Nov. 2, 2019 14:00-14:35

Asia Communications and Photonics Conference:
PR Workshop on Microcavity Photonics
Talk 6

Broad bandwidth phase-matched four-wave mixing in dispersion-engineered microresonators

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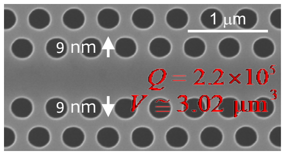
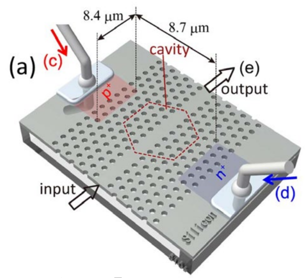
Projects in my group

□ High-Q PhC nanoresonator



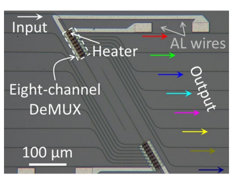
Y. Ooka, *et al.*, Sci. Rep. **5**, 11312 (2015).

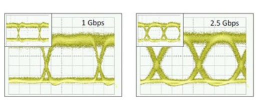
□ Si PhC photo receiver/modulator



N. Daud, *et al.*, AIP Adv. **8**, 105224 (2018).
Y. Ooka, *et al.*, Opt. Express, **24**, 11199 (2016).

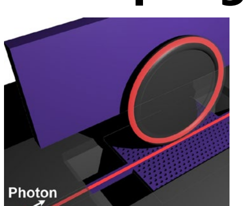
□ Si PhC WDM filter & other





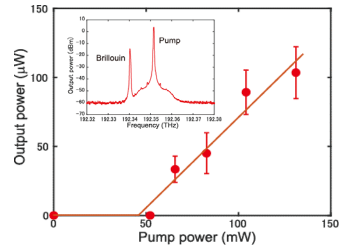
Y. Ooka, *et al.* Opt. Express **25**, 1521 (2017).

□ Coupling WGM w/ PhC



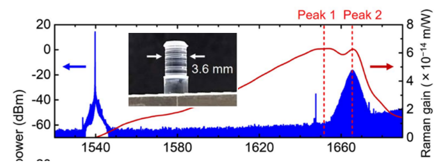
Y. Zhang, *et al.,* Opt. Lett (2019) in press.

□ Brillouin laser & opto mechanics



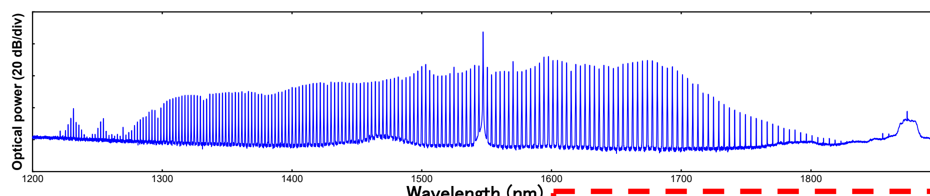
R. Suzuki, *et al*. Opt. Express **25**, 28806 (2017)
Y. Honda, *et al.,* Appl. Phys. Lett. **112**, 201105 (2018).

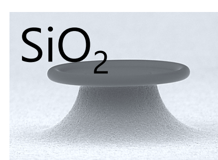
□ Raman comb & Er doped + CNT toroid

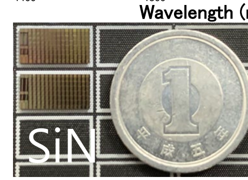


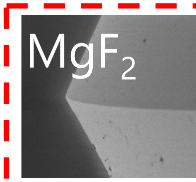
R. Suzuki, *et al*., J. Opt. Soc. Amer. B **35**, 933 (2018).
T. Kumagai, et al. J. Appl. Phys. **123**, 233104 (2018).

□ FWM & microresonator frequency comb







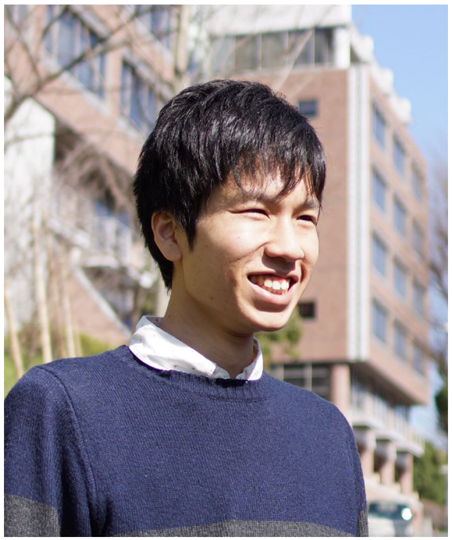


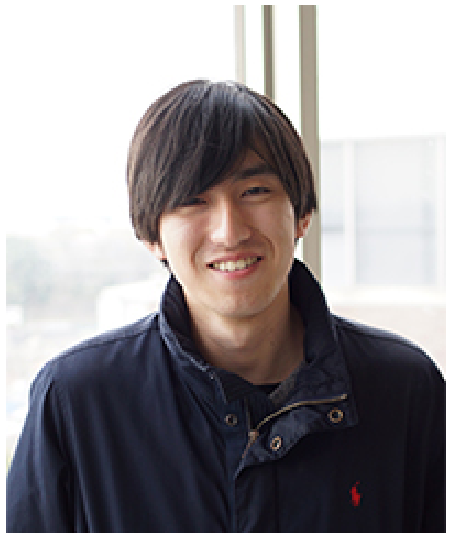
This!

S. Fujii, *et al.,* J. Opt. Soc. Amer. B **35**, 100 (2018).
S. Fujii, *et al*., Opt. Lett. **44**, 3146 (2019).

Acknowledgement

Design & measurement


Shun Fujii


Koshiro Wada

Ultra-precision fabrication


Yuka Hayama


Prof. Yasuhiro Kakinuma

Outline

1. Background and motivation
2. Dispersion engineering of MgF_2 microresonators
3. Fabrication by computer-controlled turning
4. Phase-matched four-wave mixing (µ-comb generation)
5. Conclusion

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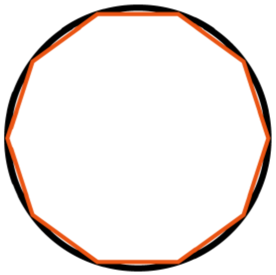
Ultrahigh-Q optical microresonators

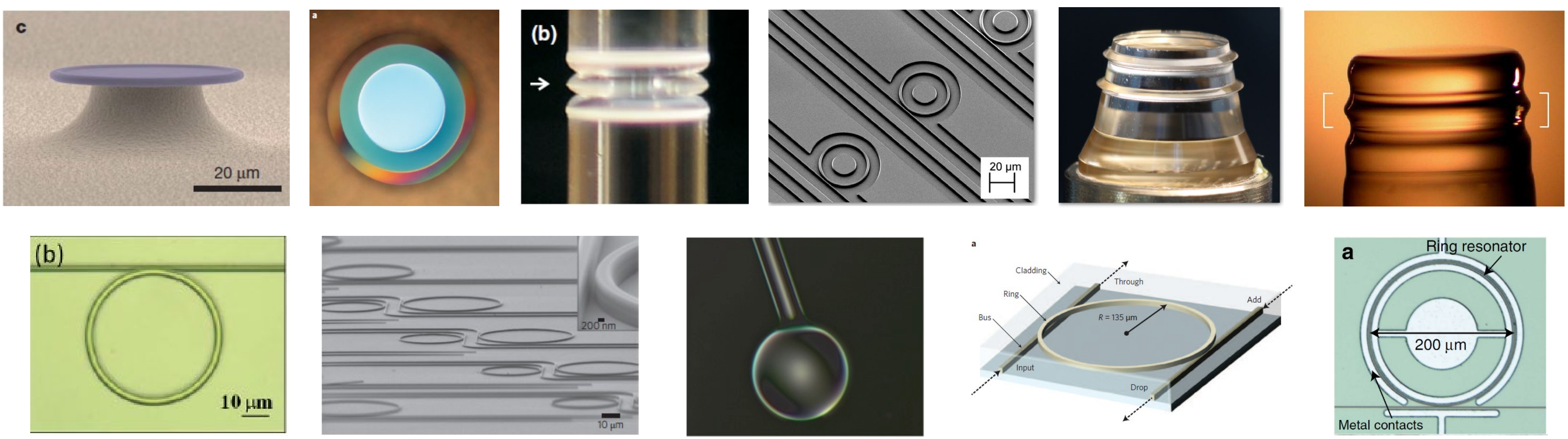


Whispering gallery mode (WGM) optical microresonator

Confines light for long photon lifetime (high Q) and has small volume

Enhances light-matter interaction in dielectric material

Dielectric microresonator platforms (Caltech, NIST, EPFL, OEwaves, Columbia, Harvard, Yale, INRS-EMT)



$$(\text{Intracavity power}) = \frac{4\eta d_1 Q}{\omega_0} \times (\text{Input power})$$

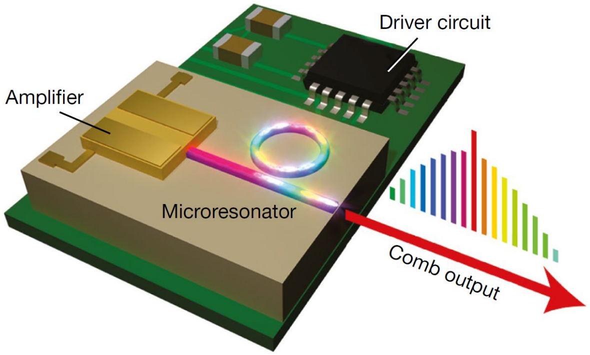
ω_0: laser frequency, d_1: cavity FSR,
Q: quality factor, η: coupling parameter

e.g. $\omega_0/2\pi = 193$ THz, $d_1 = 100$ GHz,
$Q = 1 \times 10^8$, $\eta = 0.5$ (critical coupling)

10 mW input ⇒ 165 W intracavity

Application: Microresonator comb

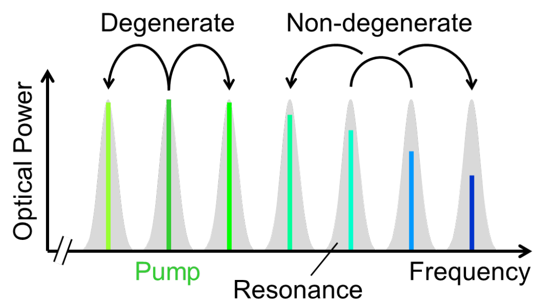
Target application: Microresonator frequency comb (Kerr comb)



