SPIE. PHOTONICS WEST
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Ultra-low loss lithium niobate nanophotonics

Ya Cheng

Shanghai Institute of Optics and Fine Mechanics
East China Normal University

XXL - THE EXTREME OPTOELECTROMECHANIX LAB

2020. 02. 04

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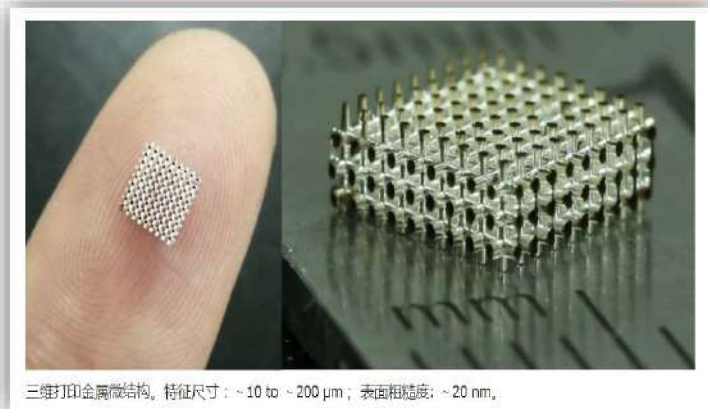
1. Who we are ?

华东师范大学极端光机电实验室 - THE EXTREME OPTOELECTROMECHANIX LAB

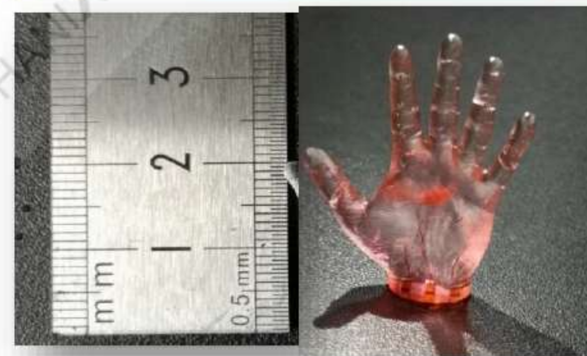
Focusing on laser printing of 3D microstructures

3D metal microprinting

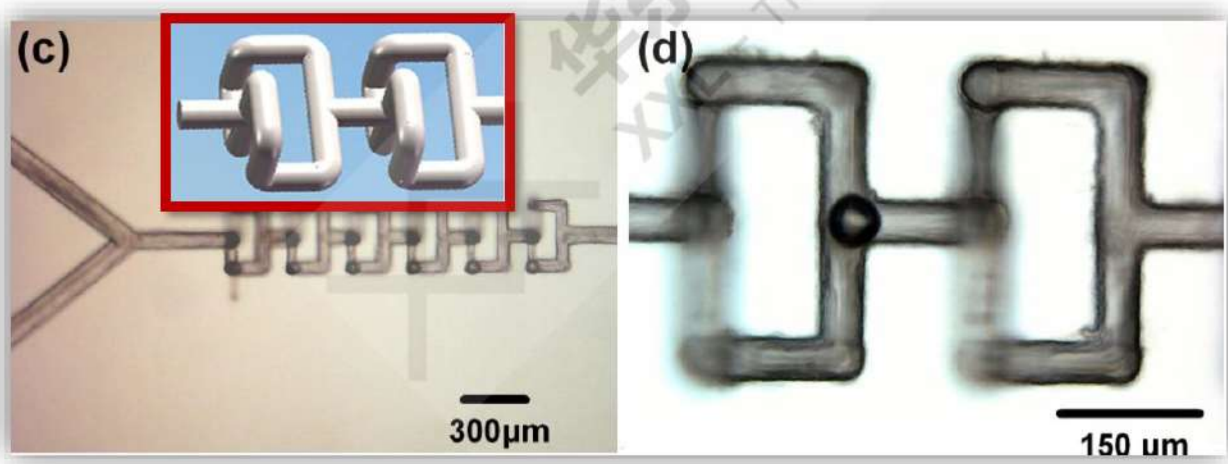


Ultrafine 3D printing (glass & polymer, world record)

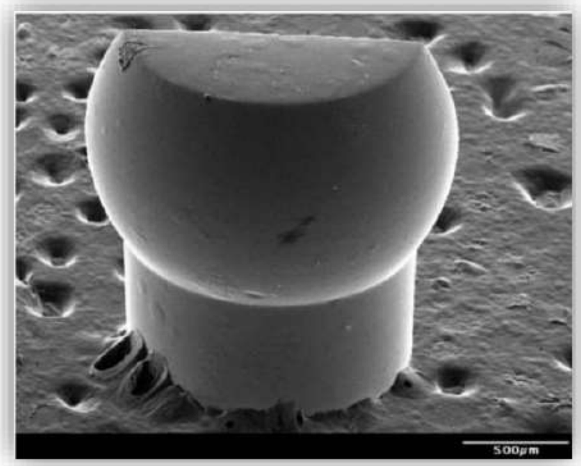
Bio-mimicking structure



3D microfluidics (world record in terms of ratio of channel length and diameter)

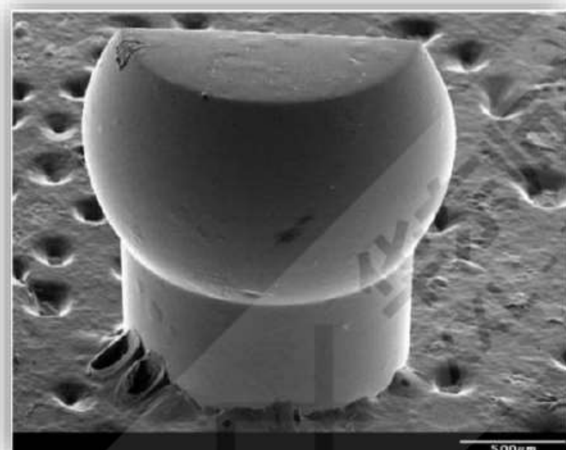


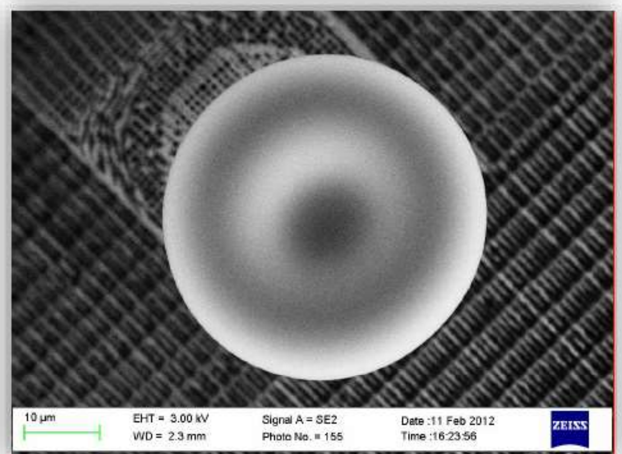
Laser printed microoptical lens



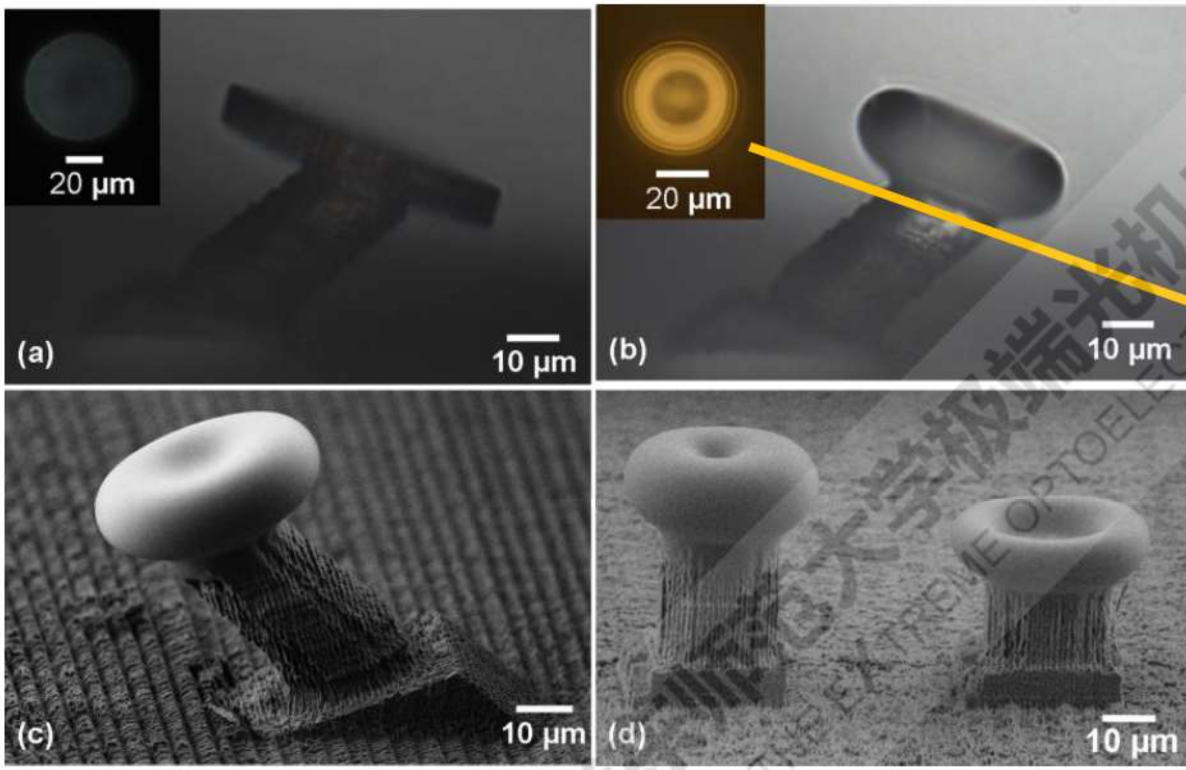
2. Extend to microresonators

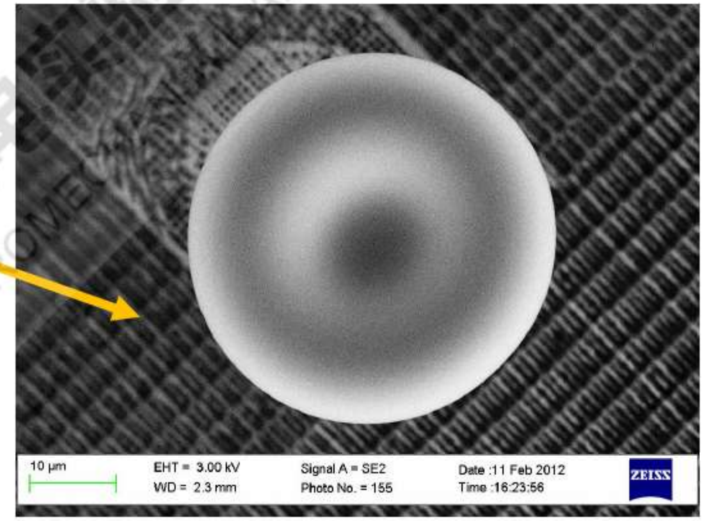
(Beginning in 2011)





3D microresonators fabricated in glass



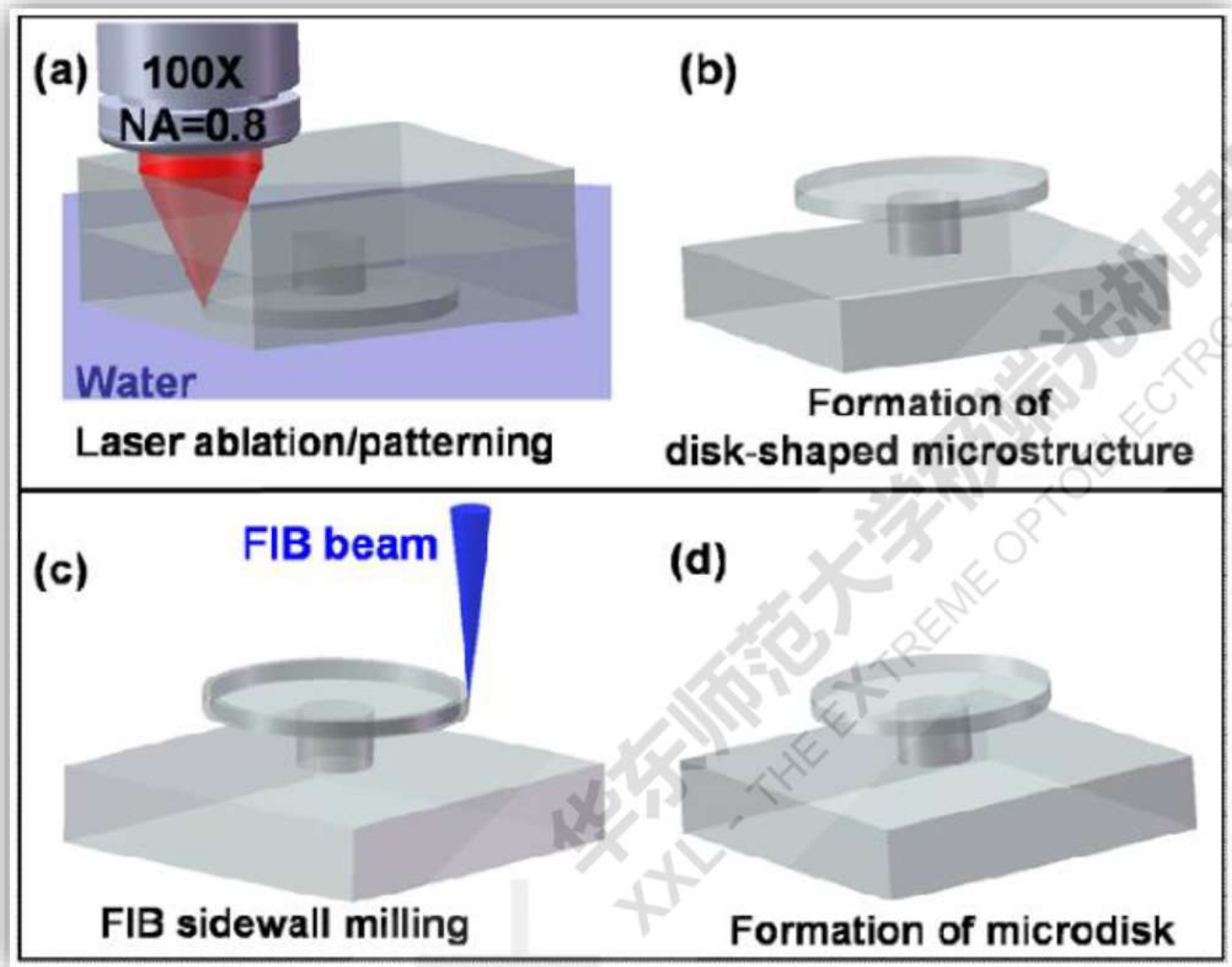


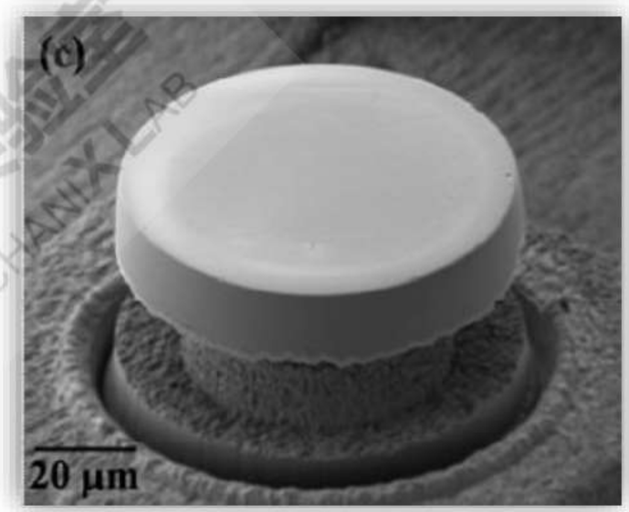
Q factor: ~7*10^7

Optical microscope images of a tilted fused silica microdisk (a) before and (b) after CO_2 laser annealing. SEM images of (c) the titled resonator, and (d) pair of resonators of different heights.

