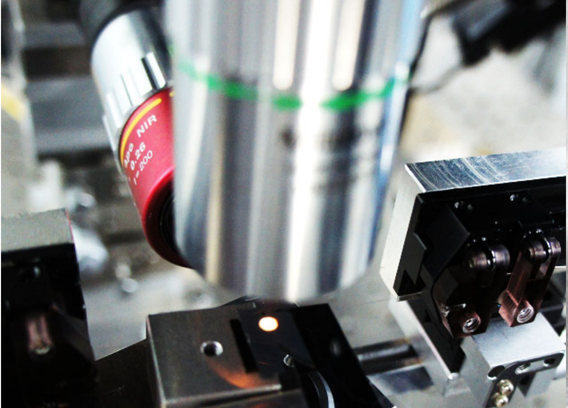
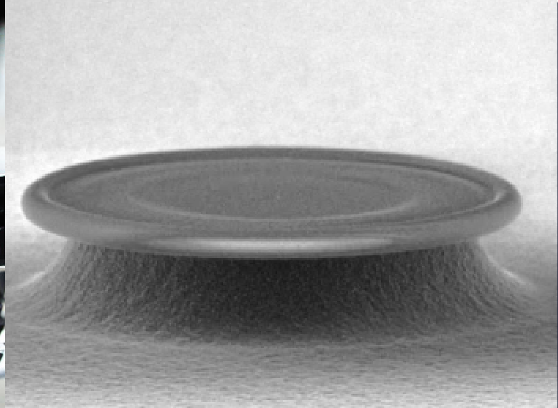
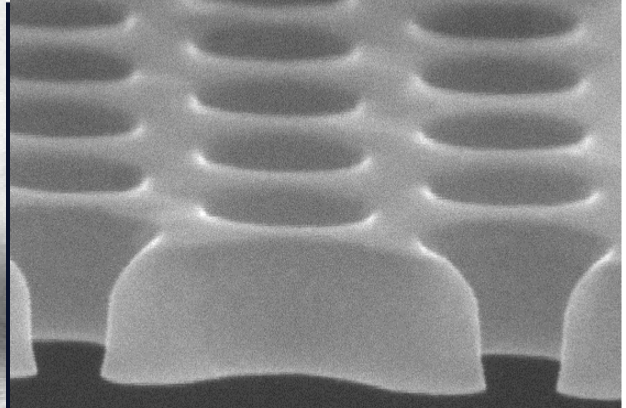
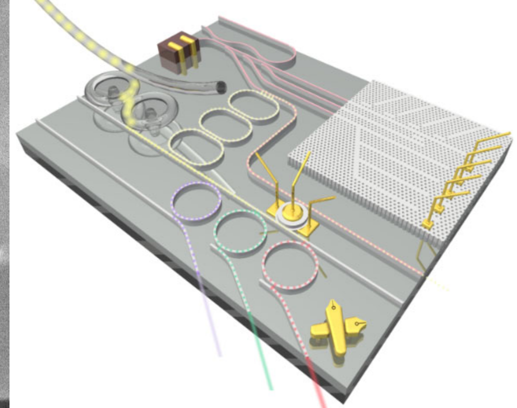





MOC2018

October 18, 2018, 10:30-11:00

Microcavity based laser sources: Microresonator frequency comb and Brillouin lasing

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

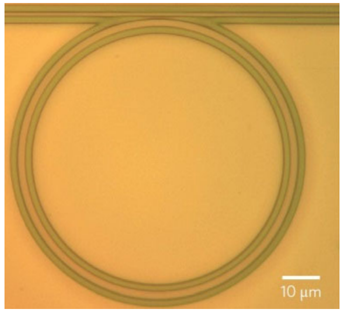
Department of Electronics and Electrical Engineering,
Faculty of Science and Technology, Keio University, Japan

Outline

1. Microcavity comb generation
    a) Theory and essence
    b) Raman comb
    c) THG conversion (broader bandwidth)

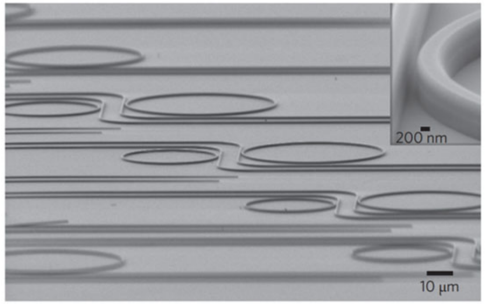
2. Brillouin lasing
    a) Coupled cavity system
    b) Brillouin lasing

High-Q whispering-gallery mode microcavities



Silicon nitride

Weiner group (Purdue)

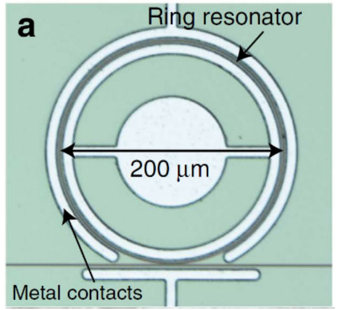


Diamond

Loncar group (Harvard)

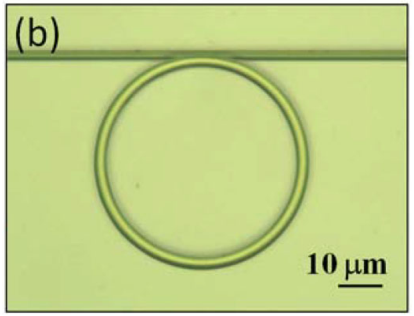
Crystalline (CaF_2, MgF_2, etc)

Kippenberg group (EPFL, Swiss),
Makei group (OE Waves)



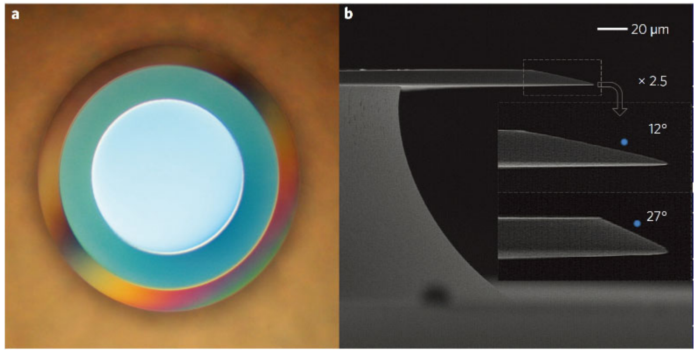
Silicon

Gaeta group (Columbia)



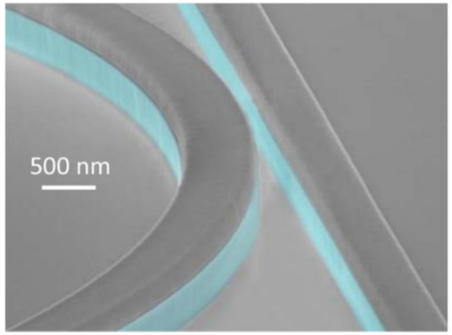
AlN

Tang group (Yale)



Silica

Vahala group (Caltech)



AlGaAs

Yvind group (DTU, Denmark)

◆Q-factor

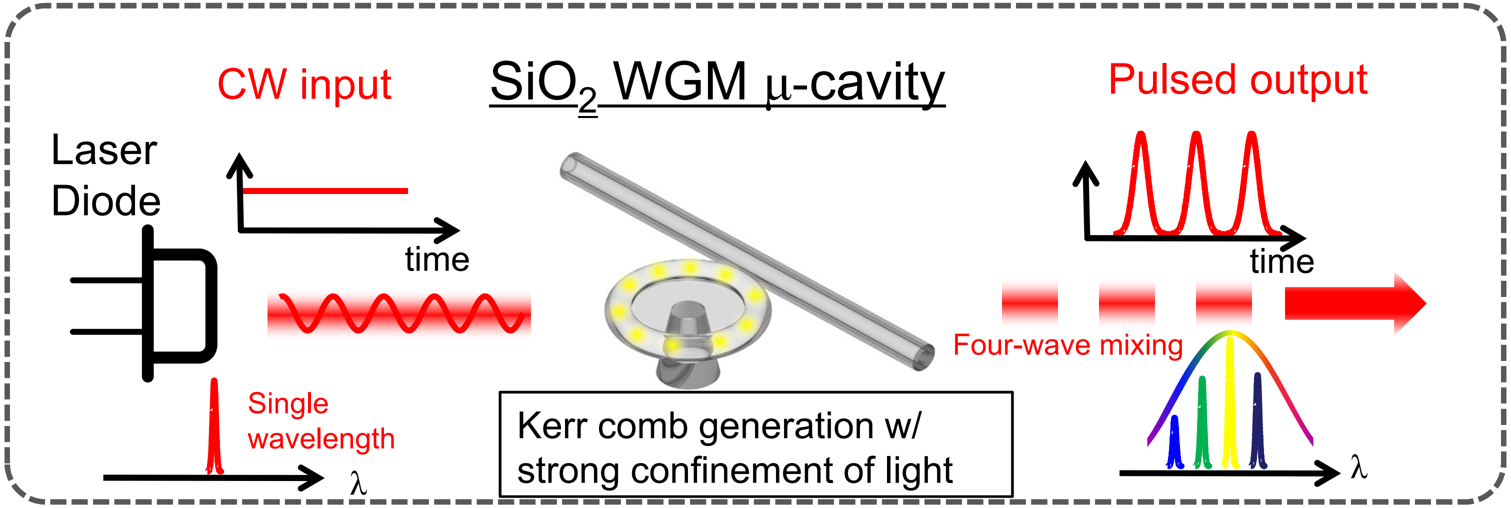
$$Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}}$$

◆Photon density

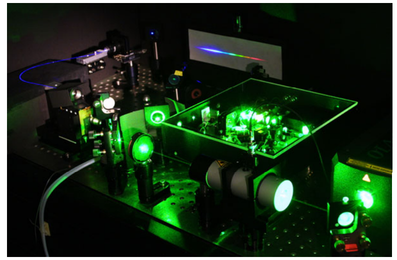
$$\propto Q/V$$

Kerr comb in microcavity system

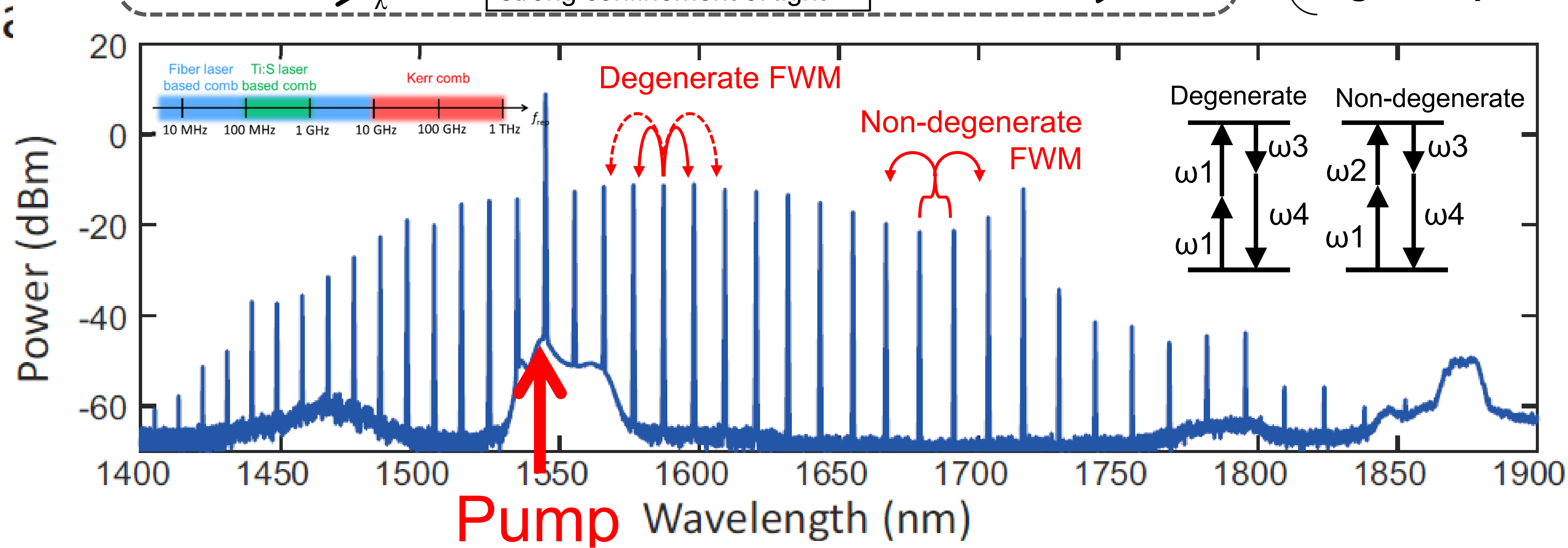
Convert CW laser to ultrashort pulse train w/ >600 GHz repetition rate



