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Precisely Dispersion Tailored Crystalline Microresonator with a Q Exceeding 10^8 Fabricated by Computer-controlled Machining

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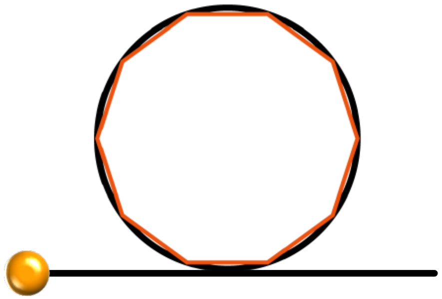
Ultrahigh-Q optical microresonators

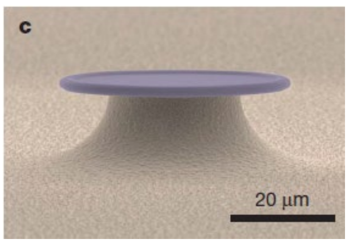


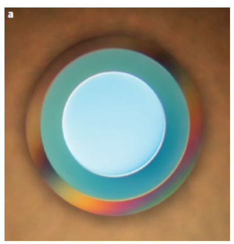
Whispering gallery mode (WGM) optical microresonator

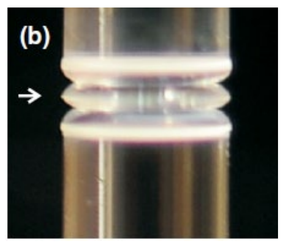
Confines light for long photon lifetime (high Q) and has small volume

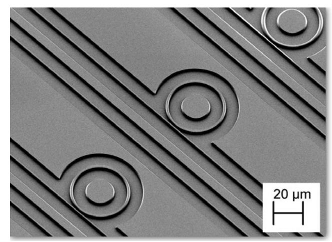
Enhances light-matter interaction in dielectric material

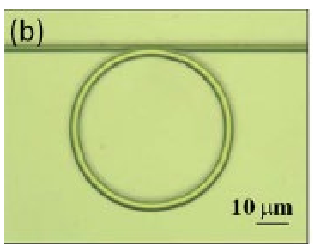
Dielectric microresonator platforms (Caltech, NIST, EPFL, OEwaves, Columbia, Harvard, Yale, INRS-EMT)

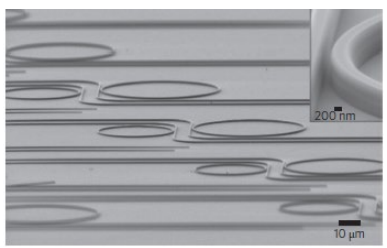


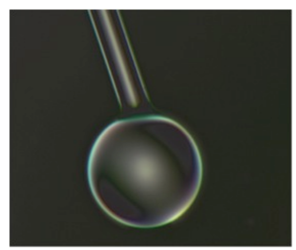


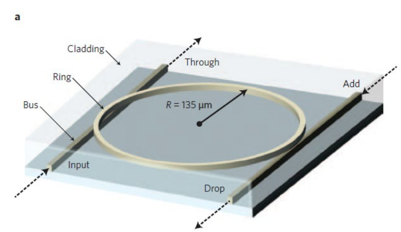


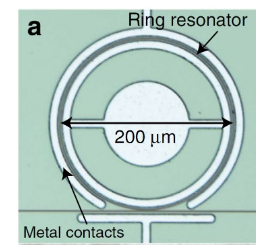












$$(\text{Intracavity power}) = \frac{4\eta d_1 Q}{\omega_0} \times (\text{Input power})$$

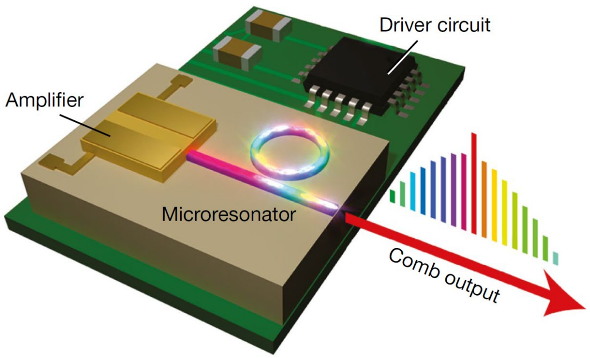
ω_0: laser frequency, d_1: cavity FSR,
Q: quality factor, η: coupling parameter

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

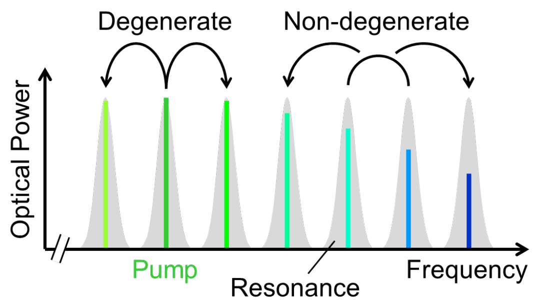
Target application: Microresonator frequency comb (Kerr comb)



Nature 562, 401–405 (2018)

Four-wave mixing (FWM)

