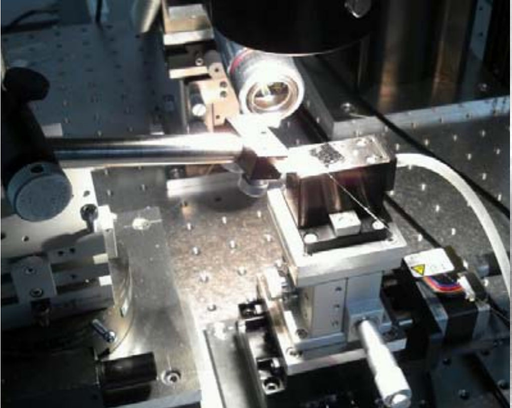
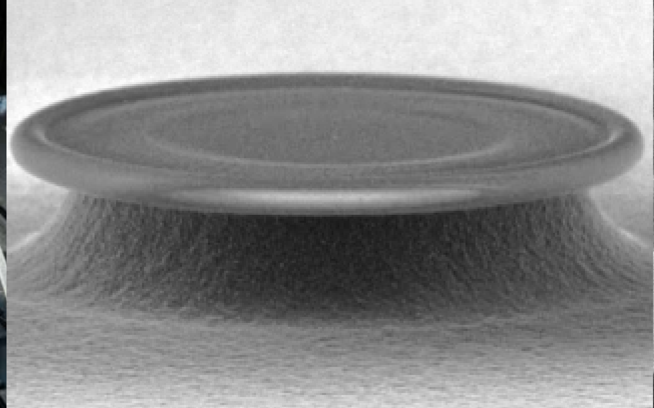
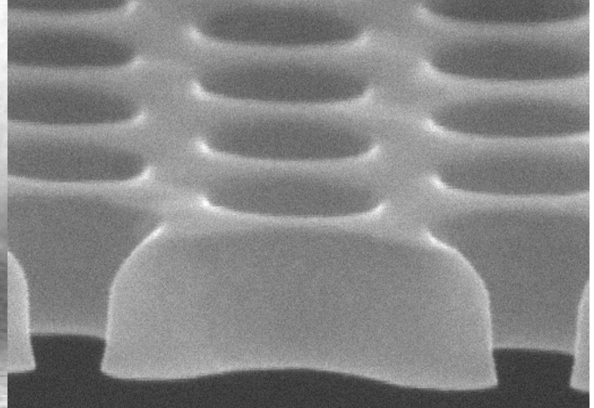
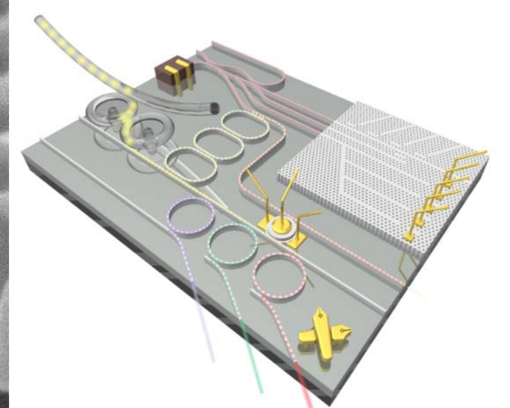

CLEO: 2016

Soliton pulse formation in a calcium fluoride whispering gallery microcavity without frequency sweeping

1. Electronics and Electrical Engineering, Keio University, Japan
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Hiroki Itobe[1], Tomoya Kobatake[1], Yosuke Nakagawa[1], Takumi Kato[1], Yuta Mizumoto[2], Hiroi Kangawa[2], Yasuhiro Kakinuma[2], and Takasumi Tanabe[1]

takasumi@elec.keio.ac.jp

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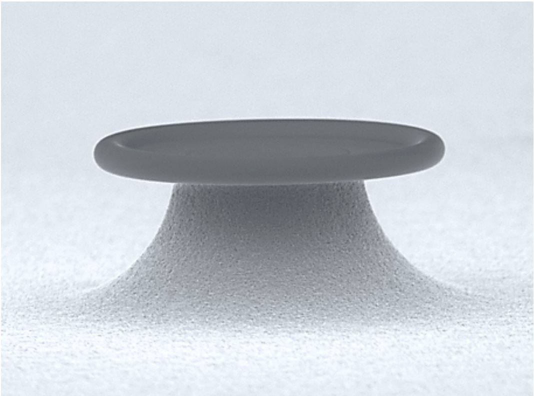
June 8, 2016, 9:00~9:15

Optical Kerr frequency comb

Kerr comb

Microcavity



- ✓ Small & Inexpensive
- ✓ High repetition rate (10GHz-1THz)
- ✓ Large bandwidth
- ✓ Low threshold pump

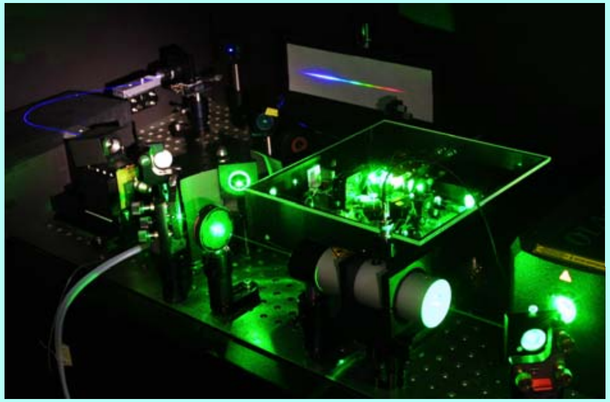
Threshold pump power for four-wave mixing

