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

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Arthur Ashkin
Optical forces and tweezer

Gerard Mourou
Chirped-Pulse-Amplification for ultrashort pulses

Donna Strickland
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

100 µm

10 µm
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?


Shape control:

Waveguide
Pre-etching irradiation

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Two-Photon Polymerization

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

Two-photon absorption:
- Absorption is proportional to the square of the intensity
- It’s a process with a threshold

Resolution well below the diffraction limit
Two-Photon Polymerization


Laser Zentrum Hannover
Optofluidic single-particle manipulation
Optical forces on transparent particles

- \( F_\perp \) pushes the particle in the direction of the light propagation (scattering force).
- \( F_\parallel \) pulls the particle toward the region of higher intensity (gradient force).

**Diagram:**
- Laser beam interacting with a dielectric particle.
- Forces \( F_\perp \) and \( F_\parallel \) acting on the particle at points a and b.

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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

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

detect illnesses from a small amount of sample

Integrating Optical Stretcher: Concept

MAIN advantages:

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

fs-Laser Microfabrication

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

Integrated Optical Sorter

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

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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 Newtonian 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.

![Graphs showing microrheology results](image)
From Newtonian to non-Newtonian fluids

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

Giovanni Nava, a b Tie Yang, b Valerio Vitali, a c Paolo Minzoni, a c Ilaria Cristiani, a c Francesca Bragheri, a c Roberto Osellame, a d Lucas Bethge, a Sven Klussmann, a Elvezia Maria Paraboschi, a b Rosanna Asselta a f g and Tommaso Bellini a b *
Integrated Photonic Circuits for Boson Sampling Experiments
Quantum computers promise a revolutionary increase in computational power.
Classical bits can be either 0 or 1.

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

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’s algorithm is very difficult.

Current best implementation: $21 = 7 \times 3$

E. Martin-Lopez et al., Nature Photonics 6, 773 (2012)
Boson Sampling Problem

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

Boson Sampling

Boson Sampling in a nutshell

CLASSICAL

QUANTUM

Galton’s board

RANDOMLY-CHOSEN UNITARY TRANSFORMATION

Sample this distribution

n bosonic particles in m modes

n bosonic particles in m modes

Sample this distribution
Quantum supremacy at hand

- 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

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

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BULK QUANTUM OPTICS

severe stability and size limitations

INTEGRATED QUANTUM OPTICS

robust operation from monolithic miniaturization

CNR Istituto di Fotonica e Nanotecnologia
Practical implementations

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

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

Experimental boson sampling
Max Tillmann1,*, Borivoje Dakić1, René Heilmann1, Stefan Nolte1, Alexander Szameit1 and Philip Walther1,2,*

Integrated multimode interferometers with arbitrary designs for photonic boson sampling
Andrea Crespi1, Roberto Osellame1,2,*, Roberto Ramponi1,2, Daniel J. Brod1, Ernesto F. Galvão1,*, Nicolò Spagnolo1, Chiara Vitelli1,2, Enrico Maiorino1, Paolo Mataloni1 and Fabio Scialli2,4,8
Experimental setup

A. Crespi et al., Nature Photonics 7, 545, 2013
Scaling up to 13 modes
Quantum validation of a Photonic computer

Experimental validation of photonic boson sampling

Suppression law of quantum states in a 3D photonic fast Fourier transform chip
Simple algorithms for validation

SIMPLE SUPPRESSION LAWS FOR THE OUTPUT STATES

CONVENIENT VALIDATION OF THE BOSON SAMPLING MACHINE

fs-laser writing of photonic circuits

- 3D photonic circuit implementing a quantum Fast Fourier Transform
Reconstruction of the unitary transformation of the devices, by measuring single-photon distributions and two-photon coincidences ($\lambda = 785$ nm).

$\mathcal{F} = 98.0\%$

$\mathcal{F} = 95.6\%$
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.

$$V_{OBS} = \frac{N_{forbidden}}{N_{tot}}$$

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.
Next step for Quantum validation

Input Quantum State → Quantum computation → Question mark

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
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
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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.

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


Barak and Ben-Aryeh *JOSA B* (2007)
Mastering 3D circuits

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

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