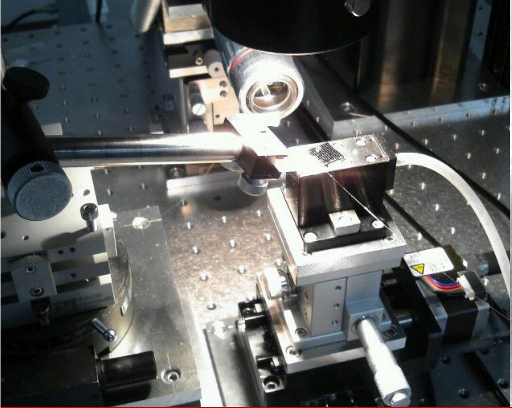
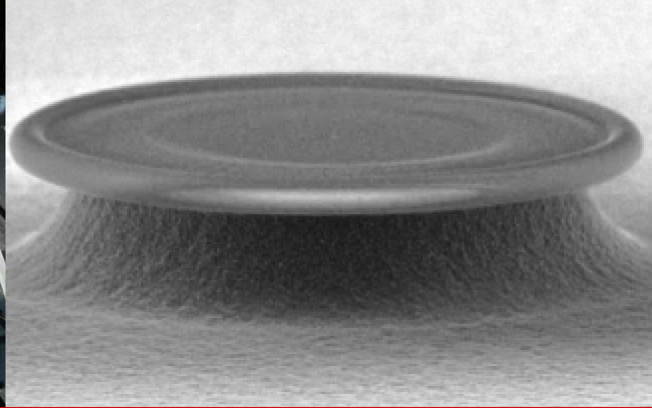
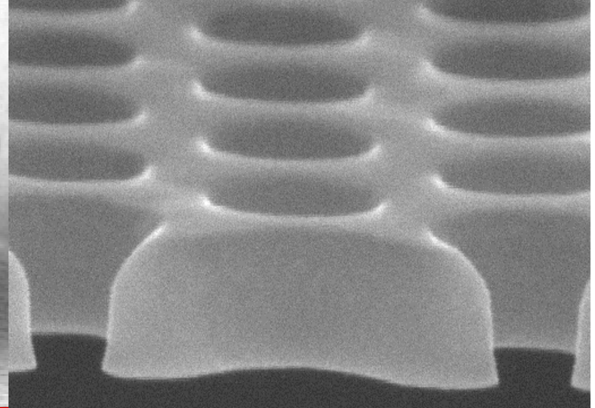
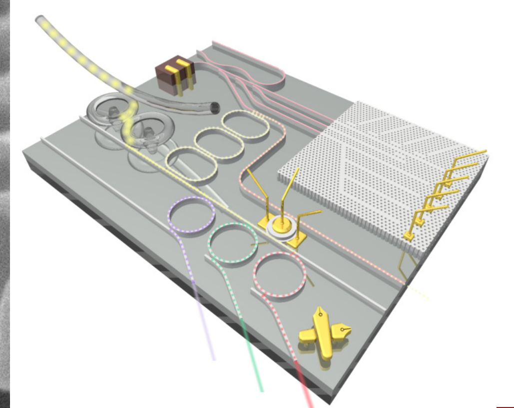





IEEE-OMN2016
We2.3 11:45-12:15 Aug. 3. 2016

Optical nonlinear control at a very low power in ultrahigh-Q microcavity systems

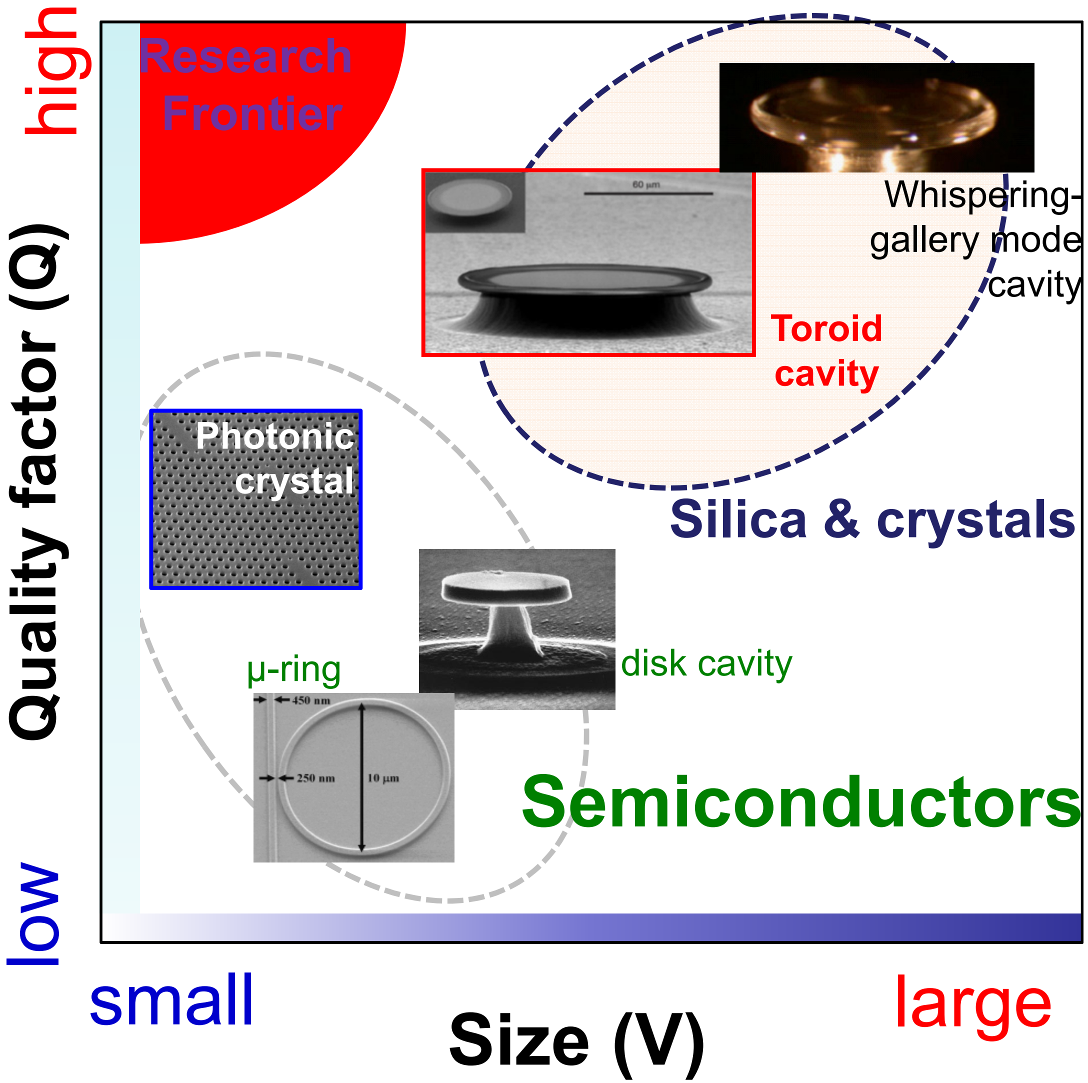
Takasumi Tanabe,
Tomohiro Tetsumoto, Hiroki Itobe, Ryo Suzuki, and Takumi Kato

takasumi@elec.keio.ac.jp

Department of Electronics and Electrical Engineering,
Keio University, Japan

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 switches
- ▸Optical sensors
- ▸Optical frequency combs
- ▸Cavity QED devices
- ▸Low-threshold lasers

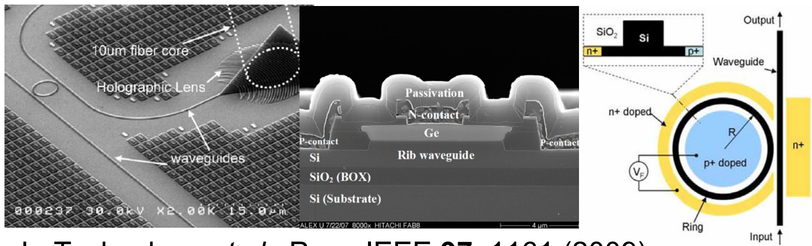
Outline

1. Background & Motivation
2. Ultrahigh Q nanocavity w/ photolithographic Si PhC
3. Electro-optic modulator w/ controlled random PhC
4. 8-ch in-plane DWDM demux demonstration
5. SiO_2 / Si hybrid system
6. Summary

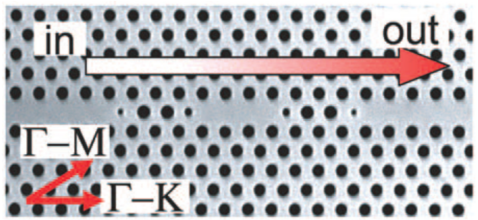
Motivation: Si-photonics vs. PhC

Si-photonics		Photonic crystals
1. SiO_2-cladding	⇔	Air-bridge
2. Photolithography	⇔	EB-lithography

Problems



L. Tsybeskov, *et al*., Proc. IEEE **97**, 1161 (2009)
Q. Xu, *et al*., Opt. Express **15**, 430 (2007)
T. Yin, *et al*., Optics Exp. **15**, 13965 (2007)



T. Tanabe, *et al*., Appl. Phys. Lett. **87**, 151112 (2005).
T. Tanabe *et al*., Nature Photon. 1, 49 (2007).

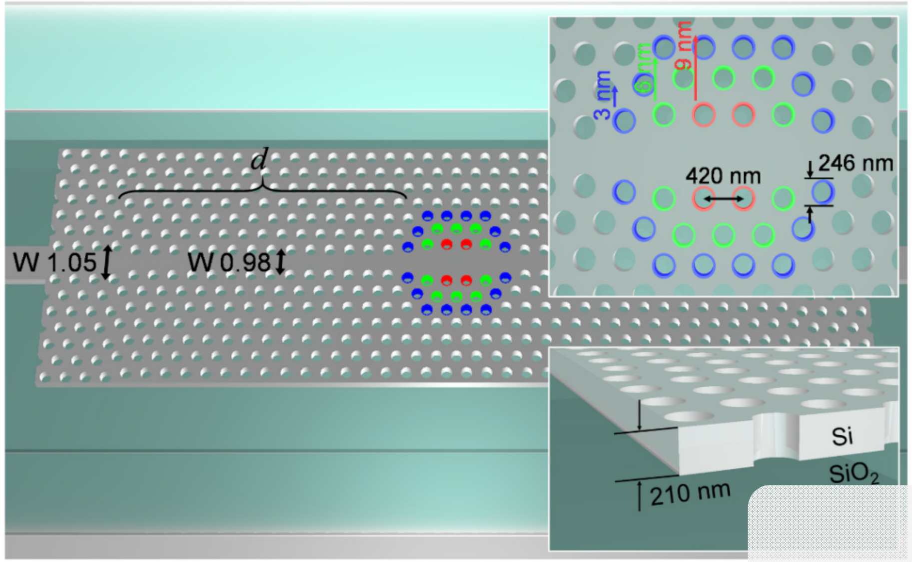
Fusion of

Si-photonics & Photonics crystals

Design & Simulation

▶Width-modulated line defect cavity

T. Tanabe, *et al.*, Nature Photon. 1, 47 (2007).



Mechanism

- Waveguide width is large at the center
- Mode-gap confinement

Characteristics

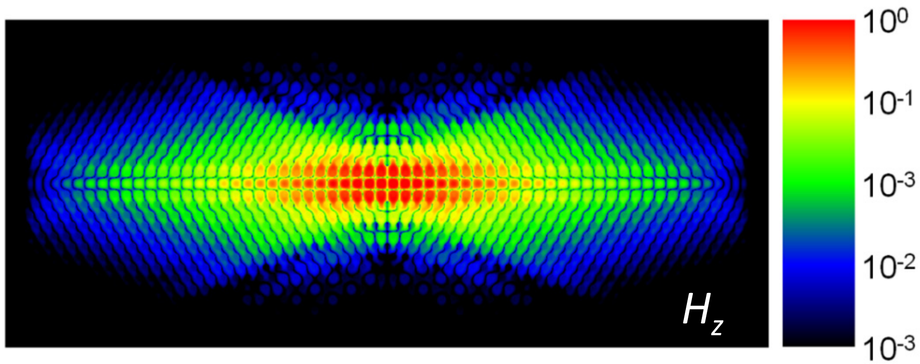
- High-*Q* w/ small shift of air-hole position

Proximity effect ↓

Photolithographic fabrication?

▶FDTD – w/ SiO_2 cladding

Y Ooka, *et al.*, *Sci. Rep.* **5,** 11312 (2015).



