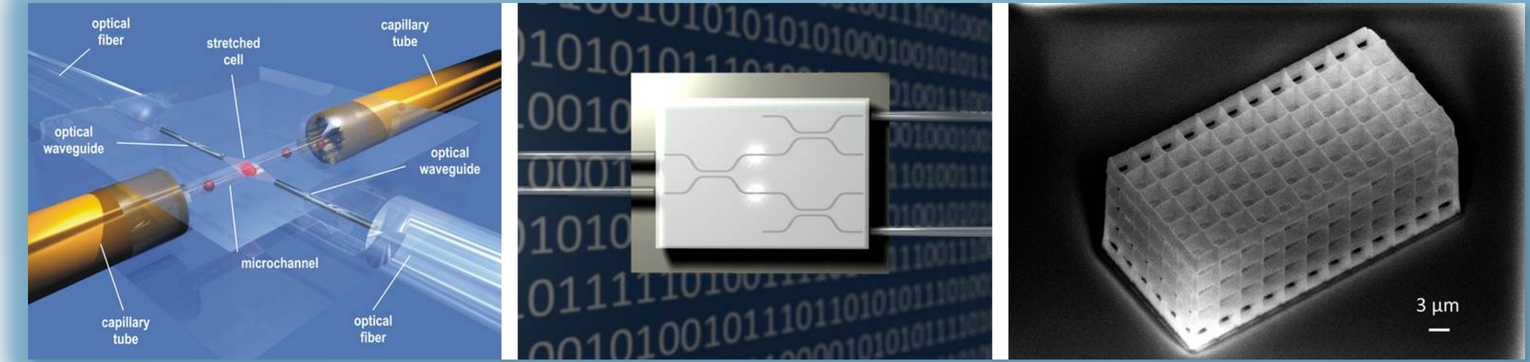


# Femtosecond-laser micromachining of transparent materials: an enabling tool for physics on a chip

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INSTITUTE FOR PHOTONICS AND NANOTECHNOLOGIES (IFN)

ITALIAN NATIONAL RESEARCH COUNCIL (CNR)

MILAN - ITALY

CNR IFN Istituto di Fotonica e Nanotecnologie

# Nobel Prize in Physics 2018

Arthur Ashkin

Optical forces and tweezer

Gerard Mourou

Donna Strickland

Chirped-Pulse-Amplification for ultrashort pulses

# Outline

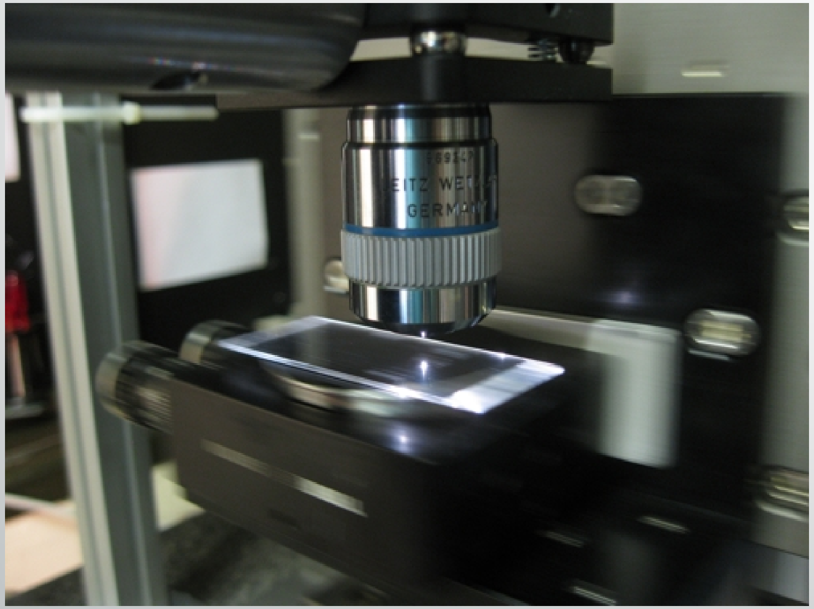
- Introduction to femtosecond laser micromachining of transparent materials

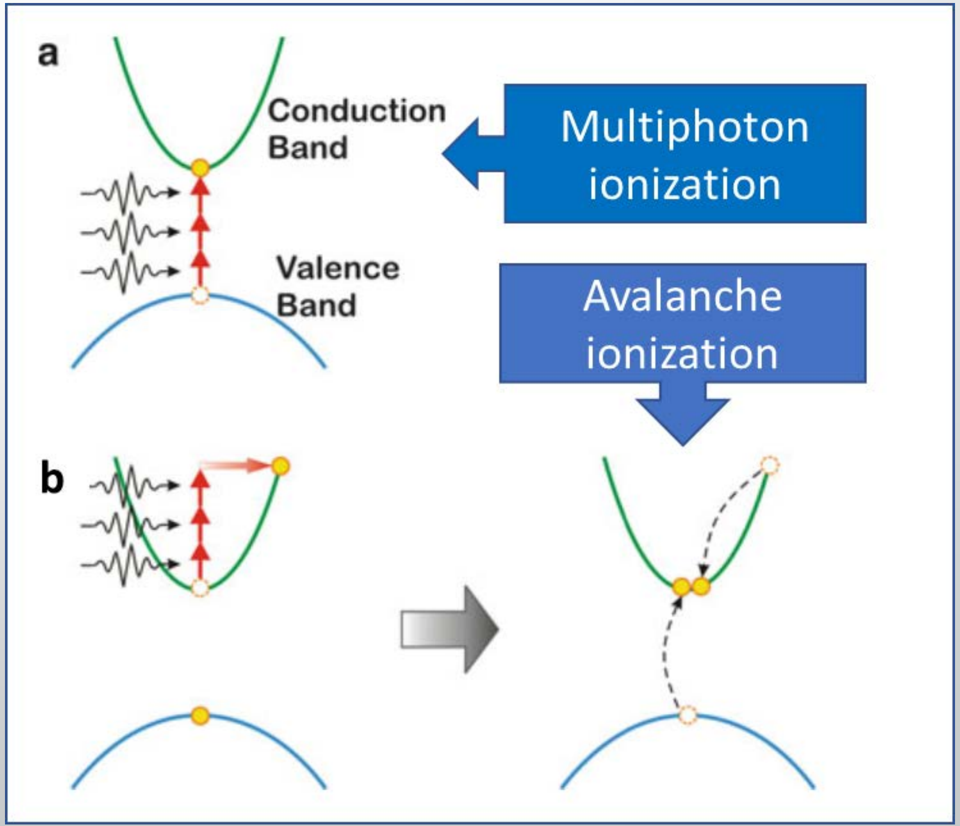
- Optical manipulation of particles
  - Optical cell stretcher and sorter
  - Integrated rheometer

- Quantum Supremacy
  - Boson Sampling
  - Quantum device validation

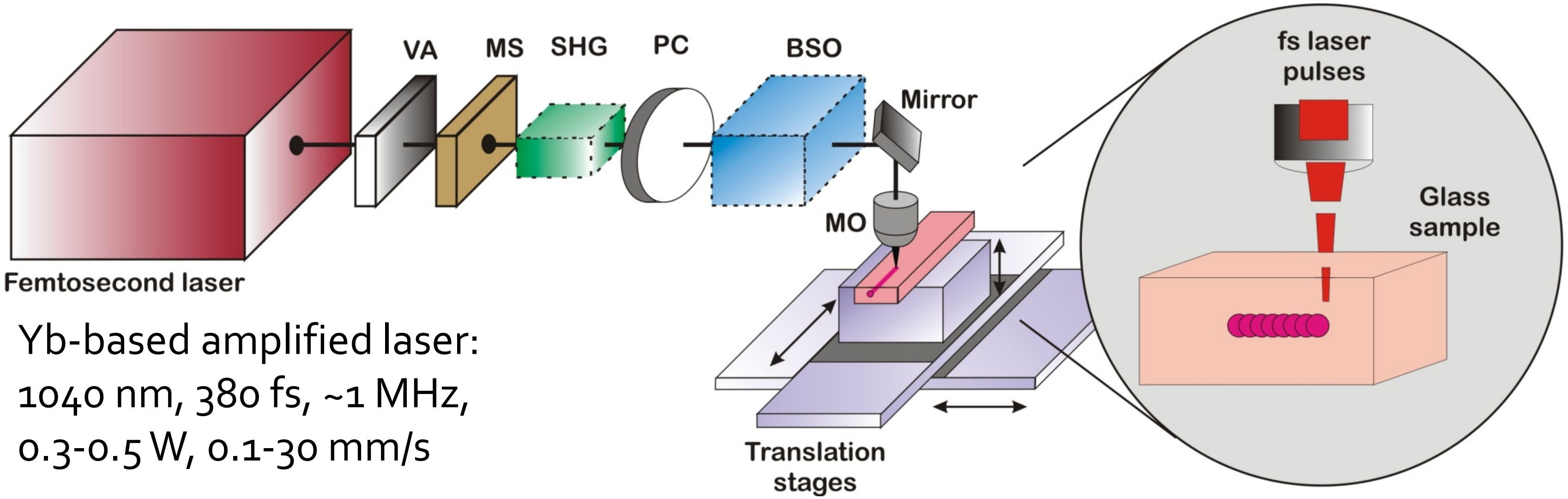
# Femtosecond laser micromachining (FLM)

- Nonlinear absorption of femtosecond laser pulses → structural modifications
- Devices can be fabricated by translation of the sample



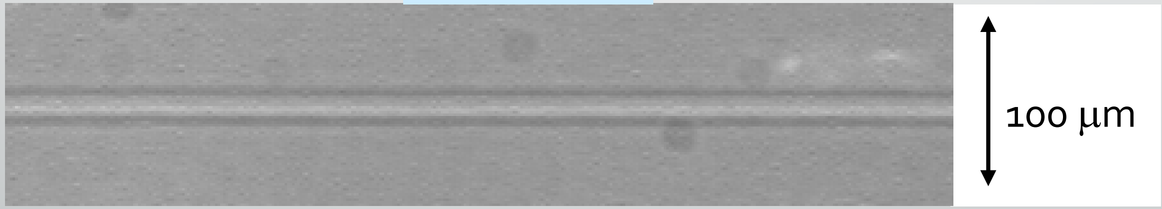


# Waveguide writing in glass

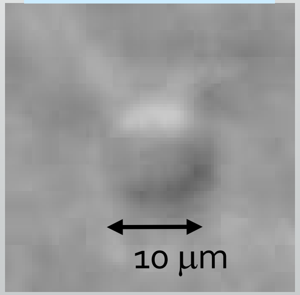



Yb-based amplified laser:
1040 nm, 380 fs, ~1 MHz,
0.3-0.5 W, 0.1-30 mm/s

**Top view**

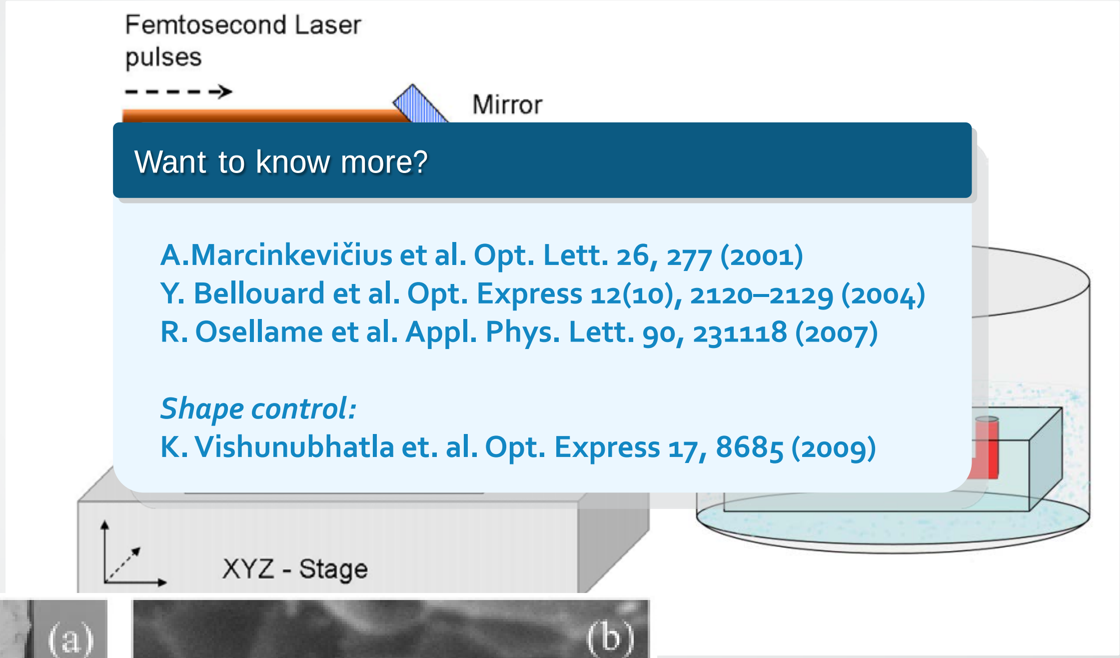



**End view**



# Microfluidic channel fabrication in glass

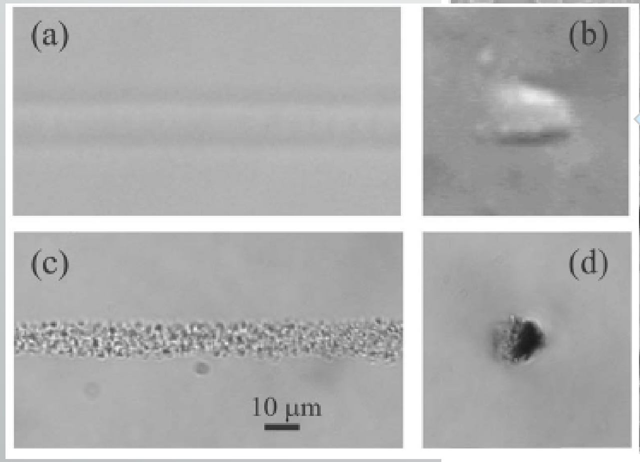
Irradiation: 1 MHz, 350 fs
0.3 μJ @ 515 nm
0.2 mm/s
0.6 NA
0.1-2 mm buried
Etching: 20 % HF in water
Ultrasonic bath
~3 h time

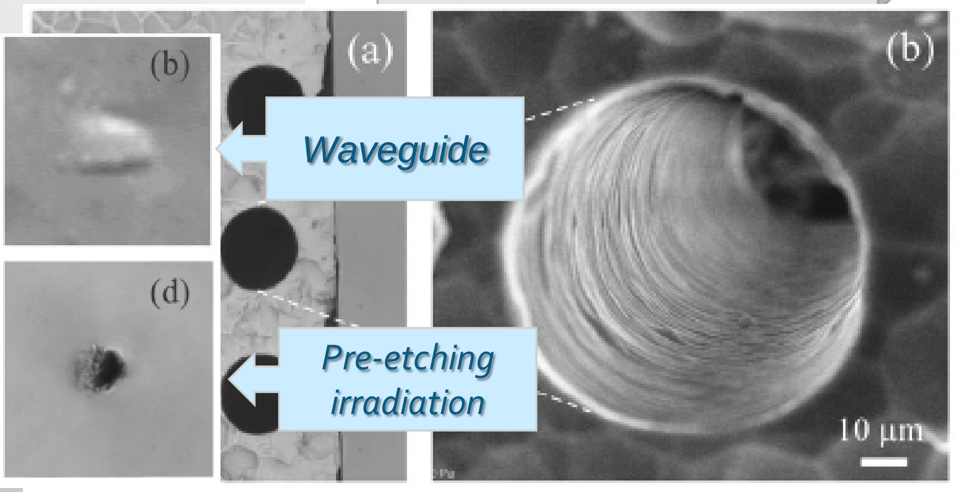



Want to know more?

