SPIE. PHOTONICS WEST LASE

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Advancing integrated photonics and microreactor technologies with ultrafast laser processing

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1. Background:

The impact of ultrafast laser processing for photonics and fluidics applications

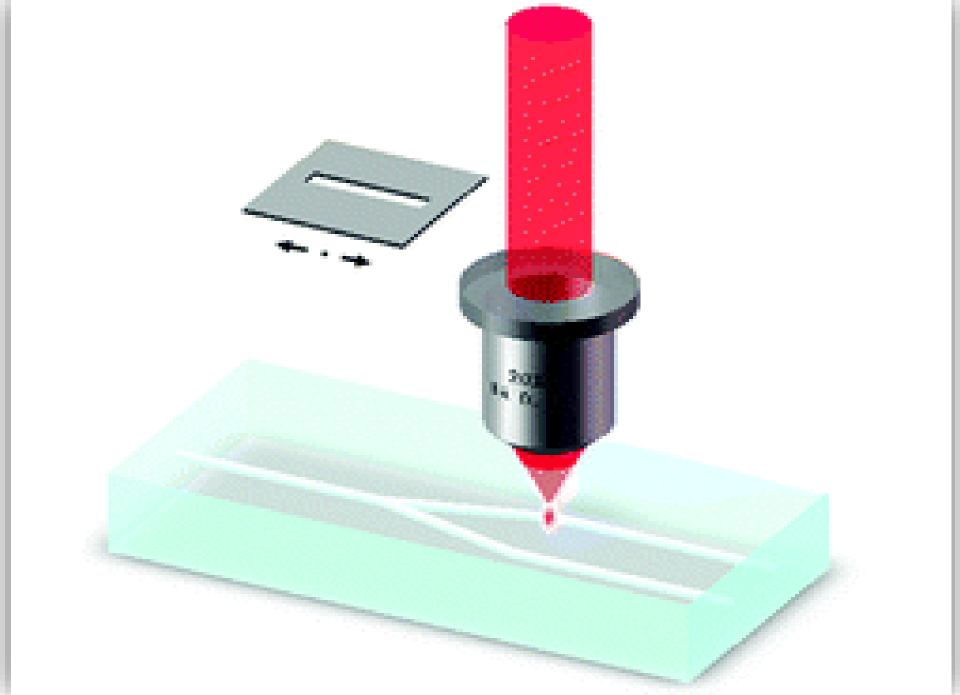
Femtosecond laser writing of waveguides and fluidic channels

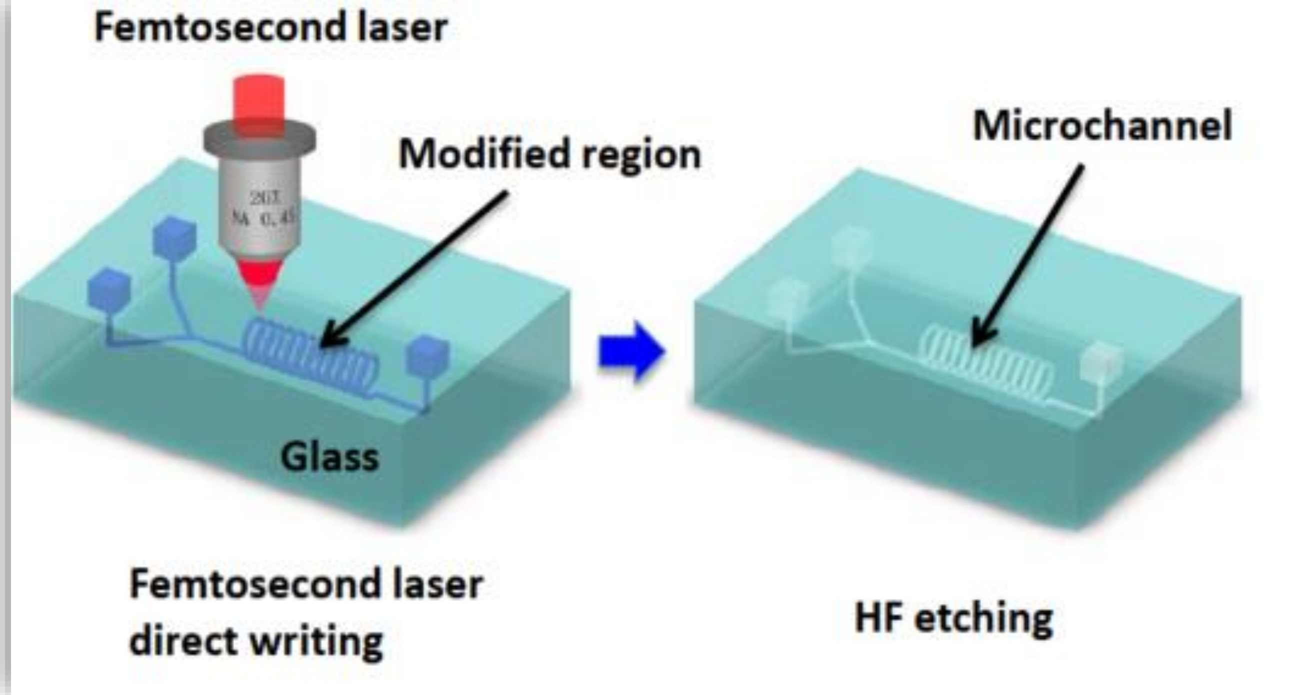
Writing of waveguides：

enabling 3D photonic circuits

Writing of fluidic channels:

enabling 3D fluidic networks buried in glass





Davis, K. M., et al., Opt. Lett., 21, 1729 (1996)

Marcinkevičius, A., et al., Opt. Lett., 26, 277 (2001)

The challenges being faced

Issues in photonics:

- Relatively high propagation loss;
- Small refractive index change;
- Limited tunability of the fabricated photonic circuits

Issues in fluidics:

Channel diameter and thickness limited to ~ mm scale, making it difficult to promote operation throughput

Issues in both:

- High fabrication precision maintenance with increasingly large footprint of the devices;
- Higher fabrication efficiency required

Solutions

For photonics:

Combining ultrafast laser processing with other techniques such as focused ion beam milling and chemo-mechanical polishing to achieve low propagation loss

For fluidics:

Shaping the pulses to fabricate deeply in glass without sacrificing the longitudinal resolution to produce macro-scale microfluidic structures for high-throughput reaction applications.

To enhance the efficiency:

High repetition rate laser and multi-foci focal system employed

2. Applications in

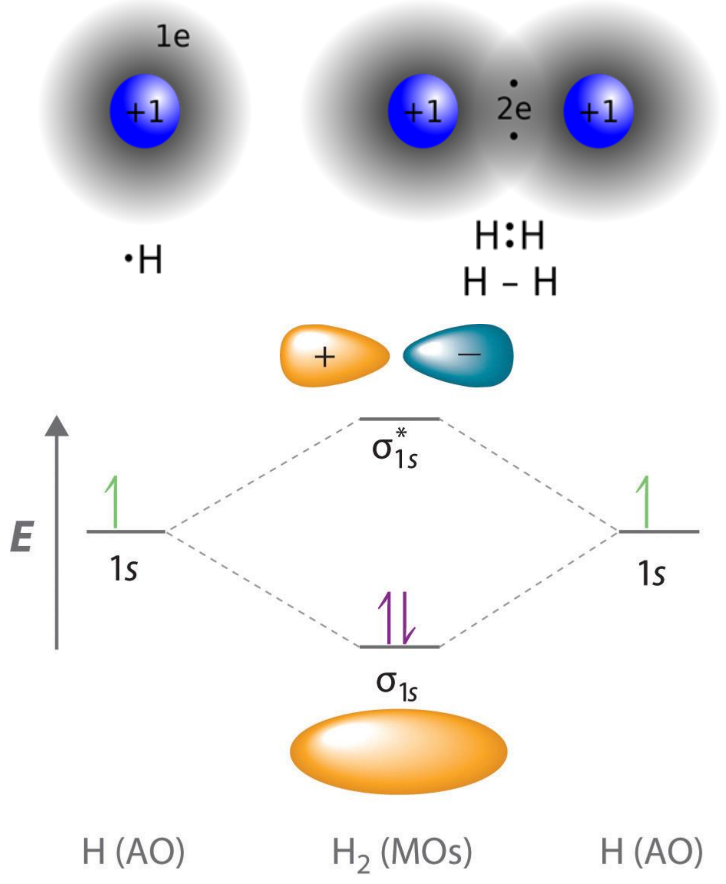
integrated photonics :

On-chip coupled lithium niobate microdisk photonic molecules

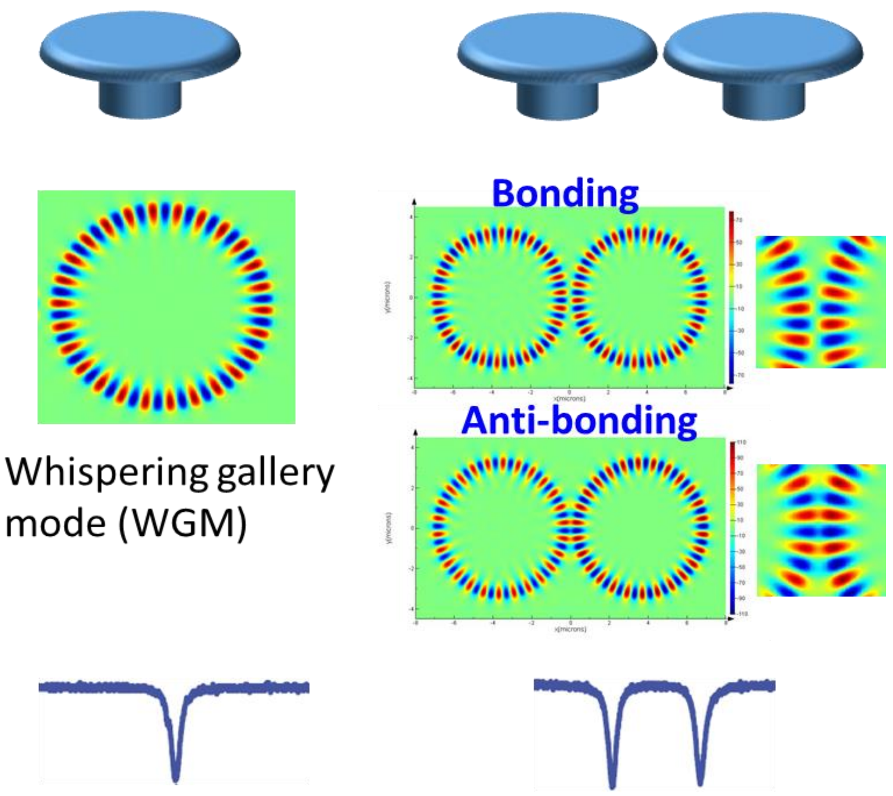
First example: photonic molecule

Real molecule ↔ **Photonic molecule**

Hydrogen atom **Hydrogen molecule**



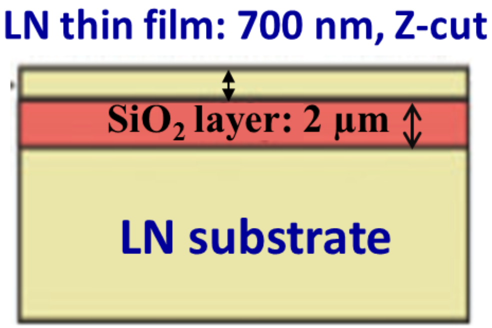
Single microdisk **Photonic molecule**



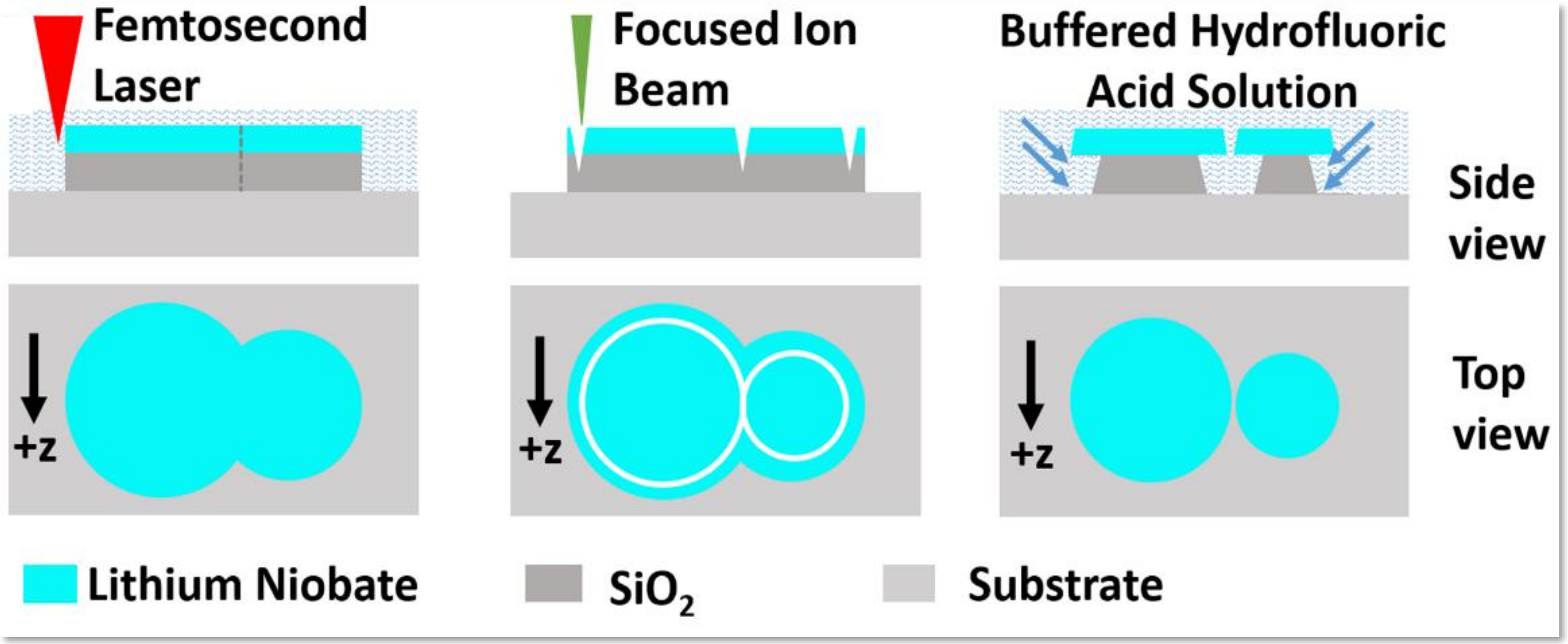
Whispering gallery mode (WGM)

