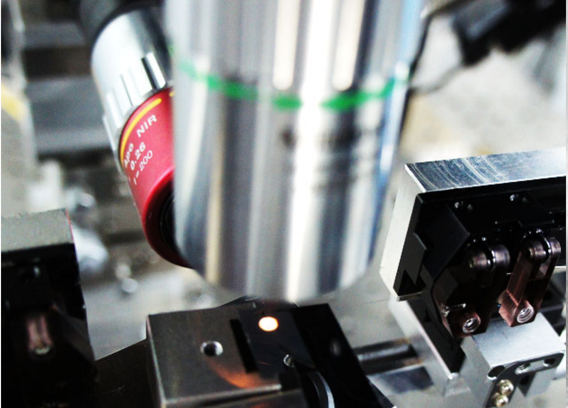
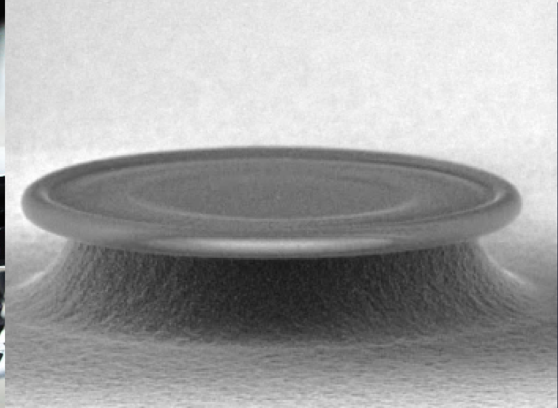
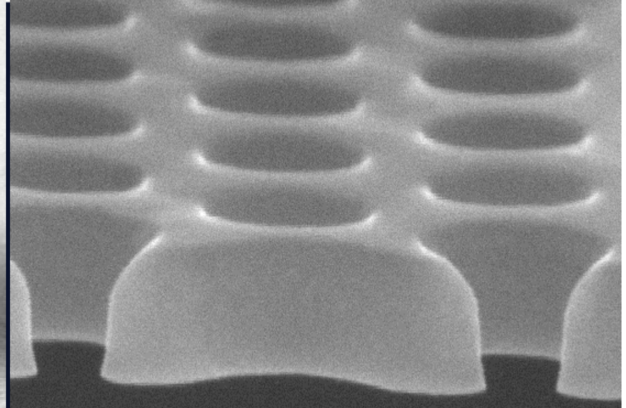
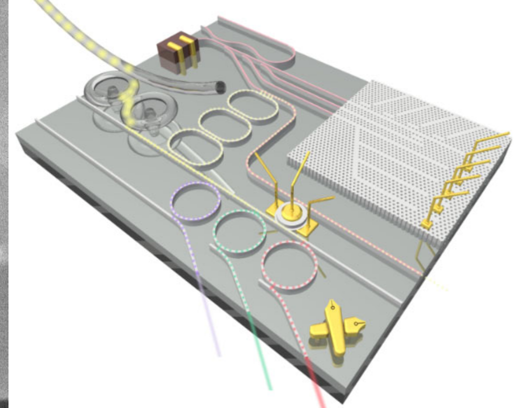





WOMBAT2019
March 27, 2019, 16:30-17:00

Brillouin lasing in coupled microresonator system

Takasumi Tanabe

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

Outline

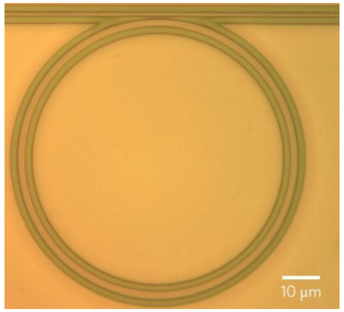
1. Brillouin laser in coupled WGMs

Y. Honda, W. Yoshiki, T. Tetsumoto, S. Fujii, K. Furusawa, N. Sekine, and T. Tanabe, "Brillouin lasing in coupled silica toroid microcavities," Appl. Phys. Lett., Vol. 112, 201105 (5 pages) (2018). (**Featured Article**) (**Scilight**)

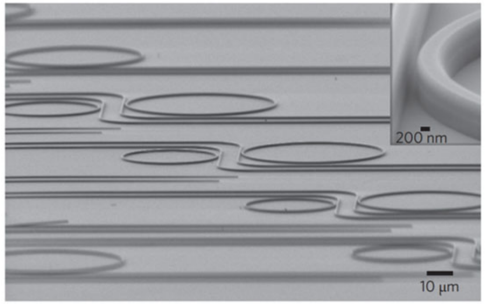
2. Optomechanics with micro-combs

R. Suzuki, T. Kato, T. Kobatake, and T. Tanabe, "Suppression of optomechanical parametric oscillation in a toroid microcavity assisted by a Kerr comb," Opt. Express, Vol. 25, No. 23, pp. 28806-28816 (2017).

High-Q whispering-gallery mode microcavities

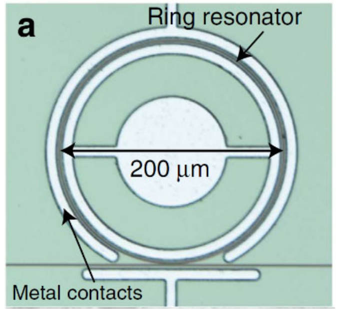


Silicon nitride
Weiner group (Purdue)

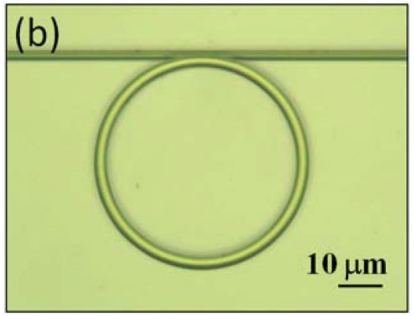


Diamond
Loncar group (Harvard)

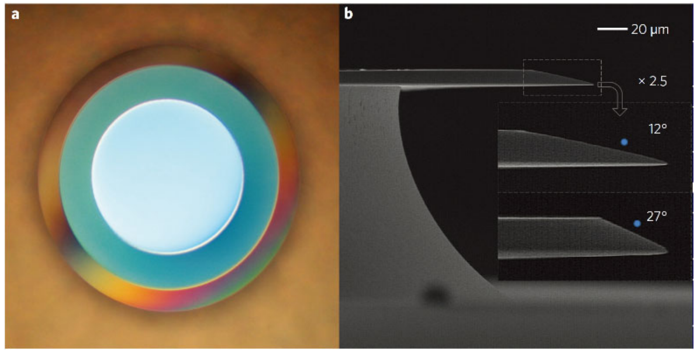
Crystalline (CaF_2, MgF_2, etc)
Kippenberg group (EPFL, Swiss),
Makei group (OE Waves)



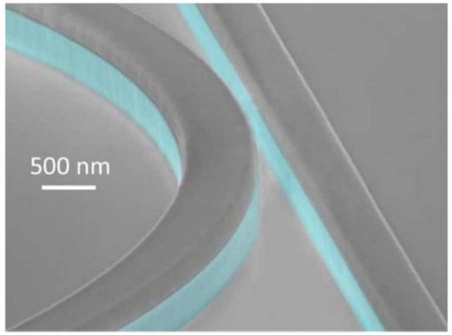
Silicon
Gaeta group (Columbia)



AlN
Tang group (Yale)



Silica
Vahala group (Caltech)



AlGaAs
Yvind group (DTU, Denmark)

◆Q-factor

$$Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}}$$

◆Photon density

$$\propto Q/V$$

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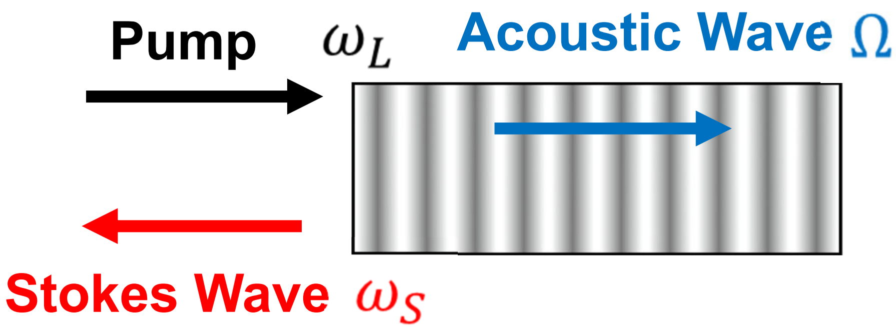
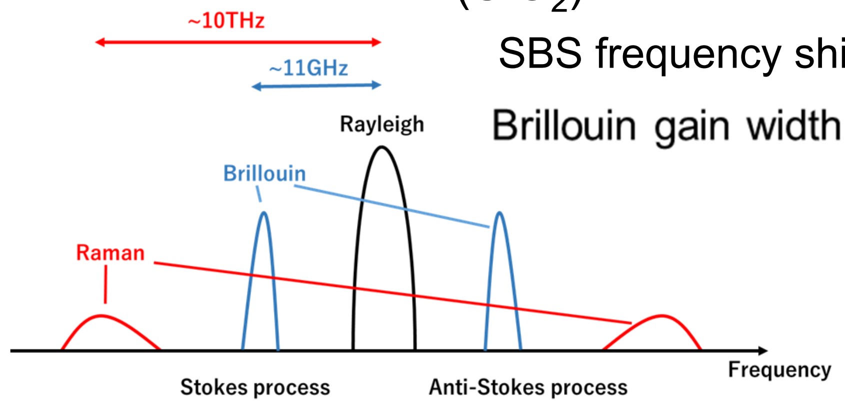
Stimulated Brillouin Scattering (SBS)

□ Schematic representation of SBS process



$$\omega_L = \omega_S - \Omega$$



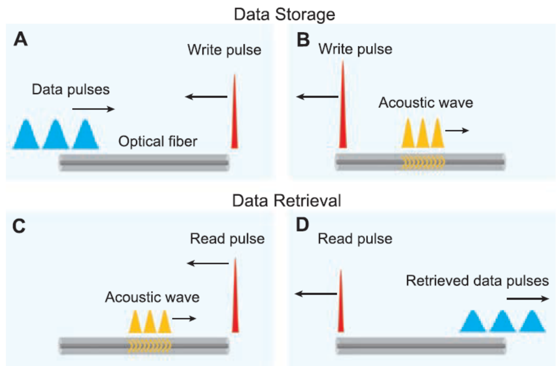
(SiO_2)

SBS frequency shift $\approx$ 11GHz

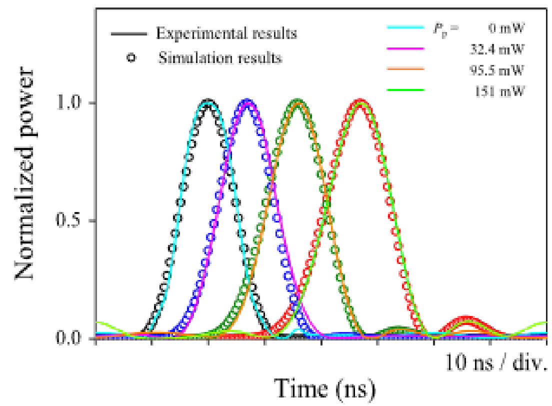
Brillouin gain width = ~50 MHz

□ SBS applications

- Light storage
- Slow light generation
- High coherence lasers
- Microwave synthesizers



Z. Zhu, D. J. Gauthier, R. W. Boyd, Science **318**, 1748-1750 (2007)



T. Sakamoto, T. Yamamoto, K. Shiraki, and T. Kurashima, Opt. Express **16**, 8026–8032(2008)

Stimulated Brillouin Scattering (SBS)

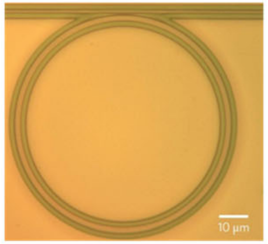
Microcavities

Crystalline (CaF_2)

$Q > 10^{10}$

$V \approx 10000\ \mathrm{um}^3$

I. Grudinin, *et al.*, Phys. Rev. A **74**, (2006).

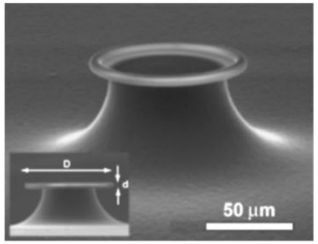


Si_3N_4 microring

$Q \approx 10^6$

$V \approx 1000\ \mathrm{um}^3$

F. Foudous, *et al.*, Nat. Photon. **5**, (2011).



Silica toroid

$Q \approx 10^8$

$V \approx 1000\ \mathrm{um}^3$

T. J. Kippenberg, *et al.*, APL **85**, (2004).

Properties

- High Q
- Small mode volume V_m
- Small device size

$$(P_{SBS})_{th} \propto \frac{V_m}{Q^2}$$

Brillouin lasing

- Low threshold power
- Small device size

Applications

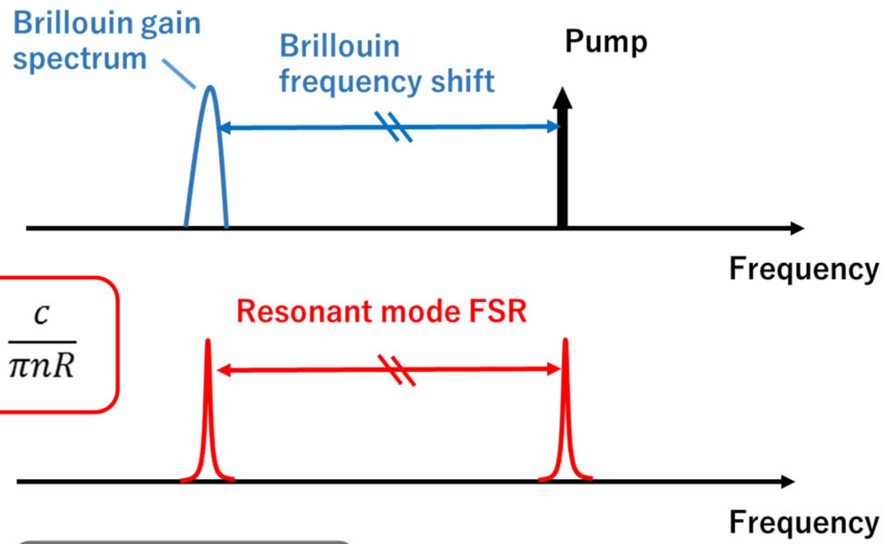
- Microwave synthesizers
- High coherence lasers

