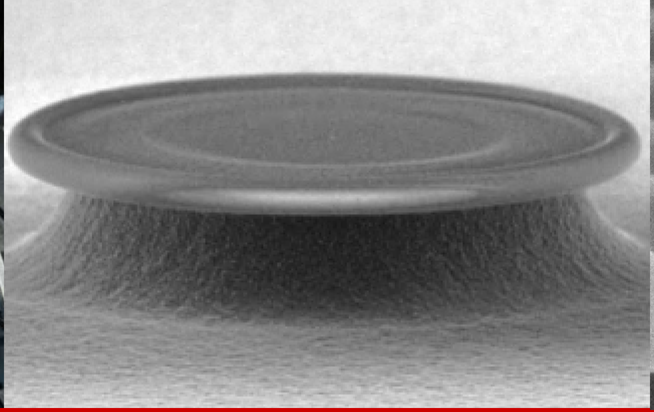
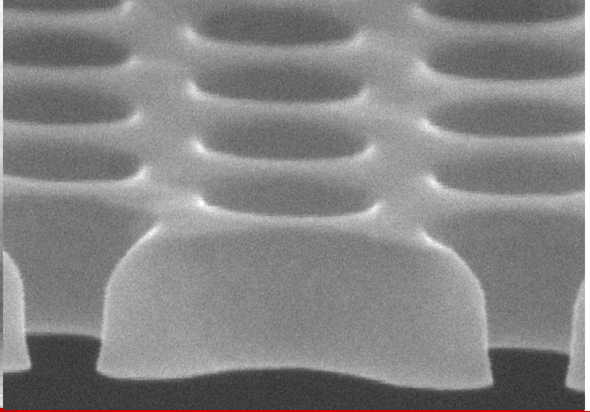
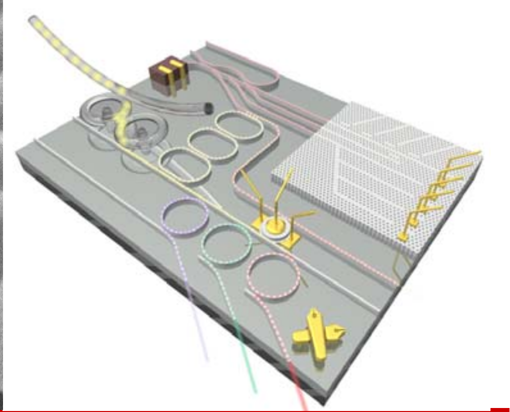





SC3: Session 3A_14
Jul. 8, 2015 9:40-10:00

Optical Kerr switching and comb generation in a silica whispering gallery mode microcavity

Takasumi Tanabe

*takasumi@elec.keio.ac.jp

Department of Electronics and Electrical Engineering,
Keio University, Japan

Outline

1. **Background (photonic crystal and WGM cavity)**

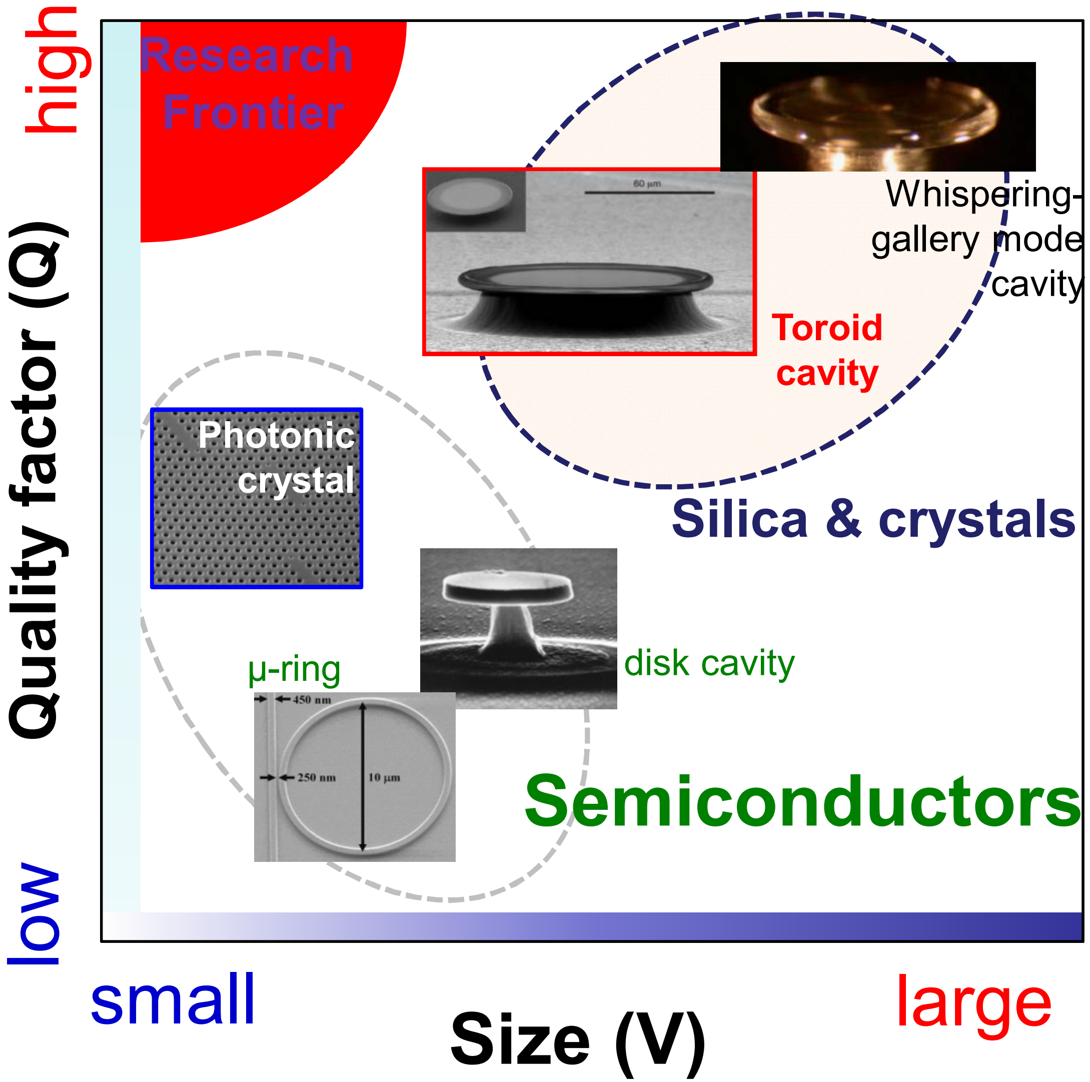
2. **Kerr switch w/ WGM cavity**

3. **Kerr comb w/ WGM cavity**

4. **Summary**

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

$$\propto Q/V$$

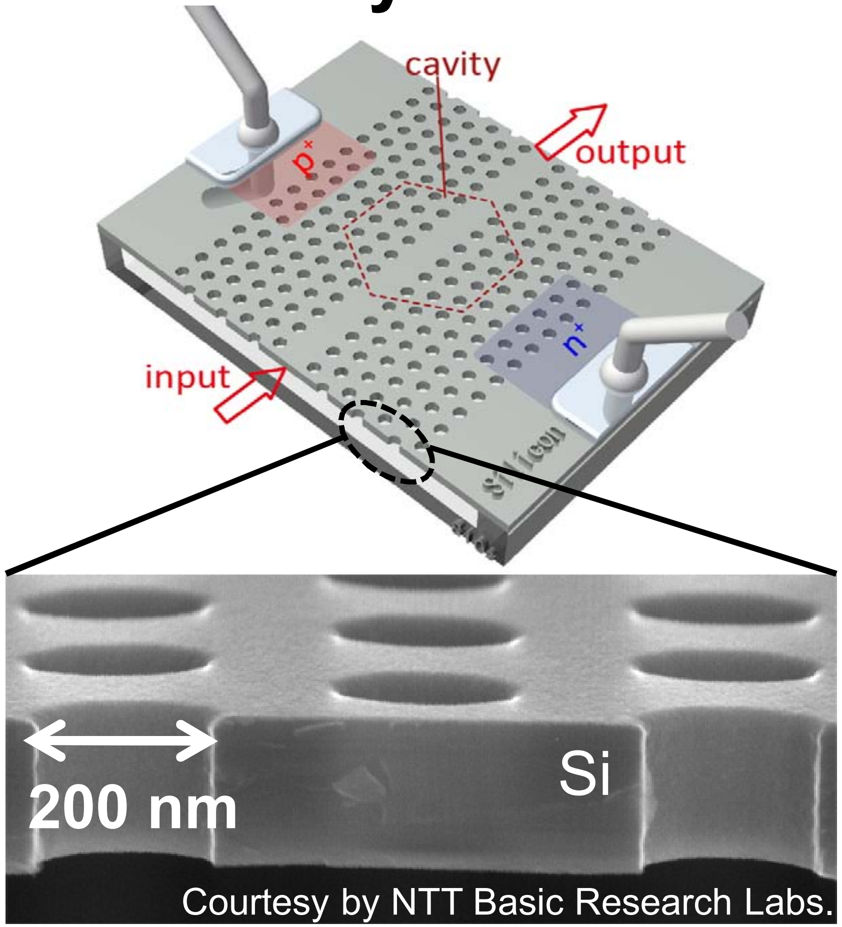
▶Applications

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

High Q/V microcavities

Microcavity = A device that cage photons

▶Photonic crystal nanocavity

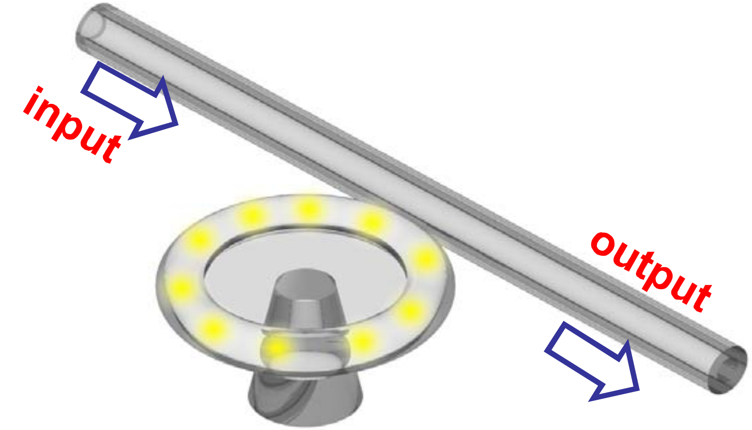


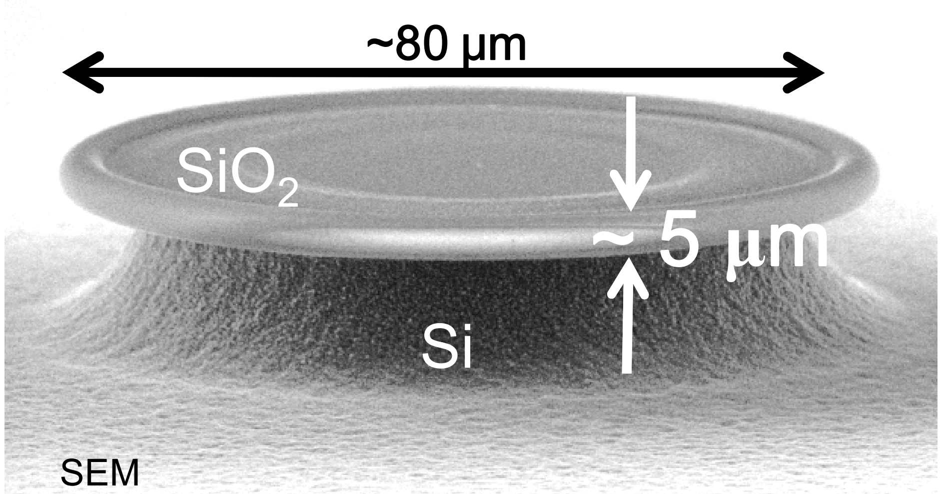
Courtesy by NTT Basic Research Labs.

$V = 1.5\ (\lambda/n)^3$

$Q = 10^6$

▶WGM microcavity



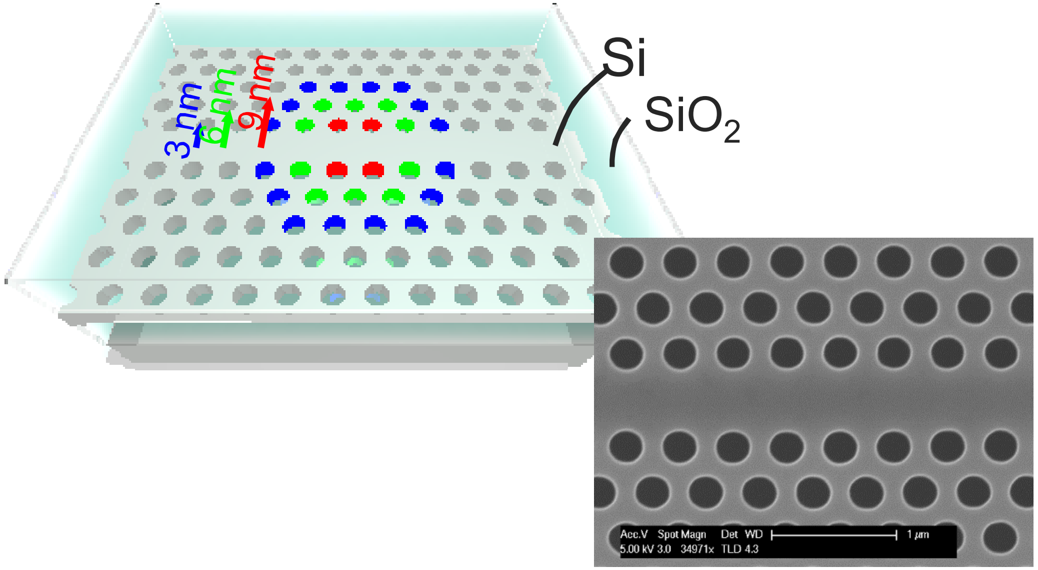


$V = >100\ (\lambda/n)^3$

$Q = 10^8$

Photonic crystal nanocavity

▶Small size and high-Q

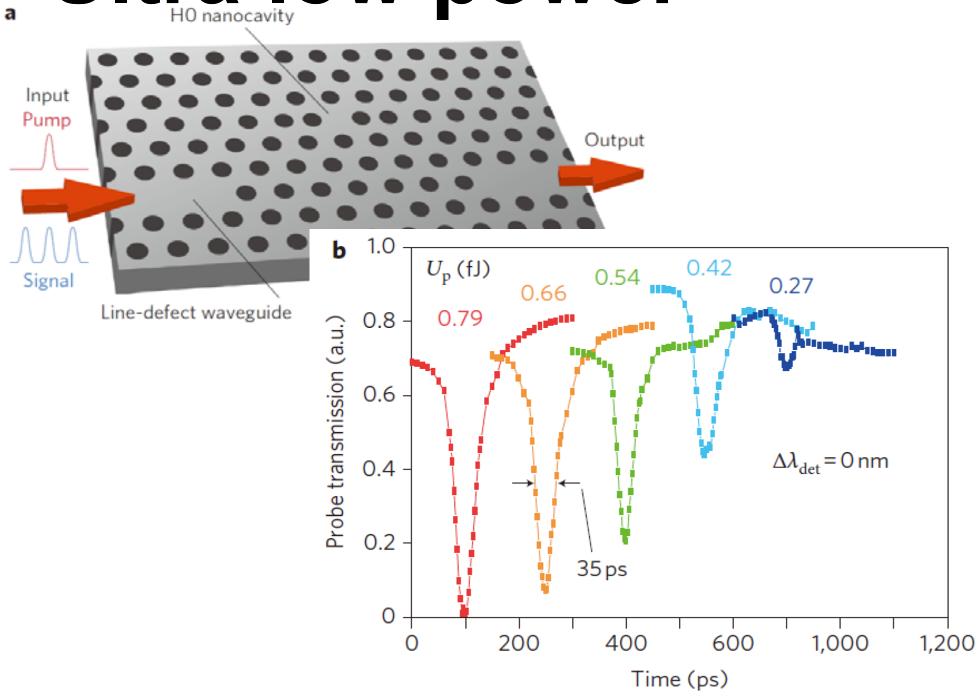


Very high Q = 1.2×10^6
T. Tanabe, *et al.* Nature Photon. **1,** 49 (2007).