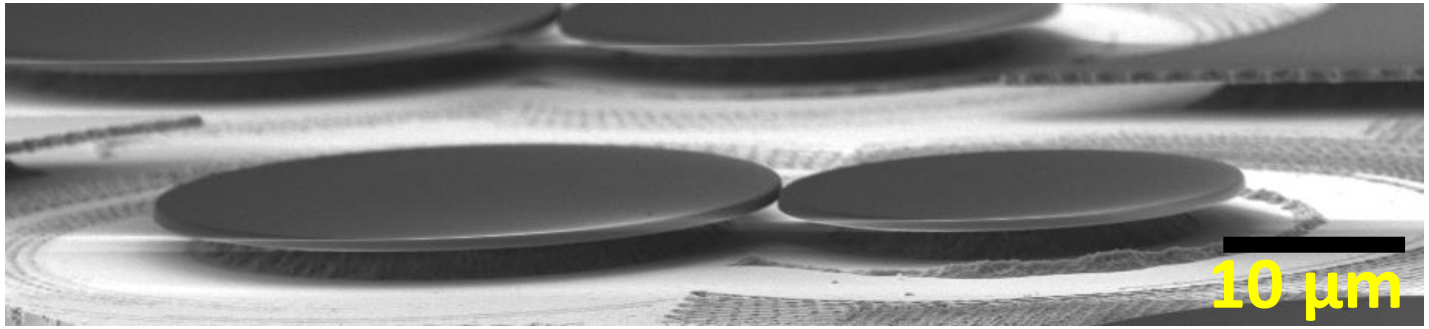
Mode splitting

Fabrication of photonic molecule



Laser Photon Rev. 6, 488 (2012)





Wang, M., Yao, N., et al., New J. Phys., 22, 073030 (2020)

Why choose lithium niobate as substrate?

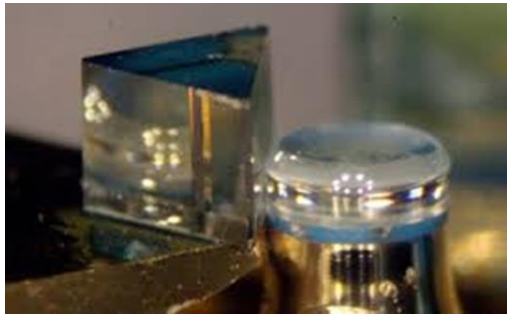
	Nonlinear optical coefficients	Electro-optic coefficients
Lithium niobite (LN)	41.7 pm/V	30.9 pm/V
Quartz	0.3 pm/V	0.93 pm/V

Opportunities：

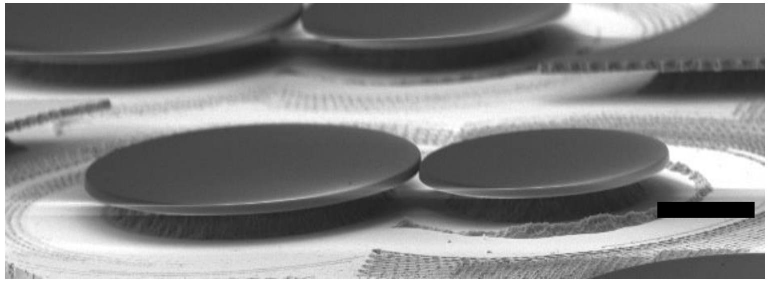
- **Broad transmission window**
- **High nonlinear optical / electro-optic /thermal coefficients….**

Challenges：

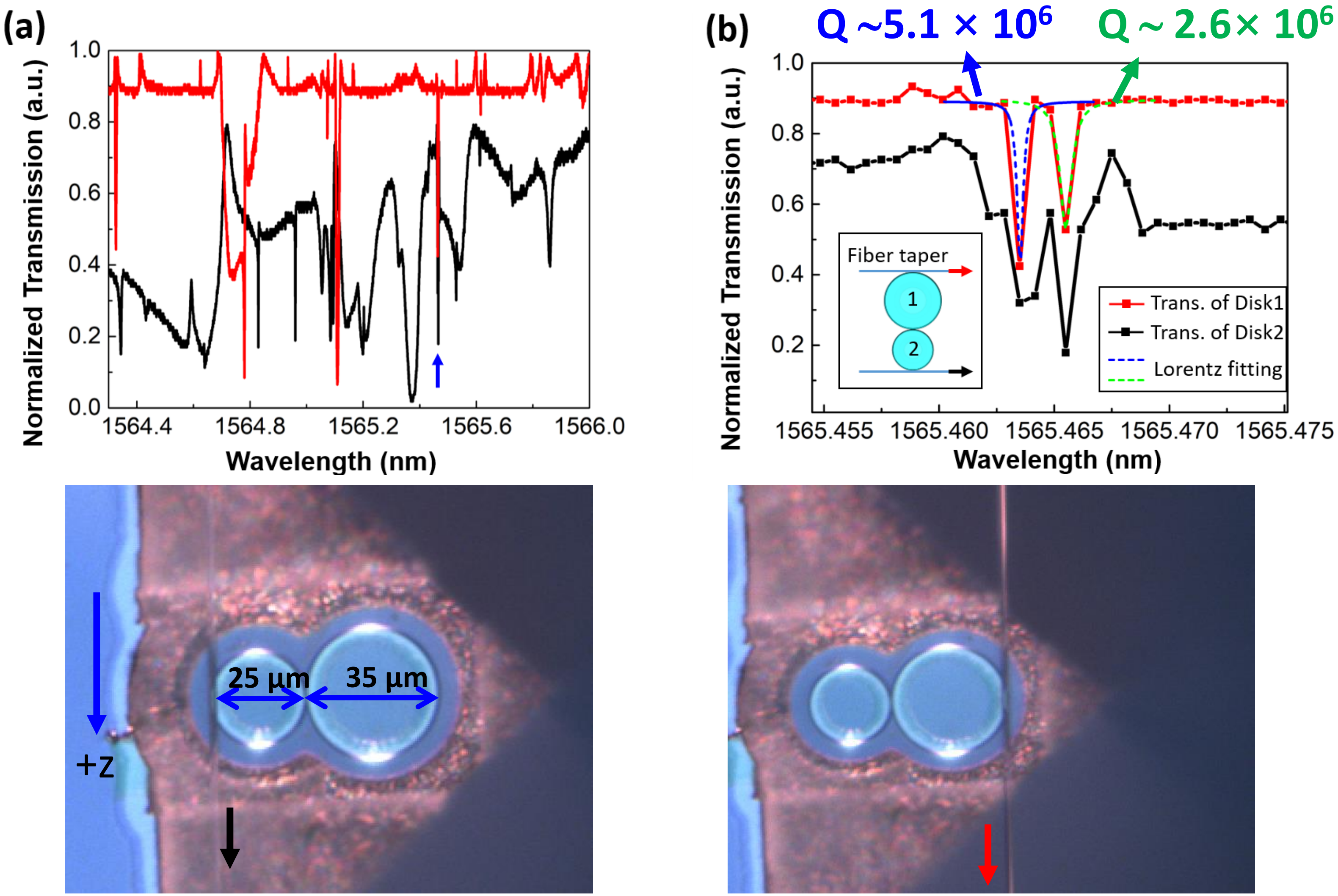
- **Hard to be patterned** by optical lithography
- High chemical stability



Measurement of Q factor

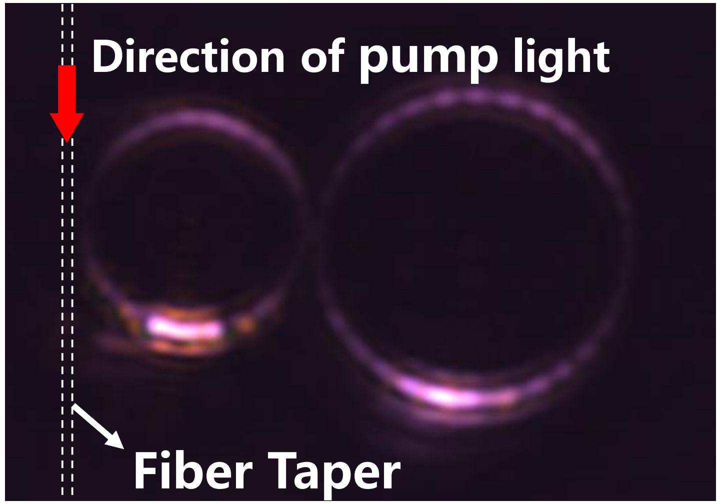


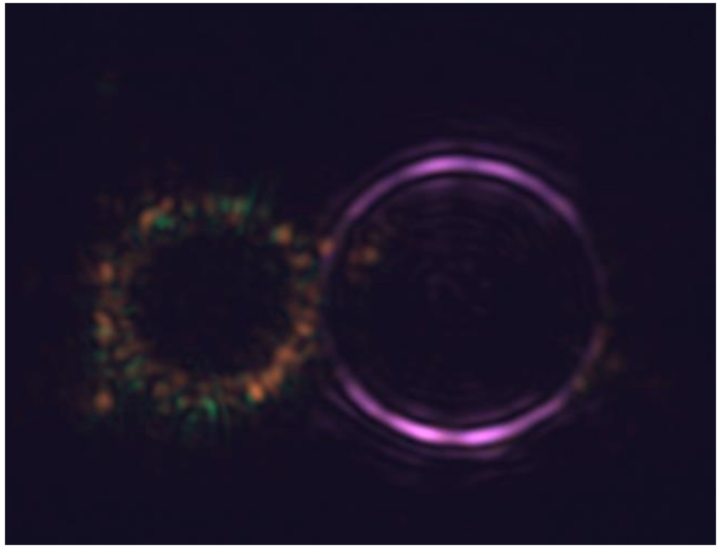
SEM of fabricated photonic molecule, showing a narrow gap width of ~130 nm between the two disks

