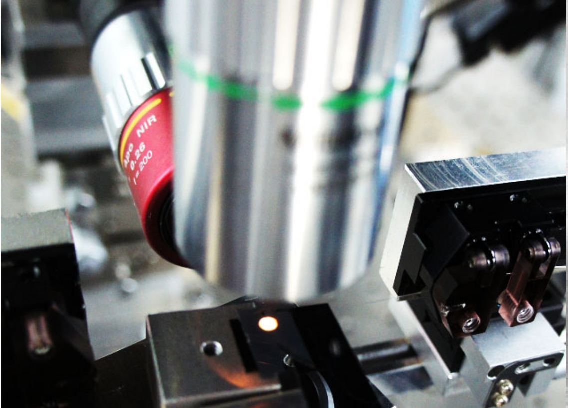
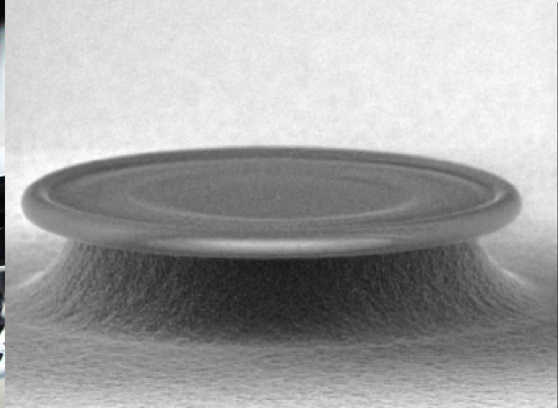
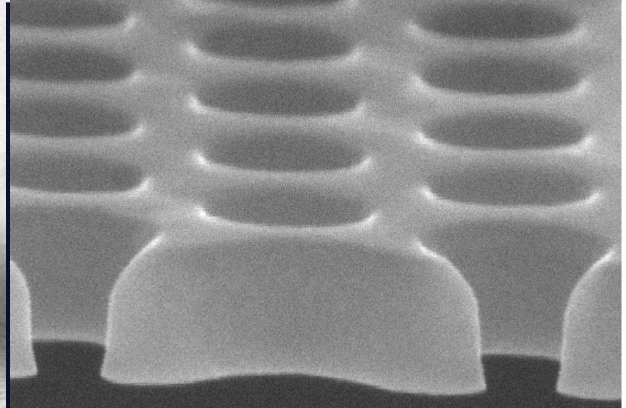
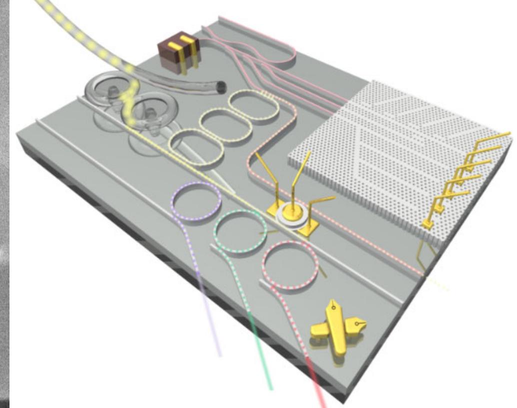





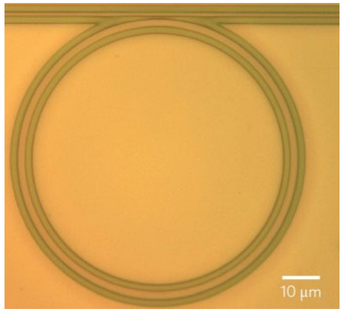
Asia Pacific Laser Symposium (APLS)
May 30, 2018, 15:50-16:20

Frequency comb and Brillouin lasing in optical microcavities

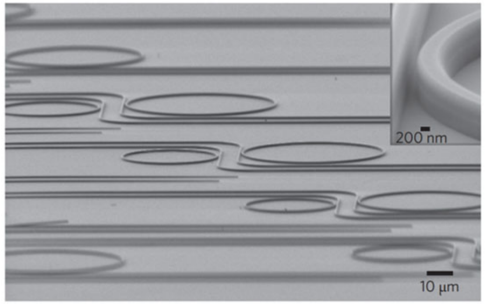
Takasumi Tanabe,
Ryo Suzuki, Yoshihiro Honda, and Shun Fujii

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

High-Q whispering-gallery mode microcavities

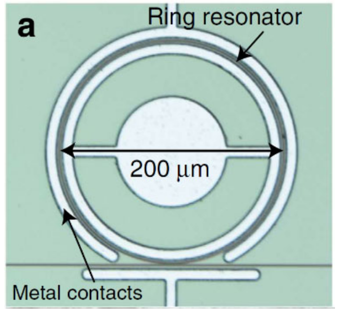


Silicon nitride
Weiner group (Purdue)

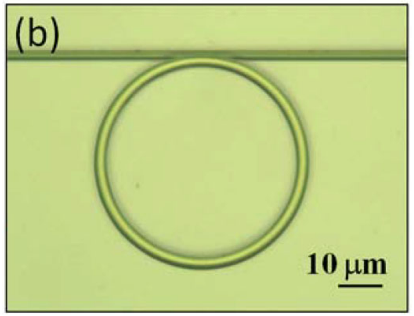


Diamond
Loncar group (Harvard)

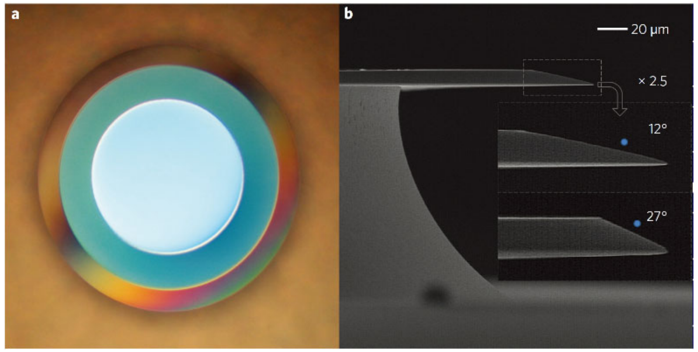
Crystalline (CaF_2, MgF_2, etc)
Kippenberg group (EPFL, Swiss),
Makei group (OE Waves)



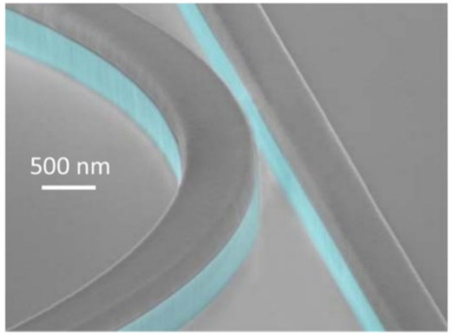
Silicon
Gaeta group (Columbia)



AlN
Tang group (Yale)



Silica
Vahala group (Caltech)



AlGaAs
Yvind group (DTU, Denmark)

◆Q-factor

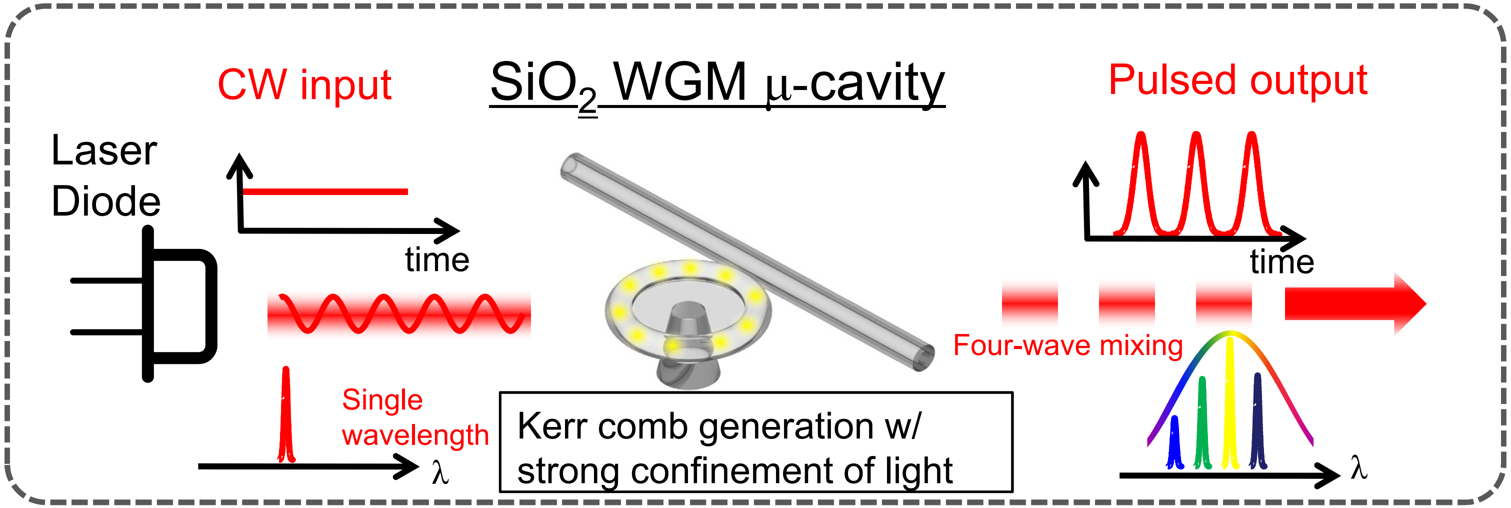
$$Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}}$$

◆Photon density

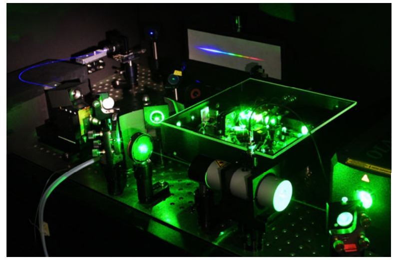
$$\propto Q/V$$

Kerr comb in microcavity system

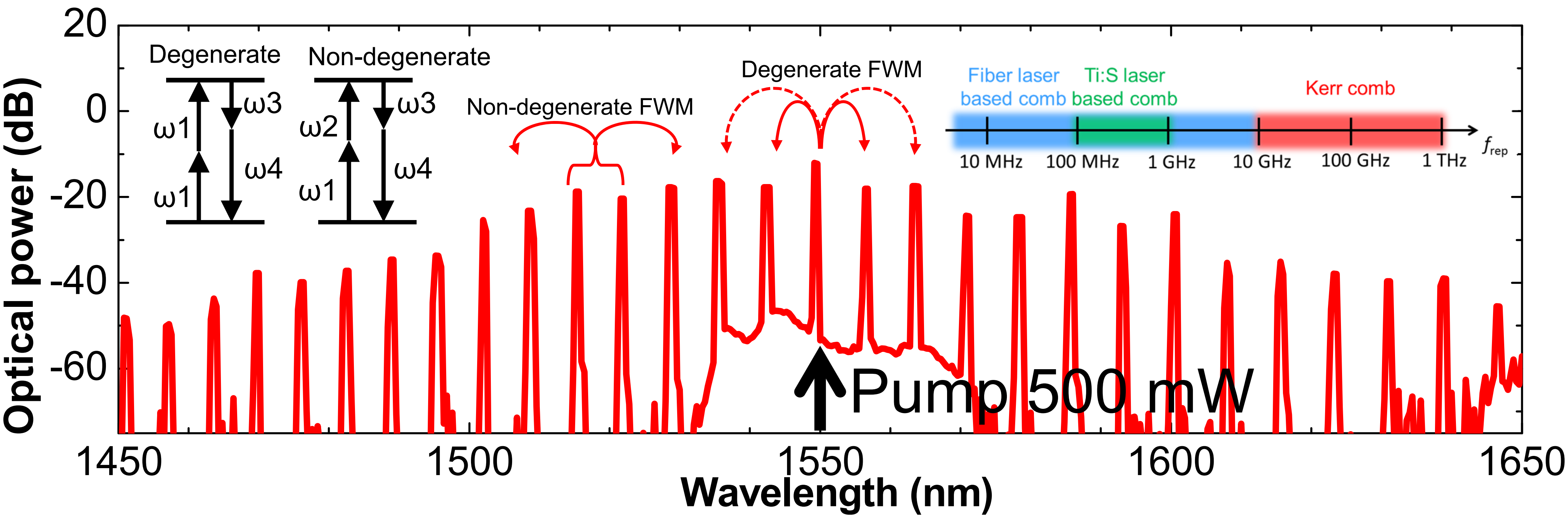
Convert CW laser to ultrashort pulse train w/ > 800 GHz rep. rate



Ti:Sapphire laser based comb



large & expensive



Outline

1. Raman comb

R. Suzuki, A. Kubota, A. Hori, S. Fujii, and T. Tanabe, "Broadband gain induced Raman comb formation in a silica microresonator," J. Opt. Soc. Amer. B, Vol. 35, No. 4, pp. 933-938 (2018). (**Editor's pick**)