Highest Q w/ CMOS process & structure
Y. Ooka, *et al.*, Sci. Rep. **5**, 11312 (2015).

High coupling w/ fiber
T. Tetsumto, *et al.,* Opt. Express **23**, 16256 (2015).

▶Ultra low power



Carrier based 100-fJ switch in Si
T. Tanabe, *et al.*, APL 90 031115 (2007).

Carrier based 0.66-fJ switch in InGaAsP
K. Nozaki, *et al.*, Nature Photon. 4 477 (2010).

Towards all-optical logic gates
A. Fushimi, *et al.*, Opt. Express 22 4466 (2014).

Motivation

▶Si based PhC

☺ **Refractive index: 3.4**

→**Small size**

☹ **Loss: 1 dB/cm**

→**$Q = 10^6$ is possible**

☹ **Band gap: @1.2 μm**

→**Carrier effect**
(absorb photons)

▶SiO_2 based WGM

☹ **Refractive index: 1.45**

→**Large size**

☺ **Loss: 0.13 dB/km**

→**$Q > 10^8$ is possible**

☺ **Band gap: @ 140 nm**

→**Kerr effect**
(operation w/o absorption)

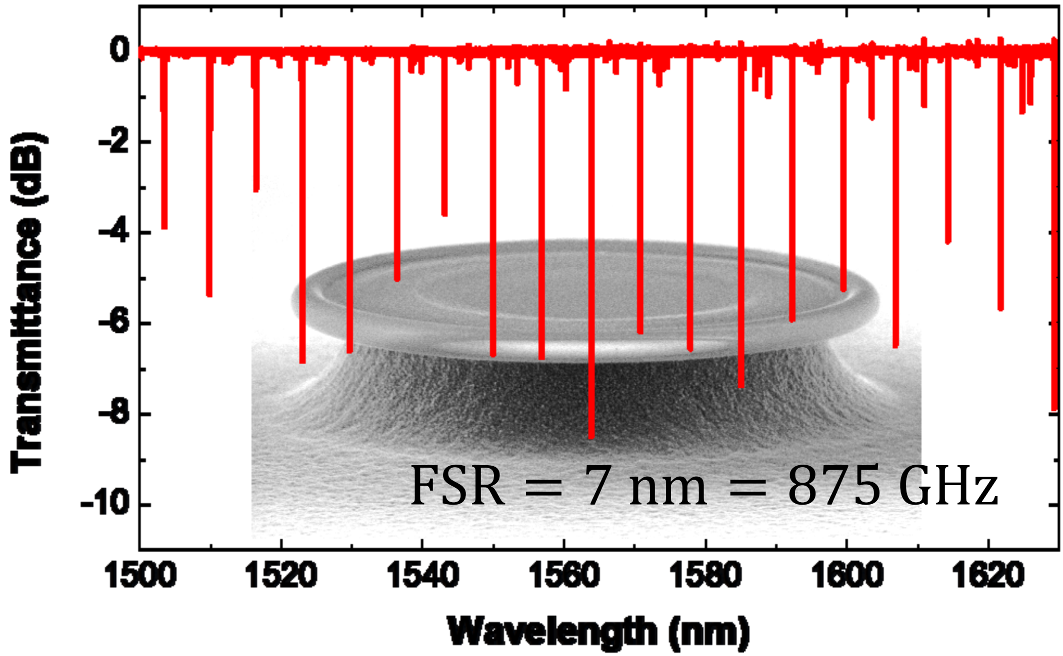
Motivation

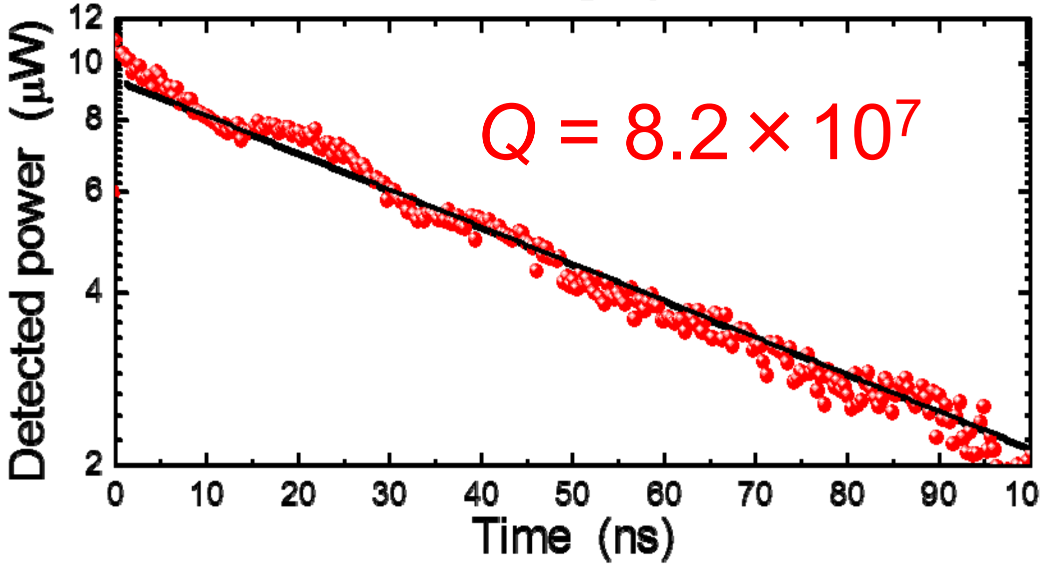
1. Is Kerr switch feasible at reasonable power

2. What is the minimum possible power w/ Kerr switch.

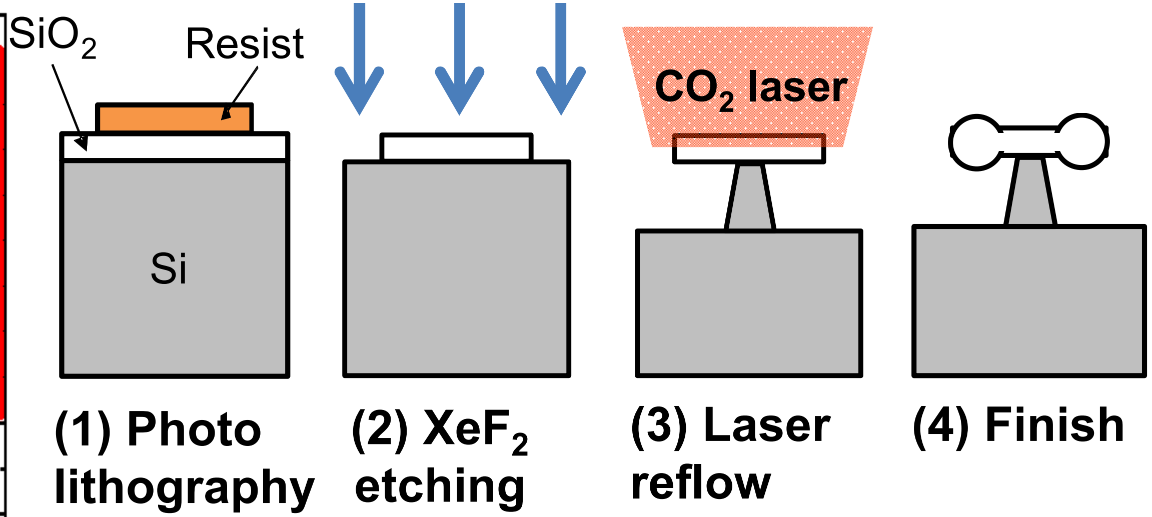
Ultra-high *Q* toroidal microcavity

▶Spectrum & photon lifetime

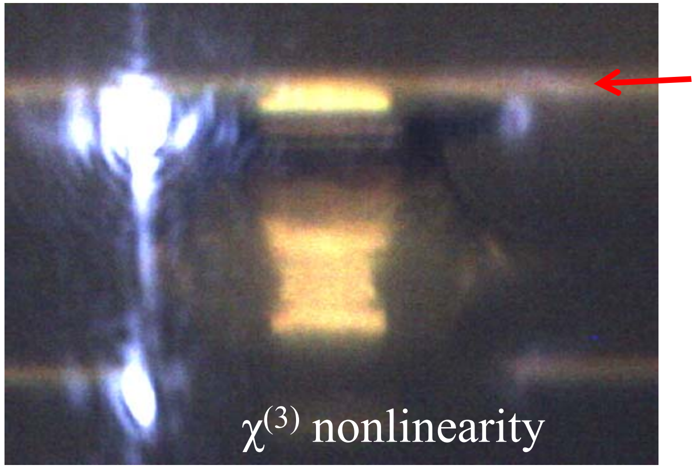


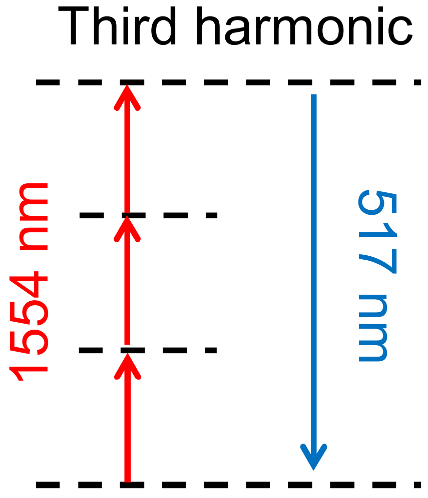


▶Fabrication



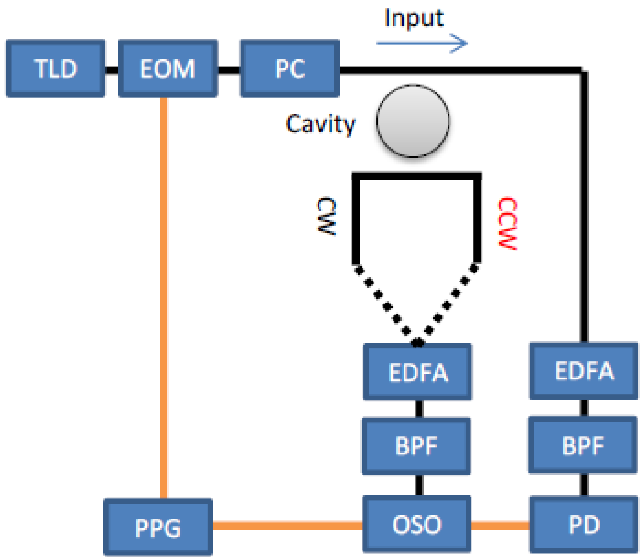
▶White light generation (Kerr effect)

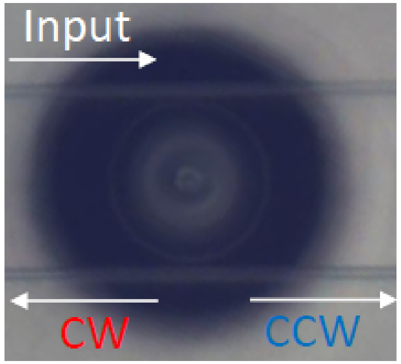




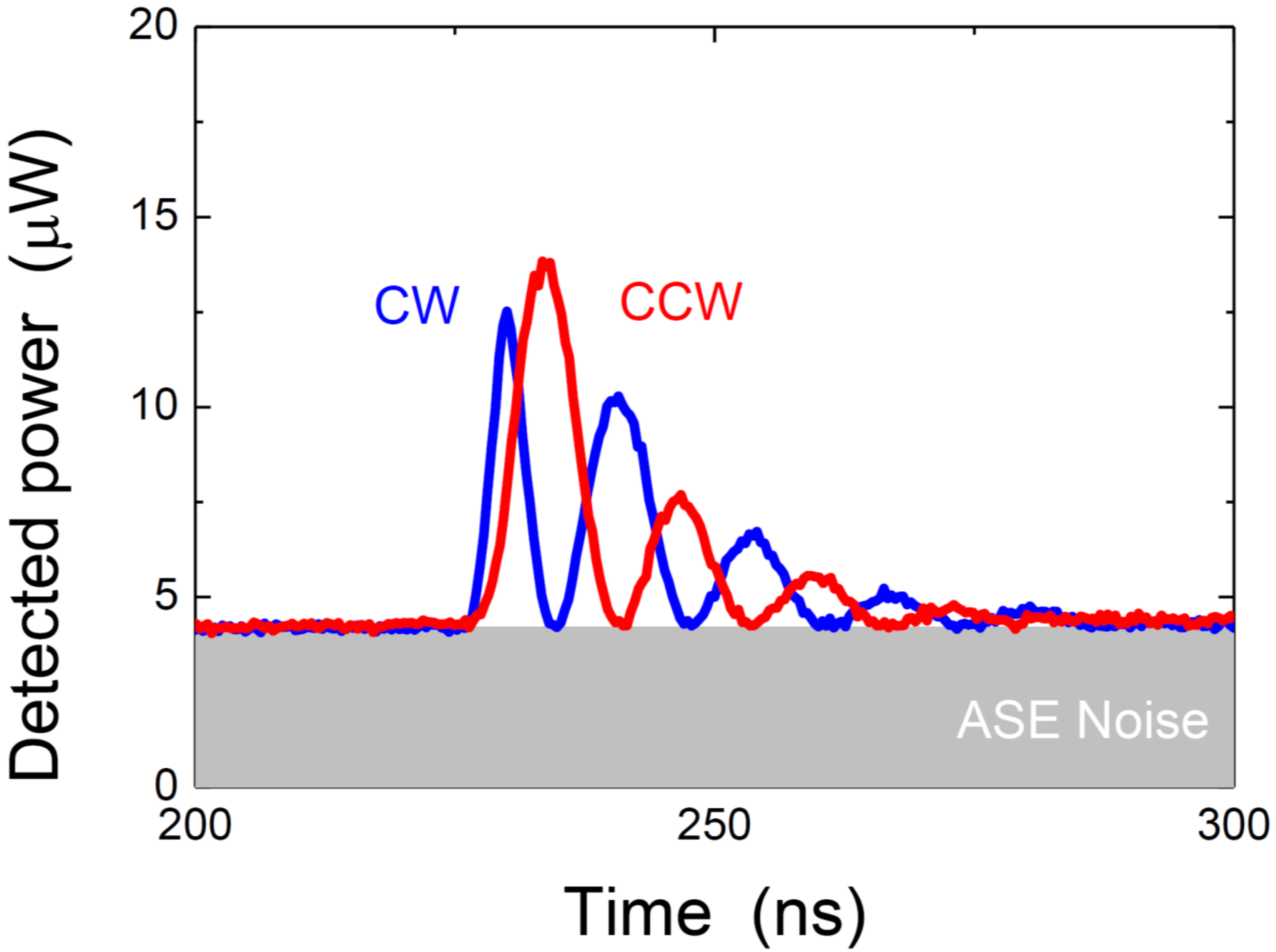
Time domain measurement: Rabi oscillation

