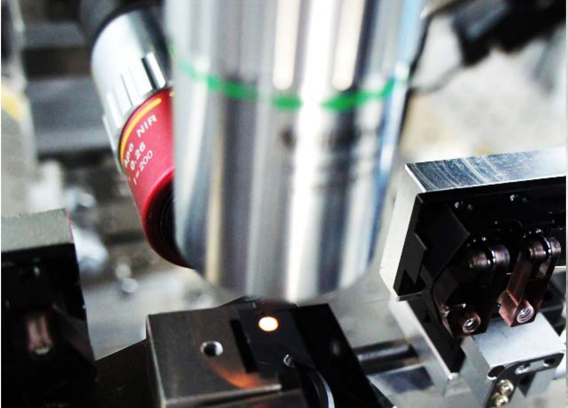
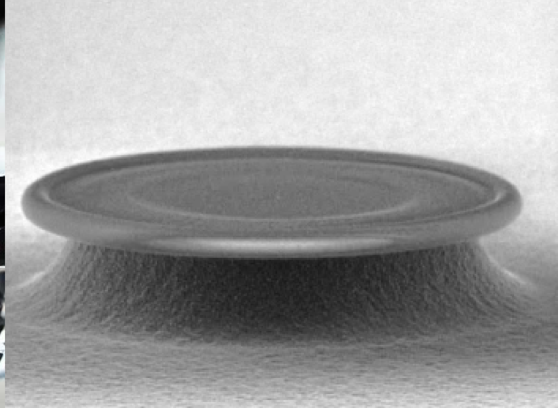
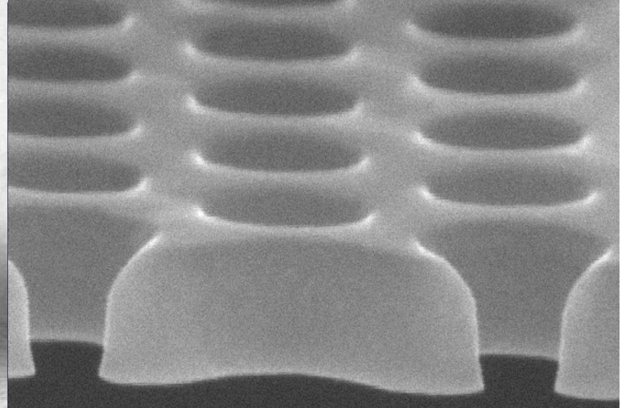
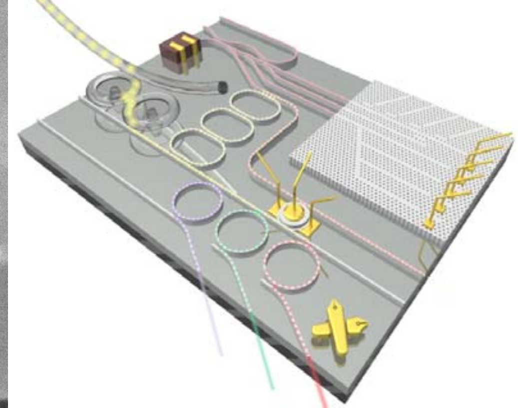

Integrated Photonics Research, Silicon, and Nano-Photonics (IPR)
IM4A.3 17:15 - 17:45 Jul. 24. 2017

Stimulated Raman Scattering Comb in a Silica Microcavity

Takasumi Tanabe

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Keio University, Japan

Outline

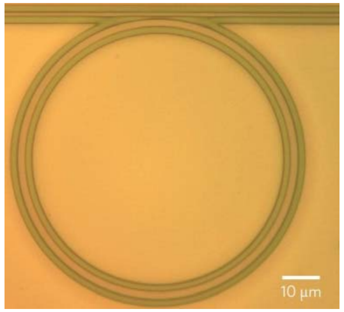
1. Introduction / Motivation

2. Competition between SRS and FWM

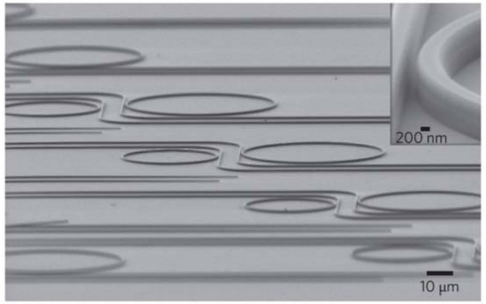
3. Transverse mode coupling w/ SRS

4. Broad bandwidth visible light via SRS & THG

High-Q whispering-gallery mode microcavities

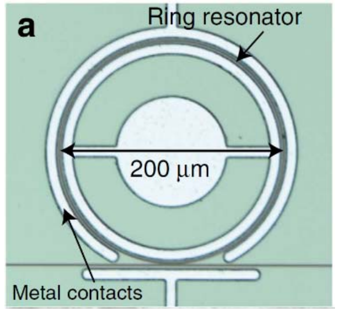


Silicon nitride
Weiner group (Purdue)

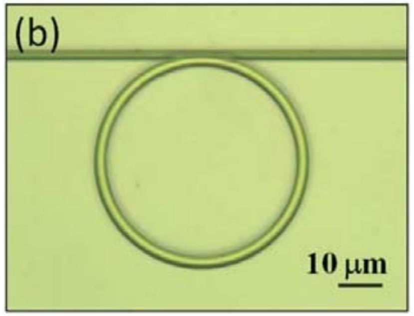


Diamond
Loncar group (Harvard)

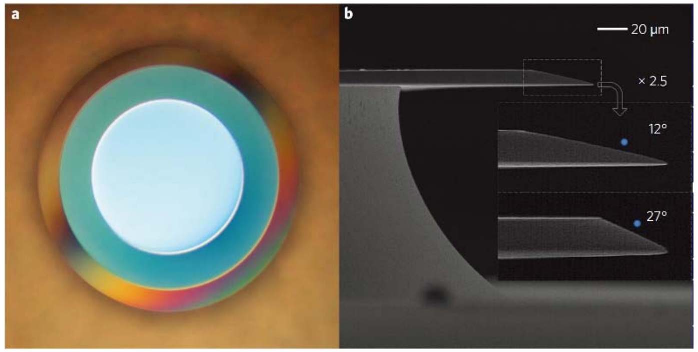
Crystalline (CaF_2, MgF_2, etc)
Kippenberg group (EPFL, Swiss),
Makei group (OE Waves)



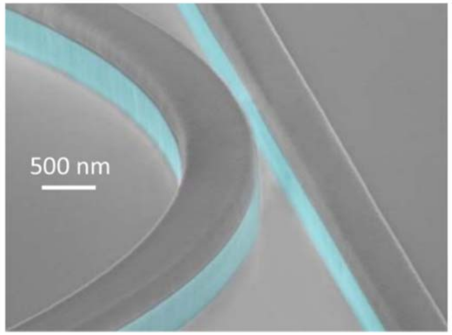
Silicon
Gaeta group (Columbia)



AlN
Tang group (Yale)



Silica
Vahala group (Caltech)



AlGaAs
Yvind group (DTU, Denmark)

◆Q-factor

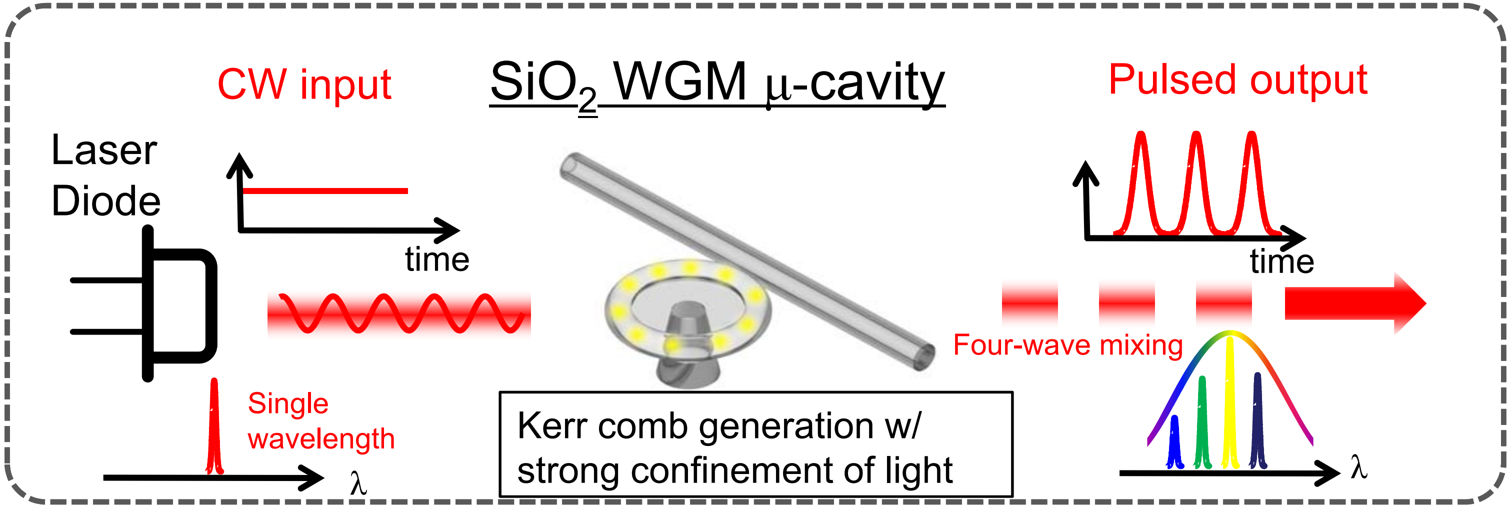
$$Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}}$$

◆Photon density

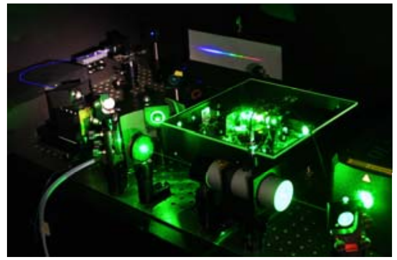
$$\propto Q/V$$

Kerr comb in microcavity system

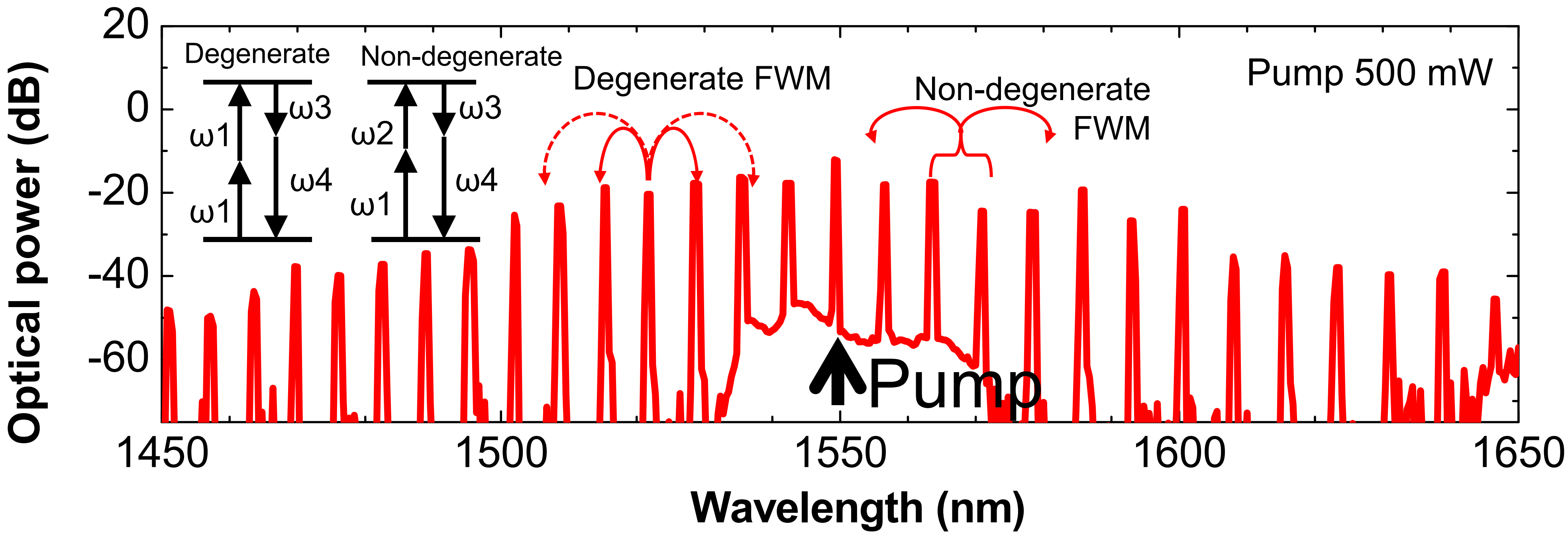
Convert CW laser to ultrashort pulse train w/ >600 GHz repetition rate