2. Brillouin laser

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**)

Outline

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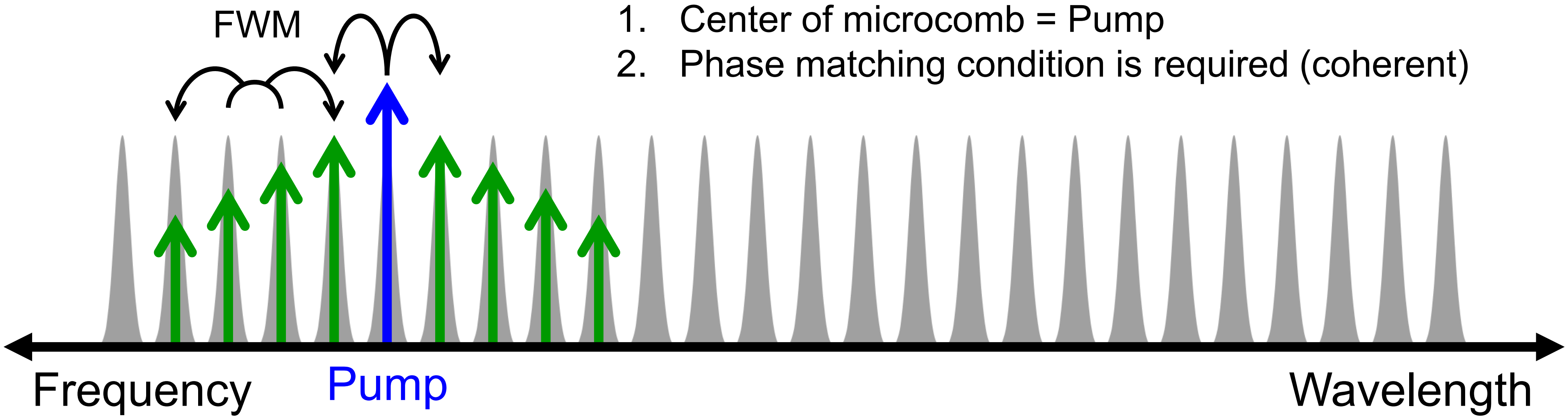
Microcomb generation via FWM/SRS

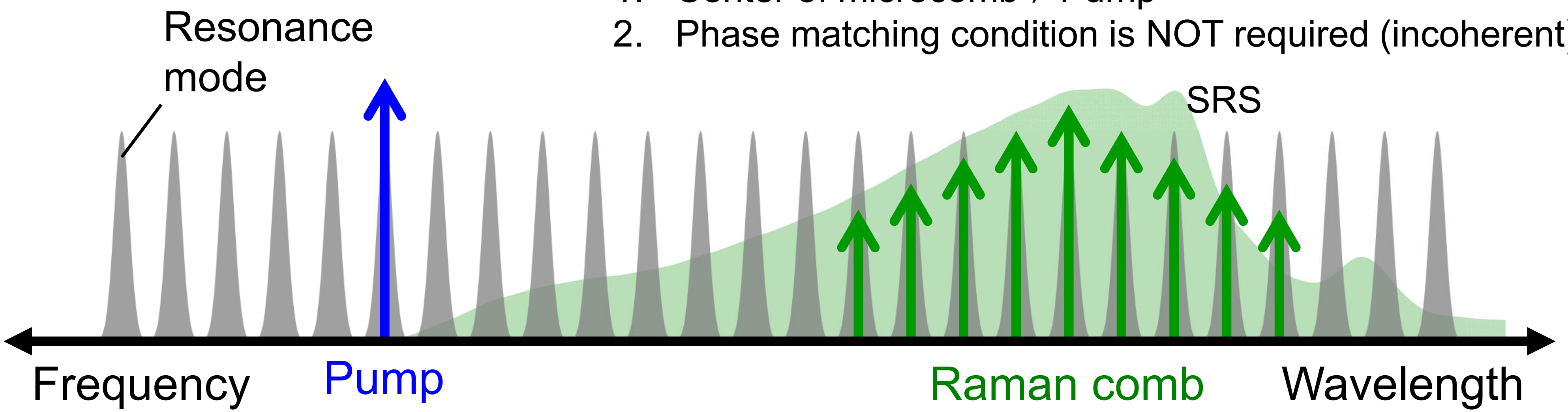
Microcomb via four-wave mixing (FWM)

1. Center of microcomb = Pump
2. Phase matching condition is required (coherent)



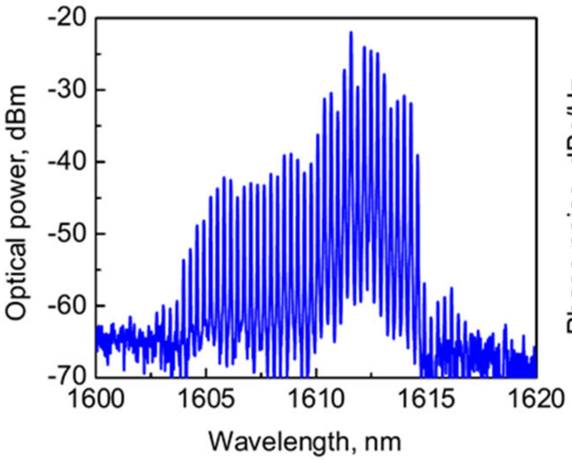
Microcomb via stimulated Raman scattering (SRS)

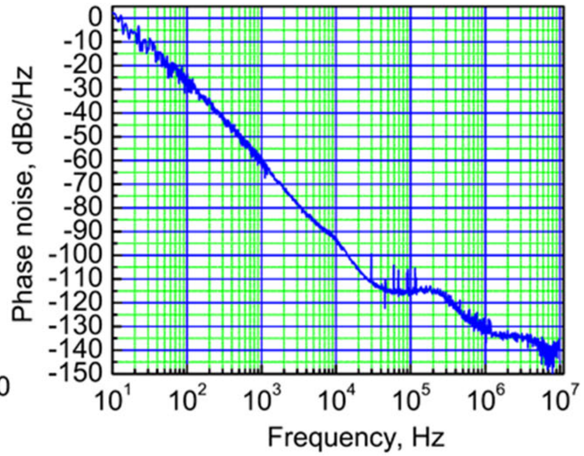
1. Center of microcomb ≠ Pump
2. Phase matching condition is NOT required (incoherent)



Stimulated Raman scattering in a microresonator

Coherent Raman comb generation





Phys. Rev. Lett. 105, 143903 (2010).

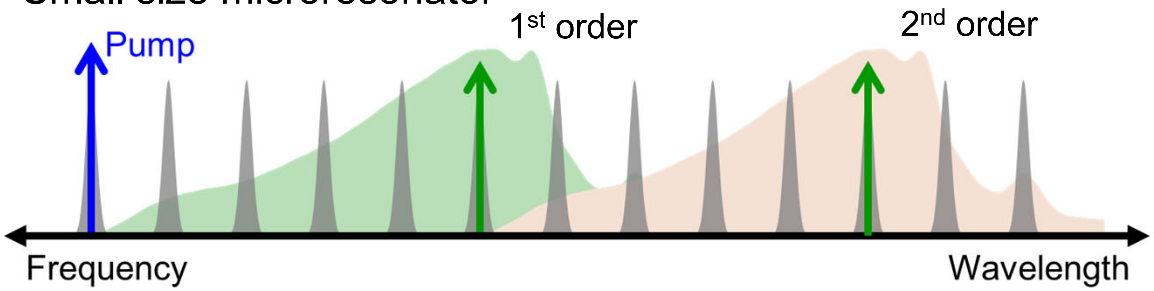
Coherent Raman comb generation has been demonstrated using CaF_2 and BaF_2 microresonators.

[1] W. Liang et al., Phys. Rev. Lett. 105, 143903 (2010).
[2] G. Lin et al., Opt. Lett. 41, 3718-3721 (2016).

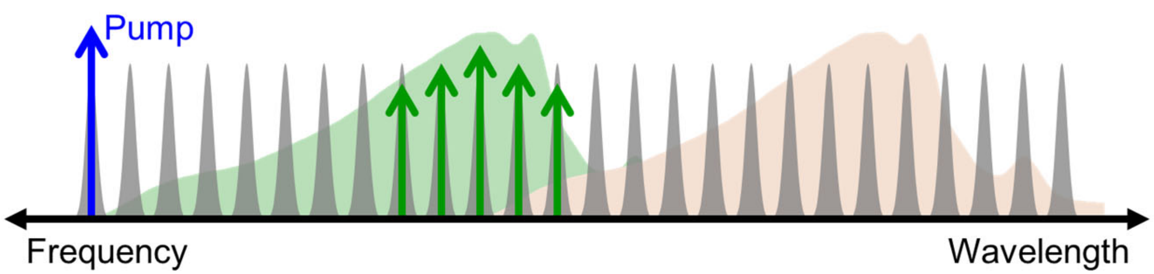
⇒ Potential for coherent comb sources, which are generated via SRS in wide wavelength regieme.

SRS dynamics inside a microresonator

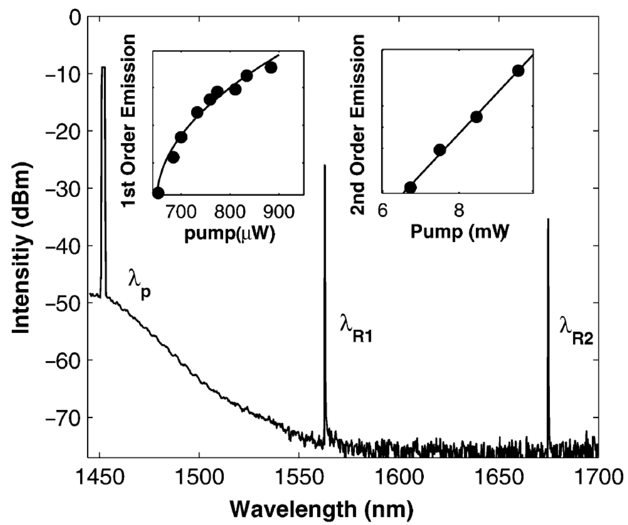
Small size microresonator



Large size microresonator [this work]



SRS formation in a small microresonator has been well studied (e.g. cascaded Raman)



IEEE J. Sel. Top. Quantum Electron. 10, 1219-1228 (2004)

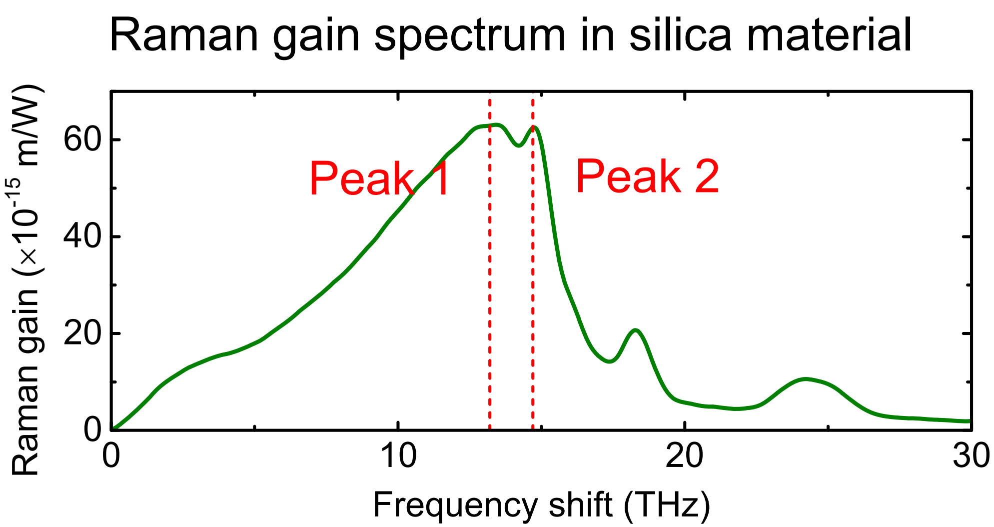
Motivation of this research

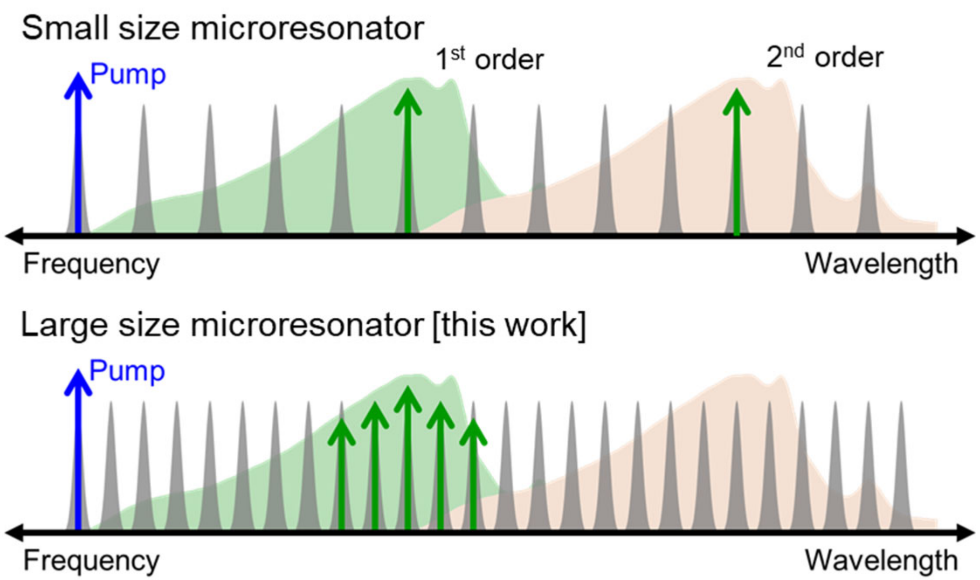
Motivation

To study the dynamics of Raman comb formation in mm-scale microresonators.
Studying the frequency shift of the generated Raman laser light between two peaks at 13.2 THz (Peak 1) and 14.7 THz (Peak 2).