Ti:Sapphire laser based comb

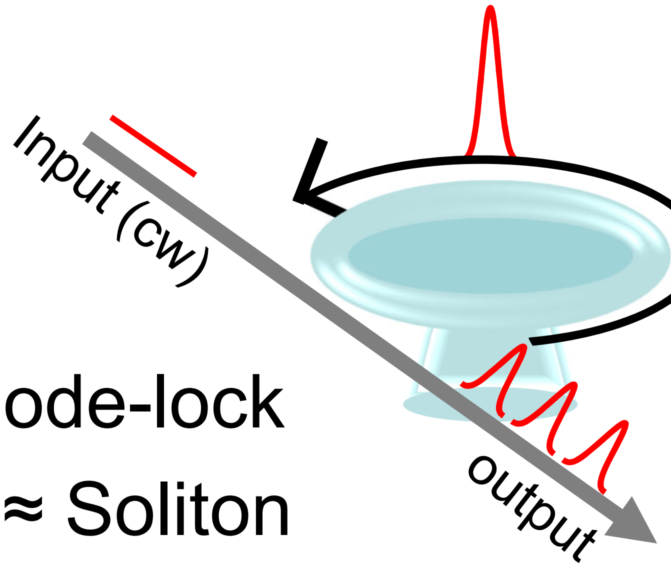


large & expensive



Required conditions for soliton formation

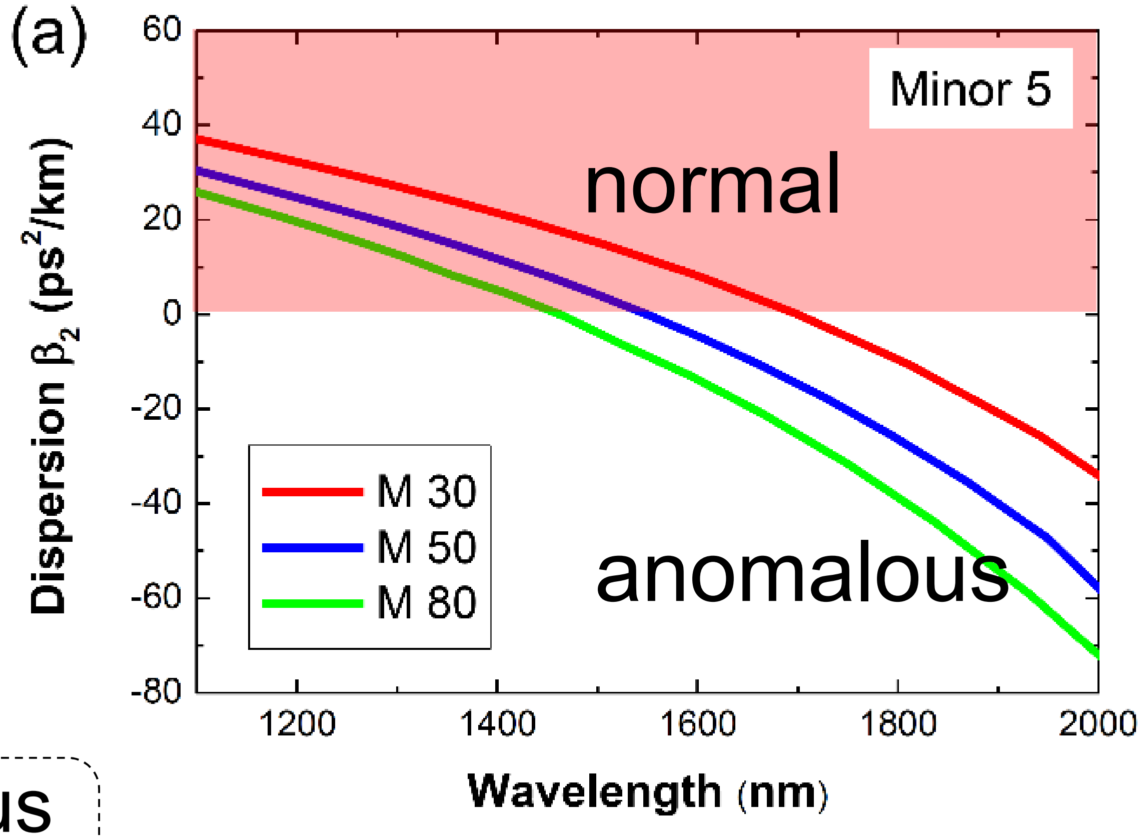
- Soliton in a μ-cavity



Mode-lock

≈ Soliton

- Dispersion in a small toroid

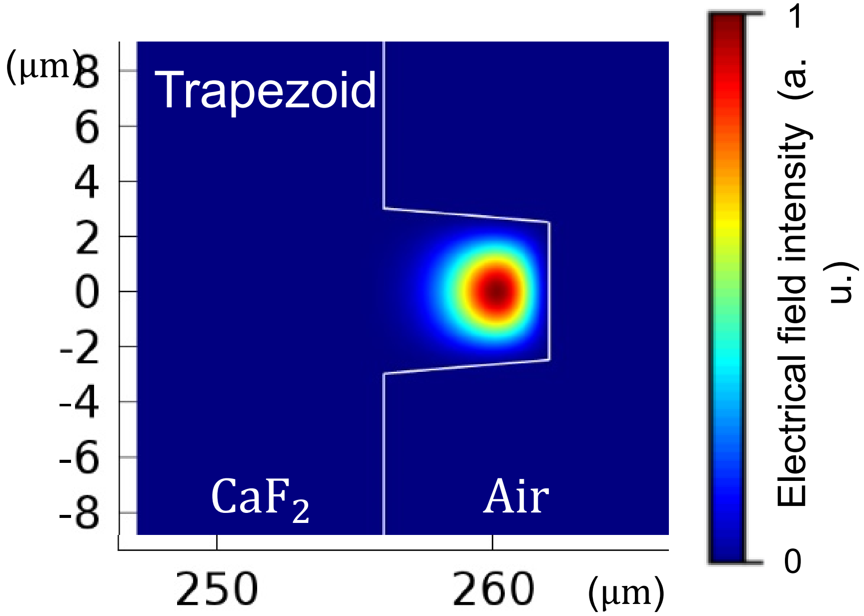


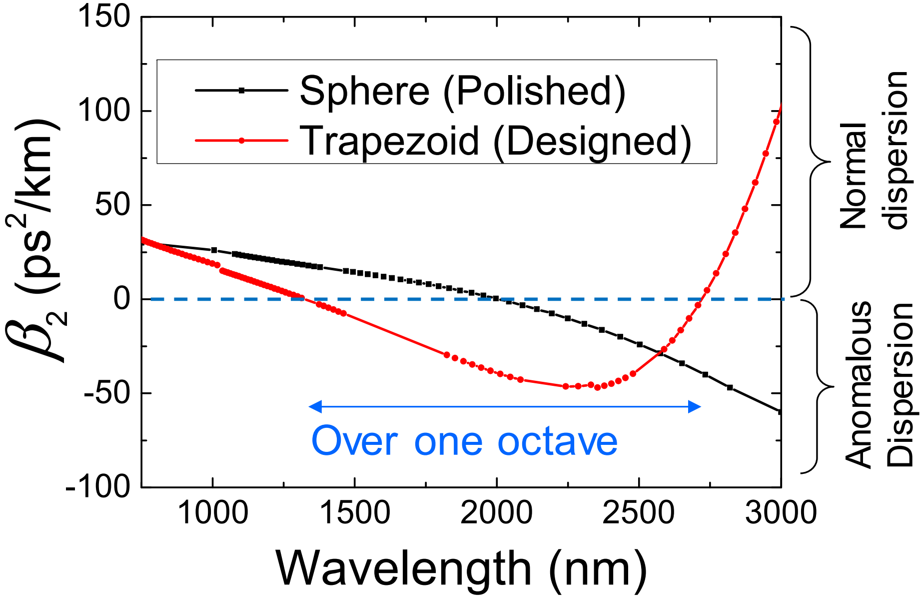
Nonlinear (Kerr) phase	≈	Anomalous dispersion

- Material dispersion
- Geometric dispersion

Fabrication of CaF_2 WGM cavity w/ cutting

▶ Designing geometric dispersion

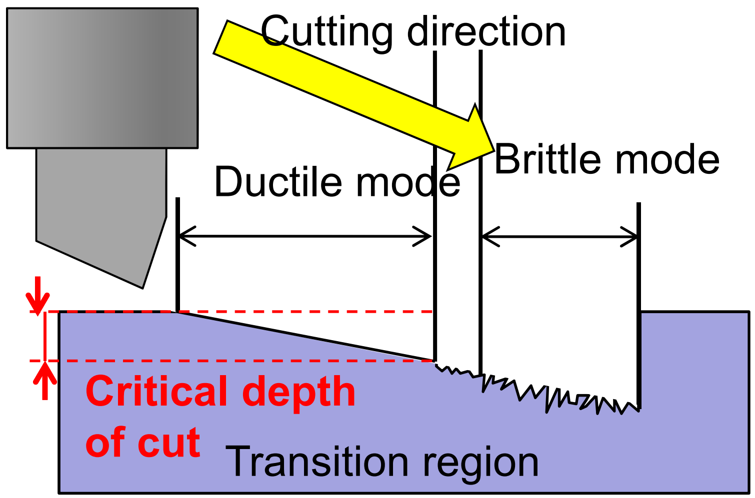


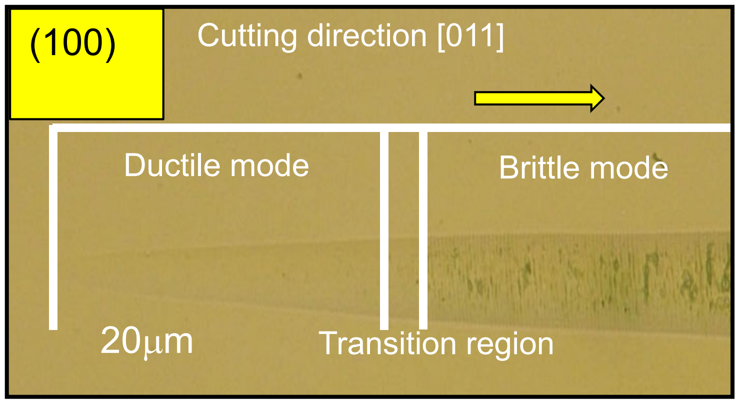


▶ Precise machining process

Y. Mizumoto, *et al*., Procedia Eng. **19,** 264 (2011).

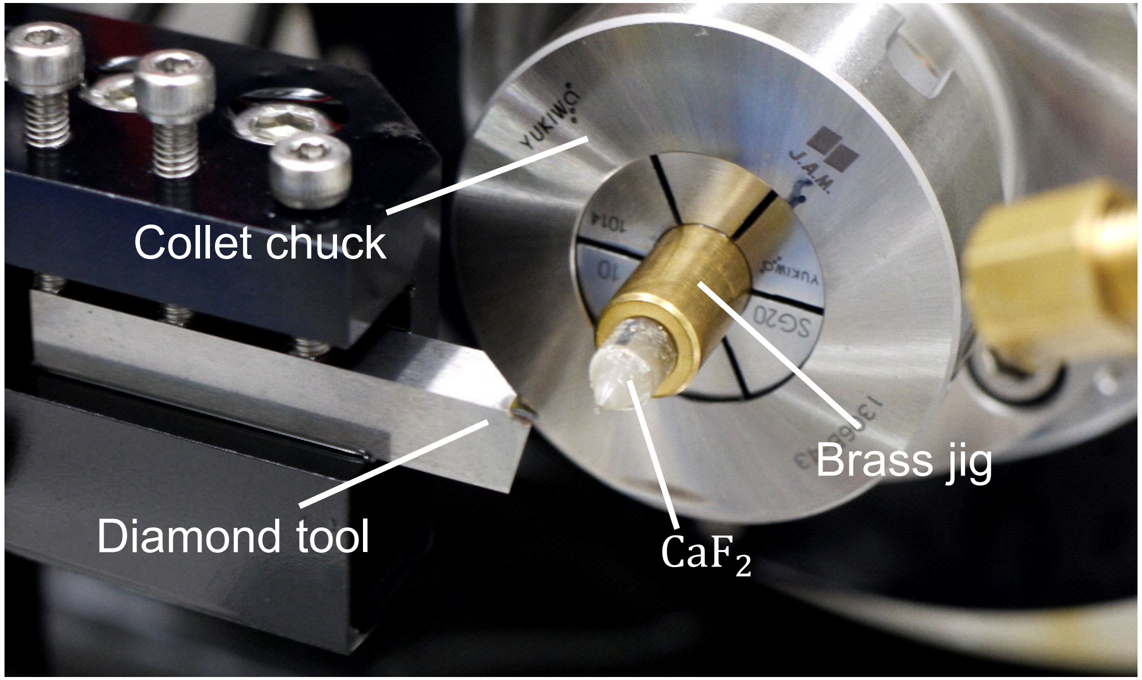
S. Azami, *et al*. Procedica CIRP **13,** 225 (2014).