Ti:Sapphire laser based comb

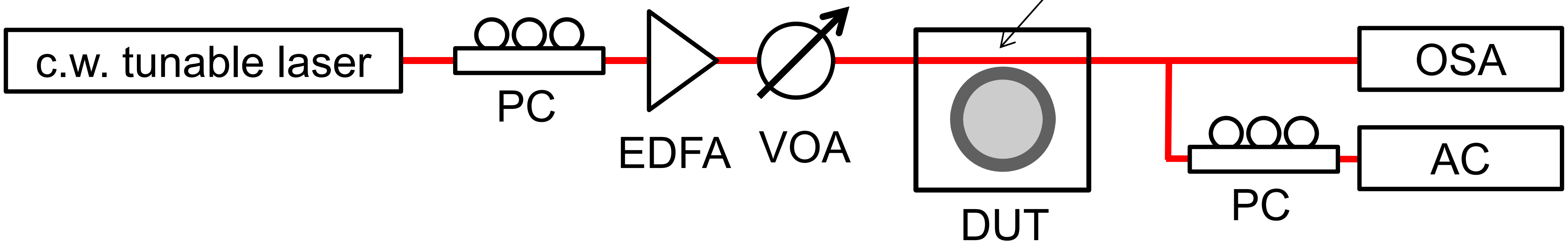


large & expensive

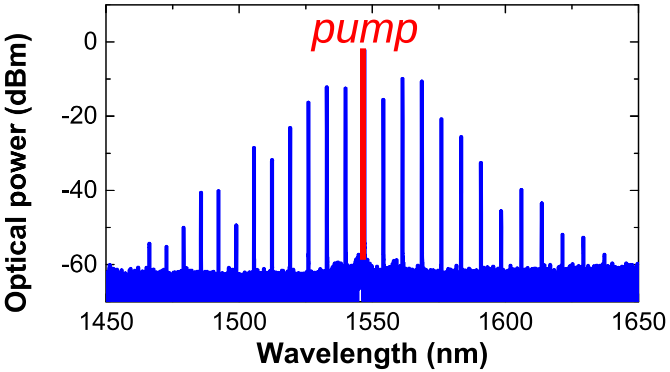


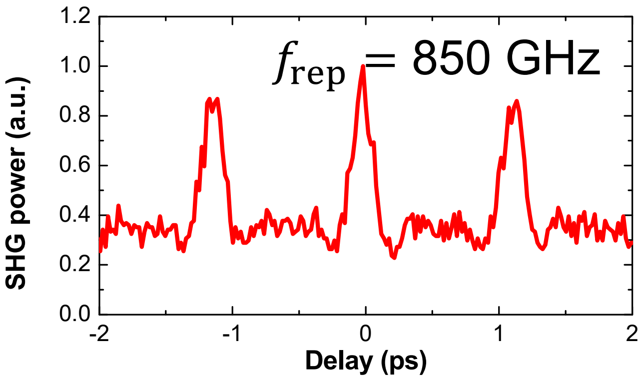
Kerr comb in a silica toroidal microcavity

▶Experimental setup

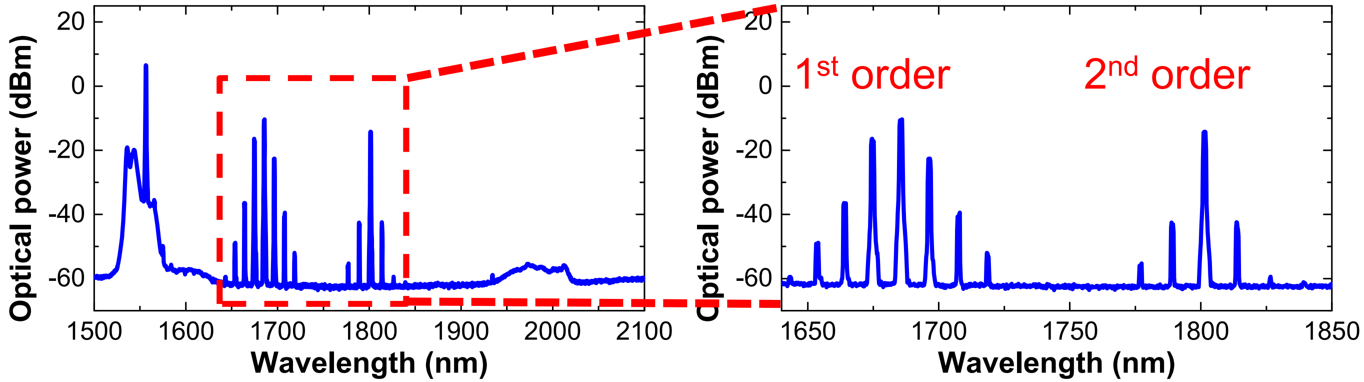


▶FWM only

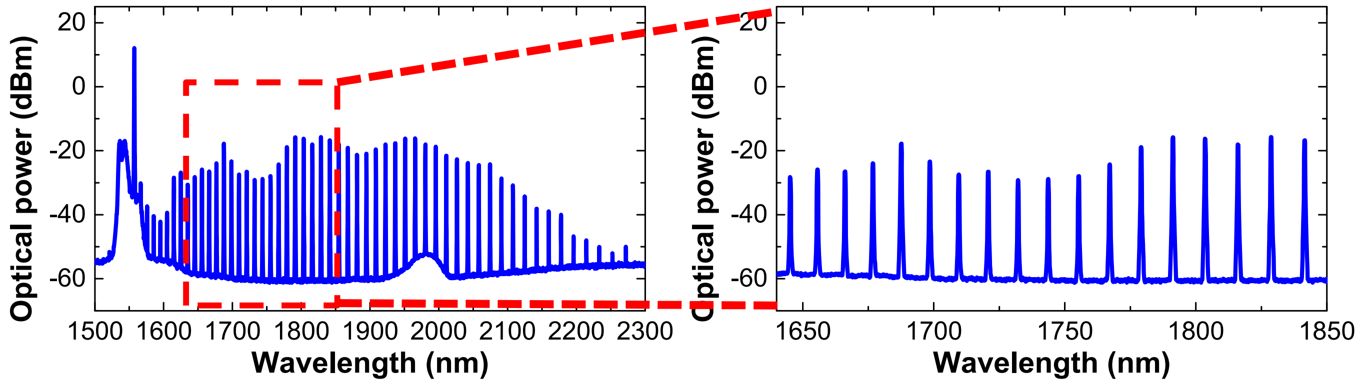




▶Raman (Pump:1556.4 nm, 250 mW)



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

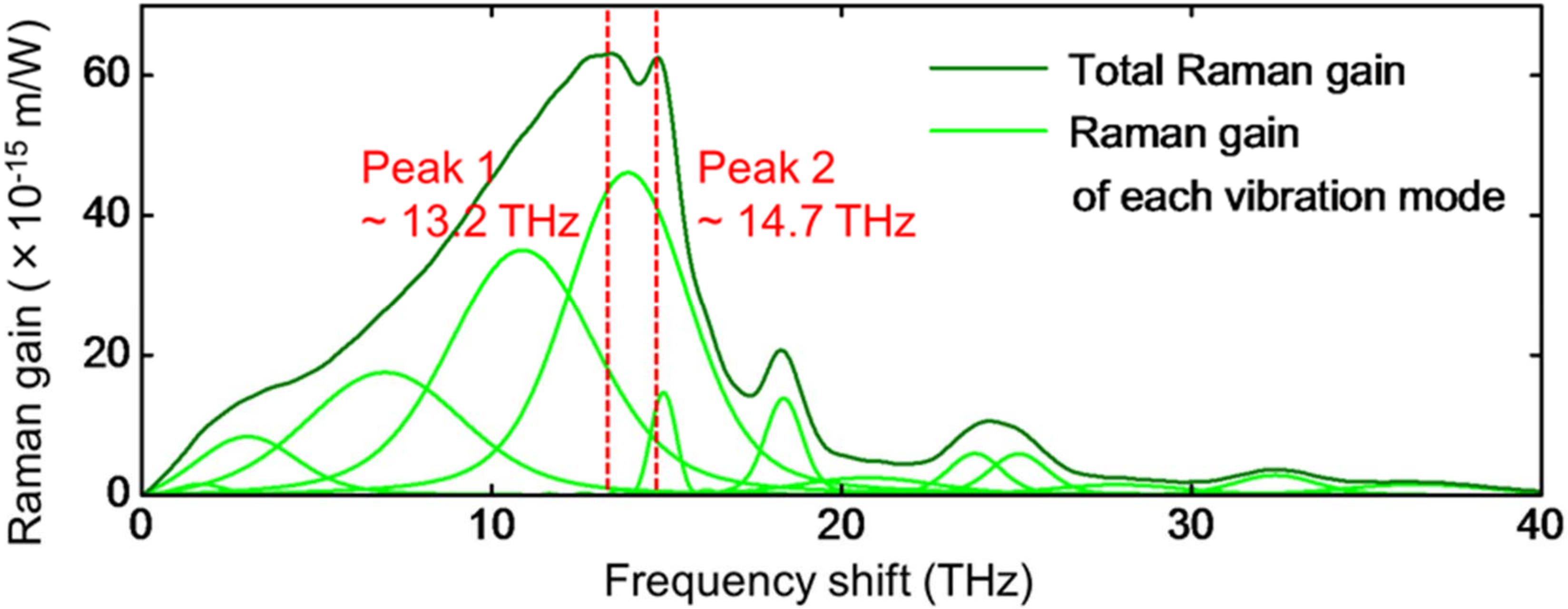


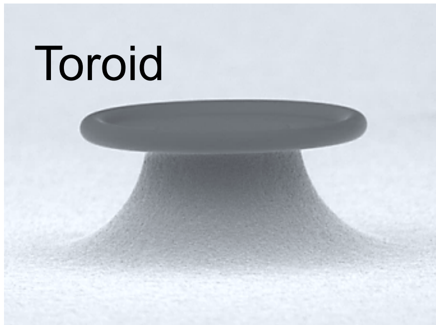
Motivation

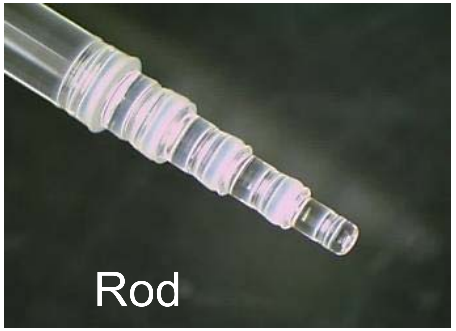
1. Understanding the effect of SRS is important for Kerr comb generation because these processes compete with each other inside a microcavity.

2. Coherent Raman combs can be used for sensors, microwave generators, and small pulse laser sources.

☞We study Raman comb formation inside silica WGM microcavities







→ Silica has broadband Raman gain

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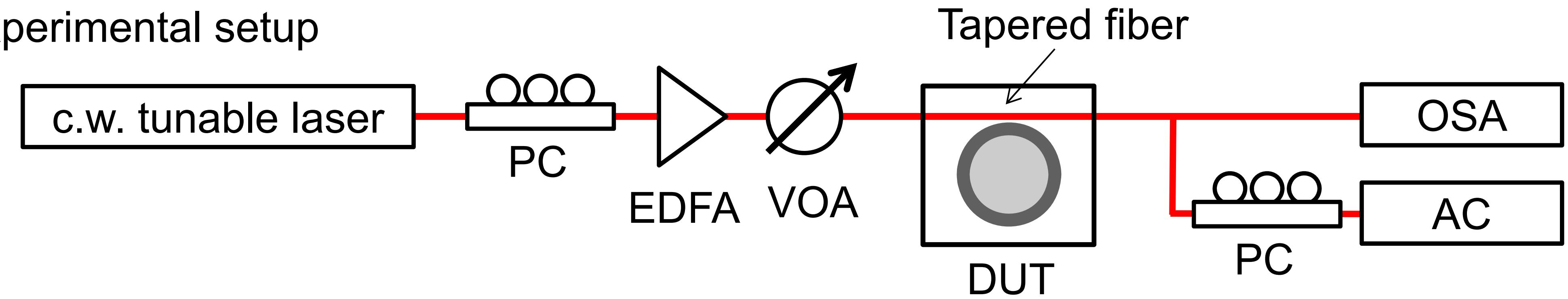
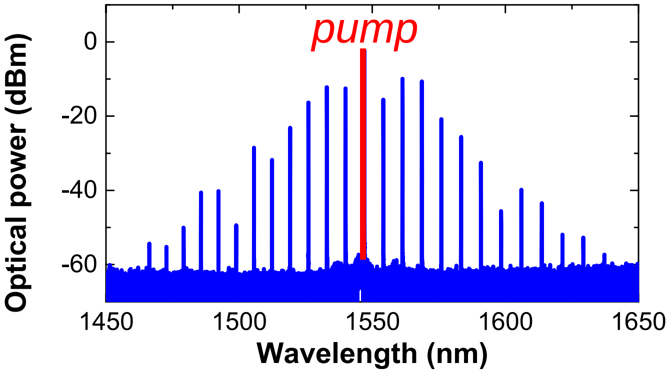
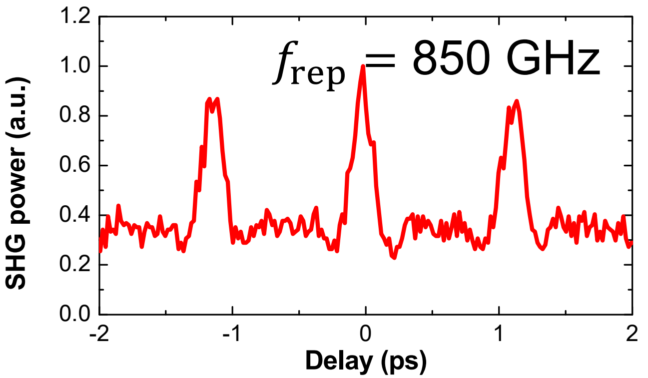
Kerr comb in a silica toroidal microcavity

