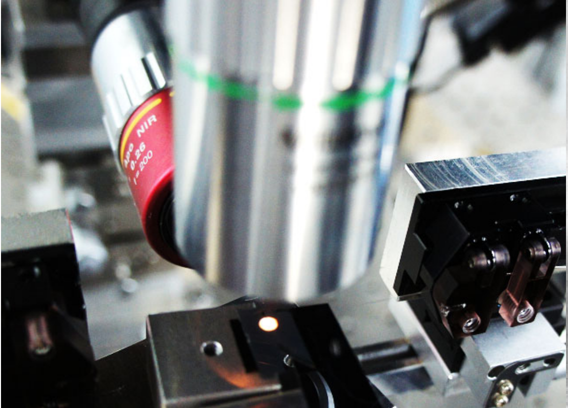
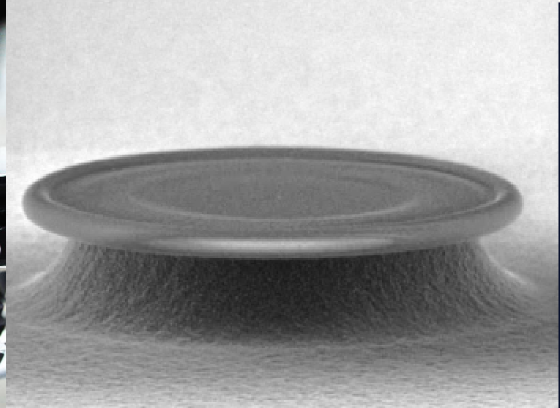
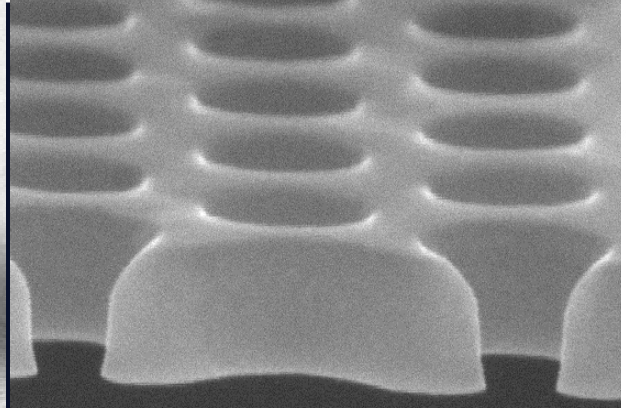
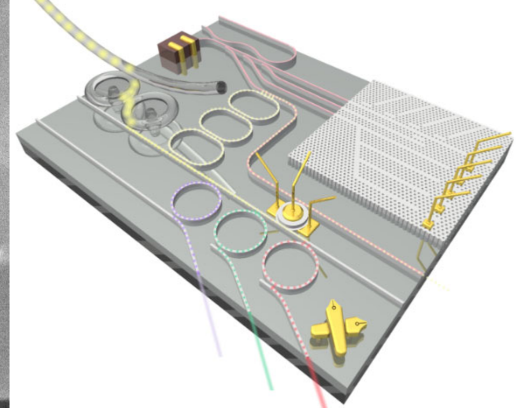


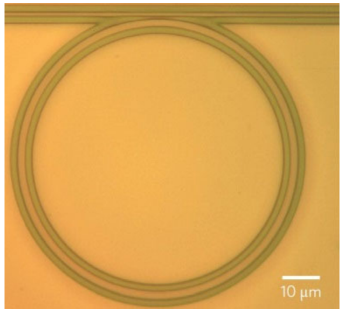
CLEO Pacific Rim
July 30, 2018, 16:00-16:25

Brillouin lasing in a coupled toroid microcavities system

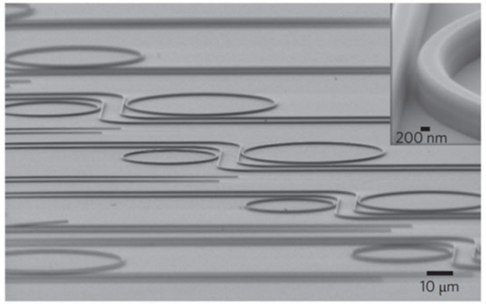
Takasumi Tanabe,
Yoshiki Wataru, and Yoshihiro Honda

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

High-Q whispering-gallery mode microcavities

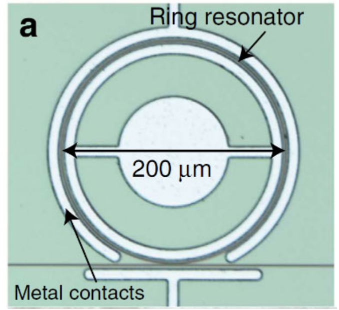


Silicon nitride
Weiner group (Purdue)

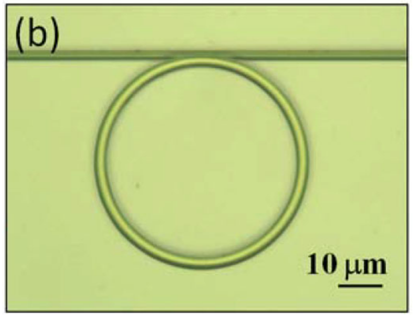


Diamond
Loncar group (Harvard)

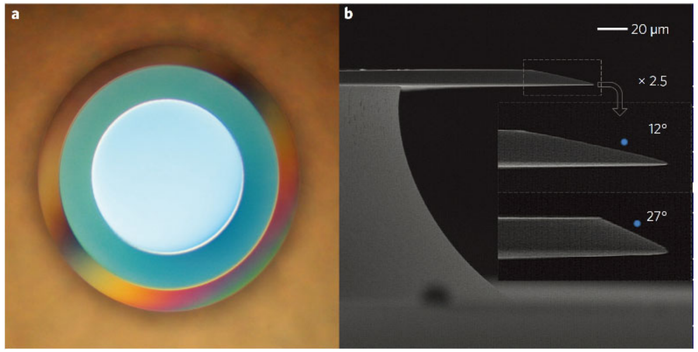
Crystalline (CaF_2, MgF_2, etc)
Kippenberg group (EPFL, Swiss),
Makei group (OE Waves)



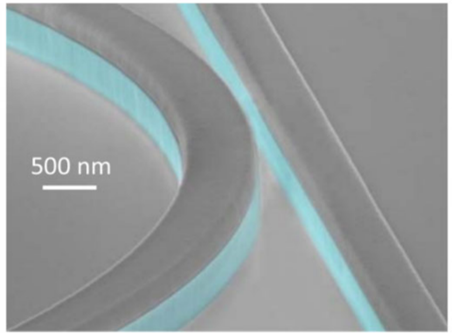
Silicon
Gaeta group (Columbia)



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

$$\propto Q/V$$

Outline

Applications of coupled cavities system:

1. Weak coupling: Photonic memory

   W. Yoshiki, Y. Honda, T. Tetsumoto, K. Furusawa, N. Sekine and T. Tanabe, “All-optical tunable buffering with coupled ultra-high Q whispering gallery mode microcavities,” Sci. Rep. Vol. 7, 10688 (8 pages) (2017).

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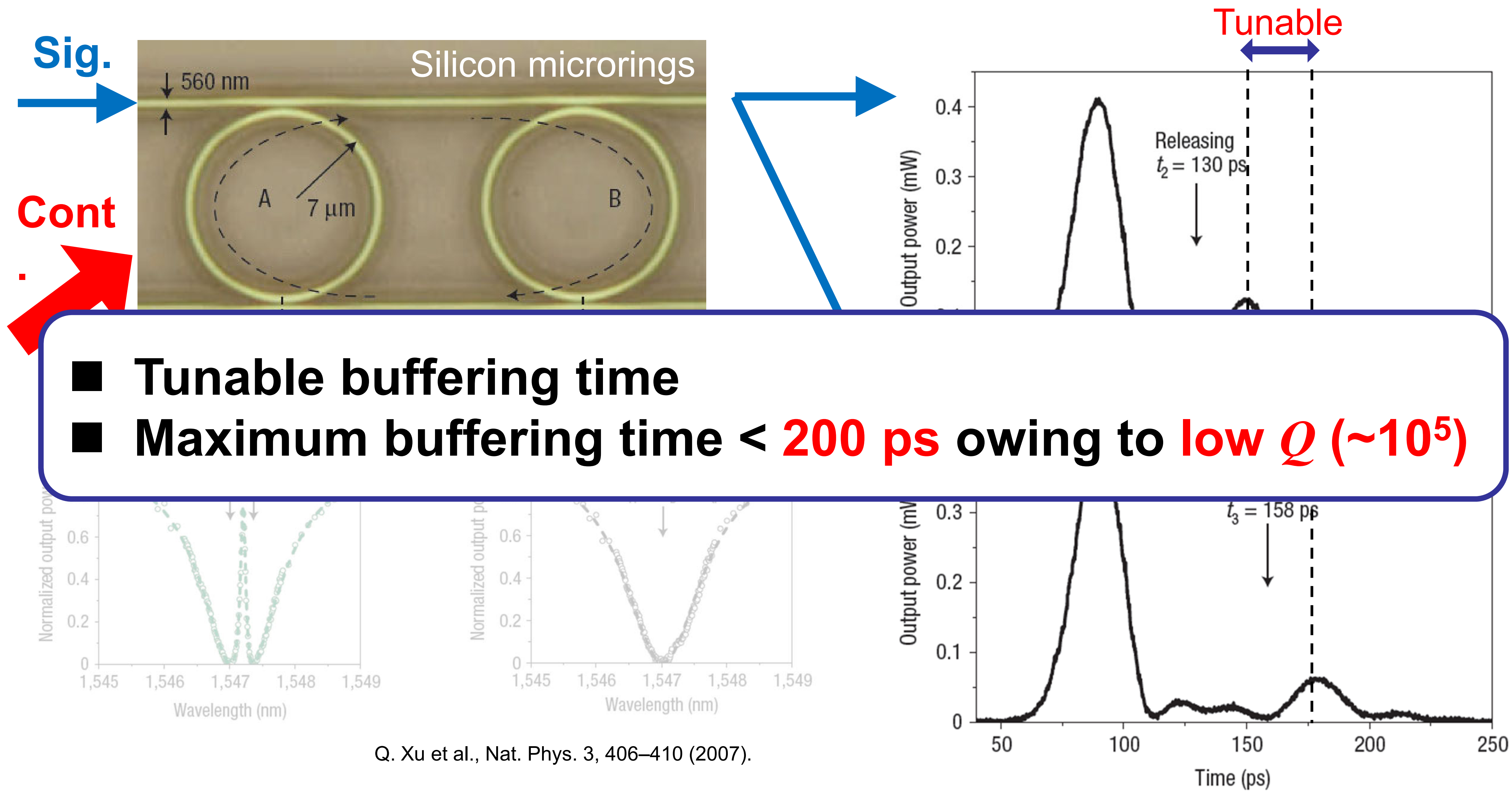
   Y. Honda, W. Yoshiki, T. Tetsumoto, S. Fujii, K. Furusawa, N. Sekine, and T. Tanabe, “Brillouin lasing in coupled silica toroid microcavities,” Appl. Phys. Lett., Vol. 112, 201105 (5 pages) (2018). (**Featured Article**) (**Scilight**)

Dynamic tuning provides tunability

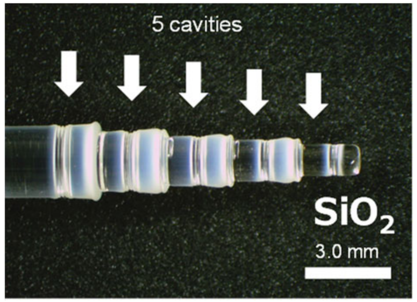


- **Tunable buffering time**
- **Maximum buffering time < 200 ps owing to low Q (~10^5)**

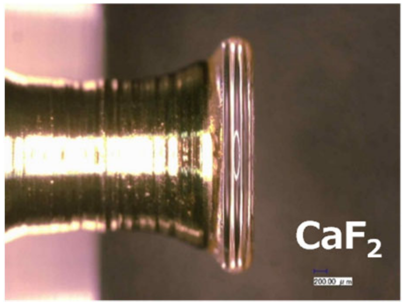
Q. Xu et al., Nat. Phys. 3, 406–410 (2007).

