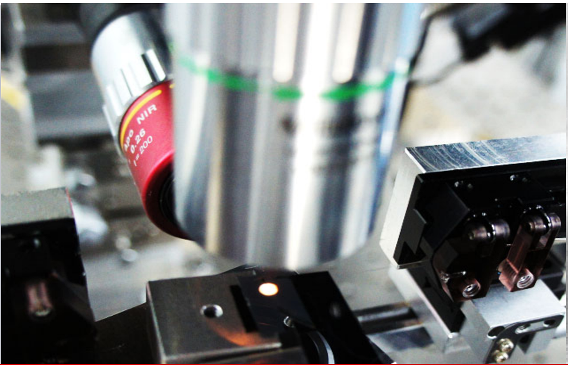
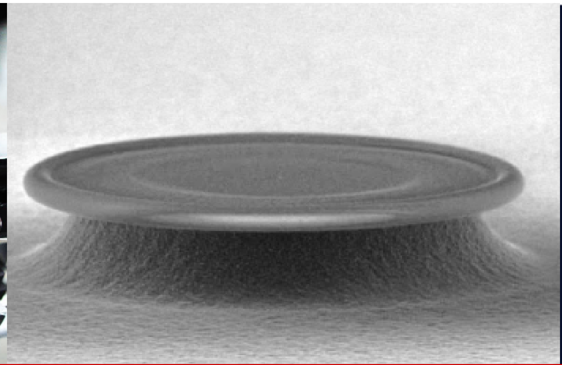
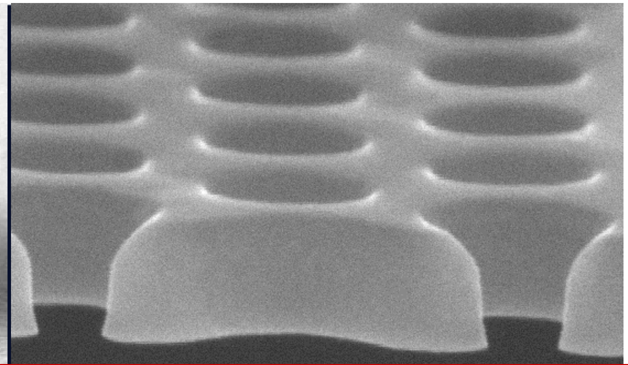
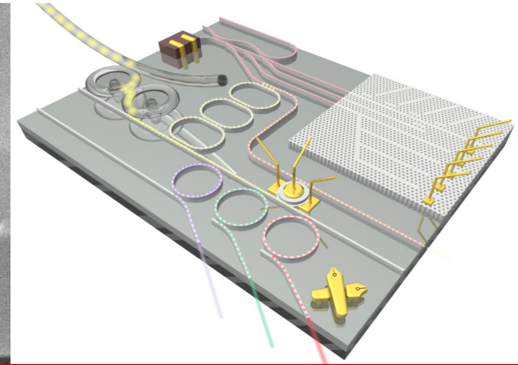

Tu3H.4

Kerr Comb Generation under Weak Dispersion Regime in High-Q Silica Microtoroids

CLEO Pacific Rim 2018 – 31, July

Shun Fujii, Ryo Suzuki, Minori Hasegawa, and Takasumi Tanabe

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Outline

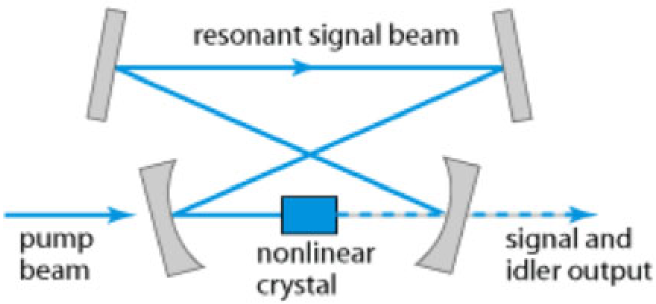
1. Background
   - Optical parametric oscillator
   - Phase-matched four-wave mixing in microresonators
2. Numerical simulation of cavity dispersion
3. Experimental observation
4. Summary

Optical parametric oscillators (OPOs)