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



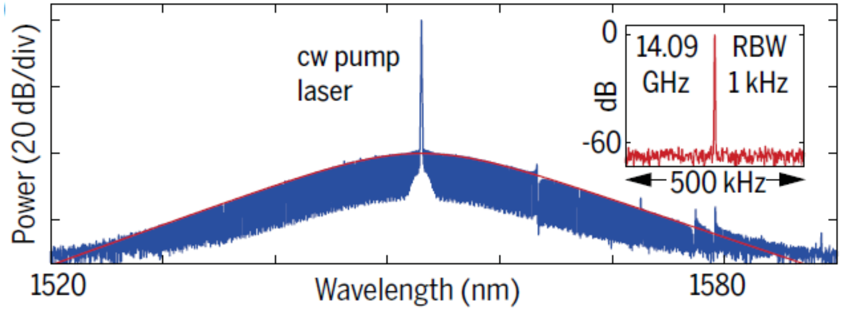
Threshold power for FWM

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

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

Optical spectrum of soliton

Science 361, 8083 (2018)

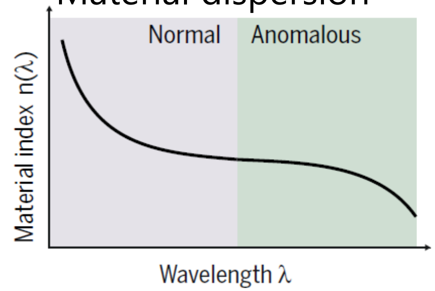


- Mode-locked state in Kerr comb (Kerr soliton)

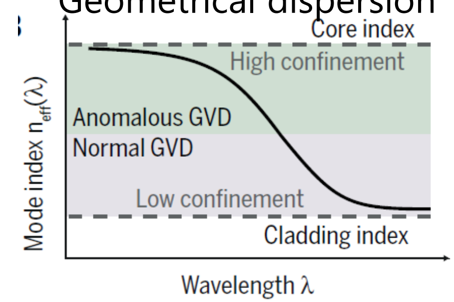
$$\Psi(\mu) = \sqrt{d_2/2}\,\mathrm{sech}\left(\frac{\pi\mu}{2}\sqrt{\frac{d_2}{\zeta_0}}\right) \qquad d_2 = D_2/\kappa, \quad \zeta_0 = \pi^2 f^2/8$$

Microresonator dispersion

Material dispersion



Geometrical dispersion

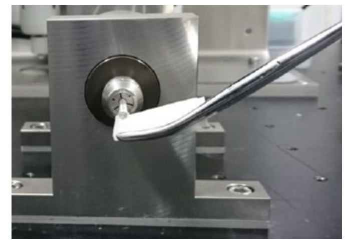
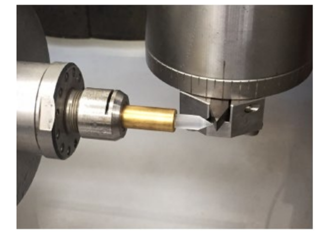


- Anomalous dispersion condition required

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

Microresonator fabrication methods

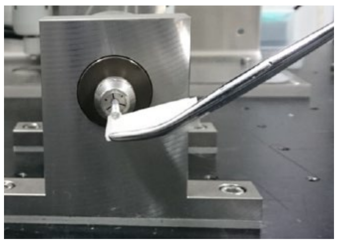
Mainstream microresonator fabrication methods

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

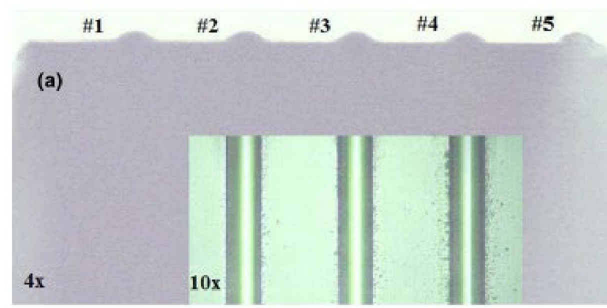
MgF_2 CaF_2 BaF_2

$LiNbO_3$(PPLN)

Polishing	Machining
Q ~ 10^{10}	Q ~ 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)

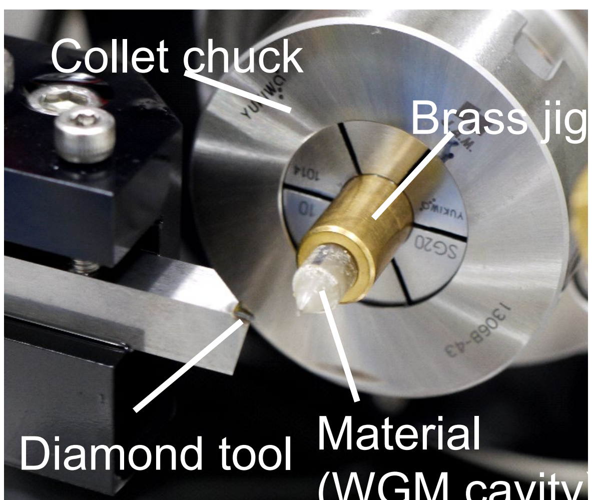
- Never again producing the standard microresonators

