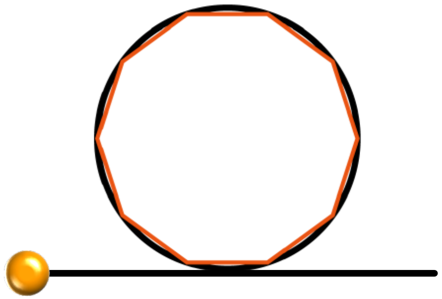
CLEO:2019 (STh4J.6)
May 9, 2019

Ultrahigh-Q Crystalline Microresonator Fabricated with Computer-controlled Machining without Polishing

Shun Fujii[1], Mika Fuchida[1], Hikaru Amano[2], Ryo Suzuki[1], Yasuhiro Kakinuma[2], and Takasumi Tanabe[1]

1. Department of Electronics and Electrical Engineering, Faculty of Science and Technology, Keio University
2. Department of System Design Engineering, Faculty of Science and Technology, Keio University

Ultrahigh-Q optical microresonators

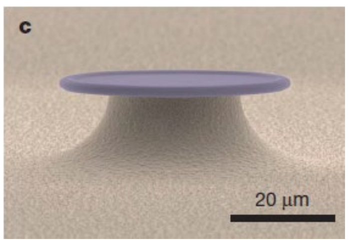


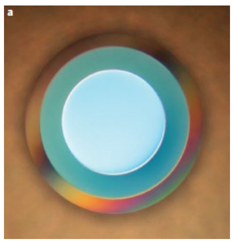
Whispering gallery mode (WGM) optical microresonator

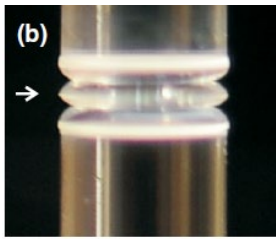
Confines light for long photon lifetime (high Q) and has small volume

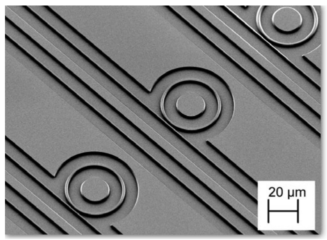
Enhances light-matter interaction in dielectric material

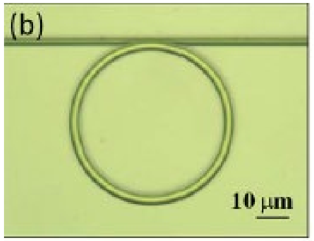
Dielectric microresonator platforms (Caltech, NIST, EPFL, OEwaves, Columbia, Harvard, Yale, INRS-EMT)

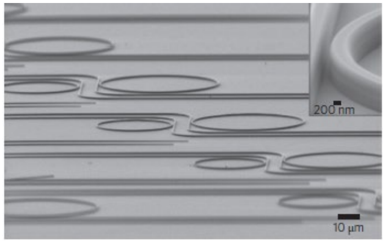


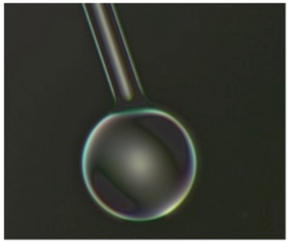


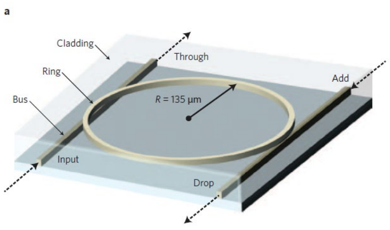


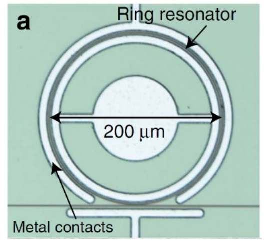












$$\text{(Intracavity power)} = \frac{4\eta d_1 Q}{\omega_0} \times \text{(Input power)}$$

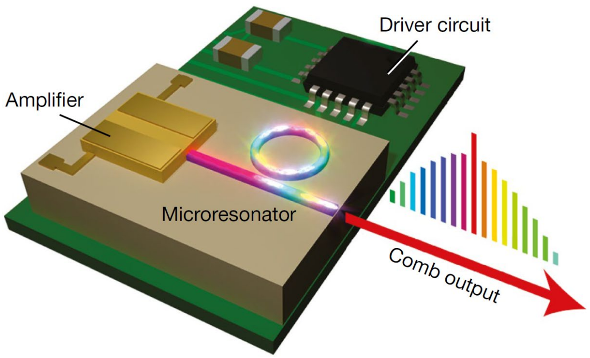
ω_0: laser frequency, d_1: cavity FSR,
Q: quality factor, η: coupling parameter

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

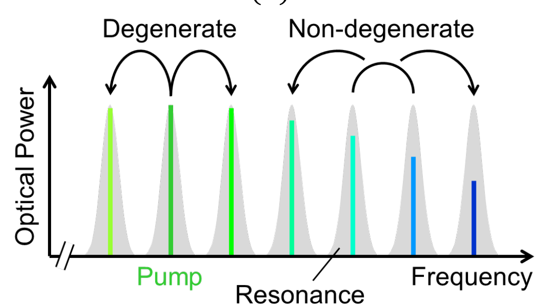
Target application: Microresonator frequency comb (Kerr comb)



Nature 562, 401–405 (2018)

Four-wave mixing (FWM)