Optimized structure

$Q = 7.1\times10^6$ $V = 2.4\ (\lambda/n)^3$

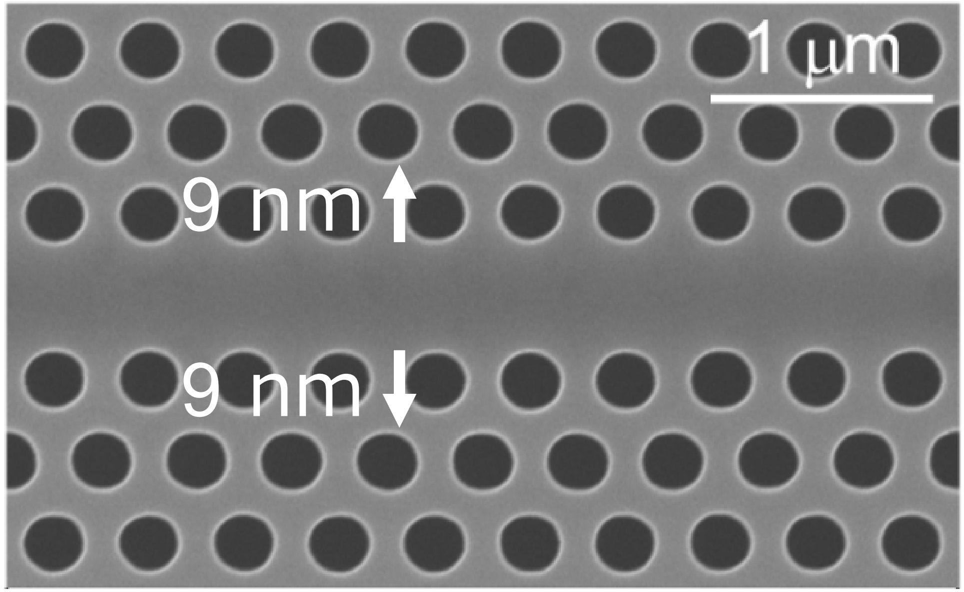
Fabricated parameter

$Q = 8.1\times10^5$ $V = 1.7\ (\lambda/n)^3$

Photolithographic fabrication & proximity effect

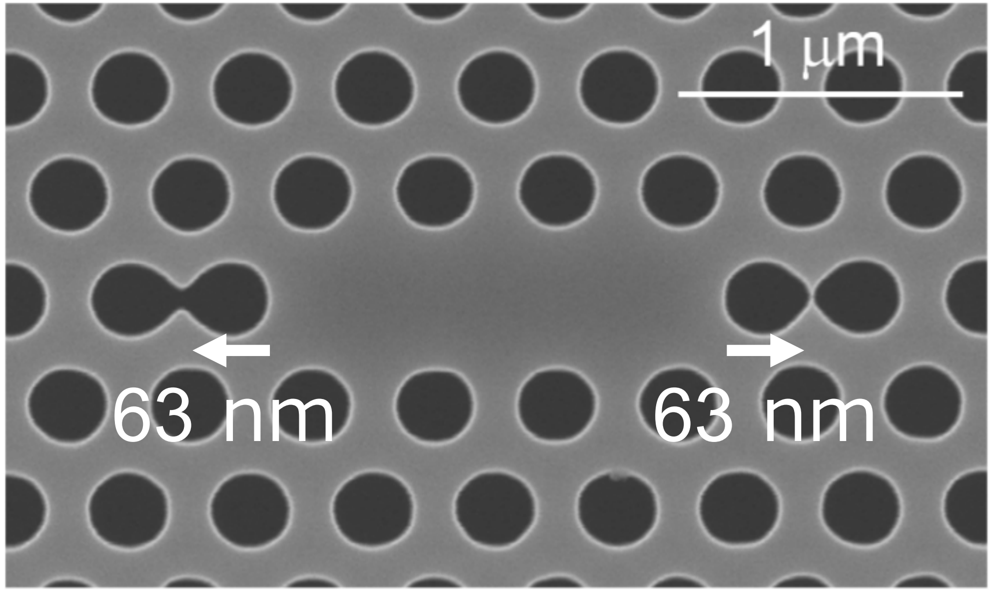
Y Ooka, *et al*., *Sci. Rep.* **5,** 11312 (2015).

SEM images (effect of fabrication error)



Width-modulated line defect cavity

Max amount of shift : 9 nm



L3 cavity

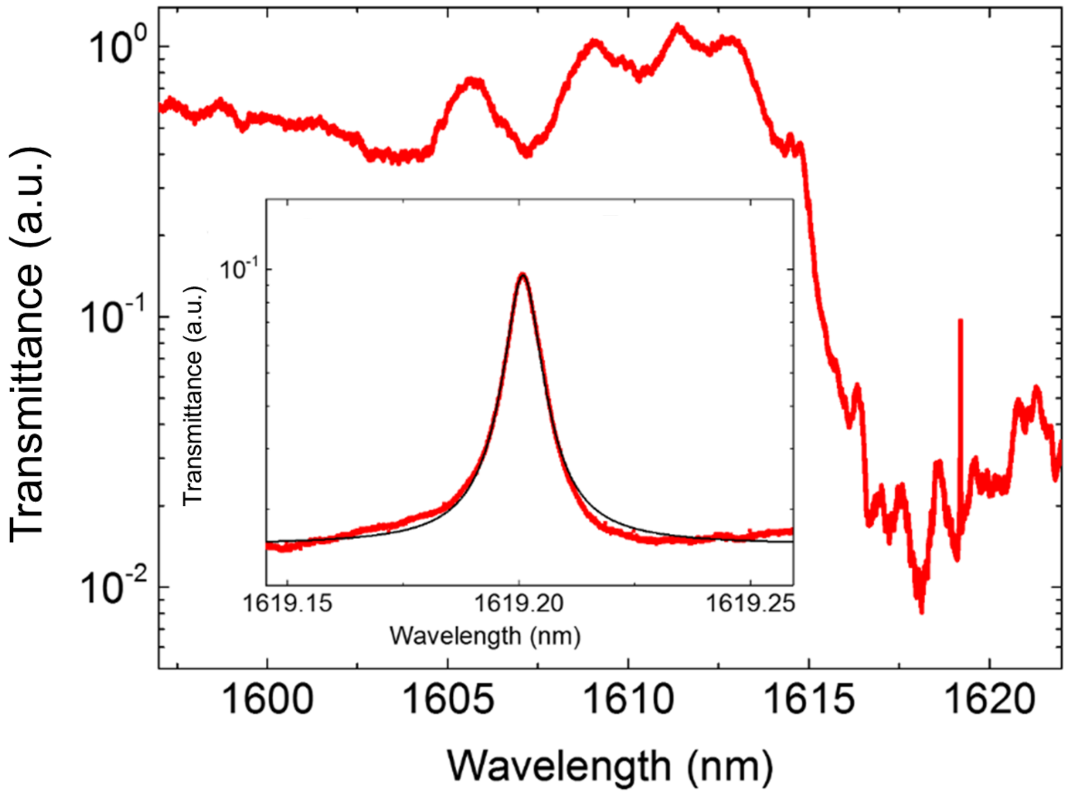
Max amount of shift : 63 nm

Width-modulated line defect cavity is
robust against the proximity effect

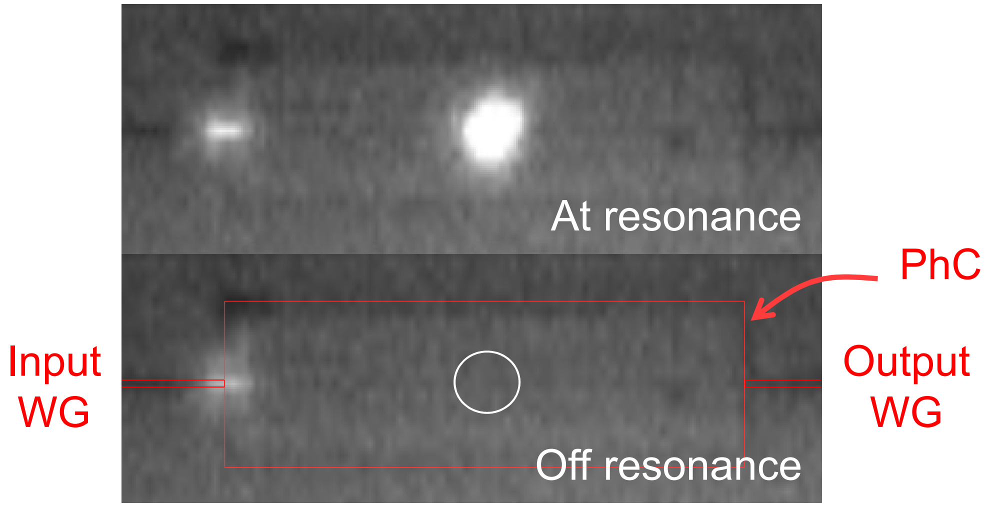
Experiment: High-Q demonstration

Y Ooka, *et al*., *Sci. Rep.* **5,** 11312 (2015).

Transmission spectrum



Top view



and w/ SiO_2-cladding!!

The highest *Q* w/ photolithography

$Q = 2.2 \times 10^5$

Outline

1. Background & Motivation

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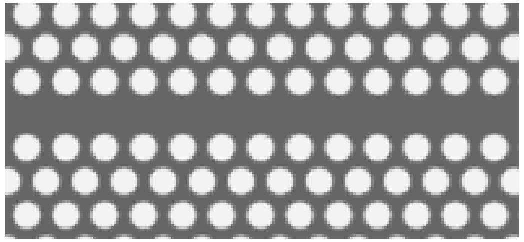
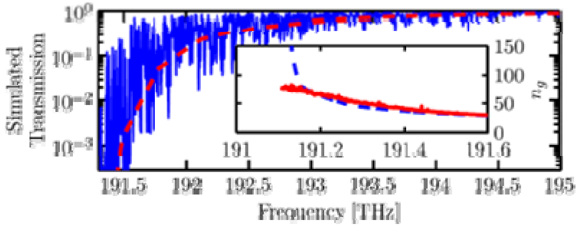
6. Summary

Random photonic crystal & our motivation

Random photonic crystal waveguide

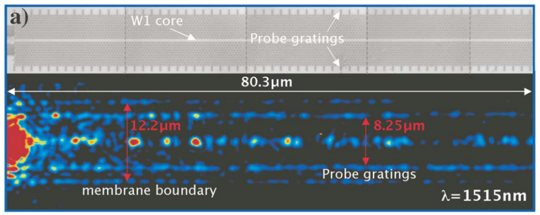


Transmittance spectrum w/ randomness



M. Patterson, *et al*., Phys. Rev. Lett. **102**, 253903 (2009)

Light localization w/ randomness



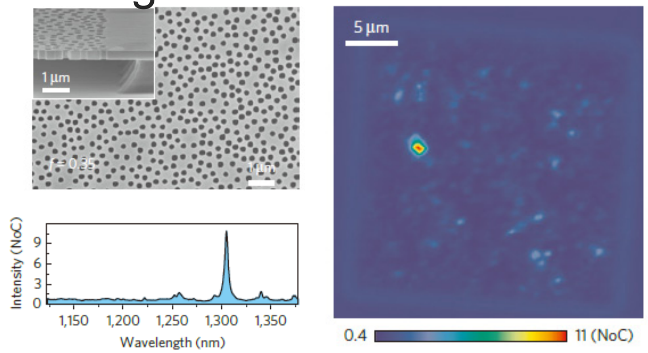
N. L. Thomas, *et al*., Phys. Rev. B **80**, 125332 (2009)

