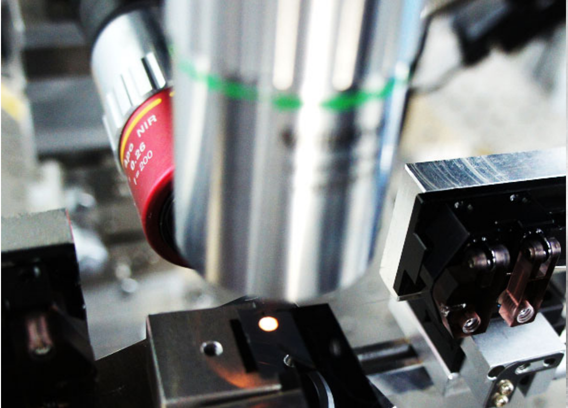
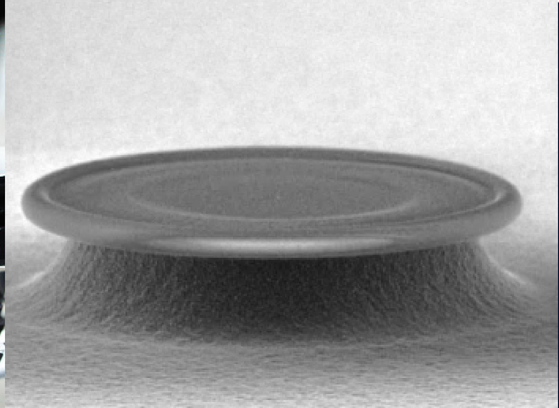
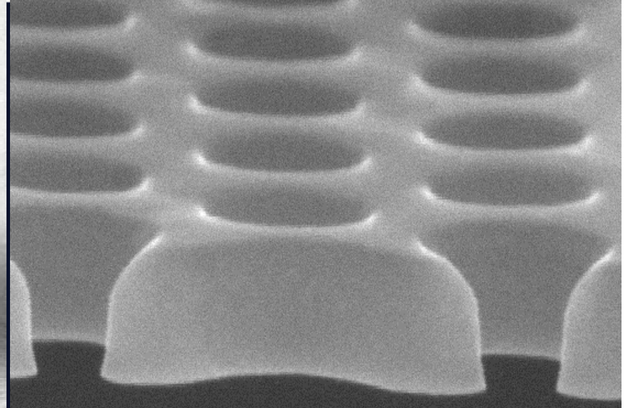
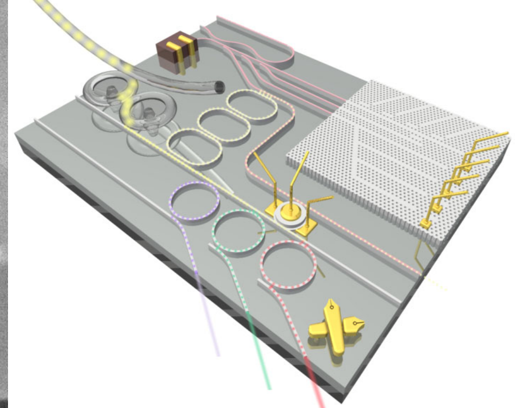





ALPS5-I1-7

Nonlinear Parametric Oscillation Phase-matched via High-order Dispersion in High-Q Silica Toroid Microresonators

ALPS2018, 24, April, 2018

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

Department of Electronics and Electrical Engineering,
Faculty of Science and Technology, Keio University, Japan

Outline

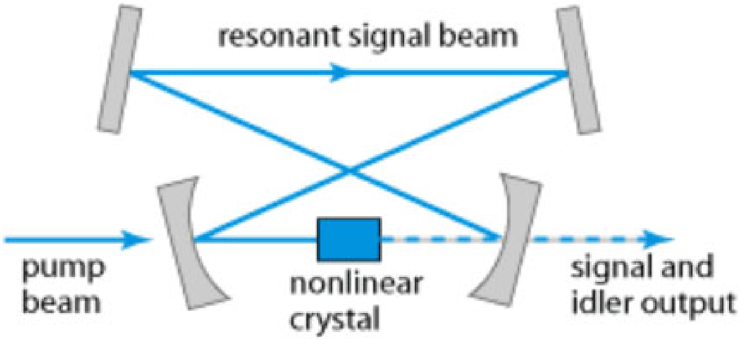
1. Background
   - Optical parametric oscillator
   - Phase-matched four-wave mixing in microresonators
2. Numerical simulation of cavity dispersion
3. Experimental observation
4. Summary

Optical parametric oscillators (OPOs)

