Femtosecond laser 3D micromachining: from research prototype to industrial tool

Ya Cheng

Shanghai Institute of Optics and Fine Mechanics
East China Normal University

XXL - THE E**X**TREME OPTOELECTROMECHANI**X** **L**AB

Why femtosecond laser for micromachining?

I. Ultrashort pulse width: suppress thermal effects

Femtosecond **Nanosecond**

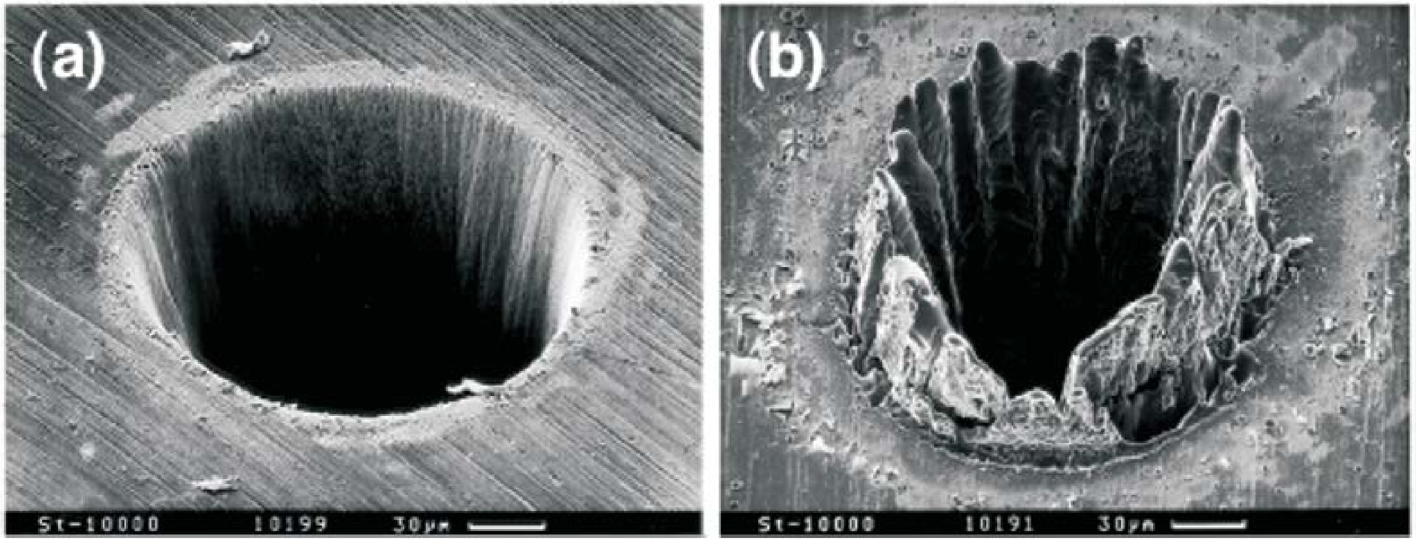
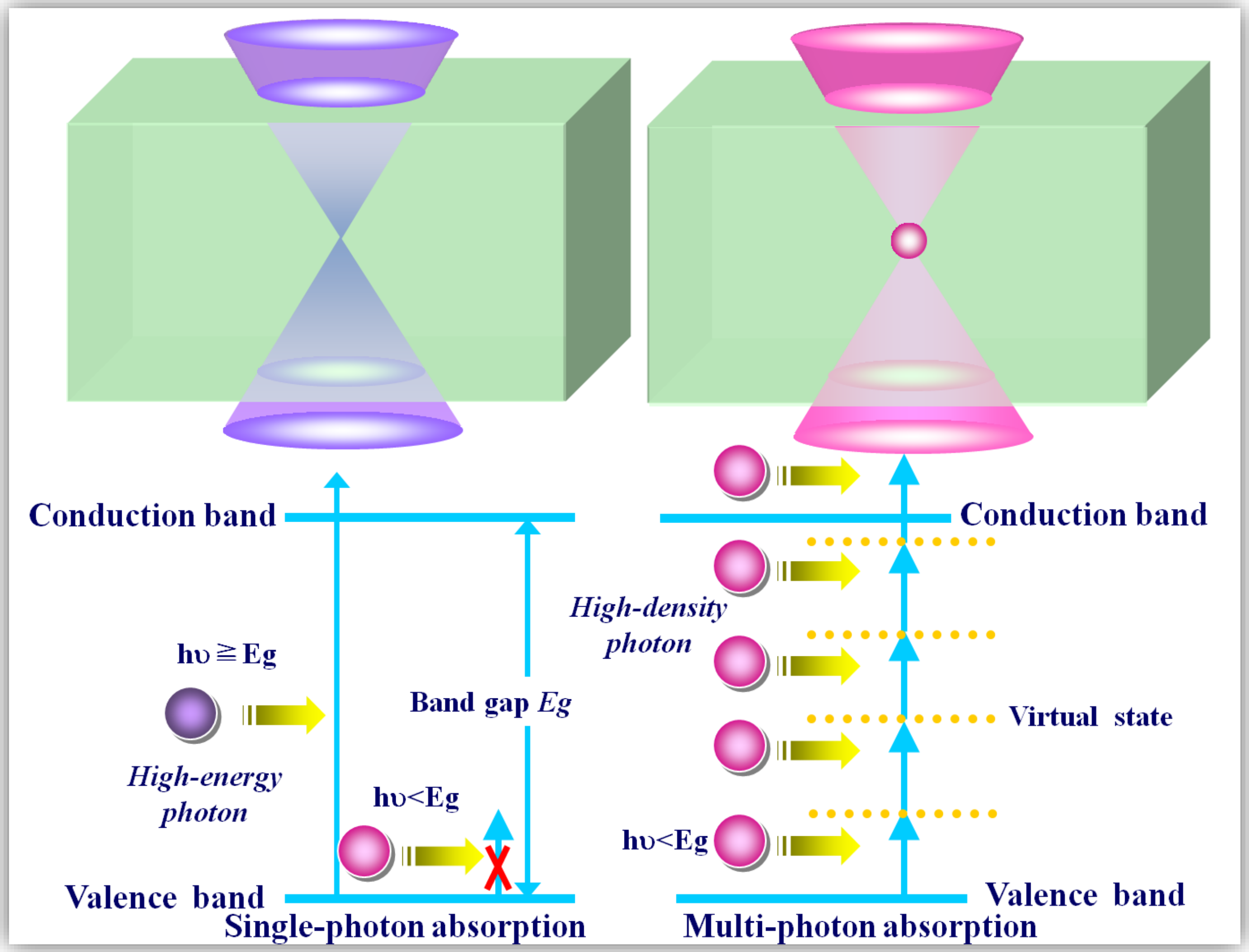


Figure 1.4 Holes drilled in 100 μm-thick steel foils by ablation using laser pulses with the following parameters: (a) pulse width: 200 fs, pulse energy: 120 μJ, fluence: 0.5 J/cm^2, wavelength: 780 nm; and (b) pulse width: 3.3 ns, pulse energy: 1 mJ, fluence: 4.2 J/cm^2, wavelength: 780 nm. The scale bars represent 30 μm. Courtesy of A. Ostendorf.

B. N. Chichkov, et al., Appl. Phys. A 63, 109 (1996)

II. Ultrahigh intensity: 3D internal processing

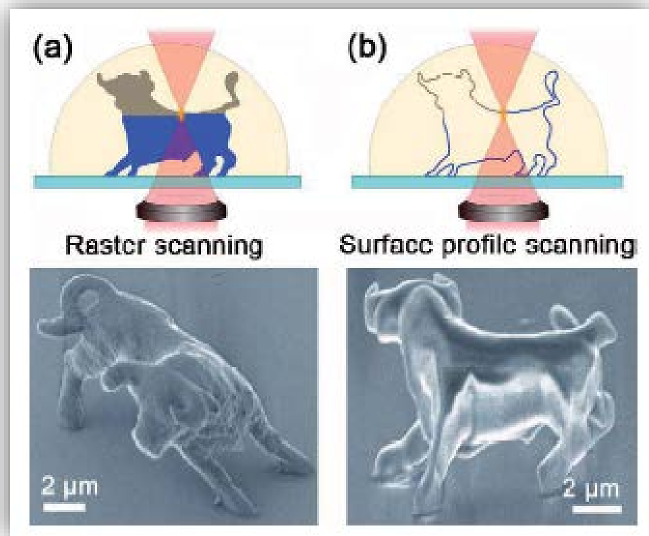


Single photon

Multi photon

III. Ultrahigh nonlinearity: break diffraction limit

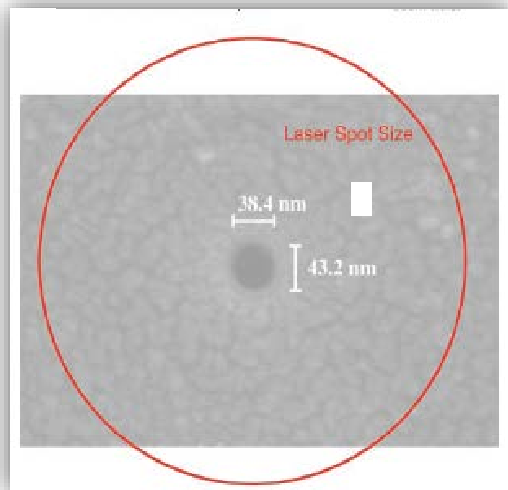
Two-photon polymerization



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

Resolution: ~ 100 nm

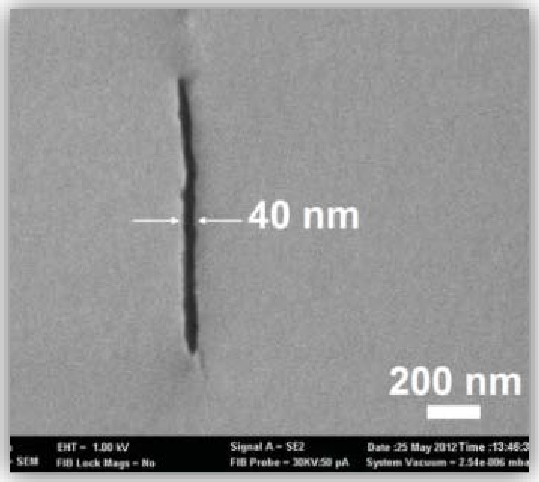
Surface ablation of glass



A. P. Joglekar, et al., PNAS 101, 5856(2004)

Resolution: ~ 40 nm

In-volume direct writing in glass



Y. Liao, et al., Lab Chip 13, 1626 (2013)

Resolution: ~ 40 nm

Nonlinear threshold effect provides a resolution far beyond that allowed by the diffraction limit

Challenges toward industrial scale applications

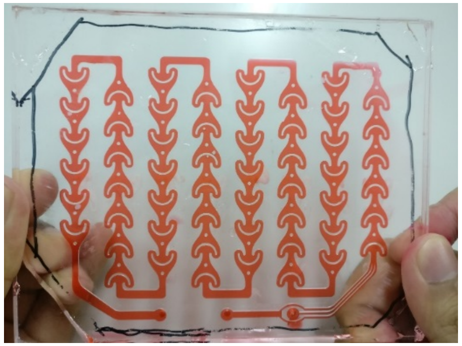
To bring femtosecond laser 3D micromachining to the commercial market, we need:

1. **High fabrication efficiency;**
2. **Large workpiece size;**
3. **Broad materials coverage !**

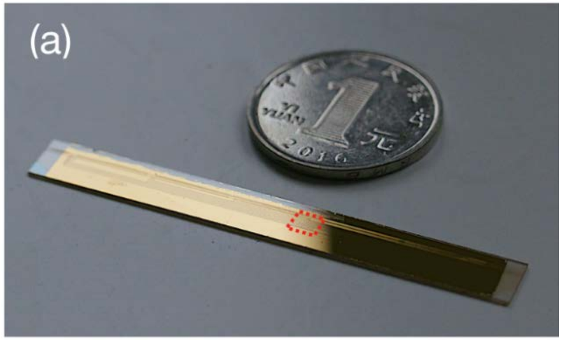
Today’s topics

I. 3D printing

II. Microfluidics & chemistry chips

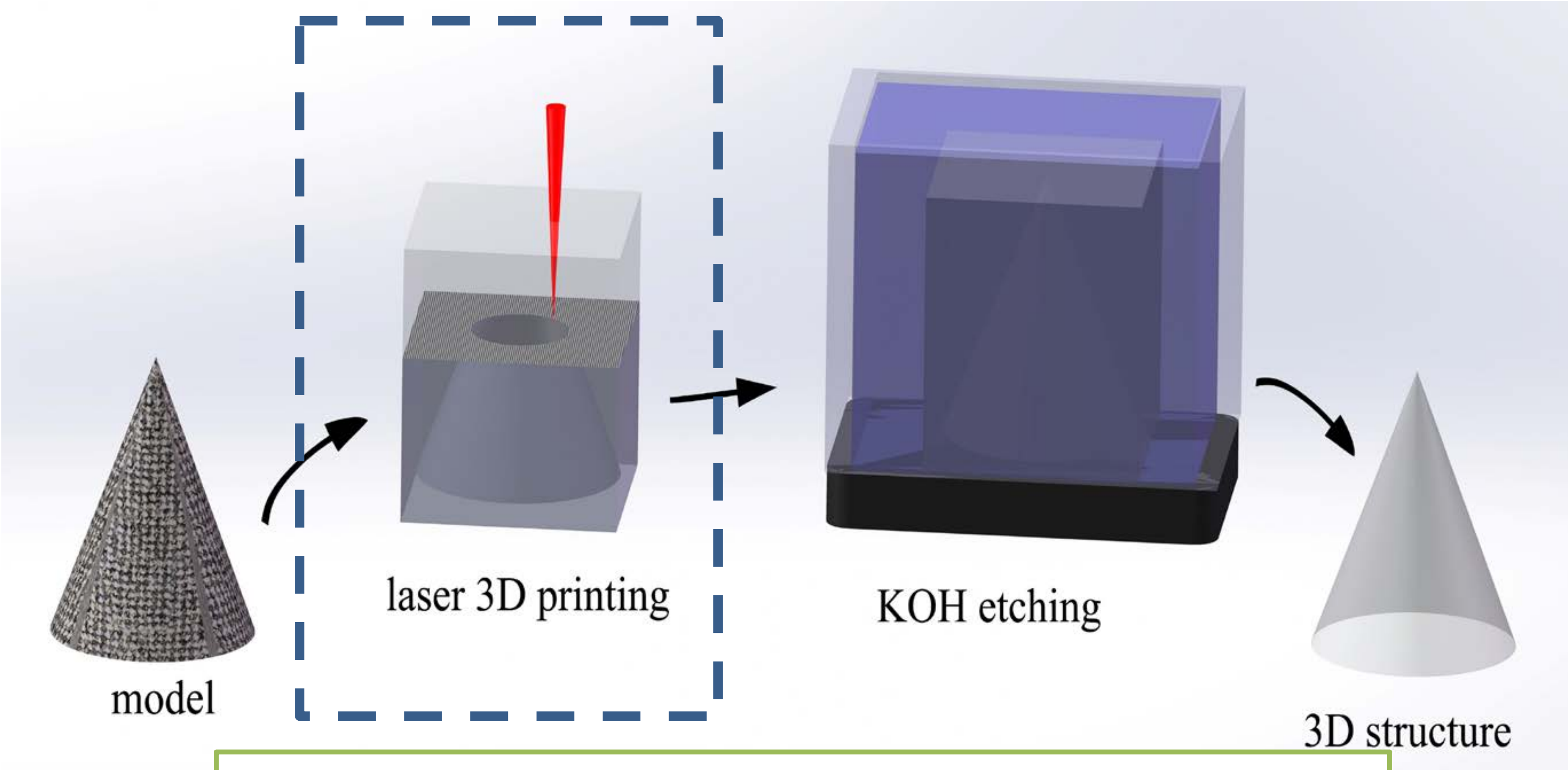


III. Photonic chips



I. 3D printing

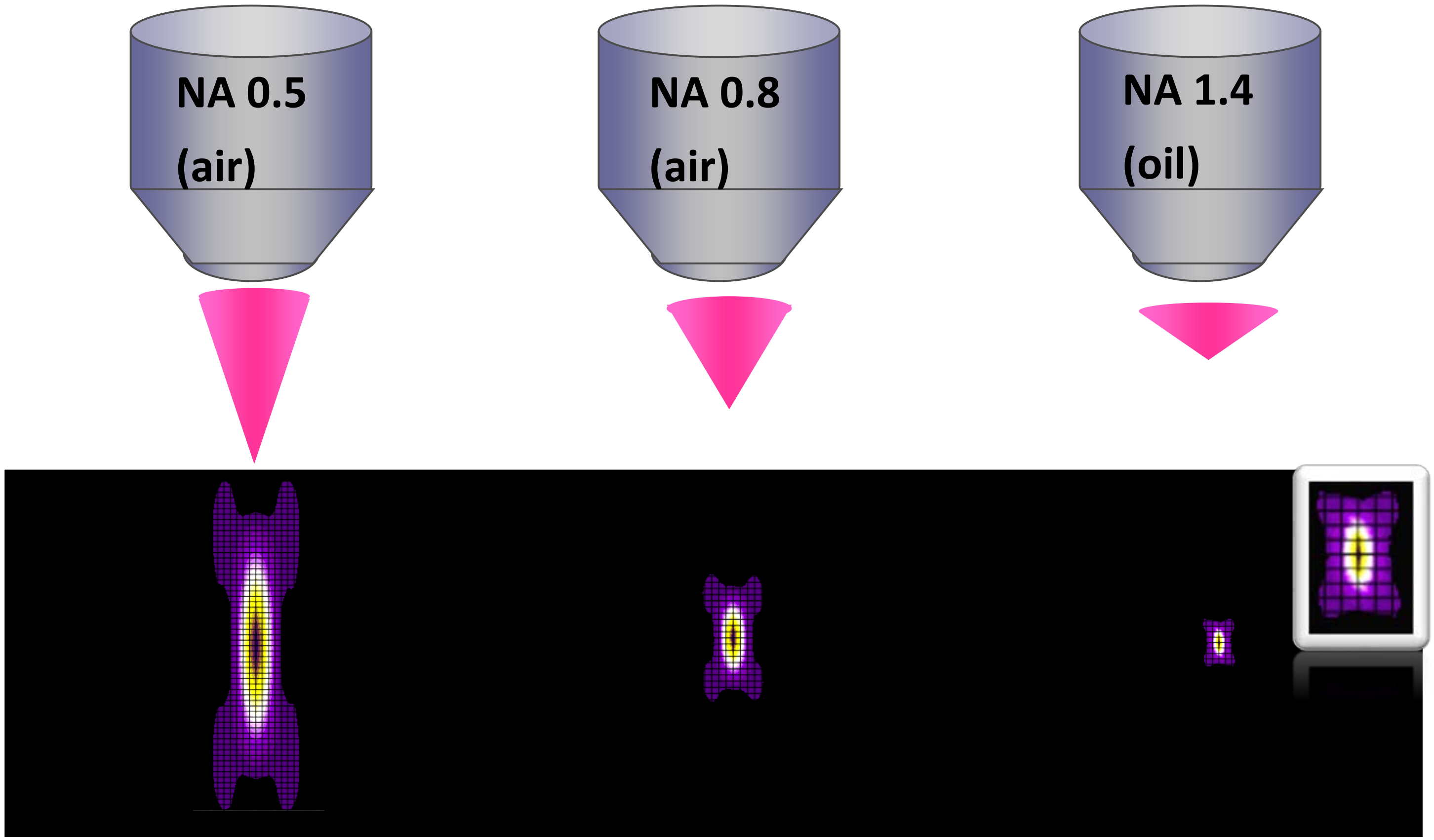
Fabricate 3D glass structures: selective laser-induced etching



Originally developed by Misawa's group in Japan in 2001 and improved by many groups around the world later

A subtractive process that can produce structures with the original material properties.

