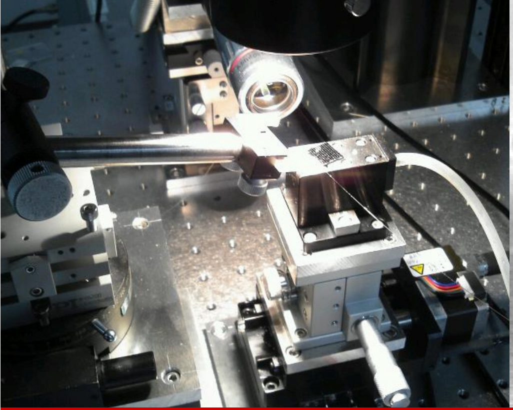

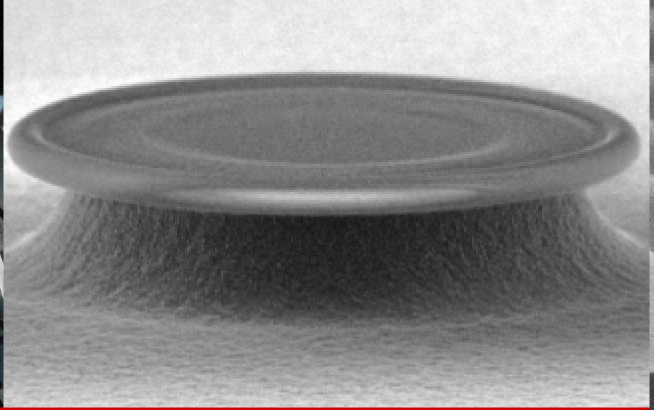

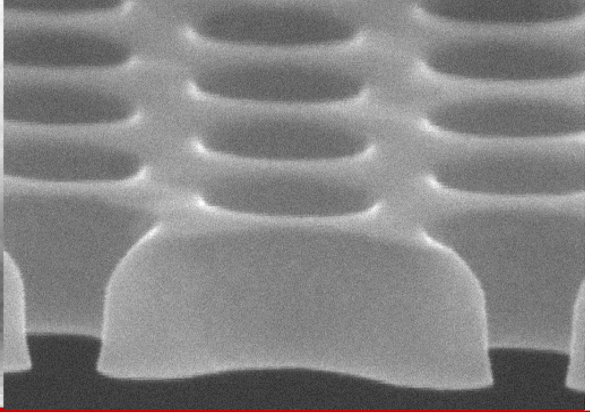

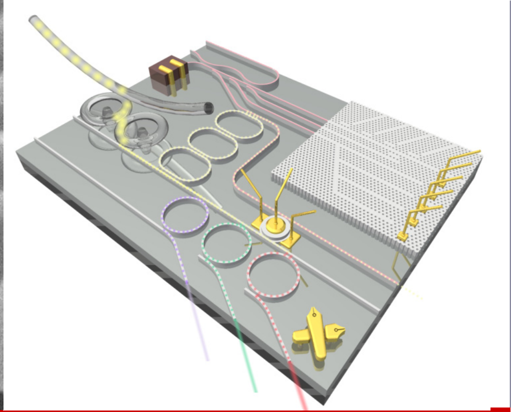

SPIE Photonics West
14:10-14:35 Feb. 15. 2016

Optical Kerr comb generation in a small toroidal microcavity

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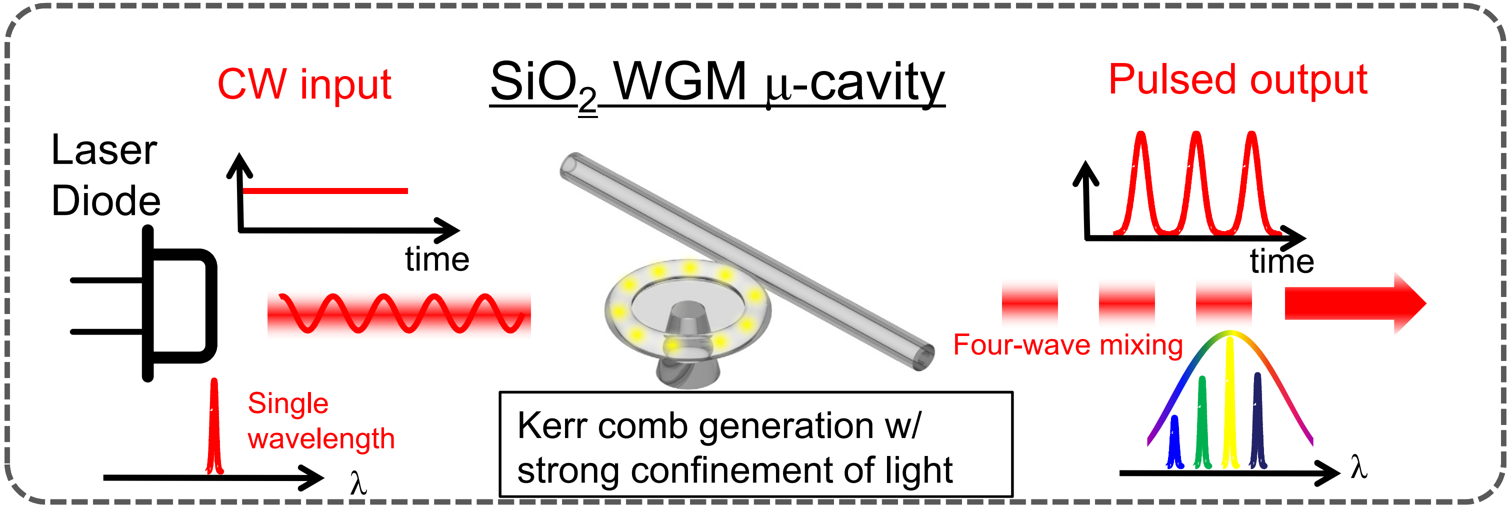
Department of Electronics and Electrical Engineering,
Keio University, Japan

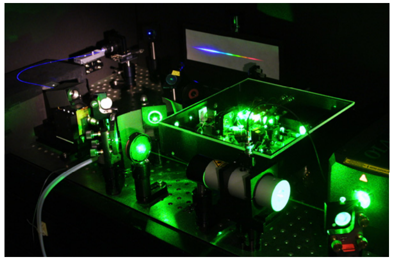
Kerr comb in microcavity system

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

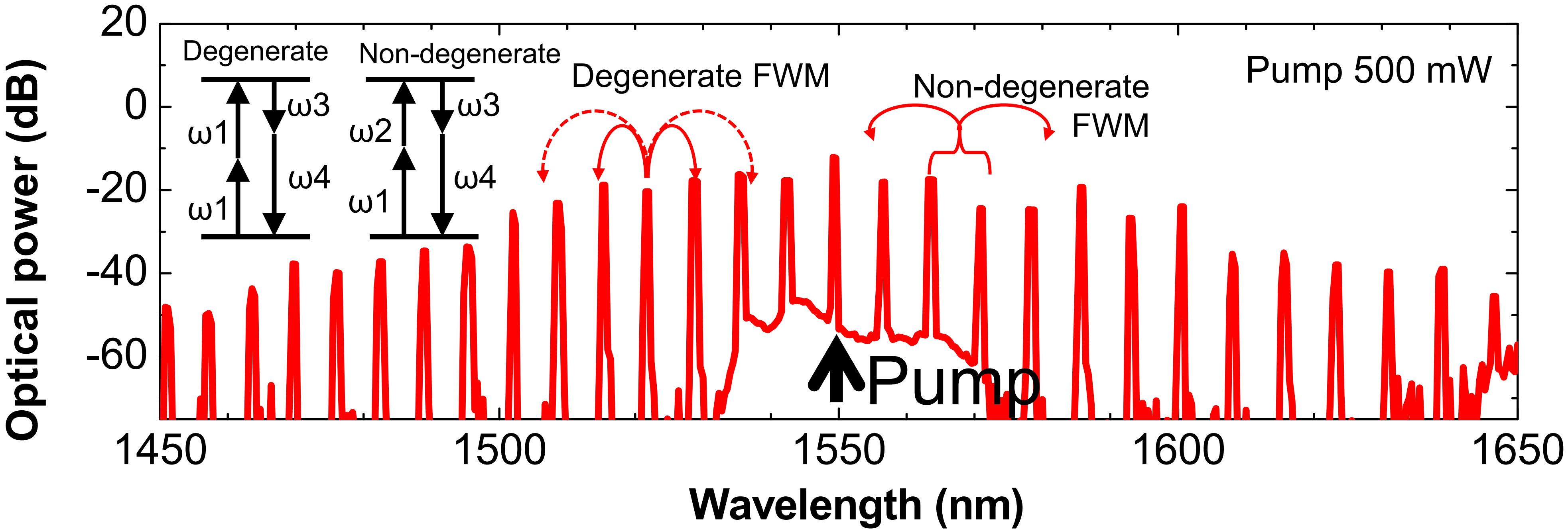


Kerr comb generation w/ strong confinement of light

Ti:Sapphire laser based comb



large & expensive



Motivation

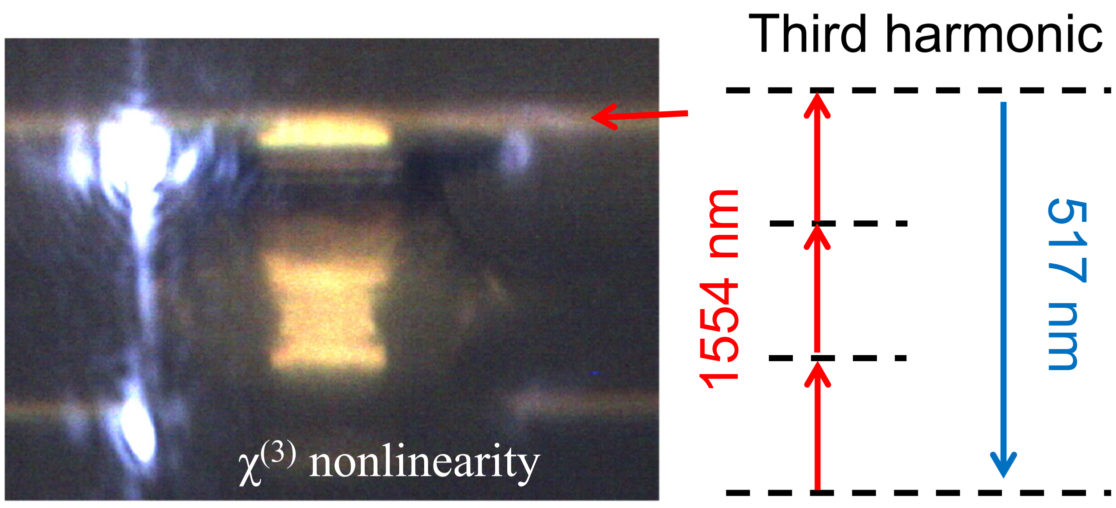
◆Q-factor

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

◆Photon density

$$\propto Q/V$$

▶Example of optical nonlinearity in cavity



Small is good

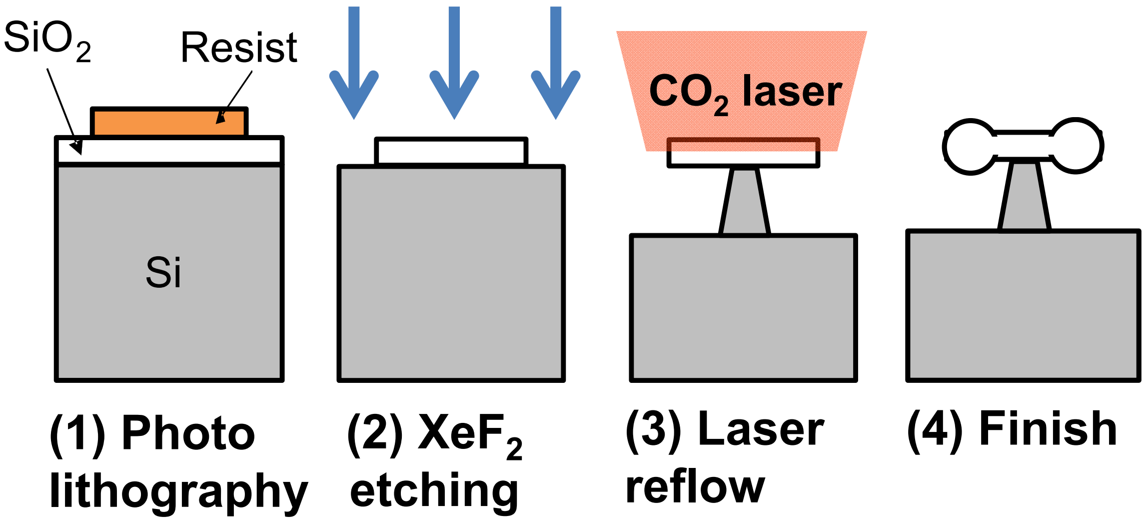
Able to generate Kerr comb at small input power w/o EDFAs

▶Challenges…

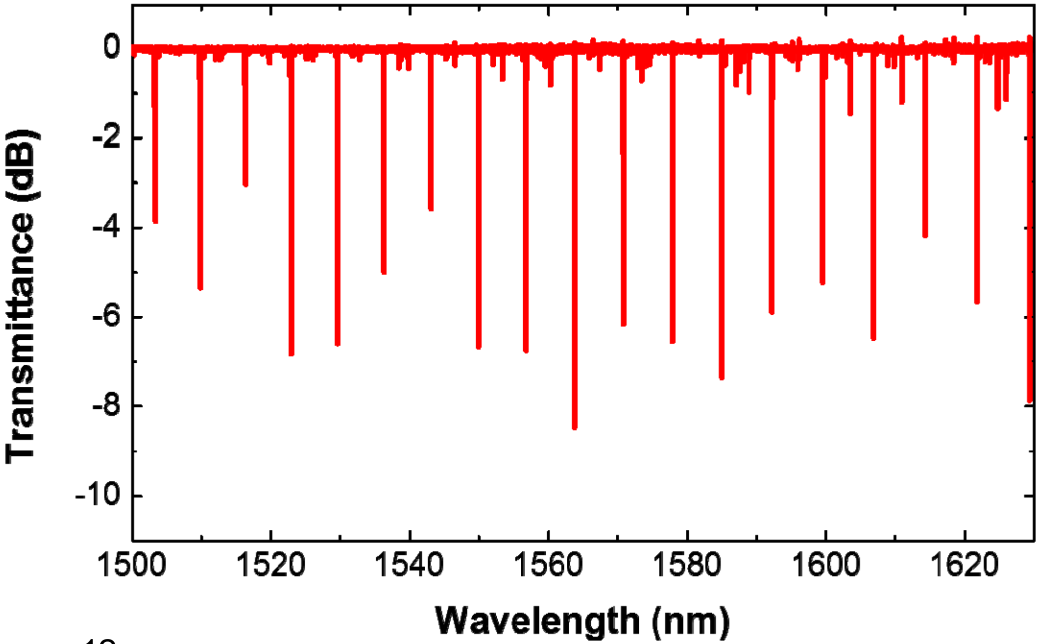
- ✓ Normal dispersion
- ✓ Large cavity opto-mechanical coupling
- ✓ Strong CW/CCW mode coupling