$\chi^{(2)}$ Nonlinear crystal

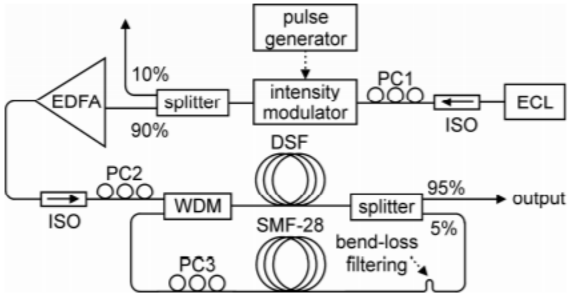
Difference frequency generation

N. Savage, Nat. Photonics **4**, 124 (2010).



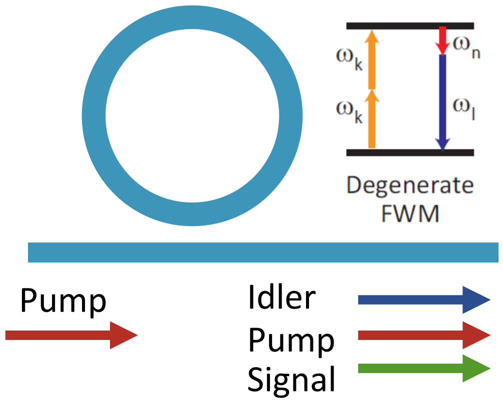
RP Photonics

$\chi^{(3)}$ Optical fiber OPO

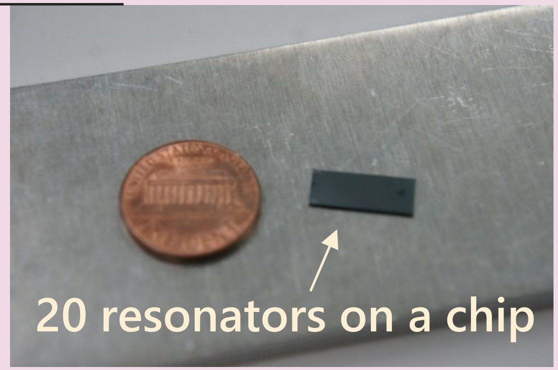


G. K. L. Wong, *et al.* Opt. Express **15**, 2947 (2007).

Degenerate FWM



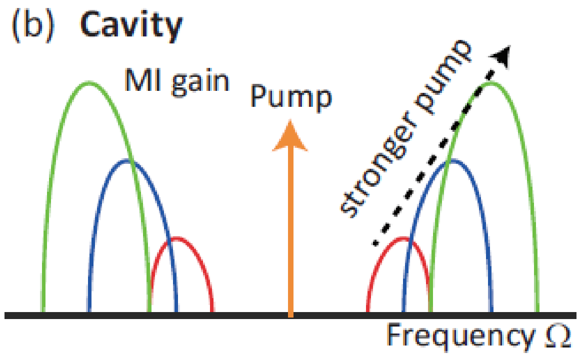
High-Q Microresonators



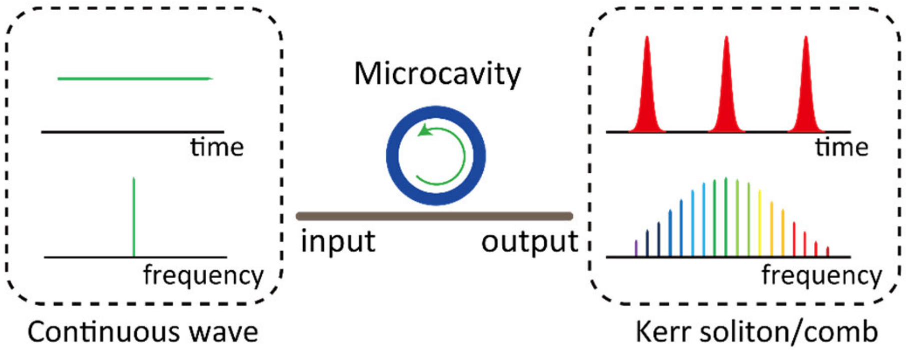
- ✓ *On-chip scale (small)*
- ✓ *Low cost*
- ✓ *Low-power drive*

Phase-matched FWM in microresonators

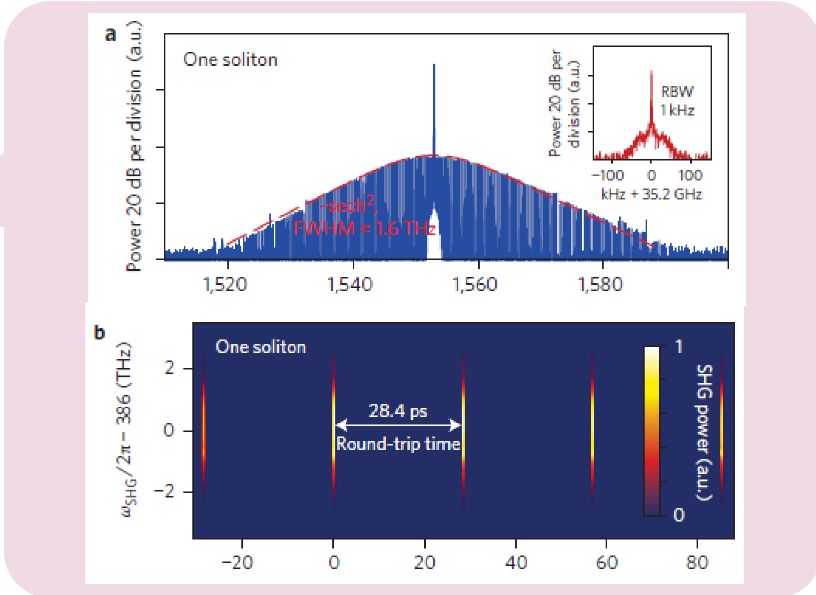
❖ Anomalous dispersion Kerr comb generation



- ✓ **Initial FWM requires modulation instability gain**
- ✓ **MI gain requires *anomalous dispersion***
- ✓ **Balance between Kerr effect and dispersion**



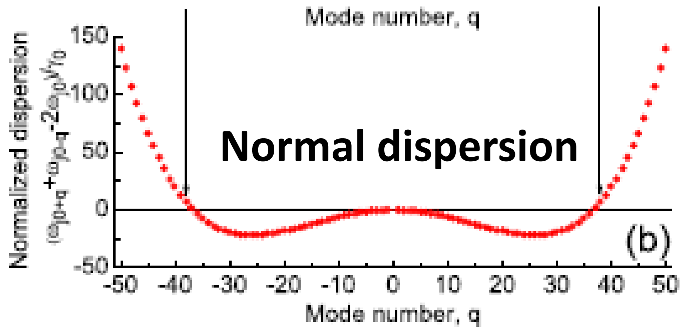
Four-wave mixing (FWM)