Methods

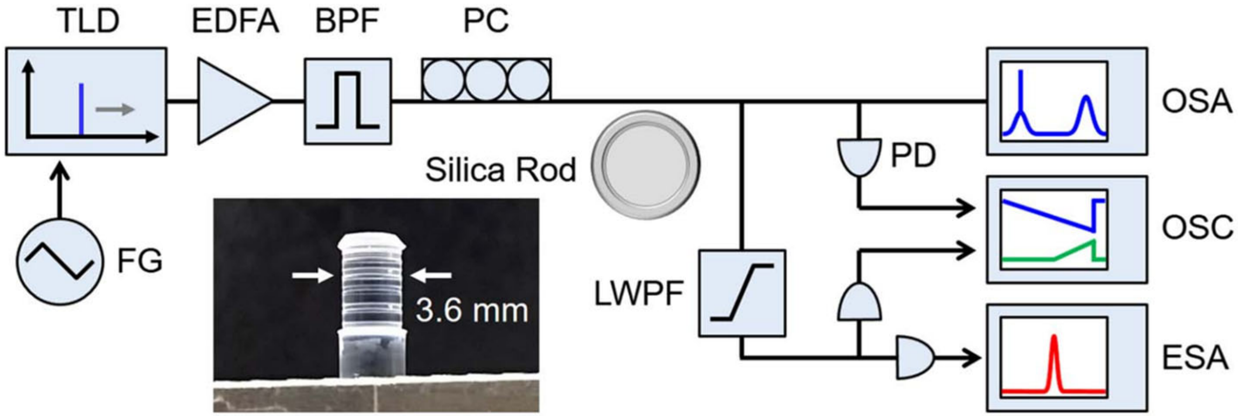
We used silica rod microresonators with cavity FSRs in microwave rates.
Silica material has broadband Raman gain spectrum.





Experimental setup & Raman comb generation

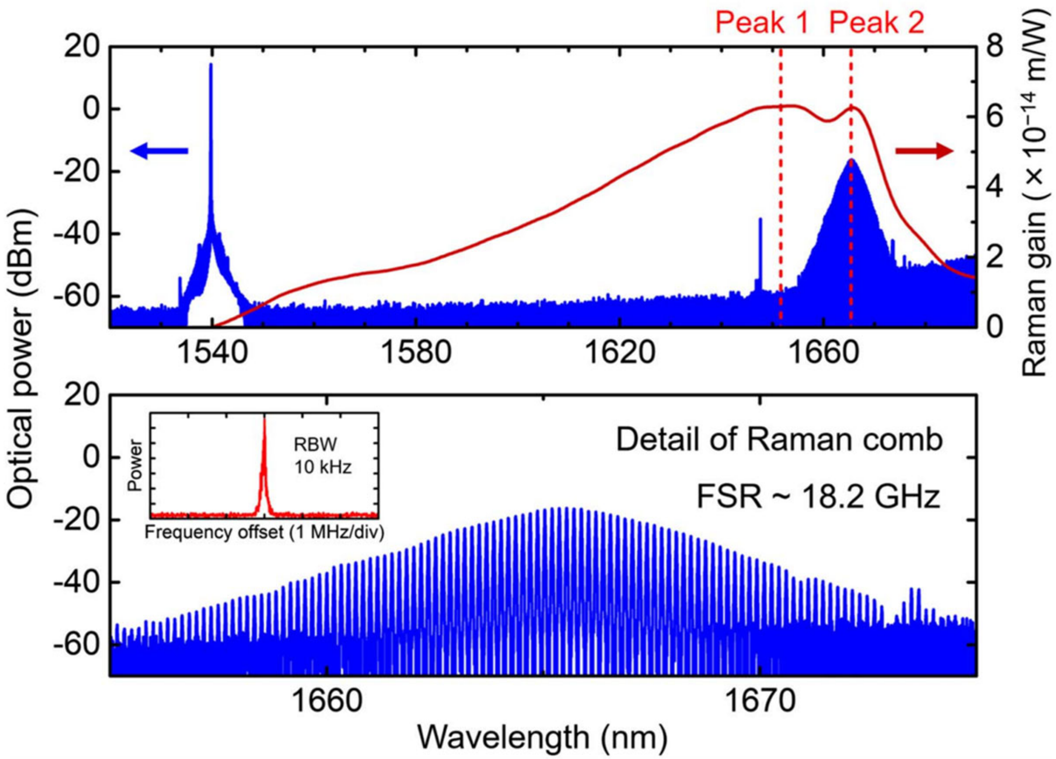
Experimental setup



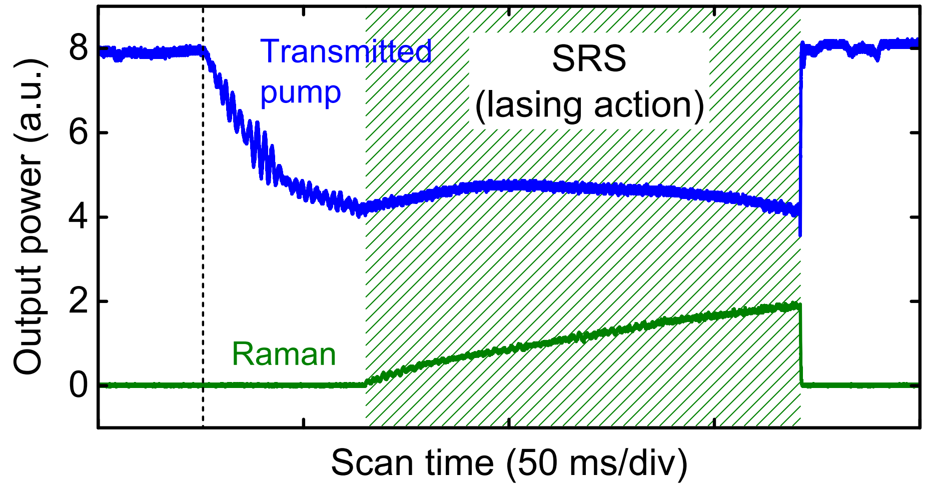
Cavity FSR: 18.2 GHz
Q factor: ~10^8
Pump power: 100 mW
Pump wavelength: 1540 nm

TLD: tunable laser diode, FG: function generator,
EDFA: erbium-doped fiber amplifier,
BPF: band pass filter, PC: polarization controller,
LWPF: long wavelength pass filter, PD: photodetector,
OSA: optical spectrum analyzer, OSC: oscilloscope,
ESA: electrical spectrum analyzer

Raman comb generation

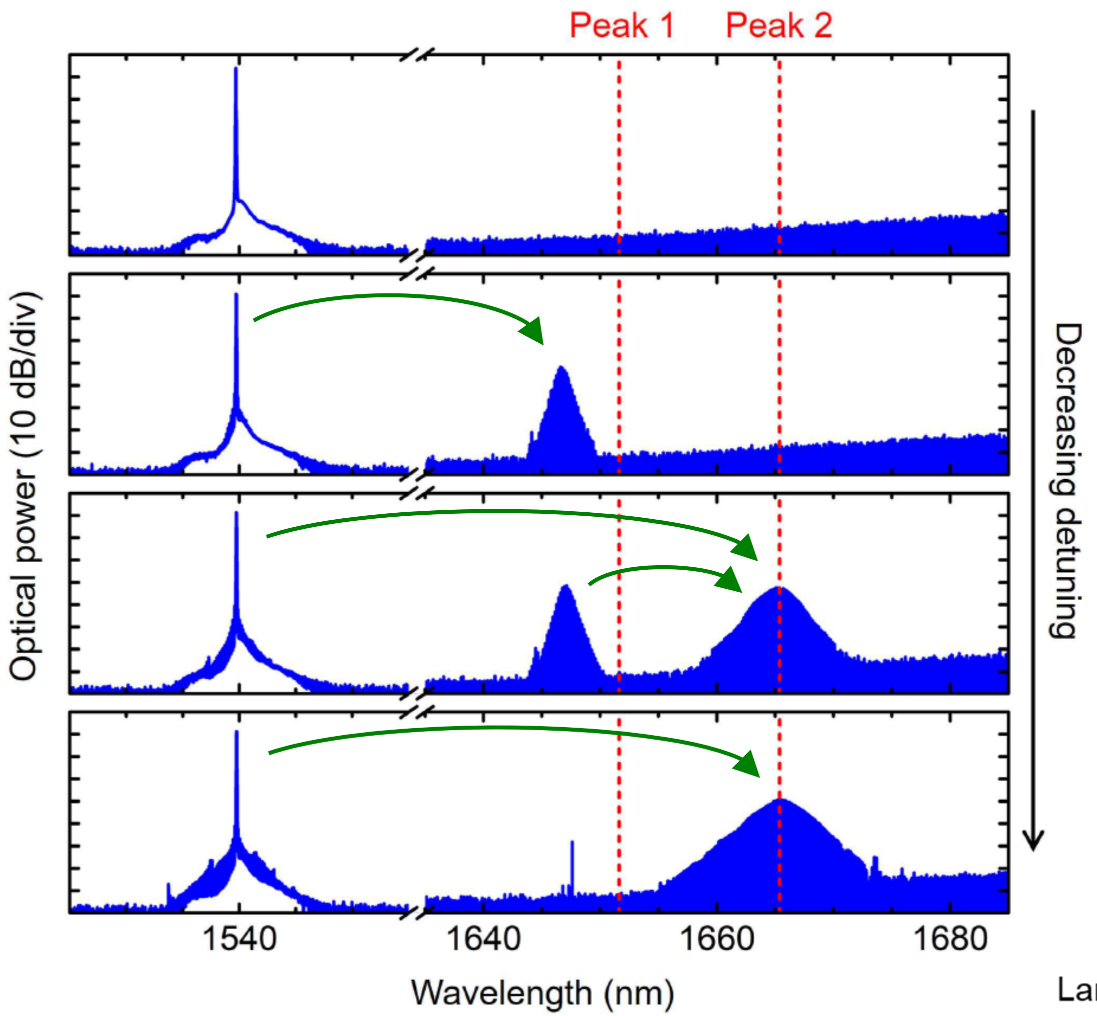


Output power during pump scanning

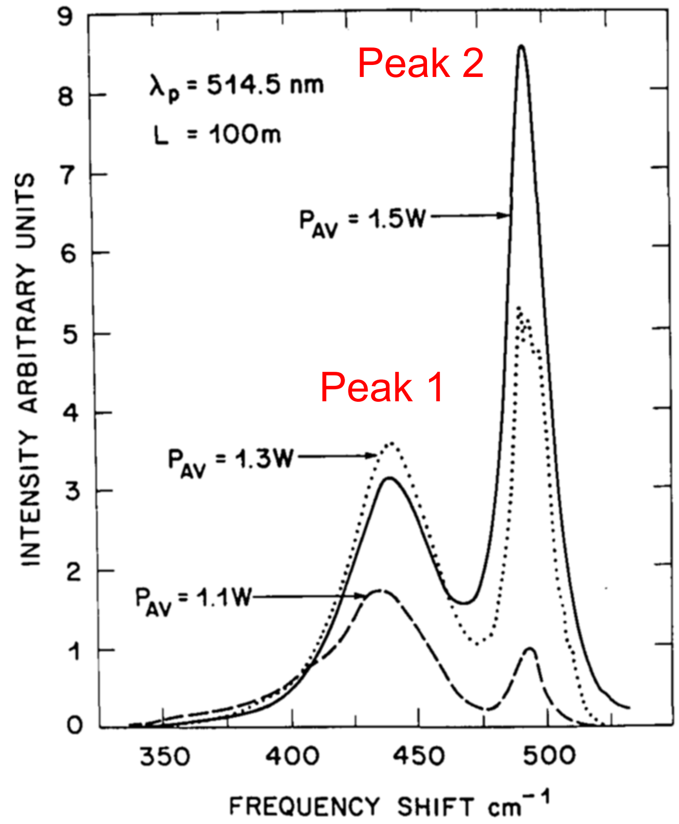


Detuning dependent Raman comb formation

Raman peak transition in a microresonator (depending on detuning) [This work]