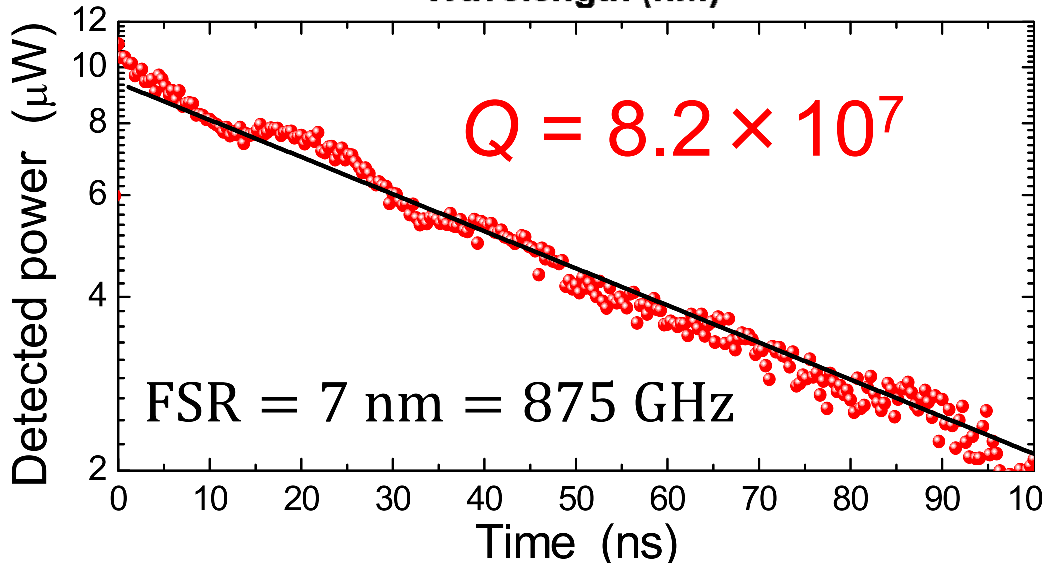
Ultra-high *Q* toroidal microcavity

▶Fabrication



▶Spectrum & photon lifetime

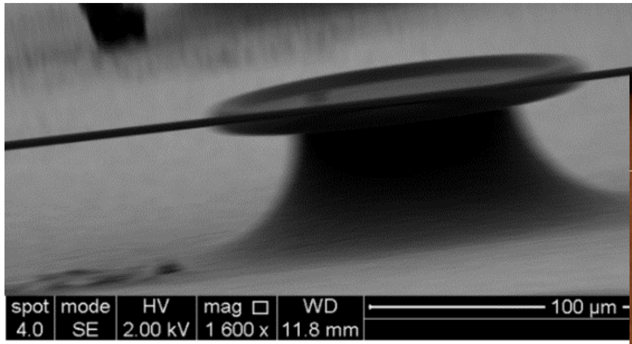


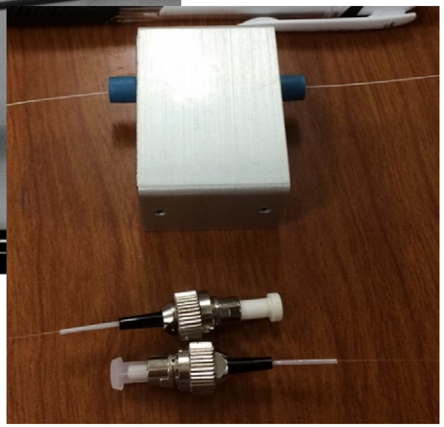


$Q = 8.2 \times 10^7$

FSR = 7 nm = 875 GHz

▶Packaging



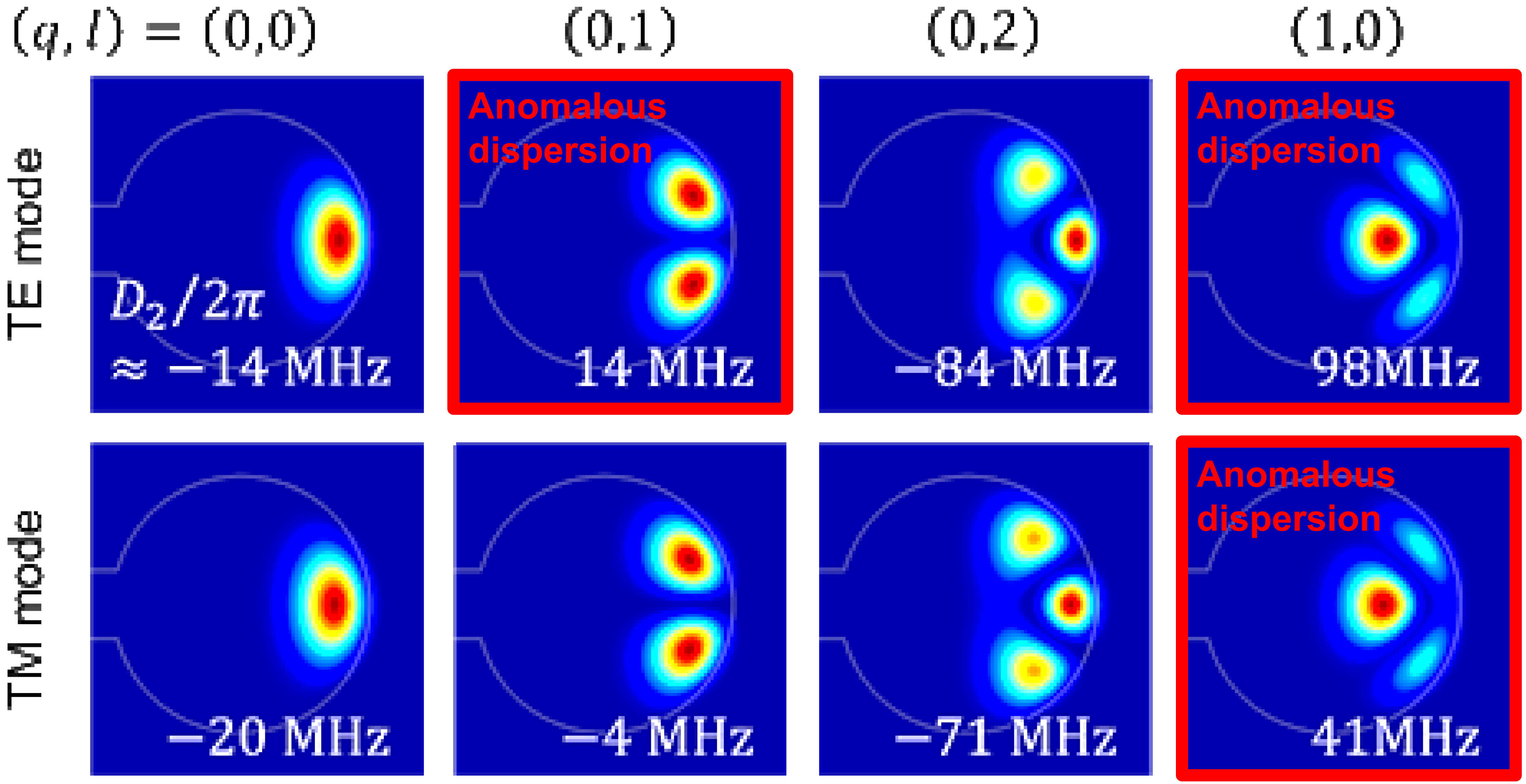


J. Nishimura, *et al.* Appl. Opt. **54**, 6391 (2015).

Outline

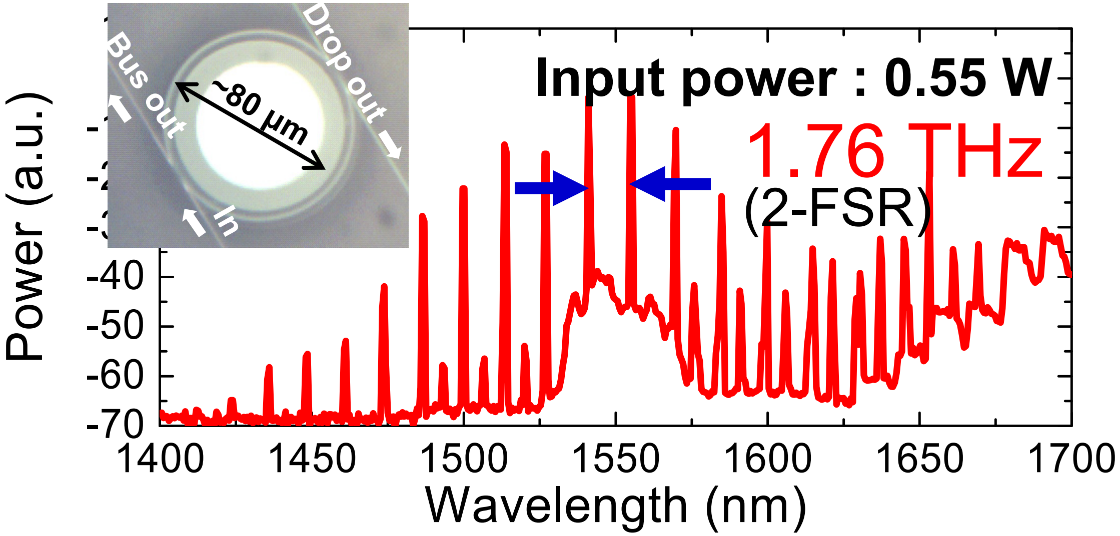
1. Dispersion in a small toroid microcavity
2. Effect of cavity opto-mechanics
3. Effect of CW/CCW mode coupling
4. Raman / FWM generation
5. Visible comb generation

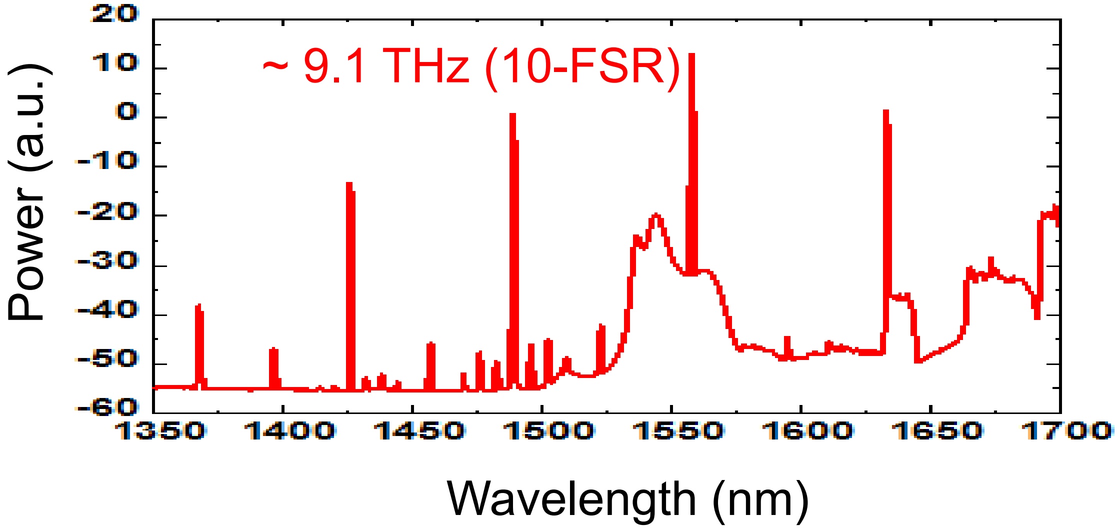
Dispersions in toroid microcavity (r = 35 μm)



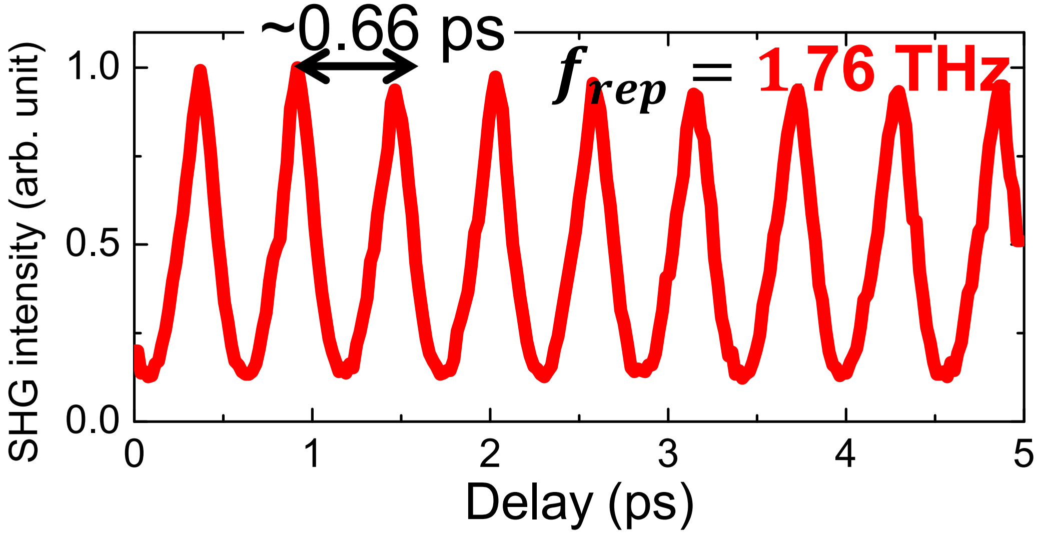
Ultrahigh repetition rate pulse generation