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



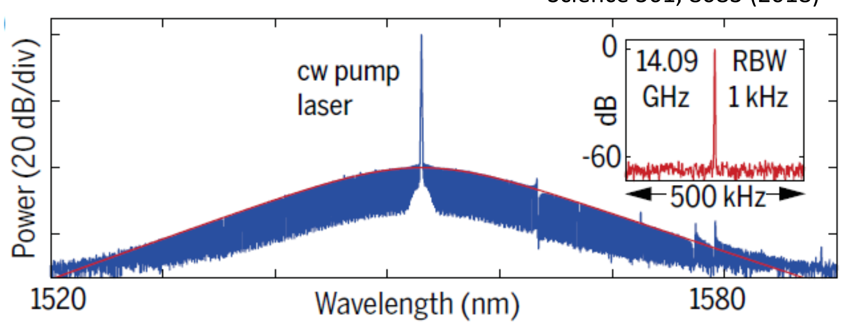
Threshold power for FWM

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

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

Optical spectrum of soliton

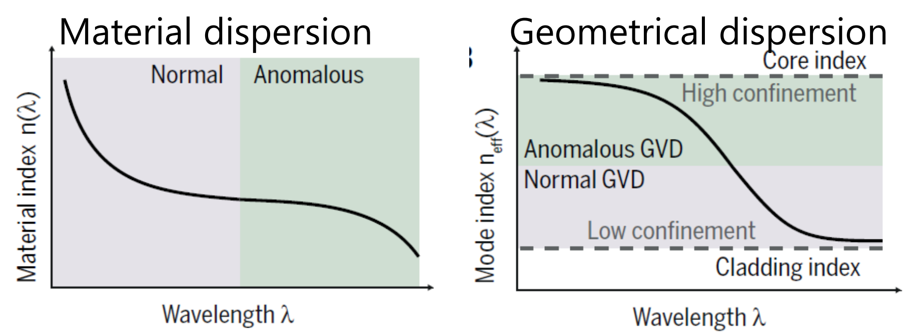
Science 361, 8083 (2018)



- Mode-locked state in Kerr comb (Kerr soliton)

$$\Psi(\mu) = \sqrt{d_2/2}\,\text{sech}\left(\frac{\pi\mu}{2}\sqrt{\frac{d_2}{\zeta_0}}\right) \qquad d_2 = D_2/\kappa, \quad \zeta_0 = \pi^2 f^2/8$$

Microresonator dispersion

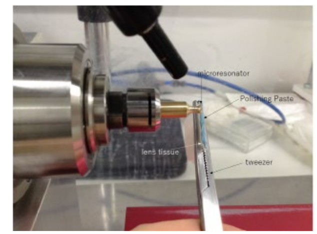


- Anomalous dispersion condition required

$$\beta_2 < 0 \ (D_2 > 0) \qquad \beta_2 = \frac{d^2\beta}{d\omega^2} = -\frac{nD_2}{cD_1^2}$$

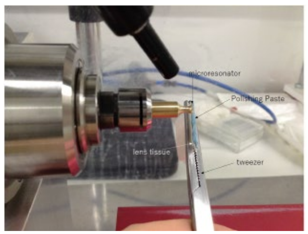
Microresonator fabrication methods

Mainstream microresonator fabrication methods

			
CO_2 laser reflow	Chemical etching	Polishing	Machining
Silica (SiO_2) Toroid / Sphere /Rod	Silica (SiO_2) disk Silicon nitride (SiN) Diamond Silicon (Si)	Fluoride crystal MgF_2 CaF_2 BaF_2 $LiNbO_3$(PPLN)	
Q ~ 10^8	Q ~ 10^7	Q ~ 10^{10}	Q ~ 10^6
Only amorphous Geometric control ✘	Various materials Geometric control ❍	Ultra-high Q Geometric control ✘	Low Q Geometric control ❍

Microresonator fabrication methods

Combination of two methods



Polishing

Machining

Fluoride crystal

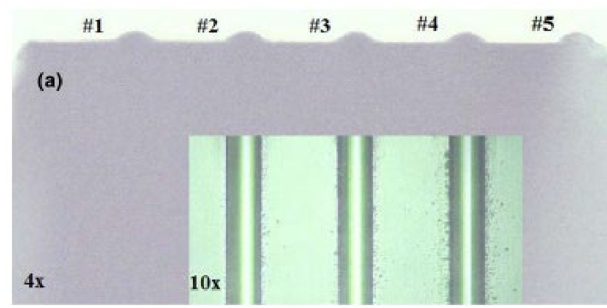
MgF_2 CaF_2 BaF_2

$LiNbO_3$(PPLN)

Polishing	Machining
$Q \sim 10^{10}$	$Q \sim 10^{6}$
Ultra-high Q	Low Q
Form accuracy ✘	Form accuracy ❍

Crystalline resonators formed by hand polishing after diamond turning process (Q exceeding 10^8)

Optica 2, 221 (2015)



Optics Letters 42, 514 (2017)

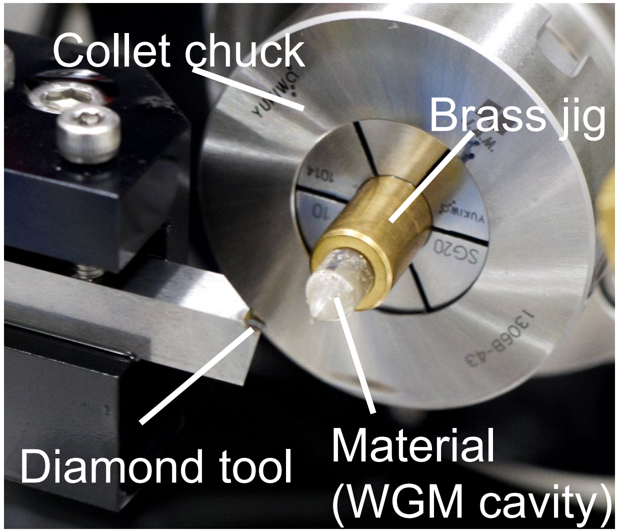
- Ultra-high Q ($Q > 10^9$) achieved by polishing after computer-controlled machining process
- Additional hand polishing degrades predesigned geometry (disadvantage for dispersion tailoring)
- Never again producing the standard microresonators