Whispering gallery mode cavity

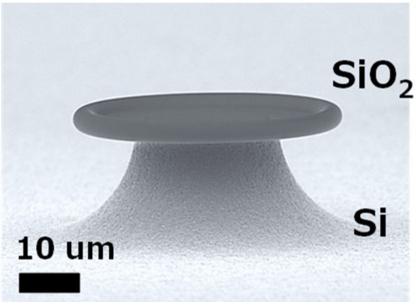
● Whispering gallery mode cavities



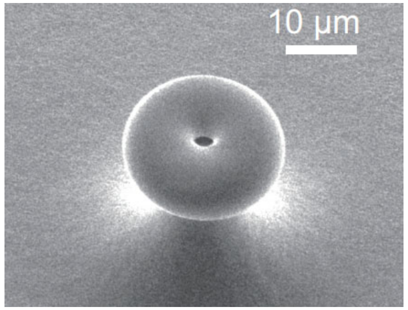
Silica rod (Q>10^8)



CaF_2 disk (Q>10^{10})

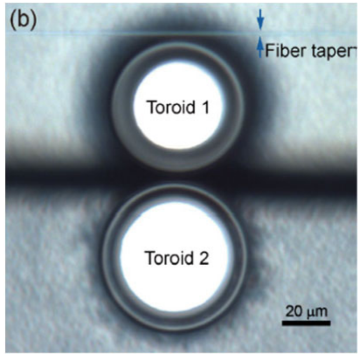


Silica toroid (Q>10^8)

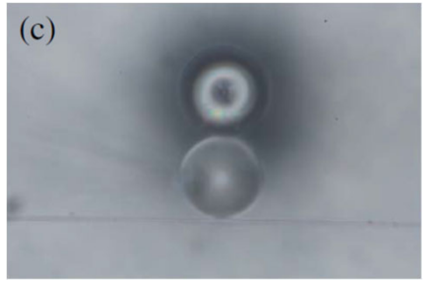


Silica sphere (Q>10^8)

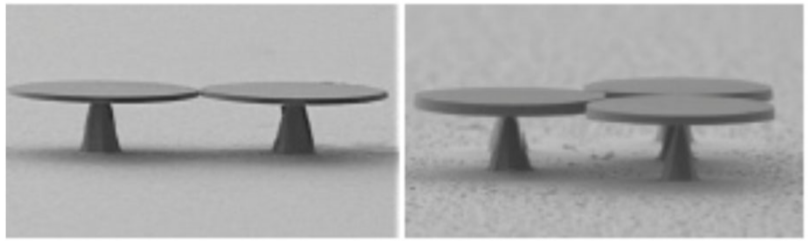
CRIT



C. Zheng *et al.*, Opt. Express 20, 18319–18325 (2012).



B. Peng *et al.*, Opt. Lett. 37, 3435-3437 (2012).



C. Schmidt *et al.*, Phys. Rev. A 85, 033827 (2012).

● Tuning methods

- Thermo-optic tuning
  (e.g. Armani et al., Appl. Phys. Lett. 22, 5439- (2004))
- Pressure tuning
  (e.g. Ilchenko et al., Opt. Commun. 145, 68- (1998))

Slow response > 1 μs

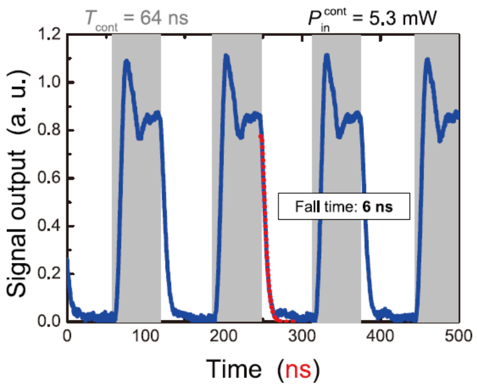
Objective

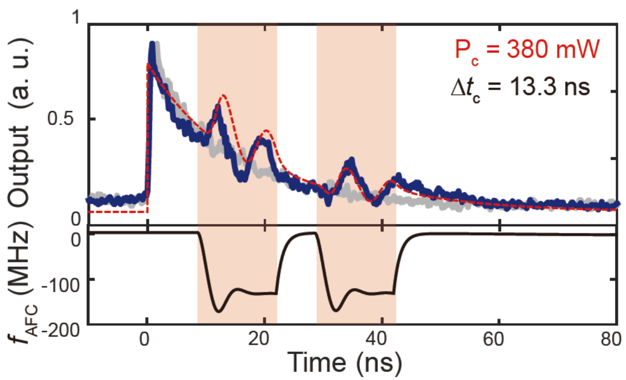
To achieve all-optical tunable buffering using the Kerr effect in coupled ultra-high-*Q* silica toroid microcavities

Kerr effect

- Changes refractive index **instantaneously**.
- Employed for **all-optical switching** and **frequency conversion**.

W. Yoshiki & T. Tanabe, Opt. Express 22, 24332-24341(2014).
W. Yoshiki, T. Tanabe et al., Opt. Lett., 41, 5482-5485 (2016).

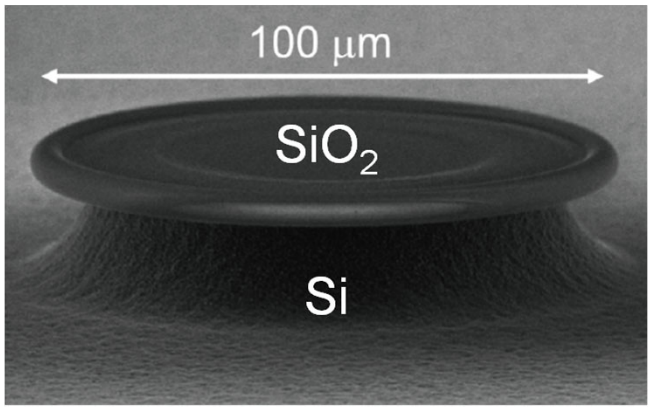




Silica toroid microcavity

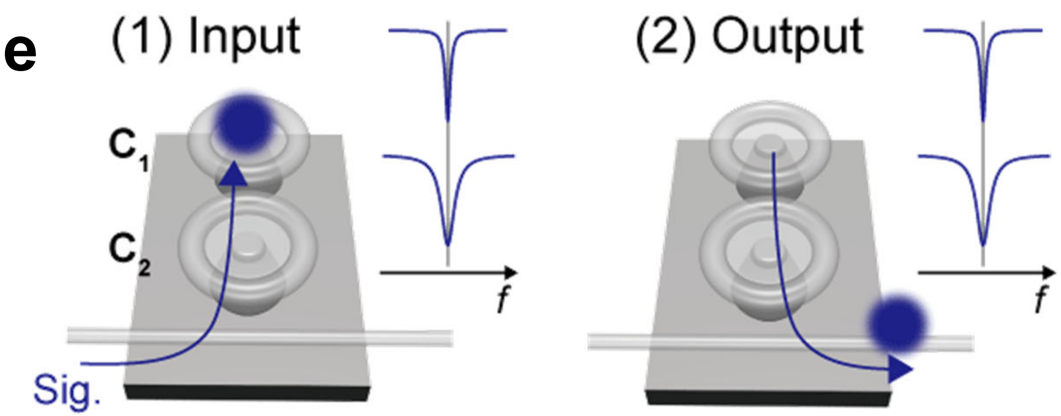
- Ultra-high *Q* factor (~4 x 10^8)
- Small mode volume (~ 200 μm^3)
- On-chip fabrication

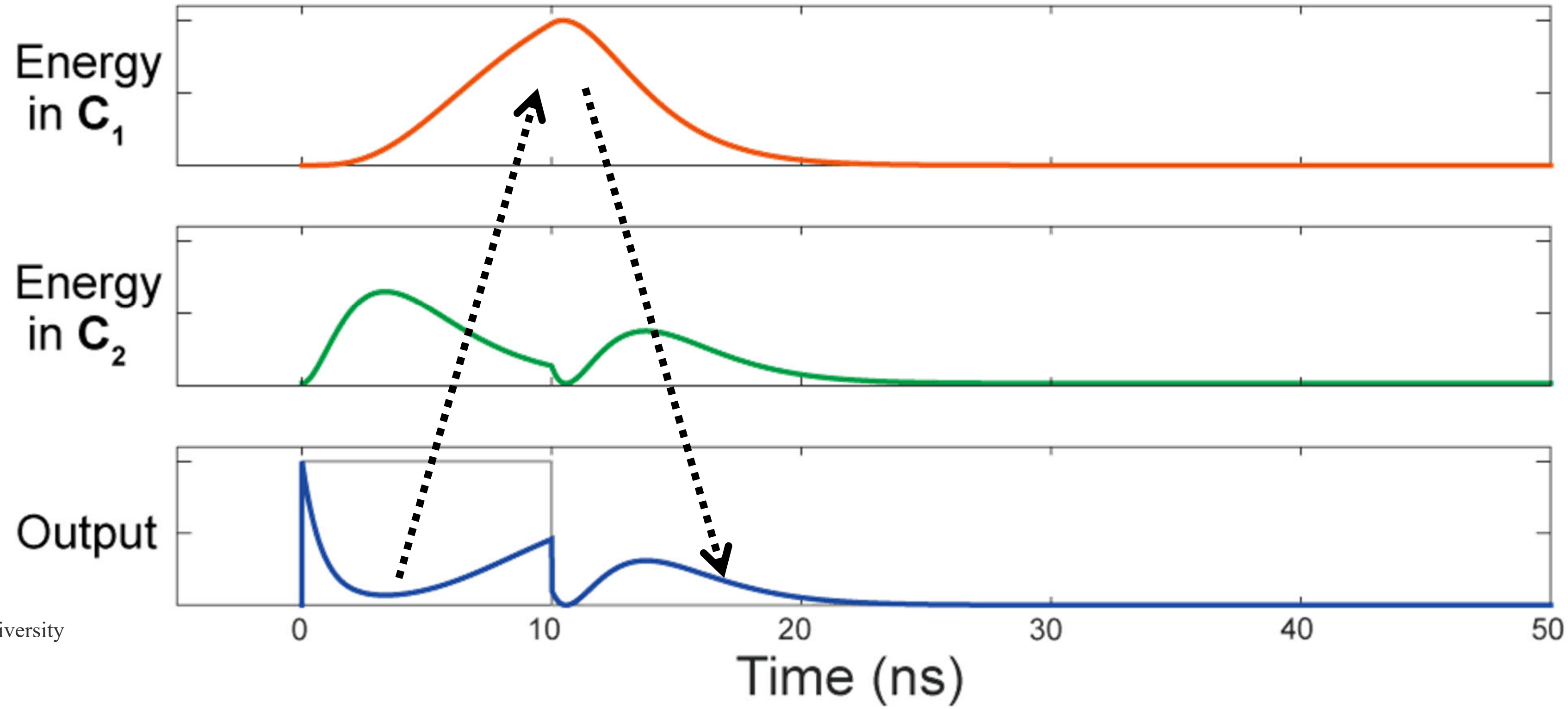
T. Kippenberg et al., Appl. Phys. Lett. **85**, 6113 (2004).