Random PhC laser

High-*Q* & easy fabrication

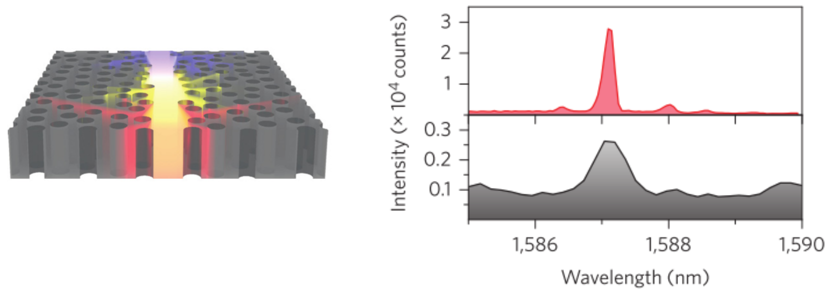
- PL tuning

F. Ribcii, *et al*., Nat. Mat. **13**, 720 (2014)



- Lasing based on Anderson localization

J. Liu, *et al*., Nat. Nanotech. **9**, 285 (2014)



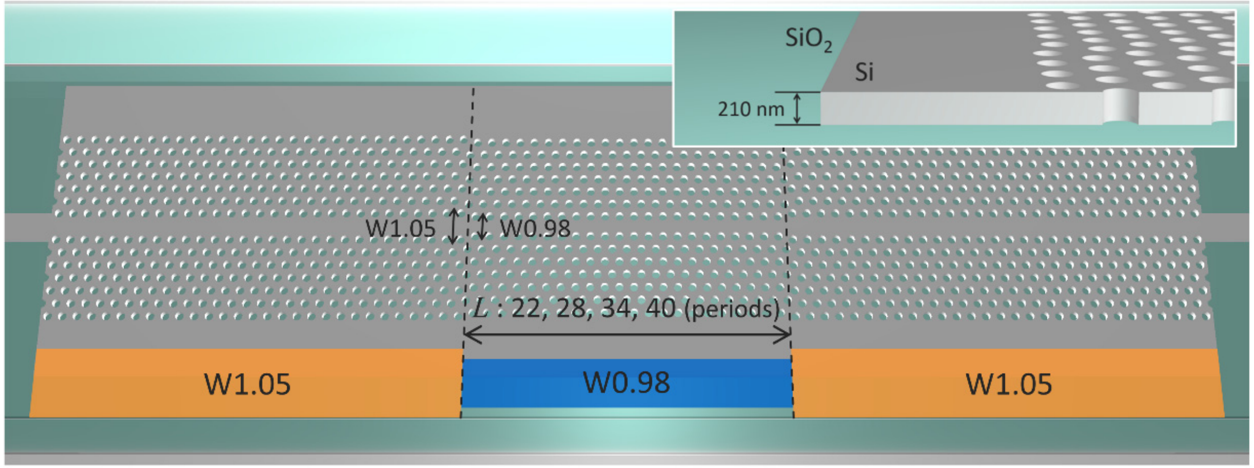
Motivation Want to use randomness for practical application

"Find a way to control the randomness"

Controlling the position of the light localization

Y. Ooka, *et al*. Opt. Express **24**, 11199 (2016).

Design of our device

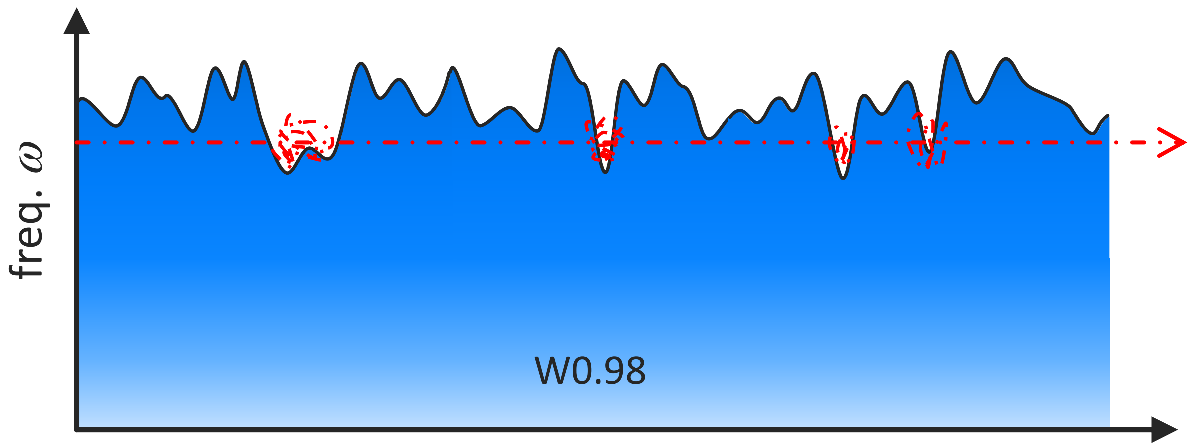


Waveguide width

W1.05 → wide

W0.98 → narrow

Cutoff frequency (mode gap)

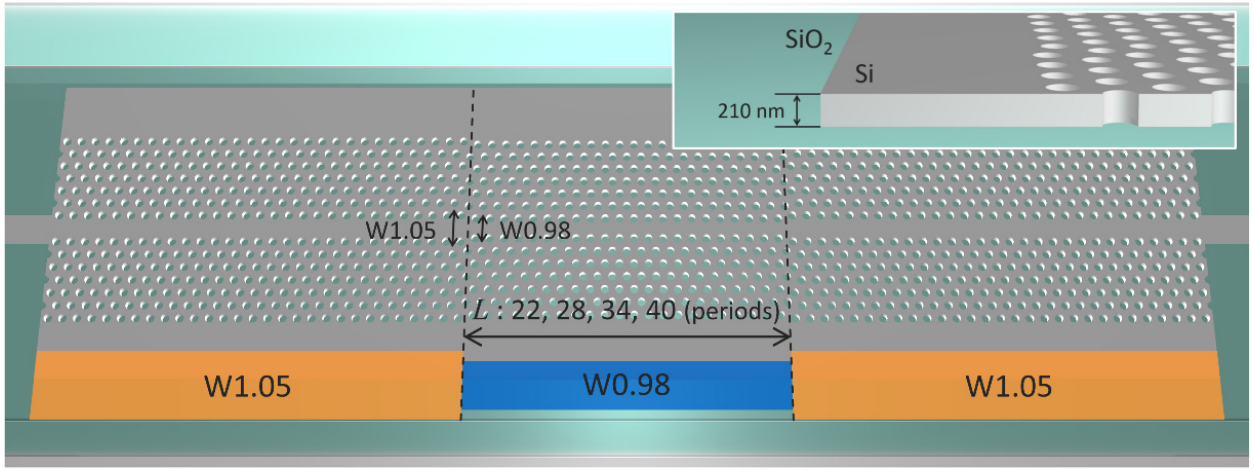


Position of light localization occurs randomly in W0.98

Controlling the position of the light localization

Y. Ooka, *et al*. Opt. Express **24**, 11199 (2016).

Design of our device

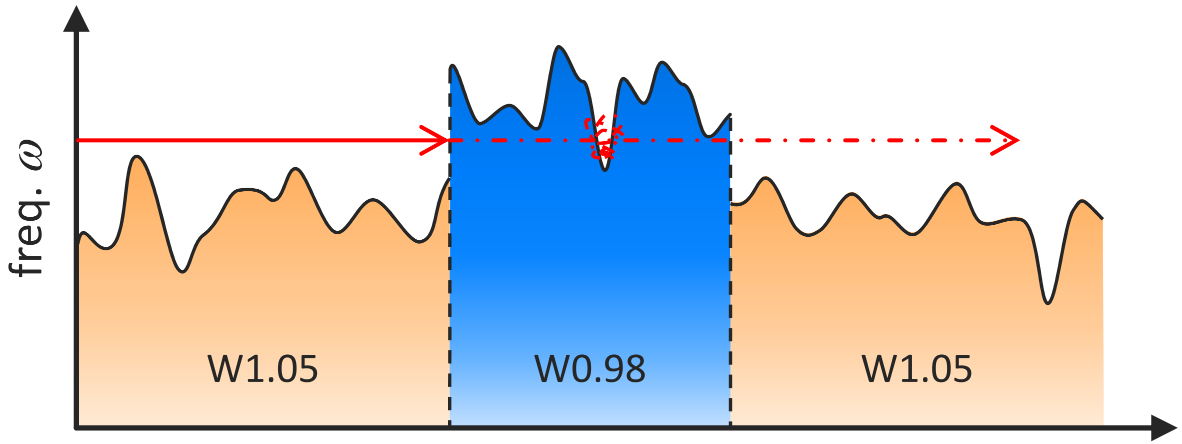


Waveguide width

W1.05 → wide

W0.98 → narrow

Cutoff frequency (mode gap)



Position of light localization

occurs only in W0.98

The effect of randomness occurs in a limited area (controlled way)

Theory & experimental result

Y. Ooka, *et al*. Opt. Express **24**, 11199 (2016).

Regime of randomness

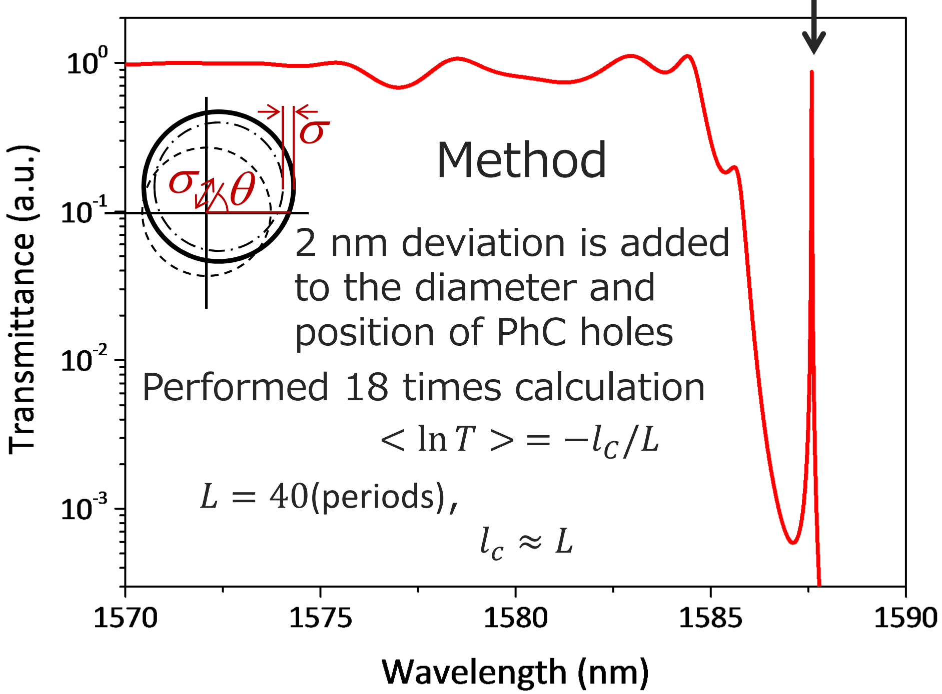
Dispersive $l_c \gg L$ | Diffusive $l_c \approx L$ | Localized $l_c \ll L$

localization starts — Strong localization

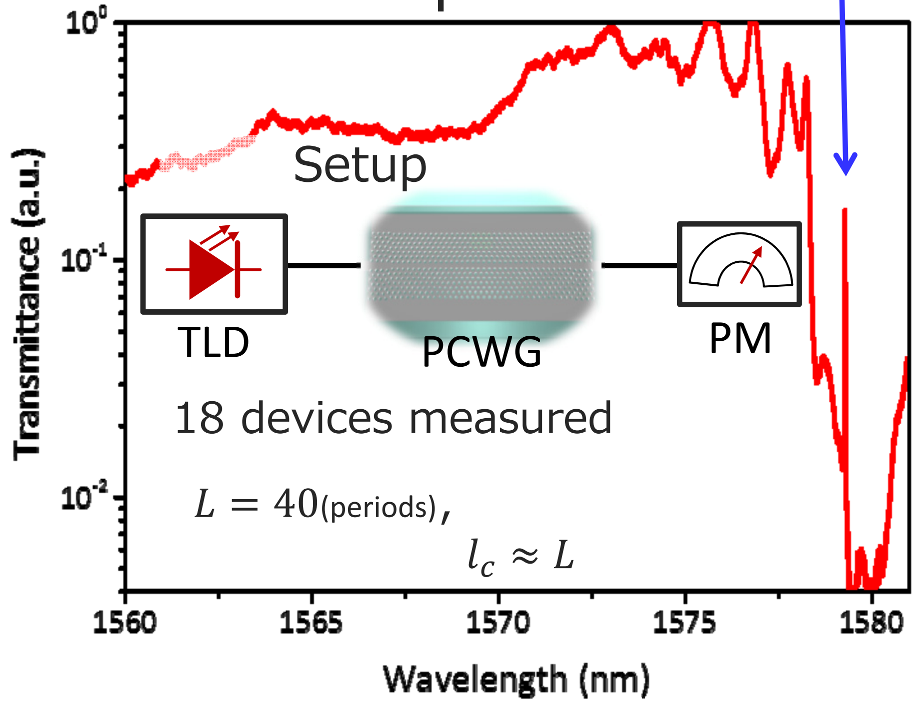
l_c : mean free length
L : Device length

