CHI-2 photonics in microresonators and beyond
online conference and doctoral school, 13-14 April 2021

On-chip ultra-high Q CHI-2 microresonators for nonlinear optics & PIC applications

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Who have contributed to the accomplishment?

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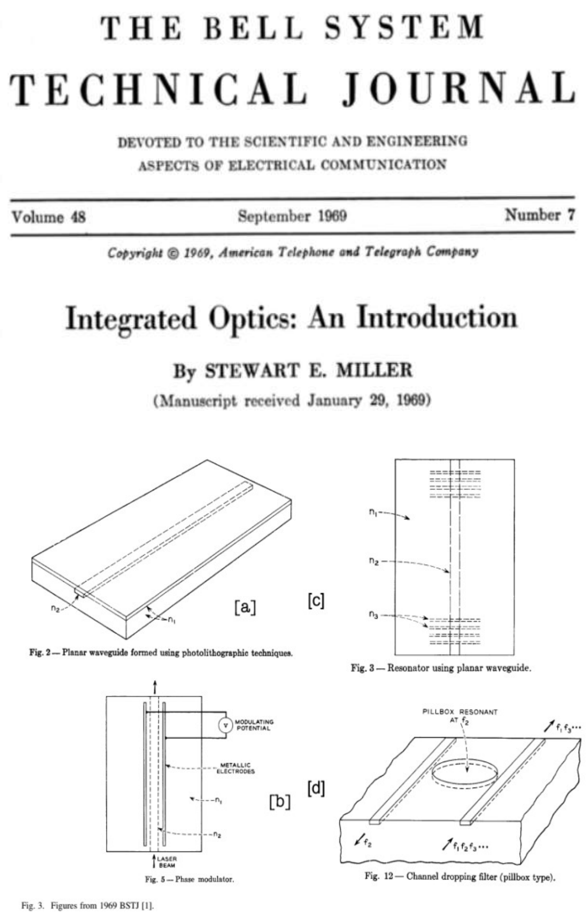
- **Prof. Tao Lu** (University of Victoria),
- **Prof. Wei Fang** (Zhejiang University),
- **Prof. Wenxue Li** (East China Normal University)
- **Dr. Ni Yao** (Zhejiang University)

Outline

1. Background
2. Fabrication technique
3. High Q lithium niobate microresonators and nonlinear optics
4. Low-loss waveguides and PICs
5. Conclusions

1. Background

Why photonic integration: technological platform for enormous applications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TECHNICAL JOURNAL

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ASPECTS OF ELECTRICAL COMMUNICATION

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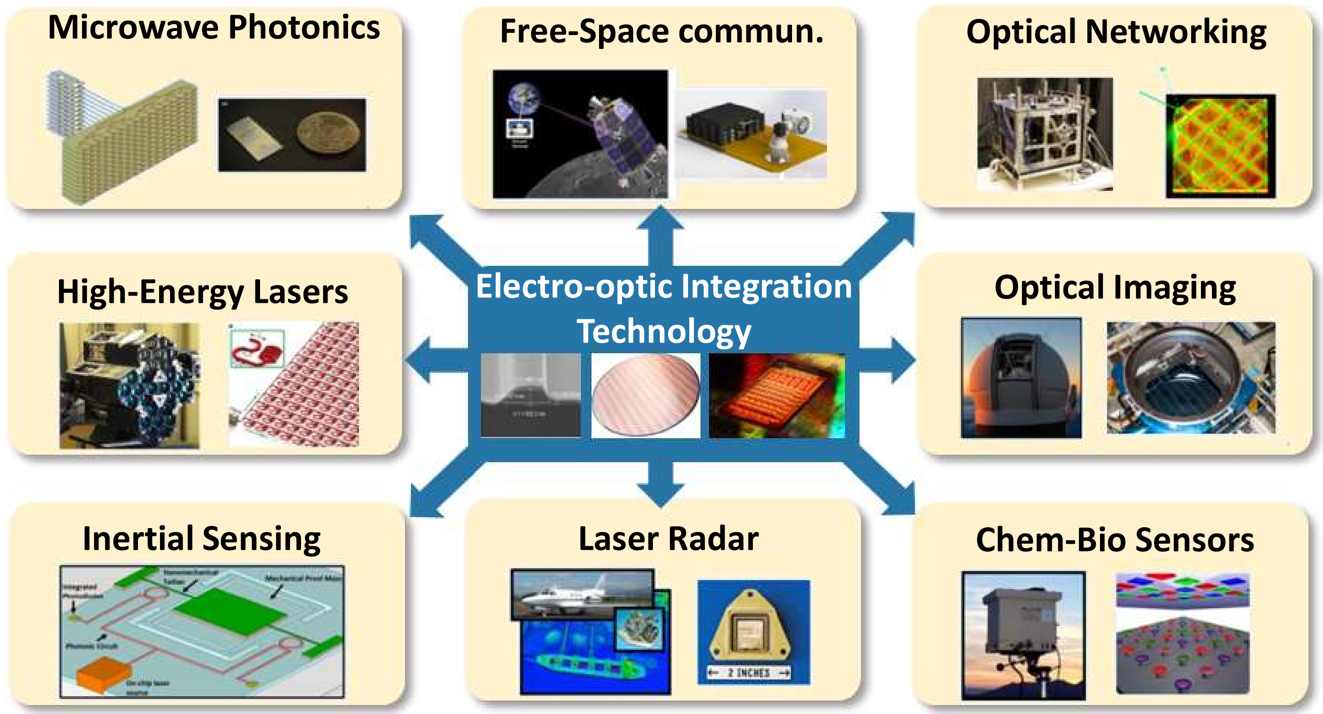
Integrated Optics: An Introduction

By STEWART E. MILLER

(Manuscript received January 29, 1969)

First conceptual proposal of PIC, 1969, Bell Lab



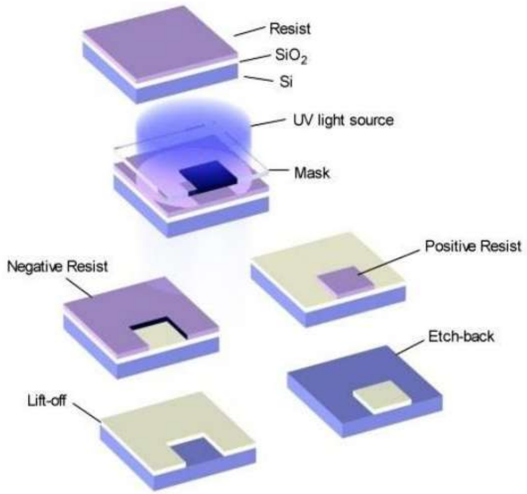
Our ambition is to make the dream of photonic integration, first proposed in 1969, come true, with a sustainable scalability similar to that of its electronic counterpart!

Major challenges in scalable PIC: lithium niobate provides key solution

1、**Low propagation loss:**	**requiring low absorption and minimum scattering**
2、**High density of integration:**	**requiring high refractive index contrast as compared with air or silica glass**
3、**Tuning speed & efficiency:**	**ideally with large electro-optic coefficient**

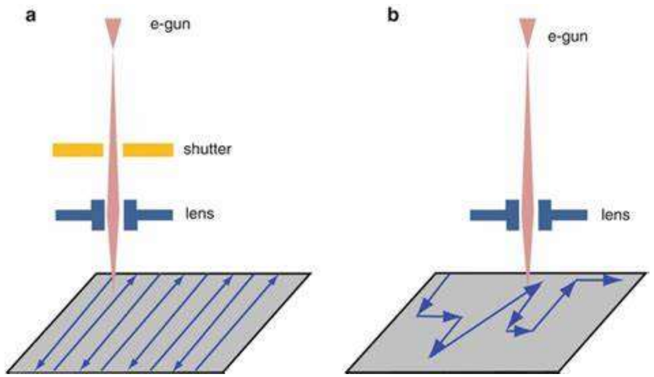
So far, lithium niobate, a crystalline material known as the "silicon of photonics", is the only optical material that fulfills all the three stringent criteria above.

Conventional fabrication approaches do not support scalable PIC development



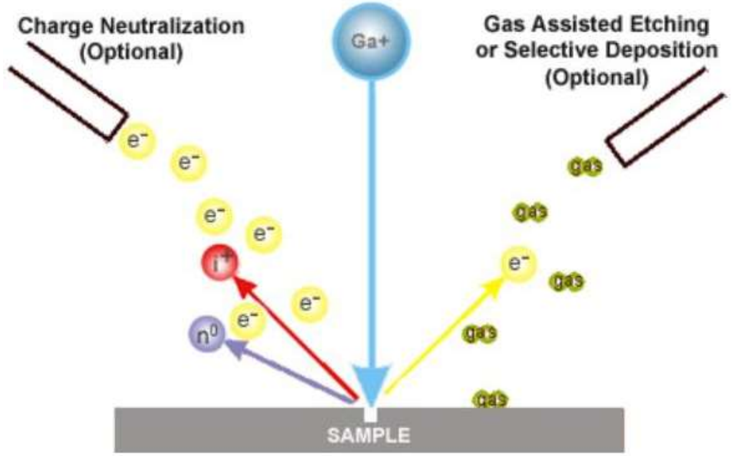
Photolithography

https://www.slideserve.com/toshi



Electron beam lithography

https://link.springer.com/referenceworkentry

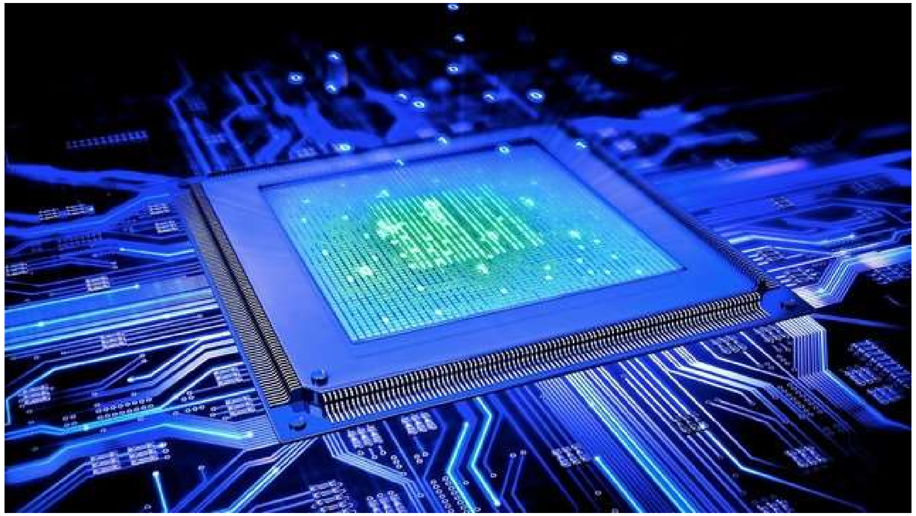


Focused ion beam lithography

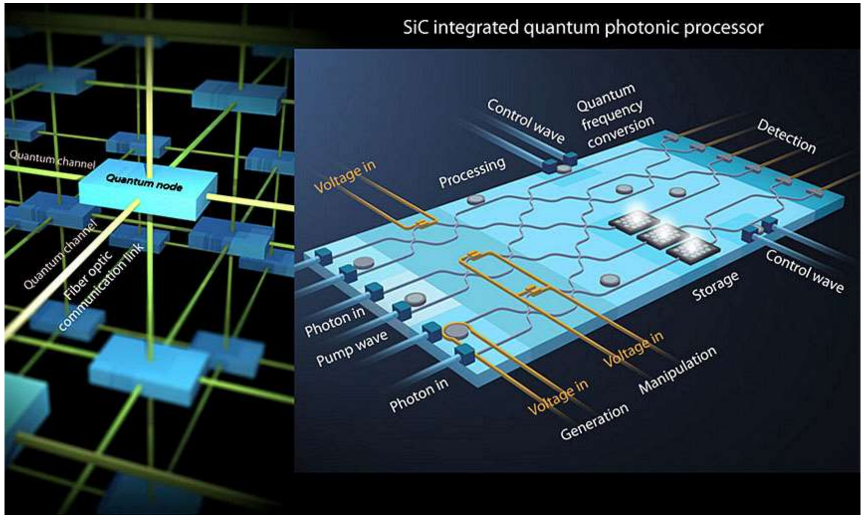
https://link.springer.com/referenceworkentry

1. ***The conventional nanofabrication approaches suffer from limited exposure area and relatively high roughness on the edge of waveguide.***
2. ***The scale of PICs is therefore difficult to expand because of the limited footprint and relatively high scattering loss.***

Essential difference between electronic and photonic integration



https://www.timetoast.com/timelines/



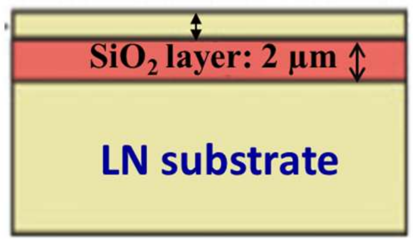
http://www.hajim.rochester.edu/news

Essential difference between electronic and photonic integration:
Very, very, very different scales of their De-Broglie wavelengths