Introduction: All-optical “tunable” buffering

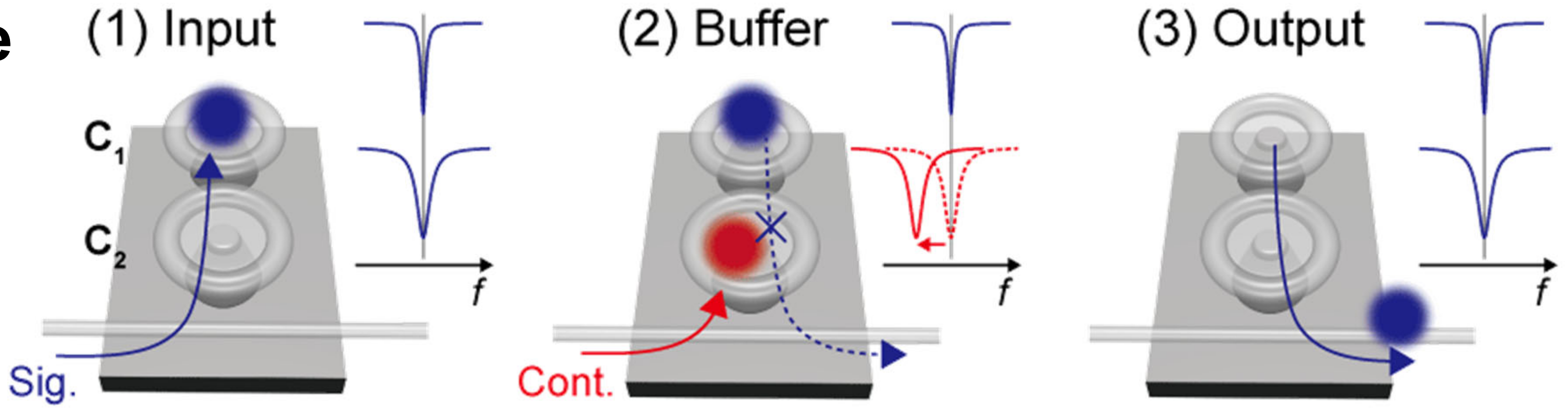
- **Principle**

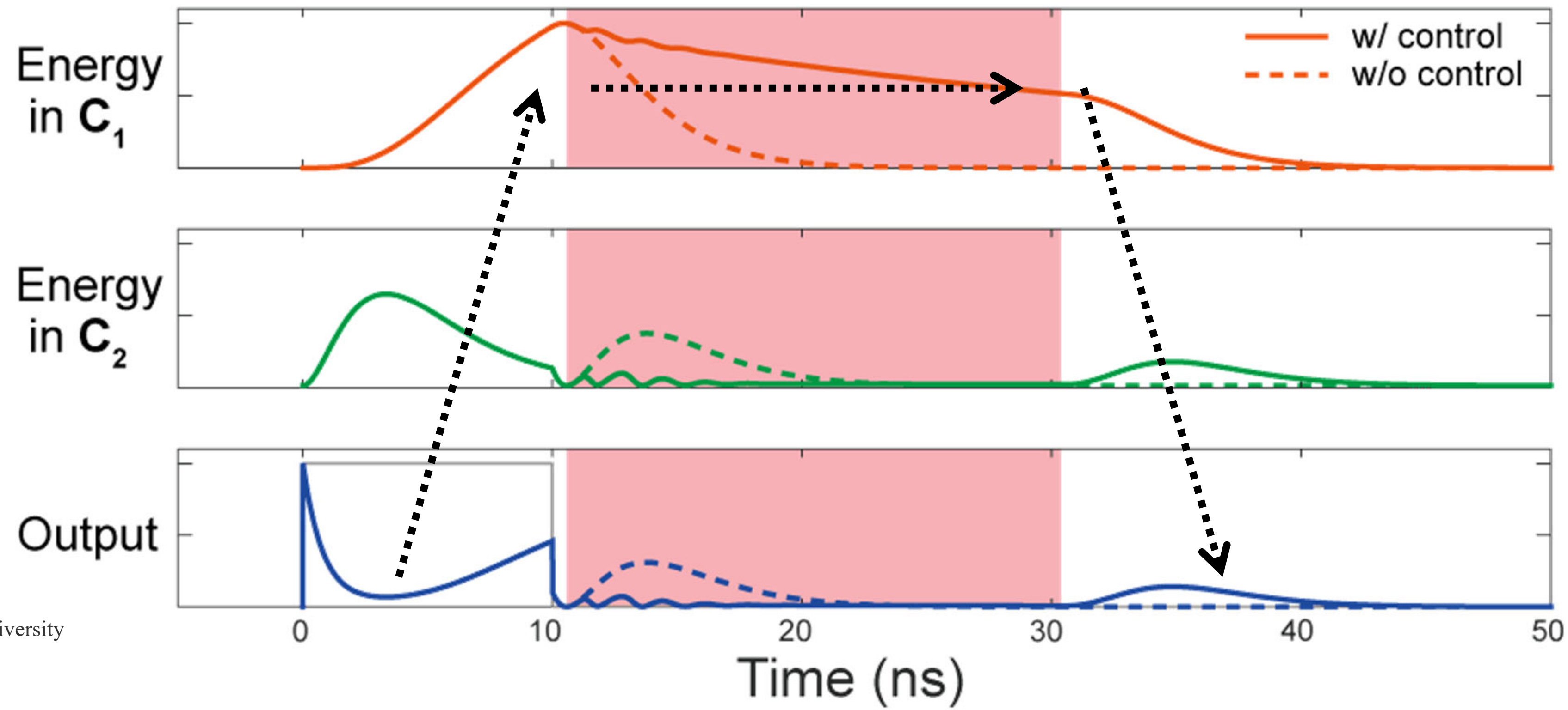




Introduction: All-optical "tunable" buffering

- **Principle**

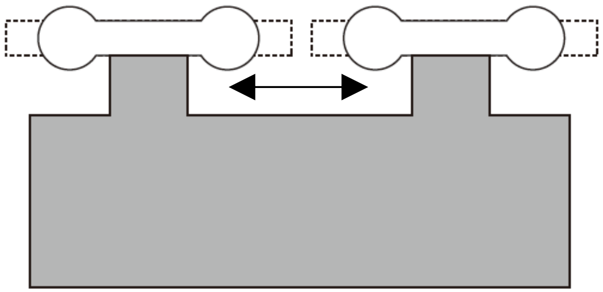




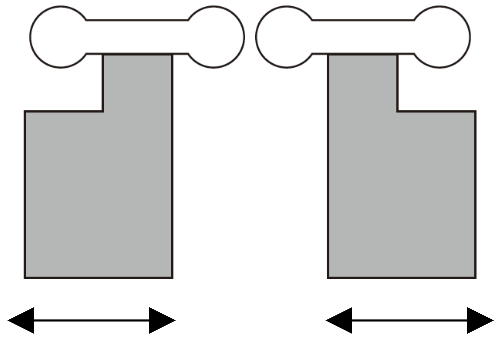
Device preparation

Silica toroid microcavity on an edge

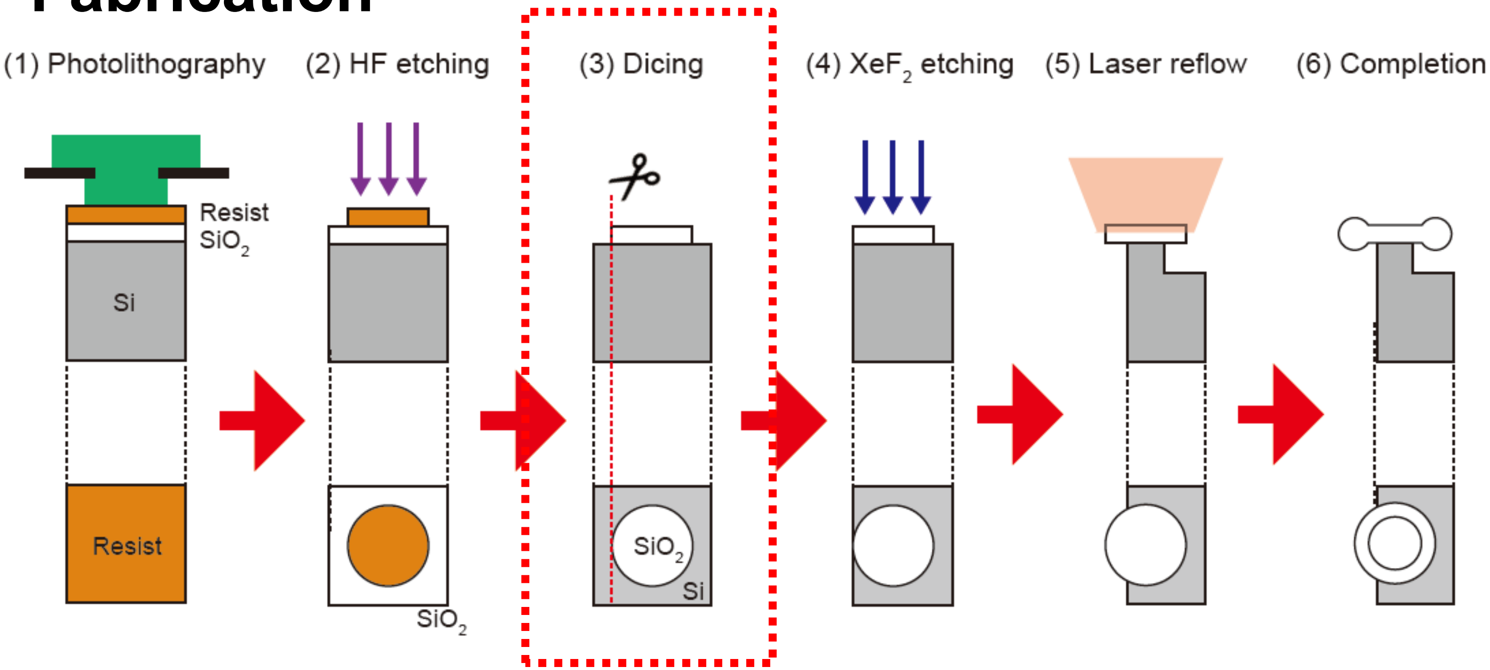
- Shrinkage owing to laser reflow

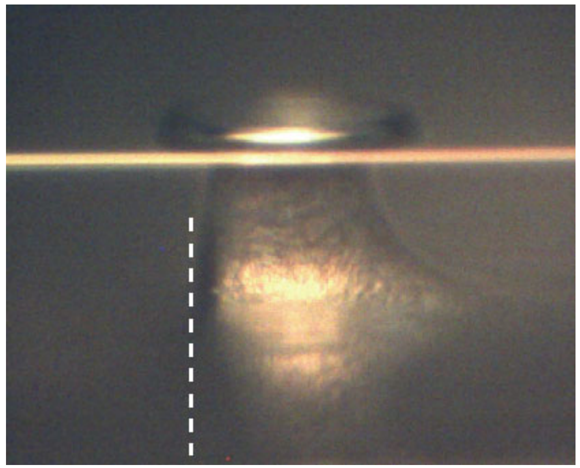


- Use of edge silica toroid microcavity



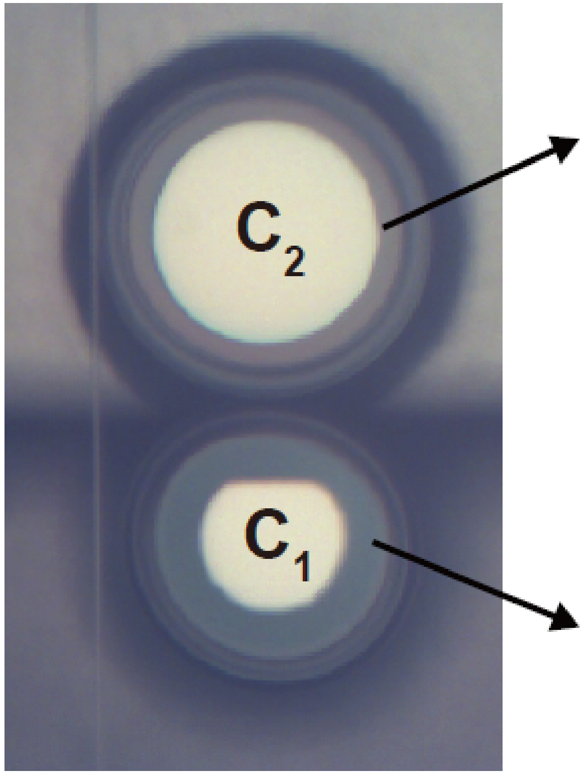
Fabrication

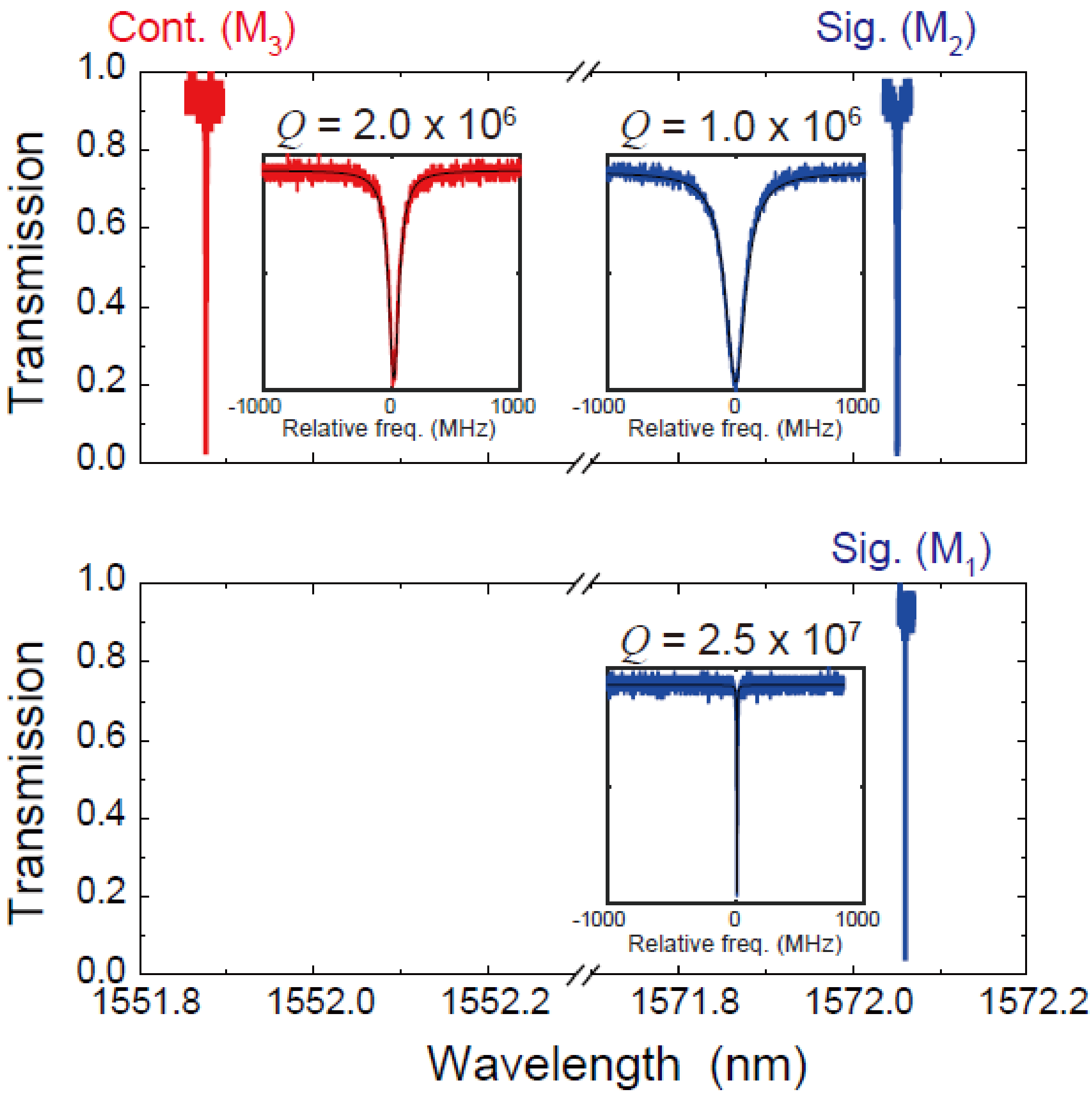




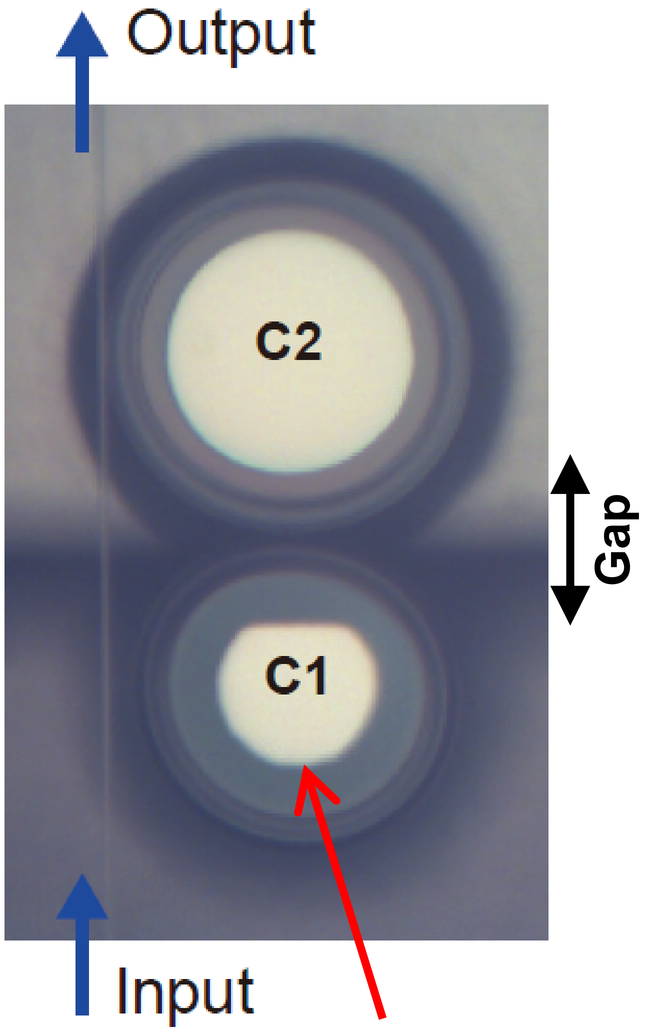
Optical modes employed for experiments

- Three modes: $\mathbf{M_1}$, $\mathbf{M_2}$ (**signal**) and $\mathbf{M_3}$ (control).
- $\mathbf{M_1}$: ultra-high Q (~2.5 x10^7)
- $\mathbf{M_2}$ & $\mathbf{M_3}$: moderate Q (~10^6)