▶Experimental setup

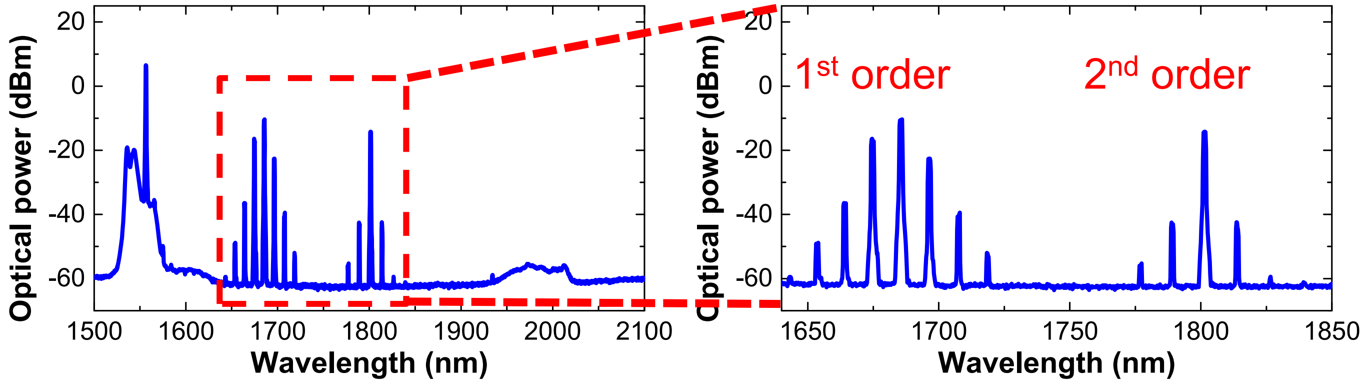


▶FWM only

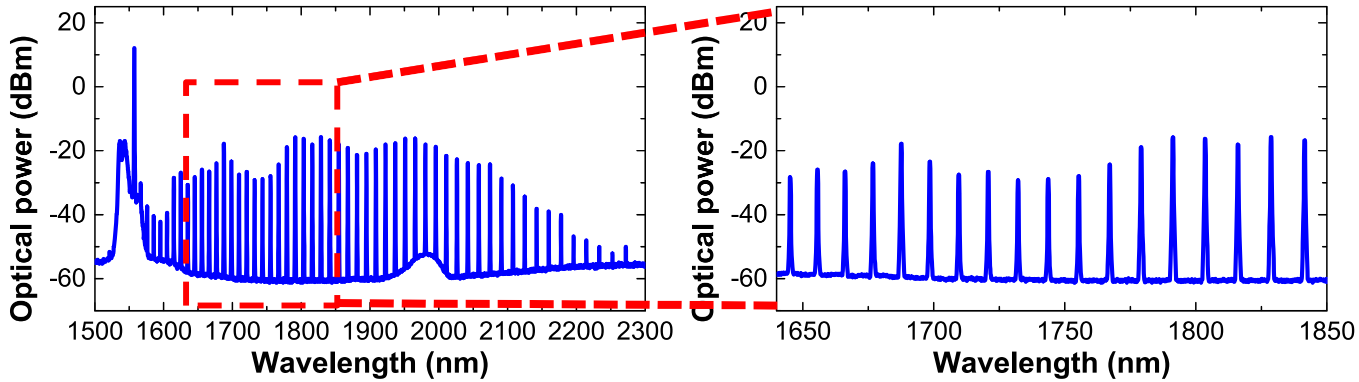




▶Raman (Pump:1556.4 nm, 250 mW)



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



Four-wave mixing gain

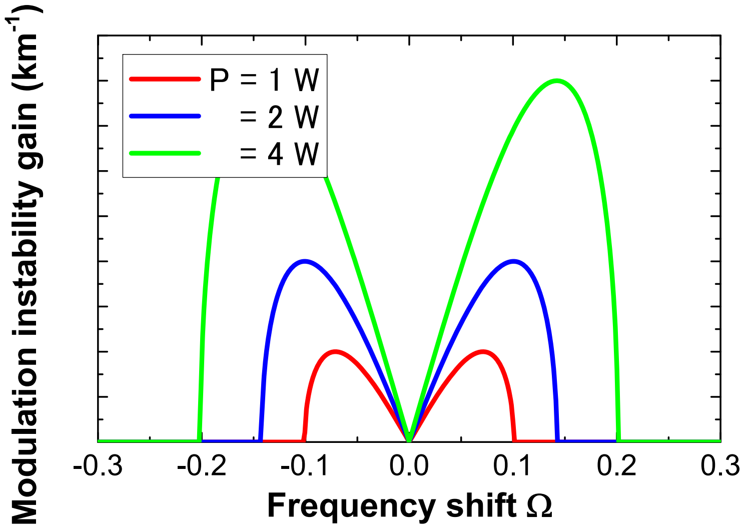
[Case 1: in fiber propagation]

$$g(\Omega) = |\beta_2 \Omega| \sqrt{\Omega_c^2 - \Omega^2}$$

$$\Omega_c^2 = \frac{4\gamma P_0}{|\beta_2|}$$

γ : nonlinear coefficient

β_2 : second-order dispersion



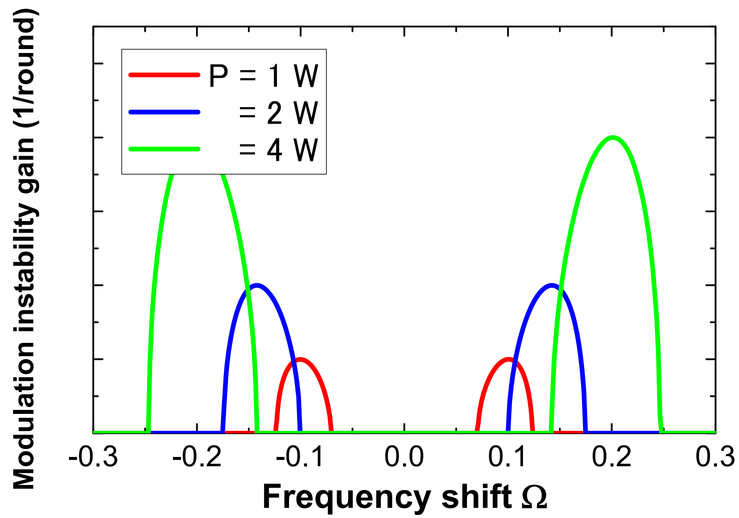
[Case 2: in cavity resonance]

$$g(\Omega) = \sqrt{(\gamma L P_0)^2 - (\delta_{\mathrm{miss}})^2}$$

- detuning from a cavity mode

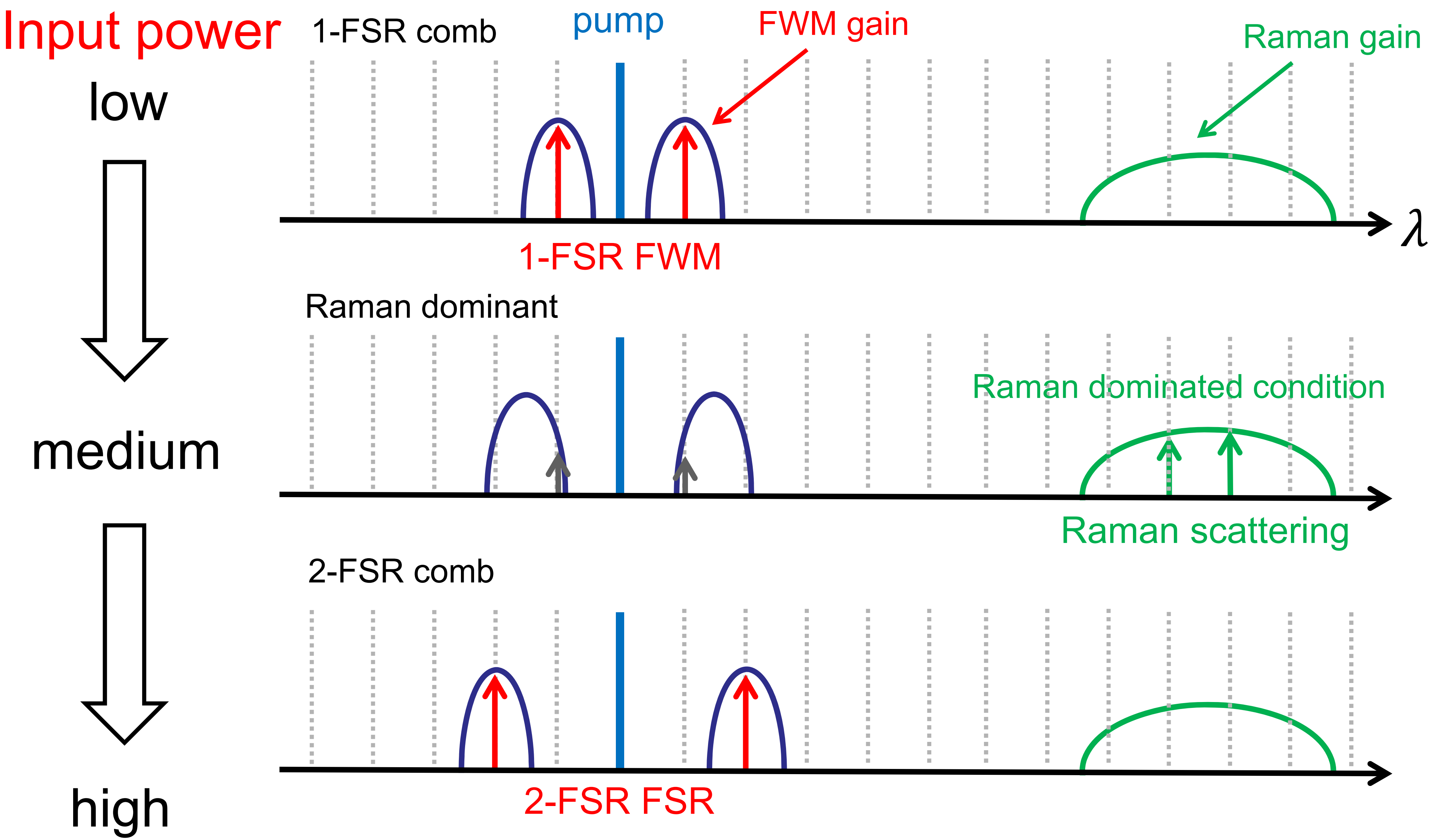
$$\delta_{\mathrm{miss}} = \delta_0 - \beta_2 L \Omega^2 / 2 - 2\gamma L P_0$$

δ_0 : detuning of input

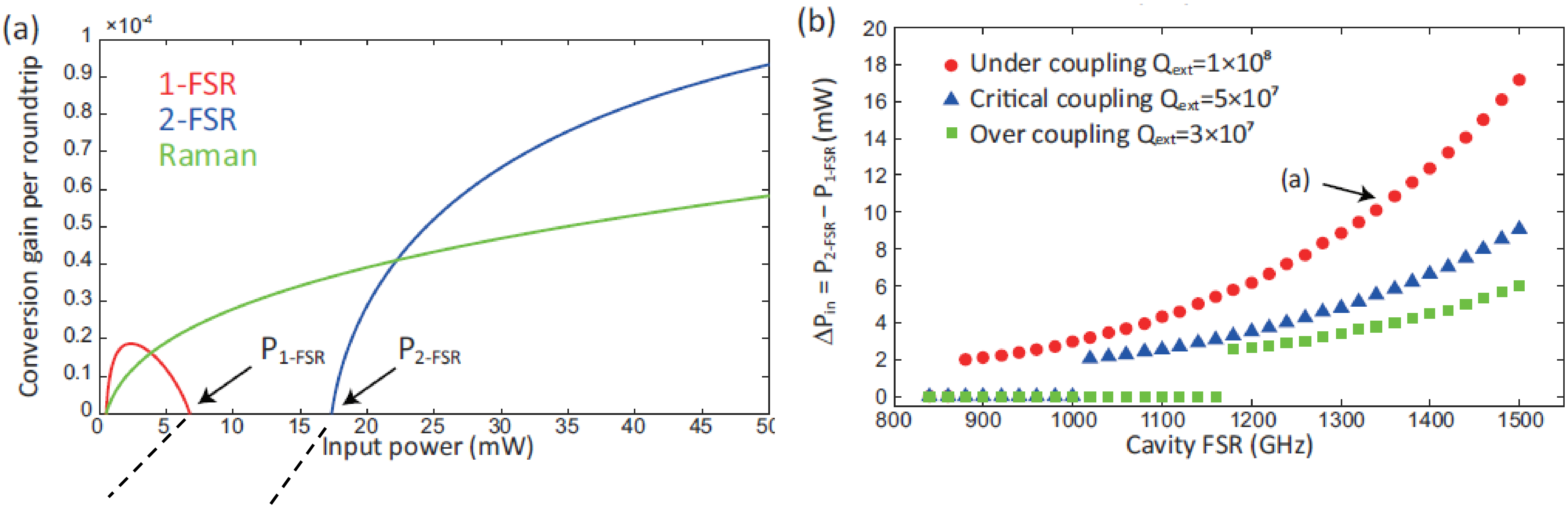


Selection of proper input power is needed to achieve gain in a desired frequency.