T. Herr, *et al.* Nat. Photonics **8**, 145 (2014).

Phase-matched FWM in microresonators

❖ **Scheme in this work (Parametric sideband generation)**

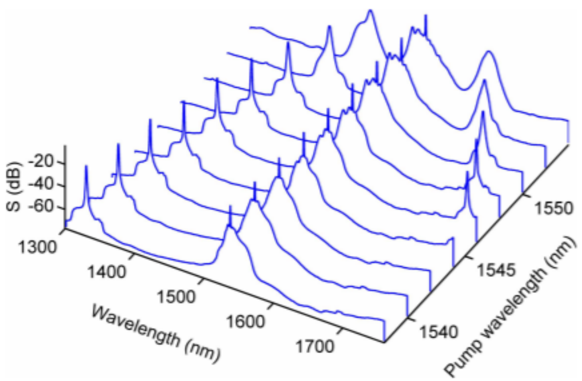


✓ **MI gain achieved by unique phase matching**

✓ **Normal dispersion near pump**

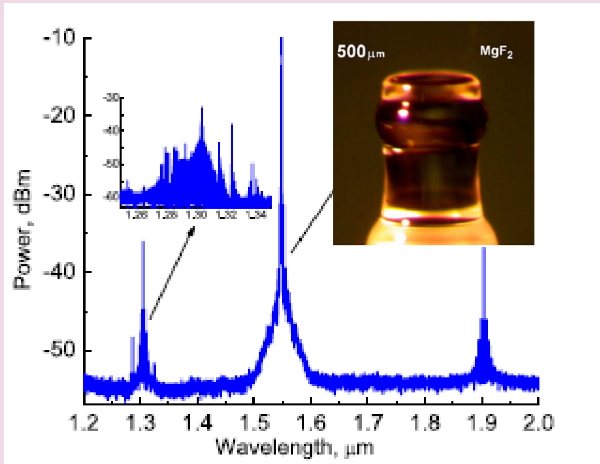
✓ **Phase matching far from pump mode**

Optical fiber OPO



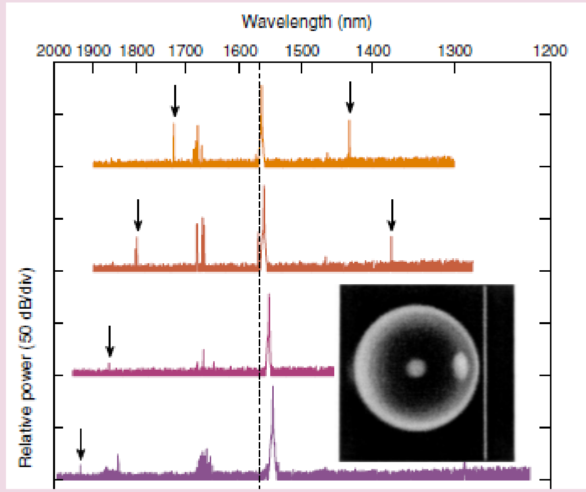
G. K. L. Wong, *et al.* Opt. Express **15**, 2947 (2007).

Bulk magnesium fluoride



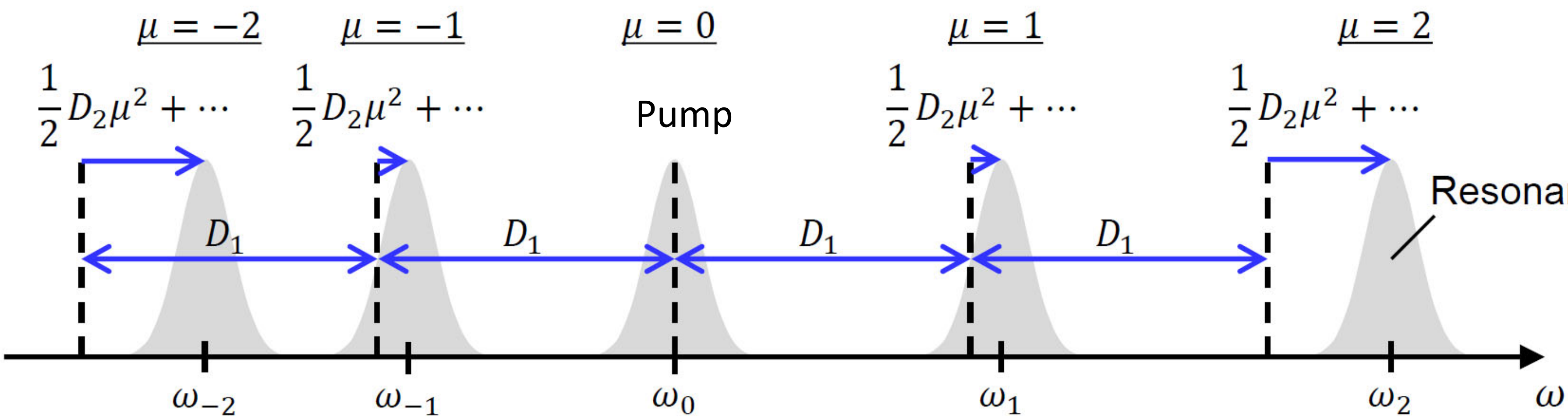
A. B. Matsko, et al., Optics Letters 41, 5102 (2016)

Silica microspheres



N. L. B. Sayson, et al., Optics Letters 42, 5190 (2017)

Definition of cavity dispersion



Resonance frequencies (μ is mode number)

$$\omega_\mu = \omega_0 + D_1\mu + \underline{\frac{1}{2}D_2\mu^2 + \frac{1}{6}D_3\mu^3 + \frac{1}{24}D_4\mu^4}$$