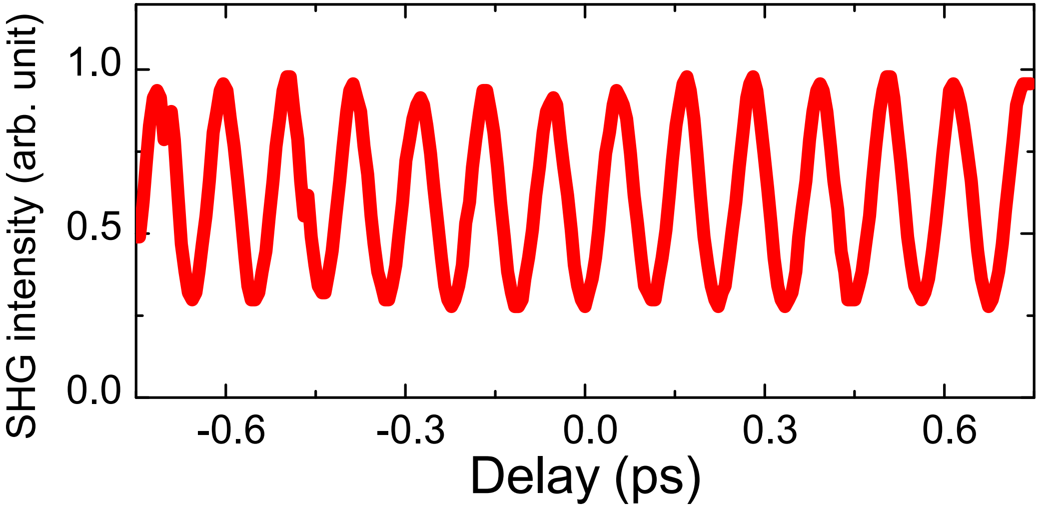
▶Kerr comb generation





▶SHG autocorrelation trace





Outline

1. Dispersion in a small toroid microcavity
2. Effect of cavity opto-mechanics
3. Effect of CW/CCW mode coupling
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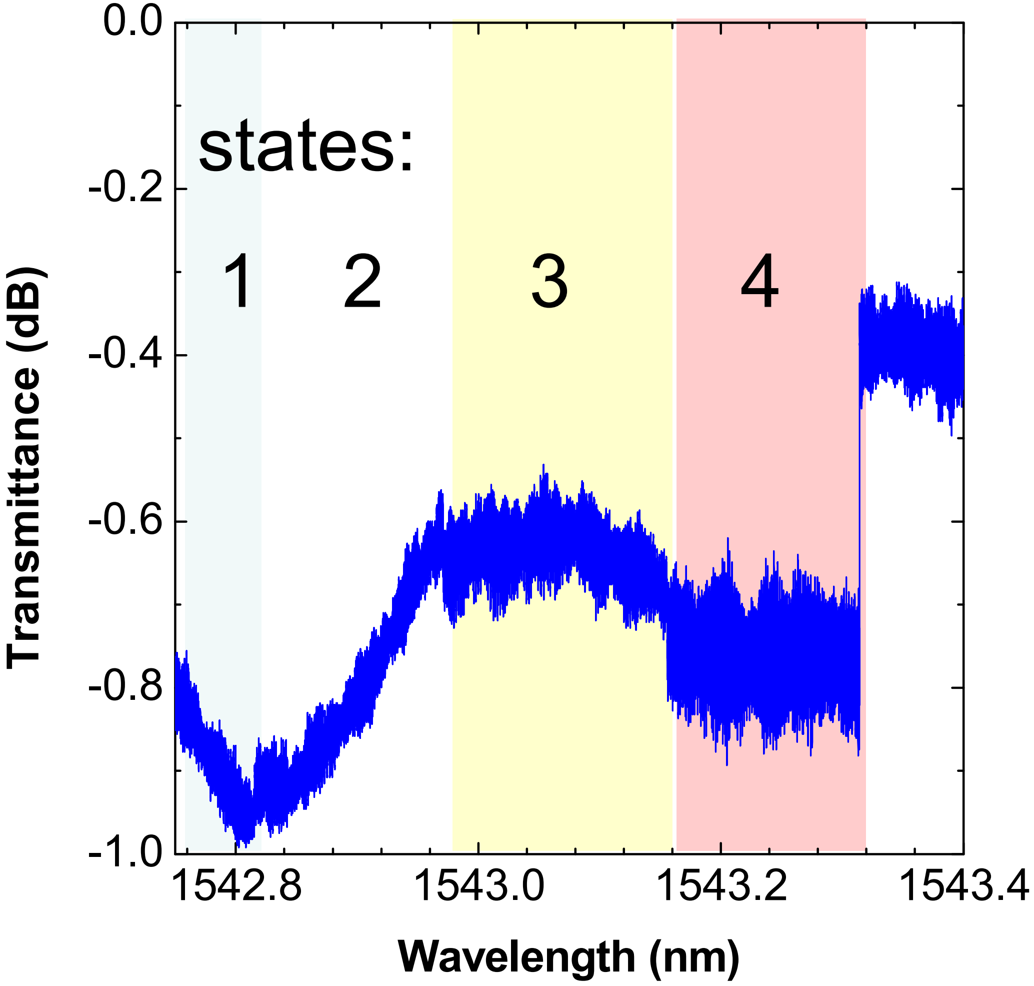
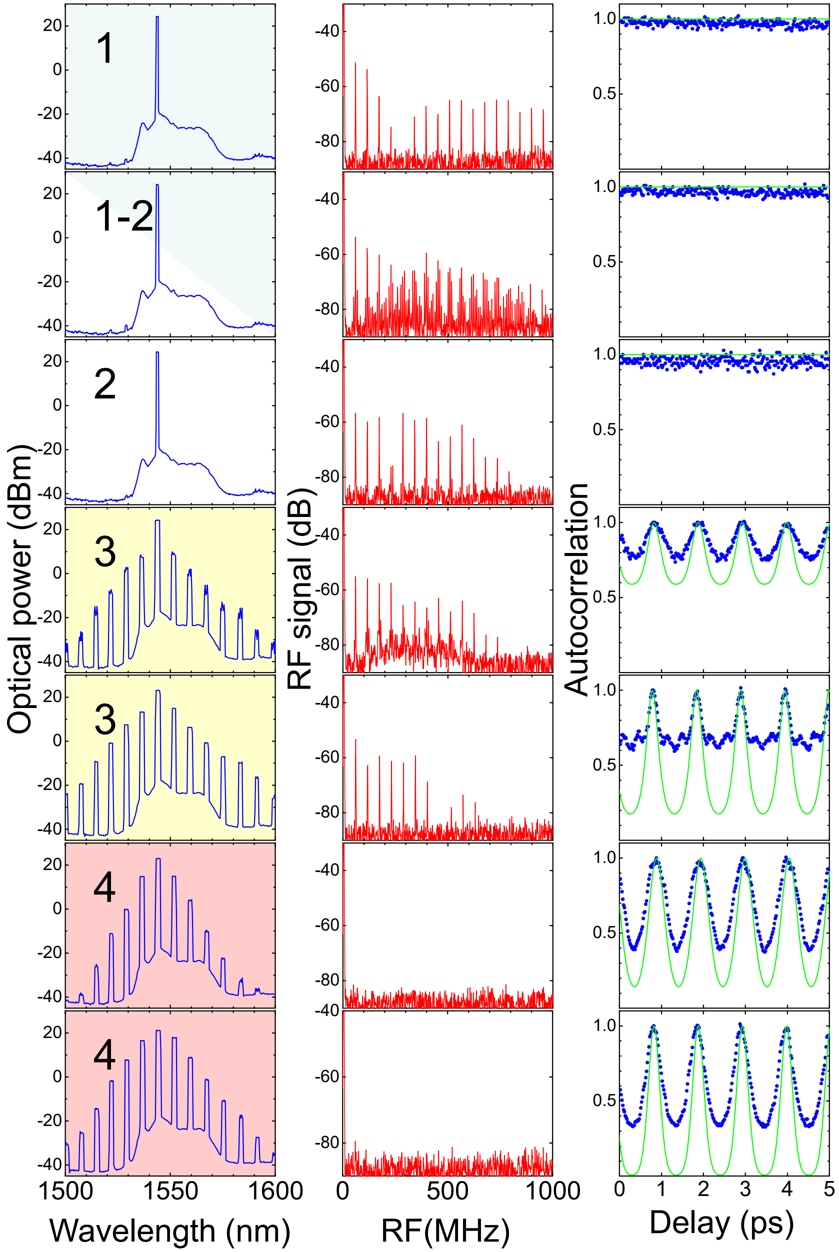
Wavelength scan with toroid microcavity

▶Transmittance spectrum



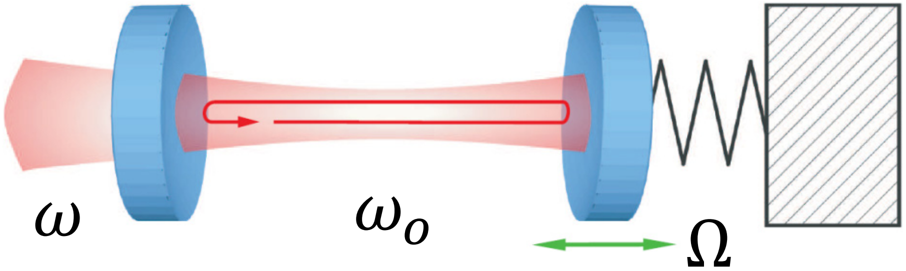
Different states appear
(opto-mechanics?)

▶Optical ▶RF ▶Autocorrelation

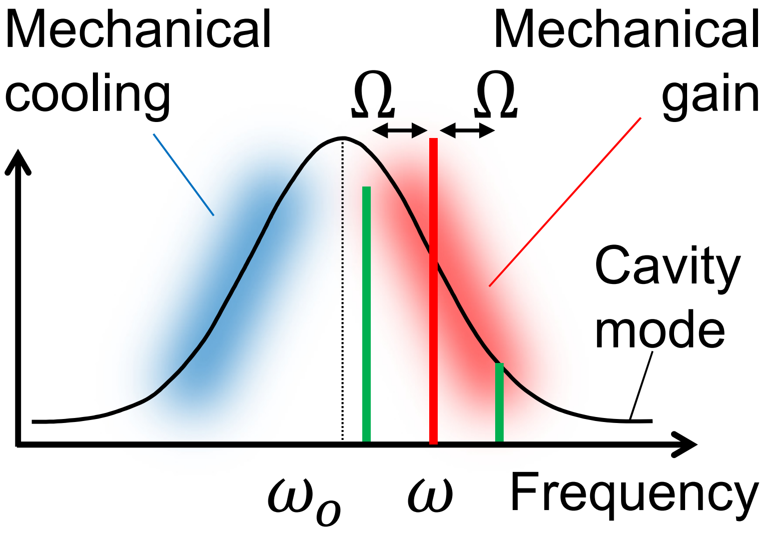


RF noise measurement (effect of cavity opto-mechanics)

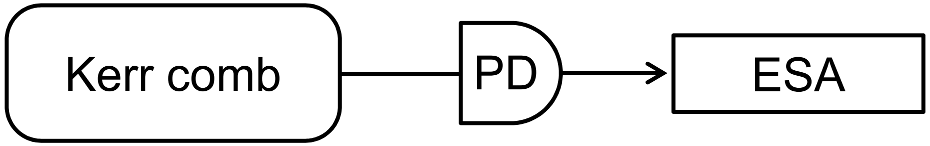
▶Cavity opto-mechanics



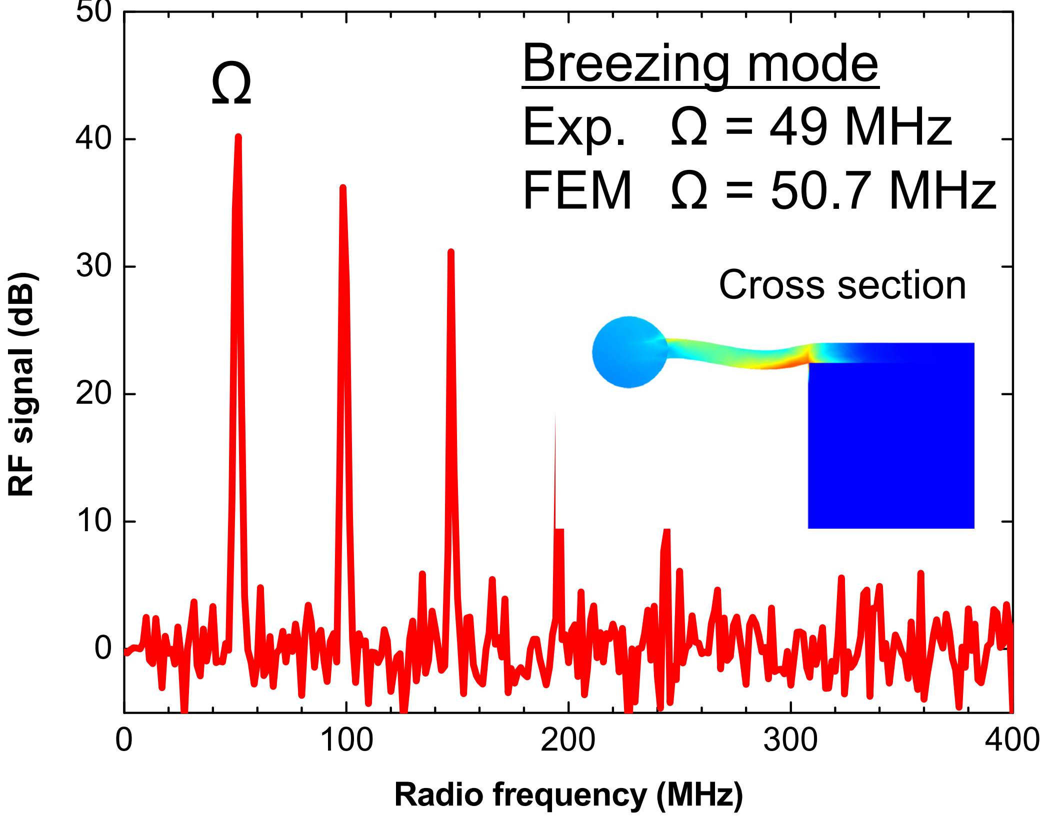
T. Kippenberg & K. Vahala, Opt. Express **15**, 17172 (2007).