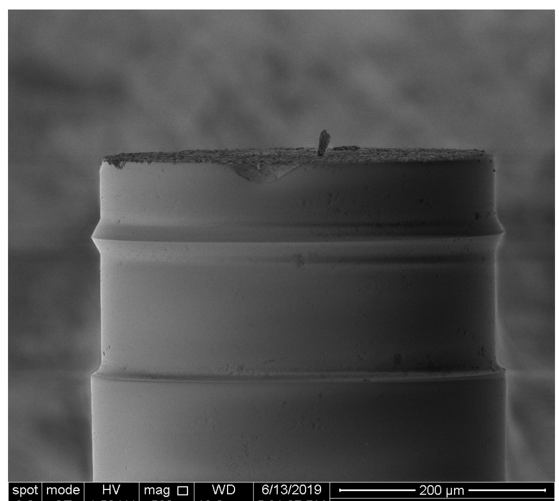
Motivation

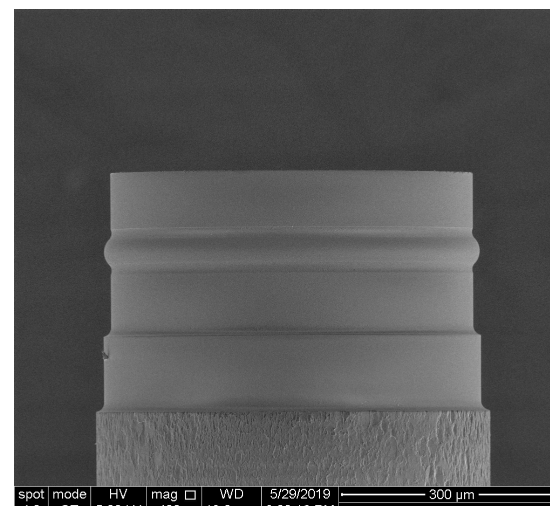
Motivation

- 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

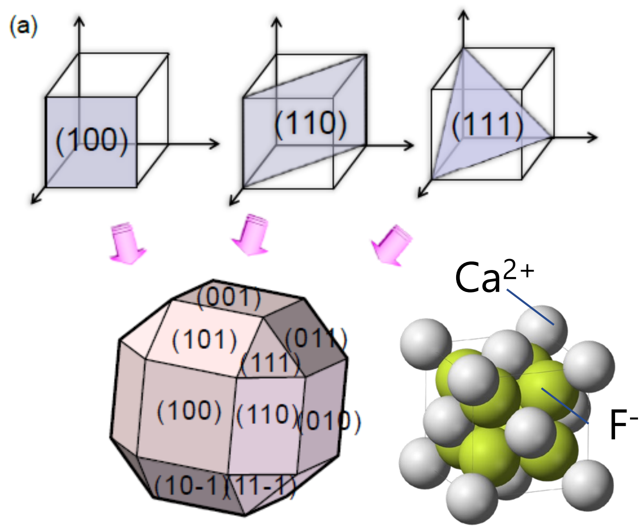






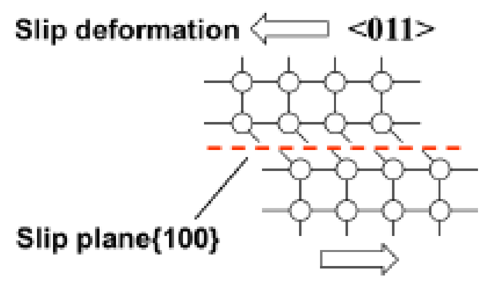
Machining of single crystal materials

Crystallographic image of CaF_2 material



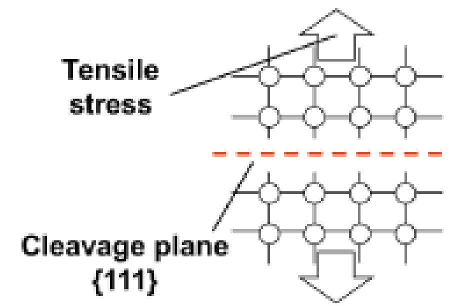
- Plane of single crystal is defined as mirror index
- CaF_2 consists of only 3 planes (100), (110), (111)
- Cutting mode transition observed with cutting depth

Slip formation (100)[110]



More ductile

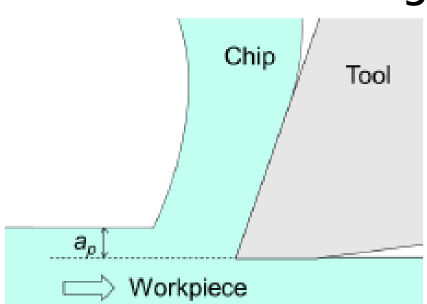
Cleavage formation (111)



Very brittle

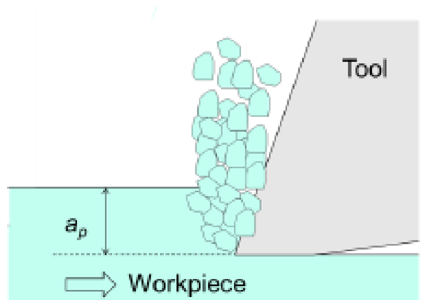
Cutting mode transition is observed depending on crystal anisotropy