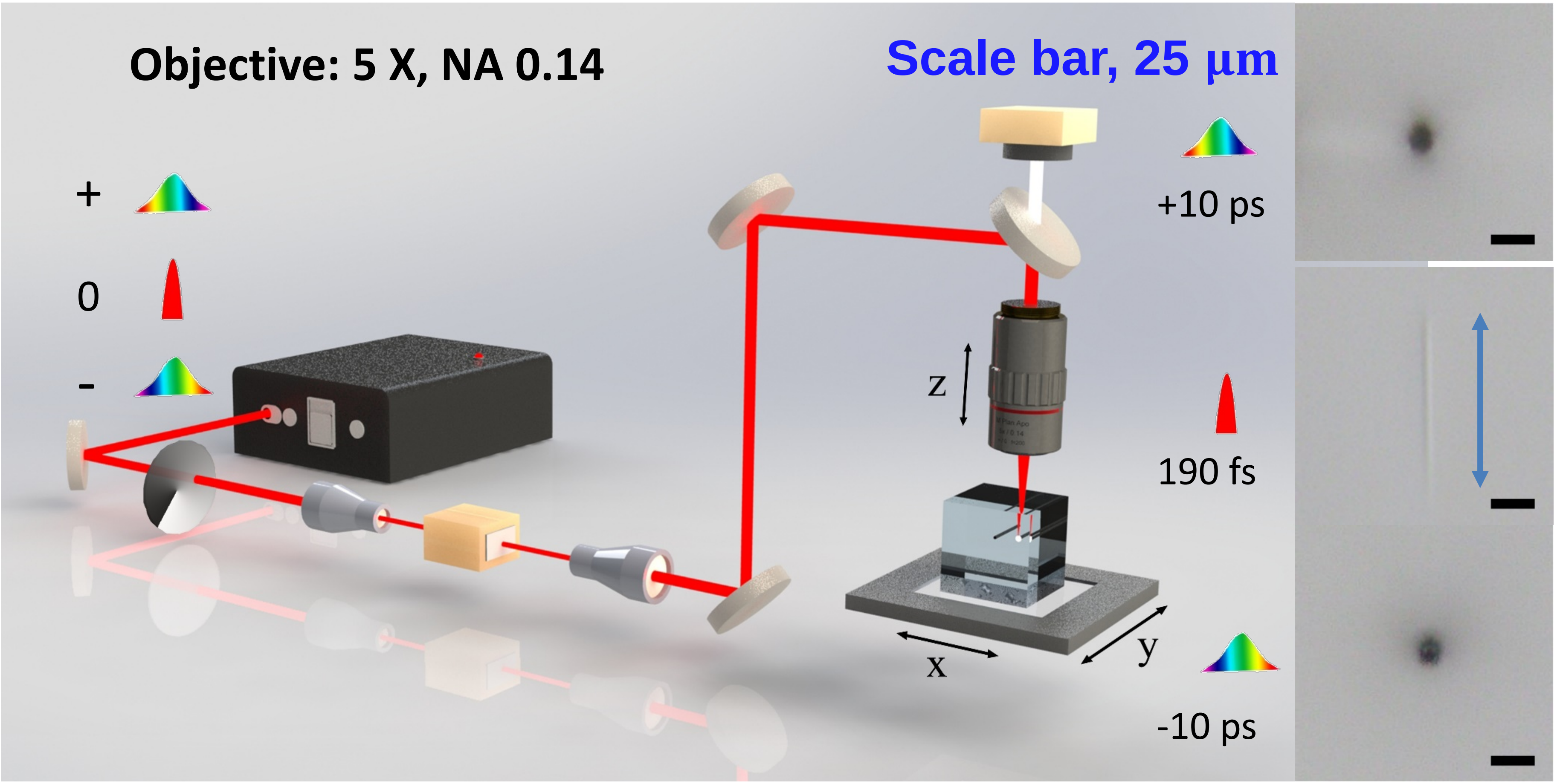
Challenges: low axial resolutions with low NAs and aberration



Large size
Low resolution

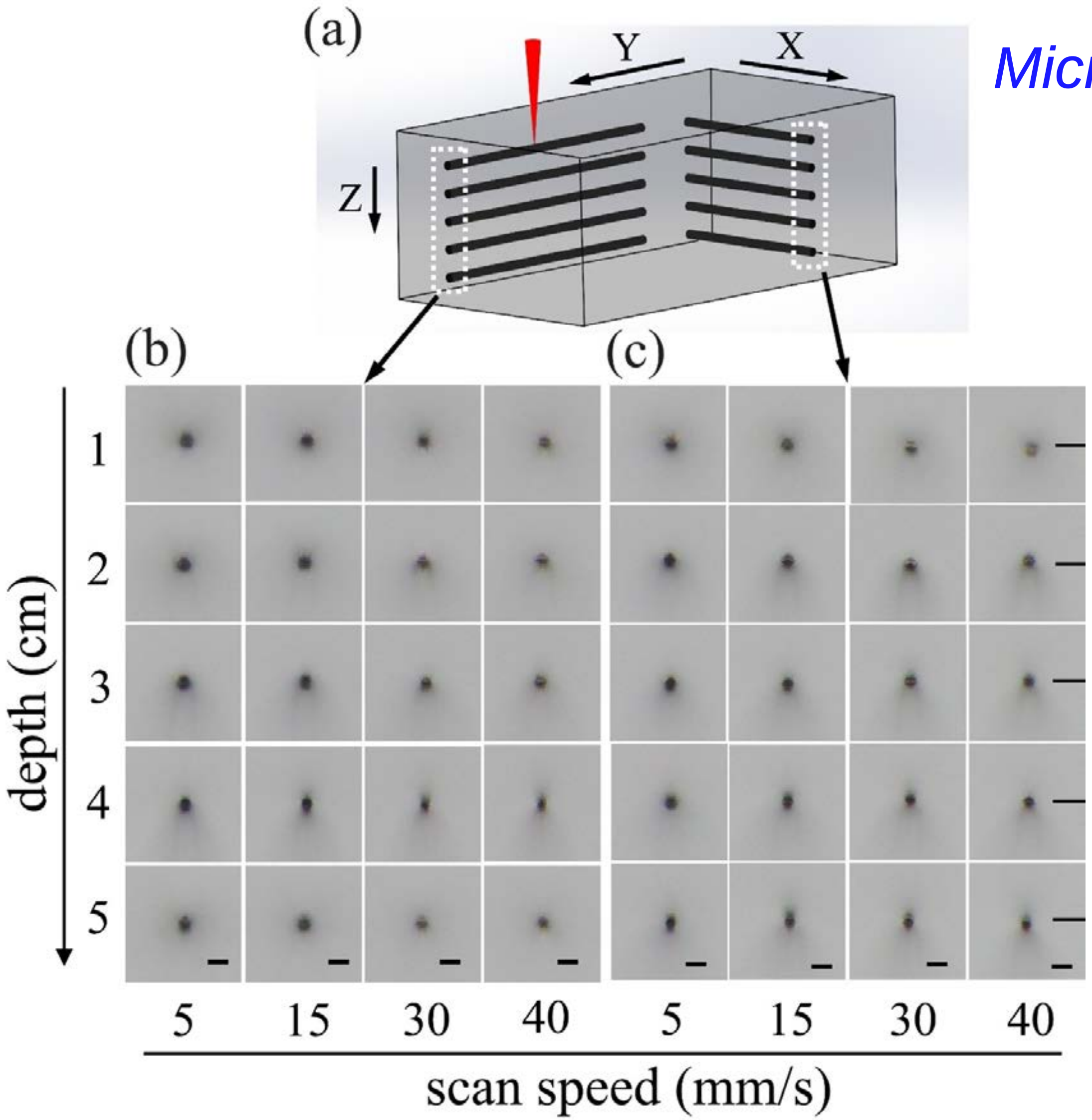
Small size
High resolution

Solution: picosecond laser modification



Y. Cheng, et al, Patent: 201910056960.2
P. Wang et al, Micromachines 2019, 10, 565

Uniform cross-section of lines at different depths

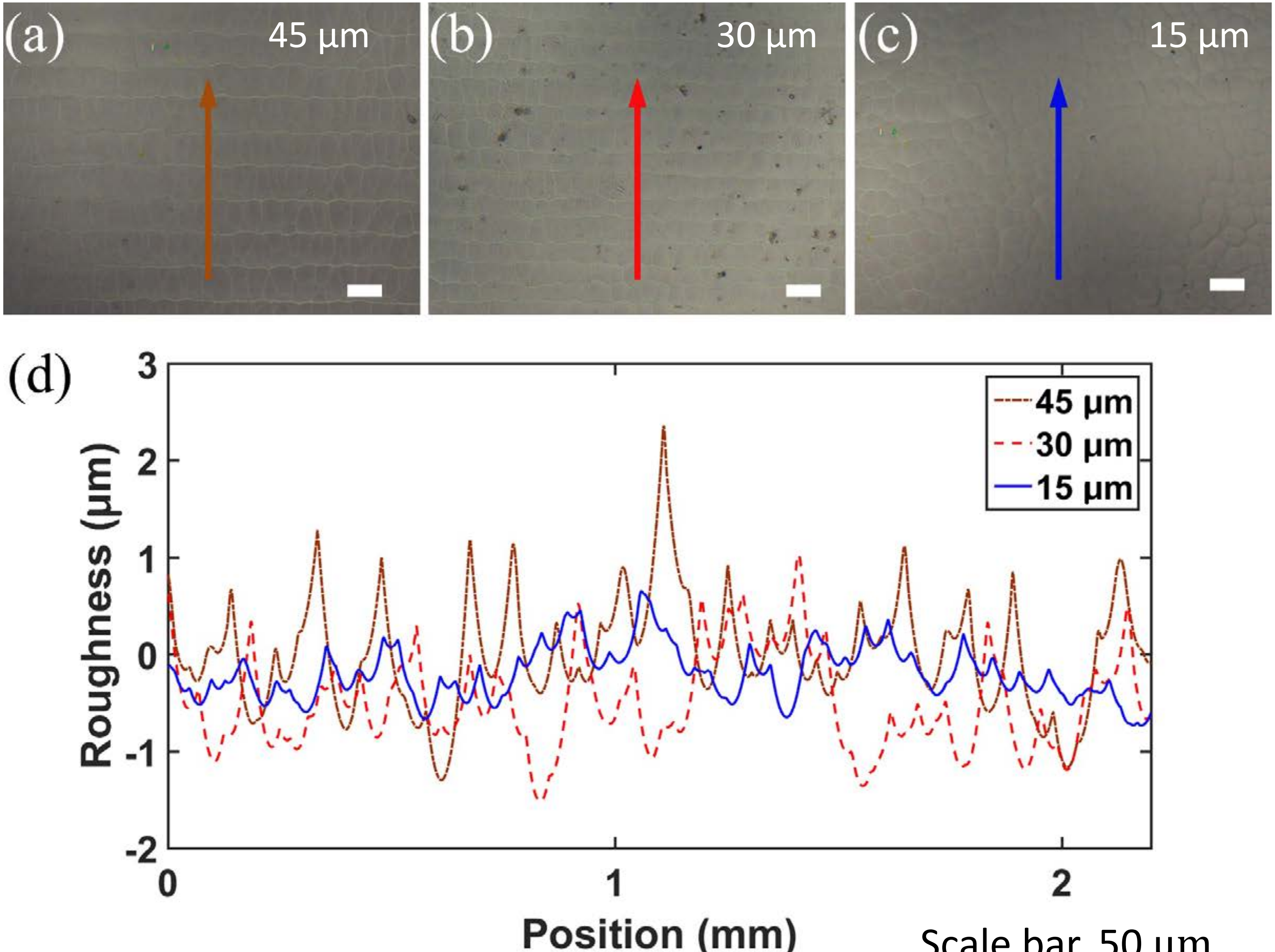


Micromachines **2019**, *10*, 565

Spherical spot independent of
- depth
- direction
- speed

Scale bar, 25 µm.

Evidence showing a resolution of ~15 μm in Z direction



Scale bar, 50 μm.

One more thing: chemical etching

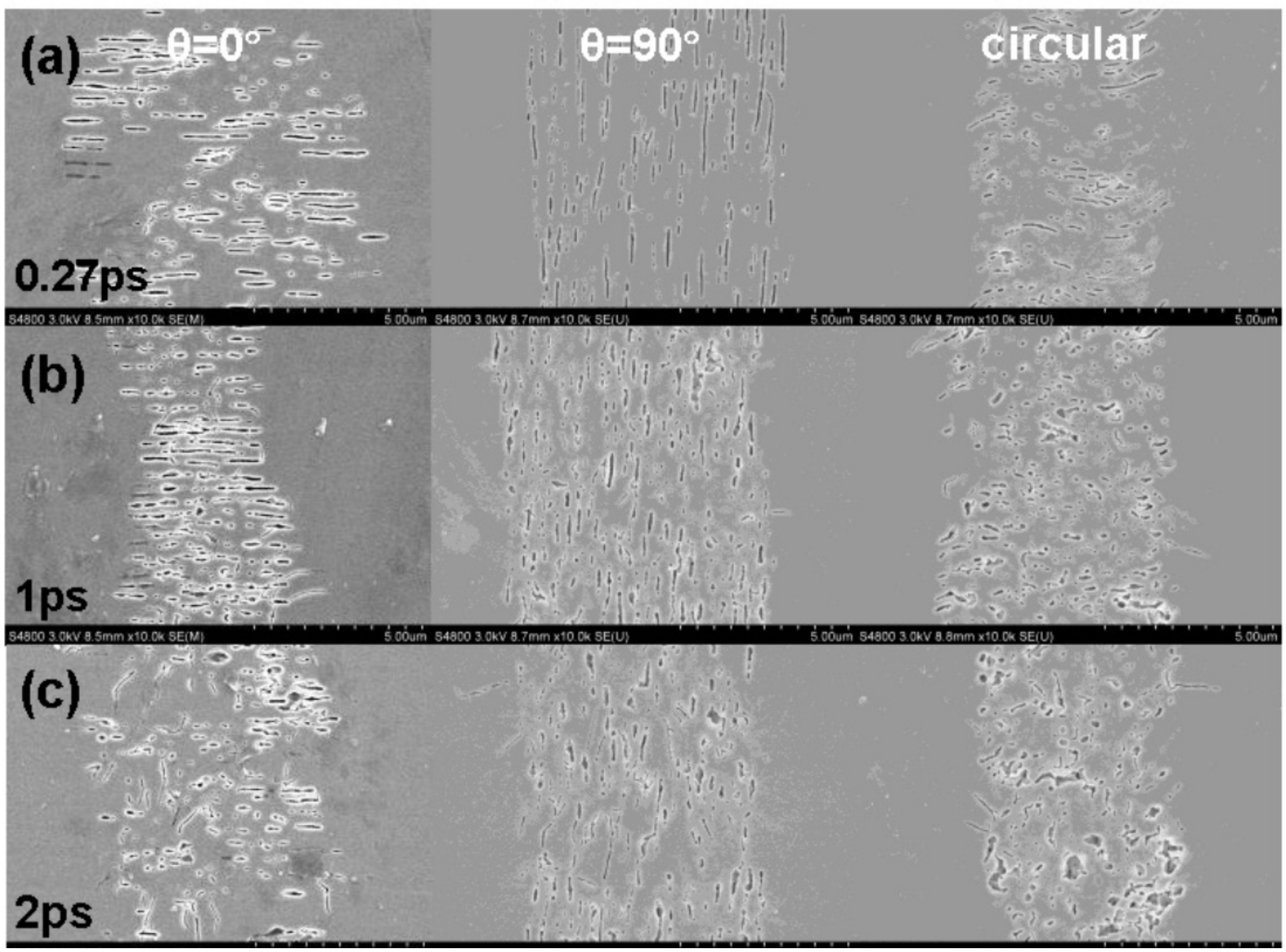
We can produce isotropic, aberration-free modification in glass.

The chemical wet etching is dependent on the orientation of polarization of the writing beam. How can we remove such dependence to achieve homogeneous writing of complex 3D structures ?