A.Marcinkevičius et al. Opt. Lett. 26, 277 (2001)
Y. Bellouard et al. Opt. Express 12(10), 2120–2129 (2004)
R. Osellame et al. Appl. Phys. Lett. 90, 231118 (2007)

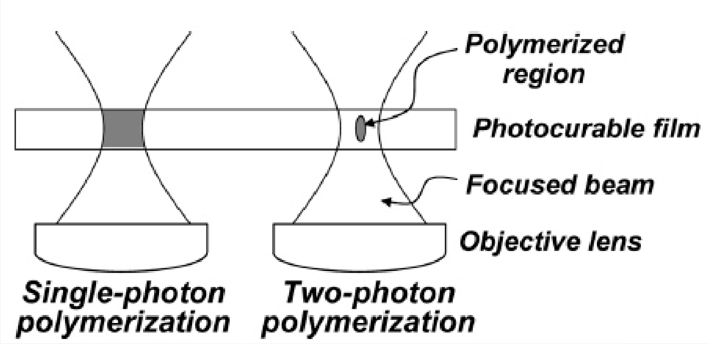
*Shape control:*
K. Vishunubhatla et. al. Opt. Express 17, 8685 (2009)

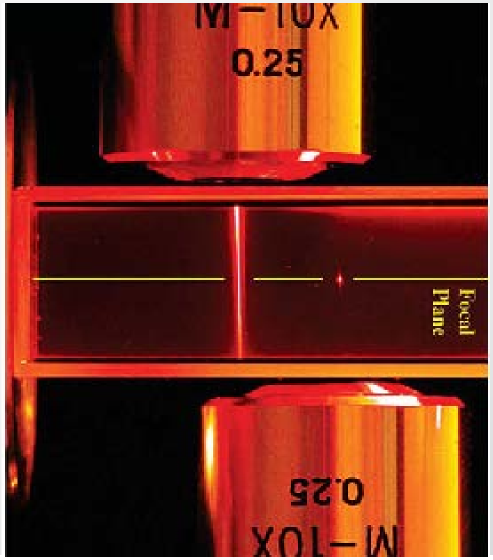


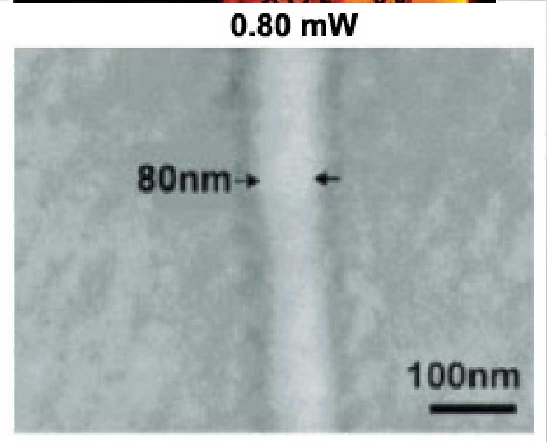



# Two-Photon Polymerization

- Femtosecond laser pulses are focused inside a UV photosensitive resin.
- Near-IR laser pulses undergo two-photon absorption




<u>Two-photon absorption</u>:

- Absorption is proportional to the square of the intensity
- It's a process with a <u>threshold</u>

**Resolution well below the diffraction limit**



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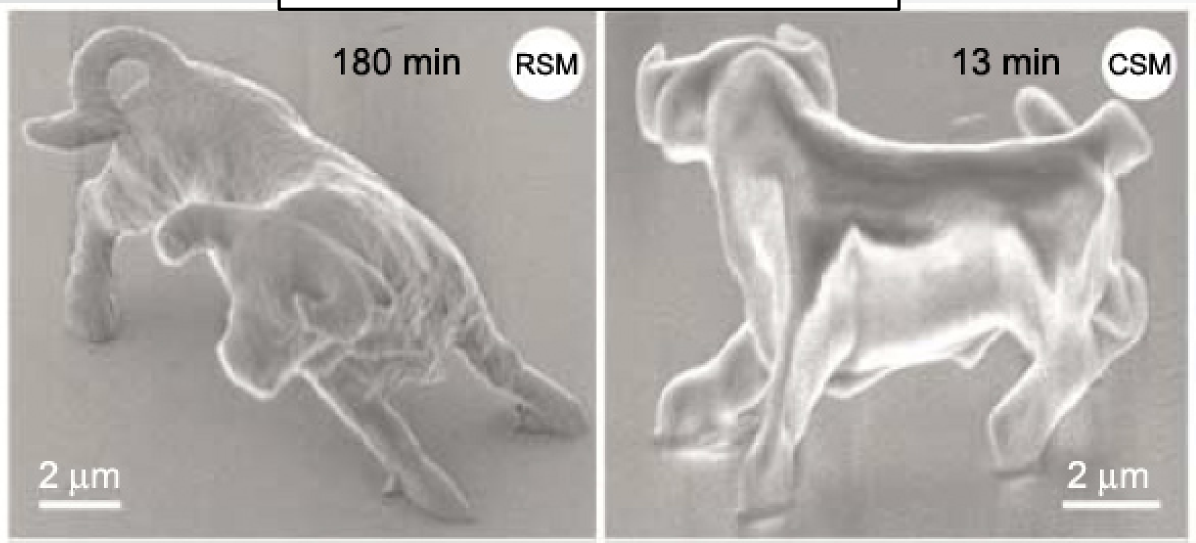
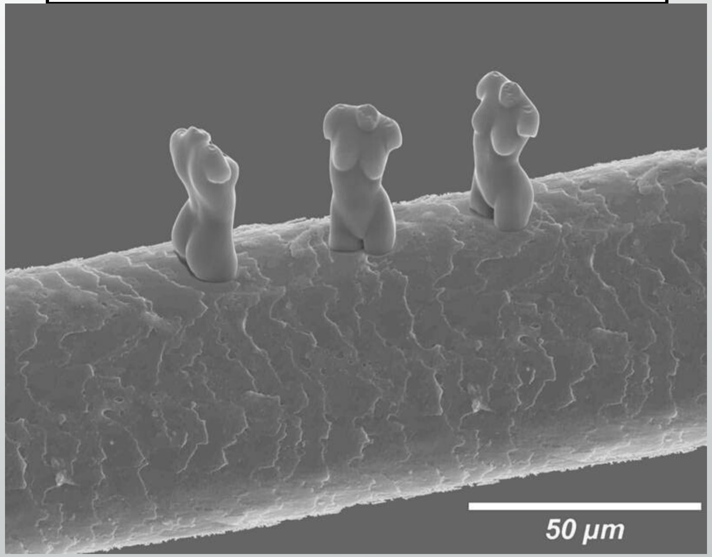
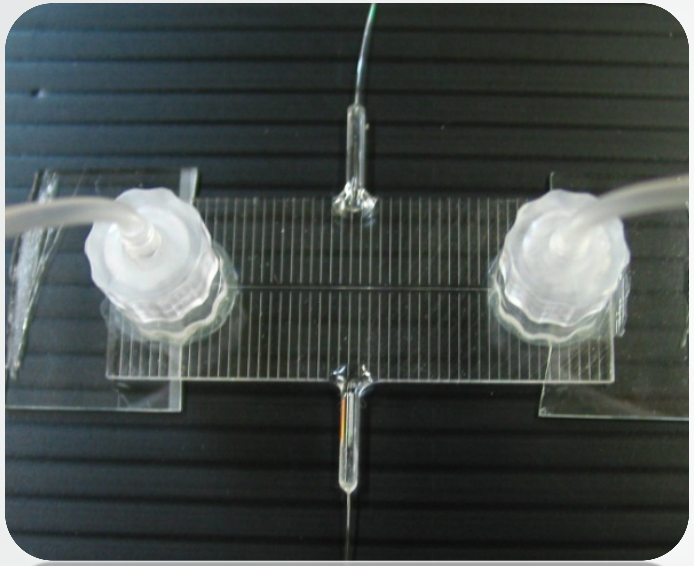
# Two-Photon Polymerization

Kawata et al. *Nature* **412**, 697 (2001)




Laser Zentrum Hannover





# Optofluidic single-particle manipulation

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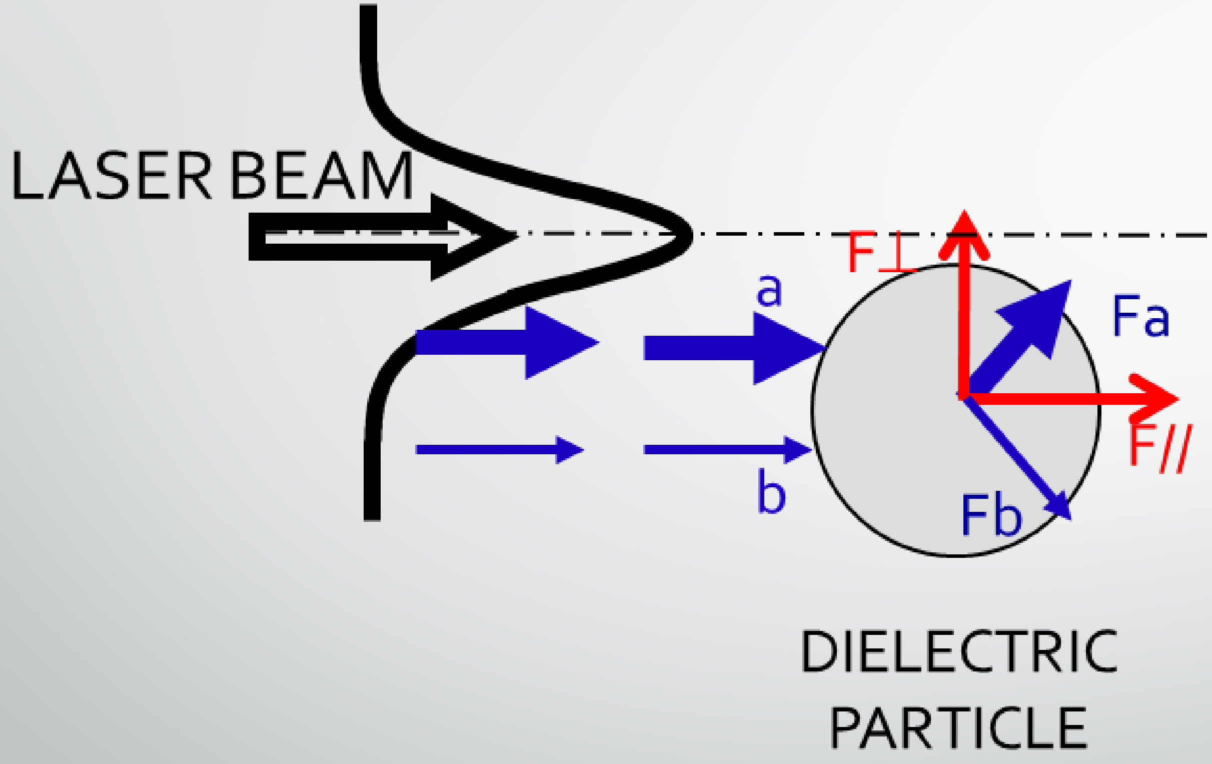
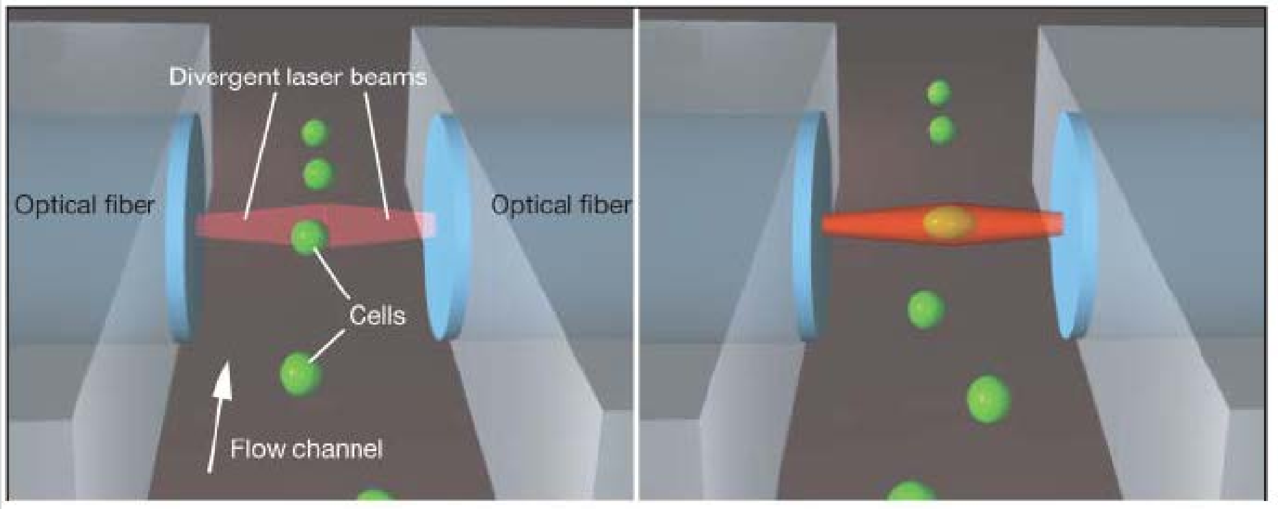
Istituto di Fotonica e Nanotecnologie

# Optical forces on transparent particles




- **F⊥:** PULLS THE PARTICLE TOWARD THE REGION OF HIGHER INTENSITIY (GRADIENT FORCE)
- **F//:** PUSHES THE PARTICLE IN THE DIRECTION OF THE LIGHT PROPAGATION (SCATTERING FORCE)

# Optical Stretcher: Principle




2 counter-propagating laser beams

- ➢ not focused beams
- ➢ cell suspension flowing in between

How does it work?

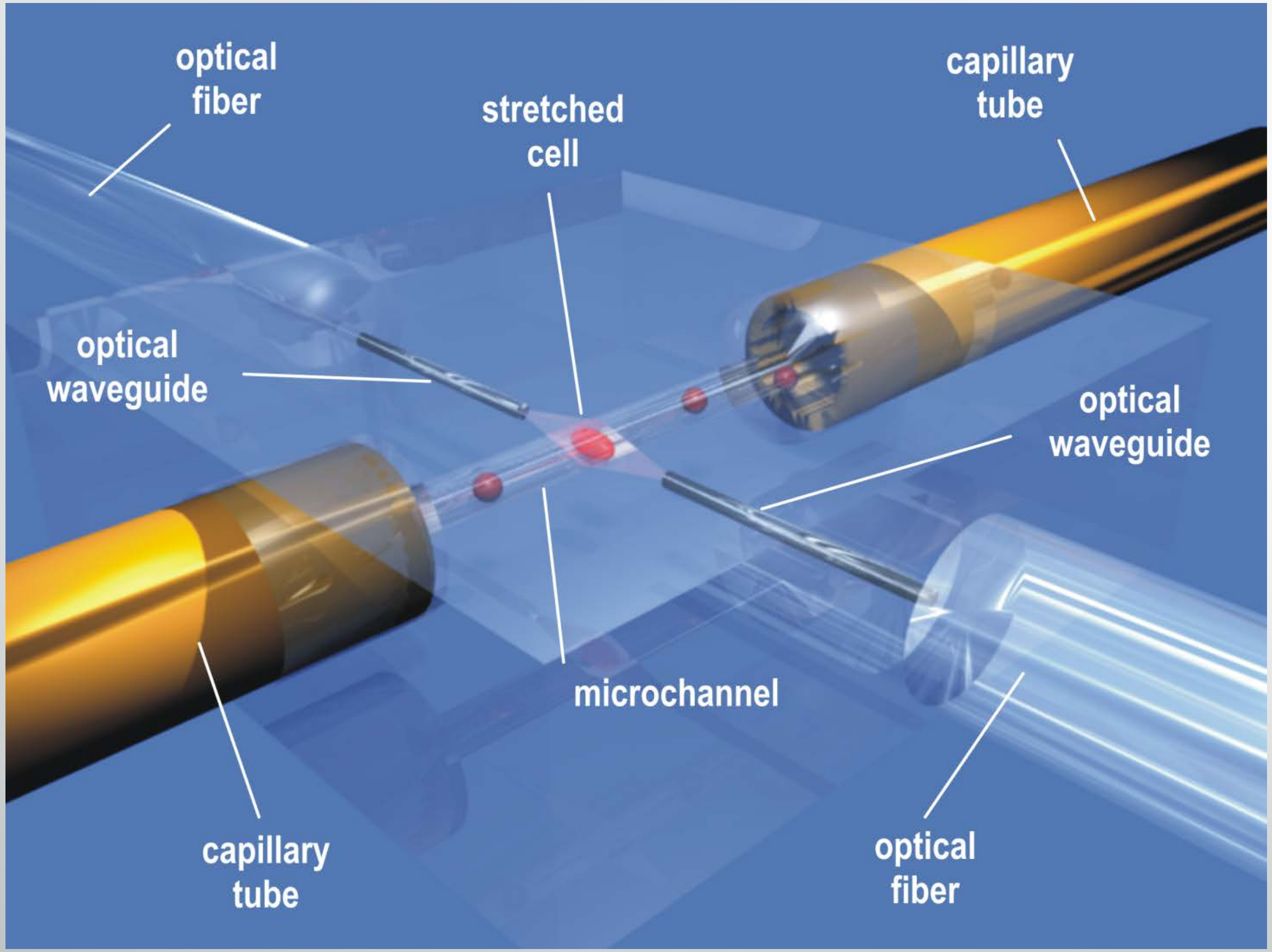
✓ reflected and refracted light at the cell surface provide optical forces for TRAPPING and STRETCHING