ω : pump frequency
ω_o : optical resonance (≈ 193 THz)
Ω : mechanical resonance



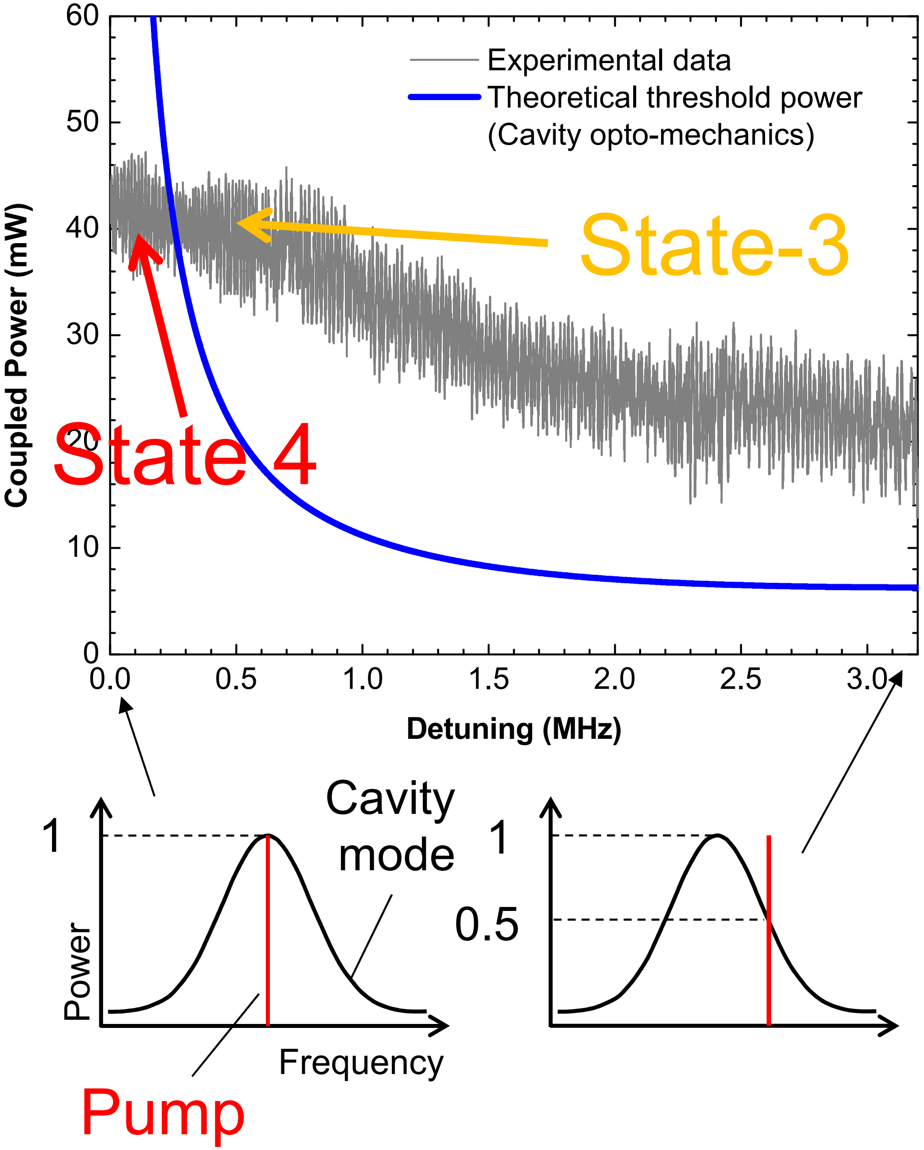
Detuning: $\omega - \omega_o > 0$
Pump power: 400 mW



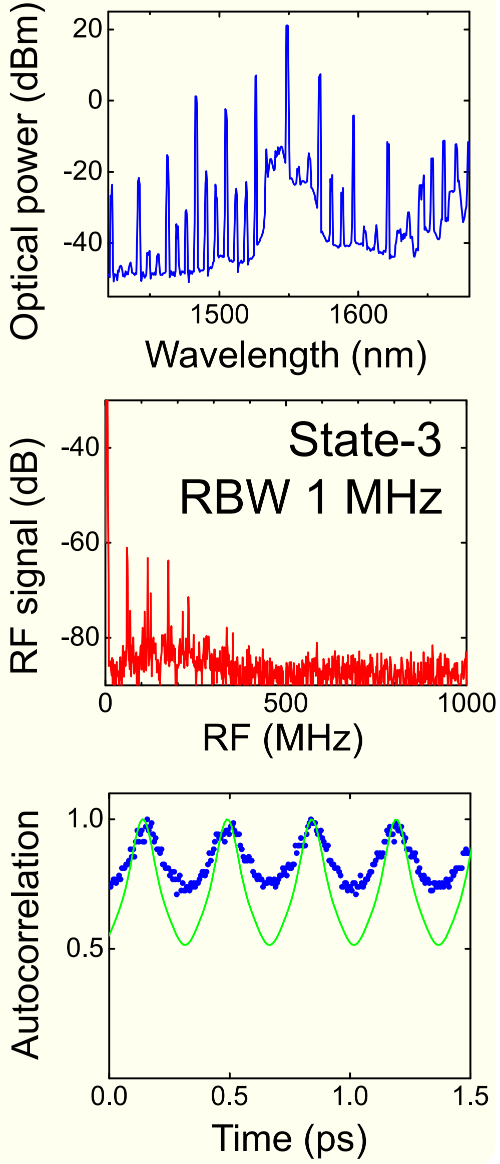
Detuning: $\omega - \omega_o \approx 0, \text{or} < 0$
→ Can we reduce mechanical oscillation?

Cavity opto-mechanics & mode-locking

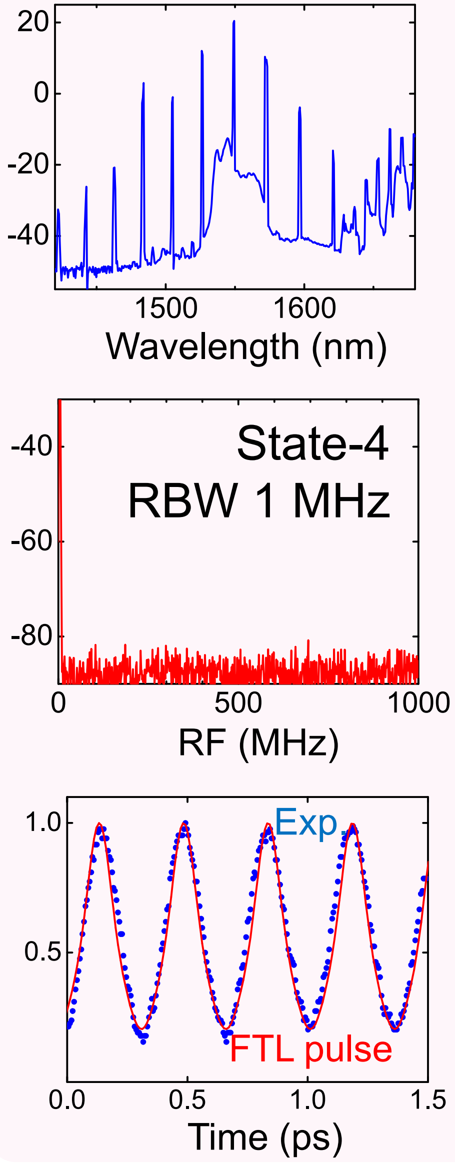
▶Detuning vs. Threshold power



▶State-3 (OM)



▶State-4 (no OM)



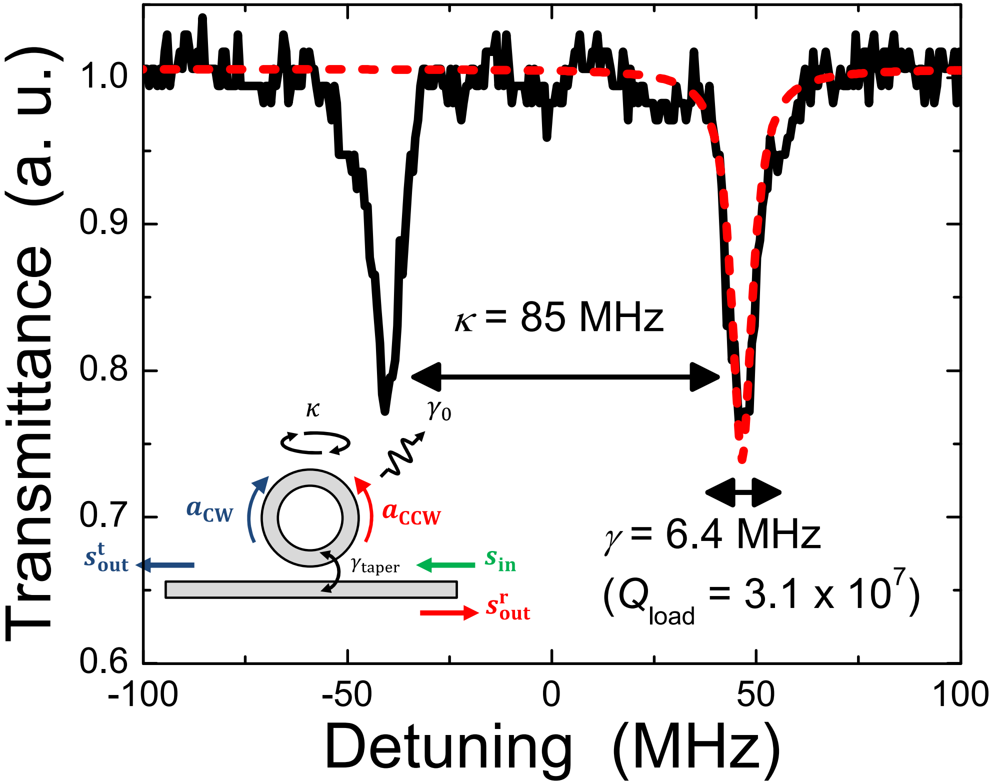
Outline

1. Dispersion in a small toroid microcavity
2. Effect of cavity opto-mechanics
3. Effect of CW/CCW mode coupling
4. Raman / FWM generation
5. Visible comb generation

Strong coupling between CW/CCW with small cavity

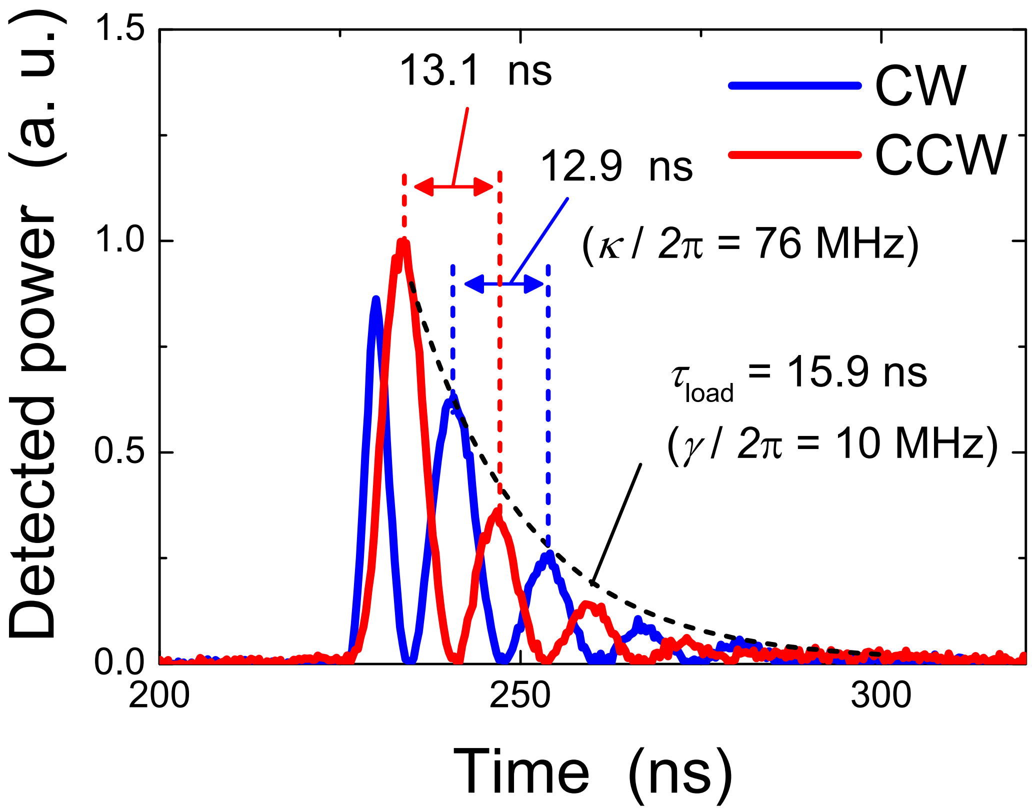
W. Yoshiki, *et al*. Opt. Express, **23**, 30851 (2015).

▶Resonance splitting (Freq. domain)



- Coupling rate: ***κ***
- Decay rate: ***γ*** = (γ_0 + γ_{taper})

▶Energy oscillation (Time domain)

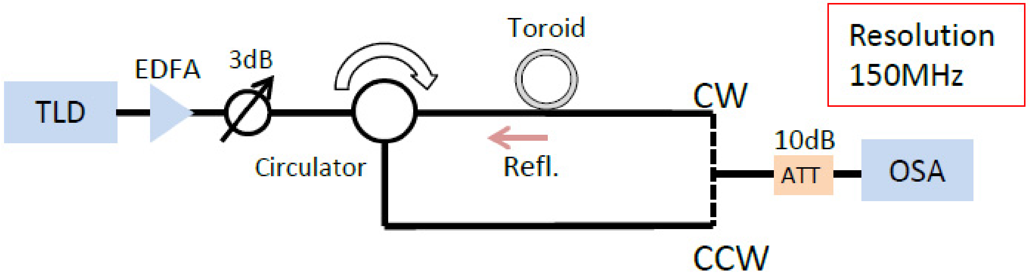


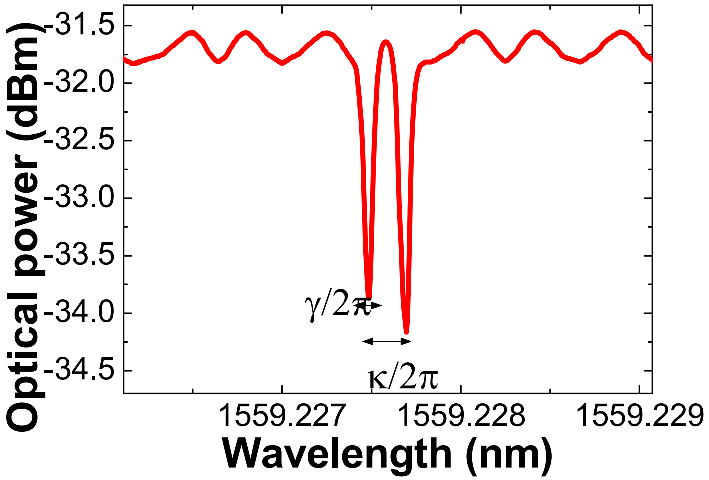
$\kappa/2\pi$ = **85 MHz**, $\gamma/2\pi$ = **6.4 MHz**