Total dispersion

$D_2 > 0$: Anomalous dispersion
$D_2 < 0$: Normal dispersion

Phase-matching condition (residual dispersion) for initial sidebands

$$\Delta\omega = \omega_\mu - \omega_0 - (\omega_0 - \omega_{-\mu}) = D_2\mu^2 + \frac{D_4}{12}\mu^4 \rightarrow 0$$

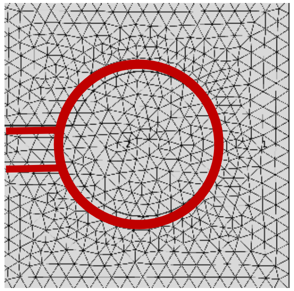
$$\mu^2 = -\frac{12D_2}{D_4} \quad (D_2 \cdot D_4 < 0)$$

Fourth-order dispersion plays important role in phase-matched FWM!

Cavity dispersion calculation method

Geometry dispersion

Finite element method



Resonance frequency (Hz)

COMSOL

Sellmeier equation

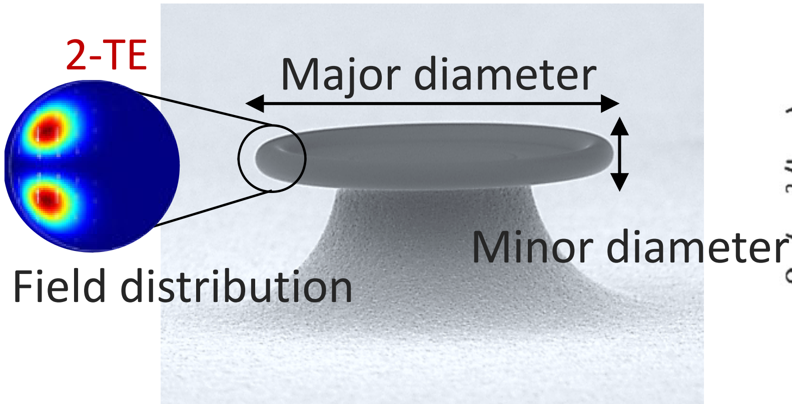
Refractive index

Material dispersion

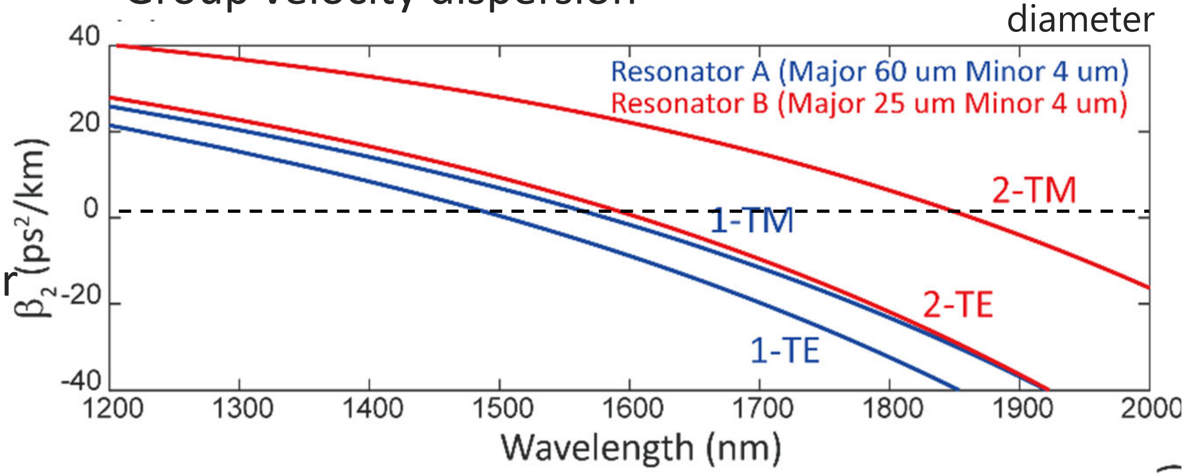
$$n^2 = 1 + \sum_i \frac{A_i \cdot \lambda^2}{\lambda^2 - B_i^2}$$

A, B : coefficient (const.)

