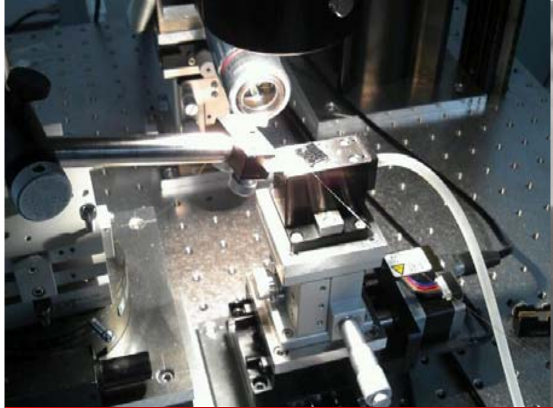
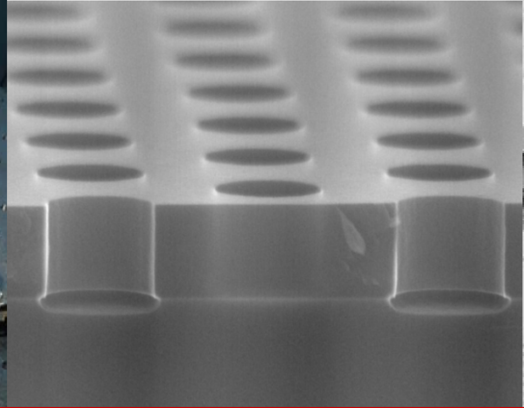




The 3rd Advanced Lasers and Photon Sources (ALPS'14), ALPS3-5

Pacifico Yokohama, Yokohama, Japan

Apr. 23, 2014, 10:15-10:30

RF noise measurement of a microcavity Kerr comb generated by dual pumping

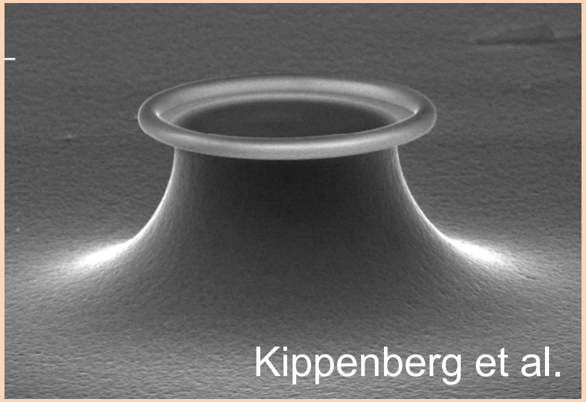
Ryo Suzuki, Takumi Kato, Tomoya Kobatake, and Takasumi Tanabe

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

Kerr comb

Kerr comb

Microcavity



- ✓ On chip
- ✓ High repetition rate (10GHz-1THz)
- ✓ Low cost
- ✓ Low pump threshold

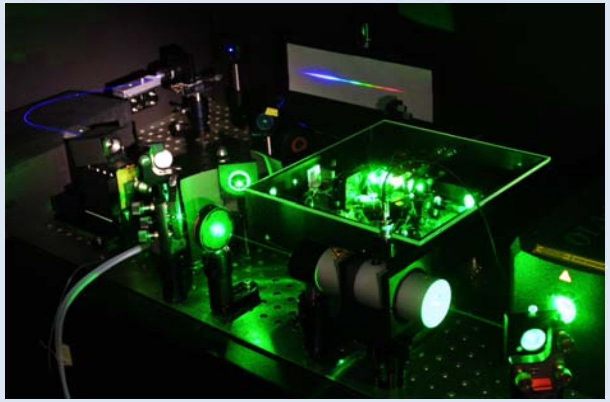
<u>Threshold pump power of degenerate four-wave mixing</u>

$$P_{threshold} \propto \frac{V}{Q^2}$$

V : mode volume, Q : quality factor

Frequency comb

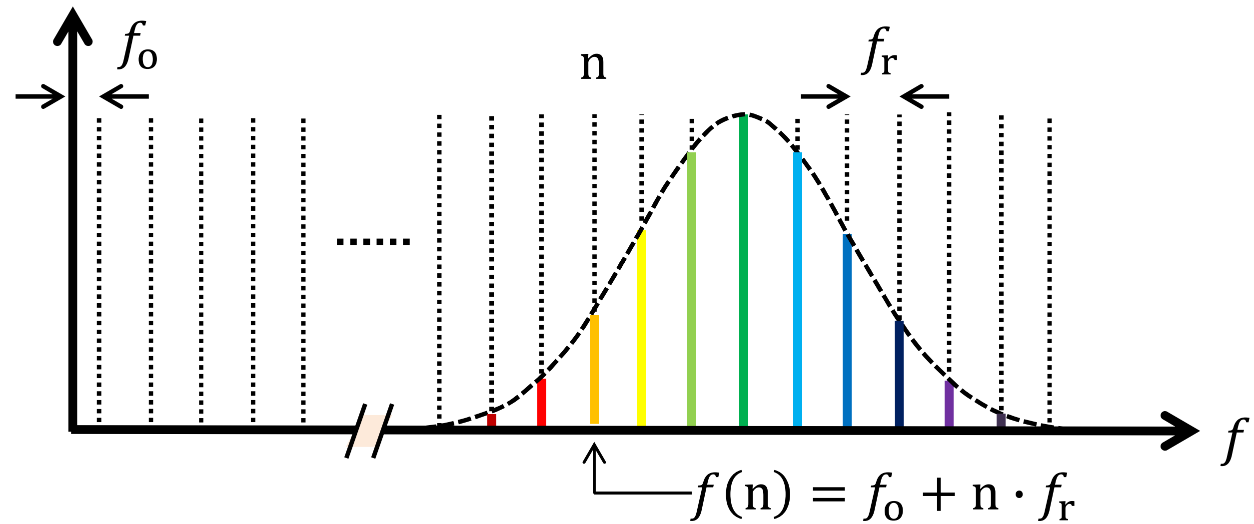
Ti:Sapphire laser



Fiber laser

Large & expensive

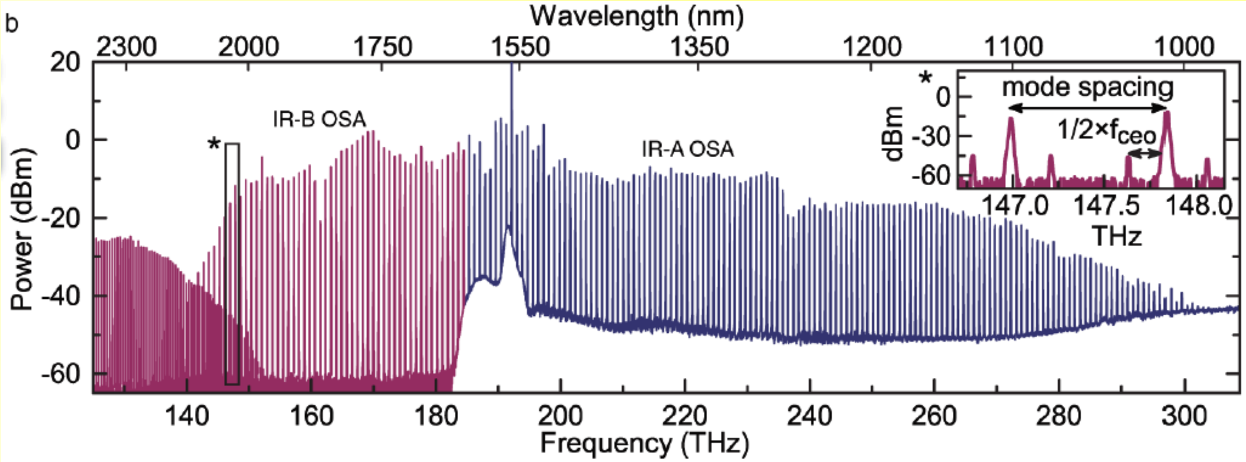
http://k-lab.epfl.ch/
http://www.mpq.mpg.de/~haensch/comb/index.html
https://www.aist.go.jp/index_ja.html



Motivation

▶ Octave spanning Kerr comb

P. Del'Haye et al., Phys. Rev. Lett. **107**, 063901 (2011)



- ✓ Silica toroid microcavity
- ✓ Pump power = 2.5 W
- ✓ No highly non-linear fiber

Kerr comb has been observed, but a *f-2f* self referencing is not achieved yet, due to,