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

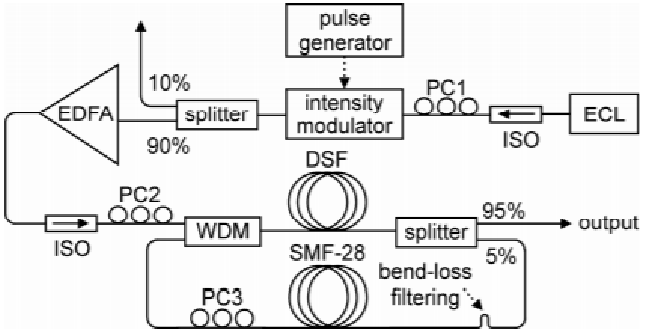
<u>Difference frequency generation</u>

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



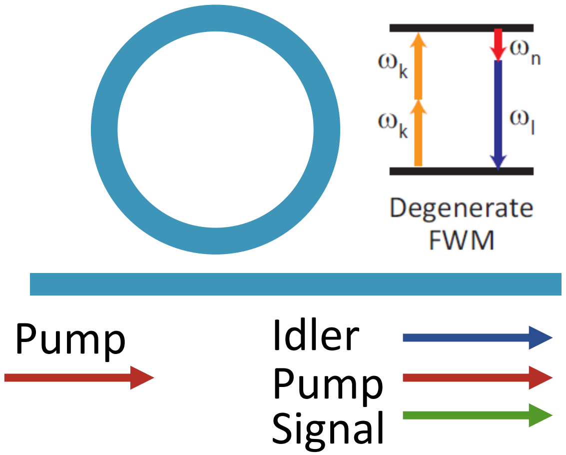
RP Photonics

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

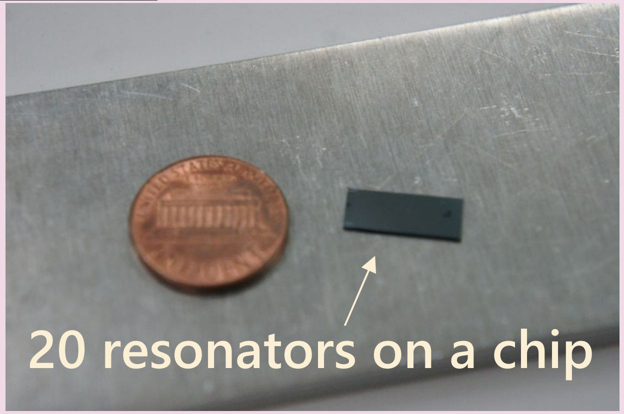


G. K. L. Wong, *et al.* Opt. Express **15**, 2947 (2007).

<u>Degenerated FWM</u>



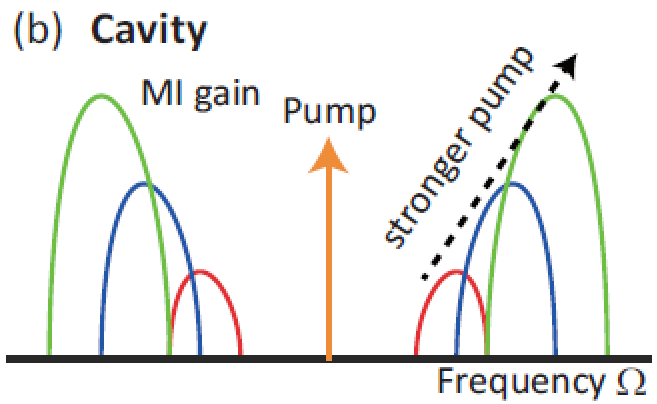
High-Q Microresonators



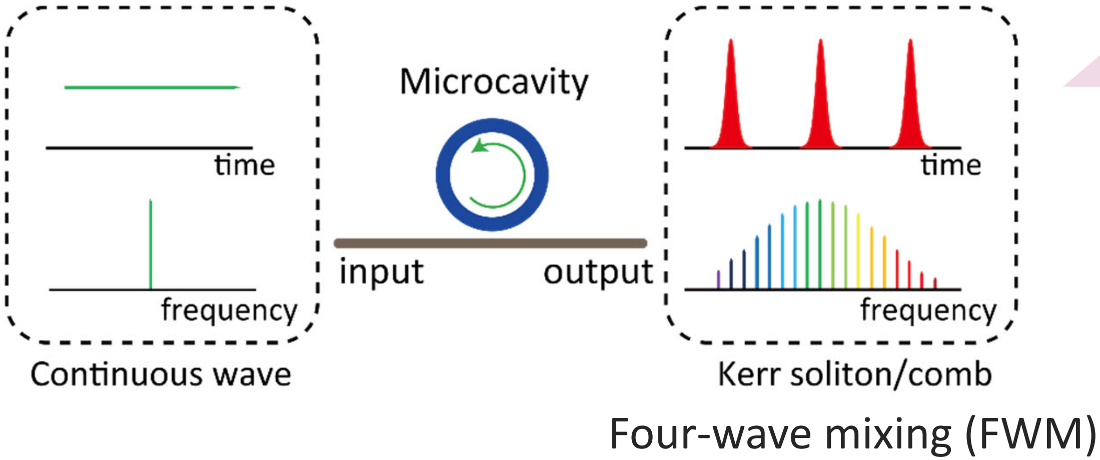
- ✓ *<u>On chip-scale (small)</u>*
- ✓ *<u>Low cost</u>*
- ✓ *<u>Low-power drive</u>*

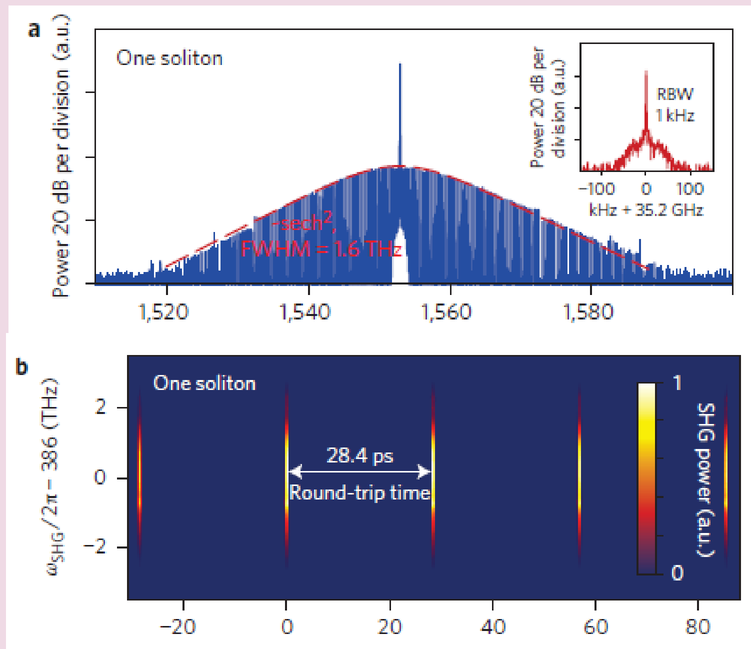
Phase-matched FWM in microresonators

❖ Anomalous dispersion Kerr comb generation



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

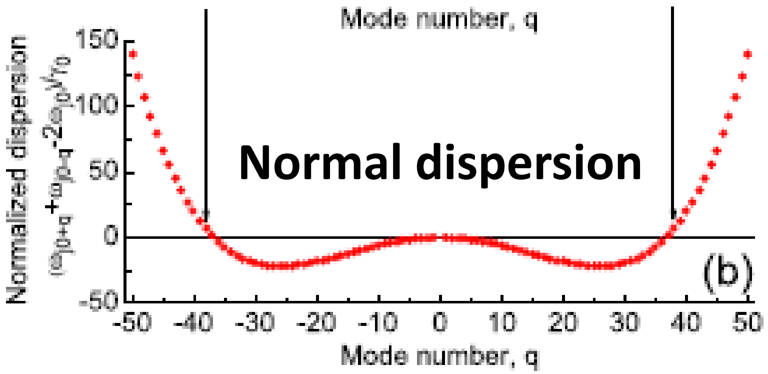




T. Herr, *et al.* Nat. Photonics **8**, 145 (2014).

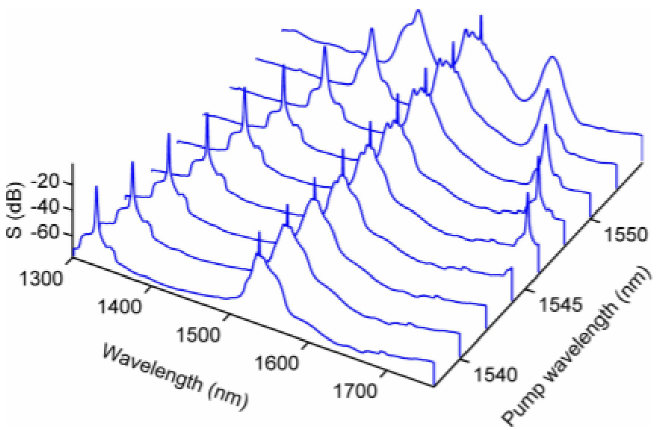
Phase-matched FWM in microresonators

❖ Scheme in this work (Parametric sideband generation)