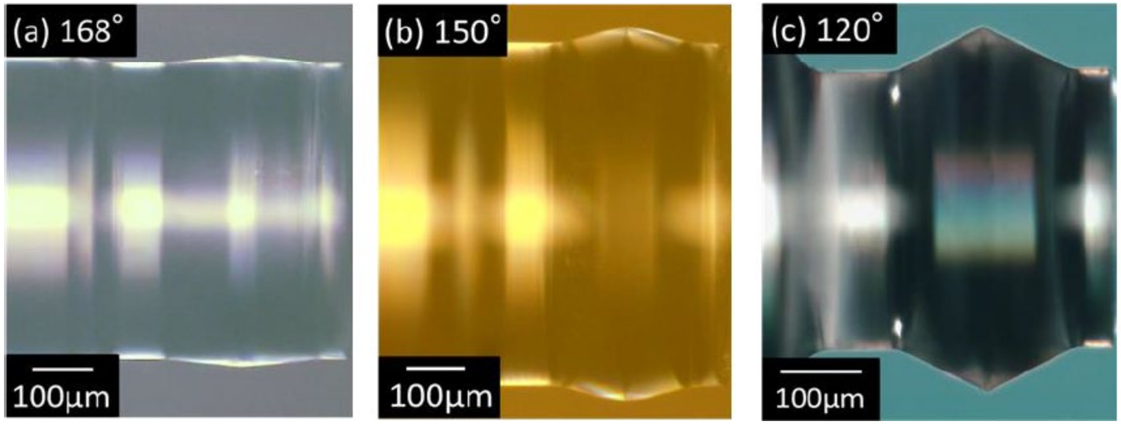
Motivation

Motivation

- Fabricate ultra-high Q crystalline microresonators ($Q>10^8$) by computer-controlled machining **without polishing**
- Explore the potential of dispersion engineering for crystalline microresonators towards soliton formation at broadband wavelengths

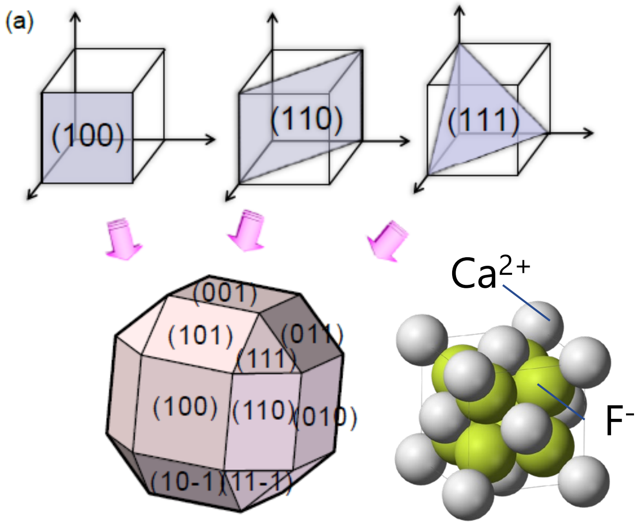
Fully computer-controlled ultra-precision machining for dispersion engineering





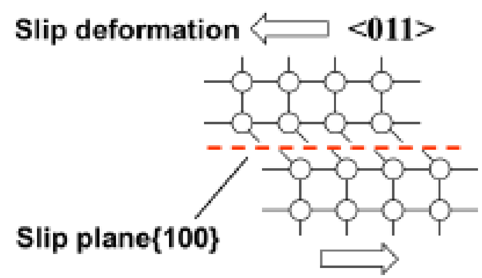
Machining of single crystal materials

Crystallographic image of CaF_2 material



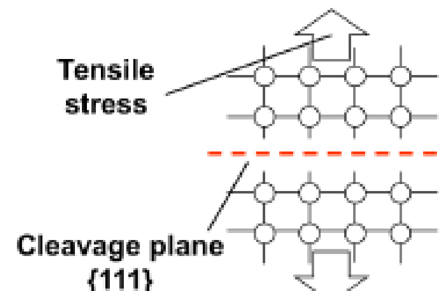
- Plane of single crystal is defined as mirror index
- CaF_2 consists of only 3 planes (100), (110), (111)
- Cutting mode transition observed with cutting depth

Slip formation (100)[110]



More ductile

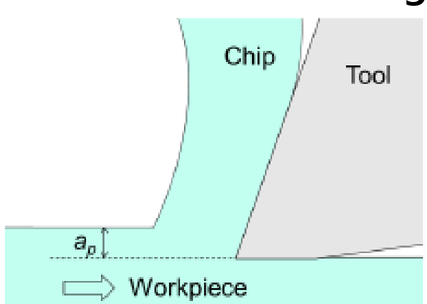
Cleavage formation (111)



Very brittle

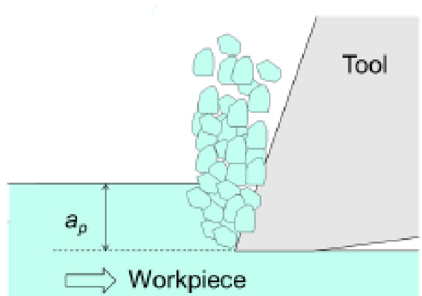
Cutting mode transition is observed depending on crystal anisotropy