Competition between Raman & FWM gain



Steady-state analysis of gain transition

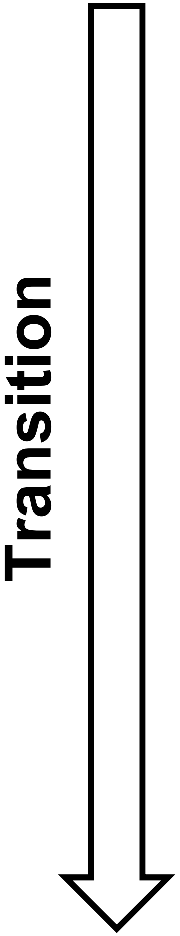


Only Raman gain $\Delta P_{\mathrm{in}} = P_{2\mathrm{FSR}} - P_{1\mathrm{FSR}}$

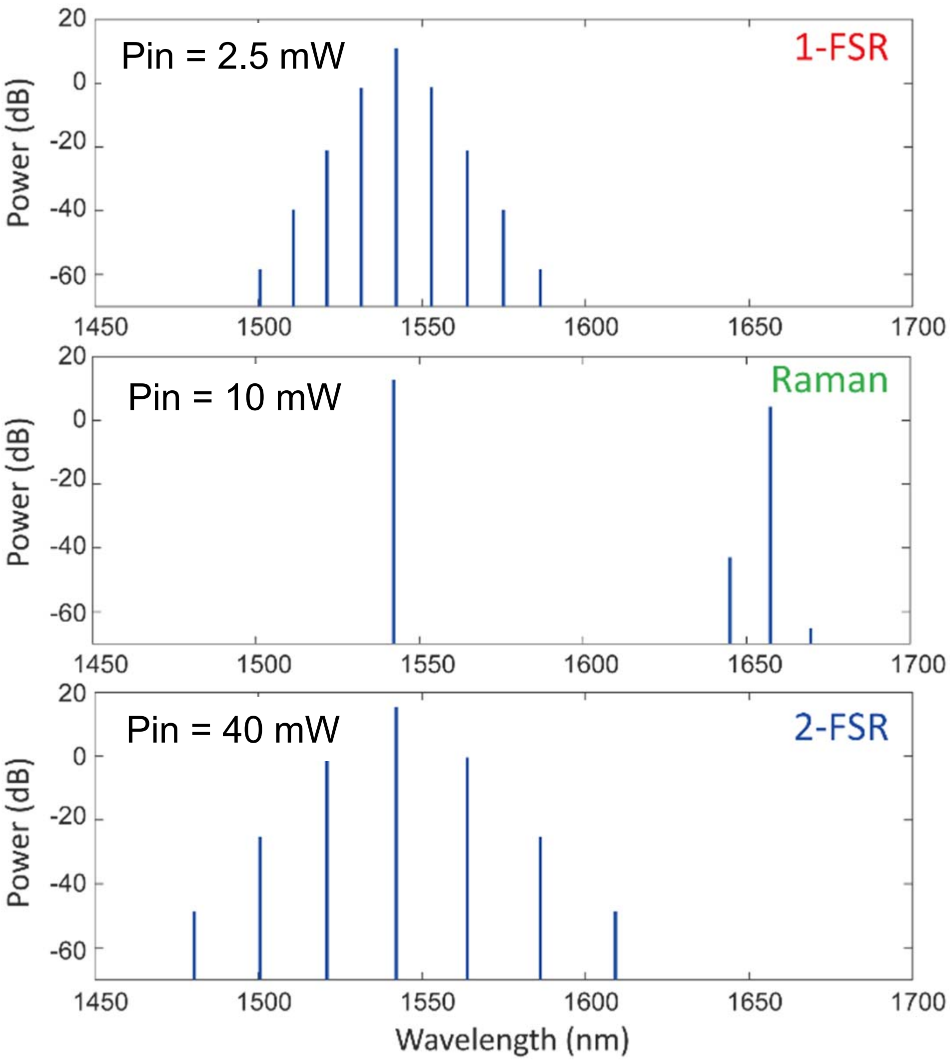
For large margin ΔP_{in} (Raman region)

- ✓ Under coupling condition
- ✓ Large cavity FSR (small diameter)

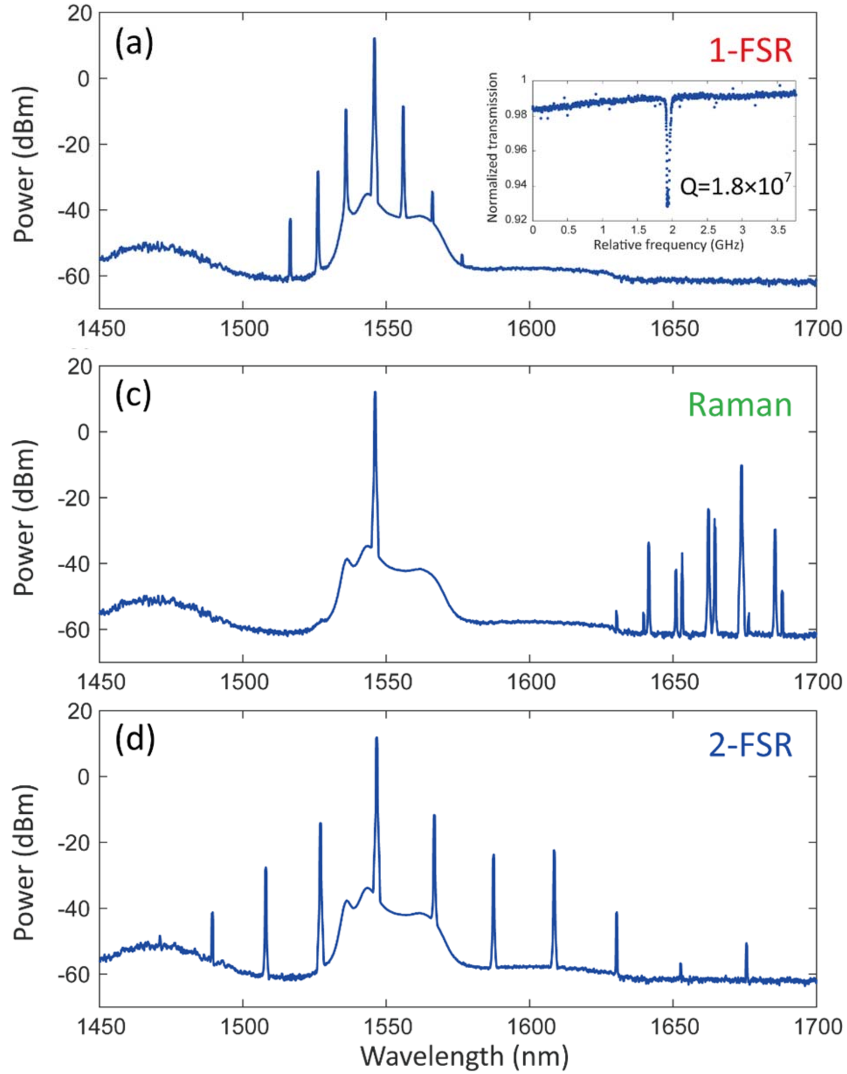
Simulation/Experiment results



Simulation (Lugiato-Lefever equation)



Experiment



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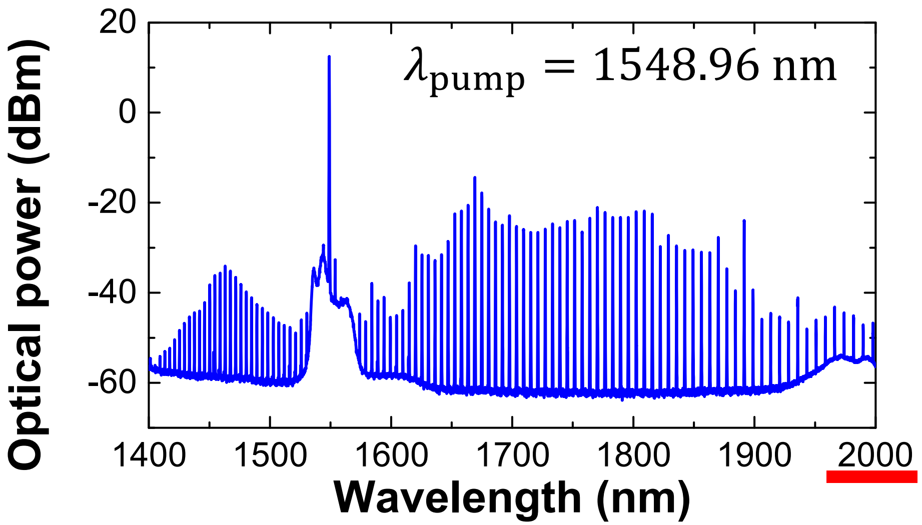
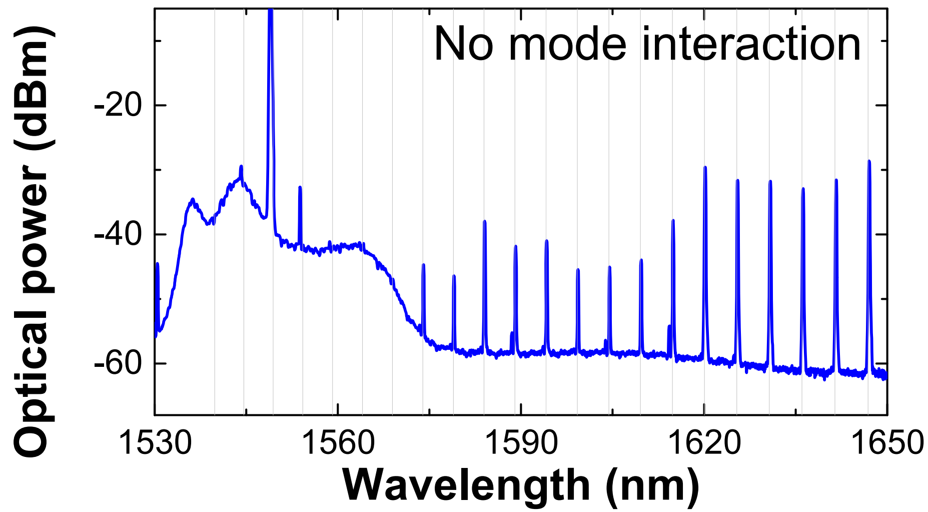
Experimental observation of mode interaction via SRS

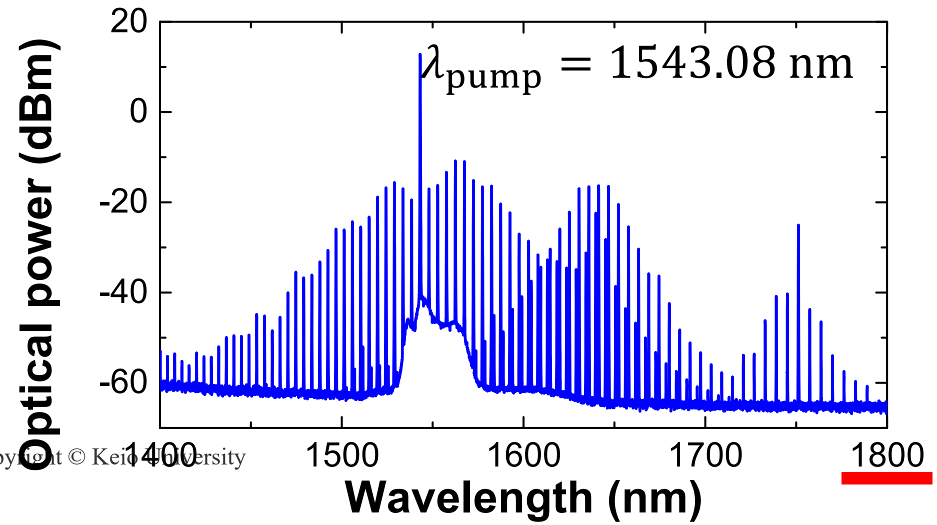
T. Kato, *et al.*, Opt. Express **25**, 857 (2017).