Nature 562, 401–405 (2018)

Four-wave mixing (FWM)

$$\omega_a + \omega_{b(a)} = \omega_c + \omega_d$$



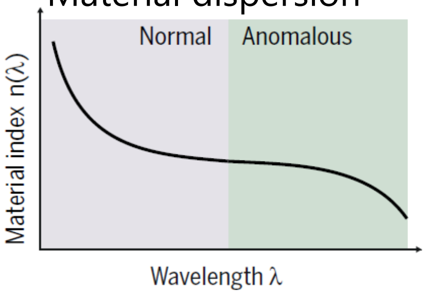
Threshold power for FWM

$$P_{\mathrm{th}} = \frac{\kappa^2 n_0^2 V_{\mathrm{eff}}}{8\eta\omega_0 c n_2} \propto \frac{V}{n_2 Q^2}$$

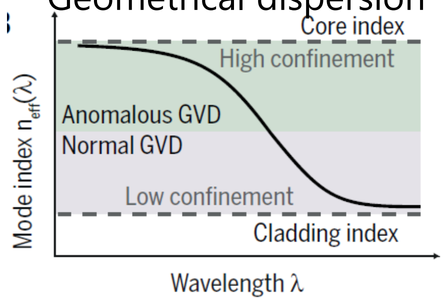
- Compact size
- Low energy consumption
- Broad bandwidth
- Large mode spacing ~1000 GHz

Microresonator dispersion and the effect on microcomb spectrum

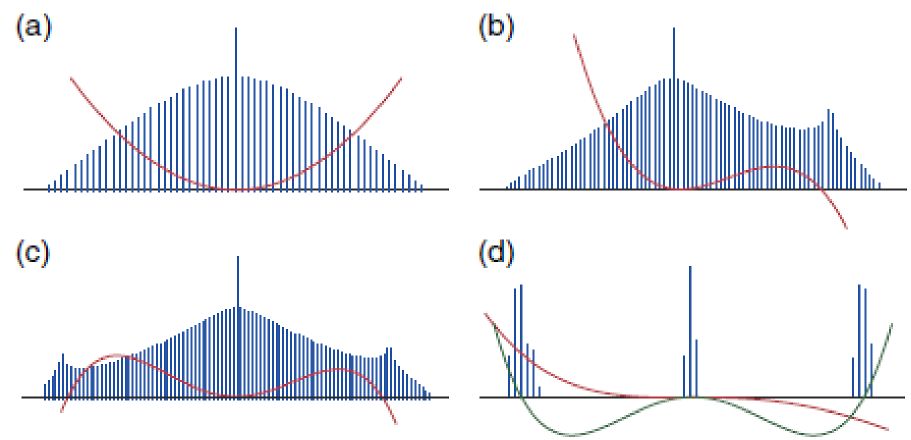
Material dispersion



Geometrical dispersion



$D_2 > 0 \;\; D_3, D_4 \sim 0$ $\qquad$ $D_2 > 0 \;\; D_3 < 0, D_4 \sim 0$



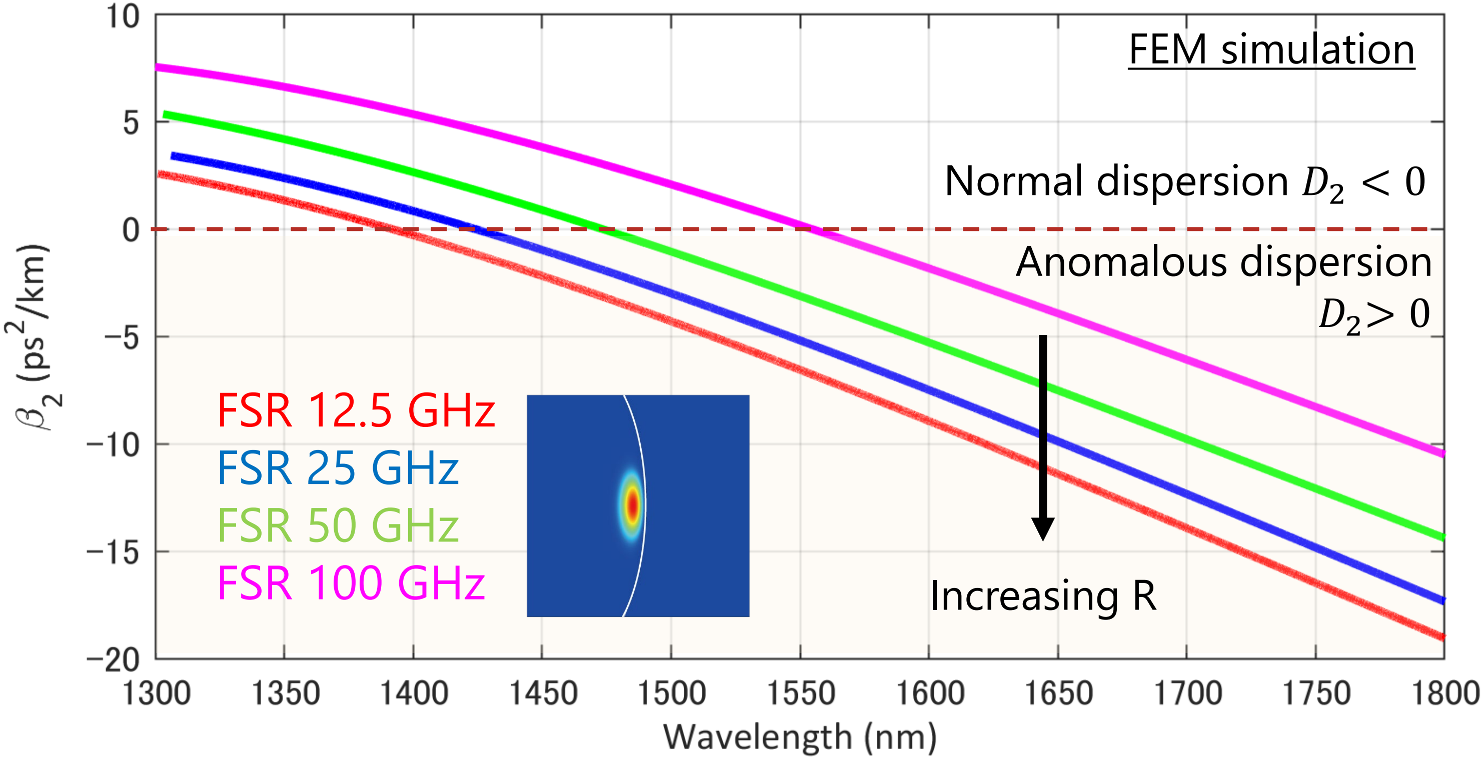
$D_2 > 0 \;\; D_3 < 0, D_4 < 0$ $\qquad$ $D_2 \leq 0 \;\; D_3 < 0, D_4 > 0$

Sign and value of D_n determines optical spectrum

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

Dispersion control in high-Q resonator

GVD parameters β_2 for MgF_2 microresonators with different FSRs



- 100 GHz FSR microresonator shows weak normal dispersion in 1550 nm band
- Geometrical dispersion limits microcomb generation in small-R MgF_2 resonator

Motivation

Fabrication method of crystalline microresonator

Hand Polishing	Fluoride crystal MgF_2 CaF_2 BaF_2 $LiNbO_3$(PPLN)	Q ~ 10^{10}	Ultra-high Q Form accuracy ✘
Machining		Q ~ 10^8	High-Q Form accuracy ❍

- Fabricate ultra-high Q crystalline microresonators (Q>10^8) by computer-controlled machining **without polishing process**

- Explore resonator cross-section which realizes anomalous dispersion for 100 GHz free-spectral range (FSR) crystalline microresonators

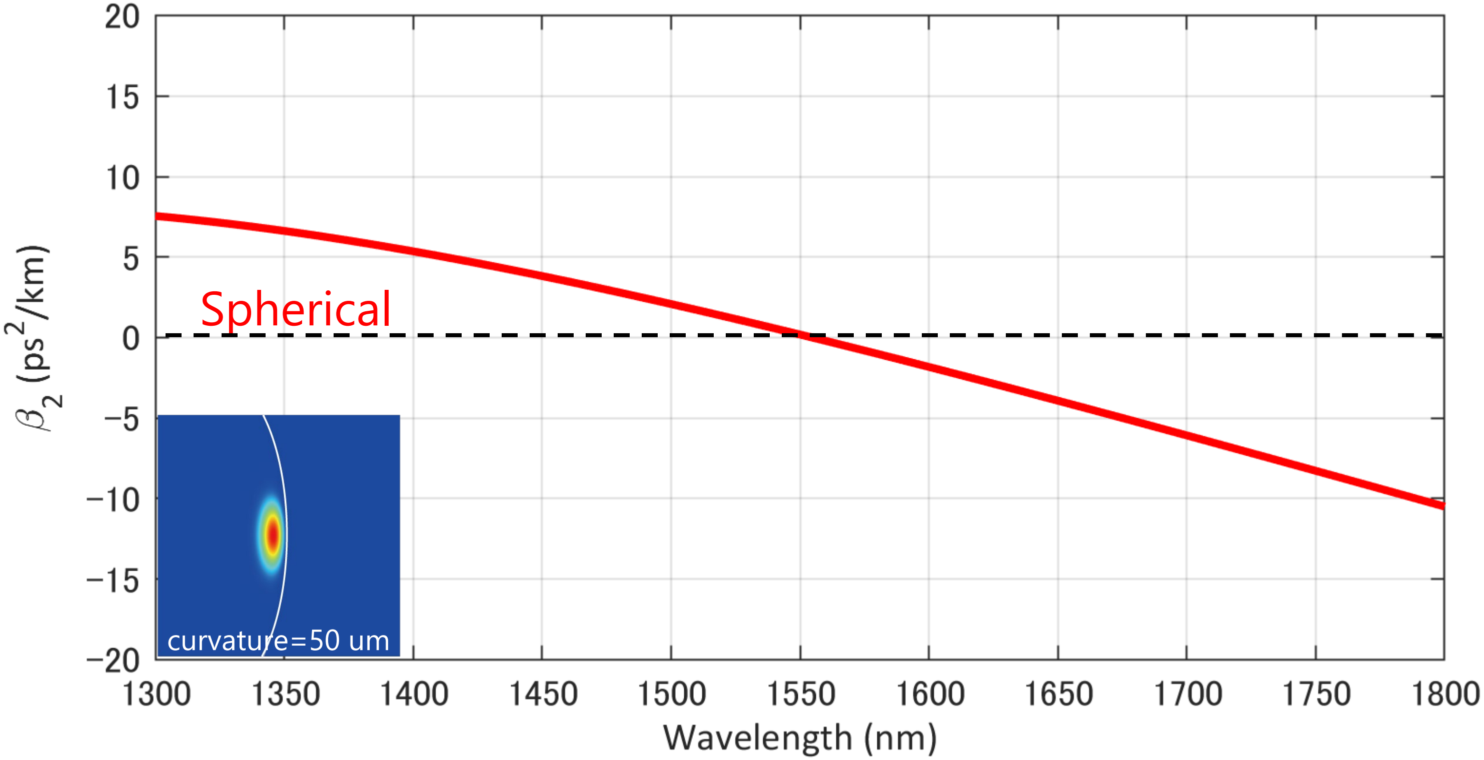
<u>Overcome Q limitation to achieve 100 GHz FSR microcomb generation</u>