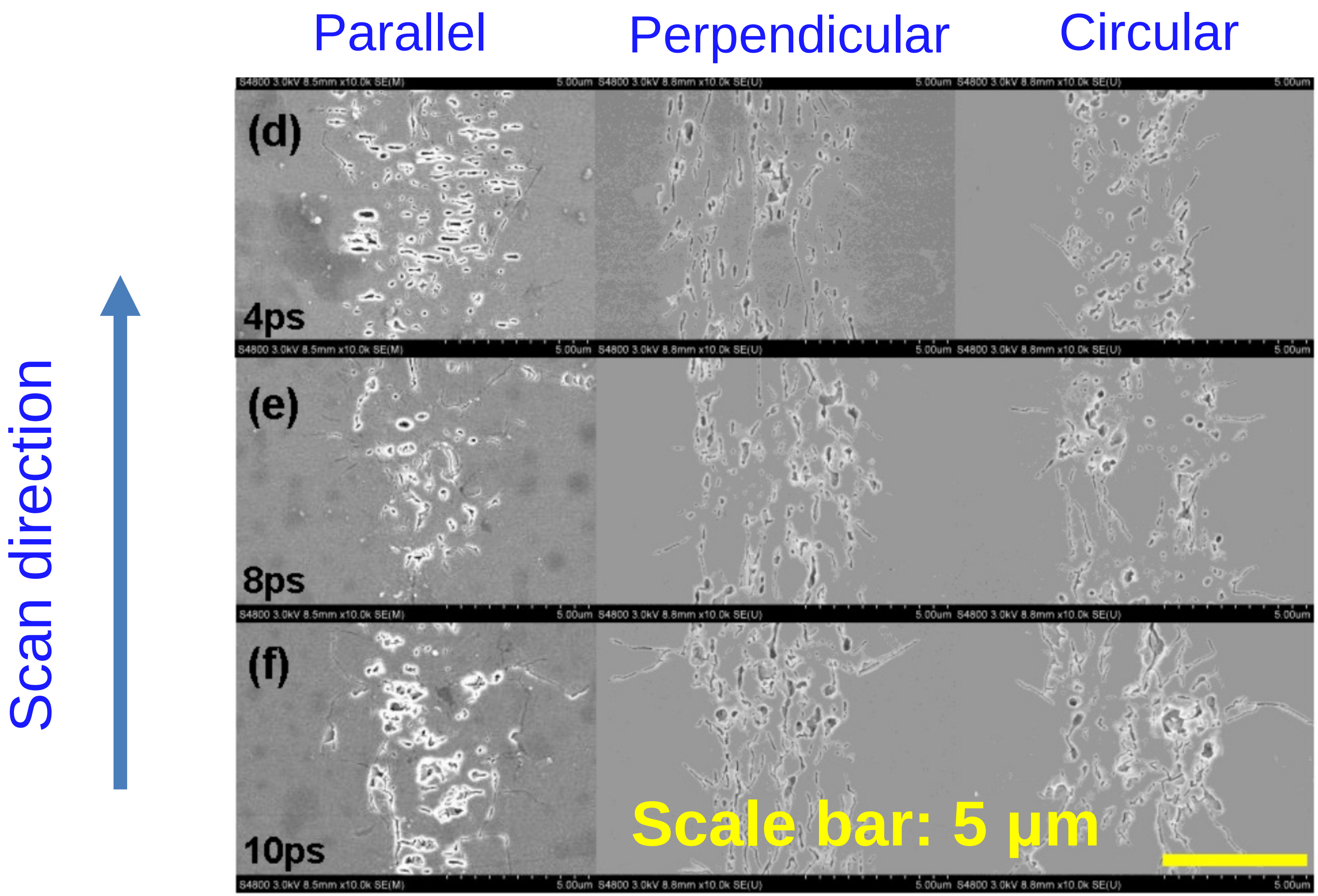
Short pulses: nanogratings

Parallel | Perpendicular | Circular

Scan direction



Longer pulses: stress induced cracks always along scan direction



Y. Cheng, et al, Patent: US16377138

Polarization sensitivity vs pulse duration

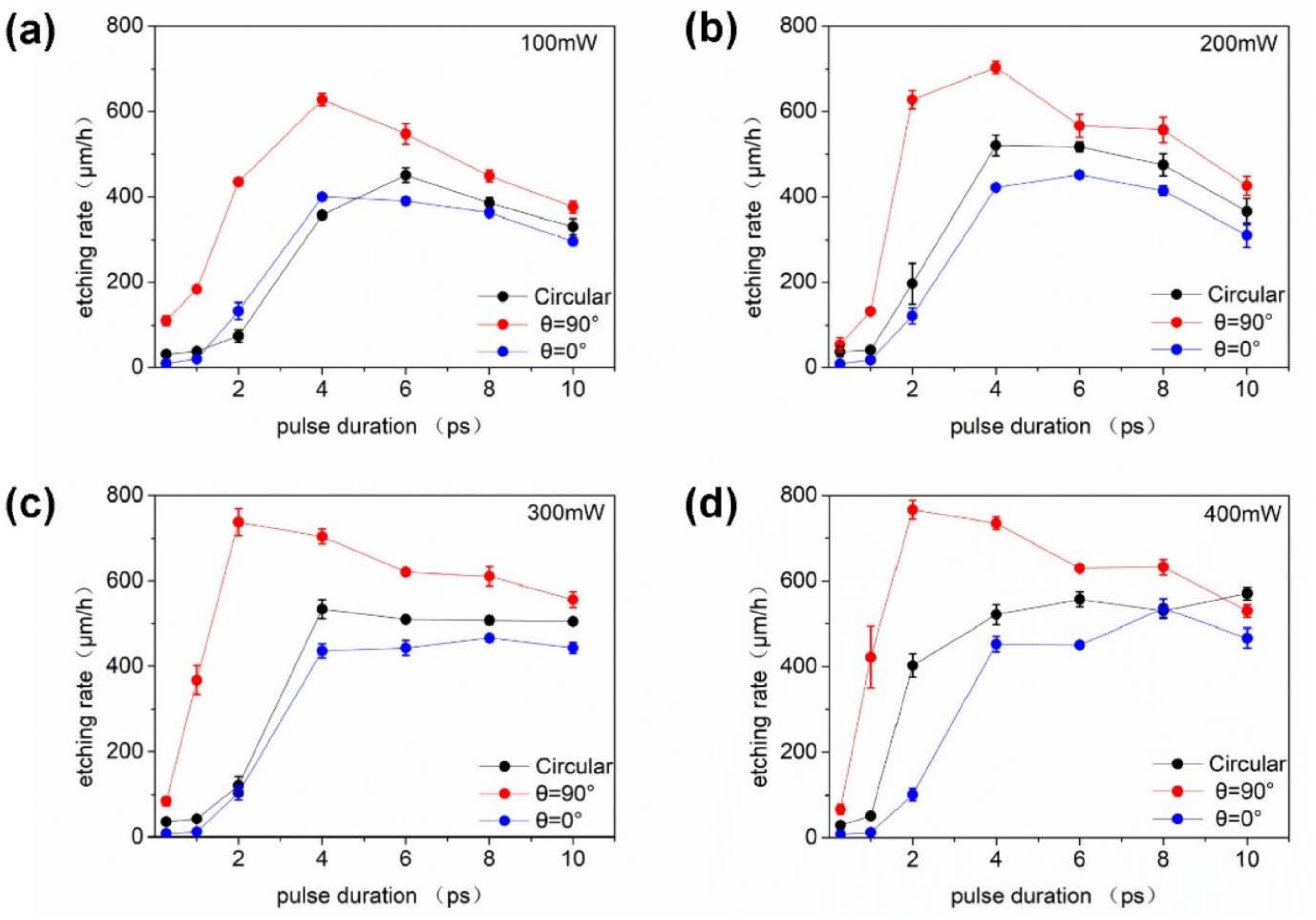
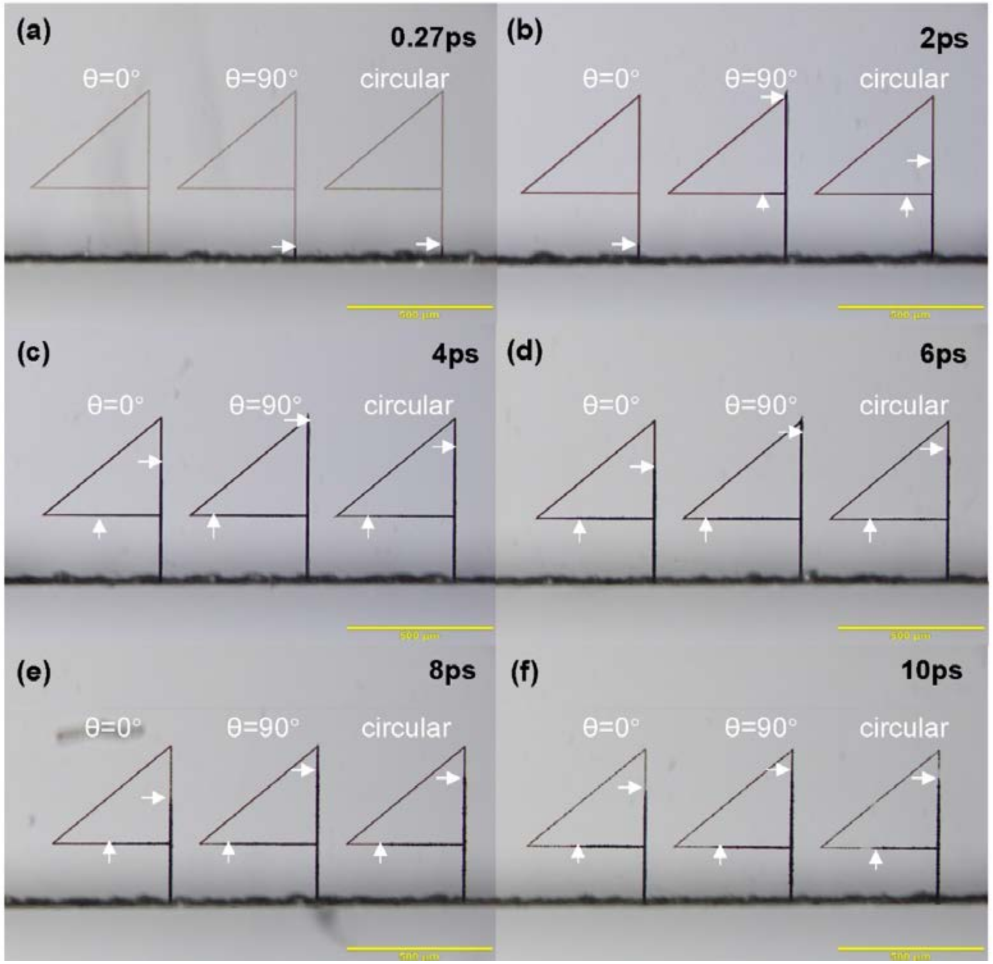


Fig. 2. Etching rates of laser modified lines in fused silica versus pulse durations at different polarization conditions and laser powers: (a) 100 mW; (b) 200 mW; (c) 300 mW; (d) 400 mW.

Applied Surface Science 485 (2019) 188–193

Selective etching independent of polarization

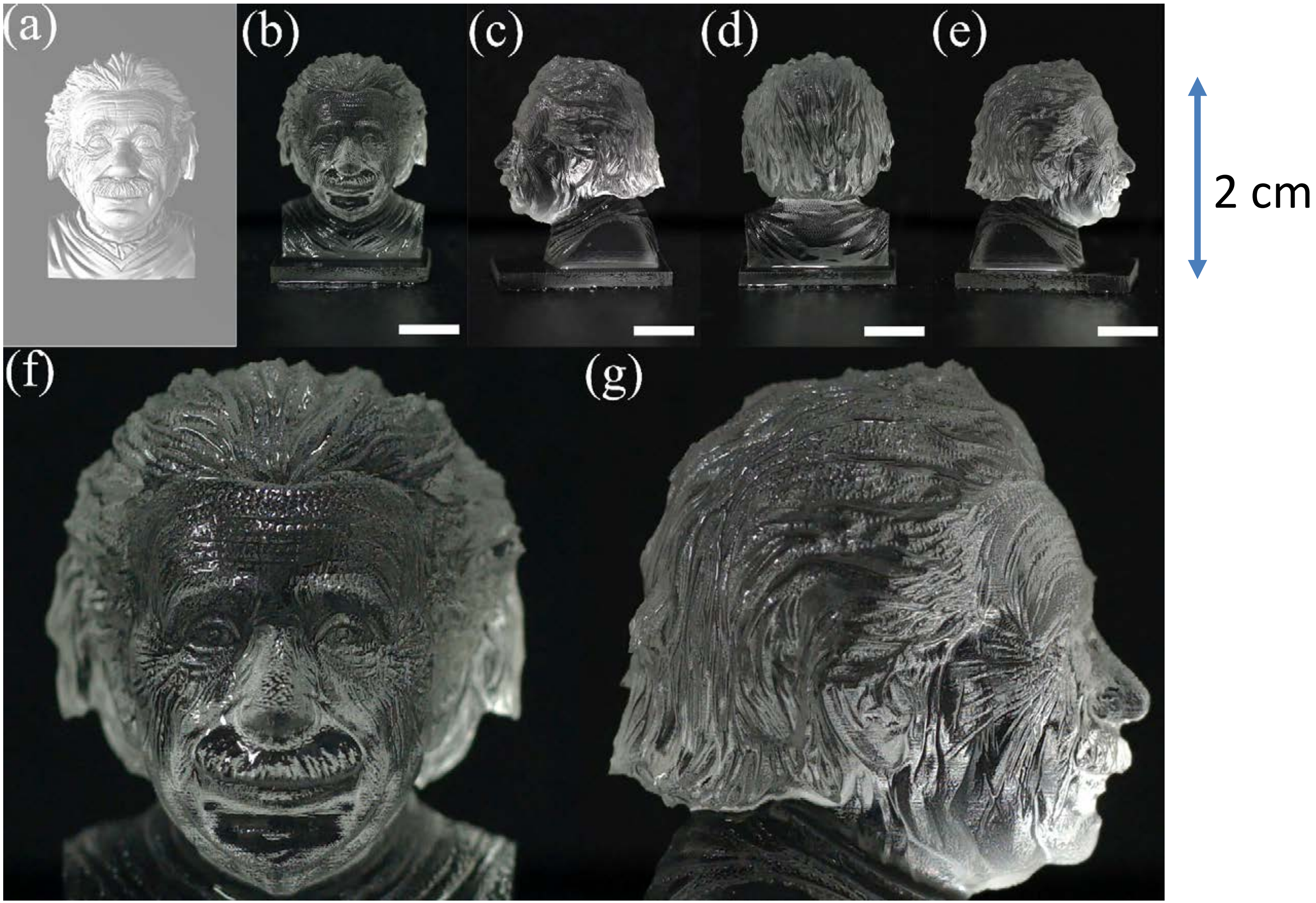


Applied Surface Science 485 (2019) 188–193

Maintain the high resolution at various depths.

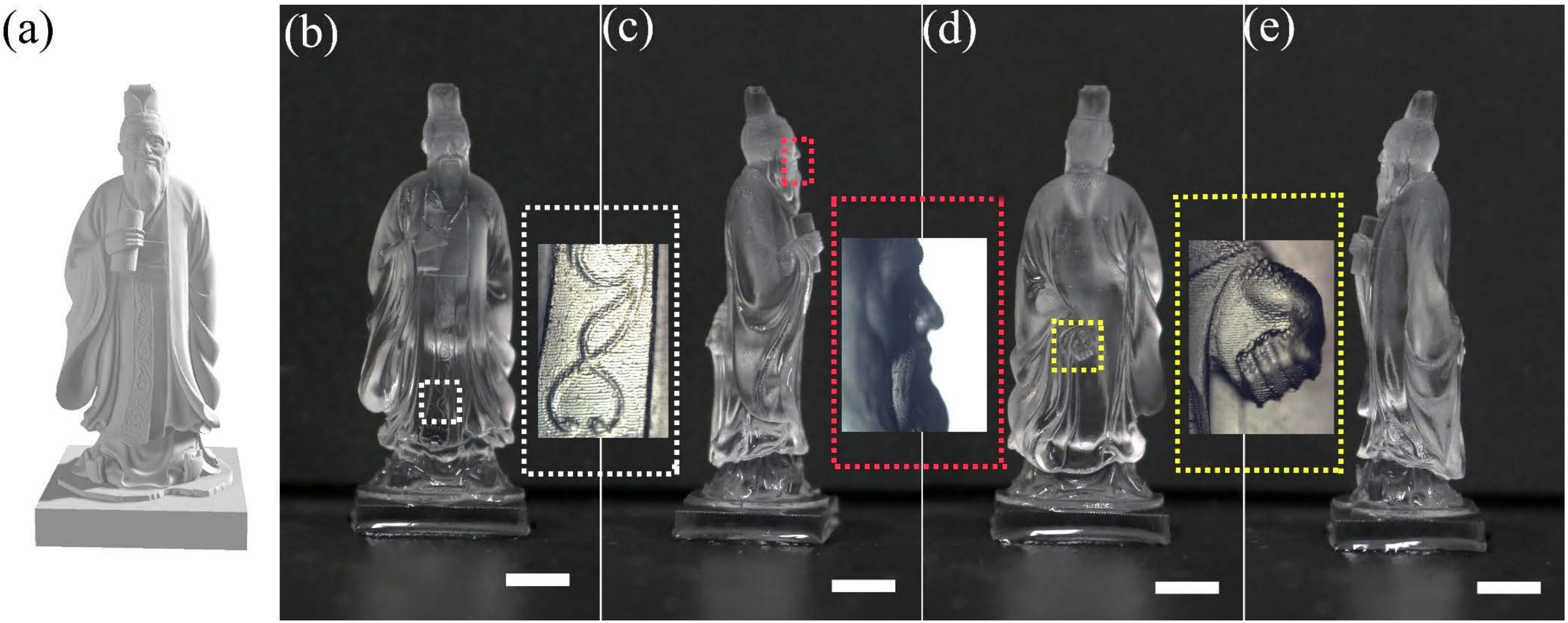
Achieve a polarization insensitive internal modification.

Structures: Einstein of a height of 2 cm



Scale bar, 5 mm.

Structures: Confucius of a height of 3.8 cm

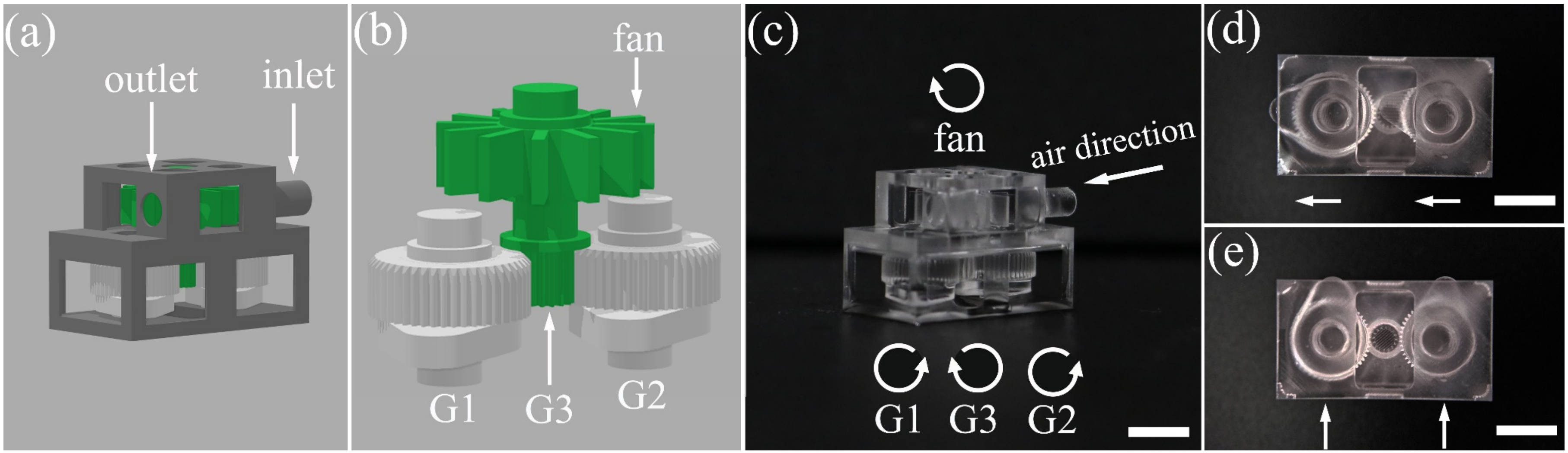


Model Front Right Back Left

Micromachines **2019**, *10*, 565

Scale bar, 5 mm.

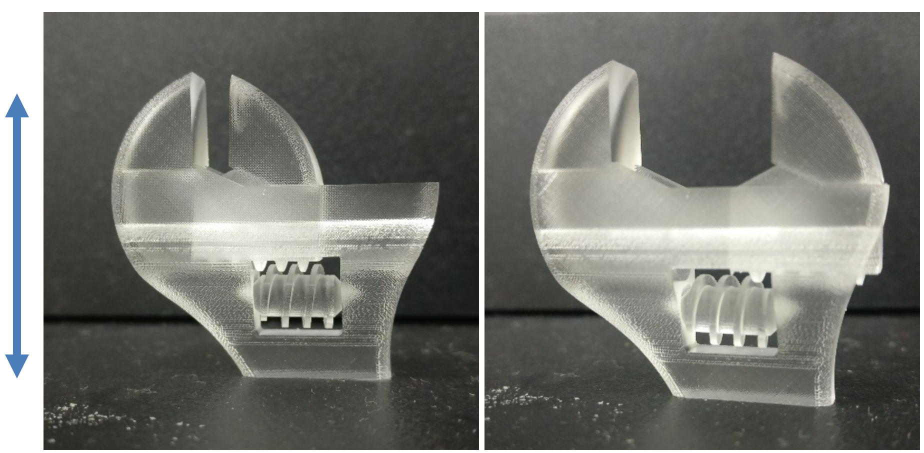
Structures: micromachines with movable parts



Air turbine

Scale bar, 5 mm.