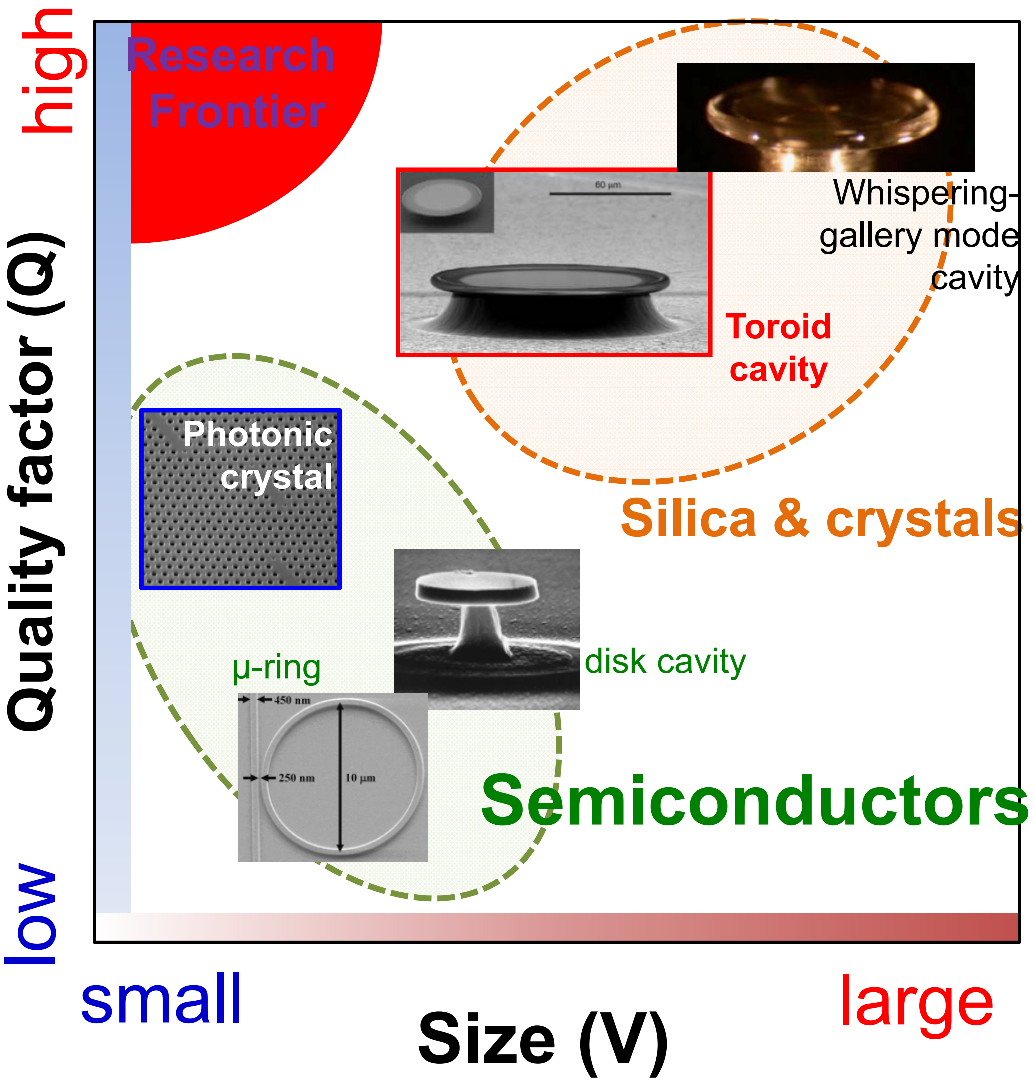
1) <u>low stability of the generated comb</u>
2) <u>unknown mechanism on mode-locking in microcavities</u>

Motivation

- ➢ Understand the mode-locking mechanism
- ➢ Increasing the stability by dual pumping

Various high Q microcavities

▶Various microcavities



▶Quality factor and mode volume

◆Q-factor

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

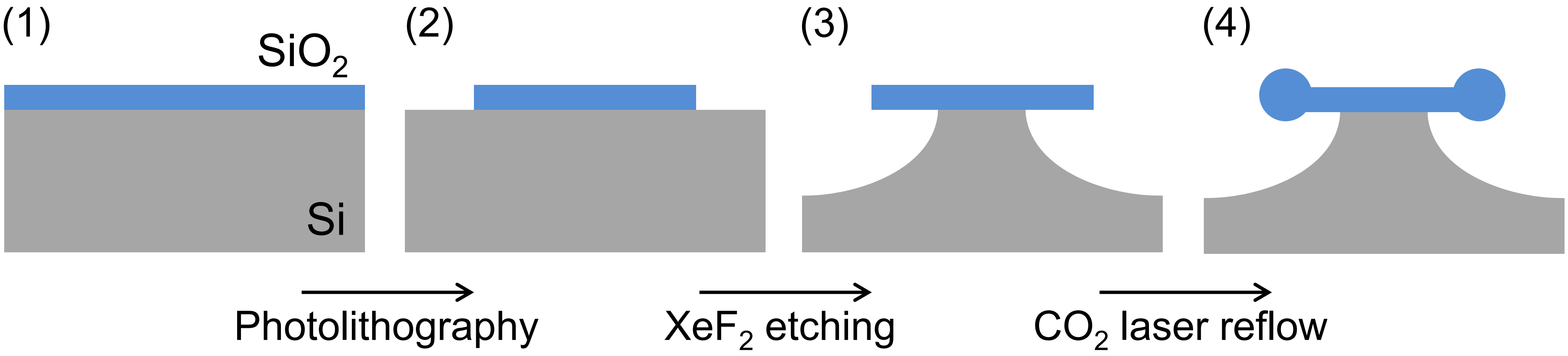
◆Photon density

$$\propto Q/V$$

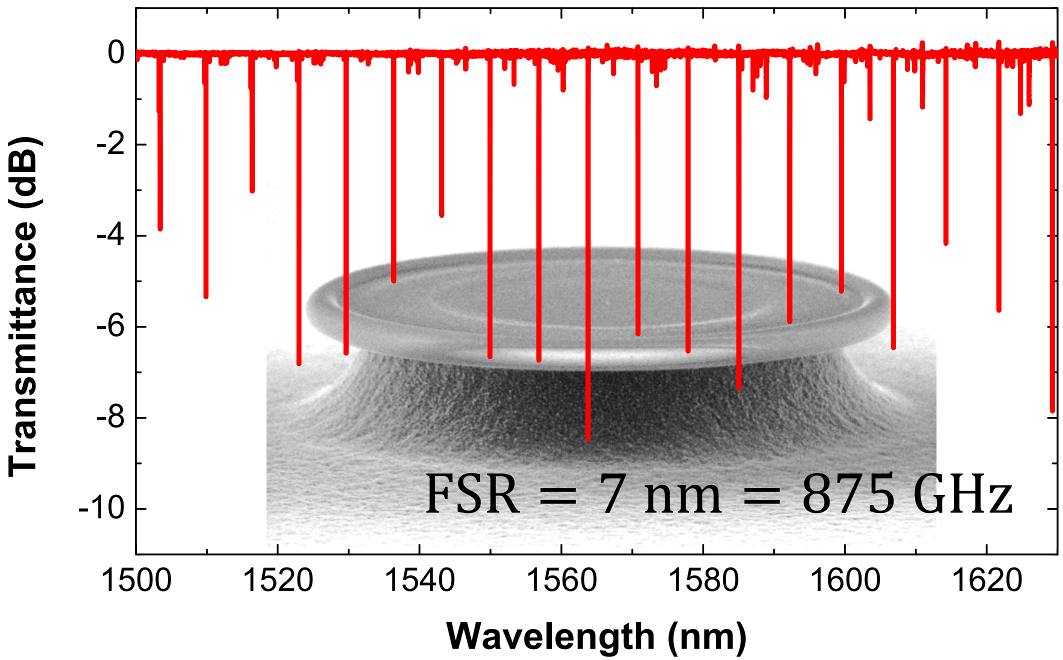
▶Applications

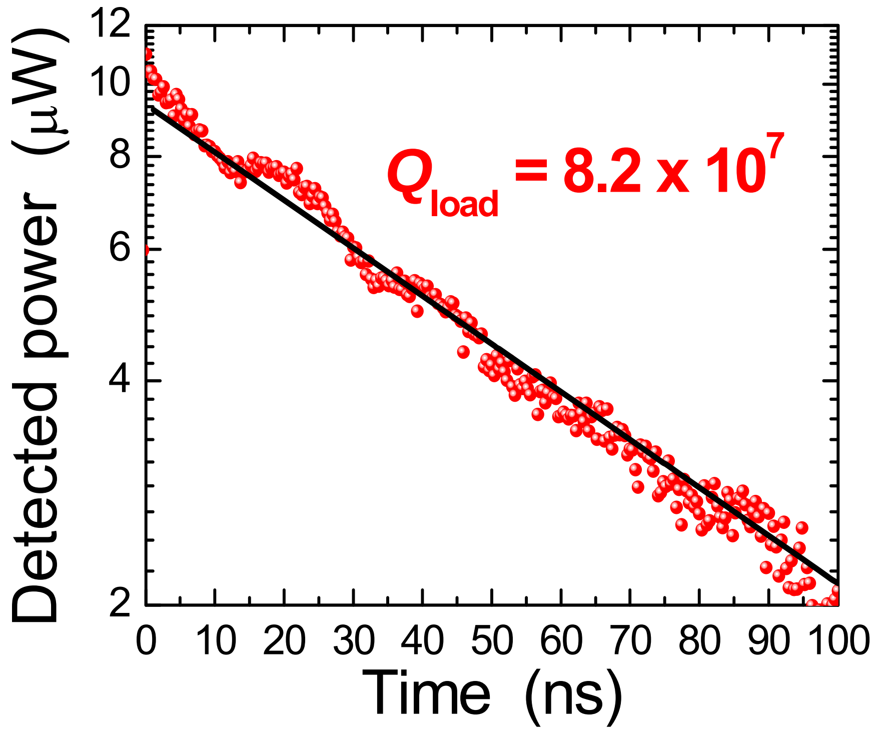
- ▸All-optical switching
- ▸Optical buffer
- ▸Cavity QED devices
- ▸Low-threshold lasers
- ▸Optical sensors
- ▸Optical frequency combs