J. Guck et al., Biophys. J., 88, 3689-3698 (2005)

Deformability of cell cytoskeleton is a reliable marker of the cell status

detect illnesses from a small amount of sample

# Integrated Optical Stretcher: Concept

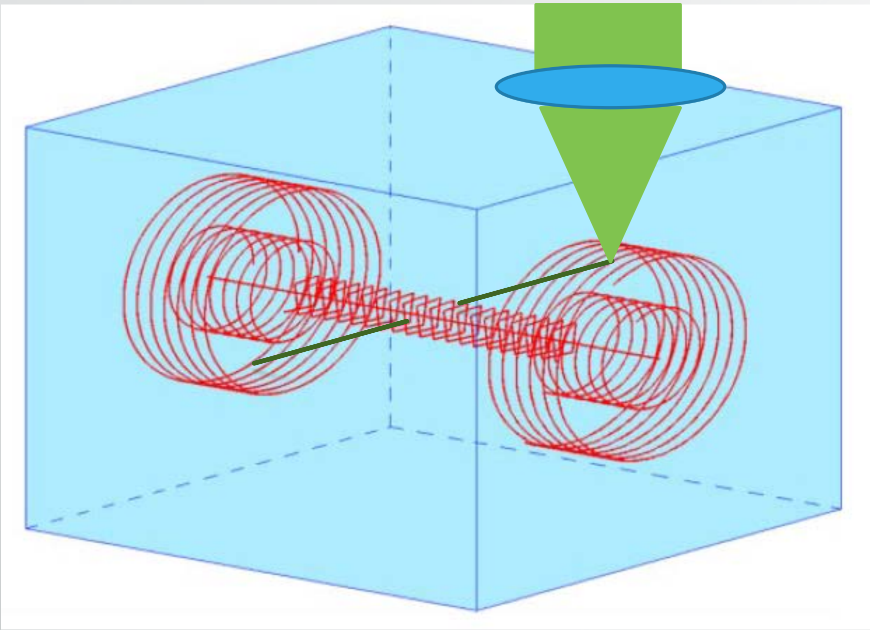


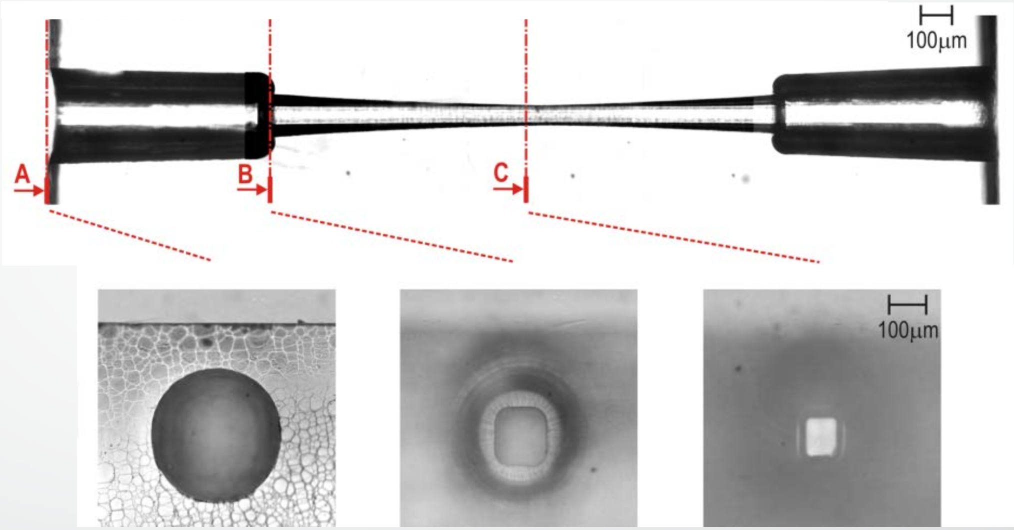

N. Bellini et al., Opt. Express, 18(5), 4679-4688 (2010)

MAIN advantages:

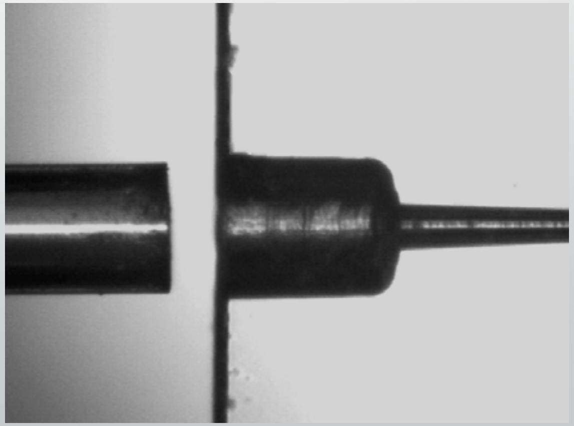
- fine alignment
- enhanced robustness
- further on-chip functionalities (fluorescence and Raman analyses, cell sorting)

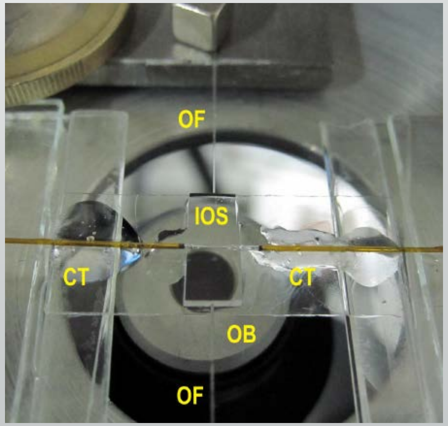
# fs-Laser Microfabrication



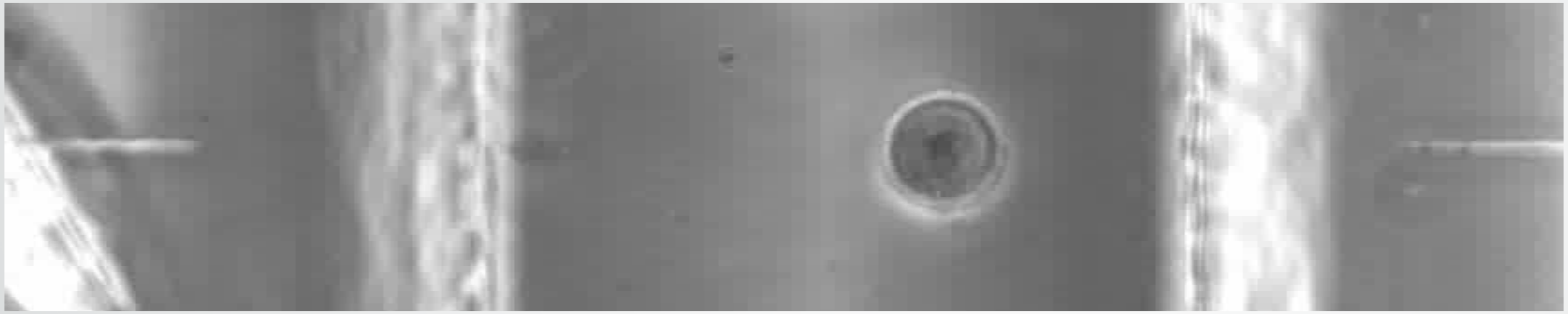



N. Bellini et al., Opt. Express, 18(5), 4679-4688 (2010)





# Cell Optical Stretching



Cell: HL-60 leukemic white blood cells

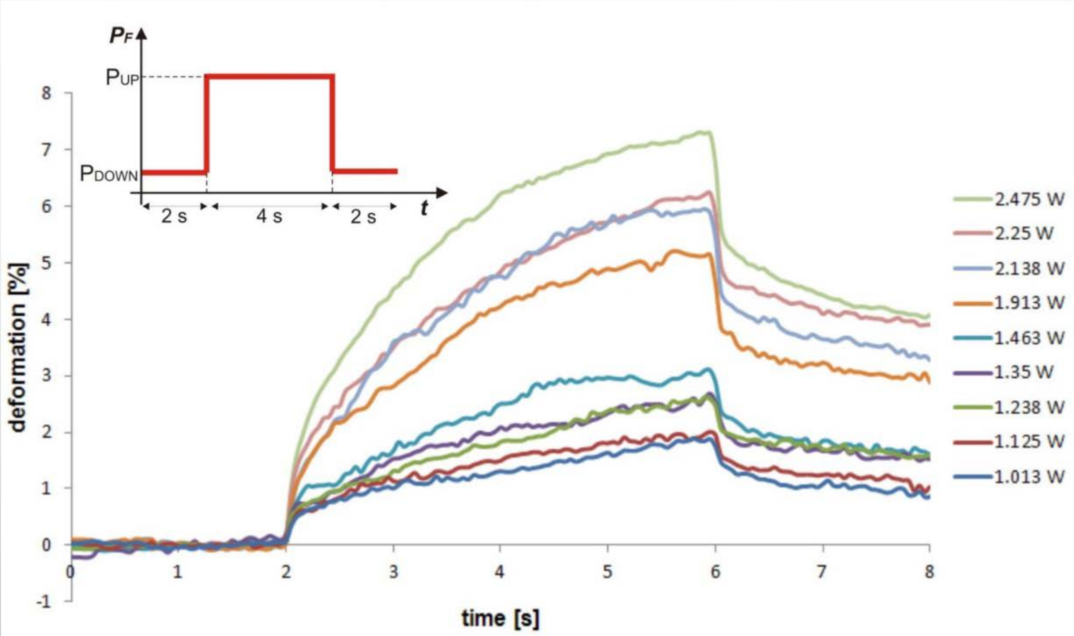
Power of the laser = 5.5 W

Power per side at the channel = 618 mW

Step stimulus: 2 s – 4 s – 2 s

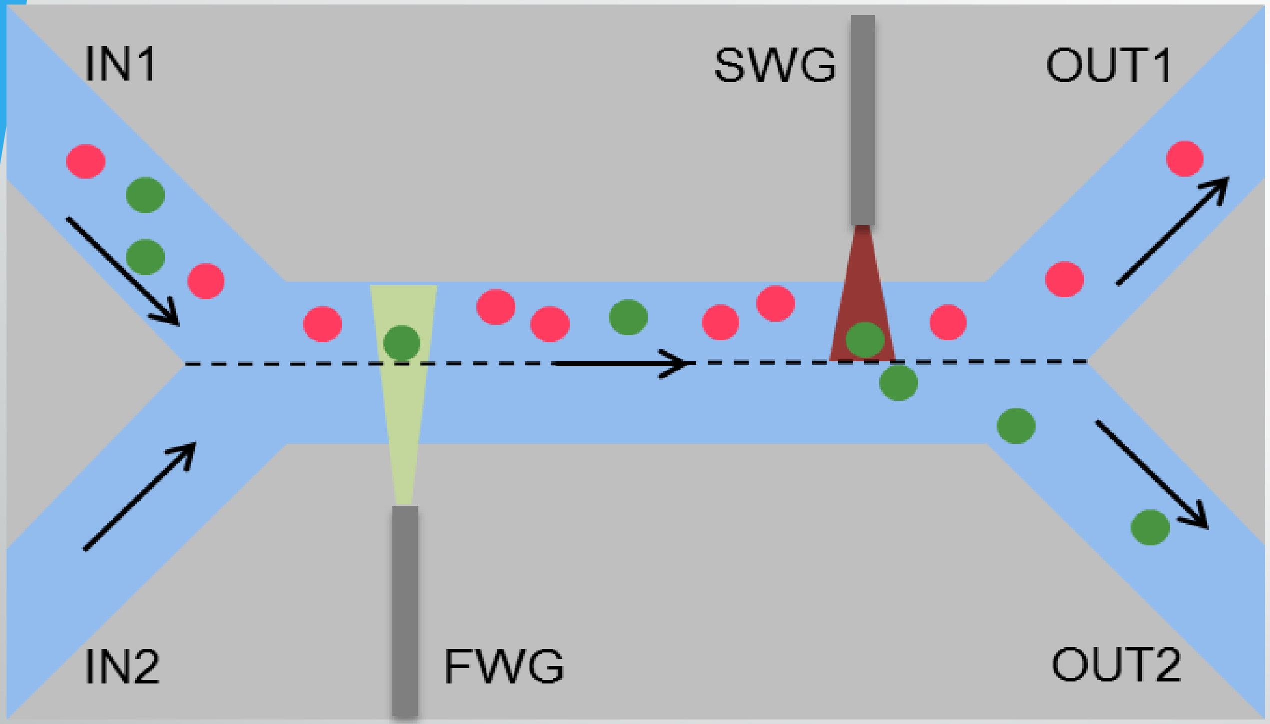
N. Bellini et al., Biomed. Opt. Express 3, 2658 (2012)

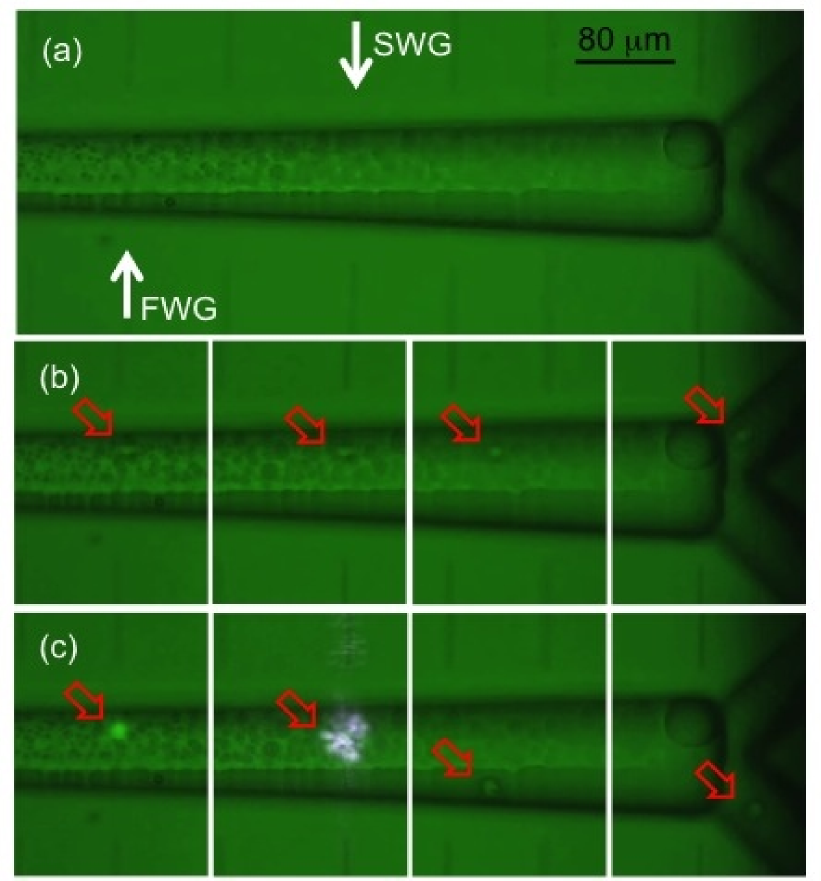
biotec
Biotechnology Center TU Dresden



# Integrated Optical Sorter

Università di Pavia
Ilaria Cristiani
Paolo Minzioni




F. Bragheri et al., Lab Chip 12, 3779 (2012)

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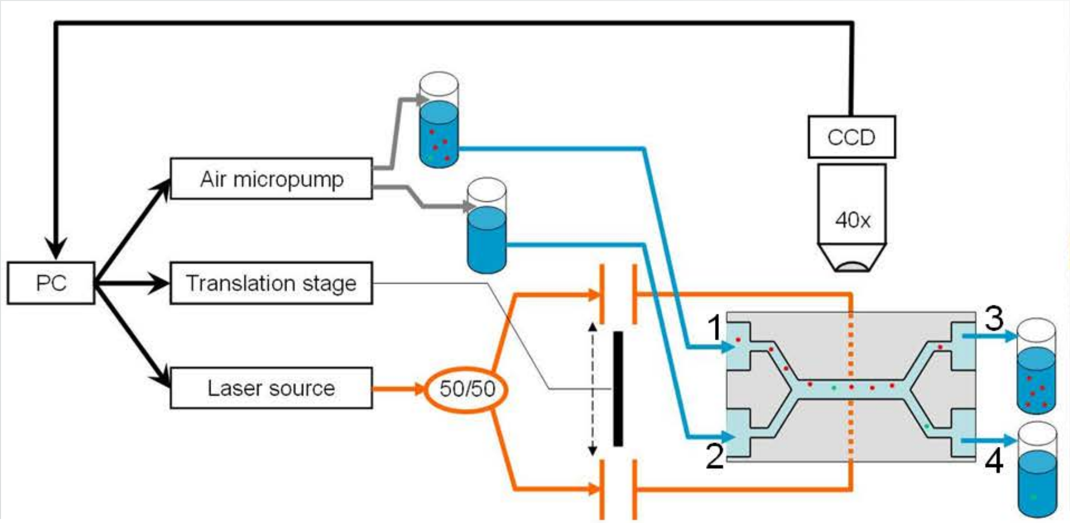
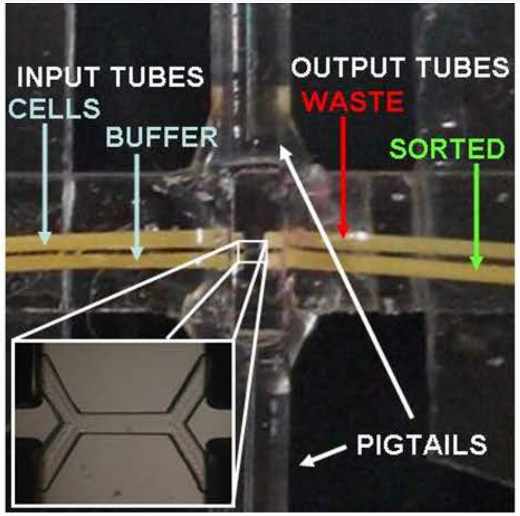
CNR IFN Istituto di Fotonica e Nanotecnologie