$Q = 2.4 \times 10^5$

Calculation



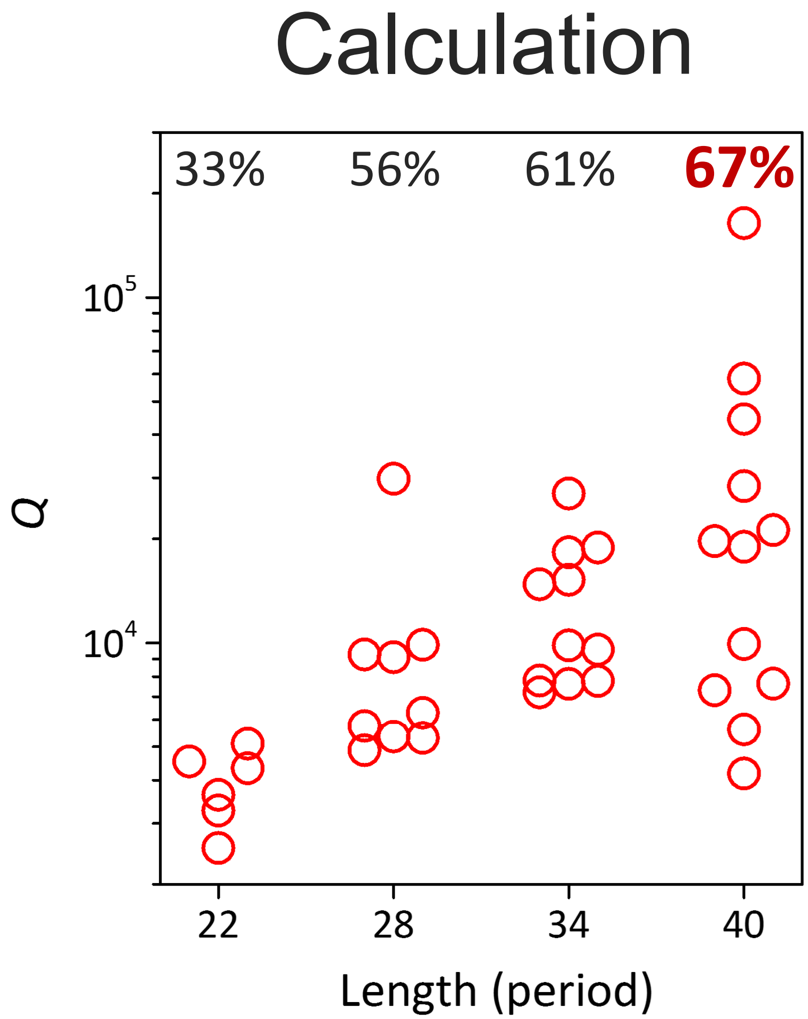
Experiment

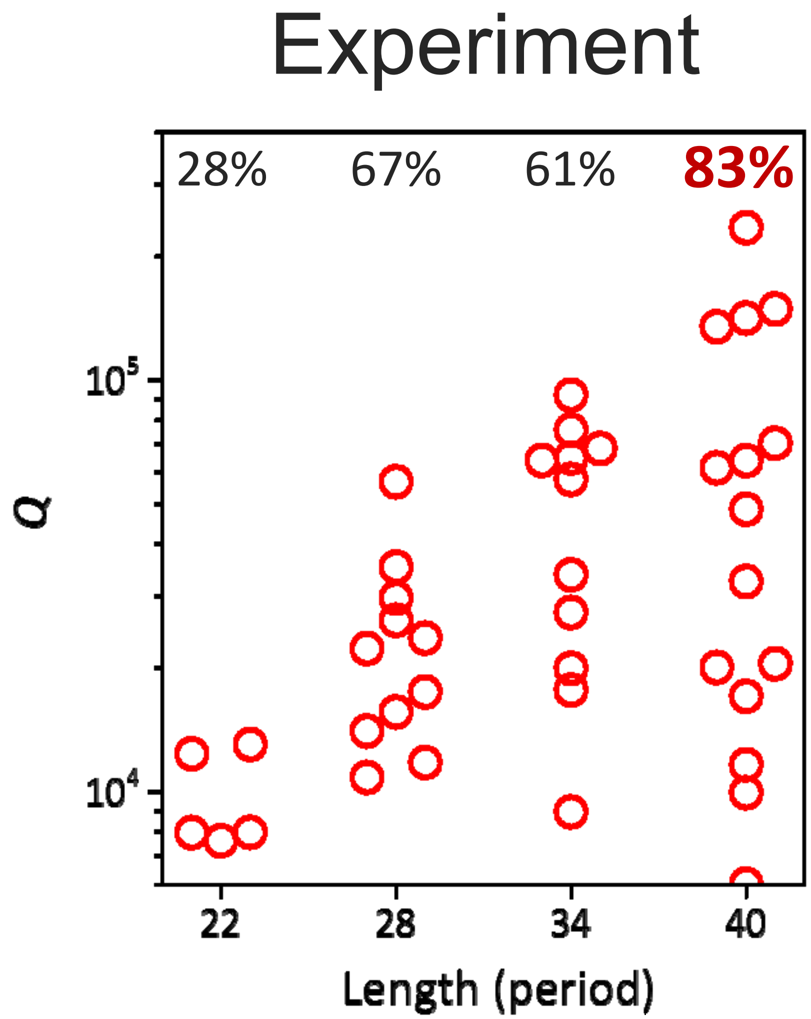


Localization observed at desired position

Yield rate of obtaining localization

Y. Ooka, *et al*. Opt. Express **24**, 11199 (2016).

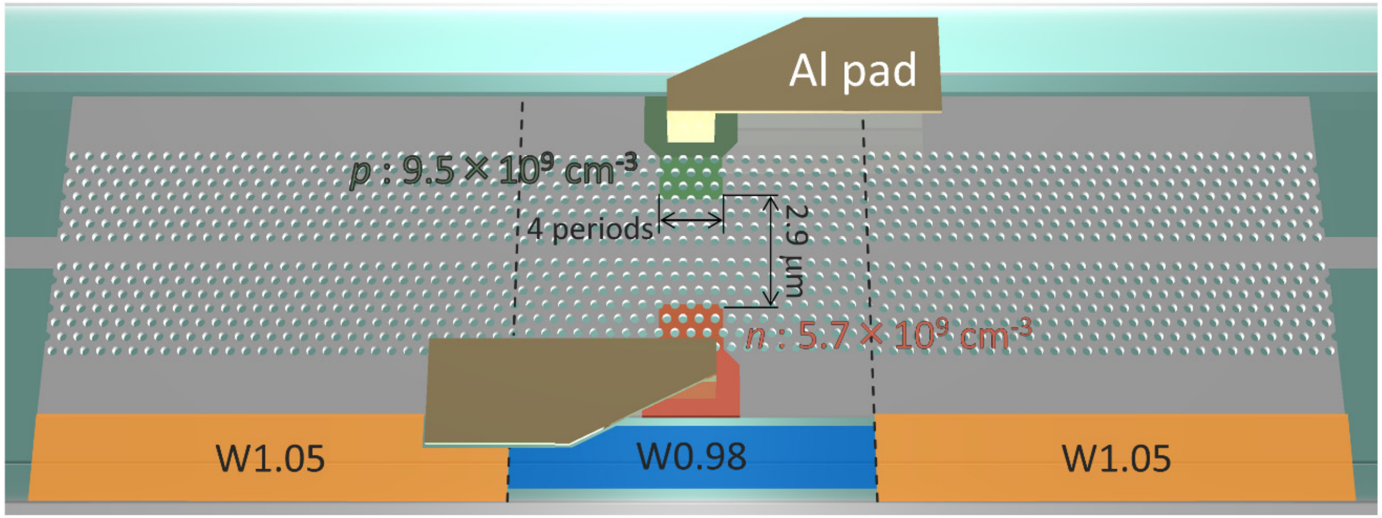


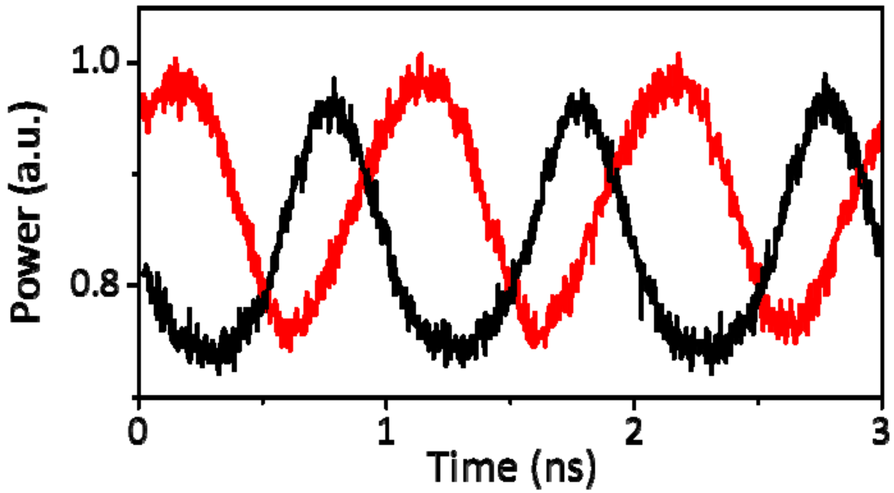


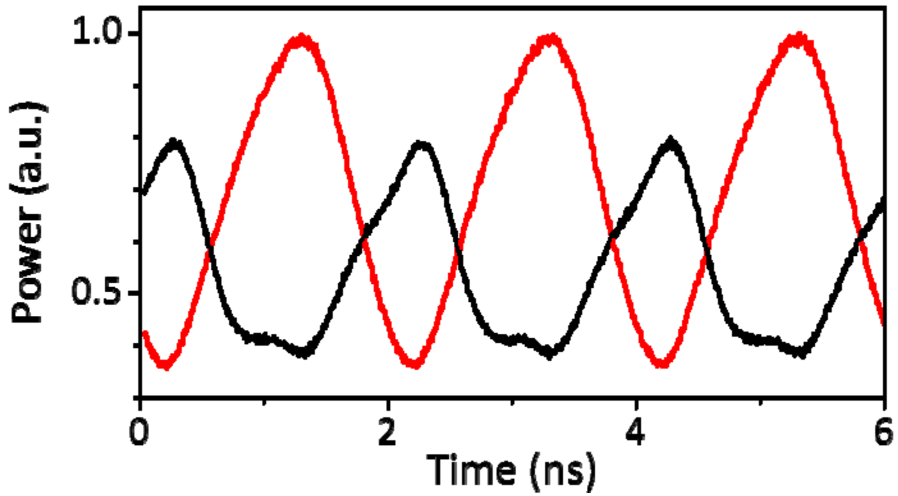
> 80% yield obtained

Using random PhC for controlled experiment

Y. Ooka, *et al*. Opt. Express **24**, 11199 (2016).







EO modulation achieved w/ pin structure integrated at W0.98 regime

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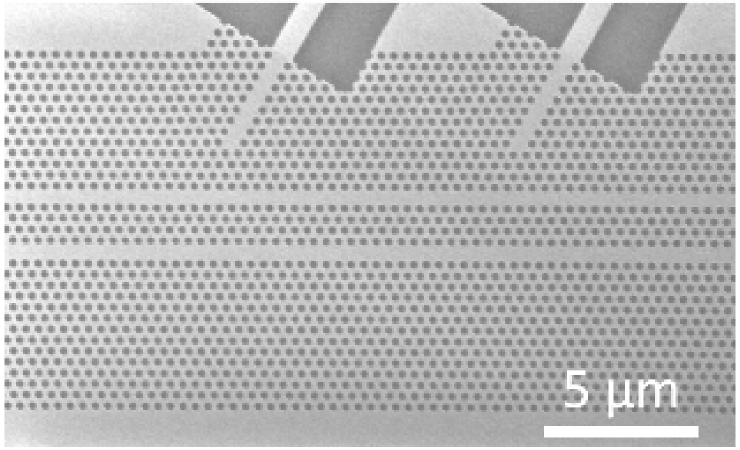
5. SiO_2 / Si hybrid system