►Experimental setup





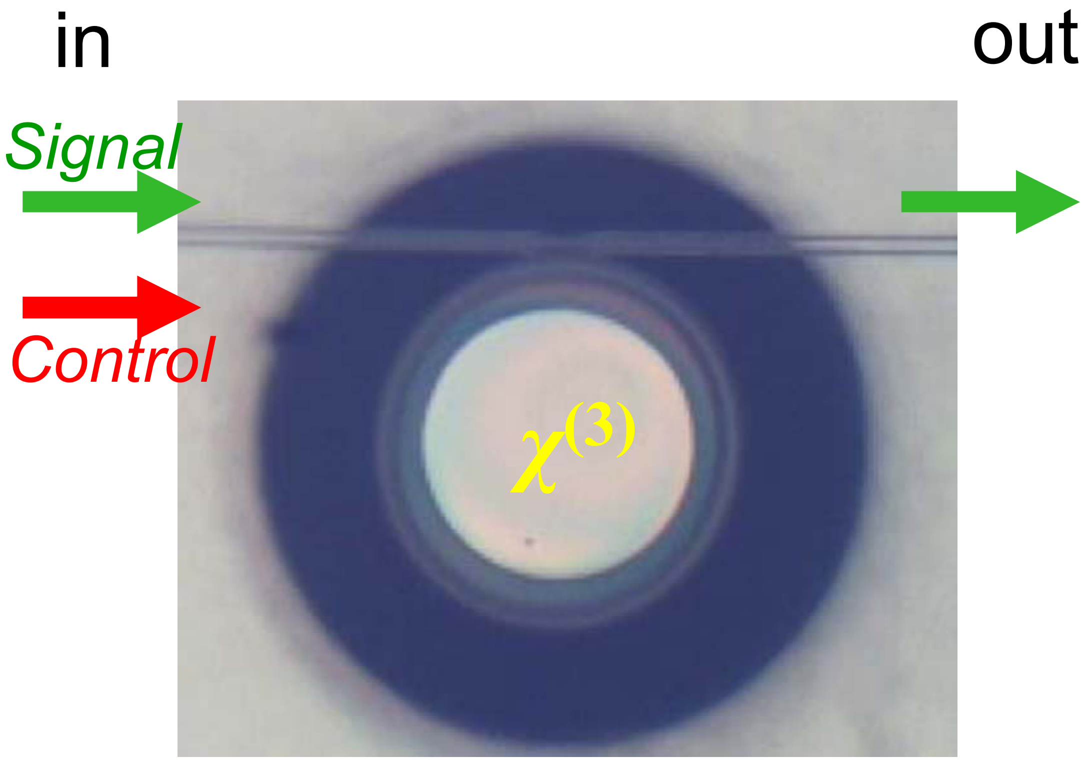
►Waveform



All optical switch (Silica / Kerr effect)

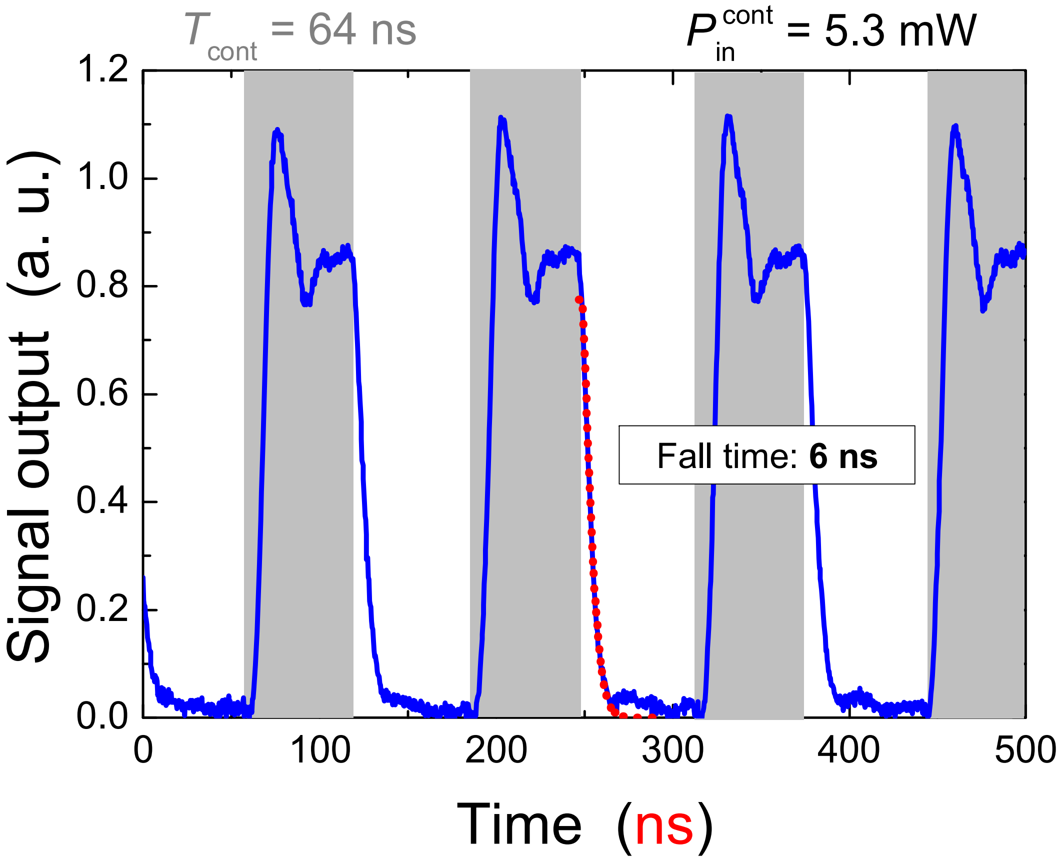
W. Yoshiki and T. Tanabe, Opt. Express **22,** 24332 (2014).

▶WGM microcavity device



Silica toroidal microcavity

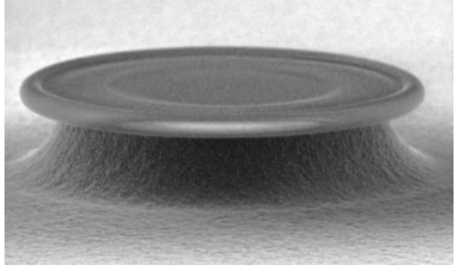
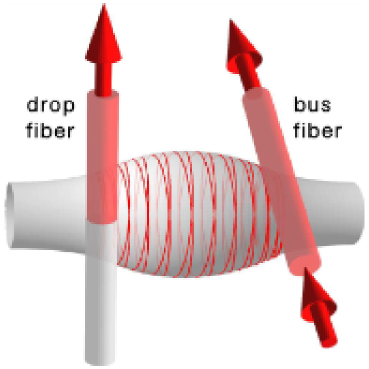
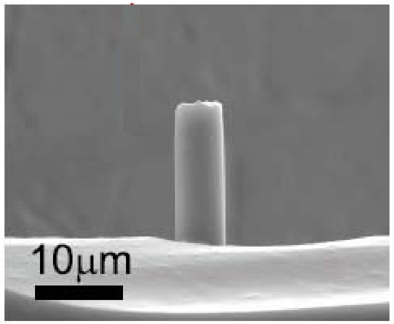
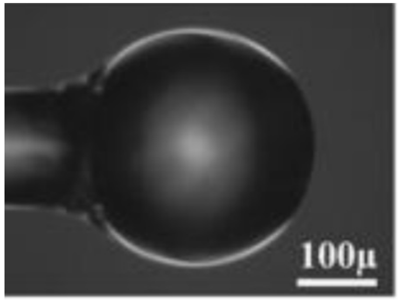
▶Low power Kerr switch



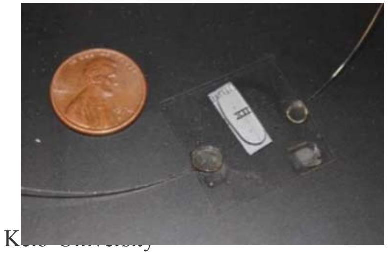
Modulation observed at 36 μW

Comparison w/ other Kerr switches

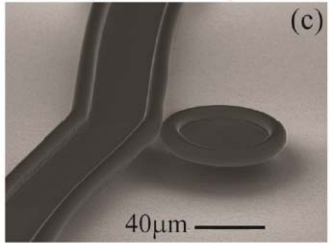
W. Yoshiki and T. Tanabe, Opt. Express **22,** 24332 (2014).

	Silica toroid	**Silica bottle**1)	**a-Si:H cylinder**2)	**Silica sphere w/ polymer coat**
				
Material	**Silica**	**Silica**	a-Si:H	Silica + Polymer
Power	**36 μW**	50 μW	5 mW	1.5 kW
On chip	**Yes**	No	No	No

Packaging w/ polimers4)



Integration w/ waveguides5)

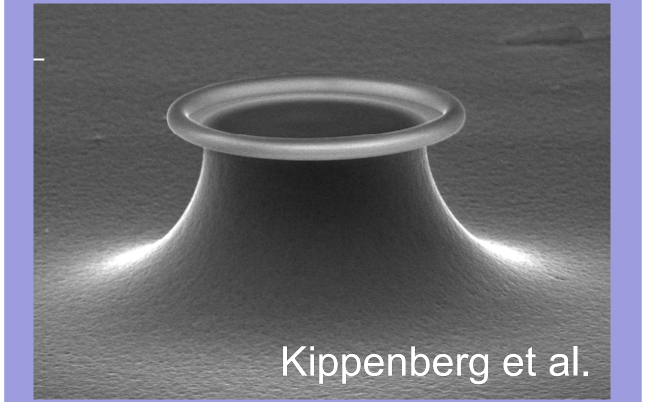


1) M. Pöllinger & A. Rauschenbeutel, Opt. Express 18, 17764– (2010)
2) N. Vukovic et al., Sci. Rep. 3, 2885-(2013).
3) I. Razdolskiy et al., Opt. Express 19, 9523- (2011).
4) X. Zhang & A. Armani, Opt. Express 21, 23592- (2013)
5) F. Monifi et al., IEEE Photon. Technol. Lett. 25, 1458- (2013)

Kerr comb

Kerr comb

Microcavity



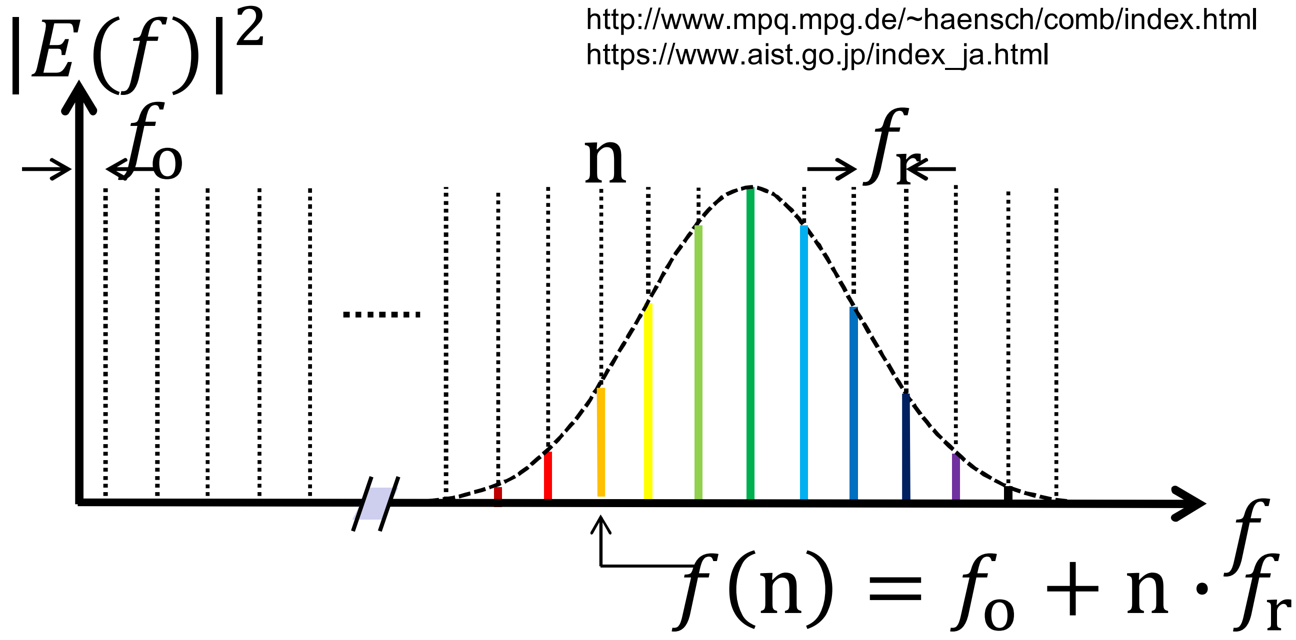
- ✓ On chip
- ✓ High repetition rate (10GHz-1THz)
- ✓ Low cost
- ✓ Low pump threshold