High-Q silica toroid microcavity

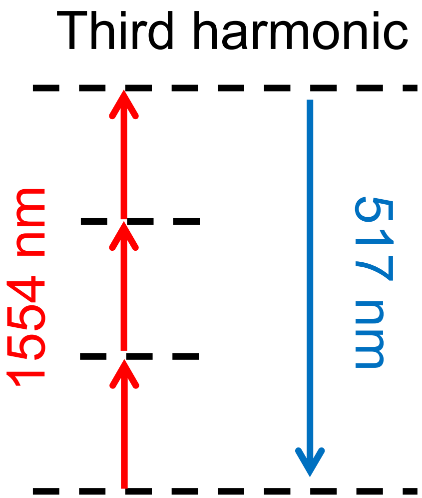


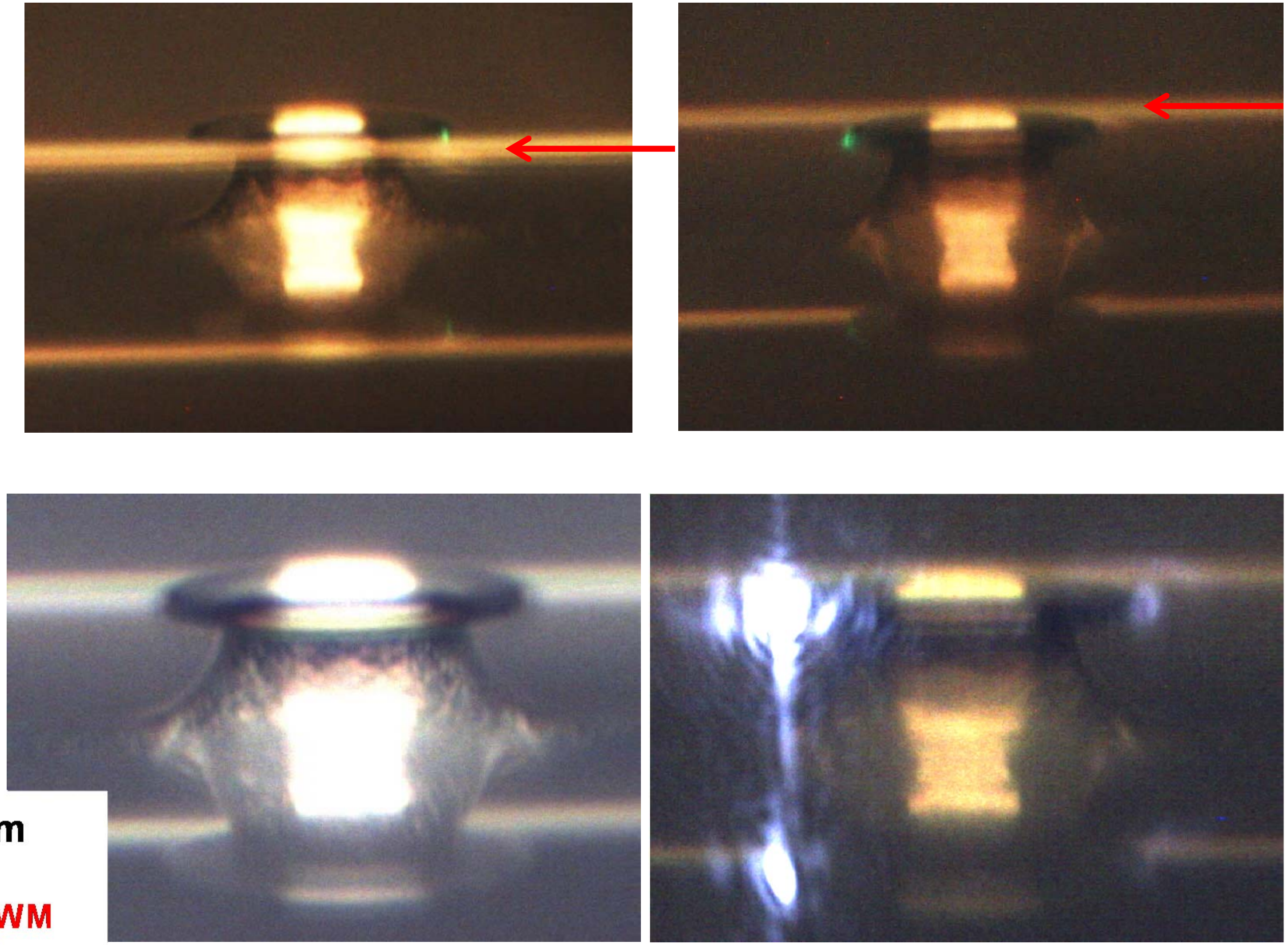
- Spectrum Measurement



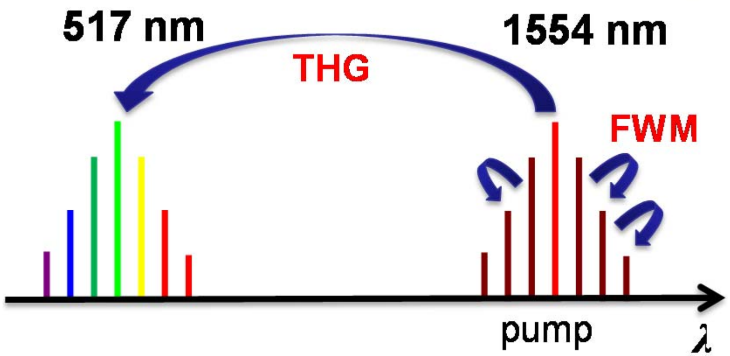


Third harmonic generation

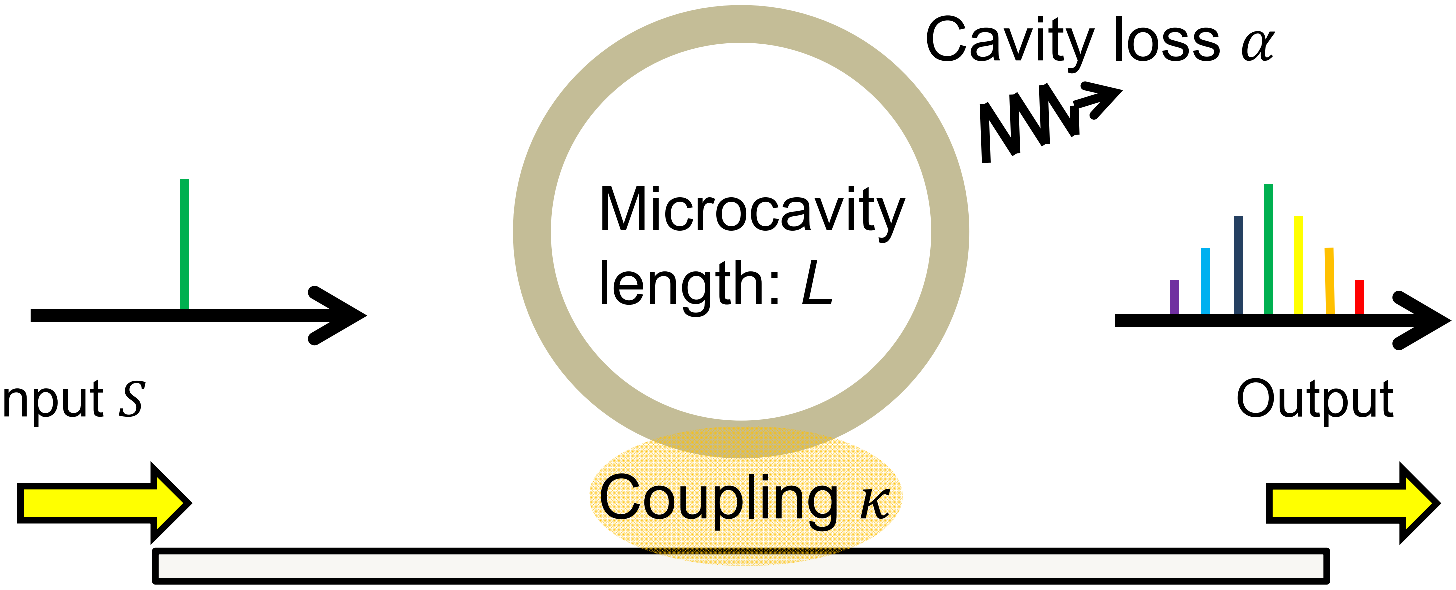




$\chi^{(3)}$ nonlinearity

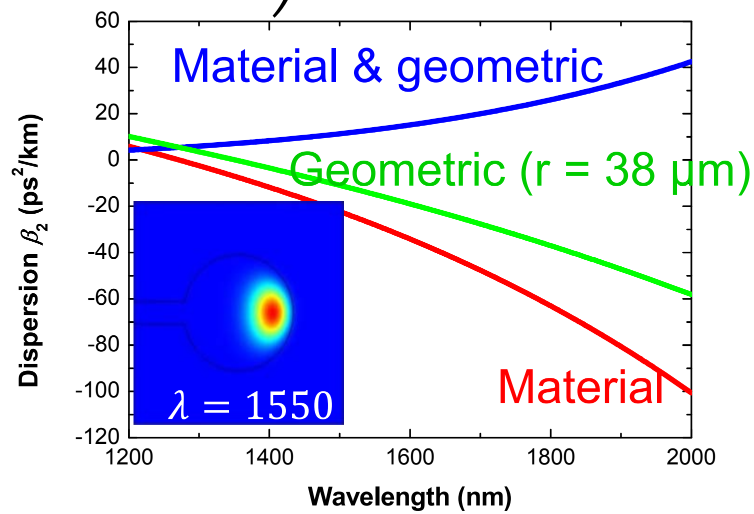


Solving Lugiato-Lefever equation w/ split-step Fourier method



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