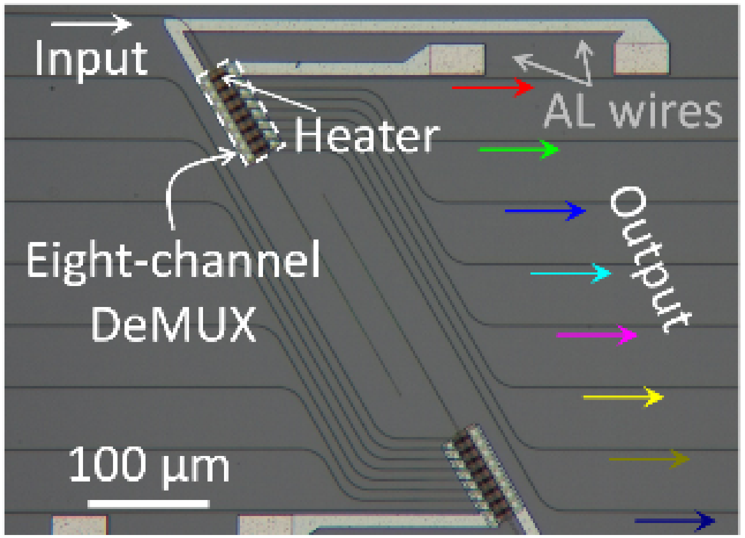
6. Summary

In-plane 8ch DWDM demonstration

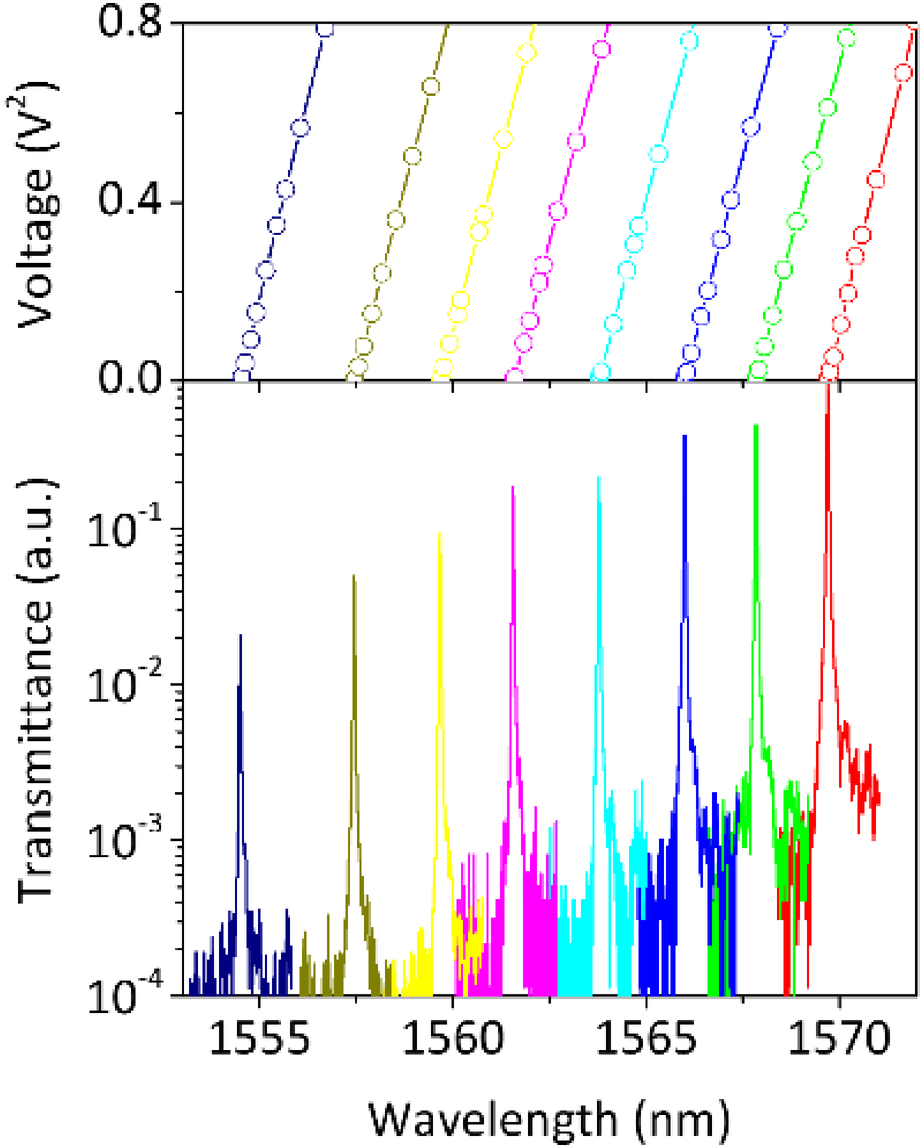
(a)



(c)

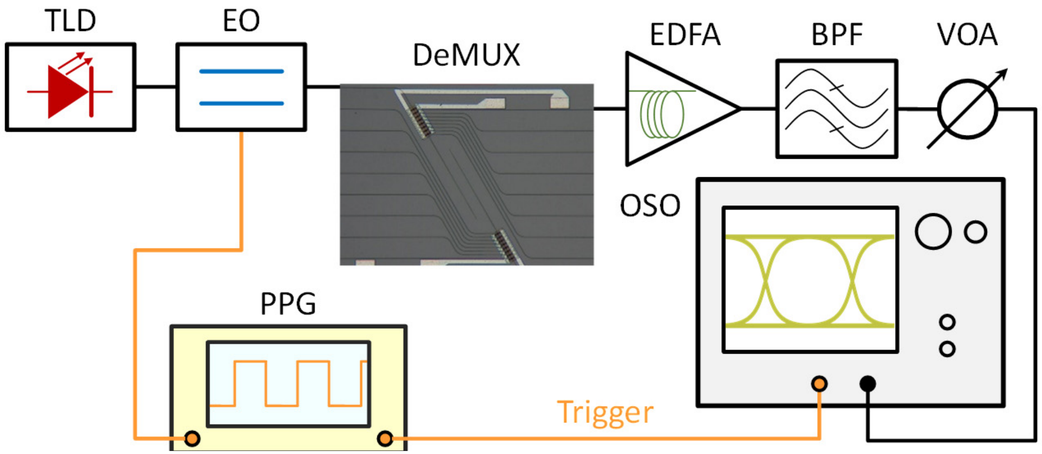


(b)

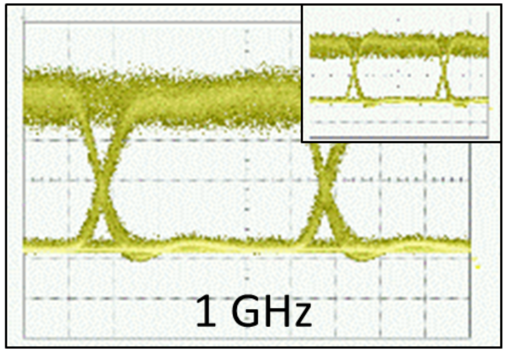


In-plane 8ch DWDM demonstration

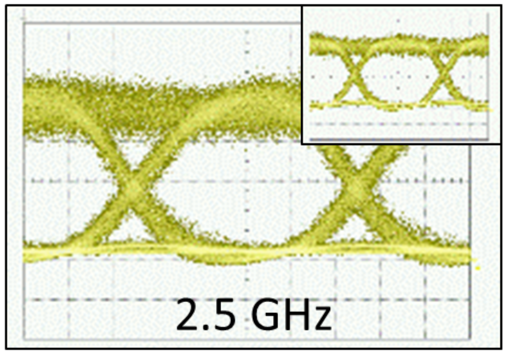
Setup

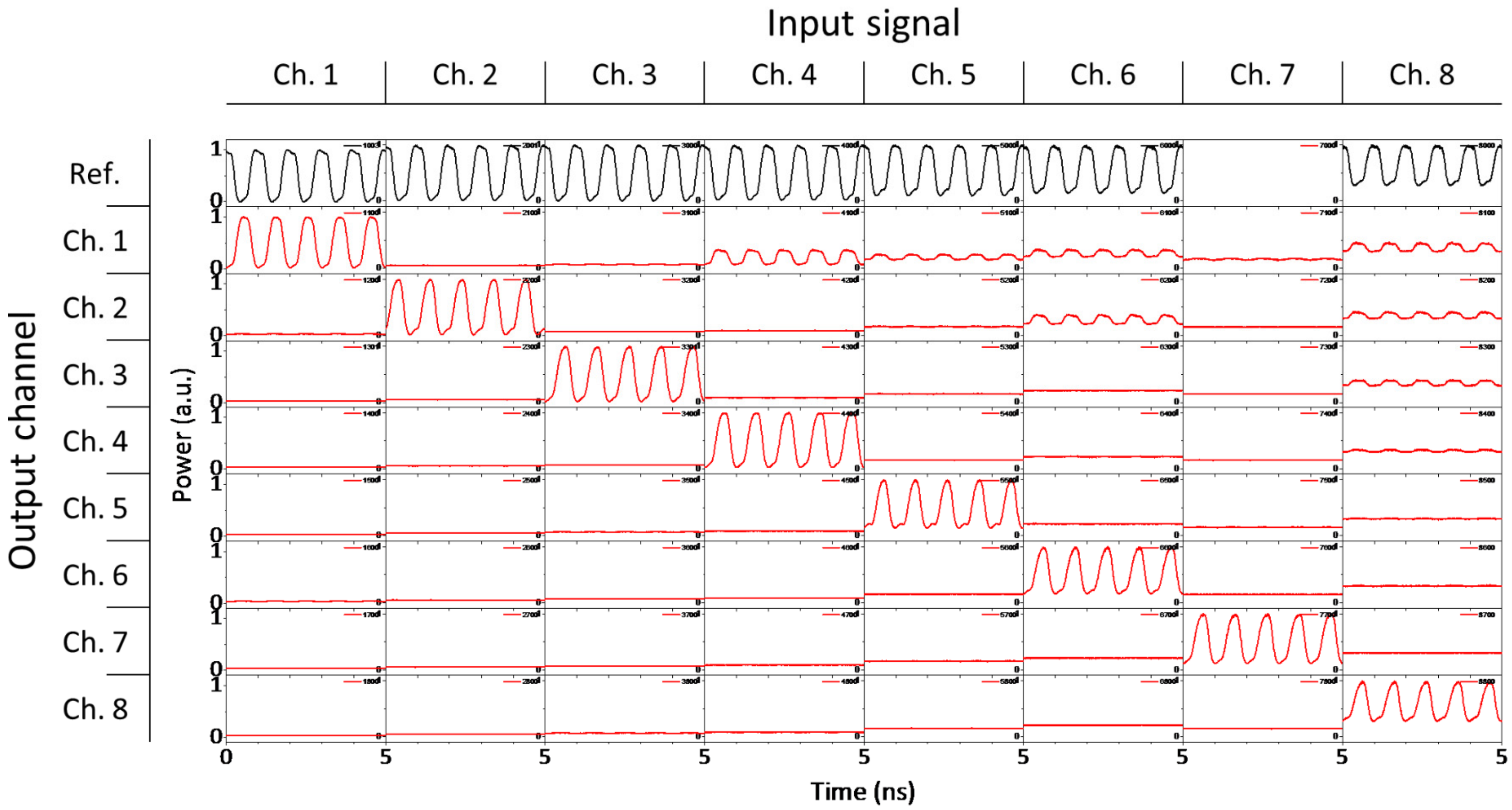


Eye pattern



(c)