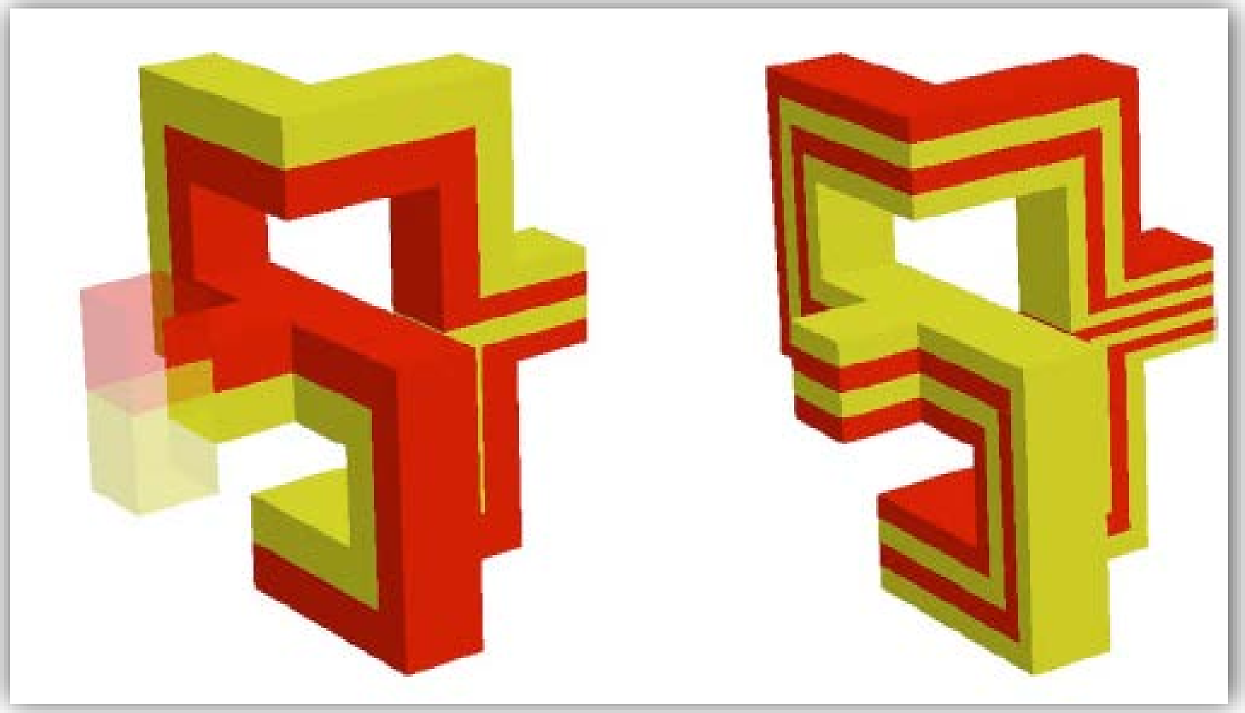
4 cm

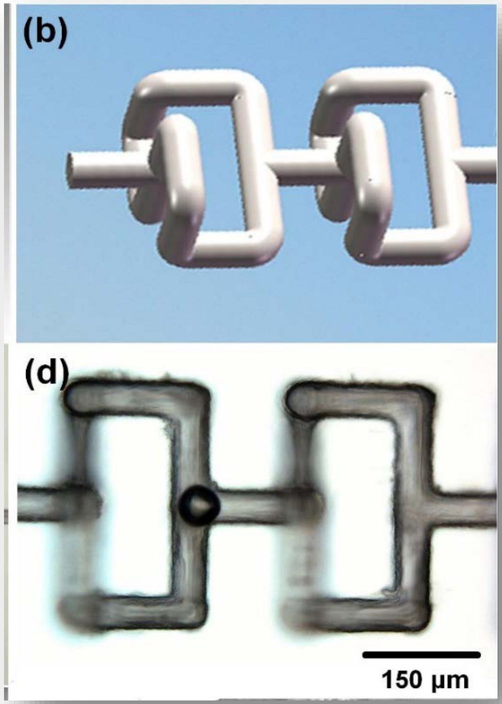


Adjustable wrench

II. Microfluidics & chemistry chips

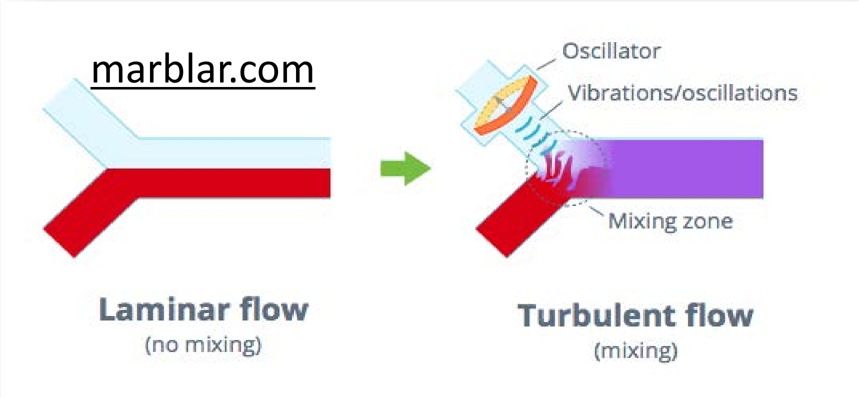
3D fluidic chip for higher mixing efficiency

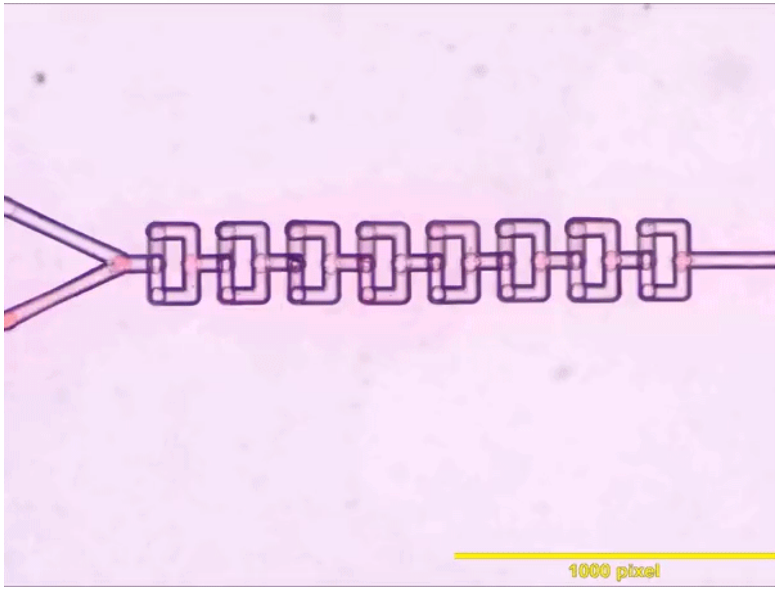


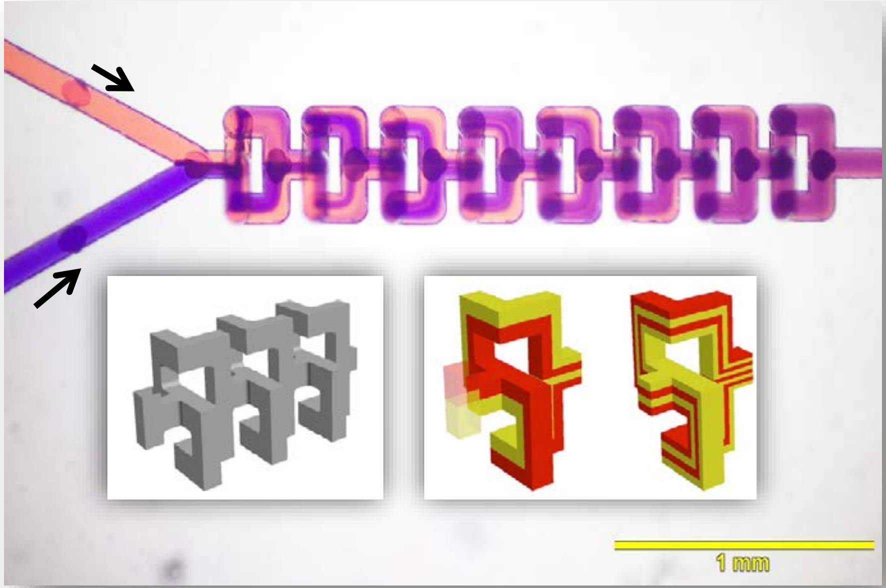


Y. Liao, et al., Lab. Chip 12, 746 (2012)

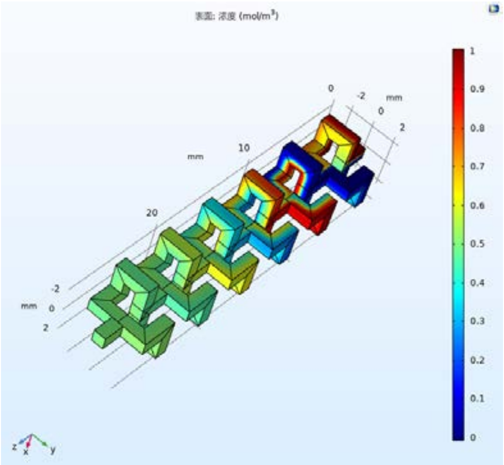
Demonstration of high mixing efficiency



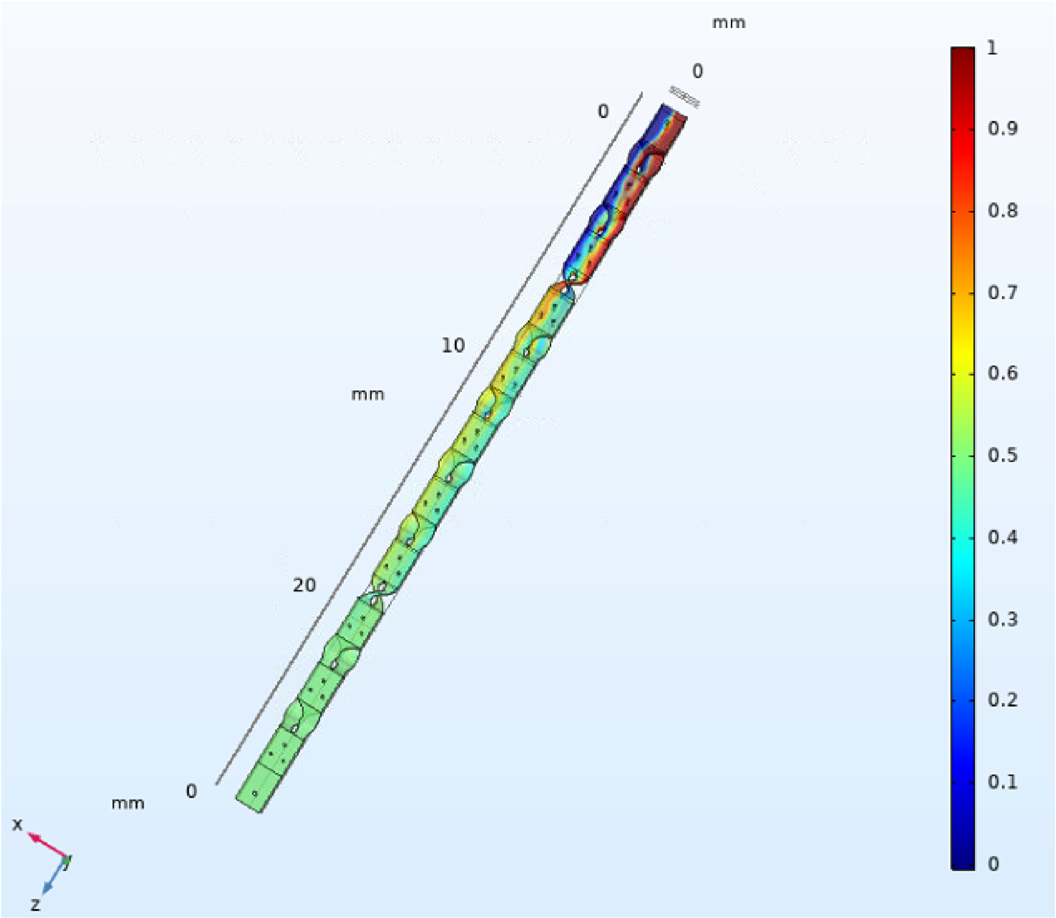




Compact 3D mixer: smaller but more powerful



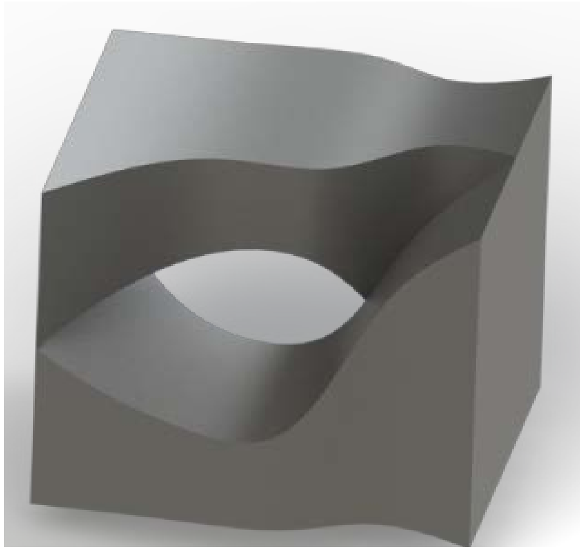
The 3D micro-mixer is efficient but it is also of a large footprint size for its "loose" 3D geometry.



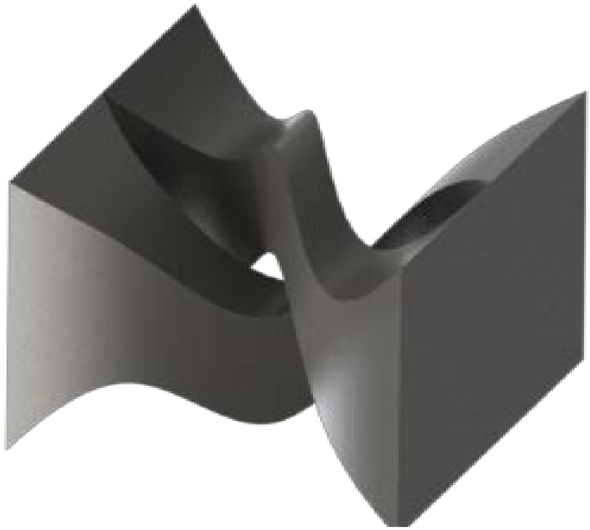
Accommodating a 3D micro-mixer in a planar channel to have a more compact geometry & higher mixing efficiency.