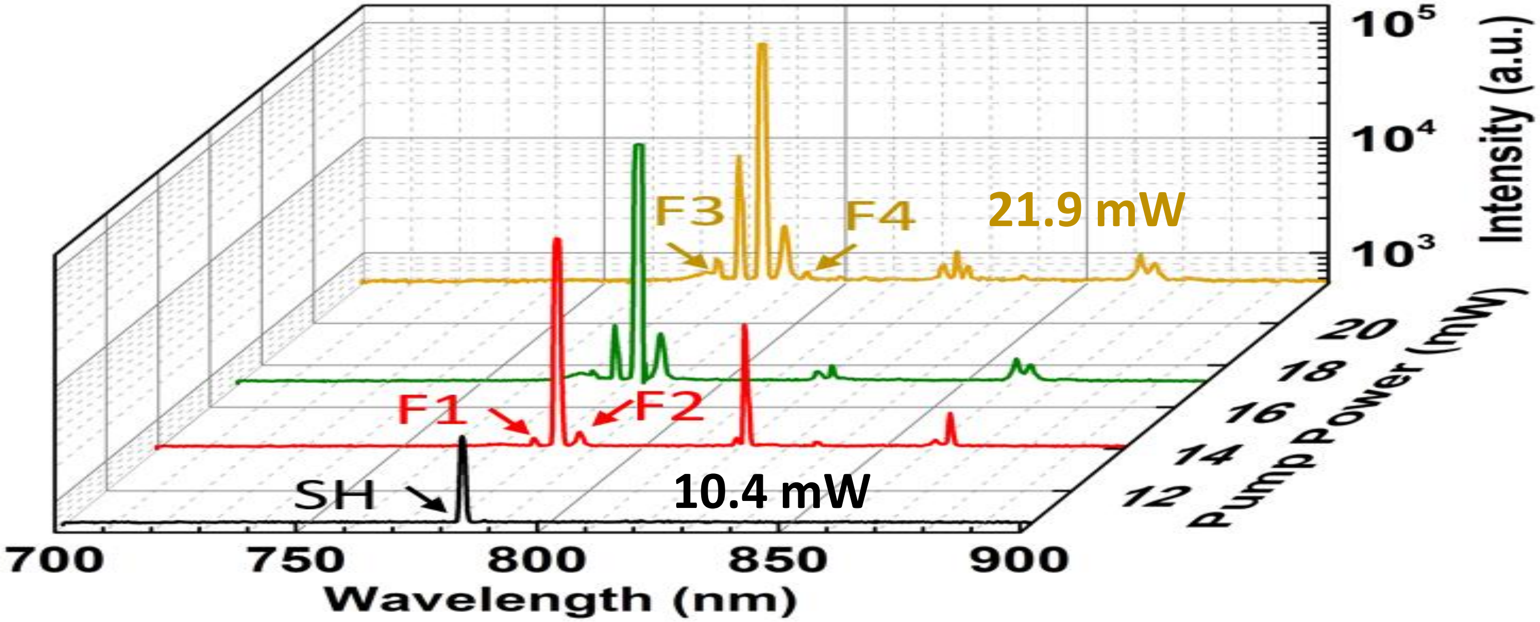


Wang, M., Yao, N., et al., New J. Phys., 22, 073030 (2020)

Boosting nonlinear optical efficiency in photonic molecule







- ◆ **Strong second harmonic generation, four wave mixing and Raman signals observed**
- ◆ **Four wave mixing conversion efficiency with 14% @ 23 mW pump**
- ◆ **These are caused by improved phase matching**

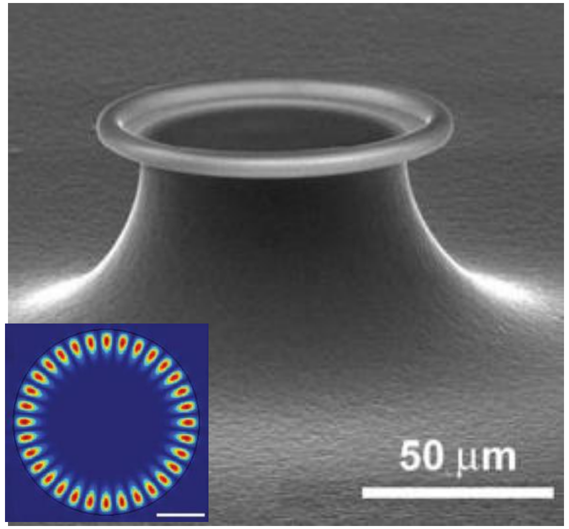
Wang, M., Yao, N., et al., New J. Phys., 22, 073030 (2020)

2. Applications in

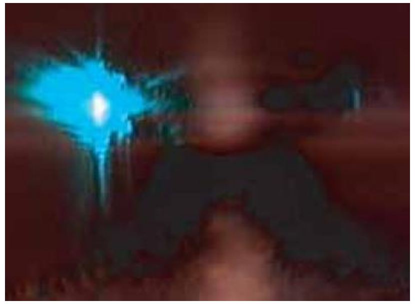
integrated photonics :

Ultra-high Q Microresonators

Applications of high Q microresonators



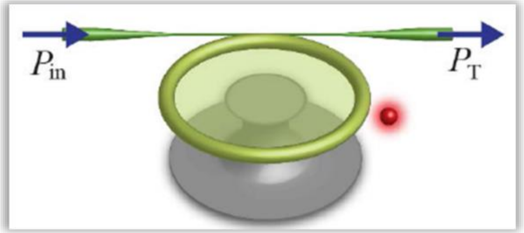
Vahala, Nature 421,925 (2003)

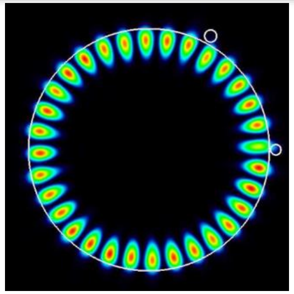


THG

Pump power <300µW

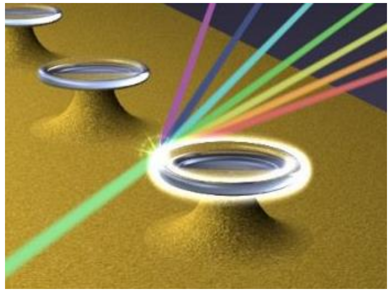
Nat. Phys. 3,430 (2008)





Label-free single-molecule detection

Science 317, 783 (2008)

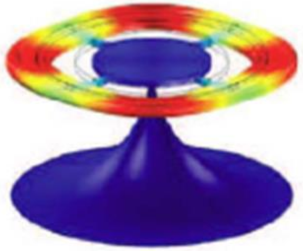


Optical frequency comb

Nature 450, 1214 (2007)

Strong coupling of a single Atom and a microresonator

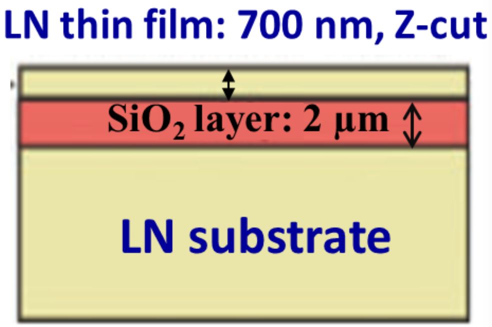
Nature 441, 673 (2006)



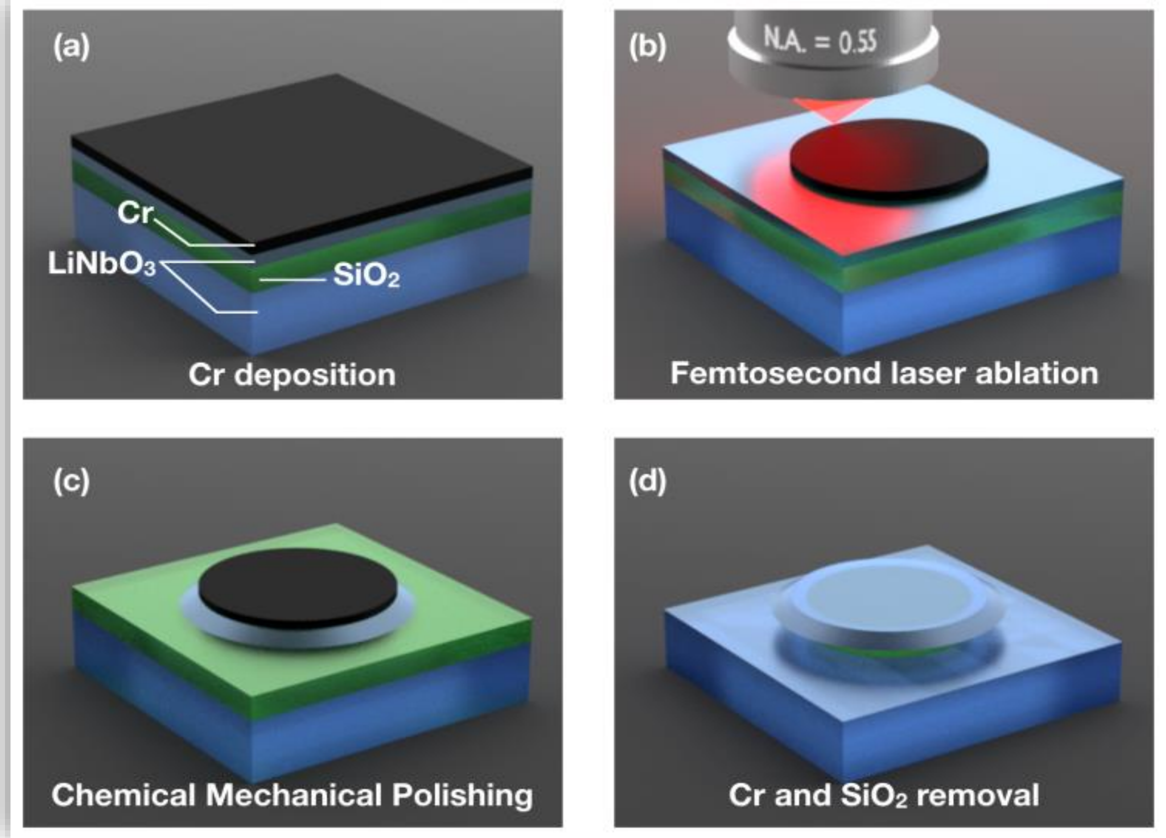
Quantum optomechanics

Nat. Phonton. 2, 627 (2007)

Fabrication of high Q microresonators with femtosecond laser



Laser Photon Rev. 6, 488 (2012)

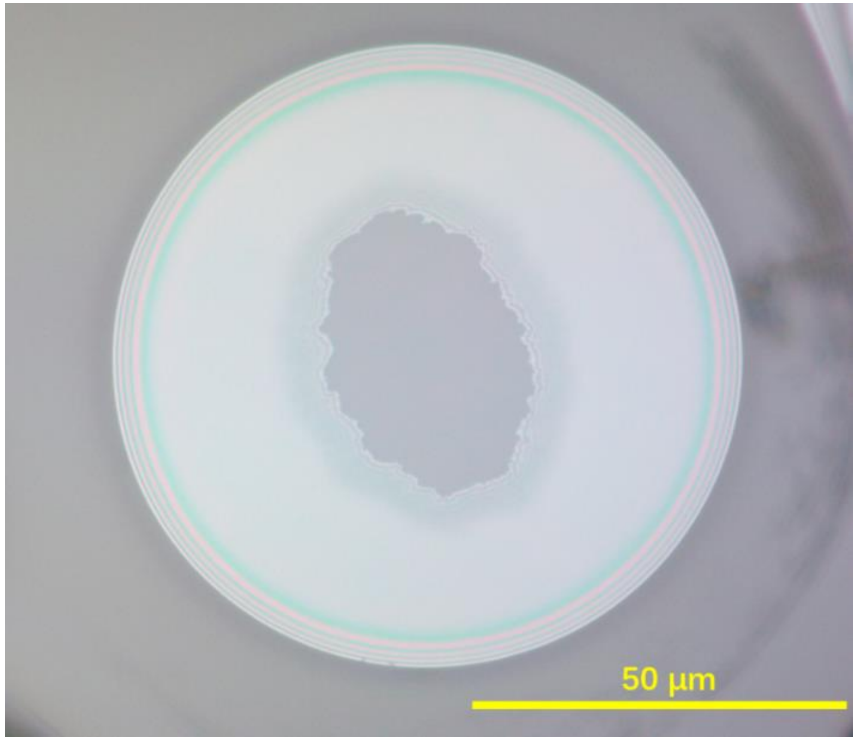


Y. Cheng, et al, Patent No.: US10670806B2

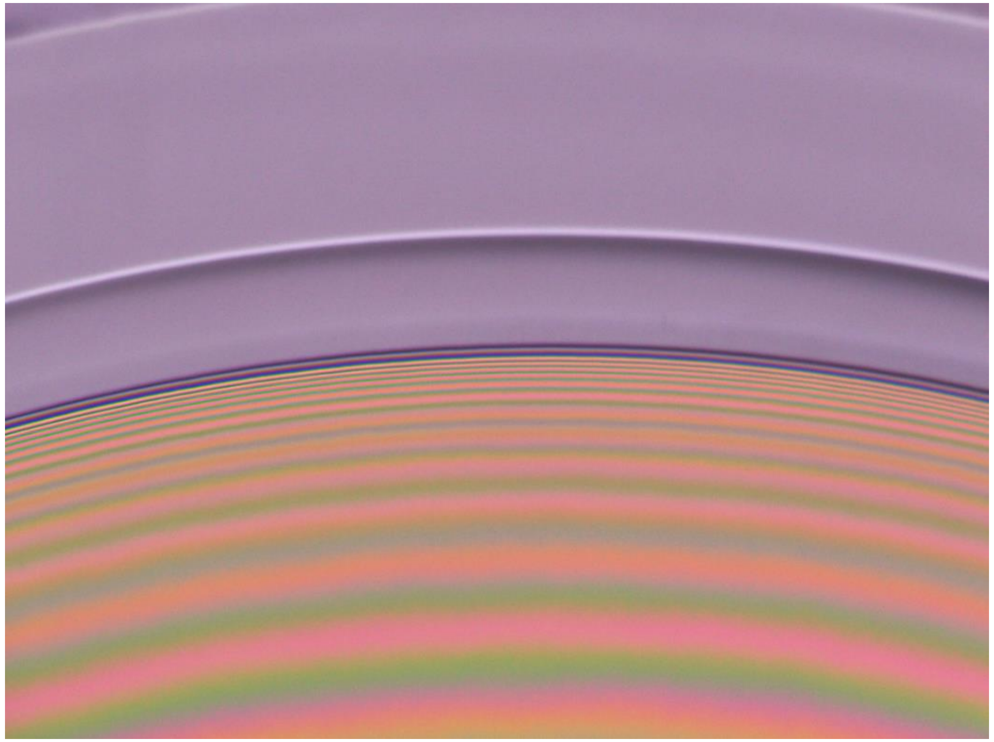
R. Wu et al, Optics Letters 43, 4116 (2018)

Fabrication flow. (a) Coat Chromium (Cr) thin film on top of the LNOI. (b) Pattern the chromium thin film into a microdisk (c) Transfer the disk-shaped pattern to the LNOI by chemo-mechanical polishing. (d) Remove the Cr thin film and the SiO_2 buffer layer with two chemical wet etching process.