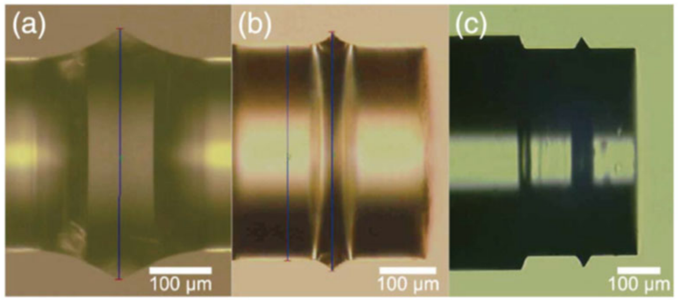


➢ CaF_2 can be smoothly cut in ductile mode cutting

Fabrication of CaF_2 WGM cavity w/ cutting

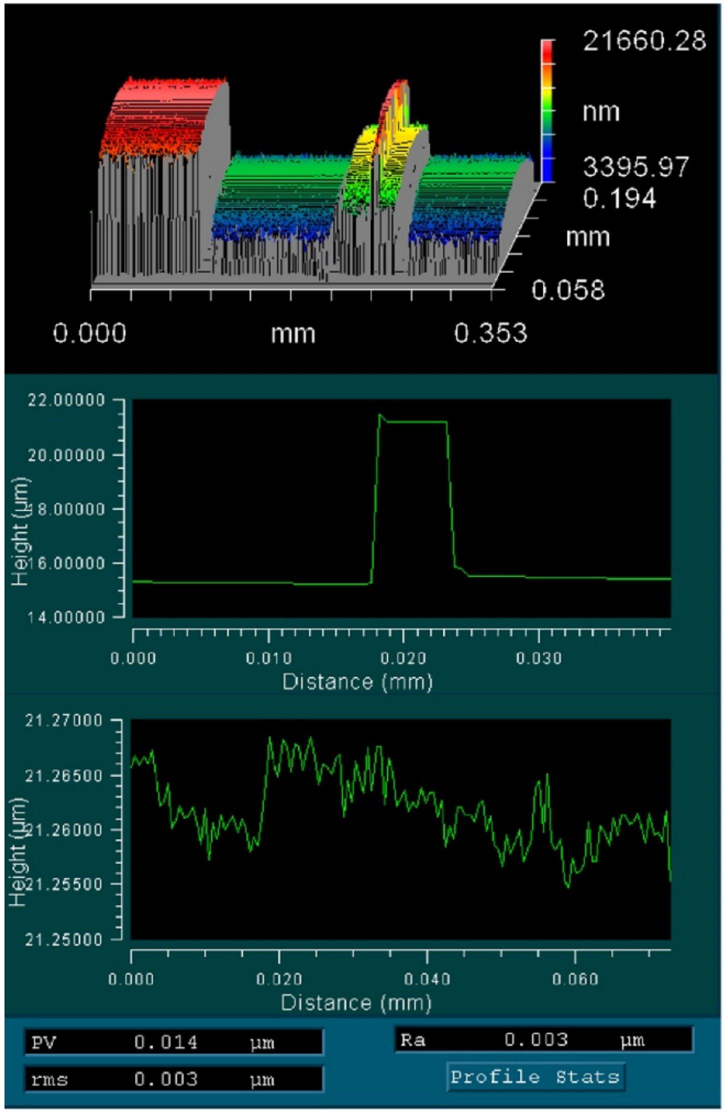


- ✓ Computer controlled (design shape)
- ✓ Ductile mode cutting possible



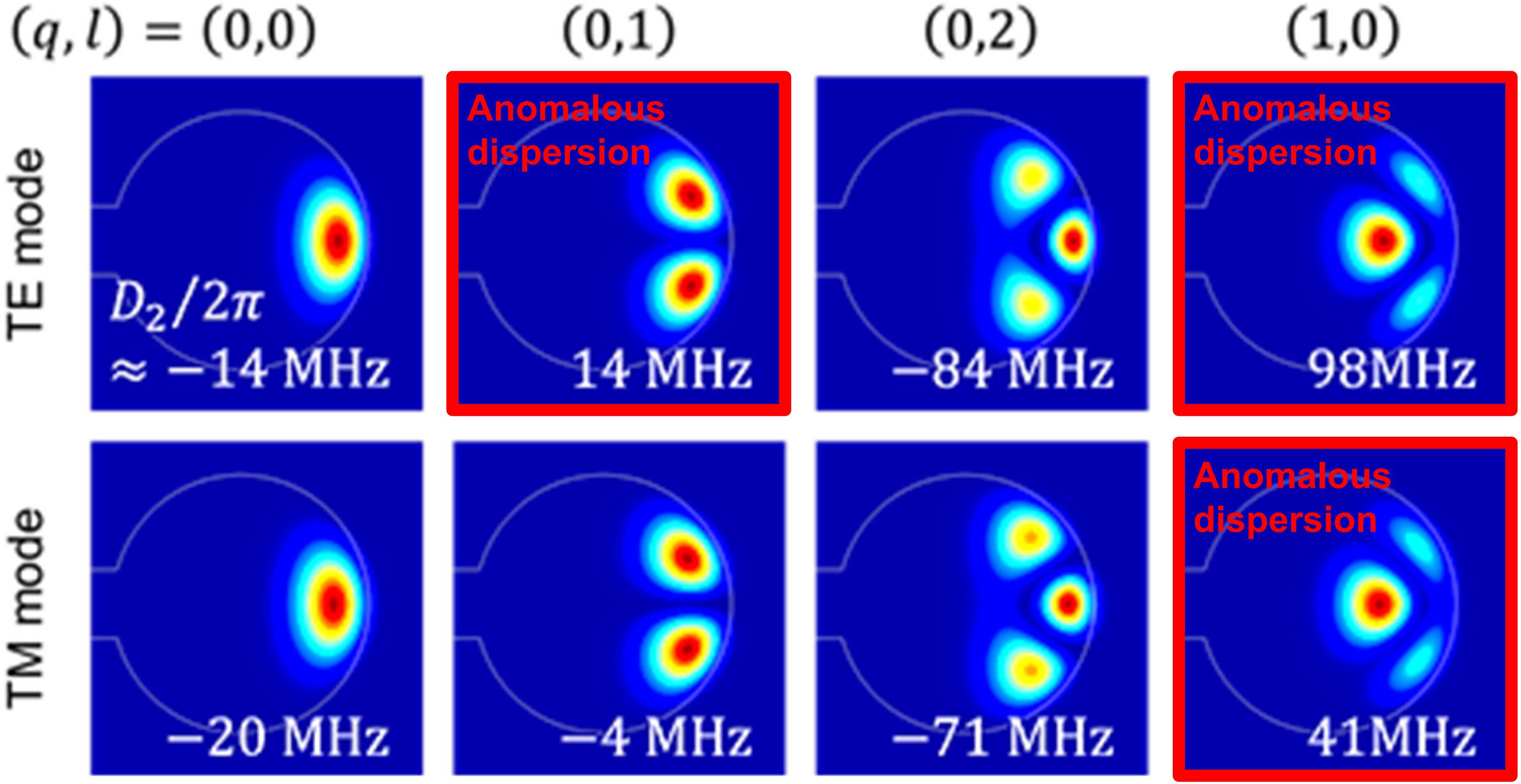
$Q = 3 \times 10^7$ with MgF_2

preliminary



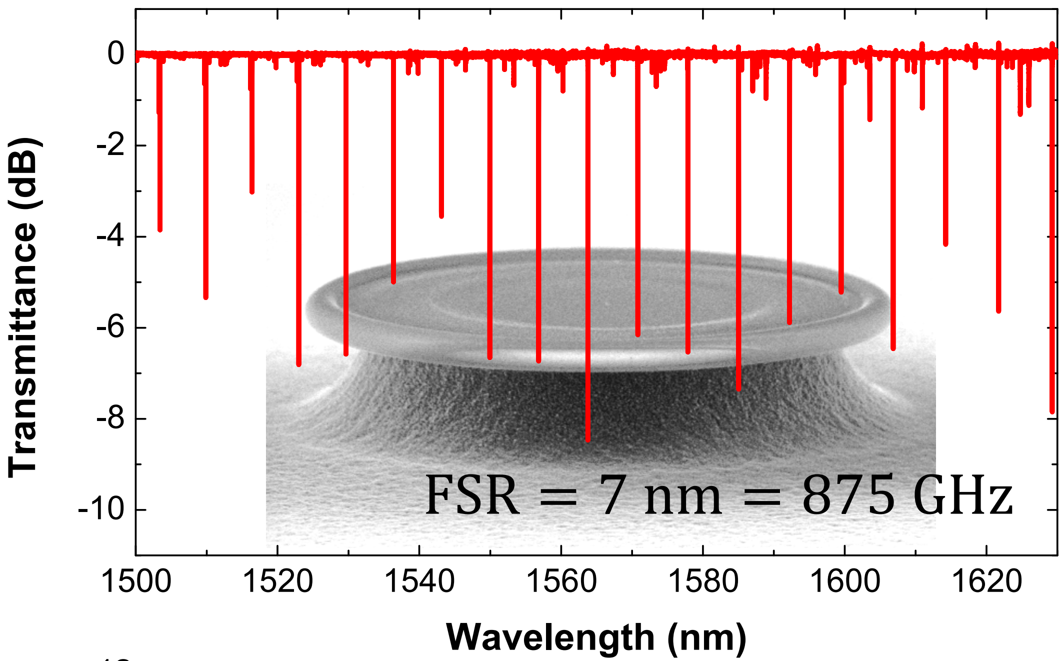
RMS = 3 nm

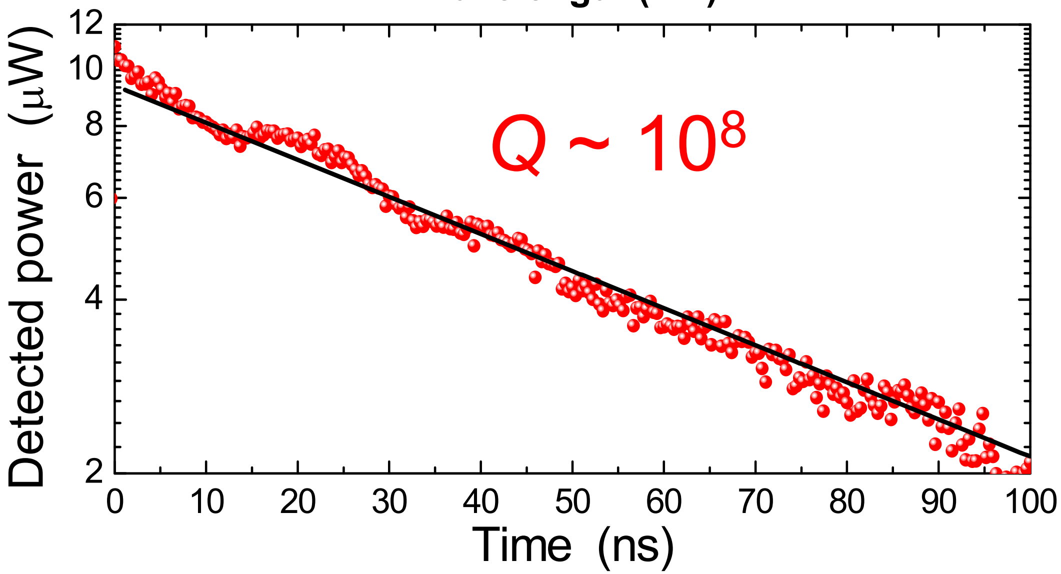
Dispersions in toroid microcavity (r = 35 μm)