Compact 3D mixer: the new design

Mixing unit 1

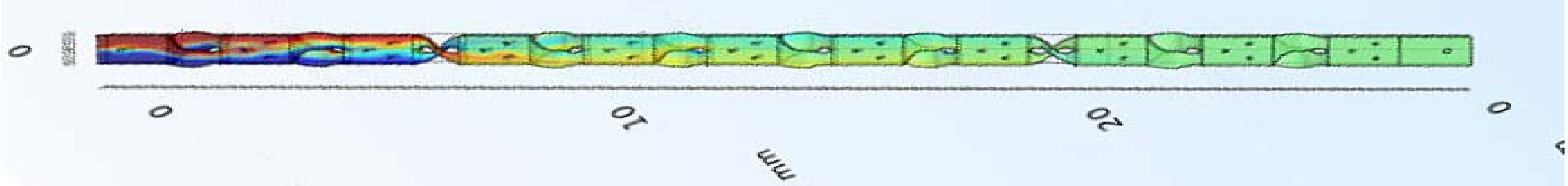


Mixing unit 2

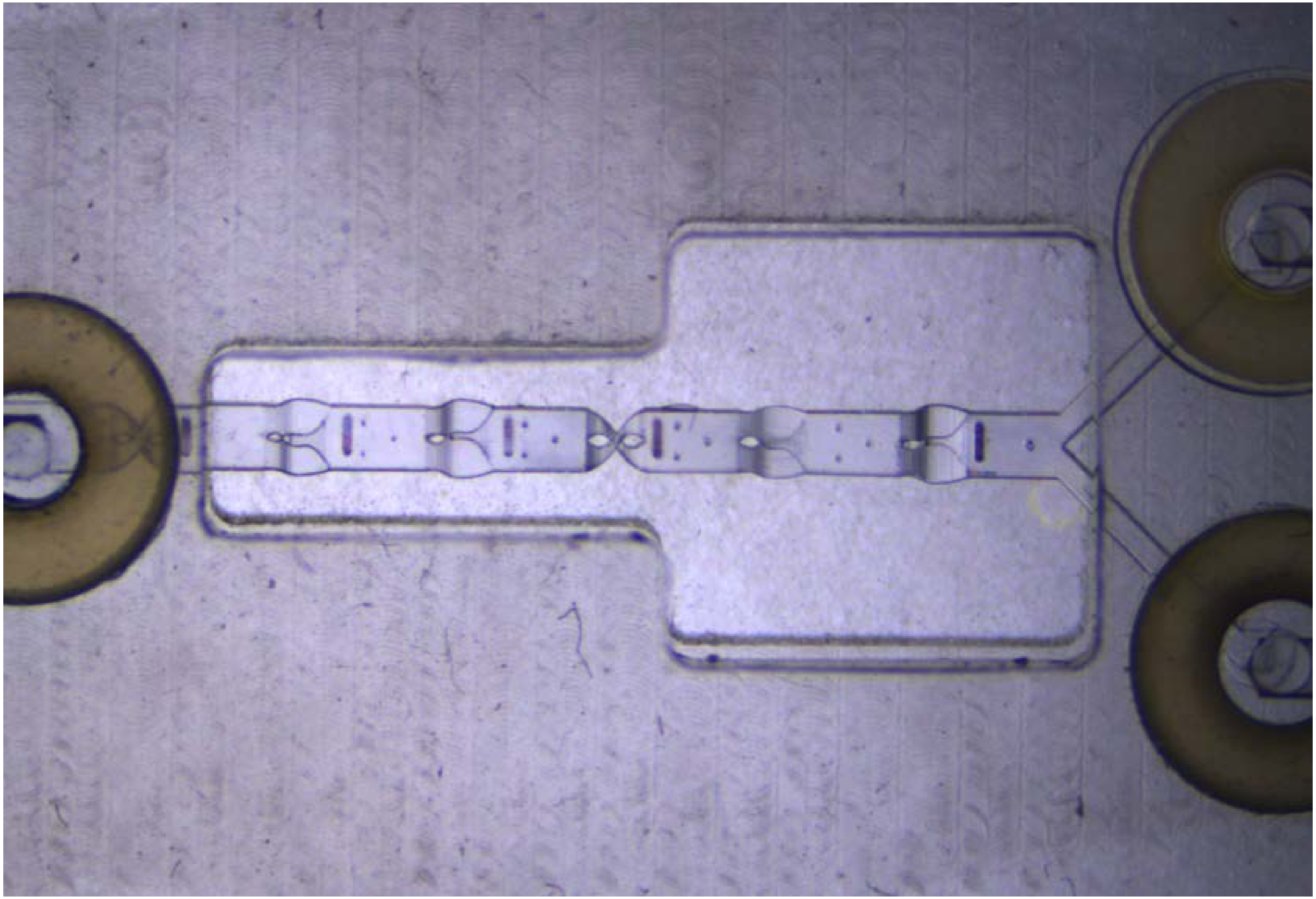


Mixing unit 1

Mixing unit 2



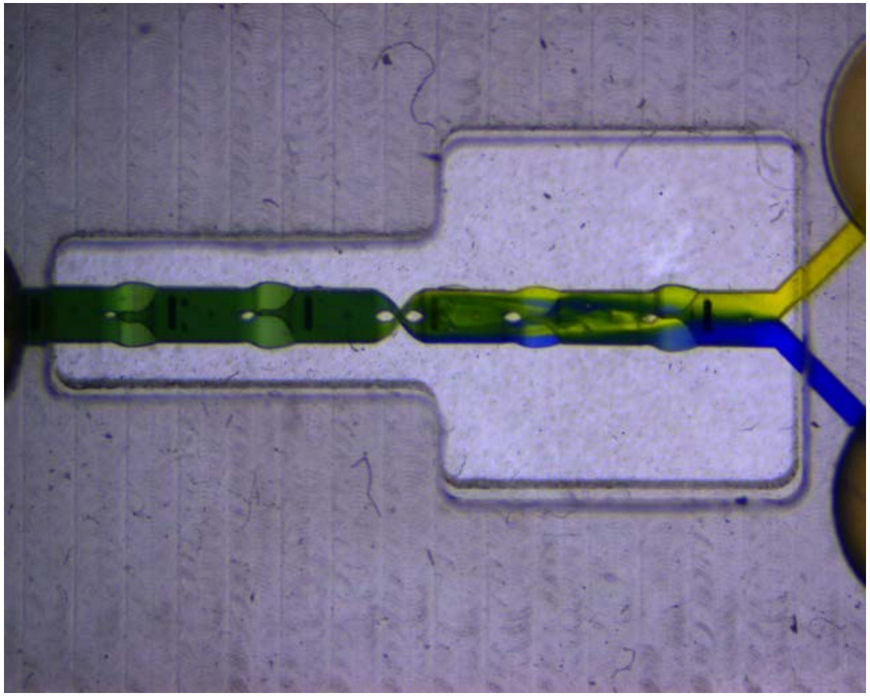
Compact 3D mixer: fabricated device

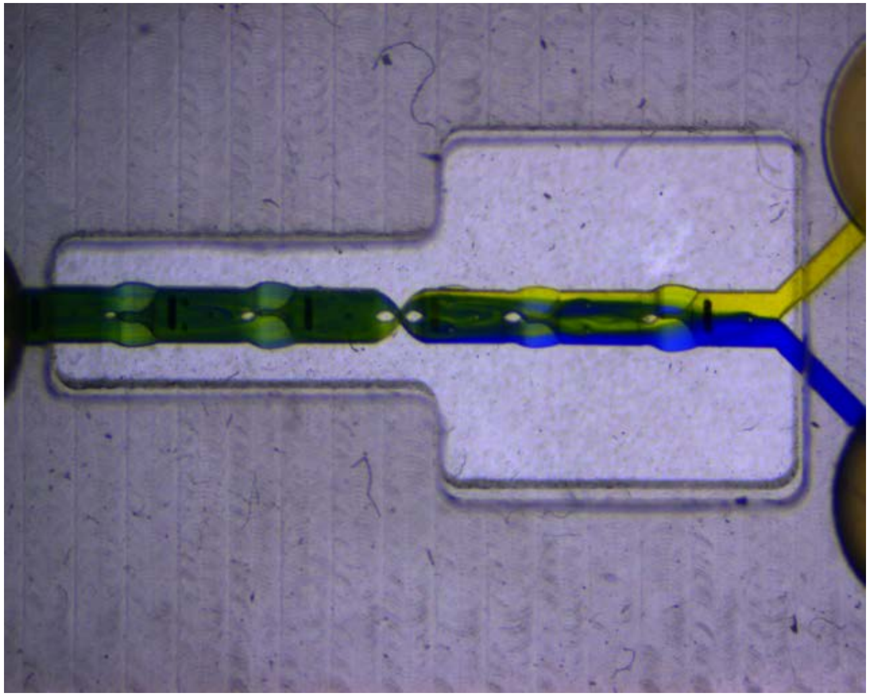


Compact 3D mixer: the functionality

3ml/min

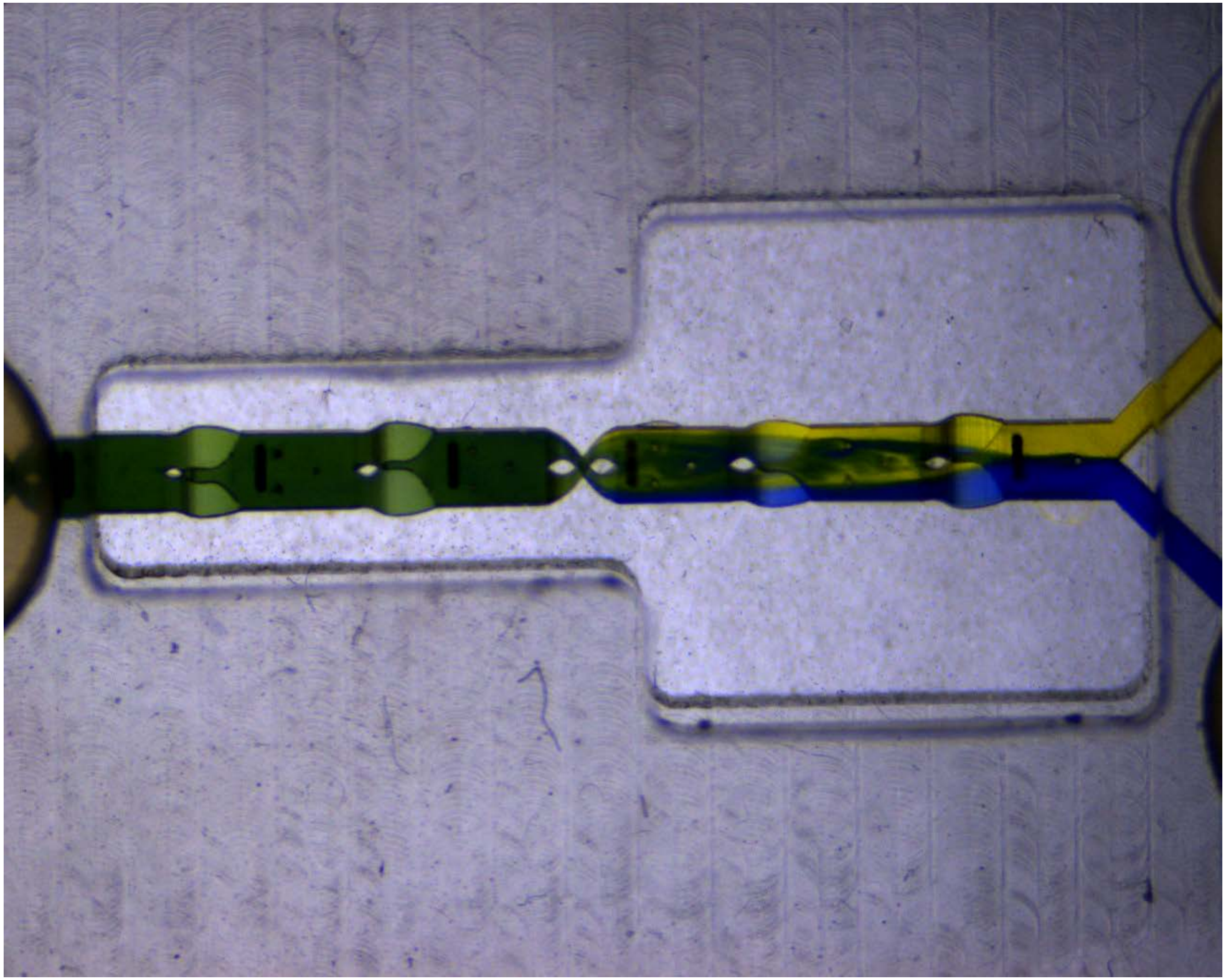
10ml/min





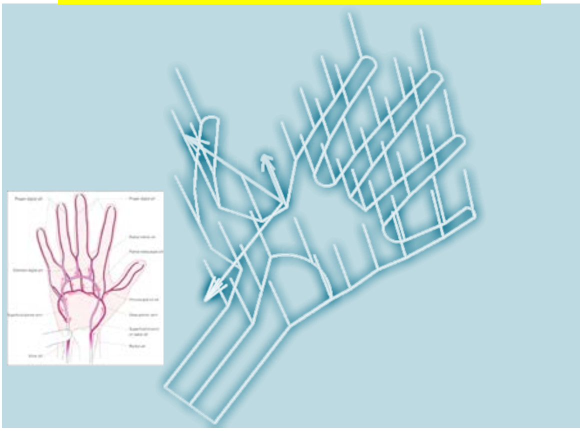
Total length: ~1 cm

Mixing in the compact 3D micromixer



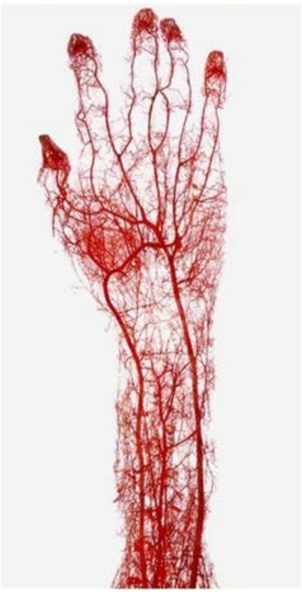
Biological microfluidic circuits within human body

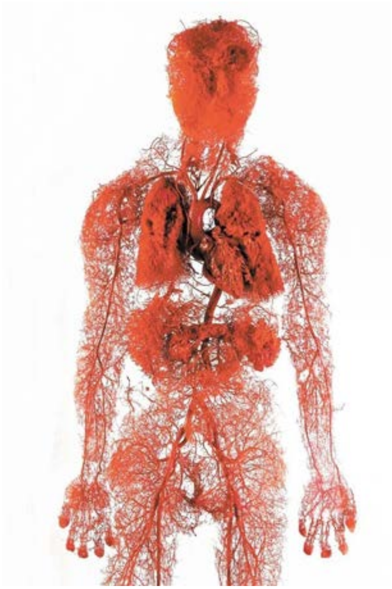
Microfluidic Circuit



Large-scale 3D printing

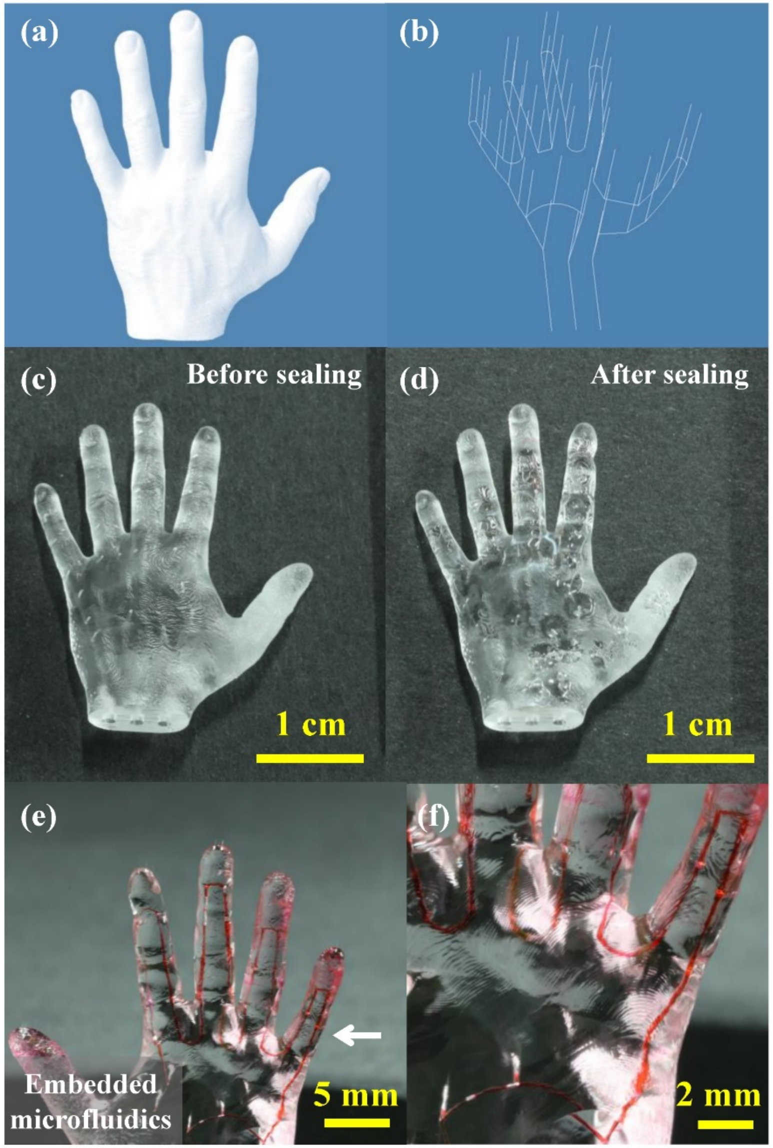
3D embedded blood vessels in glass

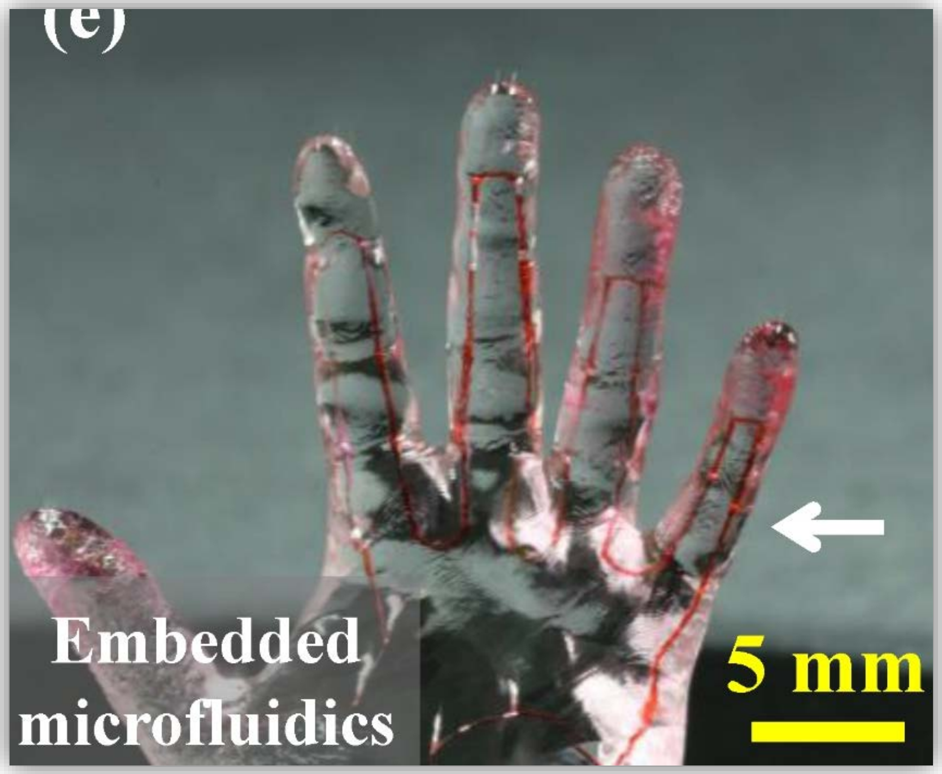




Promote understanding of the causes of human diseases such as cancers, cardiovascular diseases!

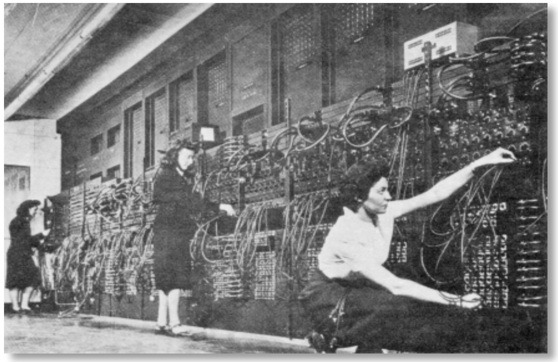
A printed hand with embedded blood vessels



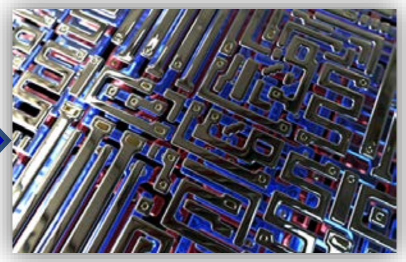


III. Photonic chips

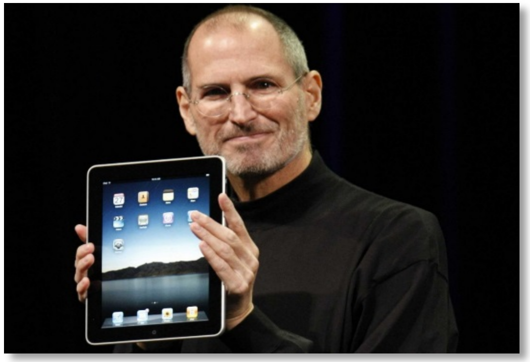
From Electronic ICs to Photonic ICs



First Generation
Electronic Computer

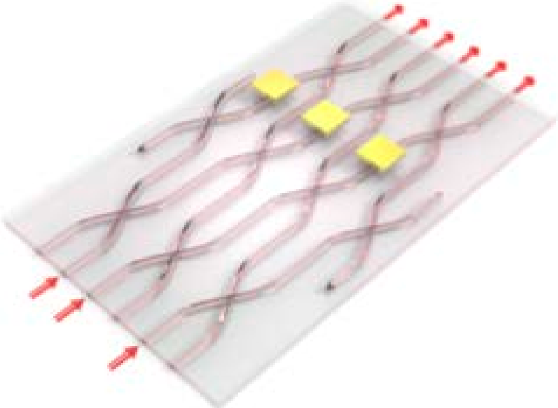


Very-large scale
integrated circuits



High-performance Electronic
Information Products

Optical information
processing platform



Photonic integrated
circuits (PICs)

Crystalline PIC: Opportunities and Challenges

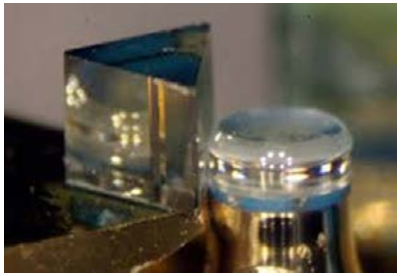
	Nonlinear optical coefficients	Electro-optic coefficients
Lithium niobite (LN)	41.7 pm/V	30.9 pm/V
Quartz	0.3 pm/V	0.93 pm/V

Opportunities:

- Broad transmission window
- High nonlinear optical / electro-optic /thermal coefficients....