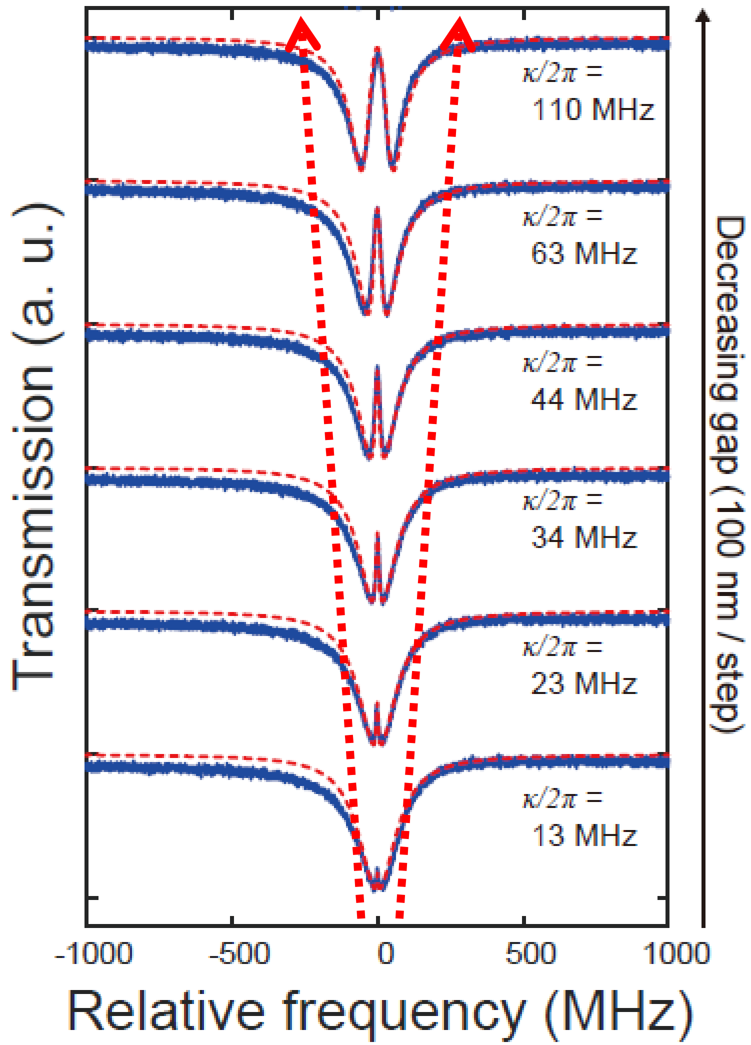




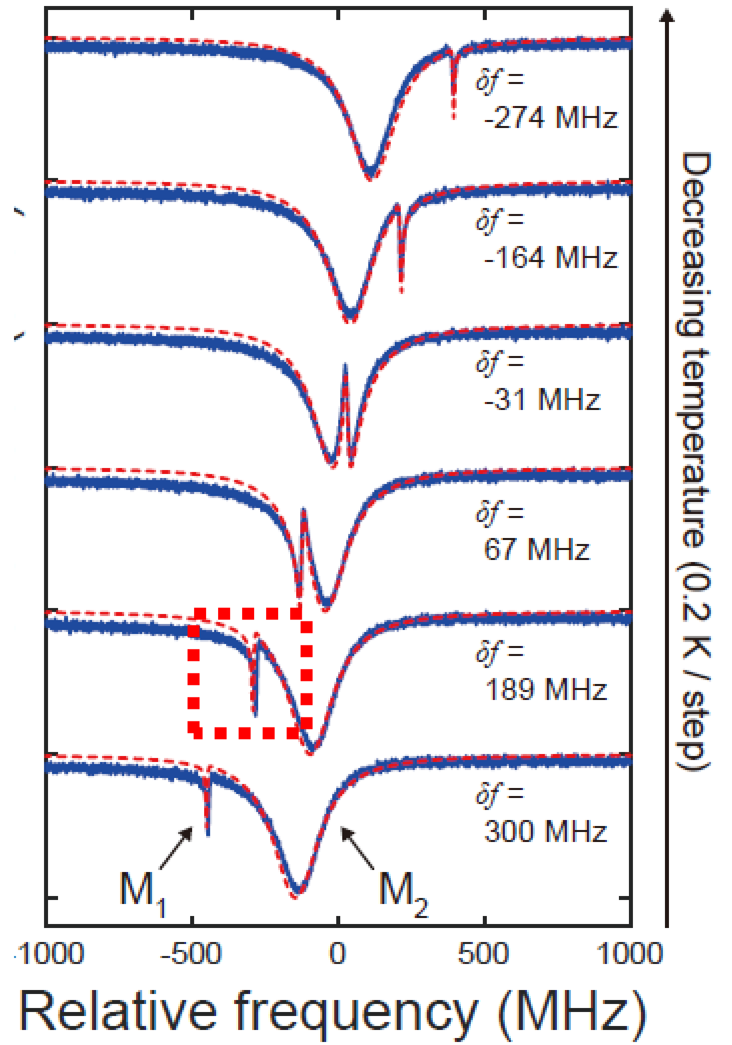
Observation of coupling



● Different gap

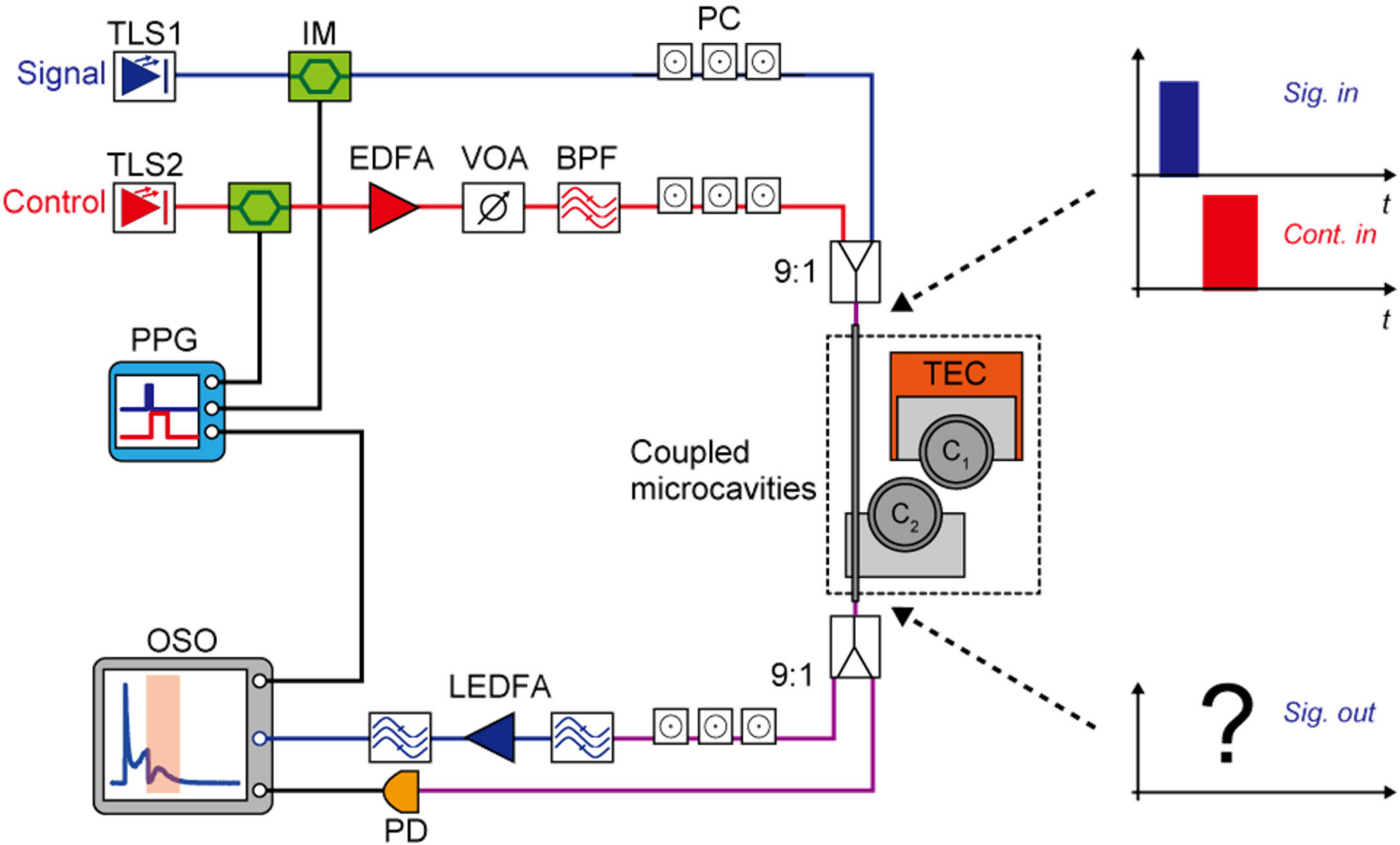


● Different temperature



Temp. change

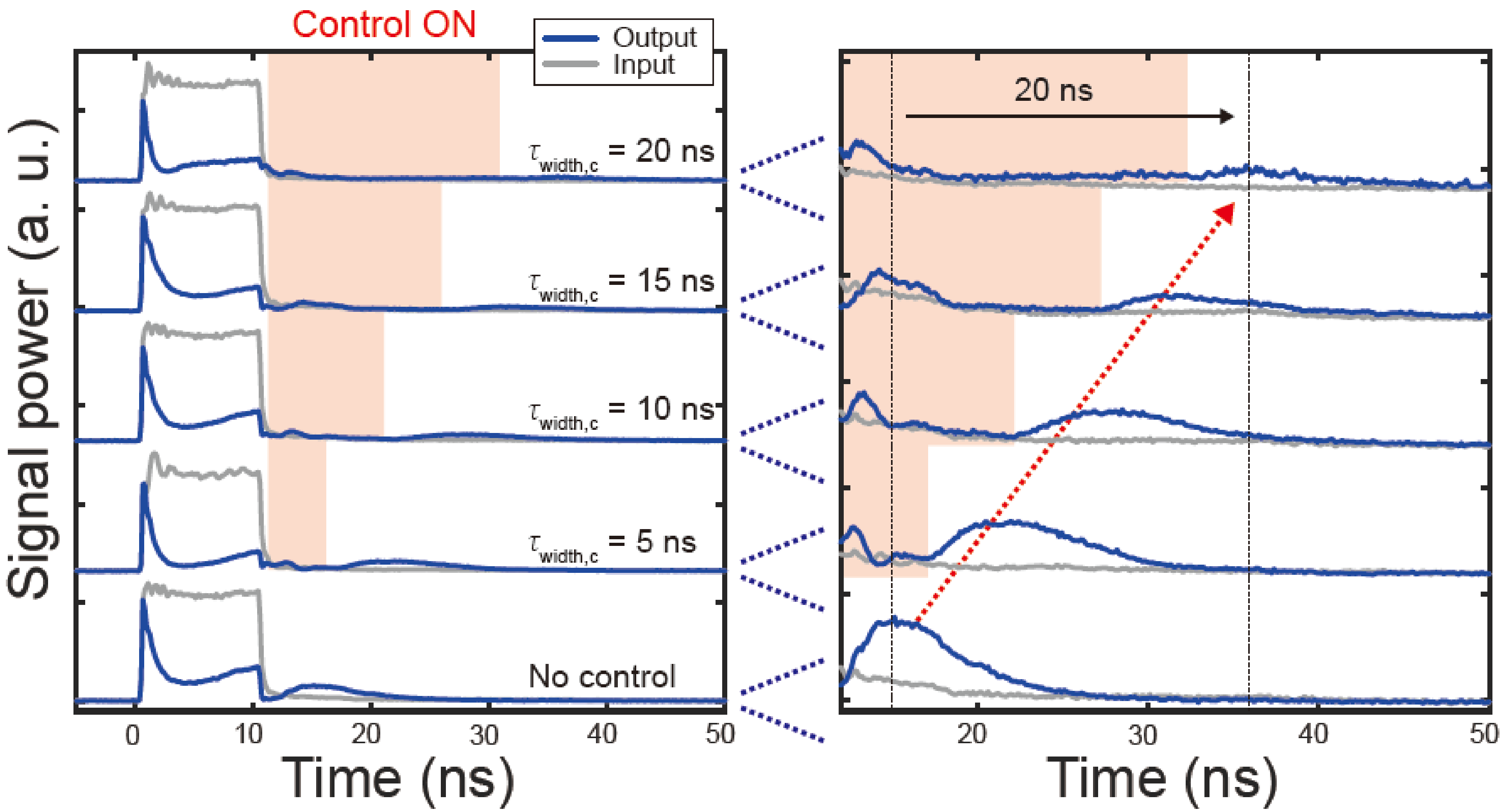
Experimental setup



TLS: Tunable laser source / **IM**: Intensity modulator / **EDFA**: Erbium-doped fiber amplifier
VOA: Variable optical attenuator / **BPF**: Band-pass filter / **PC**: Polarization controller
PD: Photodetector / **OSO**: Optical sampling oscilloscope / **PPG**: Pulse pattern generator

Experimental results (1)

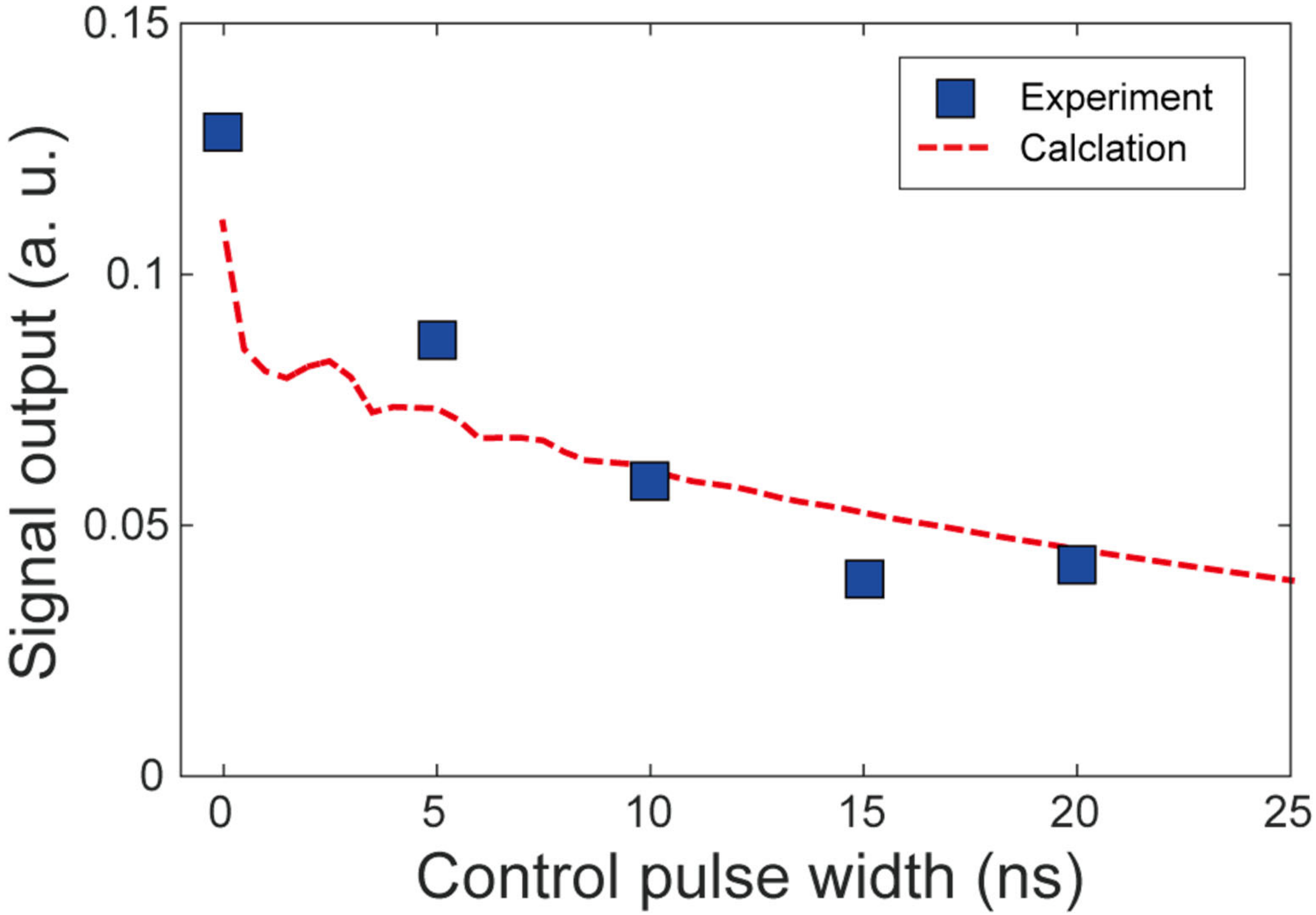
- **Buffering operation**

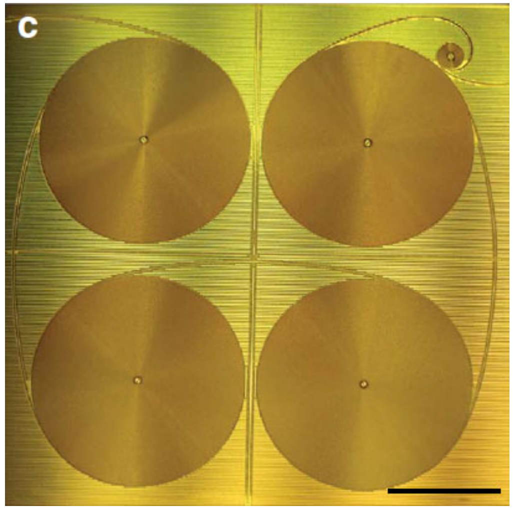


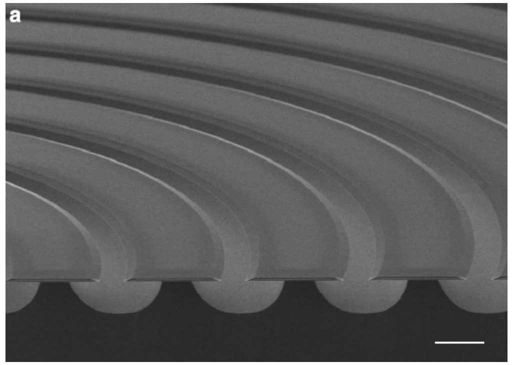
All-optical tunable buffering / 10-ns pulse buffered for 20 ns

Experimental results (2)

● Control pulse width vs Signal output







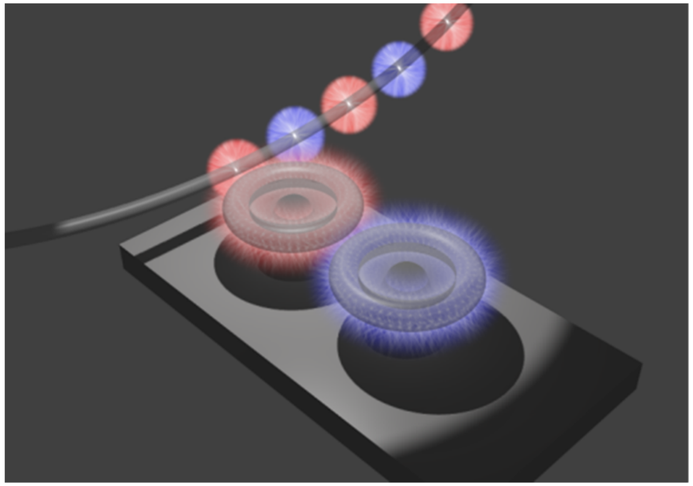
H. Lee et a., Nat. Commun. **3**, 867 (2012).

- Output efficiency: **~10%** (due to spectral mismatch)