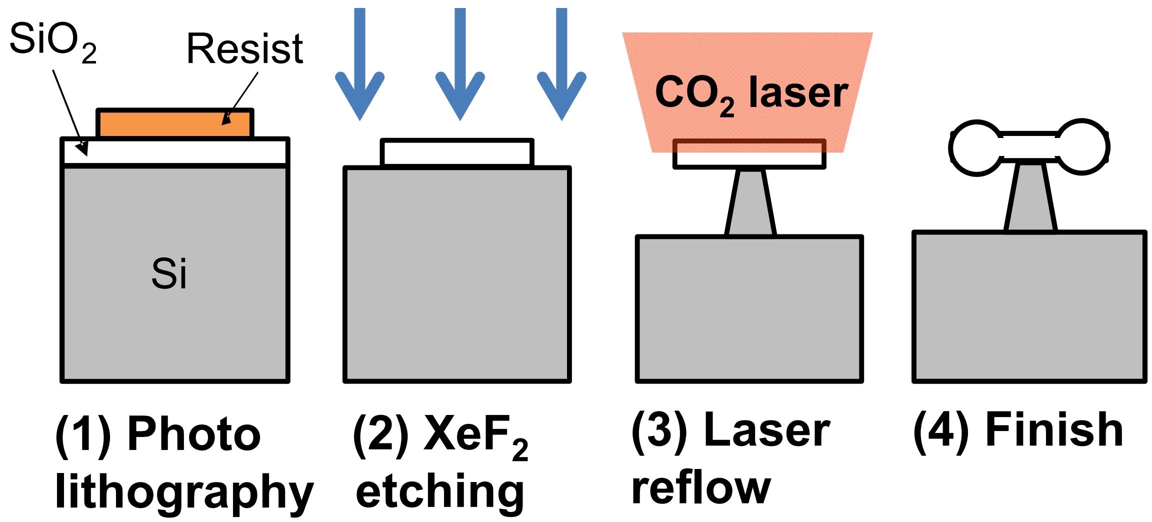
Ultra-high *Q* toroidal microcavity

▶Spectrum & photon lifetime

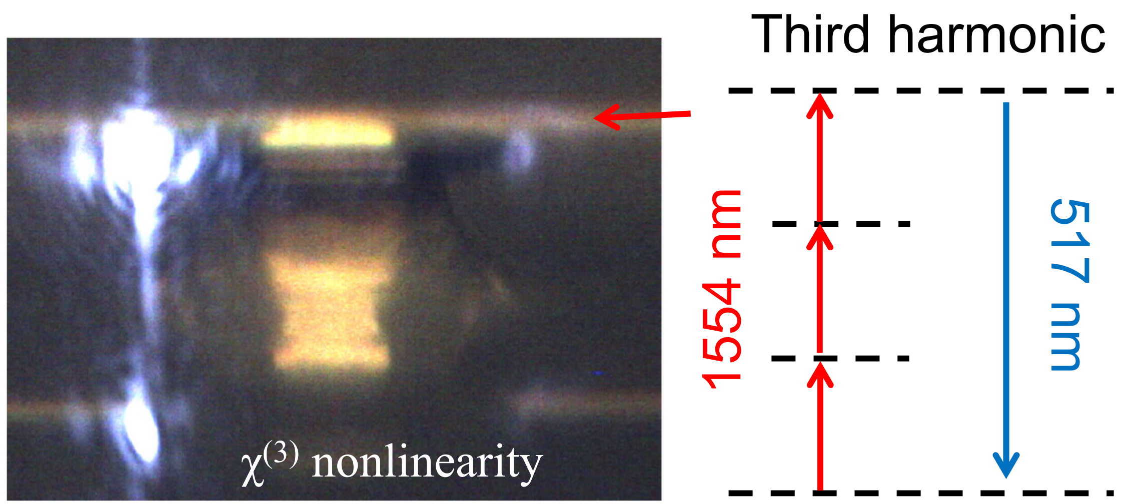




▶Fabrication

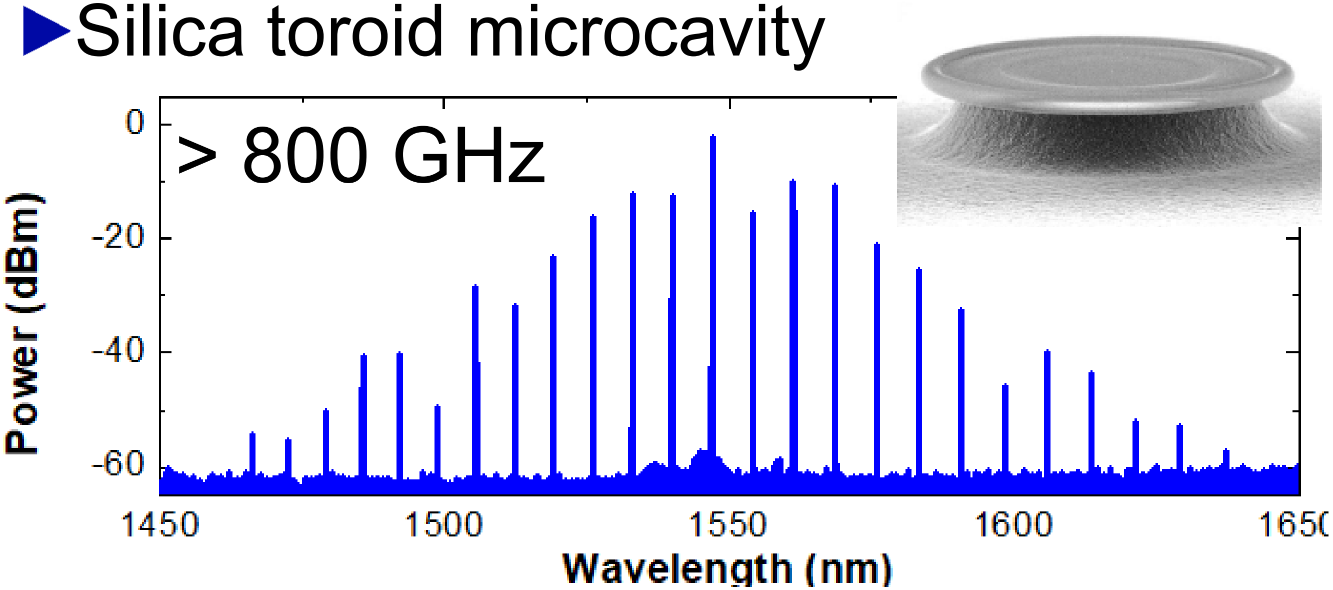


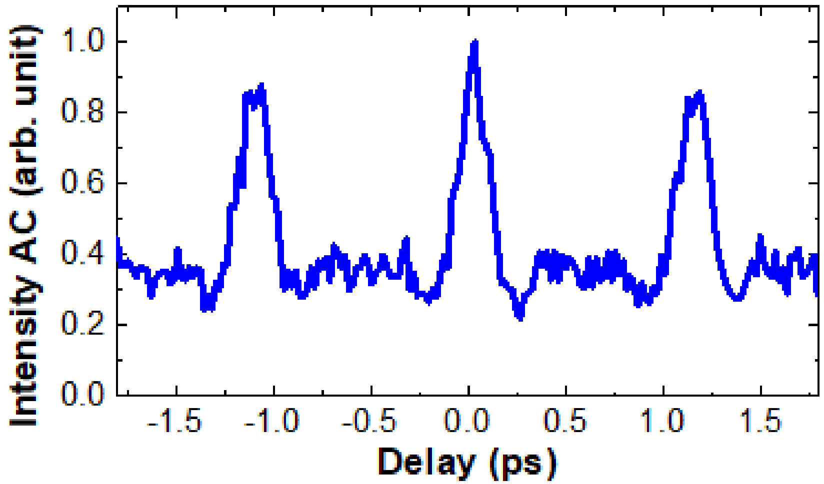
▶White light generation (Kerr effect)



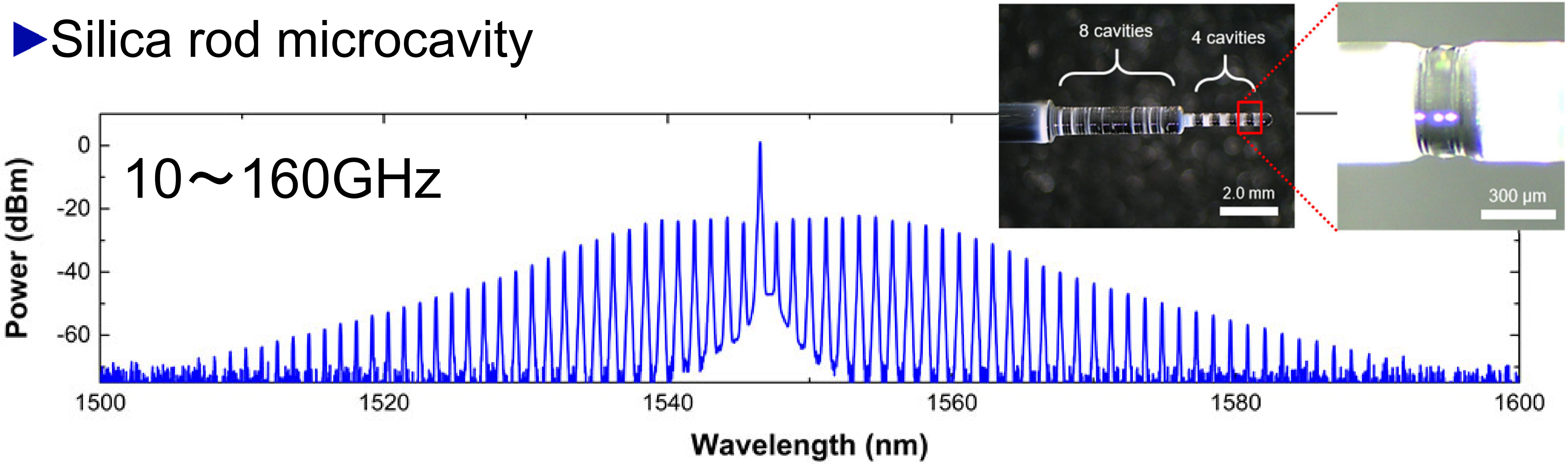
Kerr comb in microcavity system

▶Silica toroid microcavity





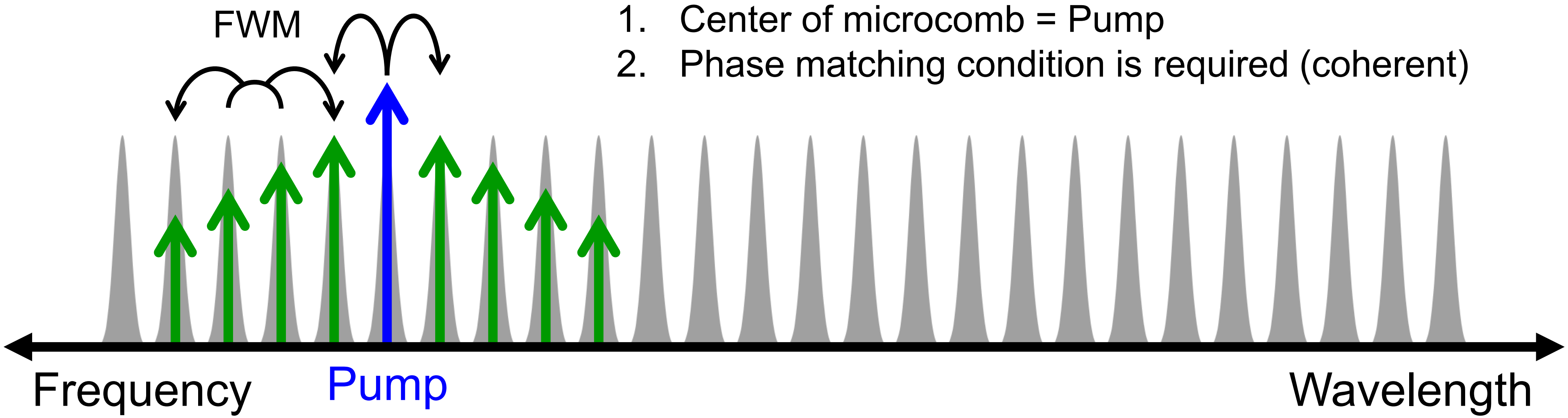
▶Silica rod microcavity



Microcomb generation via FWM/SRS

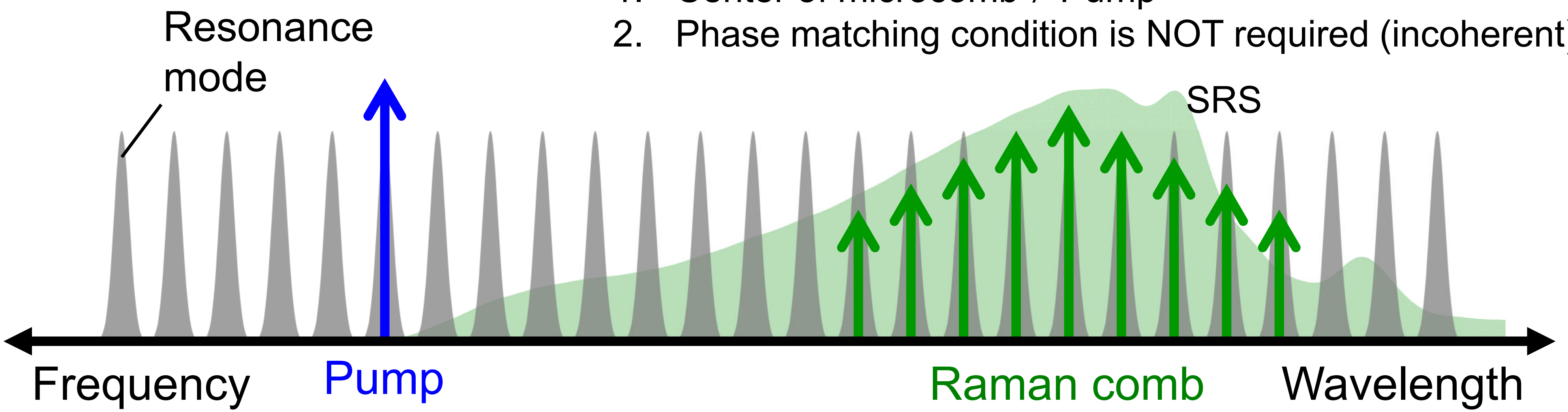
Microcomb via four-wave mixing (FWM)

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)

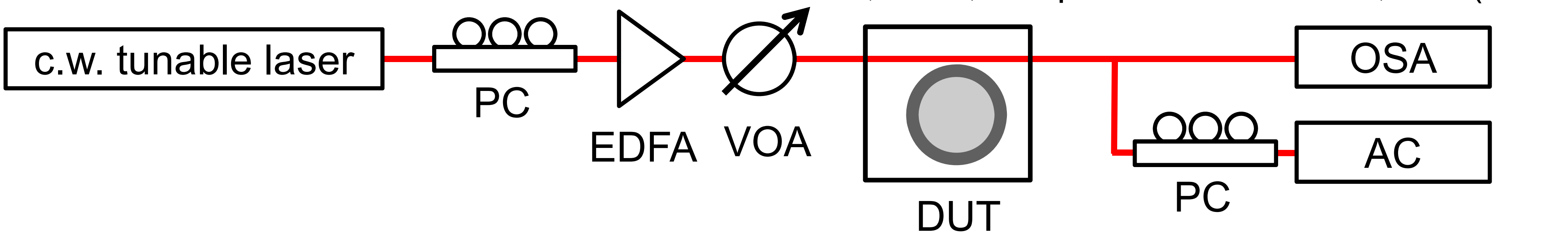


R. Suzuki, *et al.*, J. Opt. Soc. Amer. B **35**, 933 (2018).

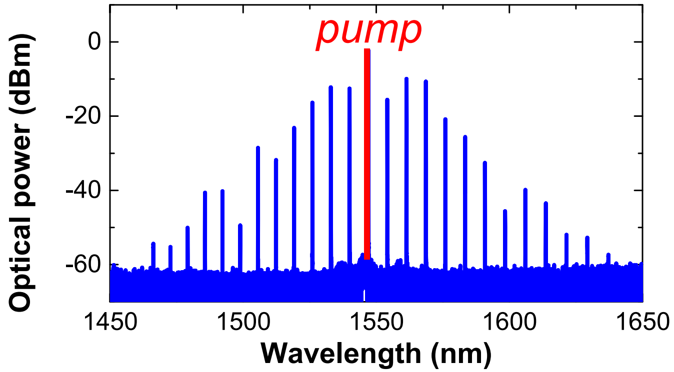
Kerr comb in a silica toroidal microcavity