Outline

1. Background and motivation
2. Dispersion engineering of MgF_2 microresonators
3. Fabrication by computer-controlled turning
4. Phase-matched four-wave mixing (μ-comb generation)
5. Conclusion

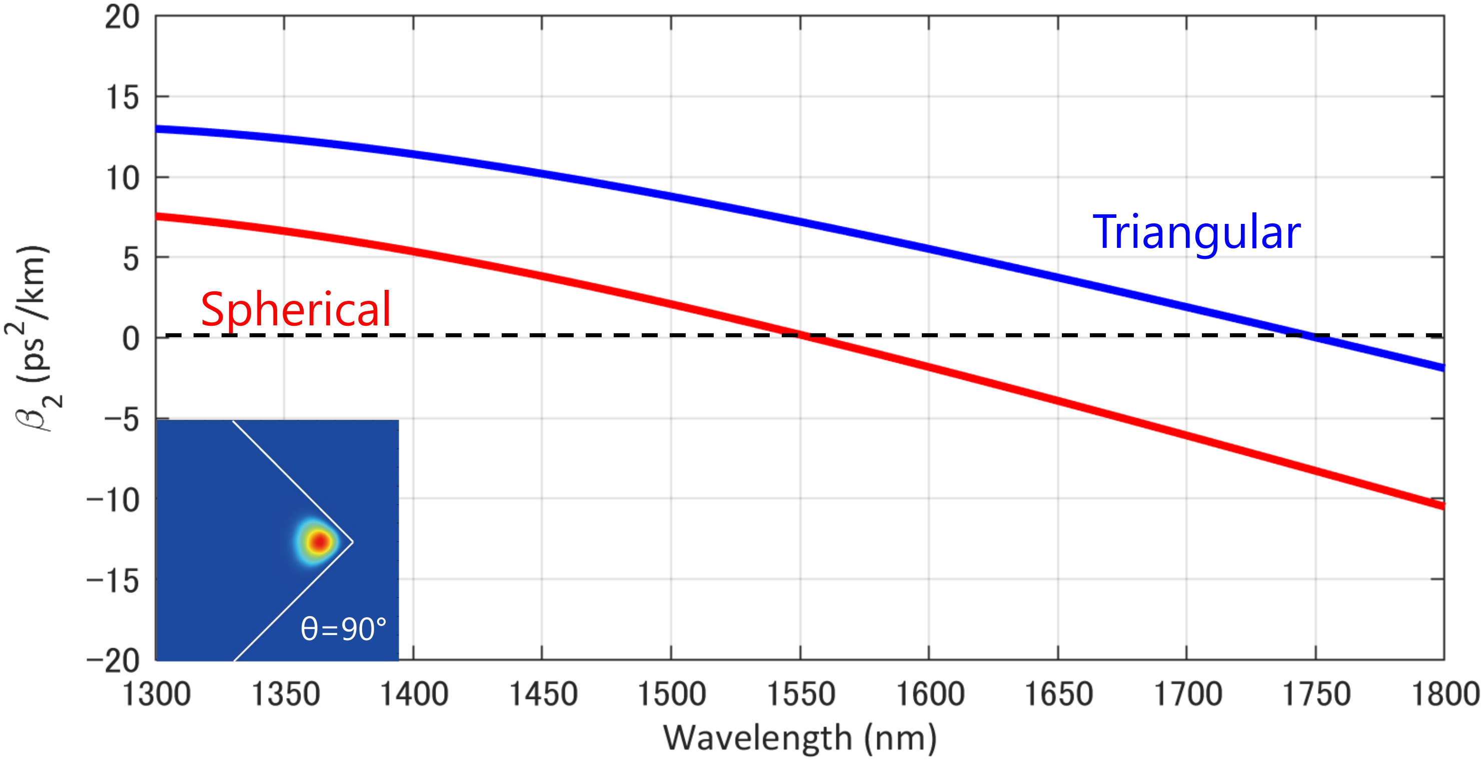
Dispersion control in high-Q resonator

GVD parameters β_2 for "100 GHz" MgF_2 microresonators



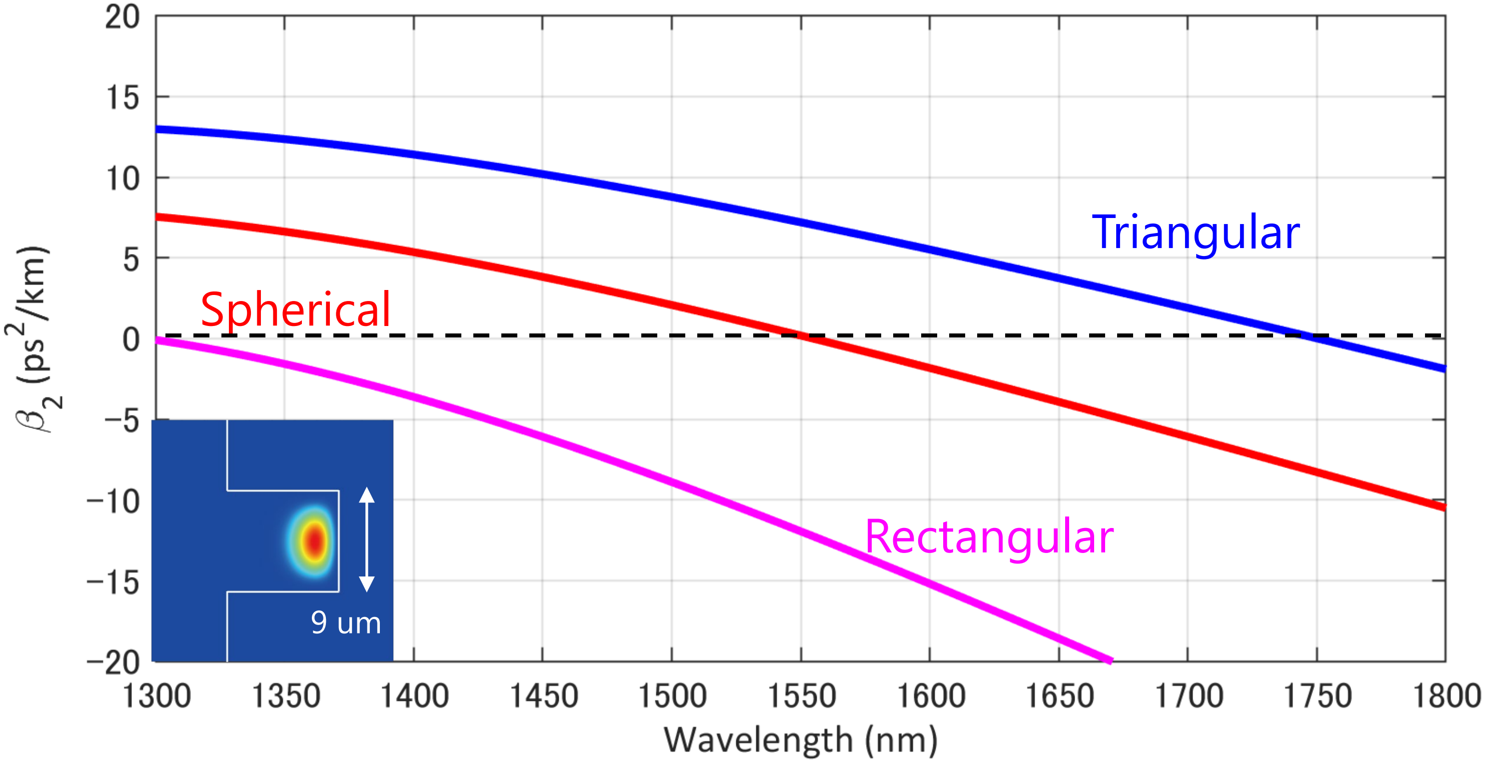
Dispersion control in high-Q resonator

GVD parameters β_2 for "100 GHz" MgF_2 microresonators



Dispersion control in high-Q resonator

GVD parameters β$_2$ for "100 GHz" MgF_2 microresonators



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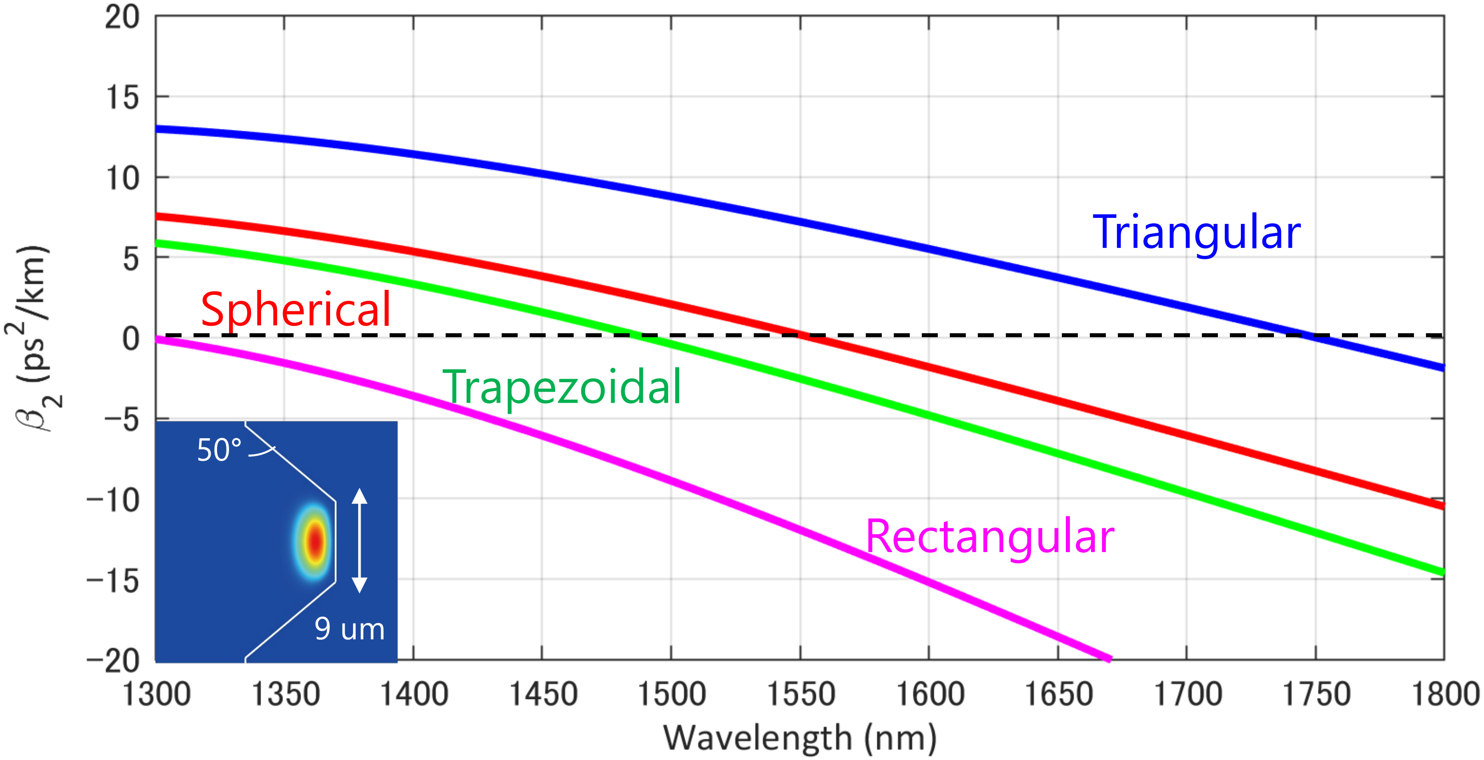

- Degree of freedom of structures allows us to control resonator dispersion
- Rectangular shape is ideal for realizing anomalous group-velocity dispersion

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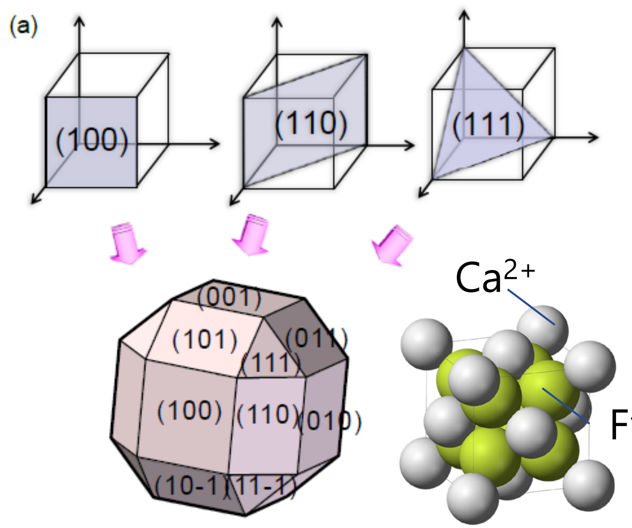
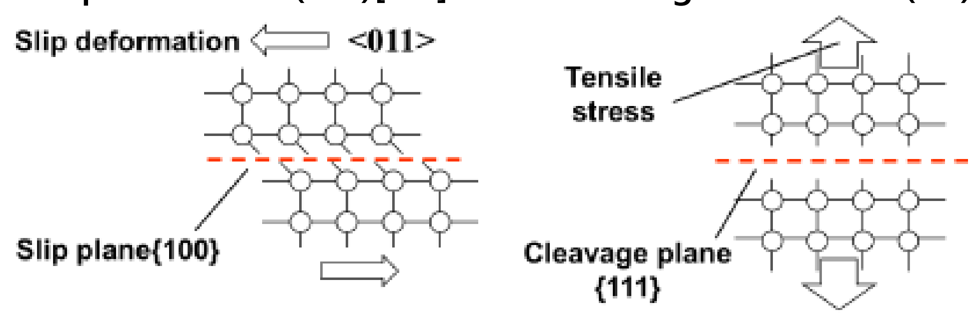