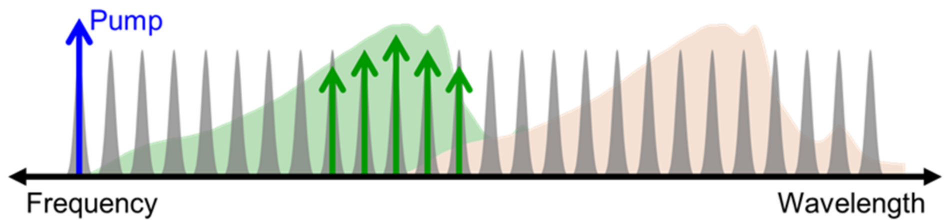
Raman peak transition in optical fibers (depending on input pulse power) [Ref]



J. Opt. Soc. Am. B 1, 652-657 (1984)

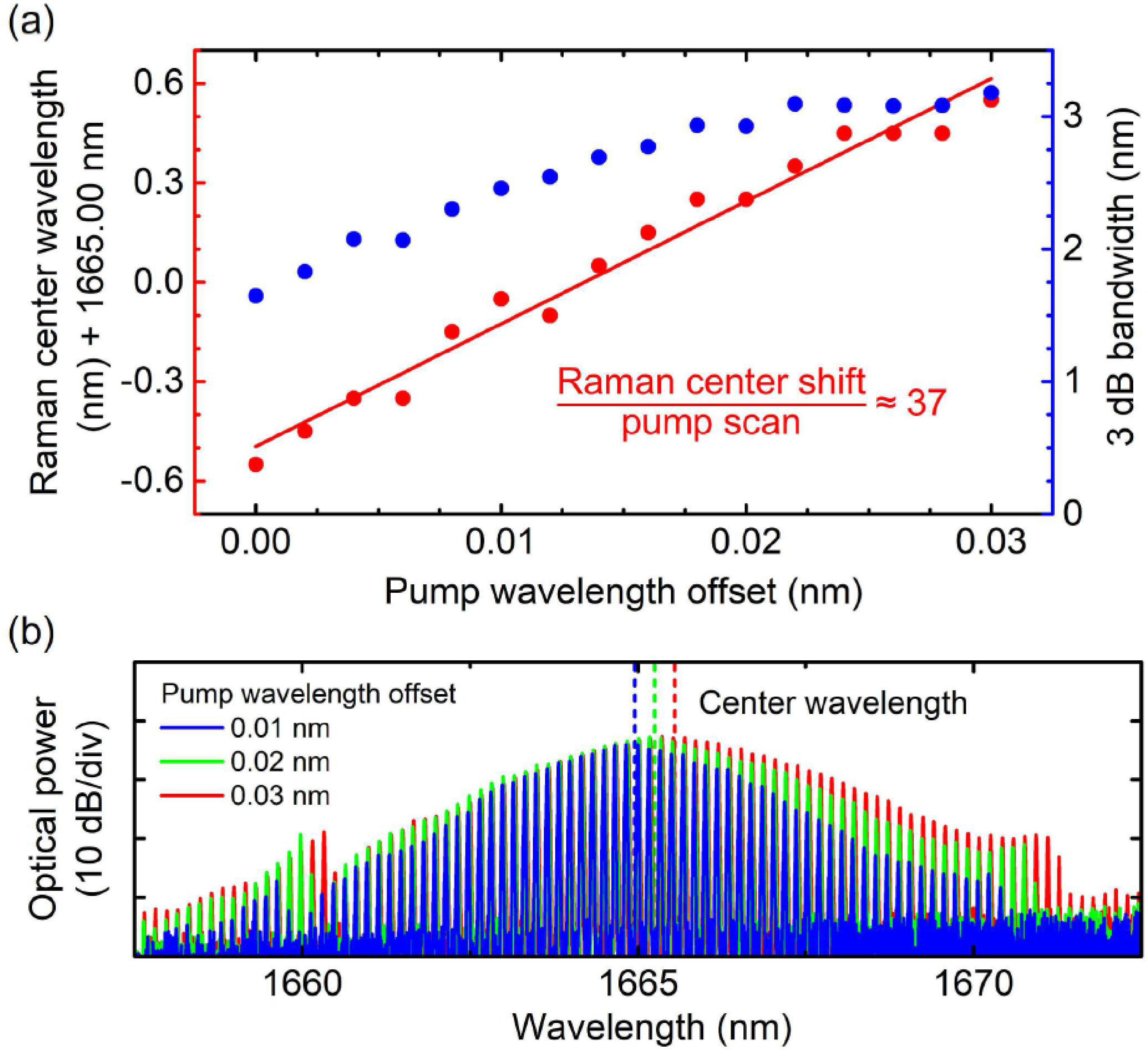
Energy transition via SRS
Larger detuning: Pump → Peak 1
Smaller detuning: Pump + Peak 1 → Peak 2

Large size microresonator [this work]



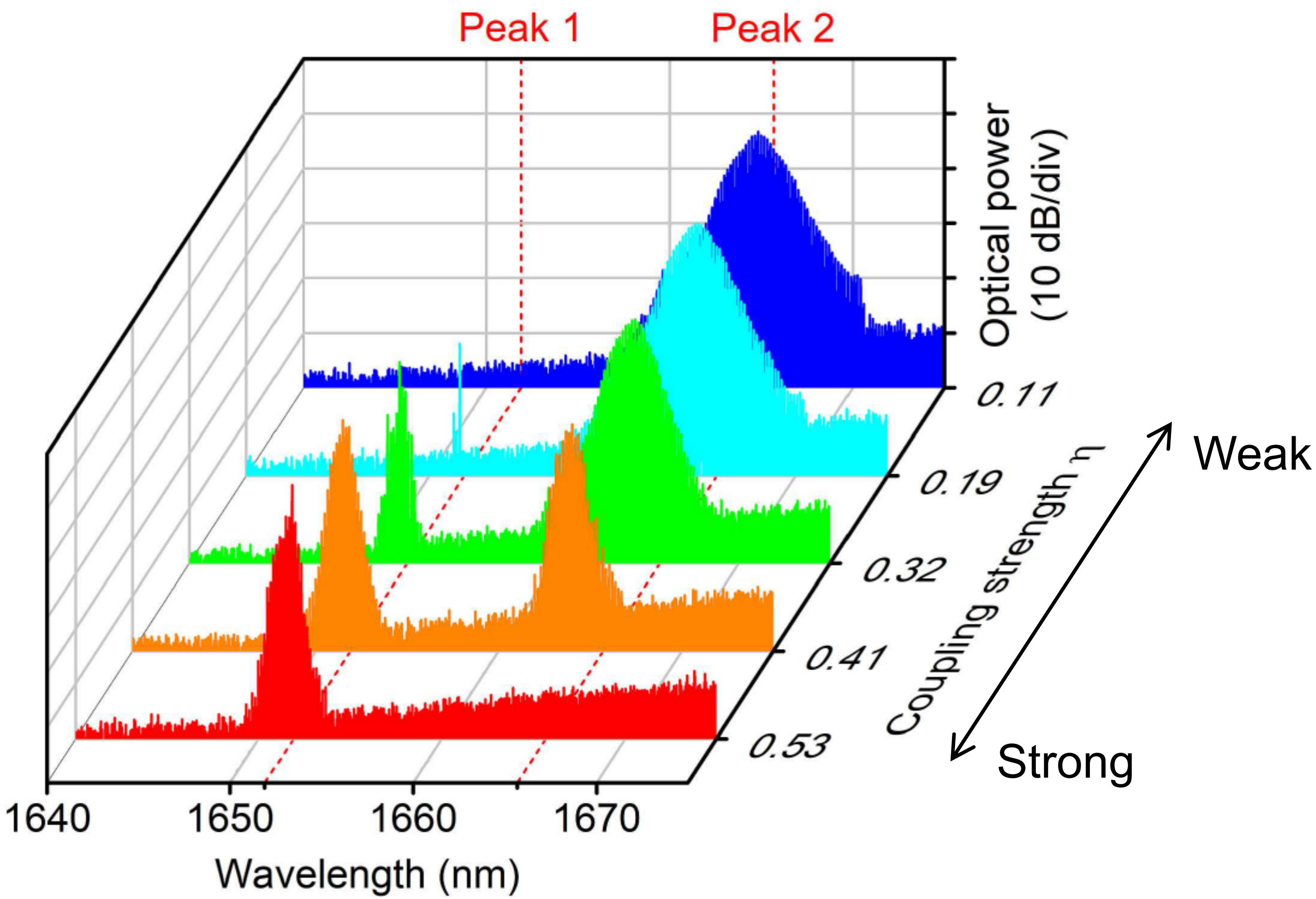
Detuning dependent center wavelength shift

Center wavelength transition in a Raman comb depending on detuning



Coupling dependent Raman comb formation

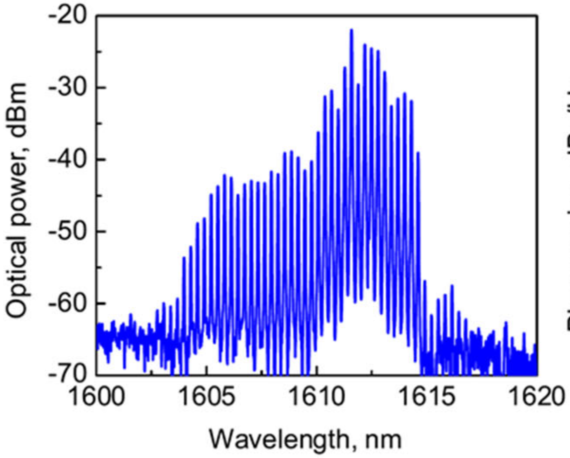
Raman comb spectra depending on coupling strength
(detuning values were close to zero)

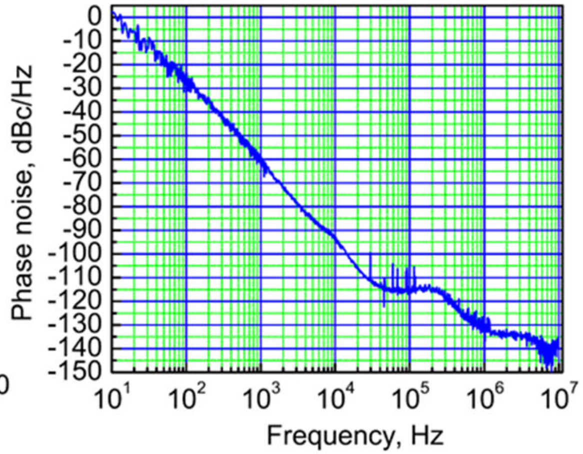


Weaker coupling condition causes efficient SRS.