$$P_{\mathrm{threshold}} \propto V/Q^2$$

V : Mode volume
Q : Quality factor

Conventional frequency comb sources

Ti:Sapphire laser

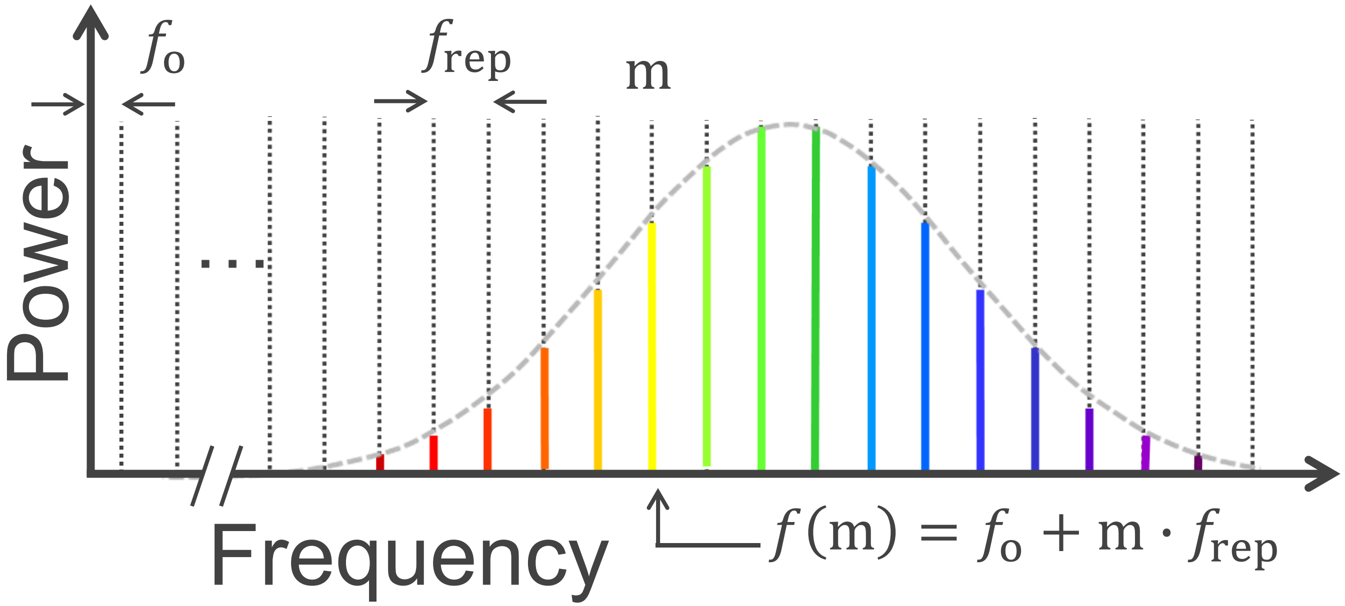


http://www.mpq.mpg.de/~haensch/comb/index.html

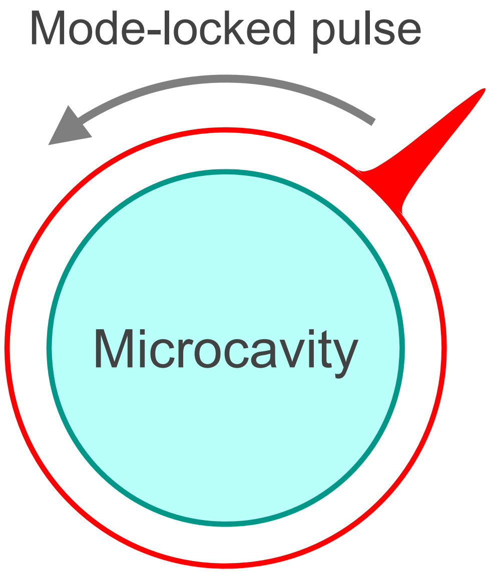
Fiber laser

https://www.aist.go.jp/index_ja.html

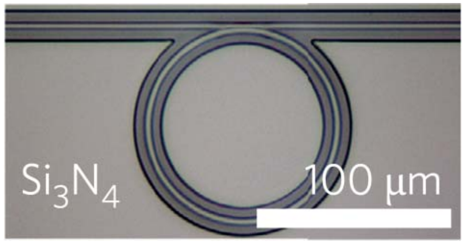
Large & Expensive



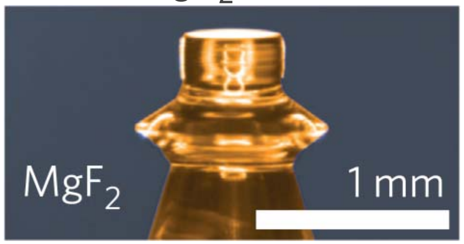
Soliton pulse generation w/ wavelength sweeping



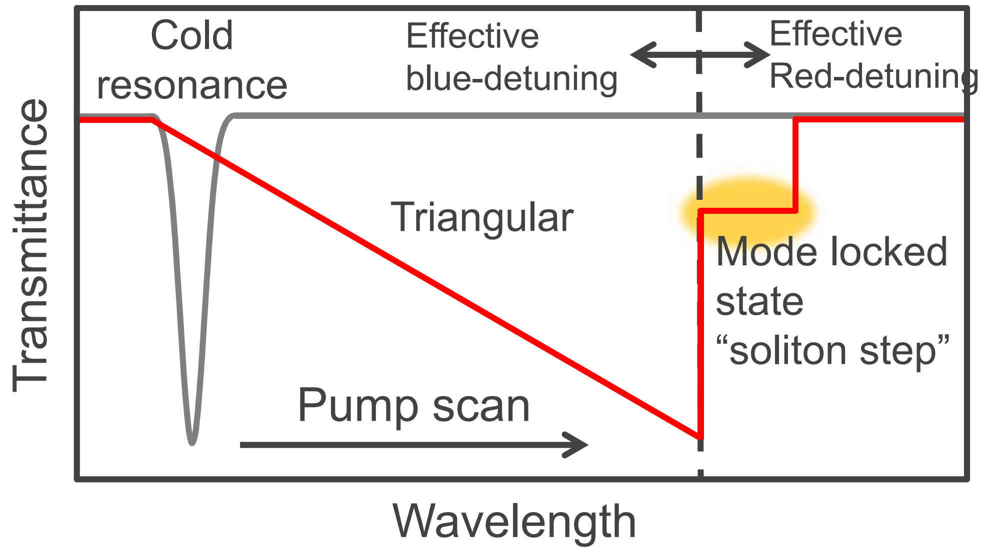
SiN microring



MgF_2 bulk



T. Herr et al., Nat. Photon. **6**, 480 (2012)



wavelength sweep is required for soliton

Kerr effect

$n = n_0 + n_2 I$: positive ↑

Thermo-optic coefficient

SiO_2, SiN, MgF_2

$\frac{\partial n}{\partial T} > 0$: positive ↑

CaF_2

$\frac{\partial n}{\partial T} < 0$: negative ↓

Research goals

By utilizing negative thermo-optic (TO) effect,

- Can we obtain soliton pulse w/o frequency sweeping?

By utilizing ultra precision machining,

- Can we fabricate a dispersion controlled CaF_2 microcavity?

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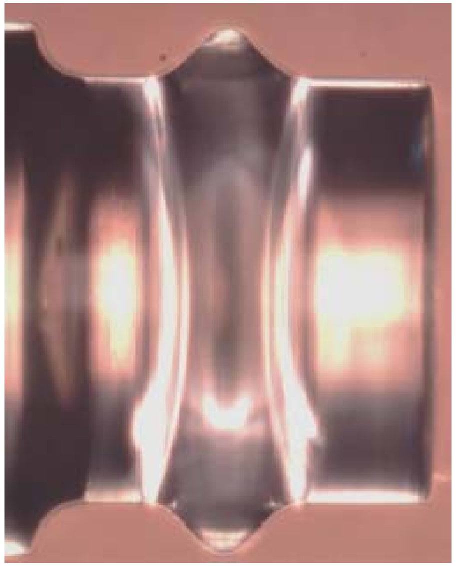
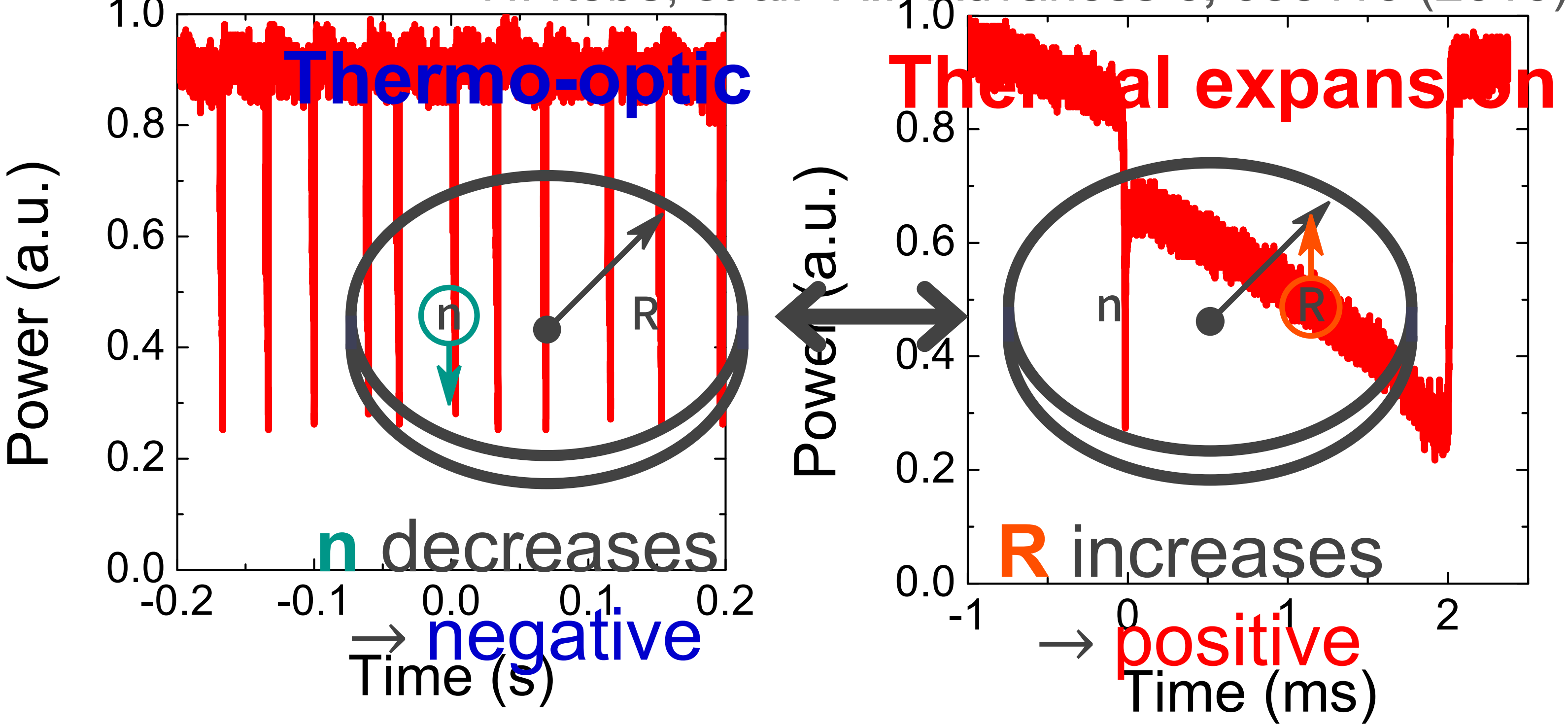
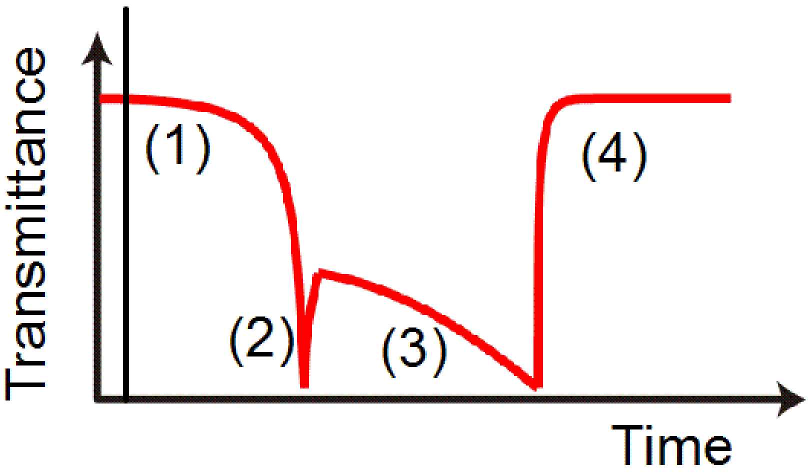
Thermo-opto-mechanical oscillation