Ductile-mode cutting



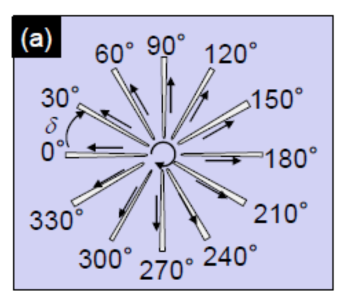
Cutting depth < Critical depth

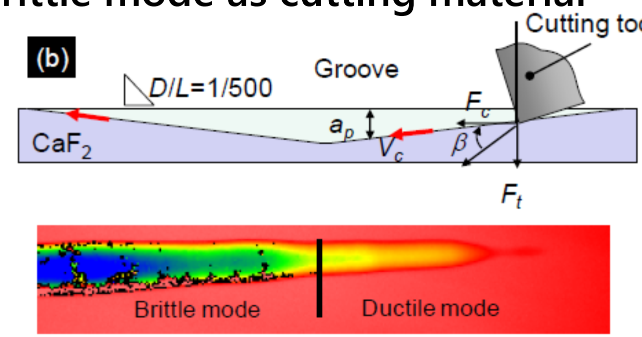
Brittle-mode cutting



Cutting depth > Critical depth

Transition to brittle mode as cutting material

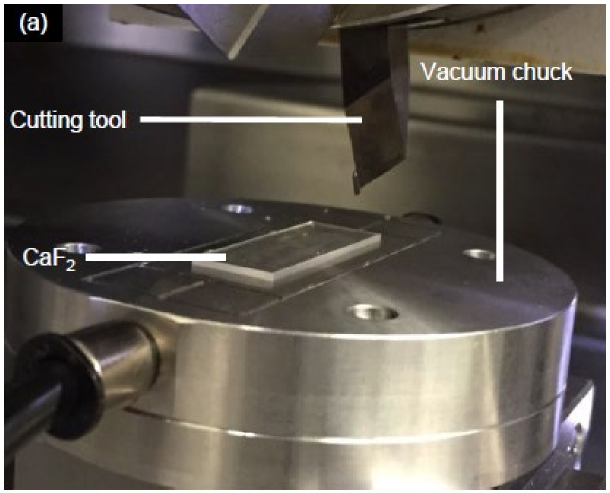




Precision Engineering 40 (2015) 172–181

Orthogonal cutting experiment

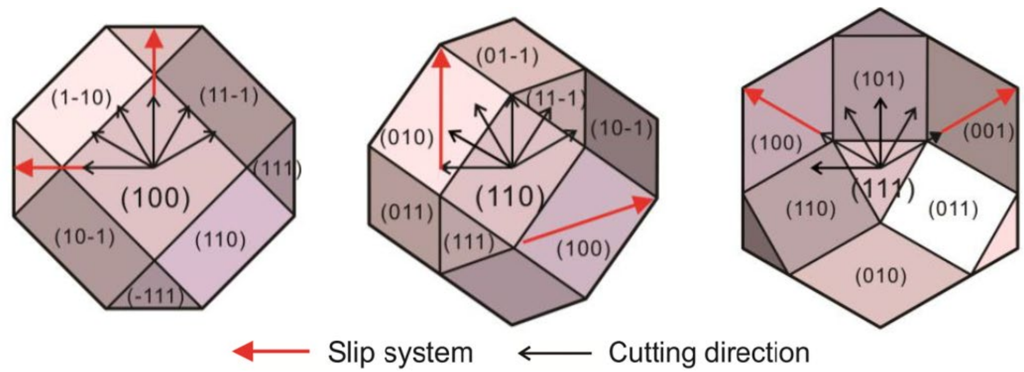
Experimental setup

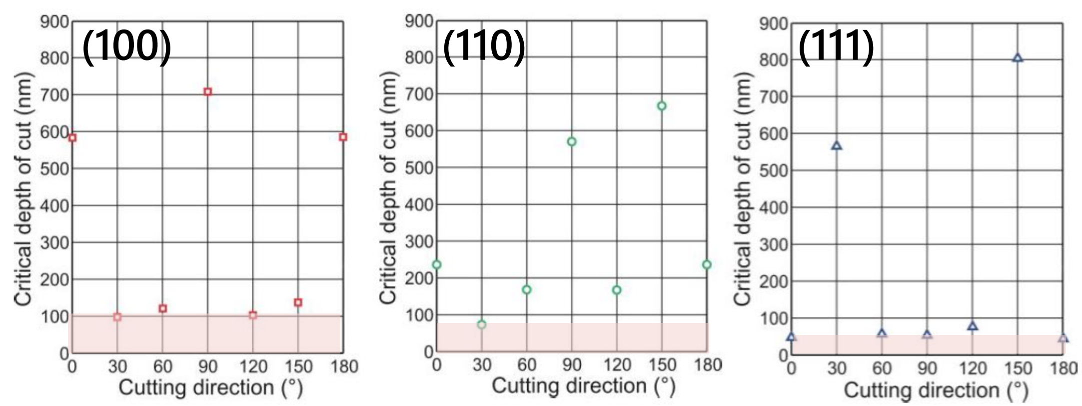


"Objective" of orthogonal cutting experiment

- Resonators must be fabricated with ductile-mode cutting
- Identify critical cutting depth for all crystal planes and cutting directions with orthogonal cutting experiment