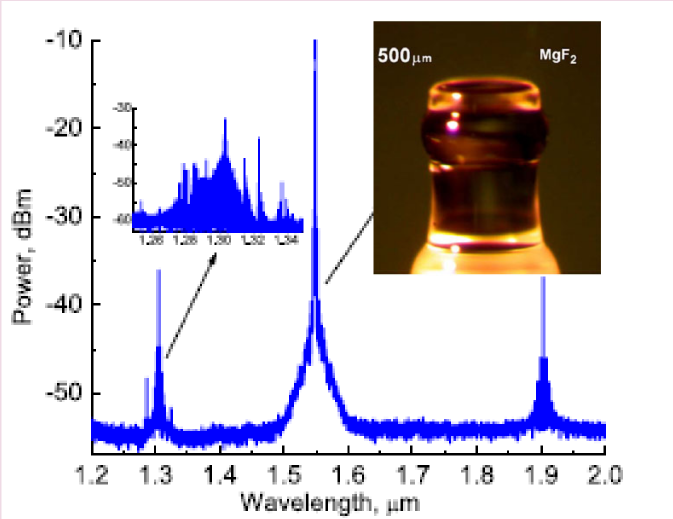
- ✓ MI gain is achieved by unique phase-matching
- ✓ Dispersion near the pump is normal
- ✓ **Phase-matching far from the pump mode**

Optical fiber OPO



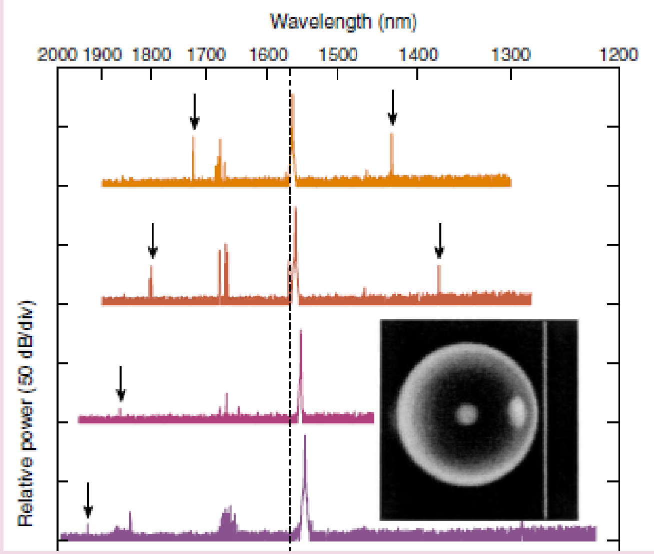
G. K. L. Wong, *et al.* Opt. Express **15**, 2947 (2007).

Bulk magnesium fluoride



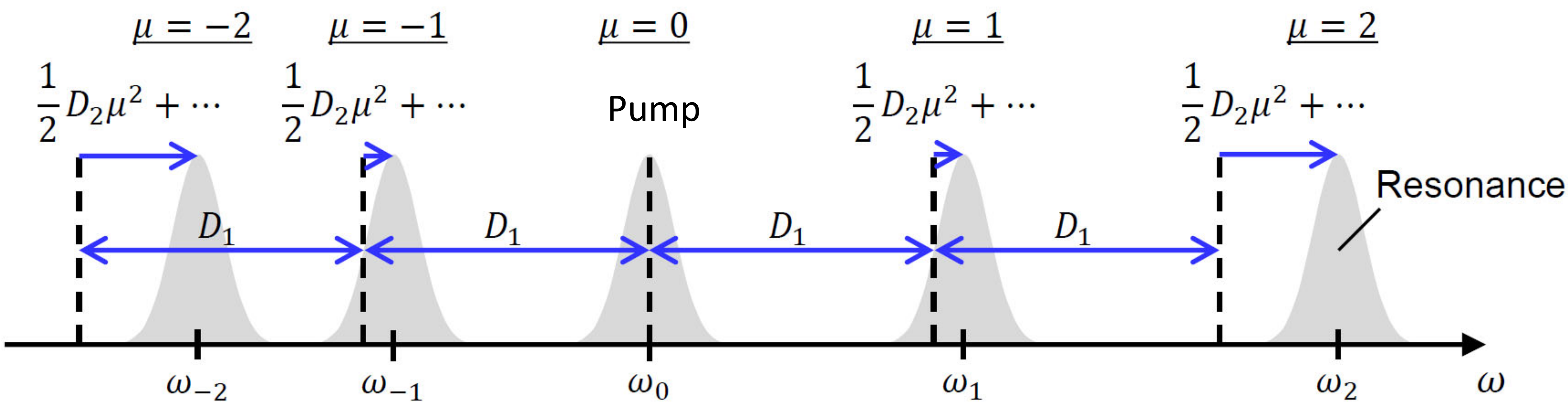
A. B. Matsko, et al., Optics Letters 41, 5102 (2016)

Silica microspheres



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

Definition of cavity dispersion



Resonance frequencies (μ is mode number)

$$\omega_\mu = \omega_0 + D_1\mu + \underbrace{\frac{1}{2}D_2\mu^2 + \frac{1}{6}D_3\mu^3 + \frac{1}{24}D_4\mu^4}_{\text{Total dispersion}}$$

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

Phase-matching condition (residual dispersion) for initial sidebands

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

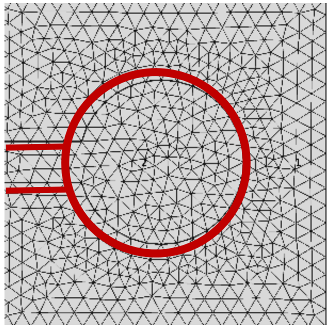
$$\mu^2 = -\frac{12D_2}{D_4} \quad (D_2 \cdot D_4 < 0)$$

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

Calculation method of cavity dispersion

Geometry dispersion

Finite-element method



Resonance frequency (Hz)