Towards coherent Raman comb generation

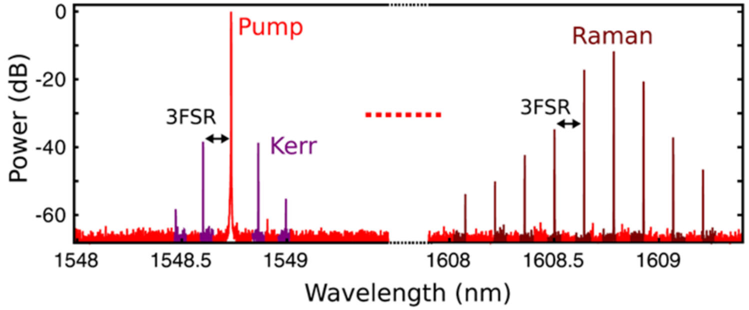
35 GHz CaF_2 microresonator

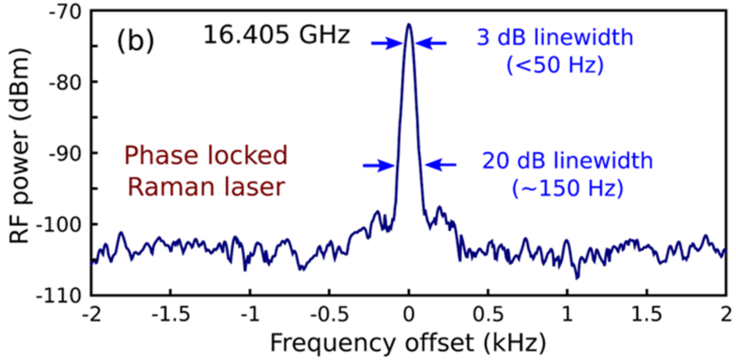




W. Liang et al., Phys. Rev. Lett. 105, 143903 (2010).

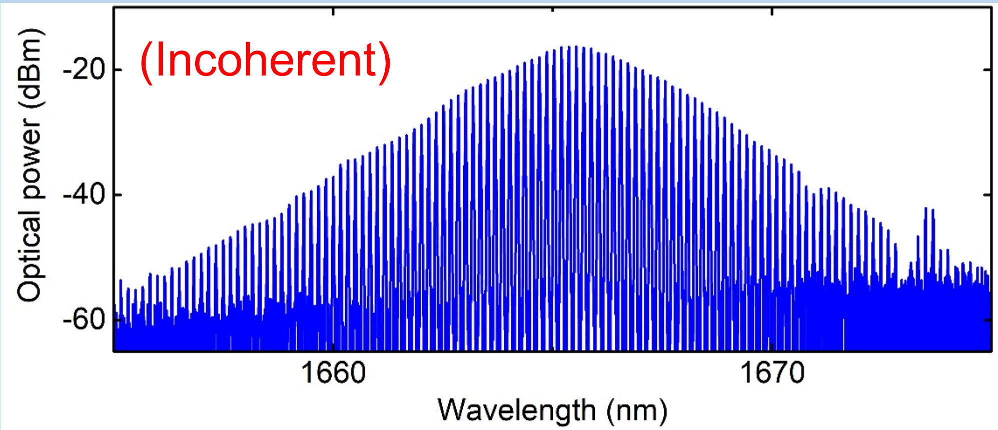
5.5 GHz BaF_2 microresonator





G. Lin et al., Opt. Lett. 41, 3718-3721 (2016).

18 GHz SiO_2 microresonator [this work]



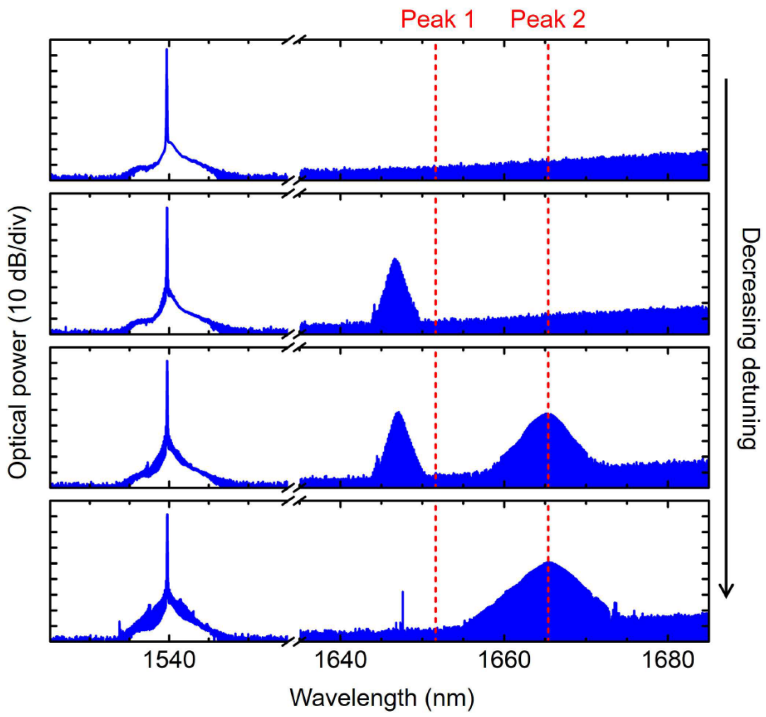
Future work

For coherent Raman combs, we will perform experiments in shorter wavelength regime with weak normal dispersion.

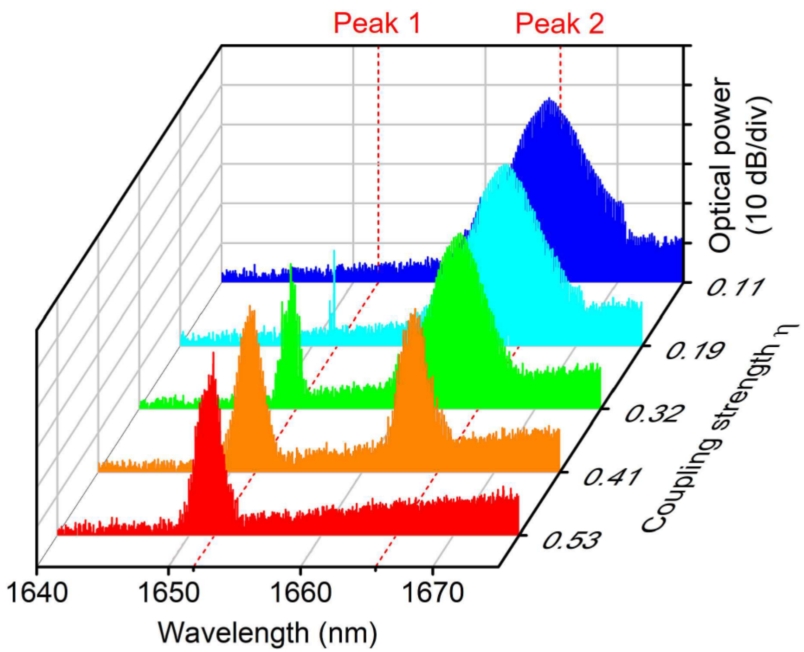
Summary (Raman laser)

- Generated Raman combs from a silica rod microresonator with an 18.2 GHz FSR.
- Controlled the Raman energy transition between Peak 1 and Peak 2 by controlling the detuning and coupling strength.
- Observed the center wavelength shift of a Raman comb, with a shift that is 37 times larger than that of pump scanning.

Detuning dependence



Coupling dependence



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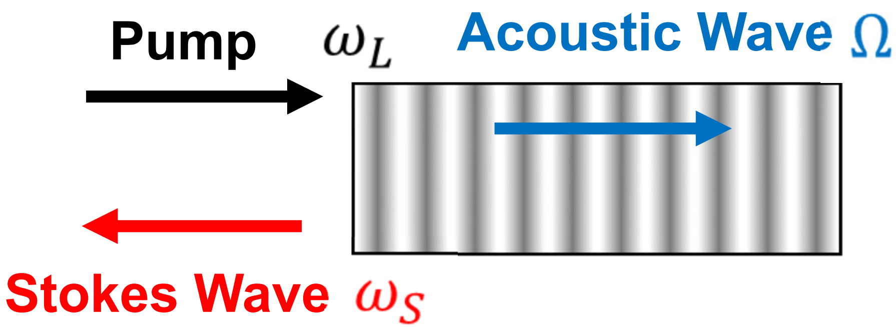
Stimulated Brillouin Scattering (SBS)

☐ Schematic representation of SBS process

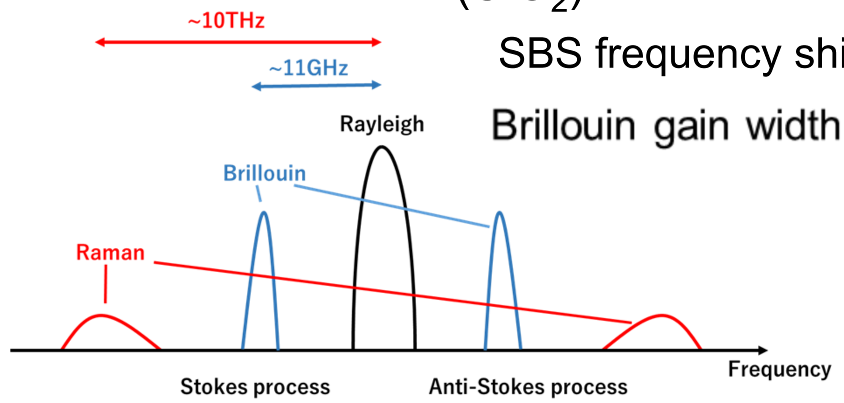


$$\omega_L = \omega_S - \Omega$$

(SiO_2)

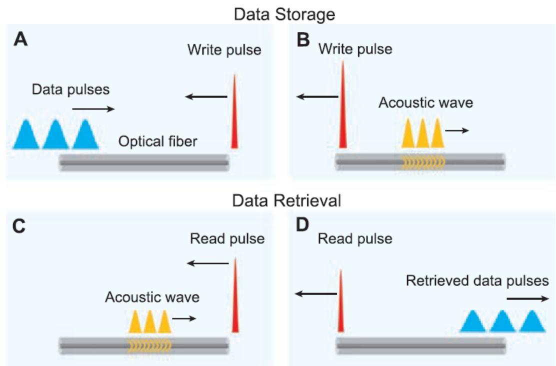
SBS frequency shift $\approx$ 11GHz

Brillouin gain width = ~50 MHz

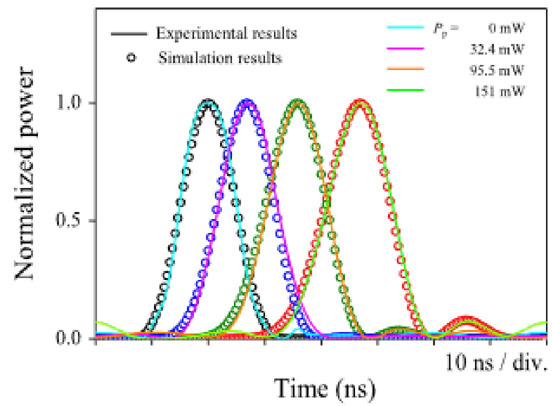


☐ SBS applications

- 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)

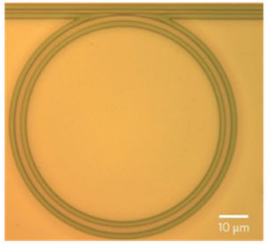
Microcavities

Crystalline (CaF_2)

$Q > 10^{10}$

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

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

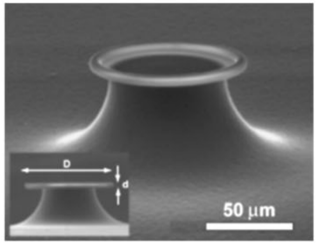


Si_3N_4 microring

$Q \approx 10^6$

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

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

Sto

Hz

Hz

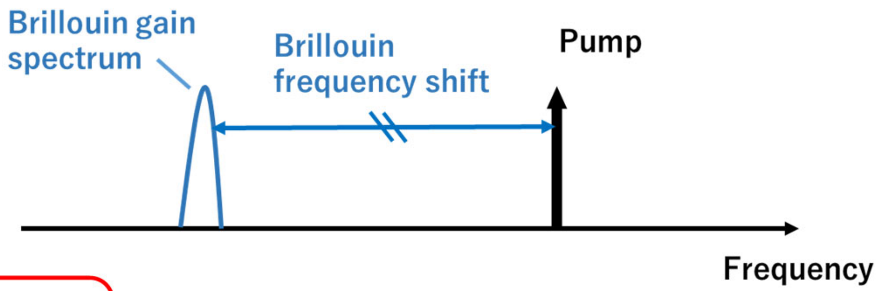
10 ns / div.