-> **Γ ≈ 13**

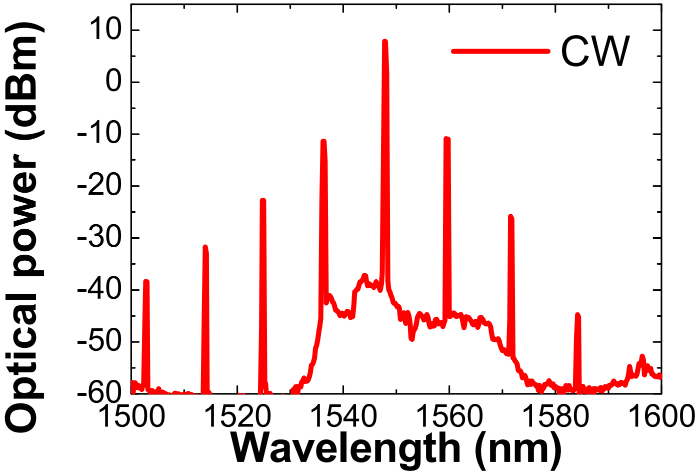
Effect of CW/CCW coupling to Kerr comb

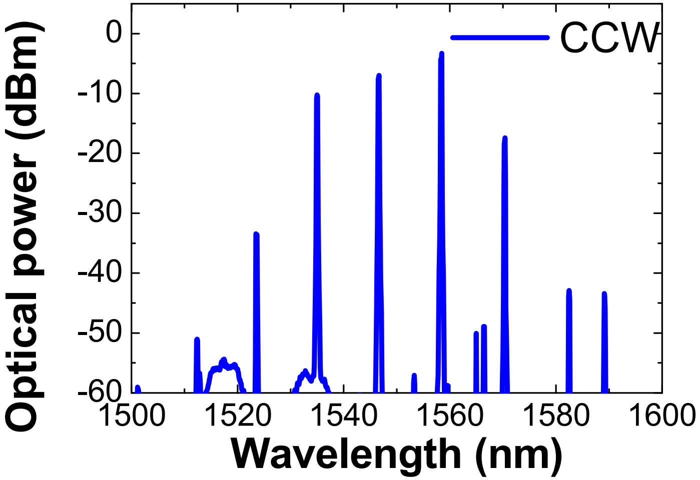
►Experimental setup

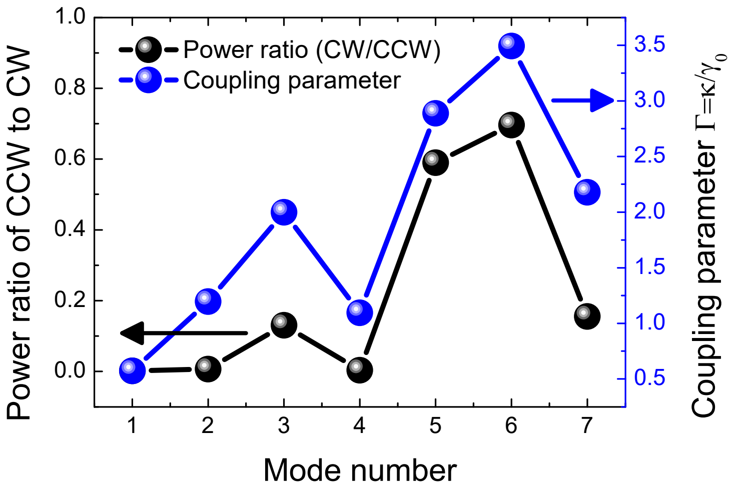




►CW/CCW comb & coupling strength

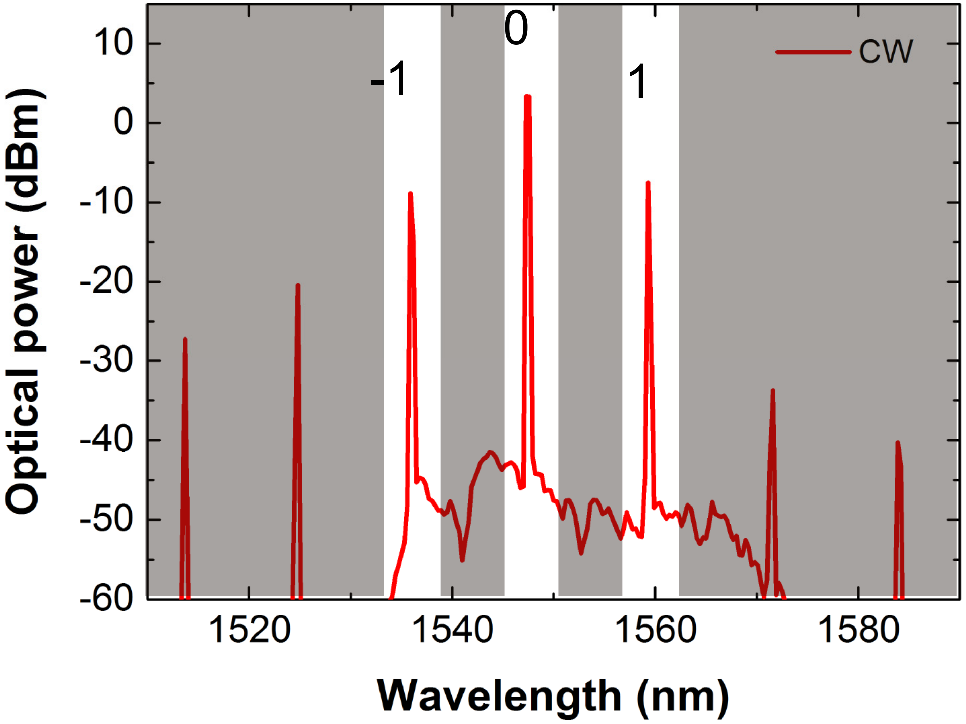




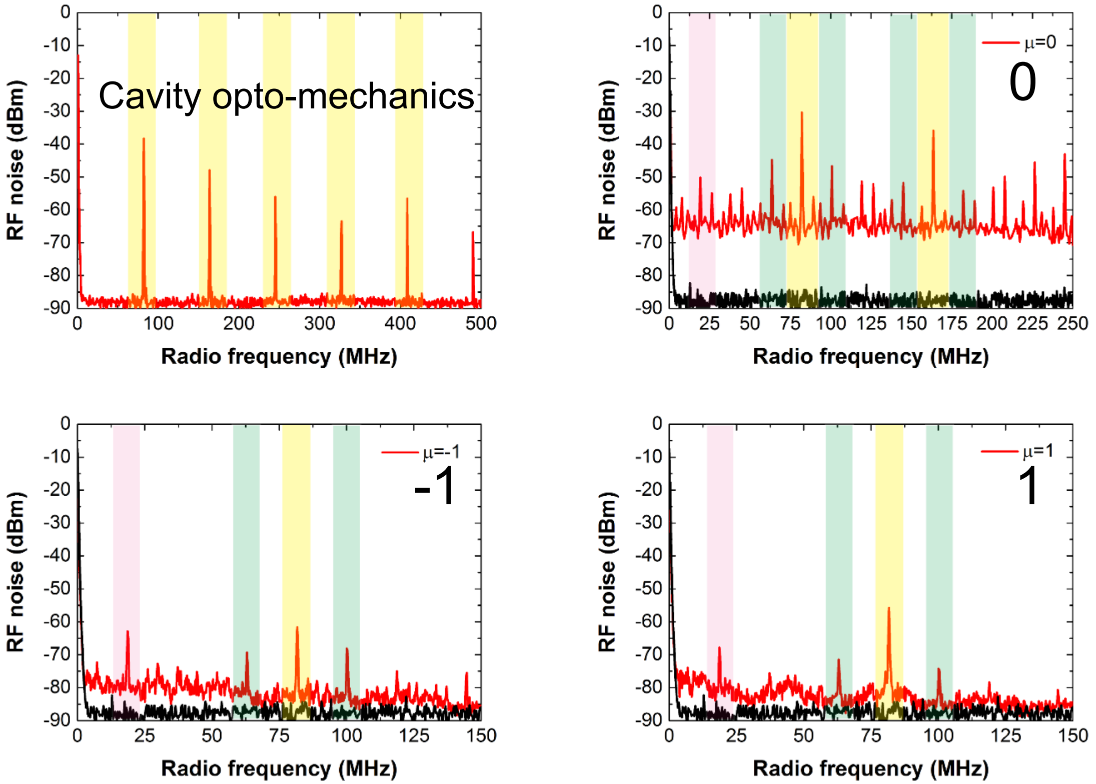


Effect of CW/CCW coupling: RF measurement

▶RF noise measurement



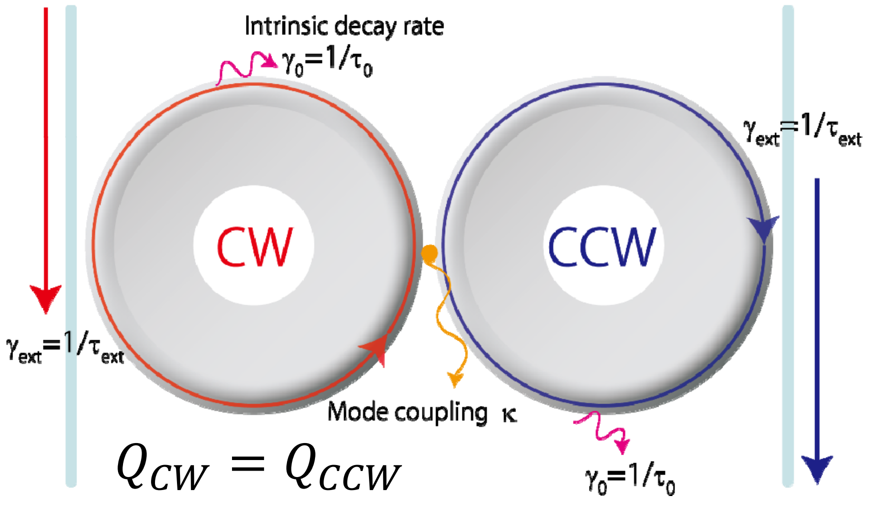
▶RF spectrum



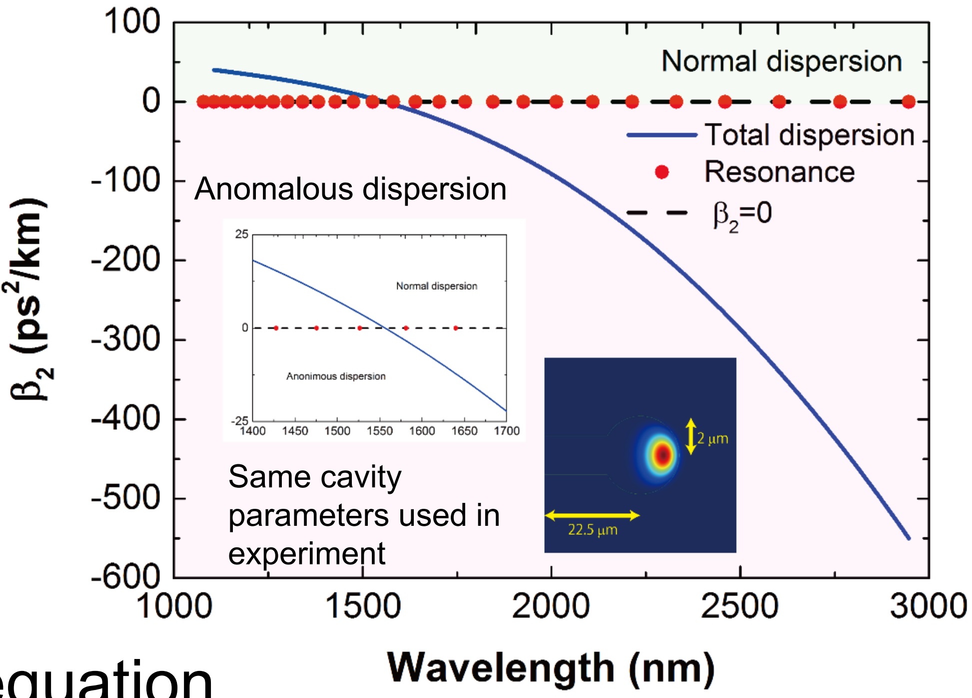
Each line is filtered out and the RF spectrum is measured

No mode splitting effect is observed (Only the effect of cavity-opto mechanics is present)

Numerical analysis of CW/CCW coupling based on nonlinear CMT equations



$$Q_{CW} = Q_{CCW}$$



Same cavity parameters used in experiment

▶Normalized nonlinear coupled mode equation

$$\frac{\partial \tilde{A}_\mu}{\partial t} = \frac{\gamma_{A_0}}{2}\left(-1 + i\Omega_{A_\mu}\right)\tilde{A}_\mu + \frac{\gamma_{A_0}}{2}\cdot i\sum_{\alpha,\beta,\gamma}\delta_{\mu-(\alpha-\beta+\gamma)}\tilde{A}_\alpha\tilde{A}_\beta^*\tilde{A}_\gamma + i\delta_{\omega_{A_\mu}-\omega_{B_\theta}}\frac{\kappa_\theta}{2}\sqrt{\frac{g_A\gamma_{B_0}}{g_B\gamma_{A_0}}}\tilde{B}_\theta e^{i\{\omega_{A_\mu}-\omega_{B_\mu}-\mu(D_{1A}-D_{1B})\}t} + \frac{\gamma_{A_0}}{2}\delta_\mu f_0$$

$$\frac{\partial \tilde{B}_\mu}{\partial t} = \frac{\gamma_{B_0}}{2}\left(-1 + i\Omega_{B_\mu}\right)\tilde{B}_\mu + \frac{\gamma_{B_0}}{2}\cdot i\sum_{\alpha,\beta,\gamma}\delta_{\mu-(\alpha-\beta+\gamma)}\tilde{B}_\alpha\tilde{B}_\beta^*\tilde{B}_\gamma + i\delta_{\omega_{B_\mu}-\omega_{A_\theta}}\frac{\kappa_\theta^*}{2}\sqrt{\frac{g_B\gamma_{A_0}}{g_A\gamma_{B_0}}}\tilde{A}_\theta e^{i\{\omega_{B_\mu}-\omega_{A_\mu}-\mu(D_{1B}-D_{1A})\}t}$$