Machining of single crystal materials

Crystallographic image of CaF_2 material



- Plane of single crystal is defined as mirror index
- CaF_2 consists of only 3 planes (100), (110), (111)
- Cutting mode transition observed with cutting depth

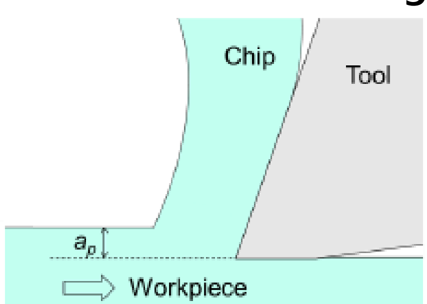
Slip formation (100)[110] **Cleavage formation (111)**



More ductile *Very brittle*

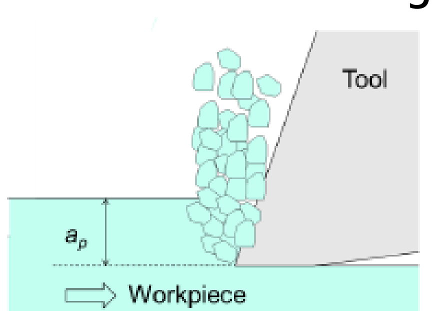
Cutting mode transition is observed depending on crystal anisotropy

Ductile-mode cutting



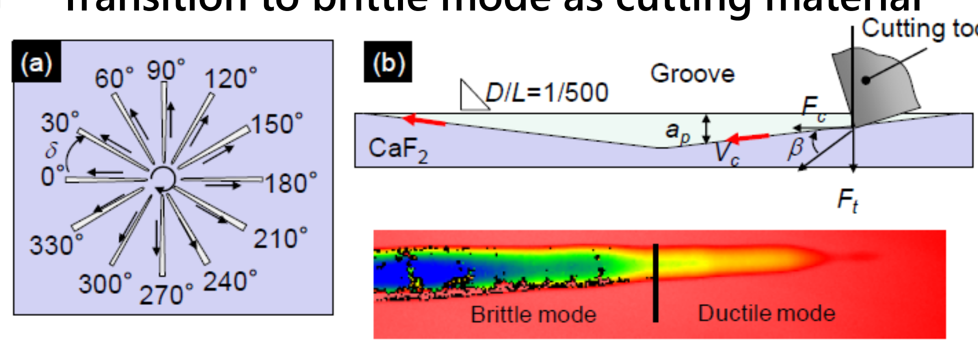
Cutting depth < Critical depth

Brittle-mode cutting



Cutting depth > Critical depth

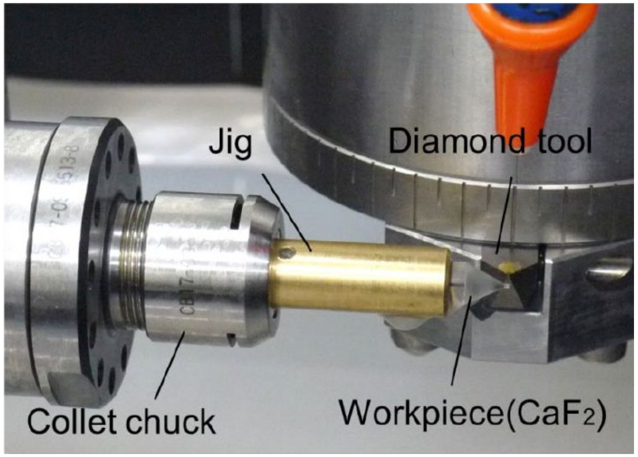
Transition to brittle mode as cutting material



Precision Engineering 40 (2015) 172–181

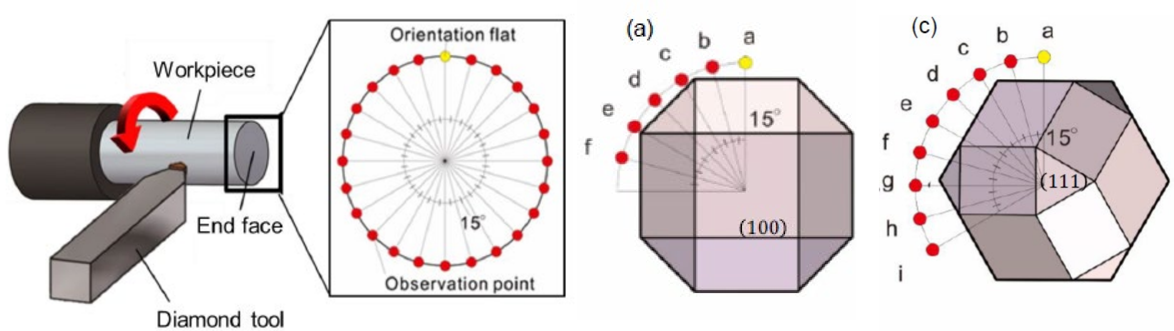
Cylindrical turning experiment

Experimental setup

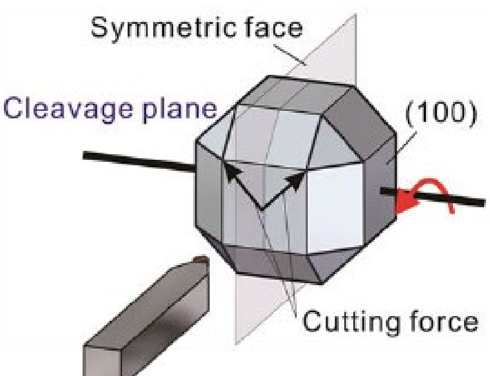


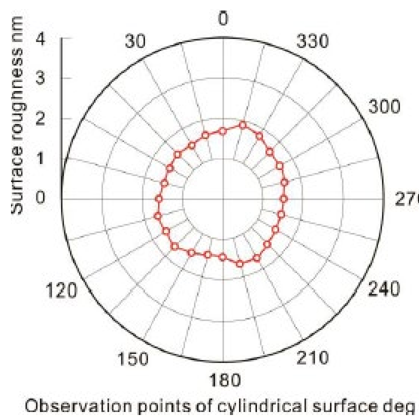
"Objective" of cylindrical turning experiment