Optical micrograph of ultra-high Q microresonator



Top view



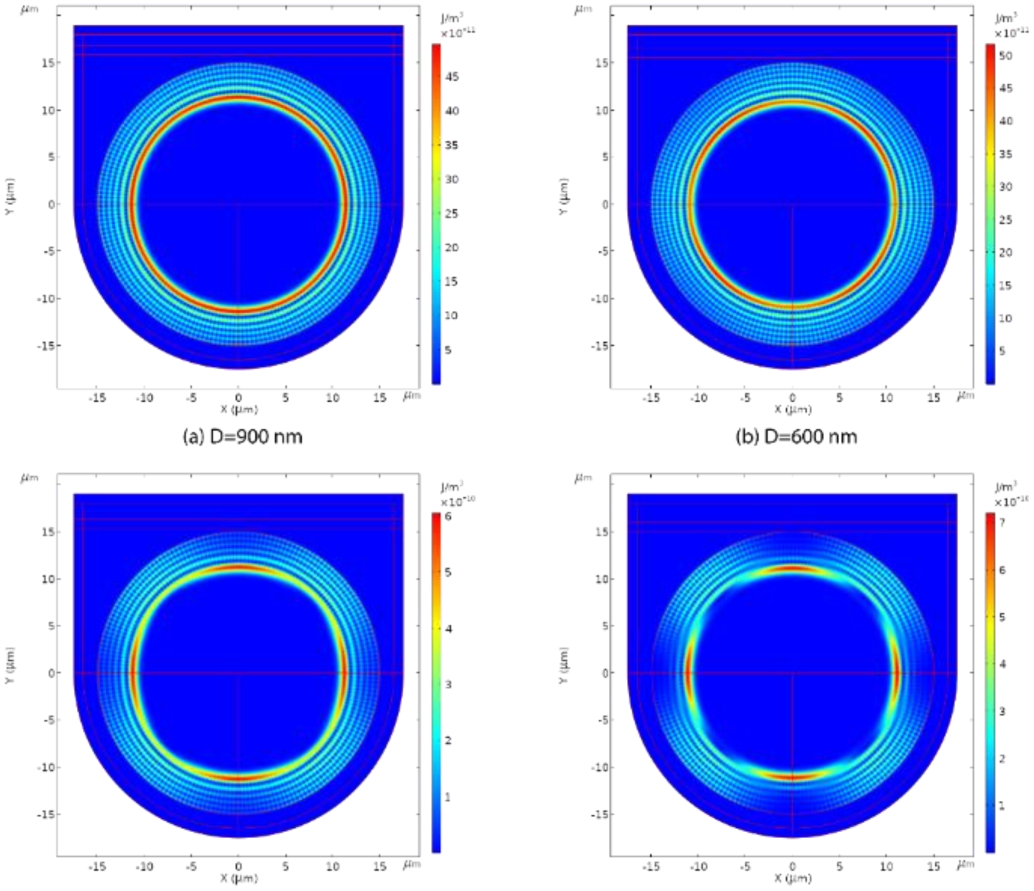
Close-up view near the edge

The highest Q factor measured in such on-chip ultra-high-Q microresonator can reach 1.5×10^8.

The micro-disk is fabricated in lithium niobate thin film using photolithography assisted chemomechanical etching, i.e., the so called PLACE technique. Photolithography is realized using femtosecond laser patterning of a thin layer of Cr film, as shown in the previous slides.

Gao, R., et al., arXiv e-prints, arXiv:2102.00399 (2021)

Observation of novel polygon modes induced by symmetry breaking



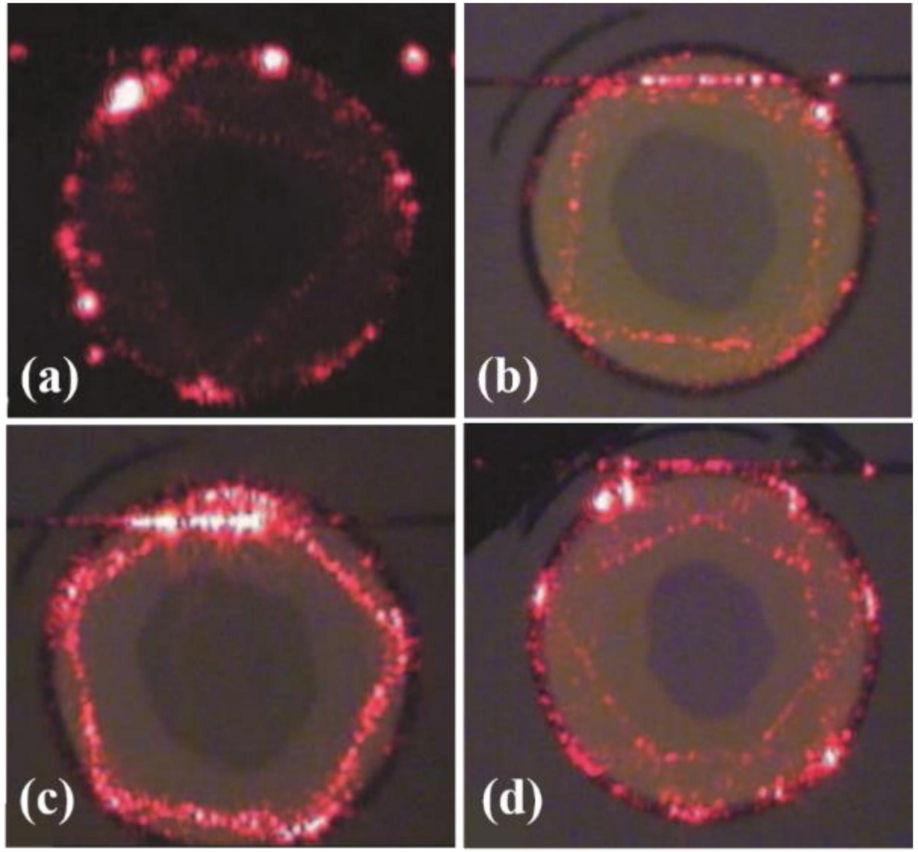
(a) D=900 nm

(b) D=600 nm

(c) D=300 nm

(d) D=0 nm

Simulation



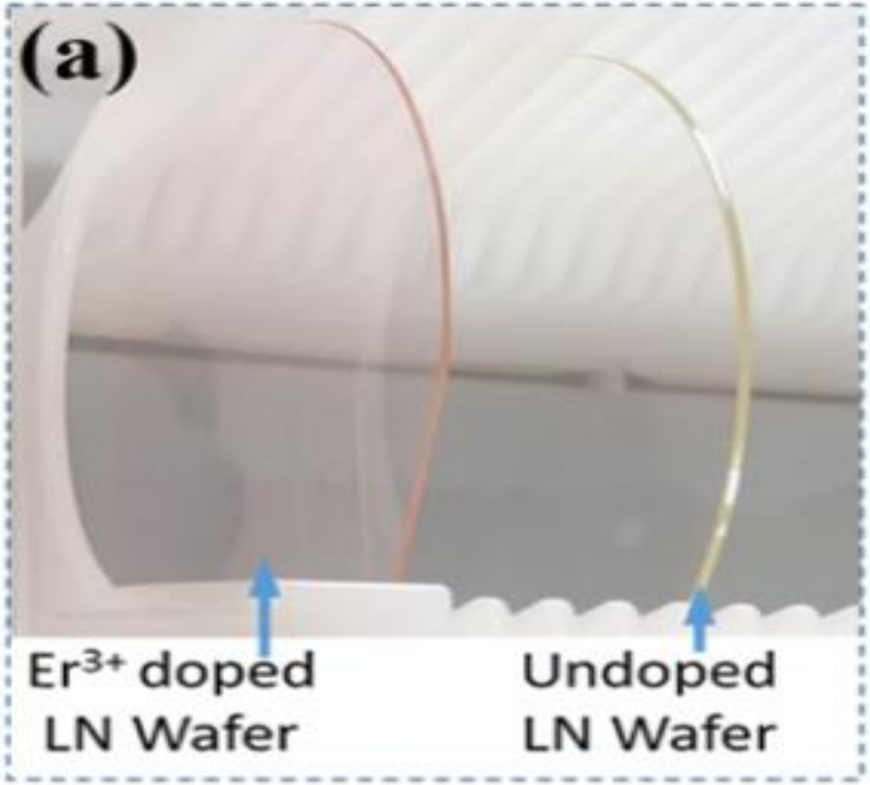
Observation

Z. Fang, et al., Phys. Rev. Lett.,125,173901(2020)

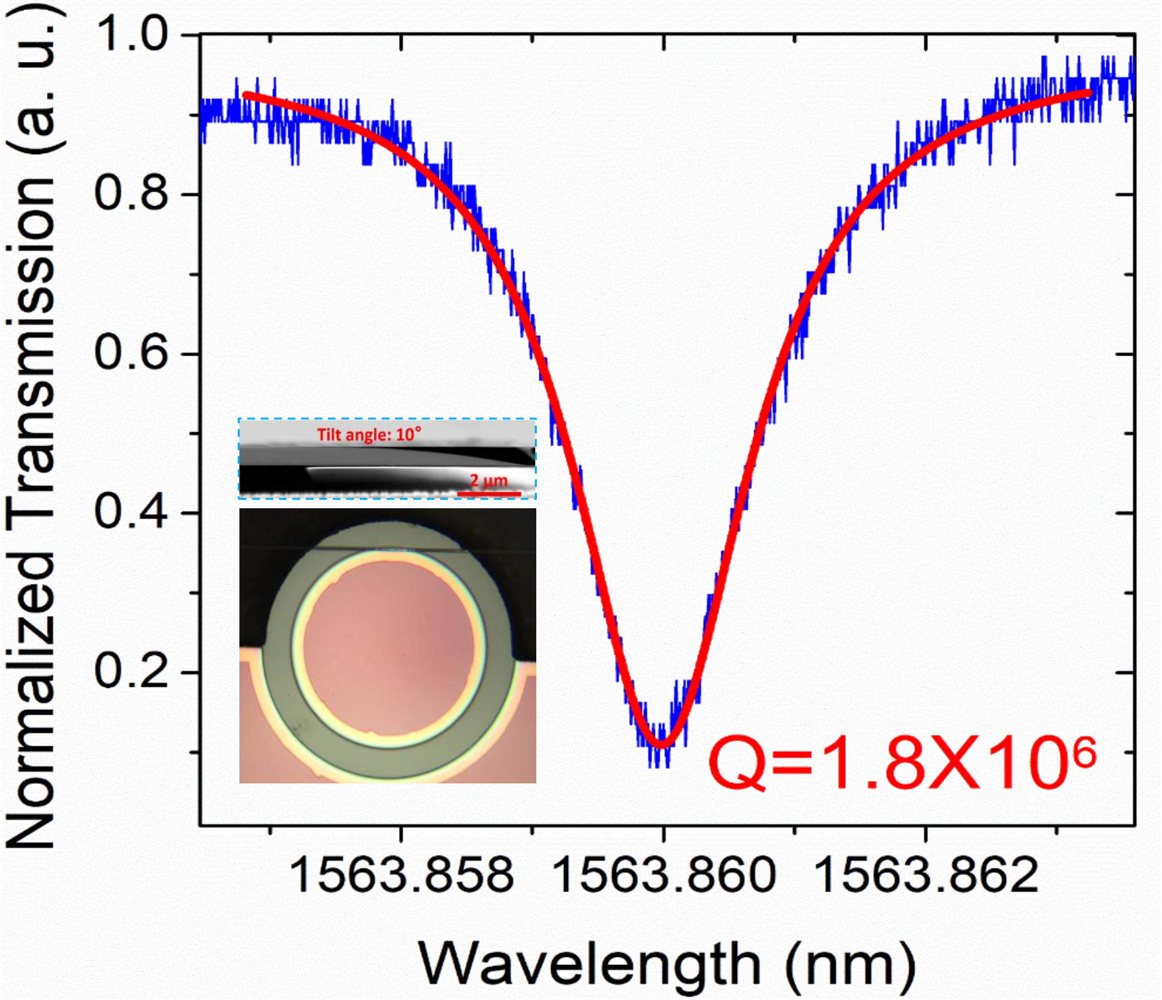
2. Applications in integrated photonics :