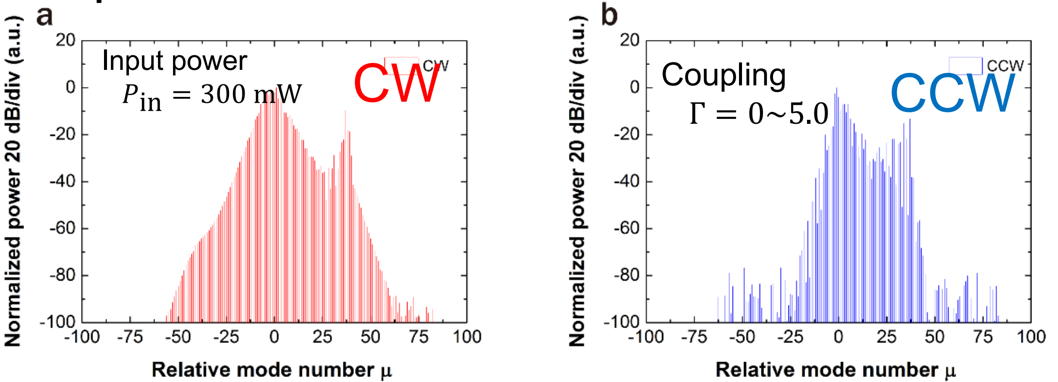
loss **FWM** **CW/CCW mode coupling** **input**

$$\tilde{A}_\mu = \sqrt{2g_A/\gamma_{A_0}}\,A_\mu e^{i\left(\omega_{A_\mu}-\omega_{in}-\mu D_{1A}\right)t}, \Omega_{A_\mu} = 2\left(\omega_{A_\mu} - \omega_{in} - \mu D_{1A}\right)/\gamma_{A_0}, f_0 = \sqrt{8g_A\gamma_{ext}/\kappa_{A_0}^3}\,A_{in}$$

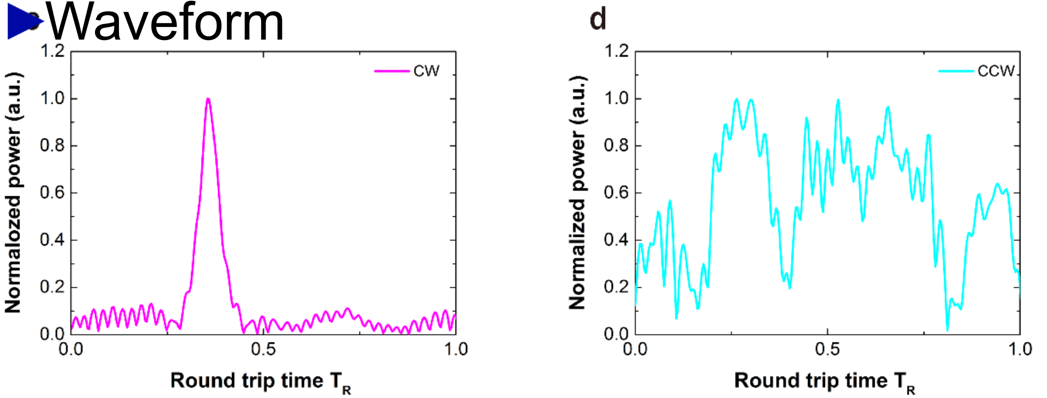
$$\tilde{B}_\mu = \sqrt{2g_B/\kappa_{B_0}}\,B_\mu e^{i\left(\omega_{B_\mu}-\omega_{in}-\mu D_{1B}\right)t}, \Omega_{B_\mu} = 2\left(\omega_{B_\mu} - \omega_{in} - \mu D_{1B}\right)/\gamma_{B_0}$$

Soliton formation in CW/CCW mode coupled system

▶Spectrum



▶Waveform



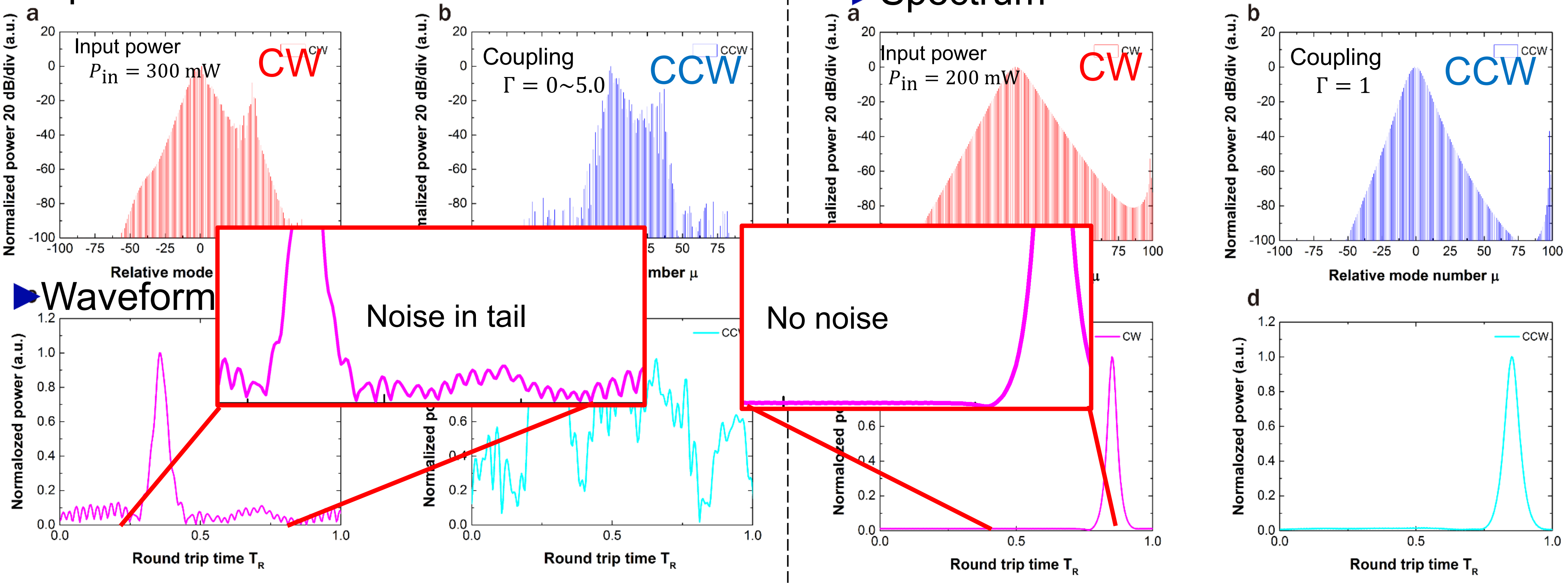
Soliton formed in CW only

Soliton formation in CW/CCW mode coupled system

▶Spectrum

▶Waveform

▶Spectrum



Soliton formed in CW only

Soliton formed in CW/CCW modes

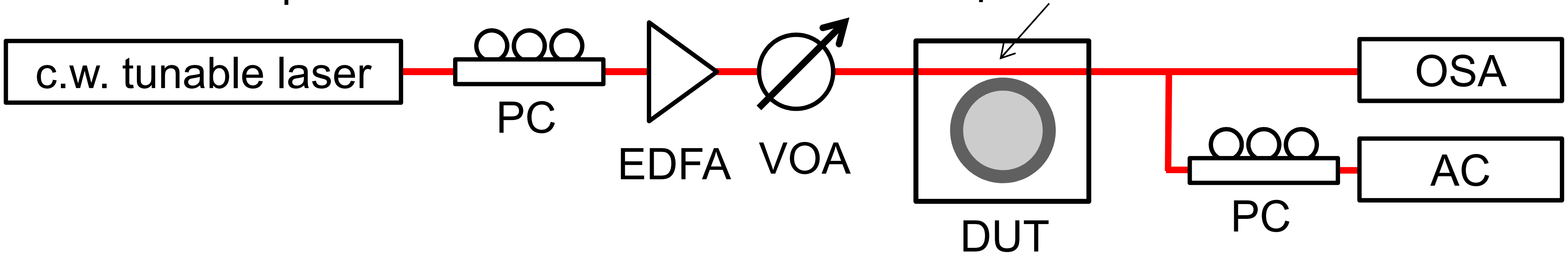
No noise appears when both CW/CCW modes are in soliton state

Outline

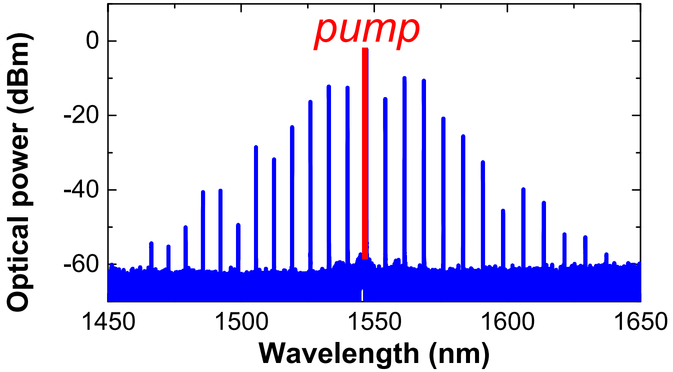
1. Dispersion in a small toroid microcavity
2. Effect of cavity opto-mechanics
3. Effect of CW/CCW mode coupling
4. Raman / FWM generation
5. Visible comb generation

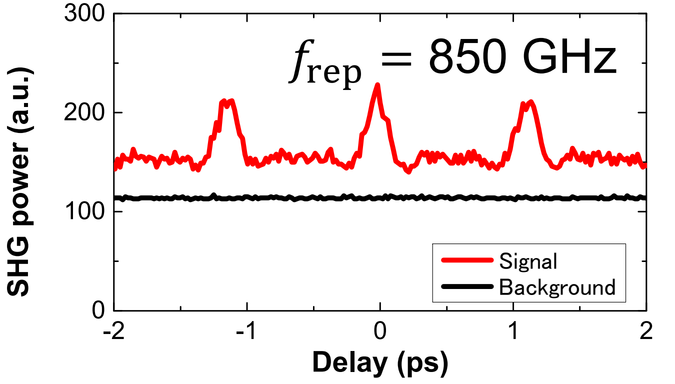
Kerr comb in a silica toroidal microcavity