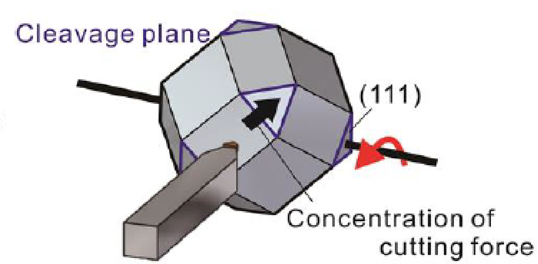
- Cutting plane and direction are continuously and simultaneously changed when resonator is turned
- Investigate surface roughness of entire cylindrical surface

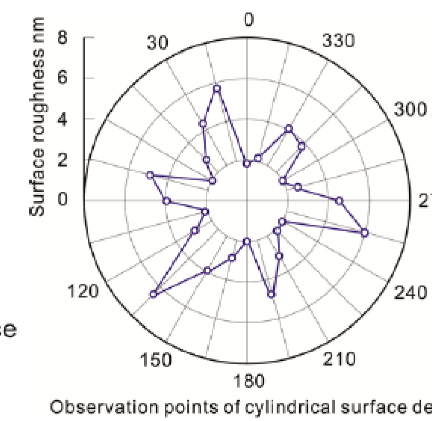


Cylindrical surface roughness for observation points with different end-faces









Observed smooth surface with end-face (100)

Observed surface clack with the end-face (111)

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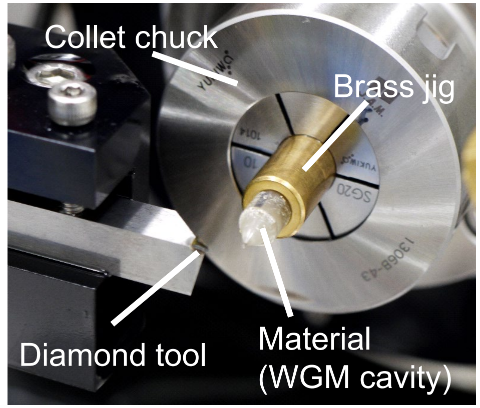
Ultra-precision machining procedure

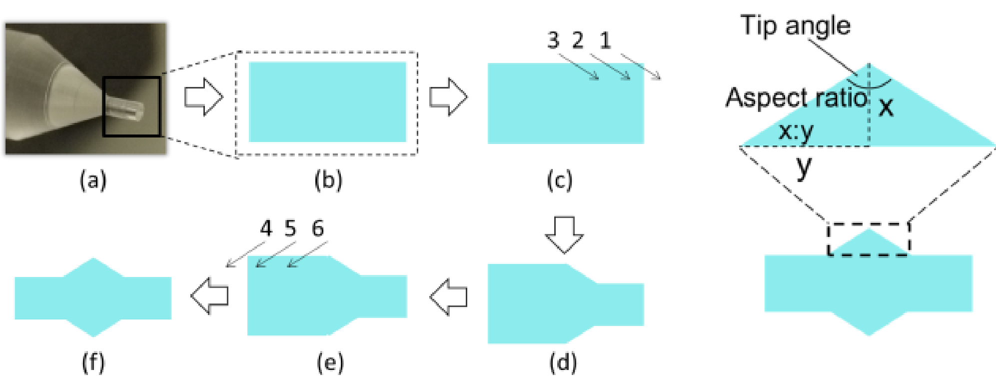
Experimental setup and machine used

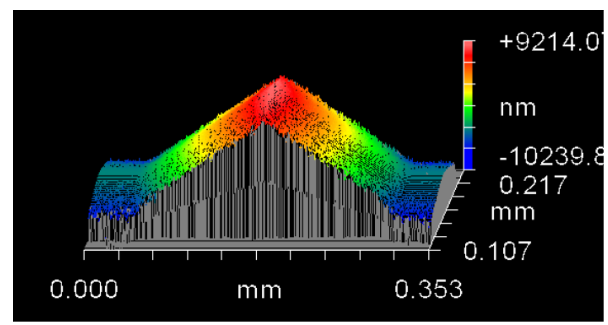


Manufacturing parameters

- Rotation speed [min^{-1}]
- Cutting speed [m/min]
- Feed per revolution [um/rev]
- Depth of cut [nm]
- End-face orientation
- Lubricant
- Nose radius (cutting tool)
- Rake angle (cutting tool)

Fabrication flow of ultra-precision turning for *triangular* cross-section microresonator



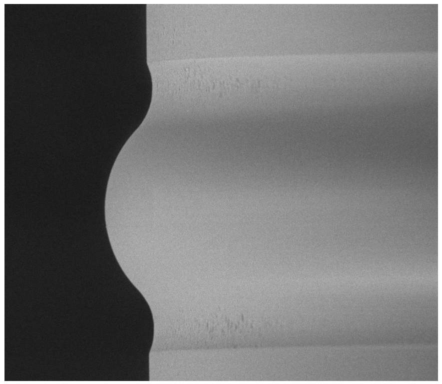


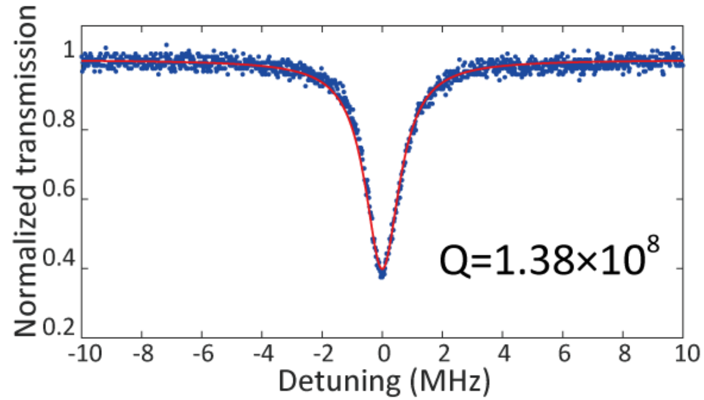
- The tip angle and the aspect ratio are pre-designed and formed by computer-controlled turning, which is attractive with respect to dispersion engineering

Measured Q-factor

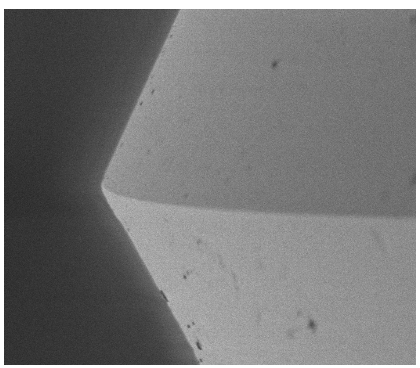
Crystalline microresonator fabricated *"without polishing"*

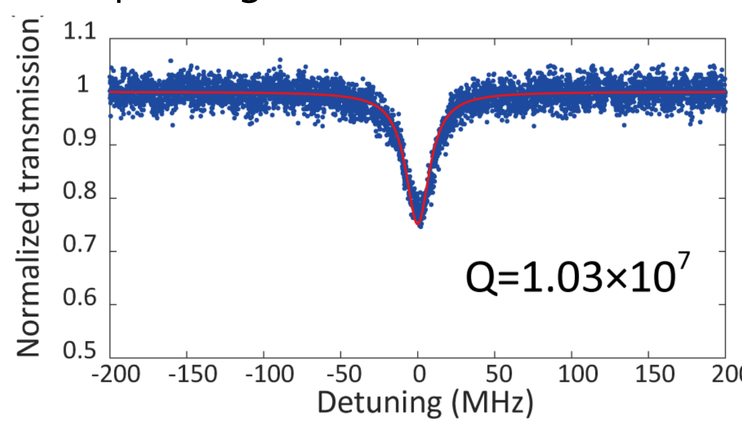
Spherical MgF_2 WGM Diameter 508 μm Curvature 36 μm





Triangular CaF_2 WGM Diameter 502 μm Apex angle 120°





- High-Q of >10^8 was obtained in MgF_2 spherical WGM resonator
- Effect of crystal anisotropy is investigated and we cut at an optimized end-face direction
- MgF_2 is more suitable for Kerr comb generation as regards thermal stability