J. Lin, et al, Opt. Express 20, 10212 (2012)

Microresonator in a bulk crystal - CaF_2





J. Lin, et al, Appl. Phys. A 116, 2019 (2014)

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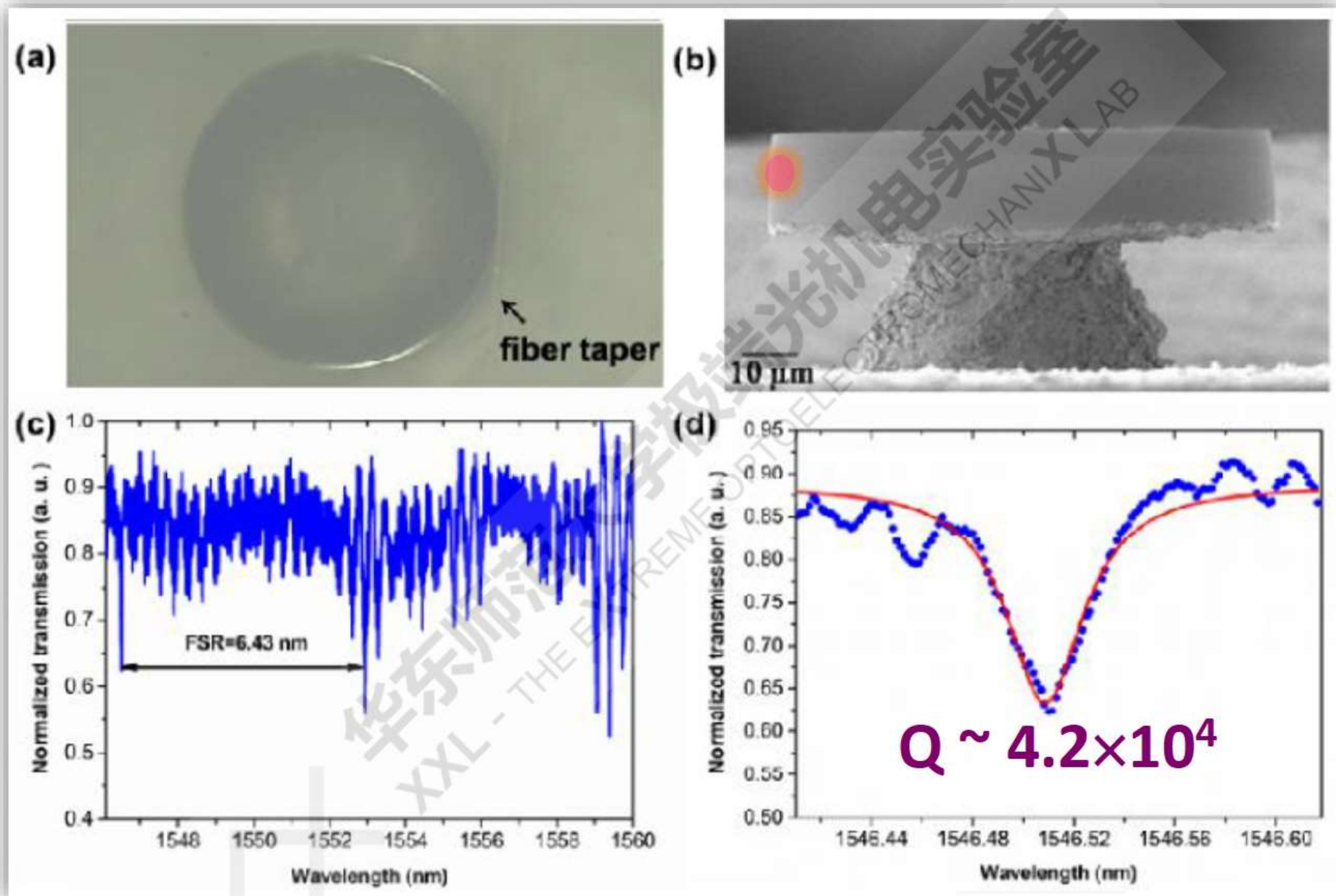
Measurement of the Q-factor



J. Lin, et al, Appl. Phys. A 116, 2019 (2014)

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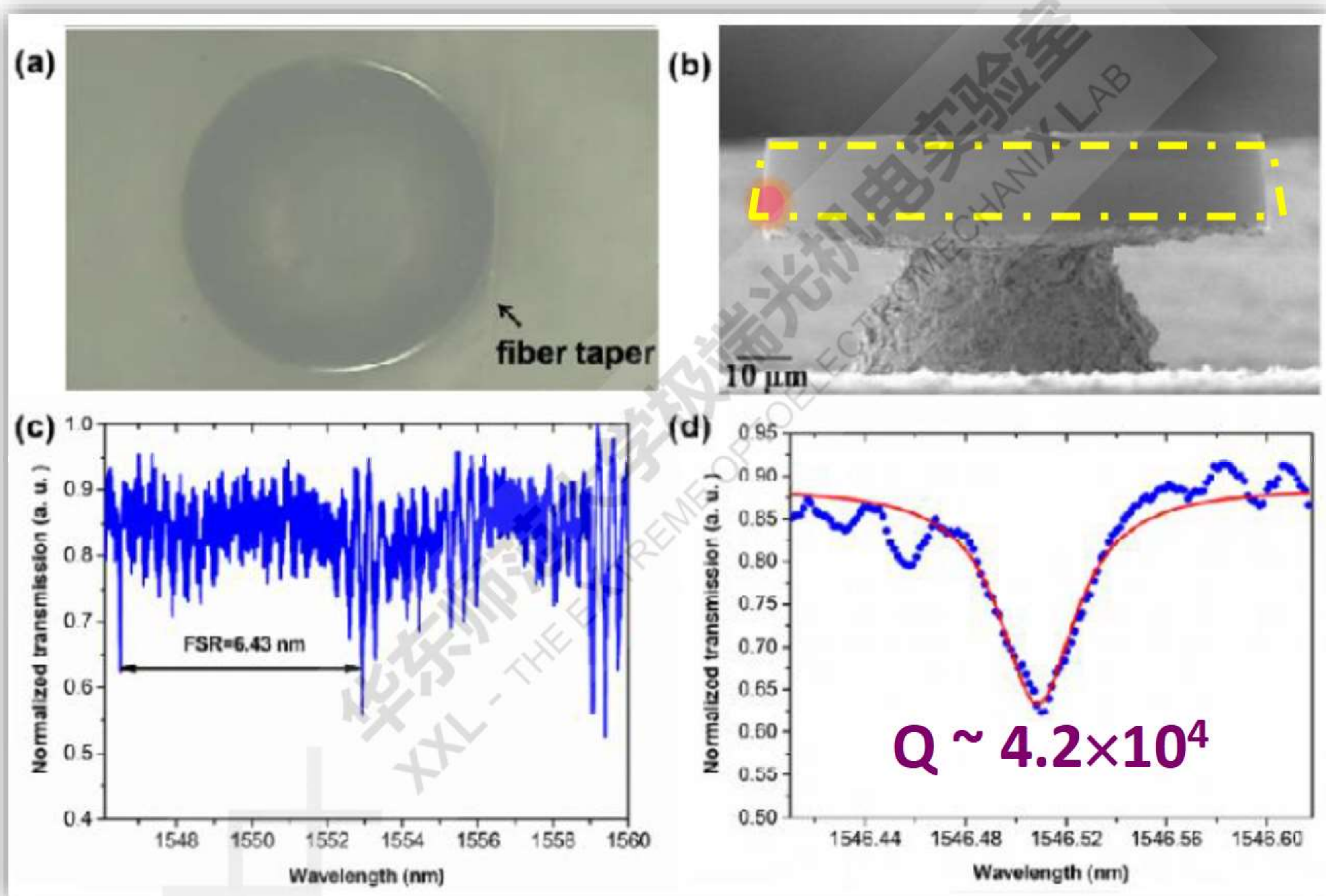

J. Lin, et al, Appl. Phys. A 116, 2019 (2014)

3. High-Q crystalline resonators

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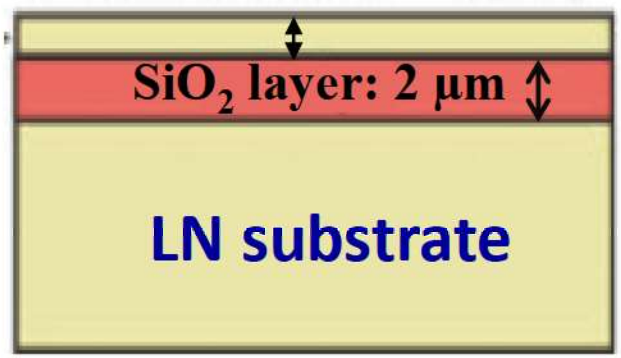
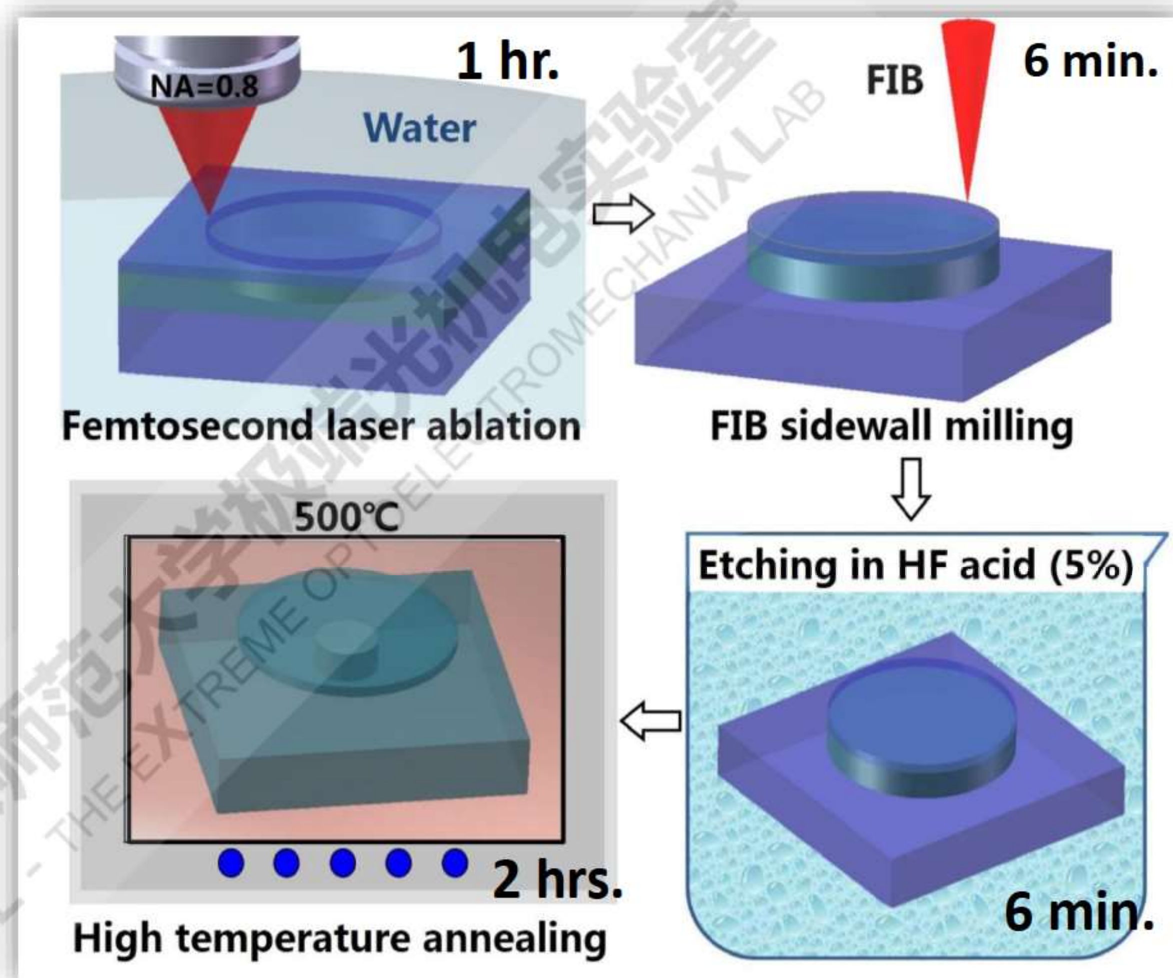
High-Q microresonators on lithium niobate (LN)

LN thin film: 700 nm, Z-cut



Laser Photon Rev.
6, 488 (2012)



Fabrication procedure

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

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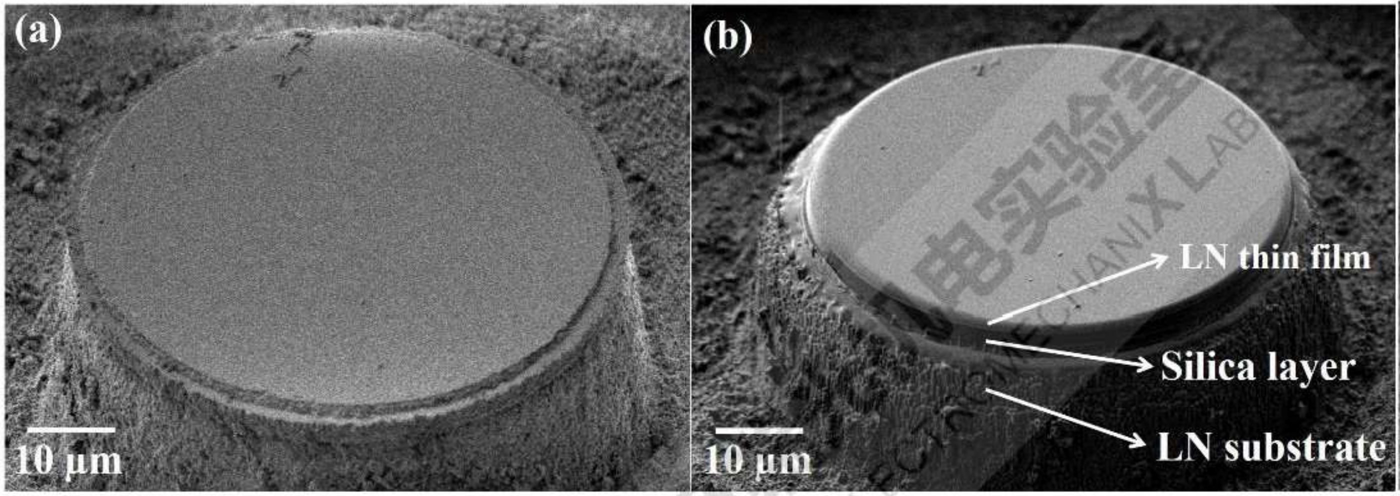
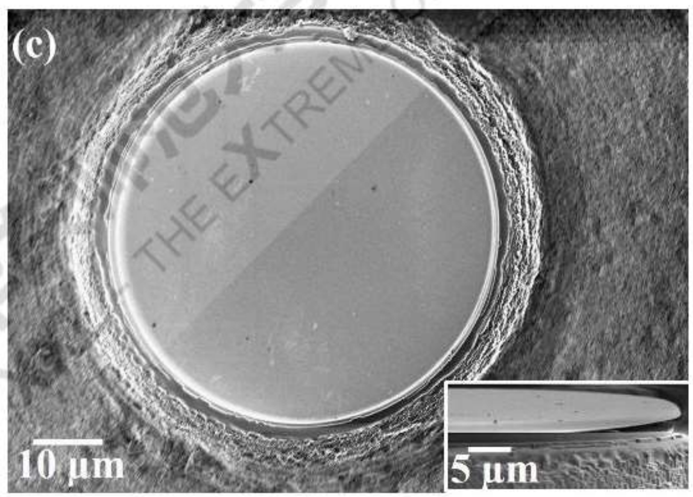
High-Q microresonators on lithium niobate (LN)



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

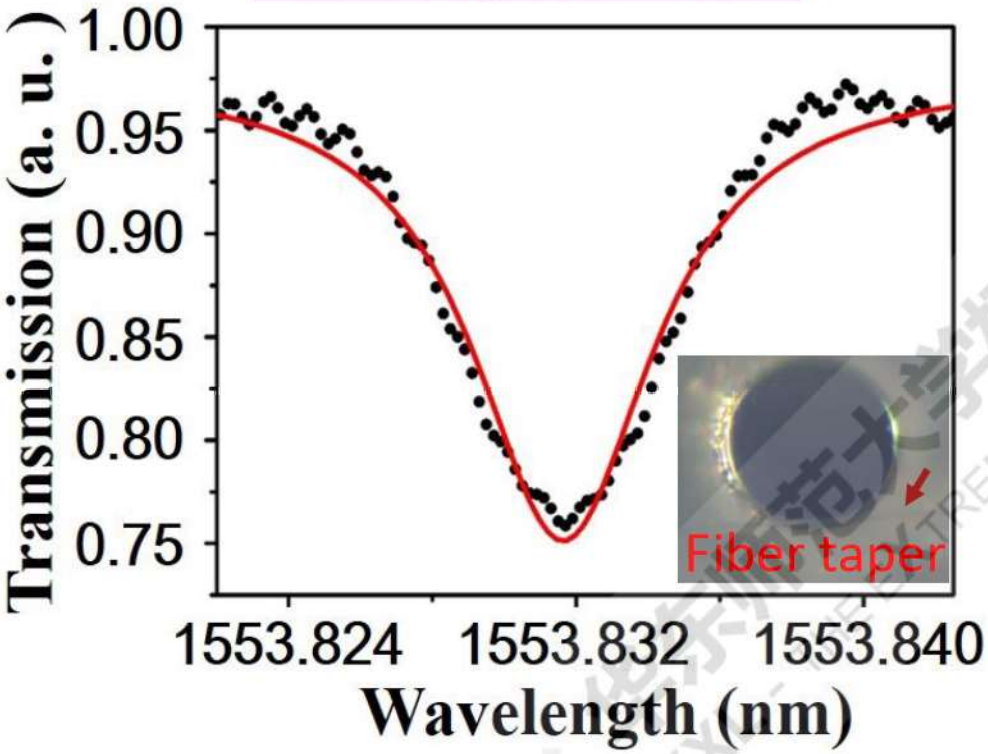


(c) SEM image (top view) of the microresonator, inset: side view.