▶Experimental setup

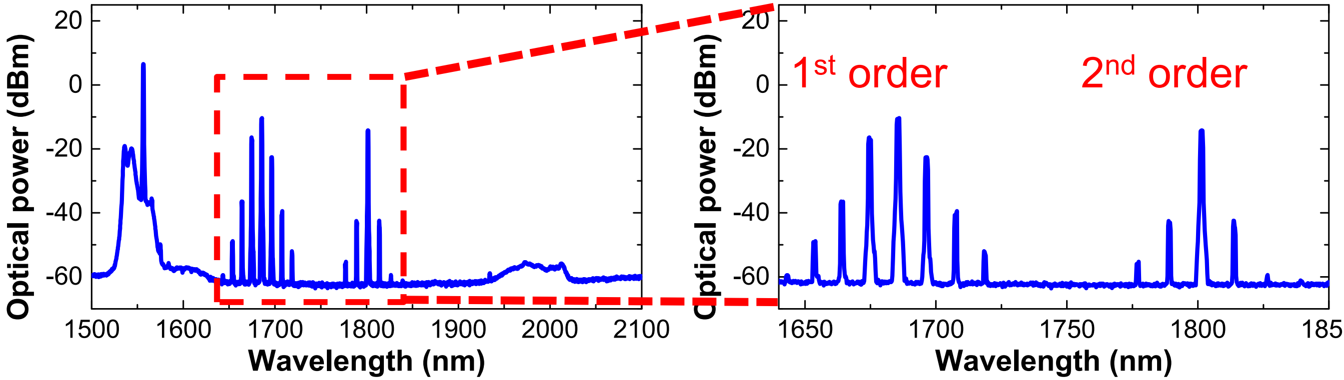


▶FWM only

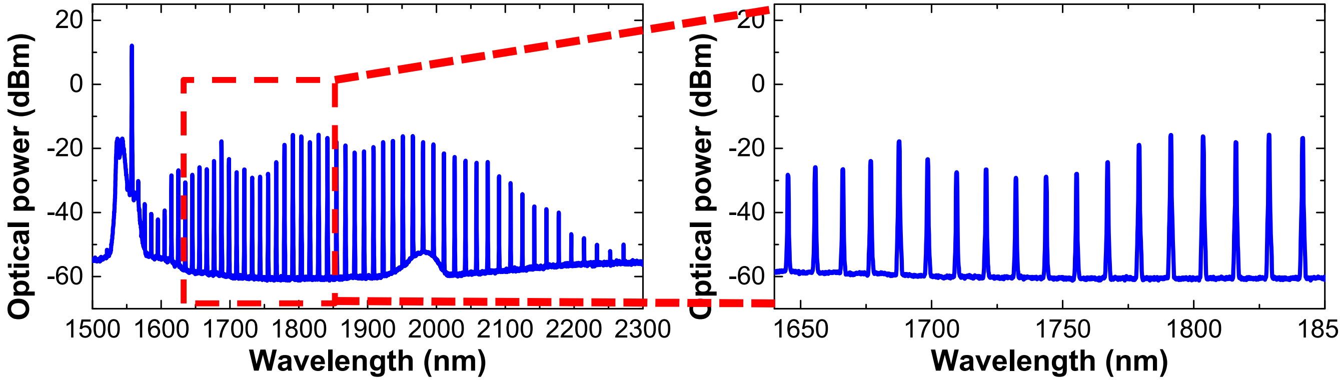




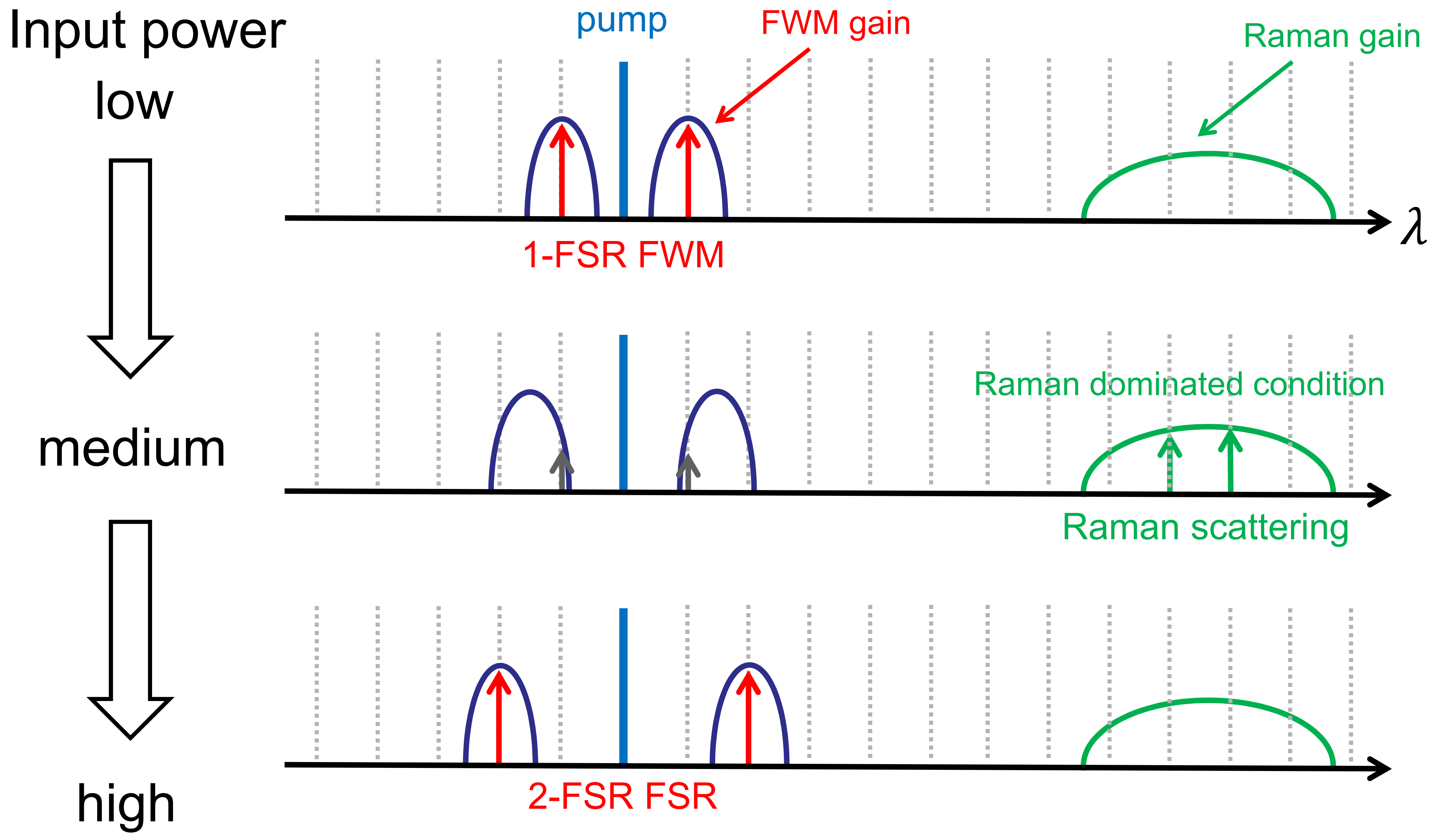
▶Raman (Pump:1556.4 nm, 250 mW



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



Explanation of competition between Raman & FWM gain



Four-Wave Mixing gain in a resonator

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

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

$$\kappa P_{\mathrm{input}} = (\gamma L)^2 P_0^3 - 2\delta_0 \gamma L P_0^2 + (\delta_0^2 + \alpha_{\mathrm{tot}}^2) P_0$$

γ : nonlinear coefficient

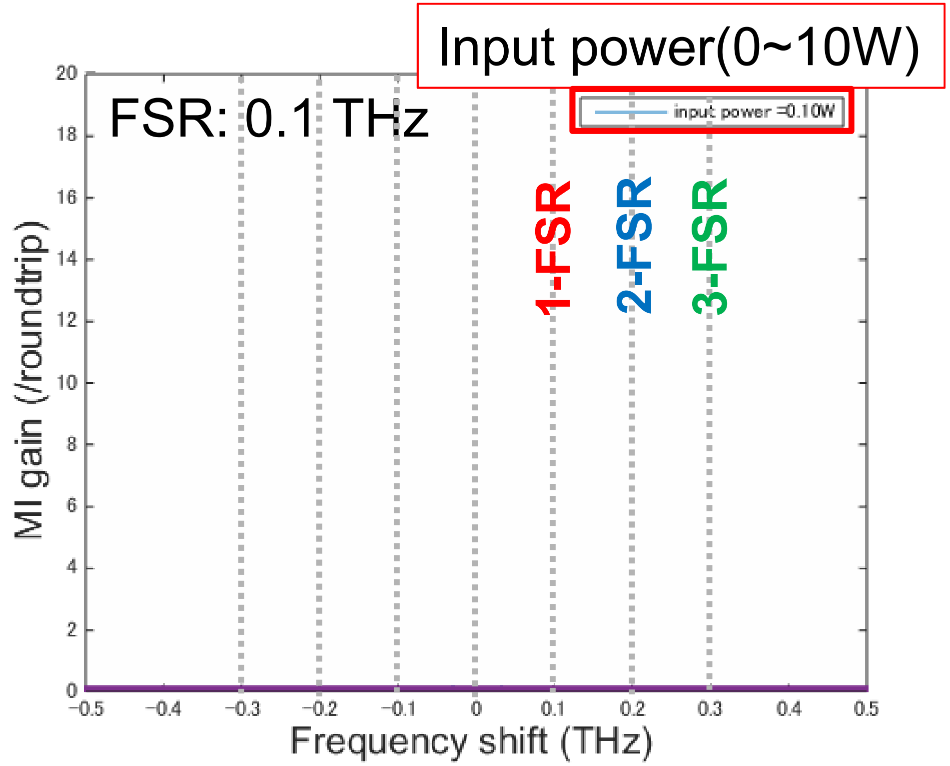
β_2 : second-order dispersion

δ_0 : detuning of input

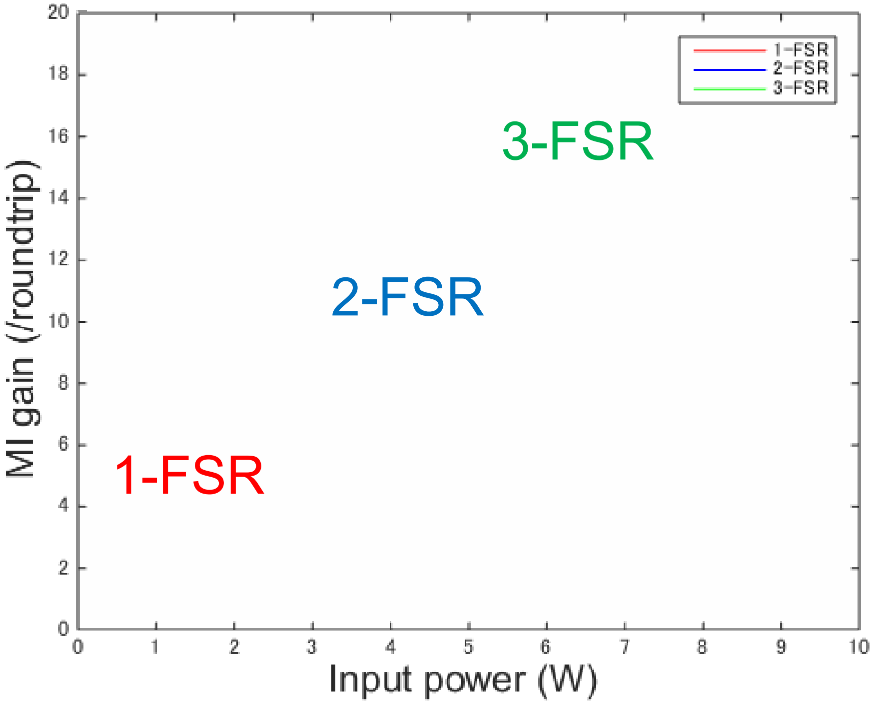
L : cavity length

κ : coupling coefficient

α_{tot} : total loss


Input power(0~10W)

FSR: 0.1 THz



Numerical simulation model

▶Lugiato-Lefever equation

$$t_R \frac{\partial E}{\partial r} = \left(-\frac{\alpha}{2} - \frac{\kappa}{2} - i\delta_0 + iL\sum_{k\geq 2}\frac{\beta_k}{k!}\left(i\frac{\partial}{\partial T}\right)^k + N\right)E + \sqrt{\kappa}S$$

$$N = i\gamma L\left(E\int_{-\infty}^{\infty} R(t')|E(t-t')|^2 dt'\right)$$

$$R(t) = (1-f_R)\delta(t) + f_R h_R(t)$$

$$h_R(t) = \frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp\left(-\frac{t}{\tau_2}\right)\sin\left(\frac{t}{\tau_1}\right)$$

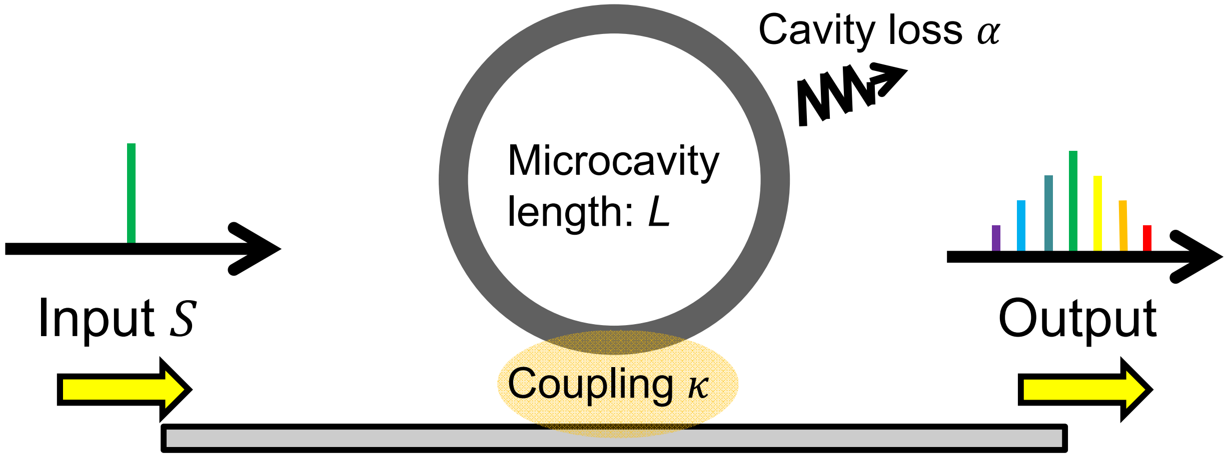
$\tau_1 = 12.2$ fs

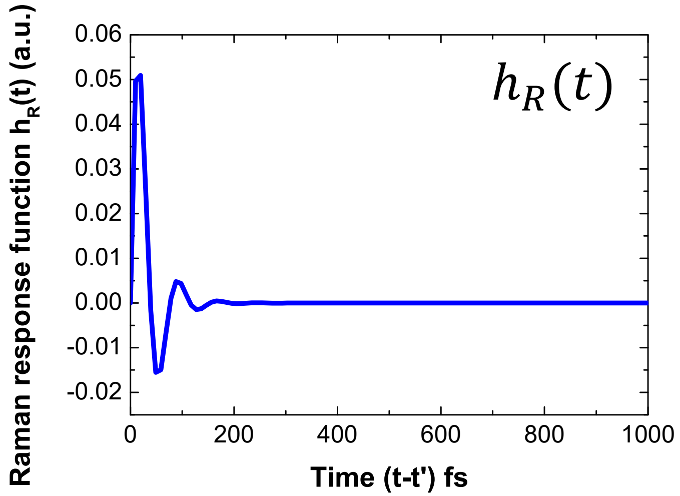
$\tau_2 = 32$ fs

$f_R = 0.18$

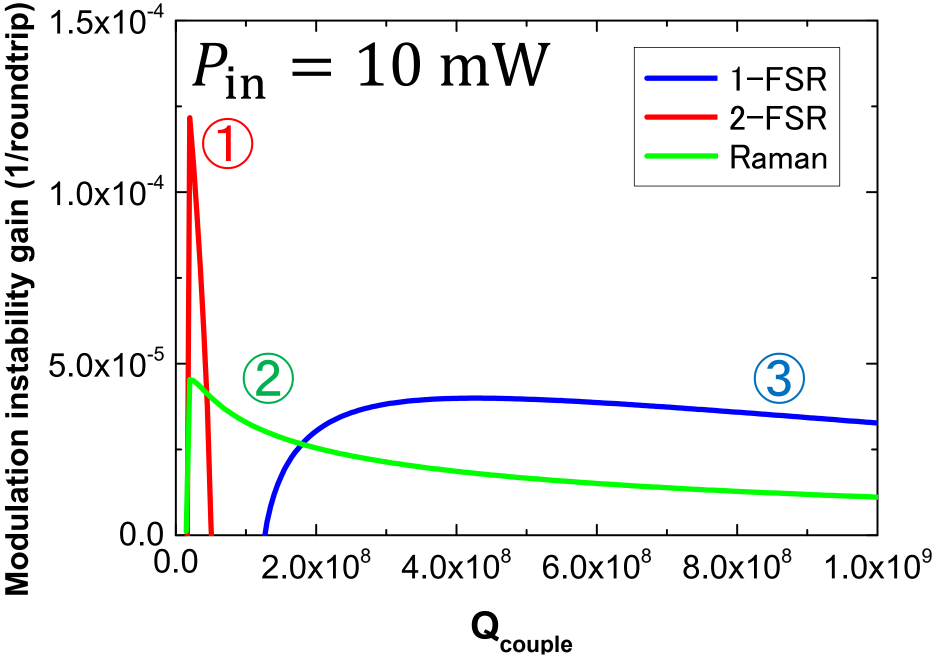
r: round trip number
t_R: round trip time
δ_0: detuning

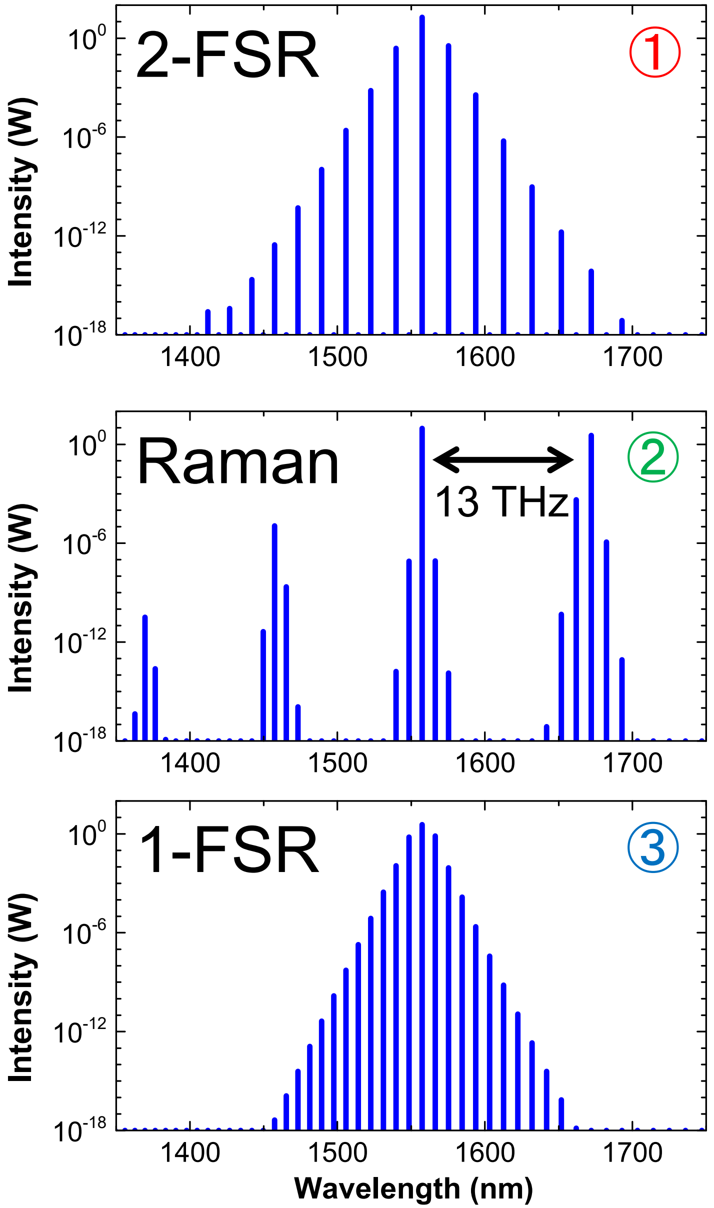
α : cavity loss
κ : coupling loss
L : cavity length
β: dispersion
γ: nonlinear coefficient