- Equivalent light attenuation: **1.1 dB/m**

⟺ State-of-art "fixed" on-chip optical buffer: **~0.1 dB/m**

Summary

Achieved all-optical tunable buffering using the Kerr effect in coupled ultra-high-Q silica toroid microcavities



- **First attempt** to dynamically control CMIT w/ ultra-high Q WGM cavities.
- **10-ns signal pulse** can be buffered for **20 ns**.

Outline

Applications of coupled cavities system:

1. Weak coupling: Photonic memory

   W. Yoshiki, Y. Honda, T. Tetsumoto, K. Furusawa, N. Sekine and T. Tanabe, "All-optical tunable buffering with coupled ultra-high Q whispering gallery mode microcavities," Sci. Rep. Vol. 7, 10688 (8 pages) (2017).

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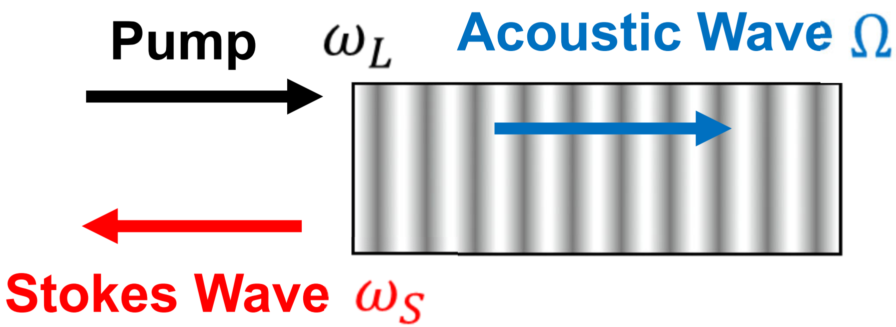
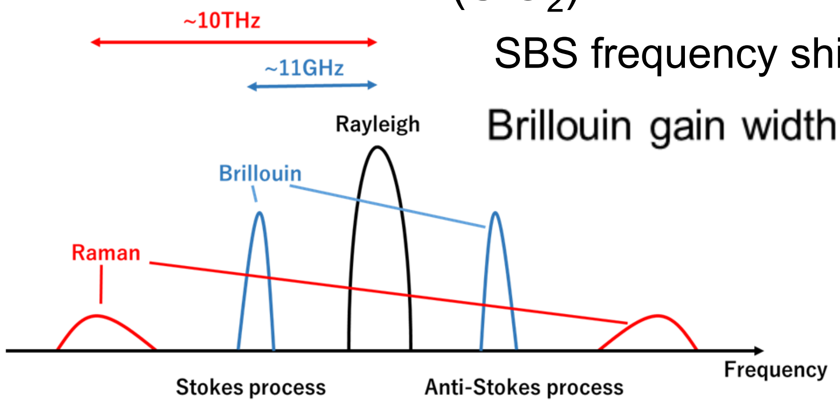
Stimulated Brillouin Scattering (SBS)

☐ Schematic representation of SBS process



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



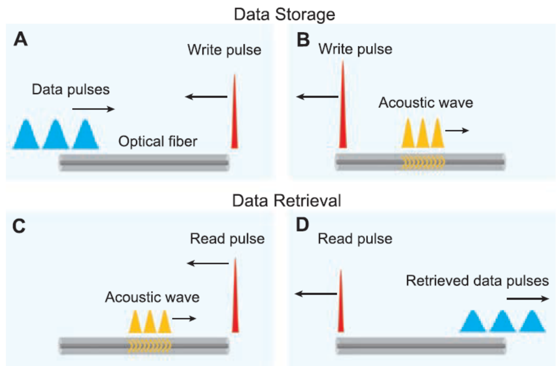
(SiO_2)