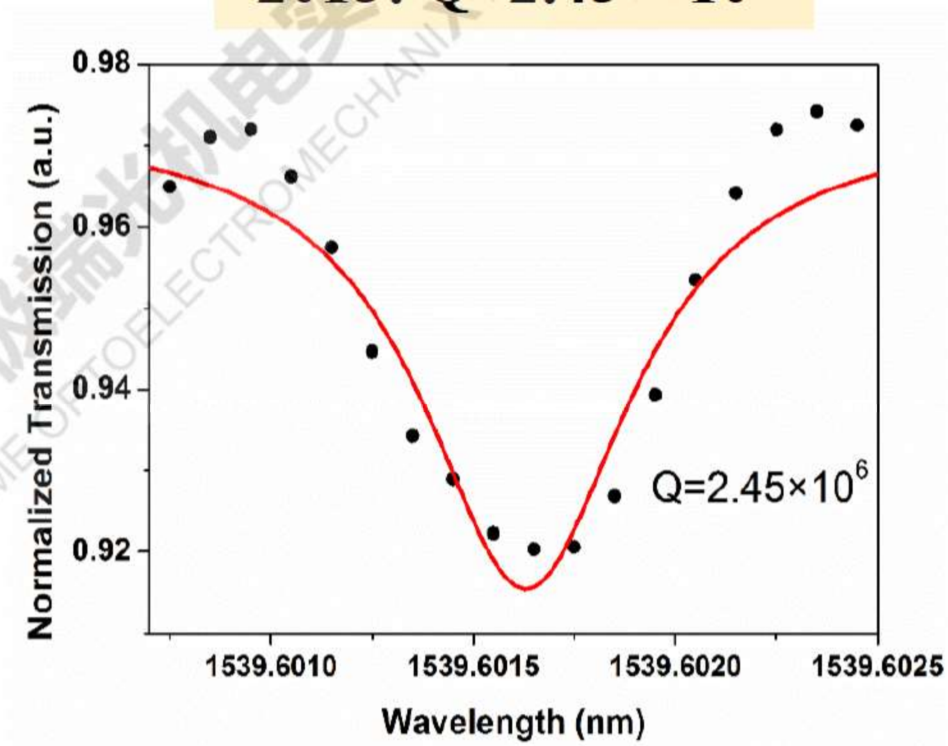
J. Lin, et al, arXiv:1405.6473 (2014); Sci. Rep. 5, 8072 (2015)

Q-factor measurements

2014: Q~2.5×10⁵

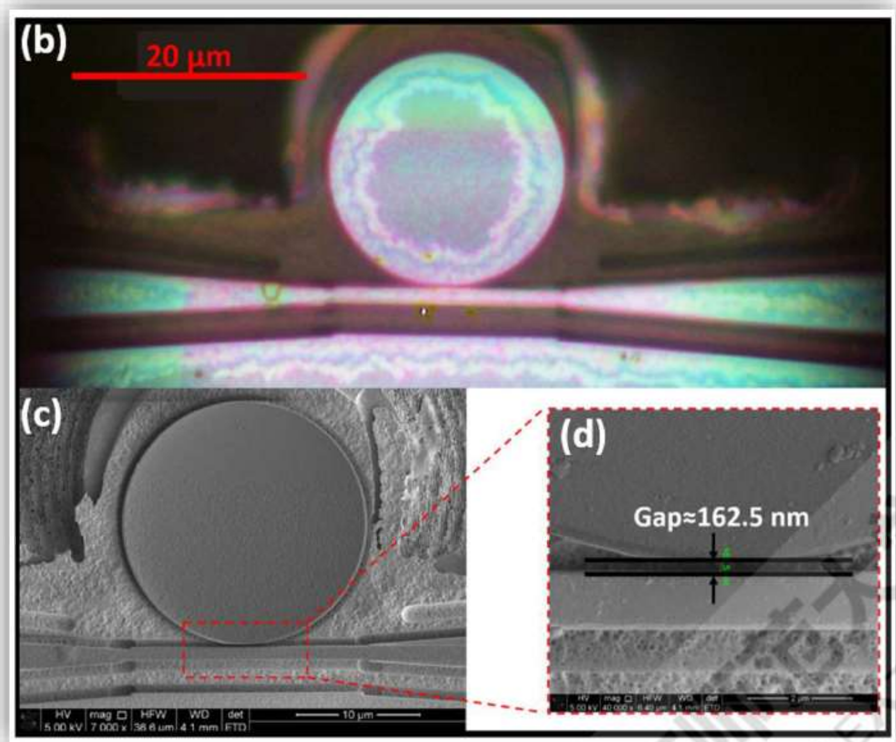


2015: Q=2.45×10⁶

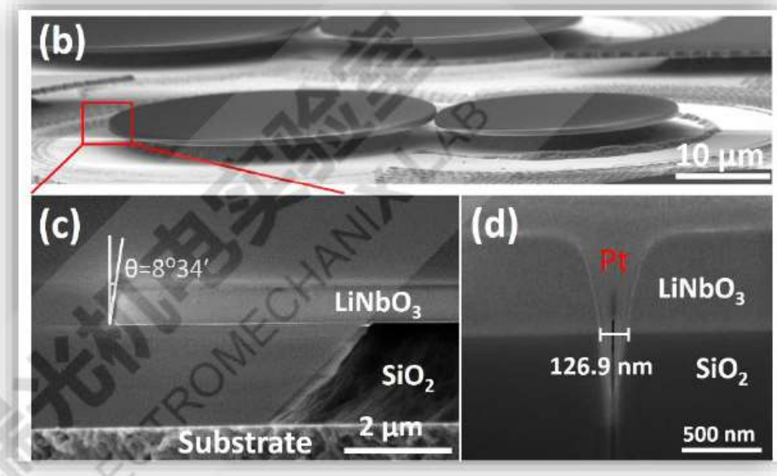


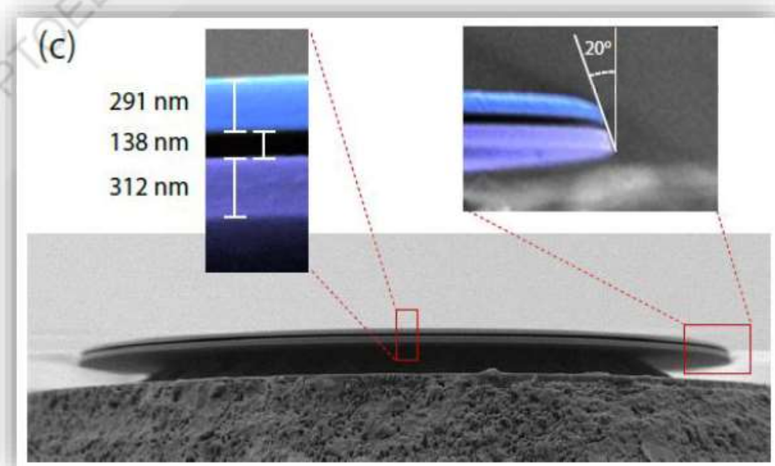
Q factor has been improved by nearly an order of magnitude with the better FIB parameters!

Enabling straightforward on-chip integration



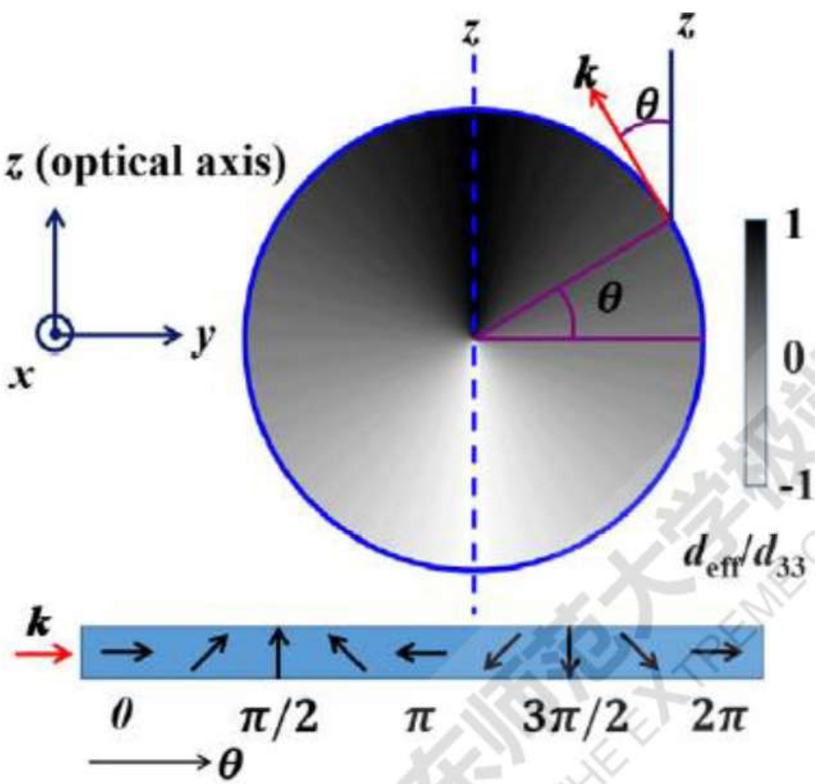
Z. Fang et al, integration between a disk and an optical waveguide

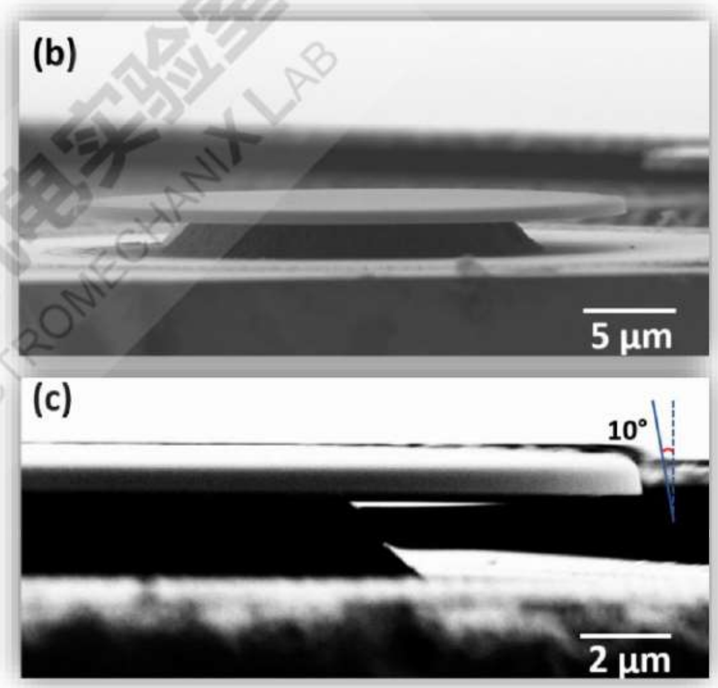




M. Wang, Z. Fang et al, integration between two disks

Nonlinear optics: phase-matching



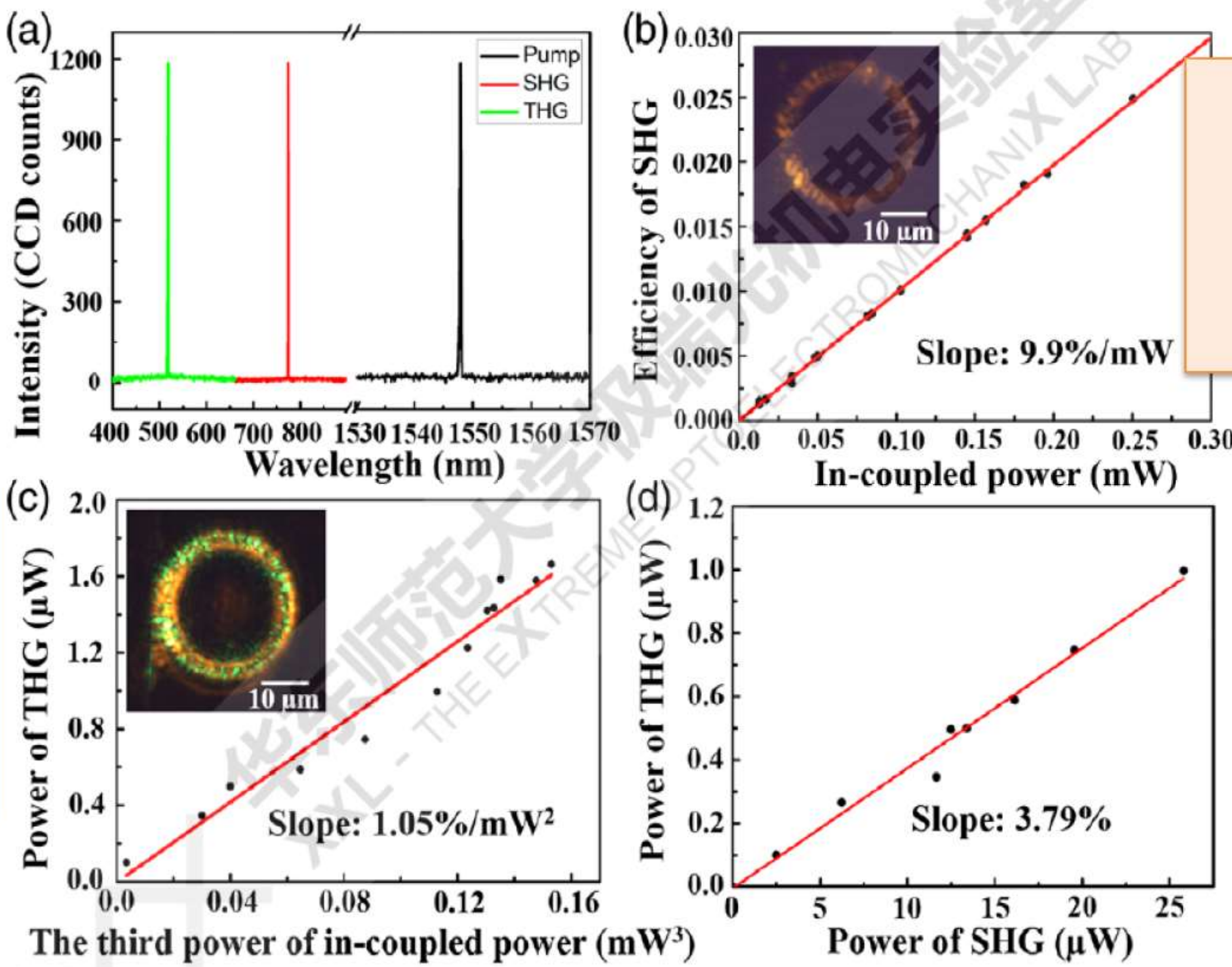


The second-order nonlinear coefficient is featured with a periodically varying refractive index which provides transient phase matching (similar to QPM in PPLN) for a broadband spectrum.

$$d_{\mathrm{eff}} = -d_{22}\cos^3\theta + 3d_{31}\cos^2\theta\sin\theta + d_{33}\sin^3\theta$$

J. Lin,et al, **Phys. Rev. Lett.** 122, 173903 (2019)

Phase-matched SHG and cascaded THG



Normalized conversion efficiency of **SHG : 9.9%/mW**

Normalized conversion efficiency of **THG : 1.05%/mW²**

For the pump laser wavelength in the range of1530 and 1570 nm, strong second-harmonic and third-harmonic signals appear at several wavelengths.