COMSOL   Sellmeier equation

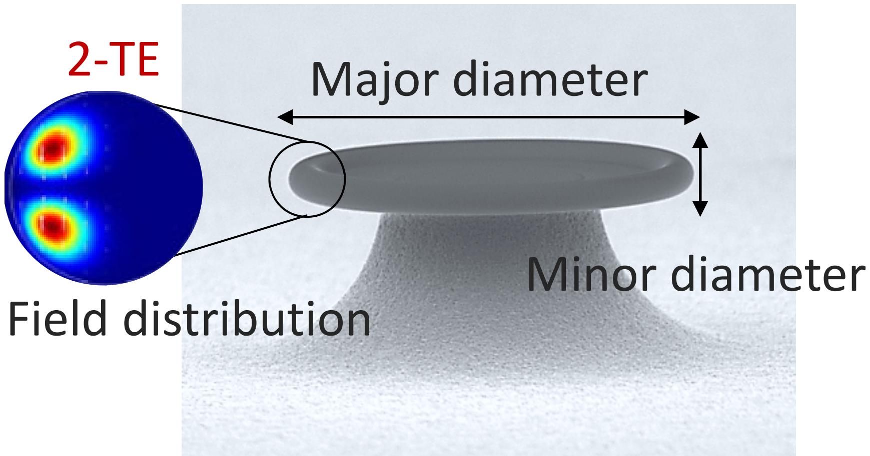
Refractive index

Material dispersion

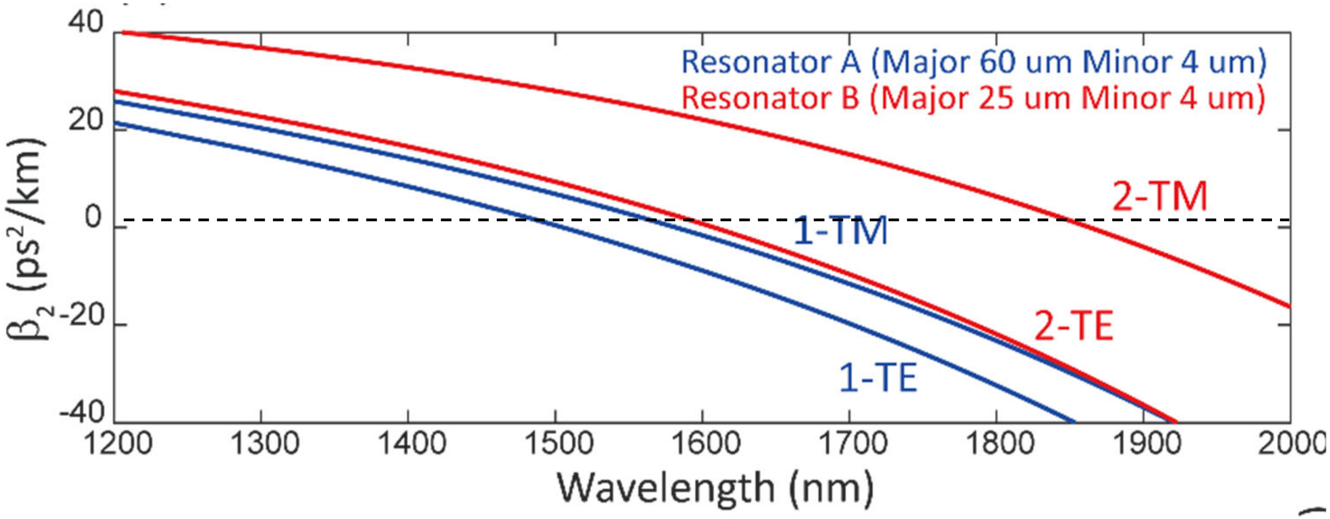
$$n^2 = 1 + \sum_i \frac{A_i \cdot \lambda^2}{\lambda^2 - B_i^2}$$

A, B : coefficient (const.)

Silica toroid microresonator



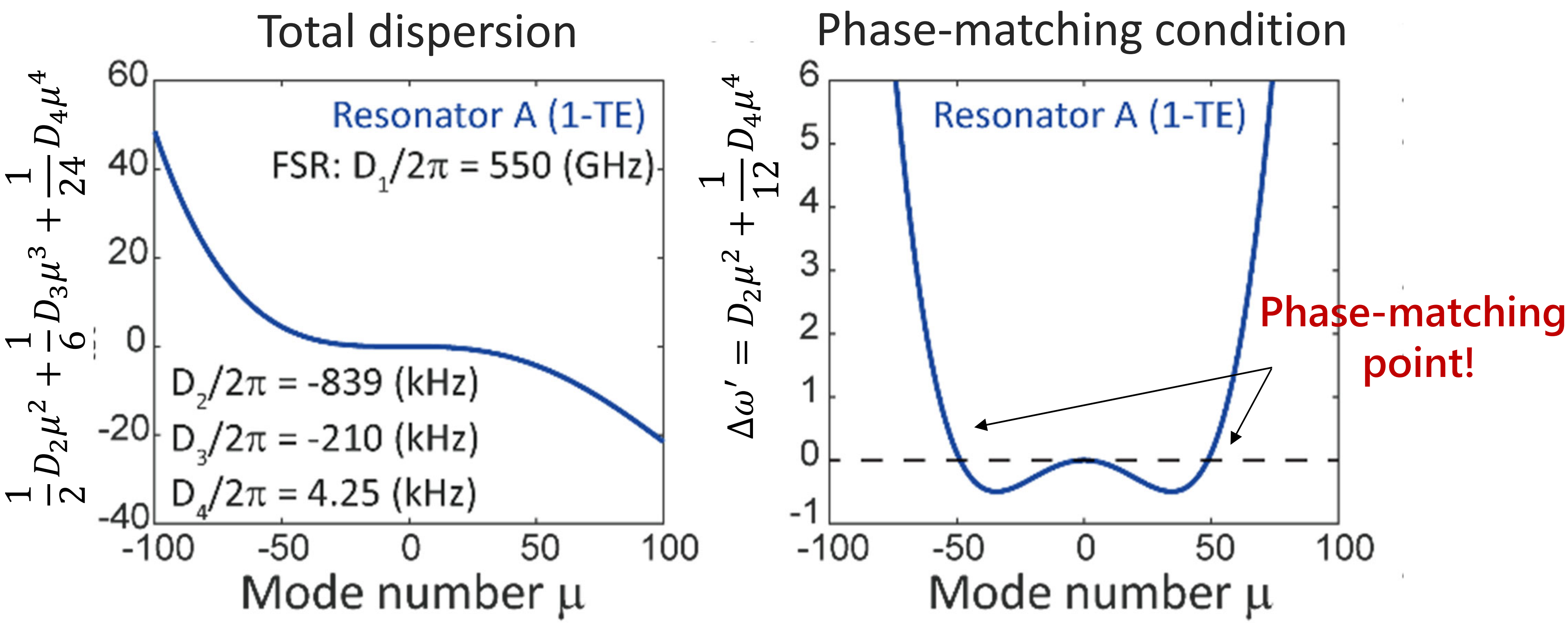
Group velocity dispersion



 |

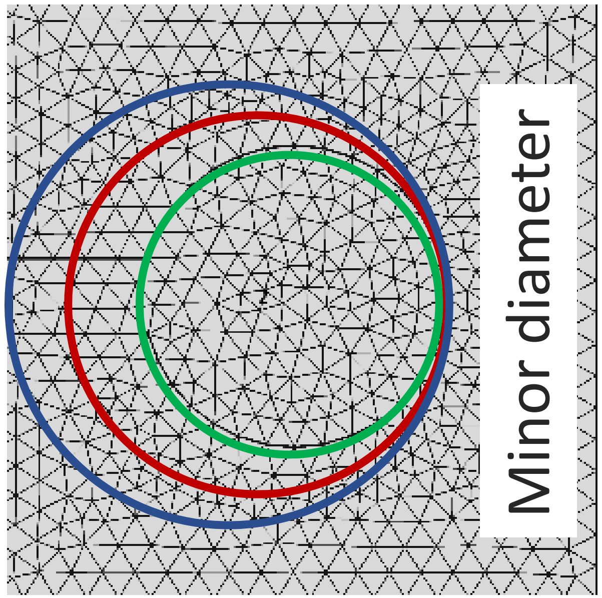
Phase-matching points depending on cavity geometry