On-chip active lithium niobate devices

Microdisk laser fabricated in active LNOI

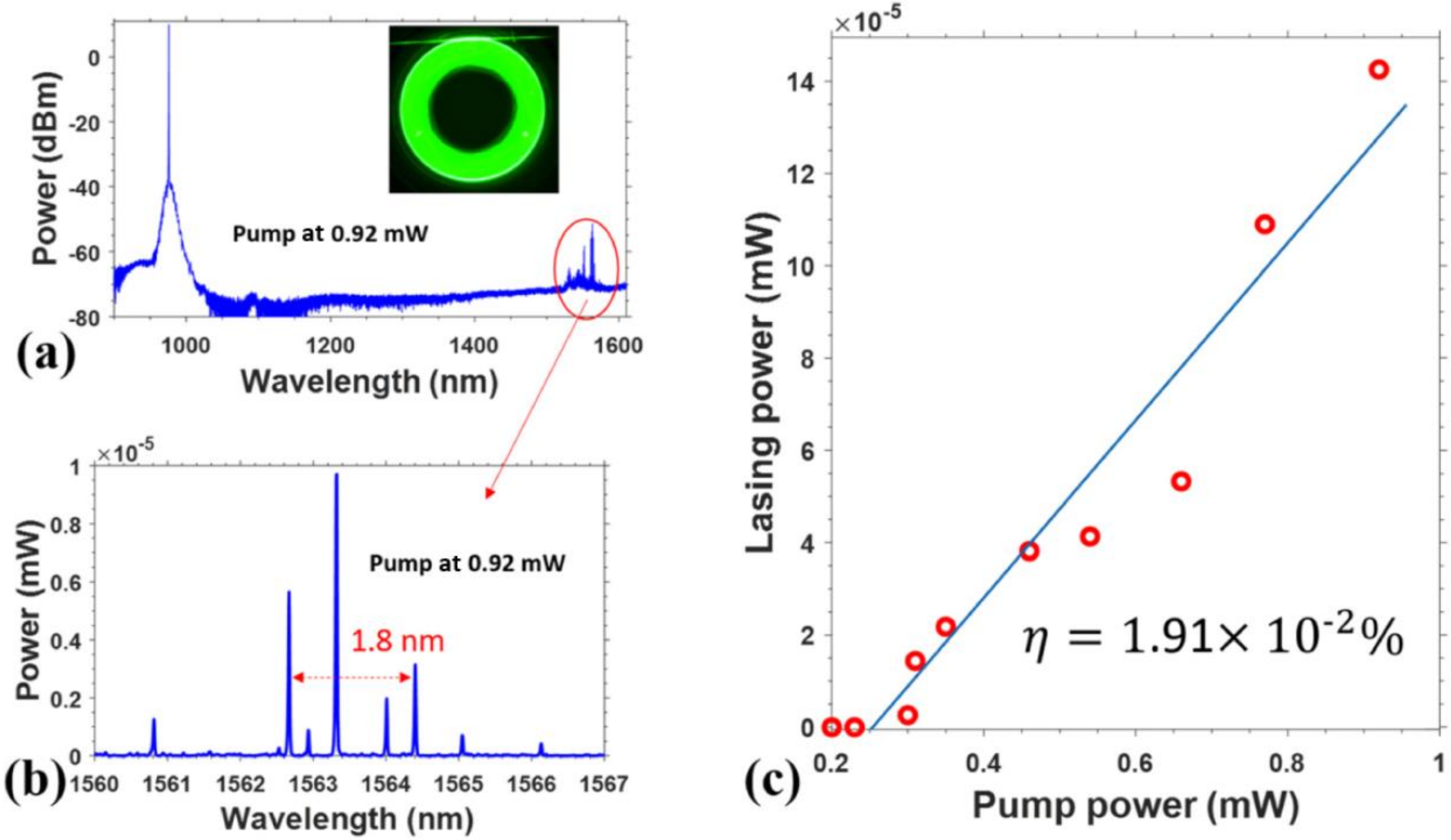


Er^{3+} doped LN wafer
Er^{3+} doped LN thin film made by ion slicing at NANOLN InC, Jinan, China



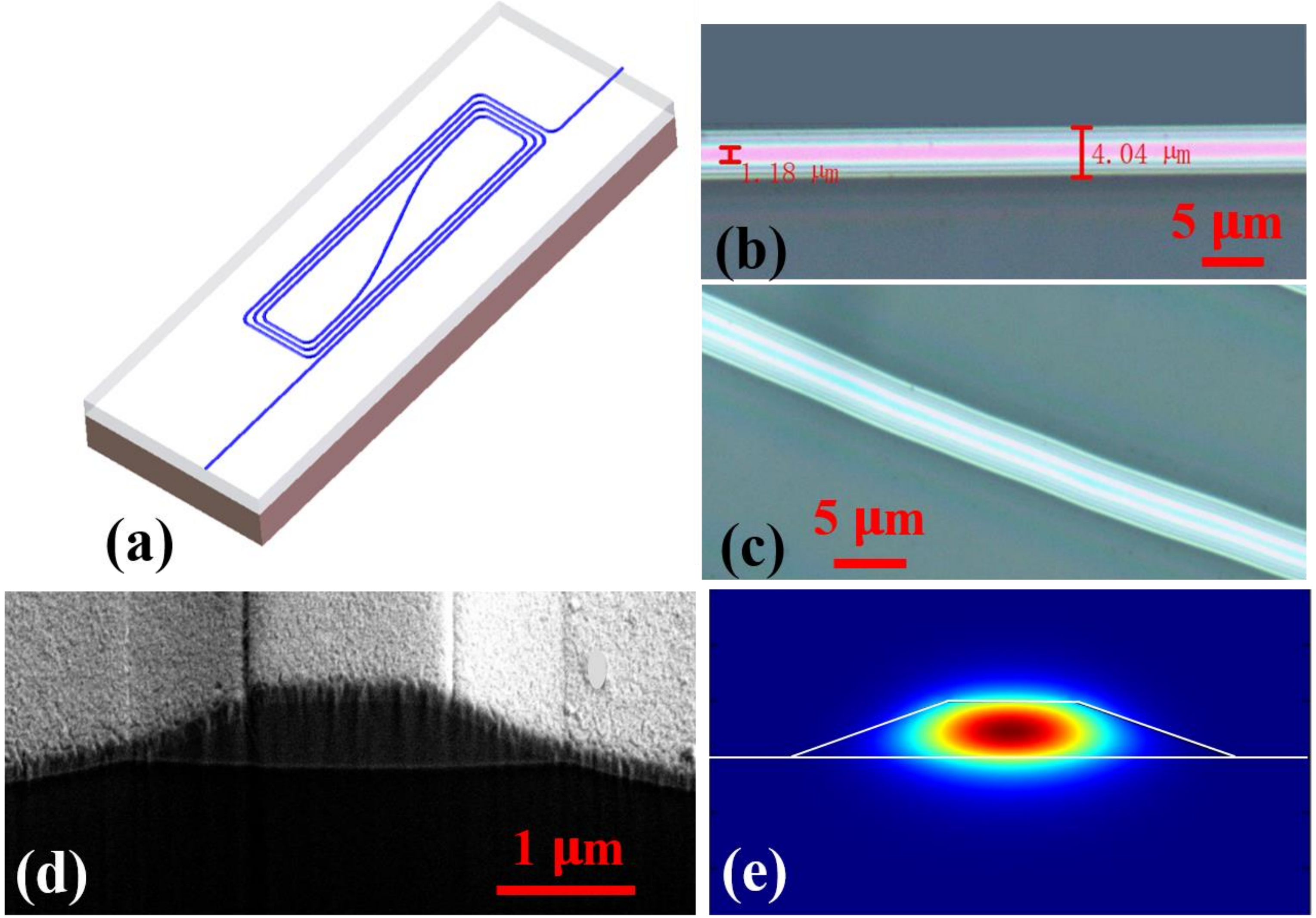
Z. Wang, et al., *Opt. Lett.* 46, 380-383 (2021).

Characterization of microdisk laser



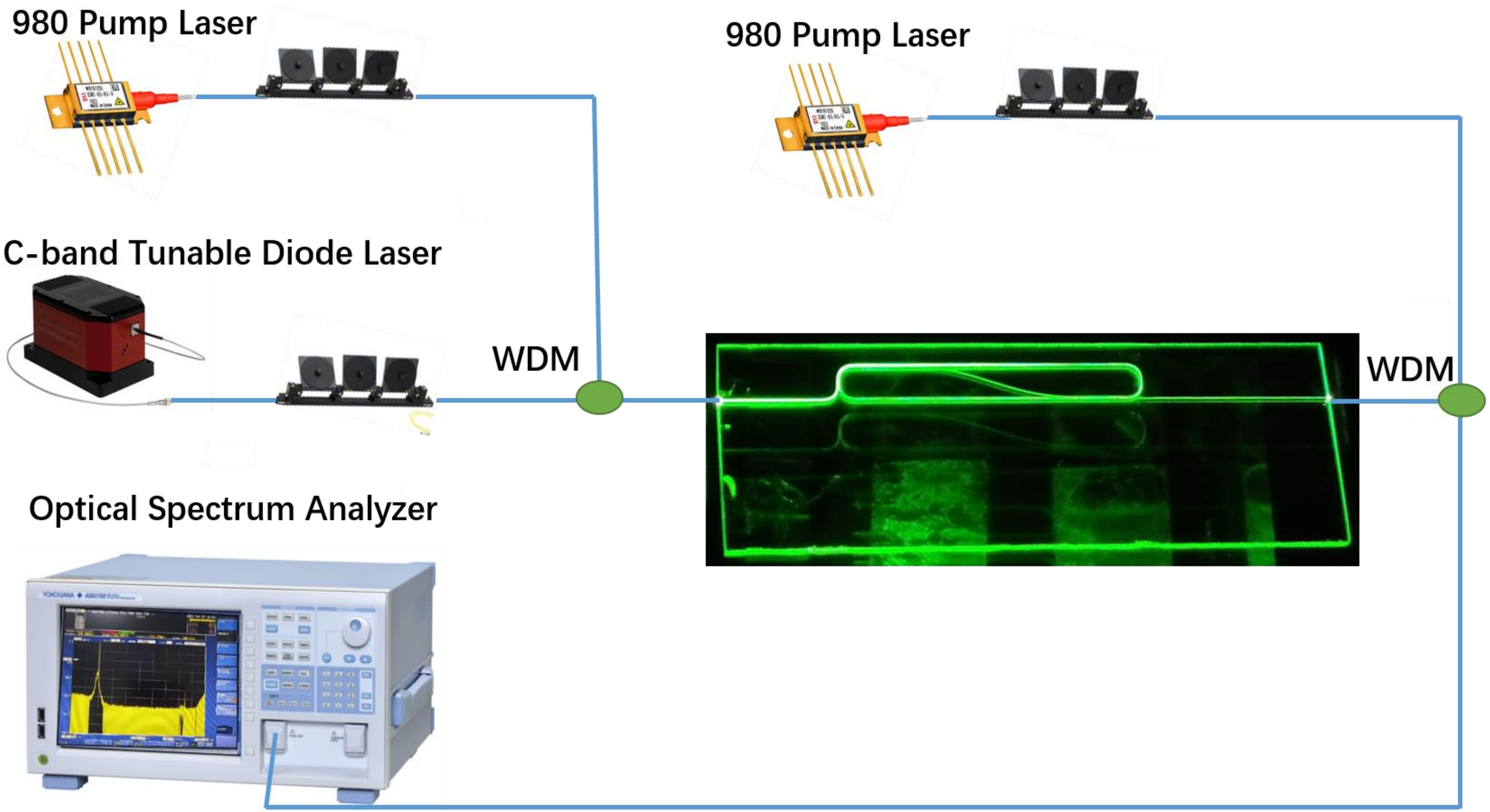
Z. Wang, et al., *Opt. Lett.* 46, 380-383 (2021).