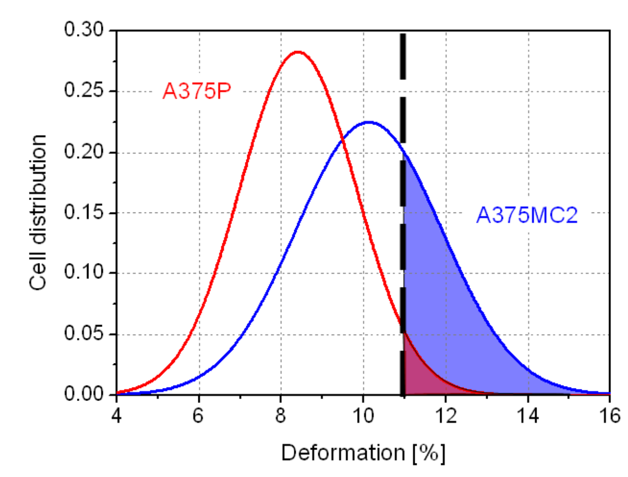
# Integrated Optical Sorter

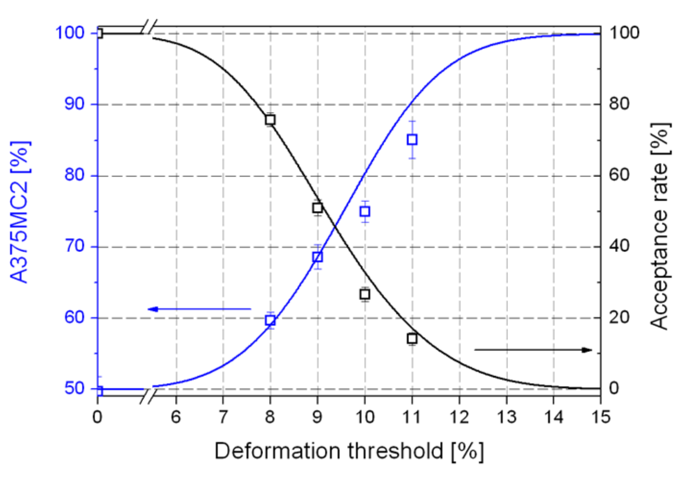
Università di Pavia

Ilaria Cristiani
Paolo Minzioni



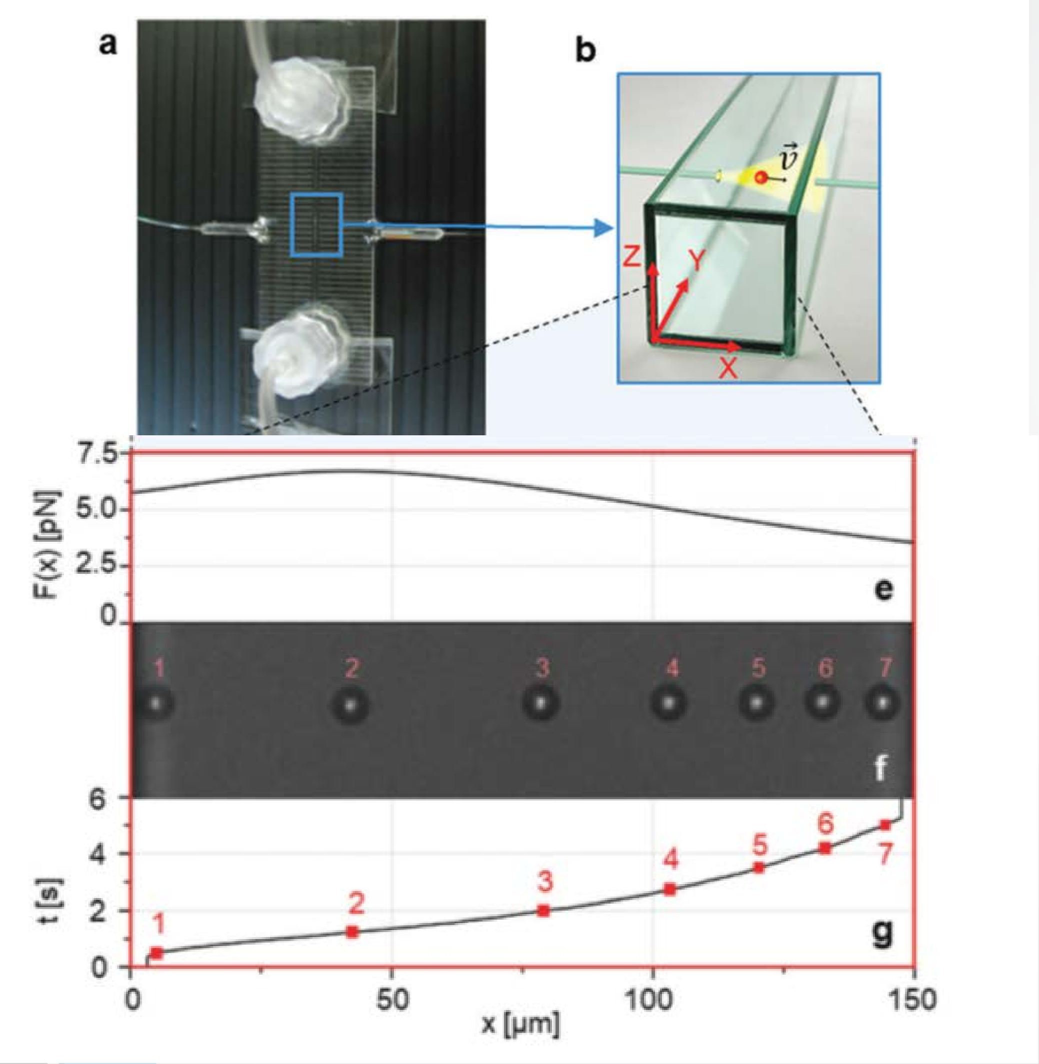



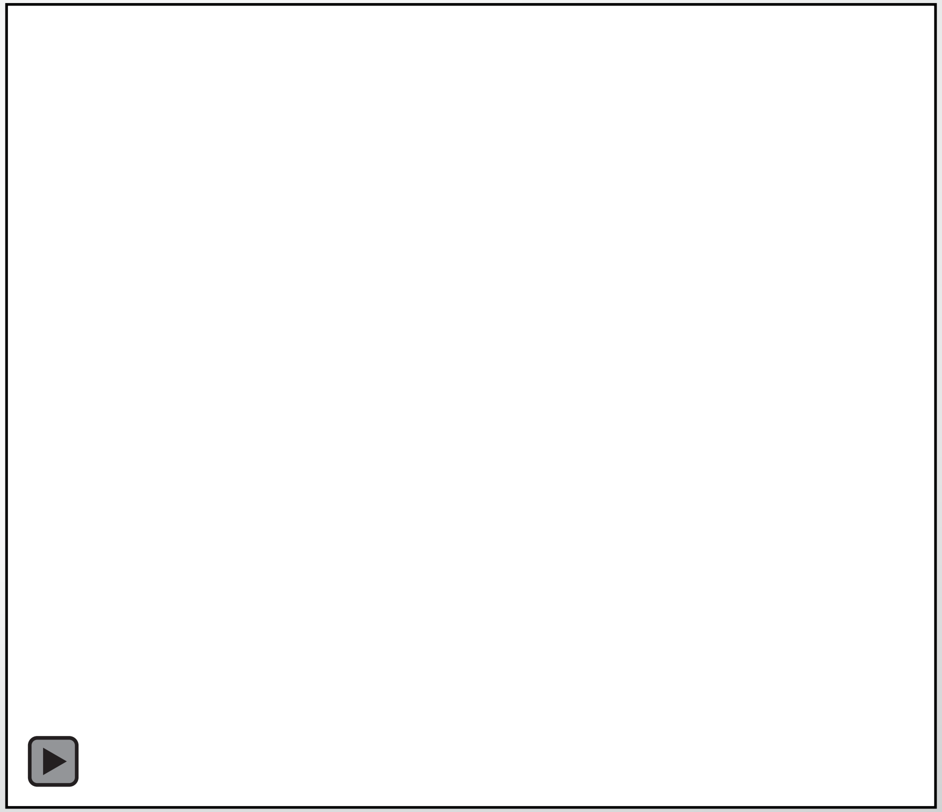




T. Yang et al., Lab Chip 15, 1262 (2015)

# Microrheology: Optical shooting



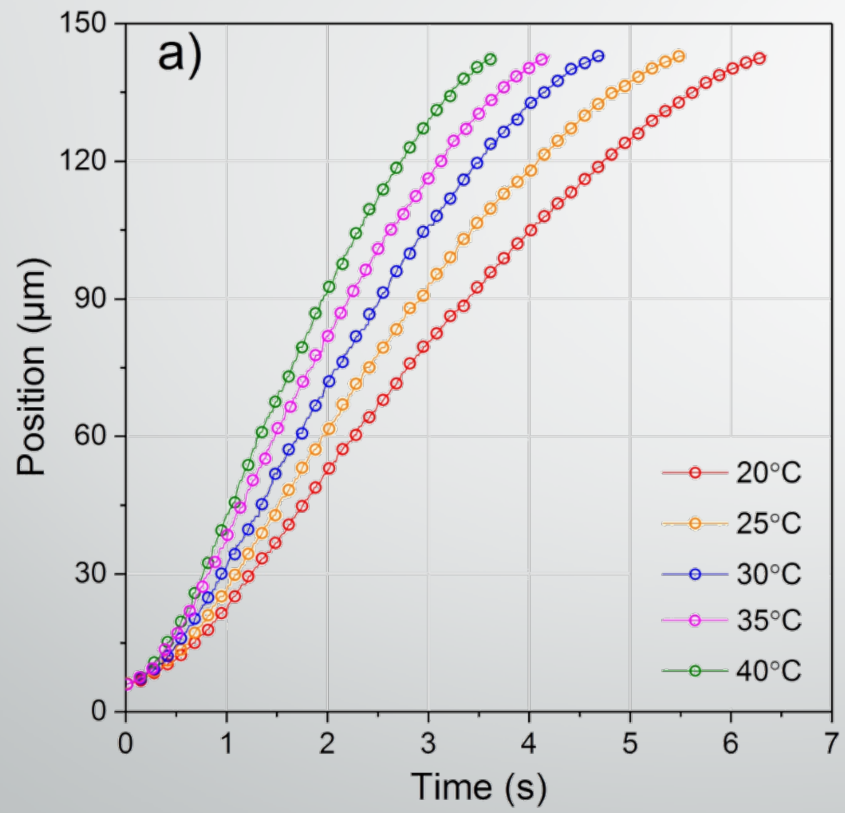



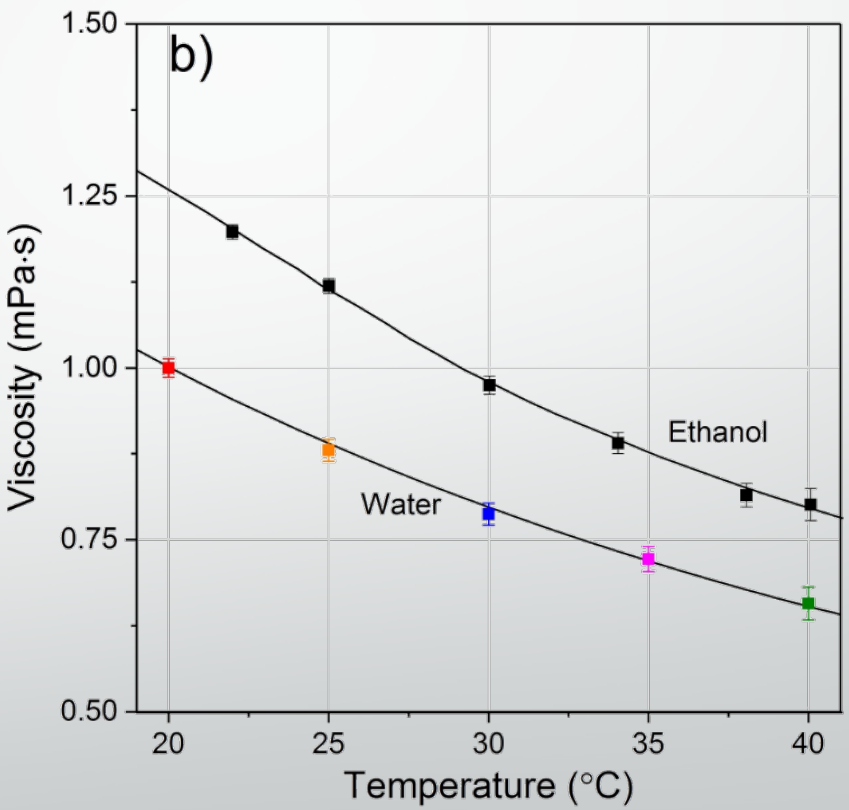
Equation of motion $m\ddot{x} = F_0 - F_V$

Neglecting the inertial contribution $F_O(x) = F_V = 6\pi R\eta\dot{x}$

# Microrheology: Results

- Various standard netwonian fluids were measured at different temperatures.
- All the trajectories could be fitted using calculated F(x) and constant $\eta$
- Viscosities in agreement with the literature ones



# From Newtonian to non-Newtonian fluids

Soft Matter

PAPER

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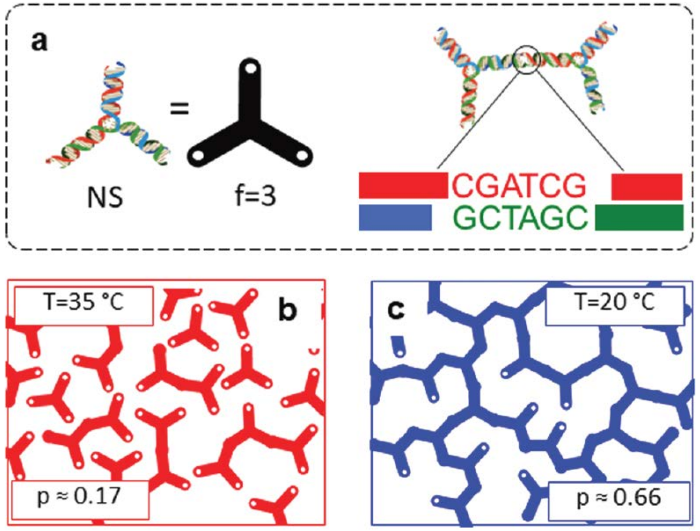
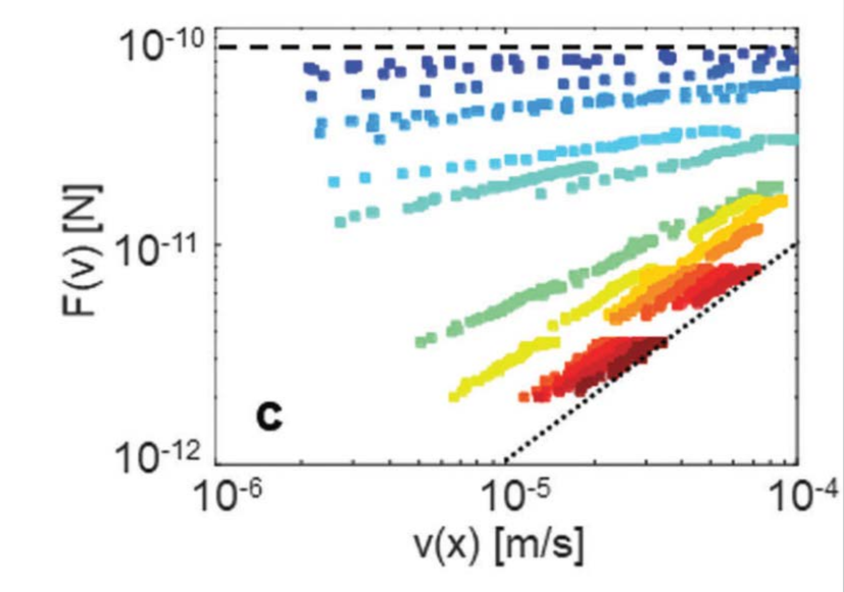
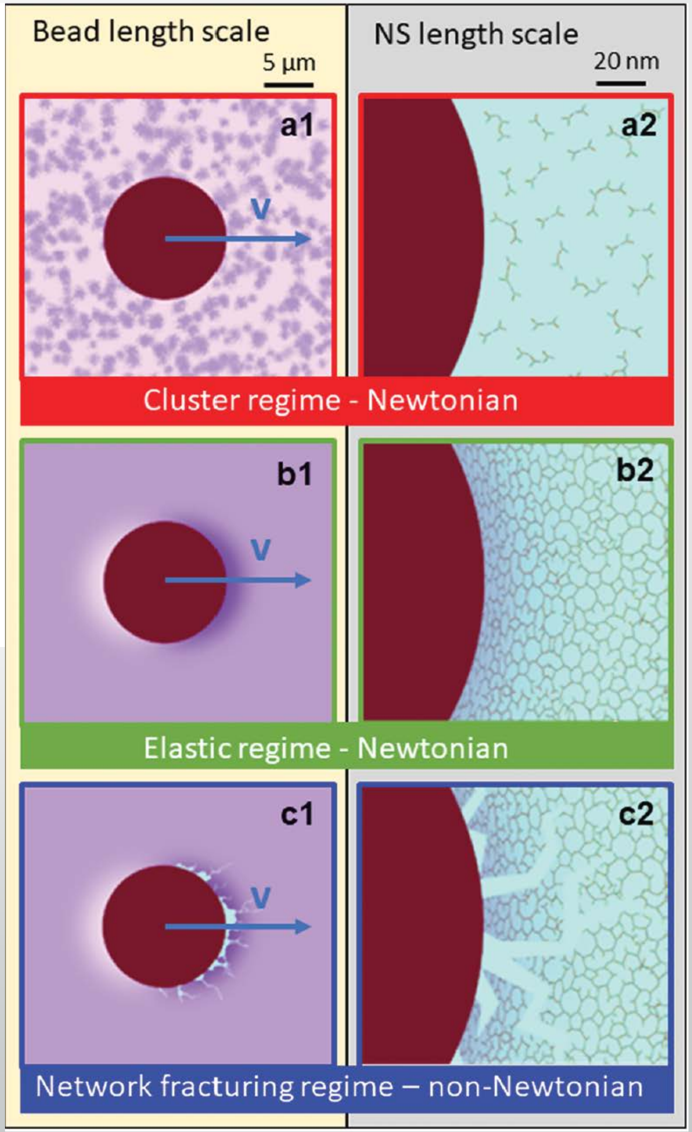
Cite this: *Soft Matter*, 2018, 14, 3288