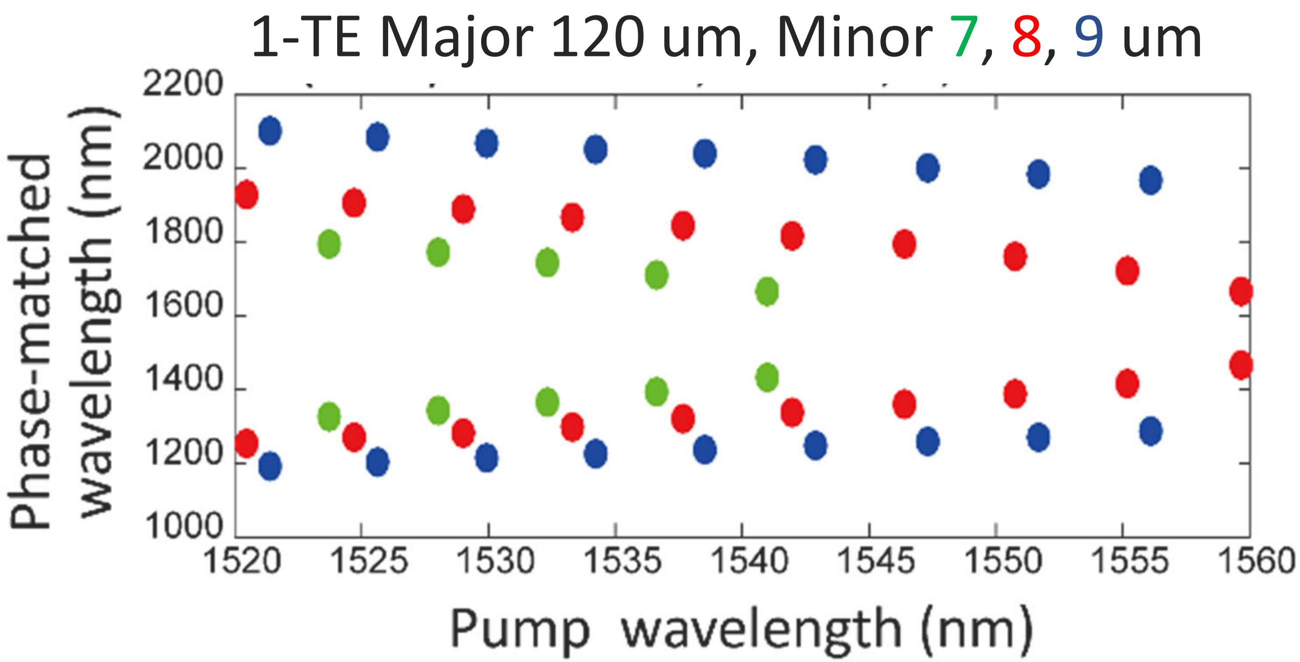
Major diameter 120 um, Minor diameter 8 um, 1-TE mode



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

Phase-matching points depending on cavity geometry

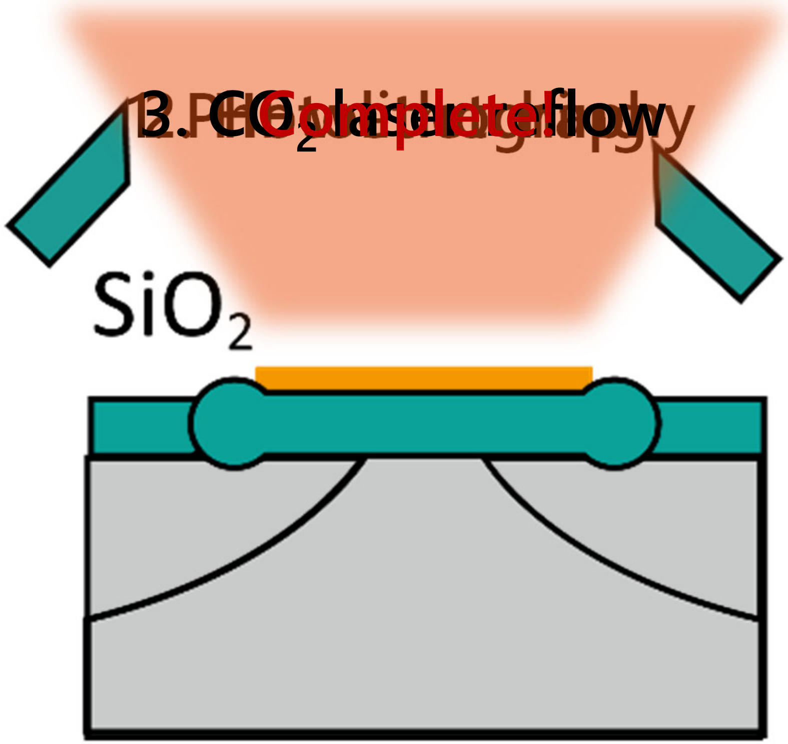




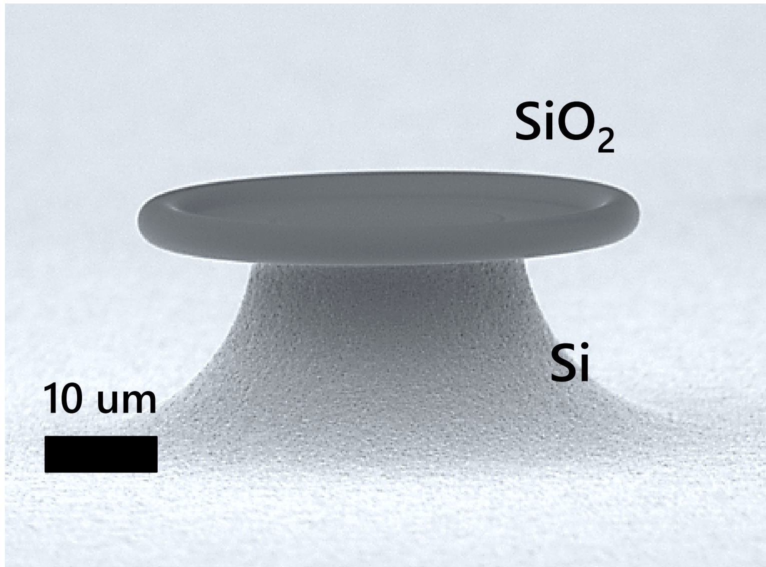
Phase-matched wavelength can be controlled by changing pump or geometry