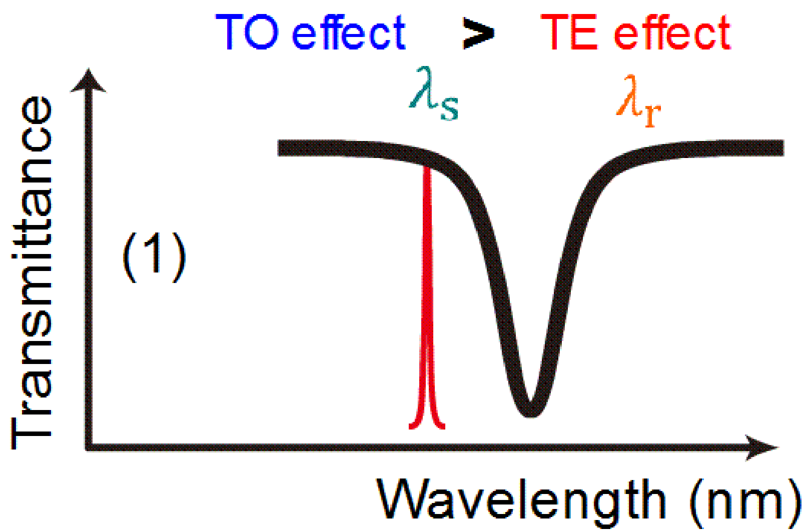
H. Itobe, *et al.* AIP Advances **6,** 055116 (2016).



$Q = 1.2 \times 10^7$

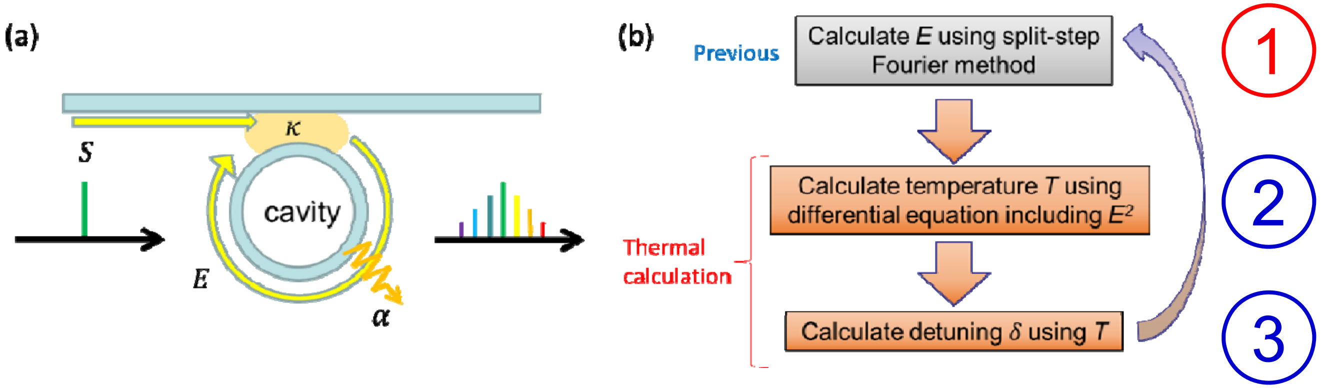






Model describing nonlinearities in CaF_2

Kerr effect + Thermal effects (TO/TE)



- 1. Lugiato-Lefever (LL) equation

$$t_R \frac{\partial E}{\partial t} = \left(\underbrace{-\frac{\alpha}{2} - \frac{\kappa}{1}}_{\text{Loss}} \underbrace{- i\delta}_{\text{Detuning}} \underbrace{- i2\pi r \frac{\beta}{2} \frac{\partial^2 E}{\partial \tau^2}}_{\text{Dispersion}} \underbrace{+ i2\pi r \gamma |E|^2}_{\text{Kerr effect}} \right) E + \underbrace{\sqrt{\kappa} S}_{\text{Pump}}$$

- 2. Thermal rate equation (cavity temperature)

$$\frac{d\Delta T_m}{dt} = -\Gamma_m \Delta T_m + \gamma_m |E|^2 \ (m = 1,2)$$

- 3. Resonant wavelength shift

$$\Delta\lambda = \lambda_0 \left(\frac{dn_1}{dT_1} \frac{\Delta T_1}{n_0} + \epsilon \Delta T_2 \right)$$

t_R	round-trip time
α	intrinsic cavity loss
κ	coupling loss
δ	detuning of the input wavelength
r	cavity radius
β	dispersion of the cavity
γ	nonlinear coefficient
S	input driving power
ΔT_1	temperature change of the optical mode volume
ΔT_2	temperature change of the entire cavity volume
λ_0	cold resonant wavelength
$\frac{dn_1}{dT_1}$	TO coefficient
ϵ	TE coefficient
n_0	refractive index of the cavity