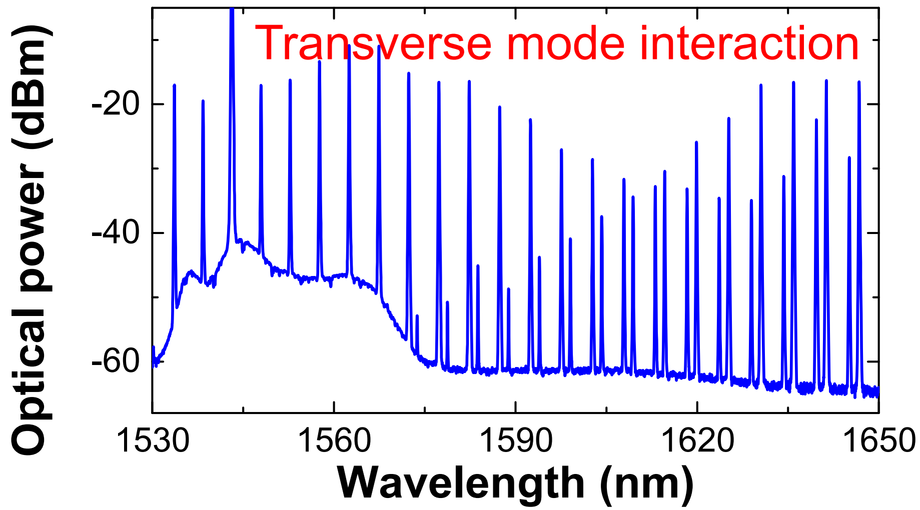
At a high power input (~1 W),

Magnified (1530~1650 nm)

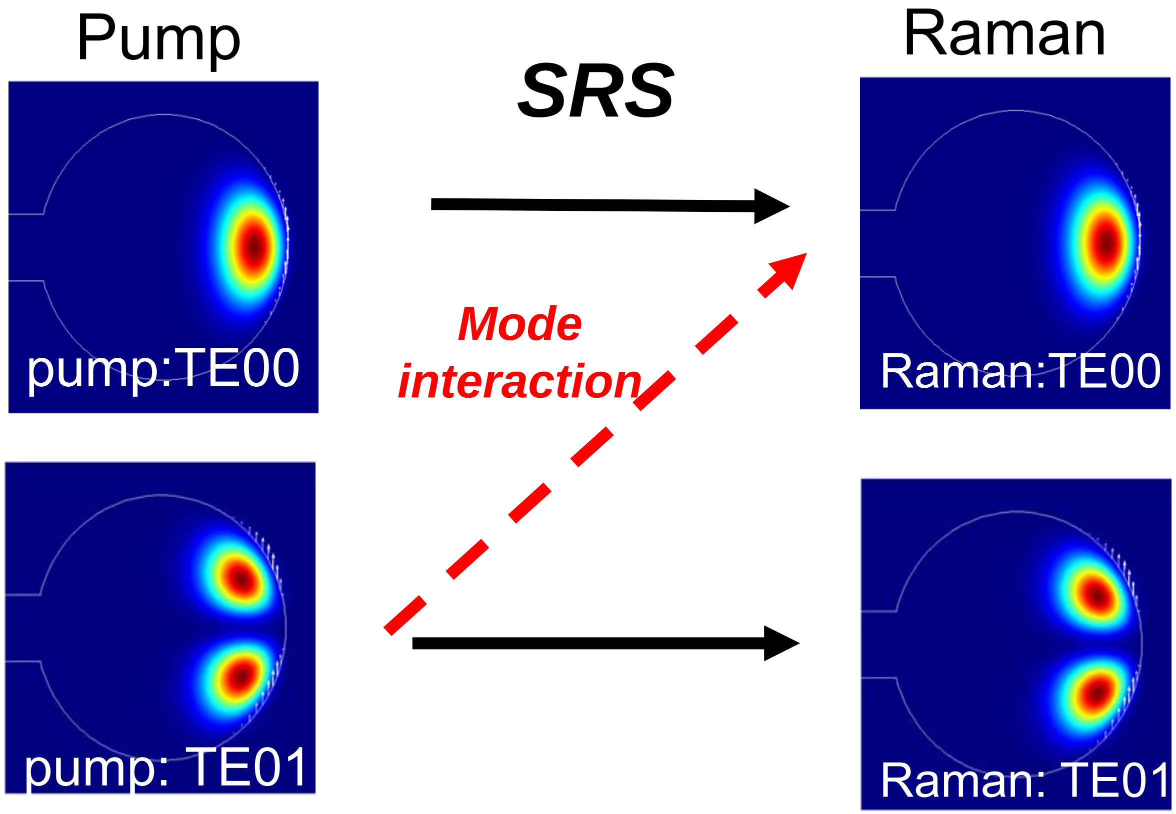








SRS threshold



Same mode family

$$P_{\mathrm{th}}(\mathrm{TE}_{00} \rightarrow \mathrm{TE}_{00})$$

Transverse mode interaction

$$P_{\mathrm{th}}(\mathrm{TE}_{00} \rightarrow \mathrm{TE}_{01})$$

SRS threshold power

$$P_{th} = \frac{\pi^2 n^2 V_{\mathrm{eff}}}{\lambda_p \lambda_R g_R} Q_e^P \left(\frac{1}{Q_T^P}\right)^2 \frac{1}{Q_T^R}$$

λ_p: pump wavelength

λ_R: SRS wavelength

g: nonlinear coefficient

V_{eff}: nonlinear mode volume

Q_e^P: external Q factor of pump mode

Q_T^P: total Q factor of pump mode

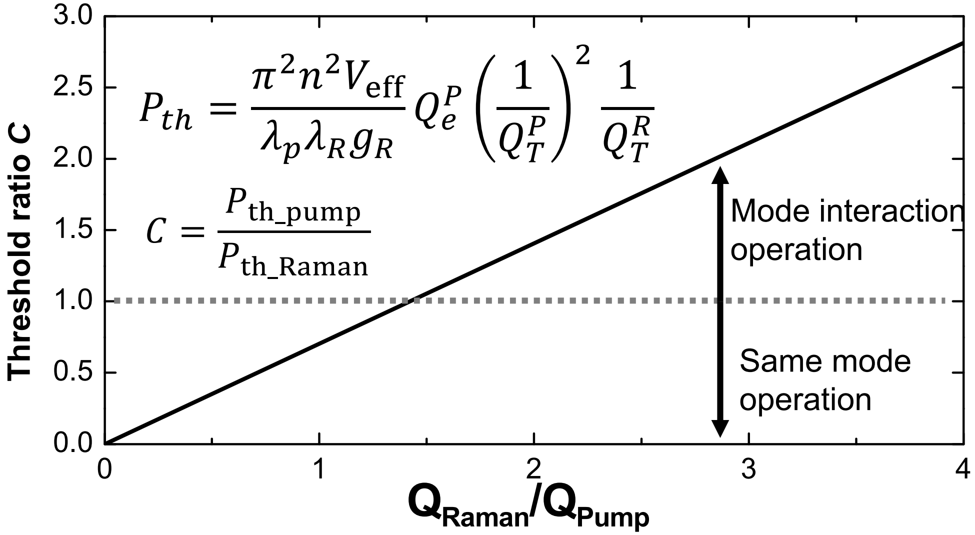
Q_T^R: total Q factor of Raman mode

T. J. Kippenberg, *et al.*, IEEE J. Sel. Top. Quantum Electron. 84, 1219 (2004).

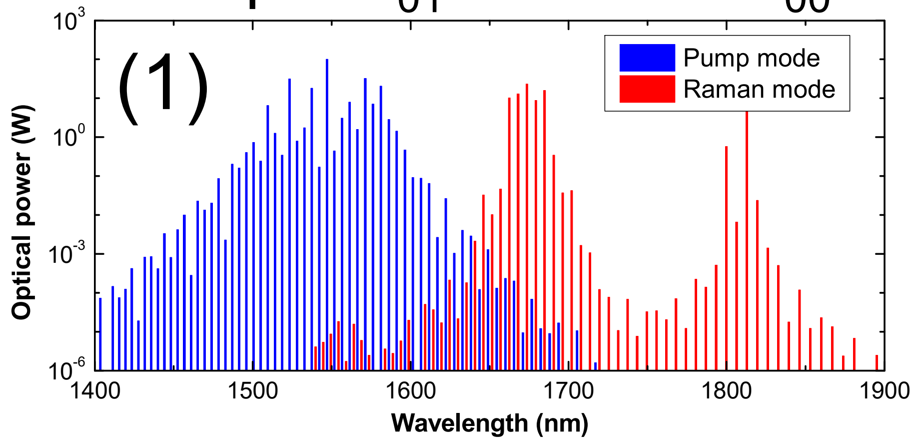
Analysis of transverse mode interaction

T. Kato, *et al.*, Opt. Express **25**, 857 (2017).

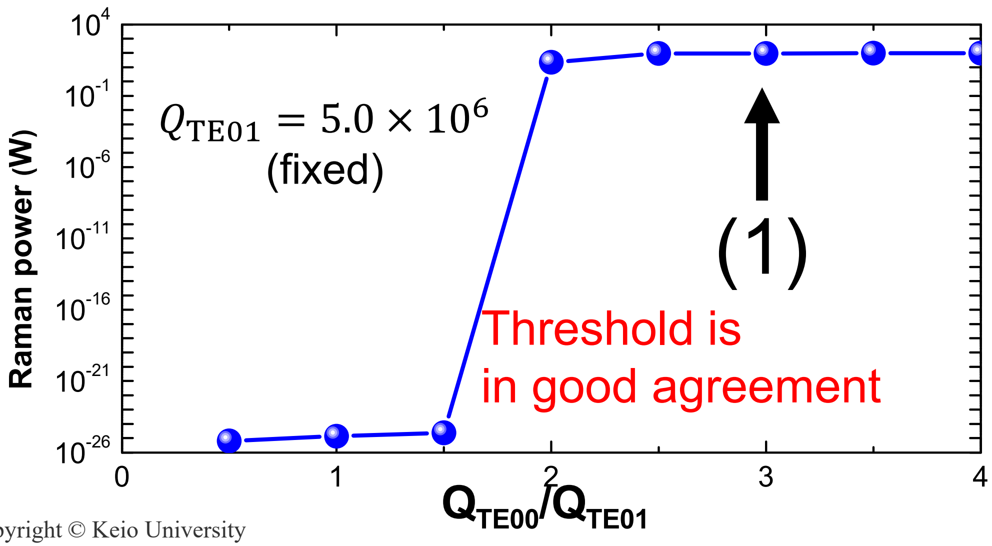
▶Q dependency (analytical)



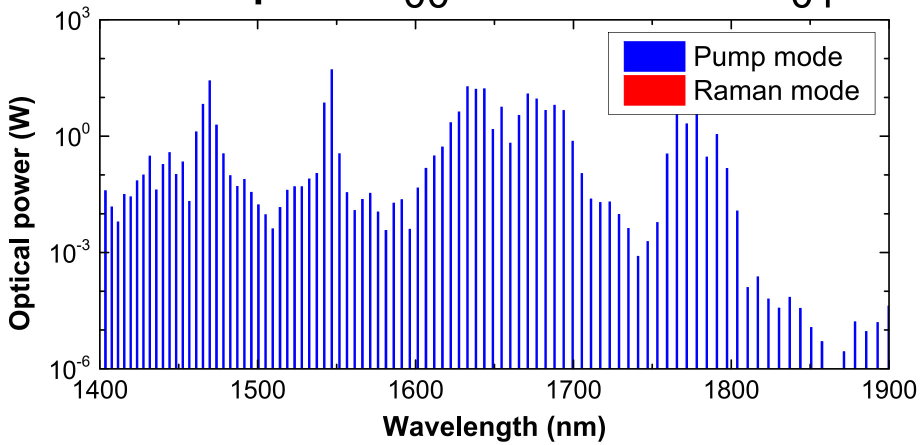
Pump: TE_{01} Raman: TE_{00}



▶Q_{TE00} dependency (numerical)