Challenges:

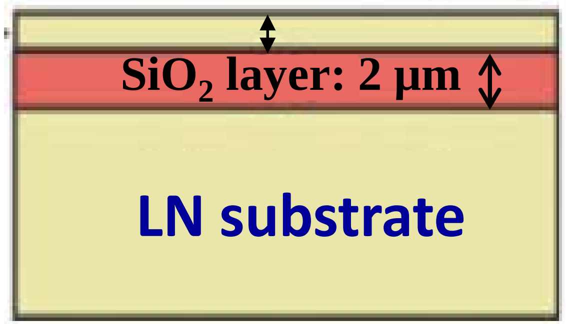
- **Hard to be patterned** by optical lithography
- High chemical stability



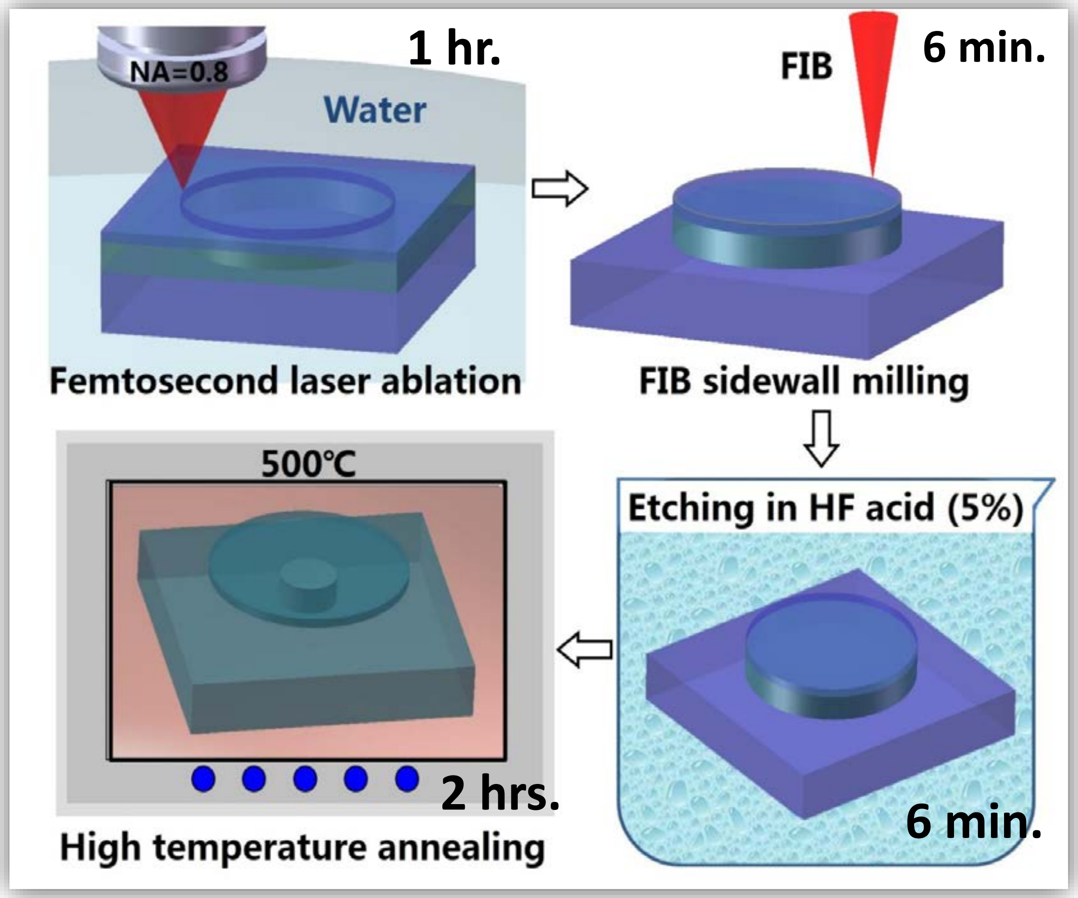
First high-Q
lithium niobate disk

High-Q microresonators on lithium niobate (LN)

LN thin film: 700 nm, Z-cut



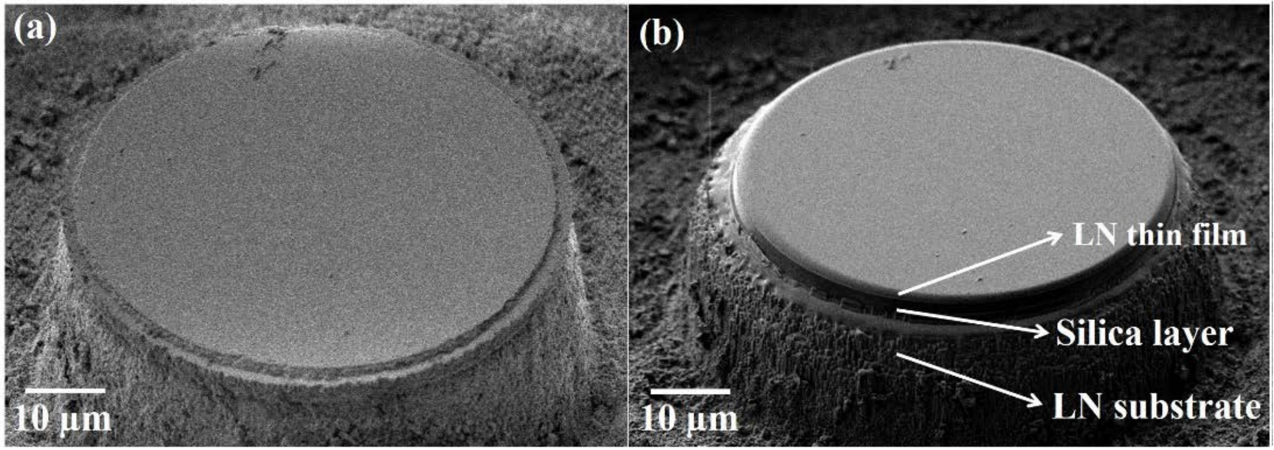
Laser Photon Rev. 6, 488 (2012)



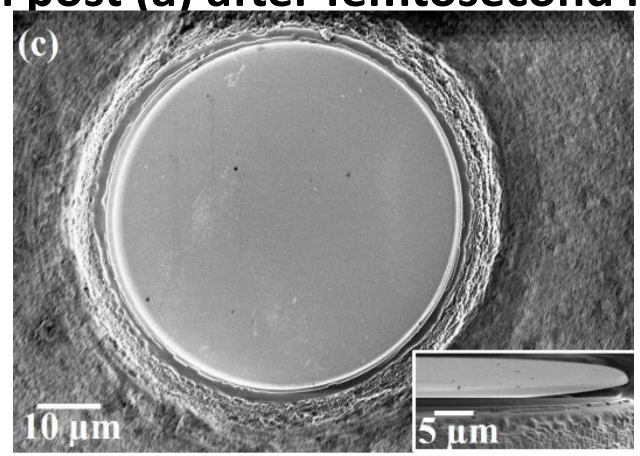
Fabrication procedure

J. Lin, et al, arXiv: 1405.6473 (Mar. 2014, beginning of on-chip high Q LN microresonators)

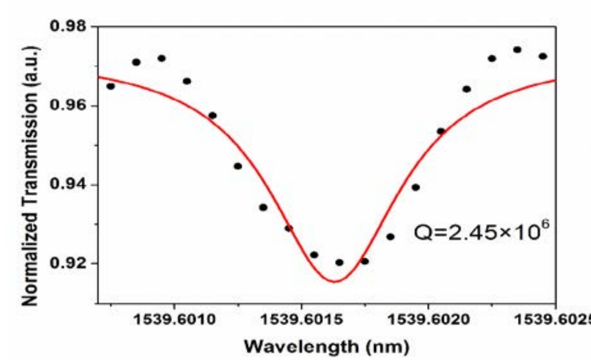
High-Q microresonators on lithium niobate (LN)



Cylindrical post (a) after femtosecond laser ablation and (b) after the FIB milling



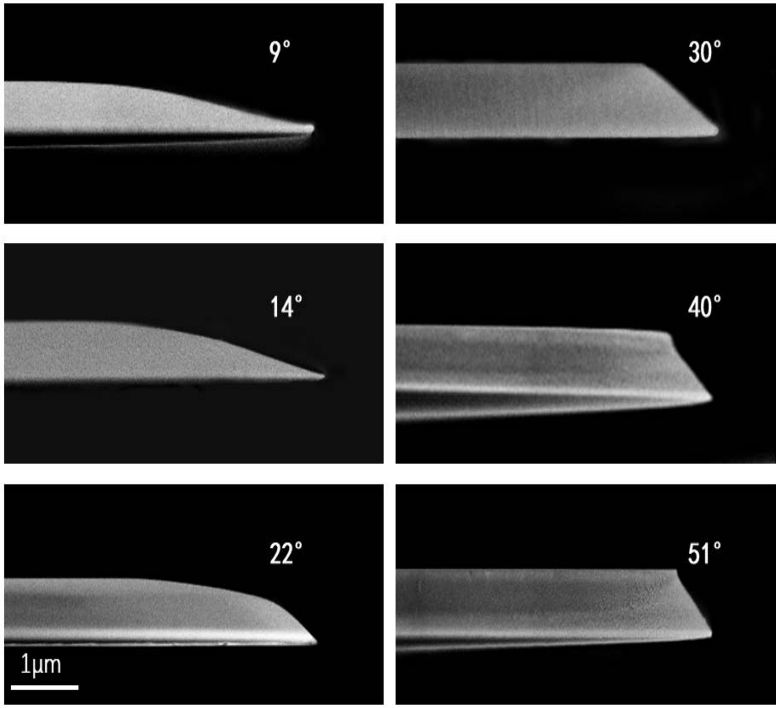
$Q=2.45\times10^6$

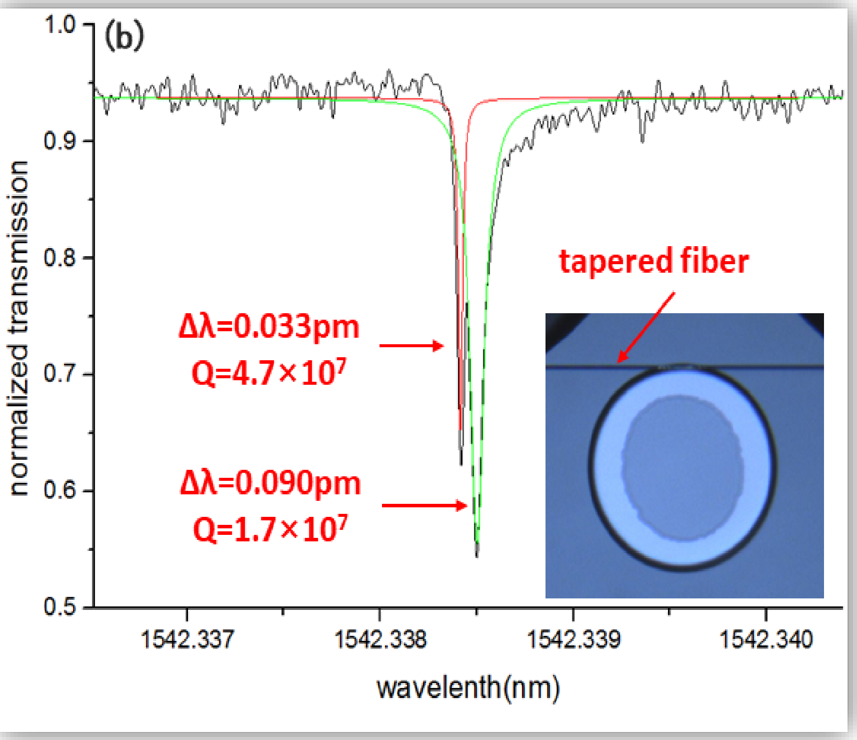


(c) SEM image (top view) of the microresonator, inset: side view.

J. Lin, et al, arXiv:1405.6473 (2014); Sci. Rep. 5, 8072 (2015)

High Q microdisks with tunable wedge angle





J. Zhang, et al, Nanomaterials 2019, 9, 1218; doi:10.3390/nano9091218

Q ~ 4.7×10^7

Nonlinear optics with the high-Q microdisks

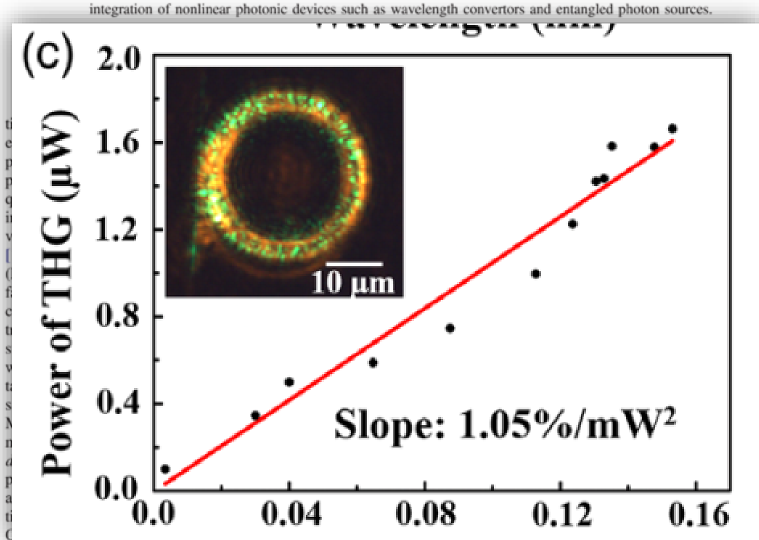
PHYSICAL REVIEW LETTERS **122,** 173903 (2019)

Broadband Quasi-Phase-Matched Harmonic Generation in an On-Chip Monocrystalline Lithium Niobate Microdisk Resonator

Jintian Lin,[1,*] Ni Yao,[2,*] Zhenzhong Hao,[3] Jianhao Zhang,[1,5] Wenbo Mao,[3] Min Wang,[4] Wei Chu,[1] Rongbo Wu,[1,5] Zhiwei Fang,[4] Lingling Qiao,[1] Wei Fang,[2,†] Fang Bo,[3,‡] and Ya Cheng[1,4,5,6,§]
[1]*State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[2]*State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China*
[3]*The MOE Key Laboratory of Weak Light Nonlinear Photonics, TEDA Applied Physics Institute and School of Physics, Nankai University, Tianjin 300457, China*
[4]*State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China*
[5]*University of Chinese Academy of Sciences, Beijing 100049, China*
[6]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China*

(Received 16 October 2018; published 3 May 2019)

We reveal a unique broadband natural quasi-phase-matching (QPM) mechanism underlying an observation of highly efficient second- and third-order harmonic generation at multiple wavelengths in an x-cut lithium niobate (LN) microdisk resonator. For light waves in the transverse-electric mode propagating along the circumference of the microdisk, the effective nonlinear optical coefficients naturally oscillate periodically to change both the sign and magnitude, facilitating QPM without the necessity of domain engineering in the micrometer-scale LN disk. The second-harmonic and cascaded third-harmonic waves are simultaneously generated with normalized conversion efficiencies as high as 9.9%/mW and 1.05%/mW^2, respectively, thanks to the utilization of the highest nonlinear coefficient d_{33} of LN. The high efficiency achieved with the microdisk of a diameter of ~30 μm is beneficial for realizing high-density integration of nonlinear photonic devices such as wavelength convertors and entangled photon sources.



PHYSICAL REVIEW LETTERS **122,** 253902 (2019)

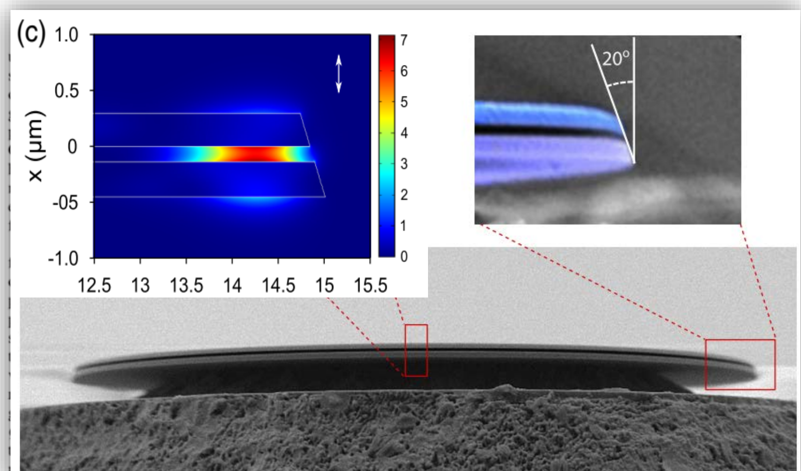
High-Q Exterior Whispering-Gallery Modes in a Double-Layer Crystalline Microdisk Resonator

Yuanlin Zheng,[1,2,*] Zhiwei Fang,[3,4,5,*] Shijie Liu,[1,2] Ya Cheng,[3,4,5,6,‡] and Xianfeng Chen[1,2,†]
[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Key Laboratory for Laser Plasma (Ministry of Education), Collaborative Innovation Center of IFSA, Shanghai Jiao Tong University, Shanghai 200240, China*
[3]*State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China*
[4]*XXL-The Extreme Optoelectromechanics Laboratory, School of Physics and Materials Science, East China Normal University, Shanghai 200241, China*
[5]*State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[6]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China*

(Received 11 April 2019; published 27 June 2019)

Exterior whispering-gallery modes (WGMs), whose mode energy is mainly confined outside the microcavity, can achieve large mode overlapping with the ambient environment, as well as a strong electric field and gradient force at the surface. Here, we demonstrate highly localized WGMs in the nanoair gap of a double-layer crystalline microdisk. The geometry is based on a horizontal slot-waveguide structure of two vertically stacked crystalline microdisks made of lithium niobate thin films. The slot WGM possesses a high quality factor in excess of 10^5 without metallic loss. The absorption and scattering loss is reduced by use of the crystalline nanofilm at sub-nm rms surface roughness. The demonstrated configuration can be highly favored in various applications including optical sensing, nonlinear optics, and optomechanics.