SBS frequency shift $\approx$ 11GHz

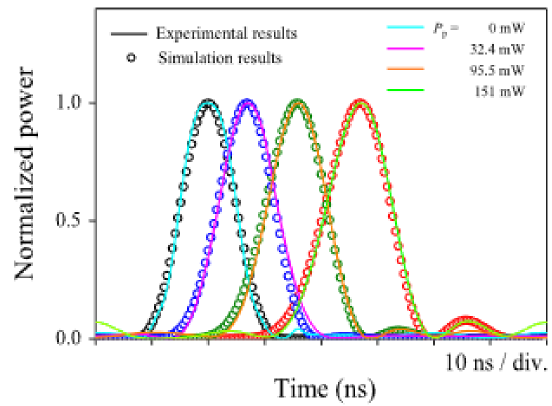
Brillouin gain width = ~50 MHz

☐ 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)

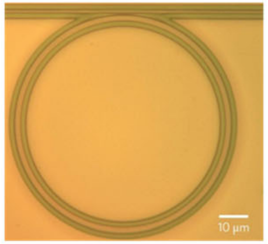
Microcavities

Crystalline (CaF_2)

$Q > 10^{10}$

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

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

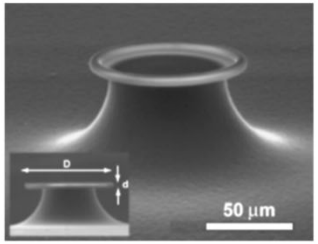


Si_3N_4 microring

$Q \approx 10^6$

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

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

S

Sto

Hz

Hz

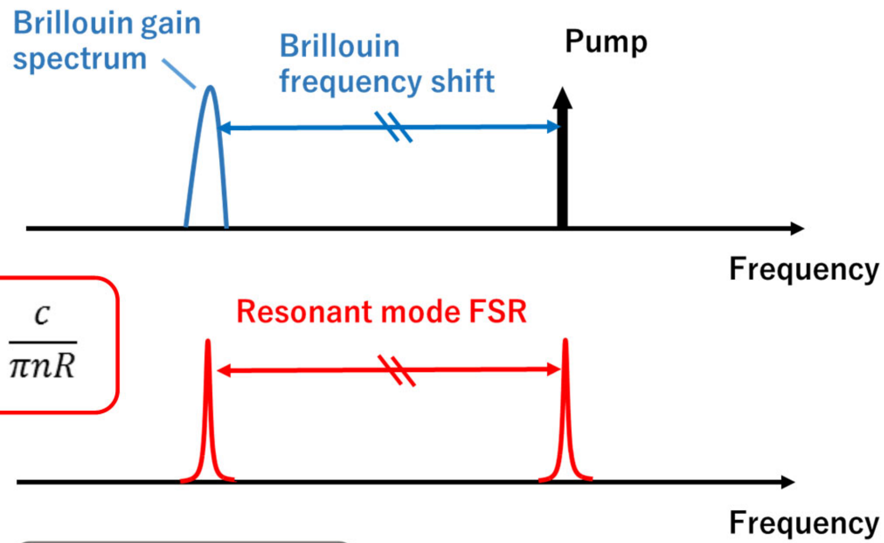
10 ns / div.

318, 1748-1750 (2007)

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

SBS in microcavities

Method1



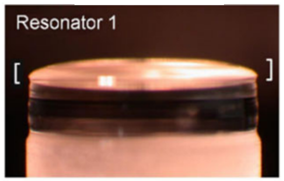
$$\nu_{FSR} = \frac{c}{\pi n R}$$

Brillouin frequency shift = Resonant mode FSR

↓

Brillouin lasing

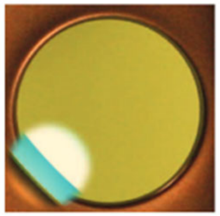
CaF_2



5.52 mm

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

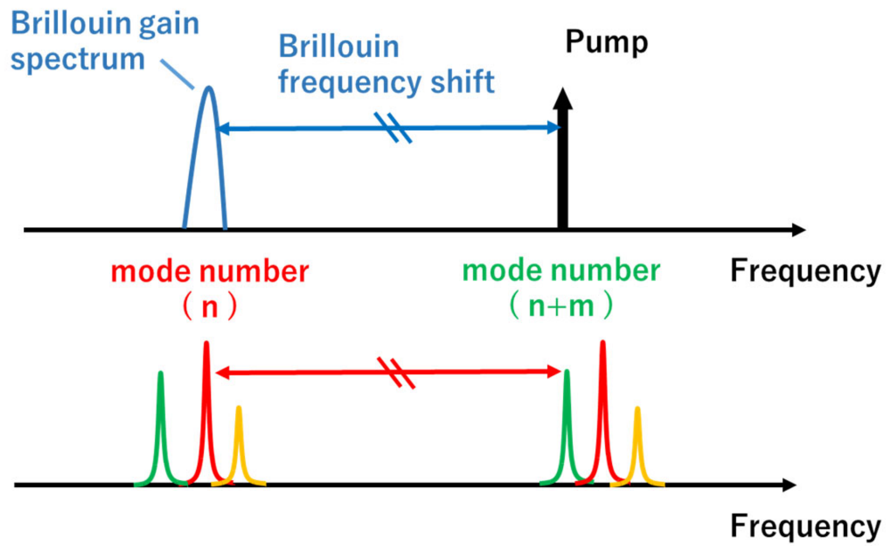
SiO_2



6.02 mm

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

Method2

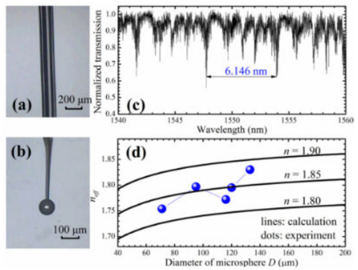


Brillouin frequency shift = High-order mode spacing

↓

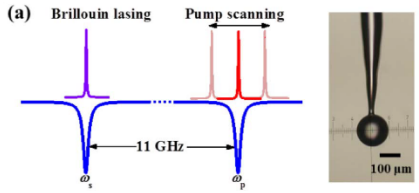
Brillouin lasing

TeO_2



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

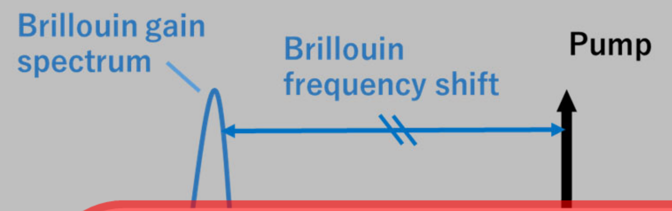
SiO_2



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

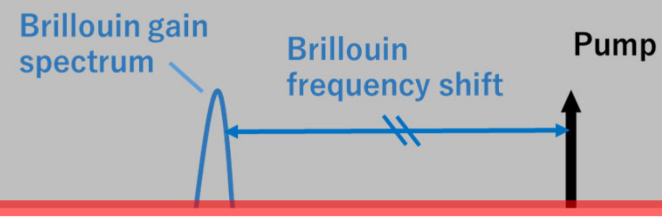
SBS in microcavities

Method1



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

Method2



Method1 &2

■ Precise control of cavity size

Brillouin lasing

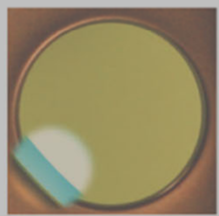
Brillouin lasing

CaF_2

5.52 mm

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

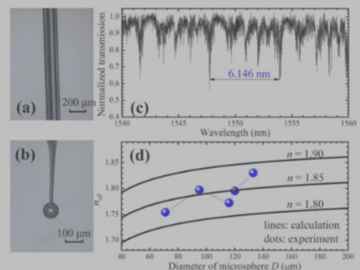
SiO_2



6.02 mm

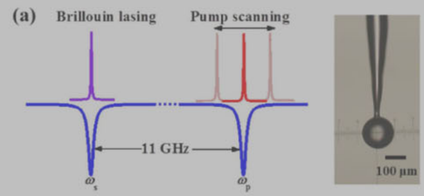
J. Li, K. Vahala et al., OE 20, 20170- (2012)