Threshold pump power of degenerate four-wave mixing

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

V : mode volume, Q : quality factor

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

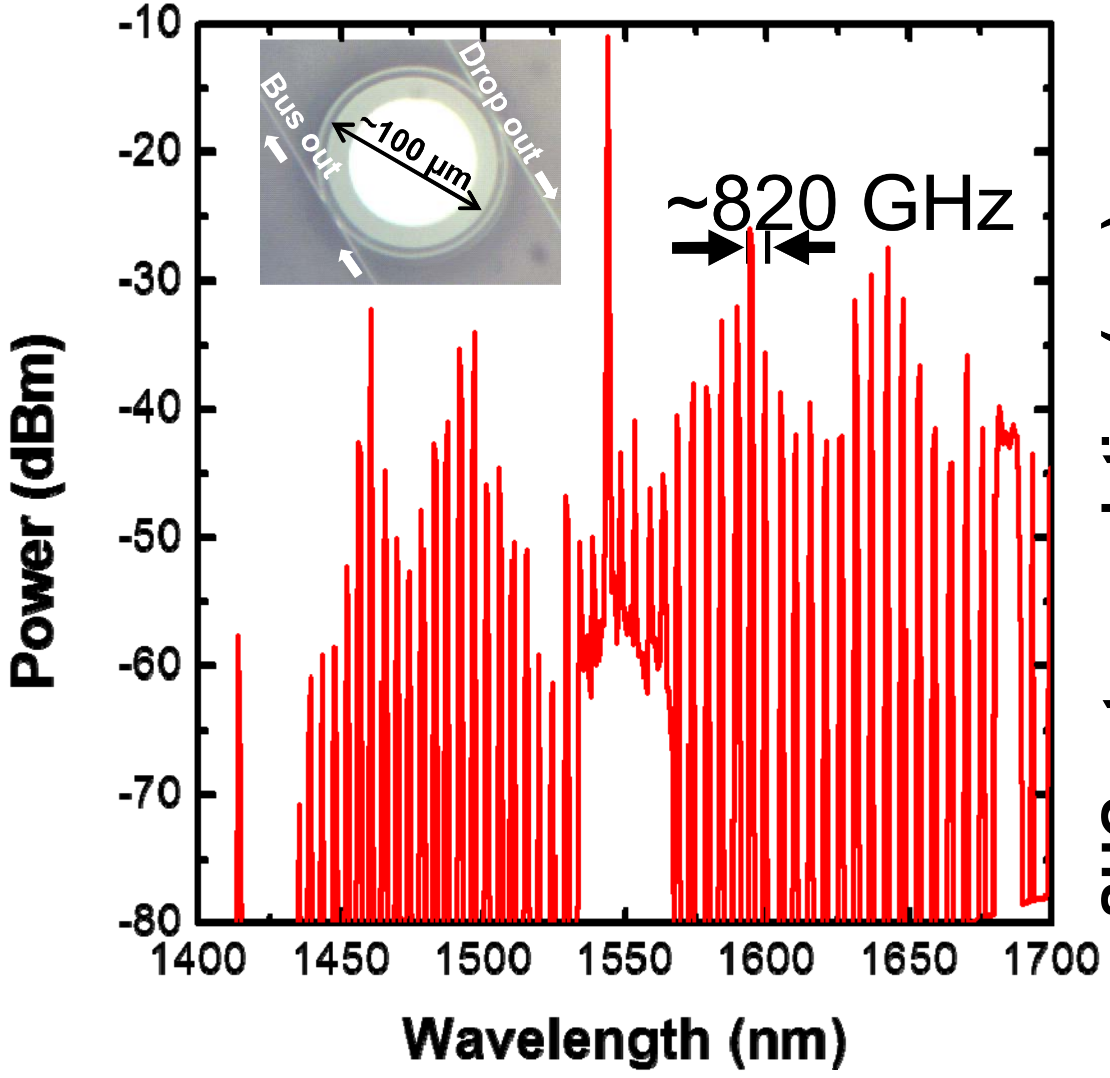


Kerr comb has been demonstrated, but still, the following must be solved:

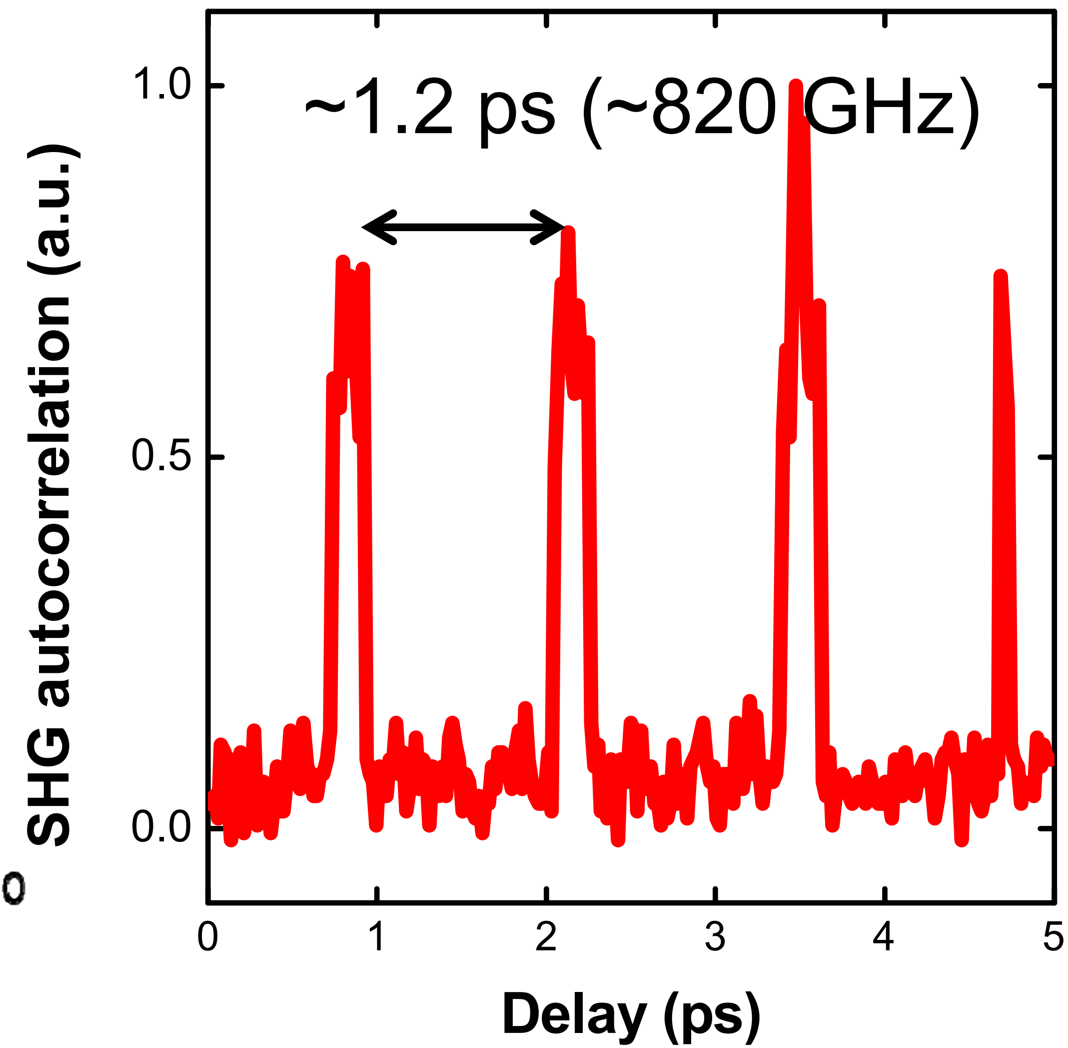
1) Dispersion management w/ high Q cavity
2) The mechanism on mode-locking in microcavities is still not fully understood