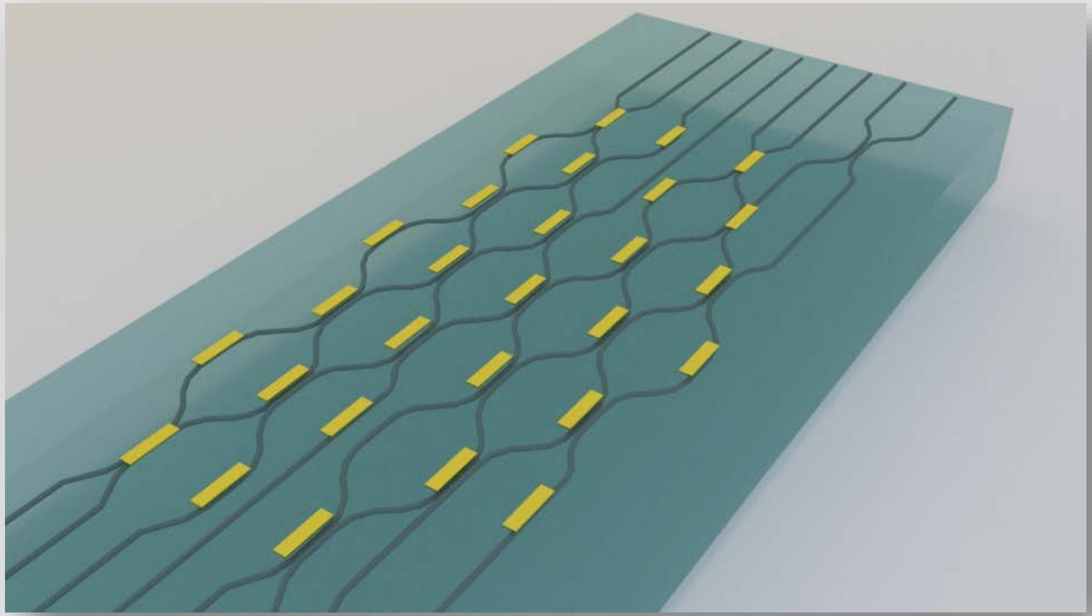
## Newtonian to non-newtonian fluid transition of a model transient network†

Giovanni Nava,[a] Tie Yang,[b] Valerio Vitali,[c] Paolo Minzioni,[c] Ilaria Cristiani,[c] Francesca Bragheri,[d] Roberto Osellame,[d] Lucas Bethge,[e] Sven Klussmann,[e] Elvezia Maria Paraboschi,[f] Rosanna Asselta[fg] and Tommaso Bellini*[a]





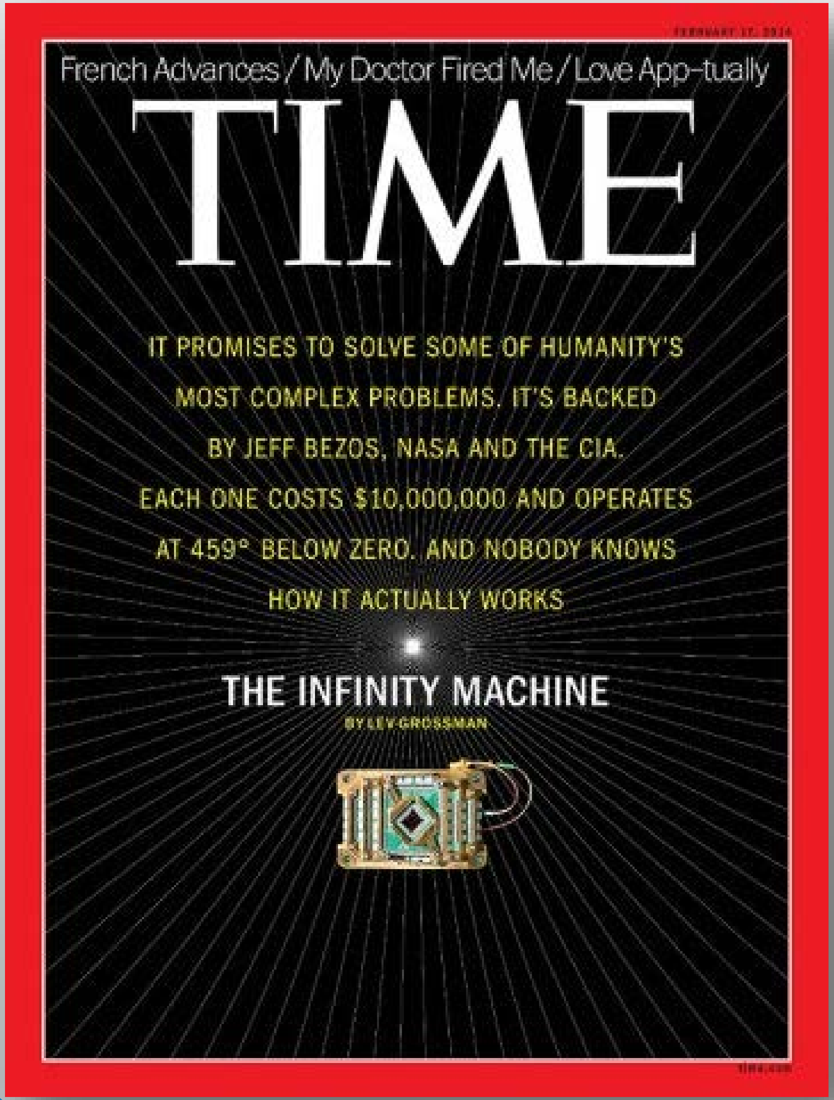
# Integrated Photonic Circuits for Boson Sampling Experiments

CNR IFN
Istituto di Fotonica e Nanotecnologie

STVDIVM VRBIS

Prof. Fabio Sciarrino

# The quantum computer revolution






Quantum computers promise a revolutionary increase in computational power

# Basics: Qubits

Classical bits can be either 0 or 1

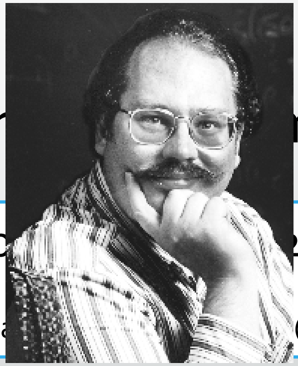

A quantum bit (qubit) is in a superposition state: $\left|\Psi\right\rangle = \alpha\left|0\right\rangle + \beta\left|1\right\rangle$

where $|\alpha|^2 + |\beta|^2 = 1$

A qubit can take advantage of peculiar properties of quantum mechanics (**quantum interference, entanglement,…**) to implement much faster algorithms

A **photonic qubit** is implemented by taking as quantum system **a single-photon** and encoding the information in one of its degrees of freedom

# Factoring large numbers

- Factoring large numbers is believed to be a computationally hard problem
- All current cryptography is based on this assumption
- 1994 - Peter Shor's proposed a quantum algorithm that could factor large numbers in polynomial time
- Demonstration of quantum supremacy by Shor  n is very difficult


Current best imp 21 = 7 x 3

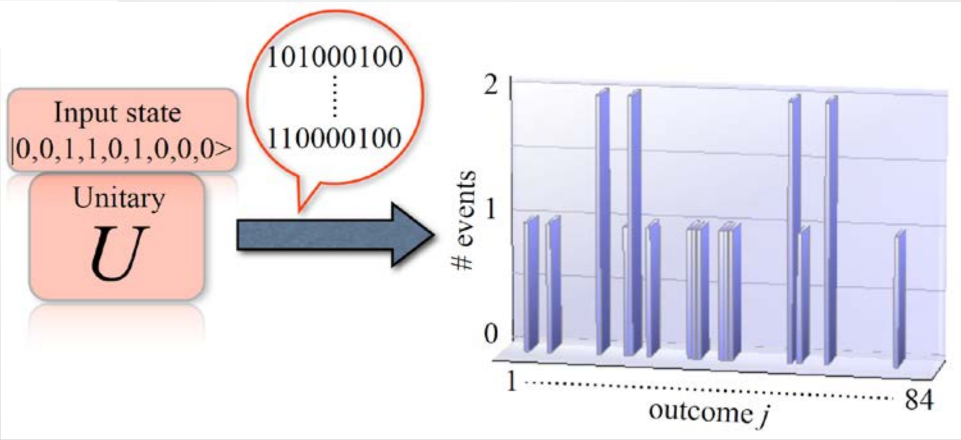
E. Martin-Lopez et al., Na (2012)

# Boson Sampling Problem

- Scott Aaronson proposed a problem that could demonstrate quantum supremacy with resources close to what we already have:

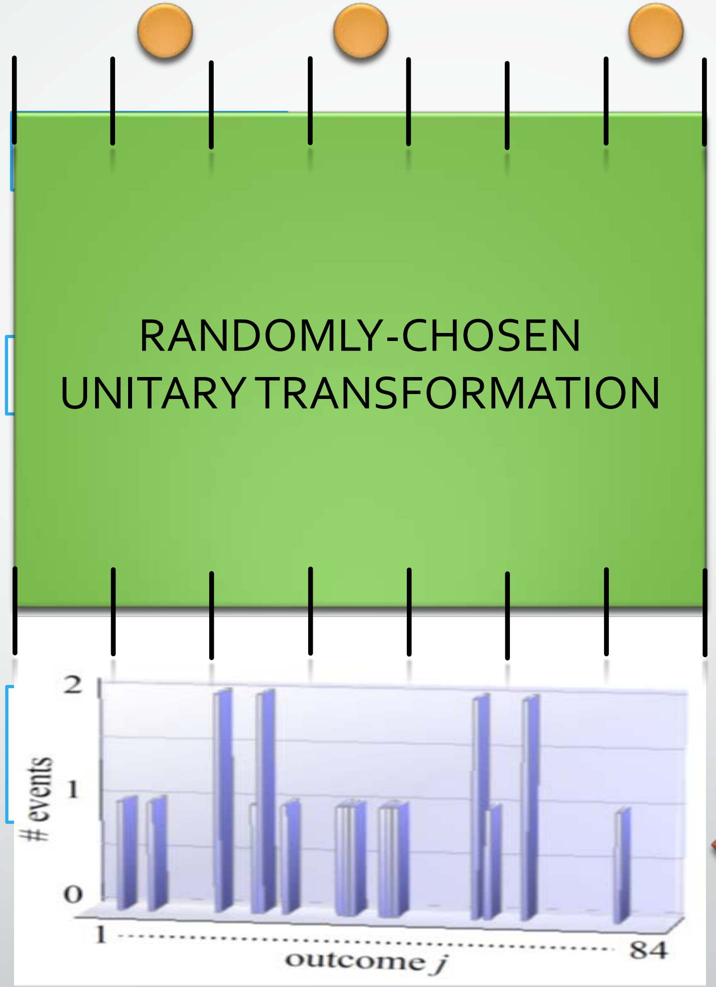
## Boson Sampling

*Aaronson, S. & Arkhipov, A., In Proceedings of the 43rd annual ACM symposium on theory of computing, 333–342 (ACM Press, 2011)*



# Boson Sampling in a nutshell

**n** bosonic particles
in
**m** modes


Sample this distribution

CLASSICAL

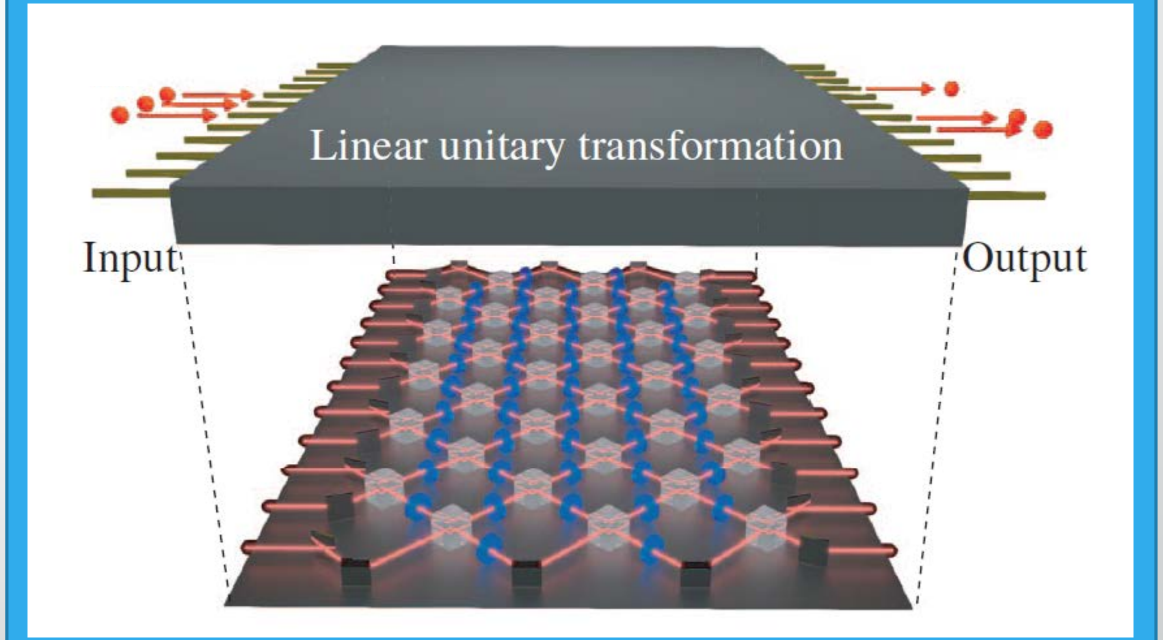
QUANTUM

# Quantum supremacy at hand

**Classical computer**

- Calculate the matrix permanent #P-complete (computationally very hard)
- Repeat calculation $\binom{m}{n}$ times to estimate the output probability distribution
- Sample from this distribution

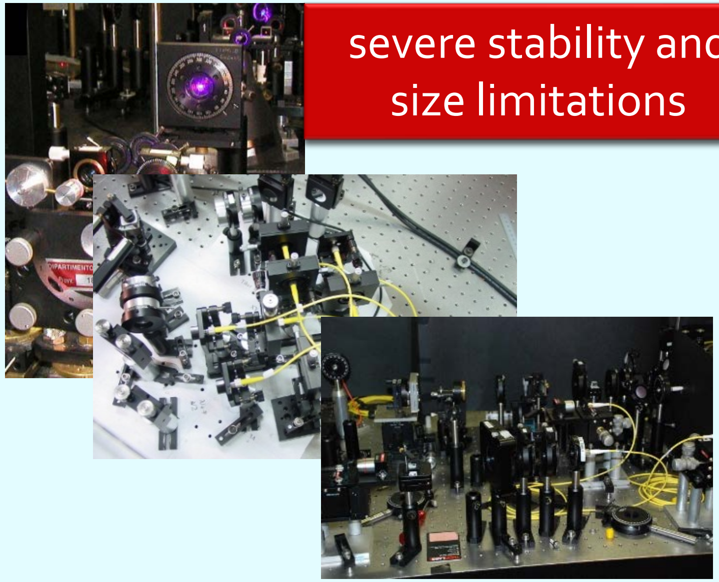
**Specialized photonic quantum computer**




Quantum supremacy could be already achieved with 50 photons in a 1000 modes interferometer

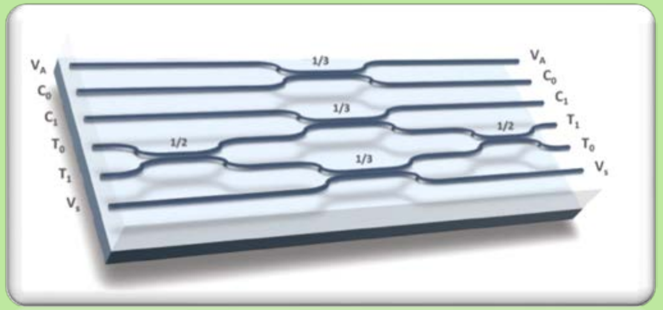
# Integrated Quantum Photonics

**BULK QUANTUM OPTICS**



severe stability and size limitations

**INTEGRATED QUANTUM OPTICS**




robust operation from monolithic miniaturization

# Practical implementations

Science AAAS

**Photonic Boson Sampling in a Tunable Circuit**
Matthew A. Broome *et al.*
*Science* **339**, 794 (2013);
DOI: 10.1126/science.1231440

Science AAAS

**Boson Sampling on a Photonic Chip**
Justin B. Spring *et al.*
*Science* **339**, 798 (2013);
DOI: 10.1126/science.1231692

LETTERS
PUBLISHED ONLINE: 12 MAY 2013 | DOI: 10.1038/NPHOTON.2013.102
nature photonics