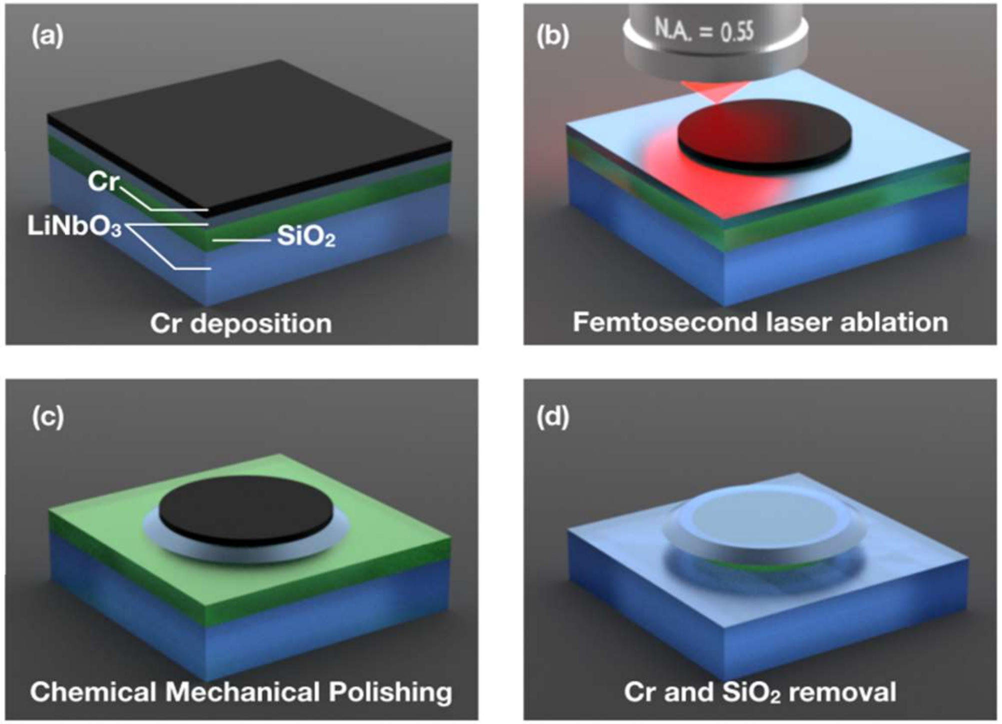
1. ***For electronics:*** *scalability achievable by improving lithography fabrication resolution*
2. ***For photonics:*** *scalability achievable by increasing the device footprint*
3. ***Point of view:*** *a different lithography technology required for PIC other than EIC*

2. Fabrication technique

Photo-Lithography Assisted Chemomechanical Etch: PLACE



Laser Photon Rev. 6, 488 (2012)

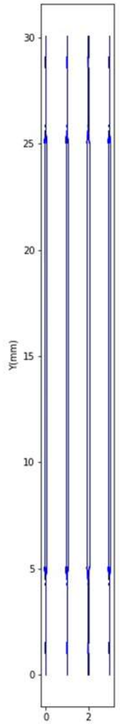


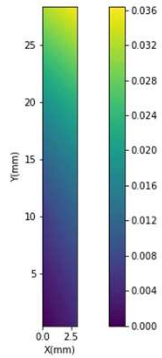
Y. Cheng, et al, Patent No.: US10670806B2

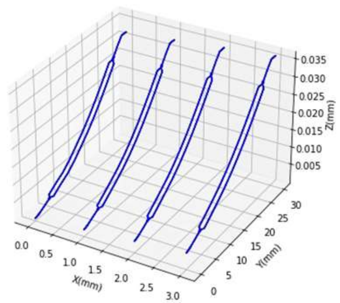
R. Wu et al, Opt. Lett. 43, 4116 (2018)

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.

[redacted]

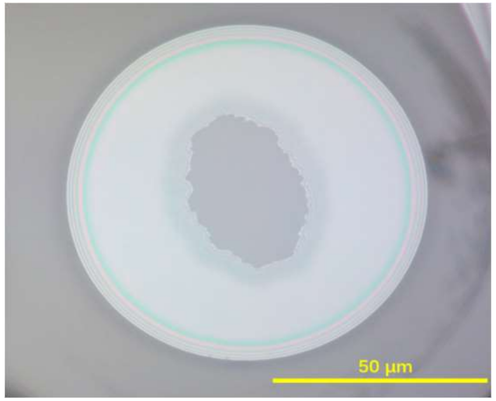




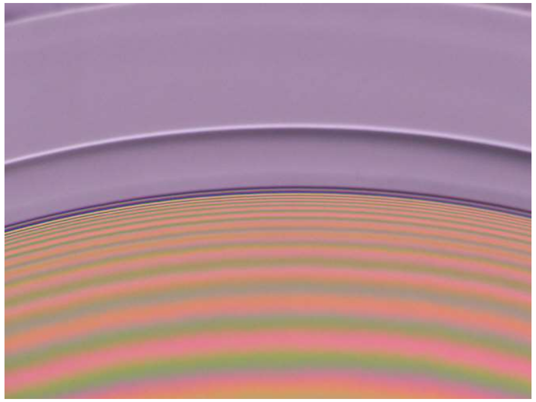


[redacted]

Characterization of a CMP microdisk: Q: ~ 10^8

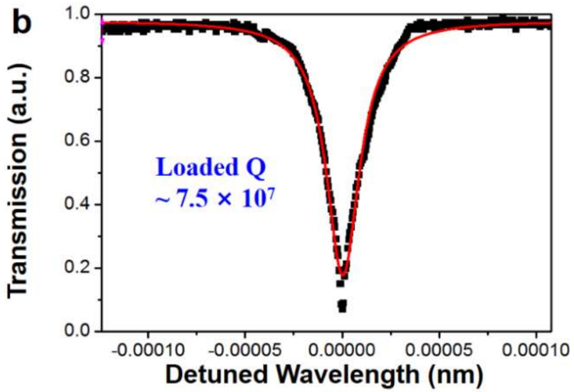


Overview of an LN microdisk

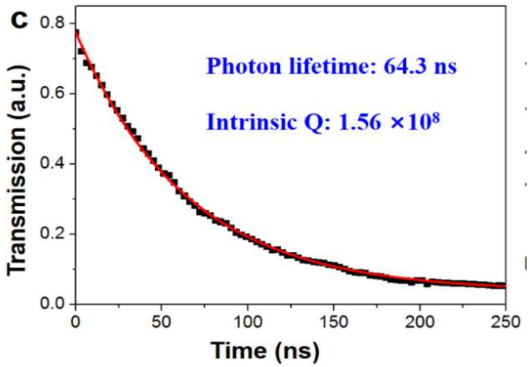


Close-up view at the edge of the disk

Fiber coupling Intrinsic Q ~1.5×10⁸



loaded Q-factor measurement

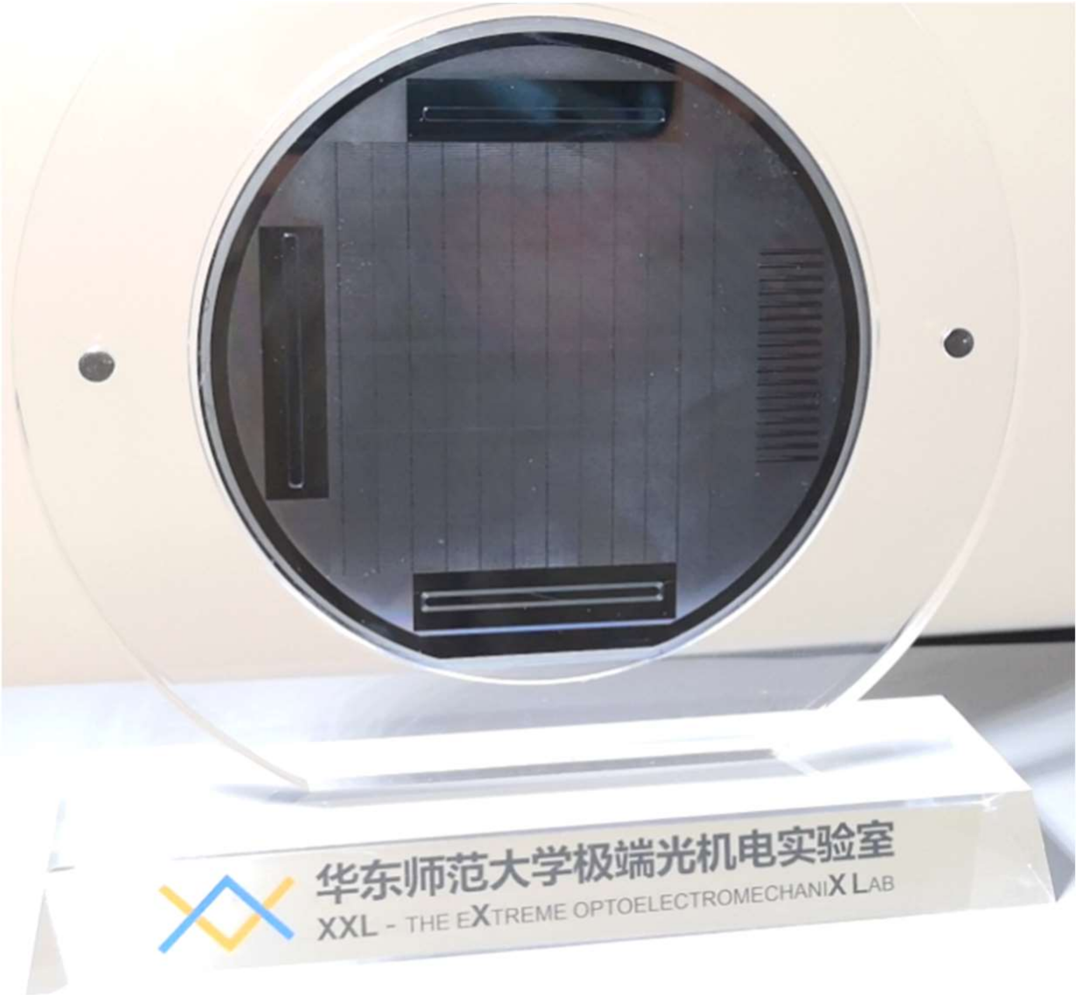


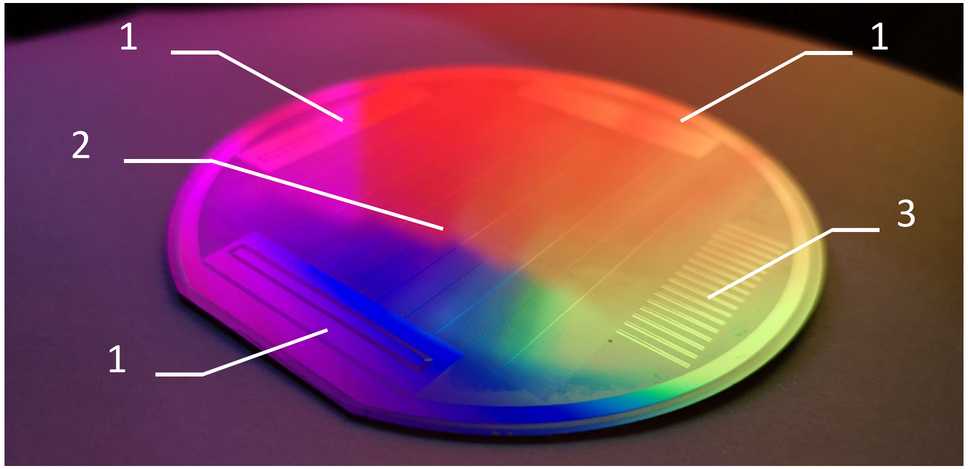
Ring-down measurement

Ring-down Intrinsic Q ~1.56×10⁸

R. Gao et al, arXiv preprint arXiv:2102.00399 (2021)

Photonic circuits continuously fabricated in a 4-inch LN wafer

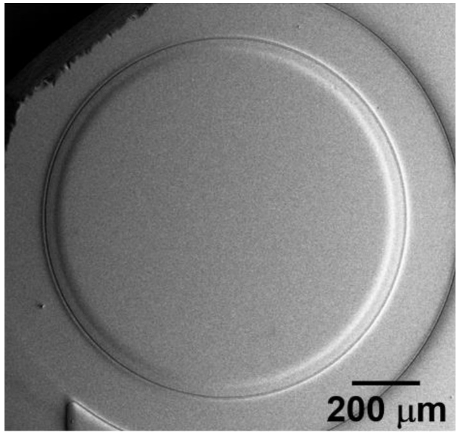


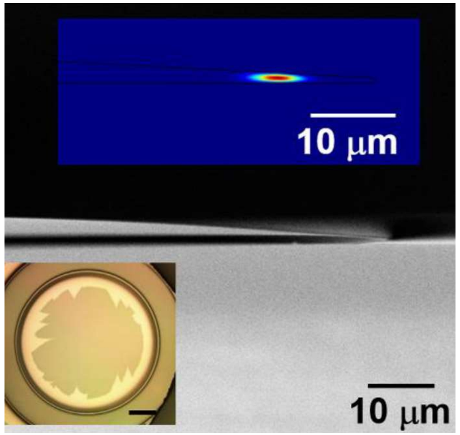


1. **Optical true delay line of a waveguide with meter-length**
   Length：0.5 m，1 m，2 m。
2. **MZI (MZ modulator) array**
   Footprint of the MZI array：6 cm×6 cm
   Number of the MZI units：120
3. **Cascaded MMI tree for insertion loss measurement**