Active waveguide amplifier



Zhou, J., et al., arXiv e-prints, arXiv:2101.00783 (2021)

Experimental setup for measuring gain factor

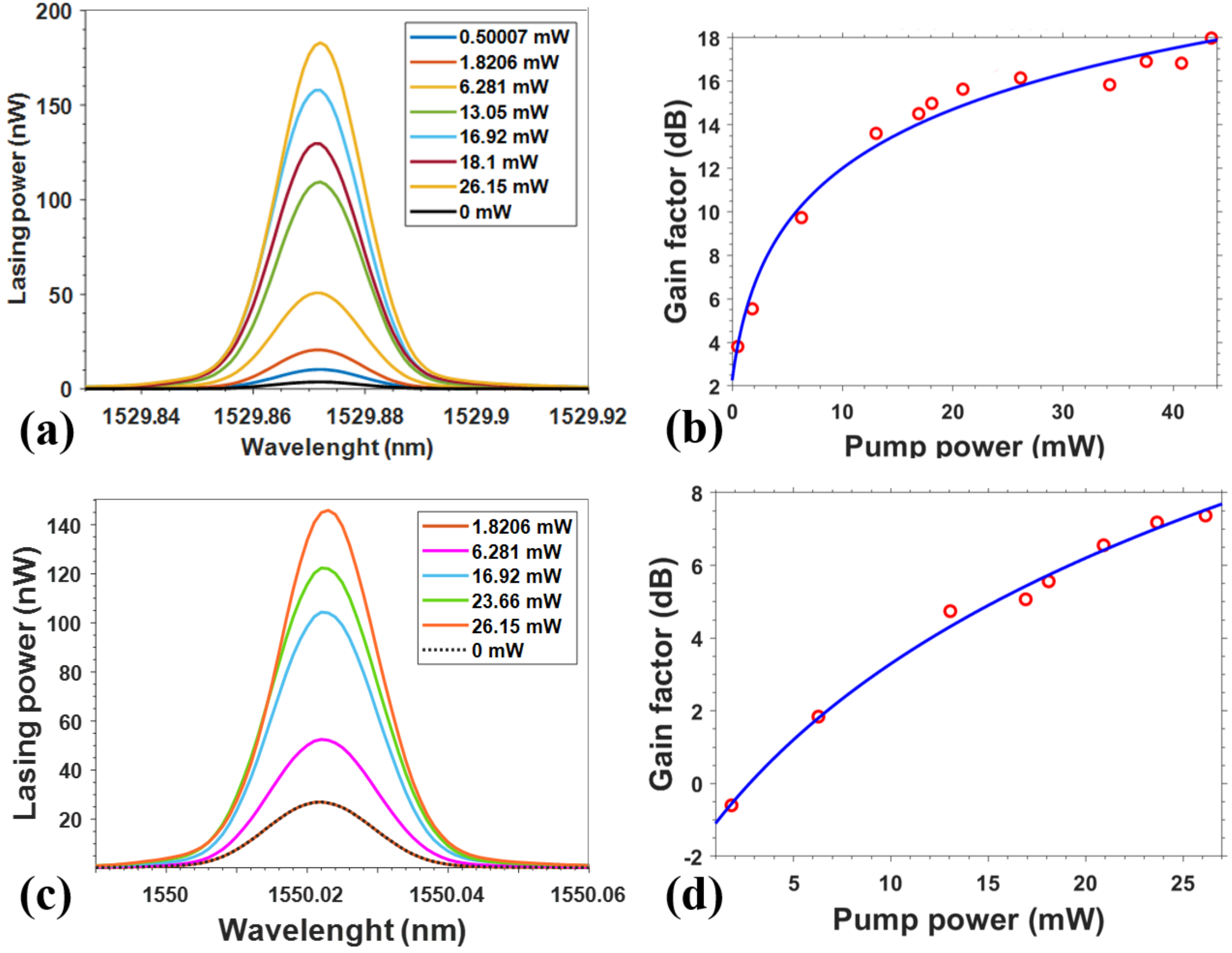


Zhou, J., et al., arXiv e-prints, arXiv:2101.00783 (2021)

Gain characterization of the Er^{3+} -doped LN waveguides

Signal spectrum
at 1530 nm

Signal spectrum
at 1550 nm



Gain factor
at 1530 nm

Gain factor
at 1550 nm

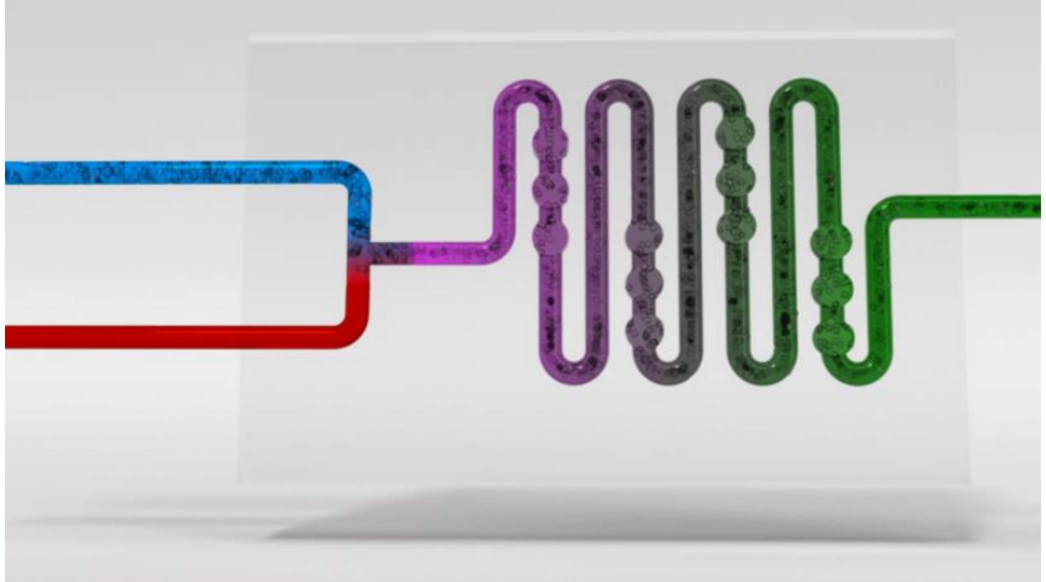
Zhou, J., et al., arXiv e-prints, arXiv:2101.00783 (2021)

3. Applications in

integrated fluidics :

3D microfluidic chemical reactor

Flow chemistry based on miniaturized reactor



http://goflow.at/research/flow-chemistry/

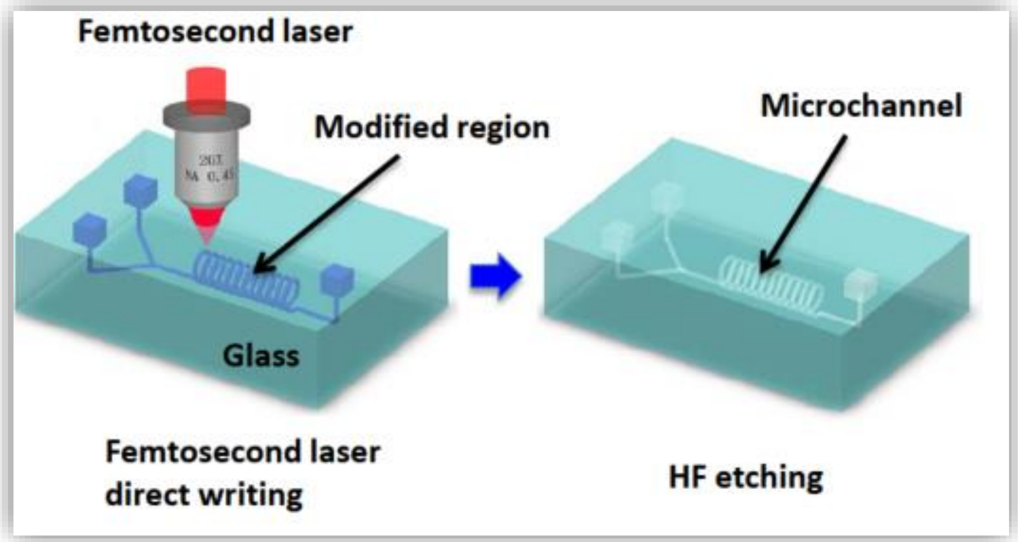
Replacing standard batch-type reactors with continuous flow microreactors

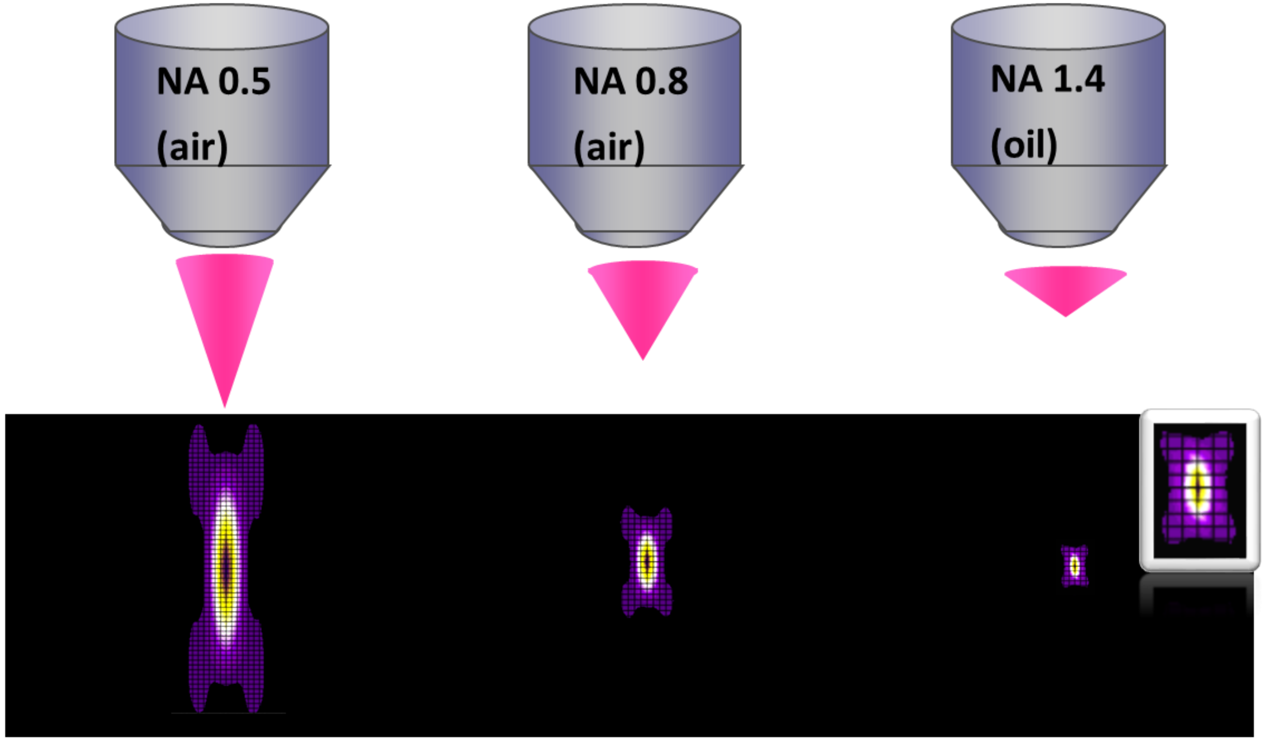
Benefits:

- **Higher** reaction rates
- **Purer** products
- **Better safty**
- **Integration of synthesis and analysis steps**
- **Rapid optimization**
- **Easy scale-up**
- Reaction conditions not possible using traditional batch chemistry methods

Challenges in making large scale flow chemical reactors

Femtosecond laser processing offers a nice way for fabricating flow chemical reactors. However, because the industry requires high production rate, so the microreactor should be of a quite significant size, that is to say, the channels in the glass typically would have a millimeter-scale diameter and the thickness of the micro-reactor could be a few millimeters.