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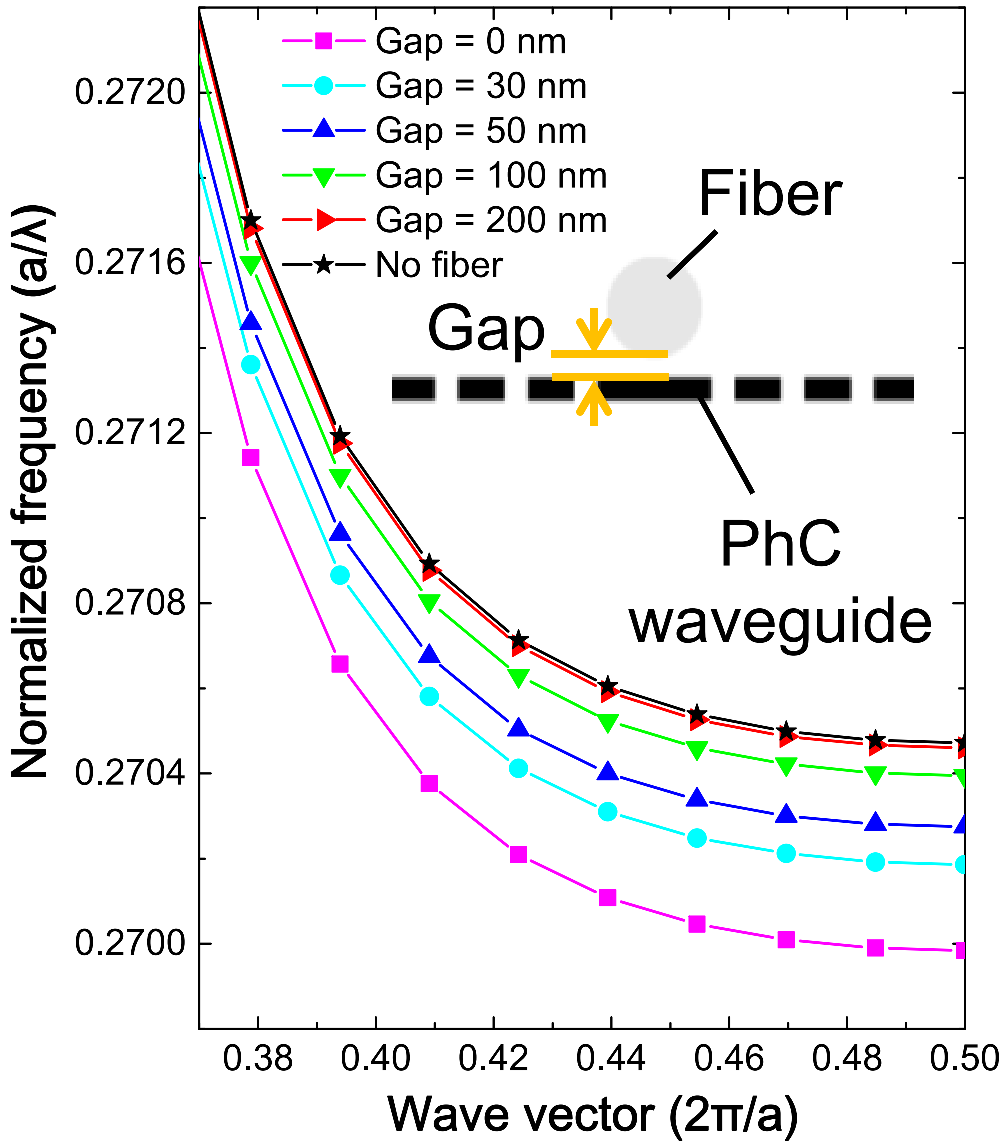
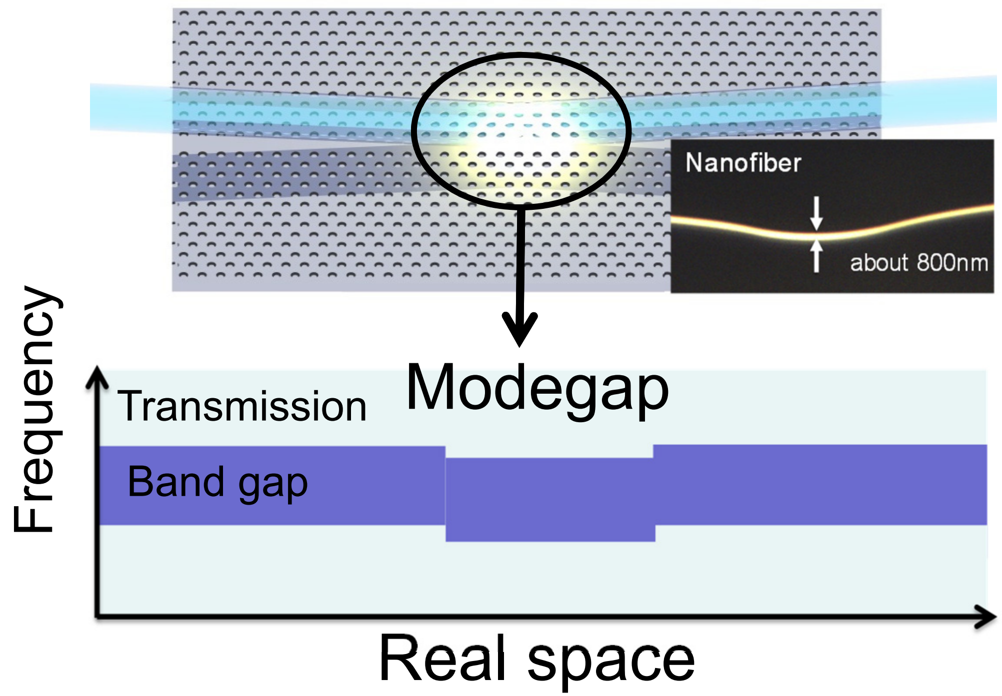
6. Summary