Ductile-mode cutting



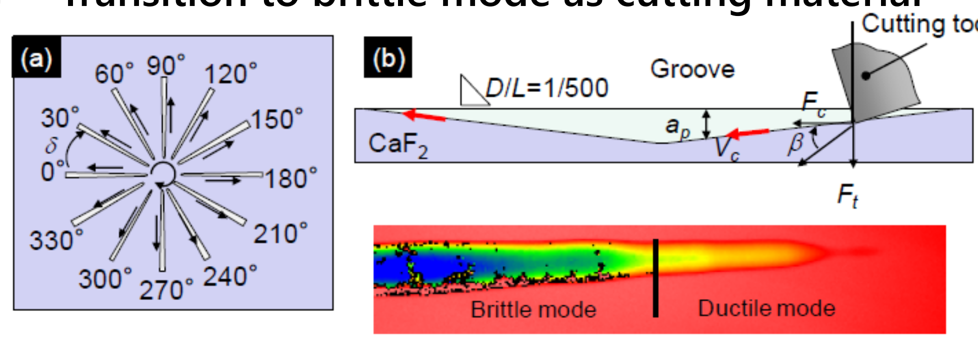
Cutting depth < Critical depth

Brittle-mode cutting



Cutting depth > Critical depth

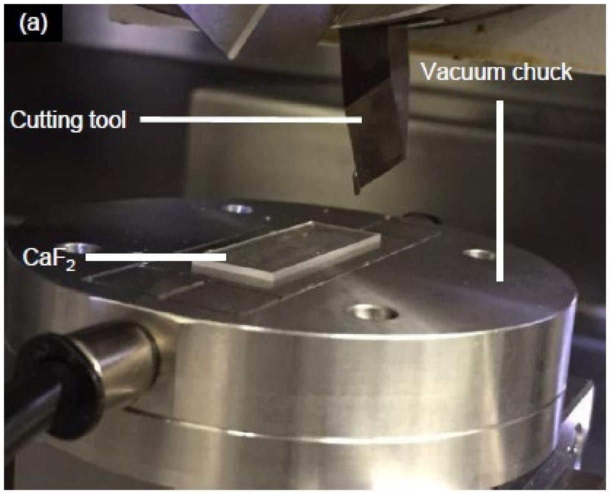
Transition to brittle mode as cutting material



Precision Engineering 40 (2015) 172–181

Orthogonal cutting experiment

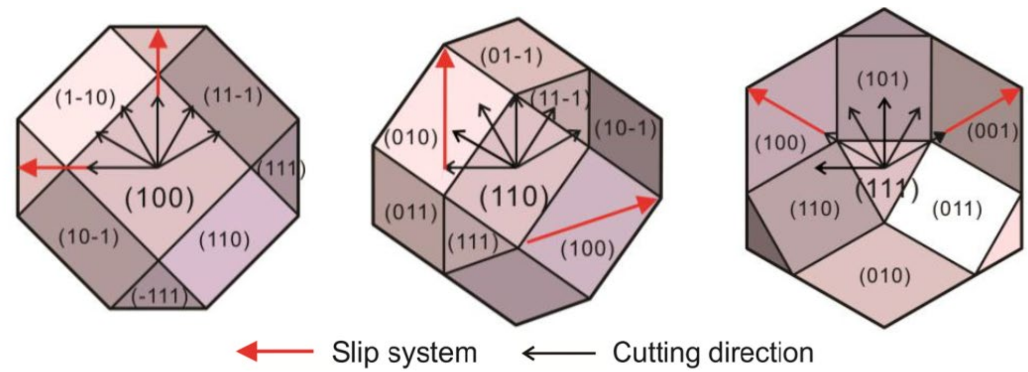
Experimental setup

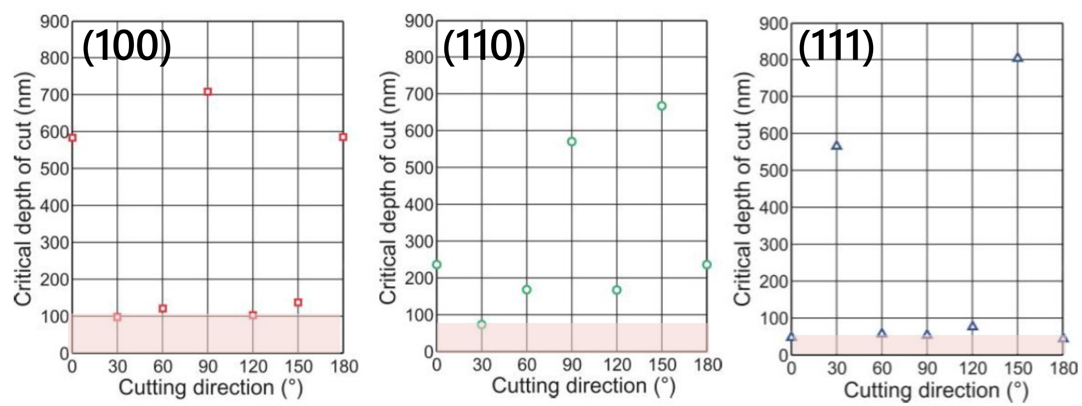


"Objective" of orthogonal cutting experiment

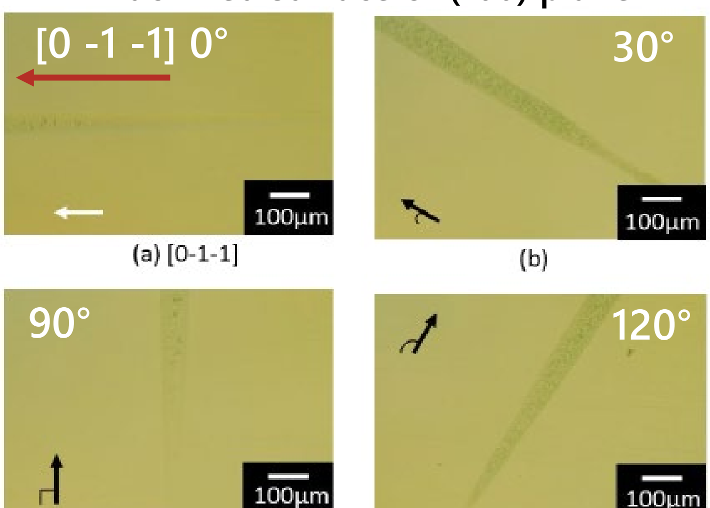
- Resonators must be fabricated with ductile-mode cutting
- Identify critical cutting depth for all crystal planes and cutting directions with orthogonal cutting experiment