Outline

1. Background and motivation
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3. Fabrication by computer-controlled turning
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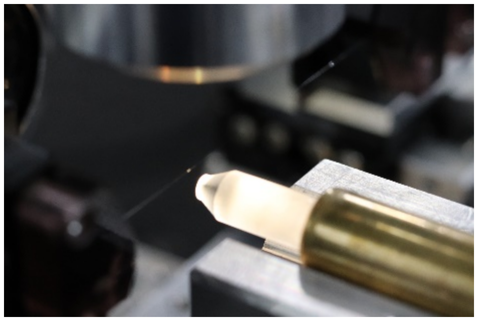
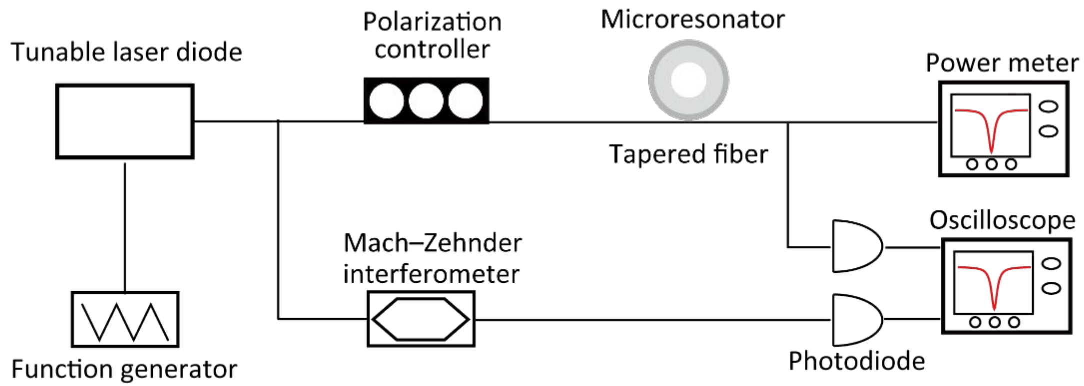
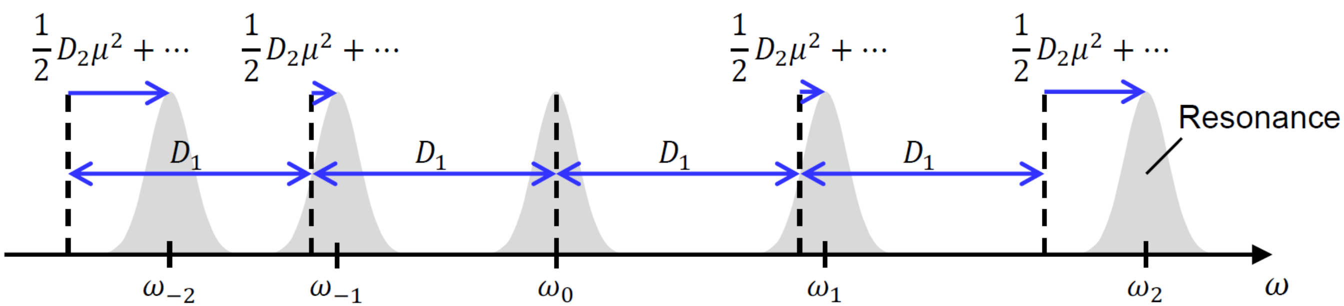
Dispersion measurement

Experimental setup for Q-factor and dispersion measurement







Group-velocity dispersion

$D_2 > 0$: anomalous
$D_2 < 0$: normal

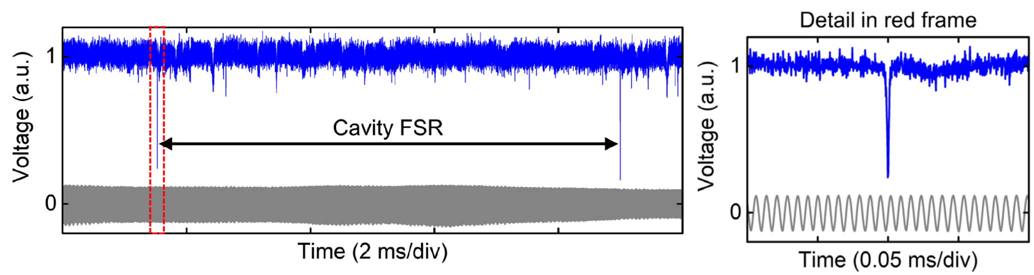
Resonance frequency: $\omega_m = \dfrac{2\pi mc}{Ln(\omega)}$

Resonance frequencies are Taylor-expanded:

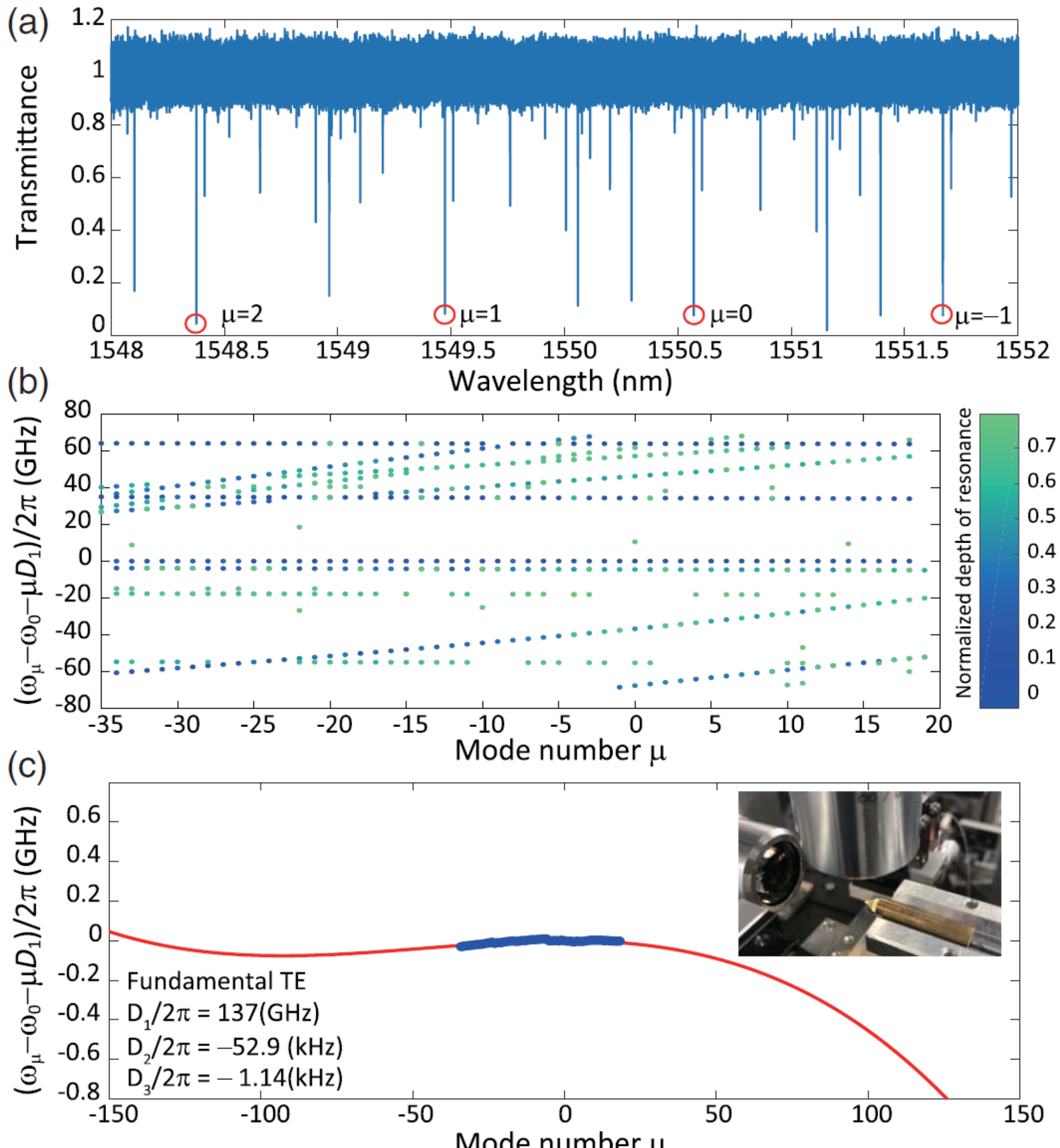
$$\omega_\mu = \omega_0 + D_1\mu + \frac{1}{2}D_2\mu^2 + \frac{1}{6}D_3\mu^3 + \cdots$$

m: mode number
μ: mode number offset (from pump $\mu = 0$)