318, 1748-1750 (2007)

T. Sakamoto, T. Yamamoto, K. Shiraki, and T. Kurashima, Opt. Express **16**, 8026–8032(2008)

SBS in microcavities

Method1



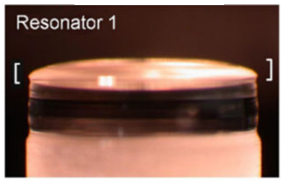
$$\nu_{FSR} = \frac{c}{\pi n R}$$

Brillouin frequency shift = Resonant mode FSR

⇓

Brillouin lasing

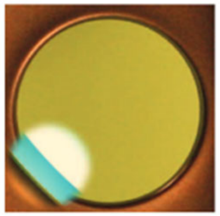
CaF_2



5.52 mm

I. S. Grudinin and K. J. Vahala, Opt. Express17, 14 088 (2009)

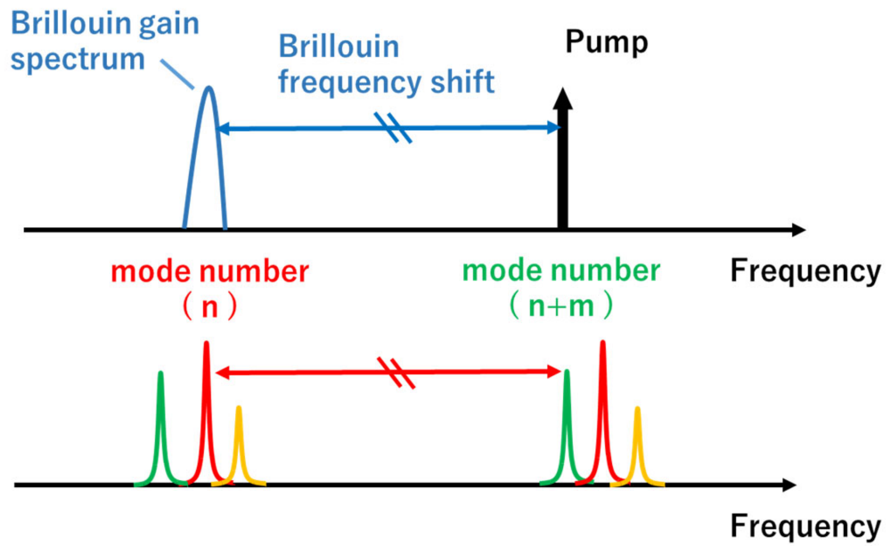
SiO_2



6.02 mm

J. Li, K. Vahala et al., OE 20, 20170- (2012)

Method2

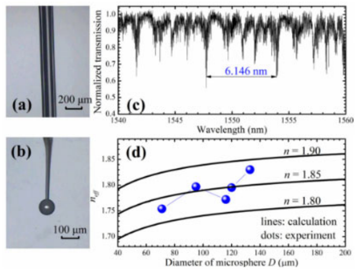


Brillouin frequency shift = High-order mode spacing

⇓

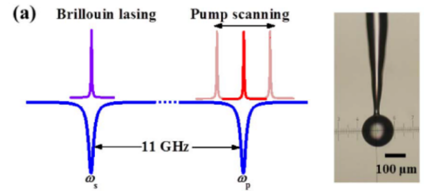
Brillouin lasing

TeO_2



C. Guo, K. Che et al., OE 23,25, 32261- (2015)

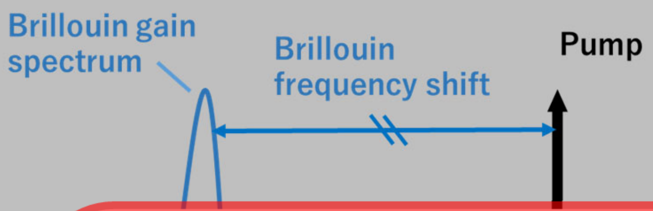
SiO_2



C. Guo, H. Xu et al., OL 40, 4971- (2015)

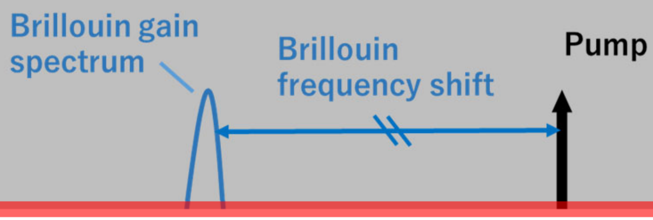
SBS in microcavities

Method1



$\nu_{FSR} = \frac{c}{\pi n}$

Method2

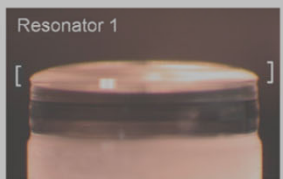


Method1 &2

■ Precise control of cavity size

Brillouin lasing

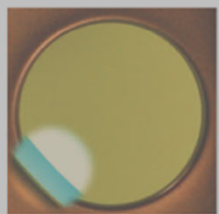
CaF_2



5.52 mm

I. S. Grudinin and K. J. Vahala, Opt. Express17, 14 088 (2009)

SiO_2 silica

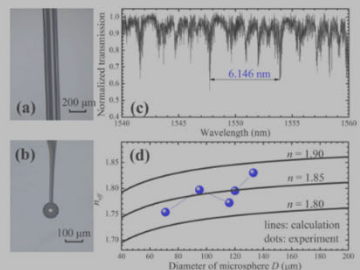


6.02 mm

J. Li, K. Vahala et al., OE 20, 20170- (2012)

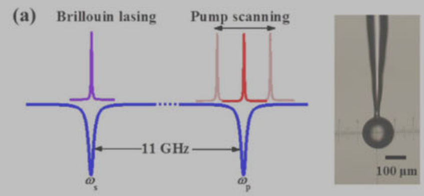
Brillouin lasing

tellurite TeO_2



C. Guo, K. Che et al., OE 23,25, 32261- (2015)