Critical cutting depth vs direction for different planes





Machined surface of (100) plane



(a) [0-1-1] (b) (d) (e)

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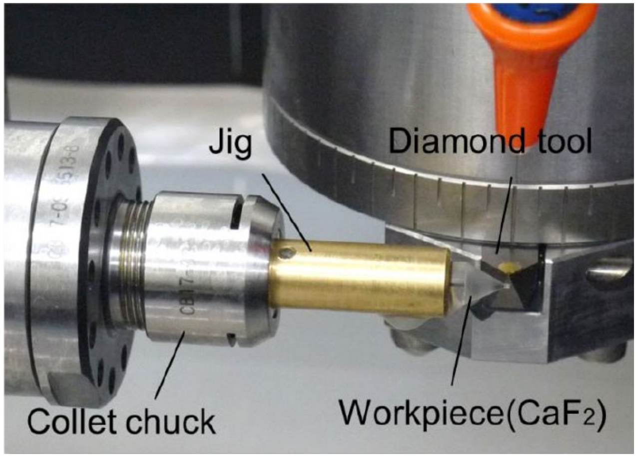
Critical cutting depth is over 50 nm for all planes

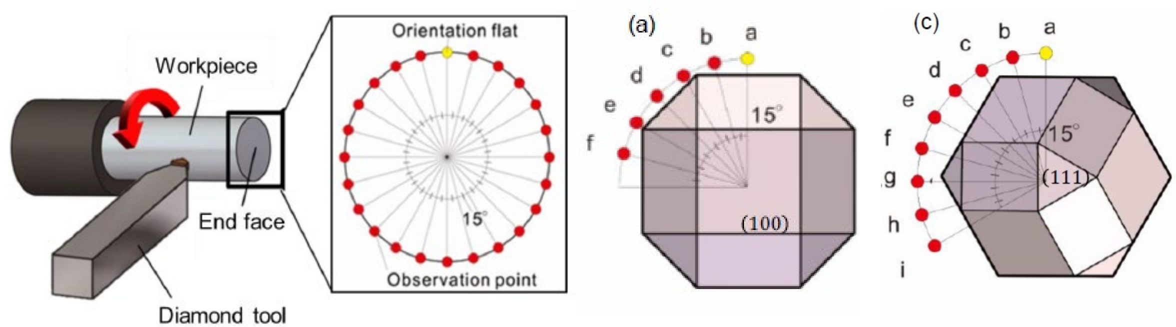
Cylindrical turning experiment

Experimental setup

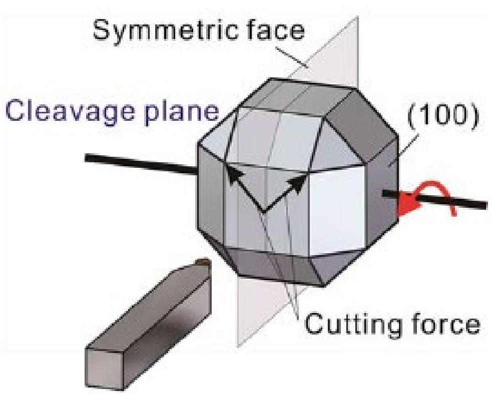


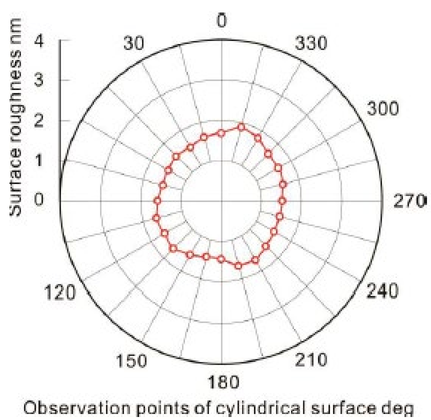
"Objective" of cylindrical turning experiment

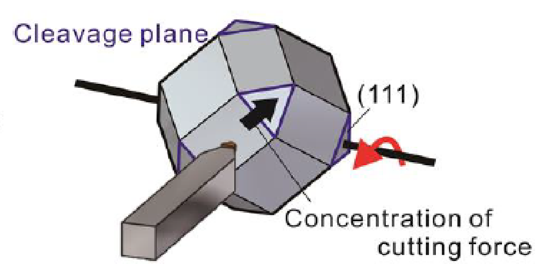
- Cutting plane and direction are continuously and simultaneously changed when resonator is turned
- Investigate surface roughness of entire cylindrical surface