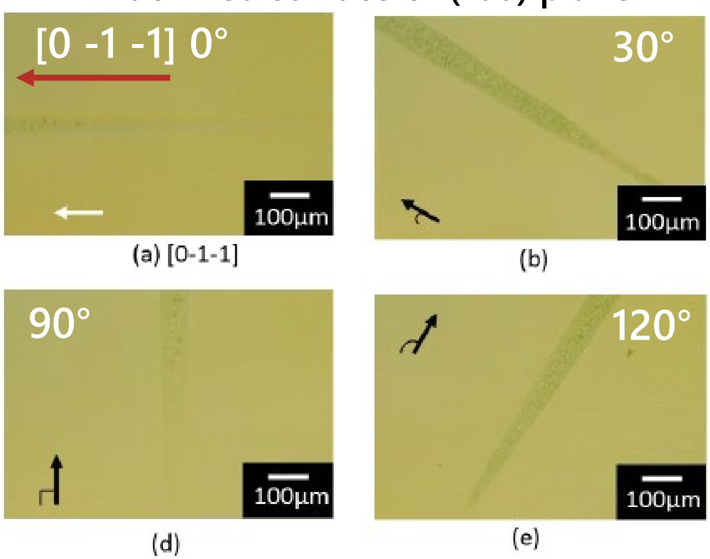
Critical cutting depth vs direction for different planes





Critical cutting depth is over 50 nm for all planes

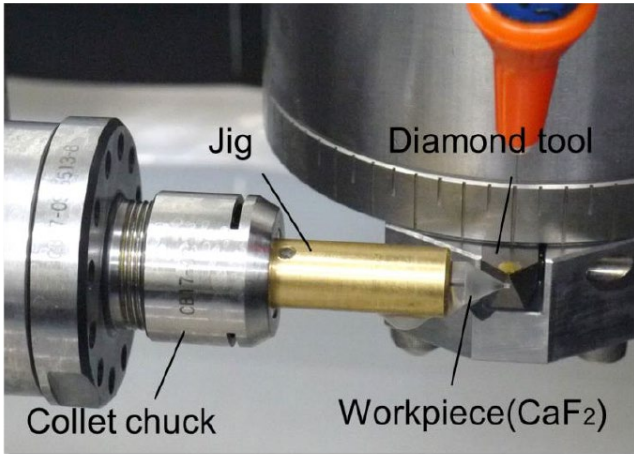
Machined surface of (100) plane



Precision Engineering 40 (2015) 172–181

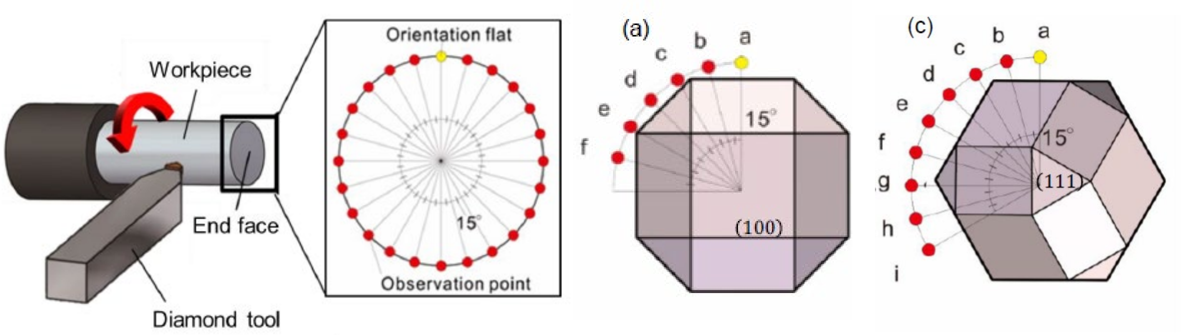
Cylindrical turning experiment

Experimental setup

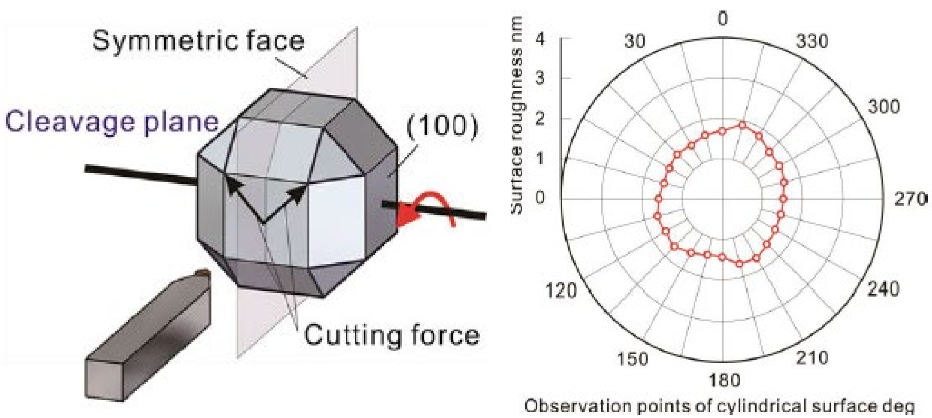


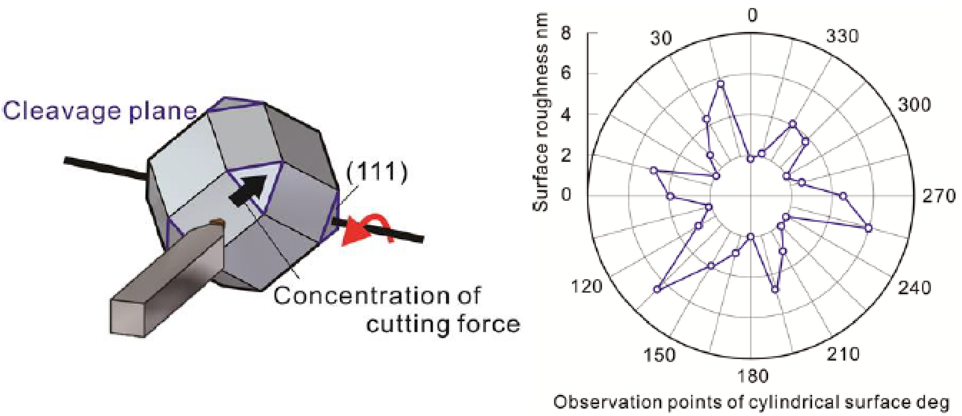
"Objective" of cylindrical turning experiment