3. Nonlinear optics

A new level of nonlinear physics in ultrahigh Q MR

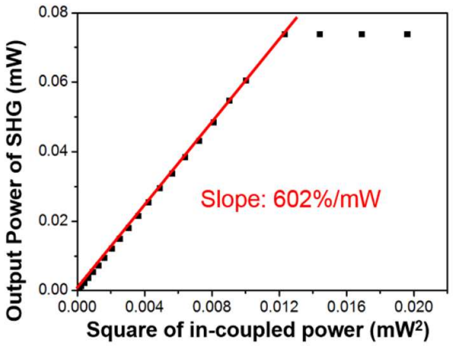


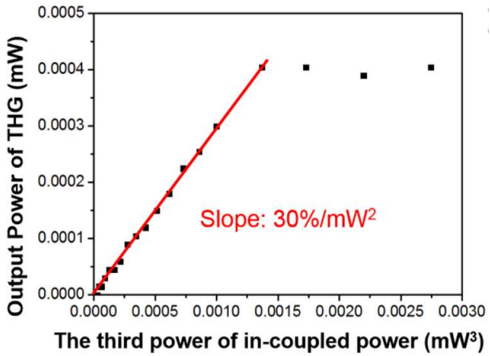


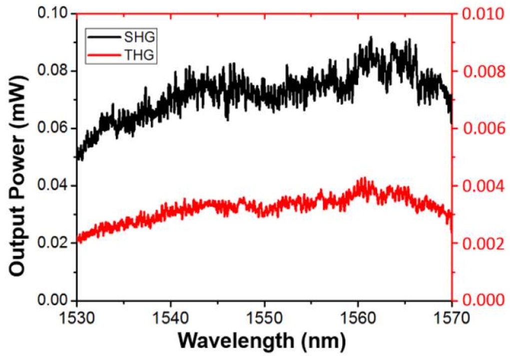
Disk dia. ~ 1 mm

Intrinsic Q ~1.23×10^8

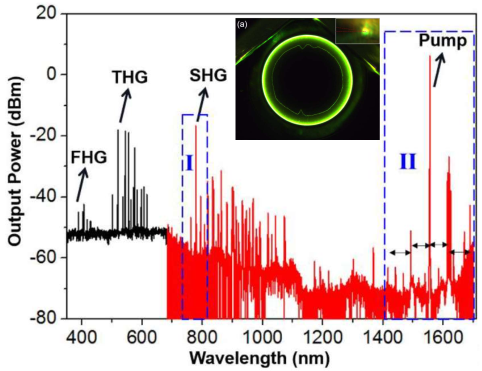
SHG & THG insensitive to broad bandwidth



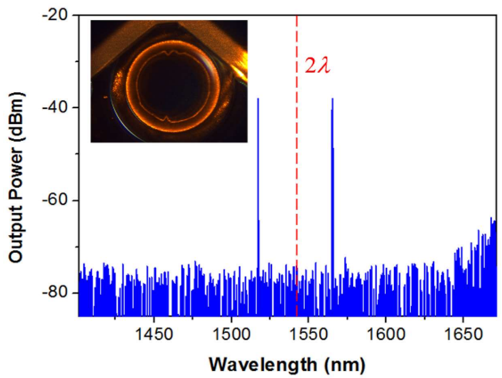


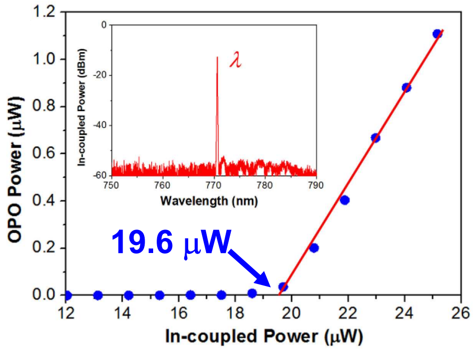


Comb generation at FW, SHG, THG & FHG



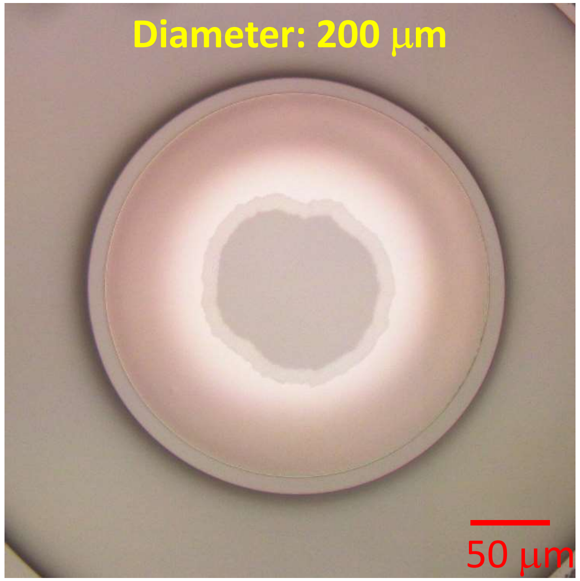
Non-degenerated OPO

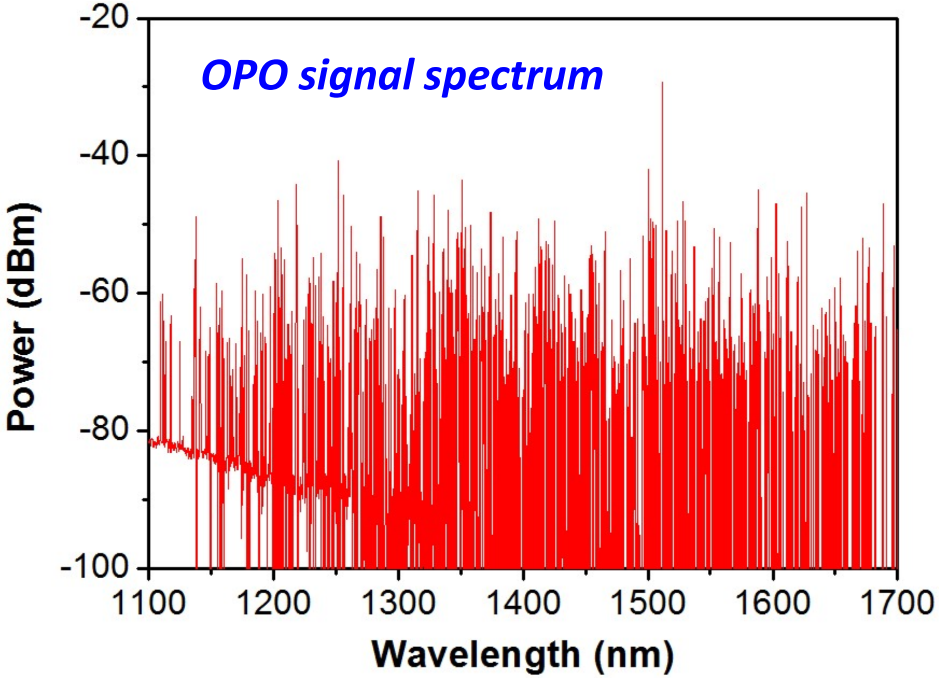


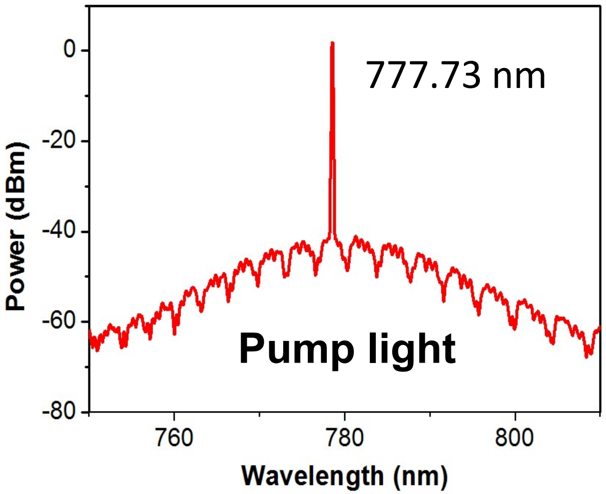


R. Gao, et al., ***arXiv e-prints,*** arXiv: 2102.00399 (2021)

Highly efficient broadband OPO comb

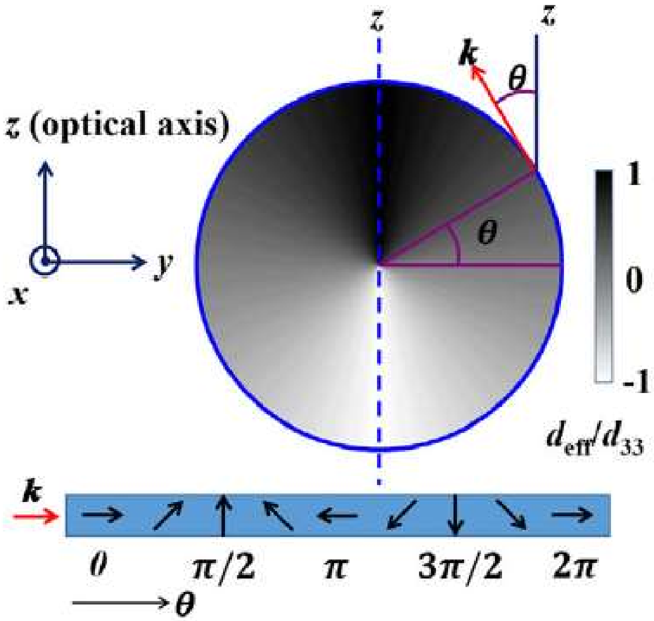


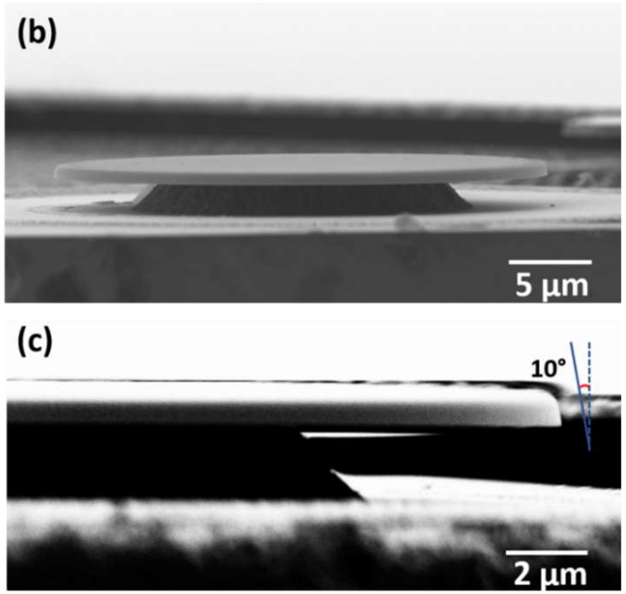




- **Efficient pumping power: 300 μW**
- **Spectral range: from 1100 nm to 1700 nm (which is the upper limit of response wavelength of the spectrometer)**
- **Comb spacing: 0.5 nm**

Transient phase matching in SHG and THG





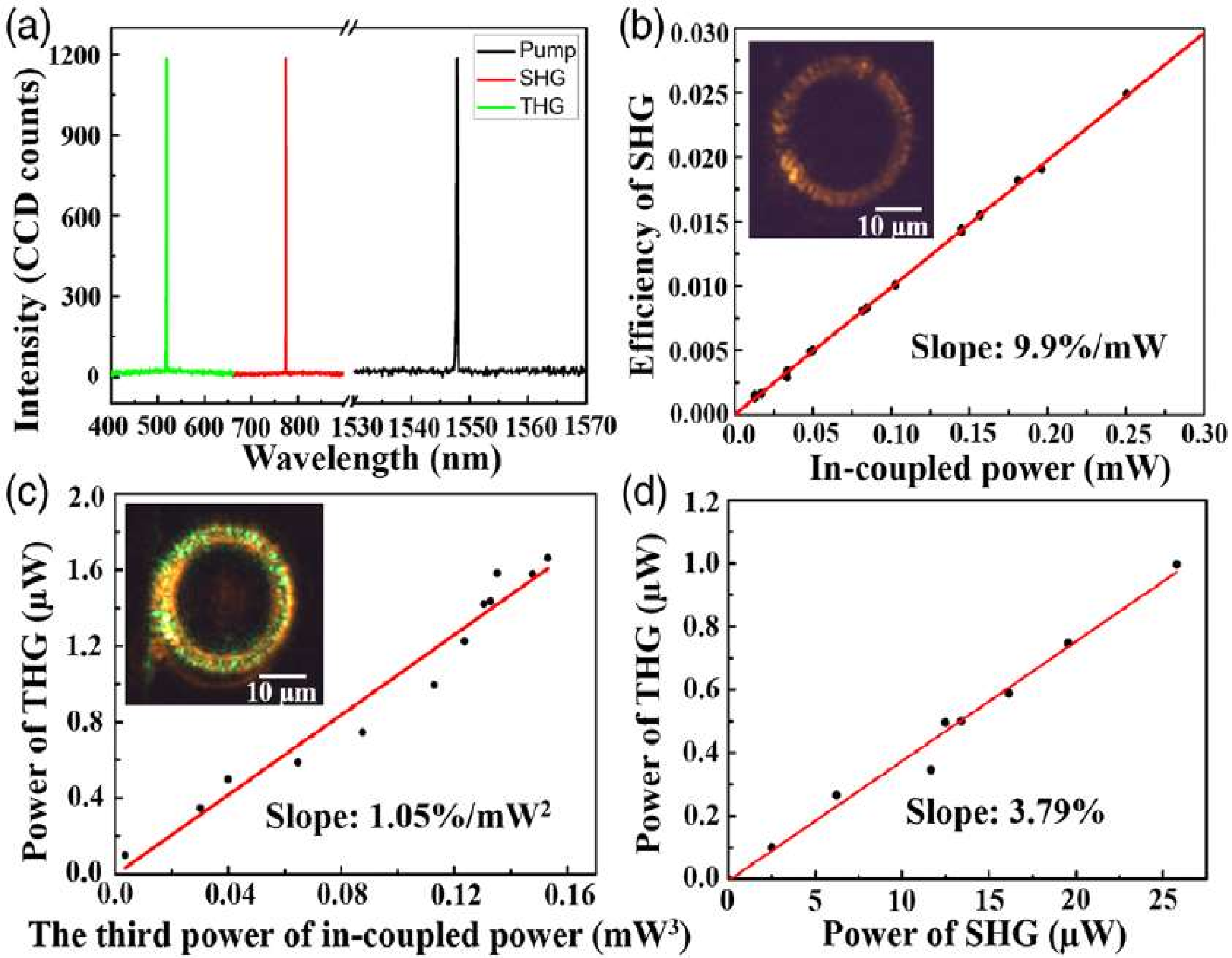
The second-order nonlinear coefficient is featured with a periodically varying refractive index which provides transient phase matching (similar to QPM in PPLN) for a broadband spectrum.