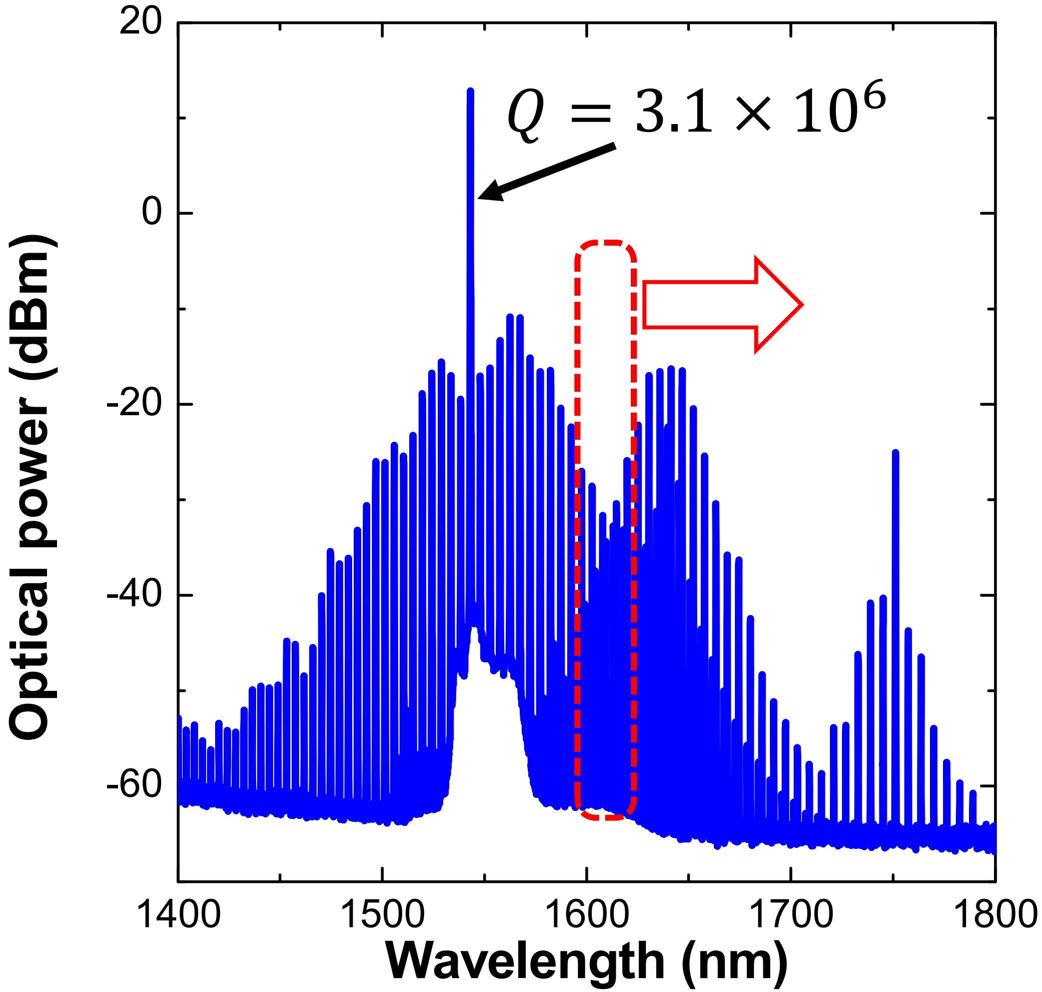


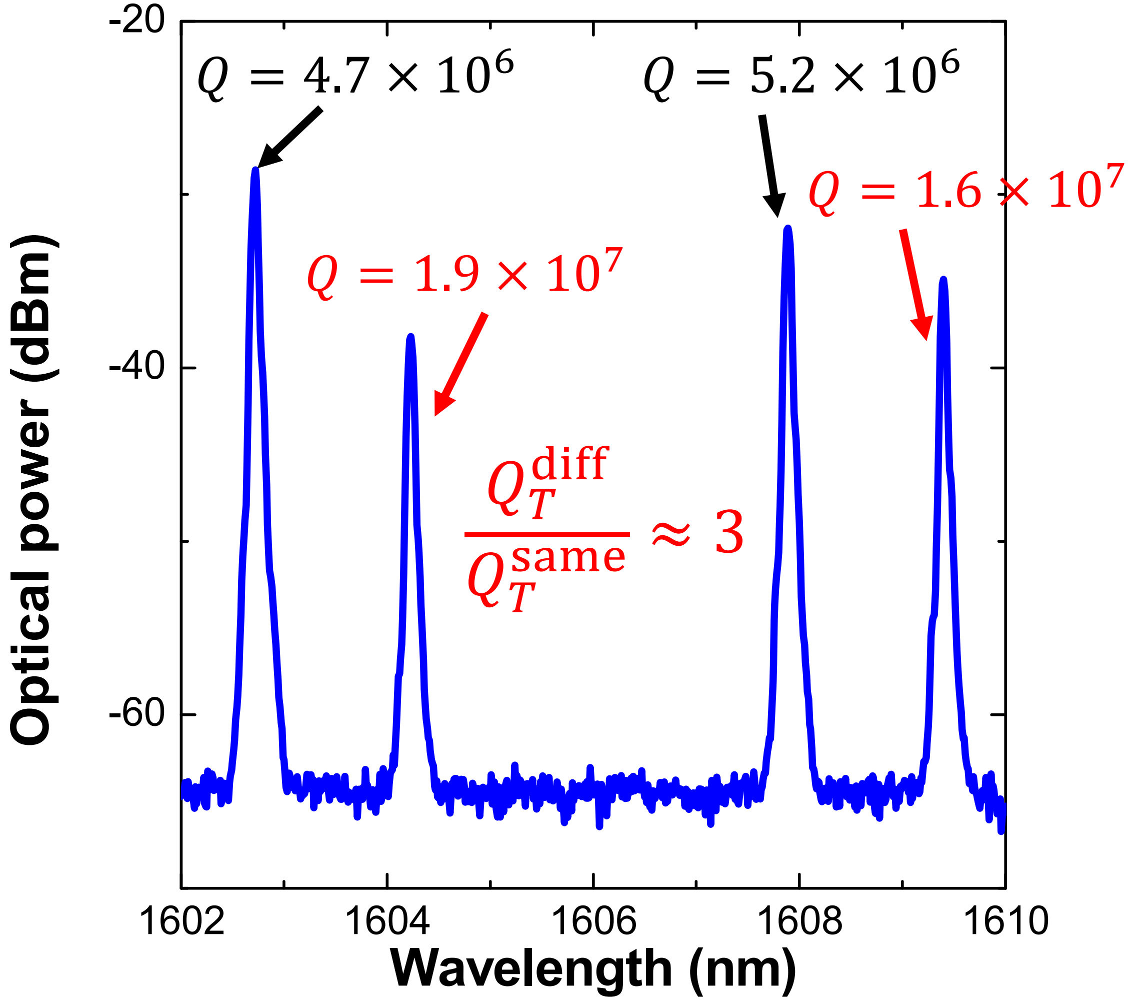
Pump: TE_{00} Raman: TE_{01}



Experiment: Transverse mode coupling via SRS

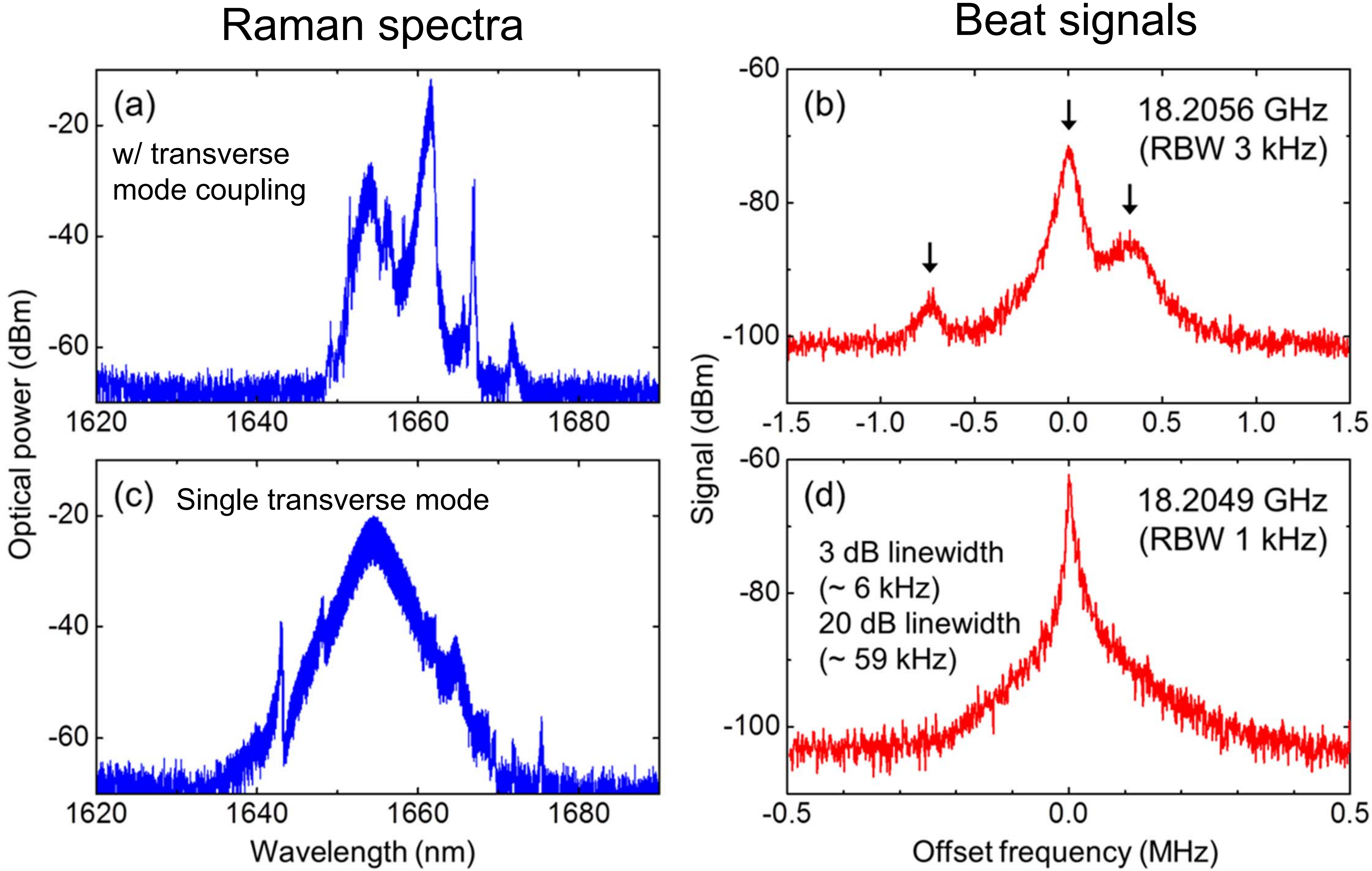
T. Kato, *et al.*, Opt. Express **25**, 857 (2017).





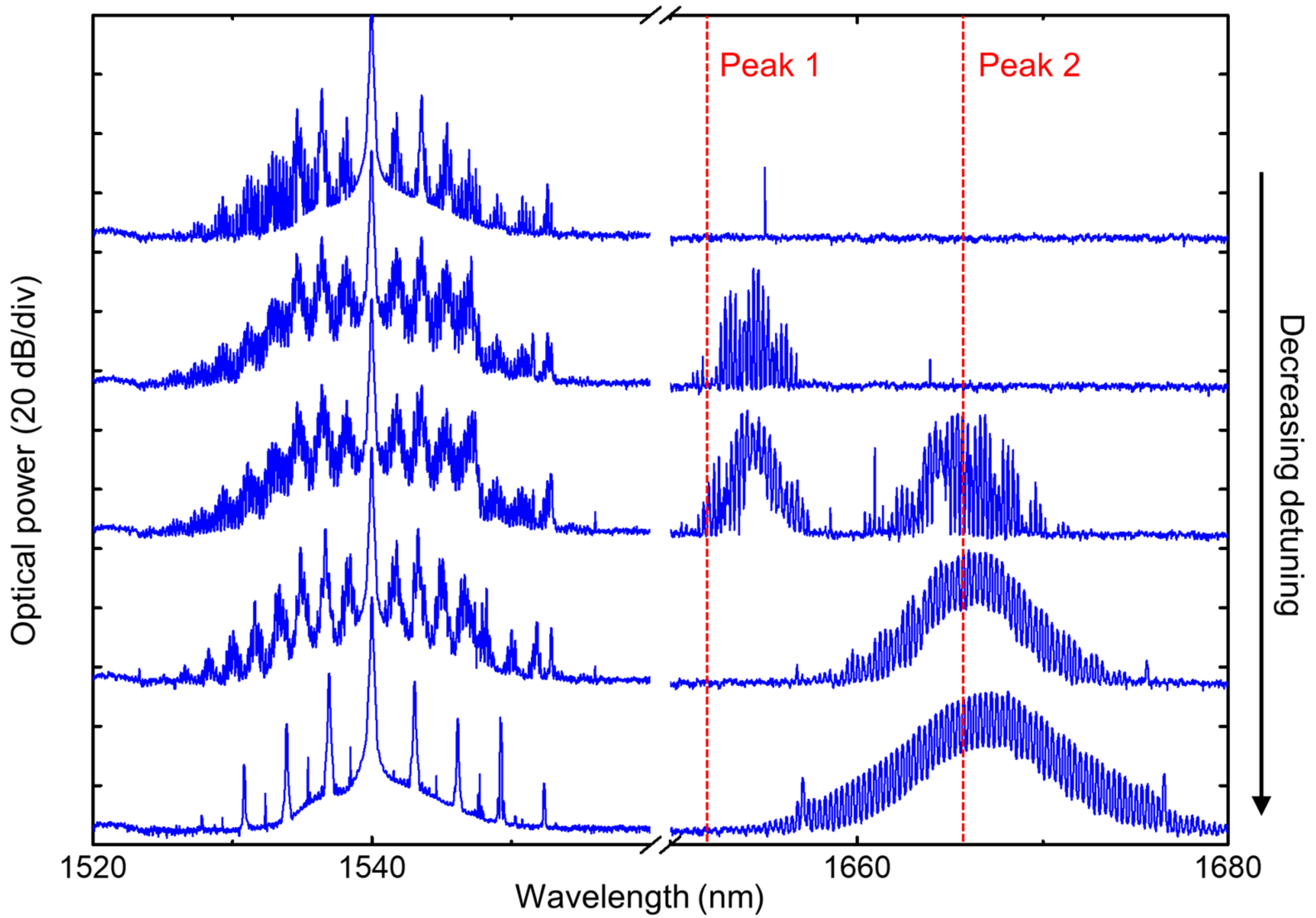
Beat signals of Raman combs

Different pump mode

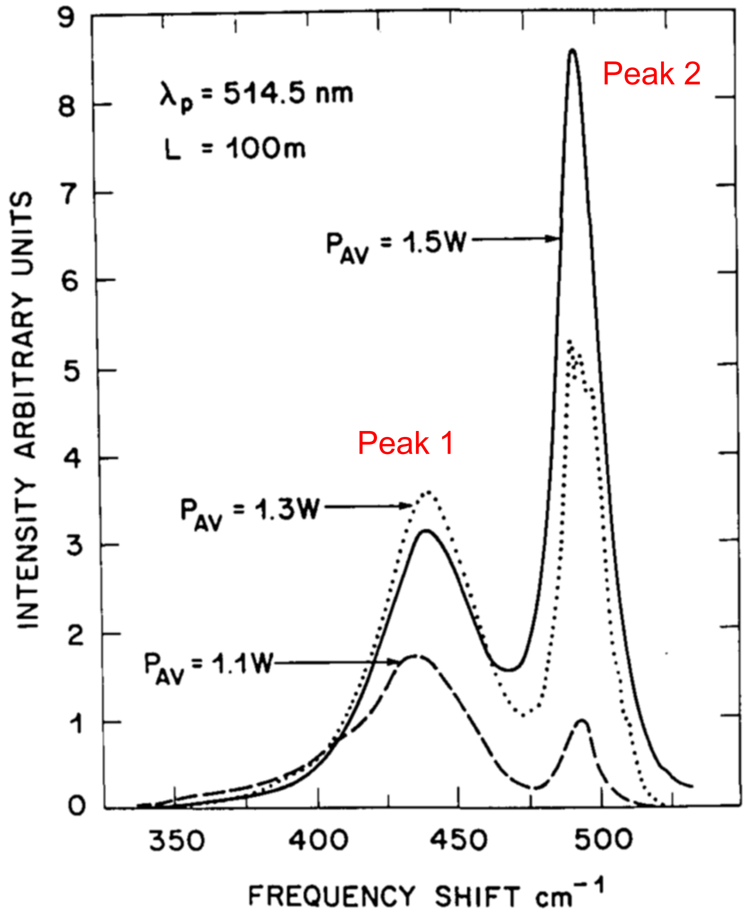


Raman comb formation in silica rod microcavity

Silica microcavity



Silica fiber



R. H. Stolen et al., JOSAB **1**, 652 (1984)

Raman comb offset was at Peak2 with a small detuning (high intracavity power), which is similar behavior to that observed in silica fibers.