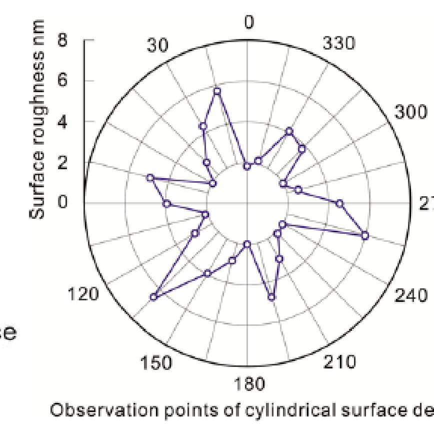


Cylindrical surface roughness for observation points with different end-faces









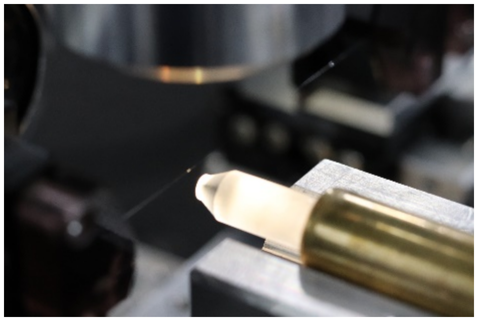
Observed smooth surface with end-face (100)

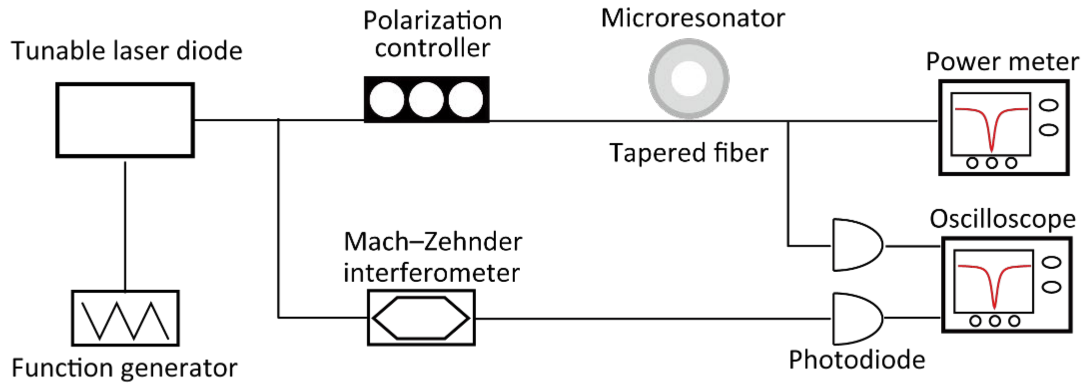
Observed surface clack with the end-face (111)

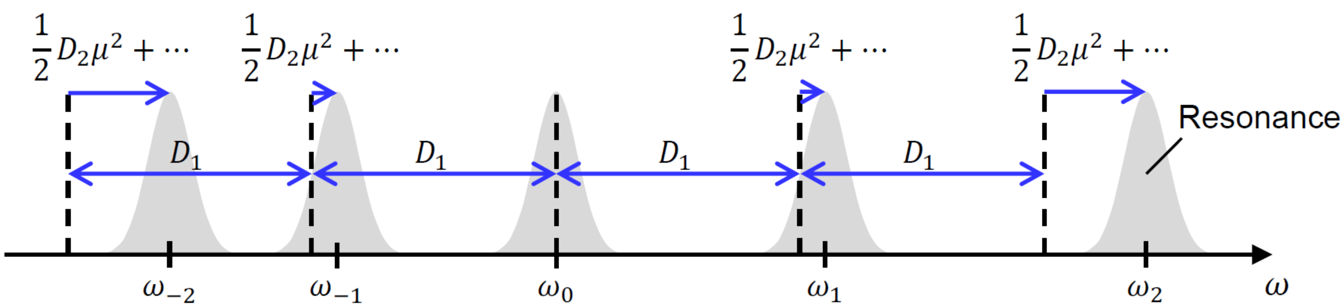
Precision Engineering 40 (2015) 172–181 Precision Engineering 49 (2017) 104–114

Experimental setup

Experimental setup for Q-factor and dispersion measurement







Group-velocity dispersion

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

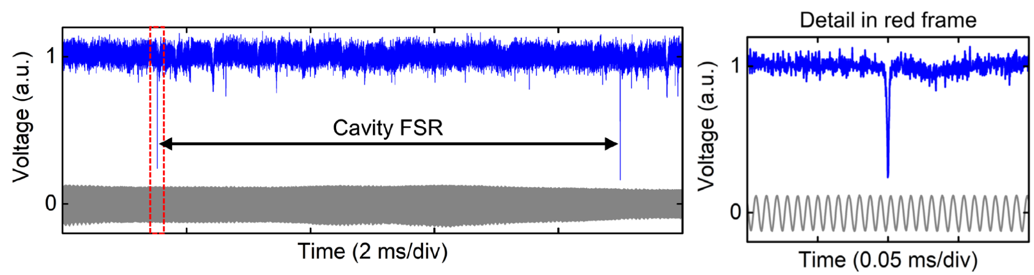
Resonance frequency: $\omega_m = \dfrac{2\pi mc}{Ln(\omega)}$