## Experimental boson sampling

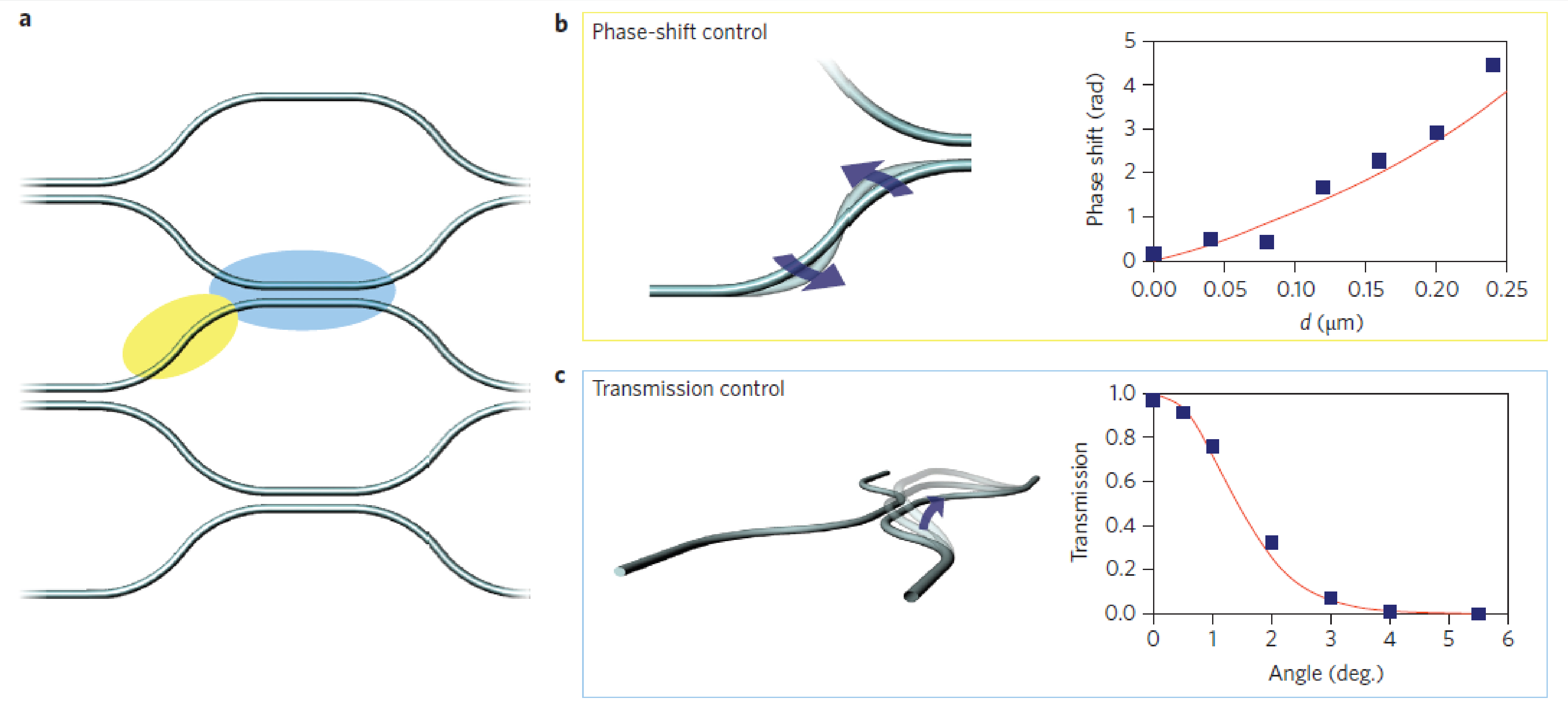
Max Tillmann[1,2]*, Borivoje Dakić[1], René Heilmann[3], Stefan Nolte[3], Alexander Szameit[3] and Philip Walther[1,2]*

nature photonics
LETTERS
PUBLISHED ONLINE: 26 MAY 2013 | DOI: 10.1038/NPHOTON.2013.112

## Integrated multimode interferometers with arbitrary designs for photonic boson sampling

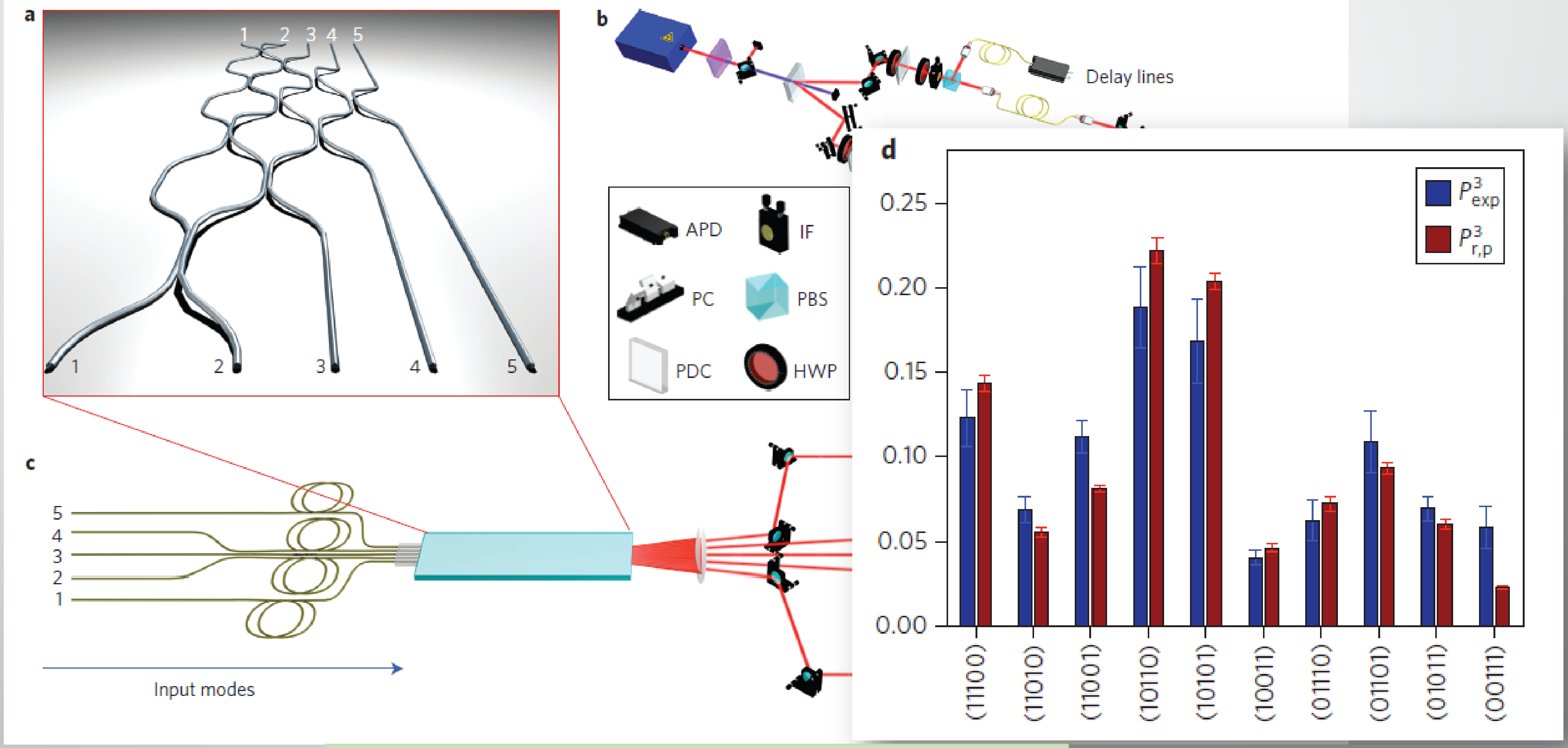
Andrea Crespi[1,2], Roberto Osellame[1,2]*, Roberta Ramponi[1,2], Daniel J. Brod[3], Ernesto F. Galvão[3]*, Nicolò Spagnolo[4], Chiara Vitelli[4,5], Enrico Maiorino[4], Paolo Mataloni[4] and Fabio Sciarrino[4]*

# Arbitrary transformation in a circuit



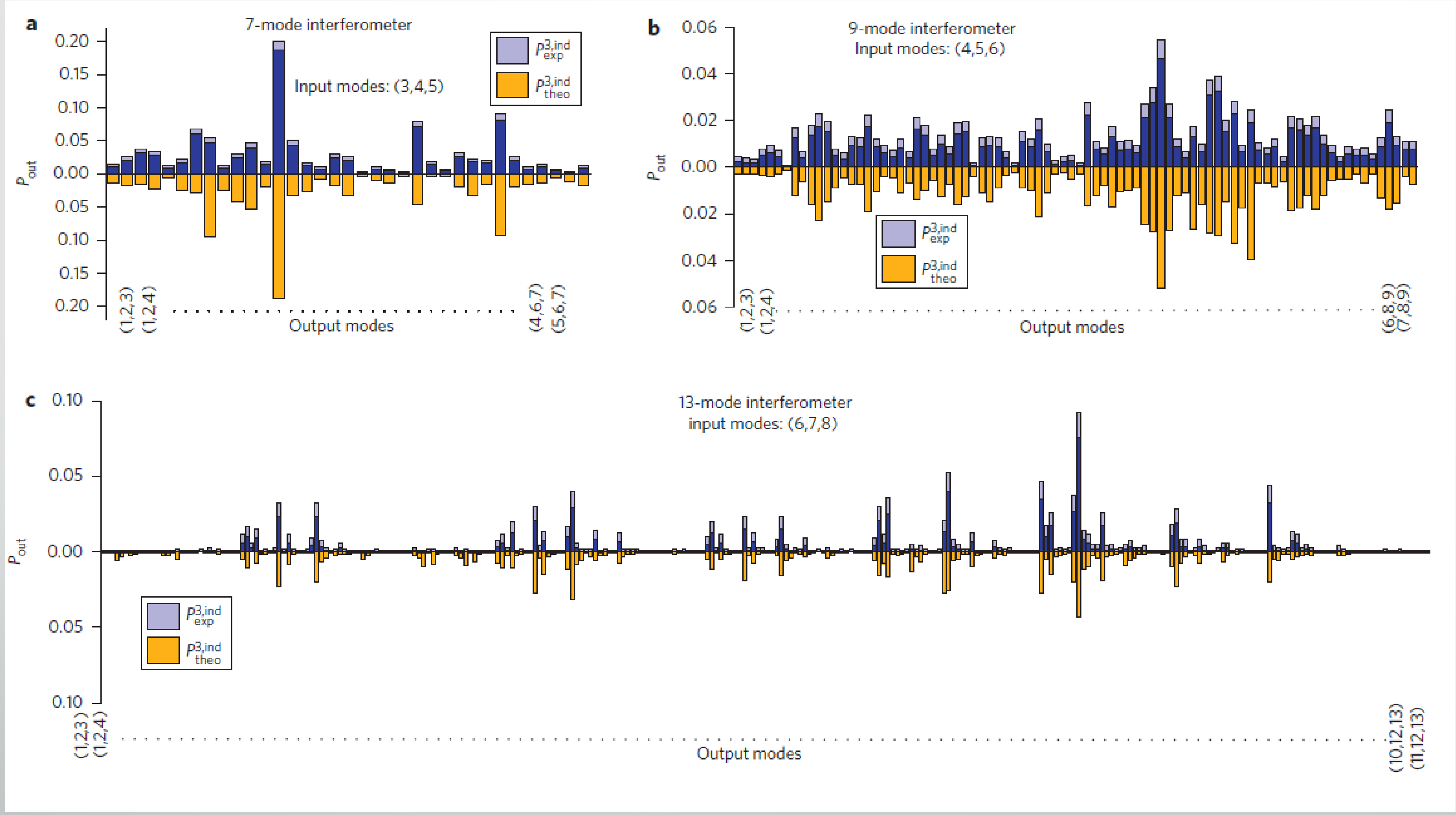

A. Crespi et al., Nature Photonics 7, 545, 2013

# Experimental setup




A. Crespi et al., Nature Photonics 7, 545, 2013

# Scaling up to 13 modes




N. Spagnolo et al., Nature Photonics 8, 615, 2014

Roberto Osellame

CNR IFN Istituto di Fotonica e Nanotecnologie

# Quantum validation of a Photonic computer

nature photonics | LETTERS
PUBLISHED ONLINE: 22 JUNE 2014 | DOI: 10.1038/NPHOTON.2014.135

## Experimental validation of photonic boson sampling

Nicolò Spagnolo[1], Chiara Vitelli[1,2], Marco Bentivegna[1], Daniel J. Brod[3], Andrea Crespi[4,5], Fulvio Flamini[1], Sandro Giacomini[1], Giorgio Milani[1], Roberta Ramponi[4,5], Paolo Mataloni[1], Roberto Osellame[4,5]*, Ernesto F. Galvão[3]* and Fabio Sciarrino[1]*

nature COMMUNICATIONS

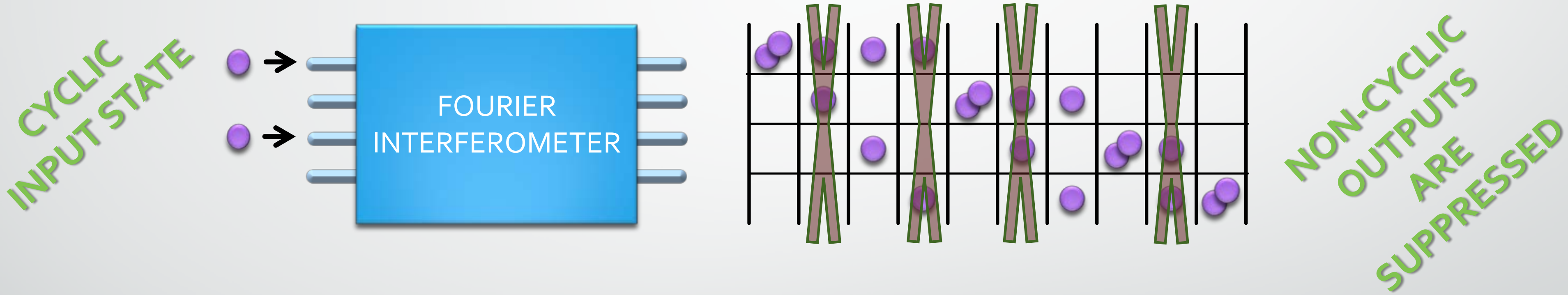
ARTICLE
Received 27 Jul 2015 | Accepted 14 Dec 2015 | Published 4 Feb 2016 DOI: 10.1038/ncomms10469 OPEN

## Suppression law of quantum states in a 3D photonic fast Fourier transform chip

Andrea Crespi[1,2], Roberto Osellame[1,2], Roberta Ramponi[1,2], Marco Bentivegna[3], Fulvio Flamini[3], Nicolò Spagnolo[3], Niko Viggianiello[3], Luca Innocenti[3,4], Paolo Mataloni[3] & Fabio Sciarrino[3]

# Simple algorithms for validation

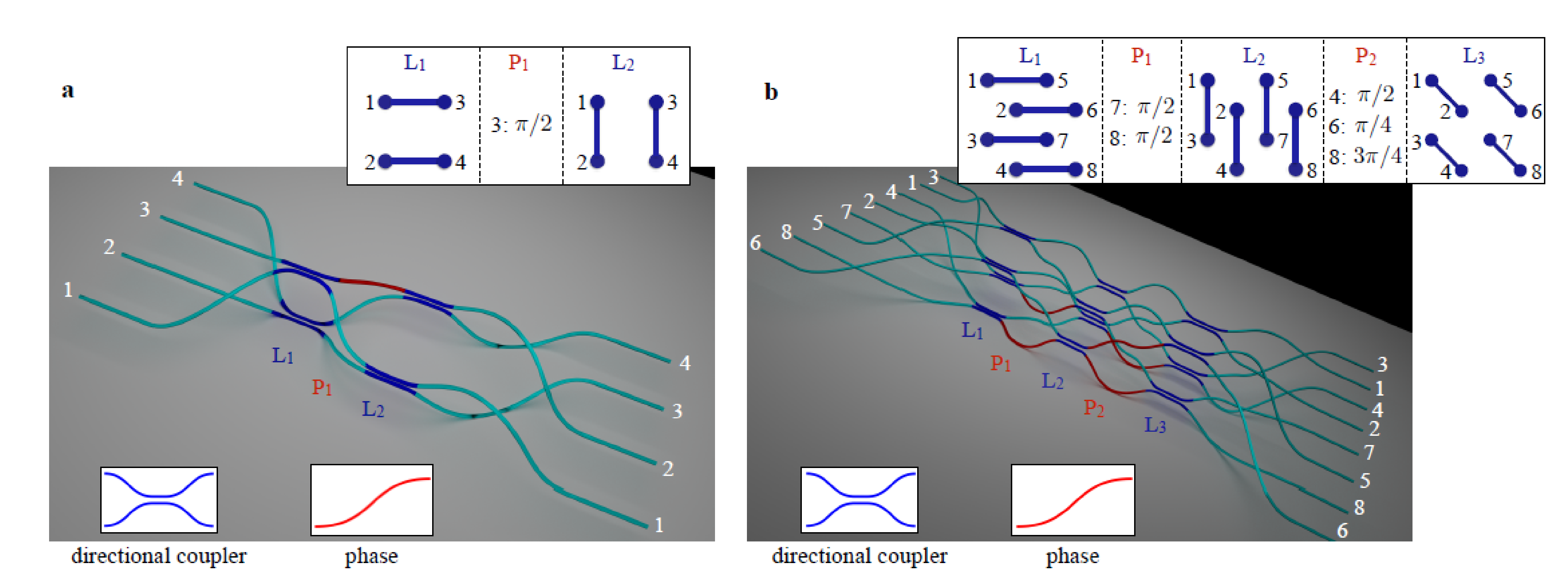
SIMPLE SUPPRESSION LAWS FOR THE OUTPUT STATES → CONVENIENT VALIDATION OF THE BOSON SAMPLING MACHINE




Tichy, M. C., Mayer, K., Buchleitner, A. & Molmer, K.
Stringent and efficient assessment of Boson-Sampling devices.
Phys. Rev. Lett. 113, 020502 (2014).