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

Fabrication process of silica toroid microresonator

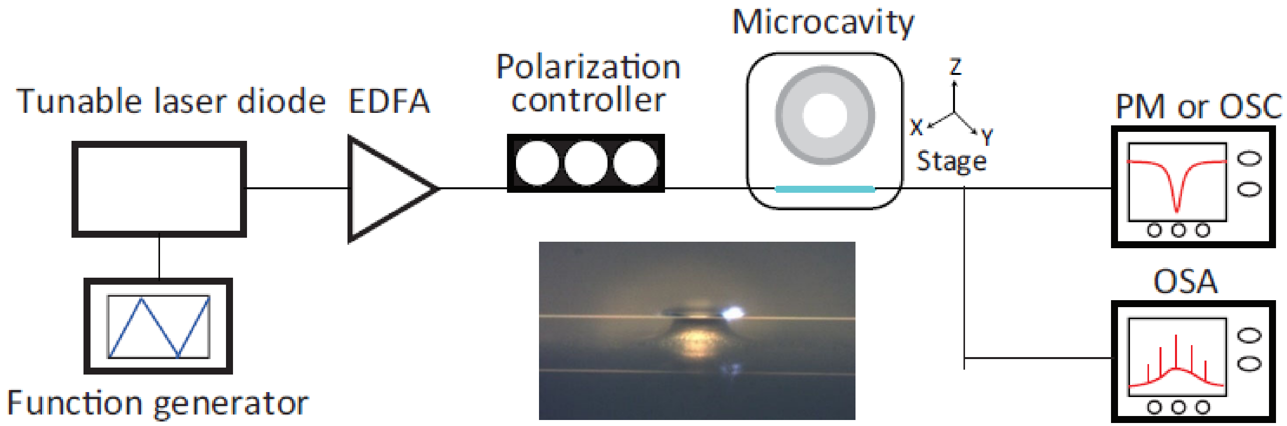


（Major diameter 20~200 μm）
（Minor diameter 3~12 μm）

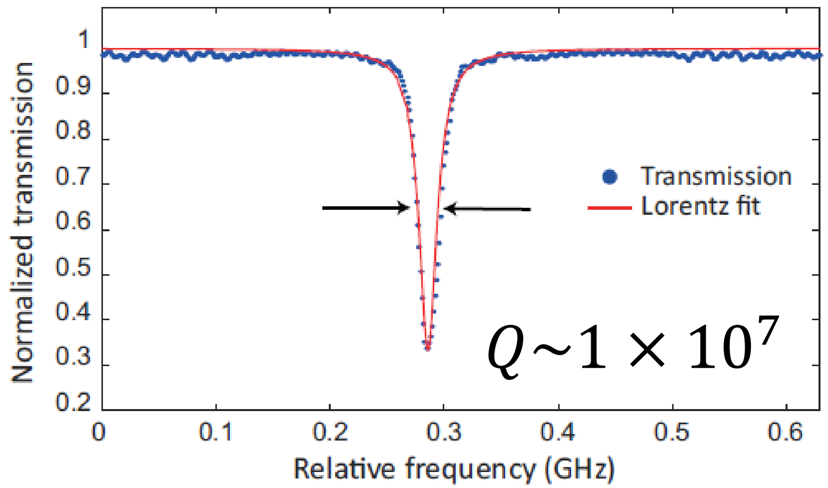


Experimental setup and optical properties

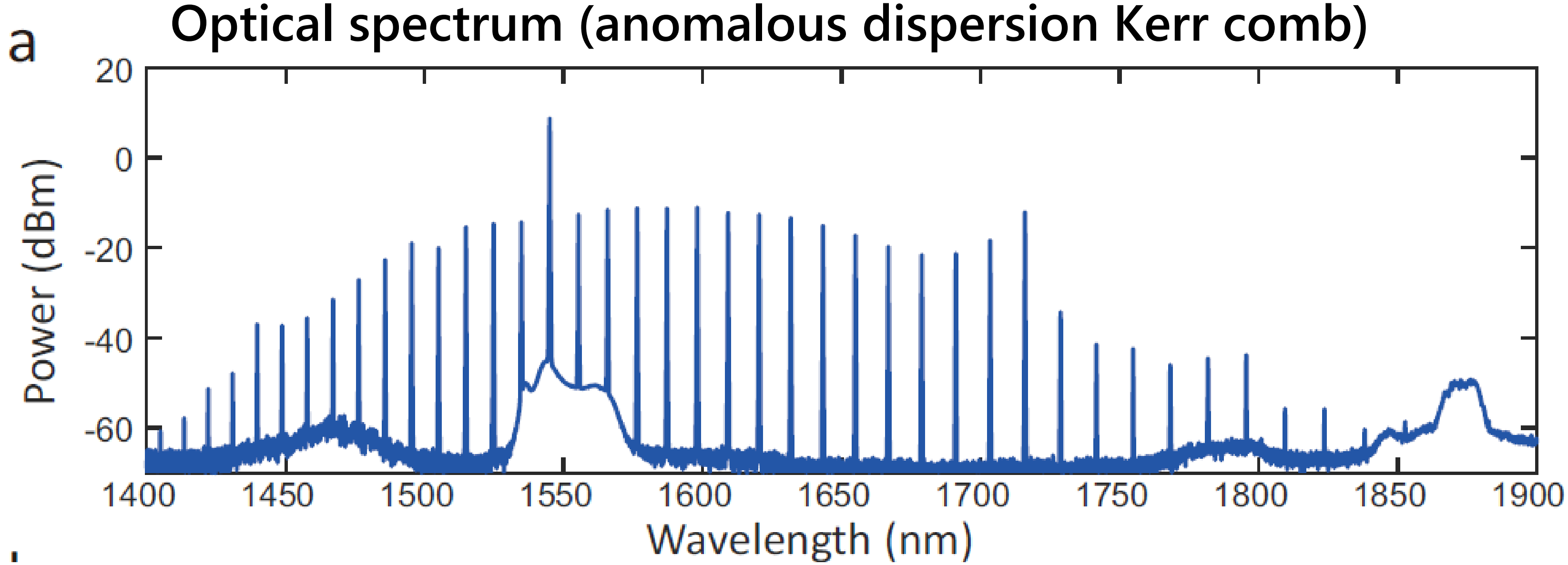
Experimental setup



Transmission spectrum

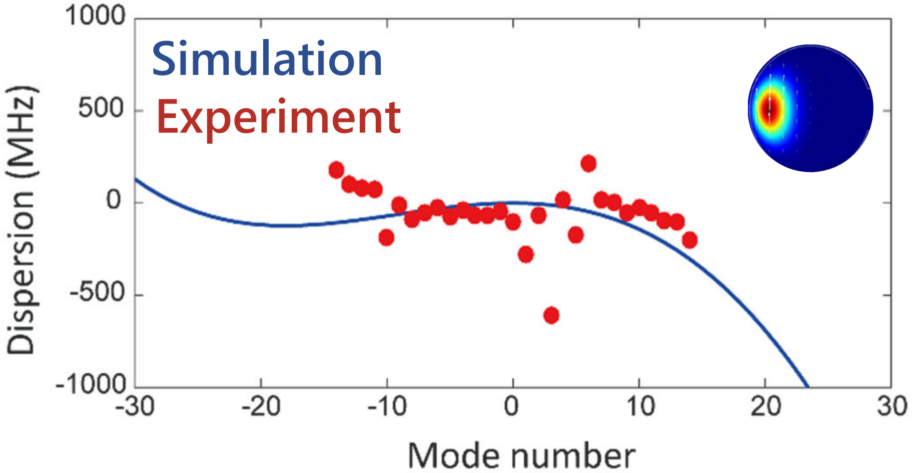


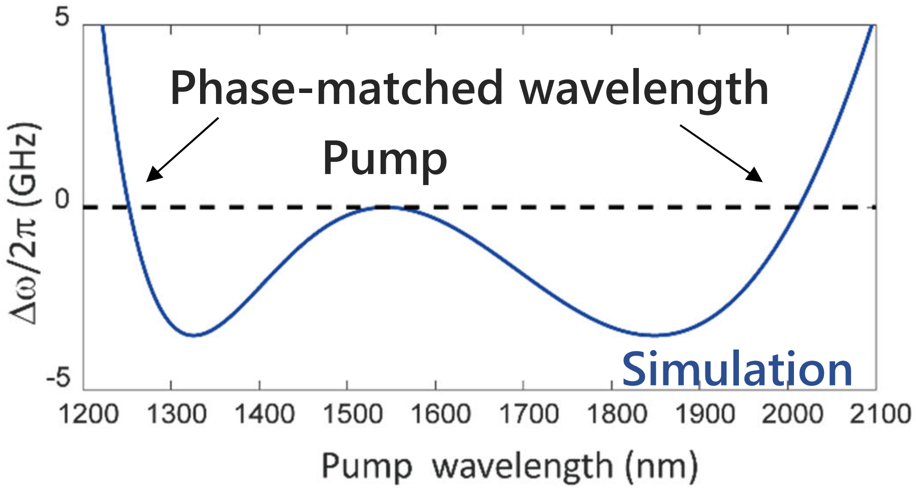
Optical spectrum (anomalous dispersion Kerr comb)