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

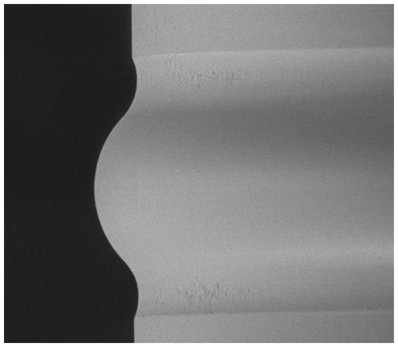


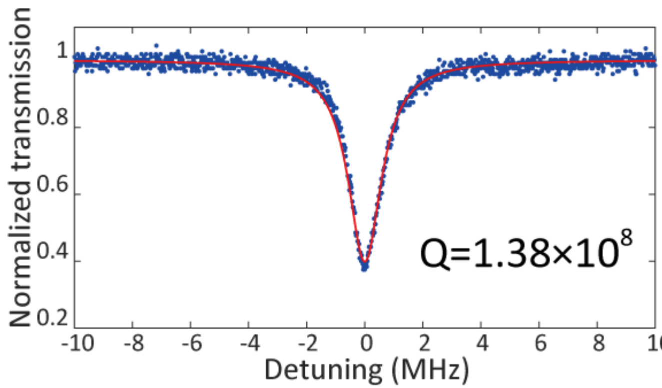
Measured Q-factor and dispersion

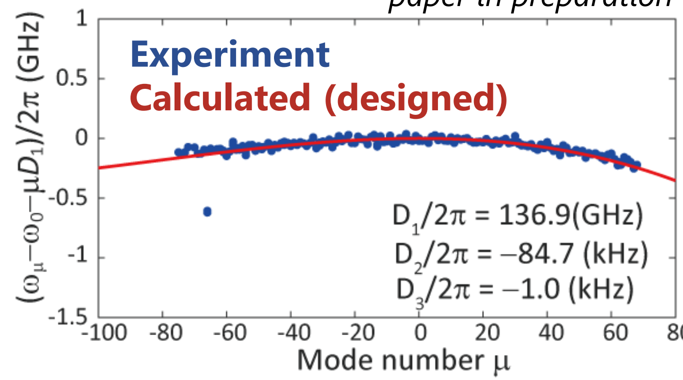
Crystalline microresonator fabricated *"without polishing"*