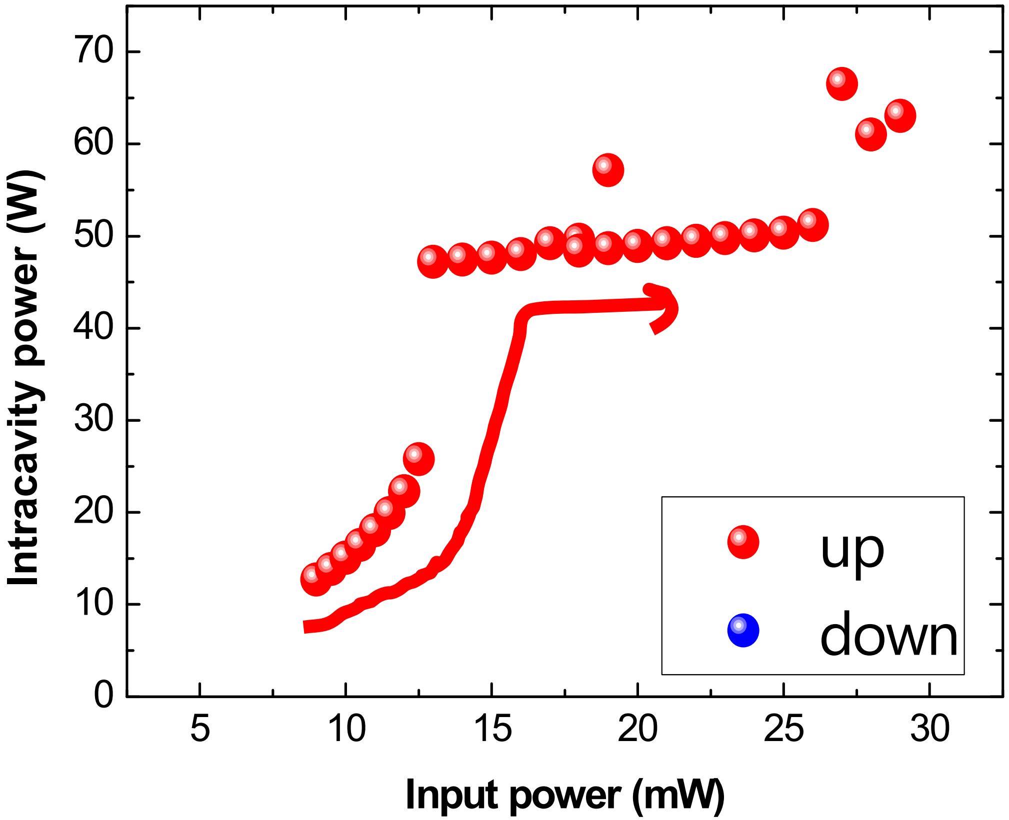
r: round trip number
t_R: round trip time
δ_0: detuning of input
β: dispersion parameter
γ: nonlinear parameter



Simulation: harmonic to fundamental mode-locking

$Q_\alpha = 7.0 \times 10^6$ $\Delta = 2$ (detuning)

$Q_\kappa = 7.0 \times 10^6$



Simulation: harmonic to fundamental mode-locking

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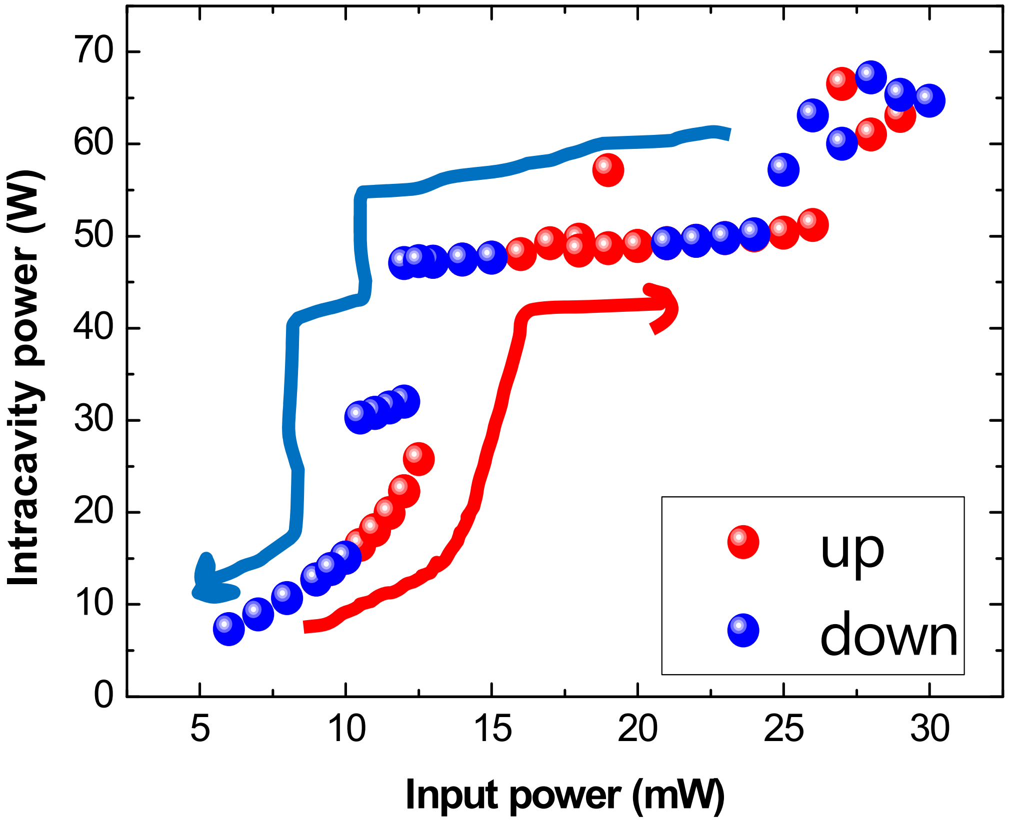