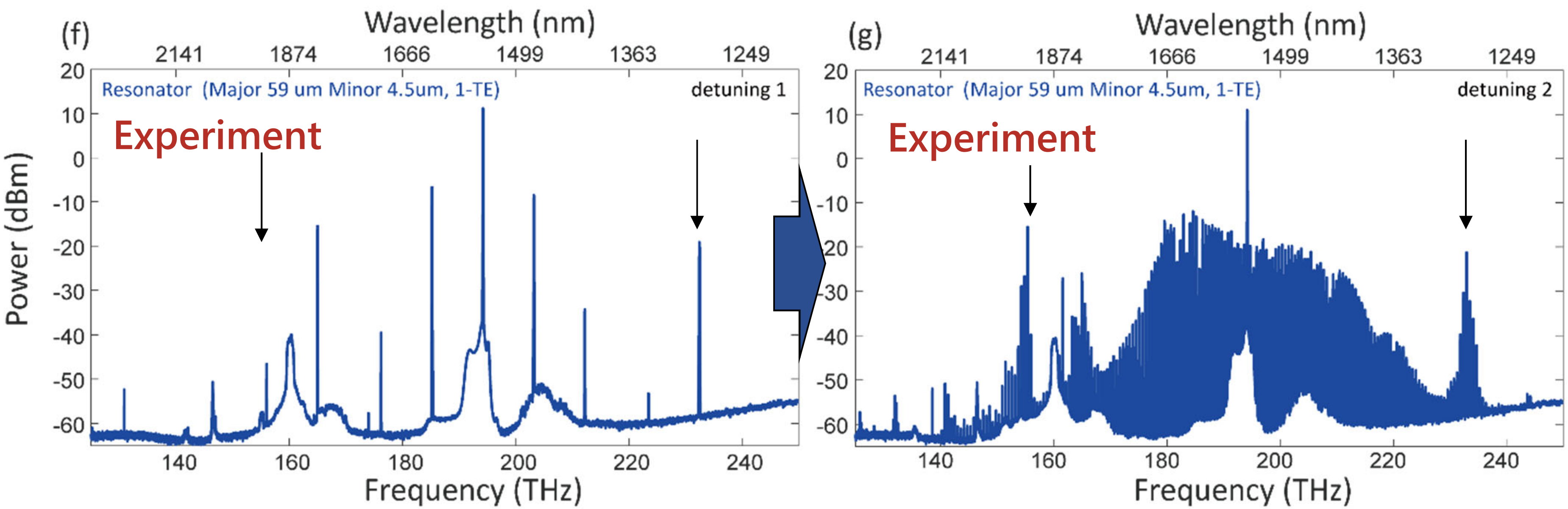


Observation of OPO in Resonator A

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

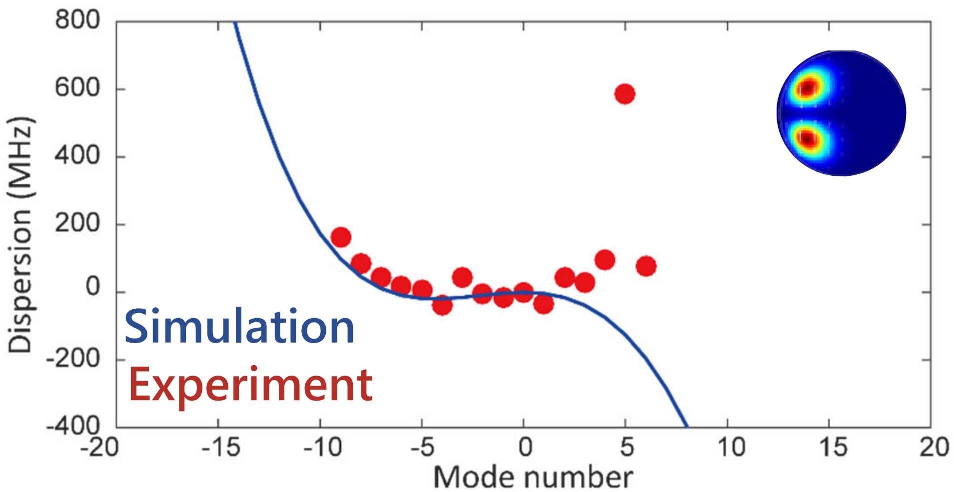


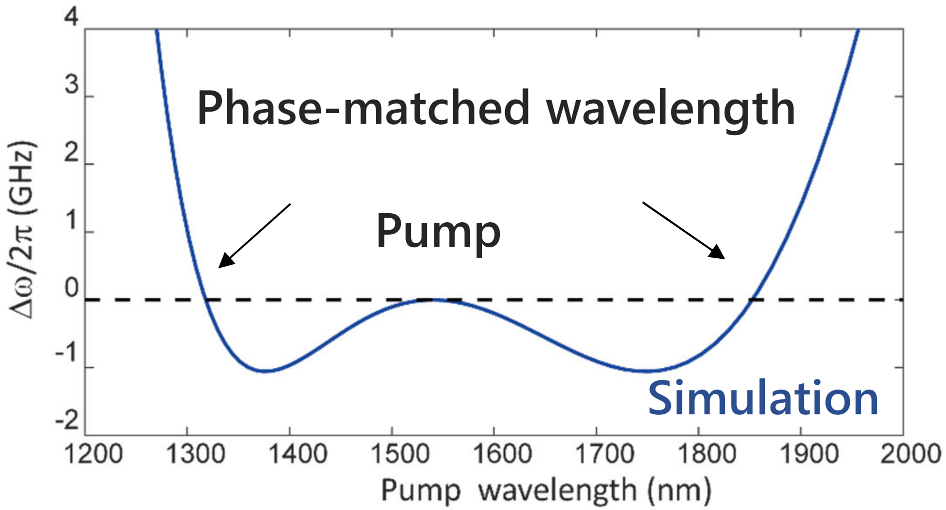


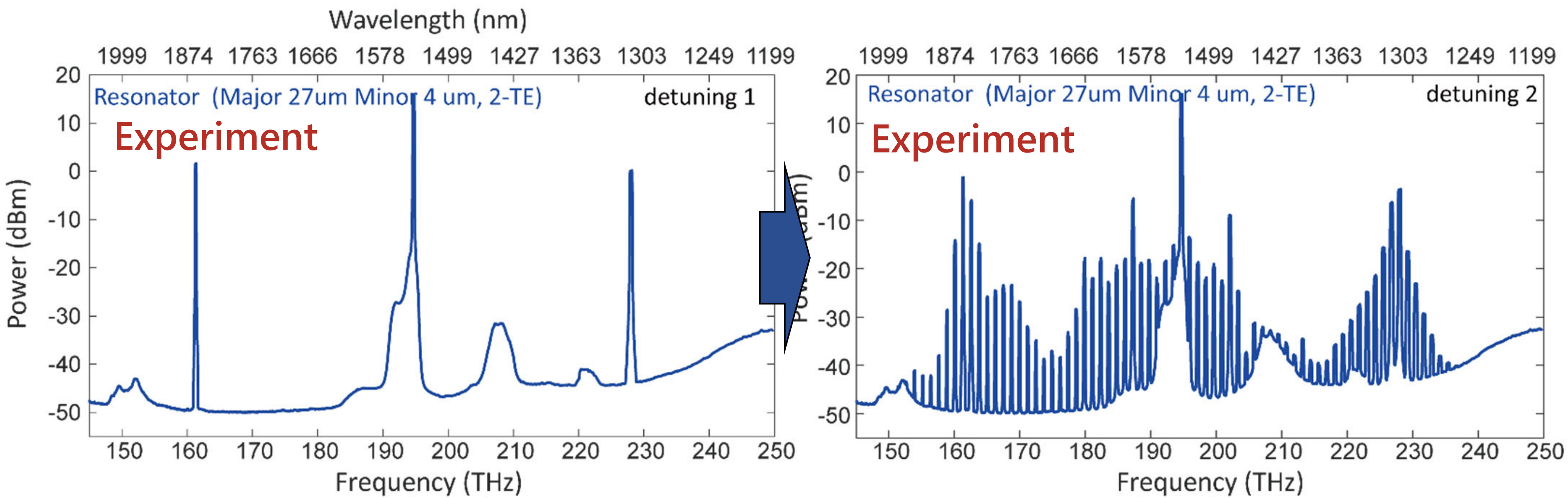


Observation of OPO in Resonator B

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