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4. Low loss photonics

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Issues

with focused ion beam:

- Too small (sample size);
- Too low (throughput);
- Too high (sidewall roughness): > 1 nm

Can we overcome these issues?

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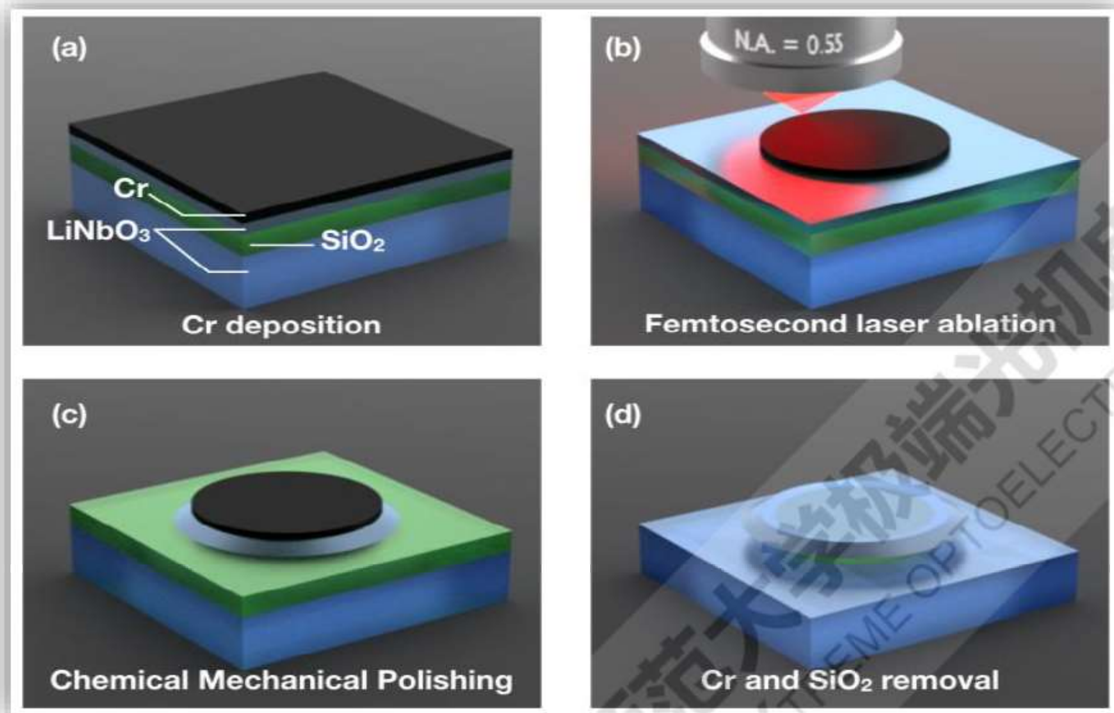
Ion-free fabrication of high Q microresonators

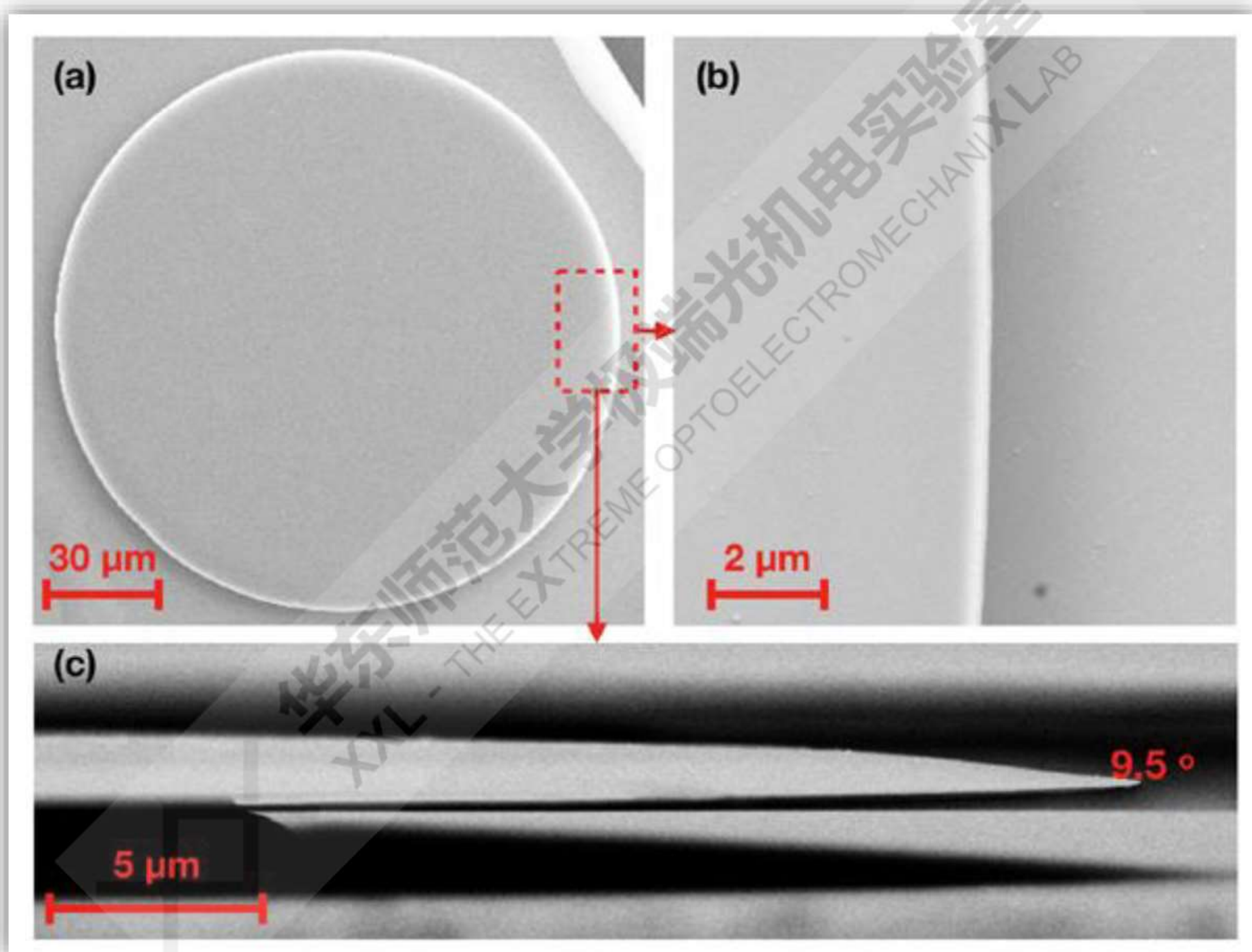


Y. Cheng, et al,
Patent No.:
201810407783.3

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. **(LNOI remains intact!)** **(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.

SEM images of the fabricated microresonators



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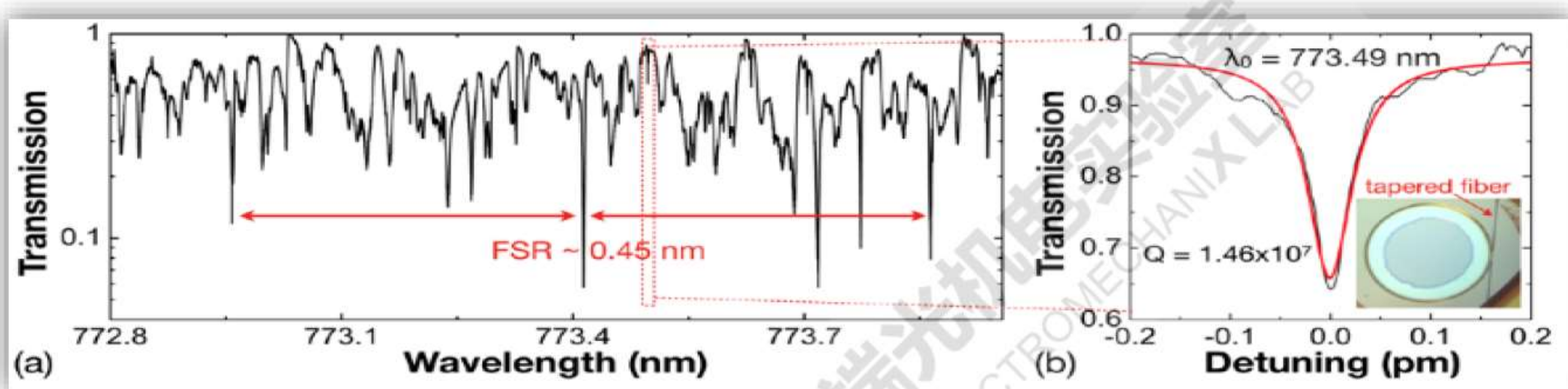
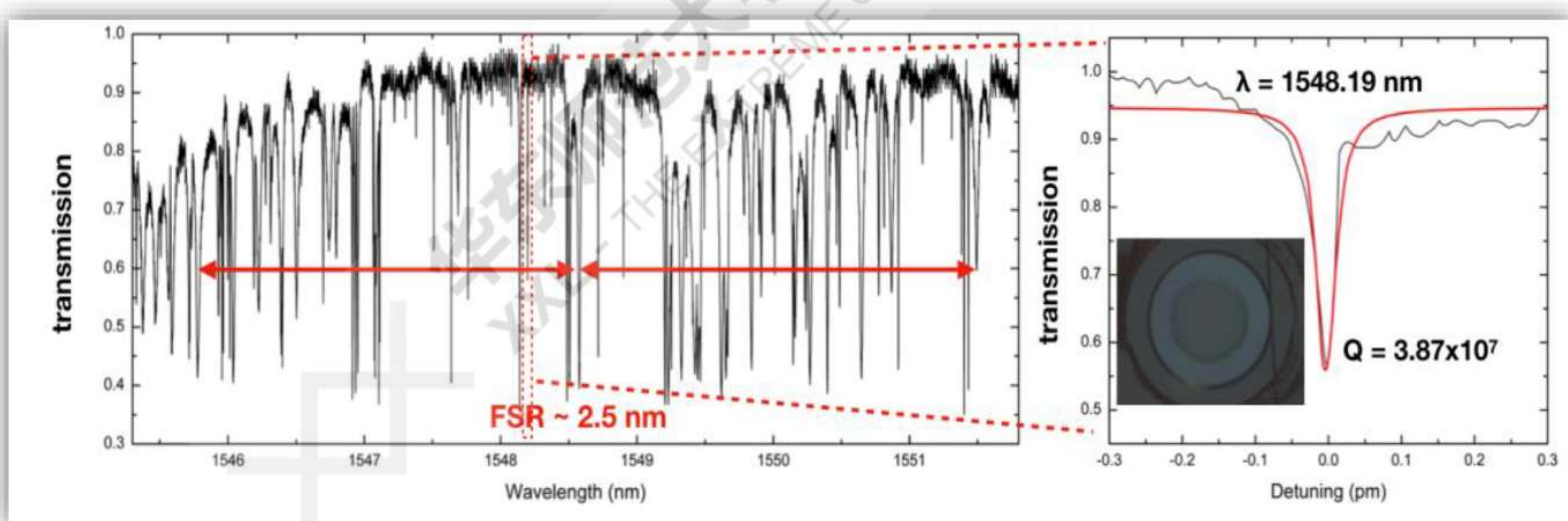
R. Wu, et al; Optics Letters 43, 4116 (2018)

Measurement of Q factors: > 10^7



Q = 1.46×10^7 @ 773 nm （total loss ~0.01dB/cm）



Q = 3.87×10^7 @ 1548 nm (total loss ~4*10^{-3} dB/cm)

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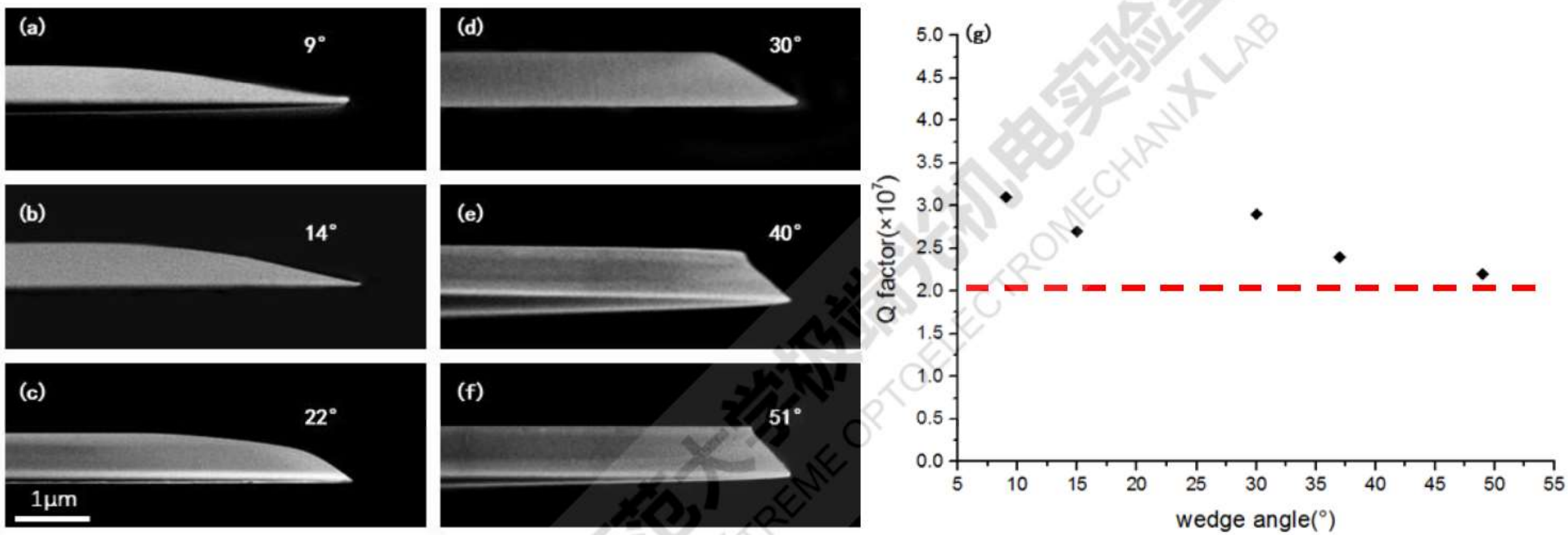
Optimization of the Q factor and wedge angle



The wedge angle tunable from 9° to 51° which is critical for nonlinear optical applications as the dispersion curve in the microdisks is a function of the wedge angle.