- 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





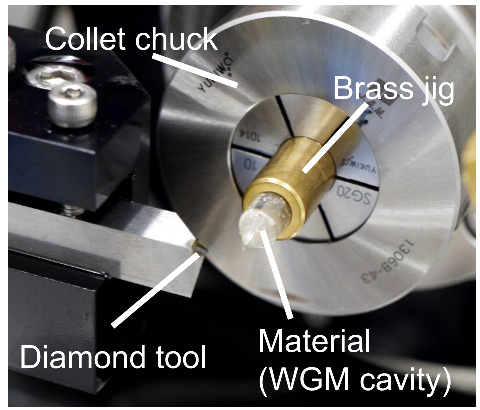
Observed smooth surface with end-face (100)

Observed surface clack with the end-face (111)

Precision Engineering 40 (2015) 172–181 Precision Engineering 49 (2017) 104–114

Ultra-precision machining procedure

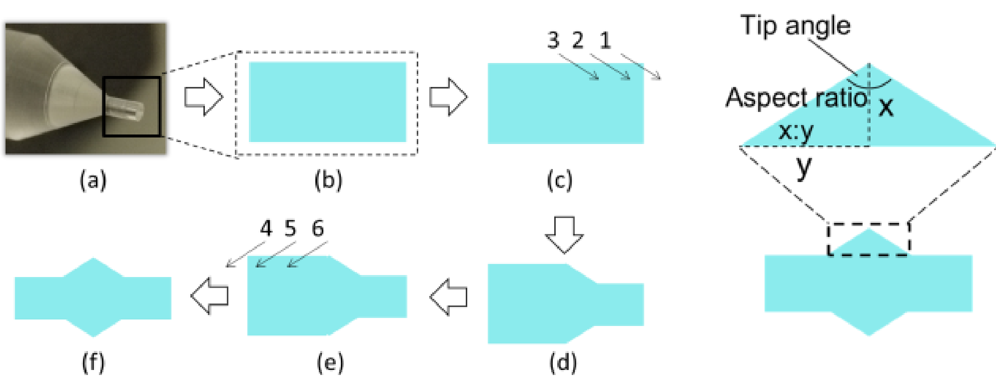
Experimental setup and machine used

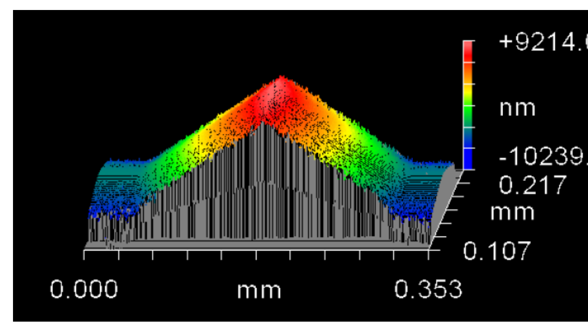


Manufacturing parameters

- 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

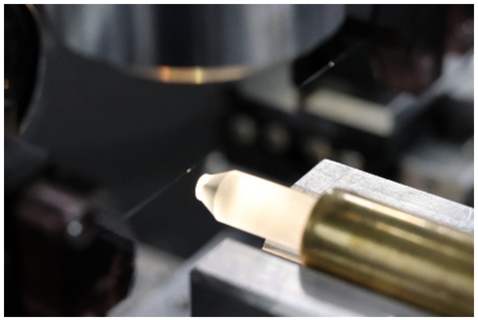


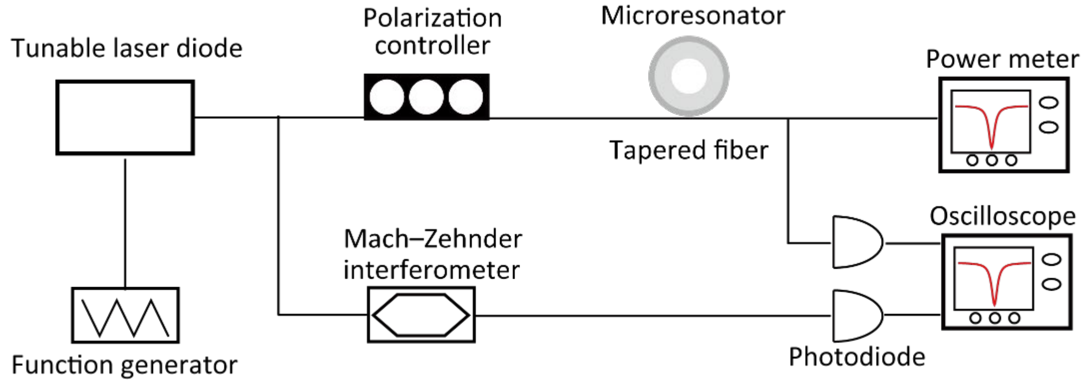


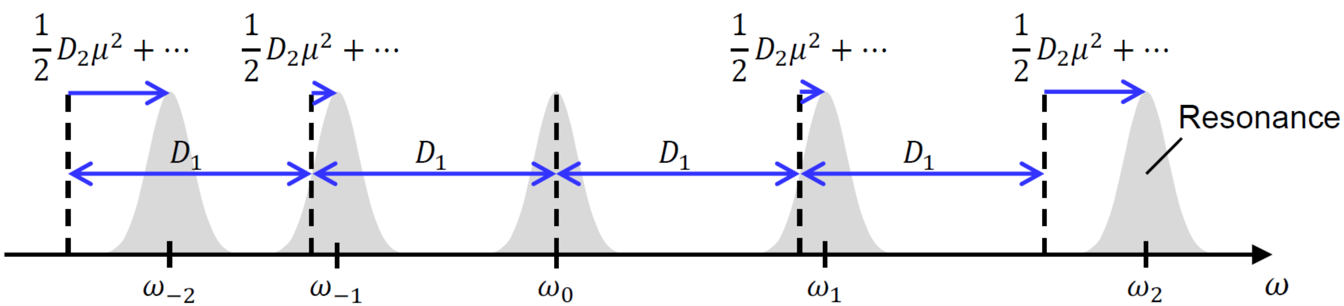
- The tip angle and the aspect ratio are pre-designed and formed by computer-controlled turning, which is attractive with respect to dispersion engineering

Experimental setup

Experimental setup for Q-factor and dispersion measurement







Group-velocity dispersion

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

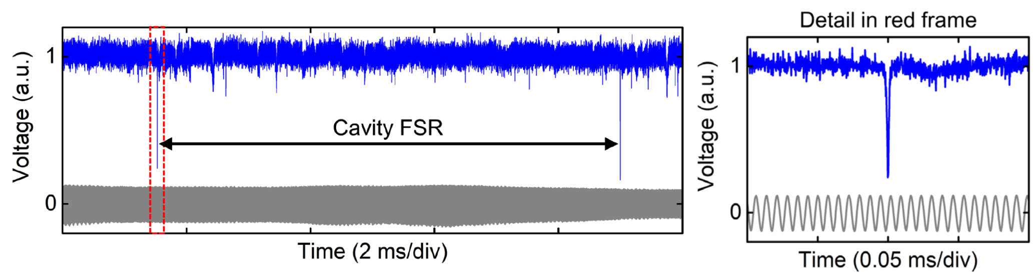
Resonance frequency: $\omega_m = \frac{2\pi mc}{Ln(\omega)}$