318, 1748-1750 (2007)

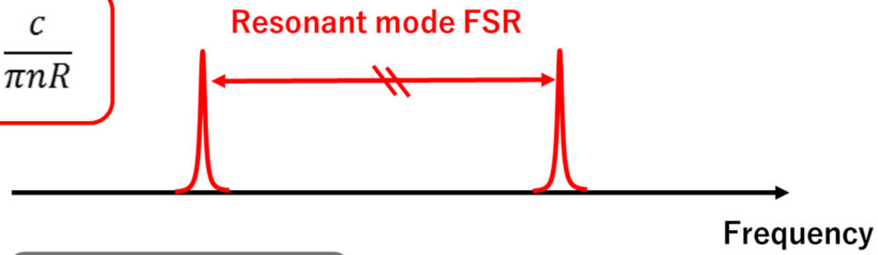
T. Sakamoto, T. Yamamoto, K. Shiraki, and T. Kurashima, Opt. Express **16**, 8026–8032(2008)

SBS in microcavities

Method1



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

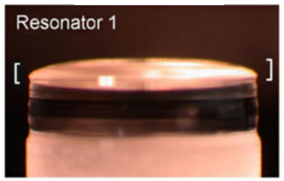


Brillouin frequency shift = Resonant mode FSR

↓

Brillouin lasing

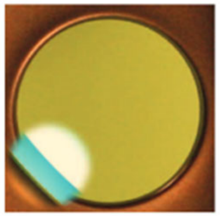
CaF_2



5.52 mm

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

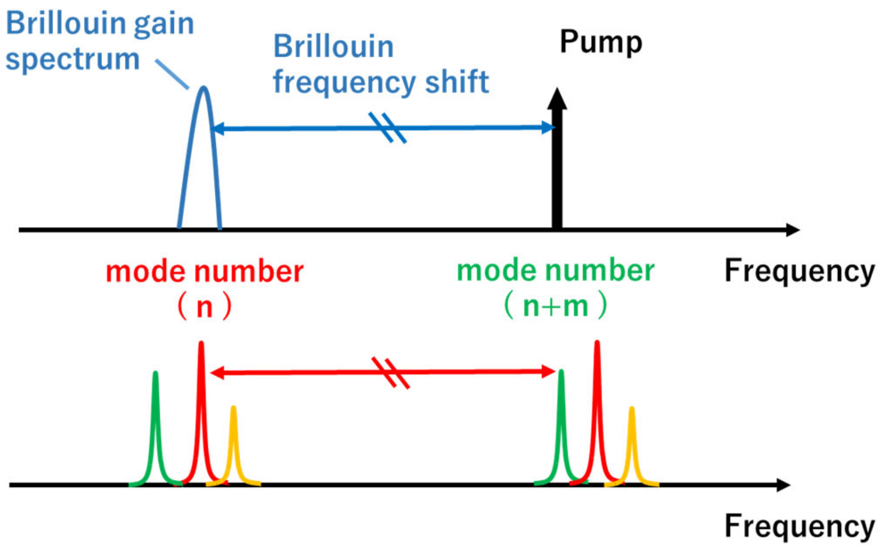
SiO_2



6.02 mm

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

Method2

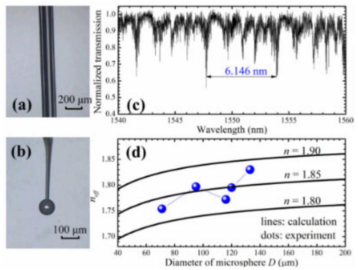


Brillouin frequency shift = High-order mode spacing

↓

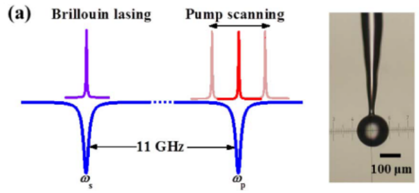
Brillouin lasing

TeO_2



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

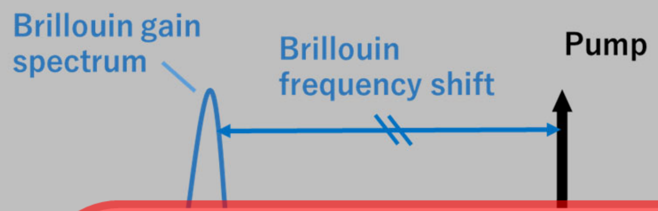
SiO_2



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

SBS in microcavities

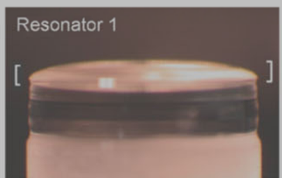
Method1



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

Brillouin lasing

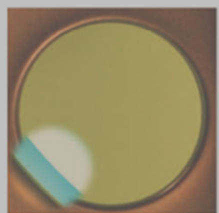
CaF2



5.52 mm

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

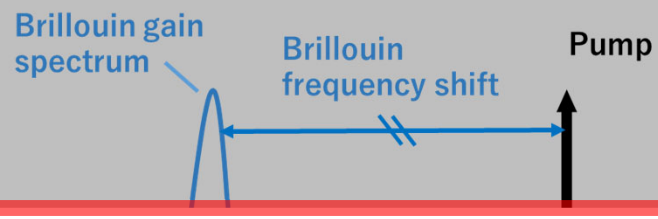
SiO2



6.02 mm

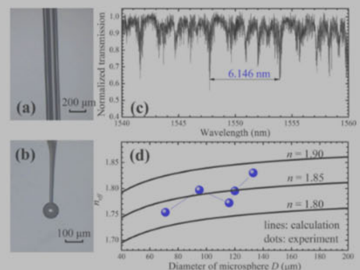
J. Li, K. Vahala et al., OE 20, 20170- (2012)

Method2



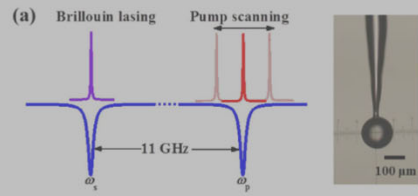
Brillouin lasing

tellurite



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

SiO_2



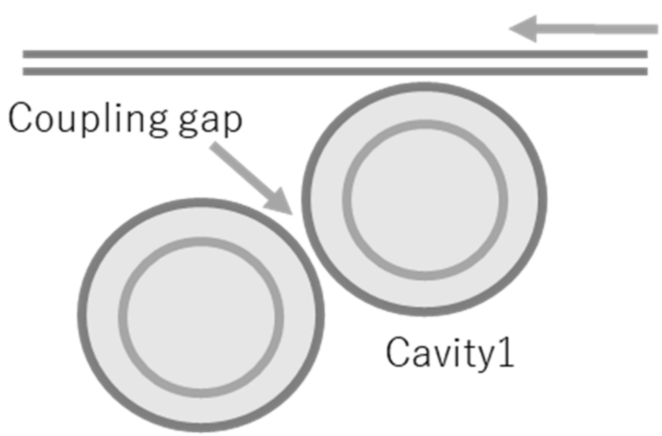
C. Guo, H. Xu et al., OL 40, 4971- (2015)