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

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

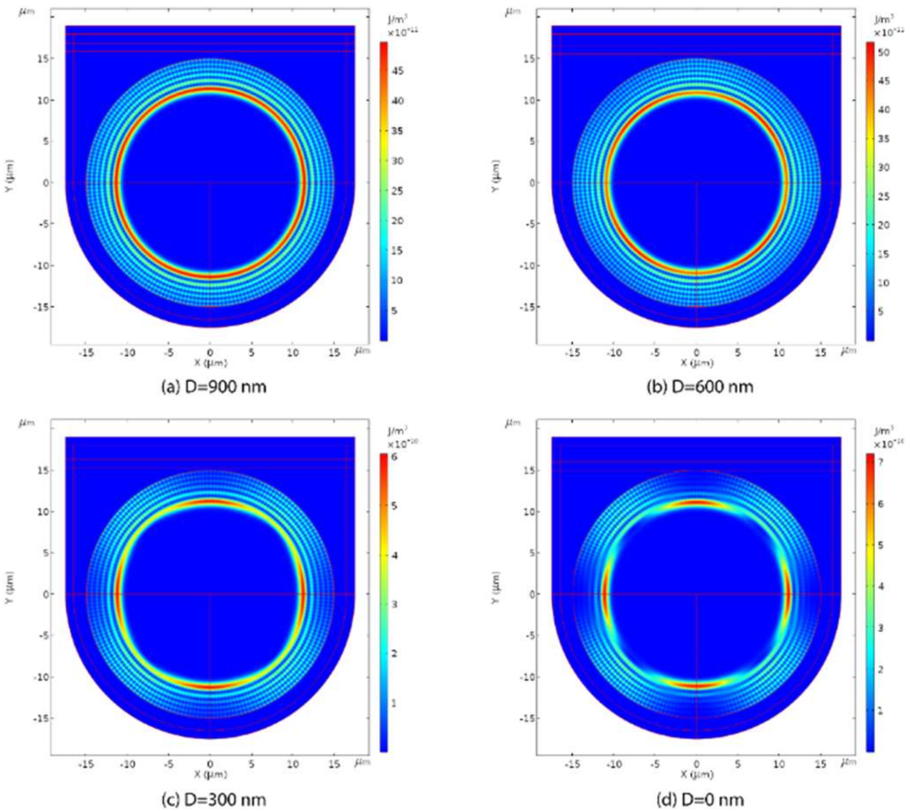
Highly efficient SHG and THG supported by QPM

Normalized conversion efficiency **THG : 1.05%/mW^2**

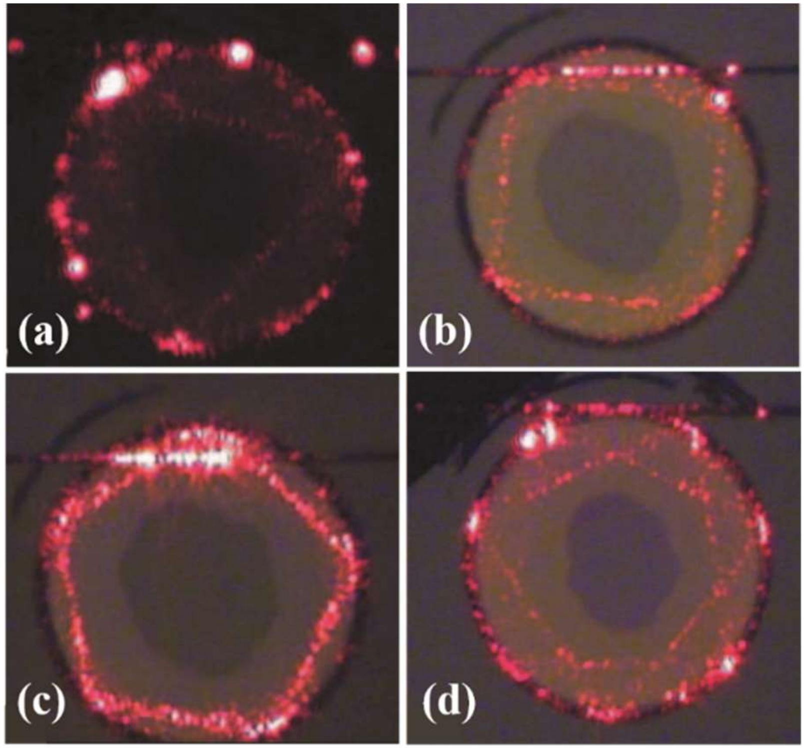


Normalized conversion efficiency **SHG : 9.9%/mW**

Novel polygon modes induced by symmetry breaking



Simulation

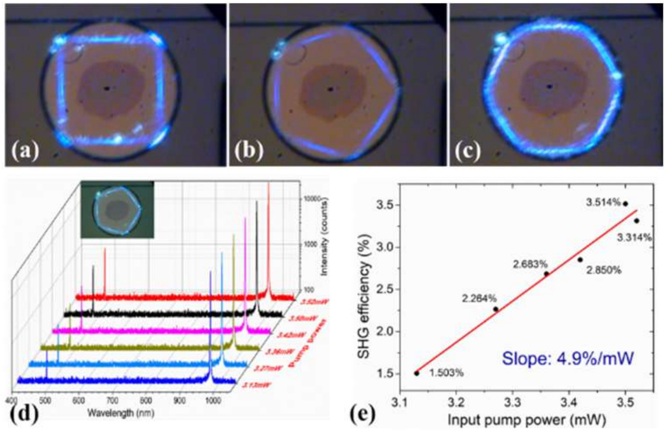


Observation

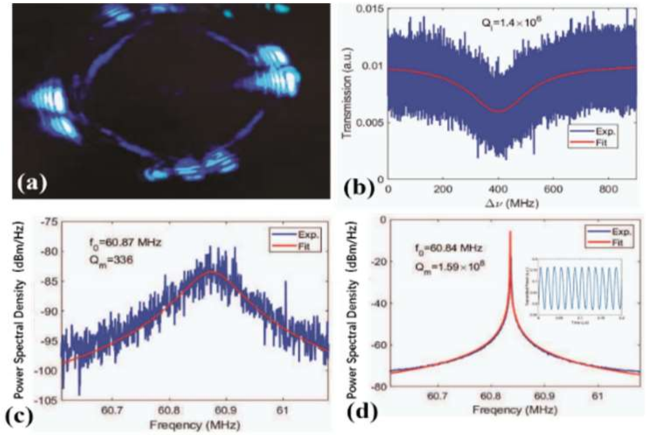
Z. Fang, et al., Phys. Rev. Lett.,125,173901(2020)

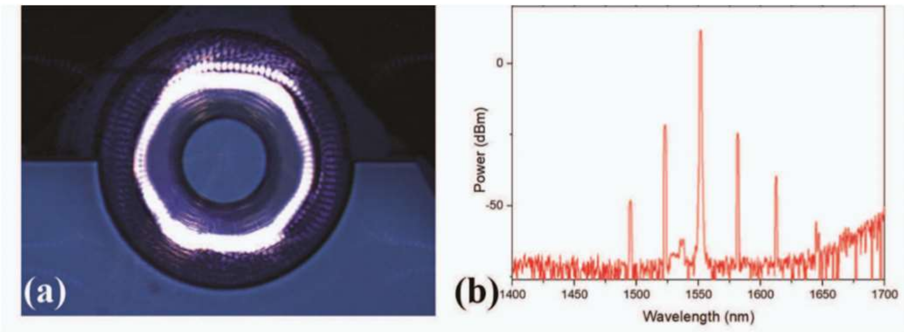
Efficient nonlinear optics with the polygon modes

Efficient SHG



Significant Optomechanics



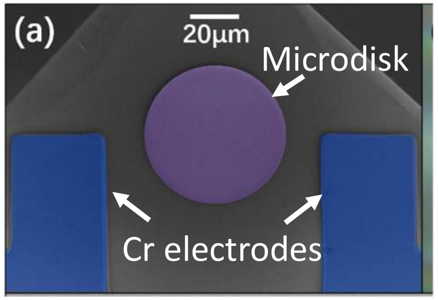


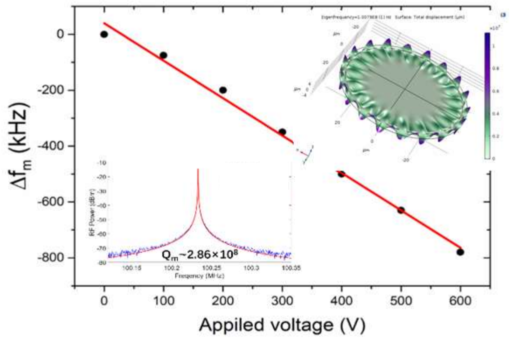
Frequency comb generated by the polygon mode

The link between the polygon modes and efficient nonlinear optics is still missing.

Tunable nonlinear optics with high-Q microdisks

Tuning of an optical spring

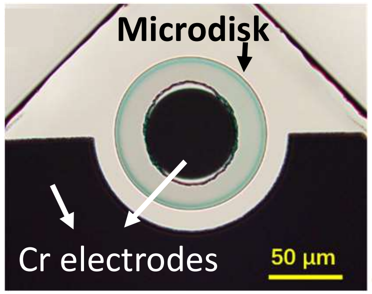


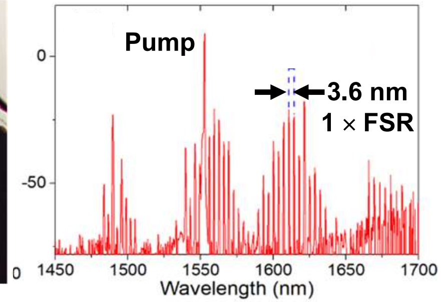


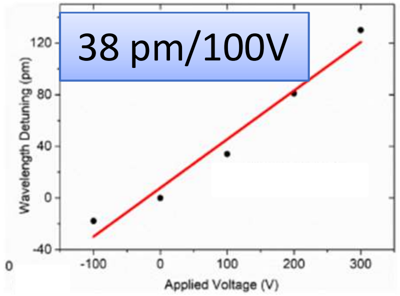
- Optical quality: Q~10^7
- Electro-mechanical tuning efficiency : -134 kHz/100V

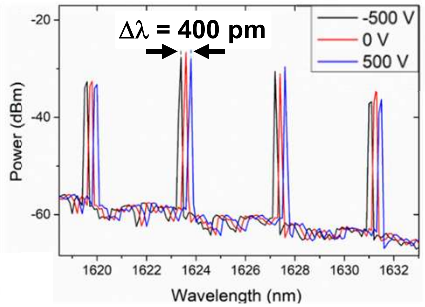
Z. Fang, et al, Opt. Lett. 44, 1214 (2019)