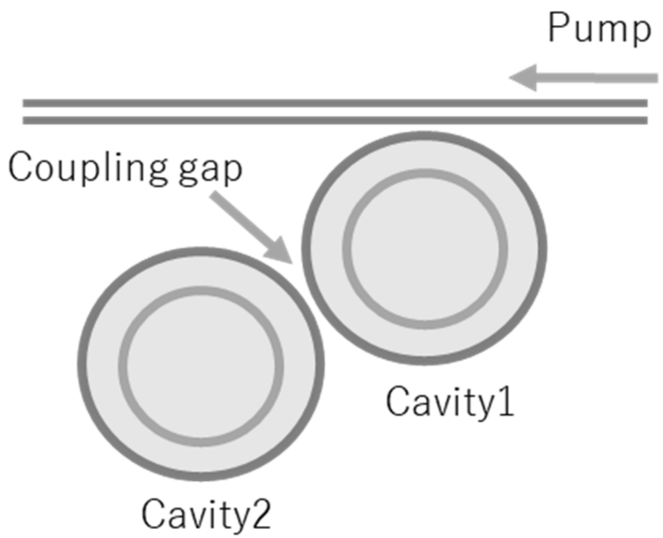
SiO_2

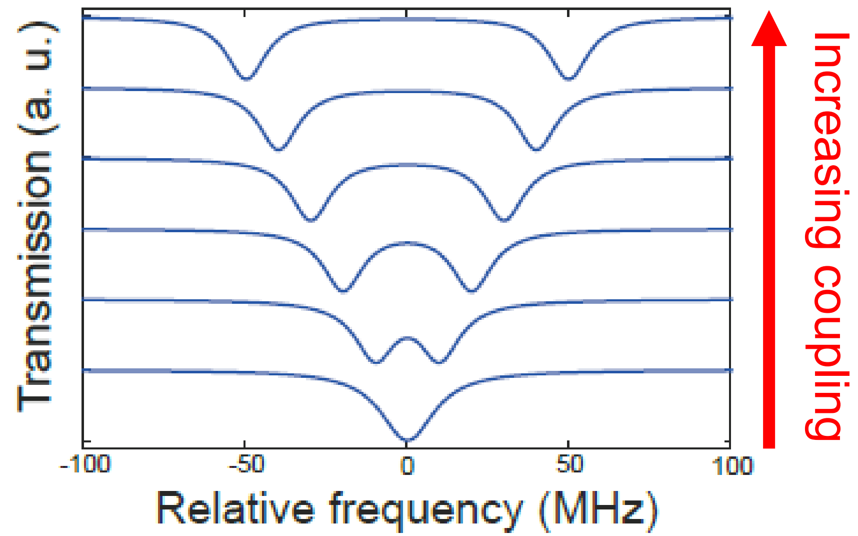


C. Guo, H. Xu et al., OL 40, 4971- (2015)

Objective

Our work





Brillouin frequency shift in silica (11GHz) = **Mode splitting of supermodes**

Tunable

Brillouin lasing

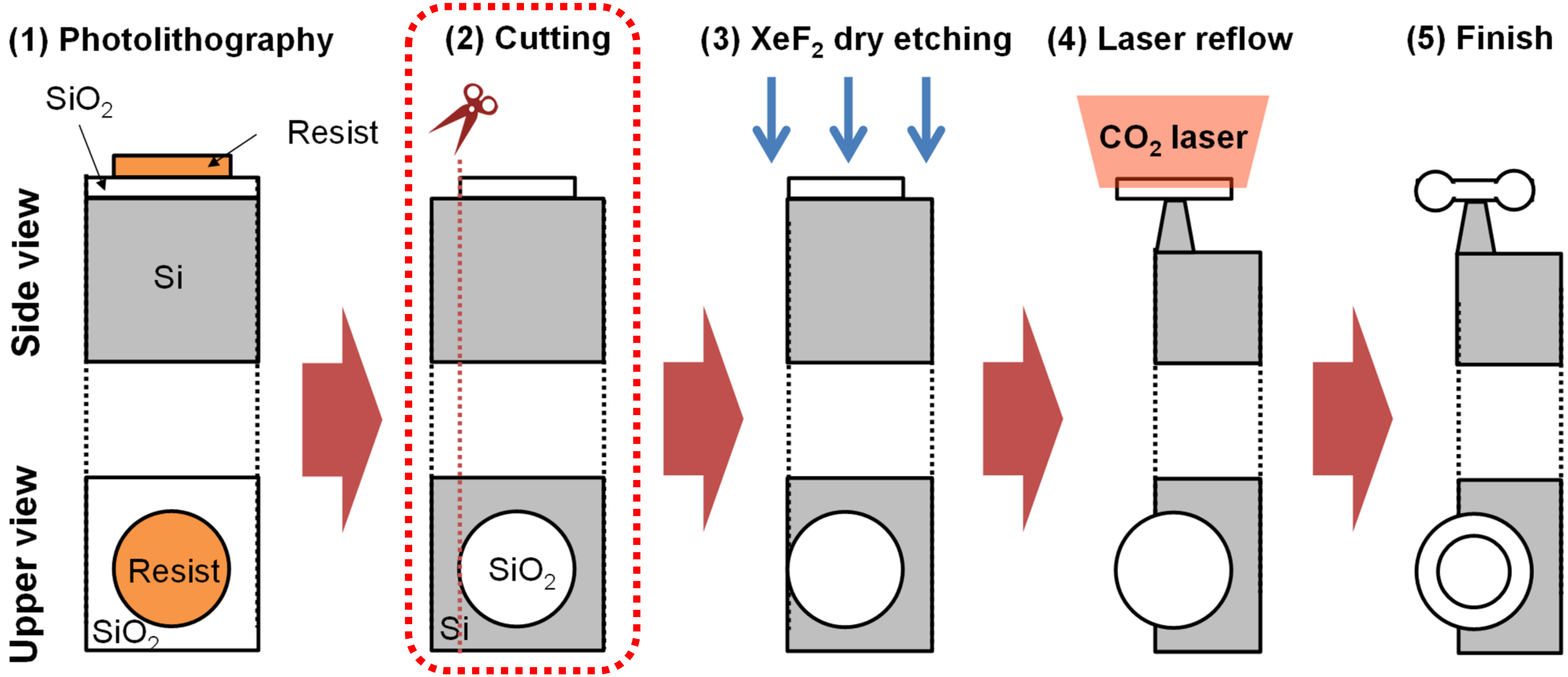
SBS in coupled microcavities ⇨

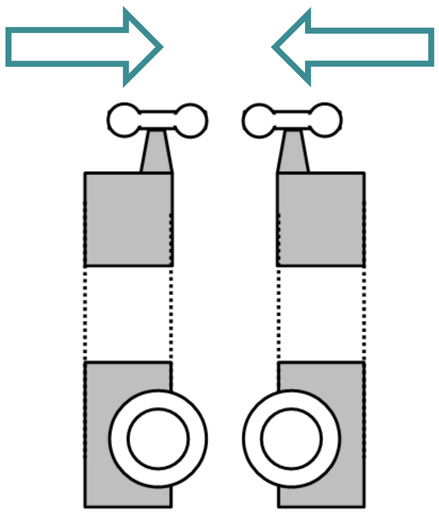
~~Precise size control~~

Low threshold

Small footprint

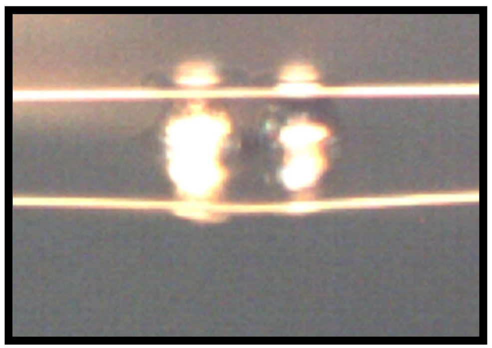
Silica toroid microcavities



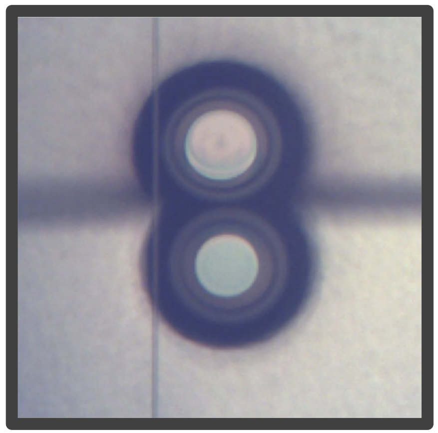


- **Precisely control coupling strength by changing distance between toroids**

Side View

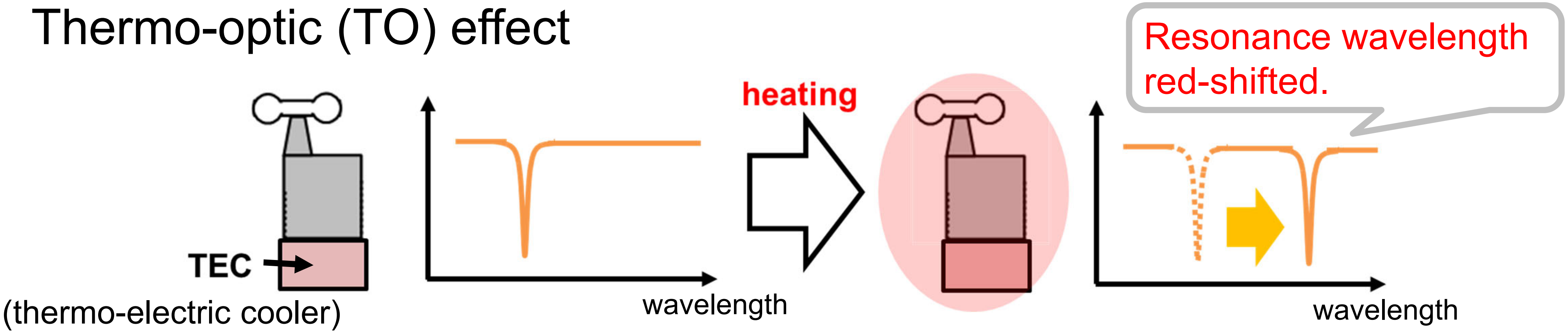


Top View



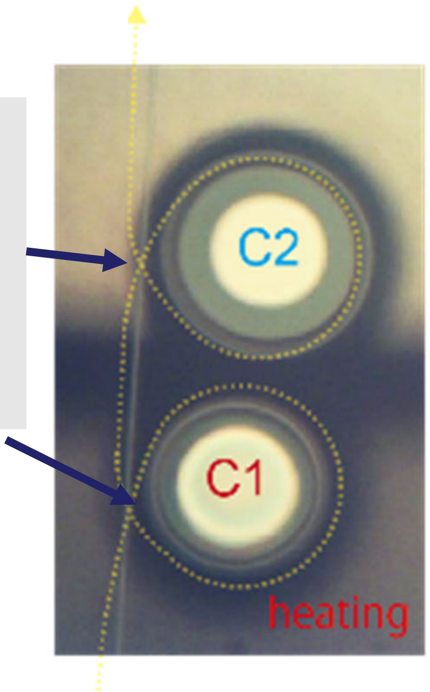
Tuning resonant frequency

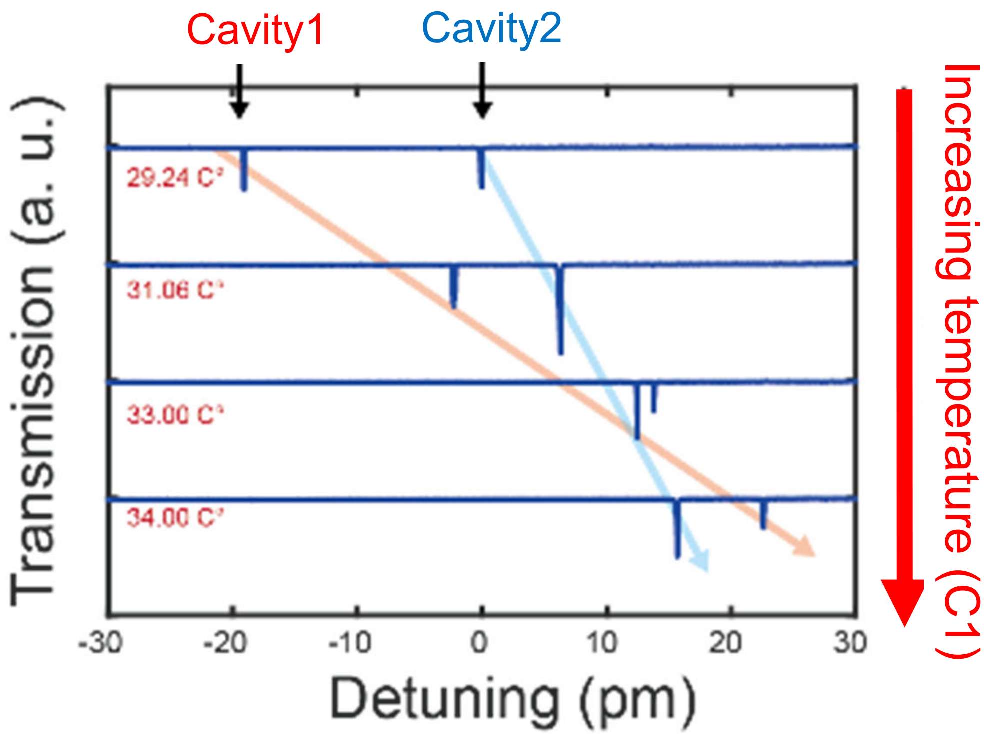
- Thermo-optic (TO) effect



- Tuning two different resonant frequencies

Couple tapered fiber to each cavity, and measure each resonant wavelength.





Supermode splitting

Calculation

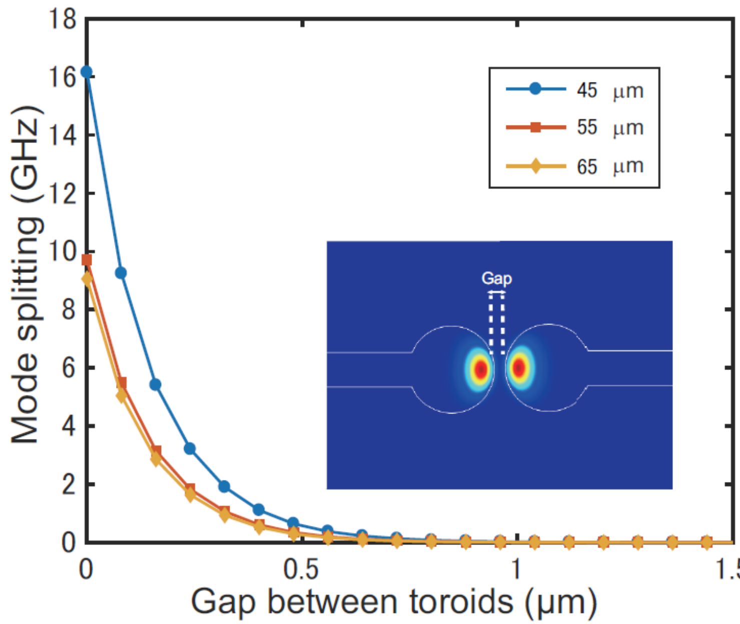
- **Mode overlap**
- **Phase matching condition**

} **Coupling coefficient**

$$\tilde{\kappa}_{C1,C2} = \frac{\omega\varepsilon_0}{4}(n^2 - n_0^2) \times N_{C1}N_{C2}\iiint_{Vc}\left(E_{C1}(x,y,z)\cdot E_{C2}(x,y,z)\right)e^{i\Delta\beta z}\,dxdydz$$

M. J. Humphrey, E. Dale et al., Opt. Commun. 271 124-131 (2007).

→ Supermode splitting is **larger** when the diameter of a microcavity is **smaller**