Silica toroid microresonator

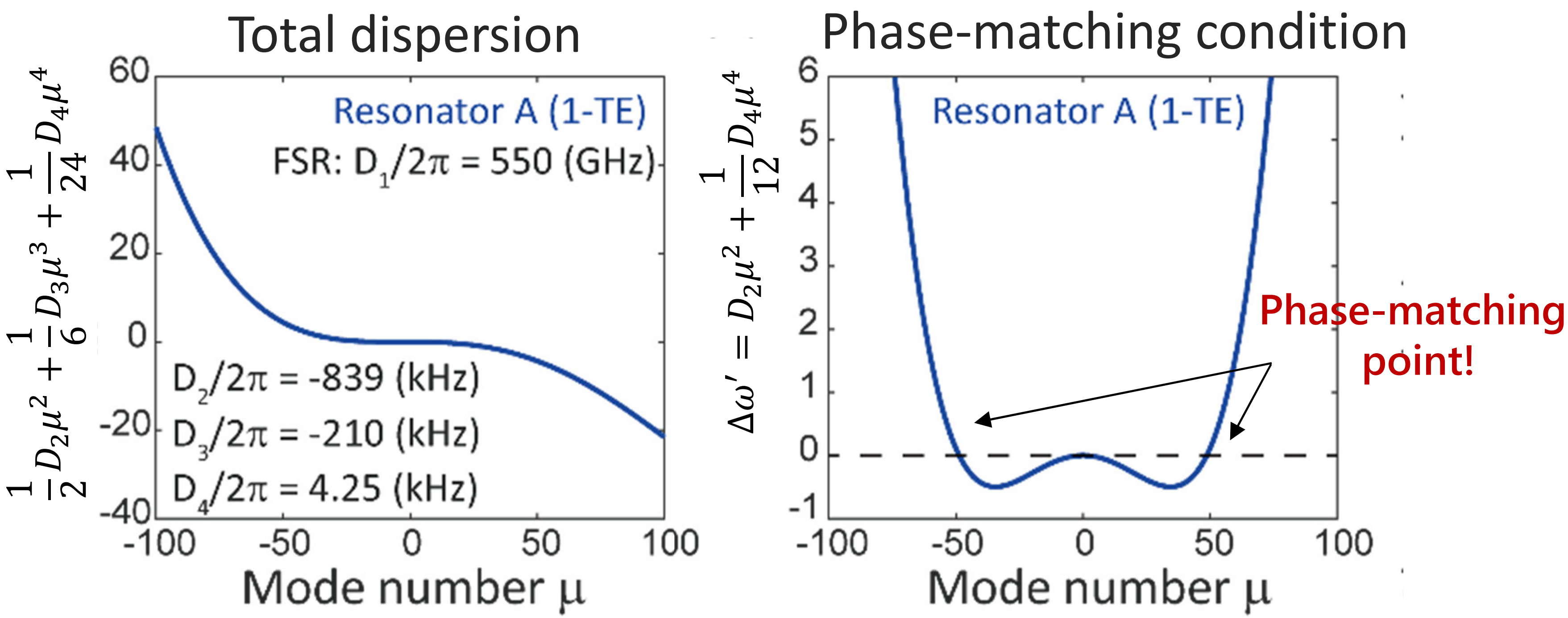


Group velocity dispersion



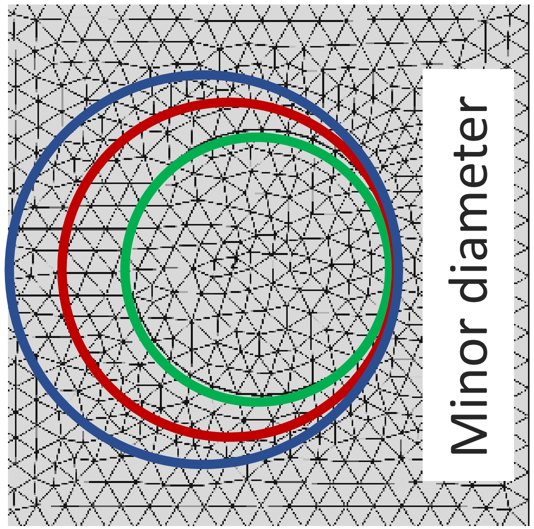
Phase-matching points depending on cavity geometry

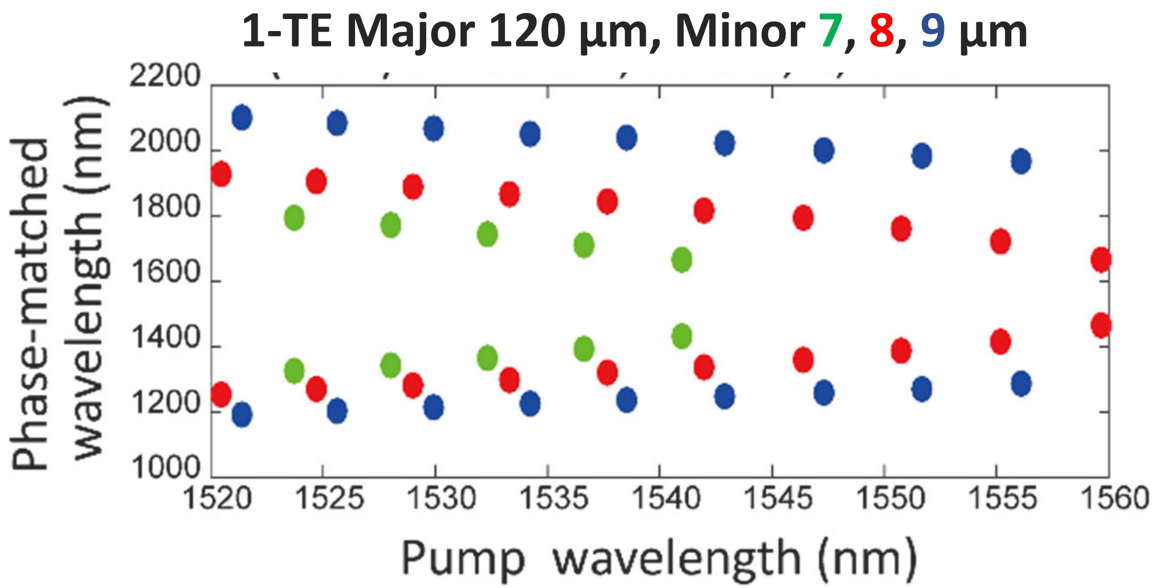
Major diameter 120 μm, Minor diameter 8 μm, 1-TE mode