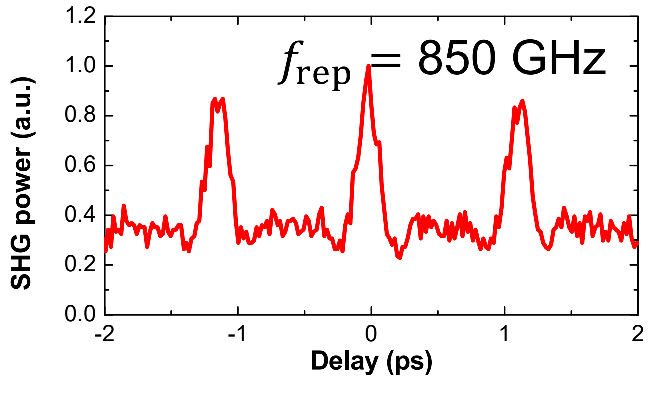
►Experimental setup

T. Kato, *et al.*, Opt. Express **25**, 857 (2017).
R. Suzuki, *et al.*, J. Opt. Soc. Amer. B **35**, 933 (2018).

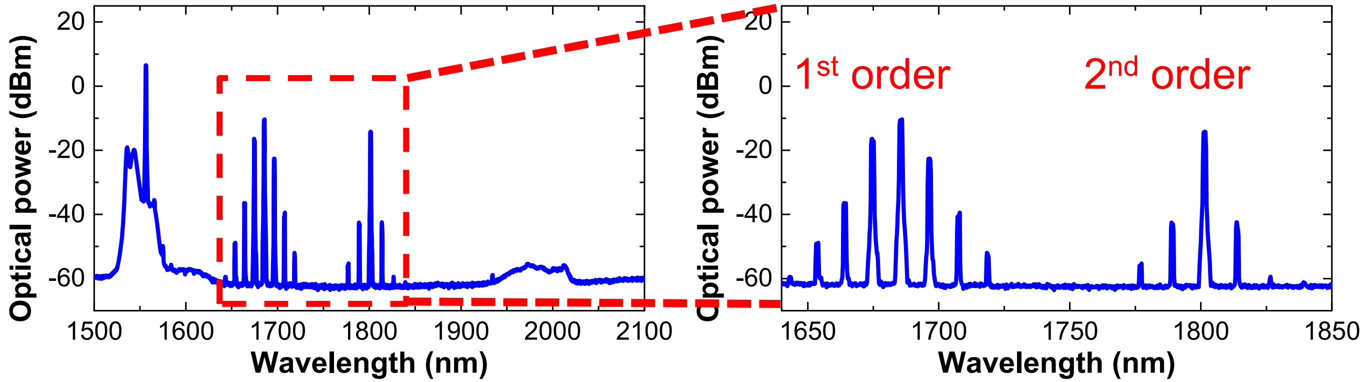


►FWM only

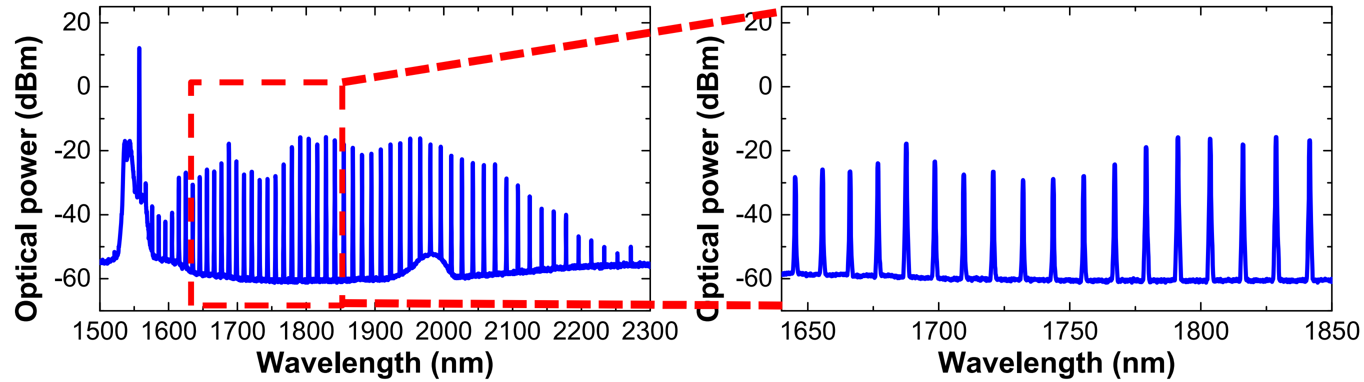




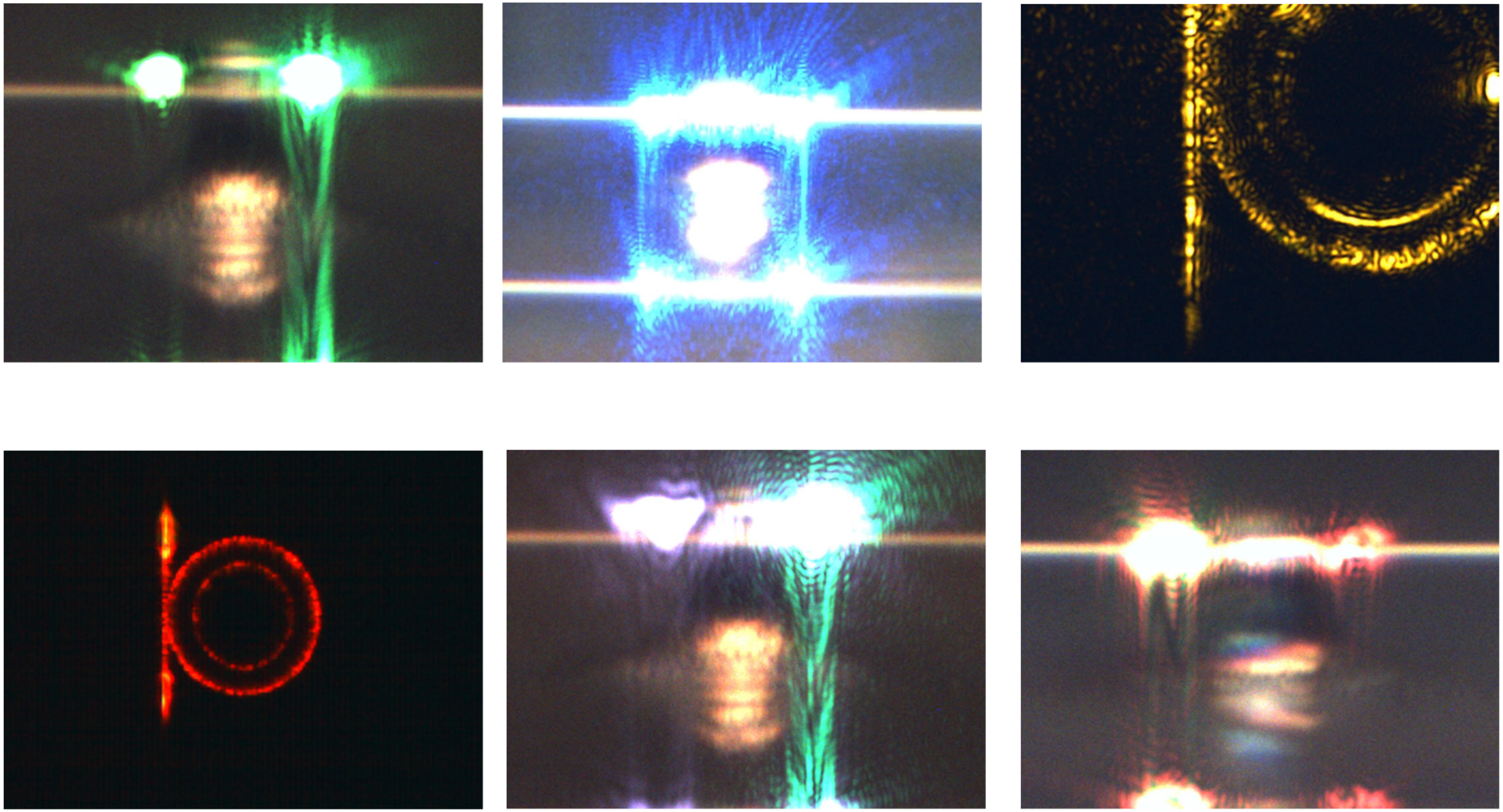
►Raman (Pump:1556.4 nm, 250 mW



►Hybrid (FWM+Raman) (Pump:1557.3 nm, 580 mW)



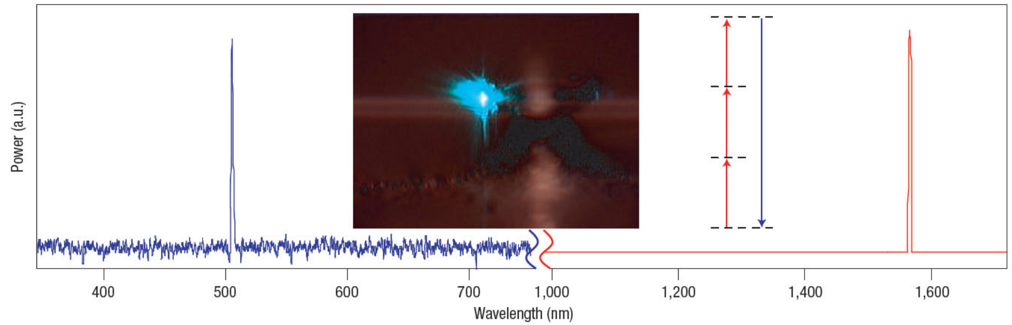
Third-harmonic generations in toroid microcavity



Visible light generation with soliton pulse

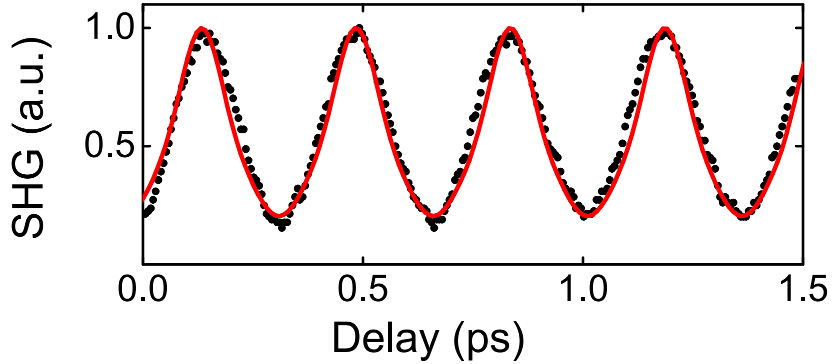
▶Efficient third-harmonic generation

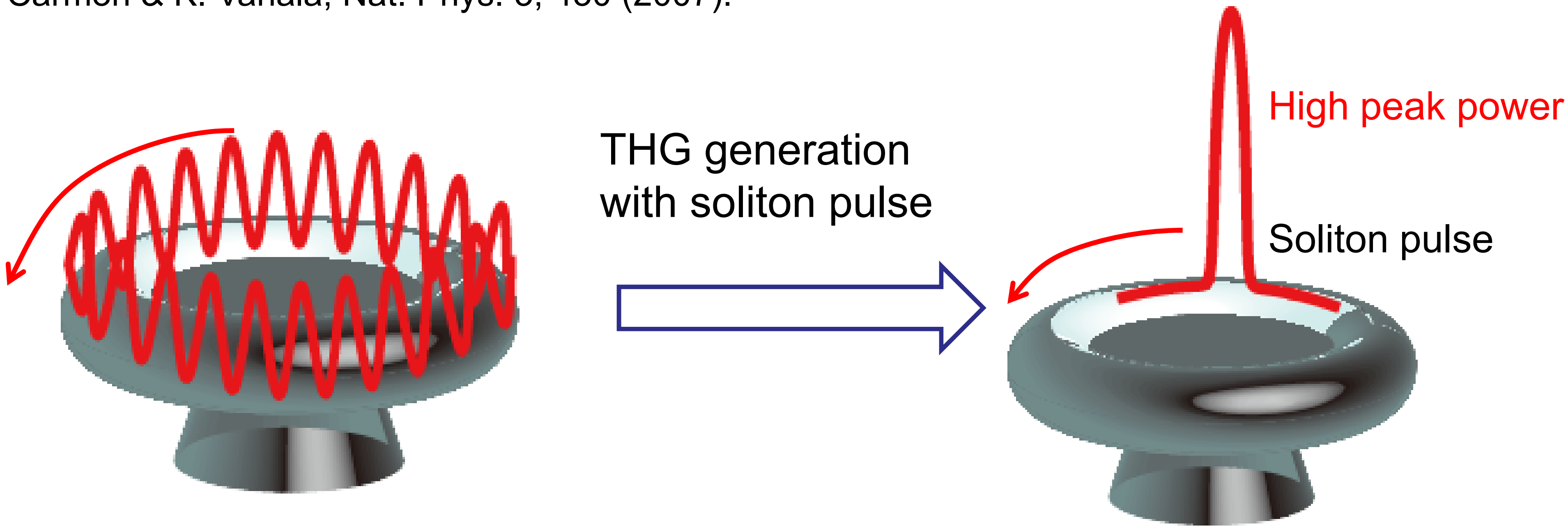
CW mode



T. Carmon & K. Vahala, Nat. Phys. 3, 430 (2007).

▶THG with pulsed mode

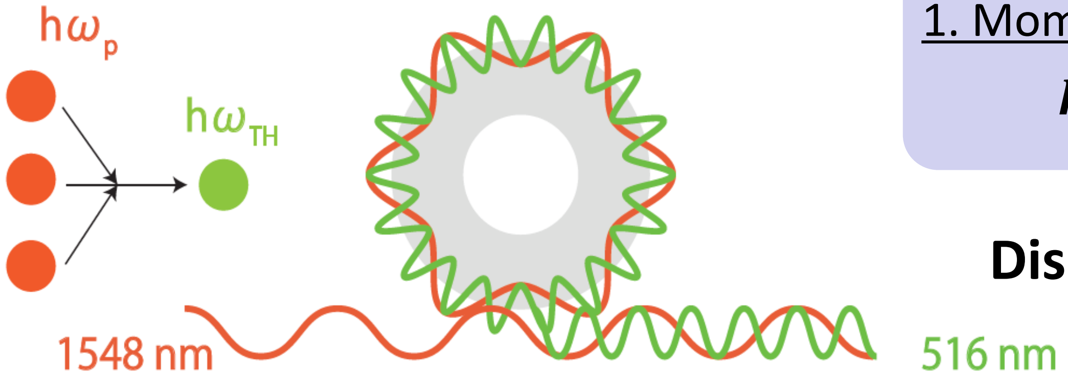




Potential for improving THG efficiency

Phase-matching condition for THG

S. Fujii, *et al.*, Opt. Lett. **42**, 2010 (2017).

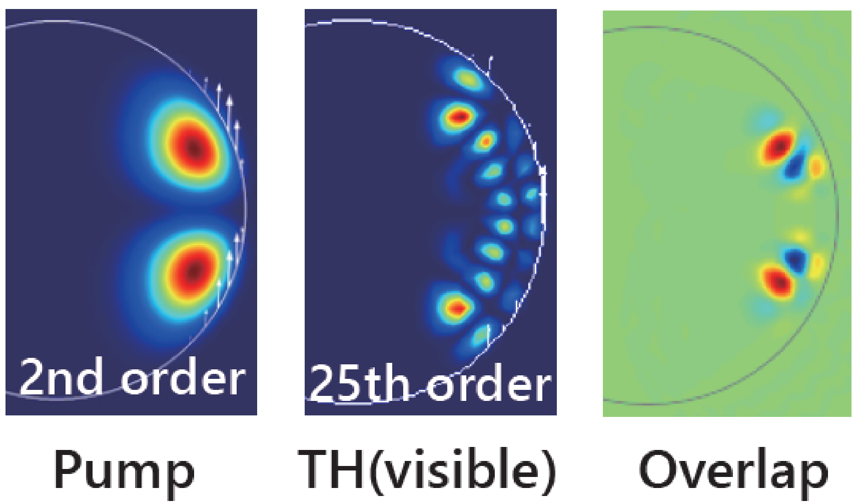


1. Momentum conservation	2. Energy conservation
$k_{THG} = 3k_p$	$\omega_{THG} = 3\omega_p$

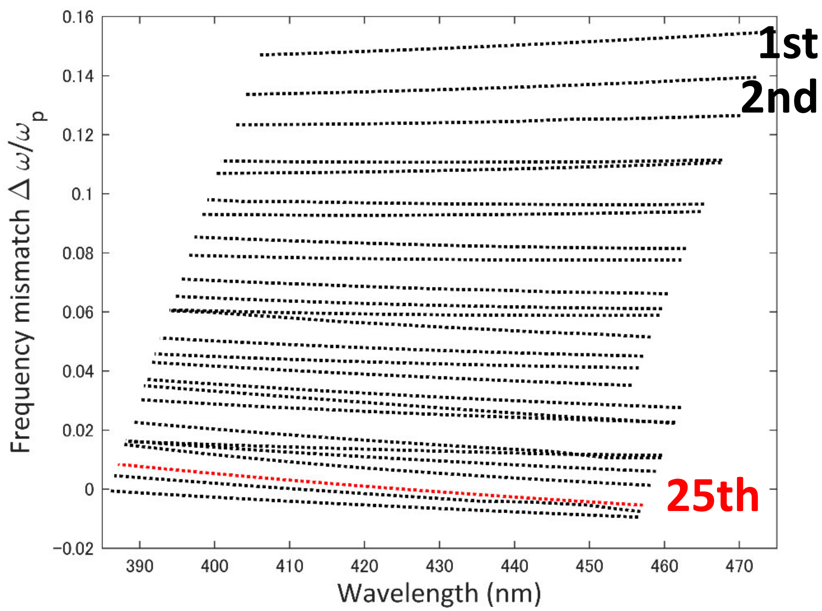
Dispersion induced resonance mismatch

$$\Delta\omega = 3\omega_p - \omega_{THG} \rightarrow 0$$

Intensity distribution (cross-section)