Experimental results

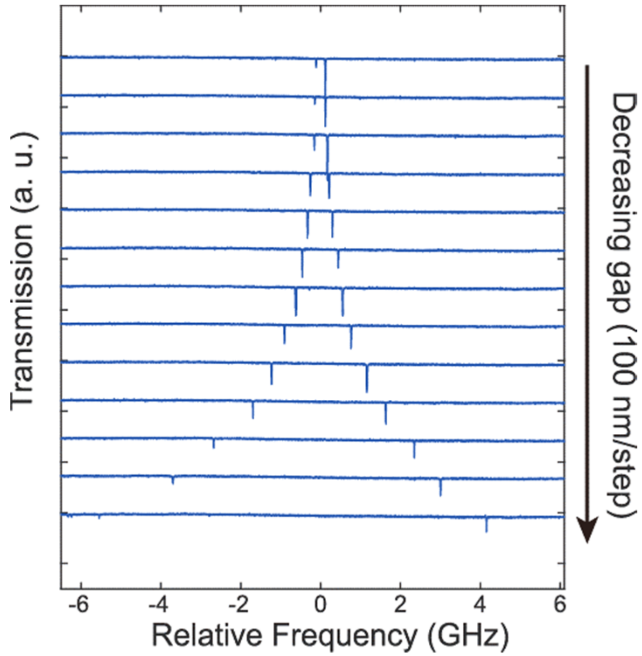
Fabricated 55-μm-diameter silica toroid

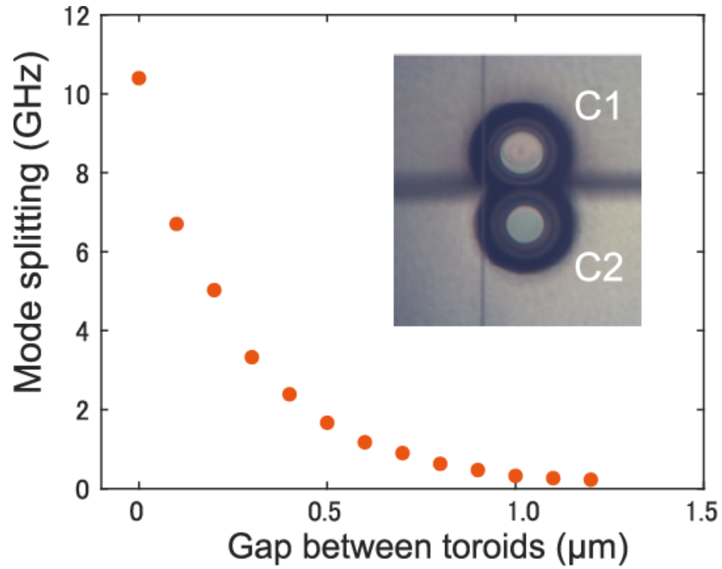
↓

Moved toroids close together

↓

Achieved more than 10GHz mode splitting

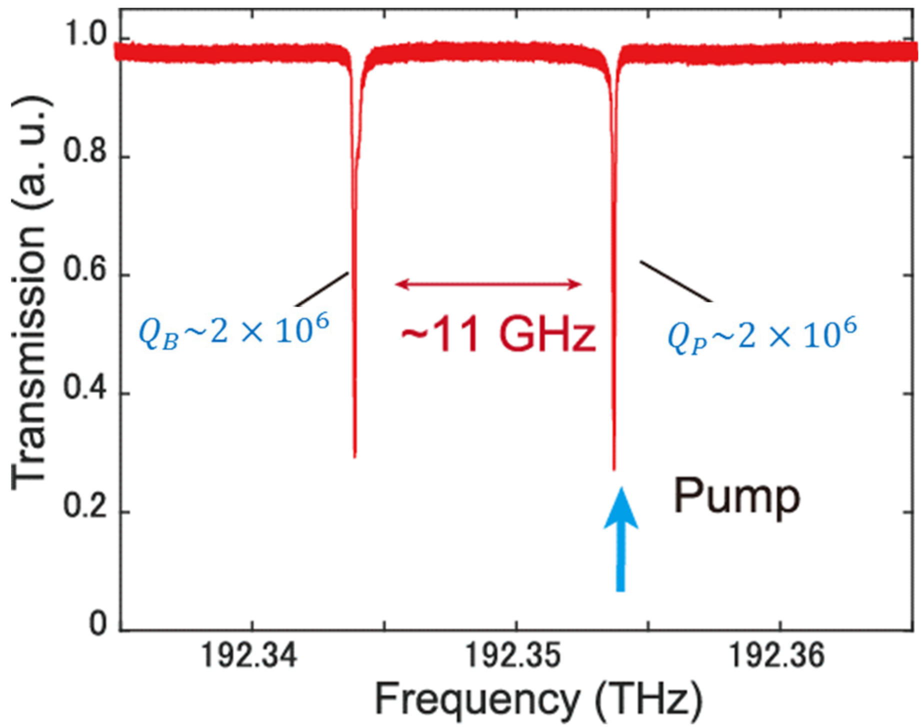




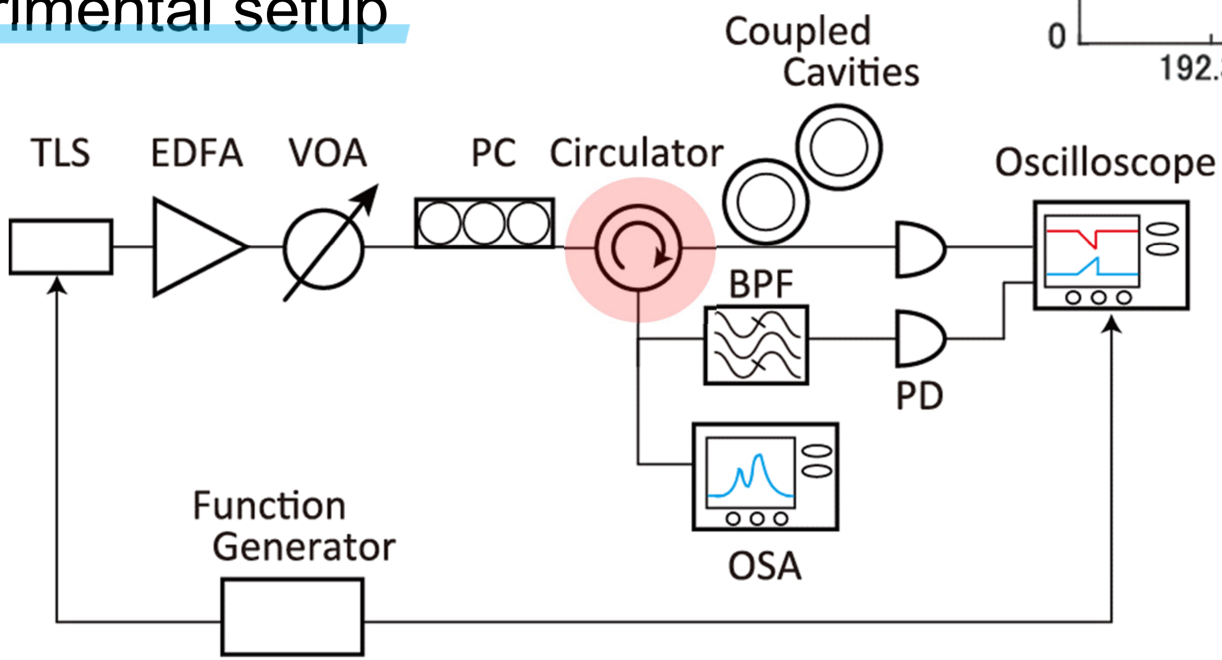
SBS in coupled cavities

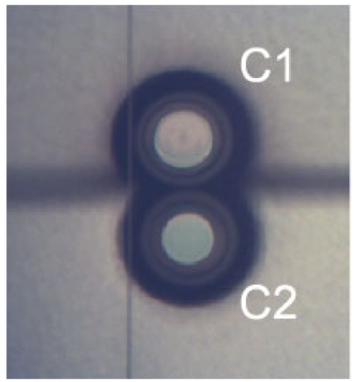
We achieved …

Brillouin frequency shift in silica (11GHz) = **Mode splitting of supermodes**



Experimental setup





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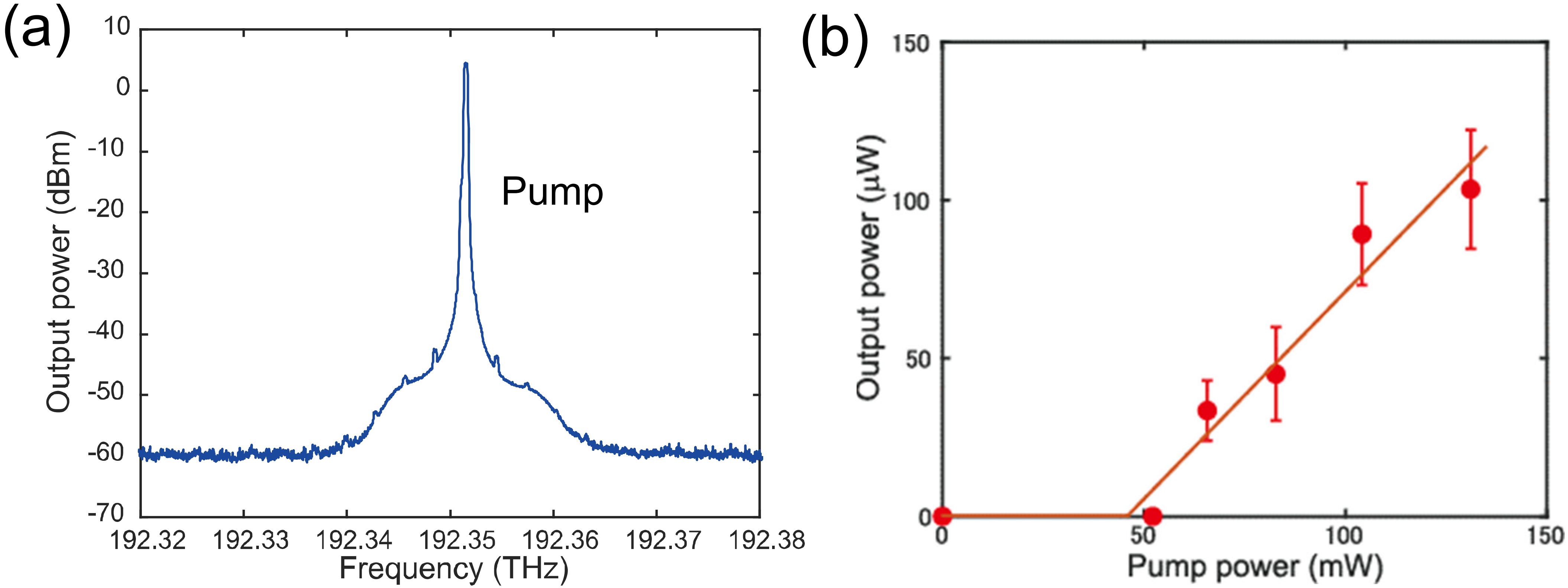
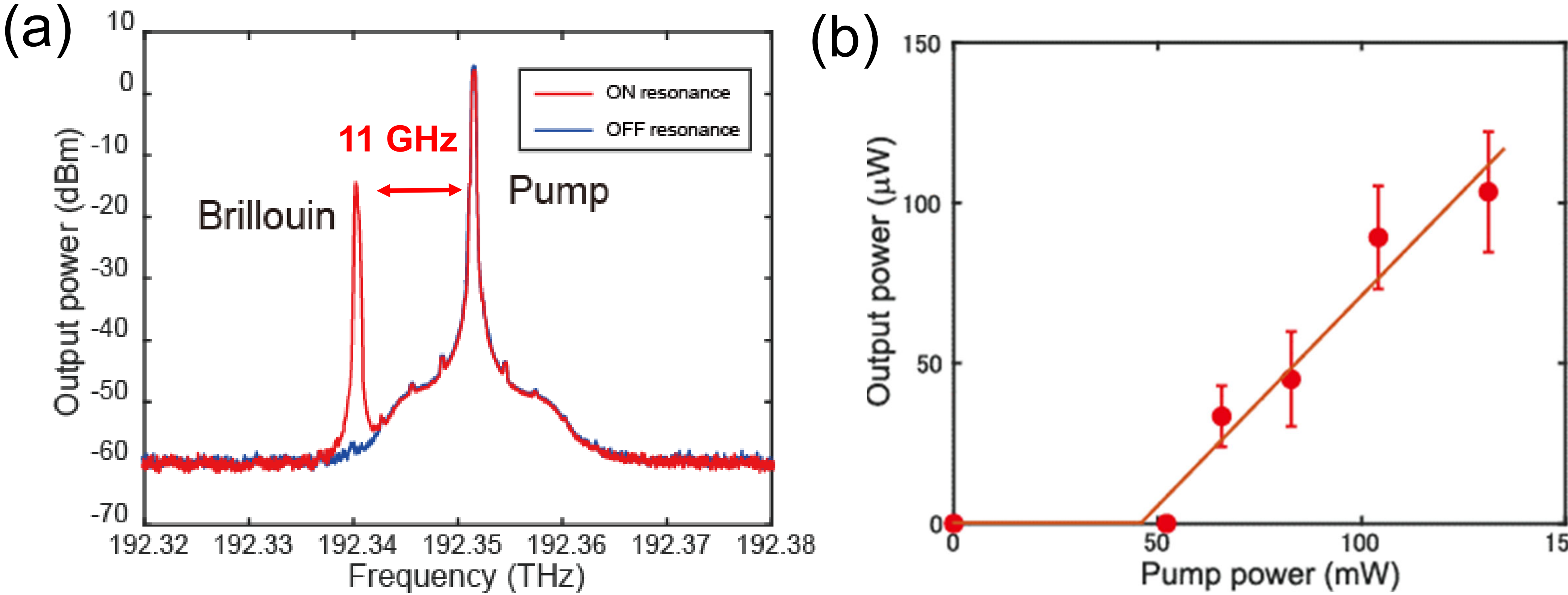


- We experimentally demonstrated SBS in coupled microcavities for the first time.
- We achieved a threshold power of about 50 mW (10 mW latest).

SBS in coupled cavities



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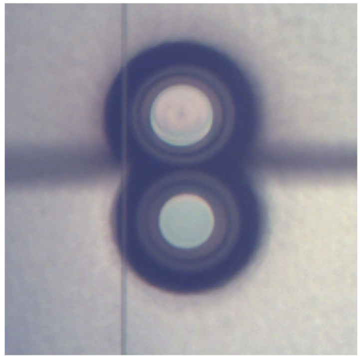
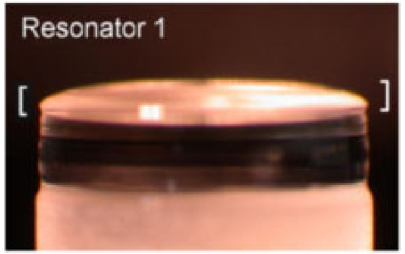
- We achieved a threshold power of about 50 mW (10 mW latest).

Comparison with other Brillouin lasing

Coupled silica toroid microcavities (This work)

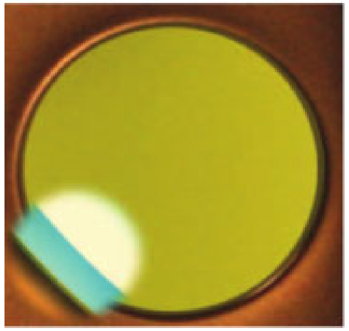


CaF_2 resonator



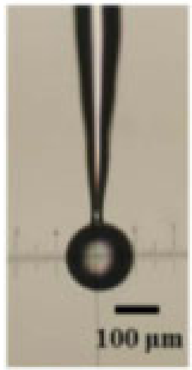
I. S. Grudinin et al., PRL, 102.4, 043902 (2009)

Wedge resonator



J. Lin et al., OE, 20. 18, 20170-20180 (2012)

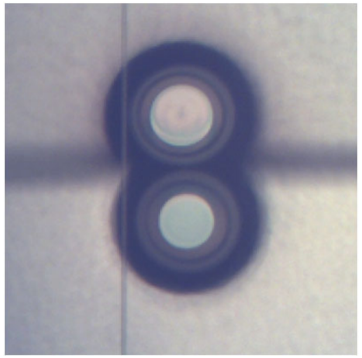
Microsphere



C. Guo, H. Xu et al., OL 40, 4971- (2015)

	Coupled silica toroid microcavities (This work)	CaF_2 resonator	Wedge resonator	Microsphere
Material	SiO_2	CaF_2	SiO_2	SiO_2
Threshold power	10 mW	3 μW	40 μW	8 μW
Device size	110 μm	5.5 mm	6 mm	172 μm
Q	2×10^6	4×10^9	$\sim 1 \times 10^9$	$\sim 3 \times 10^7$
On-chip	✓	✕	✓	✕
Precise cavity size control	Not needed	Needed	Needed	Needed

Comparison with other Brillouin lasing

	Coupled silica toroid microcavities (This work)	CaF_2 resonator	Wedge resonator	Microsphere
		 I. S. Grudinin		
Material	SiO_2			
Threshold power	500 μW			
Device size	110 μm			
Q	2×10^7	4×10	1×10	$\times 10^7$
On-chip	✓	×	×	×
Precise cavity size control	Not needed	Needed	Needed	Needed

Threshold power for SBS

$$(P_{SBS})_{th} \propto \frac{V_m}{Q^2}$$

- Improve threshold power by using mode pair with higher Q factor

Summary (Brillouin laser)

- We achieved the11GHz mode splitting of supermodes that matches the Brillouin frequency shift in silica in coupled silica toroid microcavities.
- We experimentally demonstrated SBS in coupled microcavities and achieved a threshold power of 10 mW.