Principle of cavity formation

T. Tetsumoto, *et al*., Opt. Express **23**, 16256 (2015).



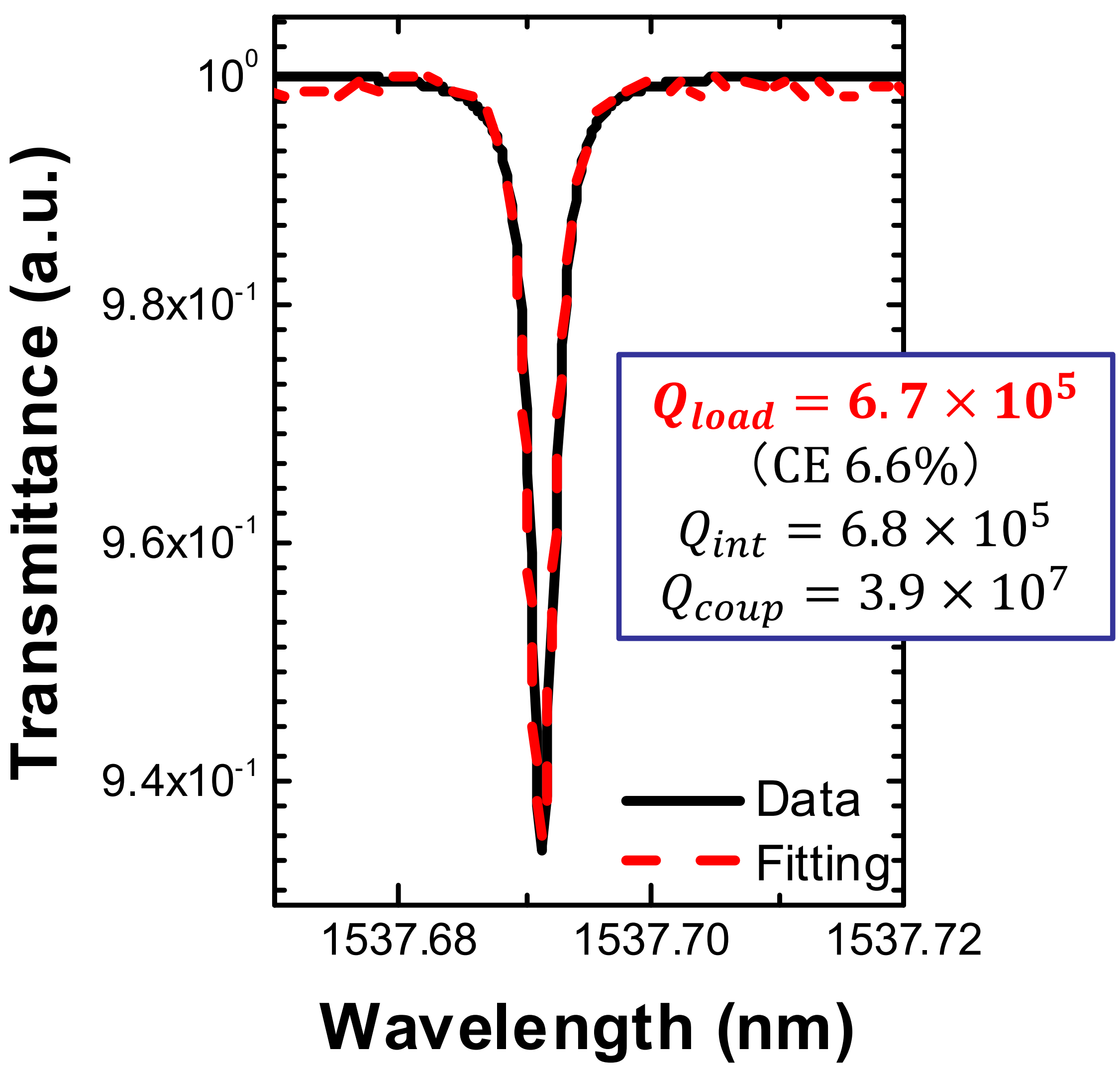


Effective refractive index change results in formation of modegap cavity

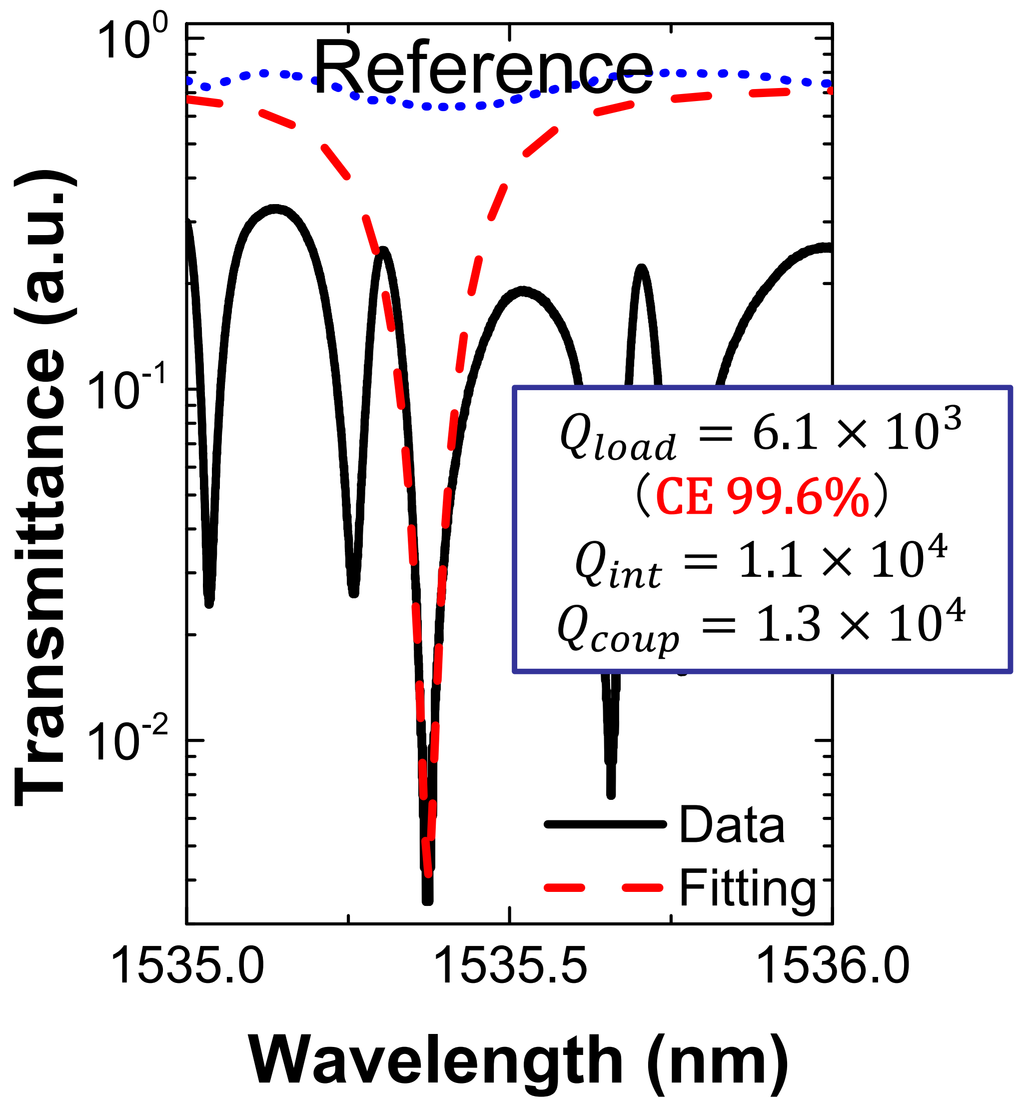
Measurement of *Q* and CE of FCPC

T. Tetsumoto, *et al.*, Opt. Express **23**, 16256 (2015).

Maximization of *Q*

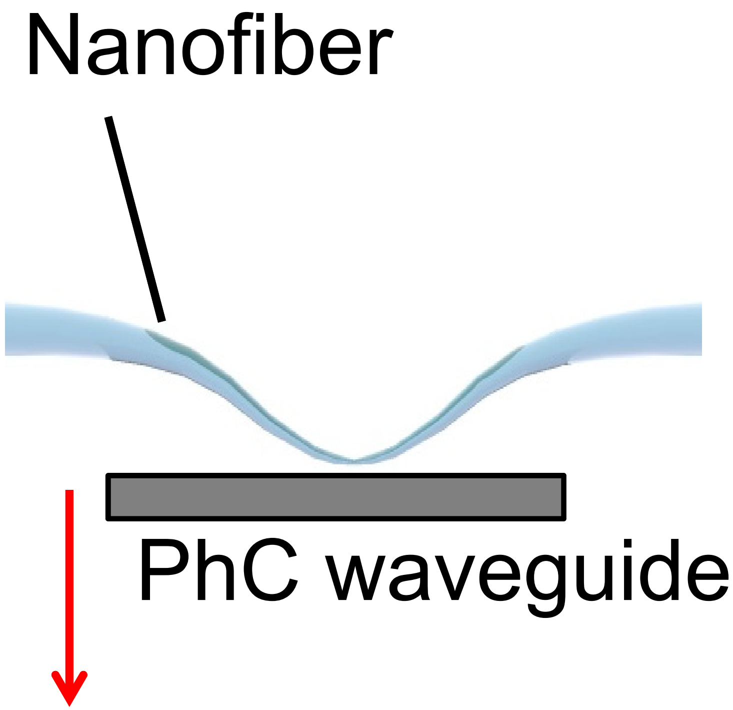


Maximization of CE

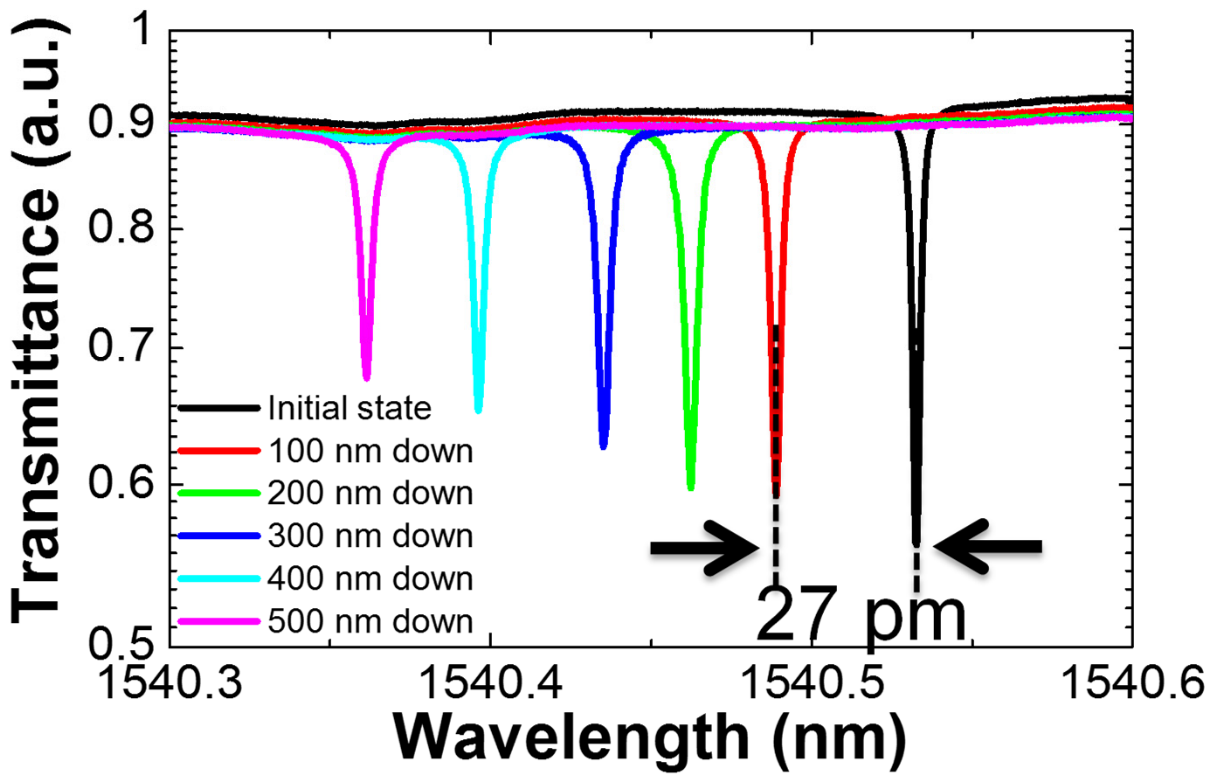


Resonant wavelength tuning

T. Tetsumoto, *et al*., Opt. Express **23**, 16256 (2015).



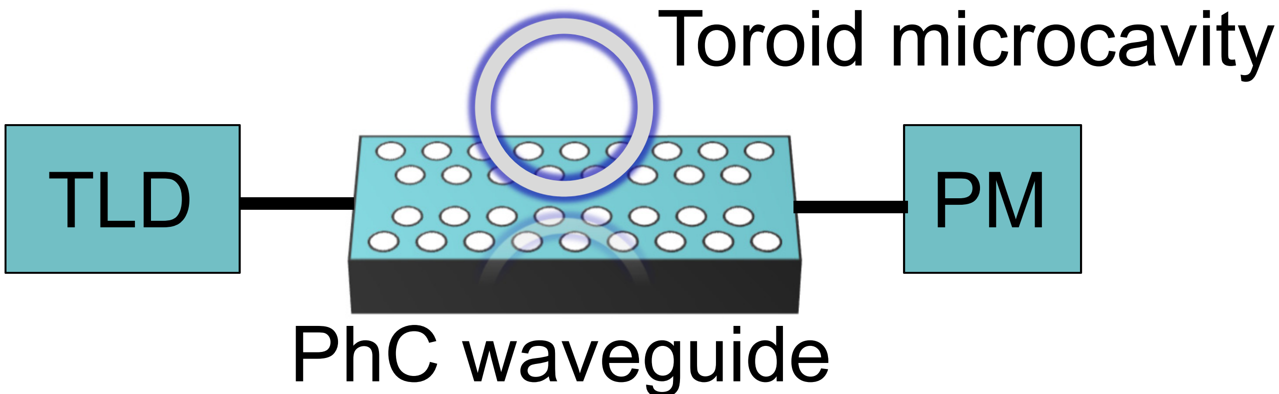
Change the position at 100-nm step



Tuning sensitivity

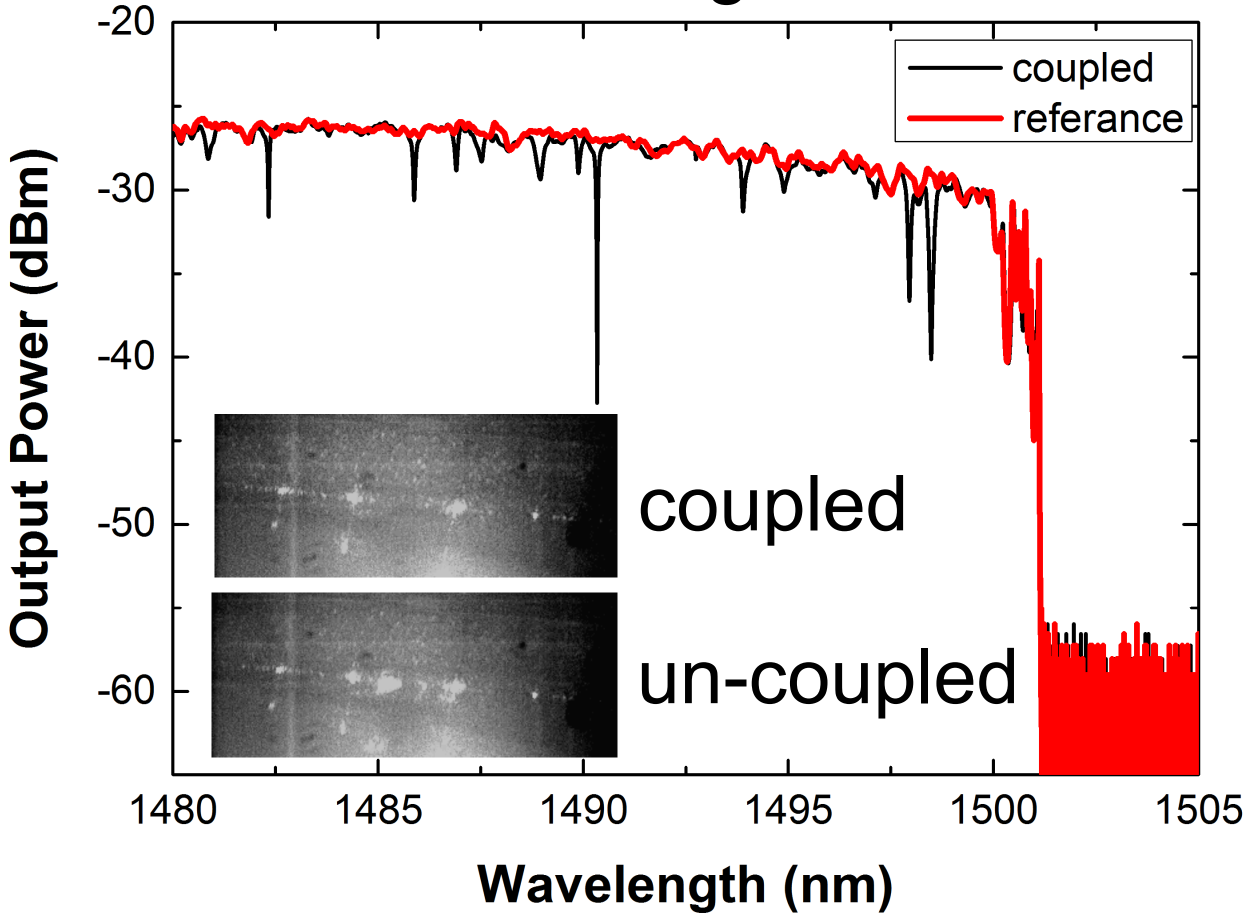
$$\frac{\text{Wavelength shift}}{\text{Stage shift}} = 0.27\ \text{pm/nm}$$

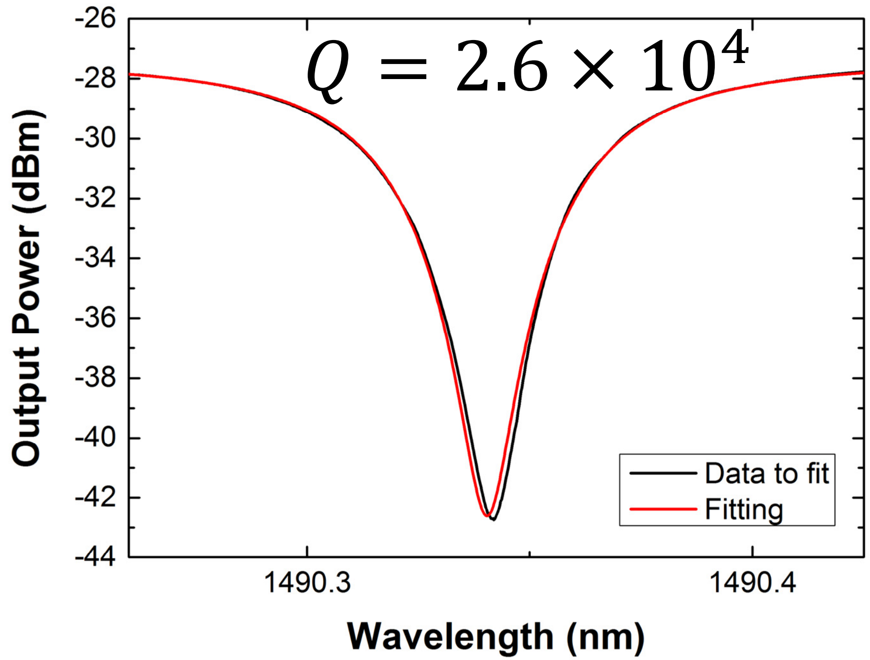
Coupling of SiO_2 WGM microcavity w/ PhC WG (preliminary)