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

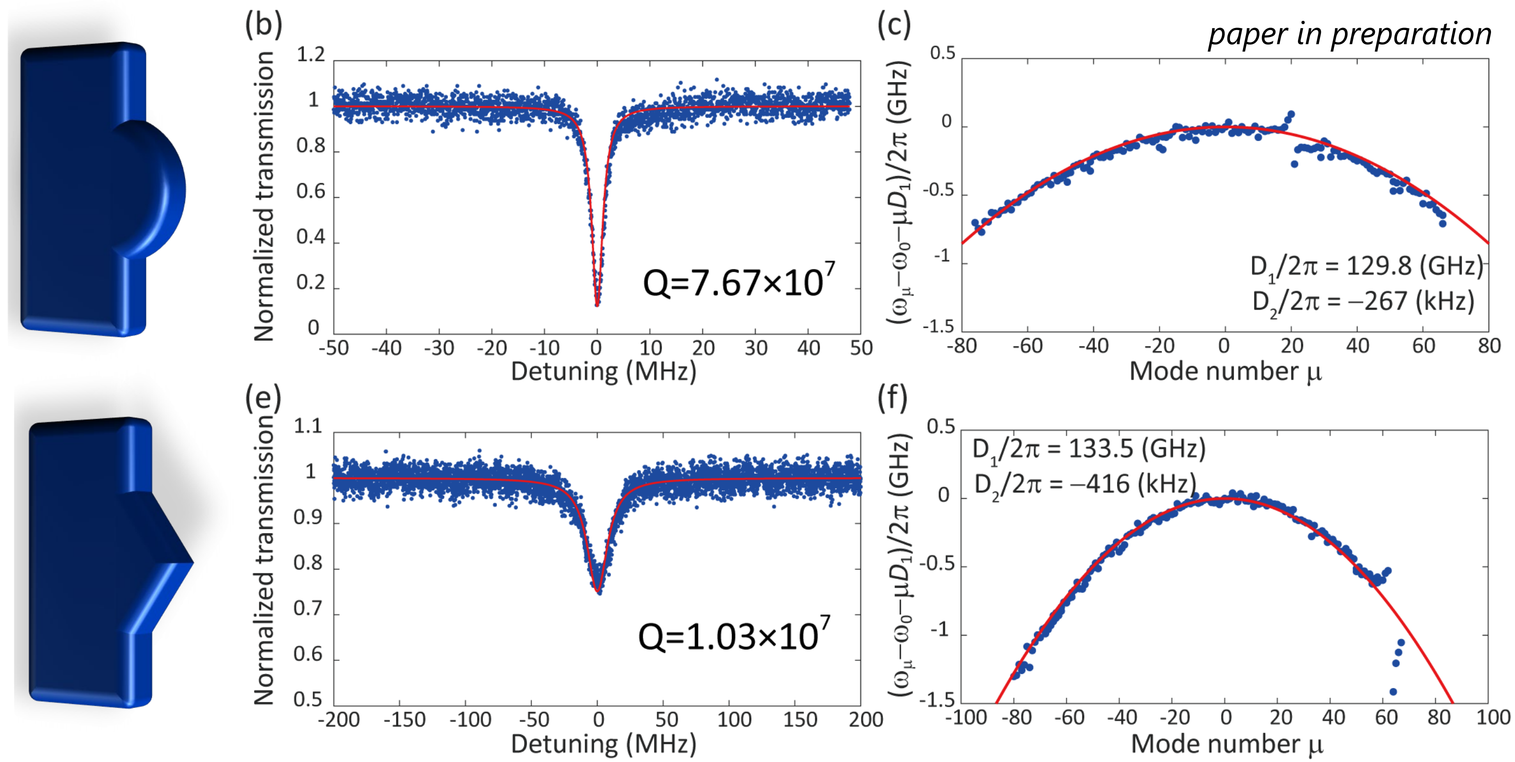


Measured Q-factor and dispersion

CaF_2 crystalline microresonator fabricated *"without polishing"*

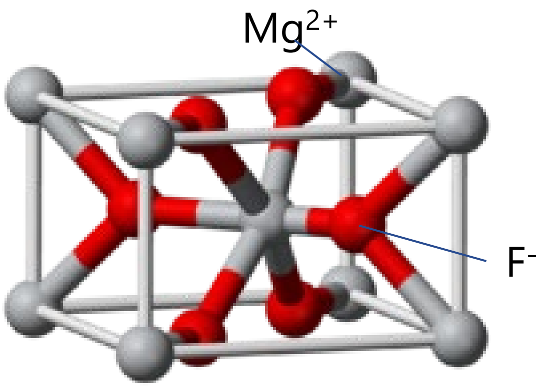
Spherical WGM
Diameter 512 µm
Curvature 36 µm

Triangular WGM
Diameter 502 µm
Apex angle 120°



- Measurements were performed after removing chips by cleaning with lens tissue
- Experimental measured dispersions agree well with simulation results
- Spherical cross-sectional shape shows higher Q than triangular shape

With MgF_2 crystal



Magnesium fluoride has a "rutile" structure

- Crystallographic image is more complex than that of CaF_2
- Cutting condition will also be complex…

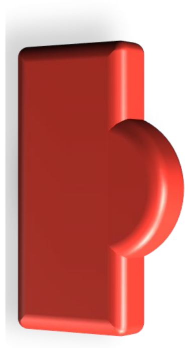
Knoop hardness (hardness of a materials)

- MgF_2 : 415 (kg/mm^2)
- CaF_2 : 158.3 (kg/mm^2)

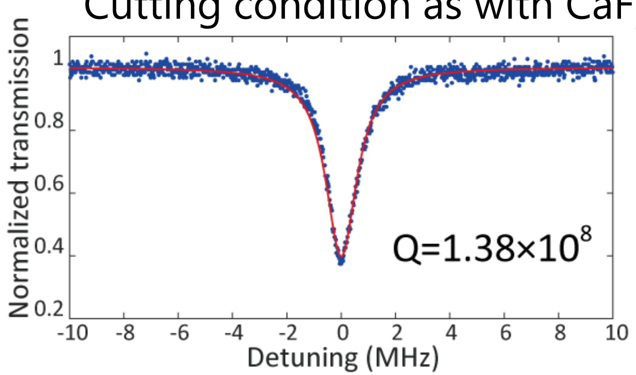
Spherical WGM

Diameter 508 µm

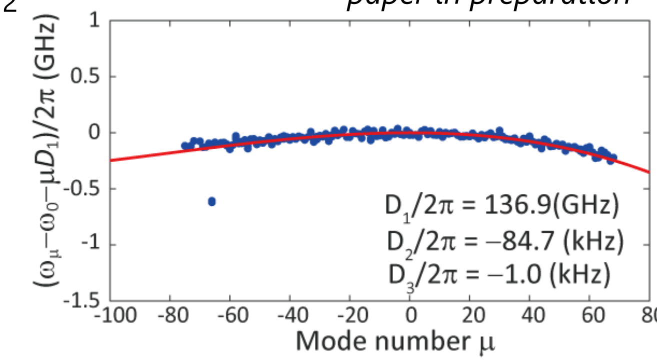
Curvature 36 µm



Cutting condition as with CaF_2



paper in preparation

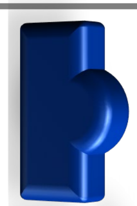
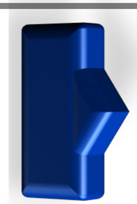
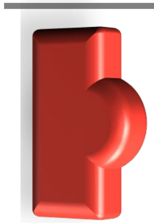


- Highest Q-factor exceeding 10^8 was observed in MgF_2 spherical WGM resonator