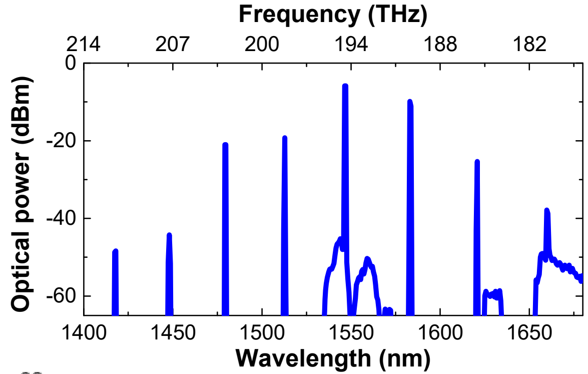
Phase-matched TH mode

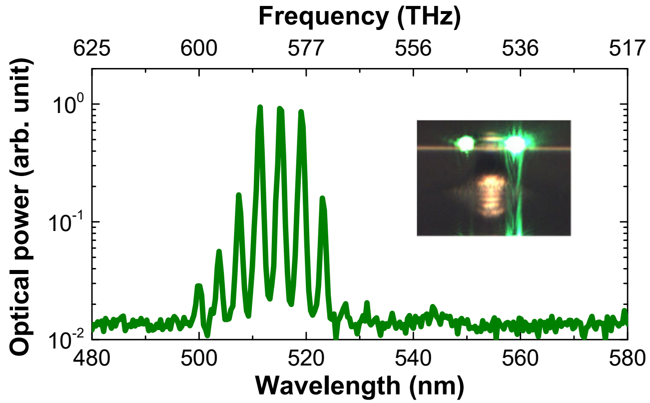


Third-harmonic generation *w/* FWM and SRS

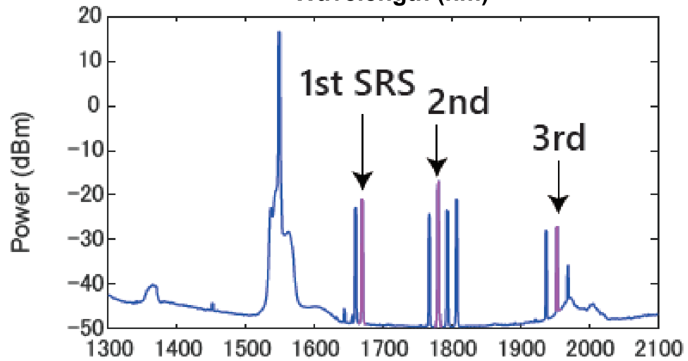
A. C-Jinnai, *et al.*, Opt. Express **24**, 26322 (2016).
S. Fujii, *et al.*, Opt. Lett. **42**, 2010 (2017).

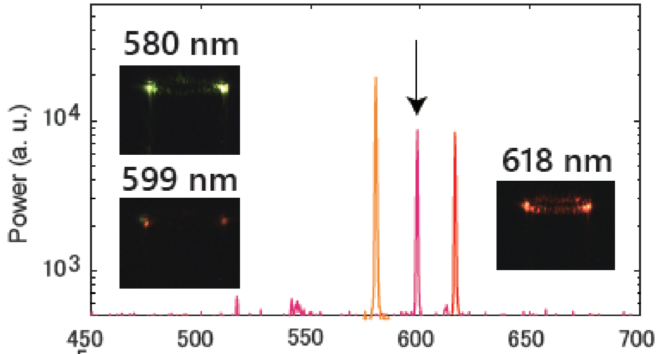
1. Visible comb generation
   - ➢ Green via THG of FWM comb



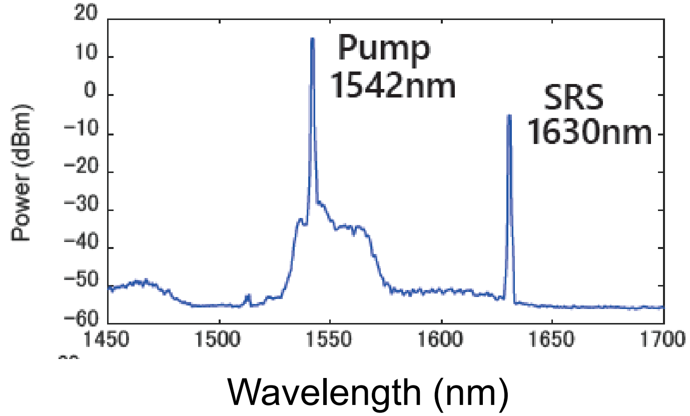


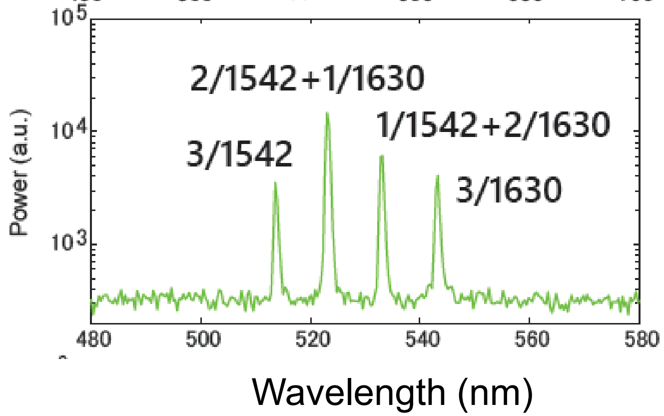
2. Multi-color emission
   - ➢ Yellow, Orange, Red color emission via TSFG of SRS





3. Comb-like spectrum
   - ➢ THG and TSFG via pump and SRS

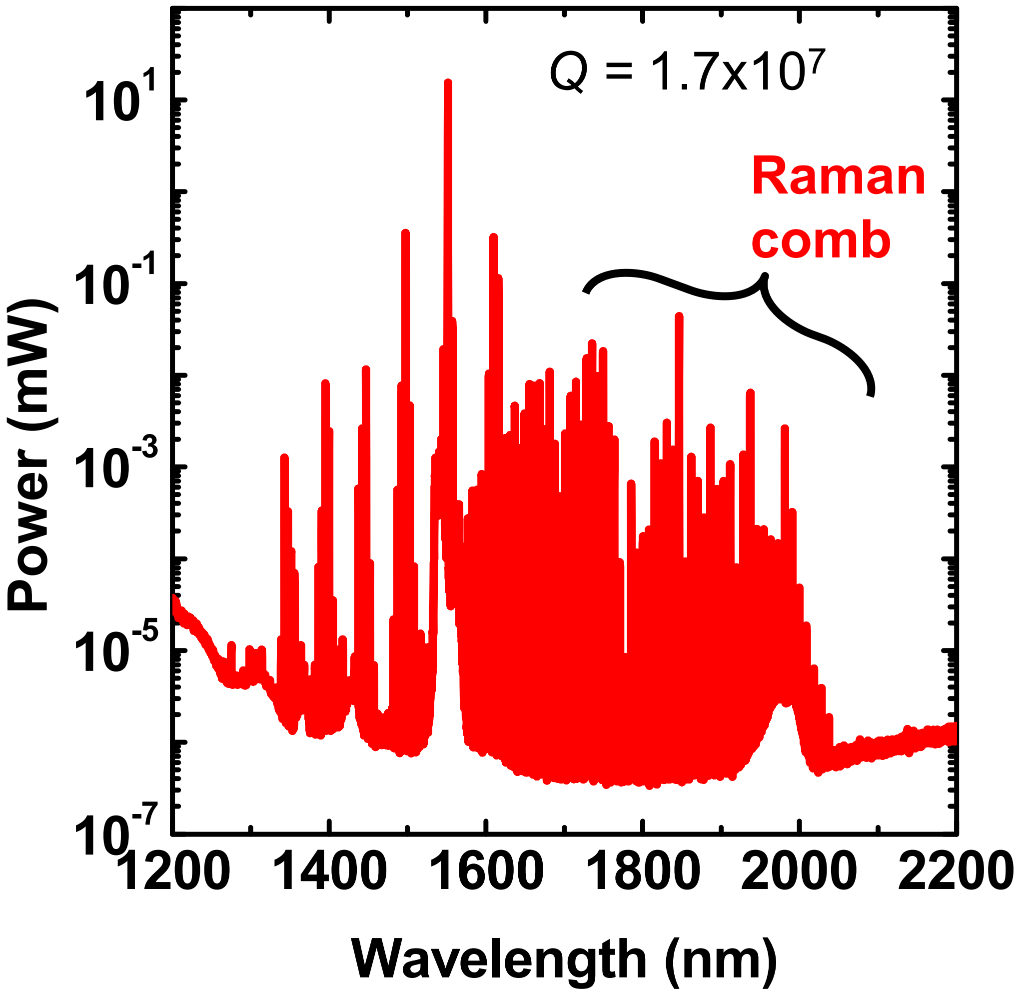


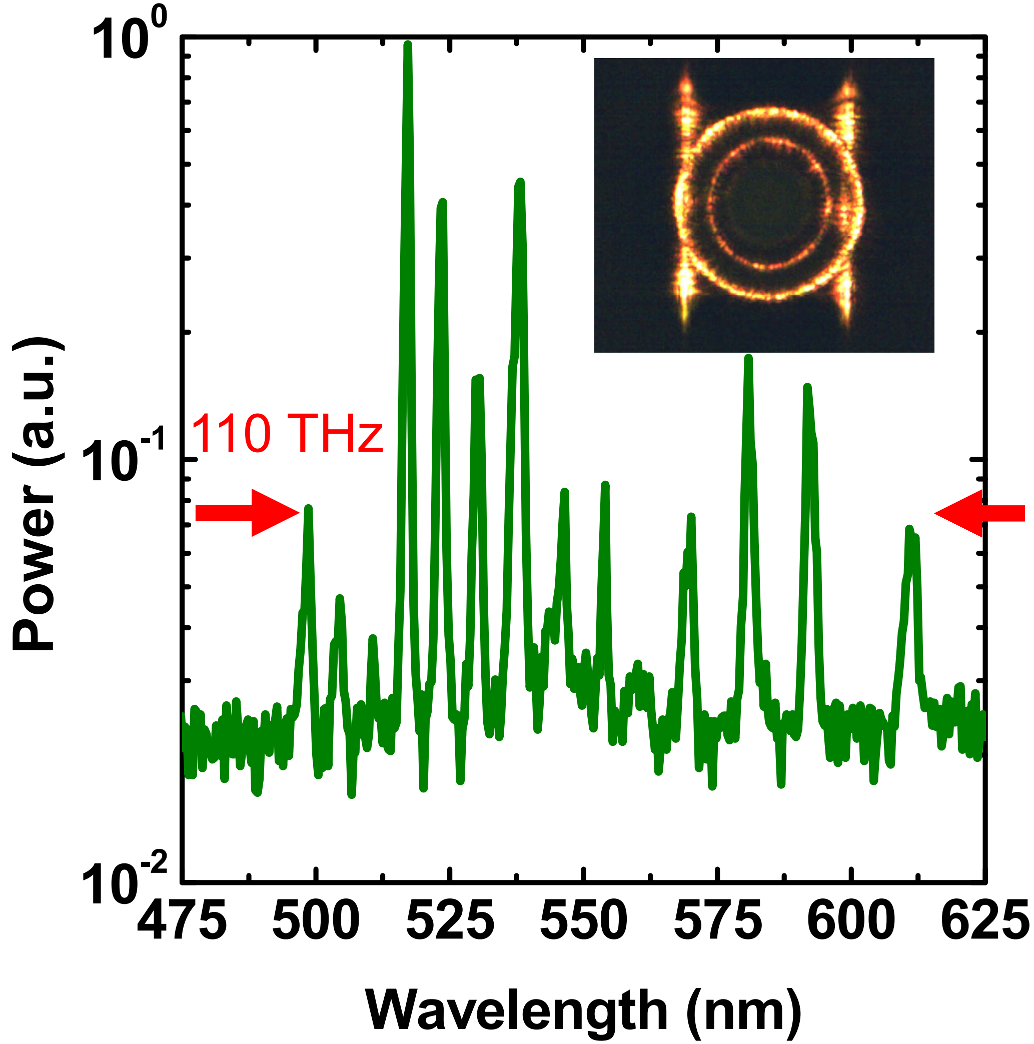


Broad bandwidth generation

A. C-Jinnai, *et al.*, Opt. Express **24**, 26322 (2016).
S. Fujii, *et al.*, Opt. Lett. **42**, 2010 (2017).

▶w/ Raman comb (Input: 1551.59 nm, 1 W)