Simulation: harmonic to fundamental mode-locking

$$Q_\alpha = 7.0 \times 10^6 \qquad \Delta = 2 \text{ (detuning)}$$

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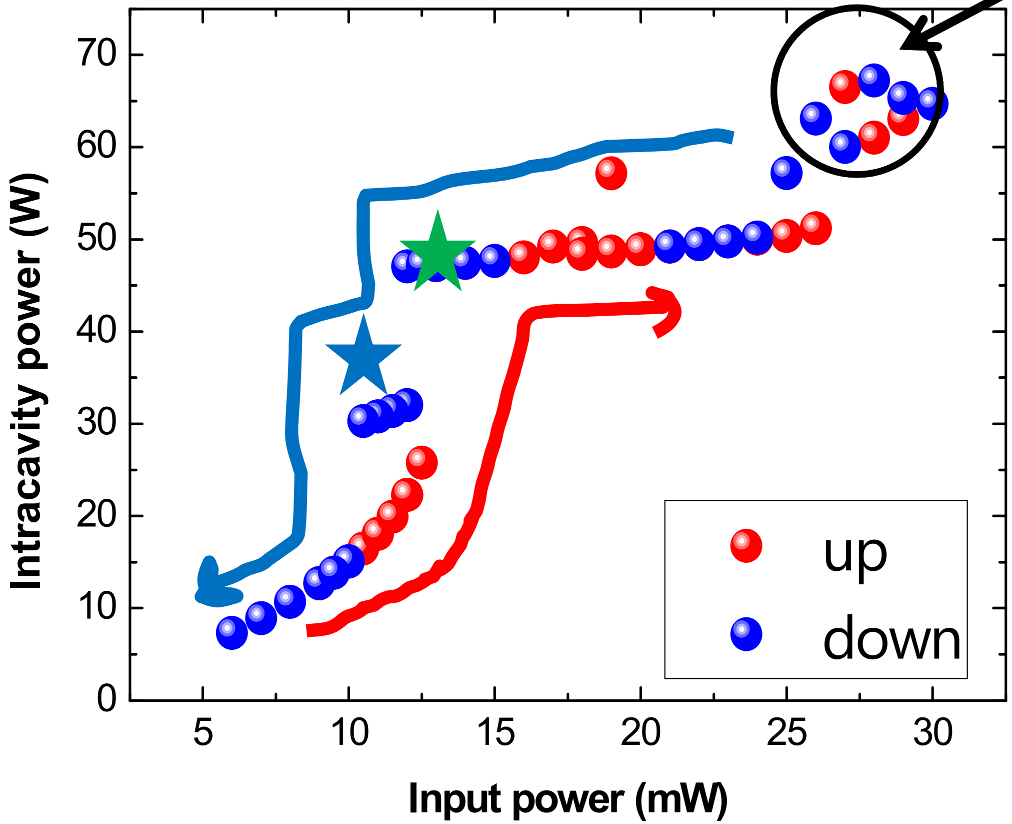
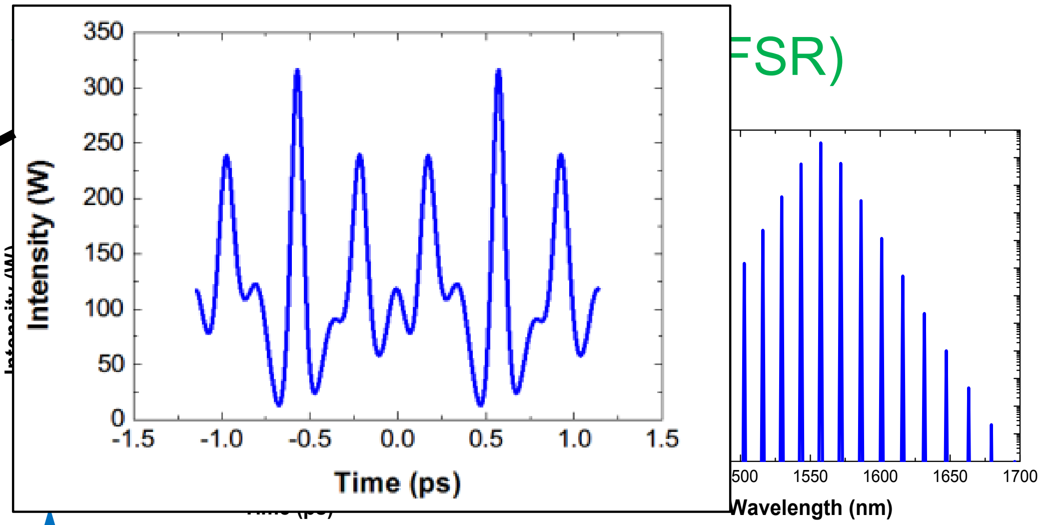
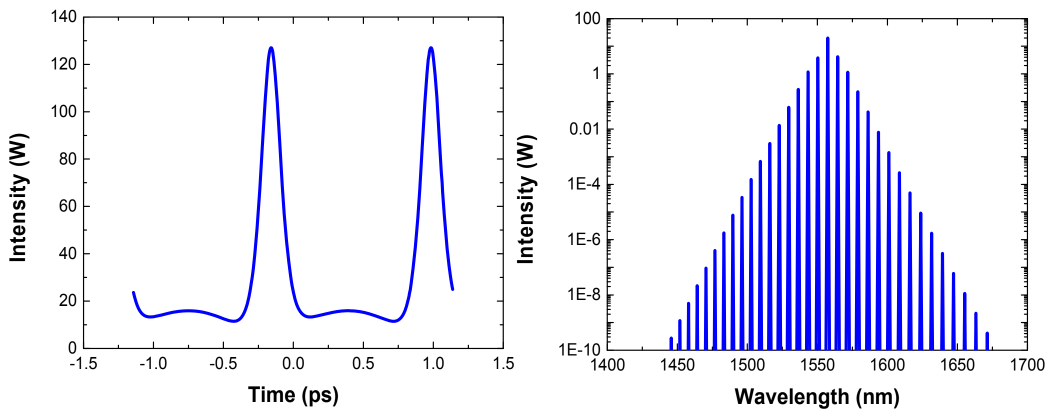
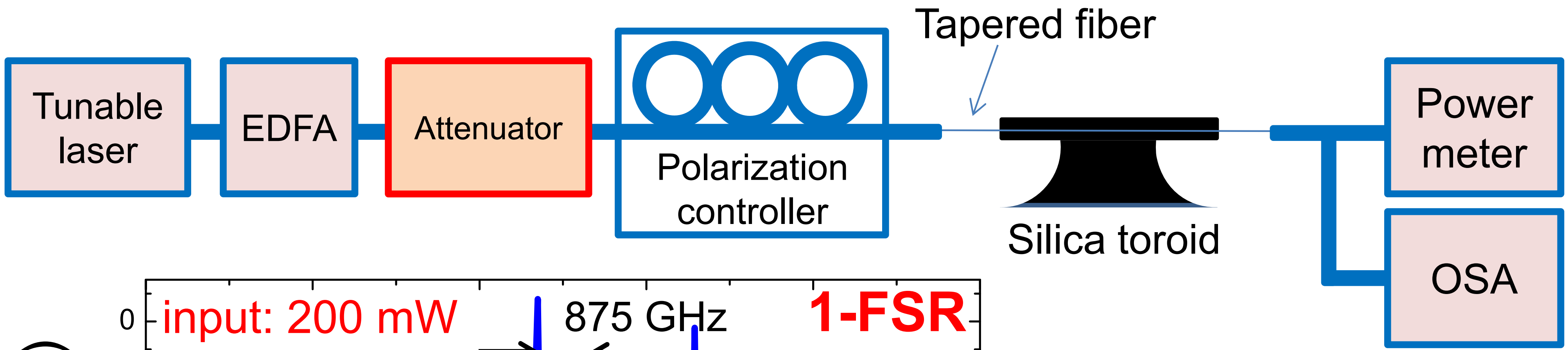


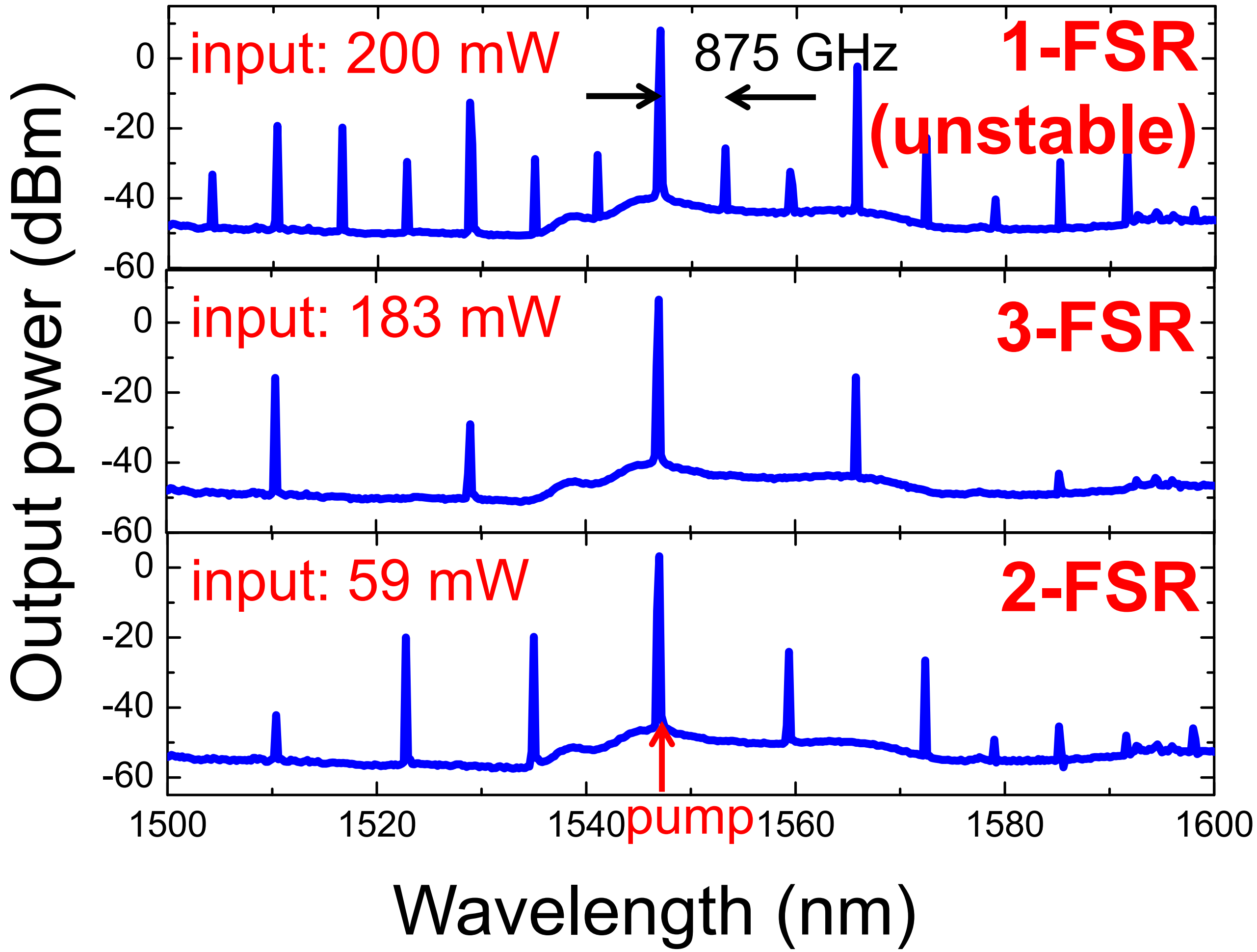


Mode locking(1-FSR)