Spherical MgF_2 WGM Diameter 508 µm Curvature 36 µm

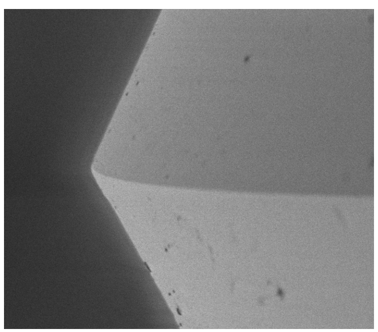
paper in preparation

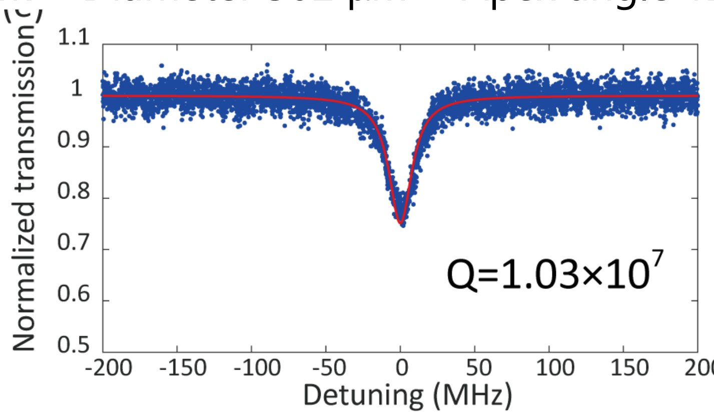


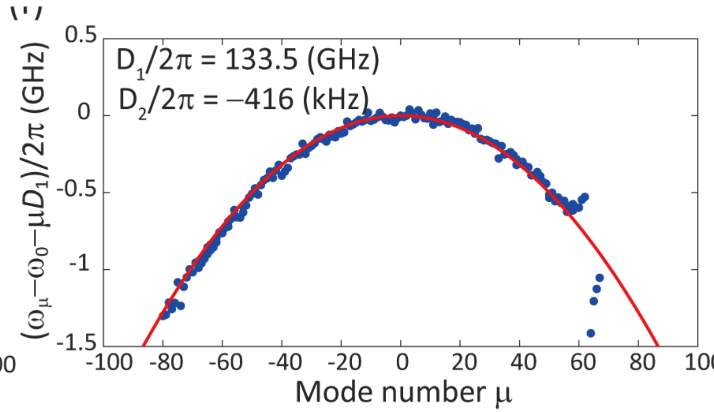




Triangular CaF_2 WGM Diameter 502 µm Apex angle 120°



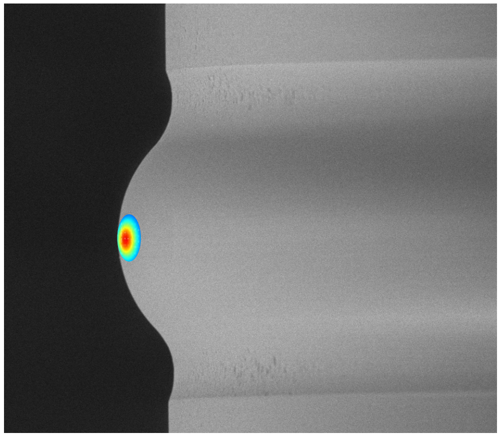


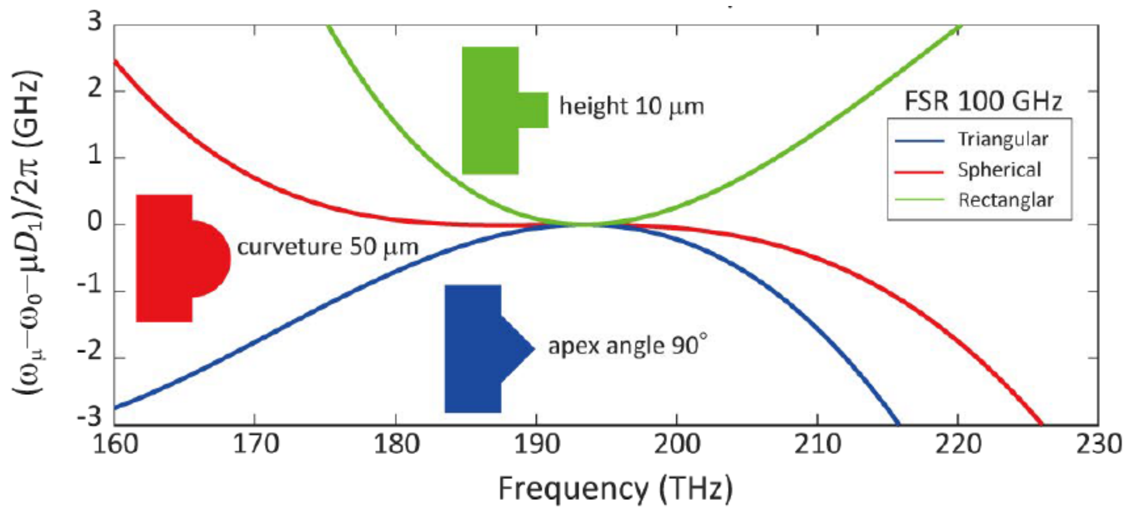


- Highest Q-factor exceeding 10^8 was observed in MgF_2 spherical WGM resonator
- Effect of crystal anisotropy and best end-face should be investigated
- MgF_2 is more suitable for Kerr comb generation as regards thermal stability

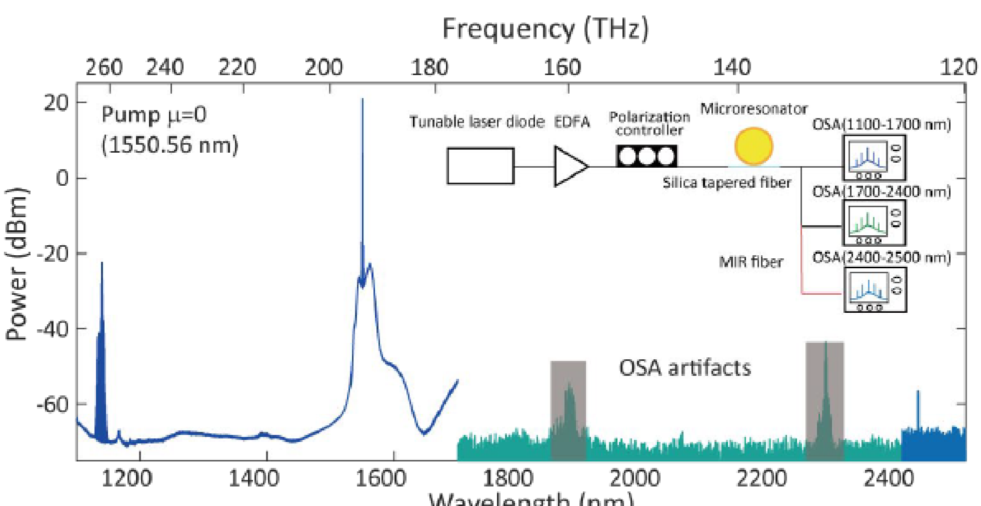
Ideal structure for μ-comb generation

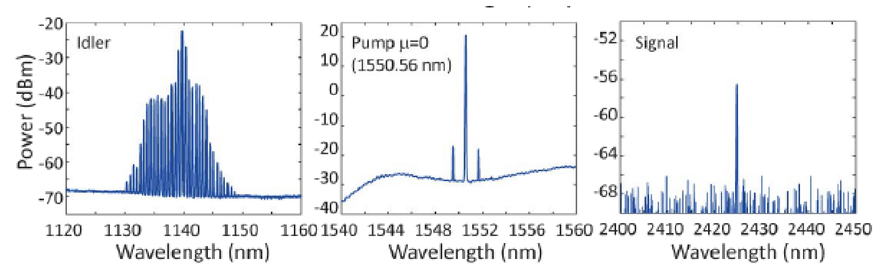
Simulated dispersion for different resonator structure with 100 GHz FSR





Phase-matched four-wave mixing (FWM) in dispersion engineered microresonator





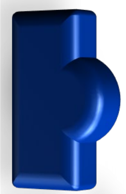
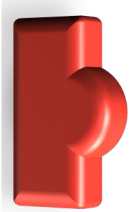
- FWM sidebands spanning 1-octave
- Phase-matching via higher-order dispersion

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

Summary

- 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 and microcomb without polishing process
- Investigated ideal WGM structure for 100-GHz FSR microcomb generation

Summary of crystalline microresonators fabricated without polishing

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

Thank you

Acknowledgment

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