Tuning of an optical frequency comb







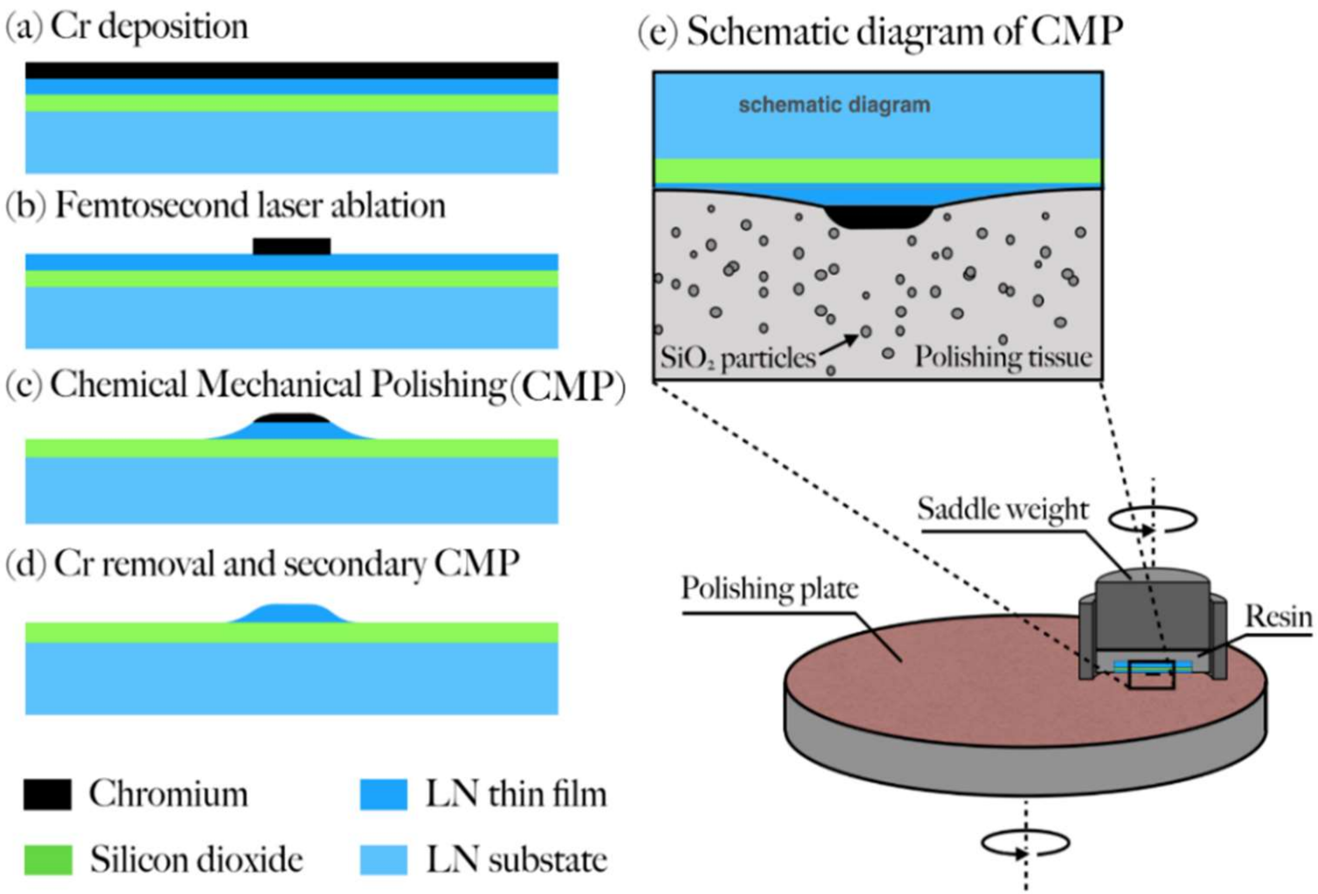


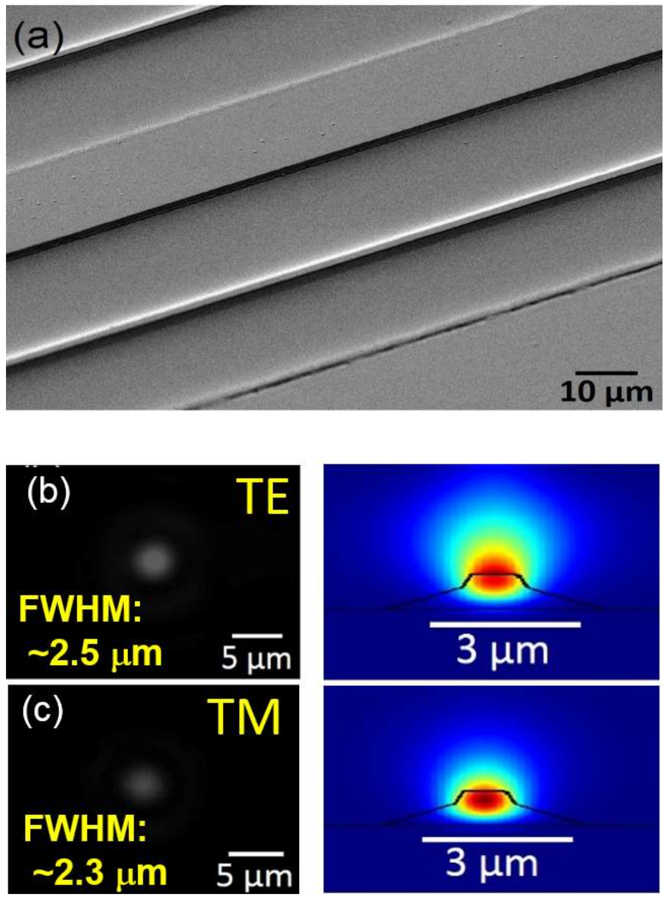
- Raman-assisted FWM microcomb: spectral bandwidth of ~200 nm
- Eletrcal tuning efficiency ~38 pm/100V

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

4. Low-loss waveguides and PICs

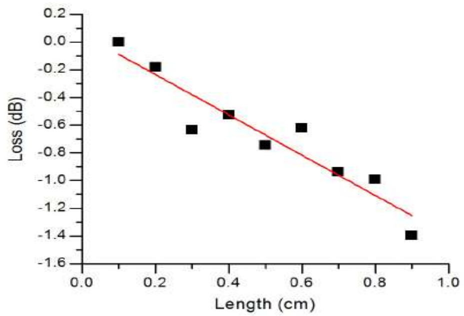
Fabrication of ultra-low loss waveguides on LNOI



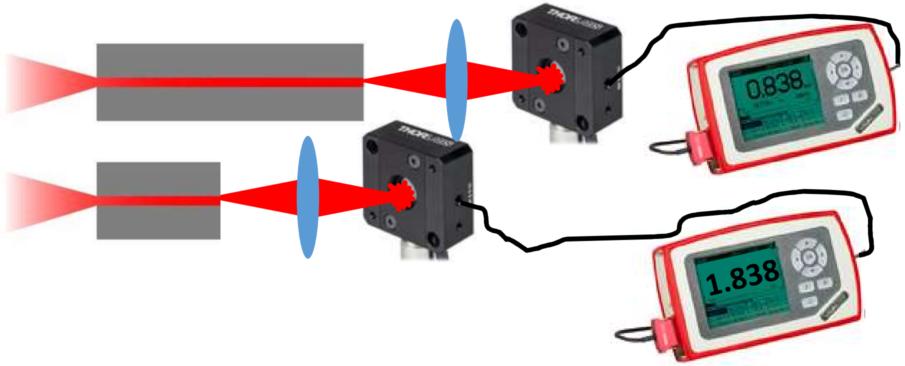


R. B. Wu, et al, Nanomaterials 8, 910 (2018)

Difficulties in measuring the ultra-low losses



Cut back measurement
Picture from F. Y. Gardes



Measure the transmission through straight waveguides of variable lengths.

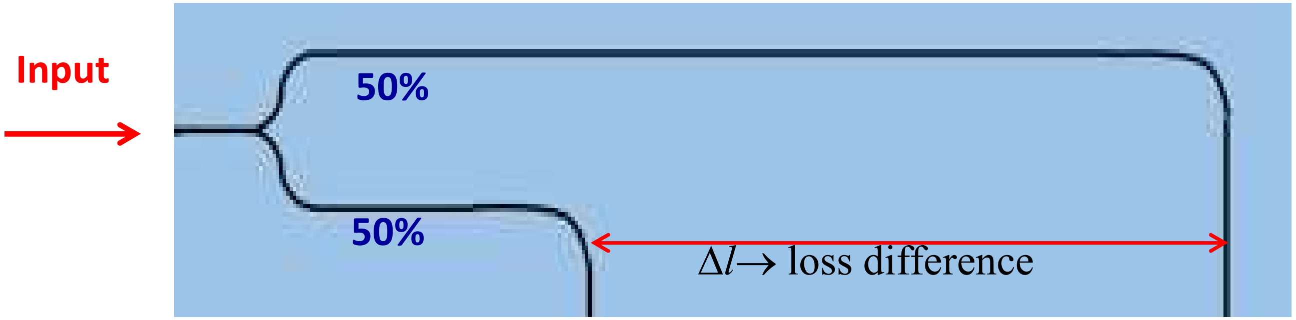
1. **Waveguide length is limited by the wafer size.**
2. **The coupling loss should be precisely controlled.**

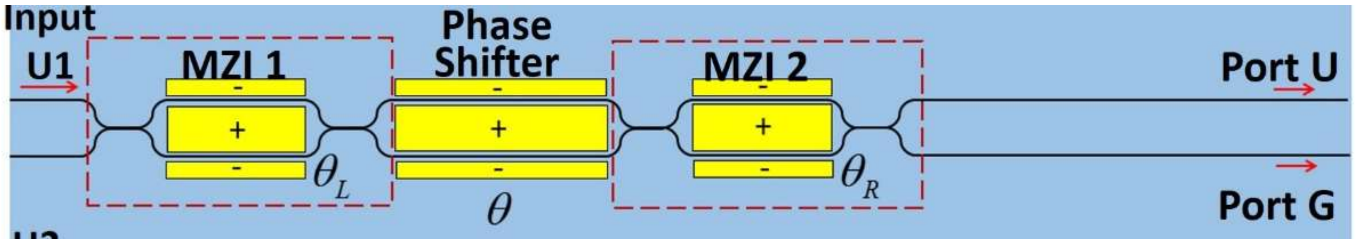
High precision measurement is challenging:

- **Only effective when propagation loss is significantly higher than the uncertainty in the coupling loss;**

New loss measurement method with a perfect beam splitter

Perfect beam splitter: splitting ratio of 50%:50%.

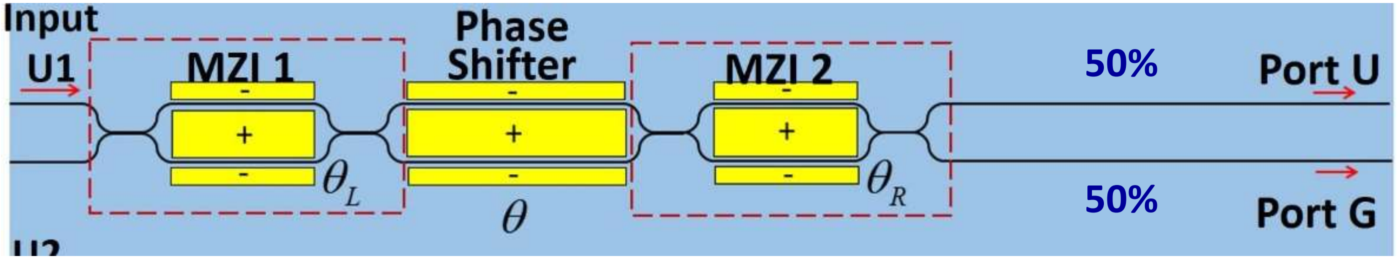




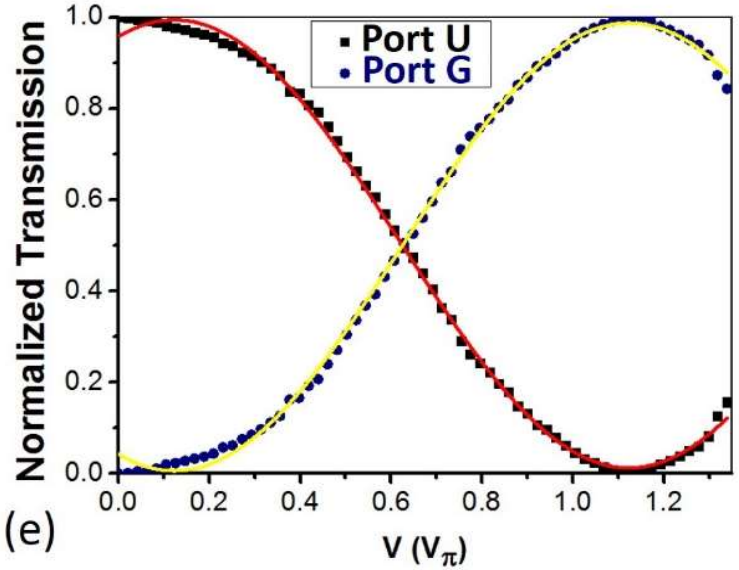
D. A. B Miller, Optica 2, 747 (2015)

Splitting ratio of the directional coupler should range from 85%:15% to 15%: 85 %, in order to obtain the splitting ratio of 50%:50%.

The perfect beam splitter: extinction ratio ~40 dB



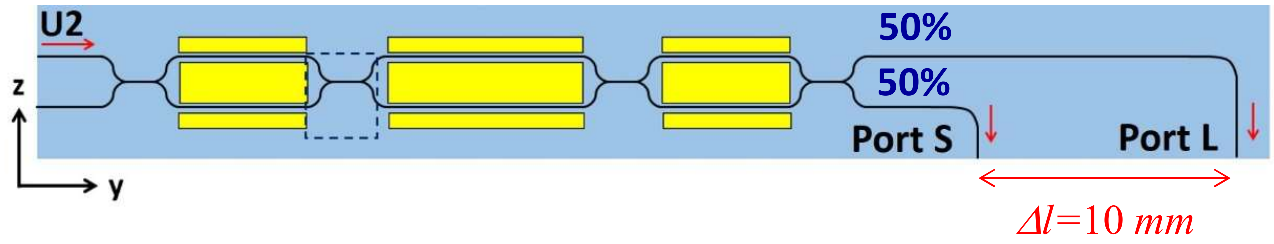
Half wave voltage of Phase shifter: 6.7 V