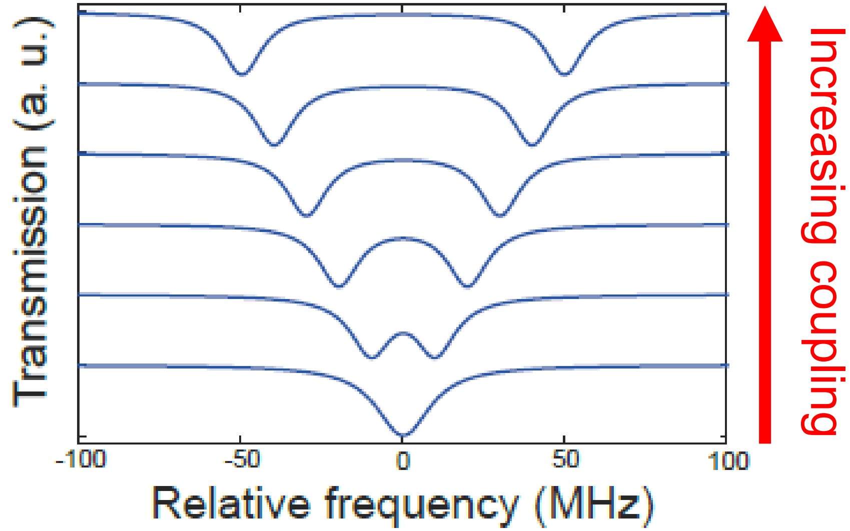
Method1 &2

■ Precise control of cavity size

Objective

Our work





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

Tunable

Brillouin lasing

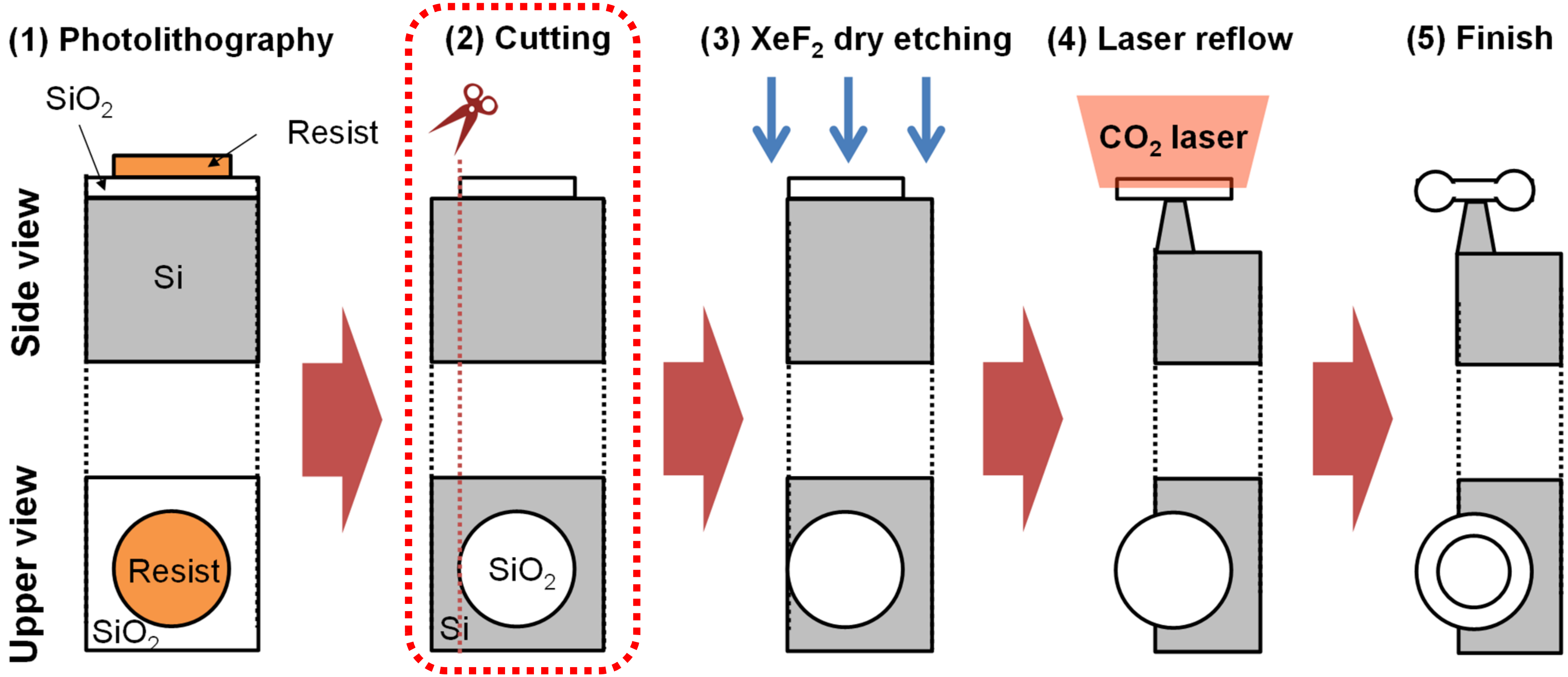
SBS in coupled microcavities ⇨

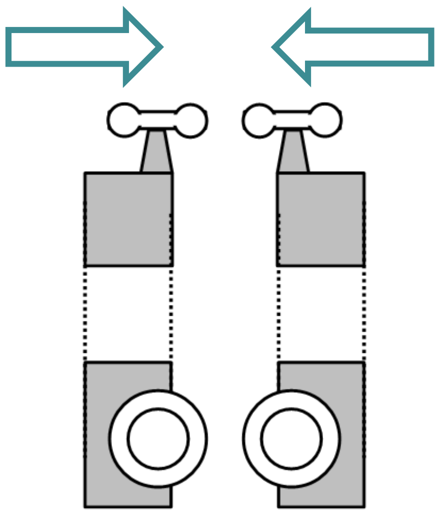
~~Precise size control~~

Low threshold

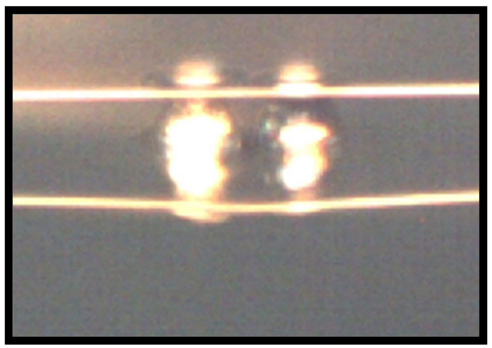
Small footprint

Silica toroid microcavities

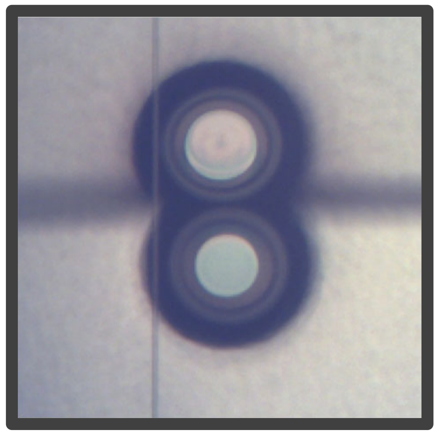




Side View



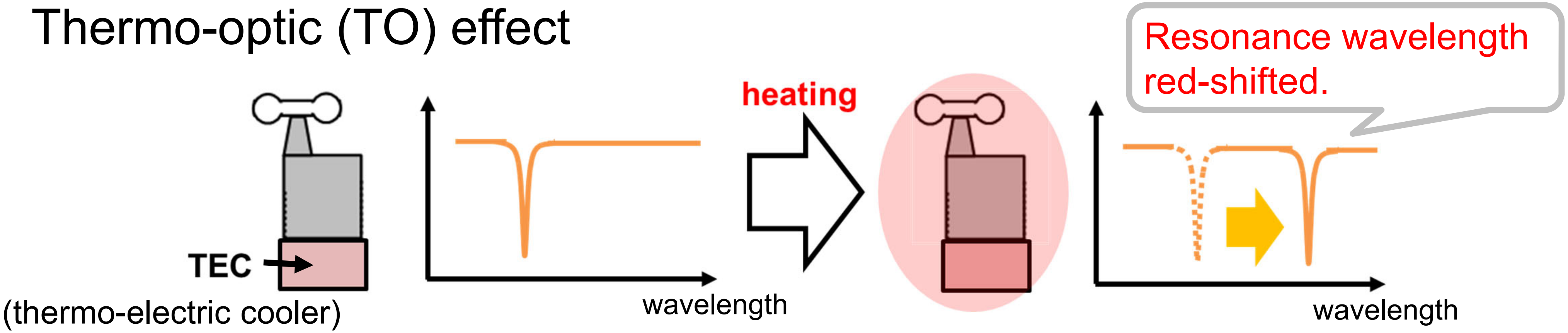
Top View



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

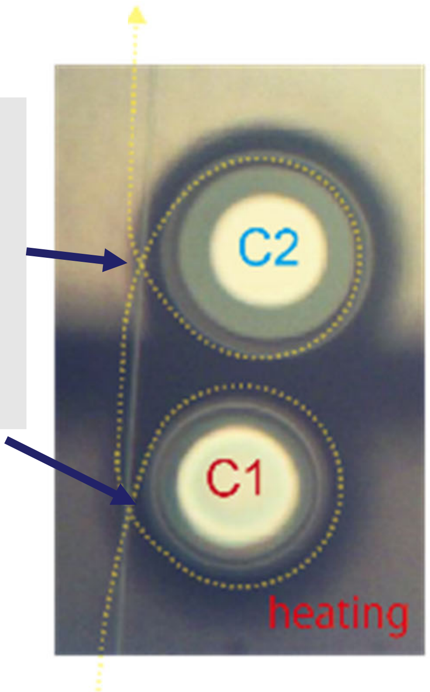
Tuning resonant frequency

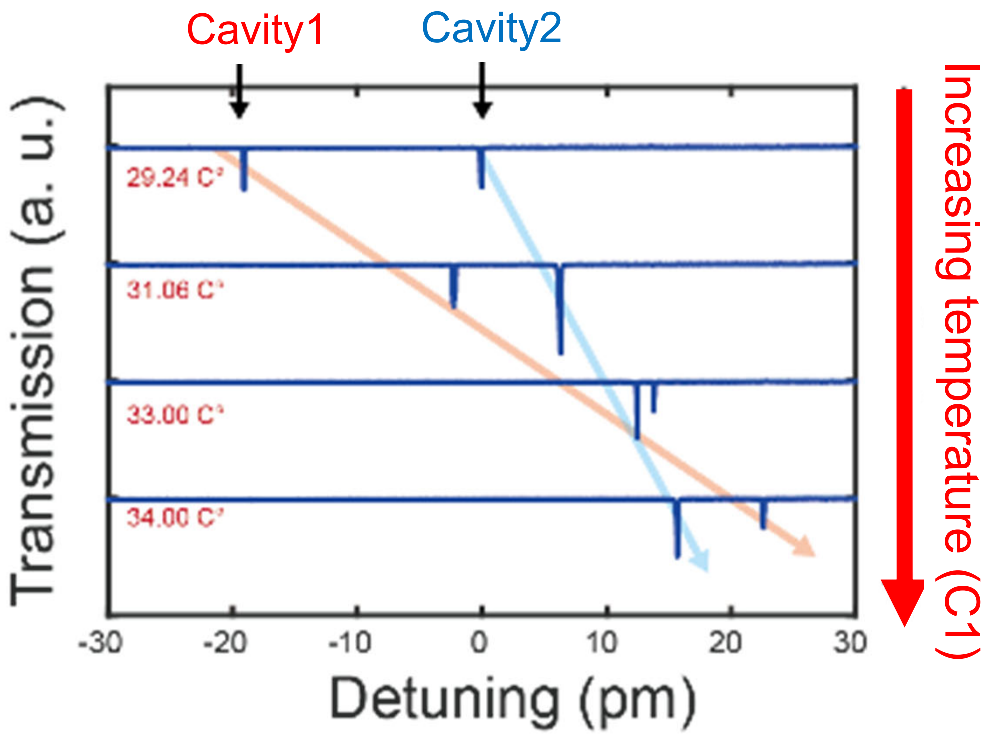
- Thermo-optic (TO) effect



- Tuning two different resonant frequencies

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





Supermode splitting

Calculation

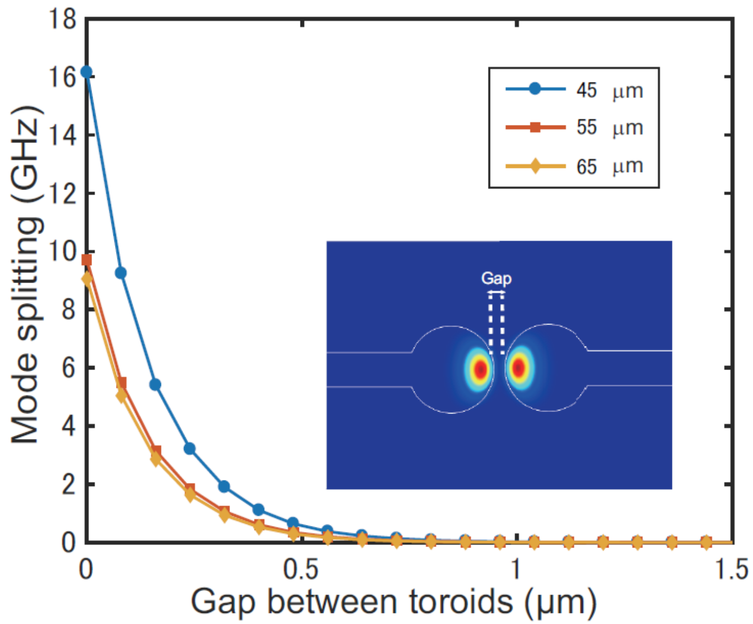
- Mode overlap
- Phase matching condition