Ultrahigh repetition rate pulse generation

▶Kerr comb generation

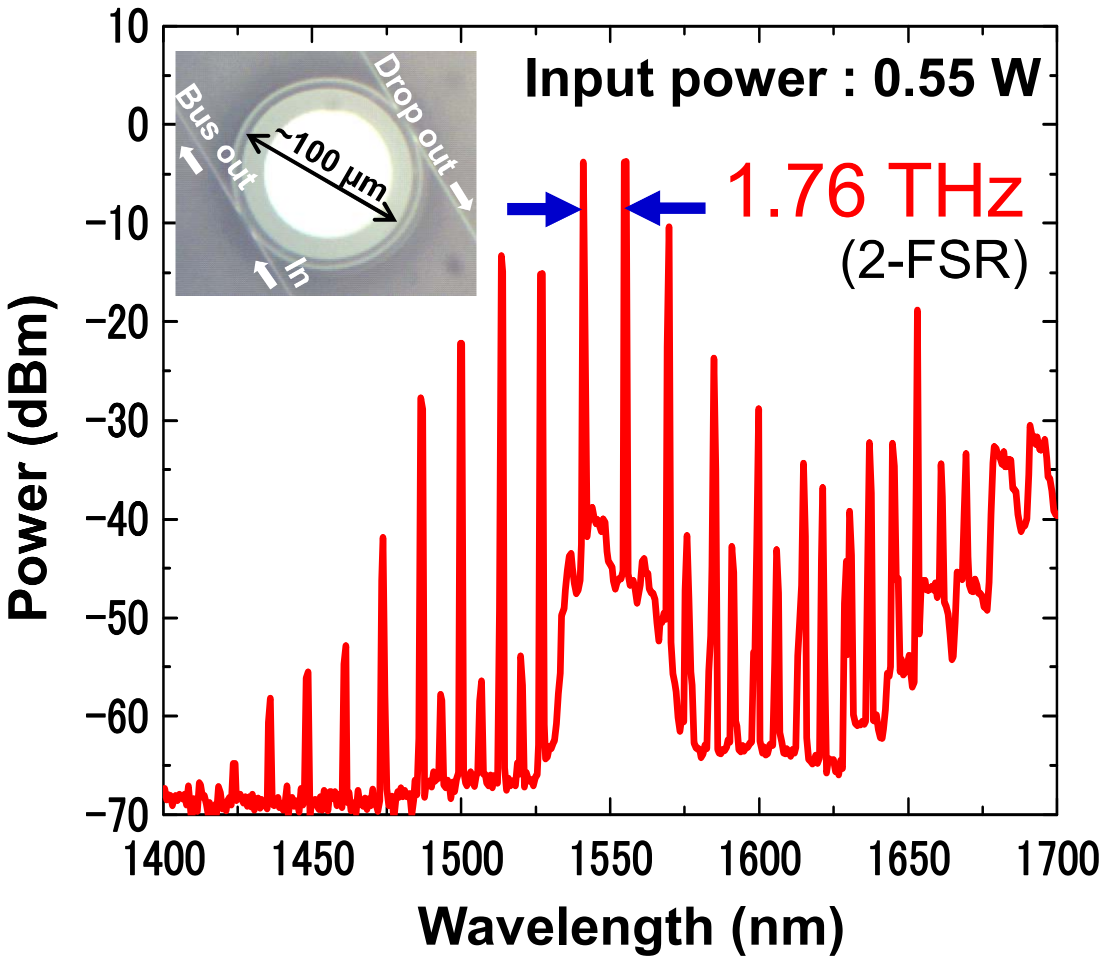


▶SHG autocorrelation trace

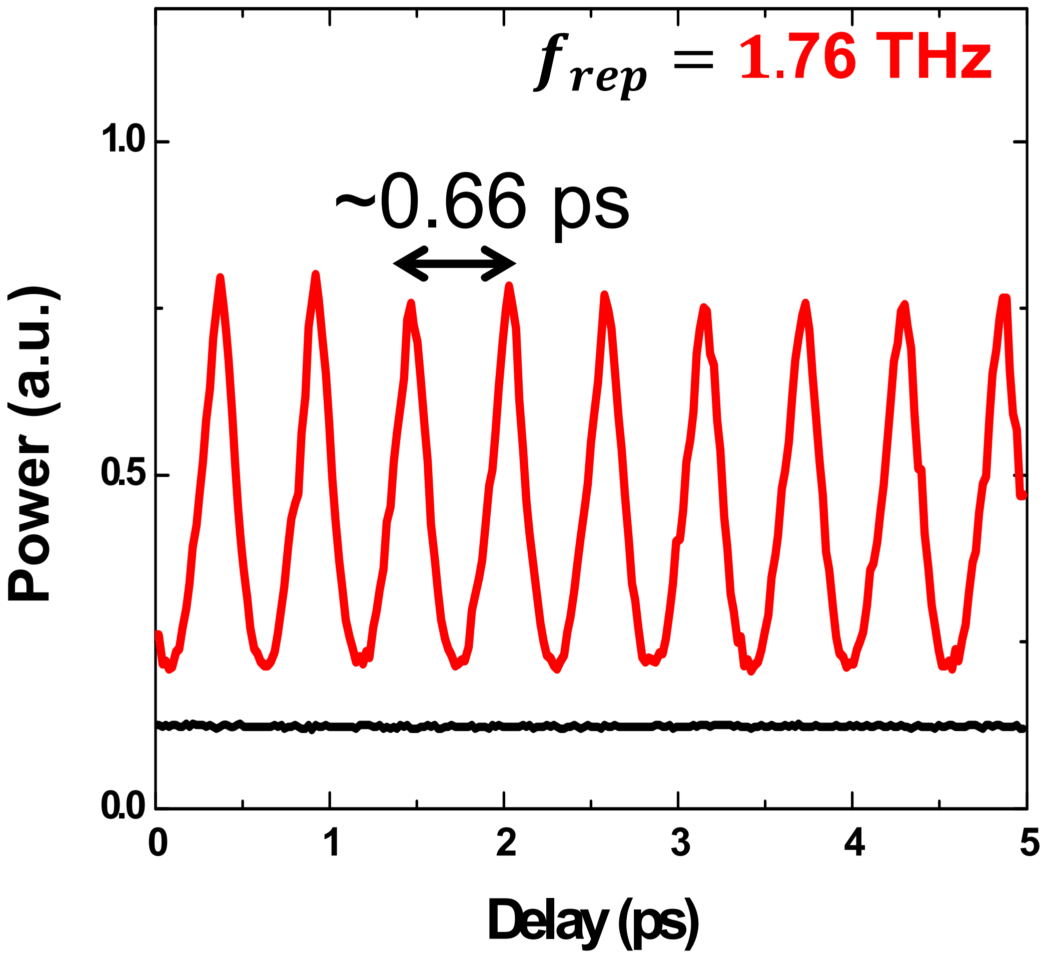


Ultrahigh repetition rate pulse generation

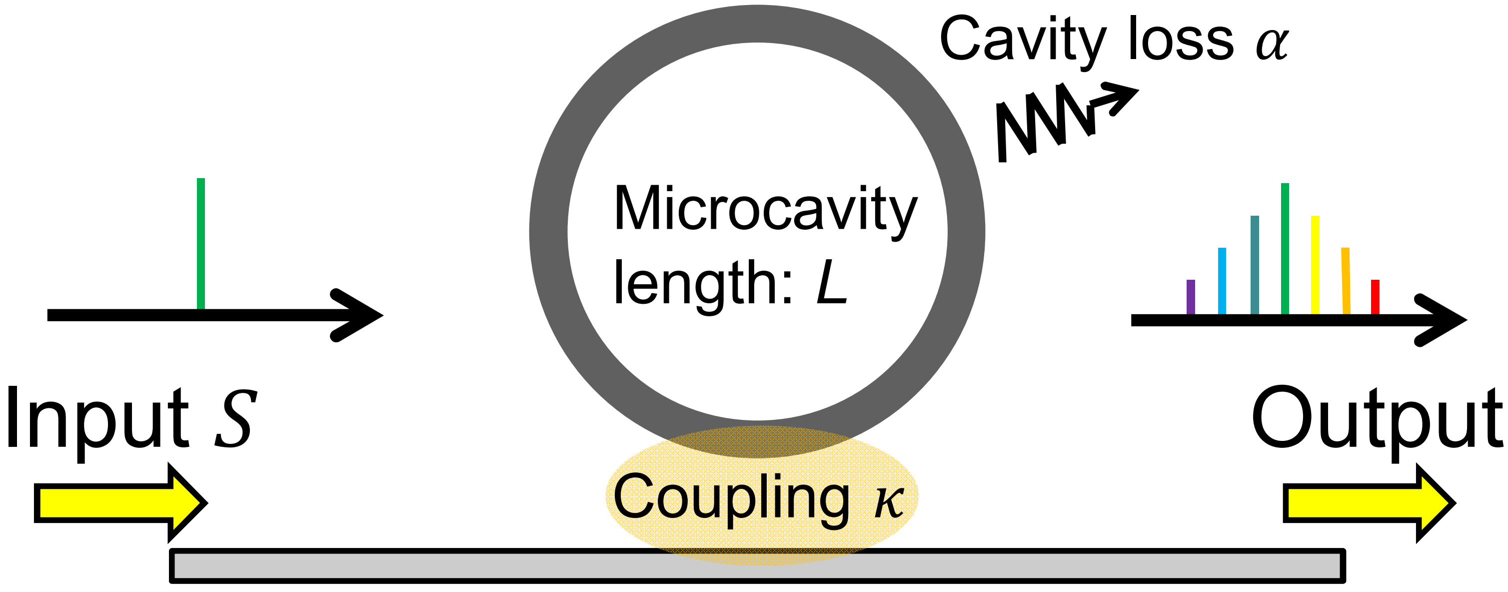
▶Kerr comb generation



▶SHG autocorrelation trace



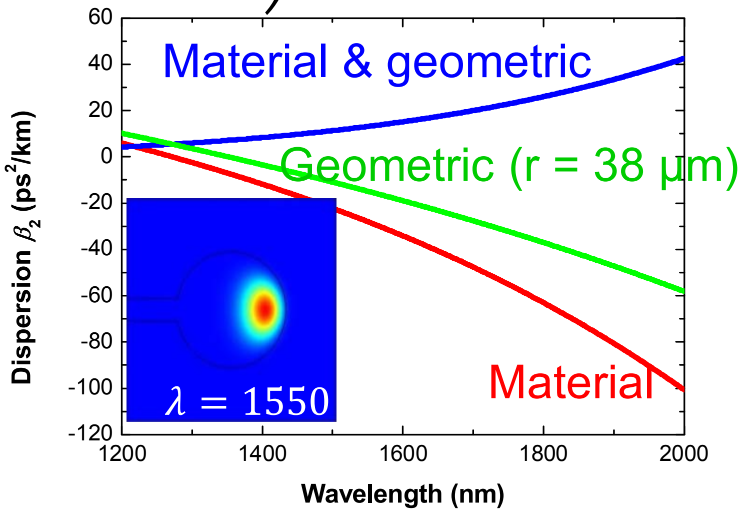
Solving Lugiato-Lefever equation w/ split-step Fourier method



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

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

β: dispersion parameter
γ: nonlinear parameter

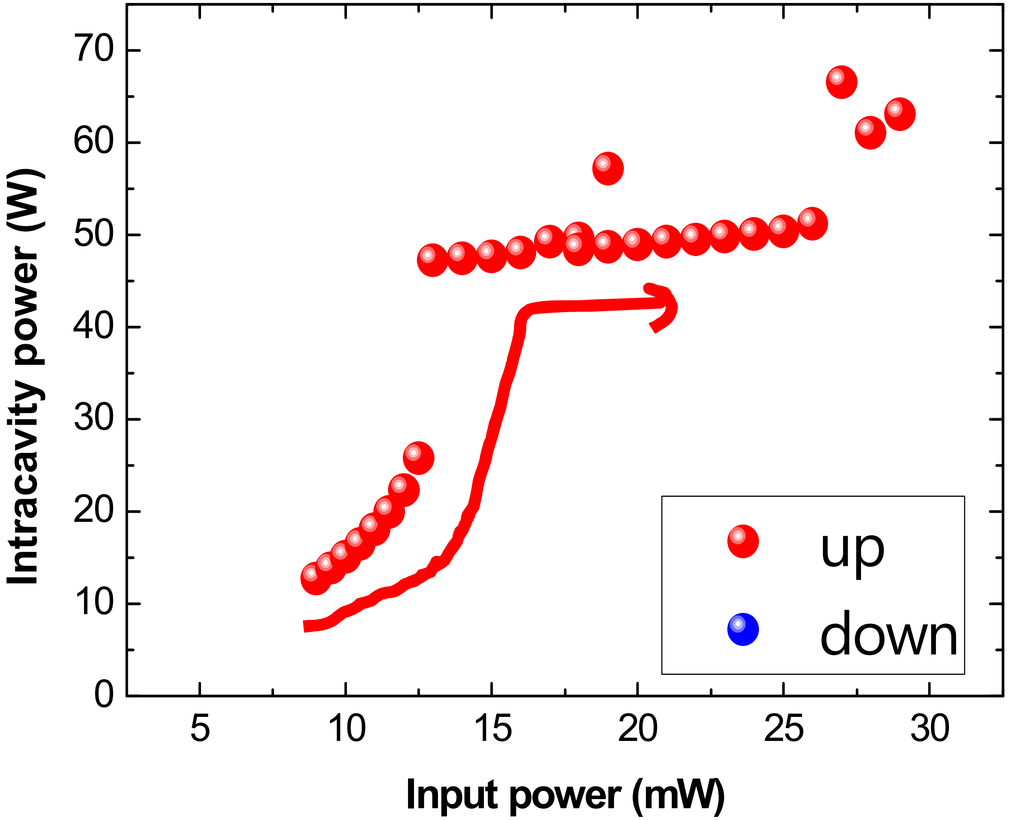


Simulation: multi-FSR to fundamental mode-locking

T. Kato, *et. al.*, arXiv:1408.1204

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

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



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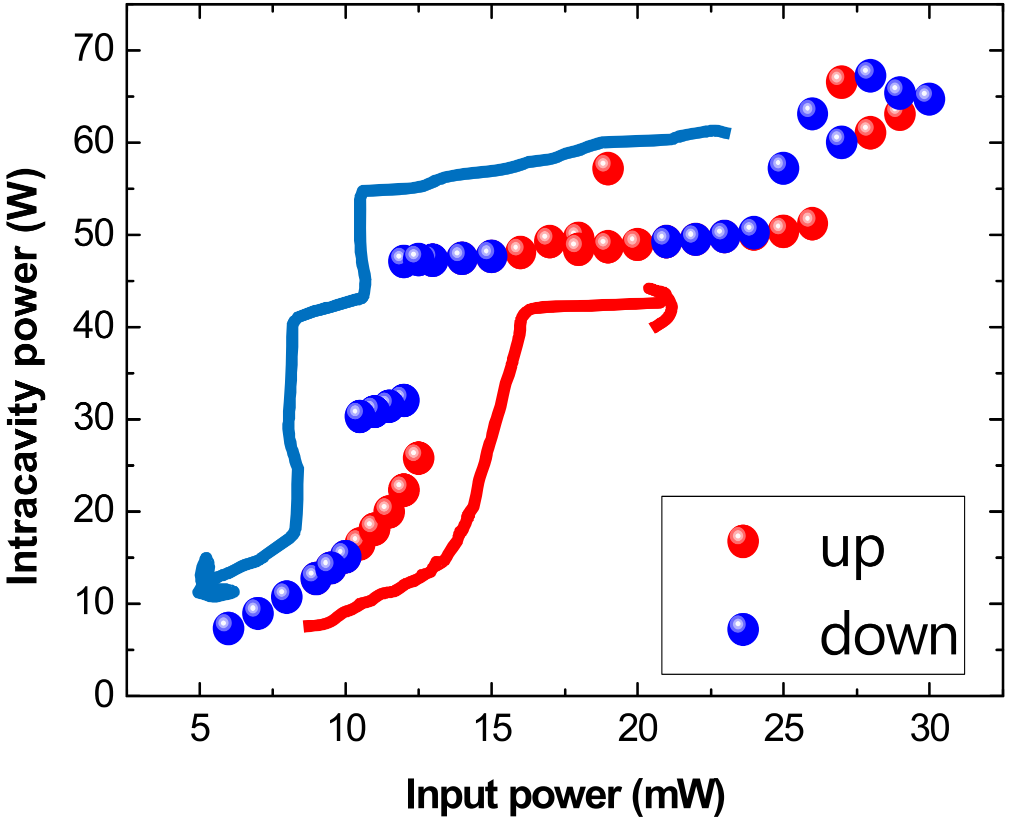

Simulation: multi-FSR to fundamental mode-locking

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

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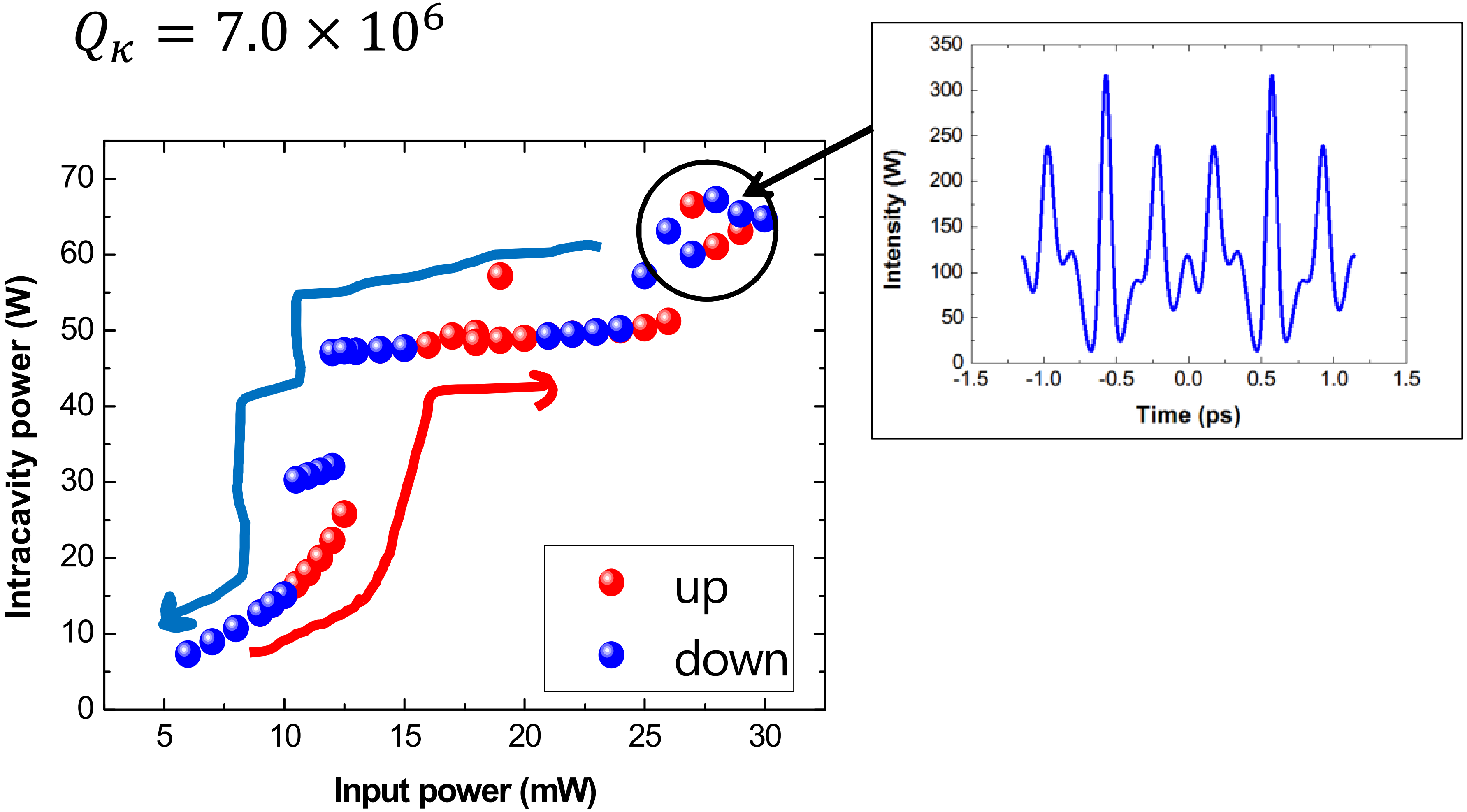