Acknowledgement

- Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the Photon Frontier Network Program.
- Grant-in-aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), (KAKEN 15H05429)

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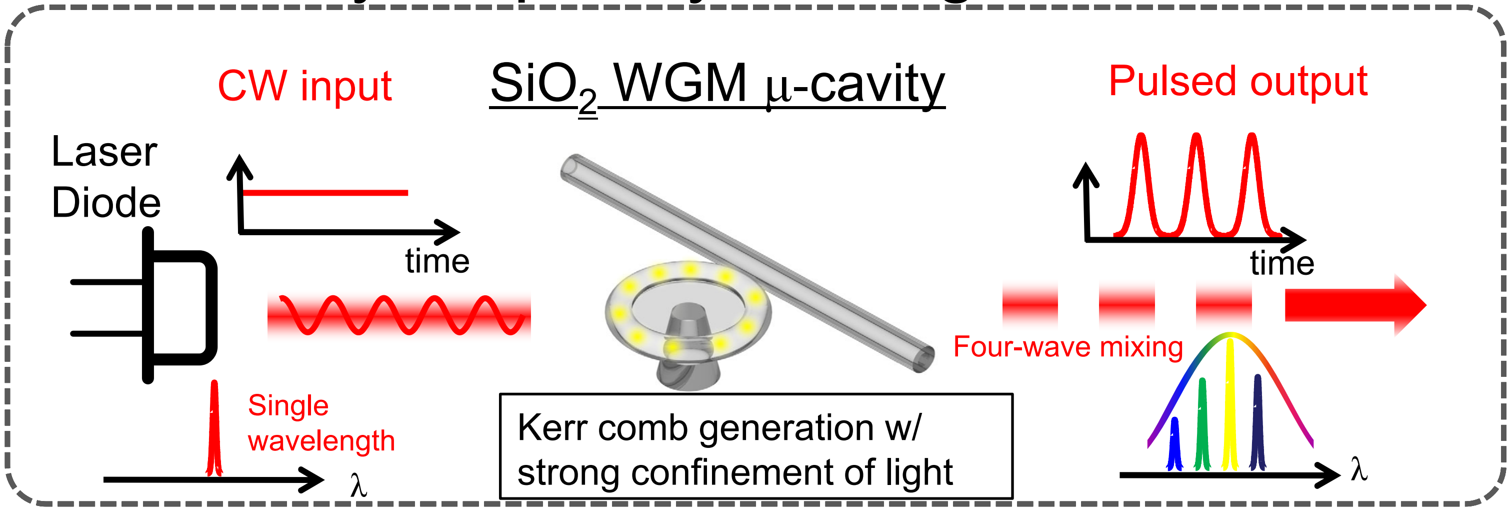
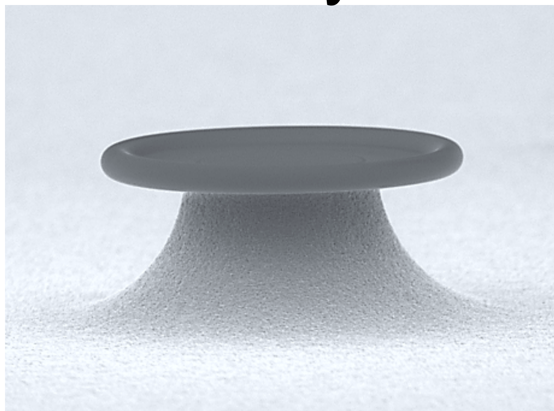
Microresonator frequency comb generation

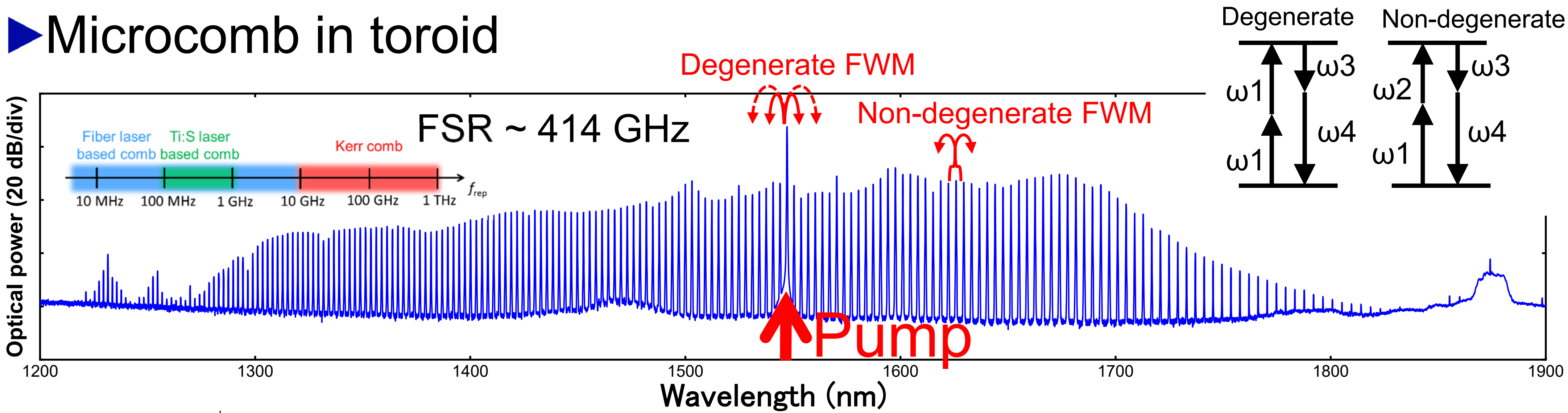
▶Microcavity frequency comb generation



▶Silica toroid microcavity

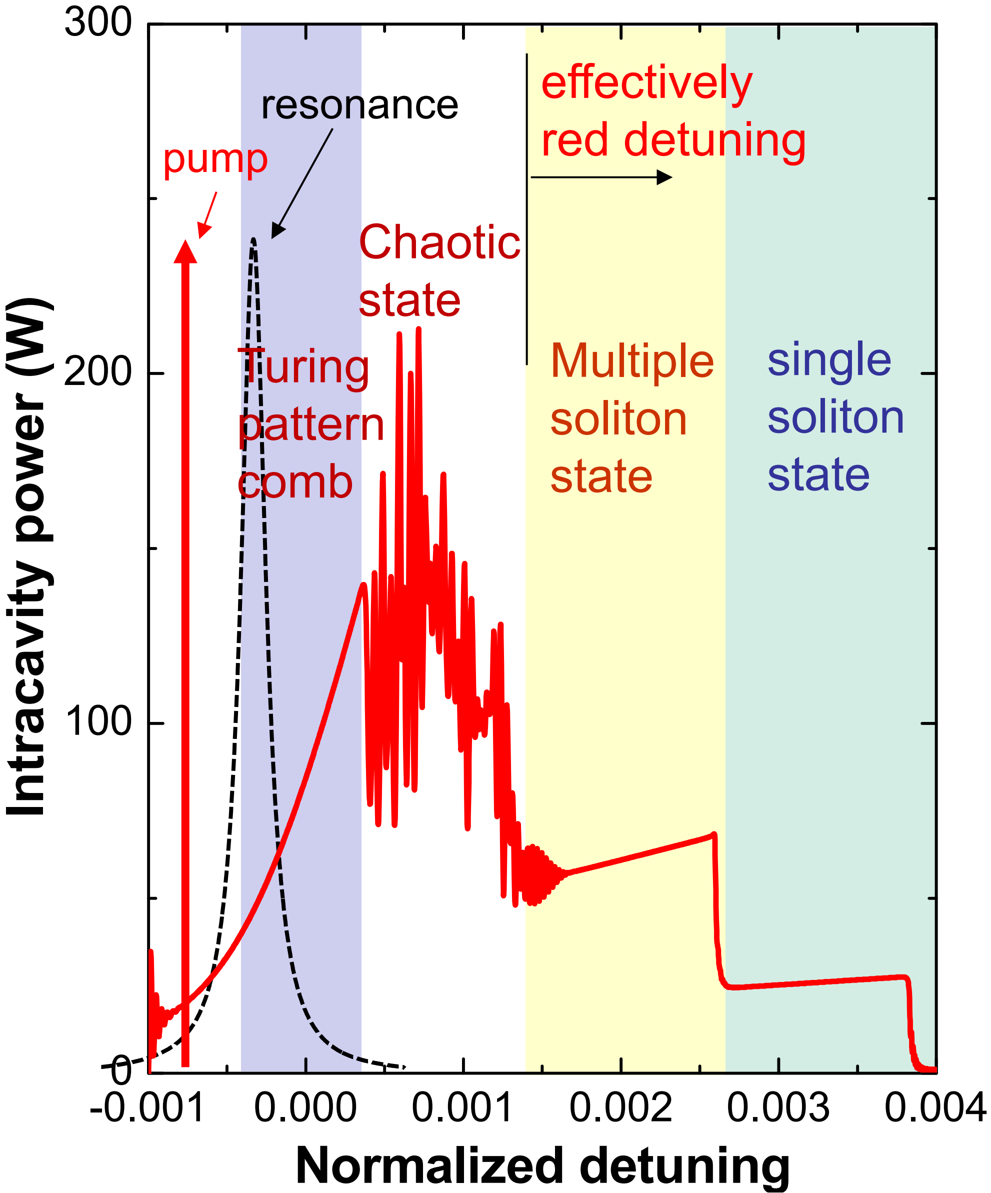


▶Microcomb in toroid

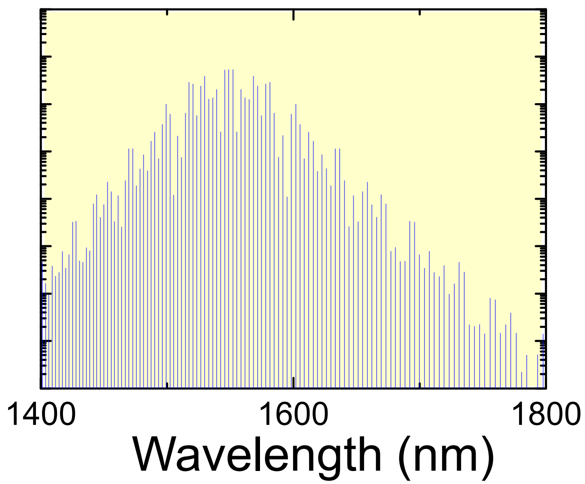


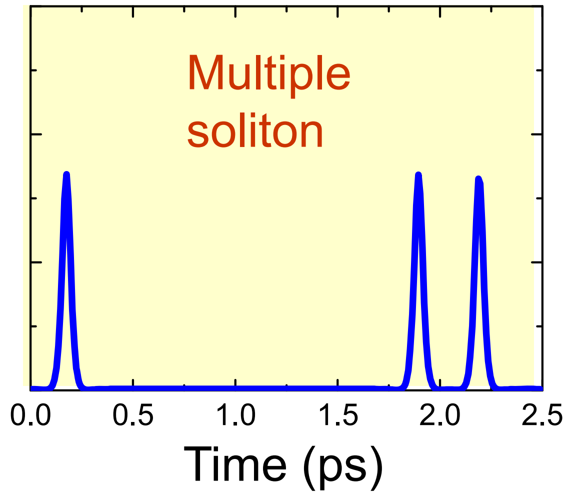
Microcomb generation w/ wavelength sweep