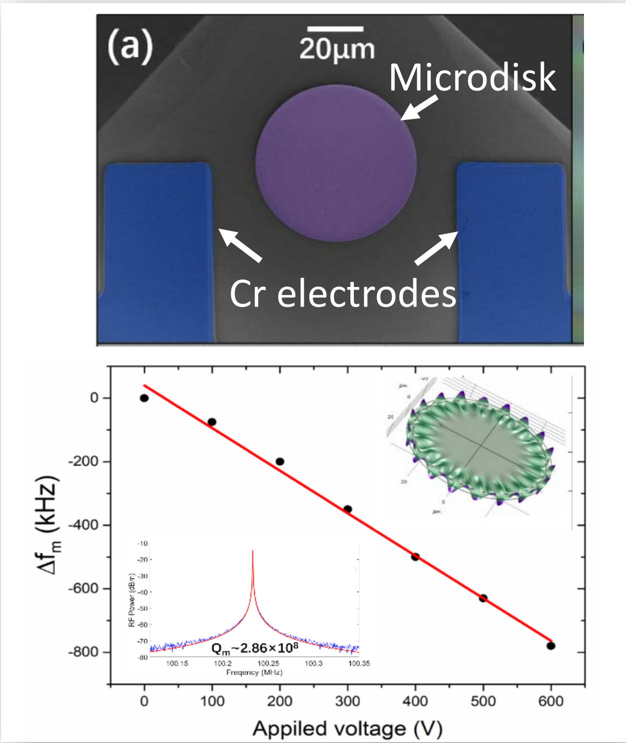
DOI: 10.1103/PhysRevLett.122.253902



principle, unavoidable. Another way to achieve exterior ... nanoscale gap, and forms a horizontal slot-waveguide

On-chip electro-optical tunable microresonator

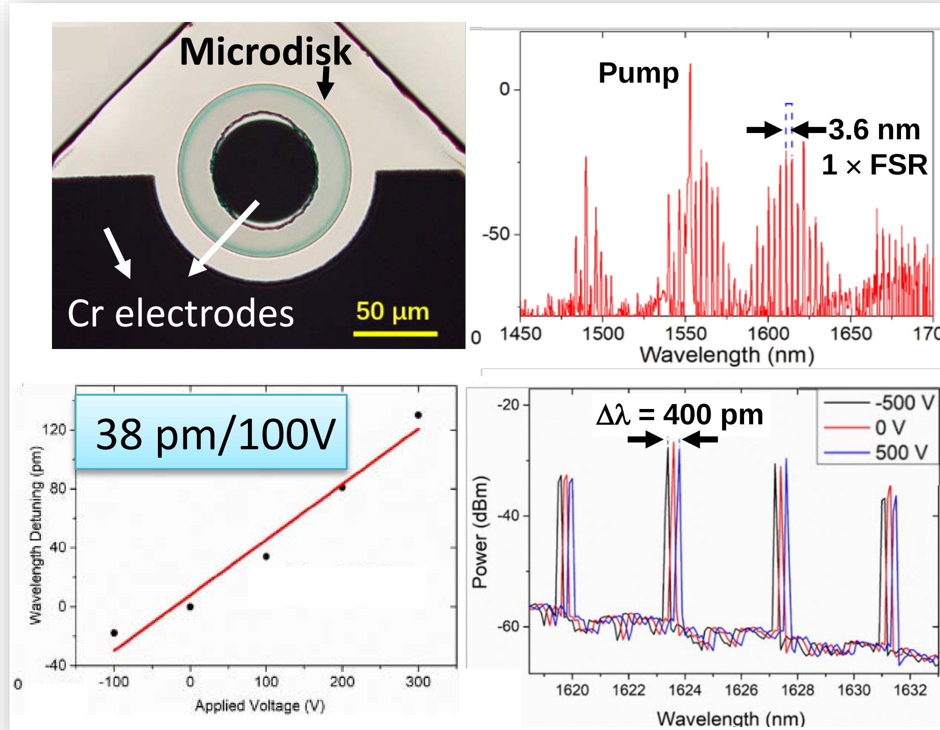
Tuning of an optical spring



- Optical quality: Q~10^7
- Mechanical quality: Q_m~2.86×10^8
- Electro-mechanical tuning efficiency : -134 kHz/100V

Z. Fang, et al., Opt. Lett. 44, 1214 (2019)

Tuning of an optical frequency comb



- Optical quality Q~7.1×10^6
- The Raman-assisted FWM microcomb: spectral bandwidth of ~200 nm
- Eletrcal tuning efficiency ~38 pm/100V

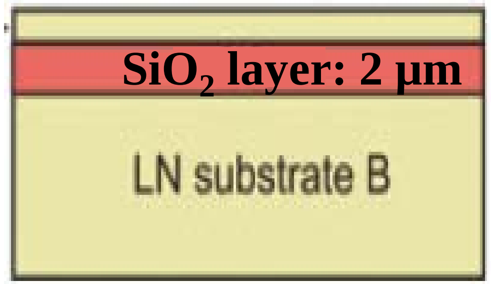
Z. Fang, et al., arXiv preprint arXiv:1909.00399 (2019)

From laboratory prototype to industrial tool:

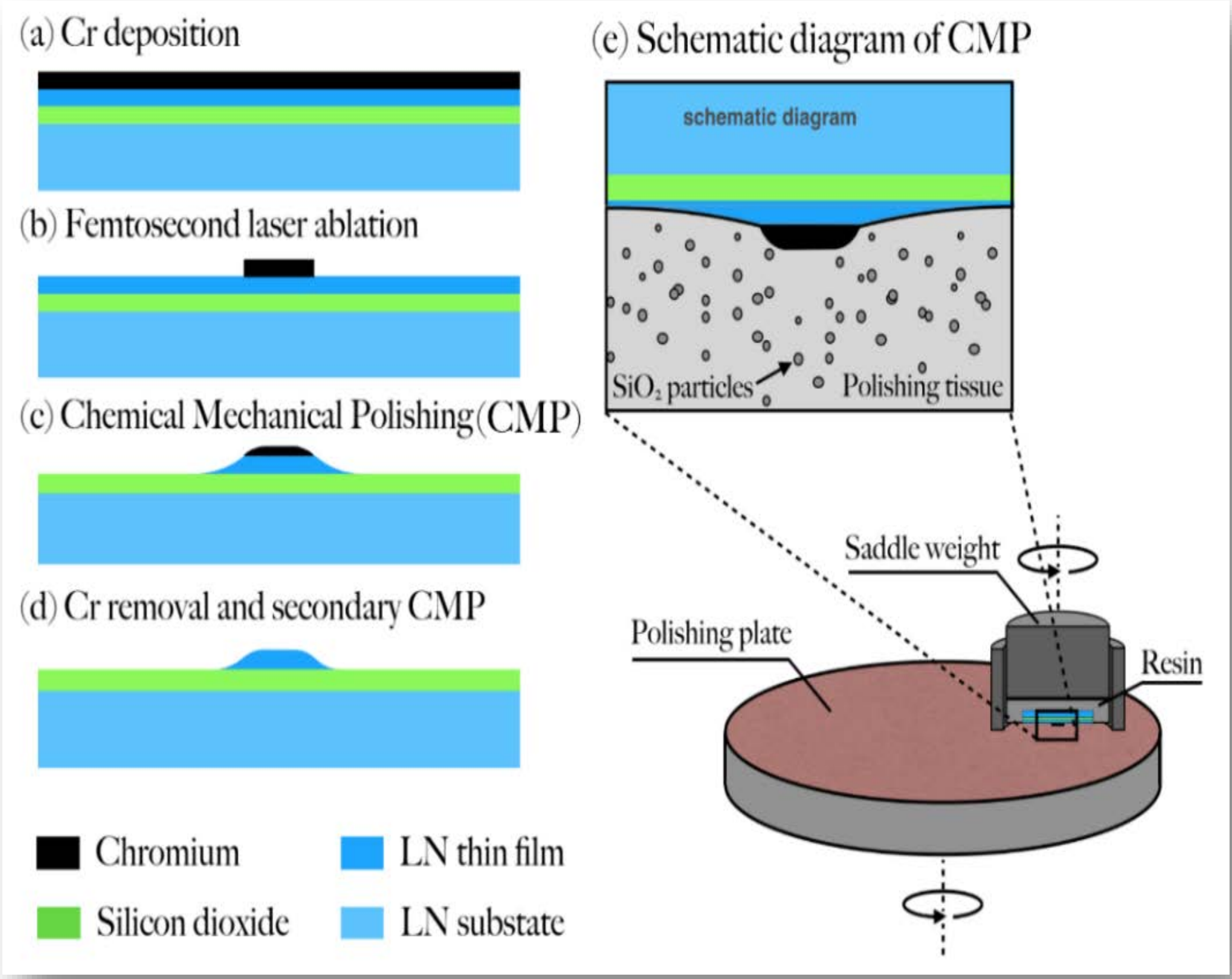
Femtosecond laser assisted chemo-mechanical polish lithography

Fabrication of low-loss LN waveguides

LN thin film: 700 nm

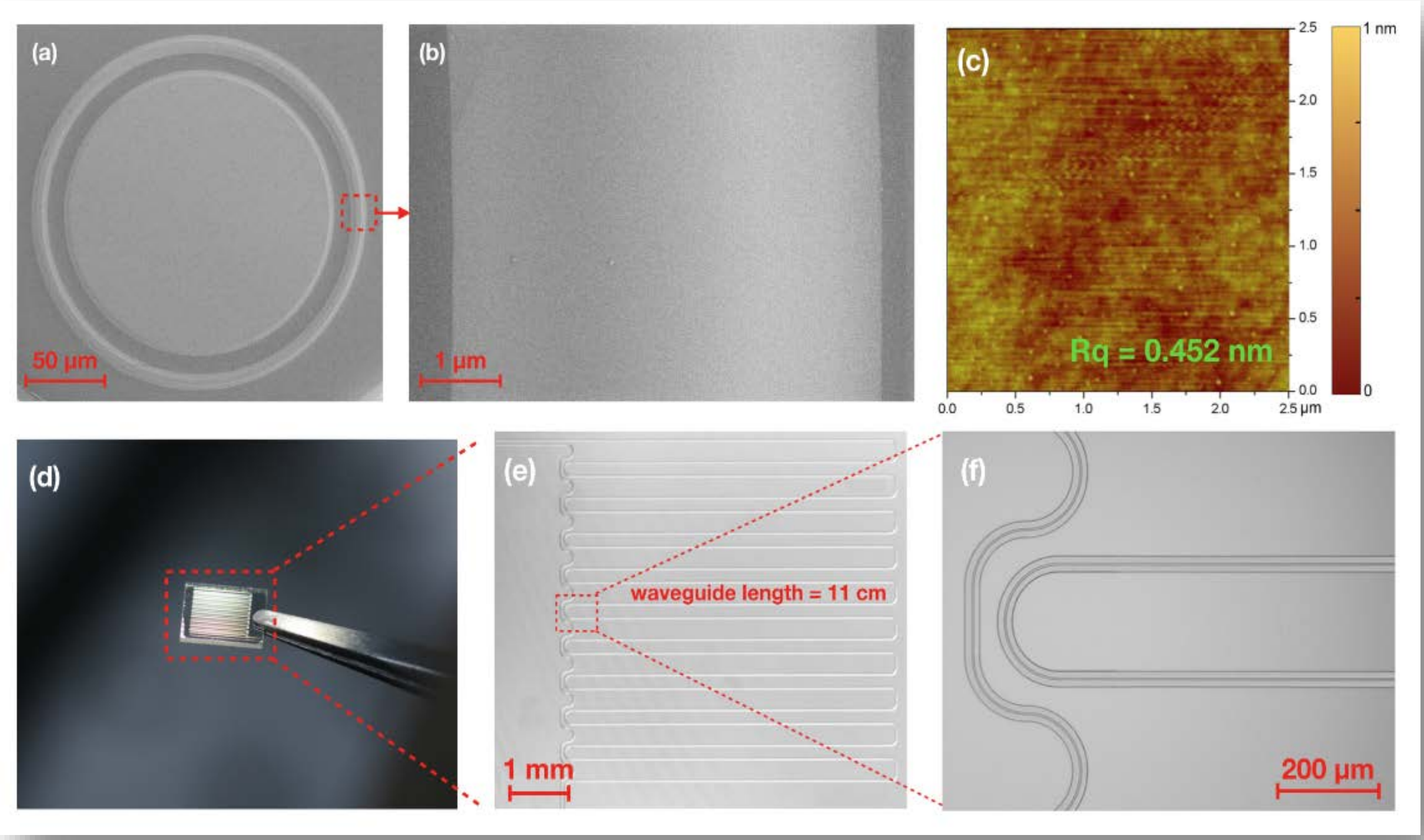


Laser Photon Rev. 6, 488 (2012)



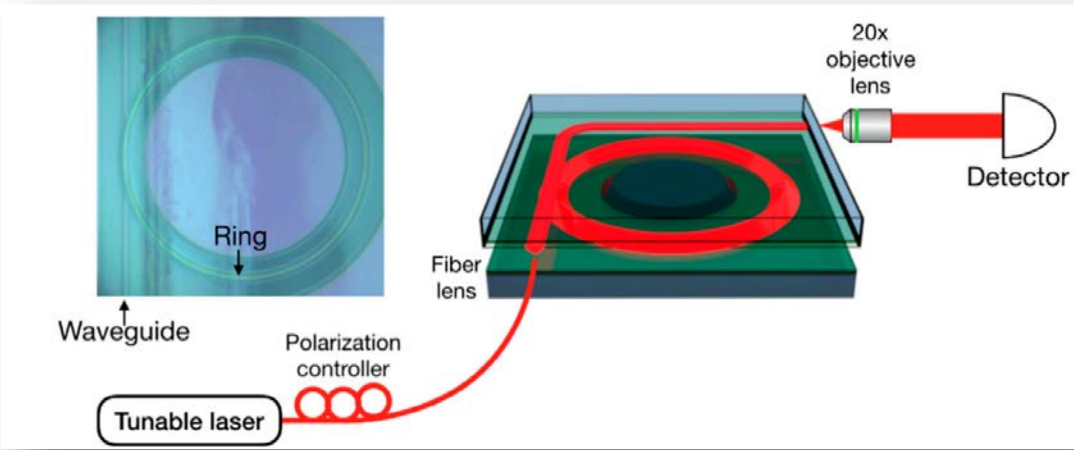
Ya Cheng et al. Patent No：201810407783.3; US patent No: 16404735
R. B. Wu, et al, Nanomaterials 8, 910 (2018)

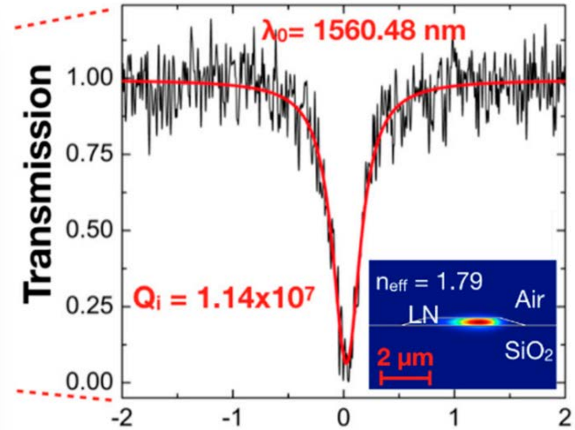
Fabrication of low-loss LN waveguides



Keypoint: extremely smooth surface with a surface roughness as low as 0.452 nm。

Propagation loss measurement



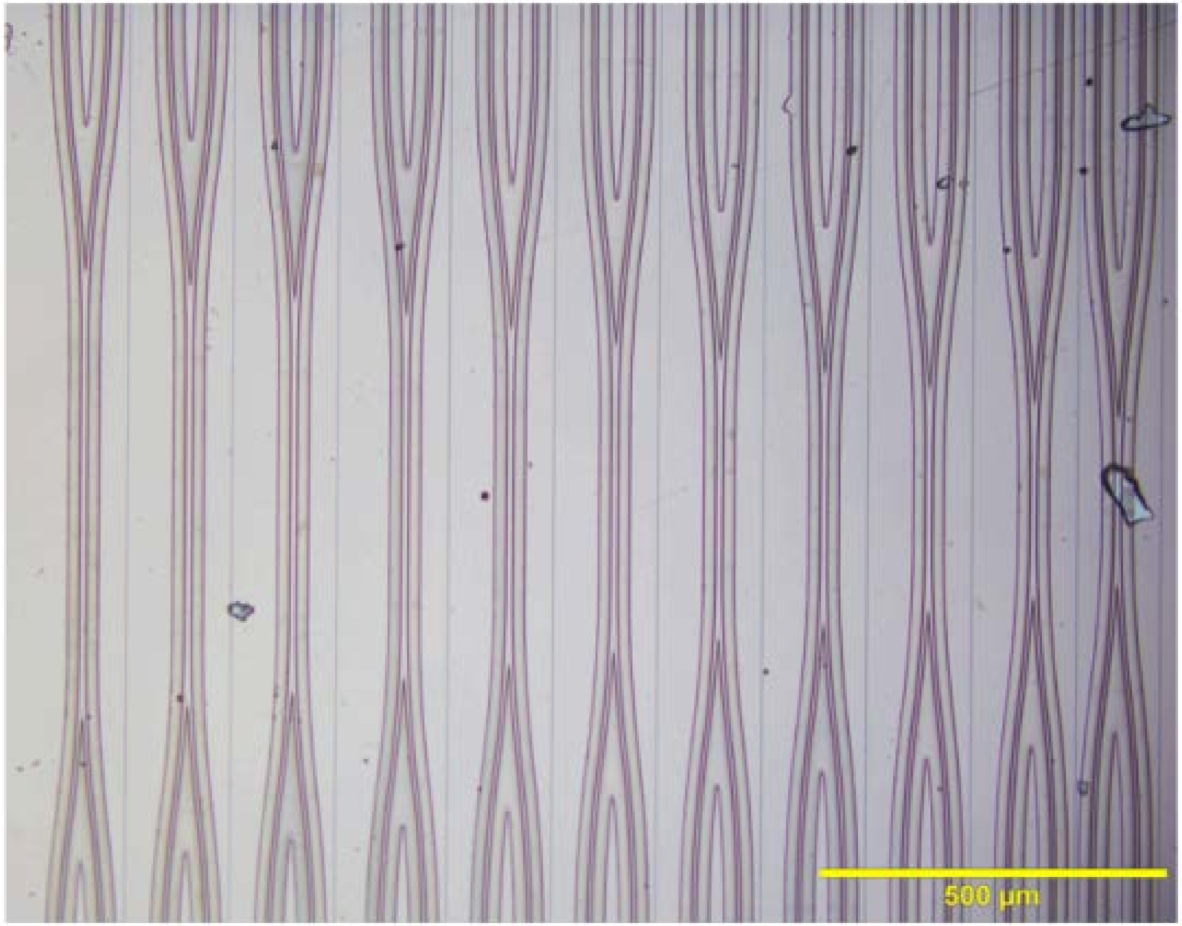


(b)

$$\alpha = \frac{2\pi n_{eff}}{Q\lambda} = 0.027\ dB/cm$$

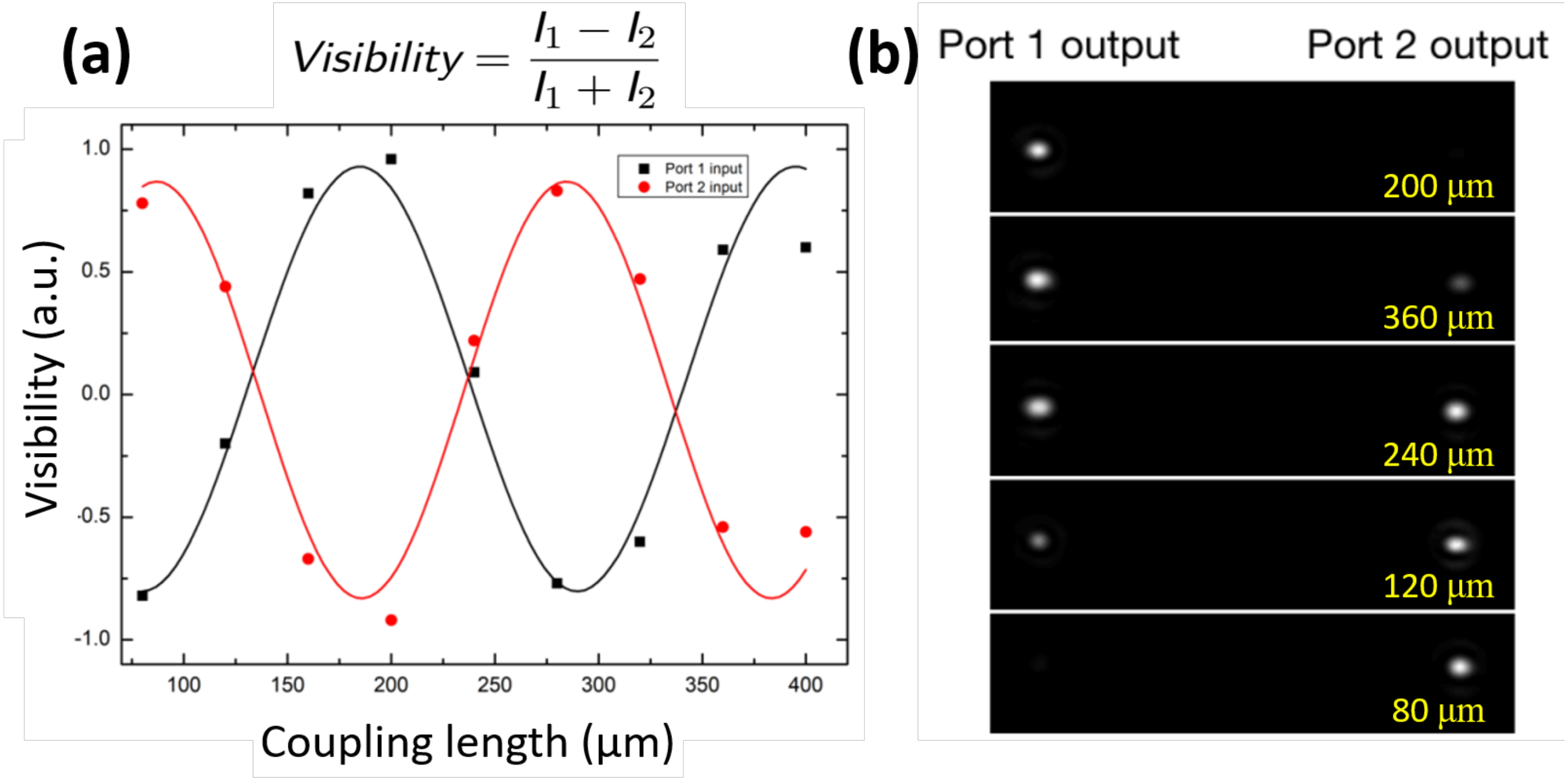
Loss measurement via measurement of Q factor of a waveguide ring resonator: **loss 0.027 dB/cm.**