Simulation: multi-FSR to fundamental mode-locking

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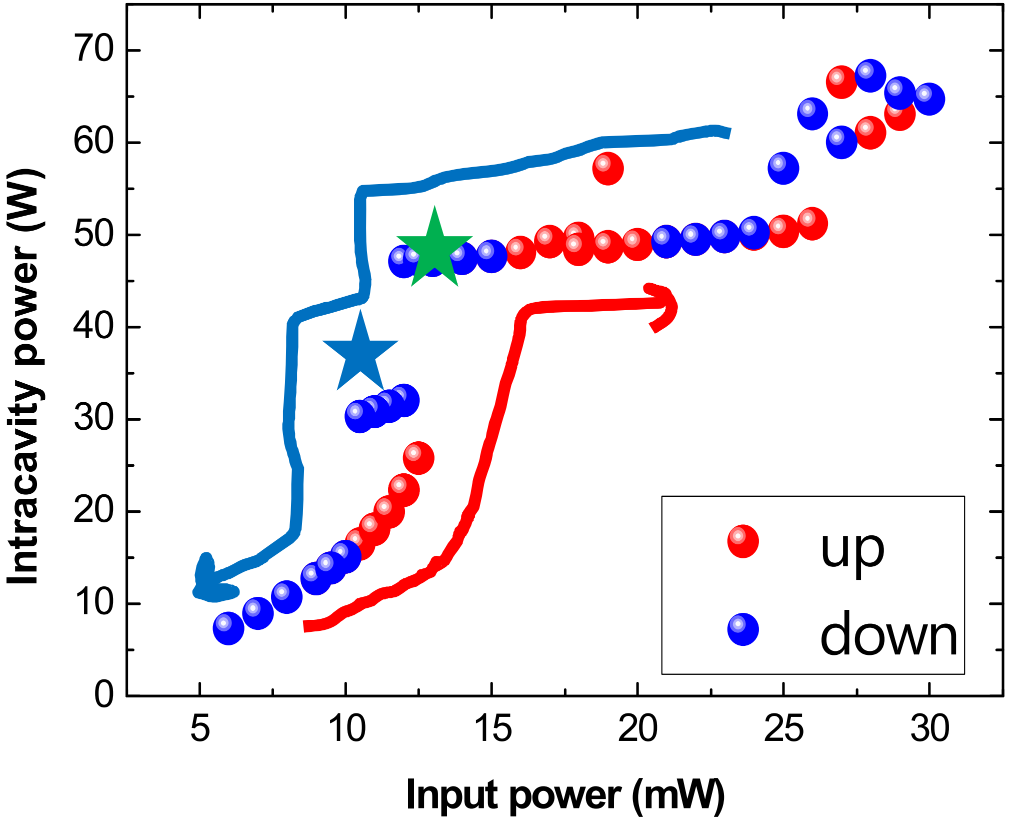
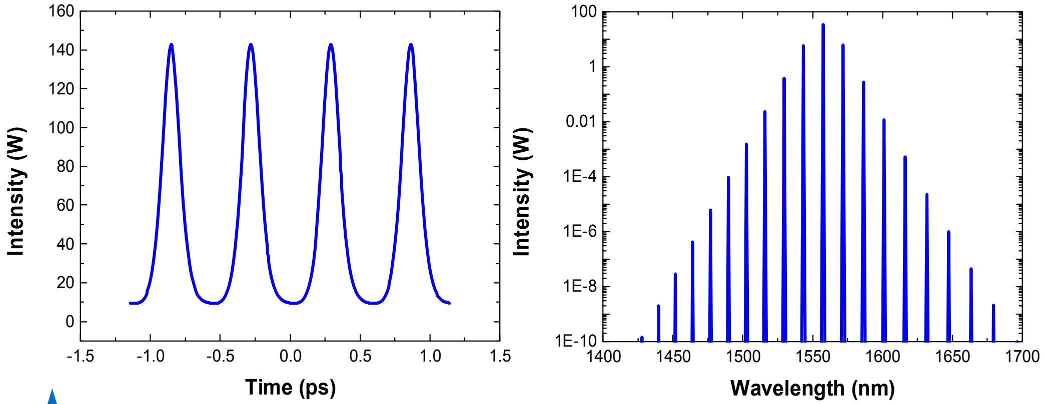
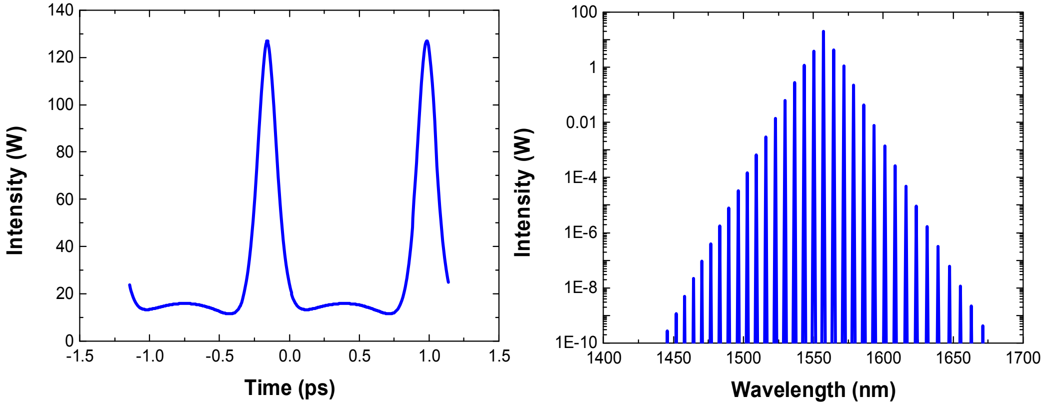


★ Harmonic mode locking(2-FSR)

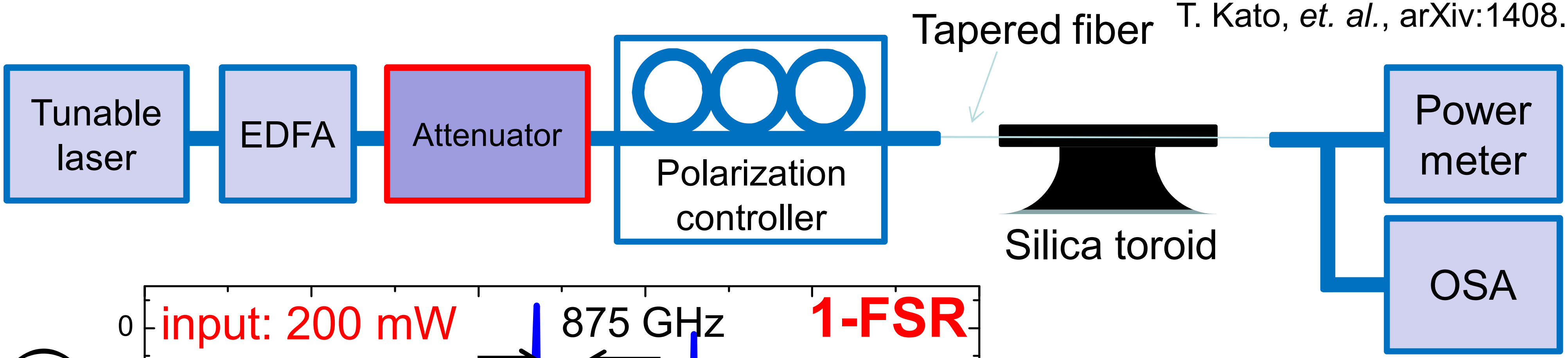


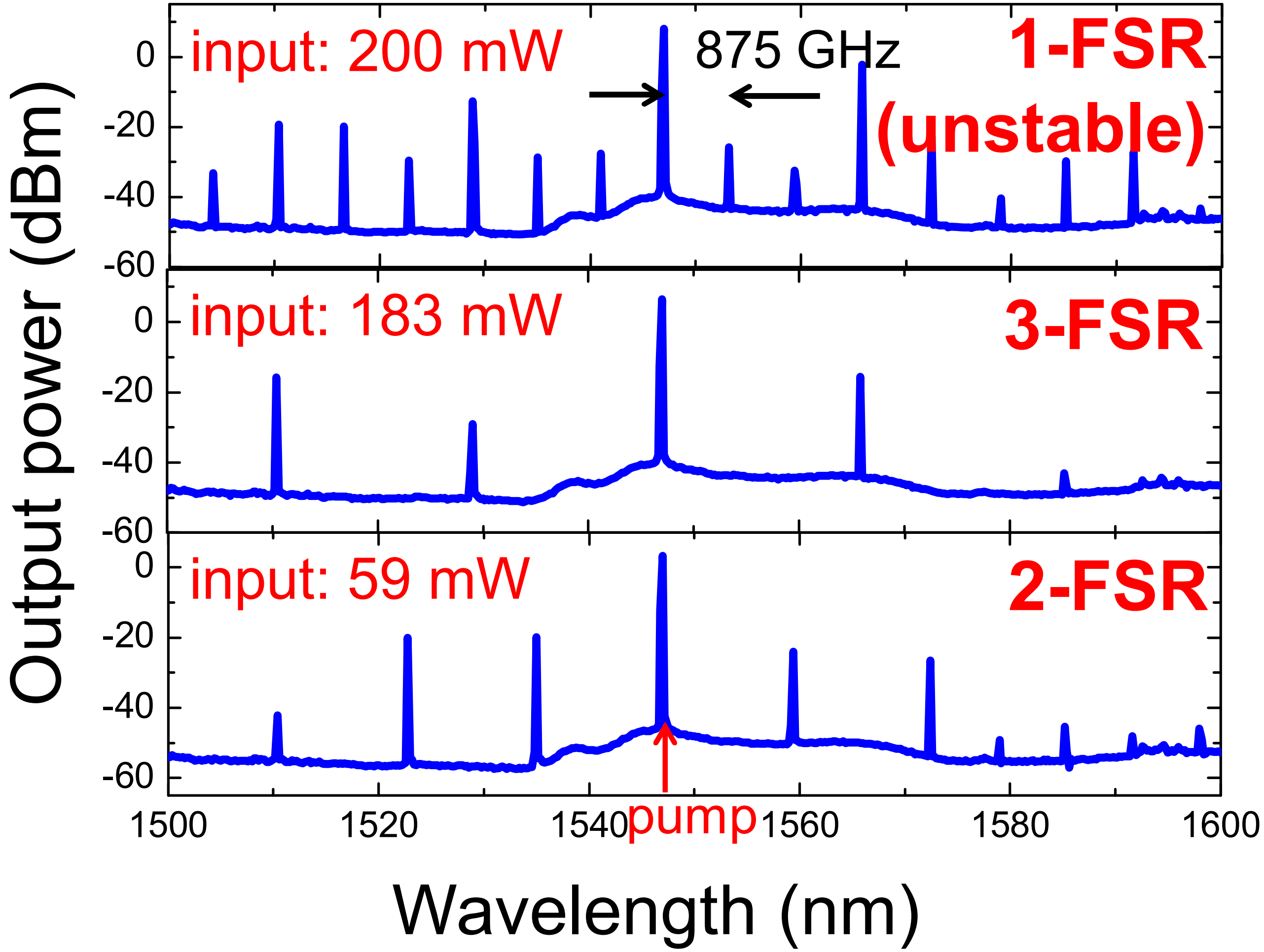
★ Mode locking(1-FSR)



Experiment: mode-locking by power control

T. Kato, *et. al.*, arXiv:1408.1204





Experiment condition

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

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

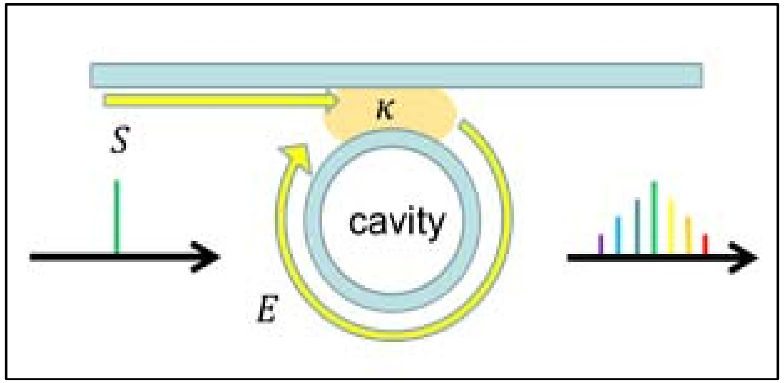
Considering Raman effect

$$\boxed{t_R \frac{\partial E}{\partial t} = \left[-\alpha - \kappa - i\delta_0 + iL\sum_{k\geq 2}\frac{\beta_k}{k!}\left(i\frac{\partial}{\partial \tau}\right)^k + N\right]E + \sqrt{\theta}E_{in}}$$

$$N = i\gamma L\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left(E\int_{-\infty}^{\infty} R(t')|E(t-t')|^2\,dt'\right)$$

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

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

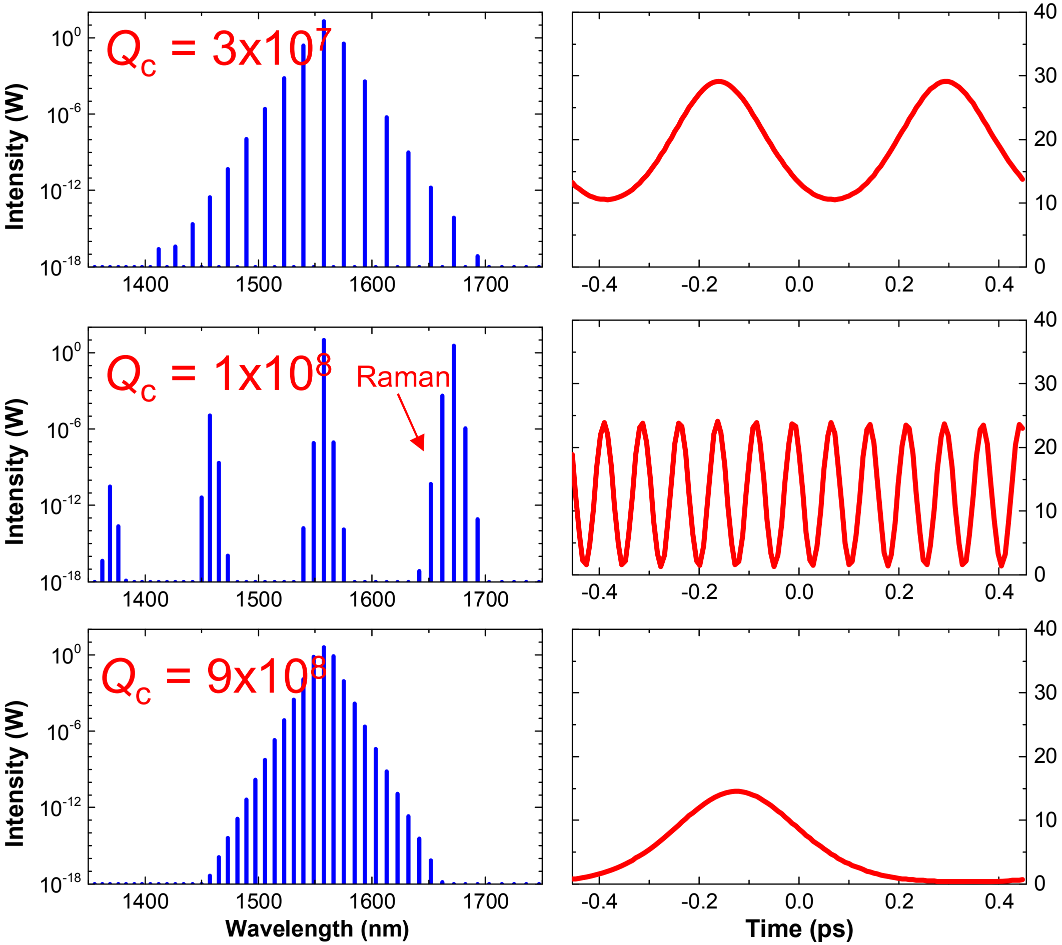


S : Input power
r: round trip number
t_R: round trip time
δ_0: detuning of input

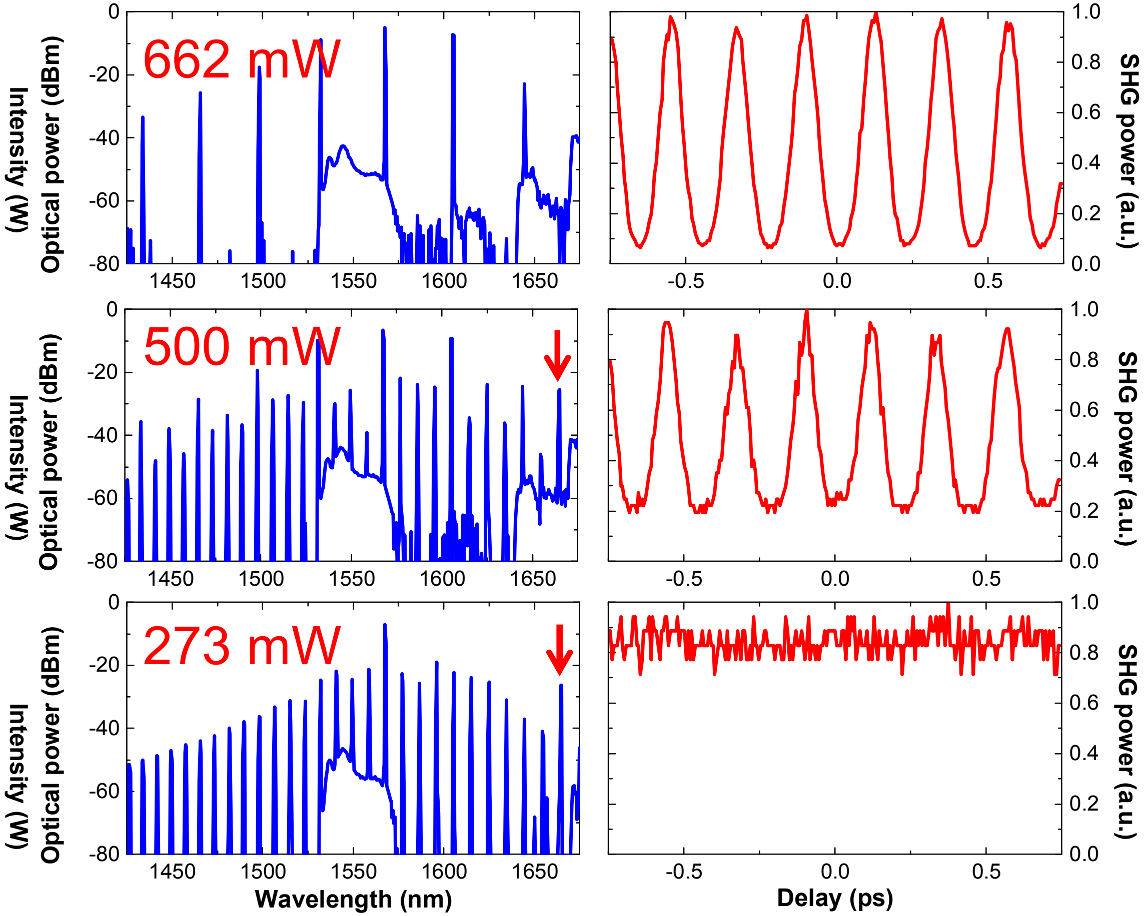
κ: coupling coefficient
β: dispersion parameter
γ: nonlinear parameter
f_R: contribution of Raman