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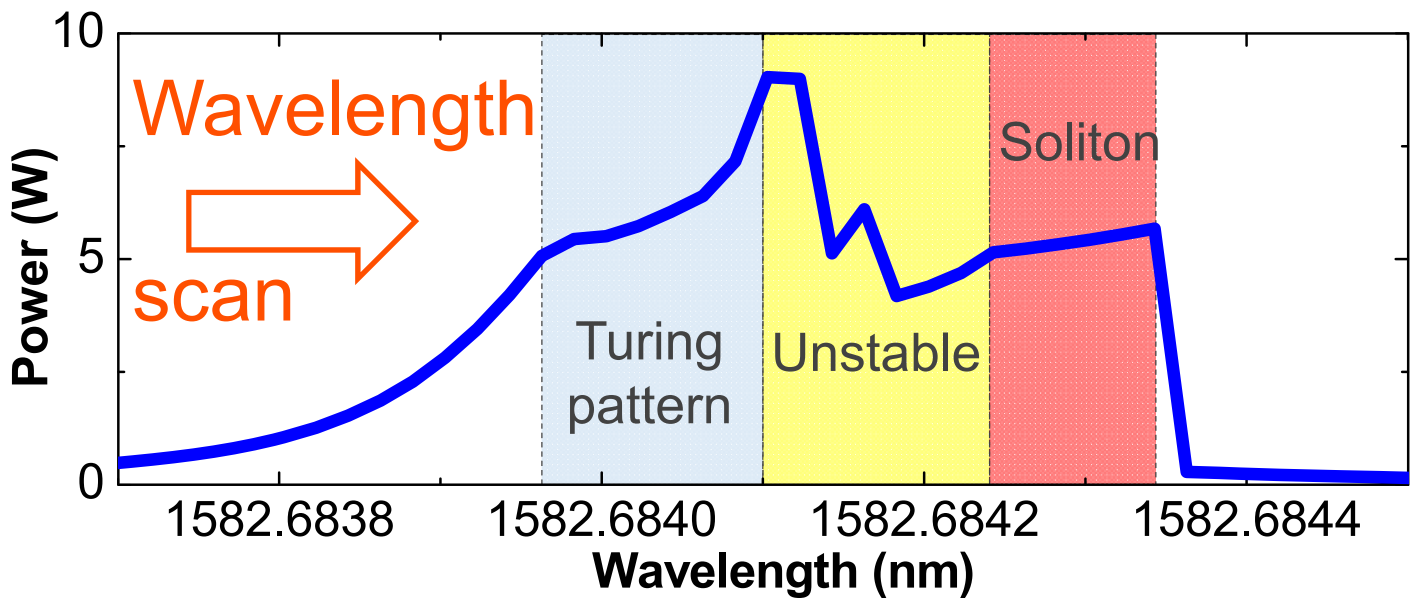
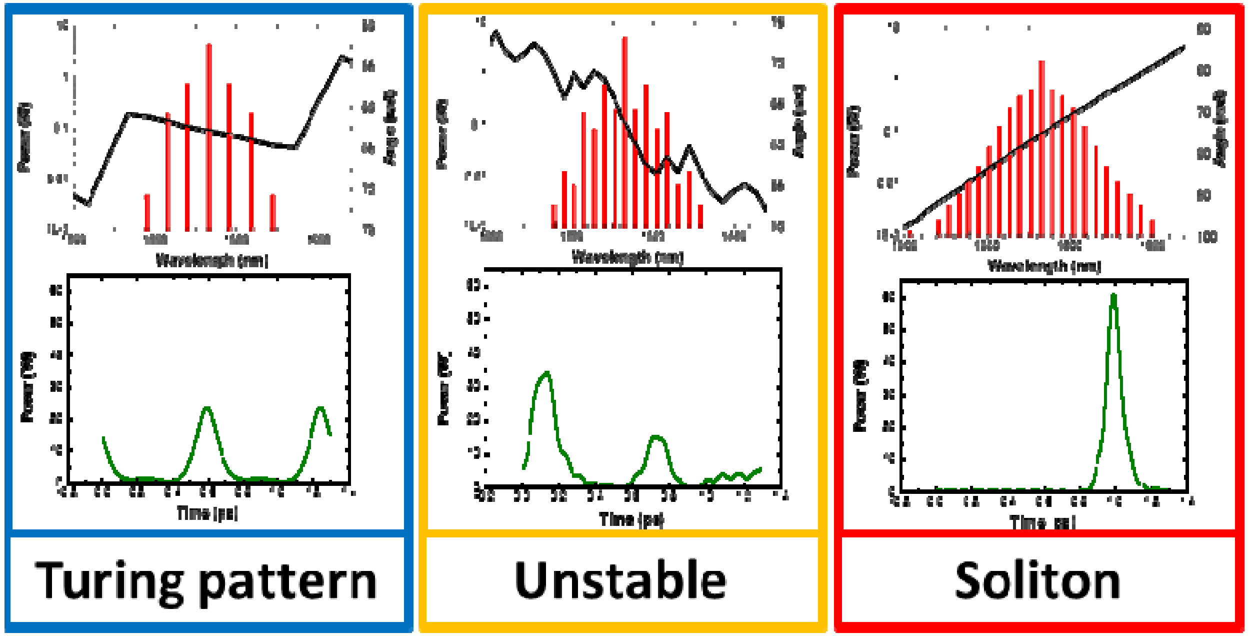
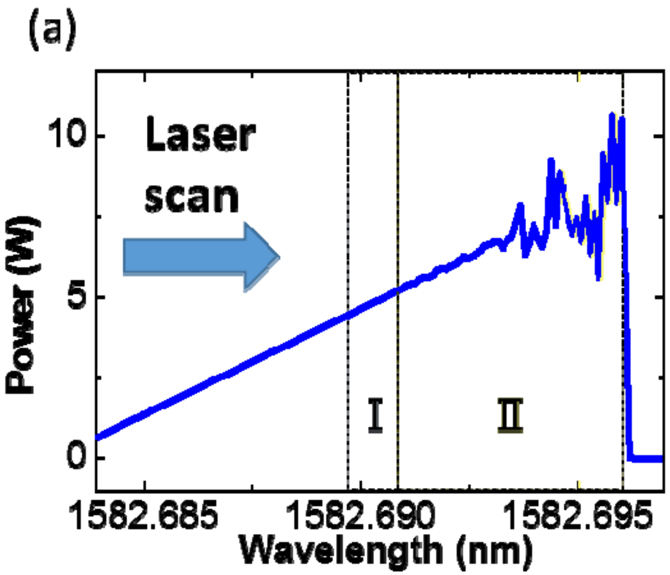
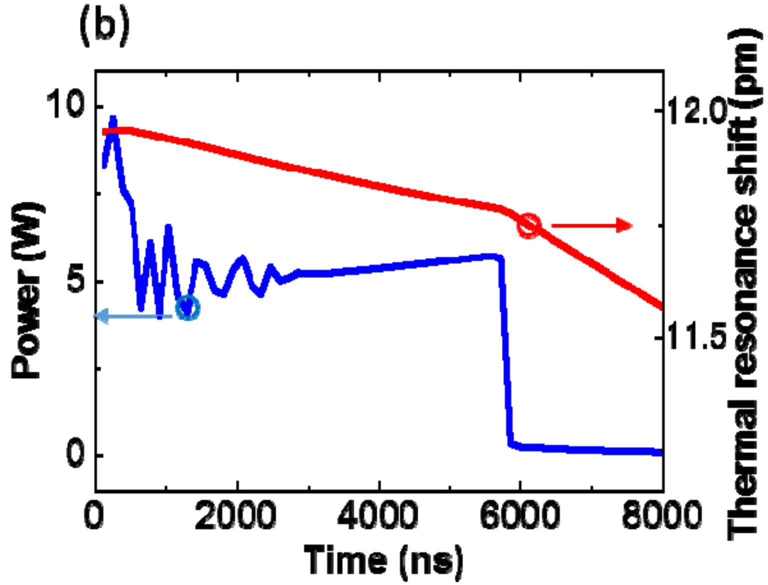
Without thermal effects (only Kerr)



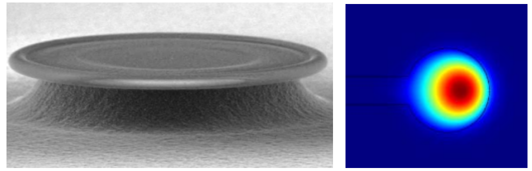


With positive TO effect (SiO_2 microcavity)