Initial FWM occurs at points $\Delta\omega$= 0

Phase-matching points depending on cavity geometry



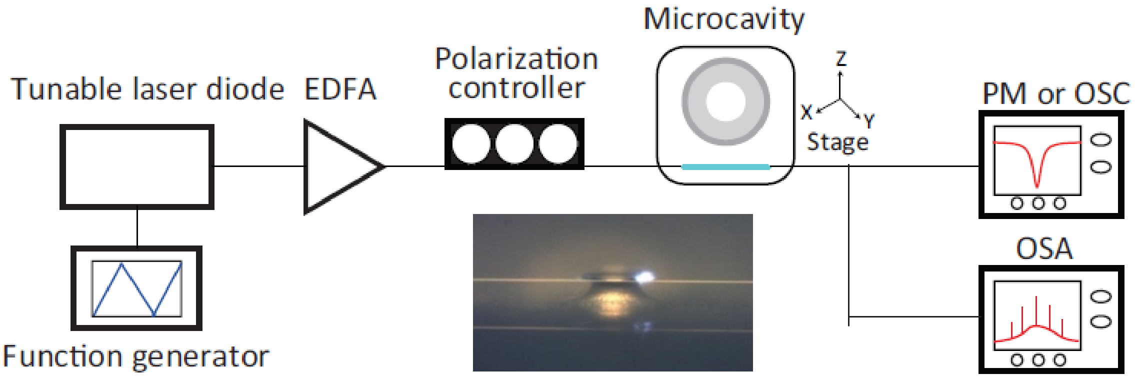


Phase-matched wavelength can be controlled by changing pump or geometry

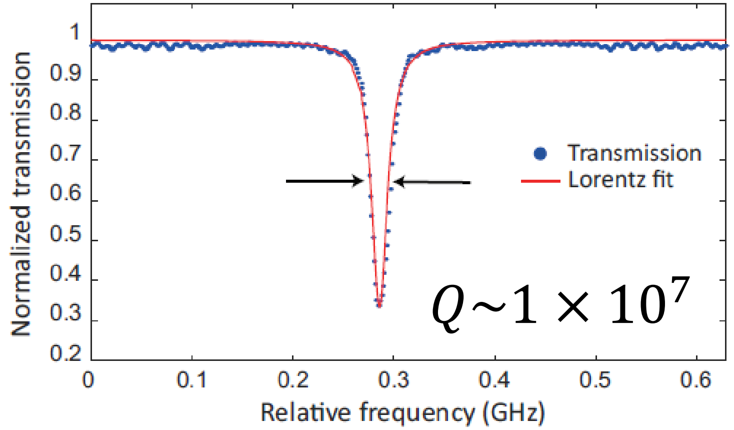
This method offers chip-scale arbitrary frequency generators (convertors)!