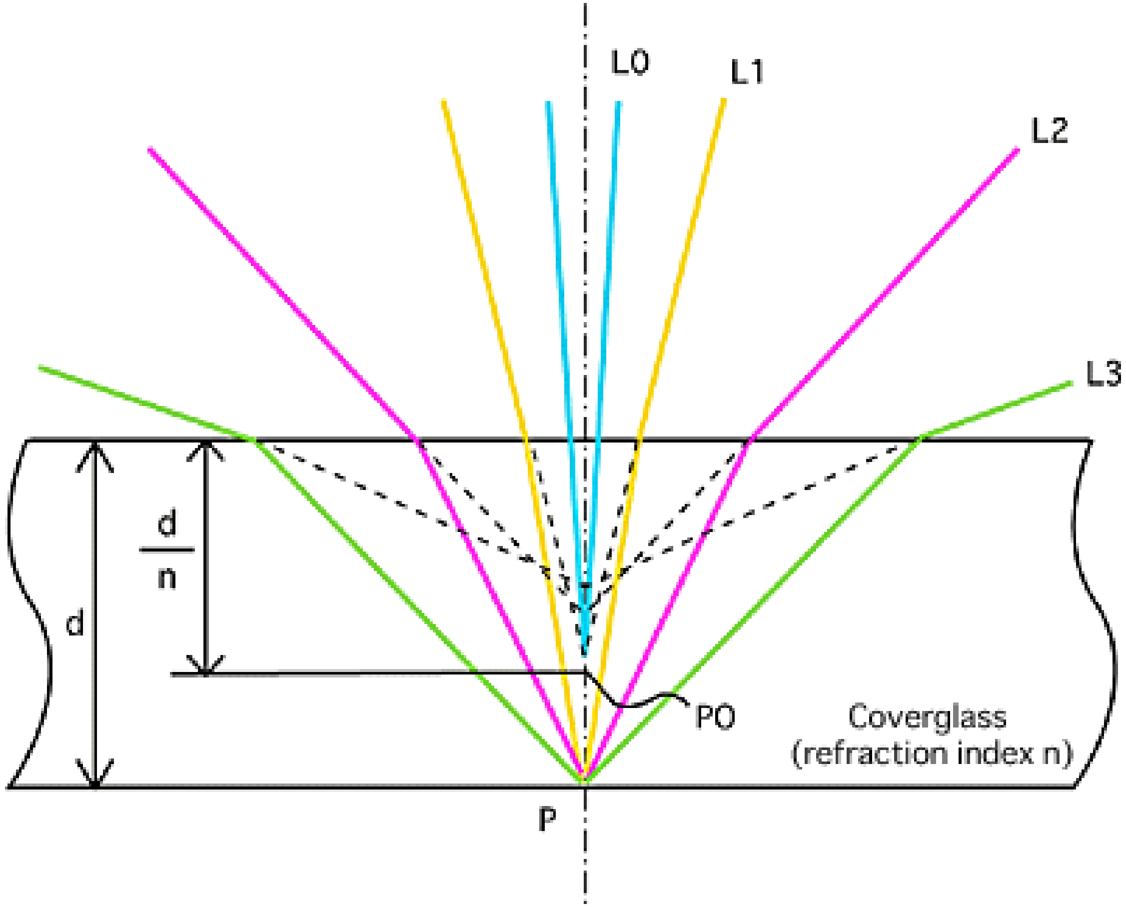


Large size
Low resolution

Small size
High resolution

1. Long working distance inherently associated with low resolution!

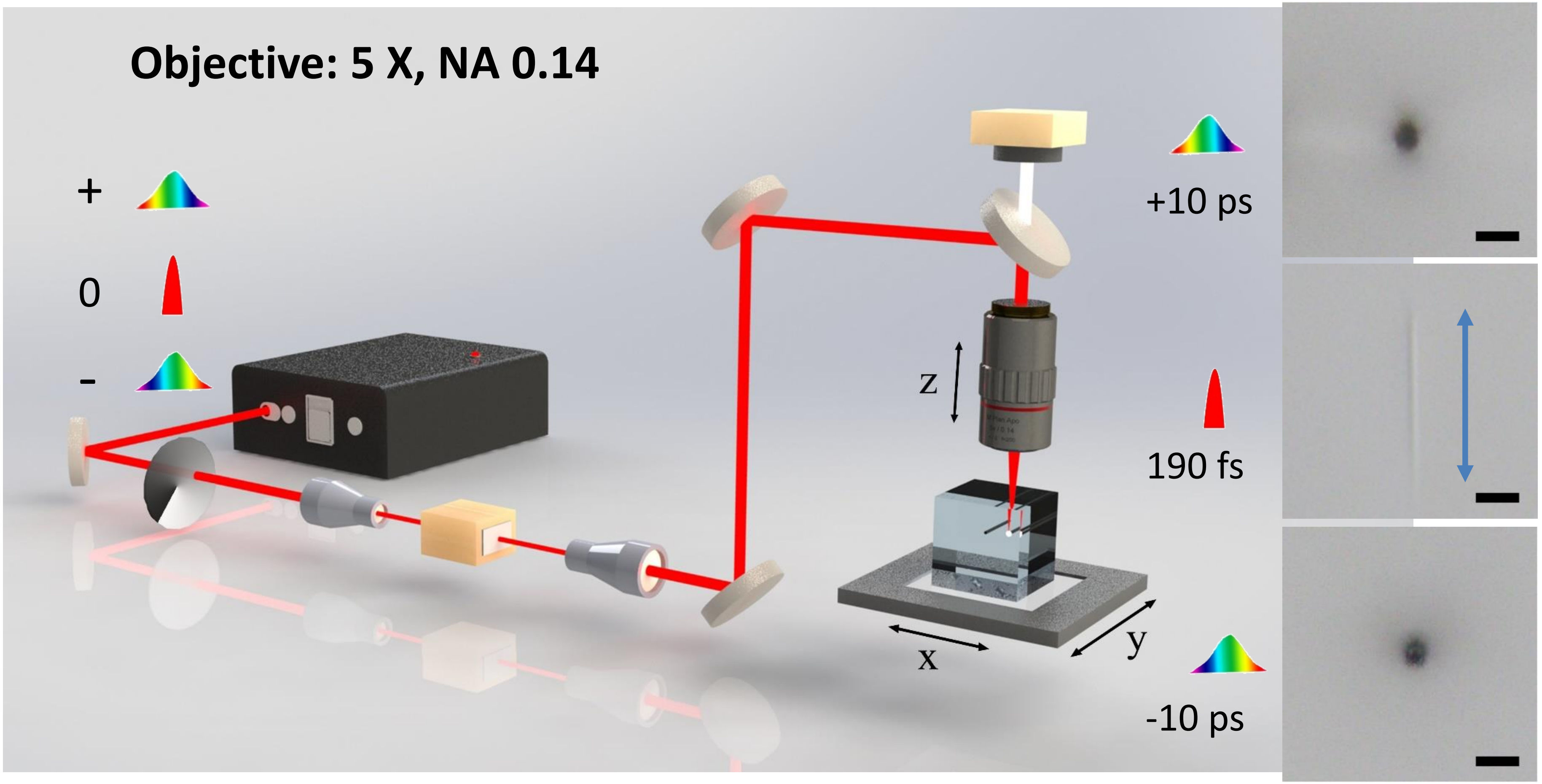
The challenges for large scale glass printing



Concept of spherical aberration

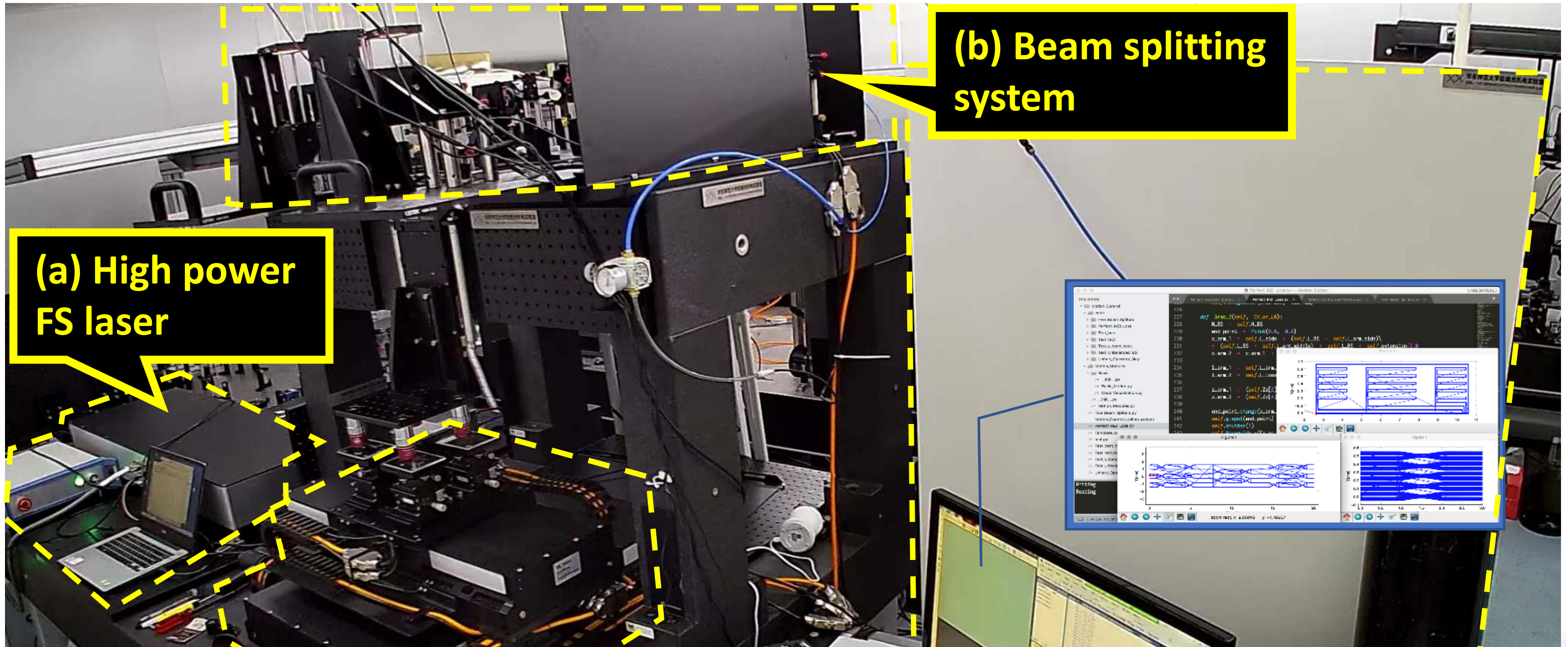
2. Focusing deeply into glass inherently leads to low axial resolution!

Our solution: chirped femtosecond laser modification



Schematic of the experimental setup. Scale bar, 25 μm.

Increase the efficiency with the chirped pulses



(a) High power FS laser

(b) Beam splitting system

(c) Large motion range XY stage

(d) Integrated multi-axial controlling system

Front view of the controlling case

Large focal volume combined with high axial resolution brings up the fabrication efficiency to an unprecedented level!

Four-foci focal system for speeding up the fabrication

Four-foci focal system for speeding up the fabrication

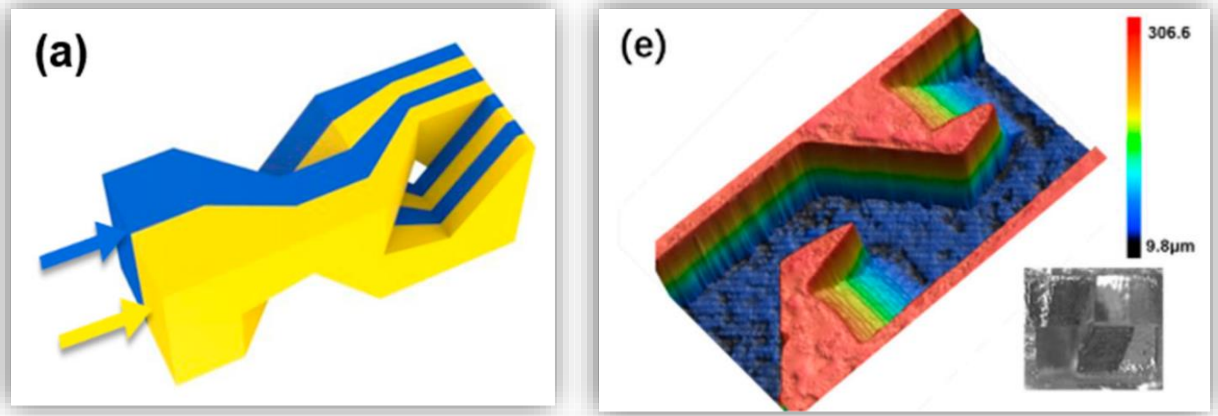
1. Four focal spots of individually tunable power
2. Large scale XY motion range of 30 cm by 30 cm
3. Inline real-time focus tracking system

……

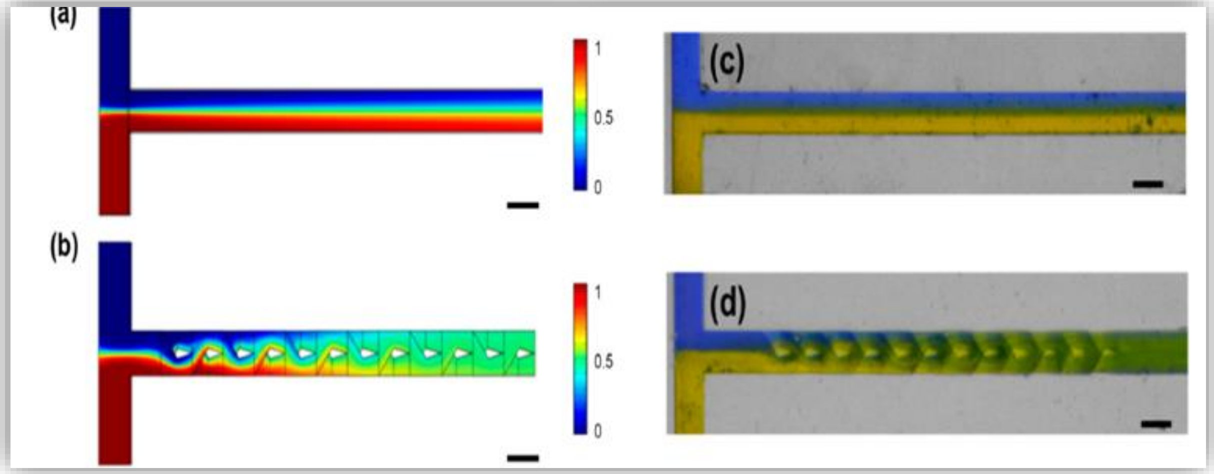
Concept of a 3D microreactor

3D mixing unit:

Schematic and internal 3D structure



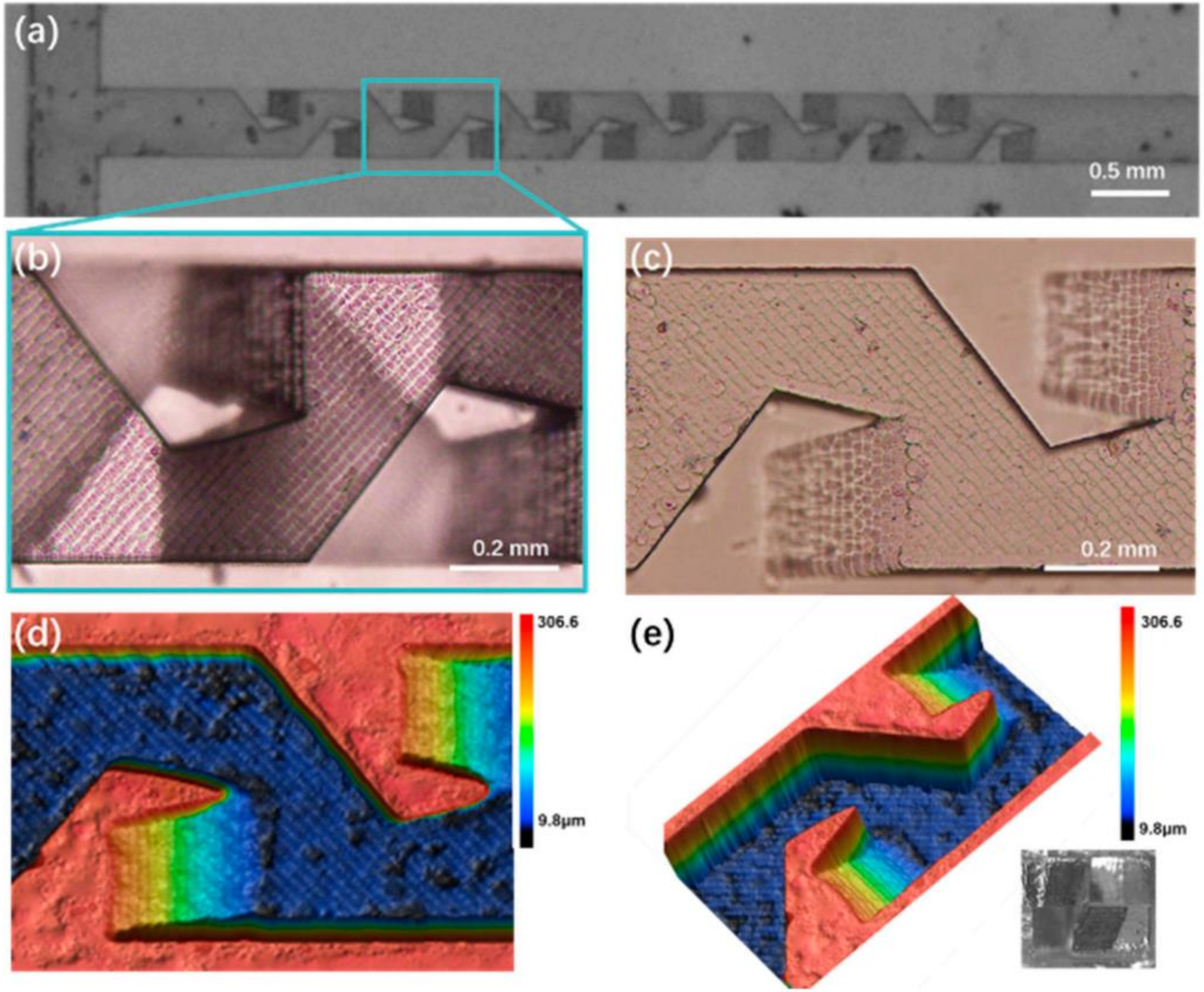
Performance comparison in 1D and 3D microchannels



Mixing performances in 1D and 3D microchannels
(Left: modeling; right: experiment)

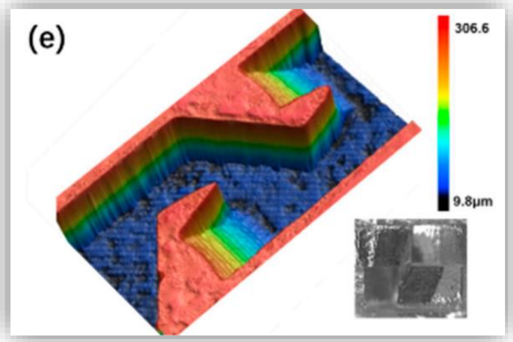
Jia Qi, et al., Micromach. **11**, 213 (2020).

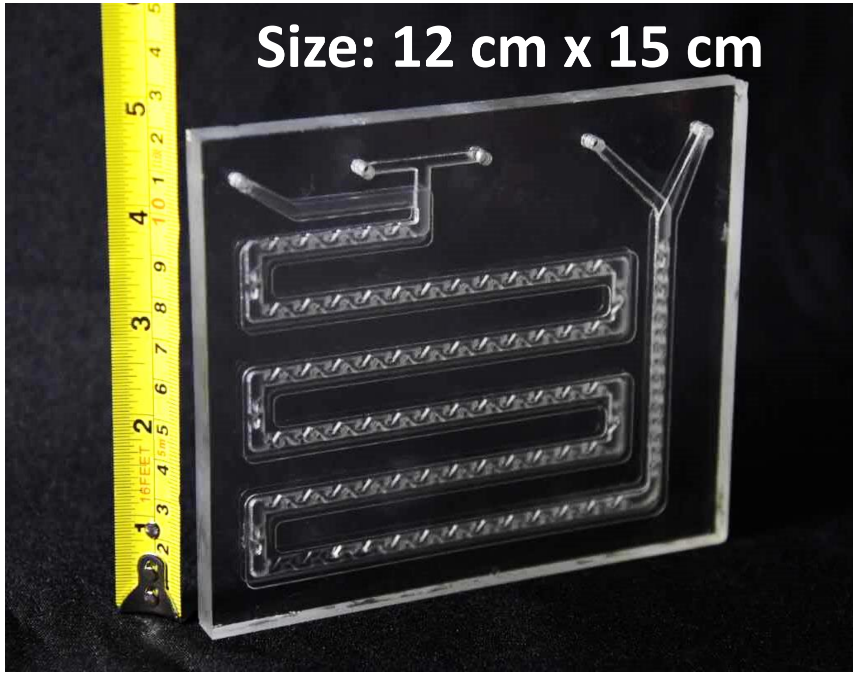
Interior 3D structure inside microreactor



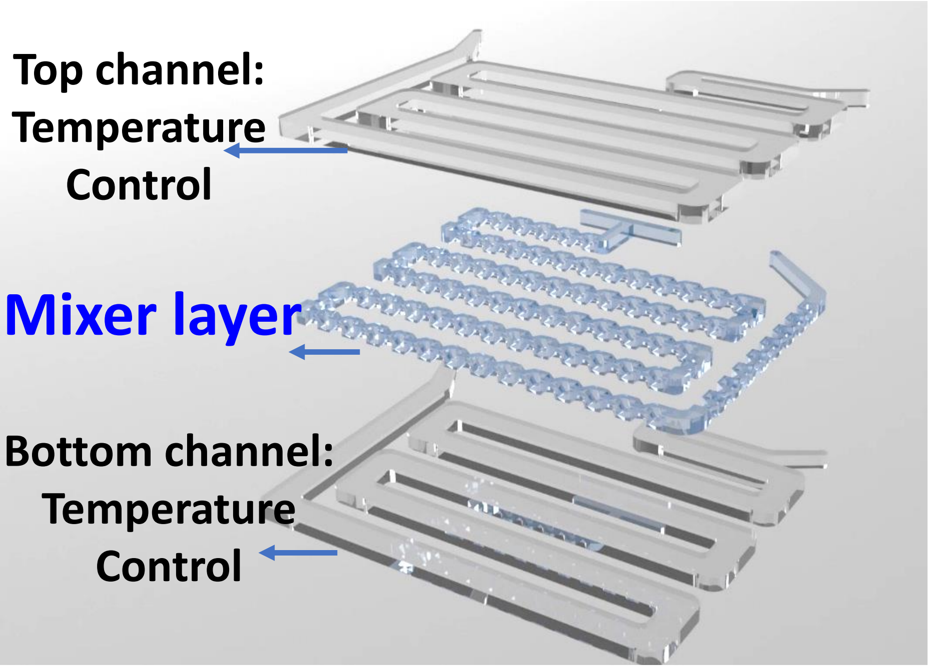
Jia Qi, et al., Micromach. **11**, 213 (2020).

Industrial scale 3D microreactor





Size: 12 cm x 15 cm



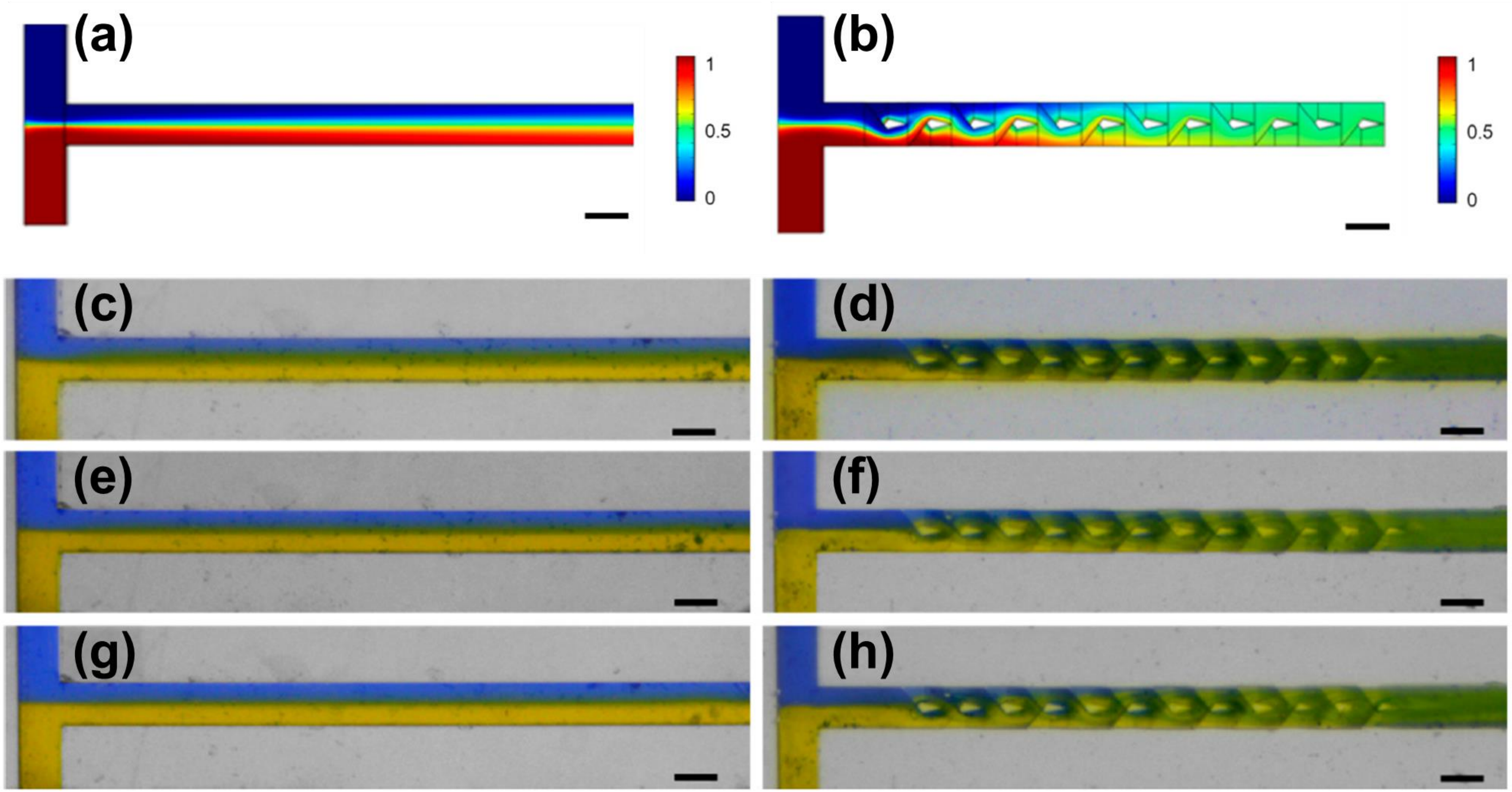
Top channel: Temperature Control

Mixer layer

Bottom channel: Temperature Control

Mixing effects at various flow rate

Straight microchannel | **3D micromixer**



Flow rate

1 mL/min

2 mL/min

6 mL/min

Conclusions

We have demonstrated

1. Ultra-high Q ($>10^8$) microresonators in lithium niobate for generating novel nonlinear optical effects;
2. On-chip active lithium niobate devices including a micro-disk laser and a waveguide amplifier;
3. A 3D microfluidic chemical reactor with high throughput fabricated in a cost-effective fashion.

The results cannot be achieved without the recent advances in ultrafast laser processing!

Thank you !