- Effect of crystal anisotropy and best end-face should be investigated
- MgF_2 is more suitable for Kerr comb generation as regards thermal stability

Summary

- Investigated machining of single crystal material
- Identified critical depth and for each end-face orientation to acheive ultra-precision machining of CaF_2 WGM microresonators
- Observed highest Q exceeding 10^8 without polishing process

Summary of crystalline microresonators fabricated without polishing

	CaF_2 Spherical WGM	$Q = 7.67 \times 10^7$ $Q = 6.07 \times 10^7$	FSR = 129.8 GHz FSR = 22.08 GHz	$D_2/2\pi$ = -267 kHz $D_2/2\pi$ = -2.3 kHz
	CaF_2 Triangular WGM	$Q = 1.03 \times 10^7$	FSR = 133.5 GHz	$D_2/2\pi$ = -416 kHz
	MgF_2 Spherical WGM	$Q = 1.38 \times 10^8$ $Q = 2.1 \times 10^7$	FSR = 136.9 GHz FSR = 21.61 GHz	$D_2/2\pi$ = -84.7 kHz $D_2/2\pi$ = 4.86 kHz

Thank you

Acknowledgment

This work is supported by Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant Number JP19H00873, JP18J21797 and Grant-in-Aid for JSPS Fellow; Amada Foundation; The Ministry of Education, Culture, Sports, Science and Technology (MEXT) Q-LEAP

We thank Dr. Y. Mizumoto, H. Kangawa, and Ms. Y. Hayama for their contribution of this work