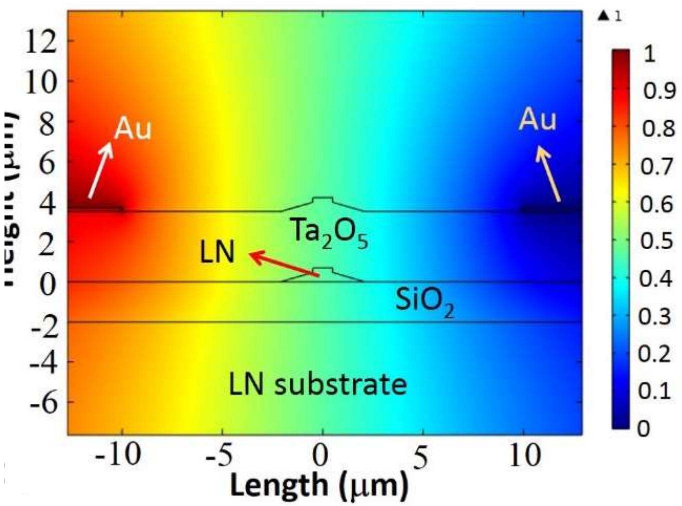


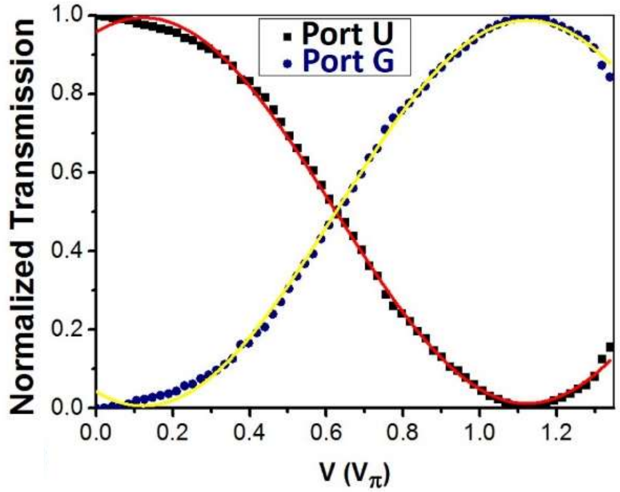
$$P_u = \frac{1}{2}(1 - \cos\theta)$$

J. Lin, et al., Micromachines 10, 612 (2019)

Measurement of loss：0.042± 0.02 dB/cm



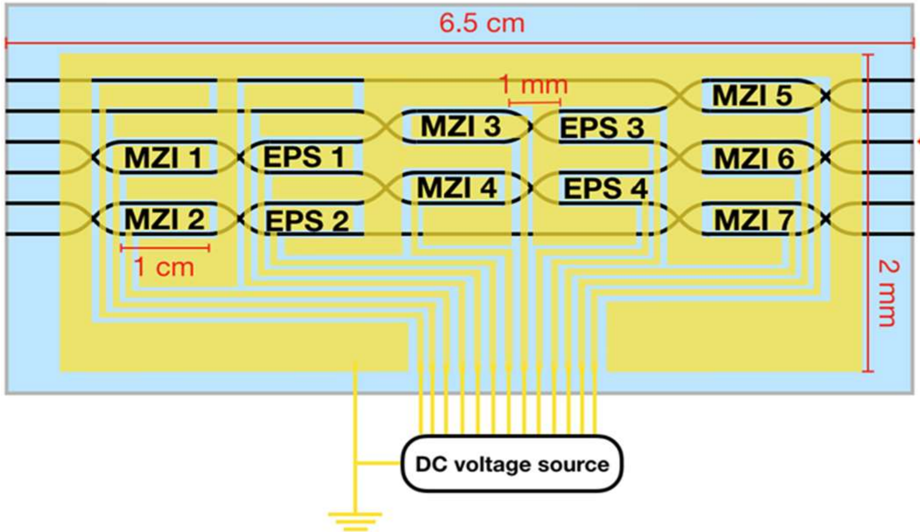


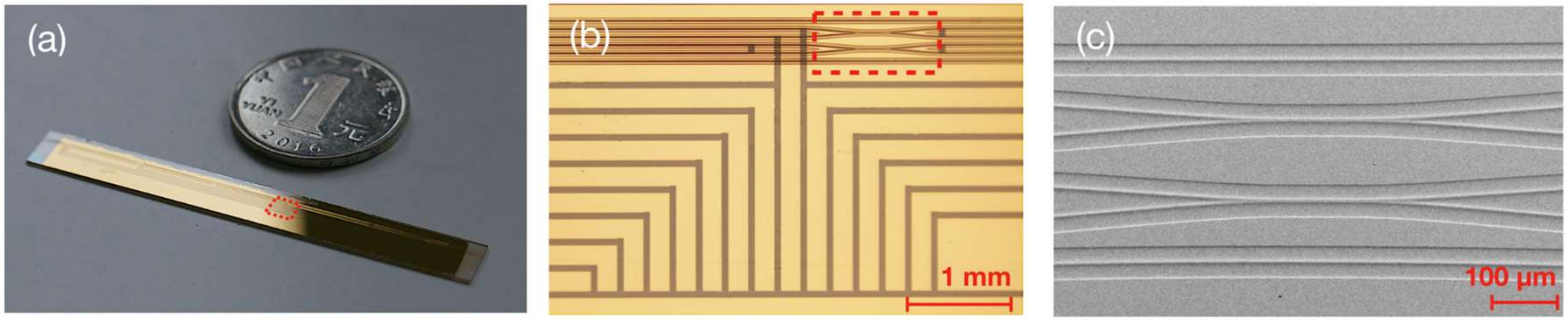


Progapation loss: 0.042 ± 0.02 dB/cm

J. Lin, et al., Micromachines 10, 612 (2019)

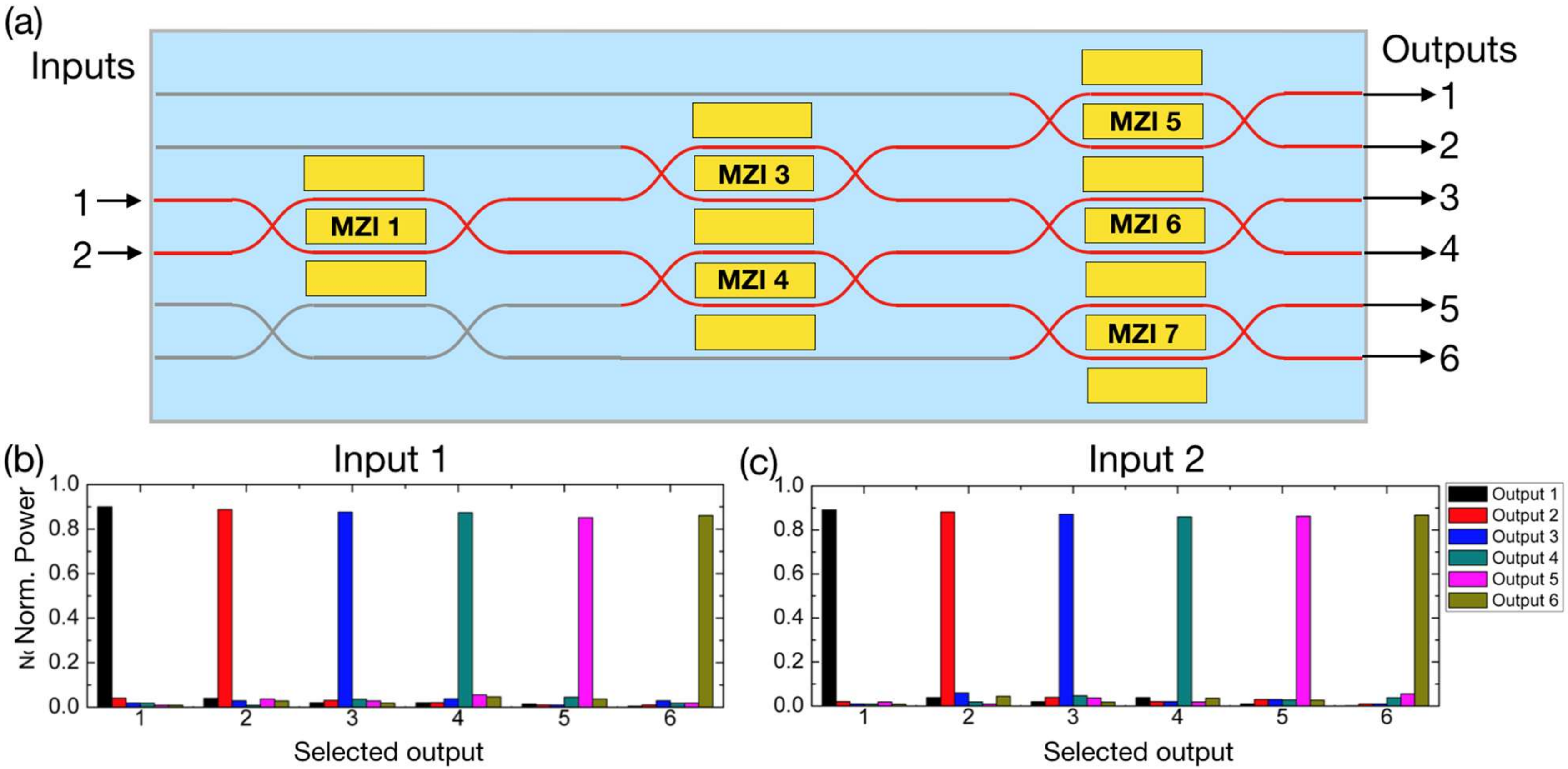
Reconfigurable multi-functional photonic integrated circuit





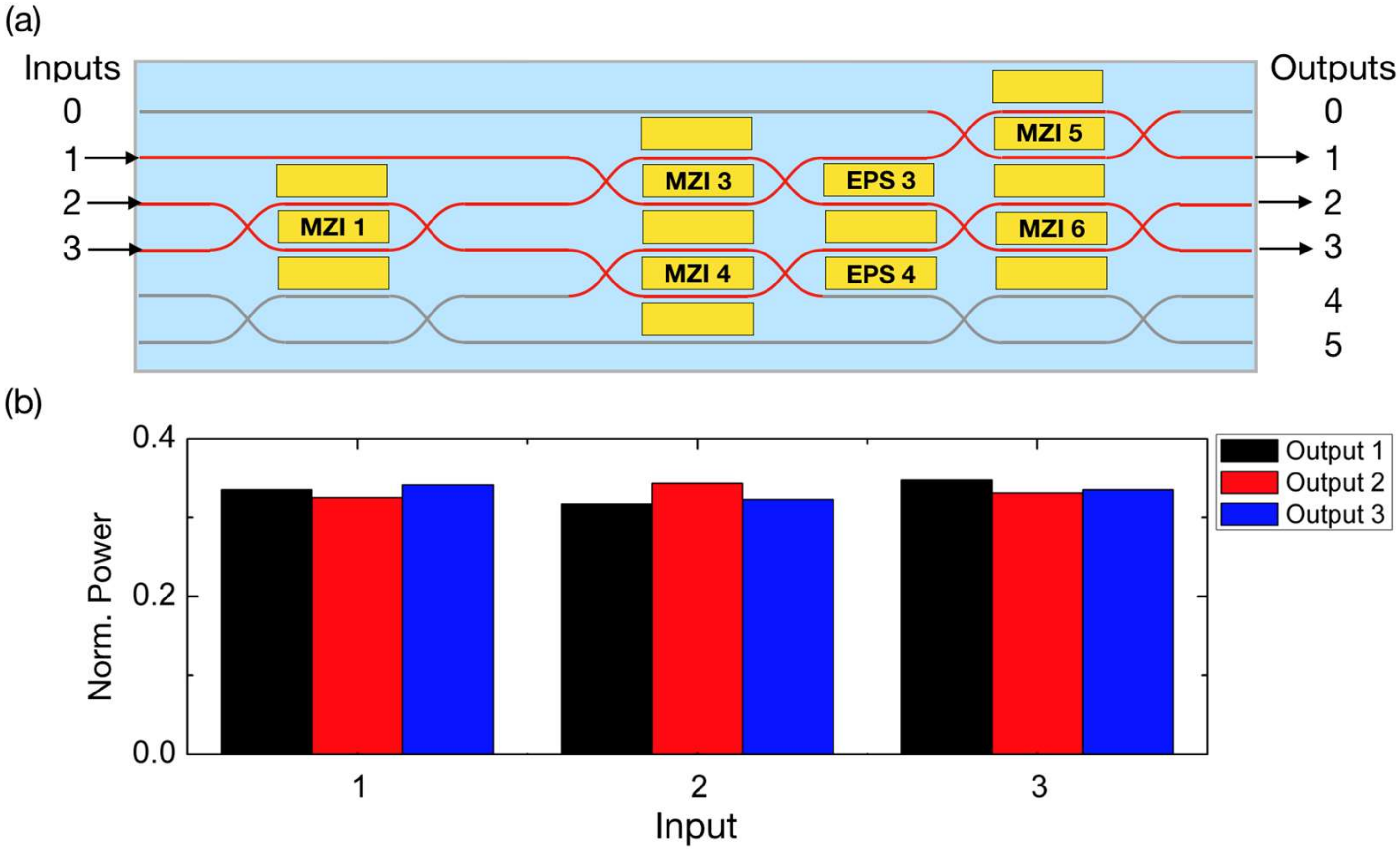
R. Wu, et al., Optics Letters 44, 4698-4701 (2019)