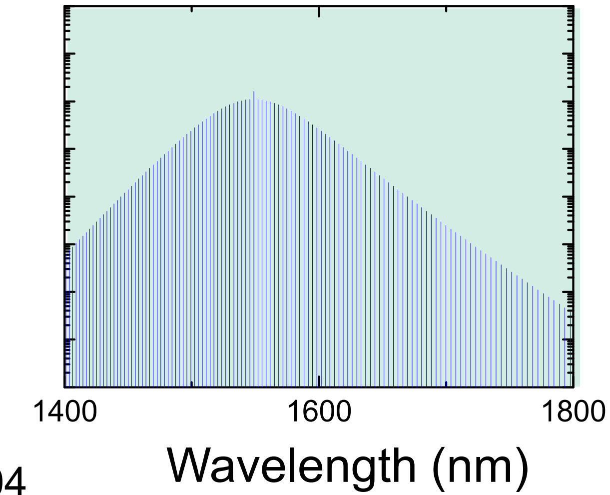
- Power in cavity vs detuning

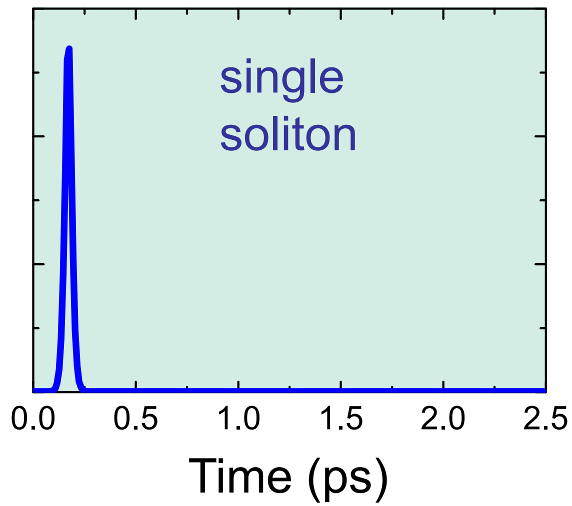


- Spectrum & waveform

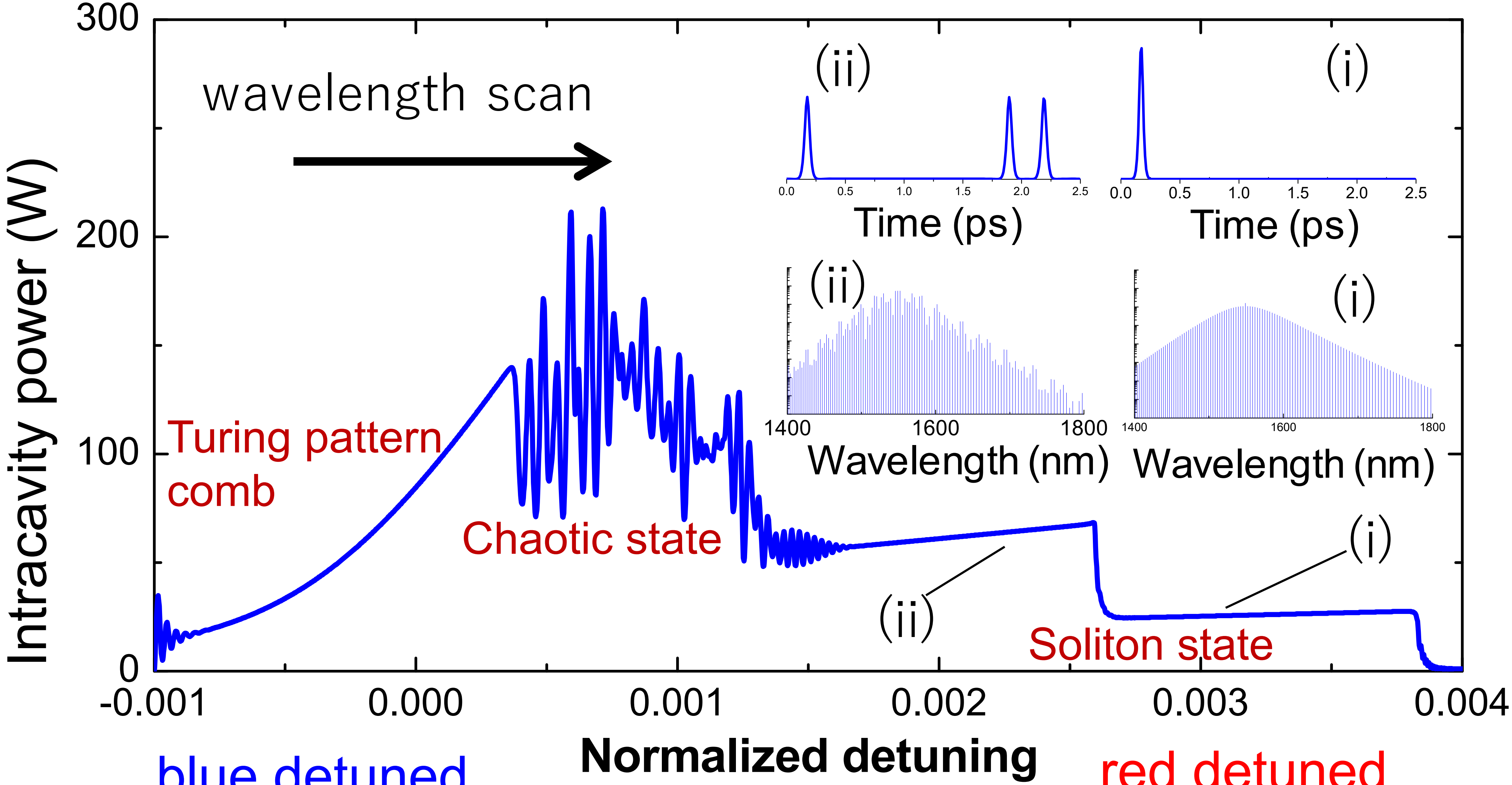








Microcomb generation w/ wavelength sweep

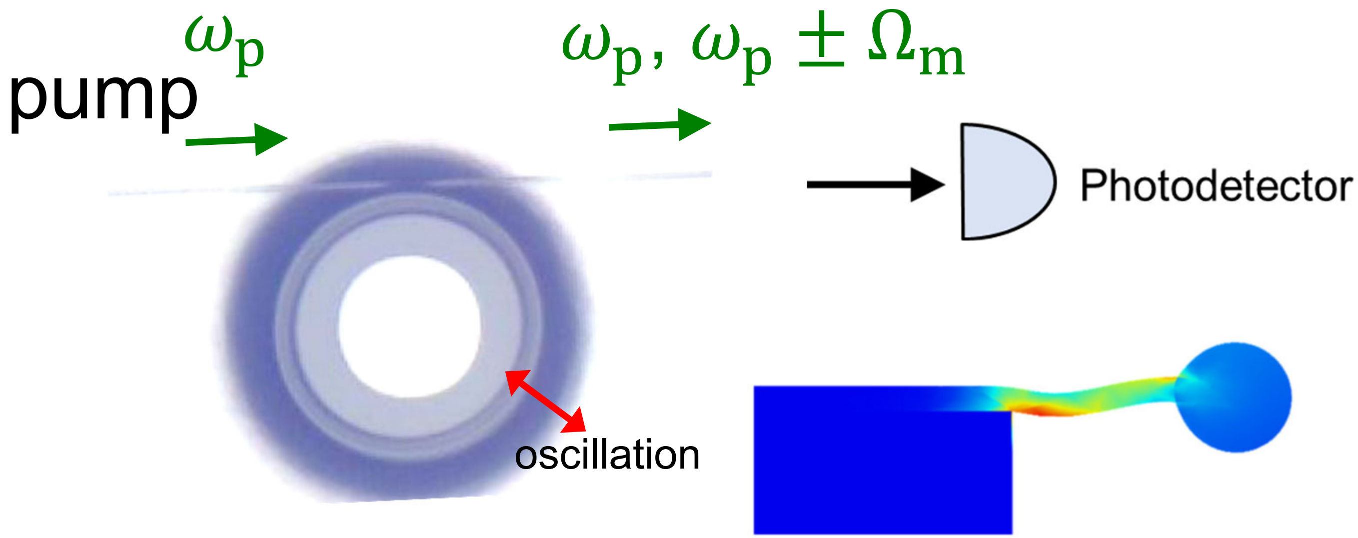


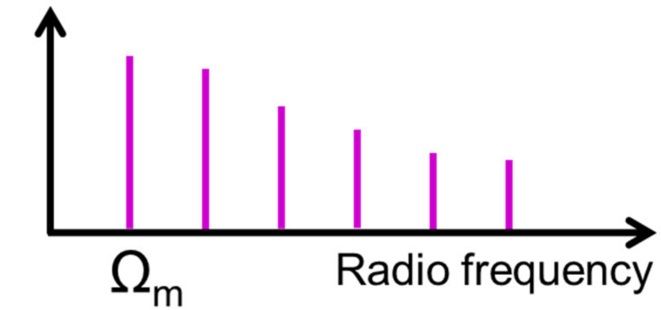
blue detuned

red detuned

Cavity optomechanics

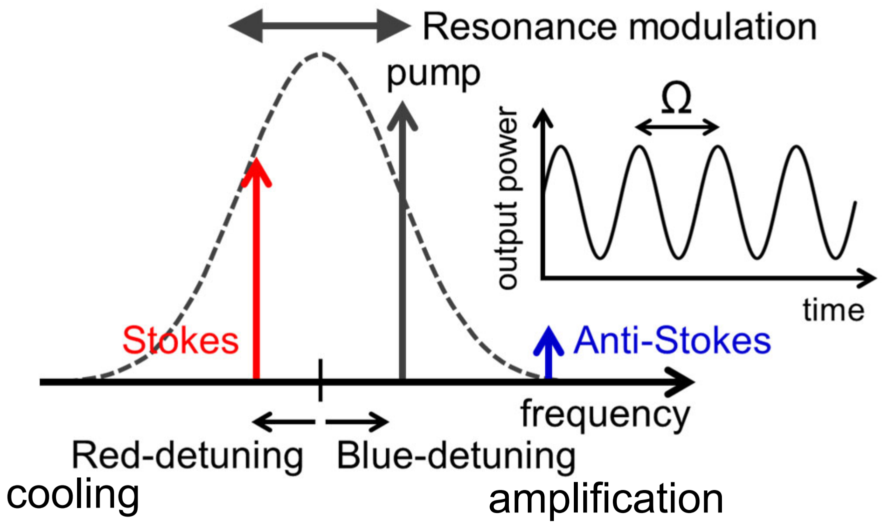
▶Modulation by mechanical mode





Can observe optomechanical oscillation by measuring RF signal

▶Amplification and cooling by different pump detuning



Blue- detuning ⇒ amplification
Red detuning ⇒ cooling

Motivation

Optomechanical parametric oscillation (OMPO)

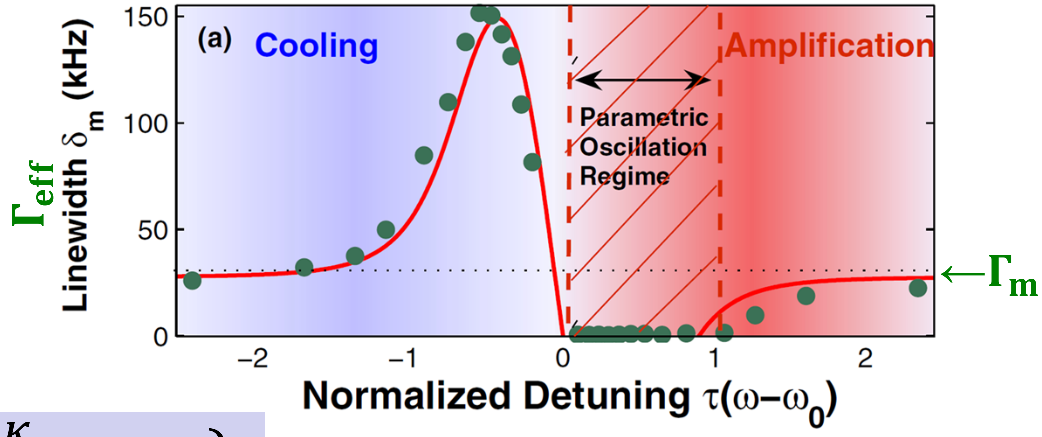
Blue-detuned pump : Amplification ($\Gamma_{eff} < 0$)
Red-detuned pump : Damping ($\Gamma_{eff} > \Gamma_m$)

$$\Gamma_{eff} = \Gamma_m + \Gamma_{opt}$$

Γ_{eff} : effective mechanical damping rate
Γ_m : mechanical damping rate
Γ_{opt}: optomechanical damping rate

$$\Gamma_{opt} = |a_0|^2 g_{om} \left\{ \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_0 + \Omega_m)^2} - \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_0 - \Omega_m)^2} \right\}$$

Phys. Rev. Lett. 97, 243905 (2006).

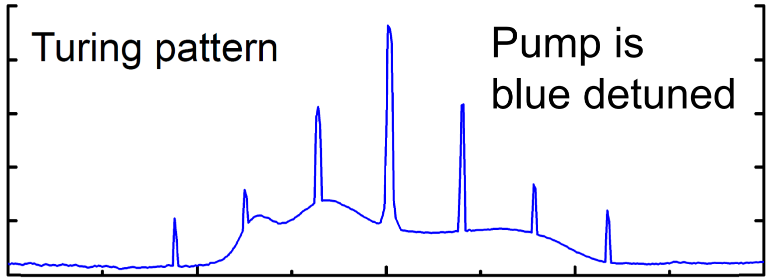


$|a_0|^2$: number of intracavity photon
$\Delta\omega_0$: laser detuning from resonance