Mach-Zehnder interferometer calibrates frequency axis



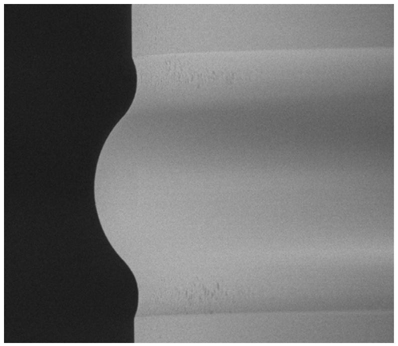
Dispersion measurement

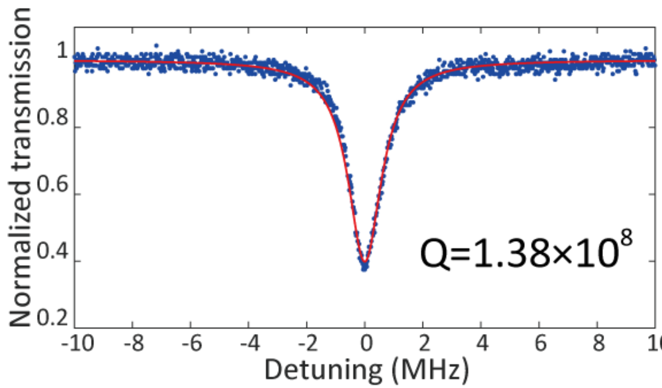


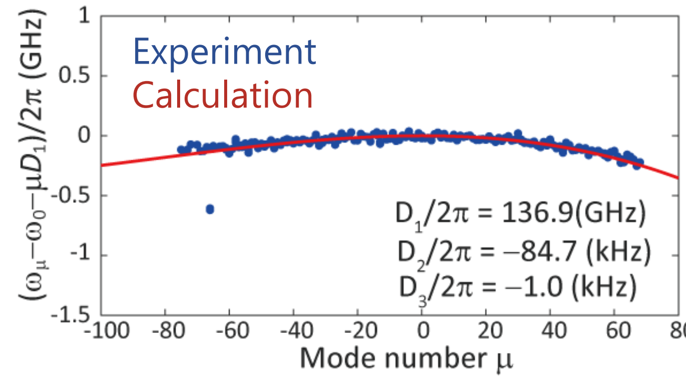
Measured Q-factor and dispersion

Crystalline microresonator fabricated *"without polishing"*

Spherical MgF_2 WGM Diameter 508 µm Curvature 36 µm







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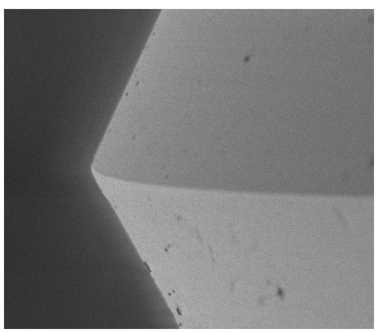
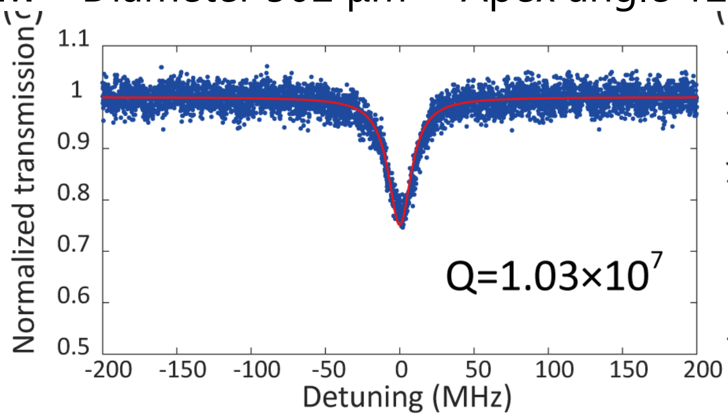
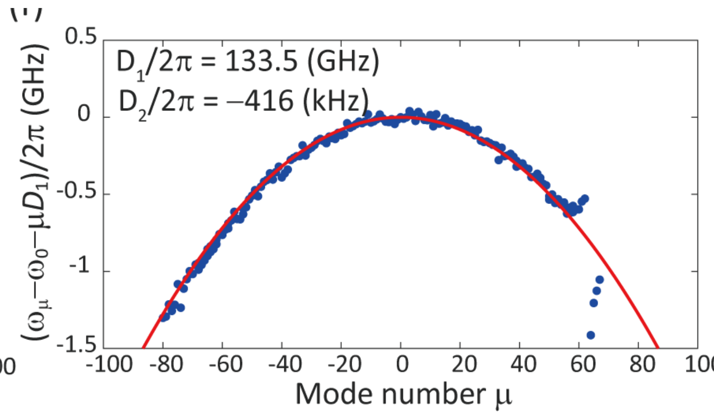


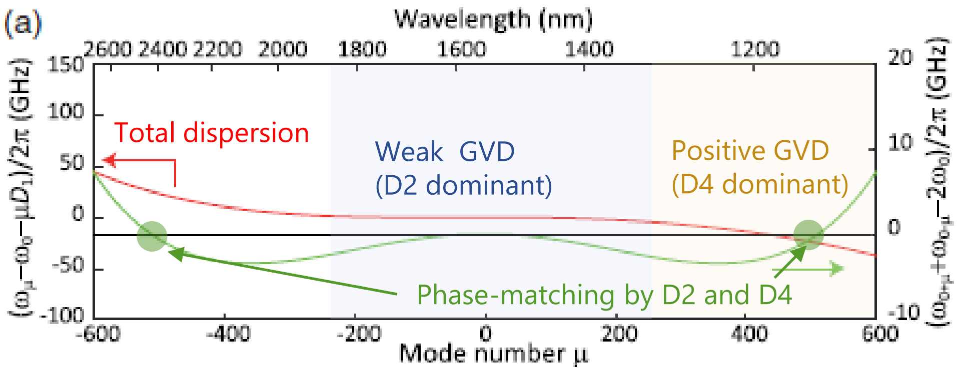




- High-Q of >10^8 was obtained in MgF_2 spherical WGM resonator
- Designed dispersion is obtained

Octave-wide phase-matched FWM

- Principle: Negative GVD (D2<0) is compensated by positive D4 far from the pump mode



Phase-matching condition (PMC) for initial sidebands μ

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

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

Negative D_2 and Positive D_4 satisfy PMC far from the pump

Strong negative D_2 enables large frequency shift

- Numerical simulation (LLE)

LLE (Lugiato-Lefever equation) w/ all order dispesion

$$\frac{\partial A(\phi,t)}{\partial t} = -\left(\frac{\kappa_{tot}}{2} + i\delta_0\right)A + i\sum_{k=2}\frac{D_k}{k!}\left(\frac{\partial}{i\partial\phi}\right)^k A + ig|A|^2A + \sqrt{\kappa_{ext}}A_{in}$$

κ_{tot} : loaded decay rate ($Q_{tot} = \omega_0/\kappa_{tot}$)

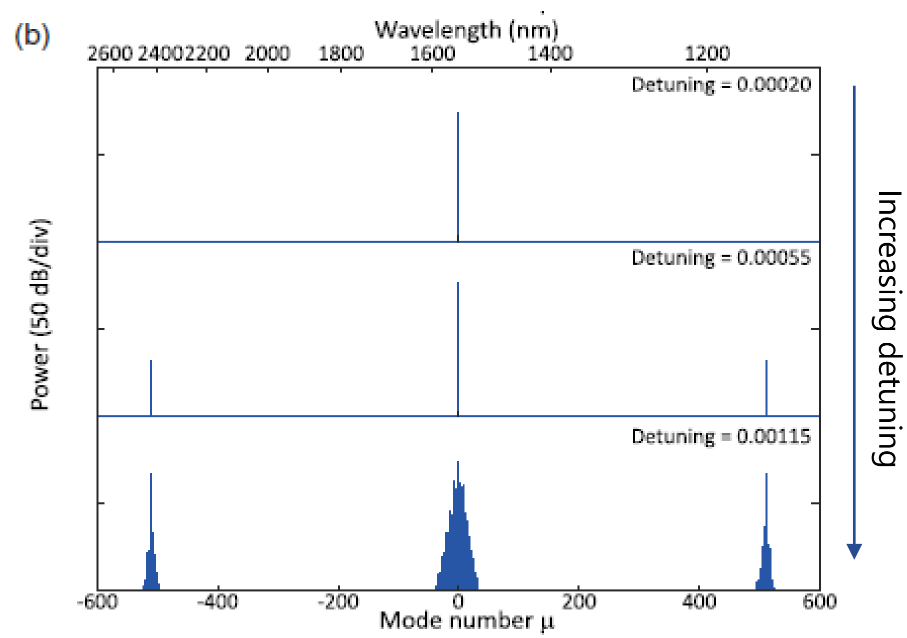
κ_{ext} : coupling rate ($Q_{ext} = \omega_0/\kappa_{ext}$)

δ_0 : pump detuning

D_k : k-order dispersion ($k \geq 2$)

g : nonlinear coefficient

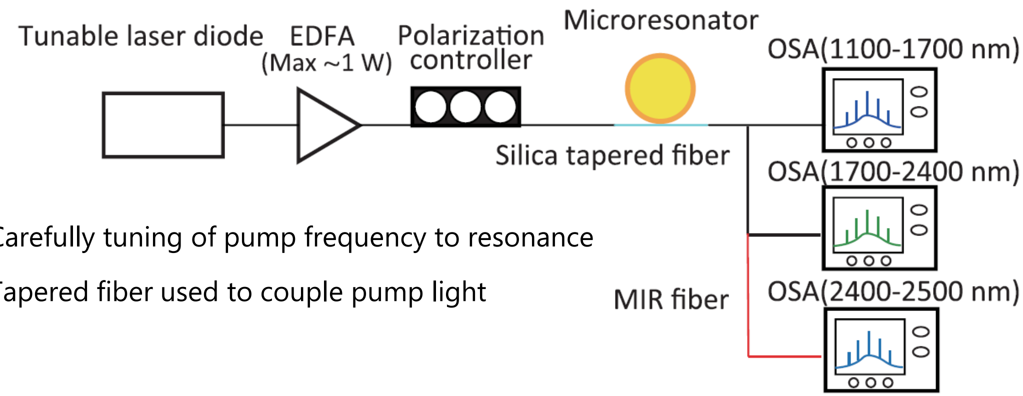
A_{in} : input field (pump)



- FWM sidebands spanning one-octave via higher-order dispersion (4th order dispersion)