tellurite



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

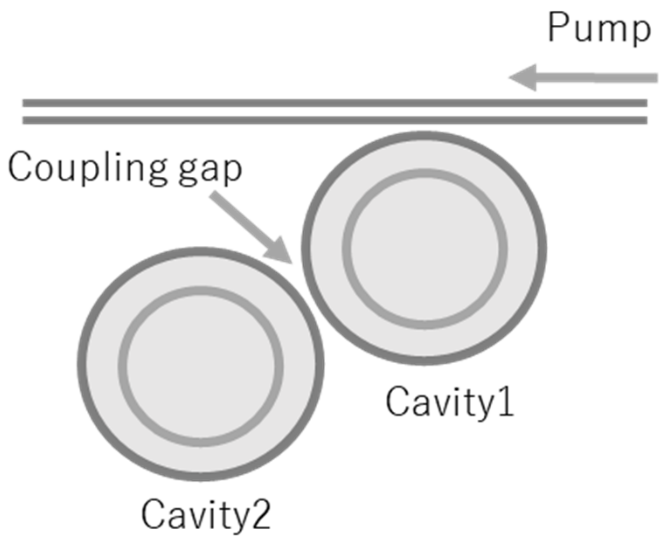
SiO_2

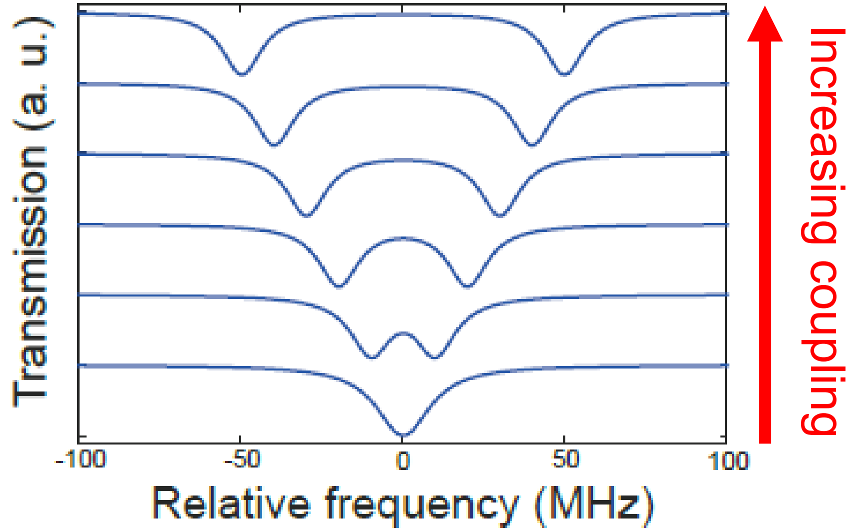


C. Guo, H. Xu et al., OL 40, 4971- (2015)

Objective

Our work





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

Tunable

Brillouin lasing

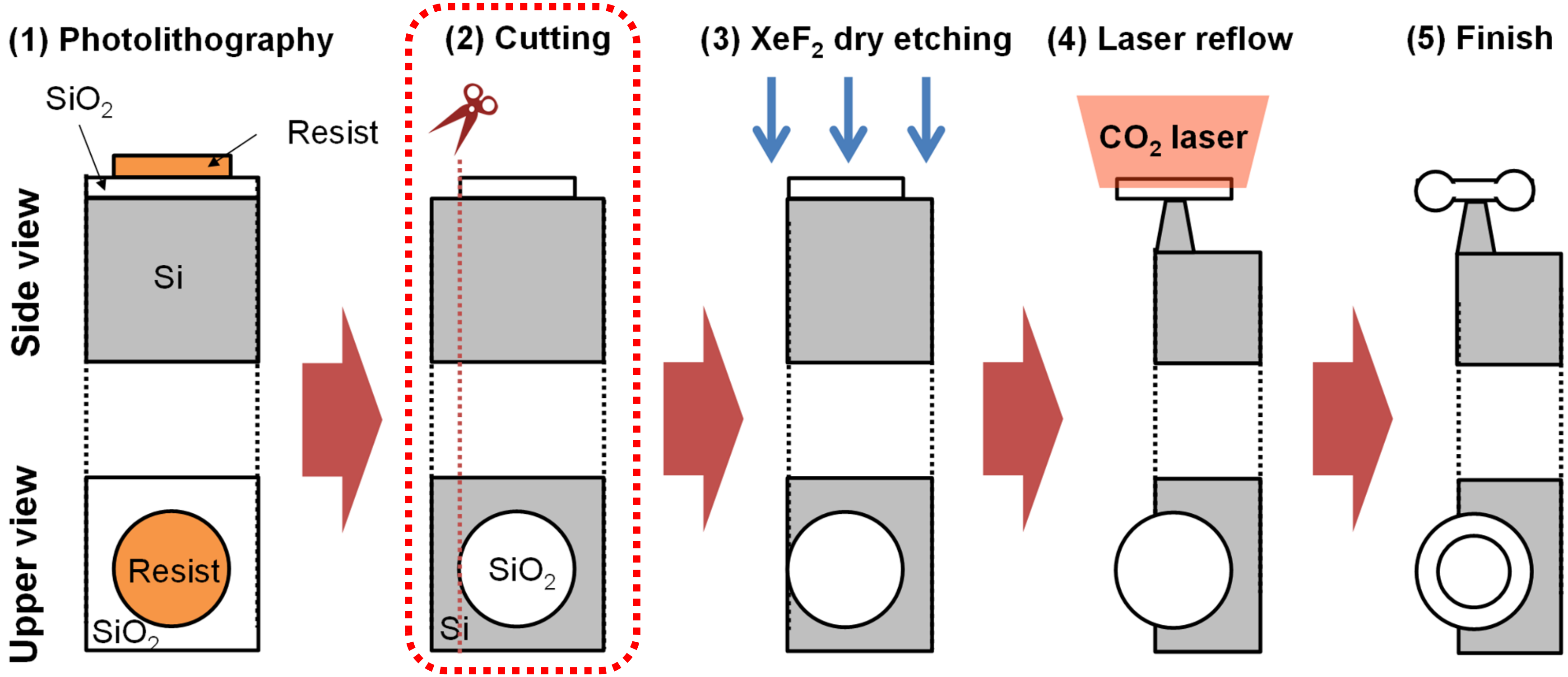
SBS in coupled microcavities ⇨

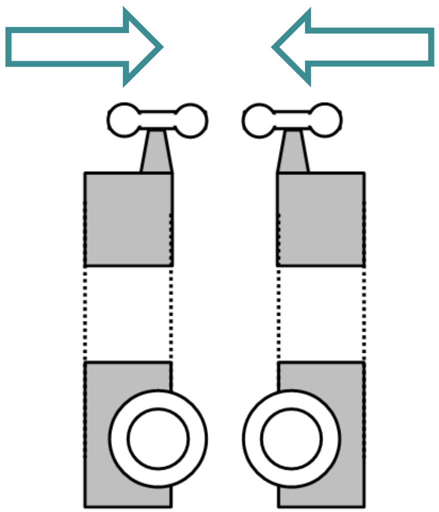
~~Precise size control~~

Low threshold

Small footprint

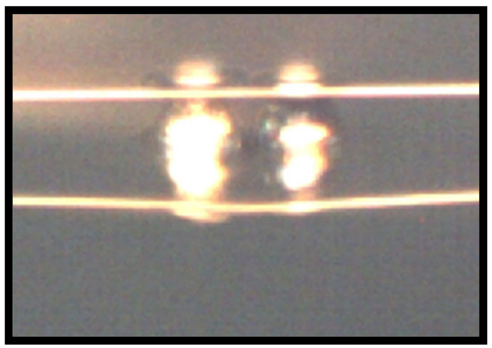
Silica toroid microcavities



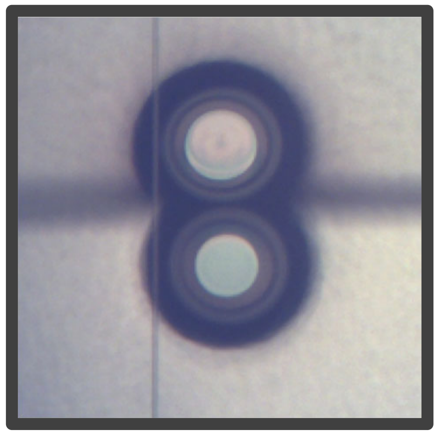


- **Precisely control coupling strength by changing distance between toroids**

Side View

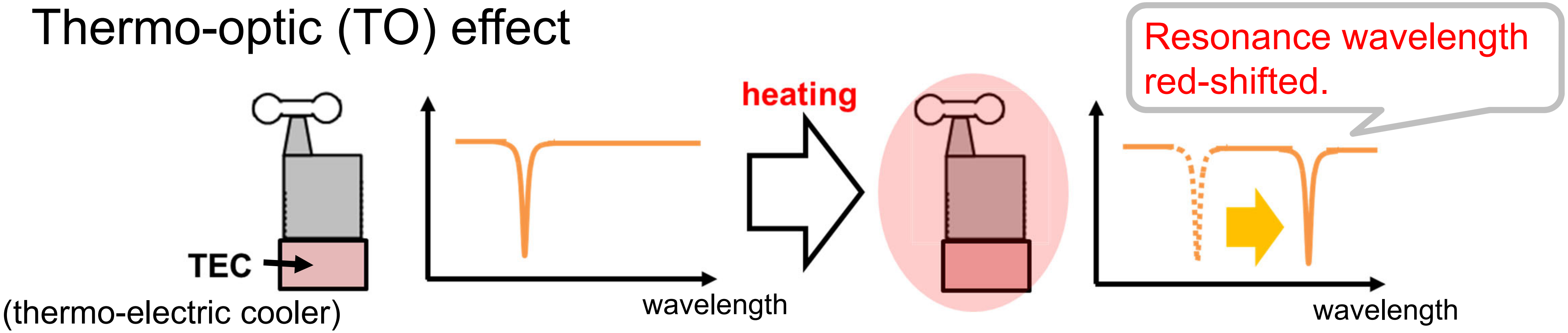


Top View



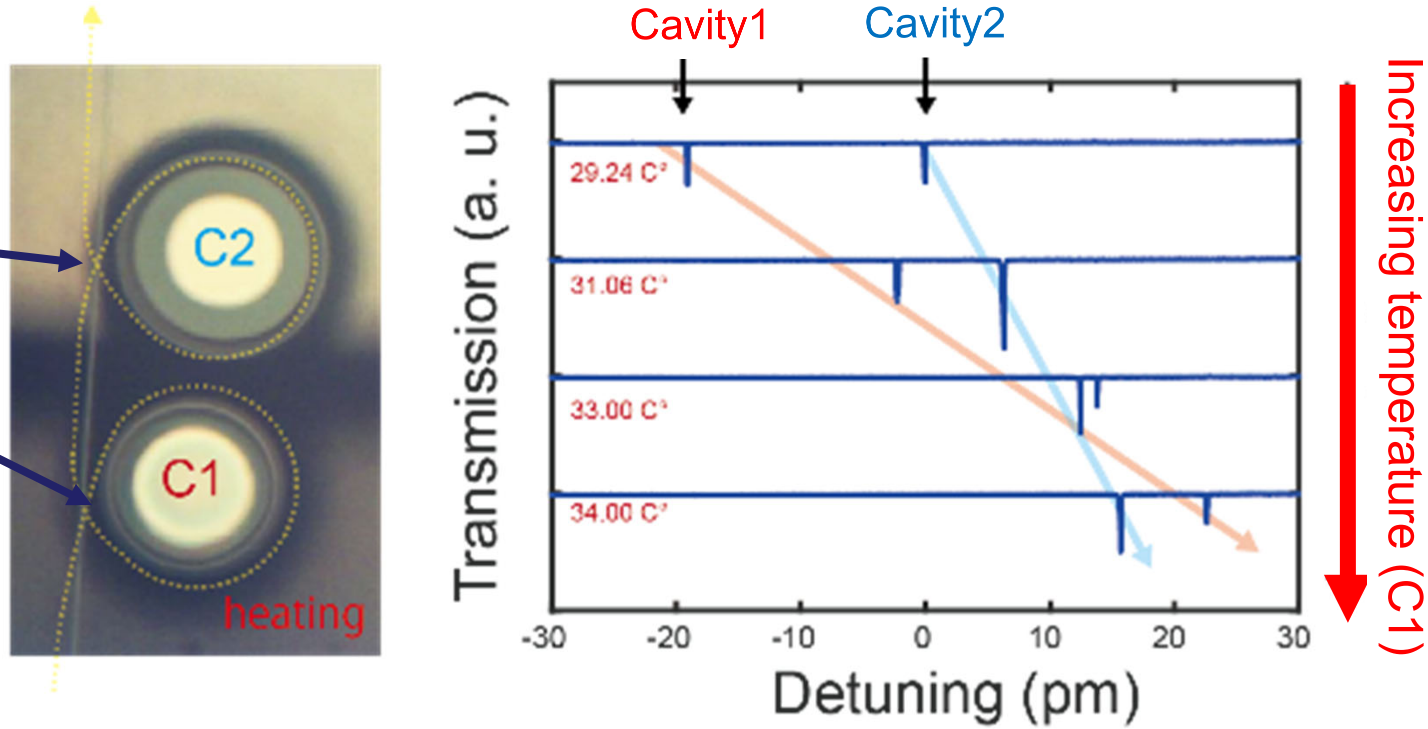
Tuning resonant frequency

- Thermo-optic (TO) effect



- Tuning two different resonant frequencies

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



Supermode splitting

Calculation

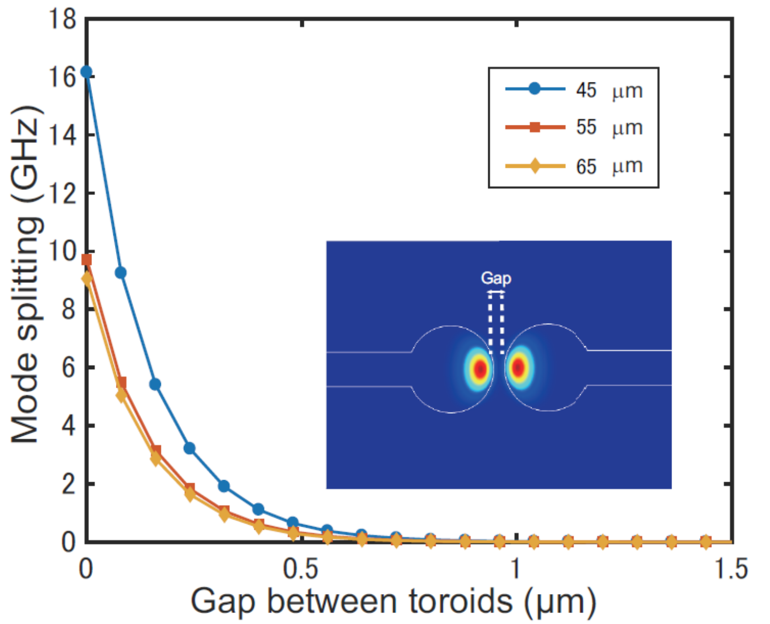
- **Mode overlap**
- **Phase matching condition**