J. Zhang, et al., Nanomaterials 9, 1218 (2019)

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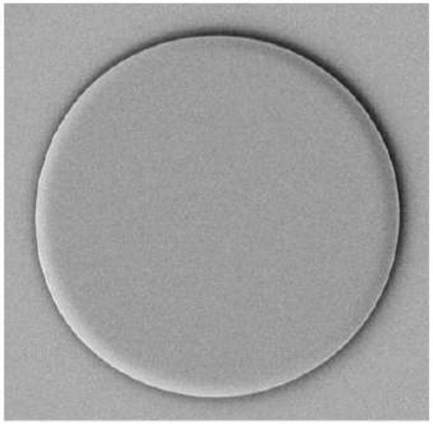
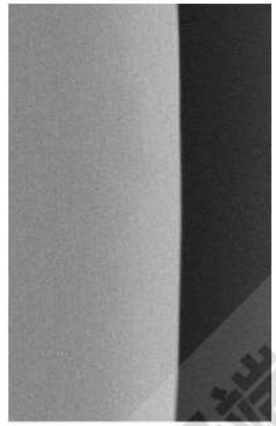
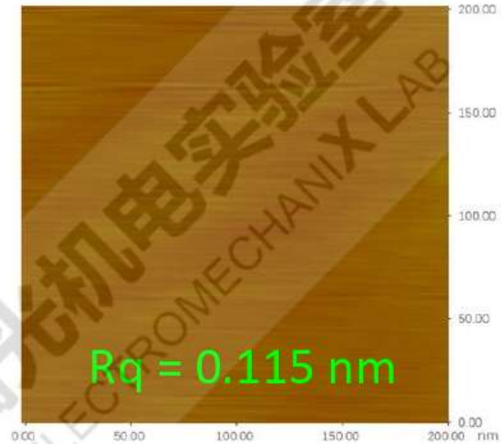
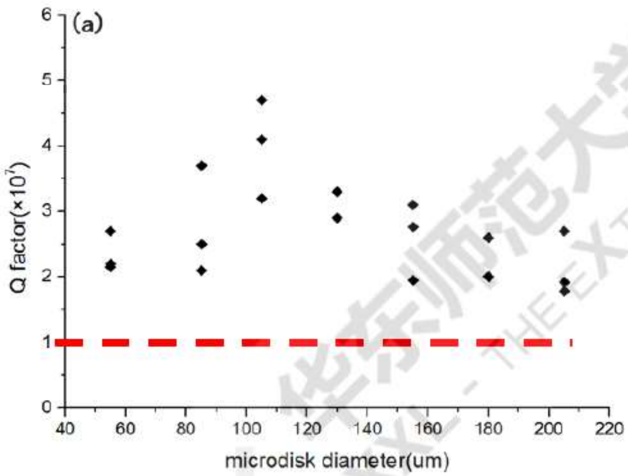
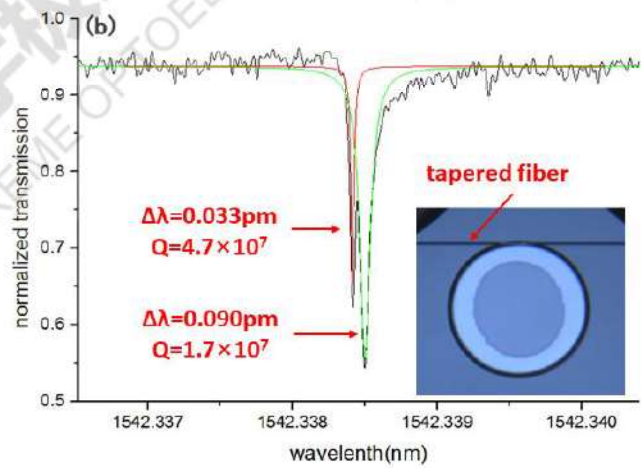
Optimization of the Q factor and wedge angle











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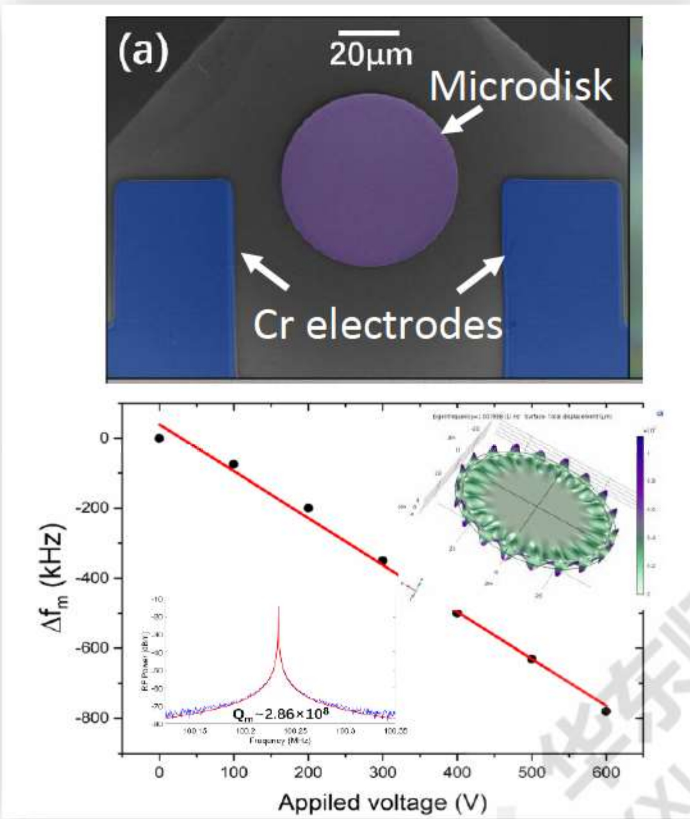
- The polished surface roughness ~ 0.115 nm.
- The highest Q factor of the microdisk $4.7*10^7$.

On-chip electro-optical tunable microresonator

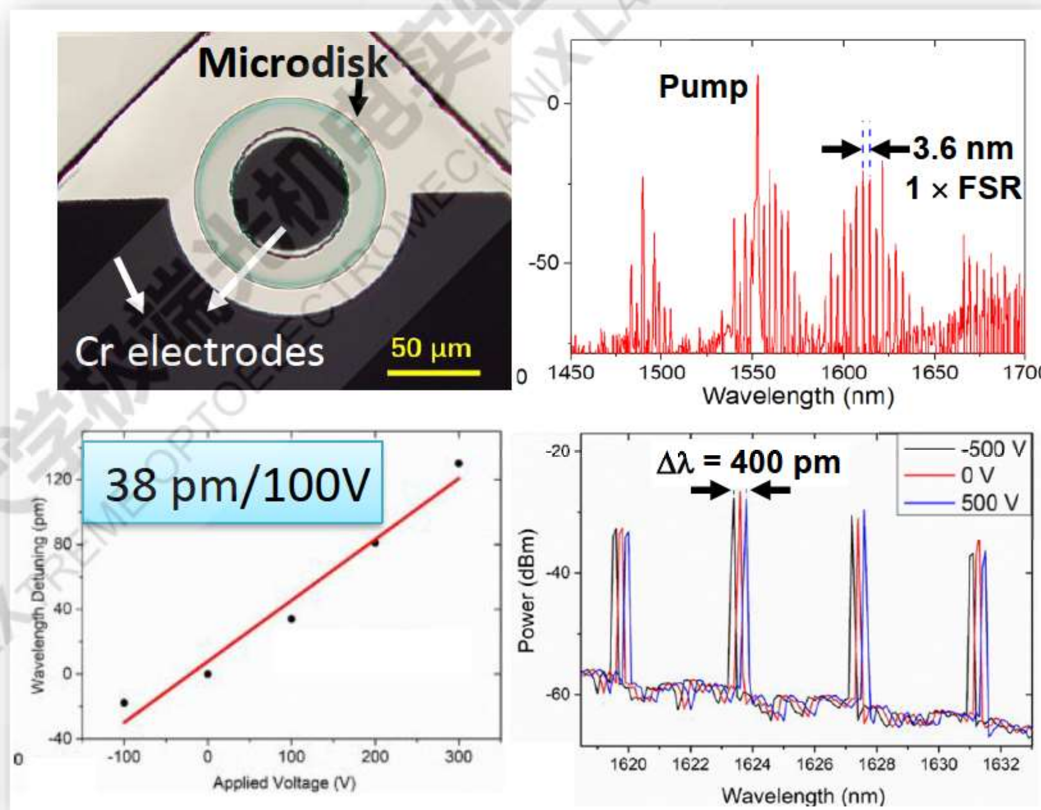
Tuning of an optical spring



- Optical quality: $Q \sim 10^7$
- Electro-mechanical tuning efficiency : -134 kHz/100V

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

Tuning of an optical frequency comb



- Raman-assisted FWM microcomb: spectral bandwidth of ~200 nm
- Eletrcal tuning efficiency ~38 pm/100V

Z. Fang, et al., Opt. Lett. 44, 5953 (2019)

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Low loss LN waveguides and beamsplitters

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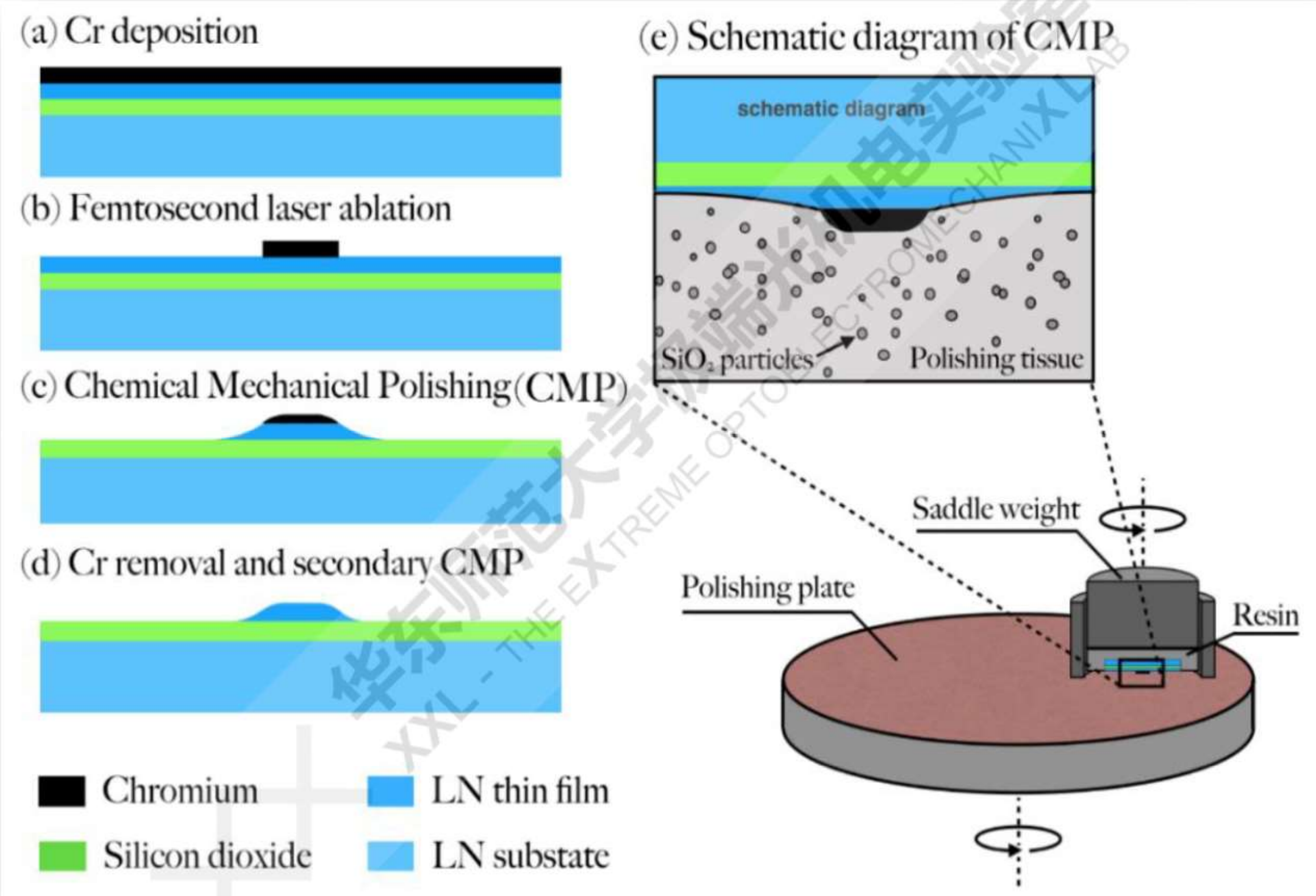
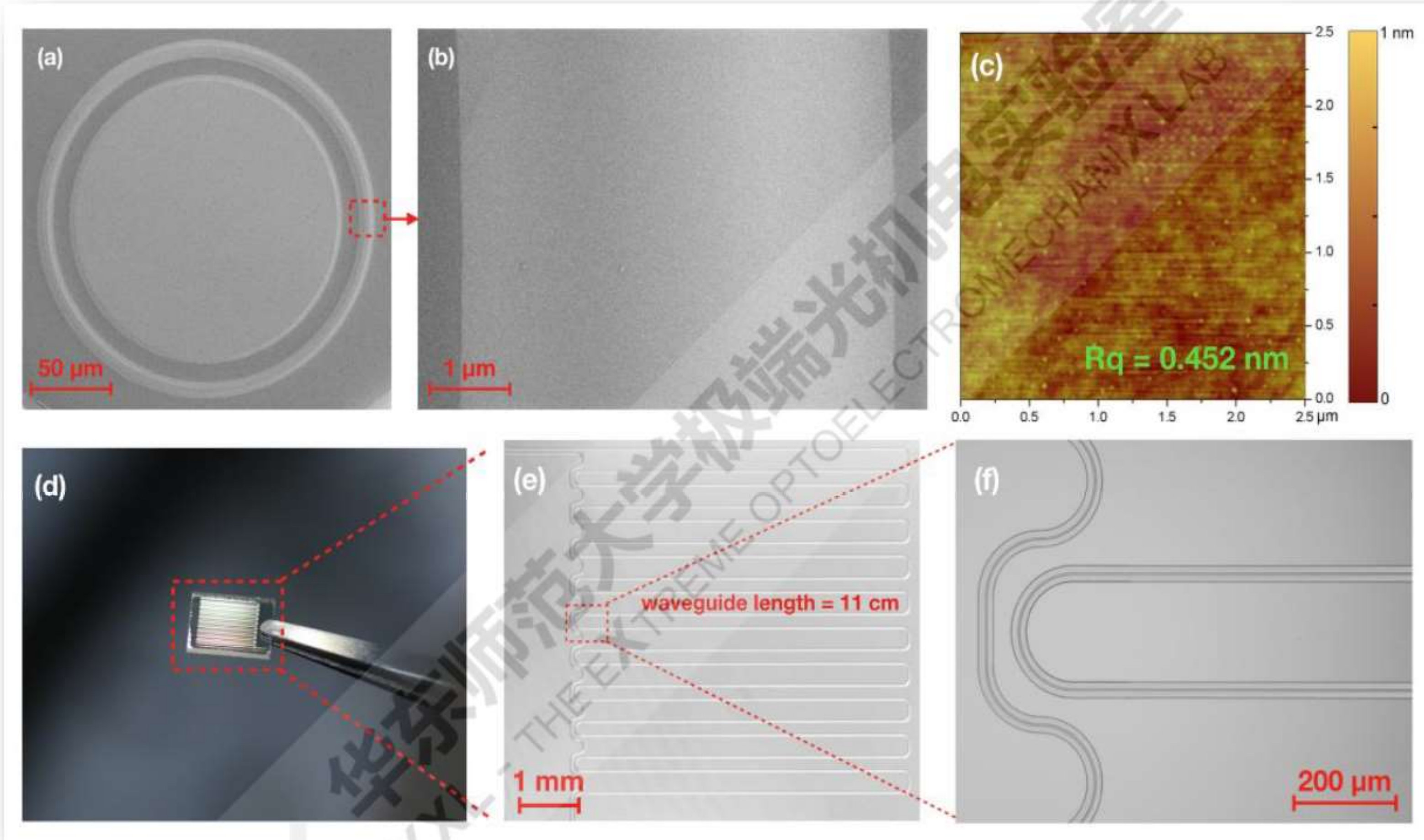
Fabrication of low-loss LN waveguides