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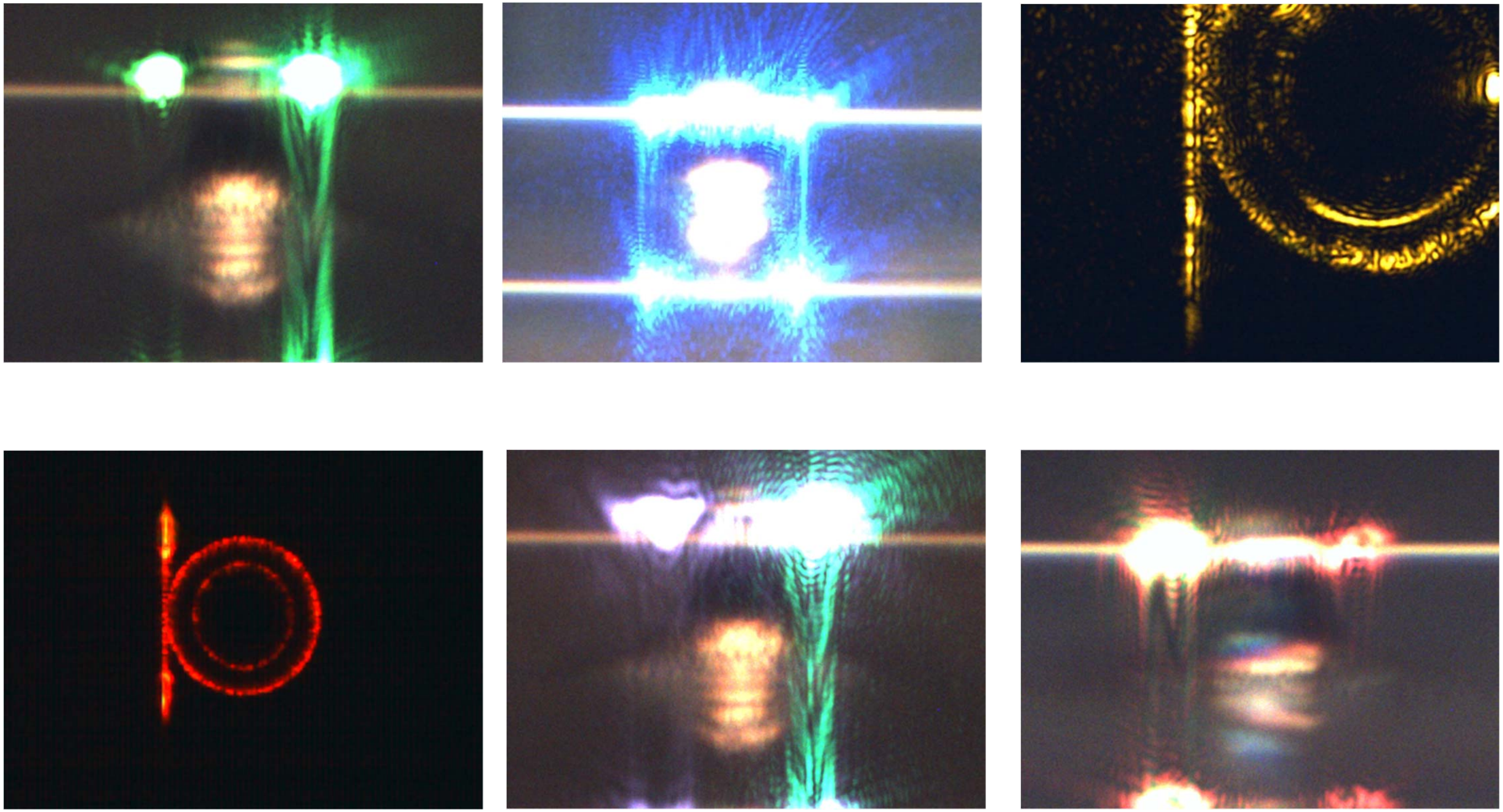
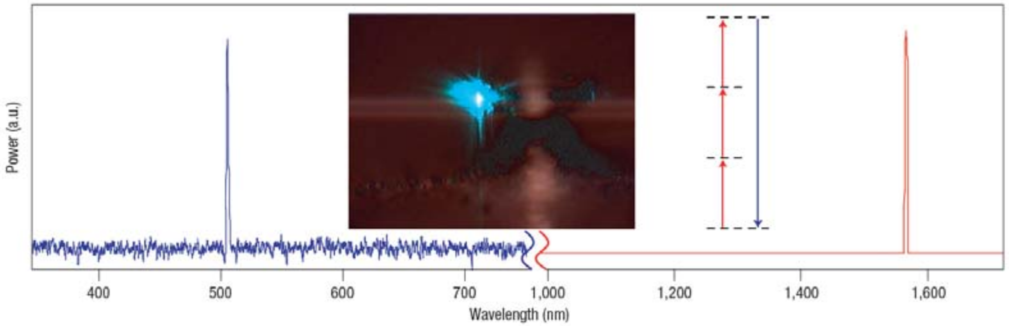
Third-harmonic generation in toroid microcavity



Visible light generation with soliton pulse

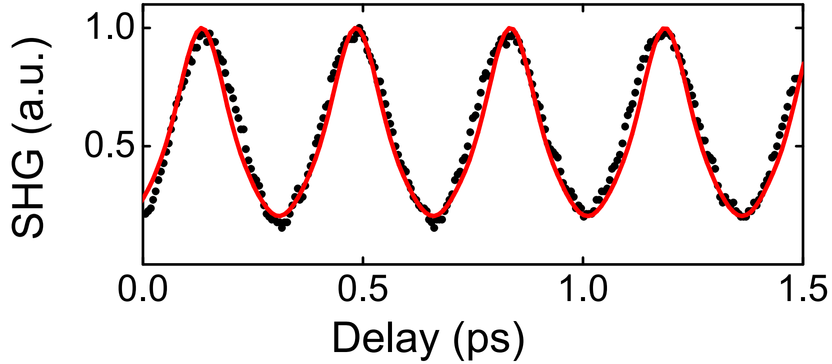
►Efficient third-harmonic generation

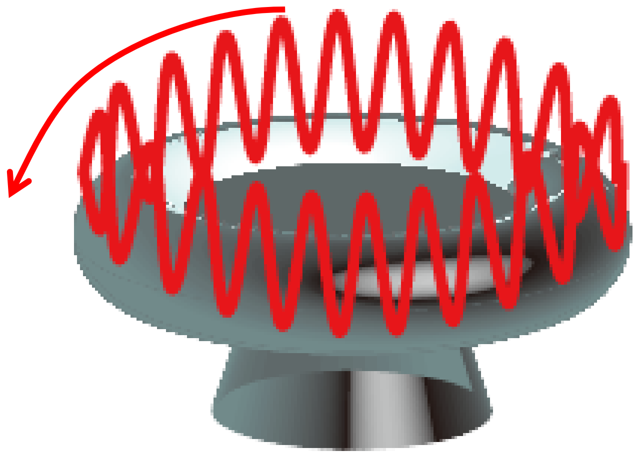
CW mode



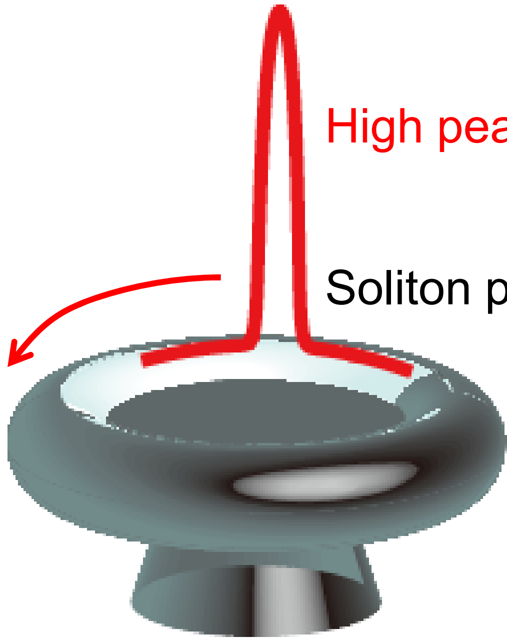
T. Carmon & K. Vahala, Nat. Phys. 3, 430 (2007).

►THG with pulsed mode





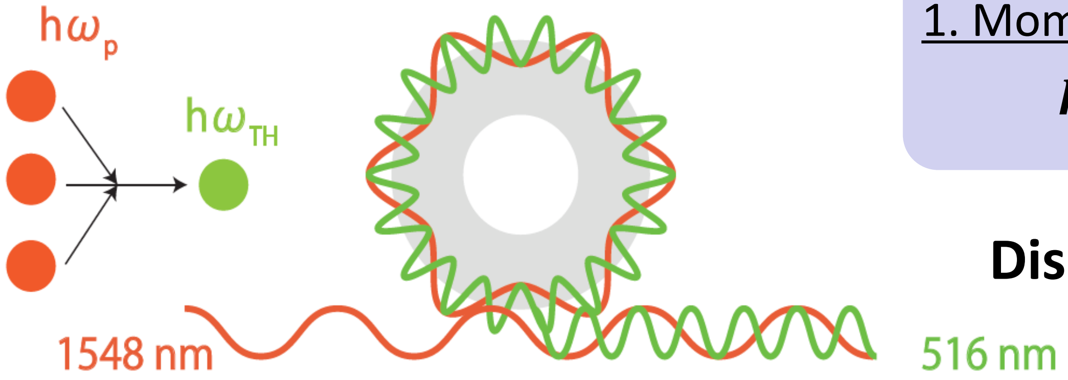
THG generation with soliton pulse



Potential for improving THG efficiency

Phase-matching condition for THG

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



1. Momentum conservation

$$k_{THG} = 3k_p$$

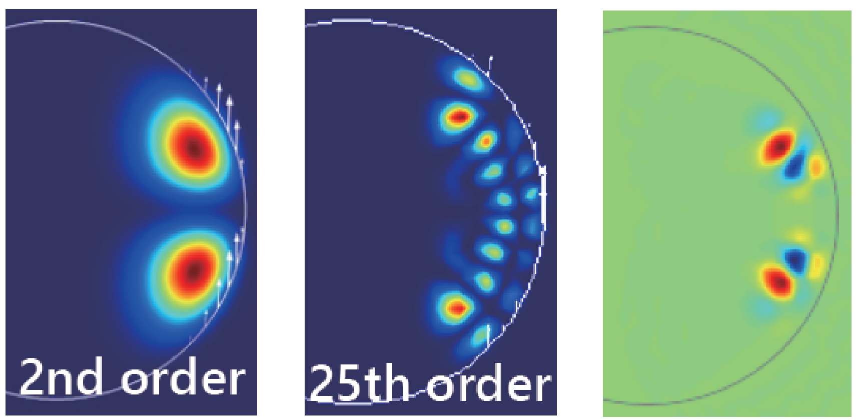
2. Energy conservation

$$\omega_{THG} = 3\omega_p$$

Dispersion induced resonance mismatch

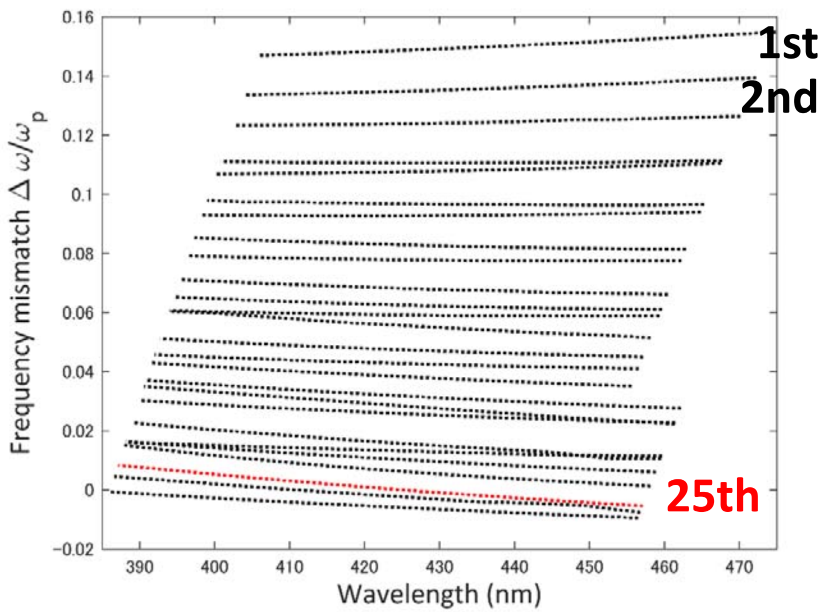
$$\Delta\omega = 3\omega_p - \omega_{THG} \rightarrow 0$$

Intensity distribution (cross-section)