} **Coupling coefficient**

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

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

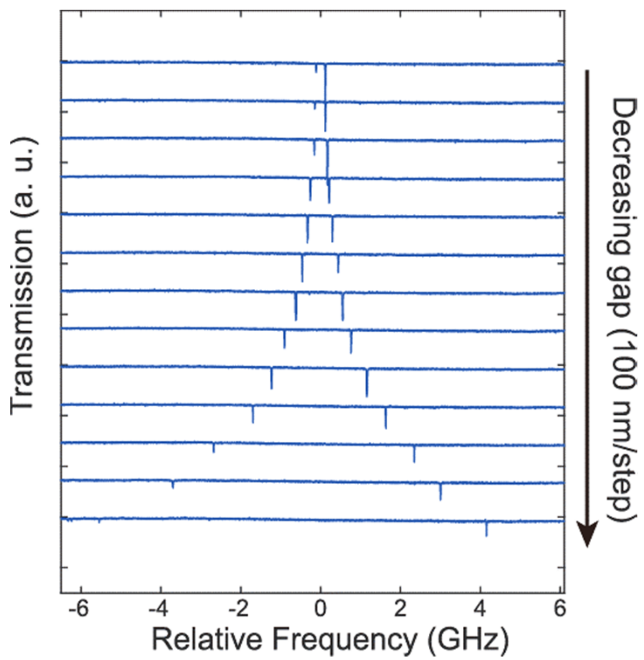
Fabricated 55-μm-diameter silica toroid

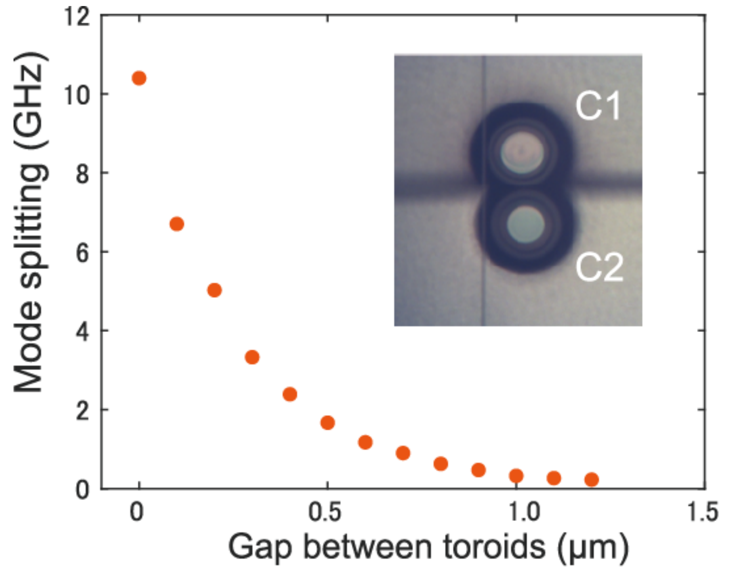
↓

Moved toroids close together

↓

Achieved more than 10GHz mode splitting

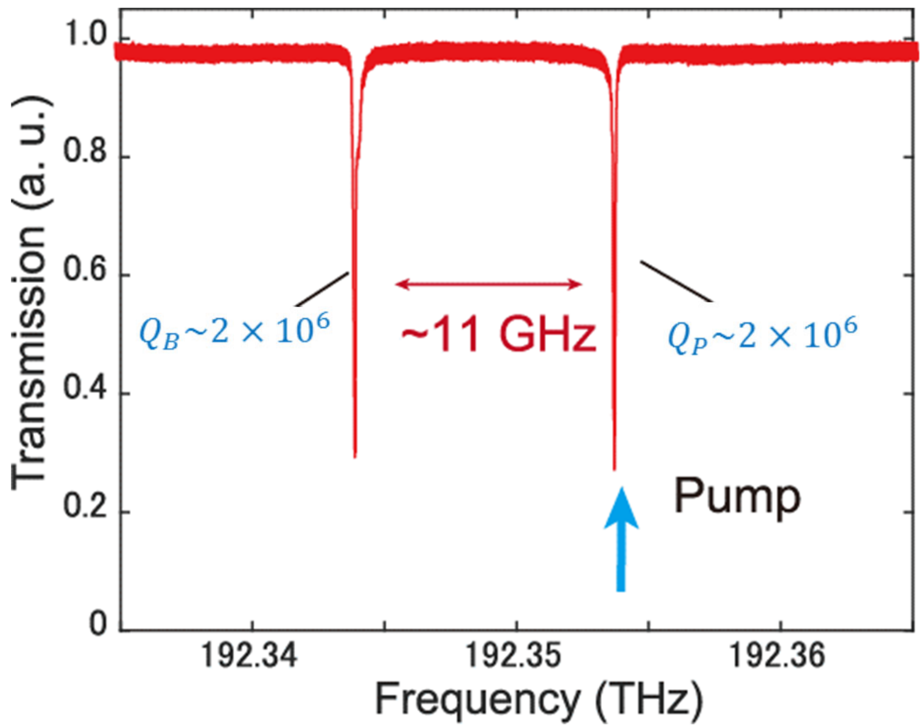




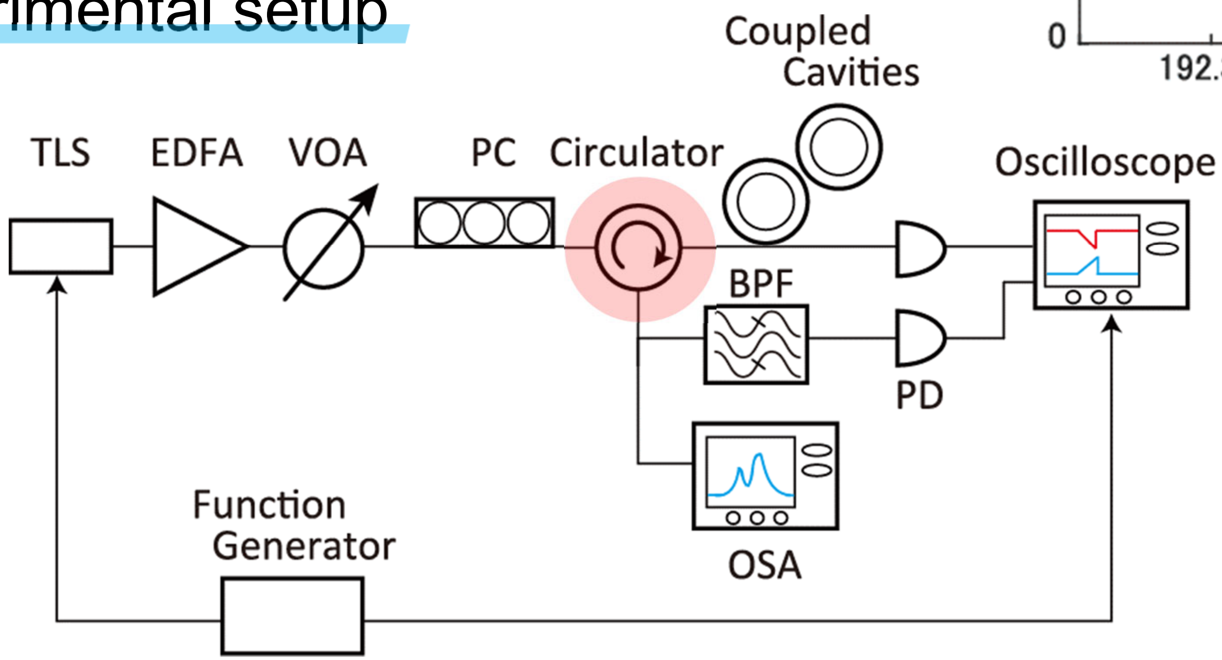
SBS in coupled cavities

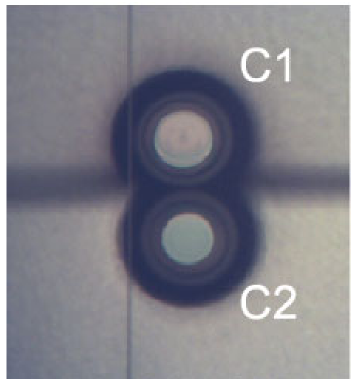
We achieved …

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

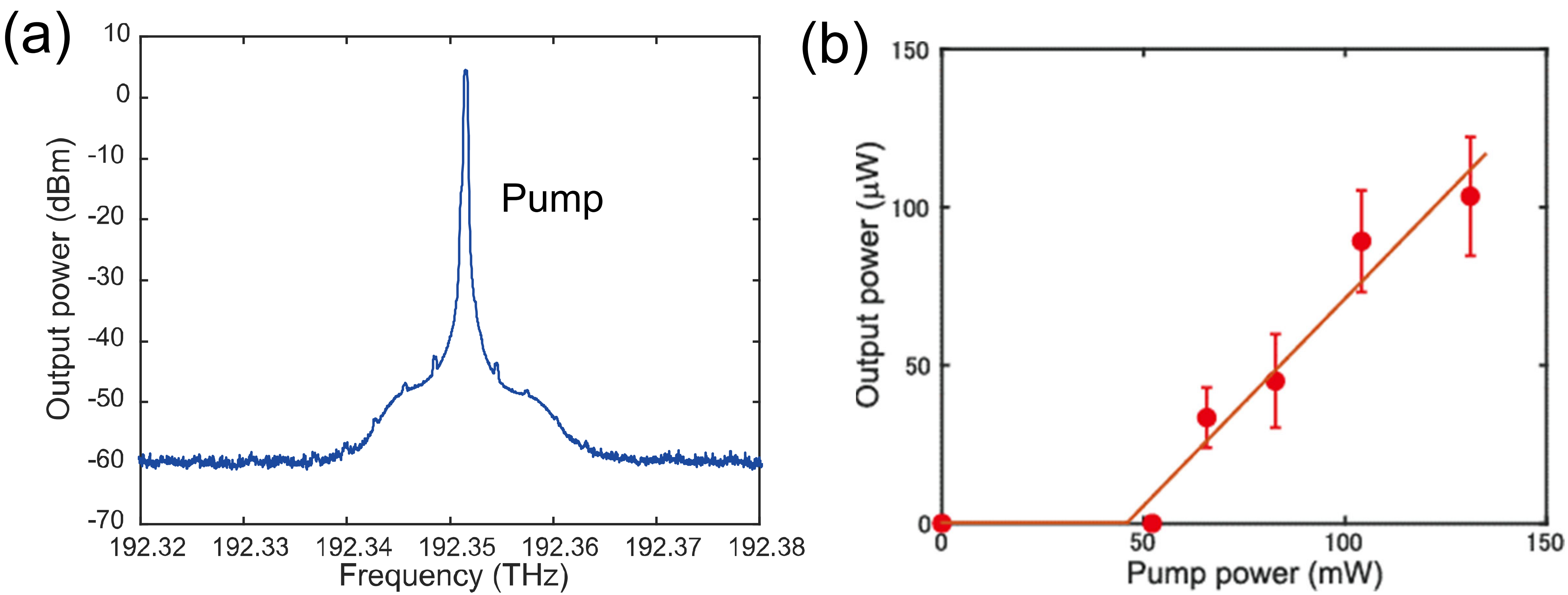


Experimental setup



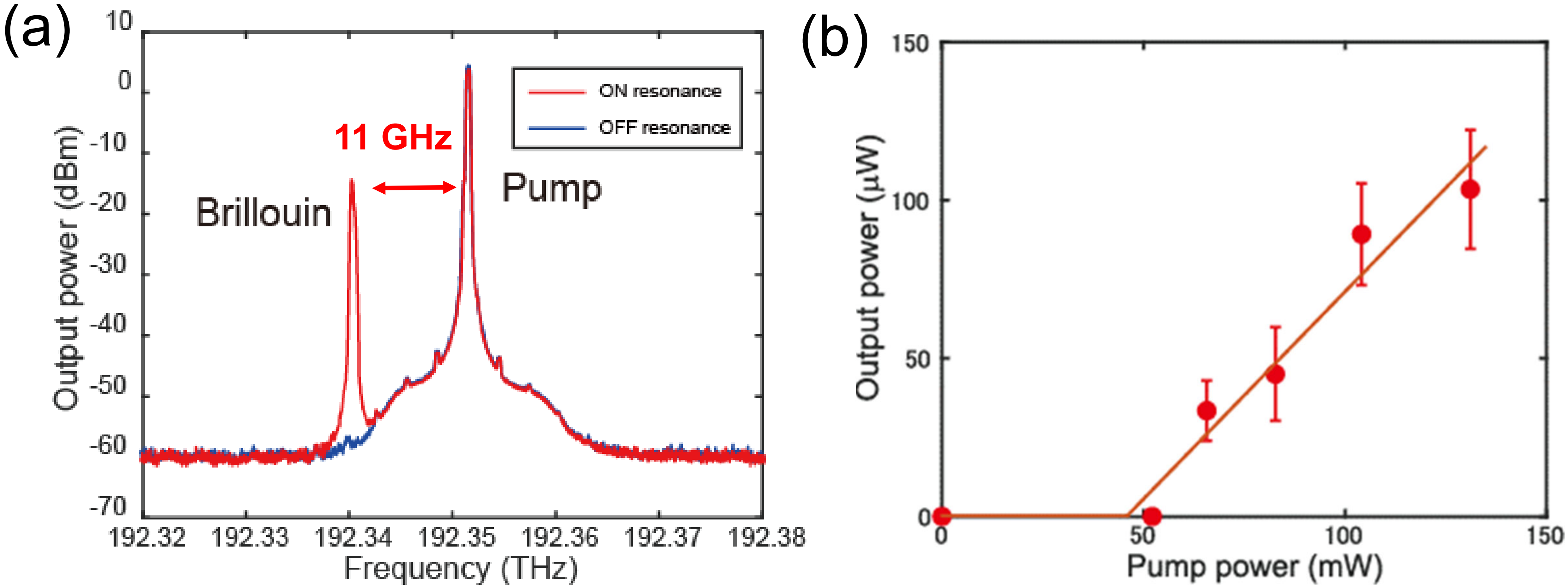


SBS in coupled cavities



- 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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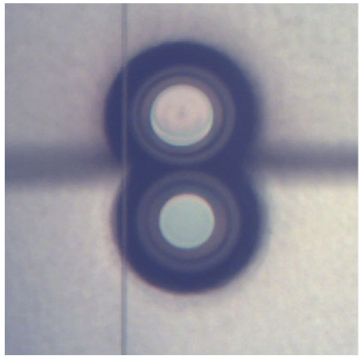
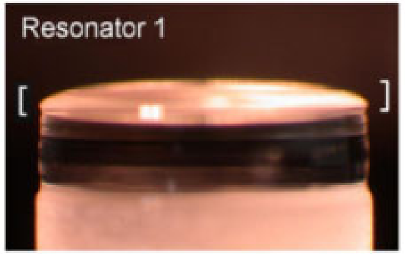
Comparison with other Brillouin lasing

Coupled silica toroid microcavities (This work)

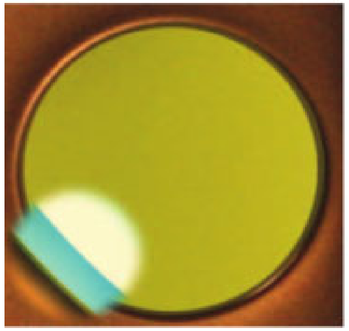


CaF_2 resonator



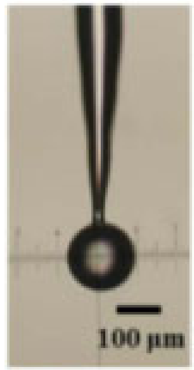
I. S. Grudinin et al., PRL, 102.4, 043902 (2009)

Wedge resonator



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

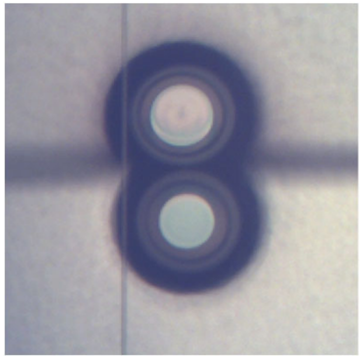
Microsphere



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
		 I. S. Grudinin		
Material	SiO_2			
Threshold power	500 µW			
Device size	110 µm			
Q	2×10^7			
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 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)

Applications of coupled cavities system:

1. Weak coupling: Photonic memory

W. Yoshiki, Y. Honda, T. Tetsumoto, K. Furusawa, N. Sekine and T. Tanabe, "All-optical tunable buffering with coupled ultra-high Q whispering gallery mode microcavities," Sci. Rep. Vol. 7, 10688 (8 pages) (2017).

2. Strong coupling: 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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