Experimental setup and optical properties

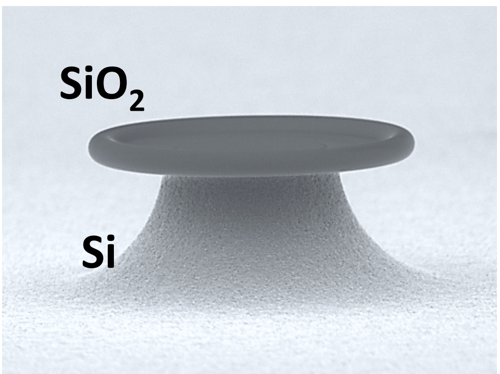
Experimental setup



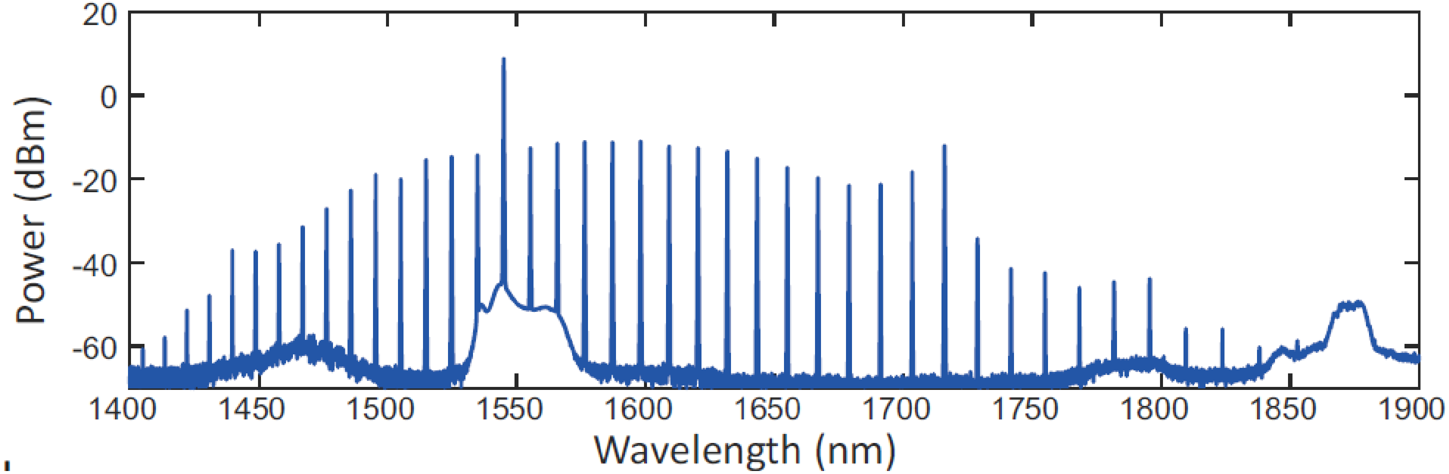
Transmission spectrum



Silica toroid microresonator

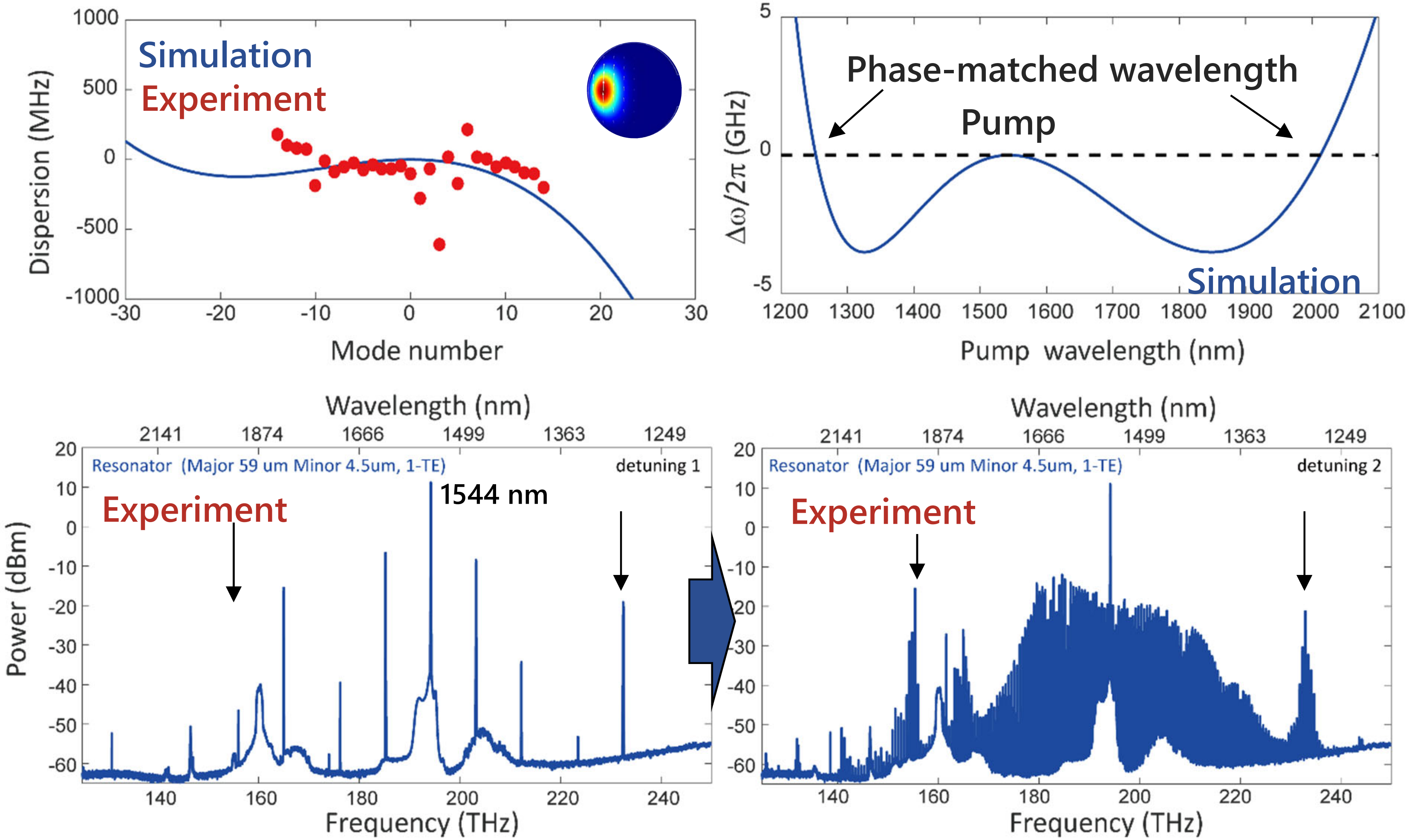


Optical spectrum (anomalous dispersion Kerr comb)