Beamsplitters built by LNOI waveguides



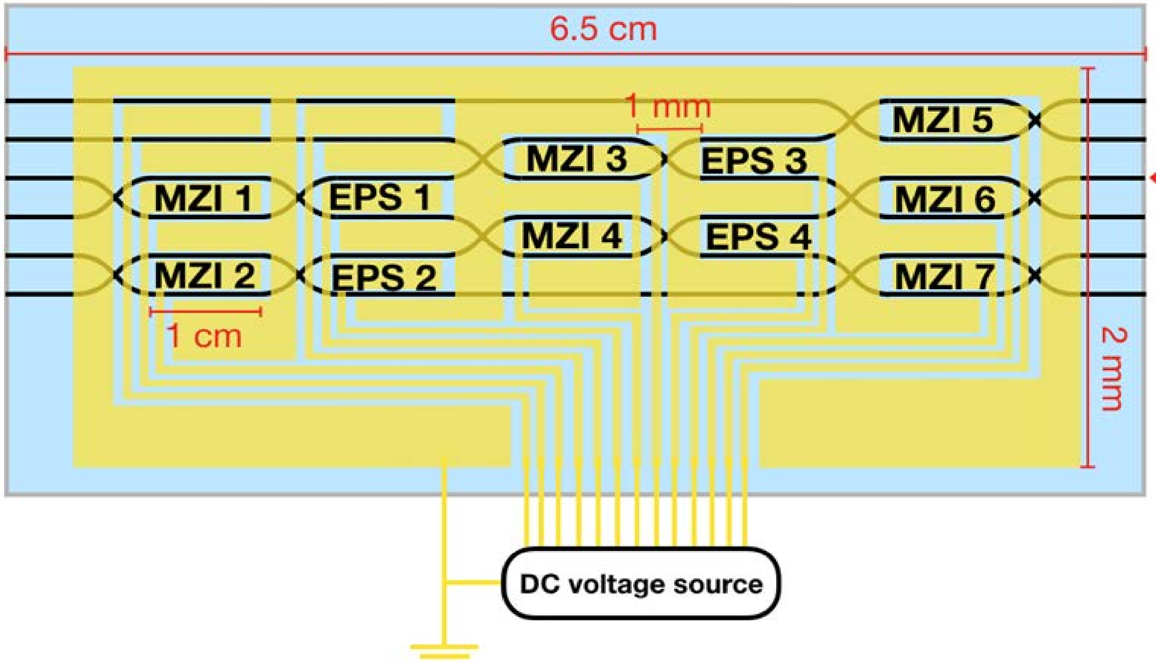
M. Wang, R. Wu, J. Lin, et al. Quantum Engineering e9, 1 (2019).

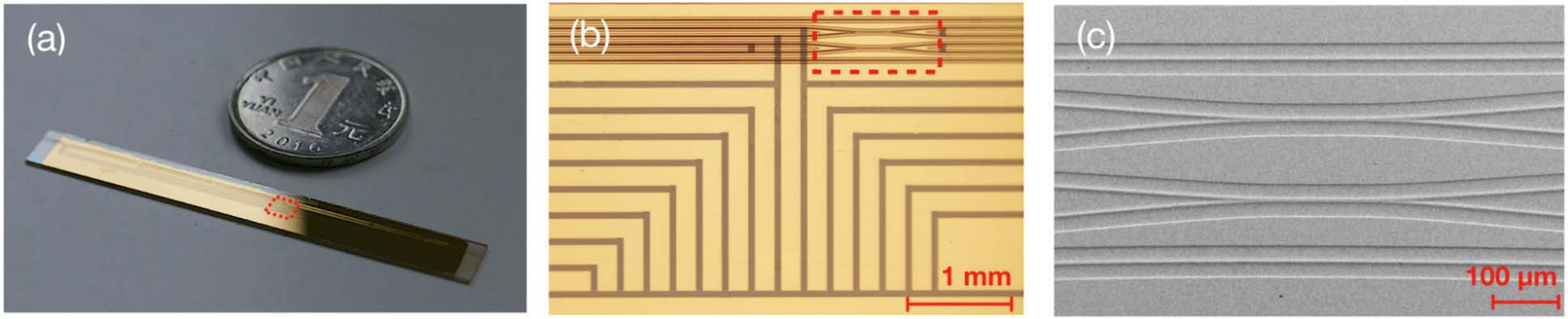
Beamsplitters built by LNOI waveguides



M. Wang, R. Wu, J. Lin, et al. Quantum Engineering e9, 1 (2019).

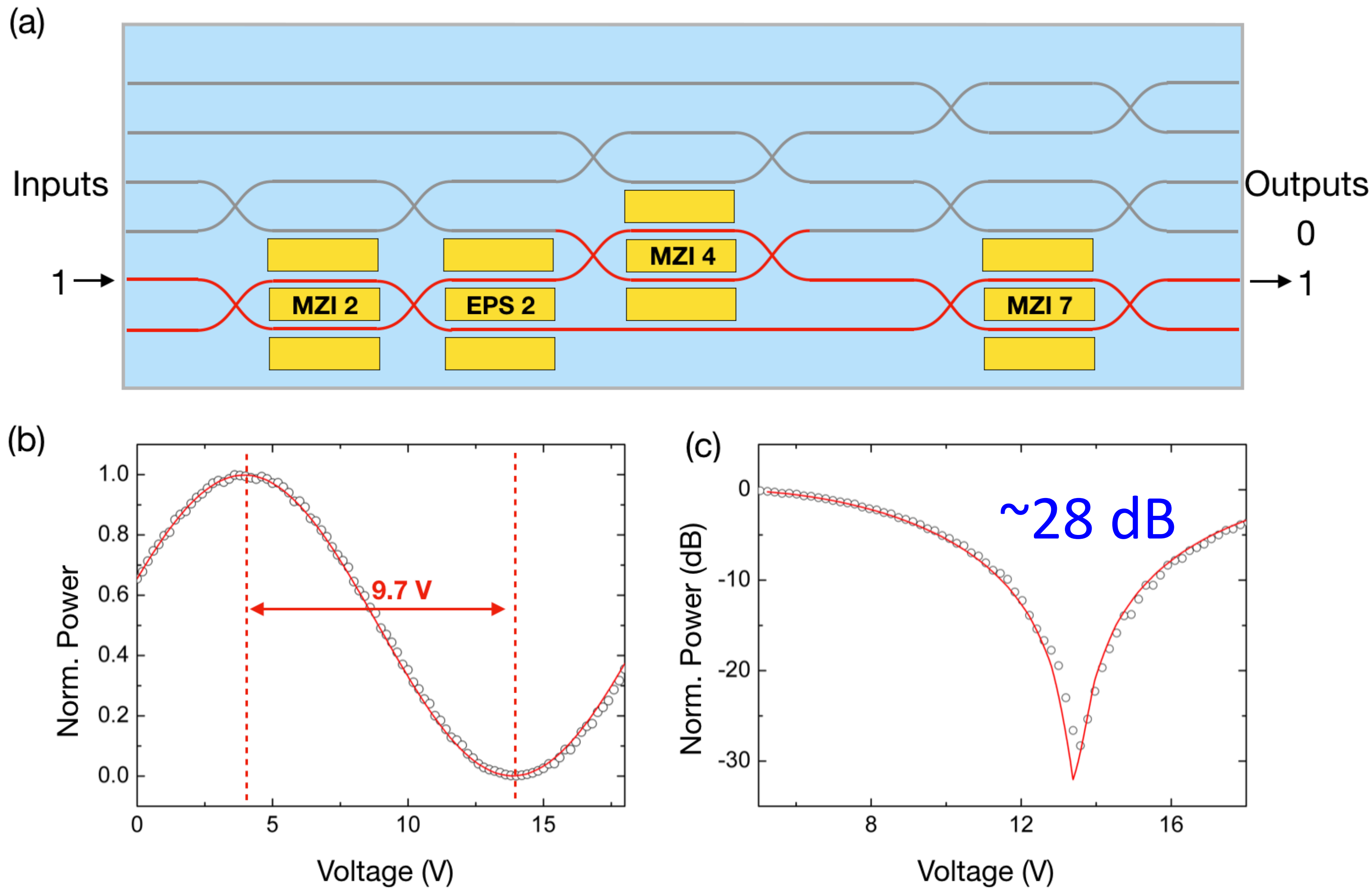
A multifunctional photonic chip on LNOI





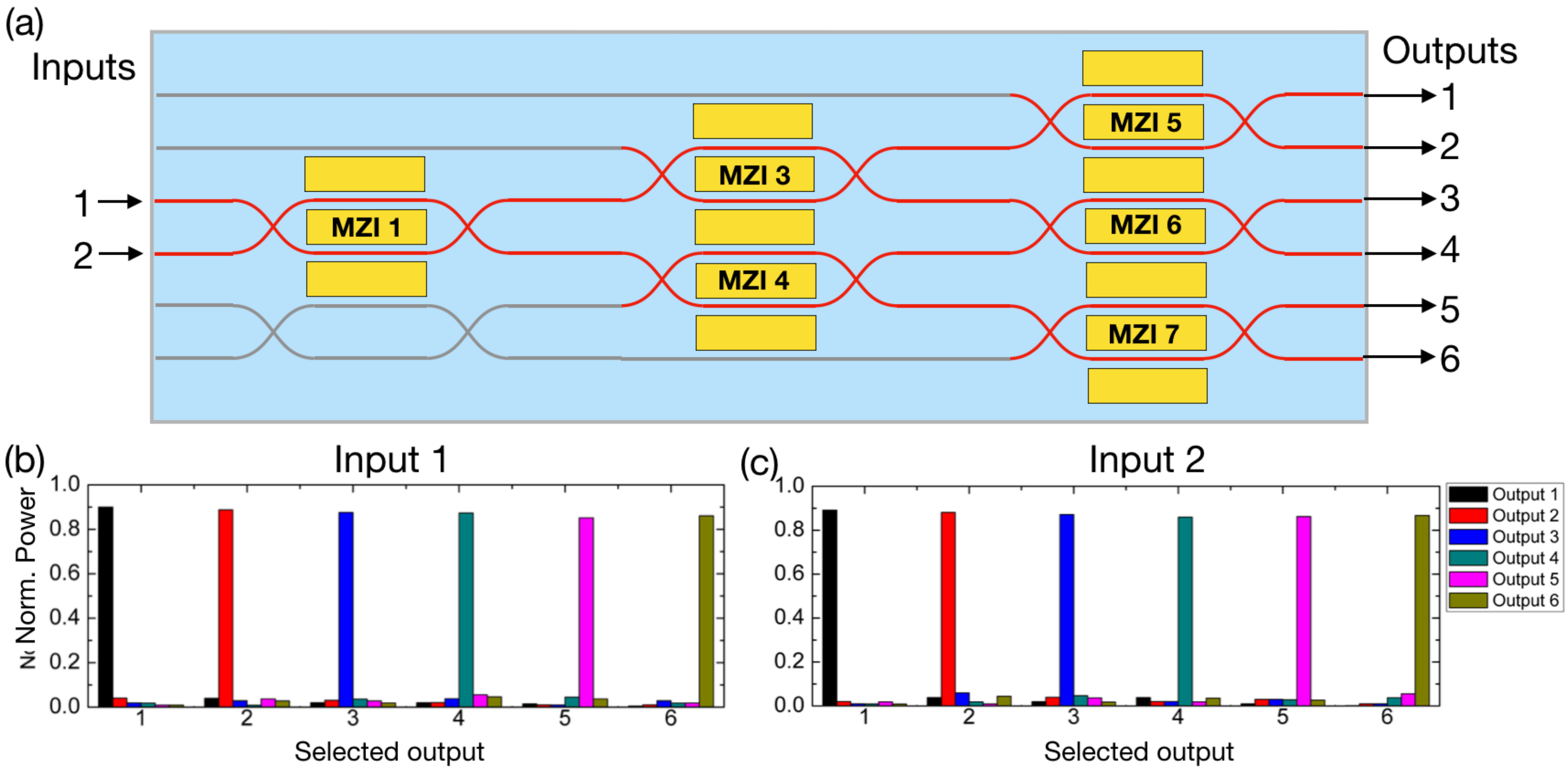
R. Wu, J. Lin, M. Wang, et. al. Opt. Lett. 44, 4698 (2019)

A perfect beamsplitter of tunable ratio



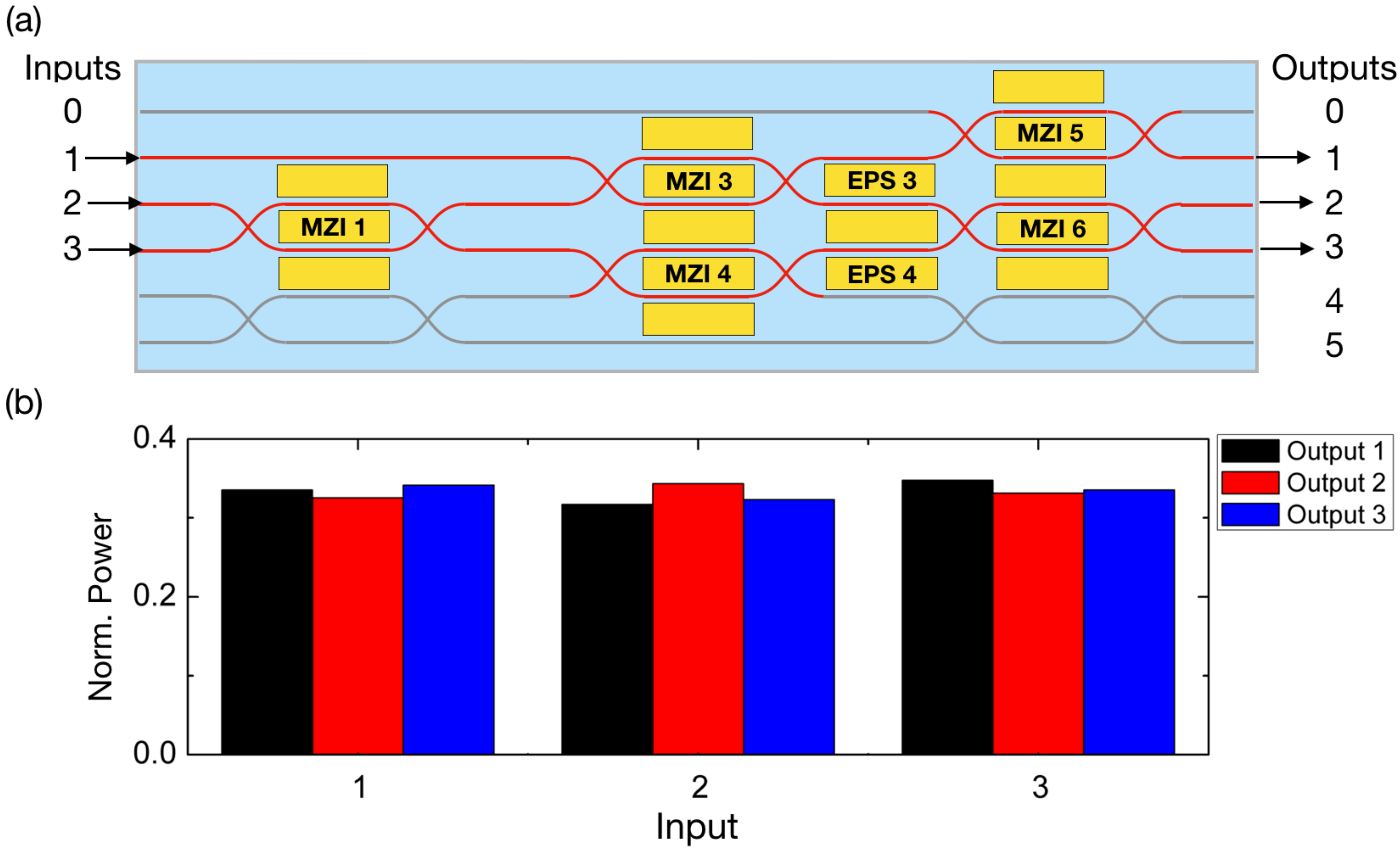
R. Wu, J. Lin, M. Wang, et. al. Opt. Lett. 44, 4698 (2019)

Demonstration of 1 x 6 optical switch



R. Wu, J. Lin, M. Wang, et. al. Opt. Lett. 44, 4698 (2019)

A balanced 3 x 3 interferometer



R. Wu, J. Lin, M. Wang, et. al. Opt. Lett. 44, 4698 (2019)

Conclusions

For the first times, we demonstrate:

1. Aberration free focusing deeply into glass;
2. Centimeter-scale microfluidic systems fabricated with high-throughput internal processing;
3. Lithium niobate waveguides of a propagation loss ~0.02 dB/cm !

Together, revolutionary products can be created in a profitable fashion!

You can buy the fluidic and photonic devices

華東師範大學
EAST CHINA NORMAL UNIVERSITY

极端光机电实验室
XXL-THE EXTREME OPTOELECTROMECHANIX LABORATORY

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Micromachines 10, 565 (2019)
https://doi.org/10.3390/mi10090565

We are producing:

- **lithium niobate microresonators** ($Q > 10^7$),
- **lithium niobate waveguides** (loss: <0.05 dB/cm, length: up to tens of centimeters),
- **customer-designed microfluidics** (channel diameters: from ~1 μm to ~1 mm; channel length: up to ~1 m).

Prices are negotiable. Free samples are available under the condition of collaboration.

Contact us or place your order by sending your emails to **xxl@phy.ecnu.edu.cn**

Please visit: xxl.ecnu.edu.cn