Function 1: 1 x 6 optical switch



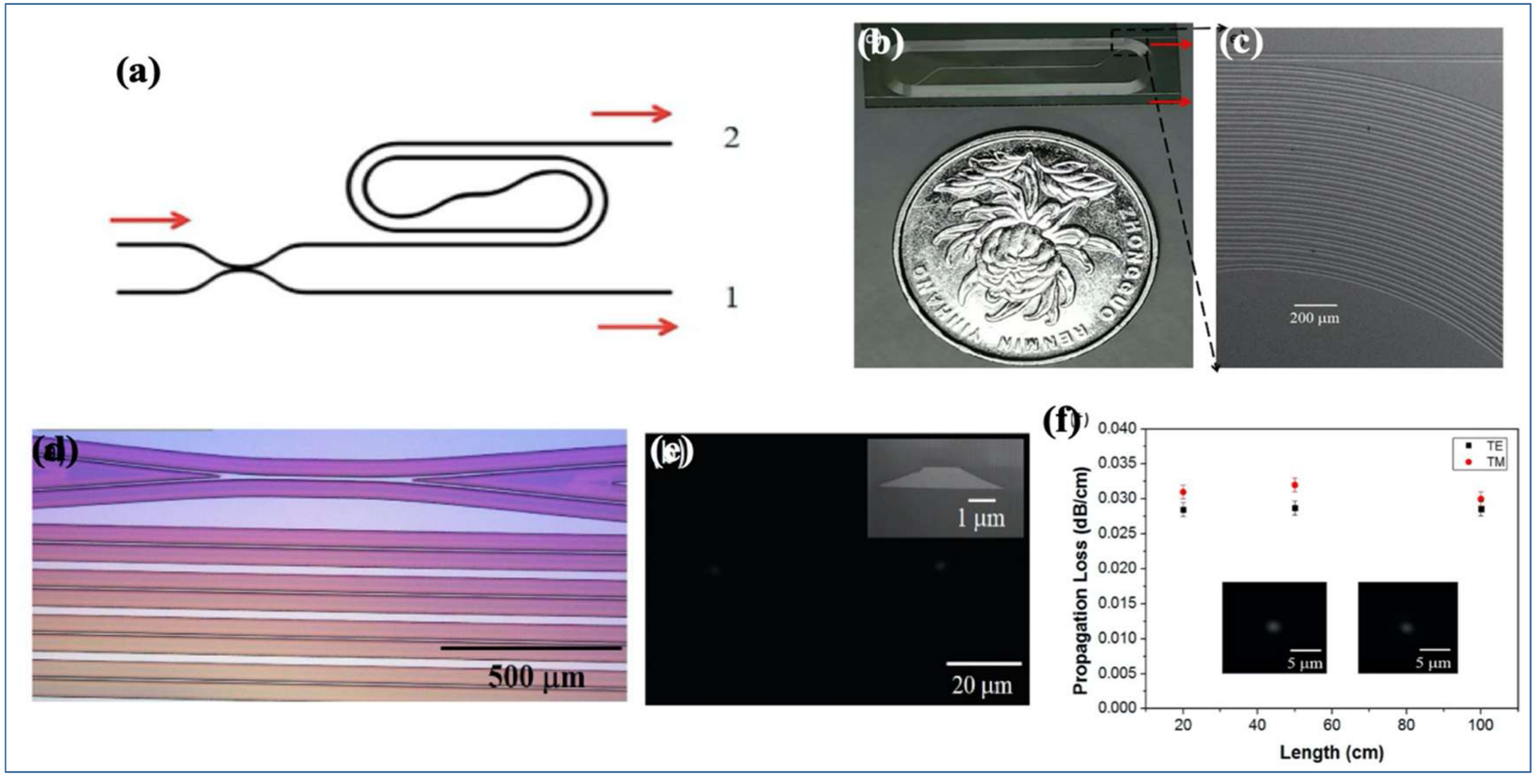
R. Wu, et al., Optics Letters 44, 4698-4701 (2019)

Function 2: 3 x 3 interferometer on chip



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

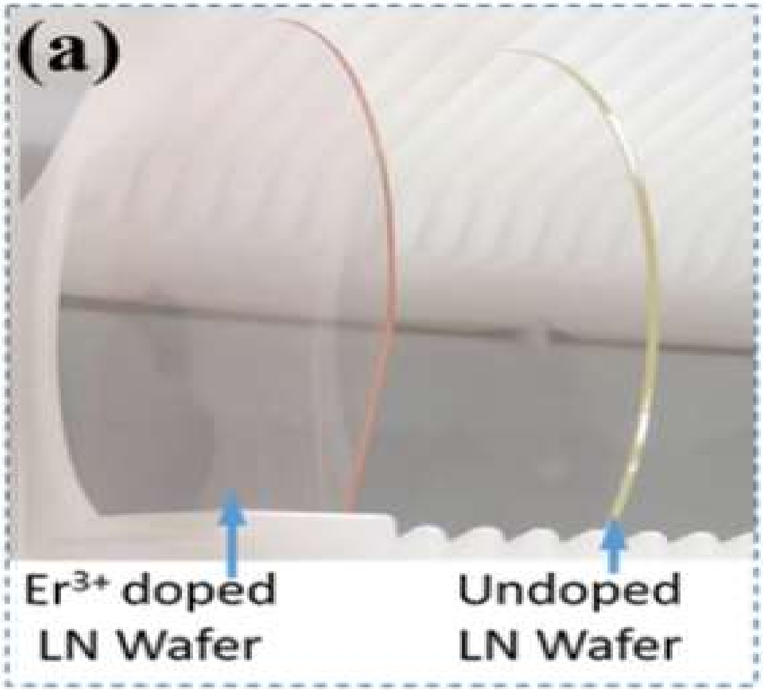
Optical true delay line of a waveguide of 1.1-meter-length

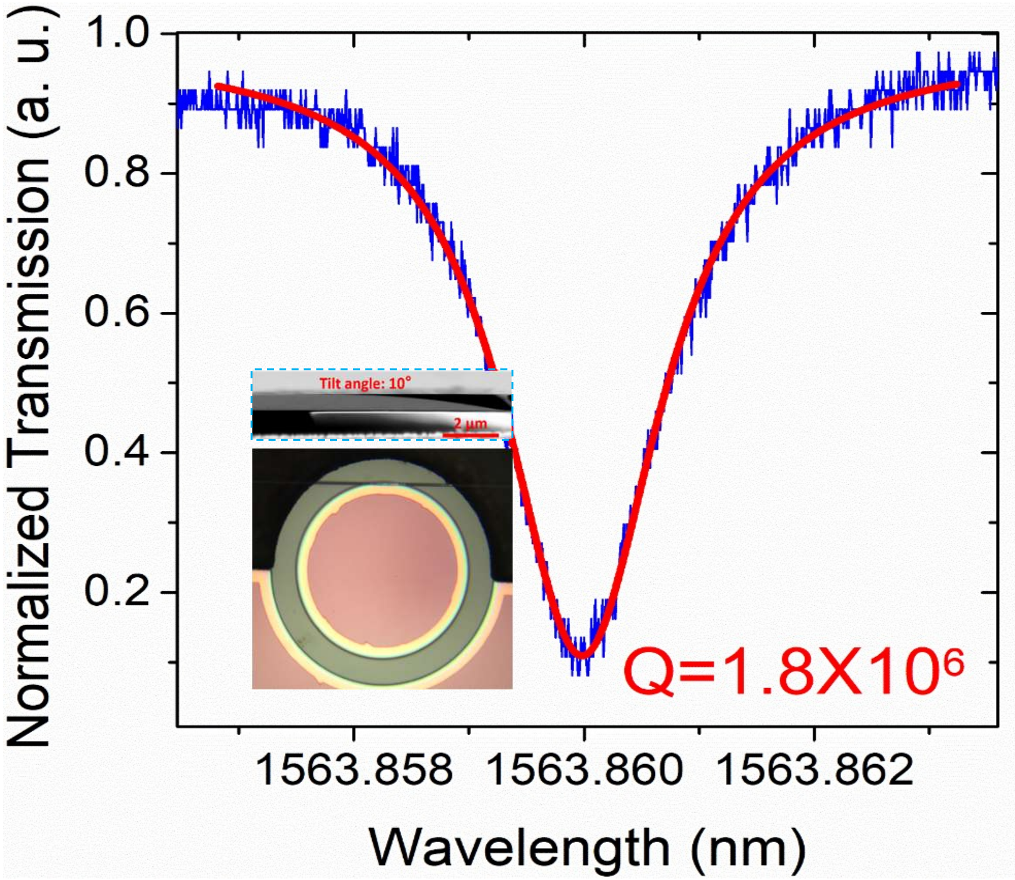


- Total time delay induced in the waveguide: 2.2 ns
- Propagation loss： < 0.03 dB/cm

J. Zhou et al Chin. Phys. Lett. 2020

Microdisk laser fabricated in active LNOI

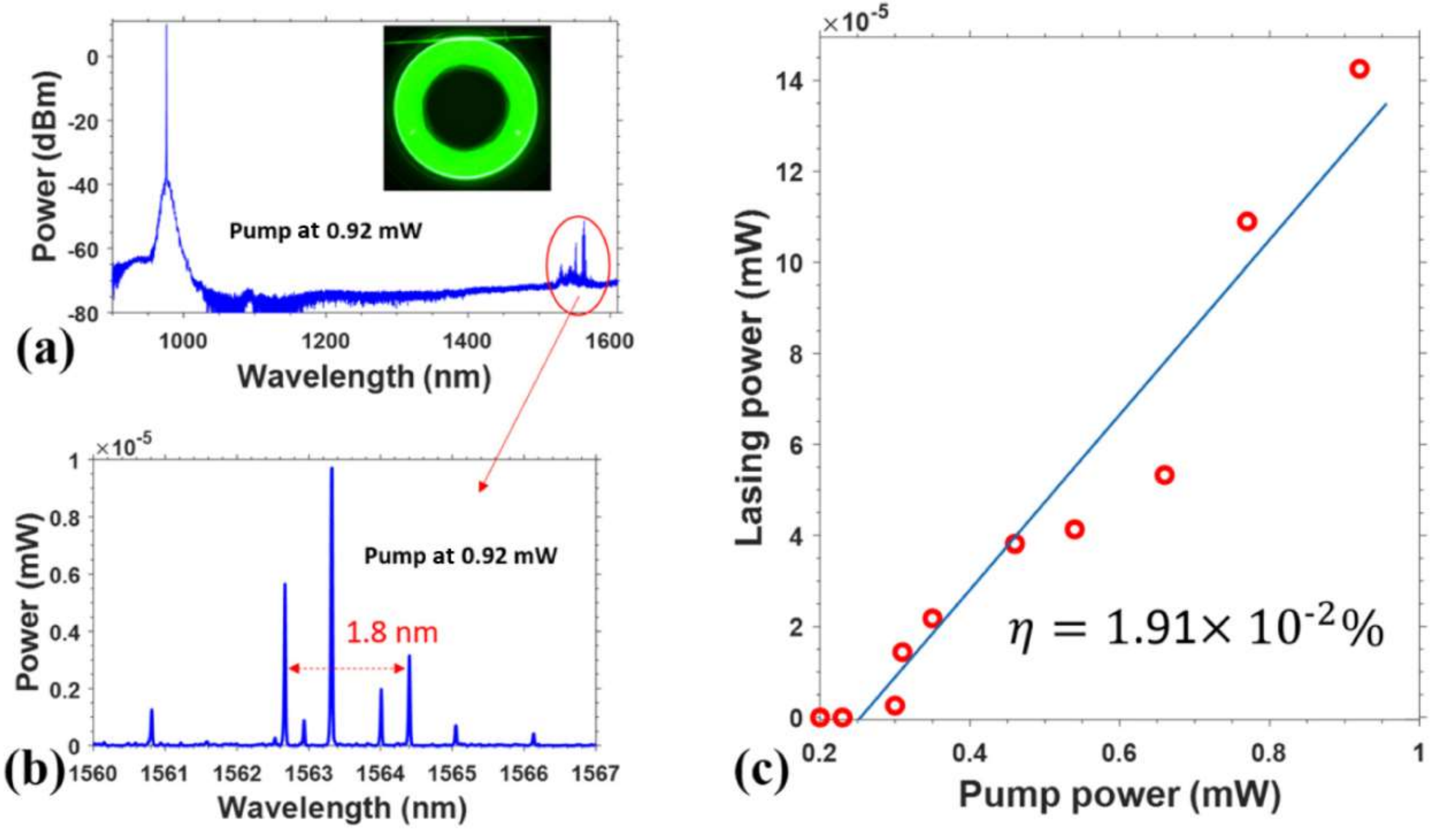




Er^{3+} doped LN wafer
Er^{3+} doped LN thin film made by ion slicing at NANOLN InC, Jinan, China

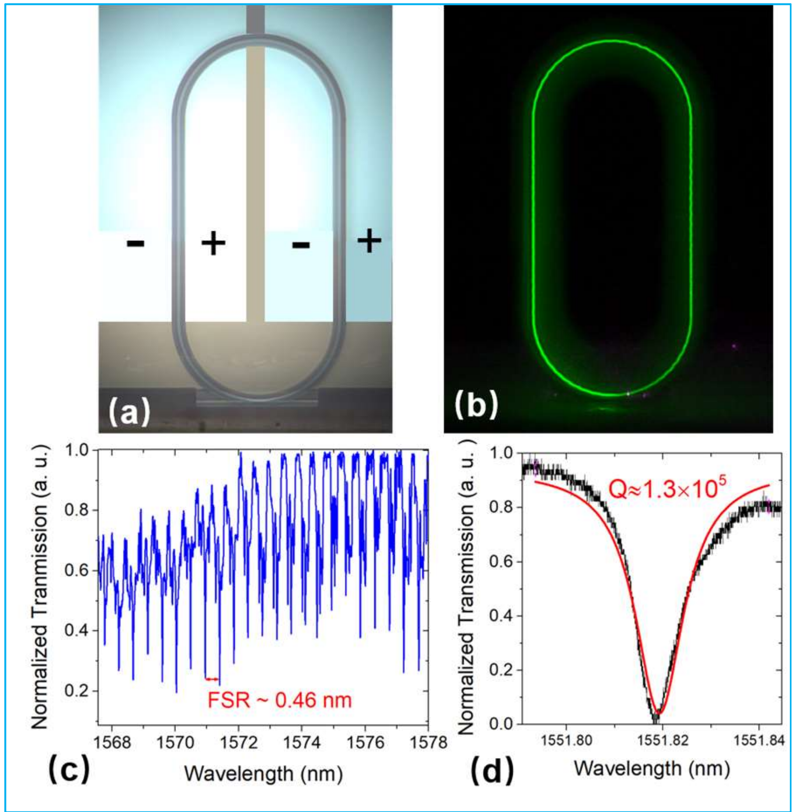
Z. Wang, et al., Opt. Lett. 46, 380-383 (2021).