Resonator model



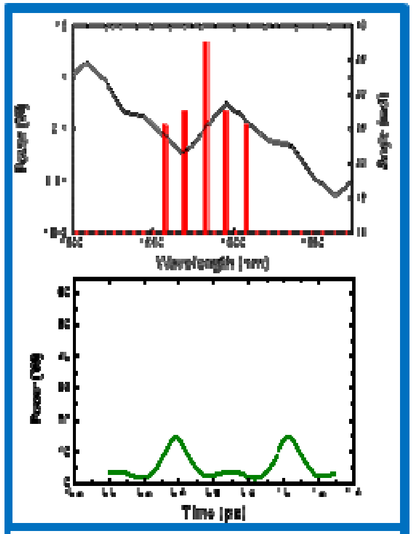
dn/dT = 1.05×10^{-4}

Input = 5 mW

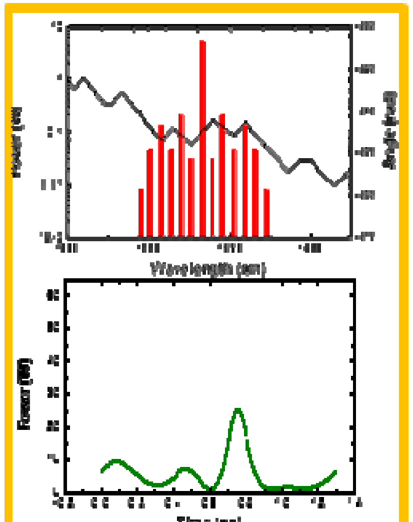
$Q_{couple} = 4 \times 10^7$

$Q_{int} = 4 \times 10^7$

radius = 42 μm



Turing pattern



Unstable

It is difficult to stay in the soliton regime because of the TO effect.

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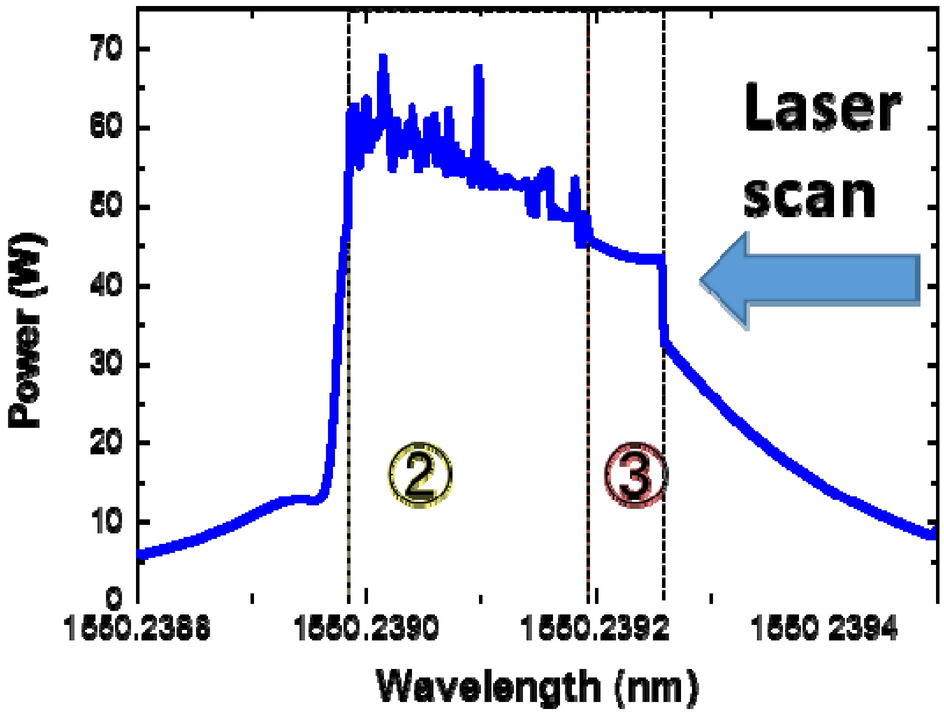
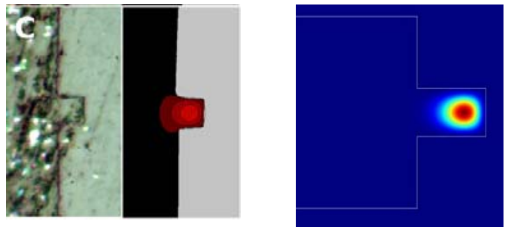
With negative TO effect (CaF_2 microcavity)



Resonator model



I. S. Grudinin *et al*., Optica **2**, 221 (2015)

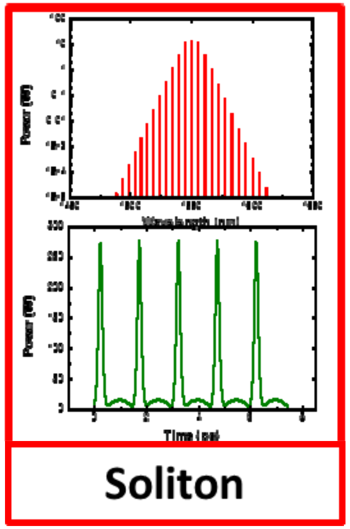
$dn/dT = -1.15 \times 10^{-5}$

Input = 70 mW

$Q_{couple} = 2 \times 10^7$

$Q_{int} = 2 \times 10^7$

radius = 500 μm



Easy to obtain soliton pulses by reverse scan.

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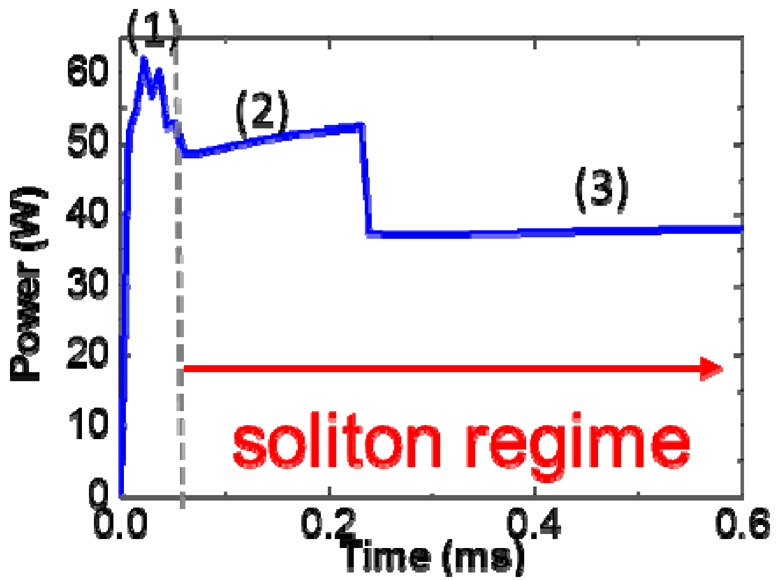
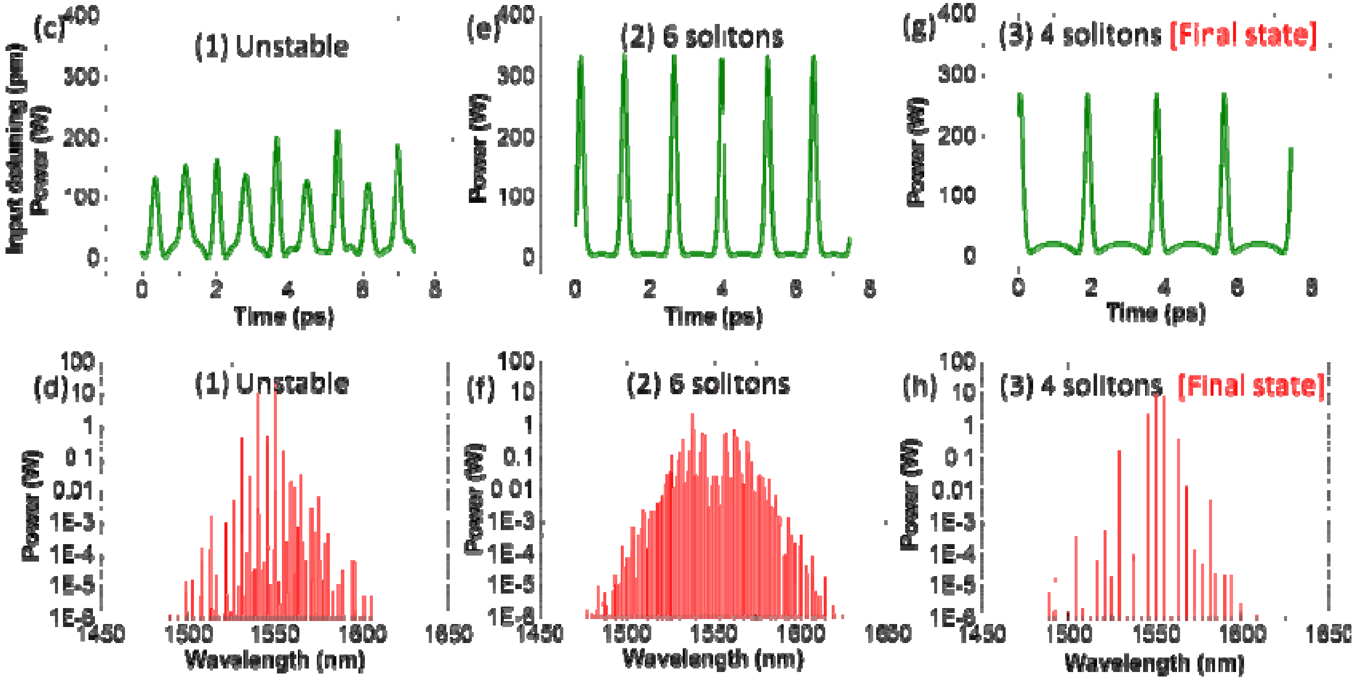
Soliton state w/o wavelength scan