# fs-laser writing of photonic circuits

- 3D photonic circuit implementing a quantum Fast Fourier Transform




4 modes

8 modes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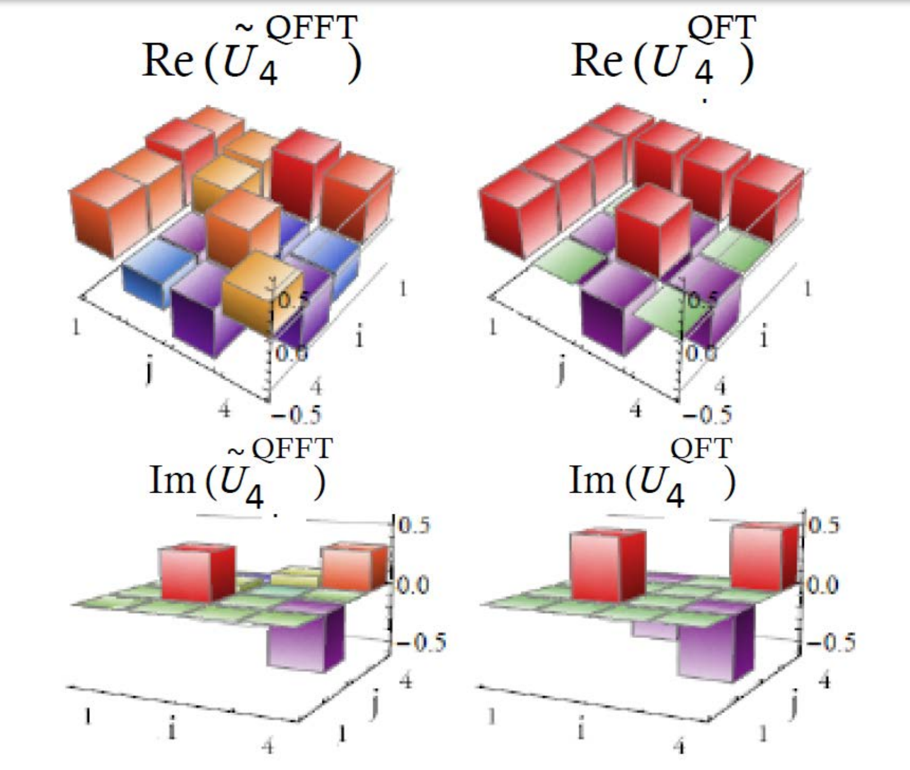
Istituto di Fotonica e Nanotecnologie

# Quantum device characterization

Reconstruction of the **unitary transformation** of the devices, by measuring **single-photon** distributions and **two-photon** coincidences (λ = 785 nm).

**4 MODES**



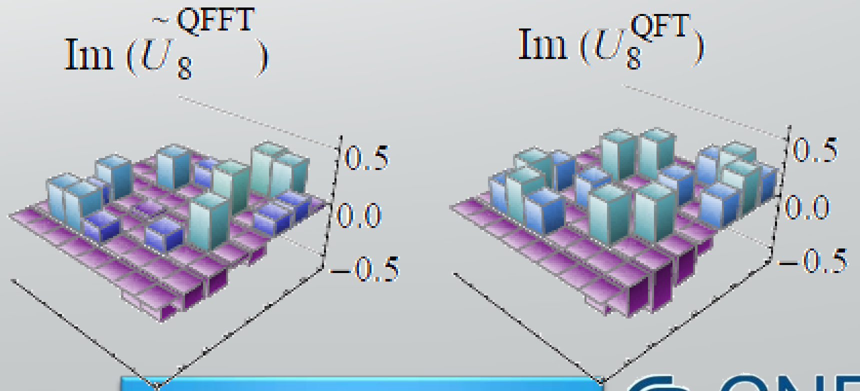

**EXP** **THEO**

$\mathcal{F}$ = 98.0 %

$\mathcal{F}$ = 95.6 %

**8 MODES**

**EXP** **THEO**



# Experiment validation

**4 modes**

- Two-photon states in different input states with cyclic symmetry are injected in the interferometers.
- Output events are recorded and violations of the suppression law are counted as a function of the delay between the photons.

$$V_{OBS} = N_{forbidden} \,/\, N_{tot}$$

**8 modes**

- Reducing the delay between the photons they become more indistinguishable: explanations with classical (distinguishable - D) particles or light in a mean-field (MF) state are progressively ruled out.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# Next step for Quantum validation

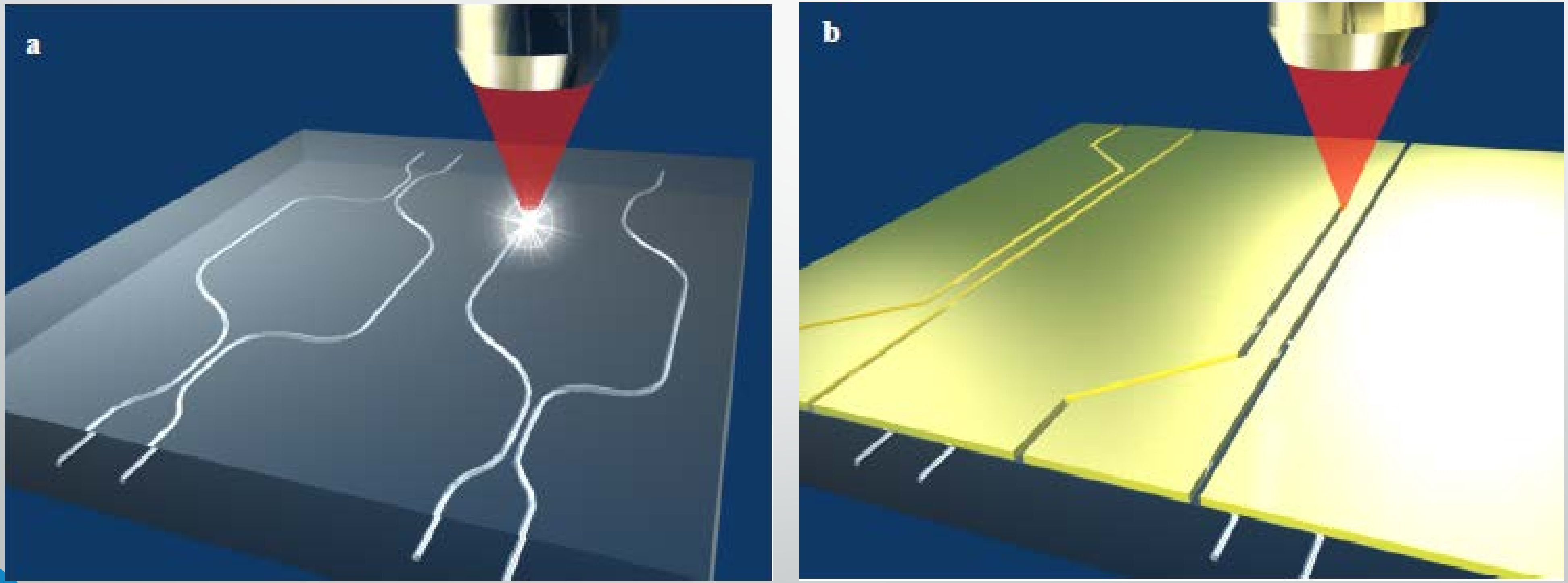
Input Quantum State

Quantum computation

**Tuneable circuits are needed!**

# Reconfigurable photonic circuits
## *Fabrication*

- Photonic circuits are laser written, then a thin gold layer is deposited
- fs-laser ablation is used to define the thermal shifters

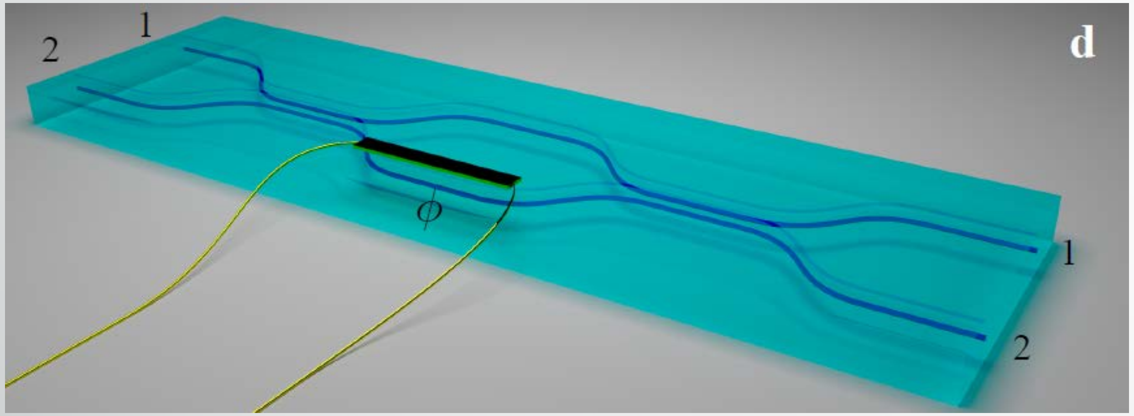


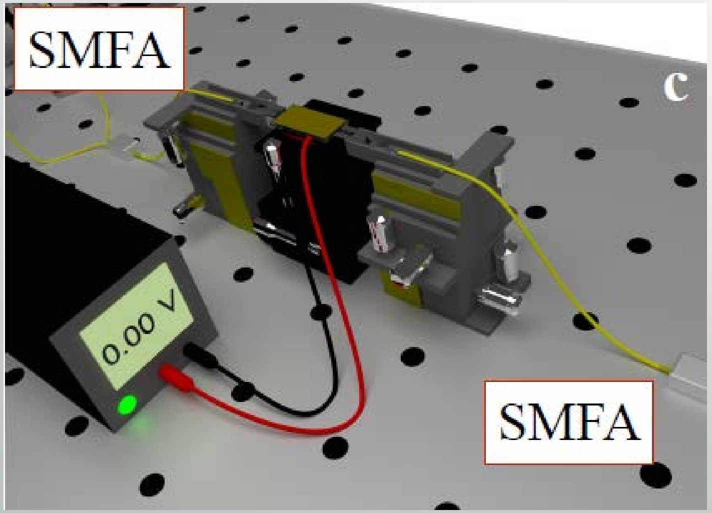

F. Flamini et al., Light Science & Applications 4, e354 (2015)

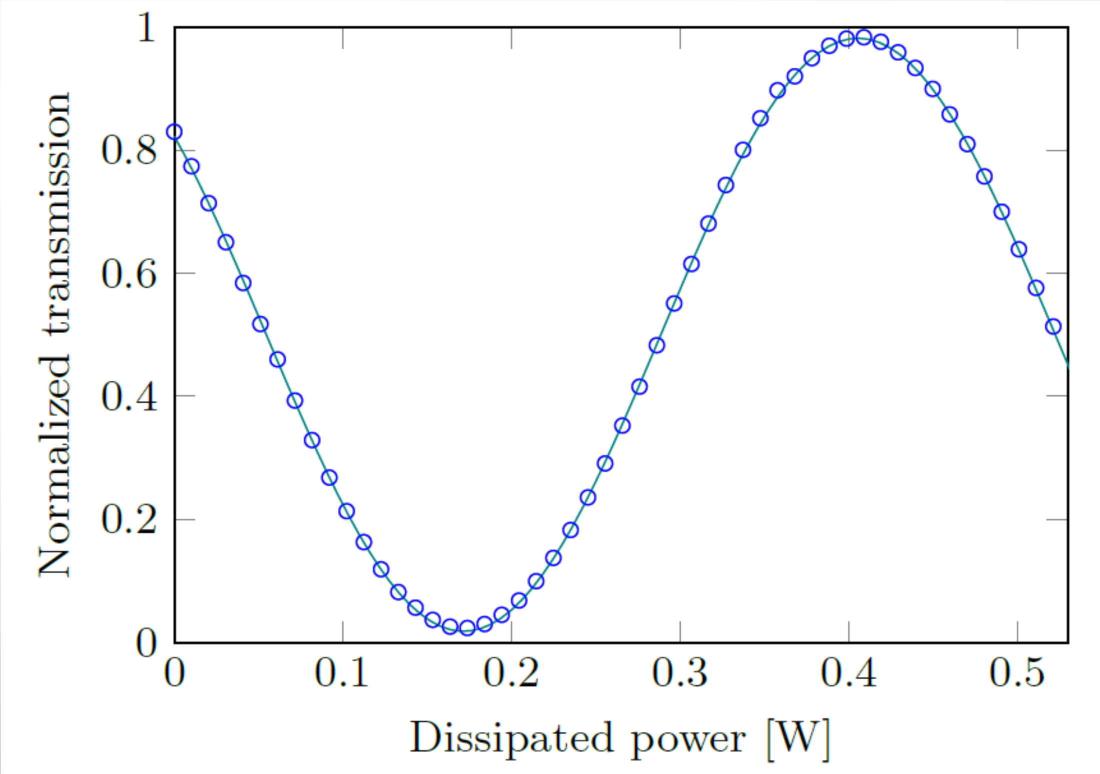
# Reconfigurable photonic circuits

## *Characterization*

- Suitably driving the surface resistors induces highly controllable phase shifts




**Fringe visibility = 97 %**

# Conclusions

- Femtosecond laser micromachining can produce both optical waveguides and microchannels, with excellent prototyping and 3D capabilities
- Application to integrated optofluidic devices and integrated quantum photonic circuits have been presented
- Several more applications can benefit from this powerful microfabrication technique

erc European Research Council Established by the European Commission
3D-QUEST
PICQUE Marie Curie Initial Training Network in Photonic Integrated Compound Quantum Encoding
erc European Research Council Established by the European Commission
3D-COUNT
HIBISCUS
micro FLUID
erc CAPABLE AdG 2016
QWAD Quantum Waveguides Applications & Design
QUCHIP Quantum Simulation on a Photonic Chip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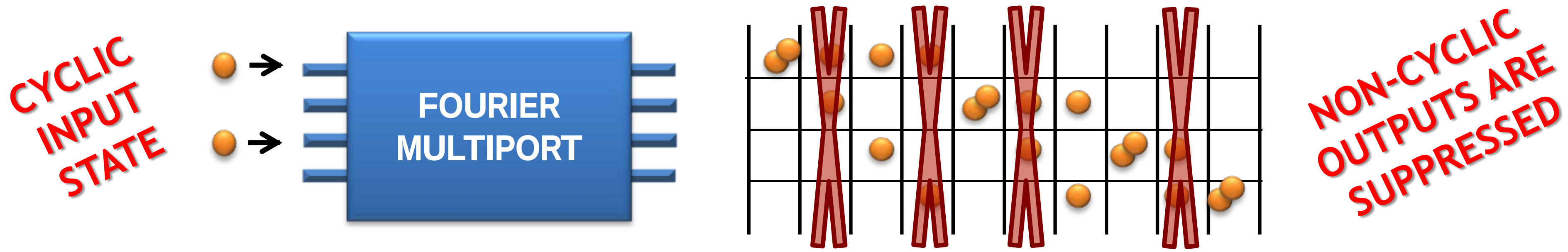
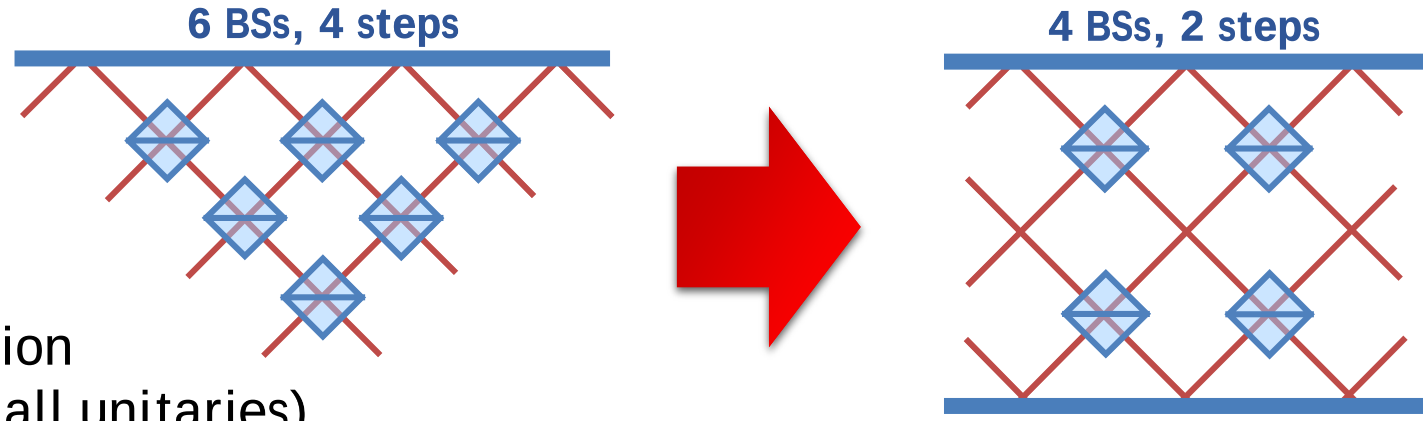
# Fourier multi-port splitters

- For more than two ports, several non-equivalent balanced splitters exist.
- An extension of the HOM effect has been formalized for Fourier multiports.