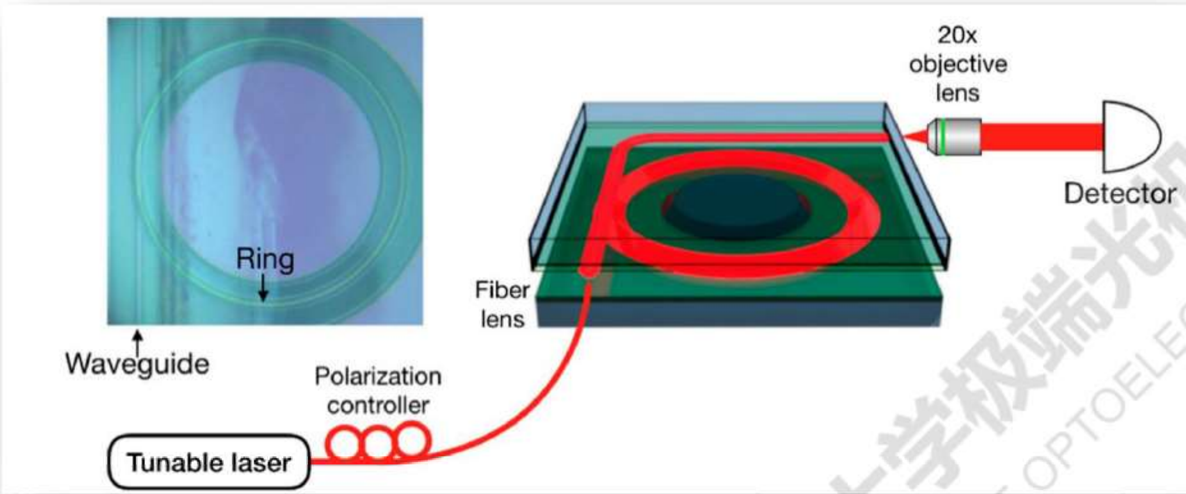
Ya Cheng et al. Patent No：201810407783.3
R. B. Wu, et al, Nanomaterials 8, 910 (2018)

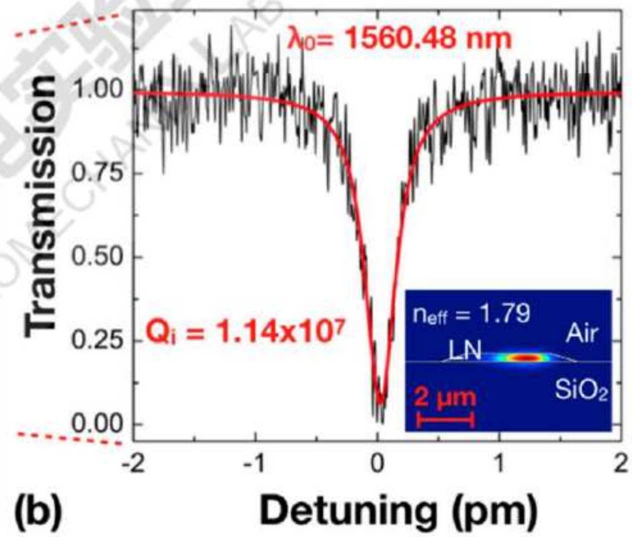
Fabrication of low-loss LN waveguides



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

Propagation loss measurement





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

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

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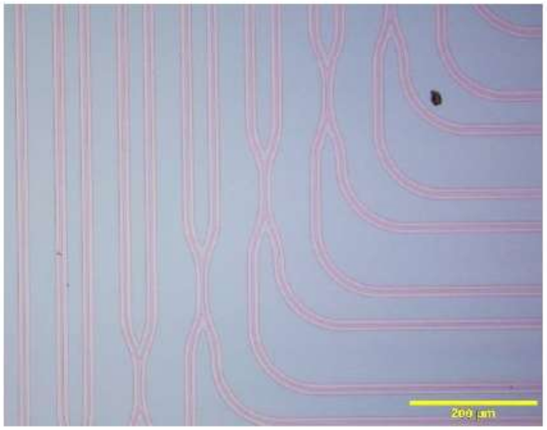
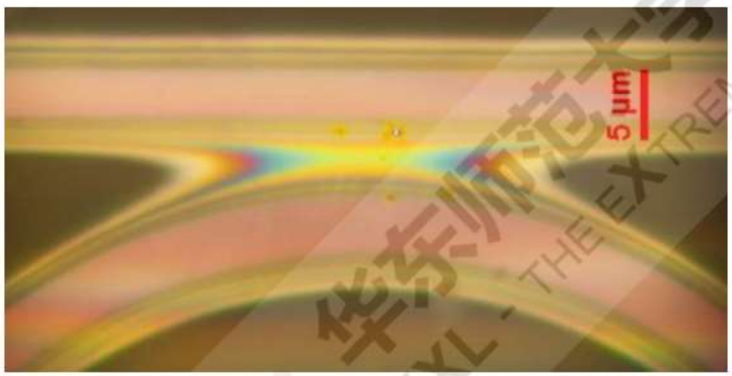
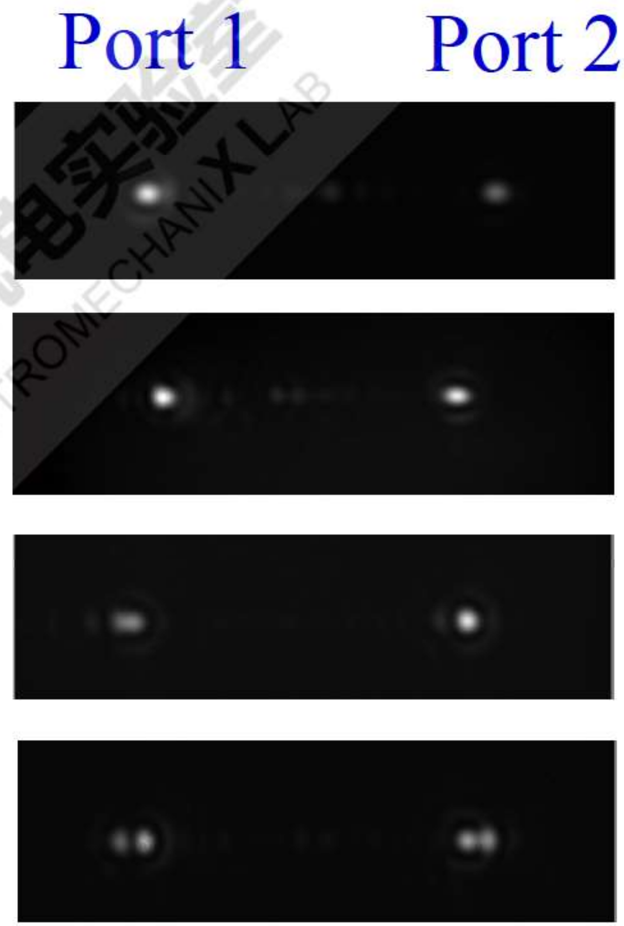
On-chip beamsplitters built by LN waveguides







Problems：multi-mode waveguide

Unstable splitting ratio

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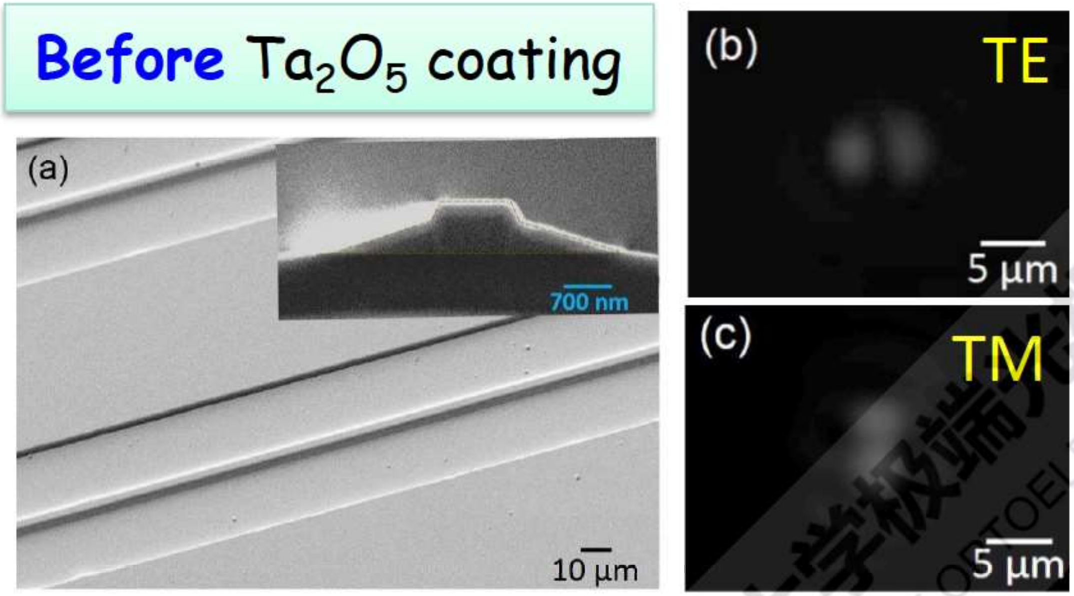
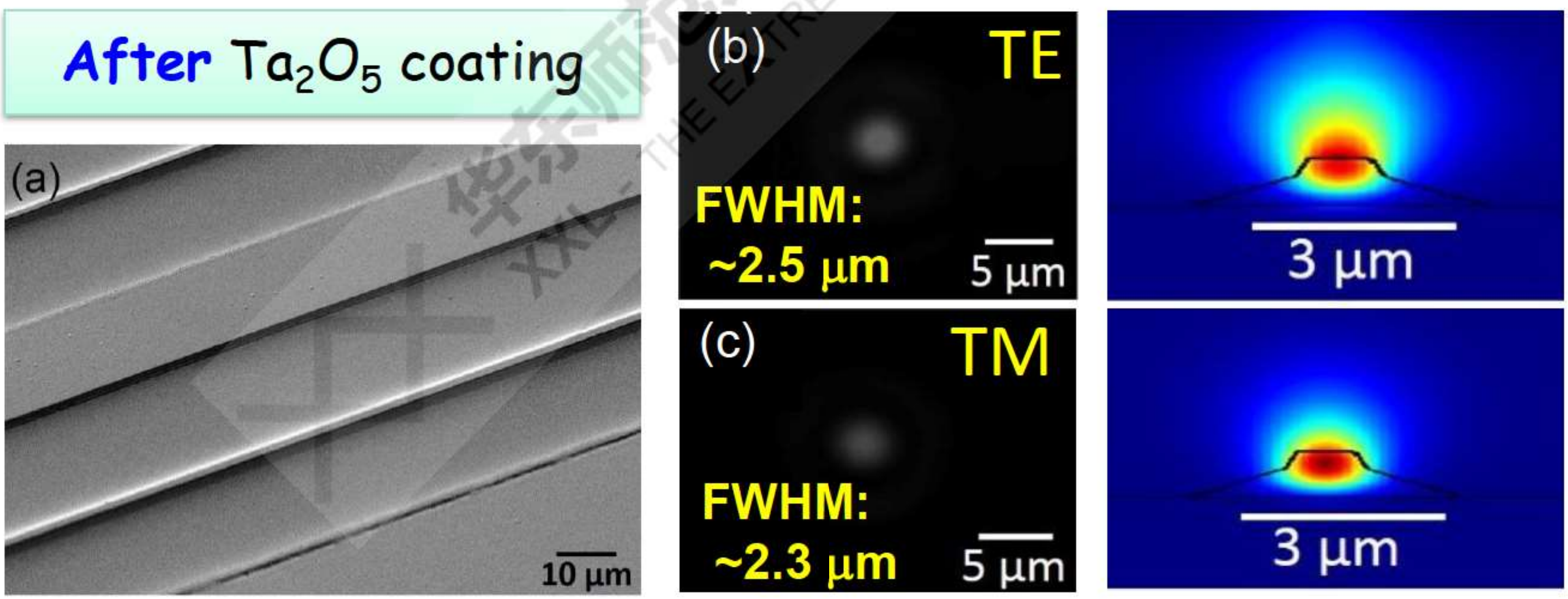
Fabrication of single mode LN waveguide

Before Ta_2O_5 coating



The waveguide supports single mode for both TE and TM mode after the Ta_2O_5 coating!

After Ta_2O_5 coating



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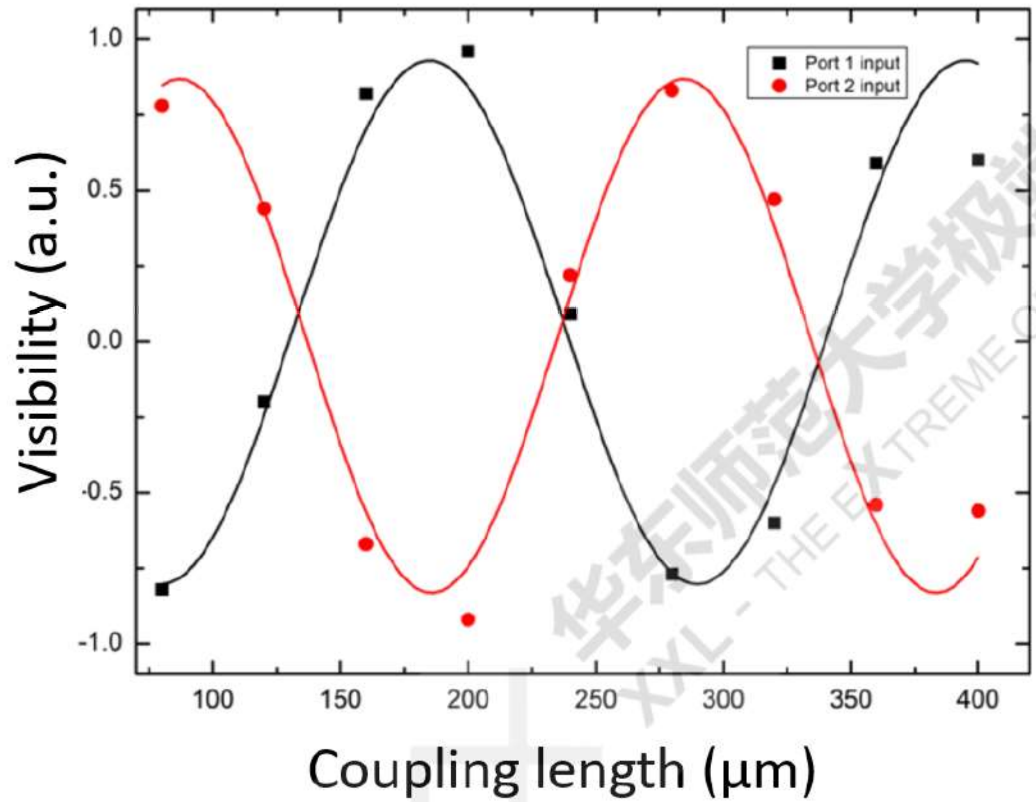
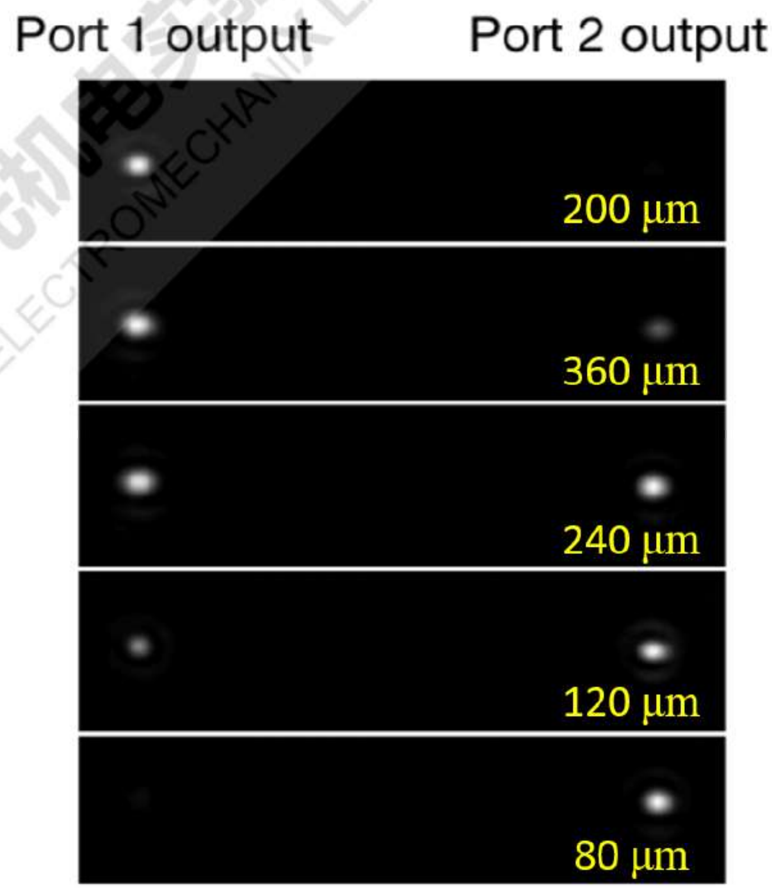
Beamsplitters built by single-mode LN waveguides