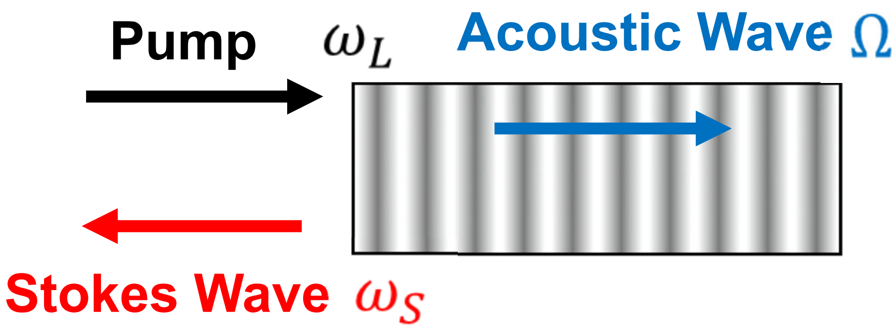
Outline

1. Microcavity comb generation
   a) Theory and essence
   b) Raman comb
   c) THG conversion (broader bandwidth)

2. Brillouin lasing
   a) Coupled cavity system
   b) Brillouin lasing

Stimulated Brillouin Scattering (SBS)

□ Schematic representation of SBS process

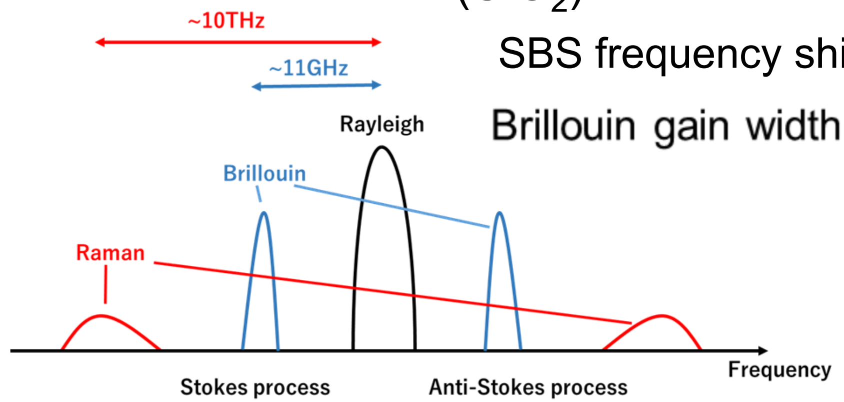


$$\omega_L = \omega_S - \Omega$$

(SiO_2)

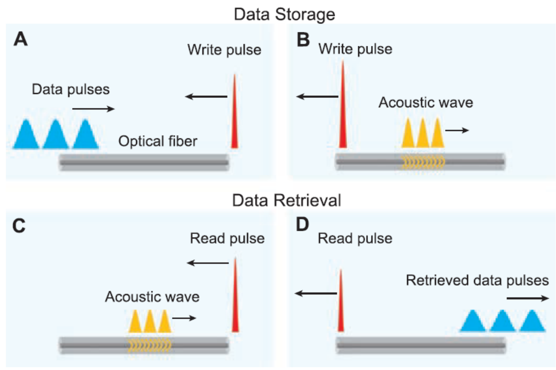
SBS frequency shift $\approx$ 11GHz

Brillouin gain width = ~50 MHz

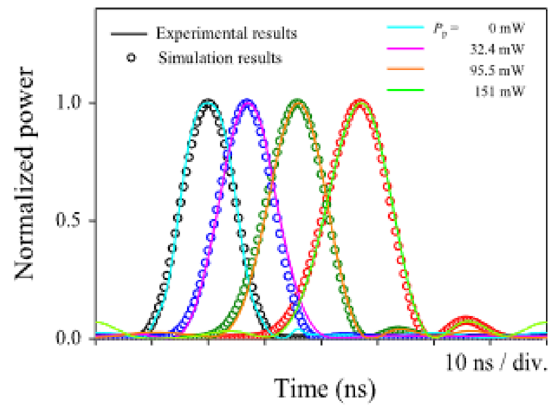


□ SBS applications

- 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)

Sto

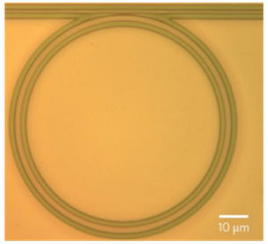
Microcavities

Crystalline (CaF_2)

$Q > 10^{10}$

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

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

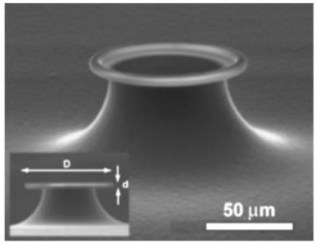


Si_3N_4 microring

$Q \approx 10^6$

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

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

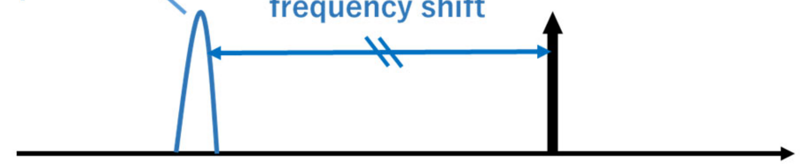
10 ns / div.

318, 1748-1750 (2007)

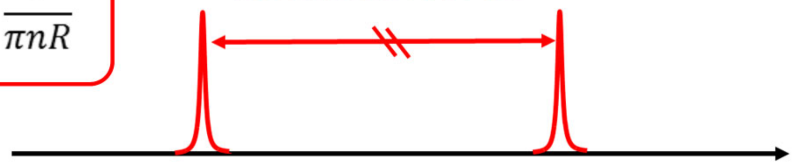
T. Sakamoto, T. Yamamoto, K. Shiraki, and T. Kurashima, Opt. Express **16**, 8026–8032(2008)

SBS in microcavities

Method1



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

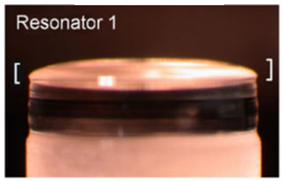


Brillouin frequency shift = Resonant mode FSR

↓

Brillouin lasing

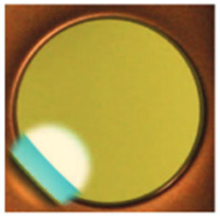
CaF_2



5.52 mm

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

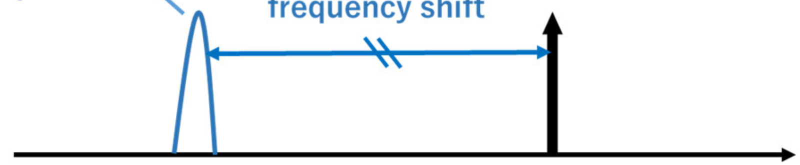
SiO_2

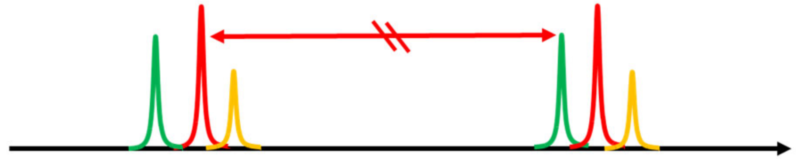


6.02 mm

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

Method2



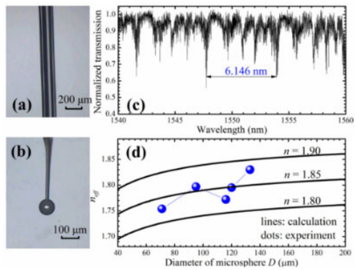


Brillouin frequency shift = High-order mode spacing

↓

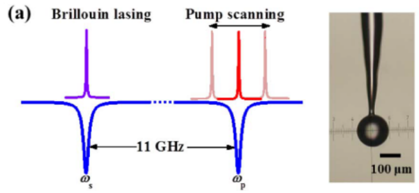
Brillouin lasing

TeO_2



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

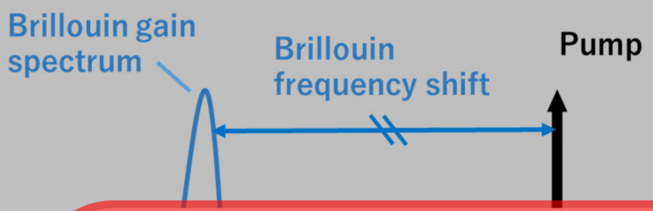
SiO_2



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

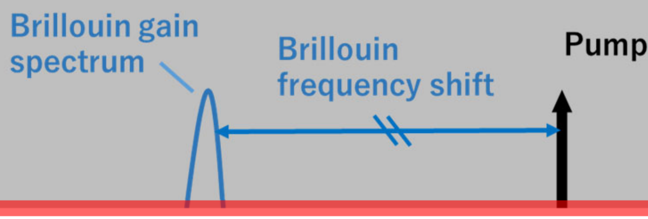
SBS in microcavities

Method1



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

Method2



ency

ency

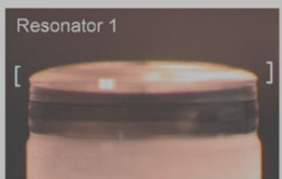
Method1 & 2

■ Precise control of cavity size

Brillouin lasing

Brillouin lasing

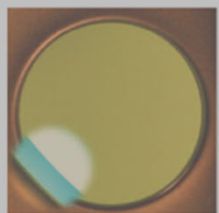
CaF_2



5.52 mm

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

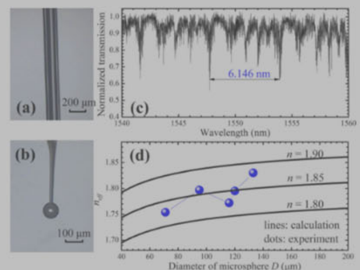
SiO_2 (silica)



6.02 mm

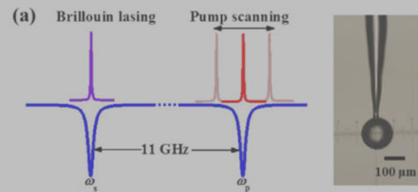
J. Li, K. Vahala et al., OE 20, 20170- (2012)

tellurite (TeO_2)



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

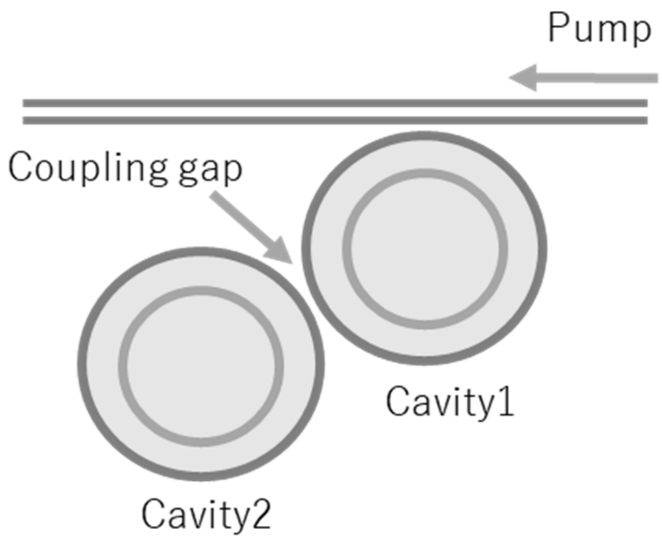
SiO_2

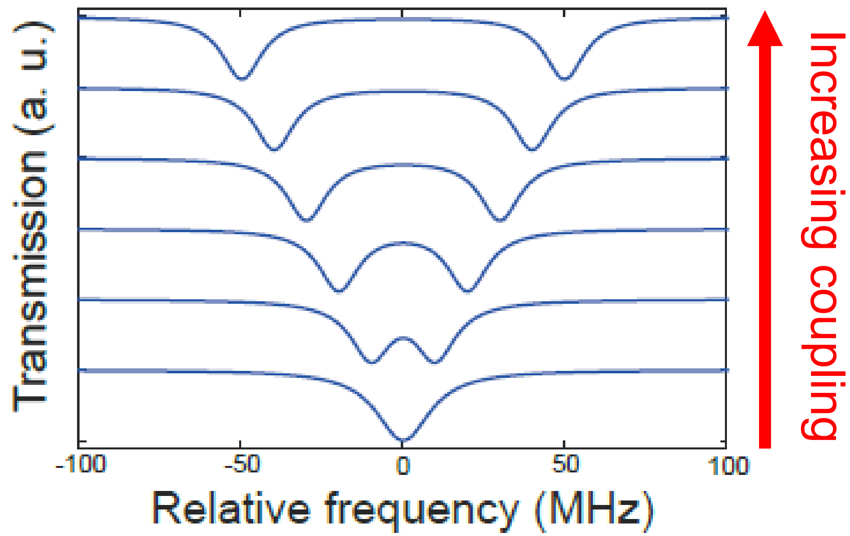


C. Guo, H. Xu et al., OL 40, 4971- (2015)

Proposed system (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

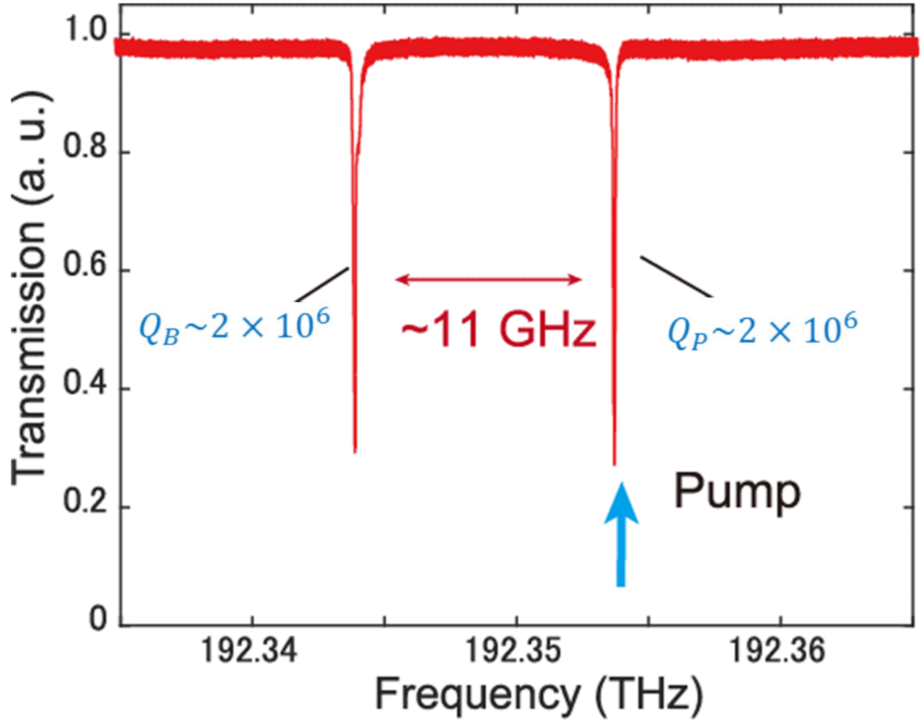
Y. Honda, et a. Appl. Phys. Lett. **112**, 201105 (2018). (**Featured Article**) (**Scilight**)