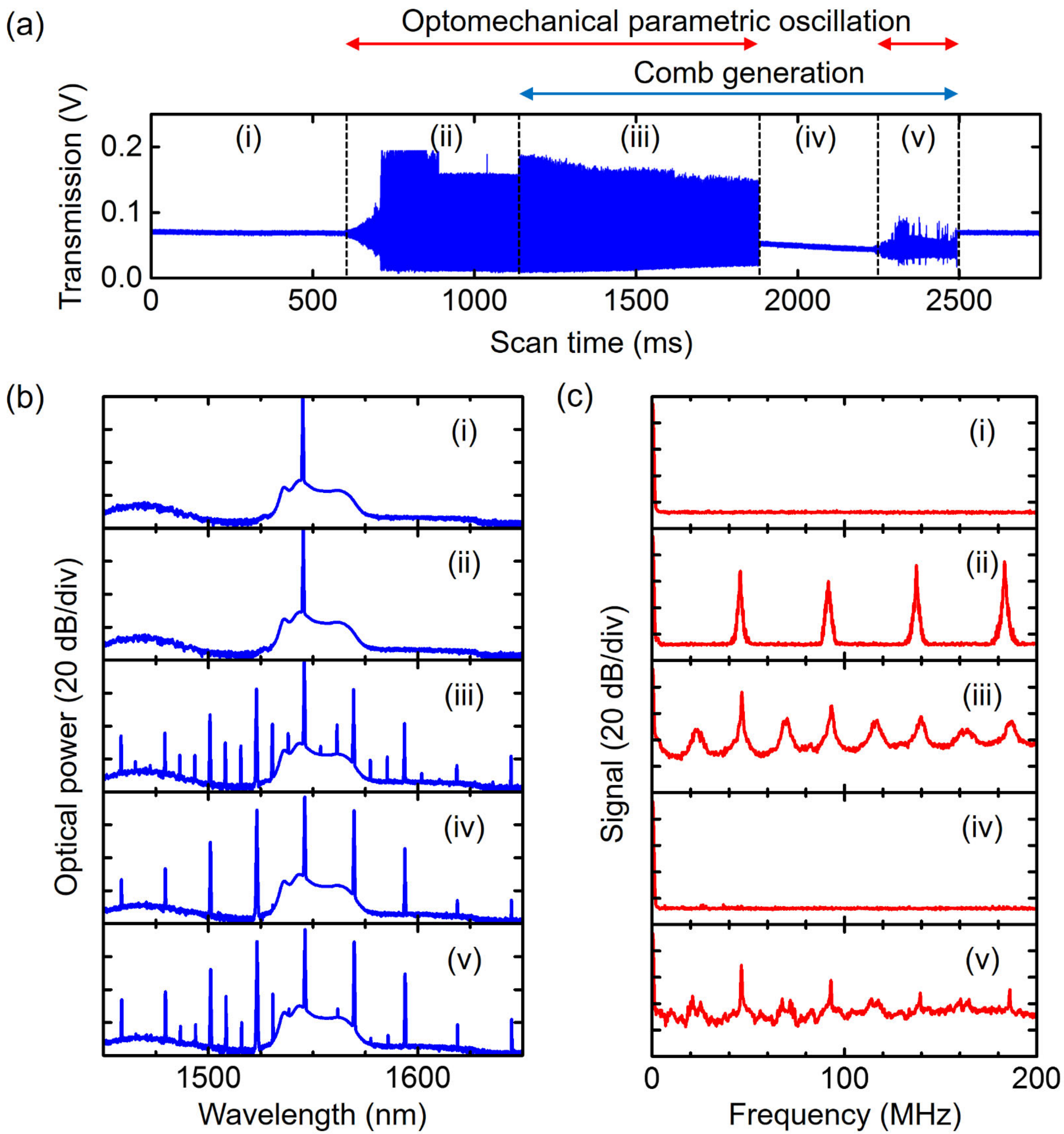
What will happen when frequency comb is generated in an opto-mechanically coupled resonator?

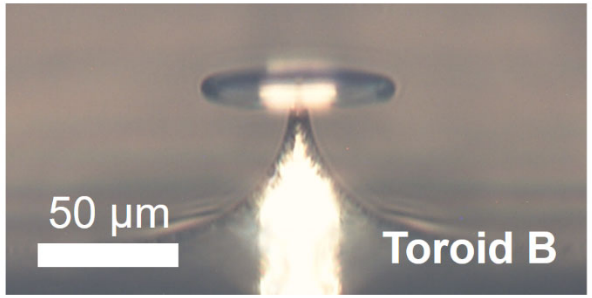
- Turing pattern microcomb in a silica toroid microresonator

  Blue-detuned pump ⇒ amplification of oscillations
  Red-detuned comb ⇒ damping of oscillations

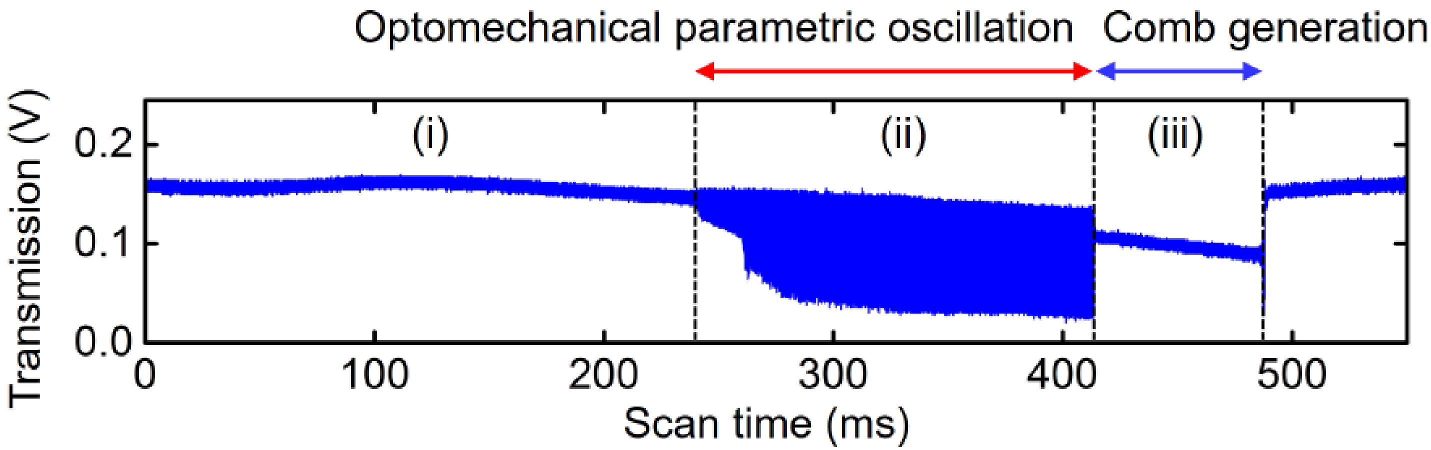


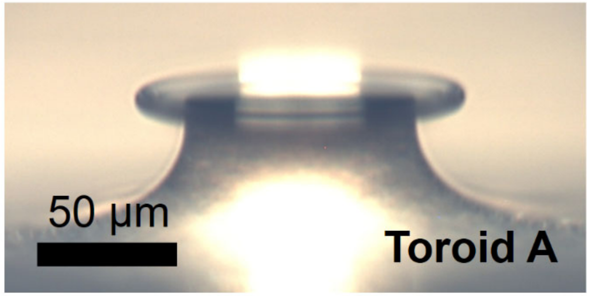
Microcomb and RF signals while scanning pump

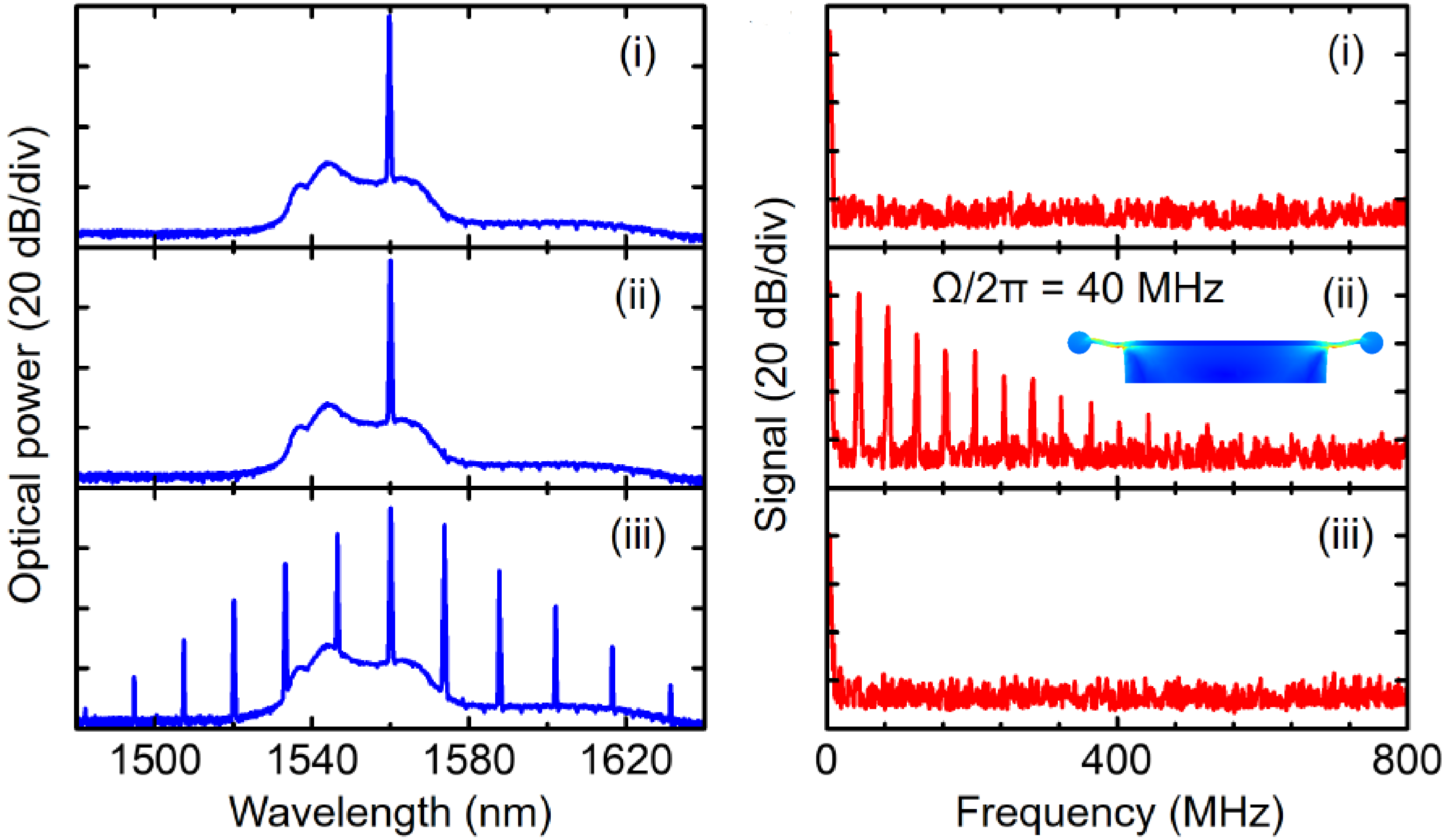




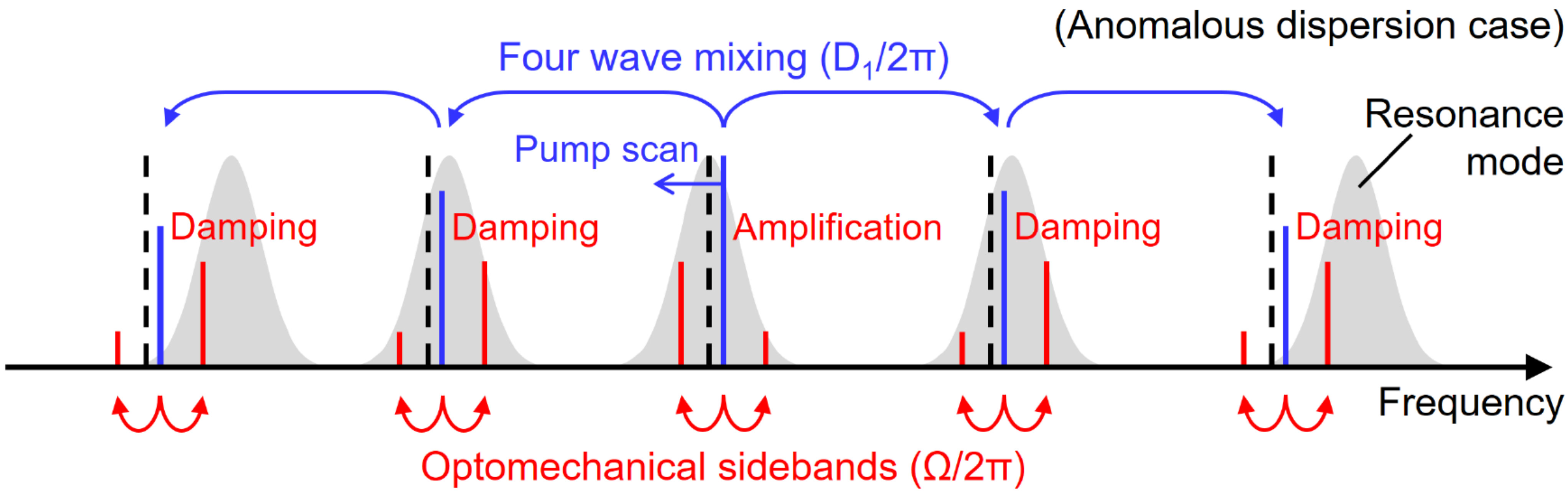
Microcomb and RF signals while scanning pump







Cooling by the generated comb lines



Single-optomechanical coupling with a resonance

$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}} + \Gamma_{\mathrm{opt}}$$

⇨

Multi-optomechanical couplings with resonances

$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}} + \sum_{\mu} \Gamma_{\mathrm{opt},\mu}$$

Comb detuning measurement

To calculate optomechanical damping rates in each resonance mode,
the comb detuning $\Delta\omega_\mu$ and the number of intracavity photon $|a_\mu|^2$ are needed.