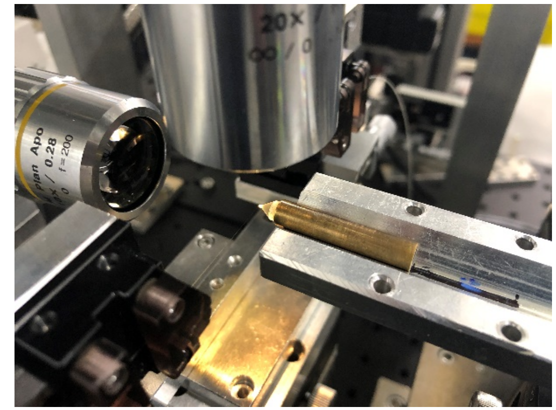
Octave-wide phase-matched FWM

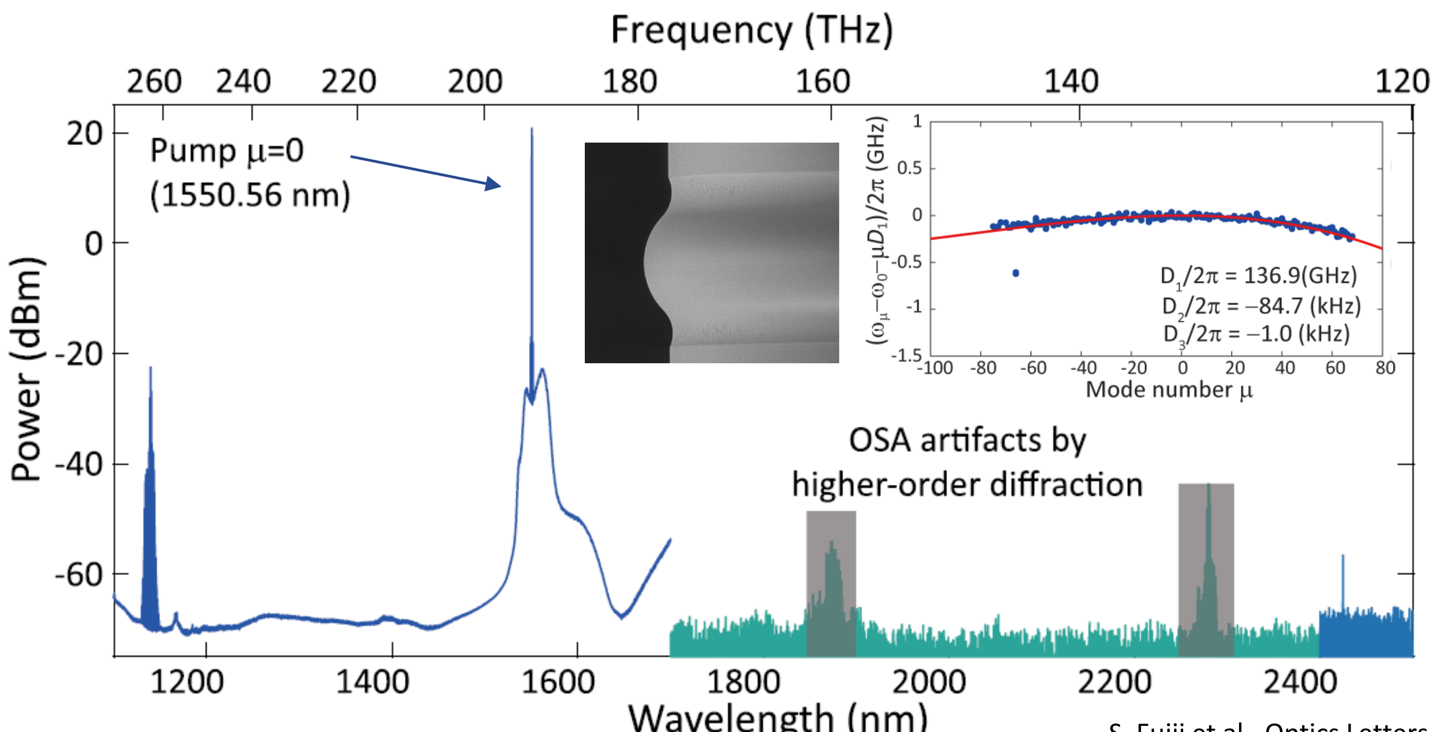
- Experiment



Carefully tuning of pump frequency to resonance

Tapered fiber used to couple pump light

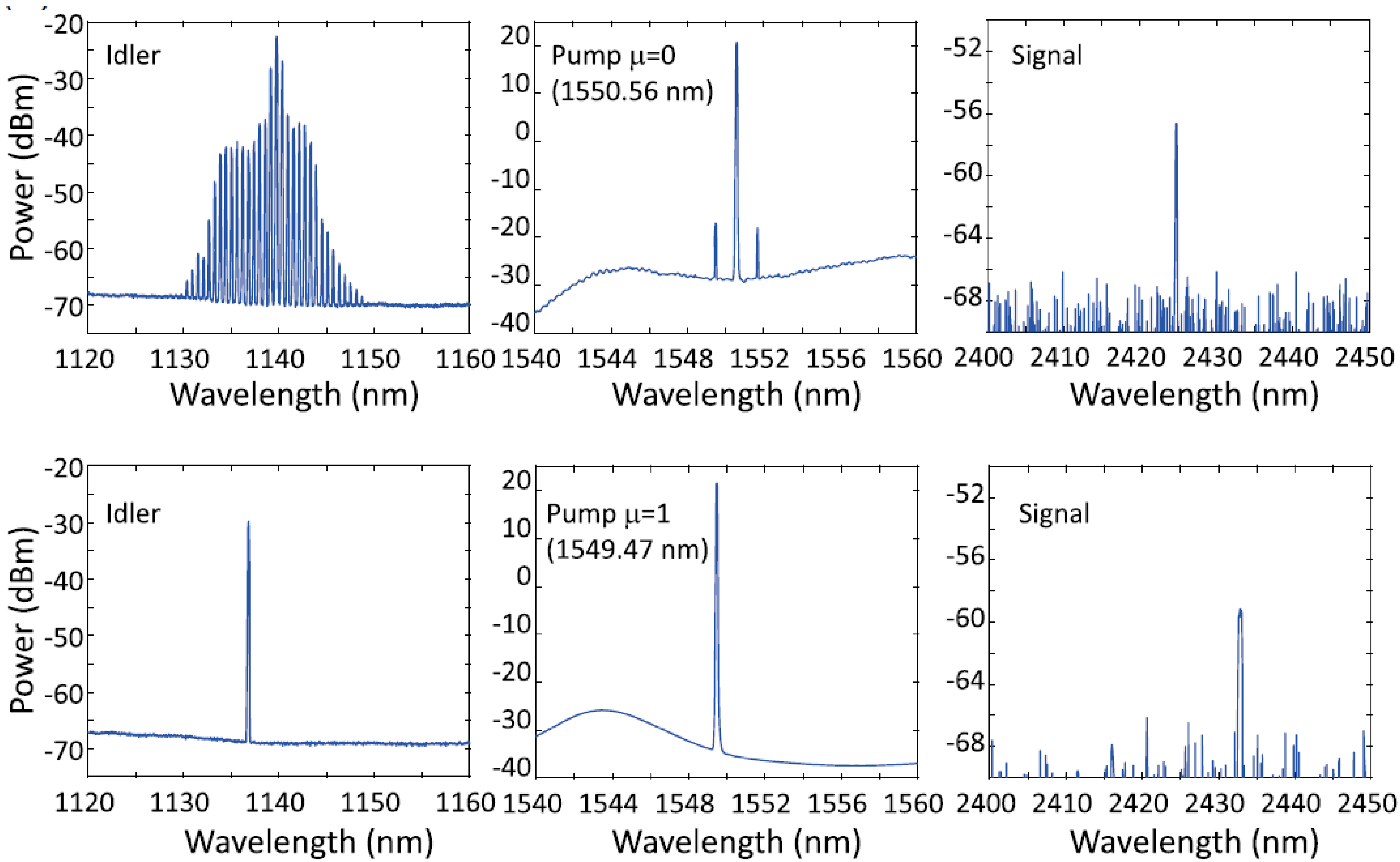




S. Fujii et al., Optics Letters 44, 3146 (2019).

Octave-wide phase-matched FWM

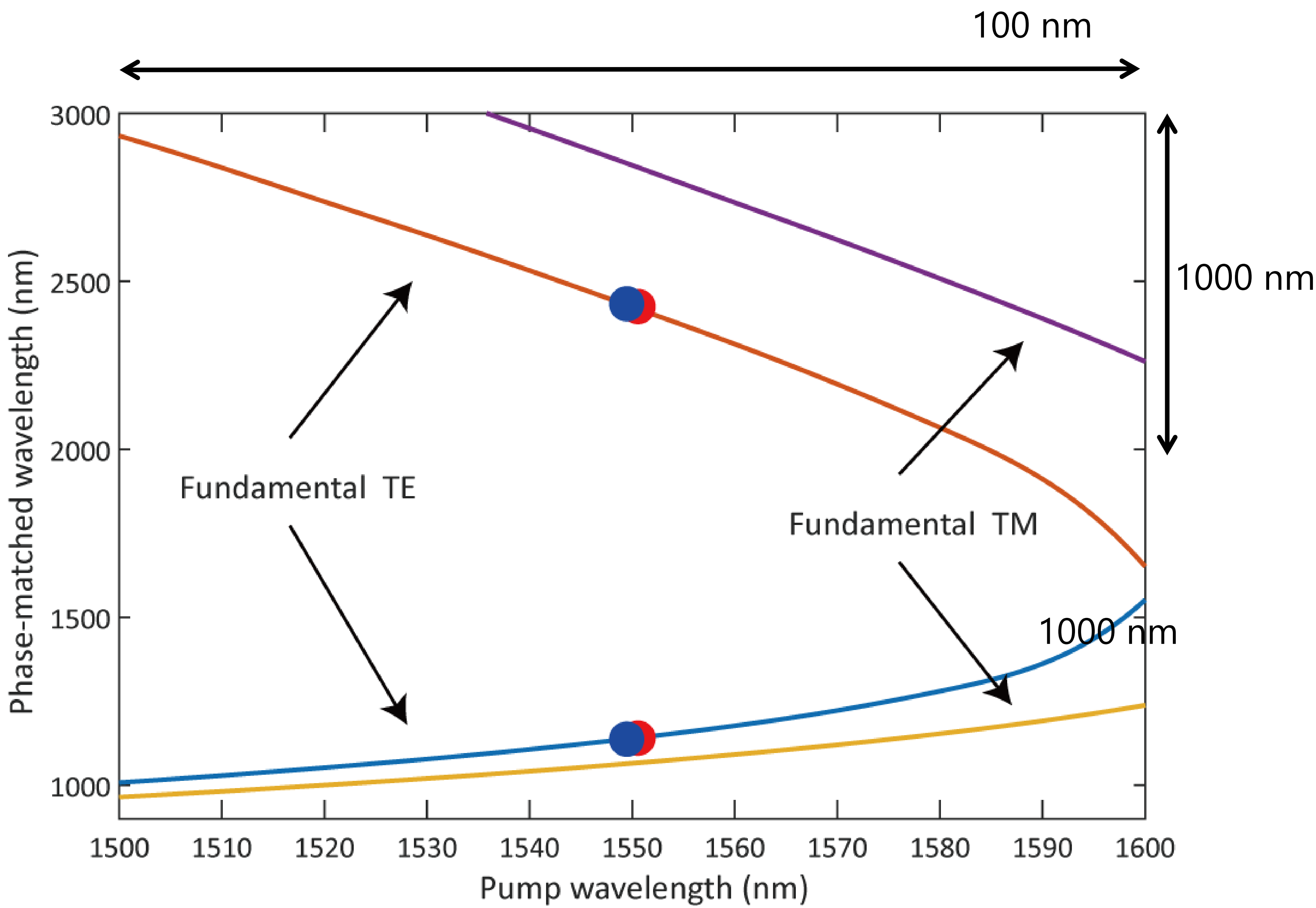
- Experiment



S. Fujii et al., Optics Letters 44, 3146 (2019).

- Shorter wavelength pump allows us to obtain larger frequency shift by the balance between D2 and D4 (Tunability of oscillation wavelegnths)

Wavelength tuning



Conclusion

- Proposed ideal WGM structure for 100-GHz FSR microcomb in MgF_2 crystalline microresonators (rectangular shapes achieve anomalous dispersion in 1550 nm)
- Identified critical depth and for each end-face orientation to acheive ultra-precision machining of crystalline microresonators
- Observed highest Q exceeding 10^8 and microcomb without polishing process
- Demonstrated octave-wide FWM in dispersion-engineered microresonators

Thank you

Publication

S. Fujii et al., "Octave-wide phase-matched four-wave mixing in dispersion engineered crystalline microresonators", Optics Letters **44**, 3146 (2019).

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