Experiment: mode-locking by power control





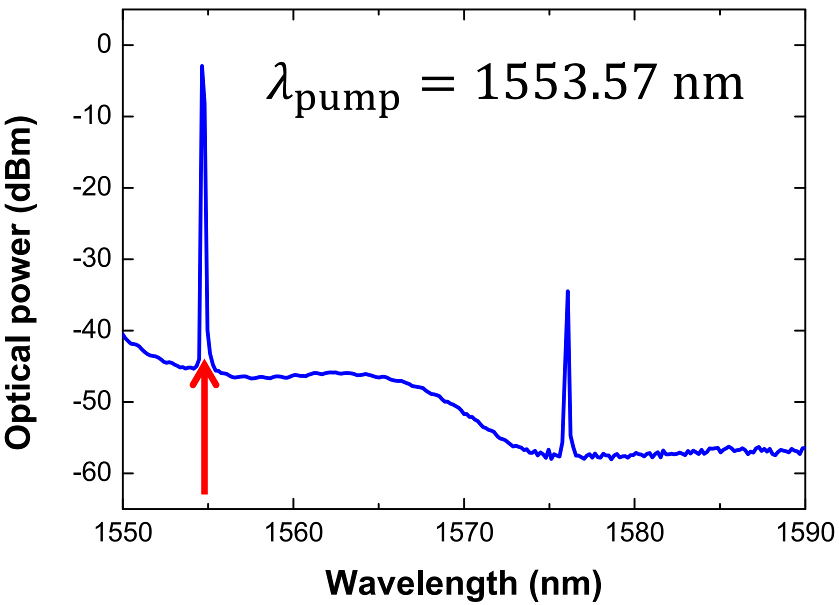
Experiment condition

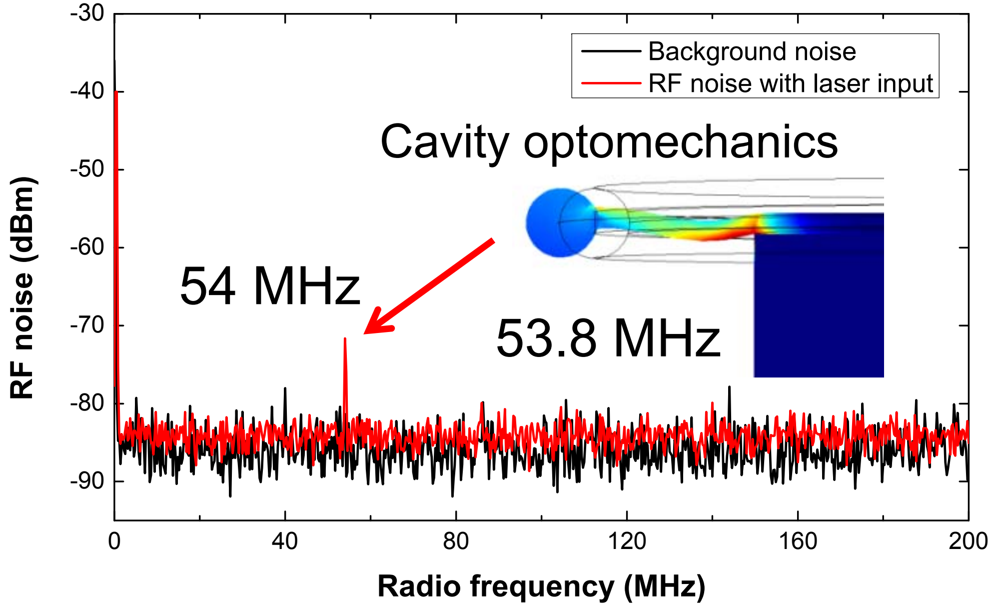
Pump linewidth = 100 kHz
Pump power = 200 mW
Taperd fiber ϕ ~ 1 μm

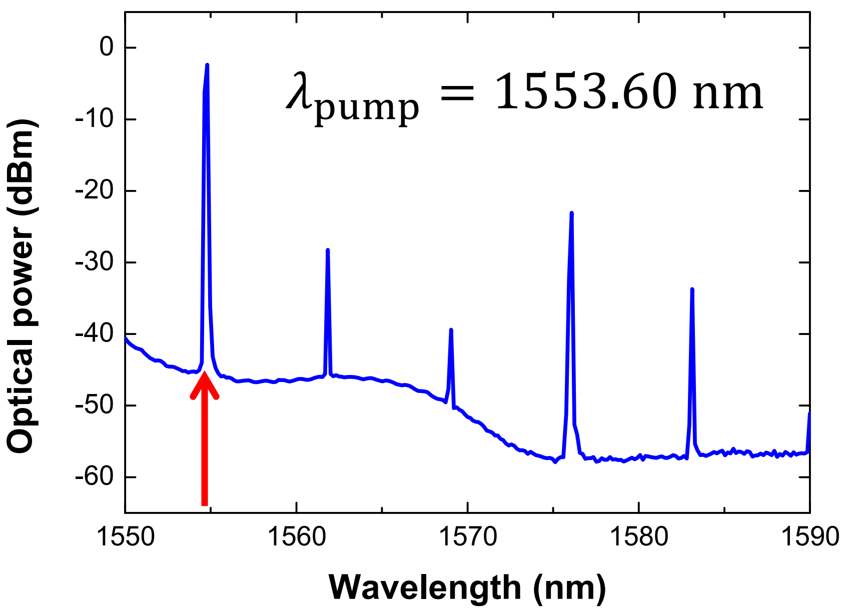
$Q = 5 \times 10^6$
$V \sim 1000\ \mu m^3$
Cavity FSR = 875 GHz

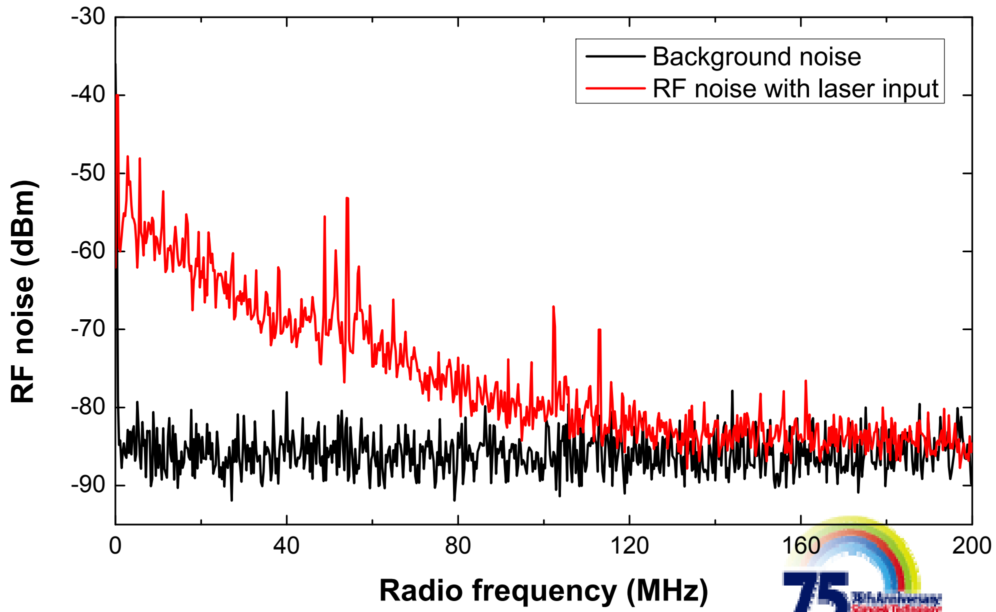
Experiment: Kerr comb spectra vs RF noise