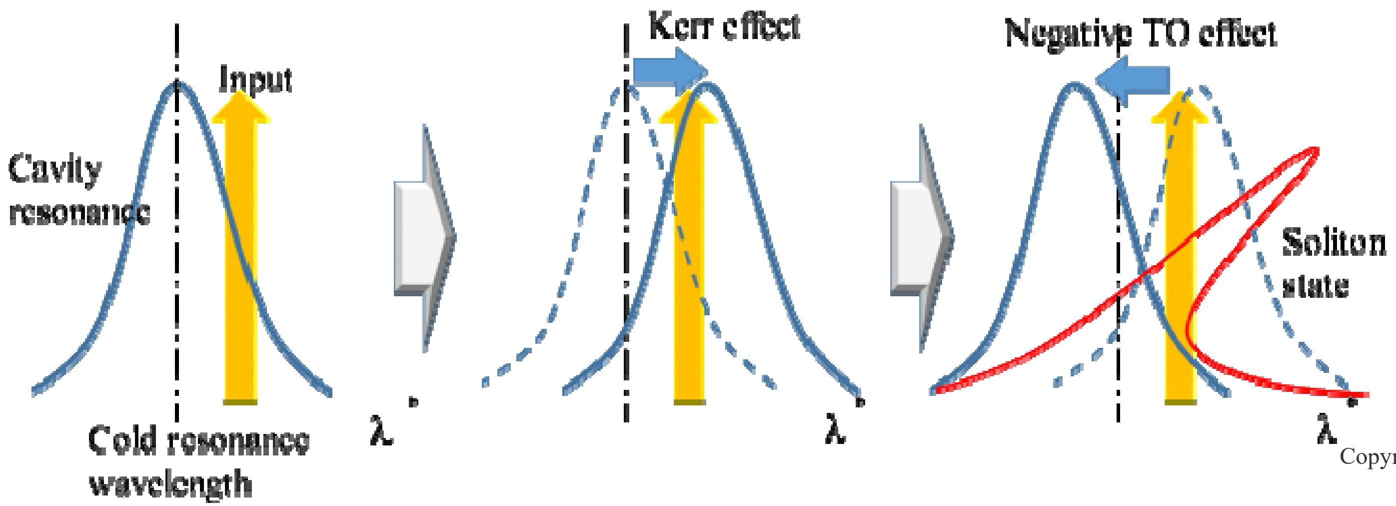
Kerr + TO + TE



(1) Unstable (2) 6 solitons (3) 4 solitons



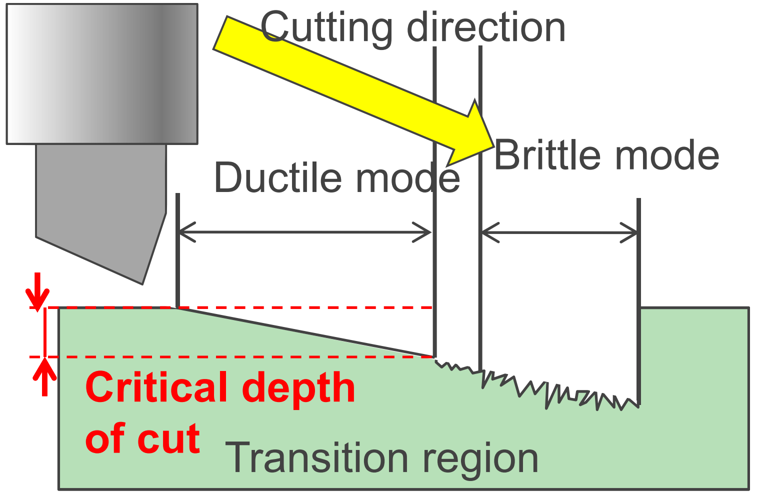
Principle of operation

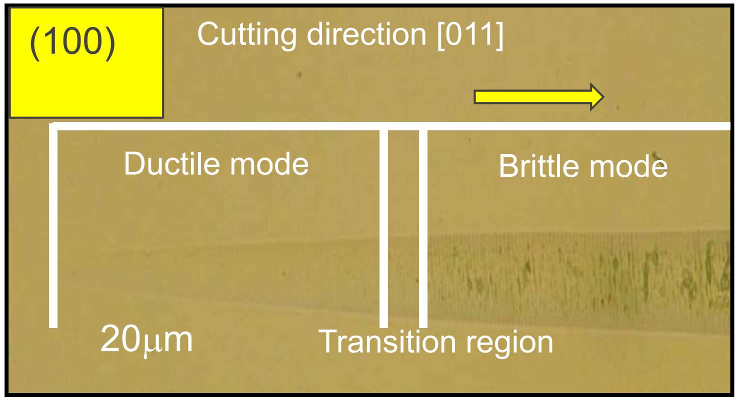


Fabrication of CaF_2 WGM cavity w/ cutting

▶ Precise machining process

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

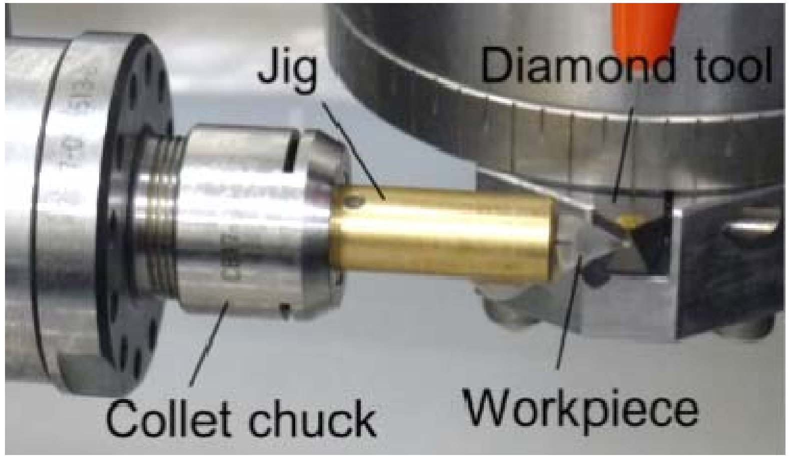


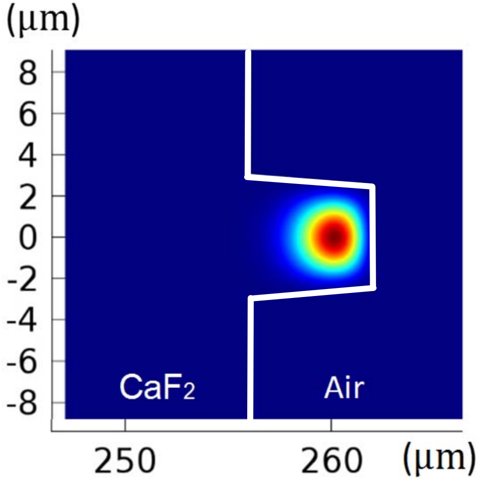


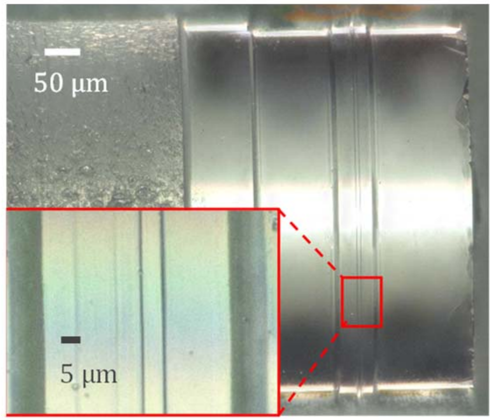
➢ CaF_2 can be smoothly cut in ductile mode cutting