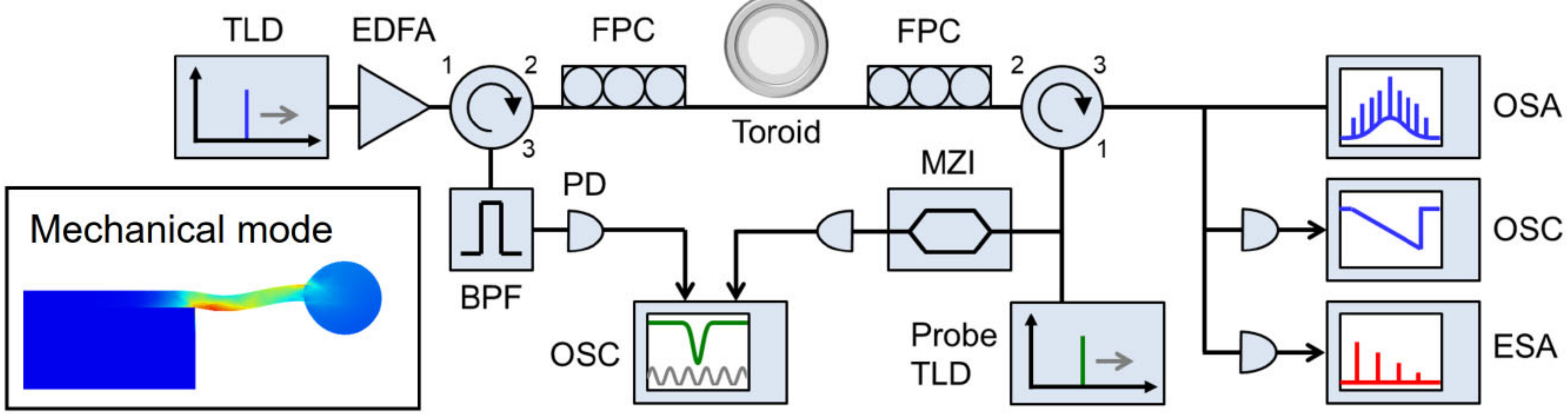
$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}} + \sum_\mu \Gamma_{\mathrm{opt},\mu}$$

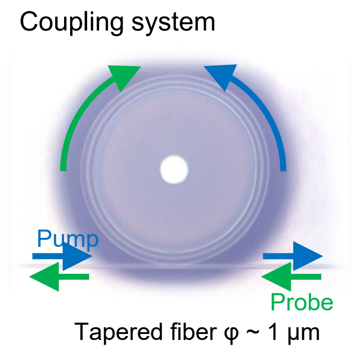
$$\Gamma_{\mathrm{opt},\mu} = |a_\mu|^2 g_{\mathrm{om}} \left\{ \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_\mu + \Omega_{\mathrm{m}})^2} - \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_\mu - \Omega_{\mathrm{m}})^2} \right\}$$

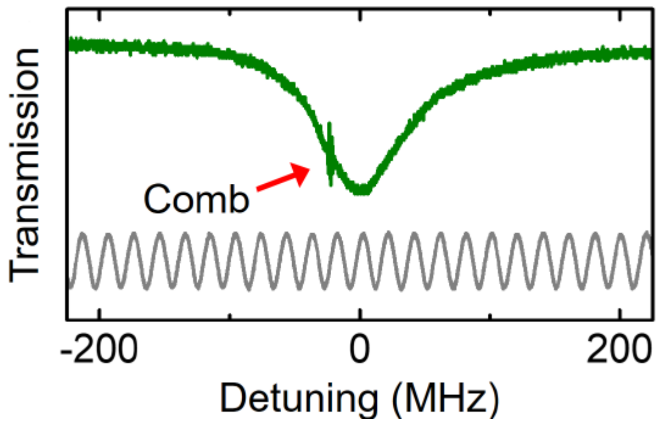
Comb detuning measurement

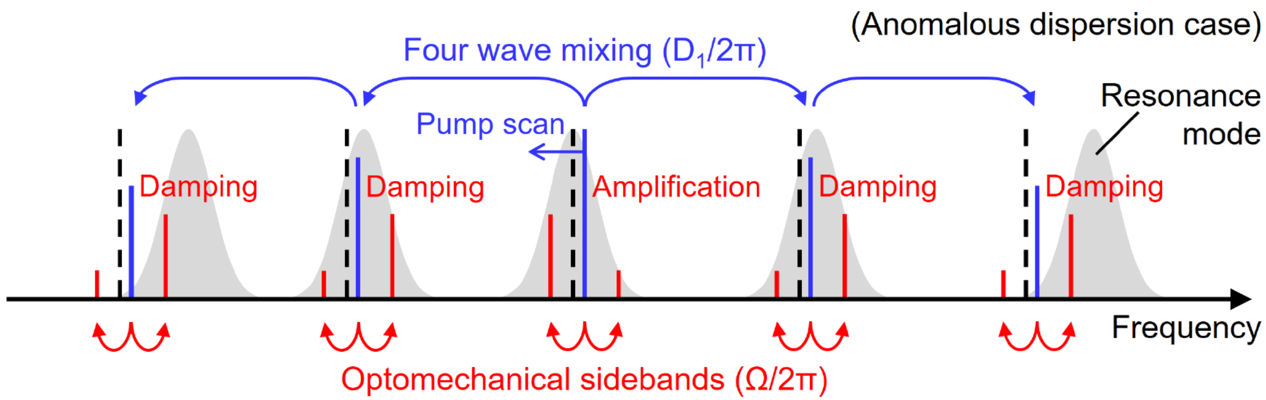
$$\Delta\omega_\mu \approx \Delta\omega_0 - \frac{1}{2} D_2 \mu^2$$

$$\Delta\omega_\mu = \omega_{\mathrm{comb}} - \omega_\mu$$







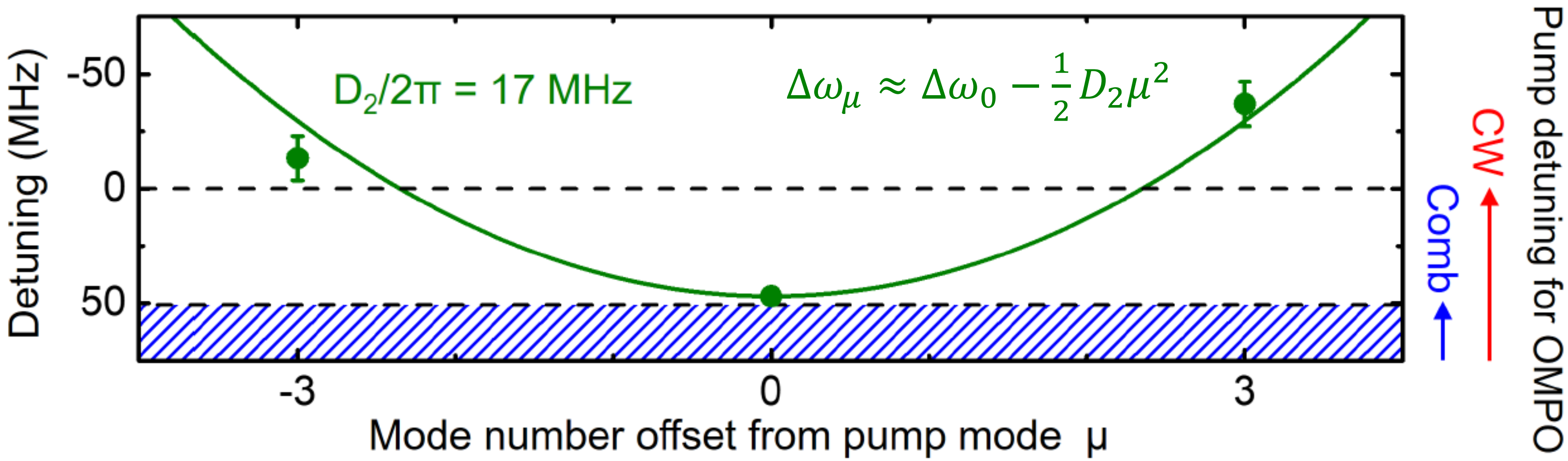


Pump detuning regime for OMPO

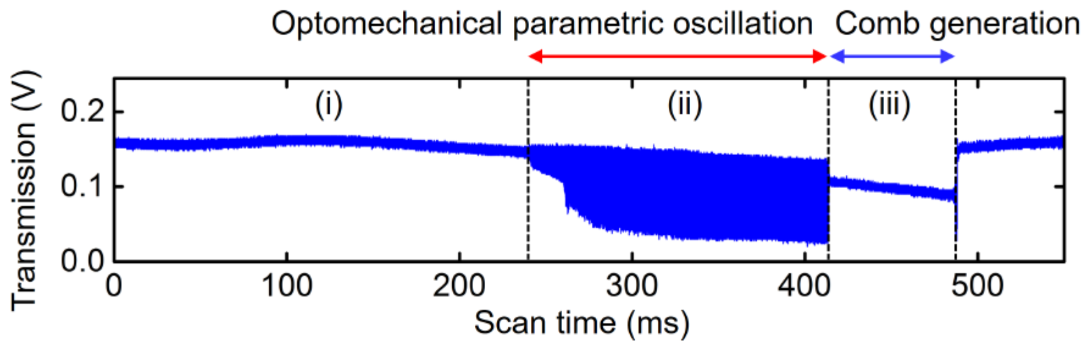
- Number of intracavity photon $|a_\mu|^2$ is obtained by measurement or LLE simulation
- Comb detuning $\Delta\omega_\mu$ follows the cavity dispersion D_2

$$\Gamma_{\text{eff}} = \Gamma_{\text{m}} + \sum_\mu \Gamma_{\text{opt},\mu} \qquad \Gamma_{\text{opt},\mu} = |a_\mu|^2 g_{\text{om}} \left\{ \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_\mu + \Omega_{\text{m}})^2} - \frac{\kappa}{\frac{1}{4}\kappa^2 + (\Delta\omega_\mu - \Omega_{\text{m}})^2} \right\}$$

Pump detuning regime for OMPO

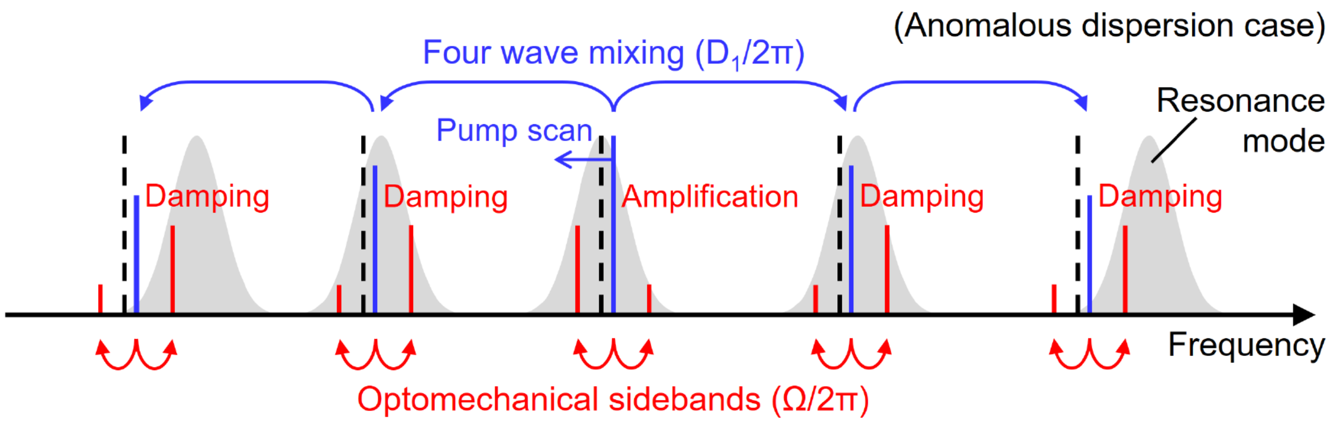


Transmission while scanning pump wavelength



Pump detuning regime that suppresses OMPO can be estimated from the cavity dispersion value and LLE simulation result

Summary



If only blue detuned pump light is present, optomechanical oscillations are always amplified. OMPO is suppressed when Turing pattern comb is generated, because all the lines appears in the red-detuning regime.

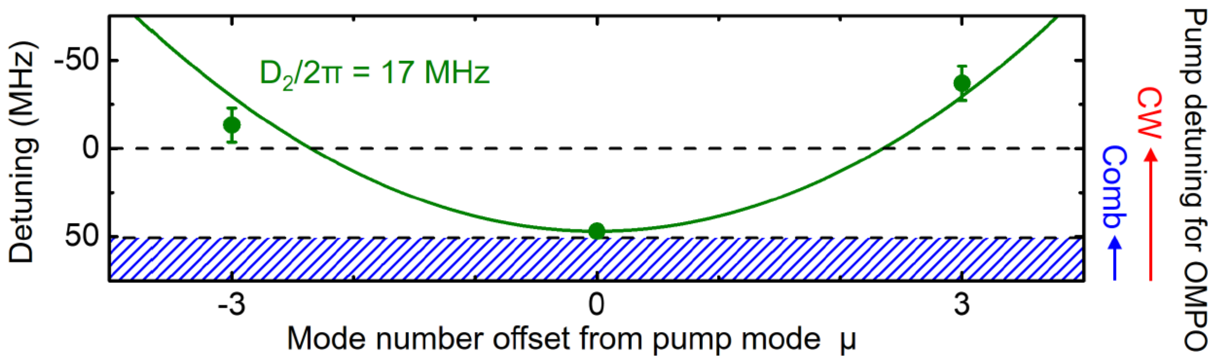
Single-optomechanical coupling with a resonance

$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}} + \Gamma_{\mathrm{opt}}$$

⇨

Multi-optomechanical couplings with resonances

$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}} + \sum_{\mu} \Gamma_{\mathrm{opt},\mu}$$



Summary

1. Brillouin laser in coupled WGMs

Achieved Brillouin lasing w/ 10 mW pump
Has potential to reduce down to 500 uW.

2. Optomechanics with micro-combs

Cooling is possible even w/ blue detuned pump when comb is present
Anomalous dispersion allows the cooling the cavity

Acknowledgement

- The team

- Support

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