Increasing pump power in microcavity





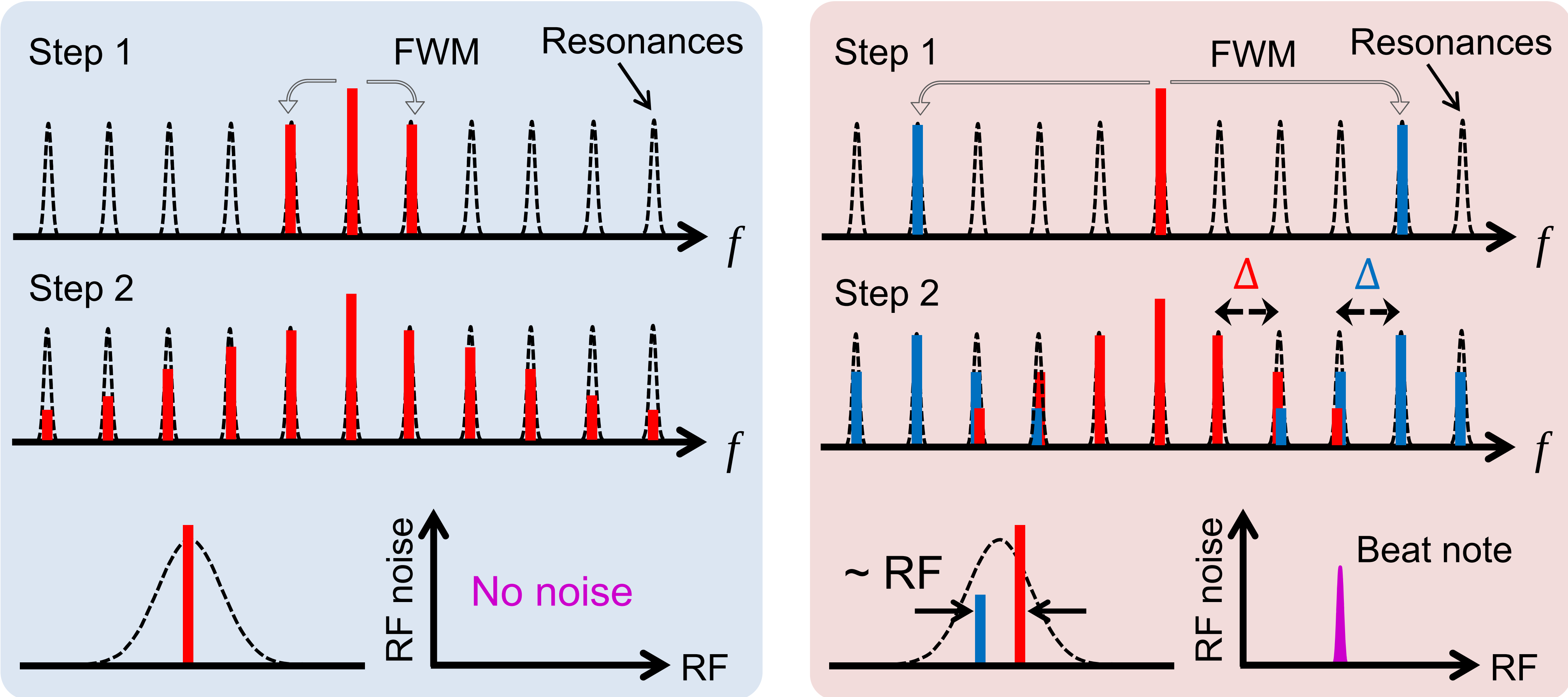




Cause of RF noise (1)

(1) different comb lines overlap in a single resonance

Type1: Low power pumping (low noise)　　Type2: High power pumping (large noise)



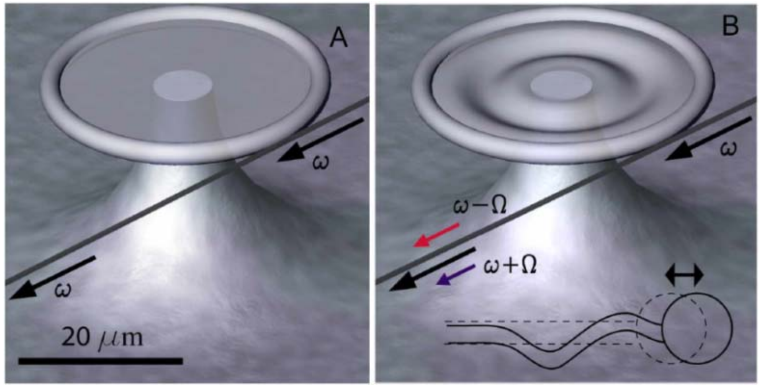
Type2: Owing to different spacing (Δ, Δ), different comb lines overlap in a single resonance.

T. Herr et al., Nature Photon. 6, 480-487 (2012).

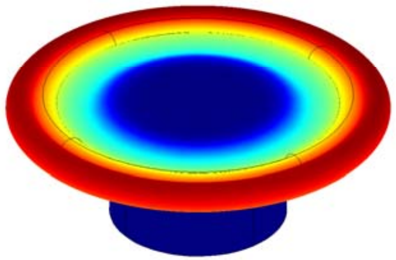
Cause of RF noise (2) & solution

(2) Cavity Optomechanics

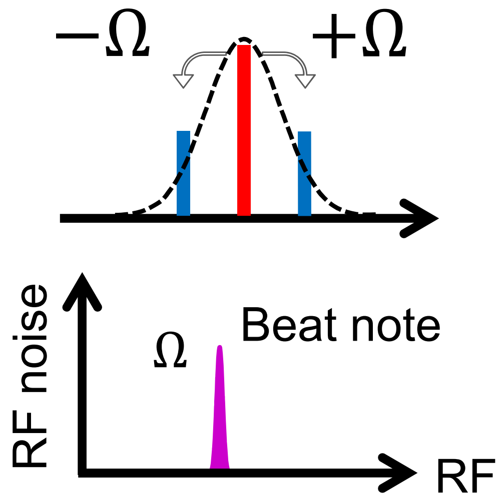
Interaction between light and mechanical objects



H. Rokhsari et al., Opt. Express **13**, 5293-5301 (2005).



Breezing mode



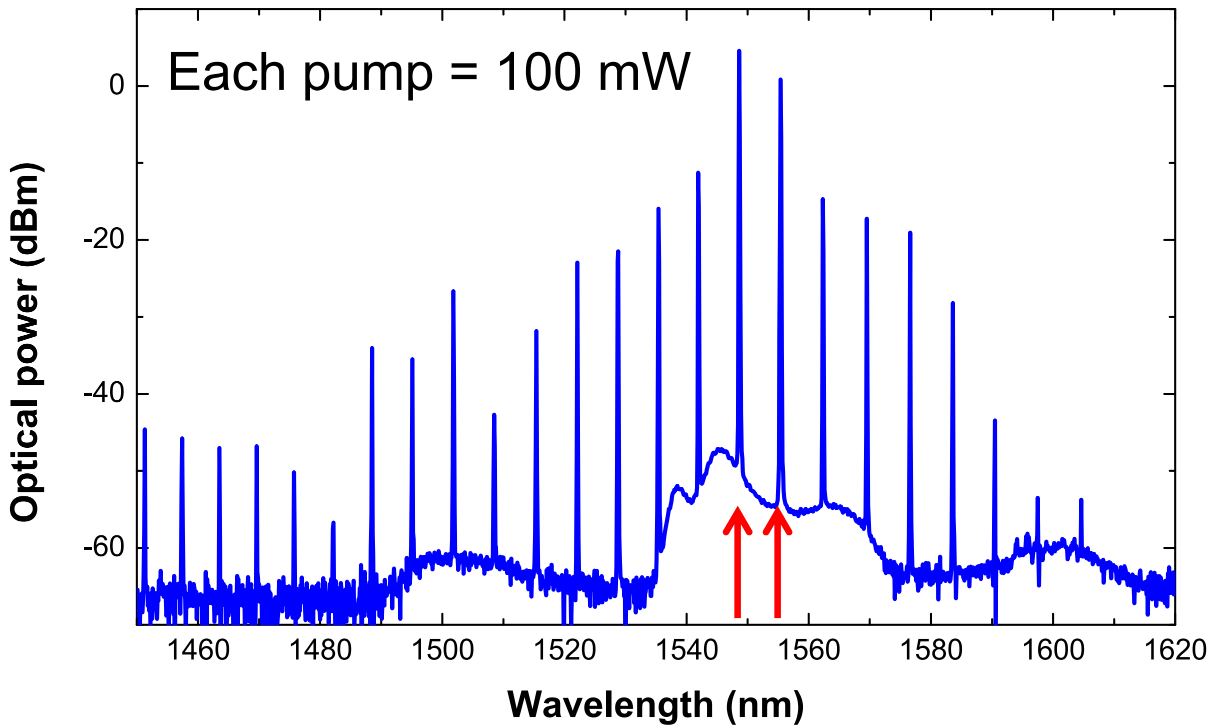
Solution

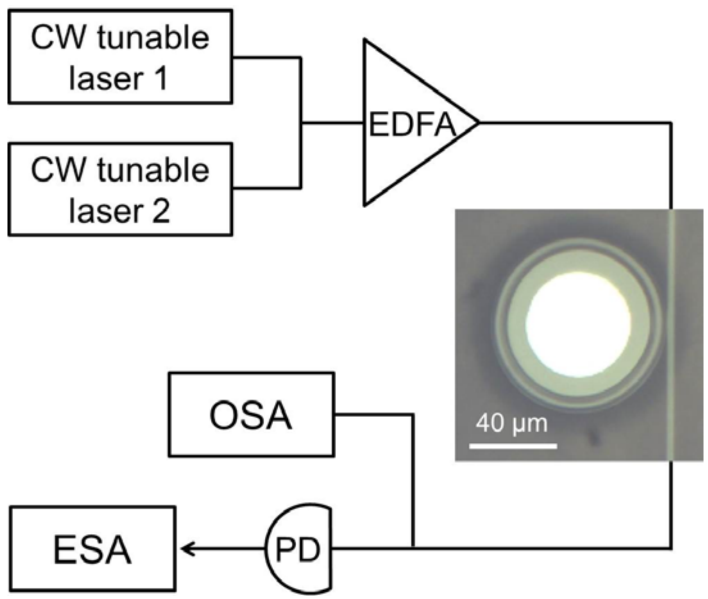
High power pumping is required for broadband Kerr comb,
but it generates large noise.