▶ Lathe cutting

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







$R_{rms} = 3$ nm

$Q = 1.2 \times 10^6$

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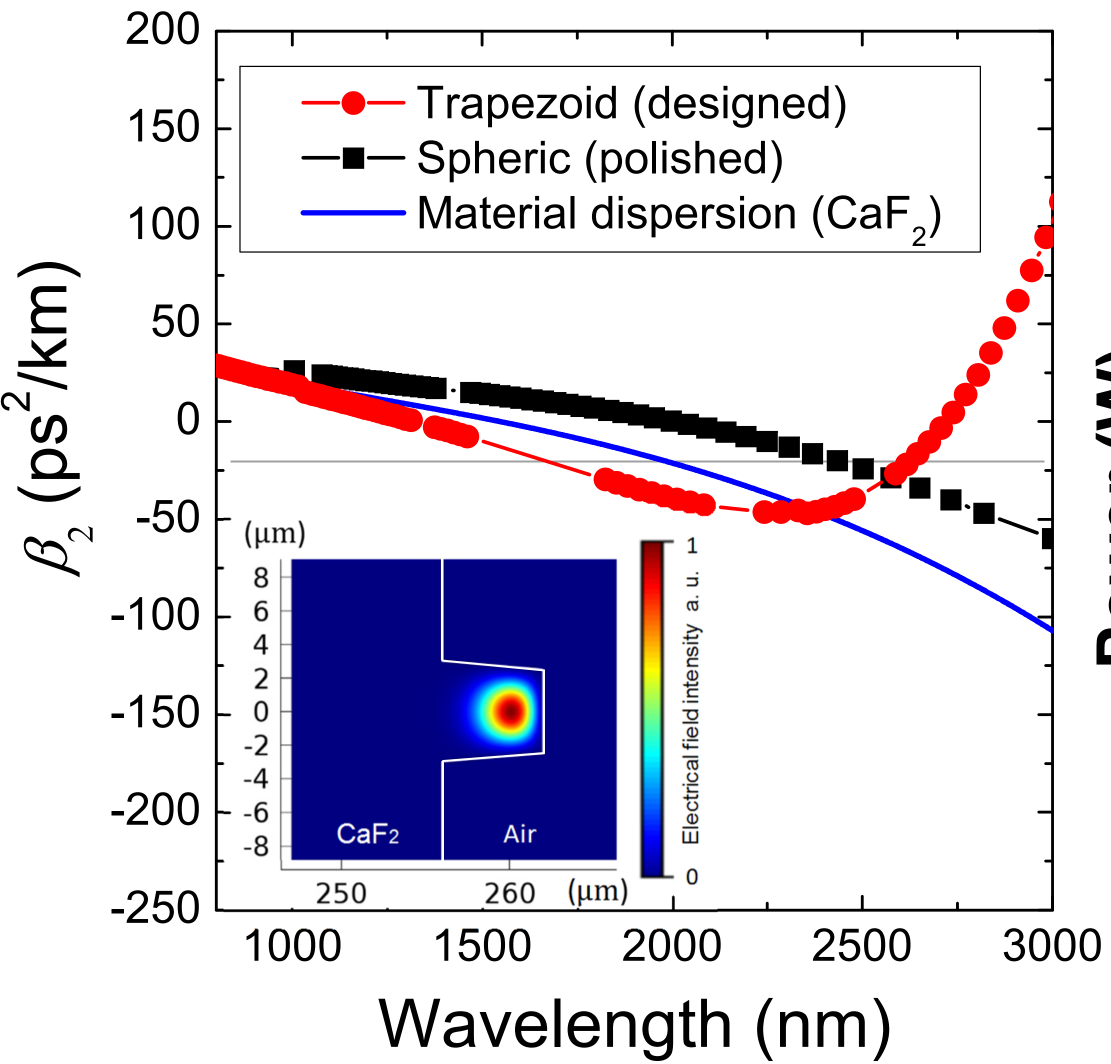
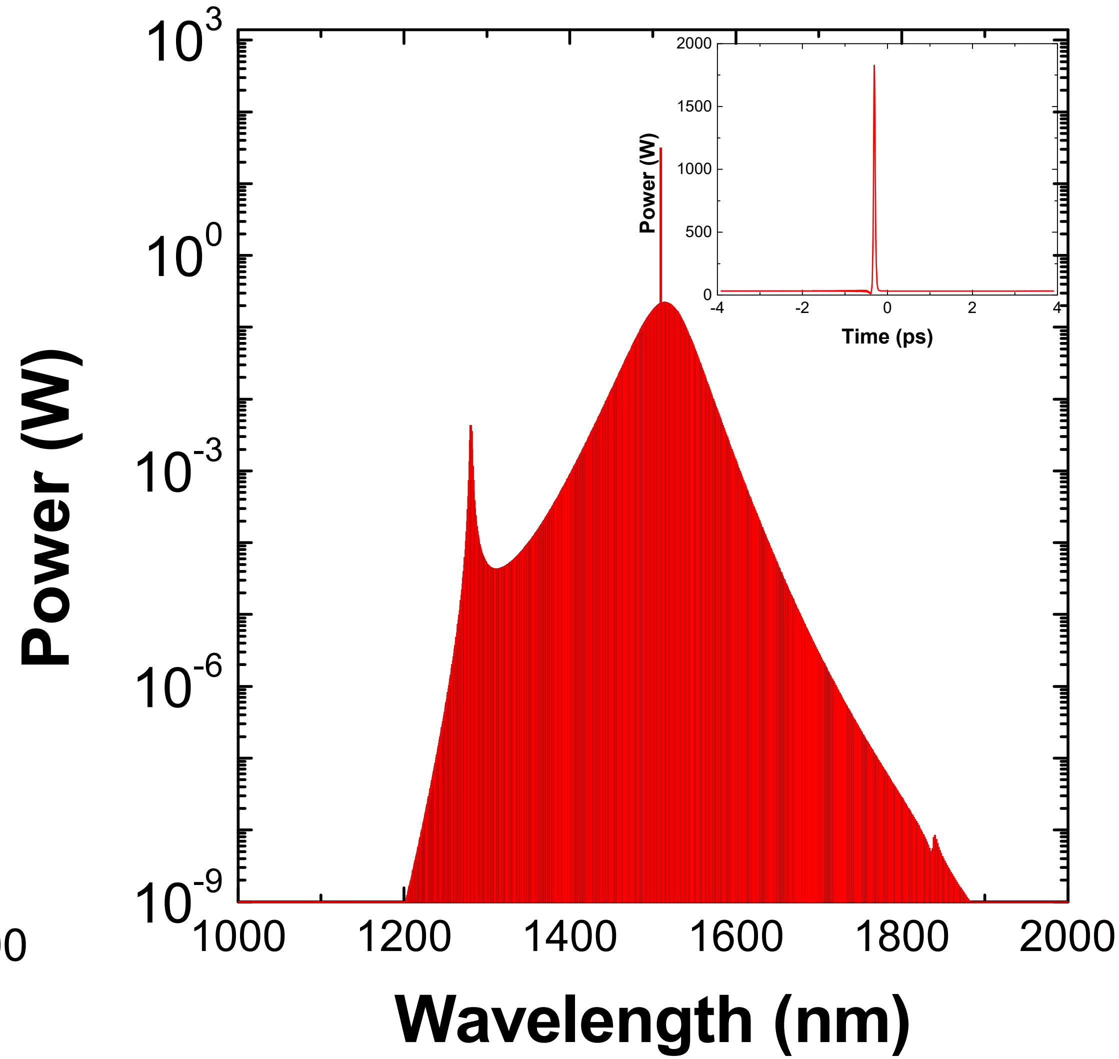
Trapezoid shaped WGM microcavity