Transition between multi-FSR mode locking: Effect of Raman

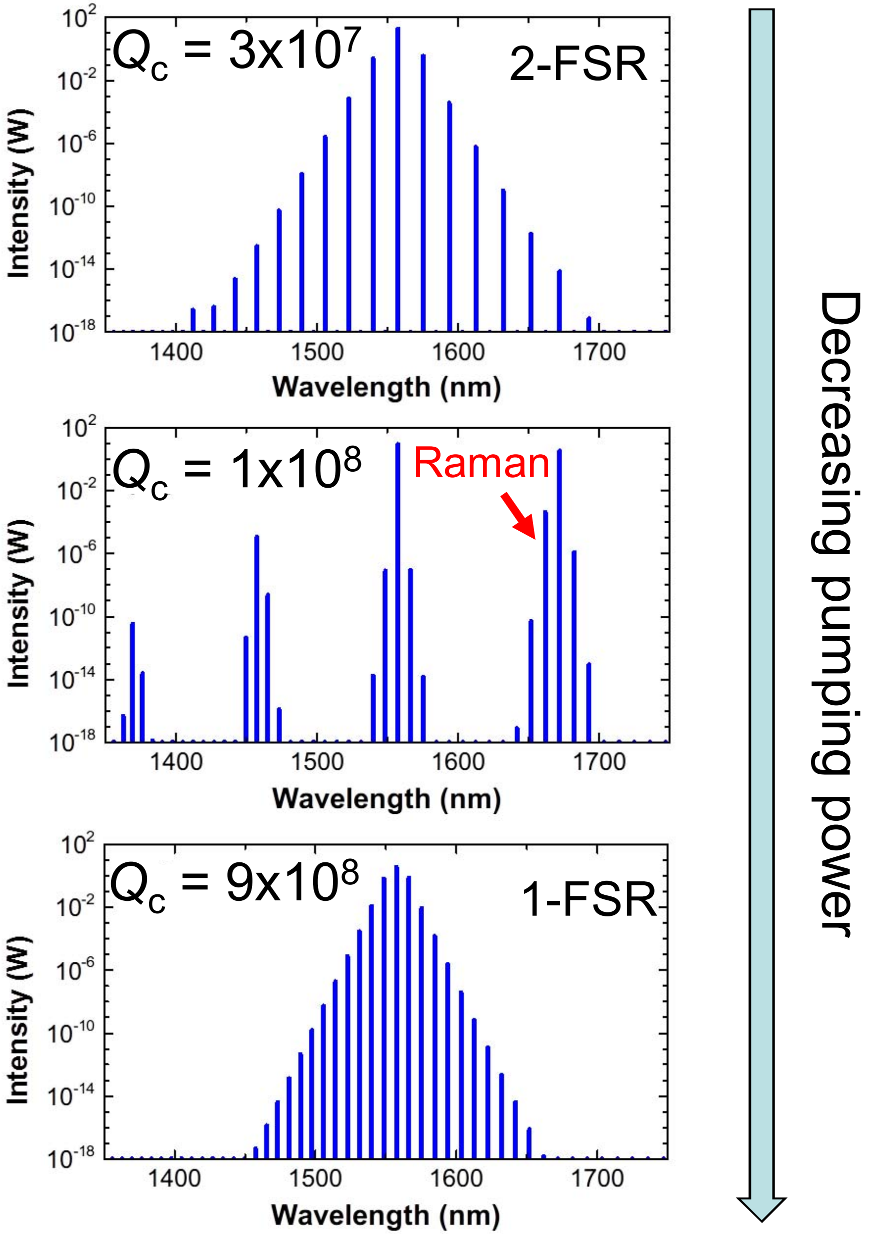
▶Calculation (coupling)



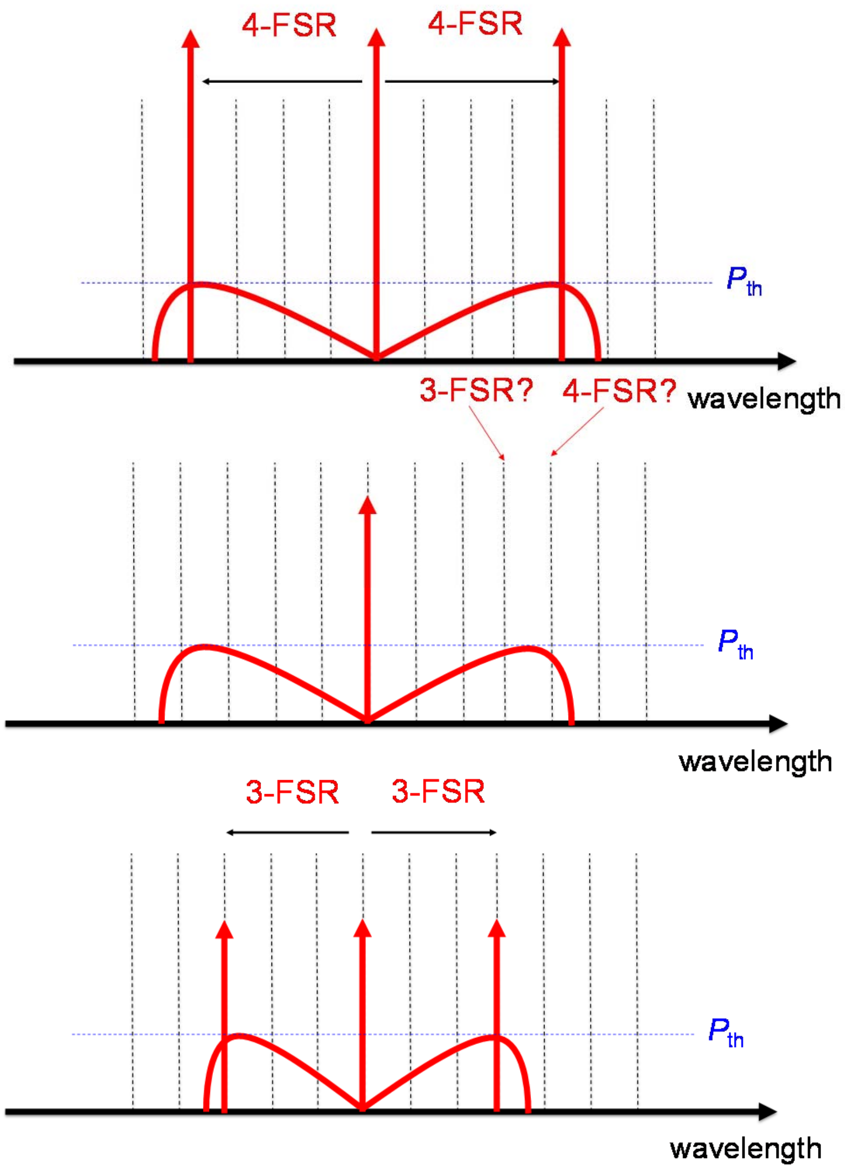
▶Experiment (power control)



Transition between multi-FSR mode locking: Effect of Raman



$$\Omega_{\max} = \sqrt{\frac{4\gamma}{|\beta_2|}\frac{Q\,f_{\mathrm{FSR}}}{2\pi f_{\mathrm{p}}}P_{\mathrm{p}}}$$



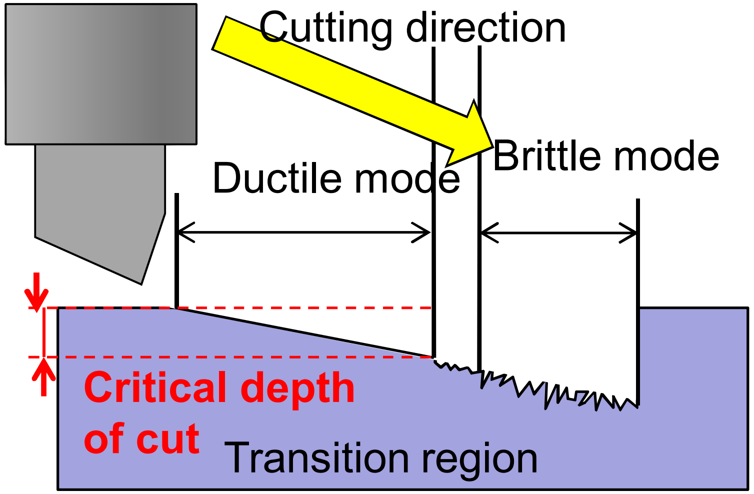
Summary & Future prospect

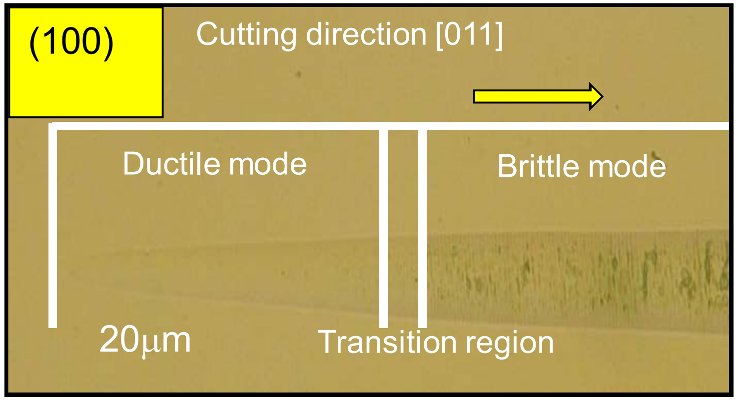
- ✓ Optical Kerr switch at lowest power demonstrated
- ✓ Kerr comb at 850-GHz spacing is generated
- ✓ 2-FSR mode locking is achieved with 60-mW power
- ✓ We found decreasing the input is essential to obtain mode locking

Fabrication of CaF_2 WGM cavity w/ cutting

Precise machining process

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

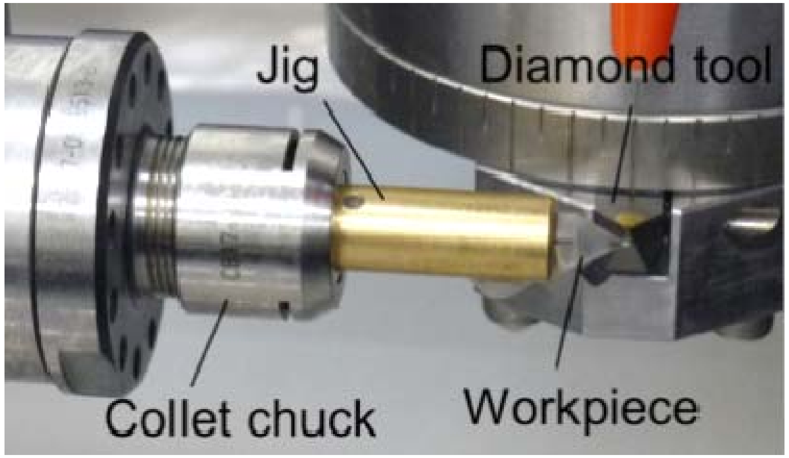


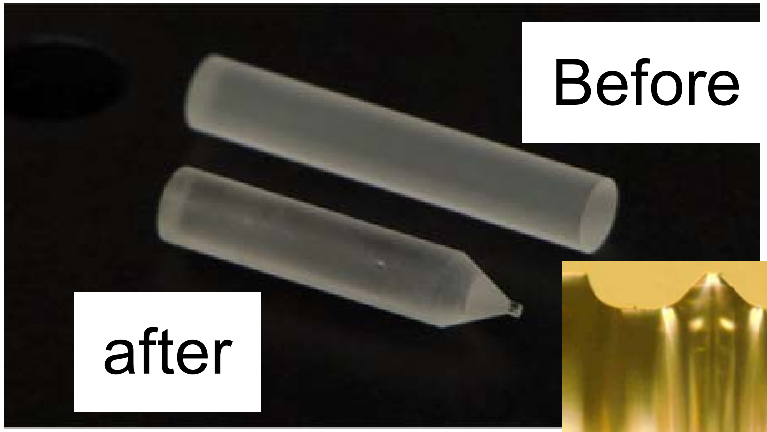


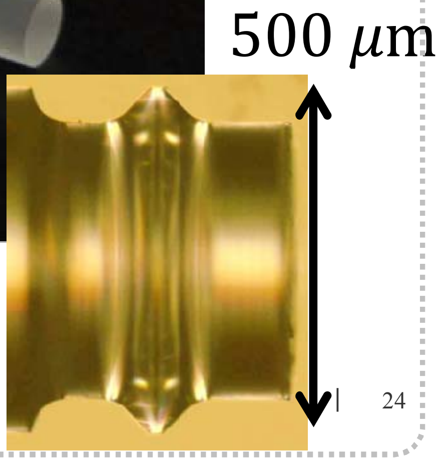
- ➢ CaF_2 can be smoothly cut in ductile mode cutting