By dual pumping,
- ✓ generating Type 1 comb intentionally
- ✓ reducing FWM threshold power

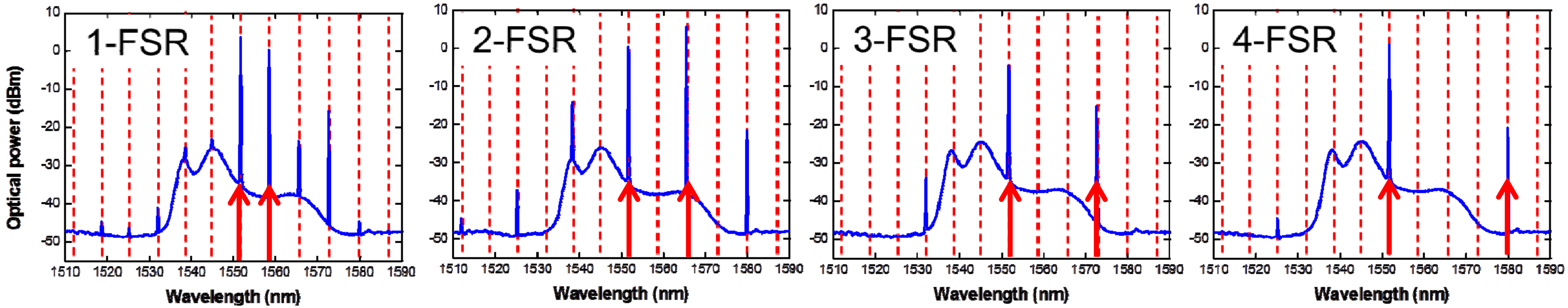
} reducing RF noise

Kerr comb generation with toroid microcavity (Dual pump)





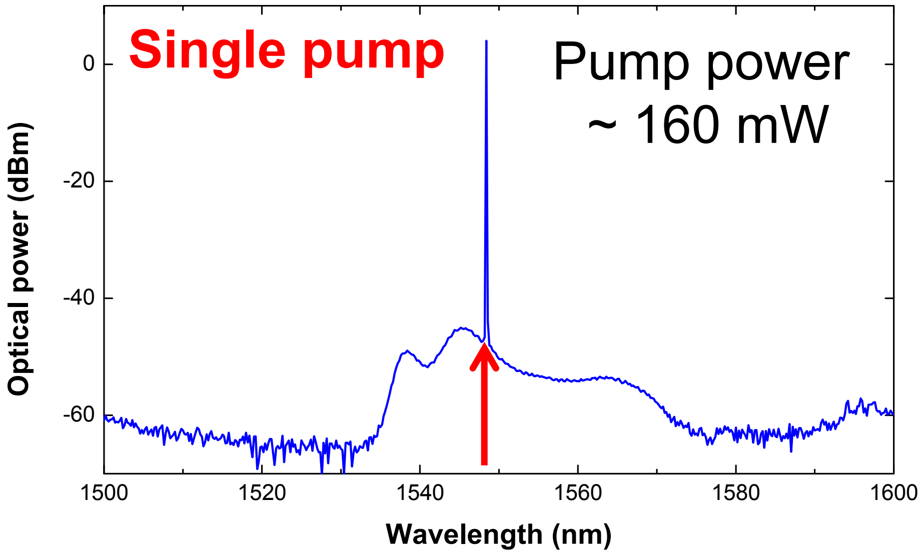
- Controllable mode spacing：generating Type1 (low noise) comb intentionally

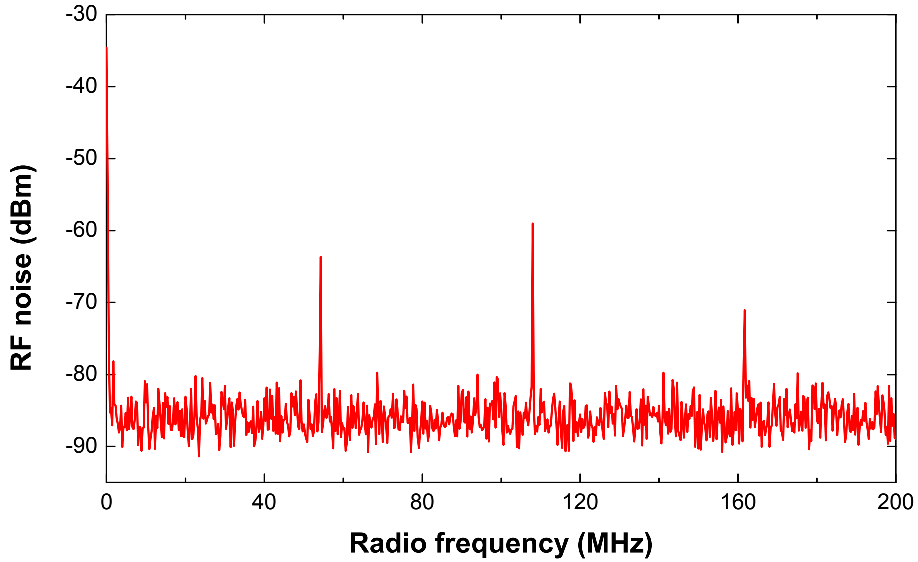


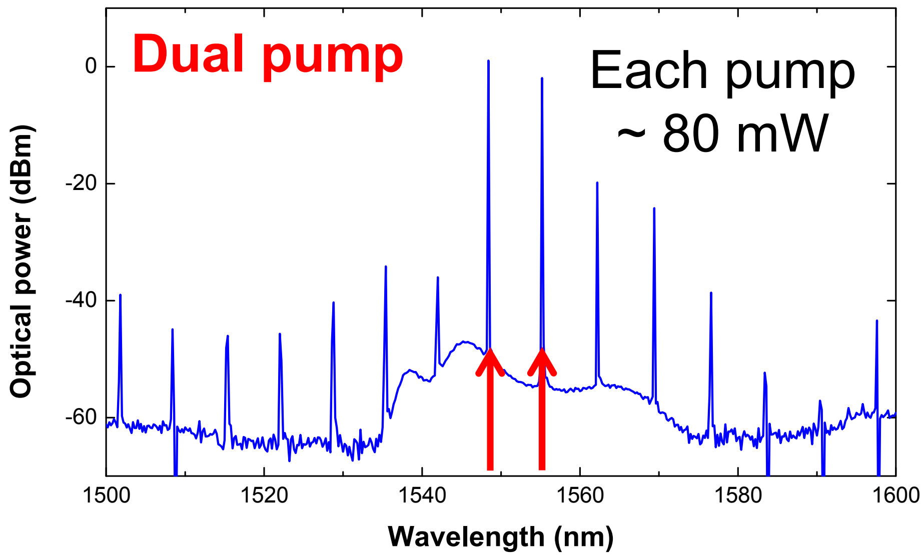
Characteristics of Dual pump Kerr comb

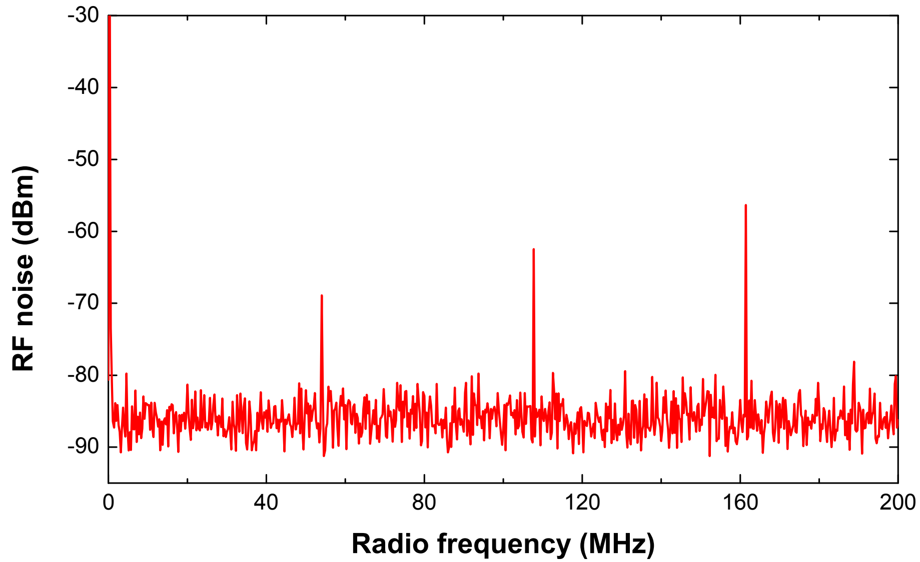
Dual pump reduces FWM threshold power

RF noises show same pattern because pump powers are 160 mW both.









Summary

- ✓ Kerr comb at 850-GHz spacing is generated
- ✓ 2-FSR mode locking is achieved with 60-mW power
- ✓ We found decreasing the input is essential to obtain mode locking
- ✓ We demonstrate lower RF noise by pumping the cavity with two wavelength

Acknowledgement: Strategic Information and Communications R&D Promotion Program (SCOPE), from the Ministry of Internal Affairs and Communications of Japan