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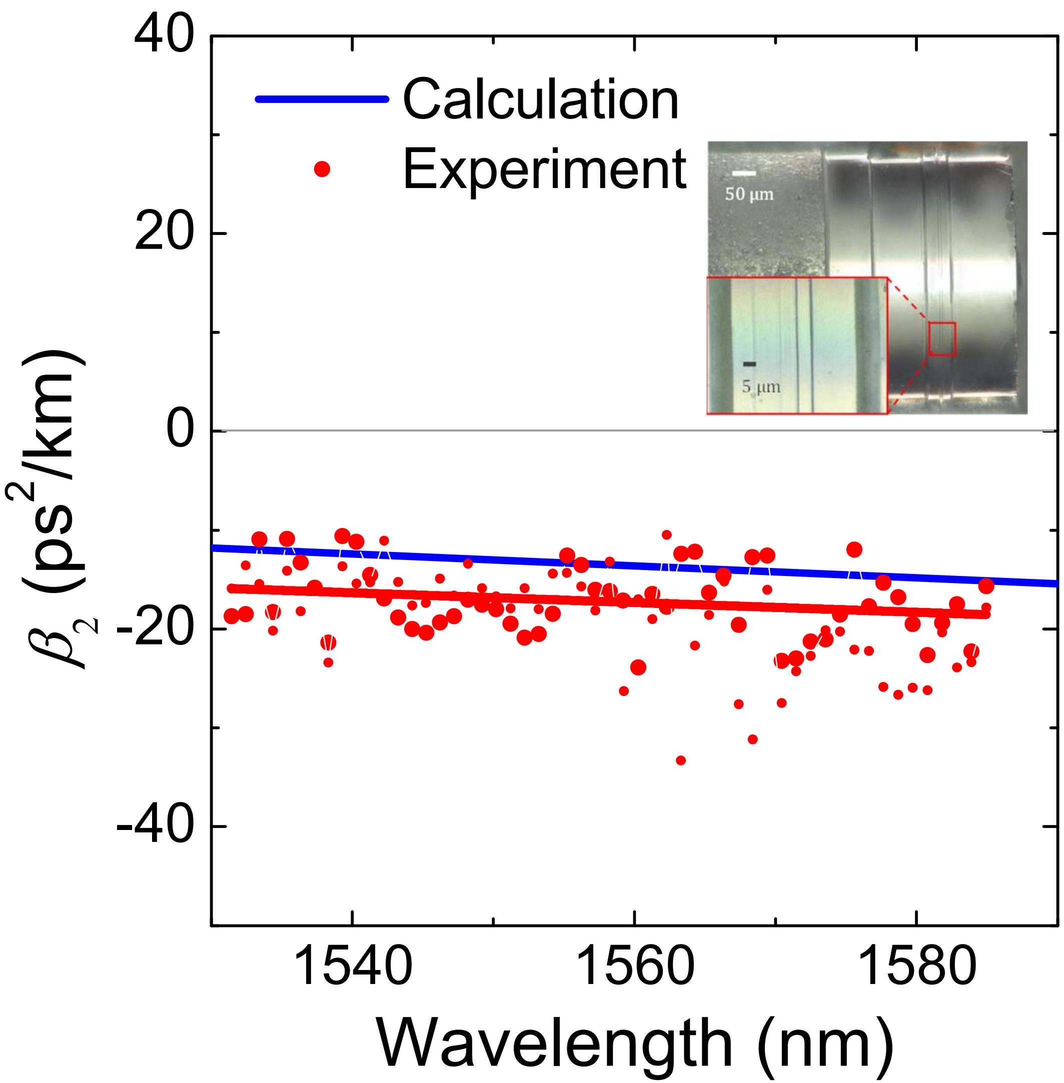
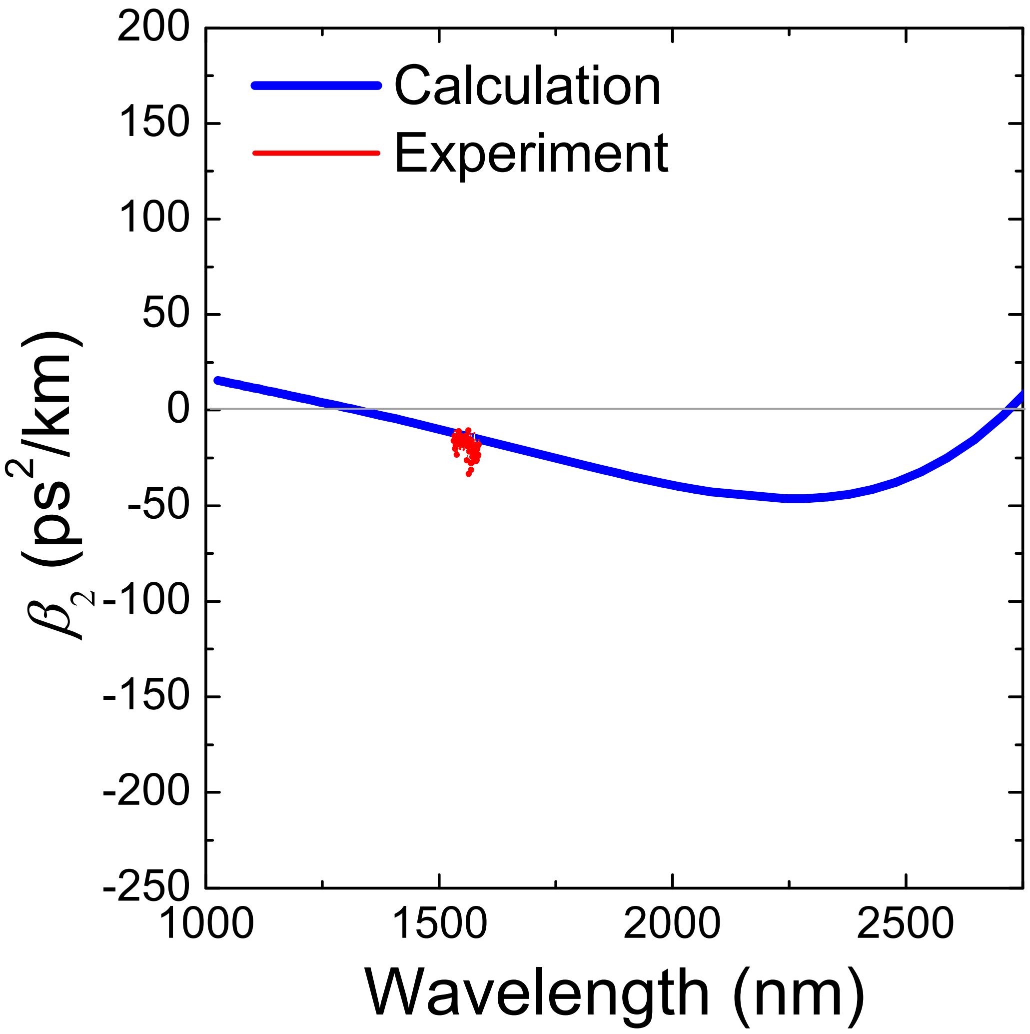
Dispersion measurement





- Anomalous dispersion obtained

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Summary

Obtained soliton pulse without wavelength sweeping

by using negative TO effect of CaF_2.

Fabricated a dispersion controlled CaF_2 microcavity

with a computer controlled ultra precision machining

Acknowledgements

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Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology, Japan for the Photon Frontier Network Program.

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