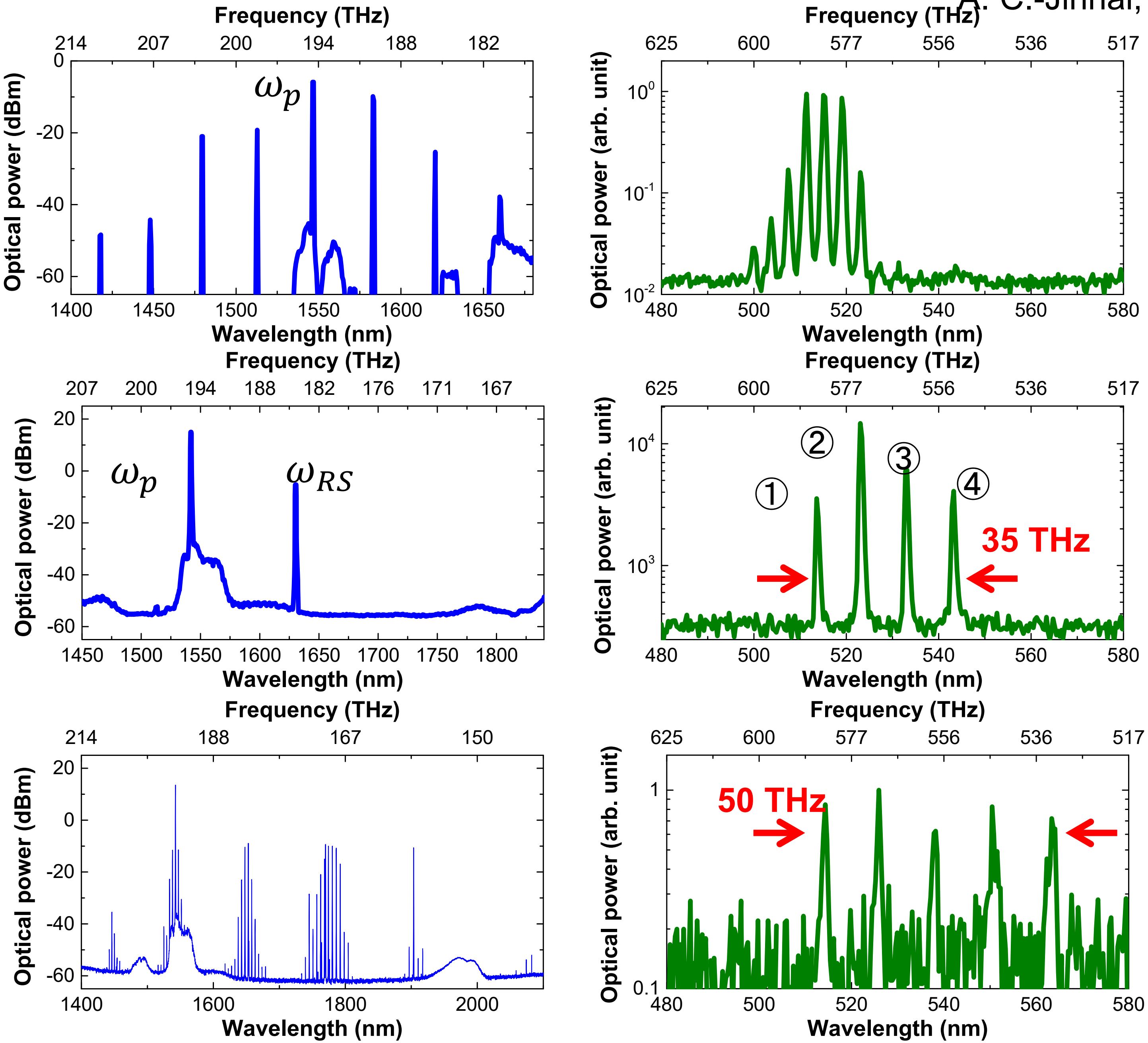
Pump TH(visible) Overlap

Phase-matched TH mode



Visible comb generation w/ THG, TSFG, and SRS

A. C.-Jinnai, *et al.*, Opt. Express 24, 26322 (2016).



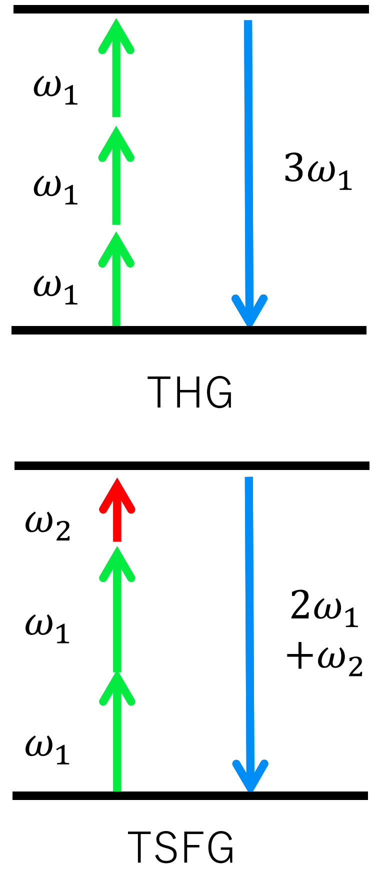
① $3\omega_p$

① $3\omega_p$

② $2\omega_p + \omega_{RS}$

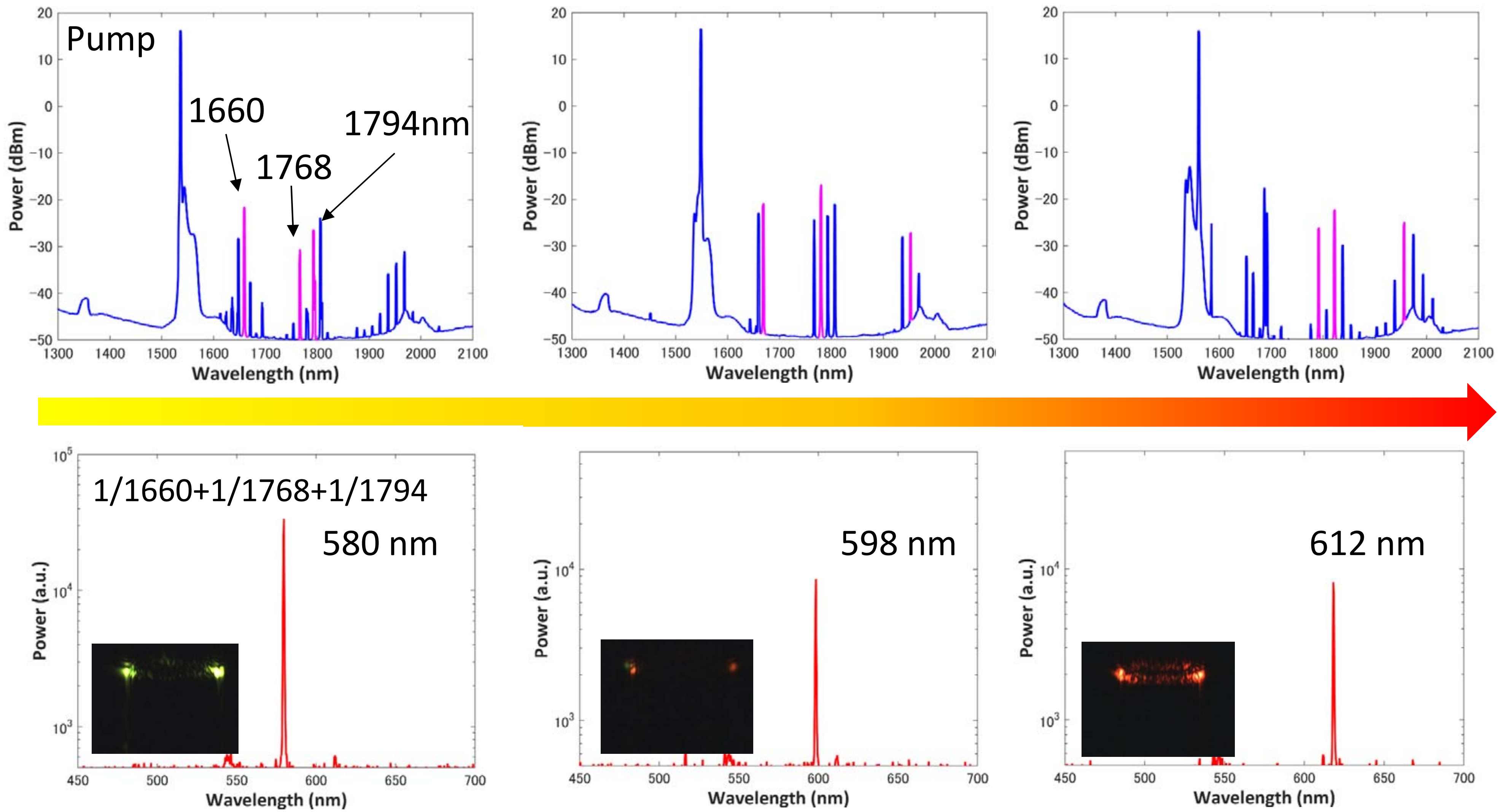
③ $\omega_p + 2\omega_{RS}$

④ $3\omega_{RS}$



Green, Orange, Red light generation w/ SRS assisted THG

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



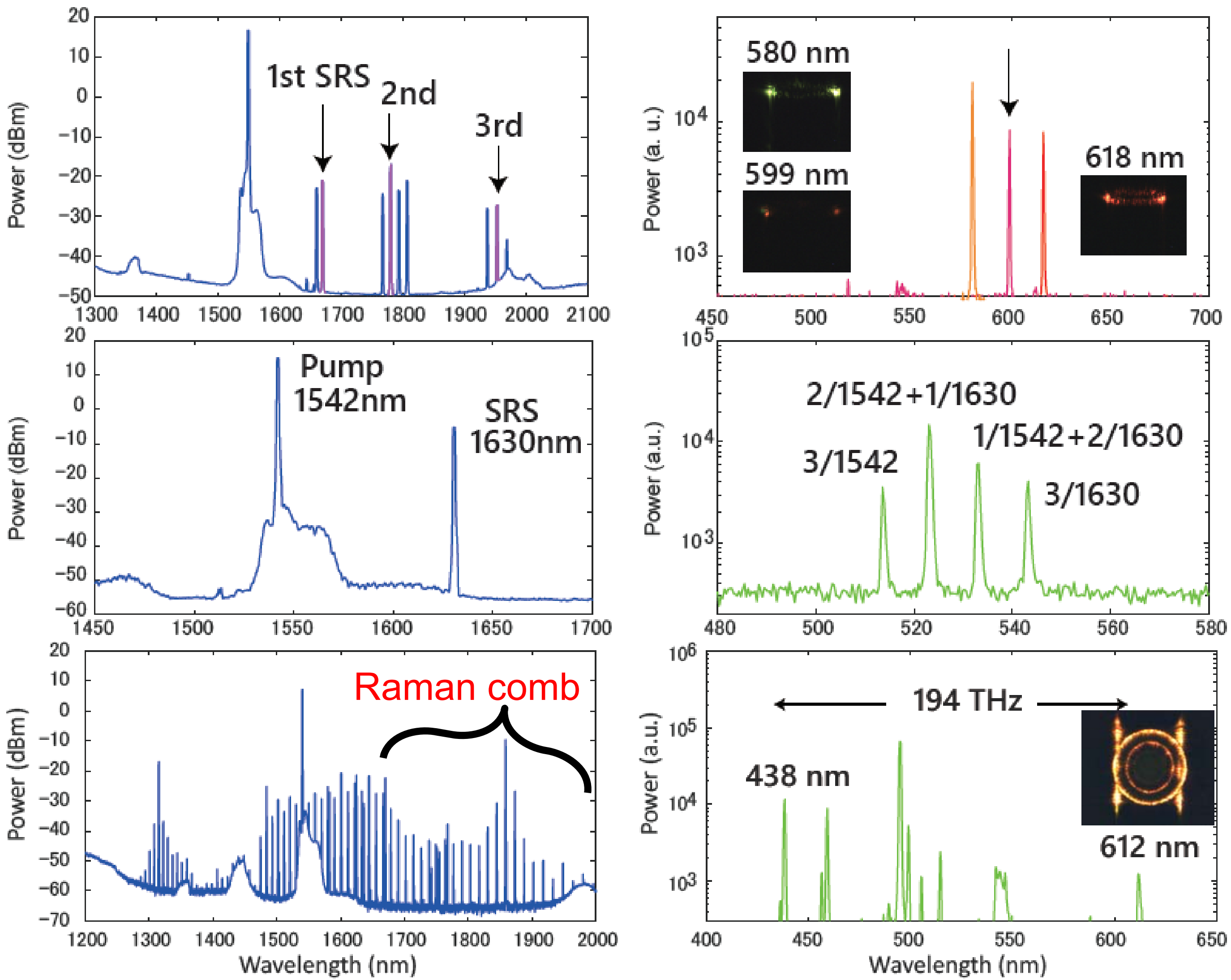
Third-harmonic generation *w/* FWM and SRS

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

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

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

3. Broad bandwidth THG
   - ➢ THG and TSFG via FWM and SRS



Summary

1. Competition between SRS and FWM

- Controlling the pump allows us to selectively use SRS and FWM

2. Transverse mode coupling w/ SRS

- Transverse mode coupling occurs when we pump in the low Q mode.
- Good coherence is observed by exciting an SRS comb in the same transverse mode

3. Broad bandwidth visible light via SRS & THG

- Better wavelength tuning achieved via SRS

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Mr. Shun Fujii (CW/CCW mode coupled FWM)
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