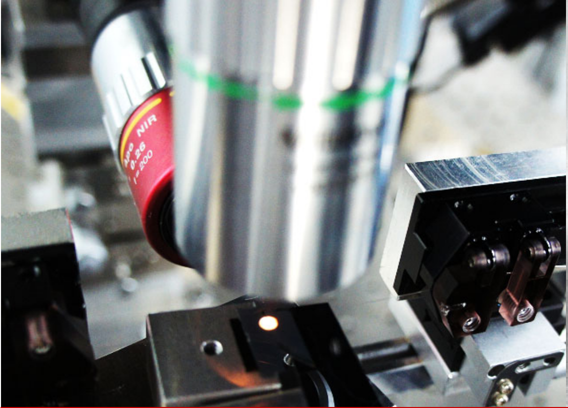


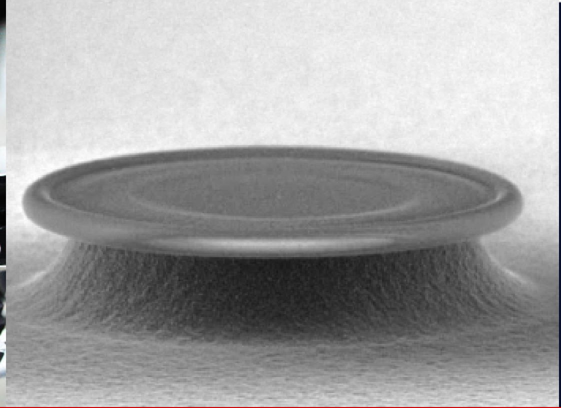


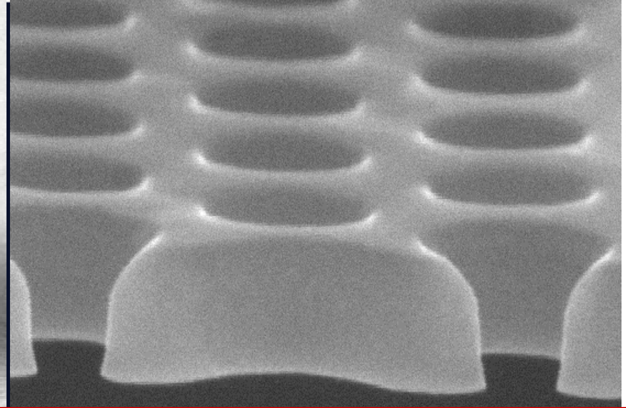


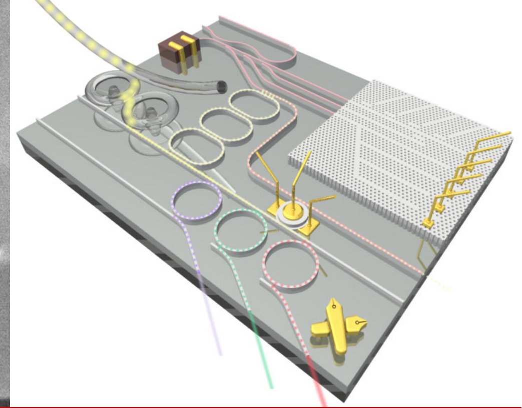
Summary

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









Thank you for your attention

Funding information

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