(a)

$$Visibility = \frac{I_1 - I_2}{I_1 + I_2}$$



(b)



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

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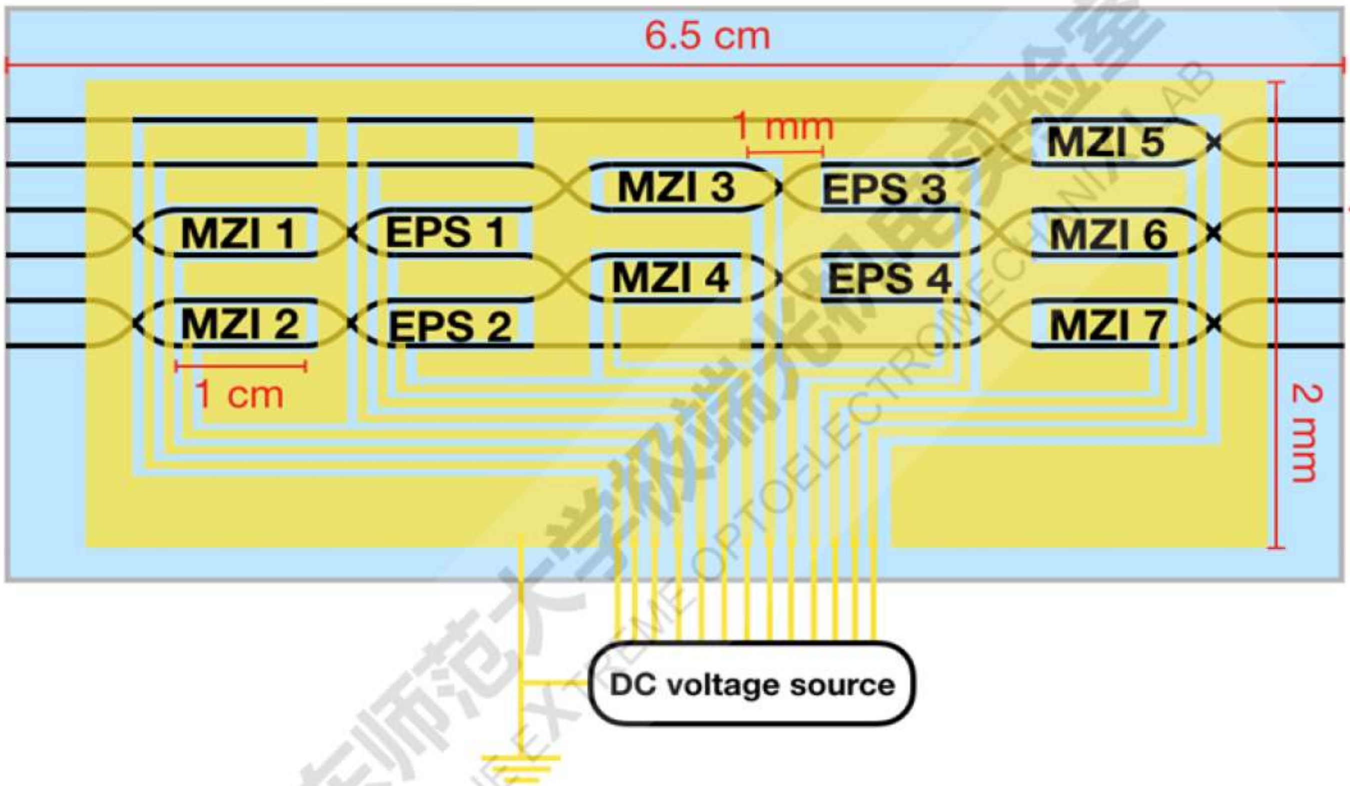
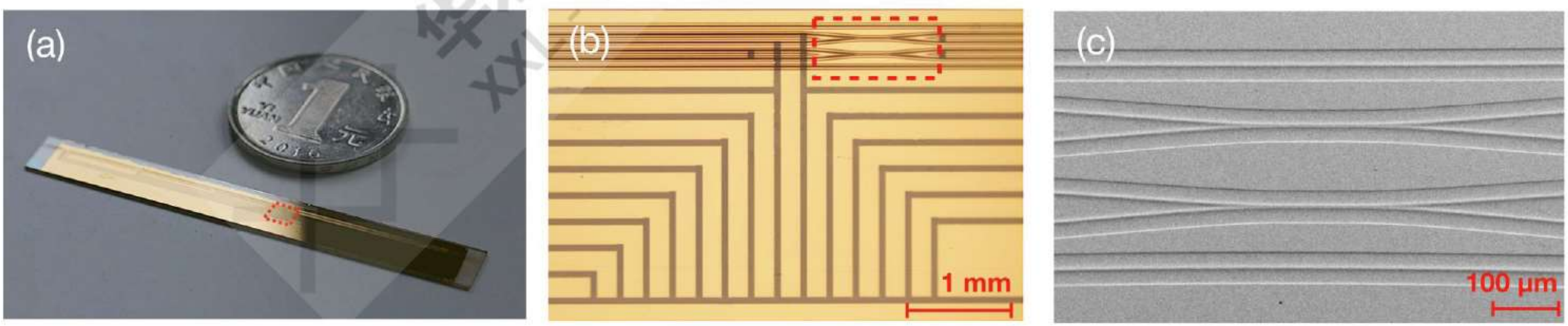
A multifunctional photonic chip on LNOI





R. Wu, et al., Optics Letters 44, 4698-4701 (2019).

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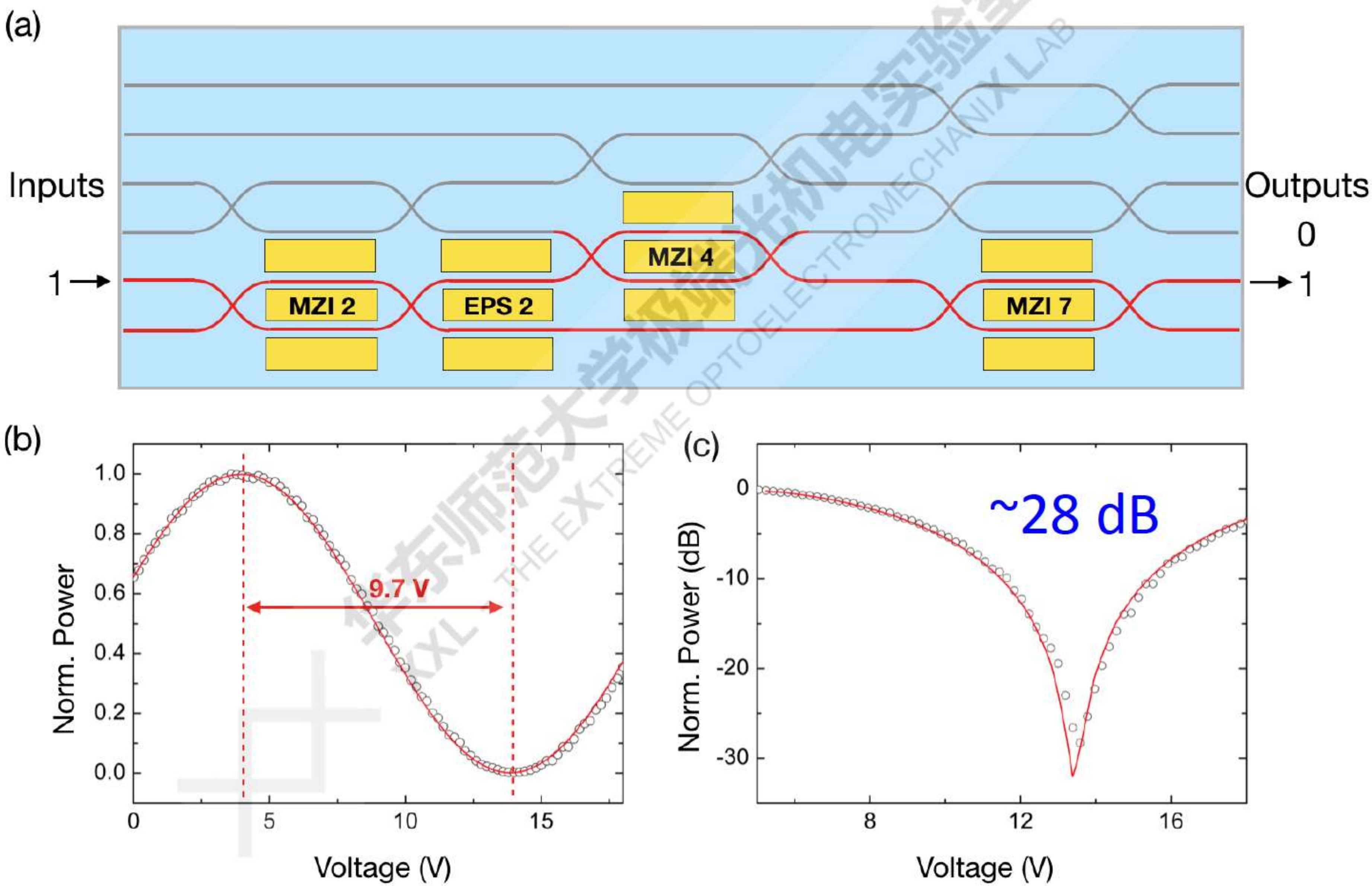
A perfect beamsplitter of tunable ratio



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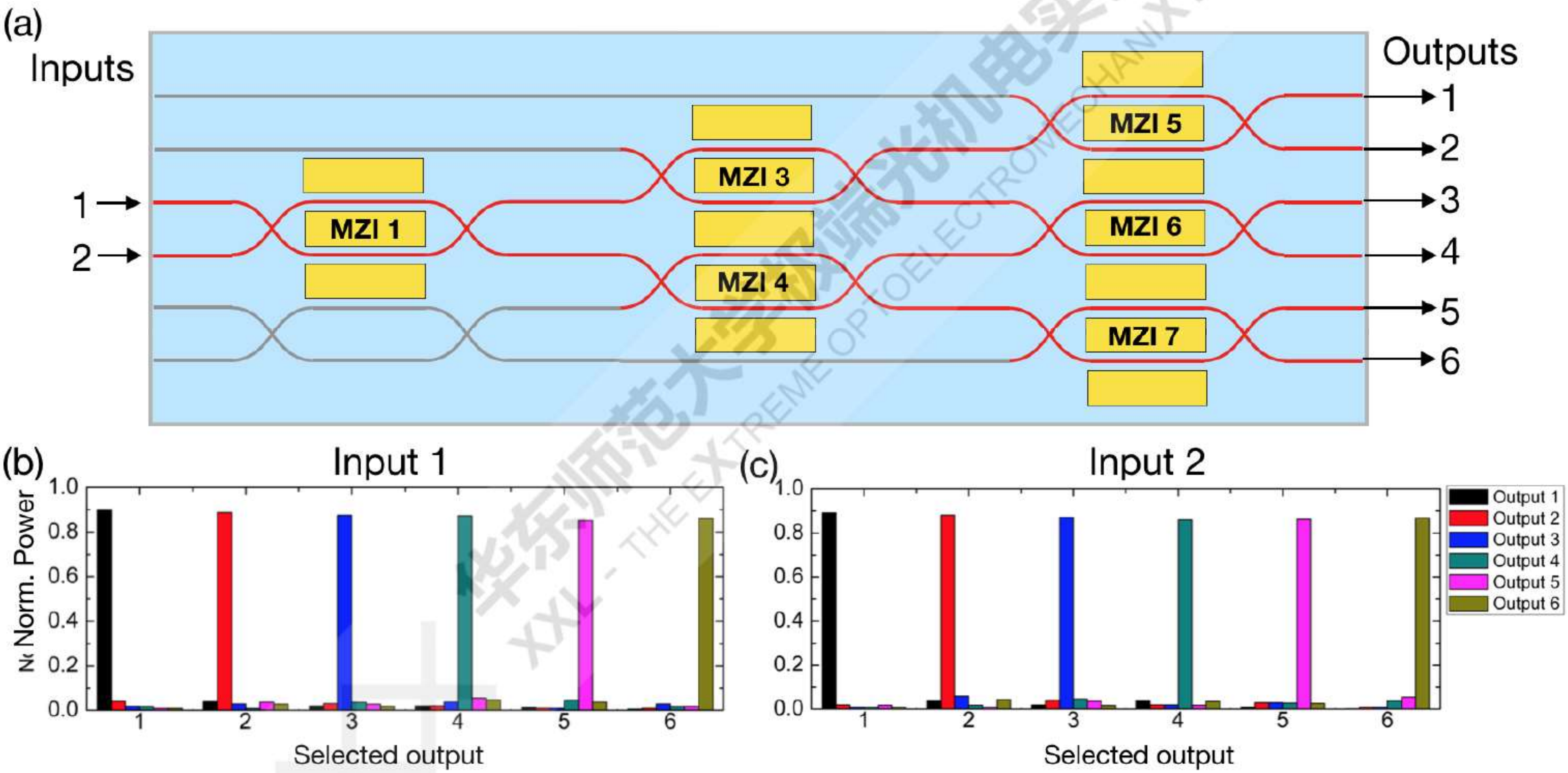
A 1 x 6 optical switch



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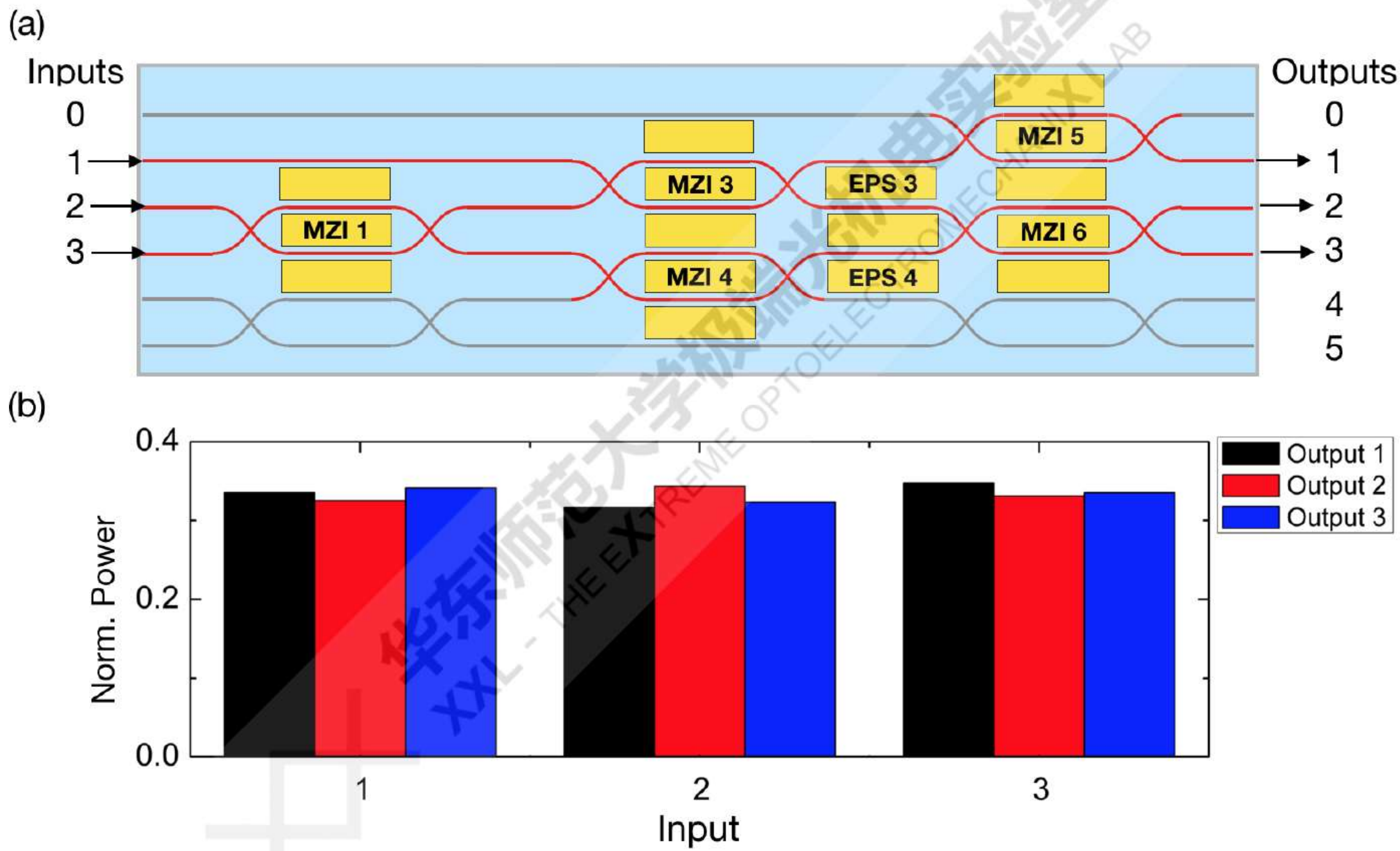
R. Wu, et al., Optics Letters 44, 4698-4701 (2019).