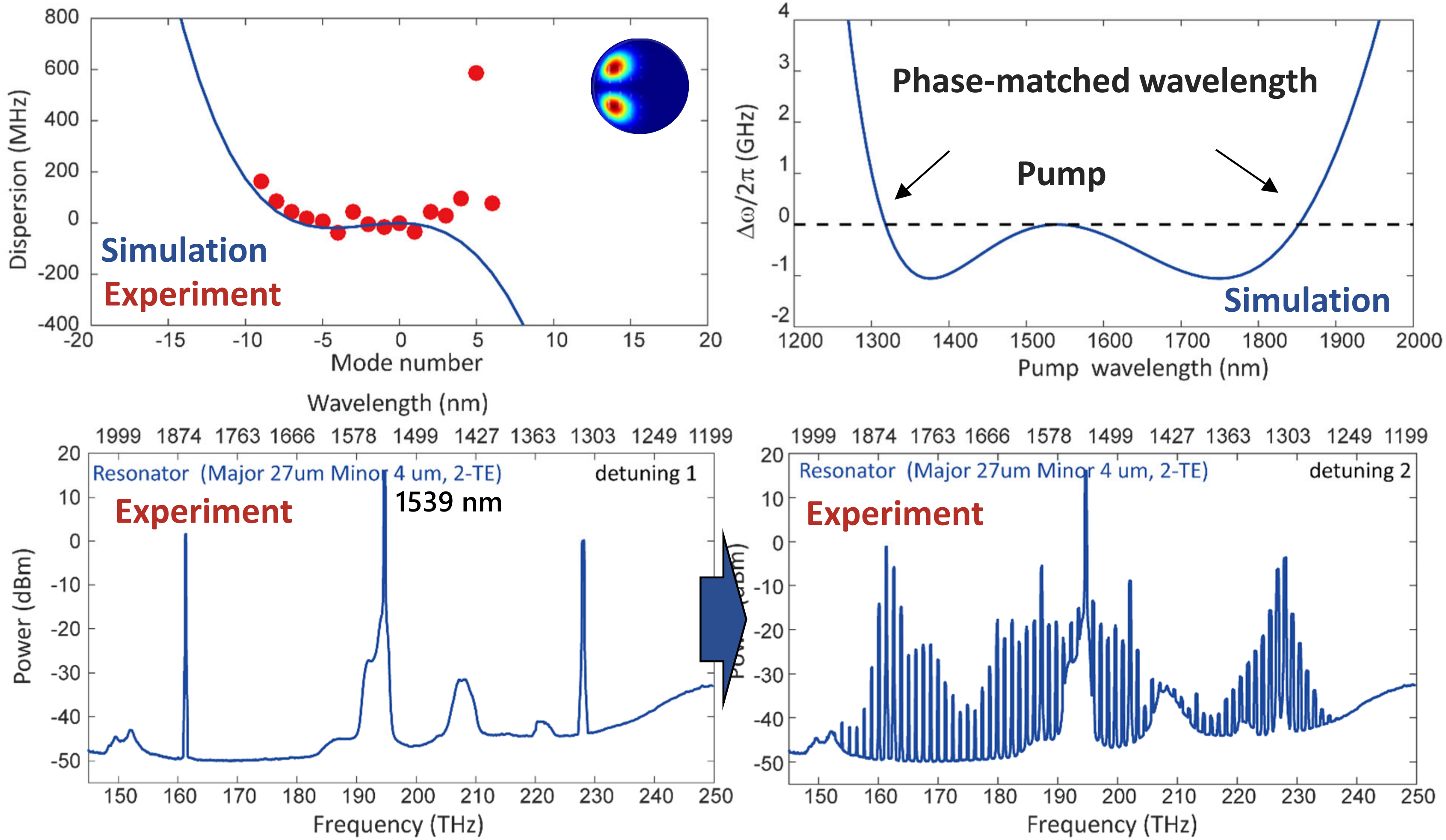
Observation of OPO in Resonator A

Major diameter 118 µm   Minor diameter 9 µm   1-TE mode



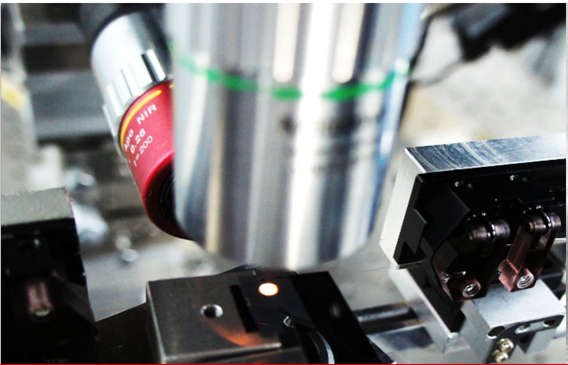
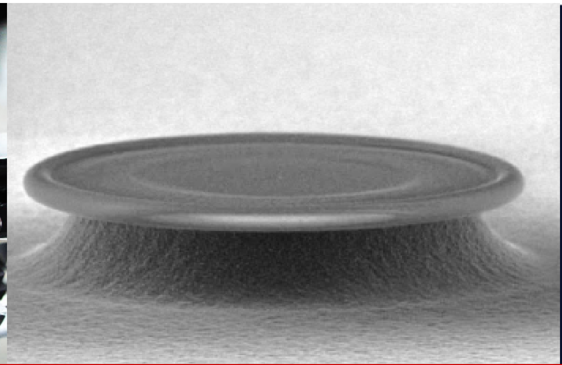
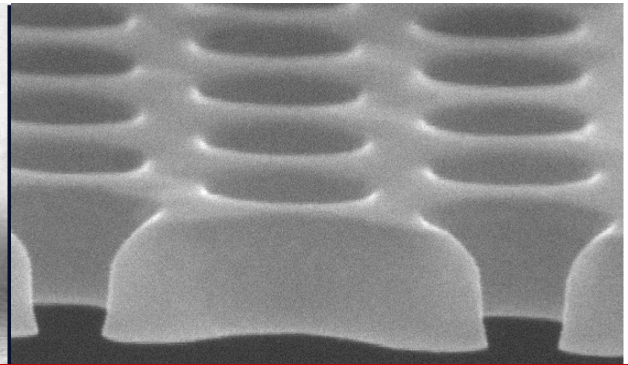
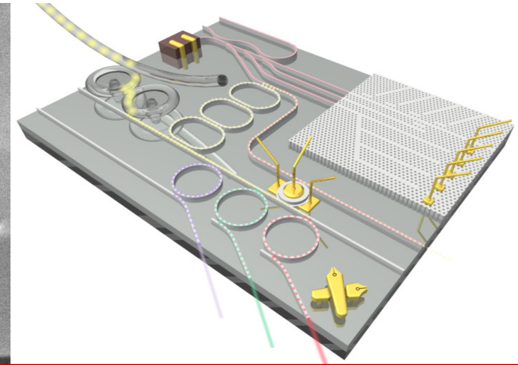
Observation of OPO in Resonator B

Major diameter 54 µm   Minor diameter 8 µm   2-TE mode



Summary

- Demonstrated optical parametric oscillation in on-chip high-Q silica toroid microresonator
- Investigated dependence of phase-matching condition on pump wavelength and cavity geometry
- Observed pure OPO signals and broadband four-wave mixing light by changing pump wavelength

Thank you for your attention

Funding information

- Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the Photon Frontier Network
- MEXT KAKENHI Grant Number JP15H05429
- JSPS KAKENHI Grant Number JP223605