} **Coupling coefficient**

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

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

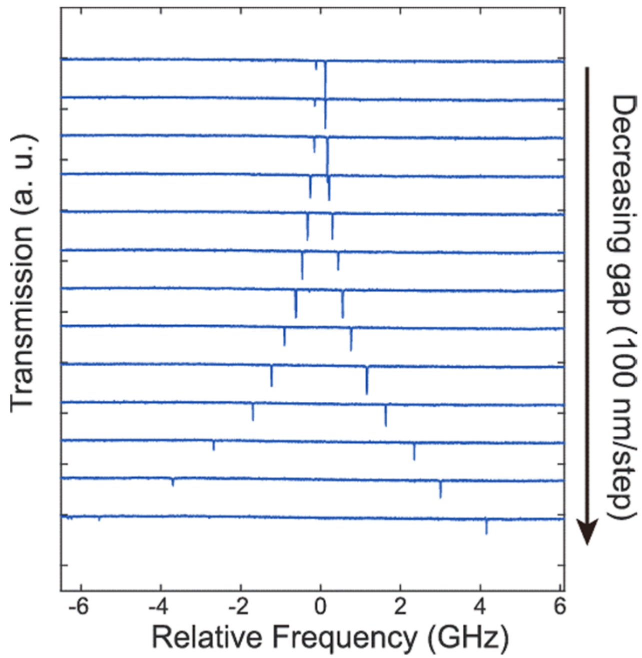
Fabricated 55-μm-diameter silica toroid

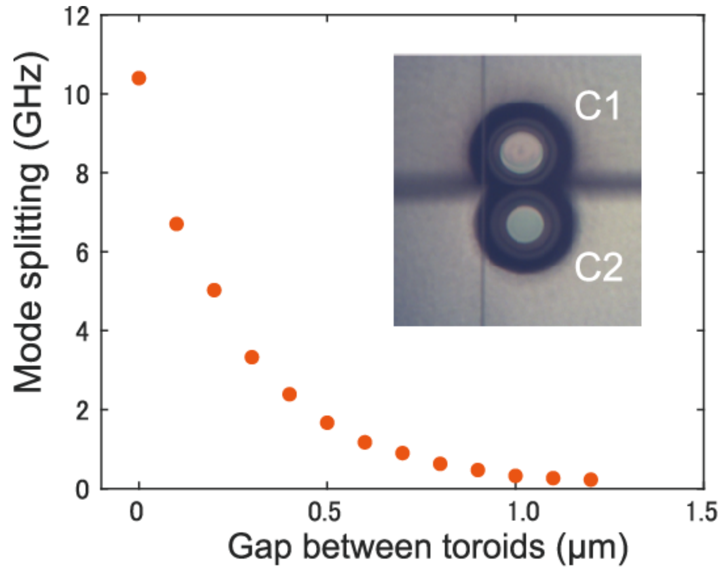
⬇

Moved toroids close together

⬇

Achieved more than 10GHz mode splitting

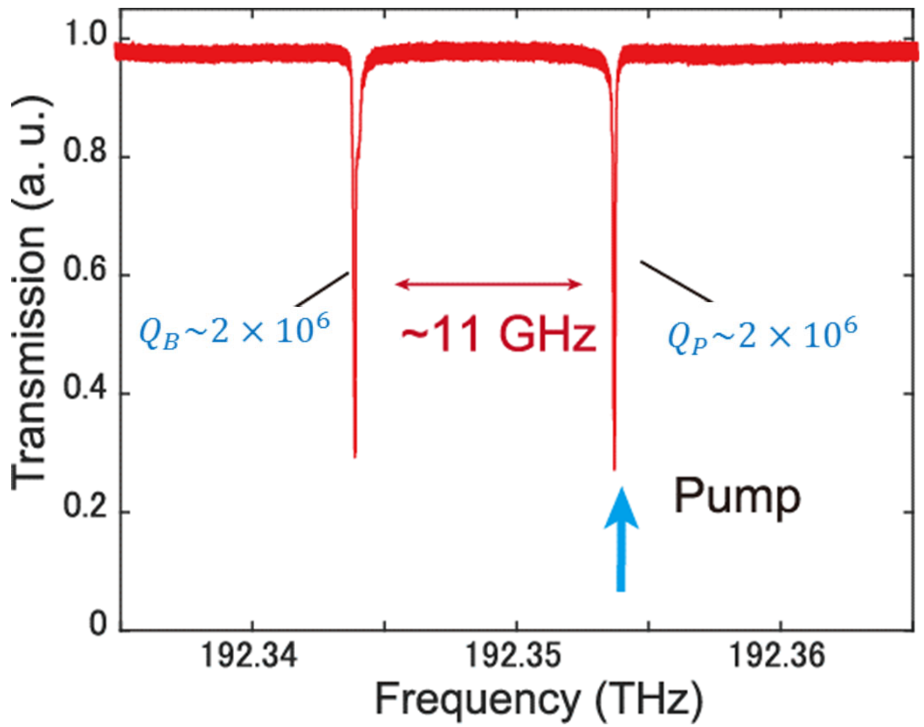




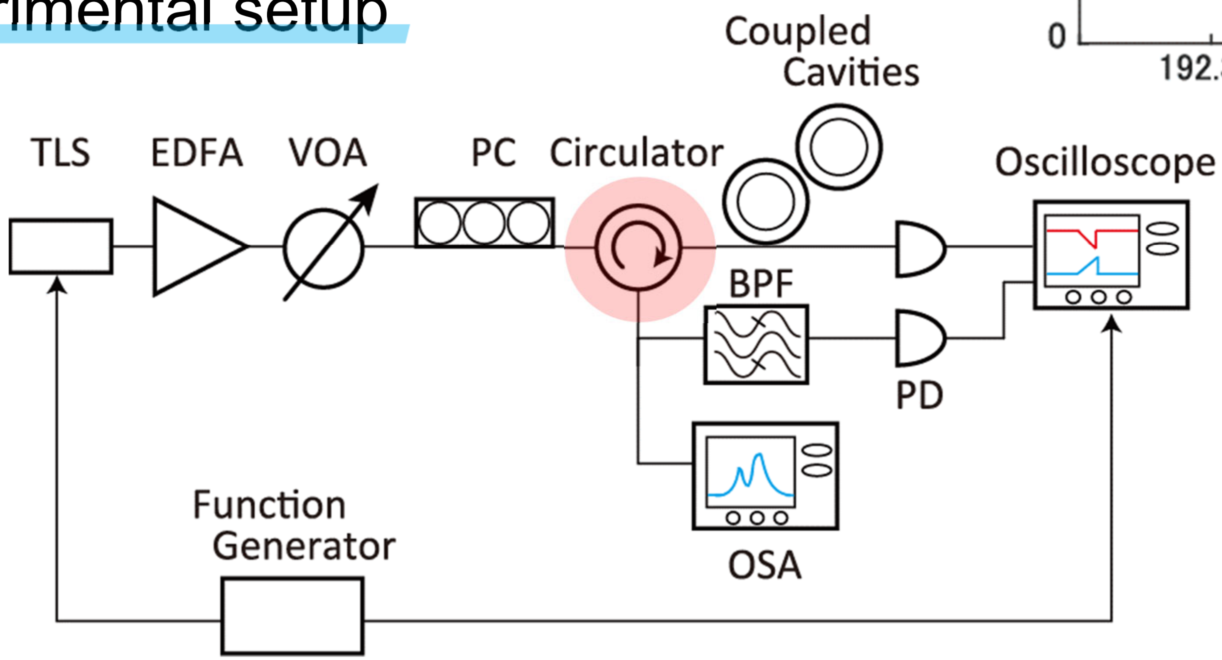
SBS in coupled cavities

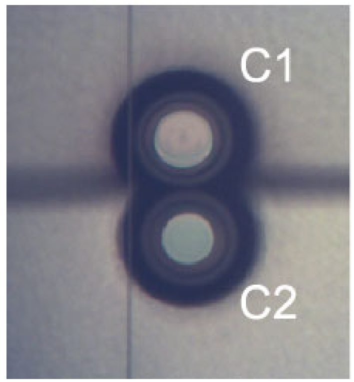
We achieved …

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



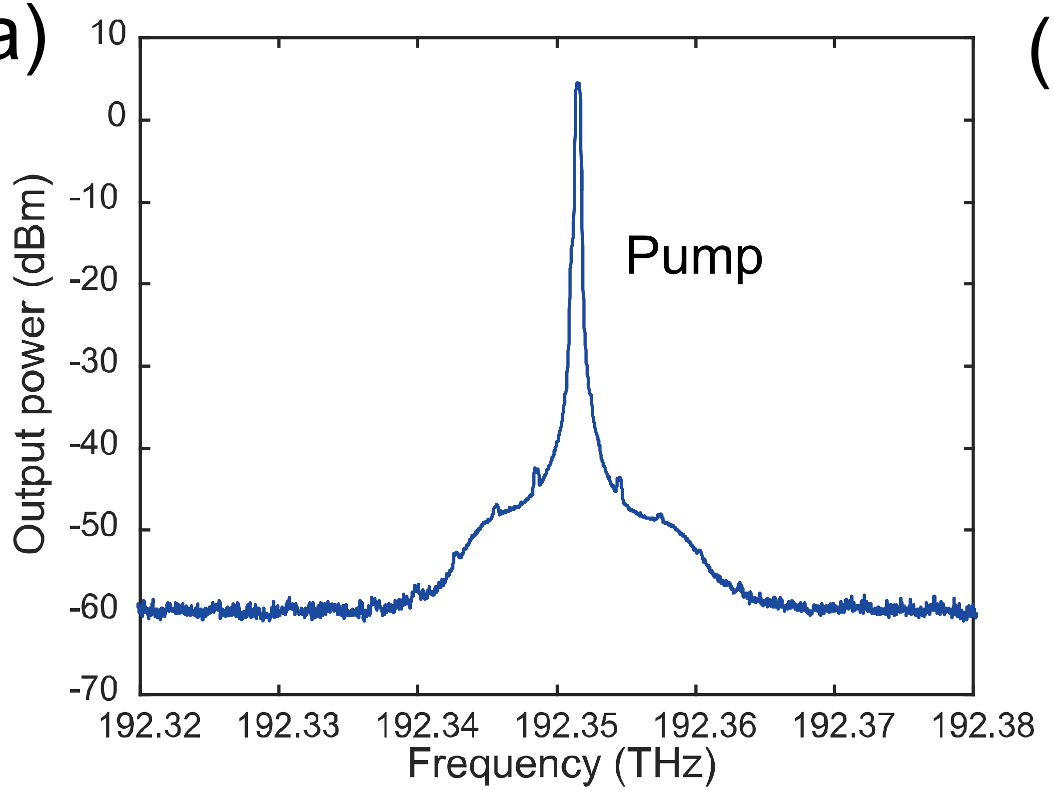
Experimental setup



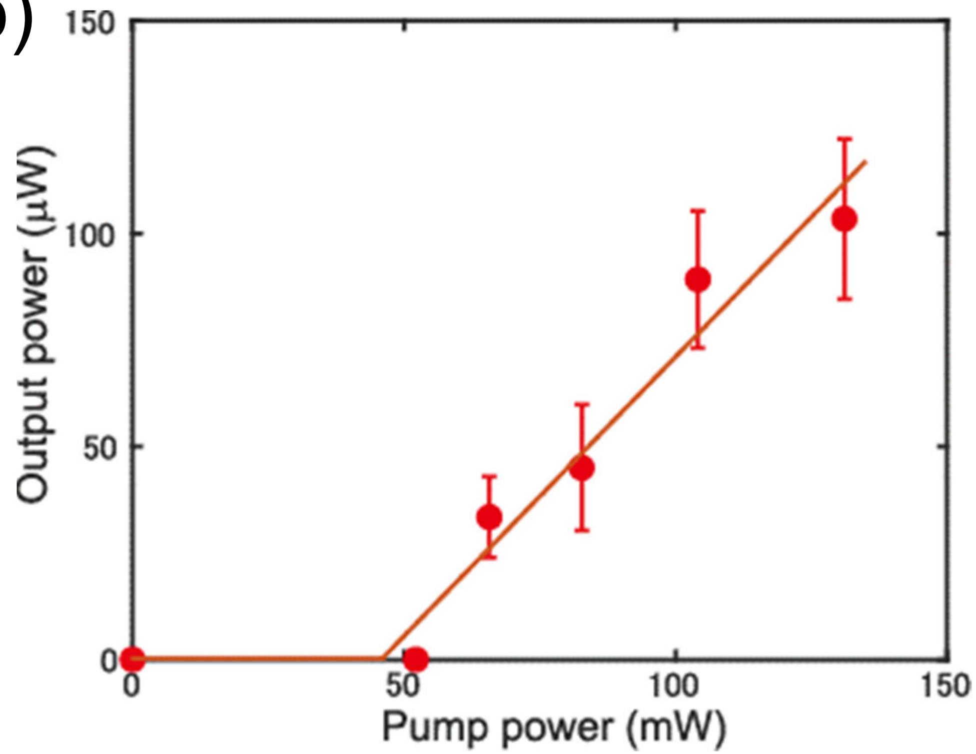


SBS in coupled cavities

(a)

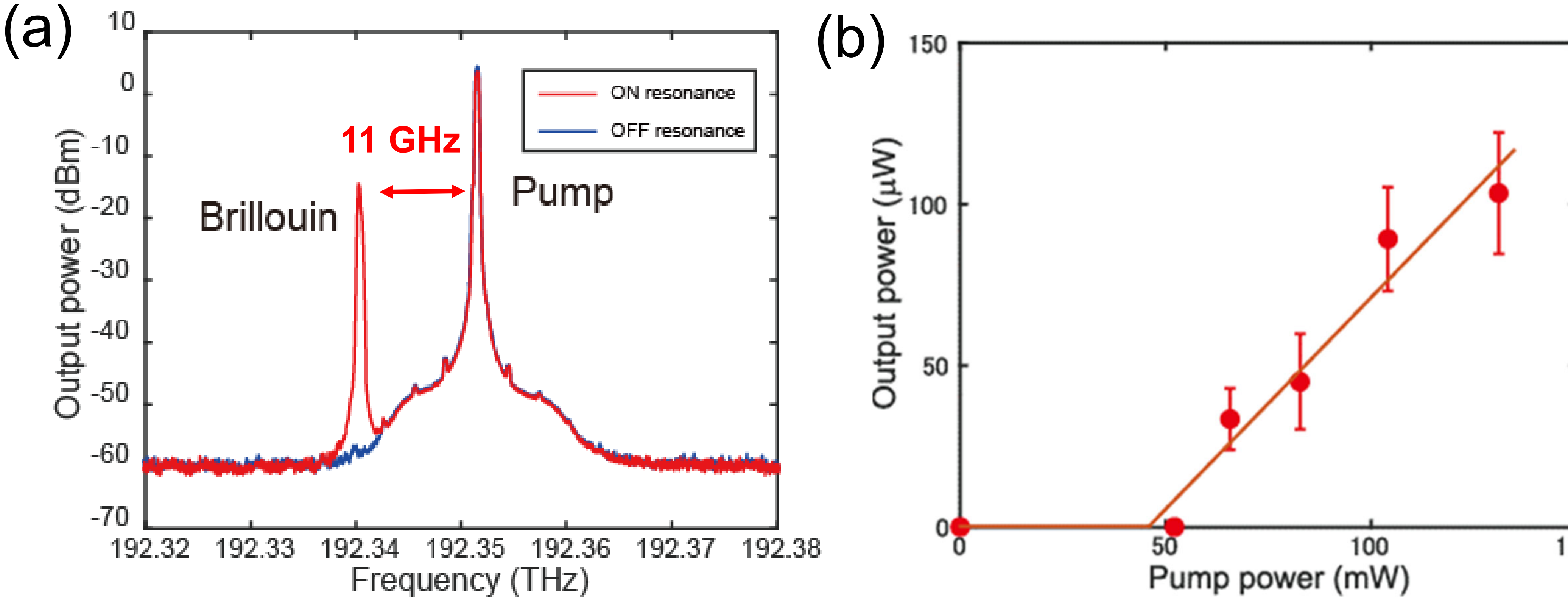


(b)



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

SBS in coupled cavities



- We experimentally demonstrated SBS in coupled microcavities for the first time.
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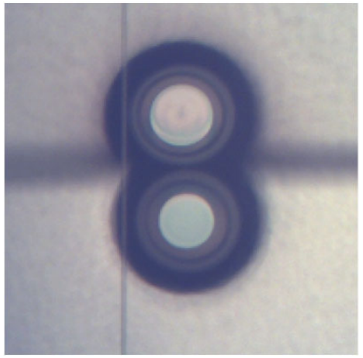
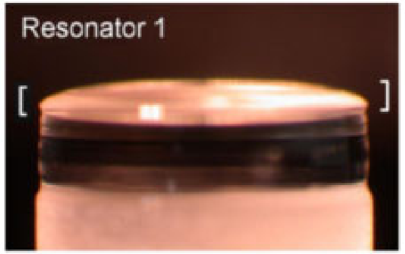
Comparison with other Brillouin lasing

Coupled silica toroid microcavities (This work)

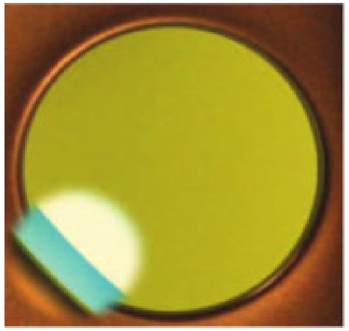


CaF_2 resonator



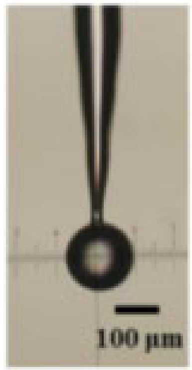
I. S. Grudinin et al., PRL, 102.4, 043902 (2009)

Wedge resonator



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

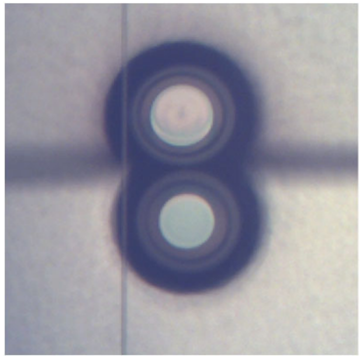
Microsphere



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	50 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
		 Resonator I. S. Grudinin		5)
Material	SiO_2			
Threshold power	500 μW			
Device size	110 μm			
Q	2×10^7	[illegible]	[illegible]	[illegible]
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 50 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)

Summary (for further reading)

1. Raman comb

R. Suzuki, A. Kubota, A. Hori, S. Fujii, and T. Tanabe, "Broadband gain induced Raman comb formation in a silica microresonator," J. Opt. Soc. Amer. B, Vol. 35, No. 4, pp. 933-938 (2018). (**Editor's pick**)

2. Brillouin laser

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**)

Acknowledgement

- The team

- Support

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