SBS in coupled cavities

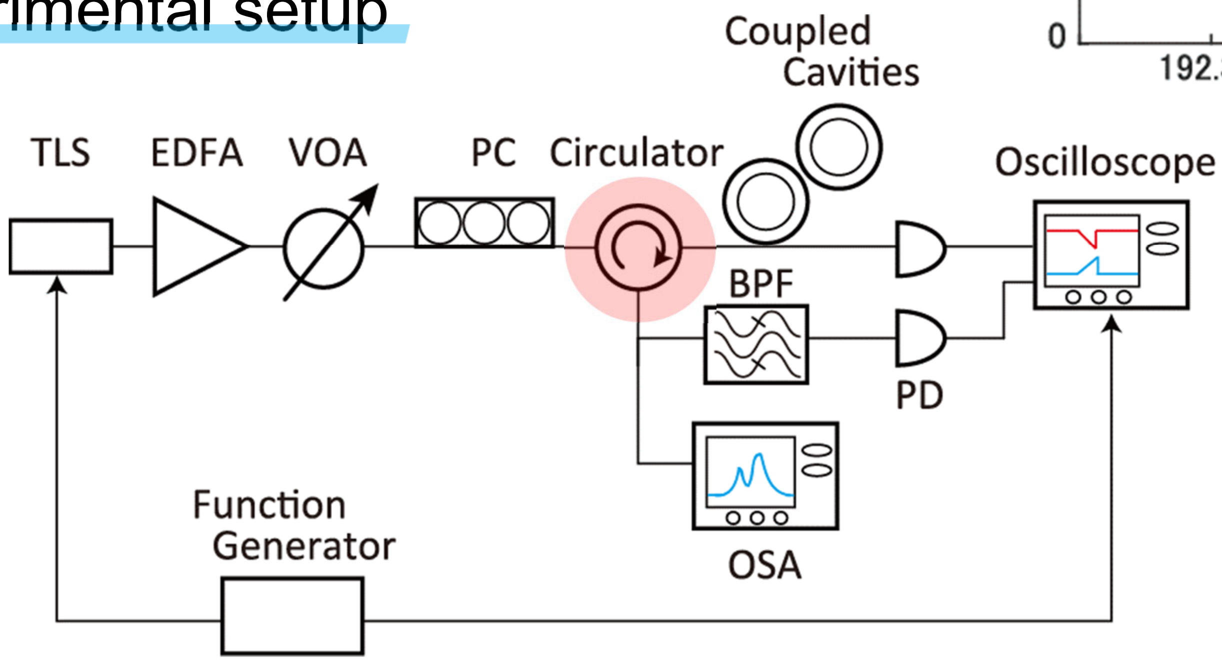
Y. Honda, et a. Appl. Phys. Lett. **112**, 201105 (2018). (**Featured Article**) (**Scilight**)

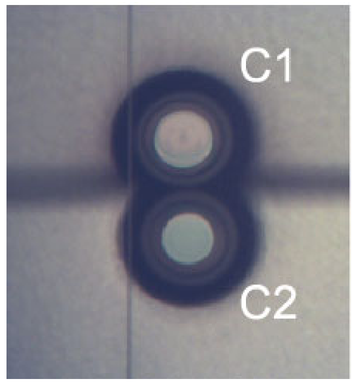
We achieved …

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



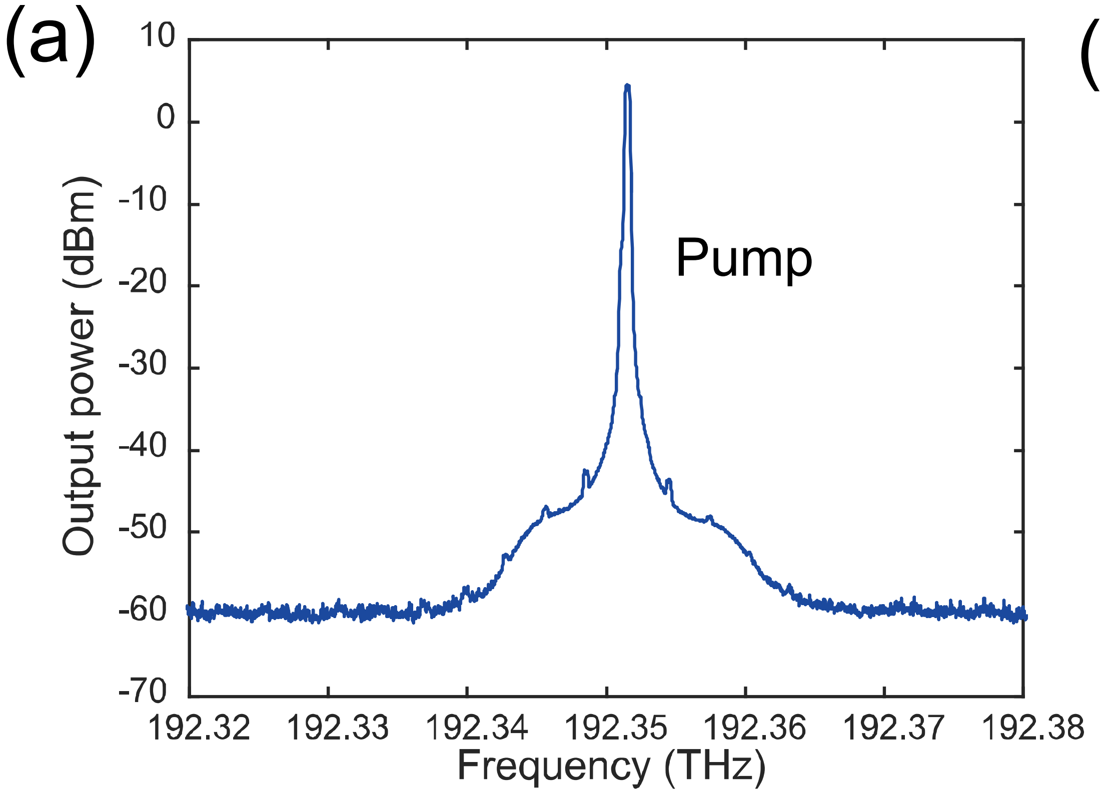
Experimental setup

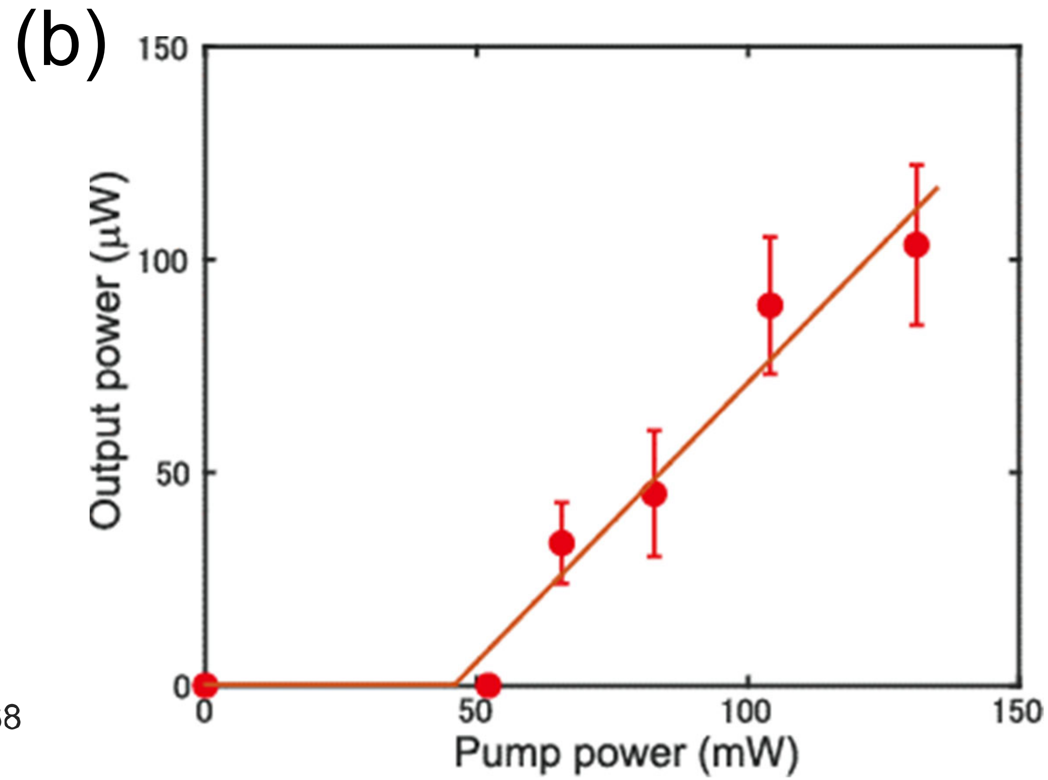




SBS in coupled cavities

Y. Honda, et a. Appl. Phys. Lett. **112**, 201105 (2018). (**Featured Article**) (**Scilight**)

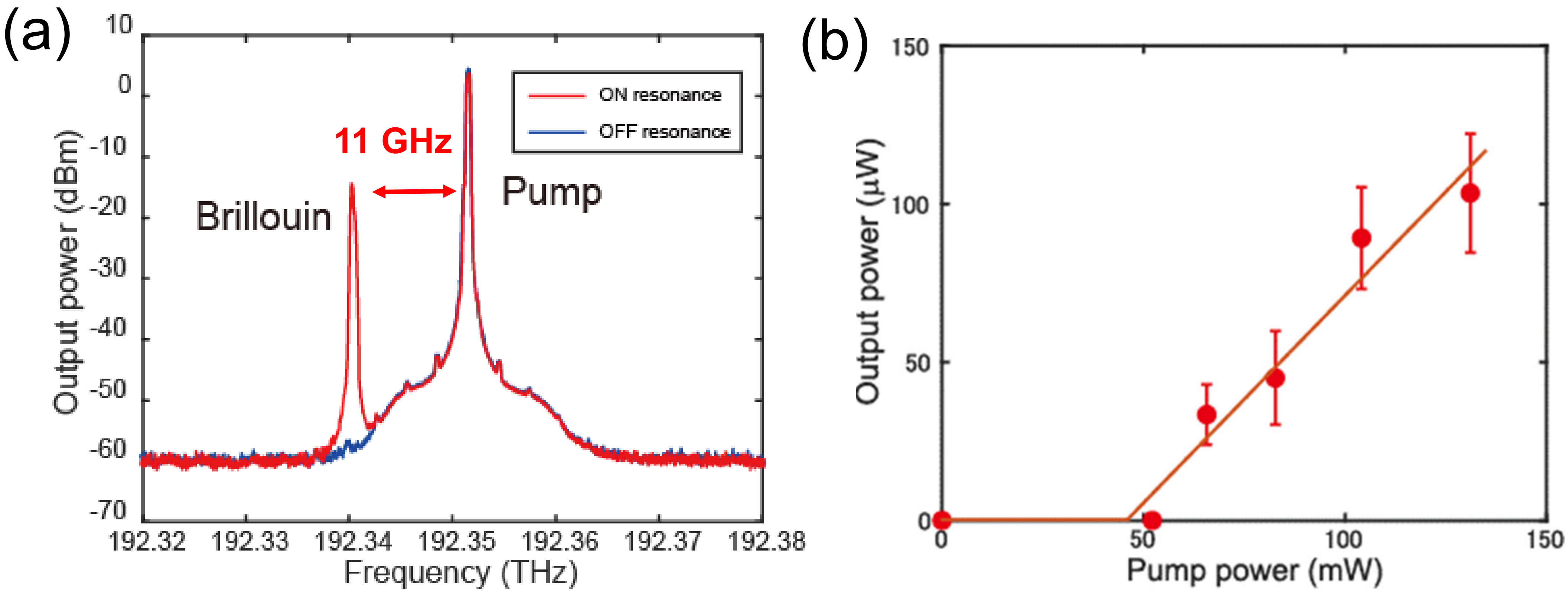




- We experimentally demonstrated SBS in coupled microcavities for the first time.
- We achieved a threshold power of about 50 mW.

SBS in coupled cavities

Y. Honda, et a. Appl. Phys. Lett. **112**, 201105 (2018). (**Featured Article**) (**Scilight**)



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

Summary

1. Microcavity comb generation
   a) Theory and essence
   b) Raman comb
   c) THG conversion (broader bandwidth)

2. Brillouin lasing
   a) Coupled cavity system
   b) Brillouin lasing