Characterization of microdisk laser

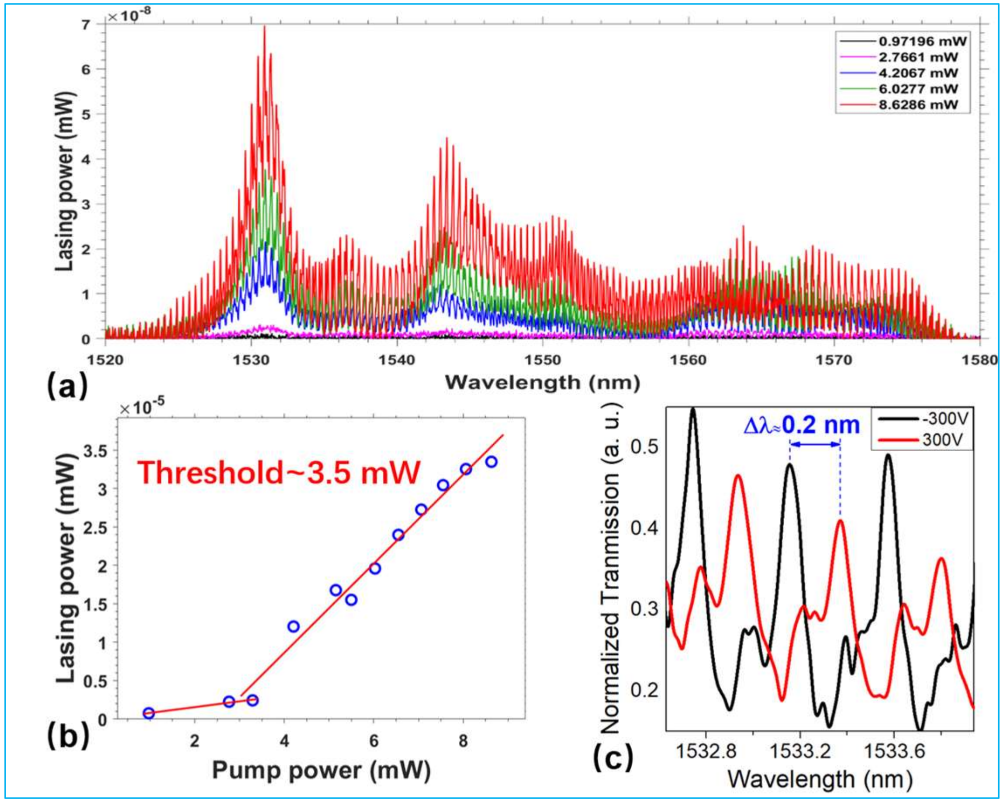


Electro-optically tunable microring laser on LNOI

LN racetrack ring laser monolithically integrated with electrodes

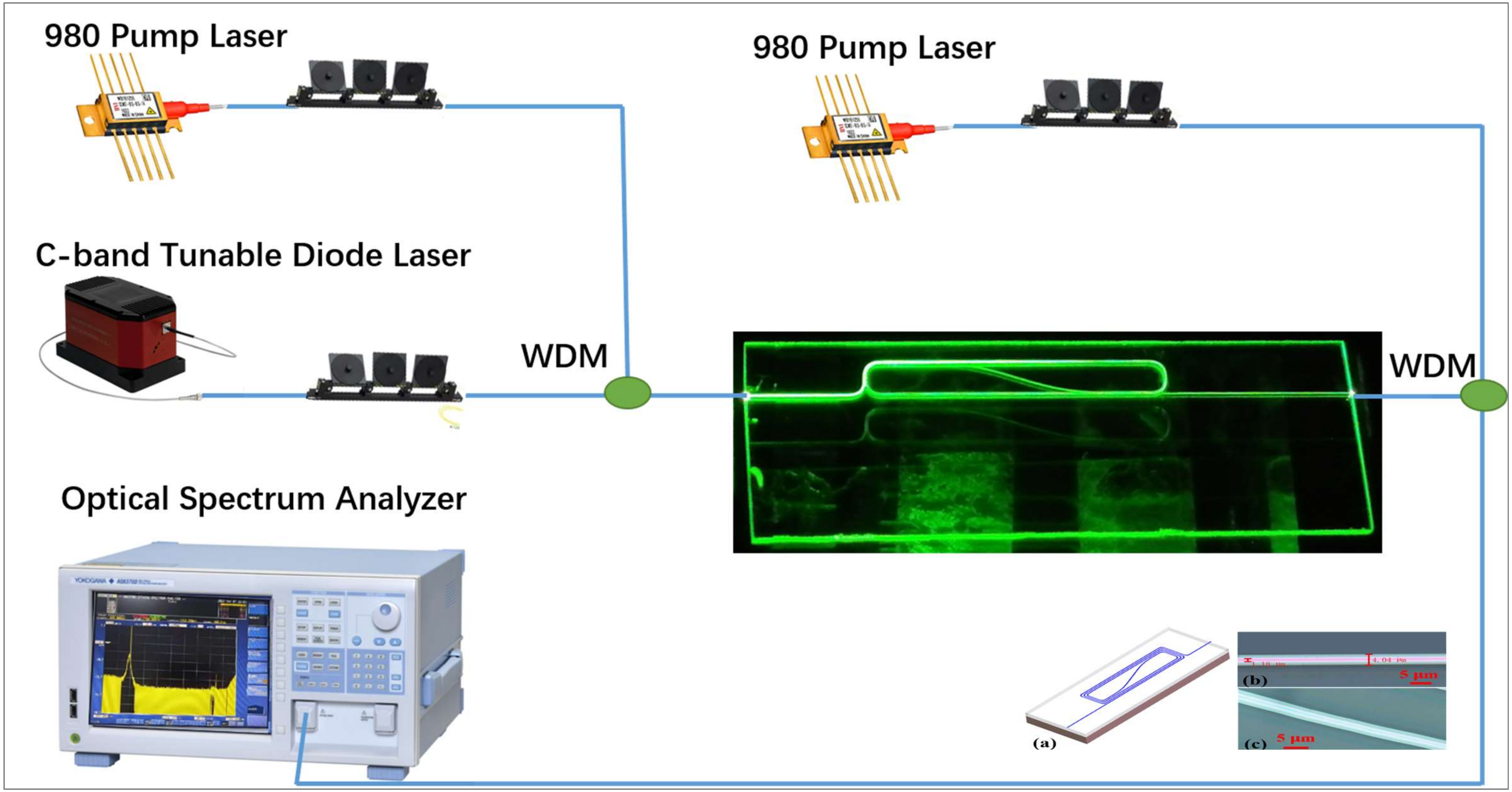


EO tuning coefficient: 0.33 pm/V



D. Yin, et al., Opt. Lett. Accepted

Active waveguide amplifier and its gain characterization



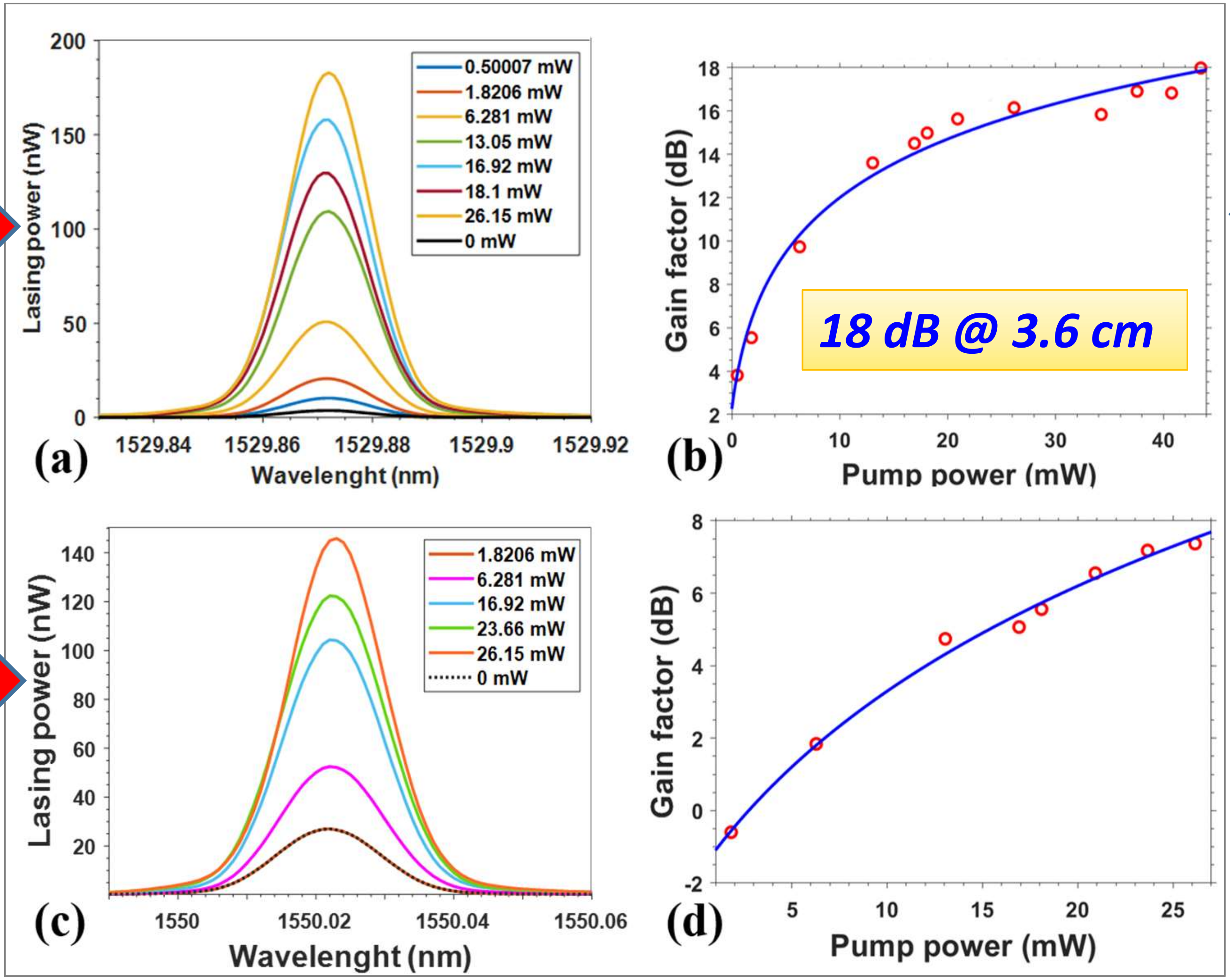
Gain characterization of the Er^{3+} -doped LN waveguides

Signal spectrum at 1530 nm

Gain factor at 1530 nm

Signal spectrum at 1550 nm

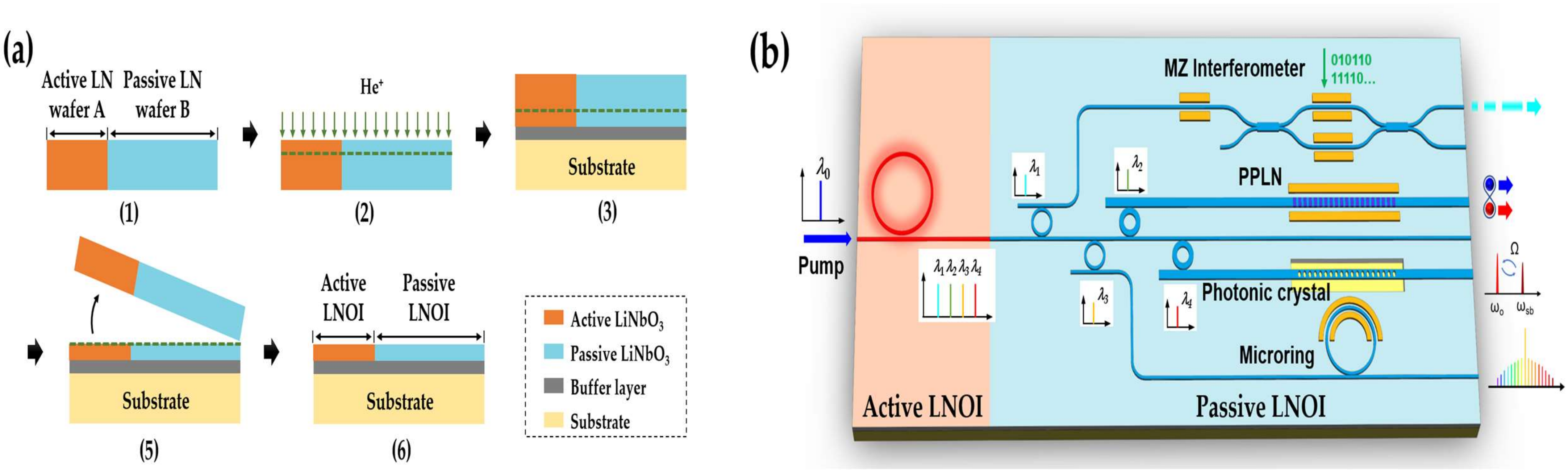
Gain factor at 1550 nm



Maximum gain: 18 dB measured for a 3.6 cm-long waveguide

5. Next milestone to be reached

Almost ready to have active/passive photonic integrated circuits



Basic idea:

1. *Arrange the active and passive components in separated areas of an integrated substrate;*
2. *Fabricate the active and passive structures at once without extra stitching and coupling steps.*
3. *High alignment precision inherently guaranteed using this strategy.*

Conclusions

1. We have developed a fabrication technology to produce large footprint ultra-low loss photonic structures and large scale photonic integrated circuits on lithium niobate.
2. We show optical microresonators with Q factors well above 10^8 and single mode optical waveguides with a loss below ~0.03 dB/cm.
3. We demonstrate highly efficient nonlinear processes from SHG, THG, OPO to optomechanics and comb generation as well as meter-long optical delay line and active waveguide lasers and amplifiers.
4. We believe that large scale active/passive photonic integration is now getting mature and will be achievable soon !

Positions available and collaborations expected, thank you !

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