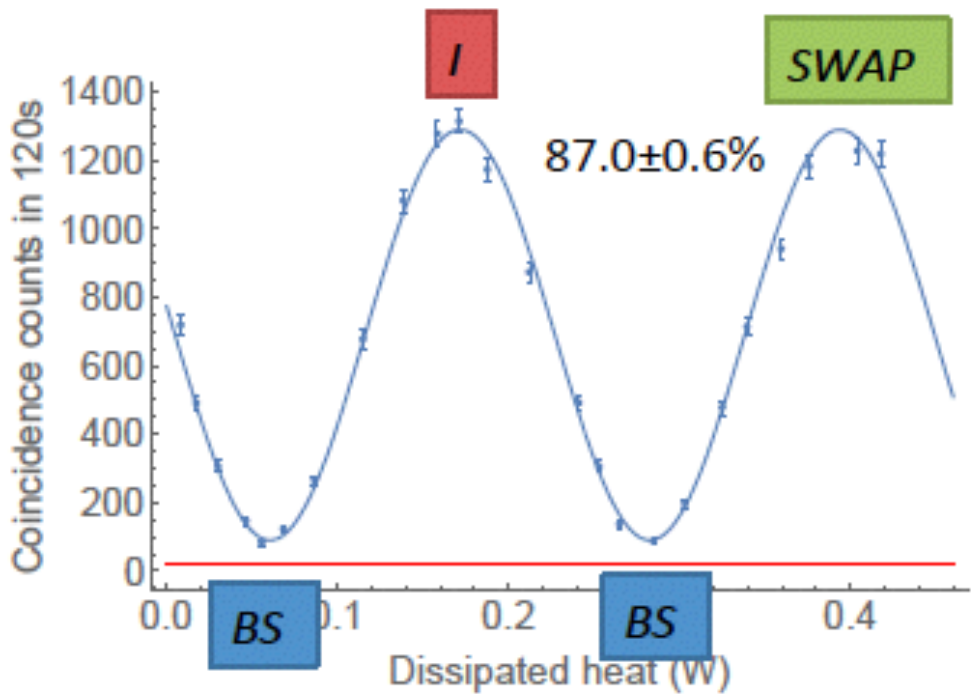
C $\frac{1}{\sqrt{2}}\left(e^{i2\phi}|20\rangle + |02\rangle\right)$

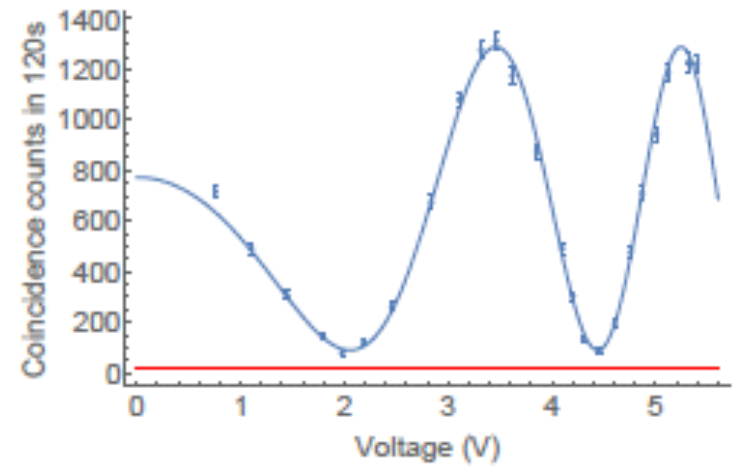
D $|11\rangle \rightarrow \frac{sin\phi}{\sqrt{2}}\left(|20\rangle - |02\rangle\right) - cos\phi\,|11\rangle$

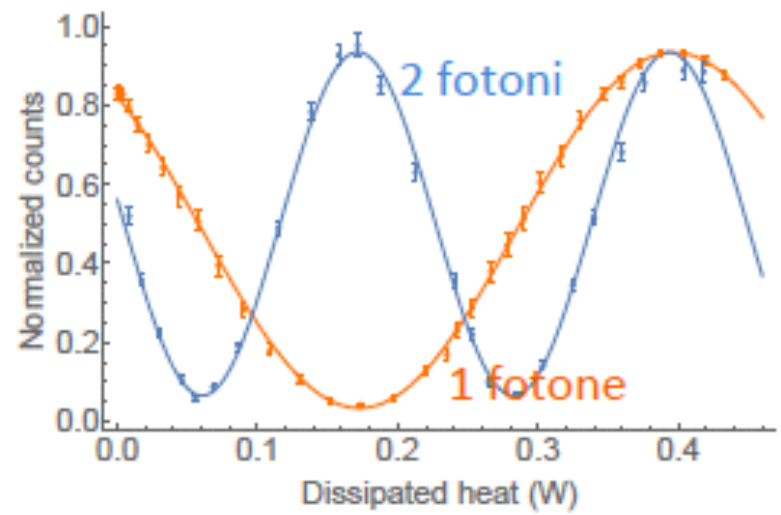


NOON effect on a chip

$$|11\rangle \rightarrow \frac{sin\phi}{\sqrt{2}}\left(|20\rangle - |02\rangle\right) - cos\phi\,|11\rangle$$







F. Flamini, L. Magrini, A. S. Rab, N. Spagnolo, V. D'Ambrosio, P. Mataloni, F. Sciarrino, T. Zandrini, A. Crespi, R. Ramponi, R. Osellame,
"Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining", *Light: Science & Applications* **4**, e354 (2015).