Lathe cutting

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





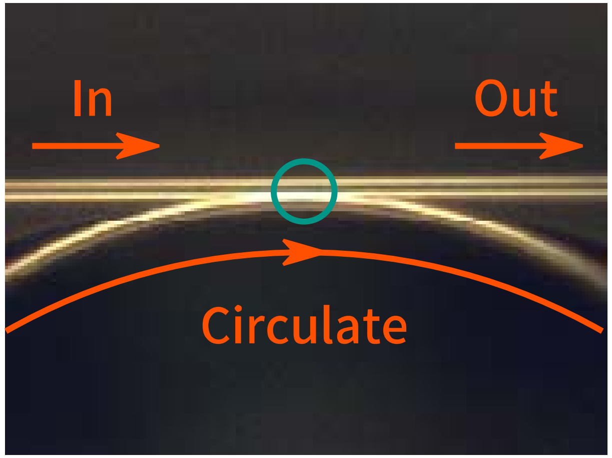


$R_{\mathrm{rms}} = 3\ \mathrm{nm}$

$\boldsymbol{Q = 3.0 \times 10^6}$ obtained

Optical measurement & Surface roughness

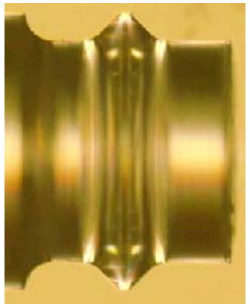
Q measurement

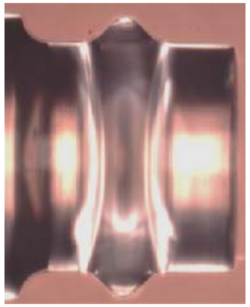


Parameters:

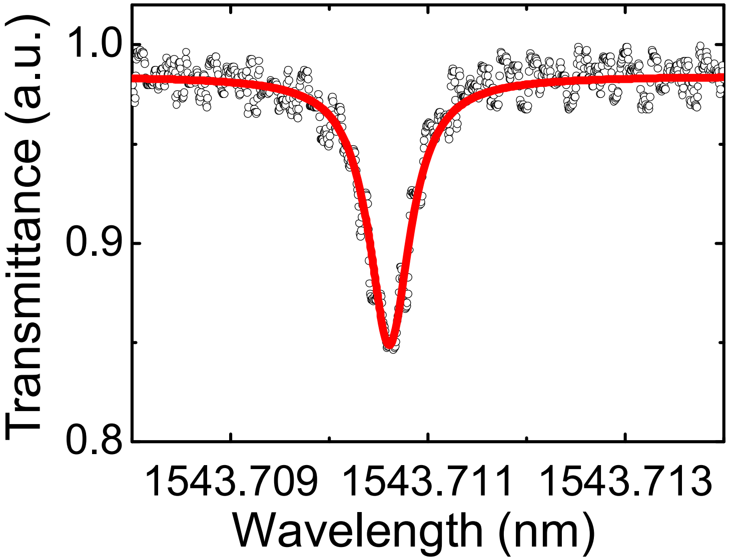
- Fiber diameter: 3~5 μm
- Input power: 1 mW
- Scan speed: 1 nm/s

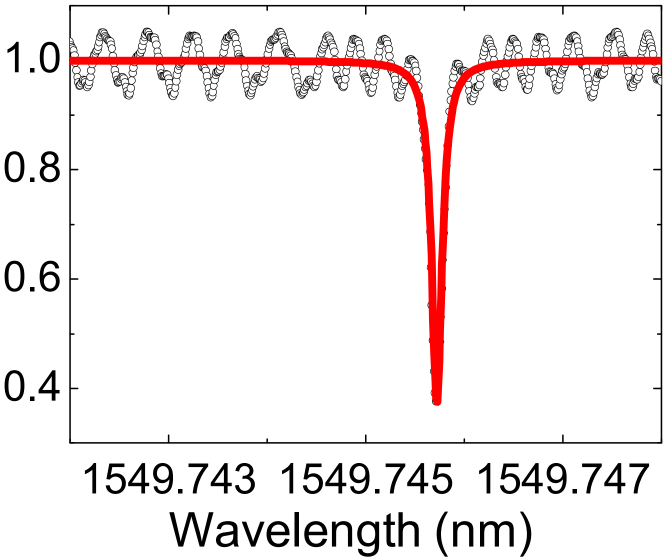
Before polishing → After polishing





$R_{\mathrm{rms}} = 3\ \mathrm{nm}$ $\xrightarrow{\text{Unchanged}}$ $R_{\mathrm{rms}} = 3\ \mathrm{nm}$

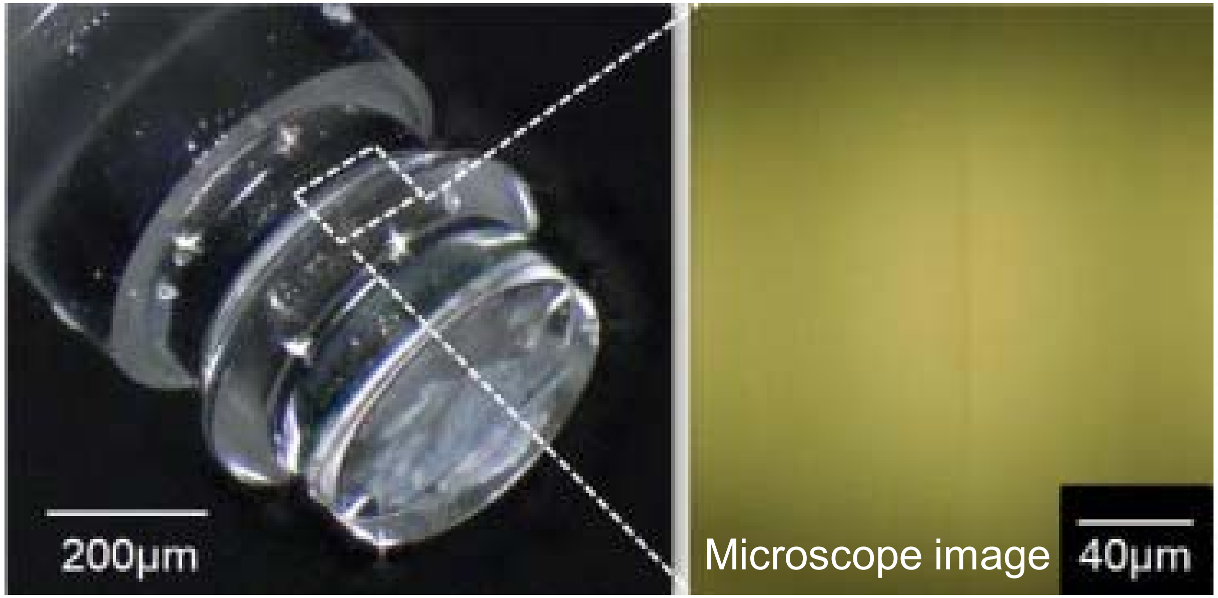


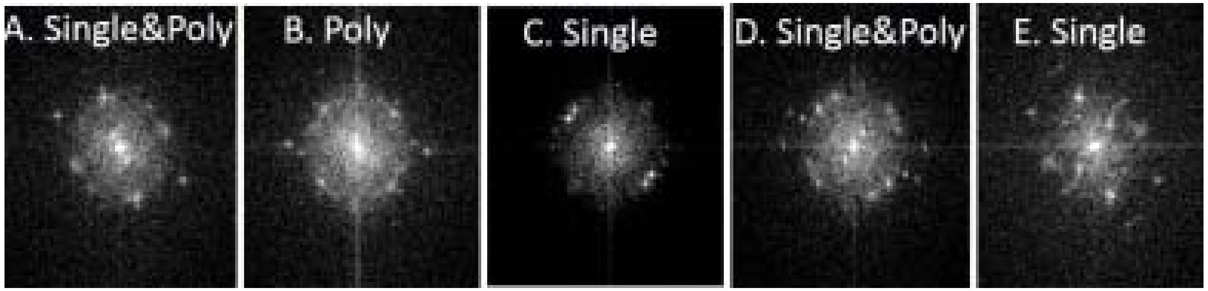


$Q = 3.0 \times 10^6$ $\xrightarrow{\text{Increased}}$ $Q = 1.2 \times 10^7$

Surface: Dislocation loops

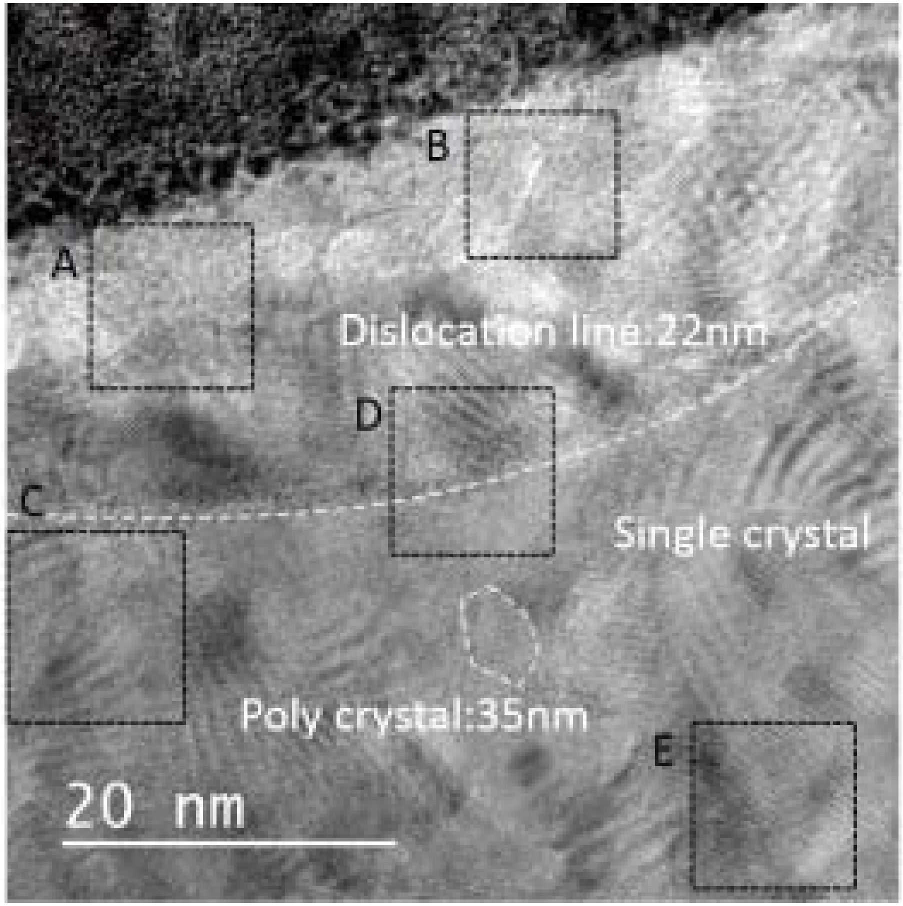
Y. Kakinuma, *et al.*, CIRP Annuals (2015) in press.





Diffraction images

TEM image



Polycrystalline layer must be removed

Acknowledgement

The team

Collaborators

Prof. Y. Kakinuma (Keio Univ.)

Dr. M. Notomi (NTT)
Dr. E. Kuramochi (NTT)

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MIC Ministry of Internal Affairs and Communications

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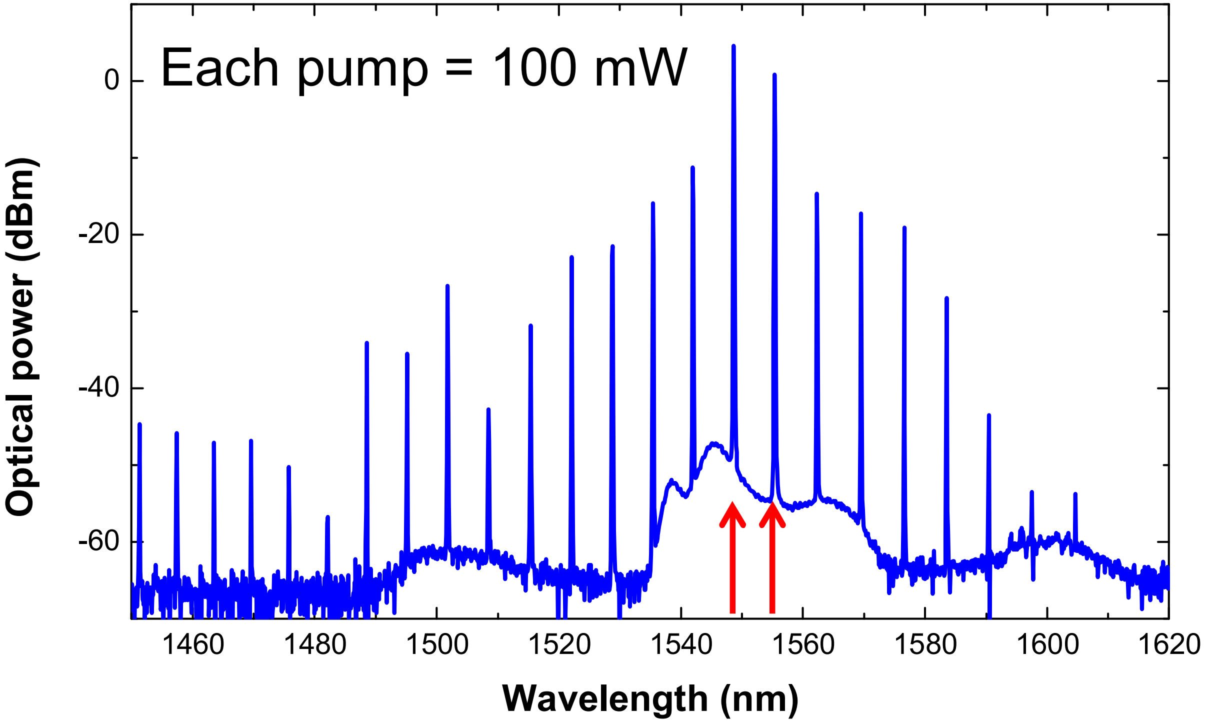
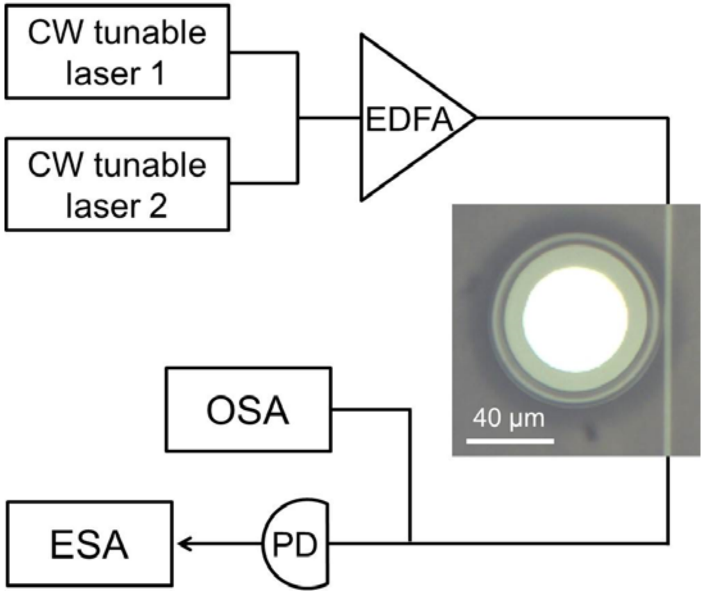
Kerr comb generation with toroid microcavity (Dual pump)




CW tunable laser 1

CW tunable laser 2

EDFA

OSA

ESA

PD

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