Simulation result for Kerr comb generation





$Q_{\mathrm{coup}} = 3 \times 10^7$

$Q_{\mathrm{coup}} = 1 \times 10^8$

$Q_{\mathrm{coup}} = 9 \times 10^8$

Good agreement with the gain analysis result

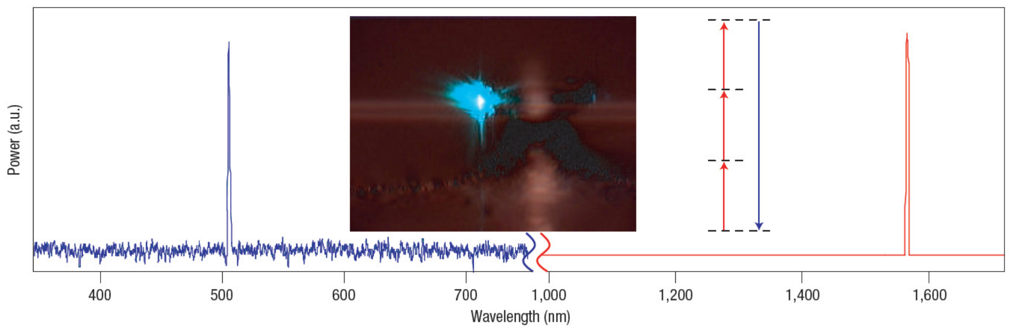
Outline

1. Dispersion in a small toroid microcavity
2. Effect of cavity opto-mechanics
3. Effect of CW/CCW mode coupling
4. Raman / FWM generation
5. Visible comb generation

Visible comb generation with soliton pulse

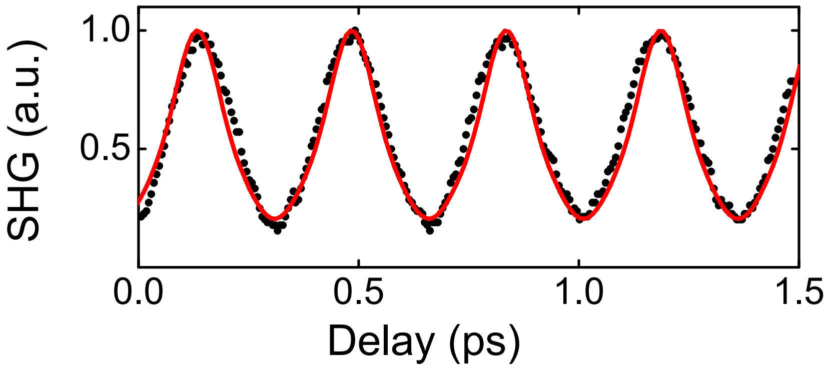
▶Efficient third-harmonic generation

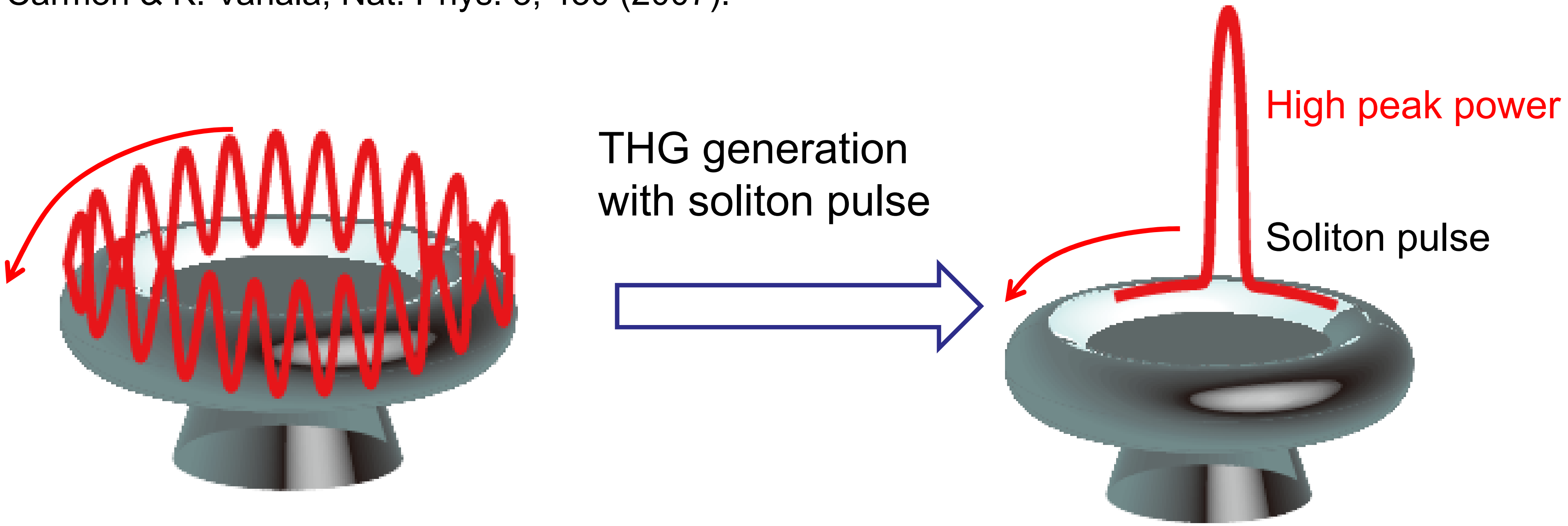
CW mode



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

▶THG with pulsed mode





THG generation with soliton pulse

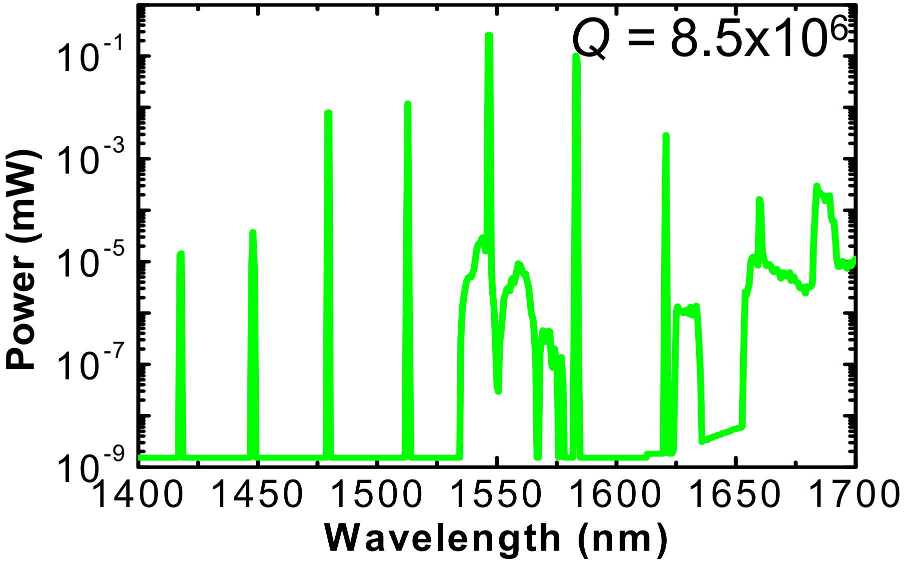
High peak power

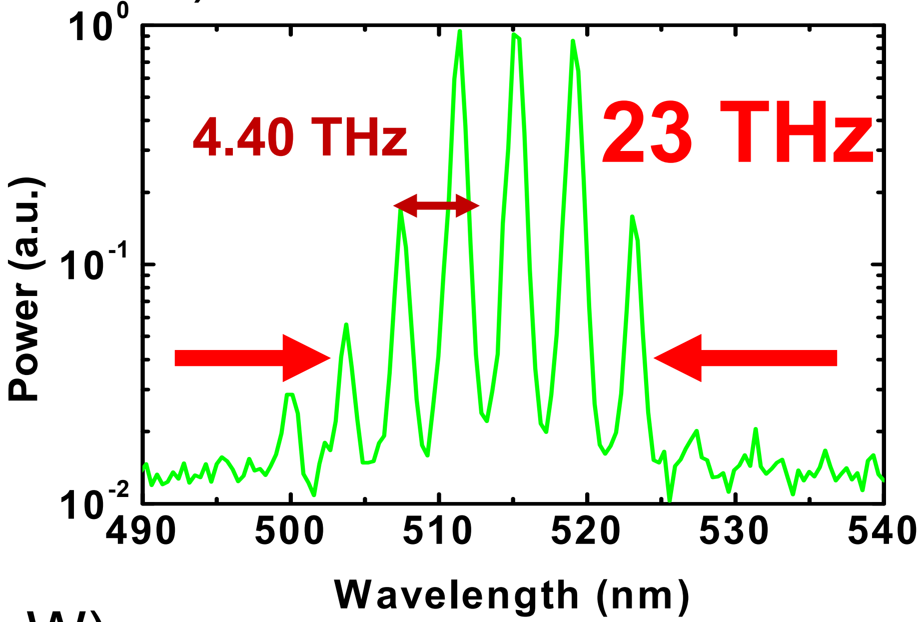
Soliton pulse

Potential for improving THG efficiency

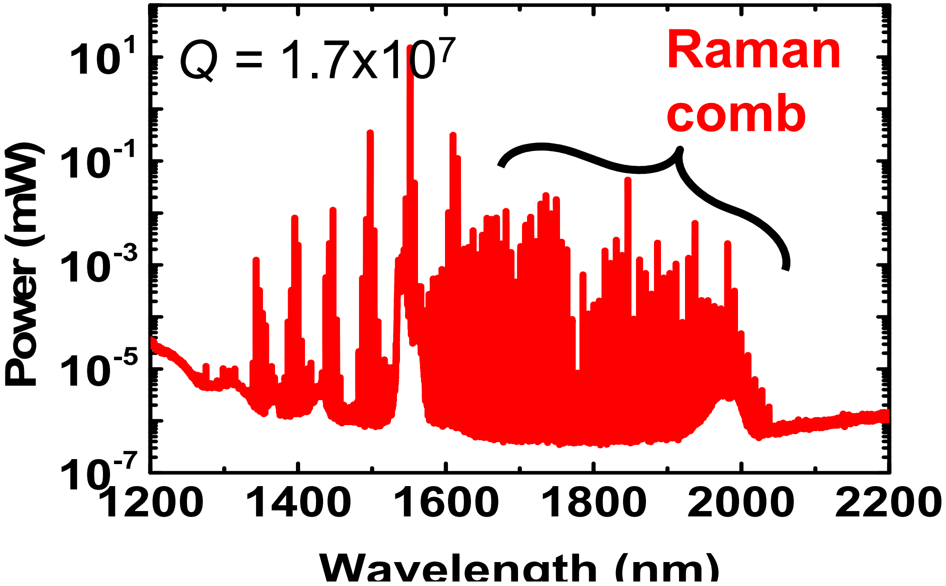
Broad bandwidth generation

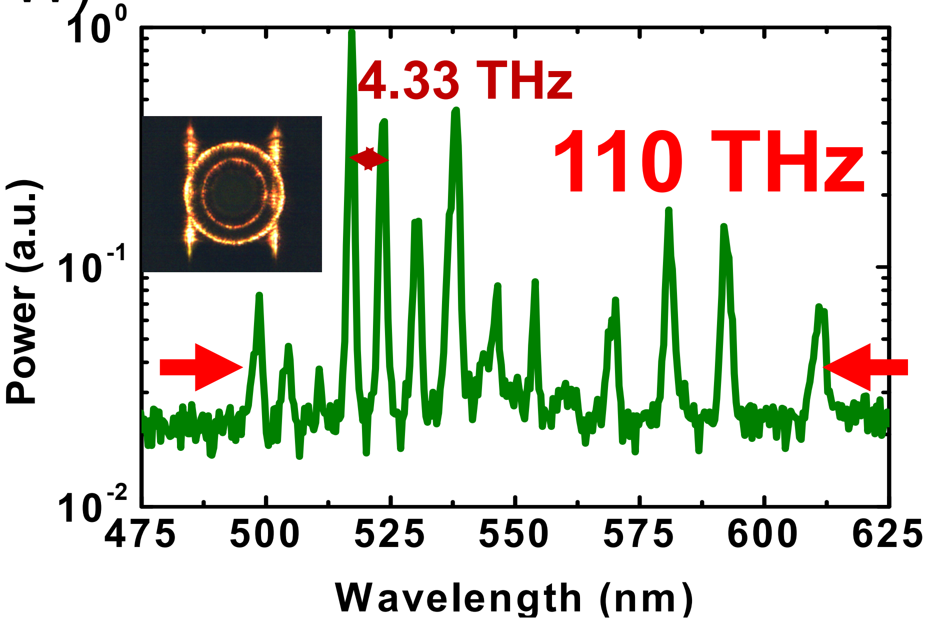
- w/o Raman comb (Input: 1545.93 nm, 0.94 W)





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





Summary

Solving problems of small WGM cavities

1. Dispersion: Anomalous dispersion is possible by using higher order modes
2. Cavity opto-mechanics: Suppressed by sweeping the wavelength (in same direction used to generate soliton pulses)
3. CW/CCW mode coupling: Small noise present from CCW mode scattering, but this can be suppressed by choosing right parameters.

Small cavity can enhance nonlinearity

- ✓ Broad bandwidth comb generation via Raman assisted FWM
- ✓ Broad bandwidth THG light generation

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The team

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Mr. Shun Fujii (CW/CCW mode coupled FWM)
Mr. Akitoshi C.-Jinnai (THG generation)
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