A balanced 3x3 interferometer



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6. Scalability and future

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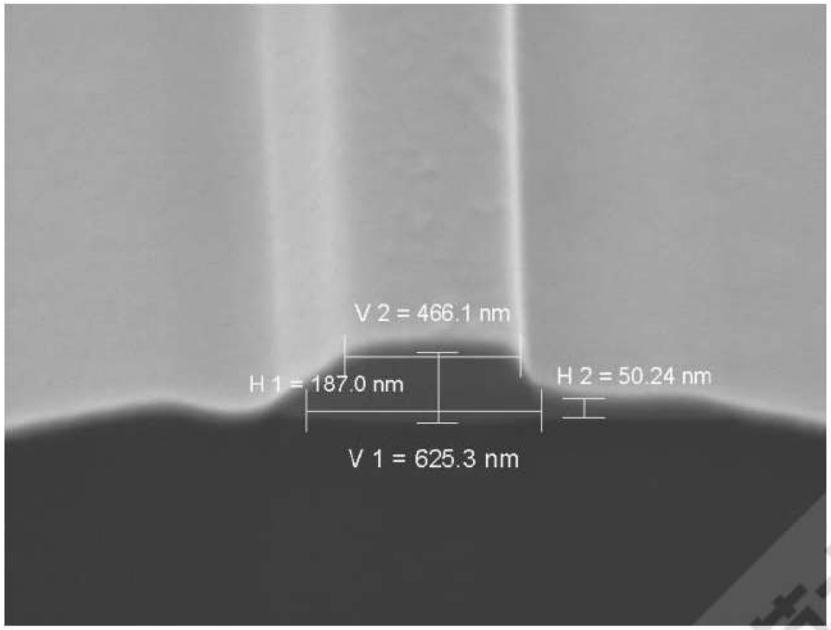
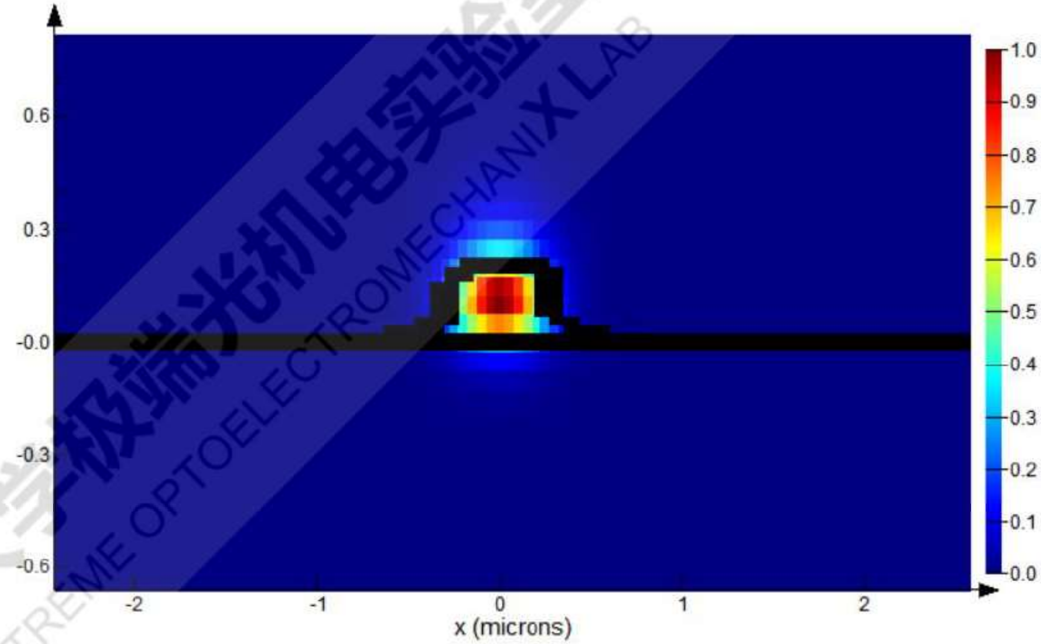
Outlook: Thinner waveguides with inversed taper





Cross section: 500 nm (width) x 190 nm (height)

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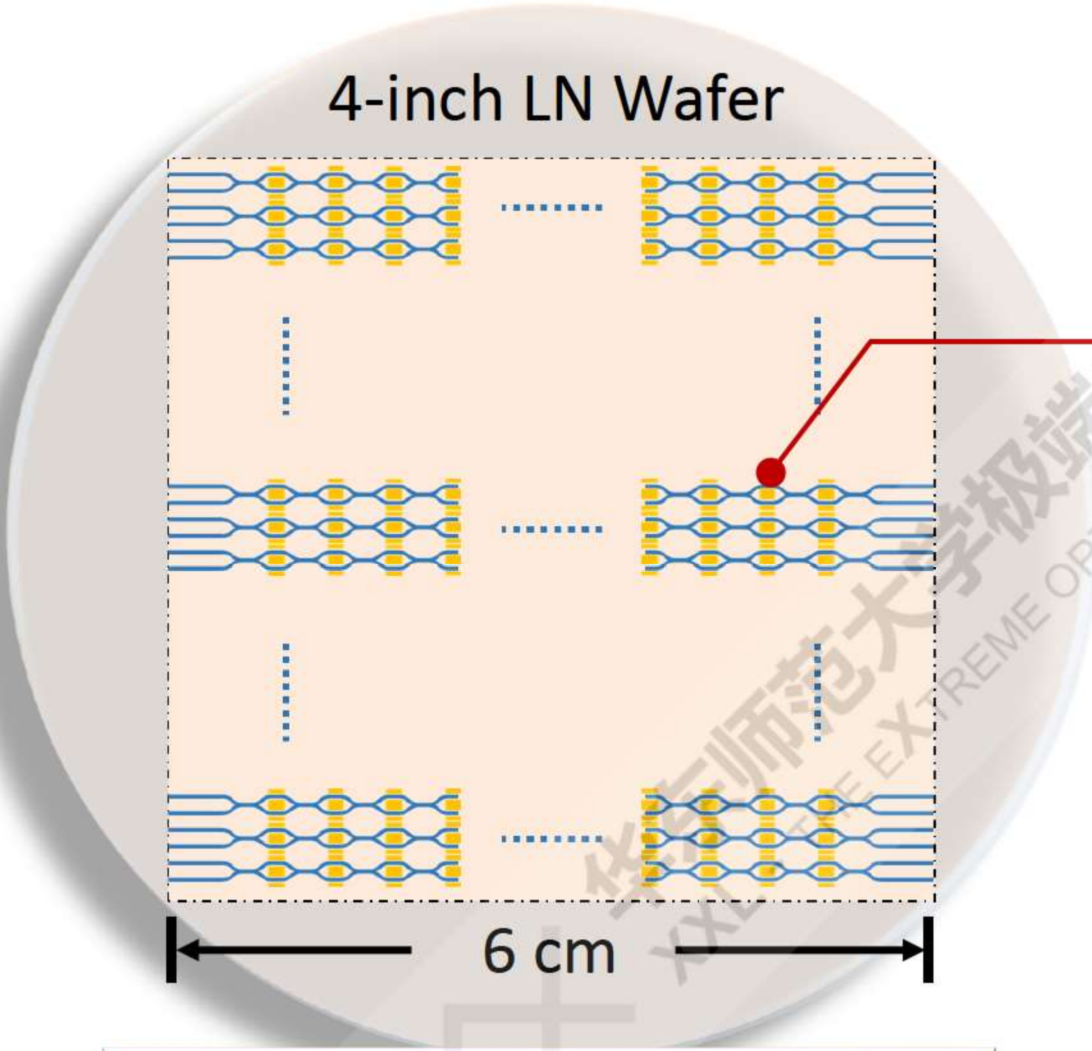
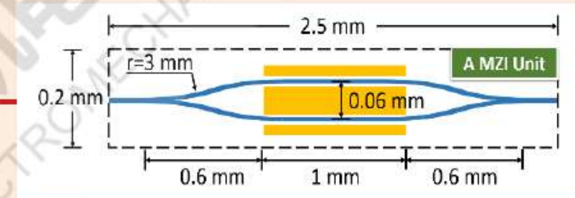
Outlook: the **integration capacity** of LN PICs



300 × 24 ~ 7200 MZI Units

LN waveguide   Microelectrode

- 4 inch LN wafer:
  6 cm × 6 cm



- Footprint of a single MZ interferometer (MZI):
  0.2 mm × 2.5 mm
- **Integration level of a single wafer:**
  300*24 = 7200 MZIs !
- **Total propagation loss：**
  < 0.05 dB/cm*6 cm
  < 0.3 dB ***or better !***

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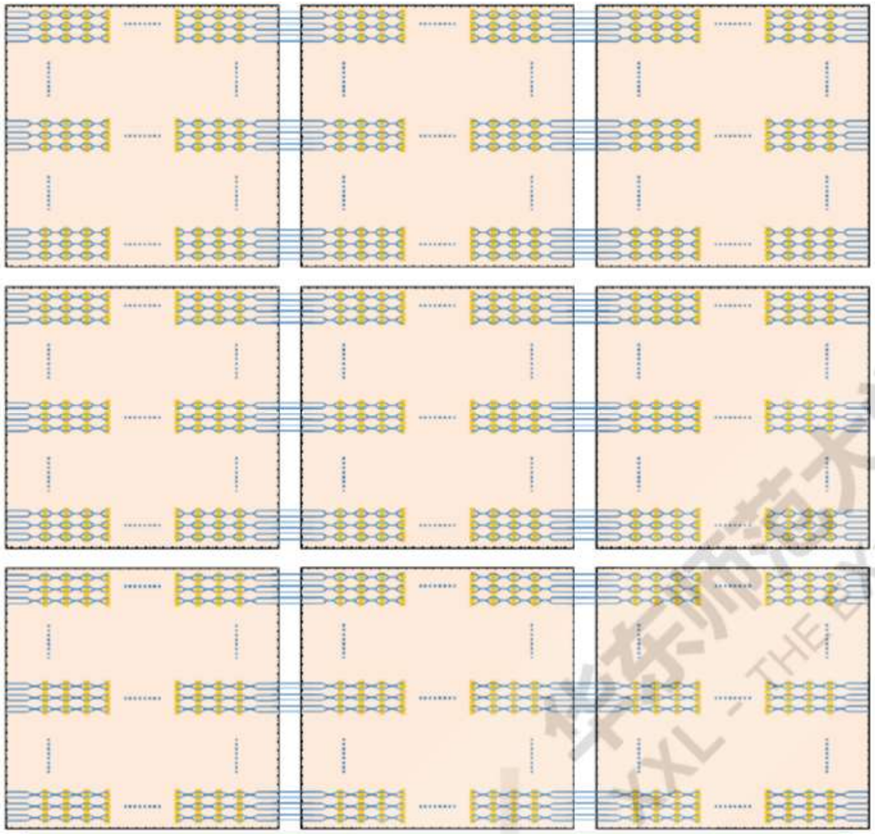
Outlook: the integration capacity of LN PICs



18 cm × 18 cm ~ 64800 MZI Units

- 4 inch LN wafer: 6 cm × 6 cm
- For our femtosecond laser microfabrication system,

  Range of the motion stage:

  20 cm × 20 cm
- 9 wafers：18 cm × 18 cm
- **Integration level of a single wafer: 300*24*9 = 64800 MZIs !**
- **Total propagation loss ：**

  < 0.05 dB/cm*18 cm

  < 1 dB ***or better !***

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

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Conclusions

We demonstrate

1. Q-factors of lithium niobate microresonators **reliably on the level of 10^7**.
2. Optical losses **as low as 0.027 dB/cm and 0.042 dB/cm** in the multi- and single-mode lithium niobate waveguides, respectively.

Thank you !

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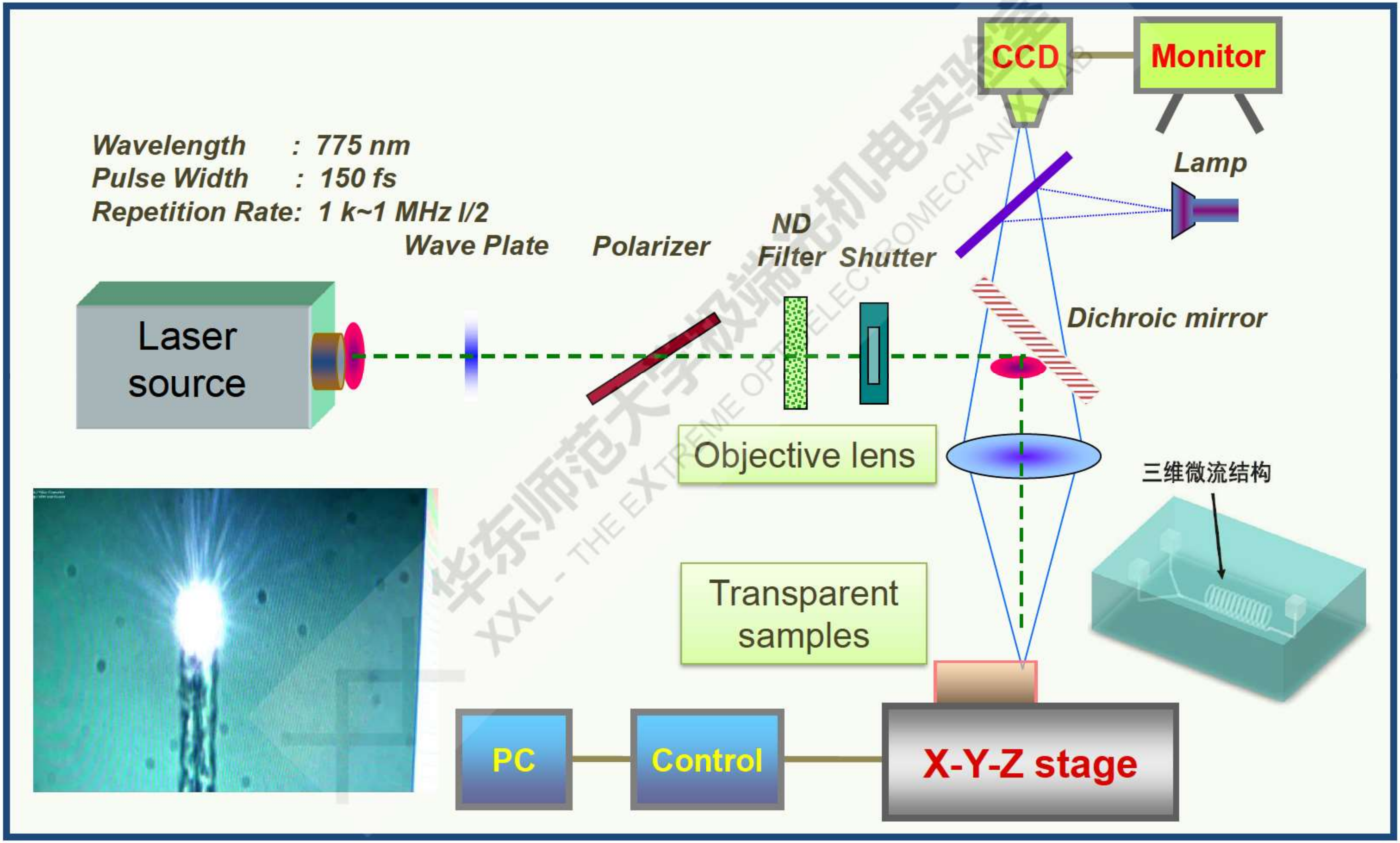
The technology



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