**Tichy et al.**
***Phys. Rev. Lett.* (2010)**

- Multi-port splitters can be decomposed in combinations of regular beamsplitters.

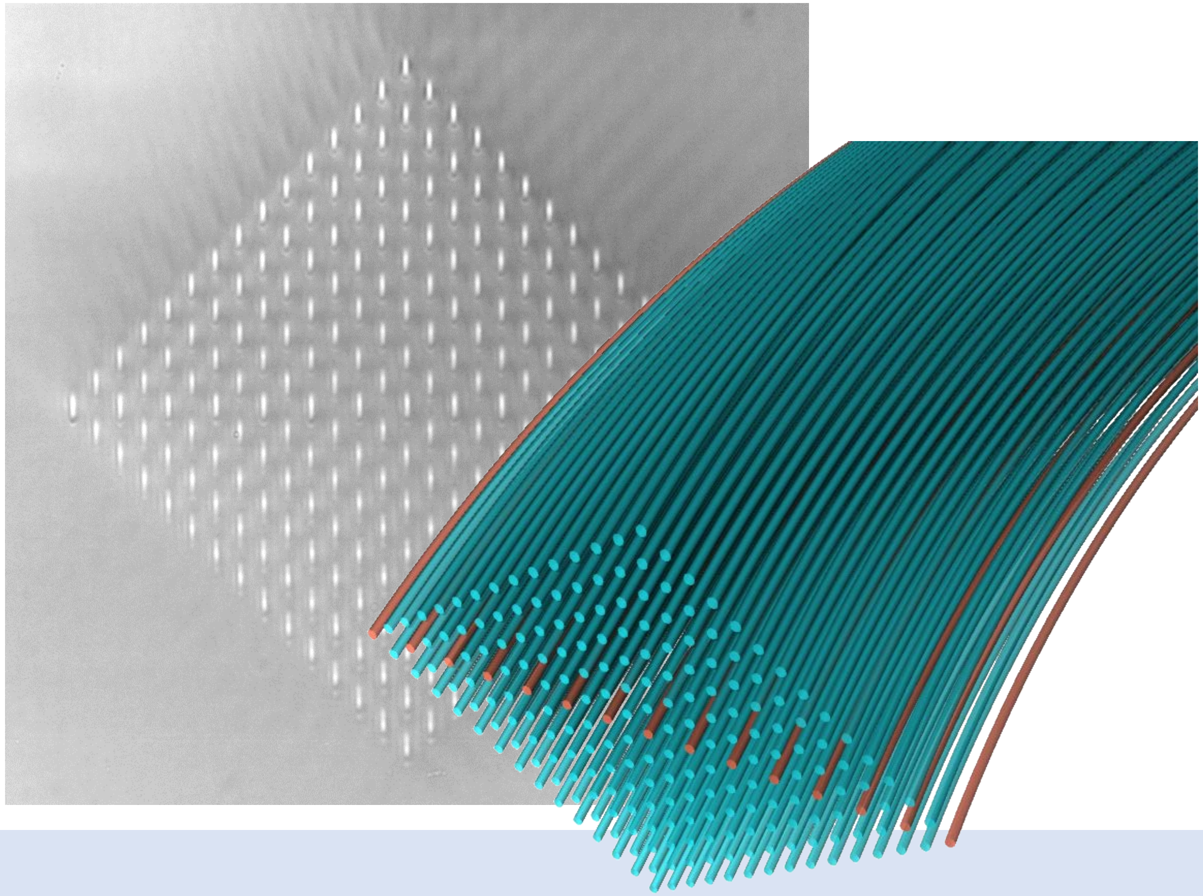


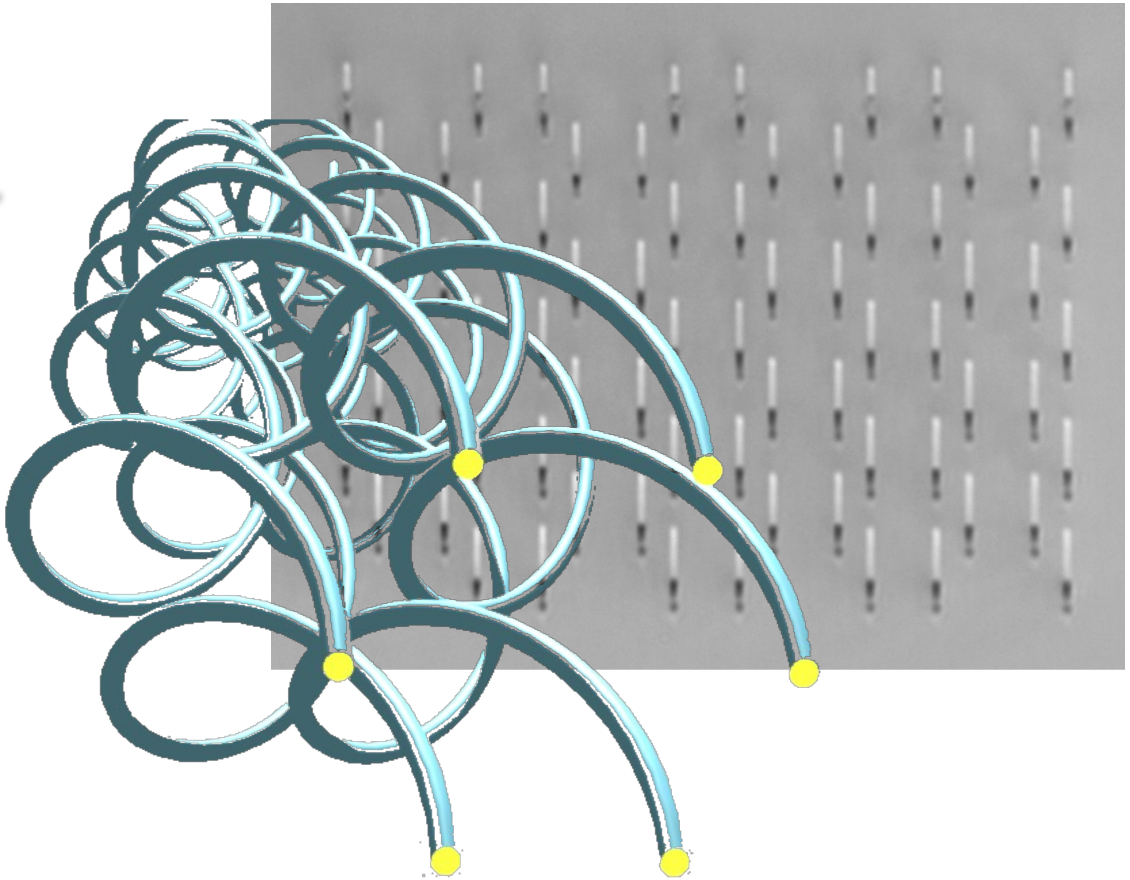

Reck's triangular decomposition (general to all unitaries)

Simpler layout:
**FAST FOURIER TRANSFORM**
algorithm

# Mastering 3D circuits

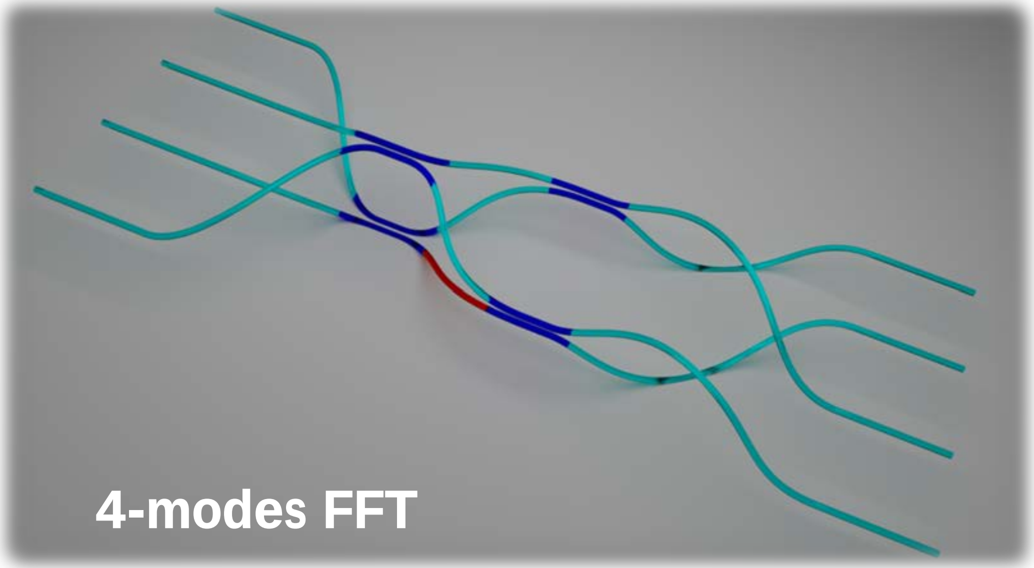
Unique capability to fabricate waveguide circuits and arrays in three-dimensions.





**Crespi et al. New J. Phys. 15, 013012 (2013).**
**Corrielli et al. Nat. Commun. 4, 1555 (2013).**

# Device fabrication

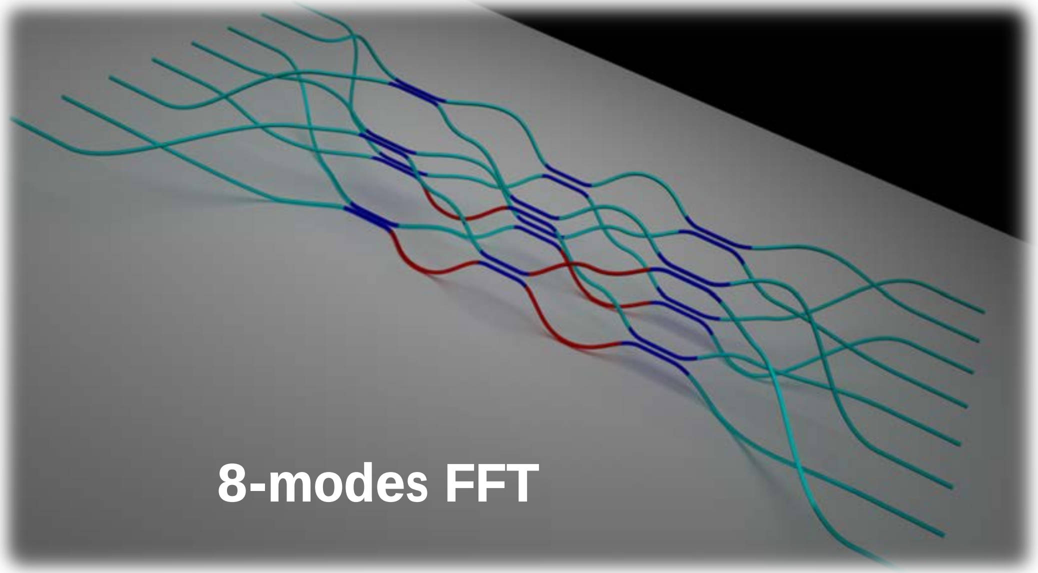



- Two different chips have been fabricated in borosilicate glass (EAGLE 2000 Corning).
- Waveguides yield single-mode behaviour at 785 nm wavelength.

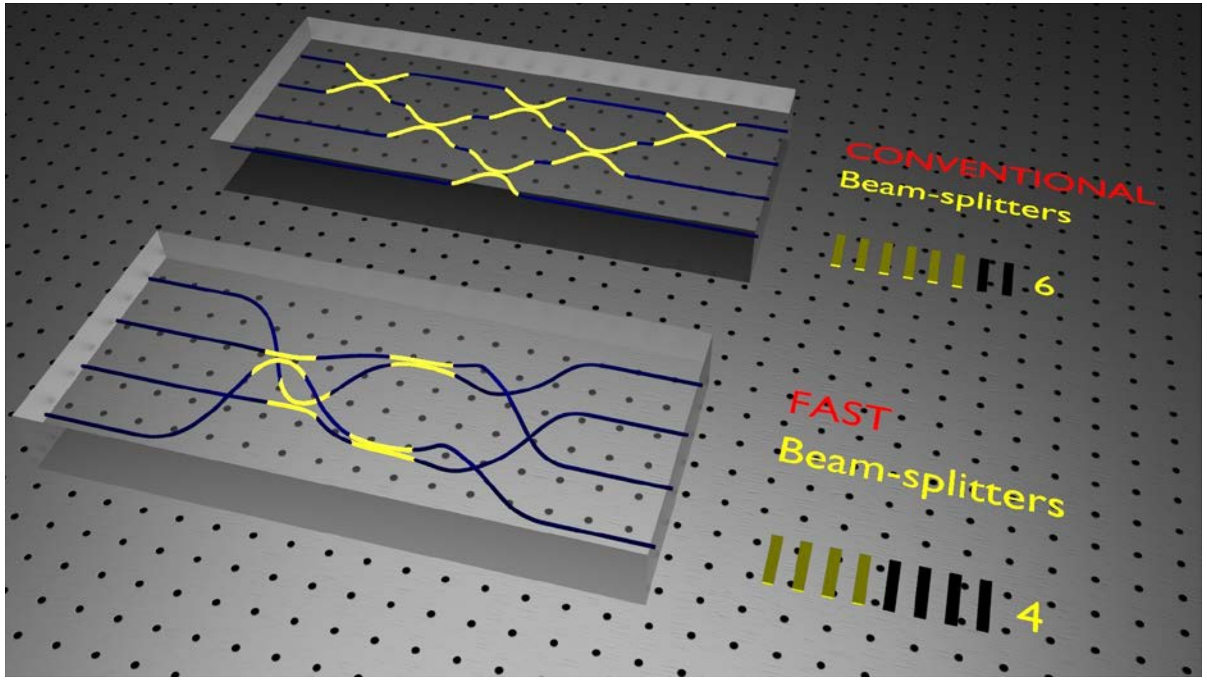
**FOOTPRINT OF THE CENTRAL PART OF THE INTERFEROMETERS**
***(excluding fan-in and fan-out)***

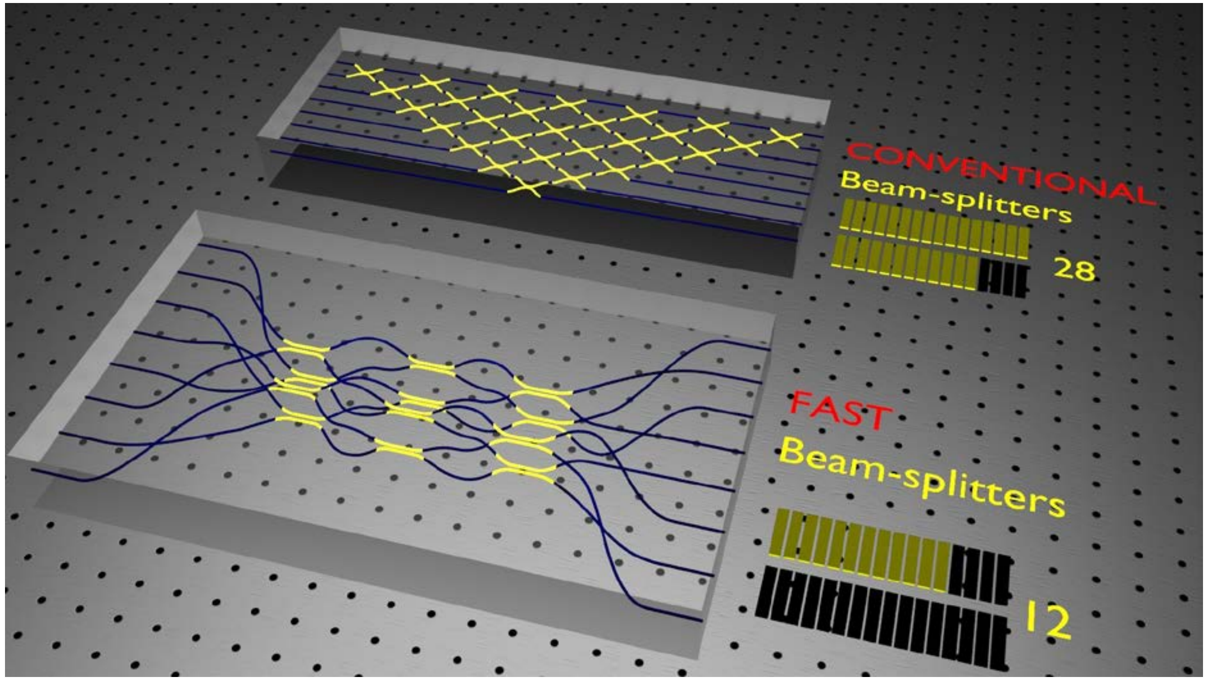
4-modes FFT: 50 µm x 50 µm x 9 mm

8-modes FFT: 95 µm x 95 µm x 15 mm



# Improved scalability




Reduction in the complexity of the circuits with respect to conventional planar implementations