PhC waveguide

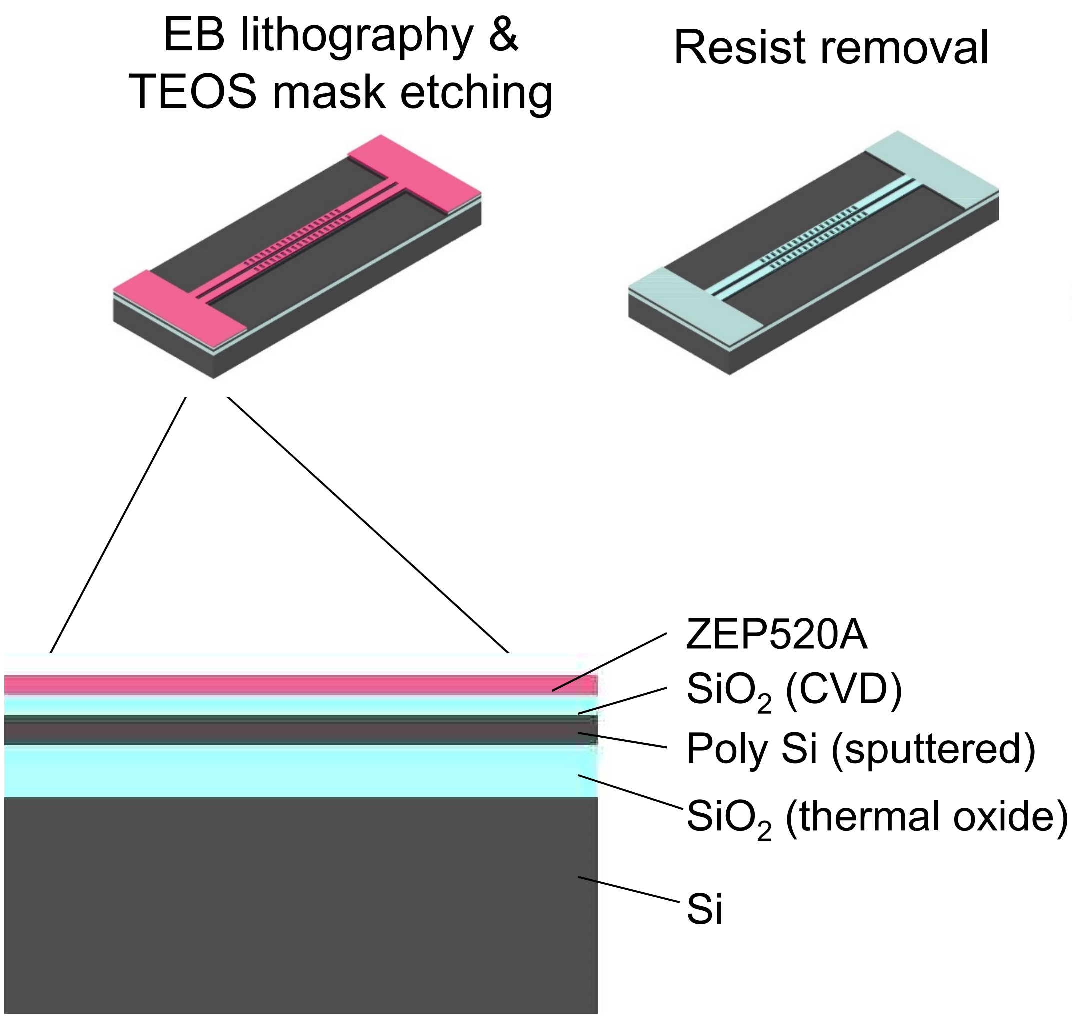
a = 410 nm, diameter: 225.5 nm,
Thickness: 210 nm, W1 waveguide

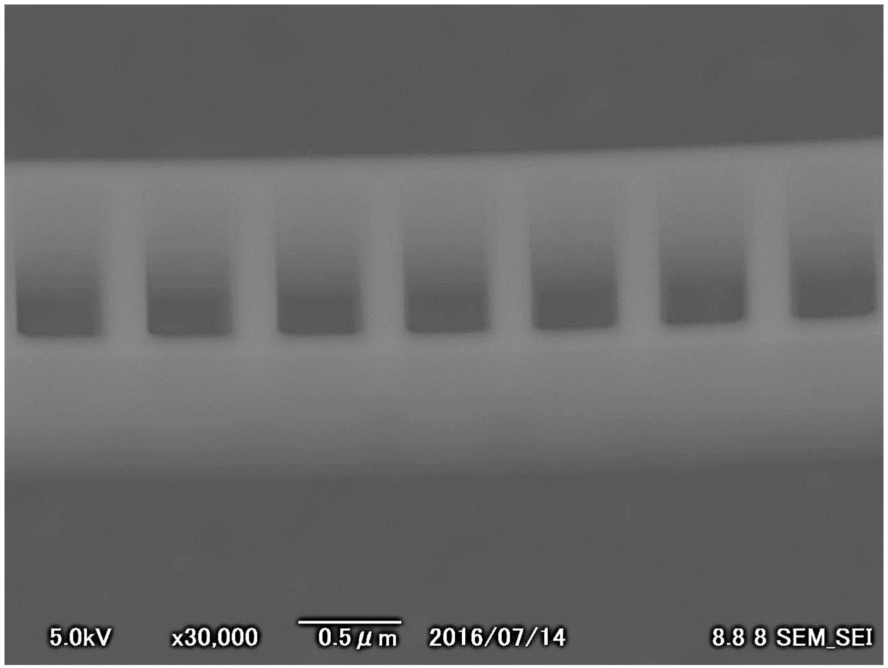




light localization at PhC WG
enabled w/ toroid microcavity

High-Q 1D photonic crystal microcavity with SiO_2



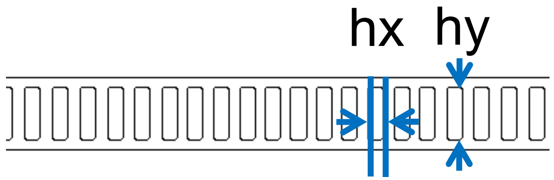


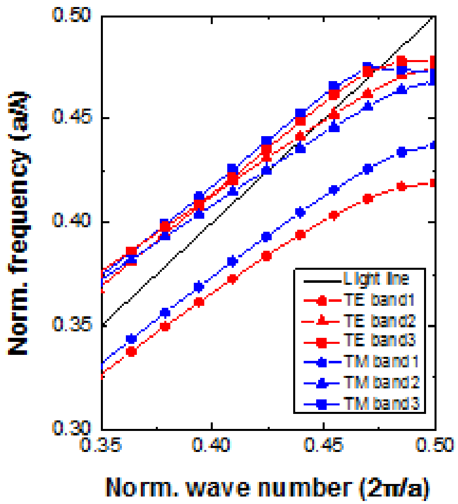
High-Q 1D photonic crystal microcavity with SiO_2

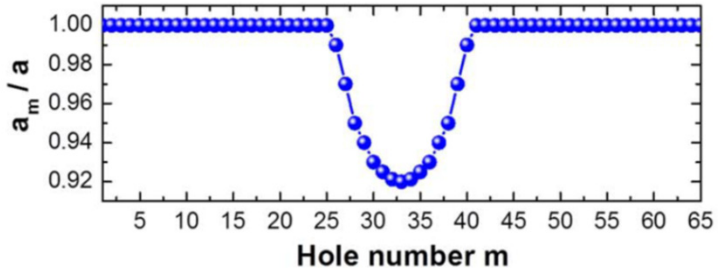
T. Tetsumoto and T. Tanabe, AIP Adv. **4**, 077137 (2014).

▶Design

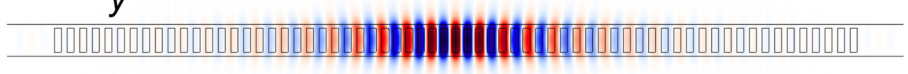
Lattice constant: a = 690 nm
Width: w = 2.6a
Hole depth : hx = 0.5a
Hole width : hy = 0.7w
Thickness: t = 1.1a





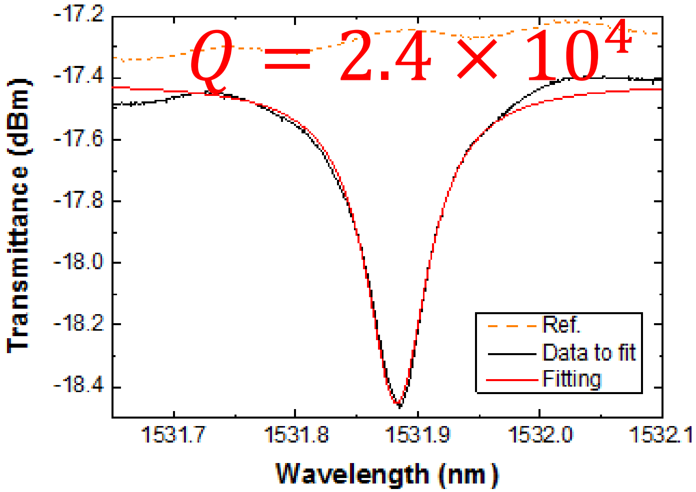


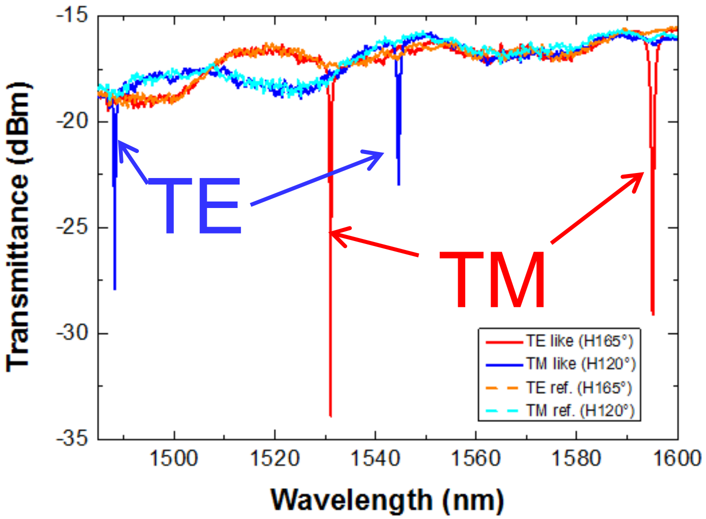
TM1 H_y

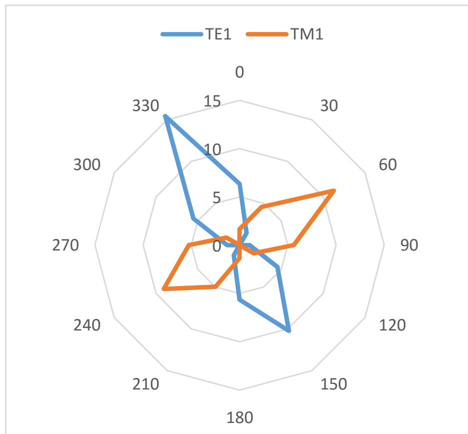


$Q = 1.7 \times 10^4$
$V = 3.7(\lambda/n)^3$

▶Optical measurement result





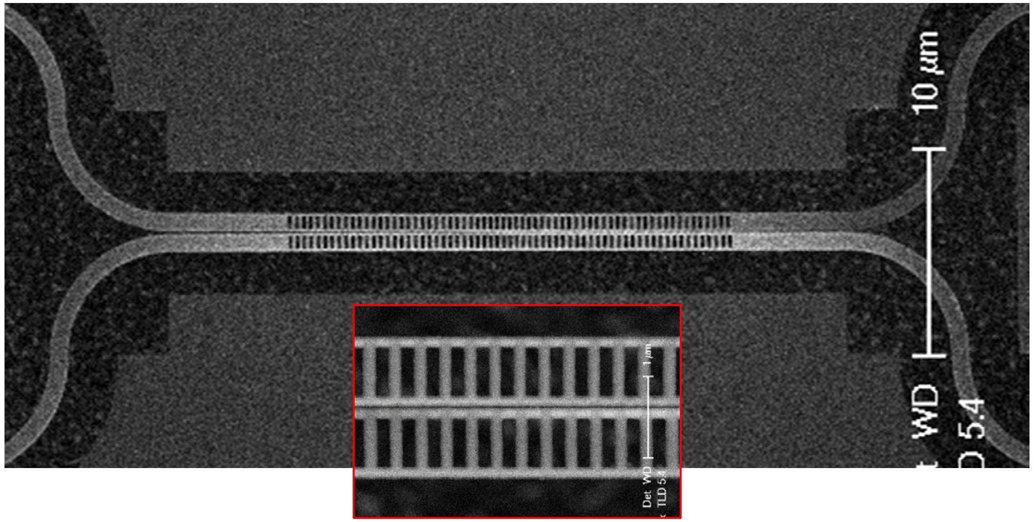


⇨ Highest Q PhC microcavity w/ low-n material

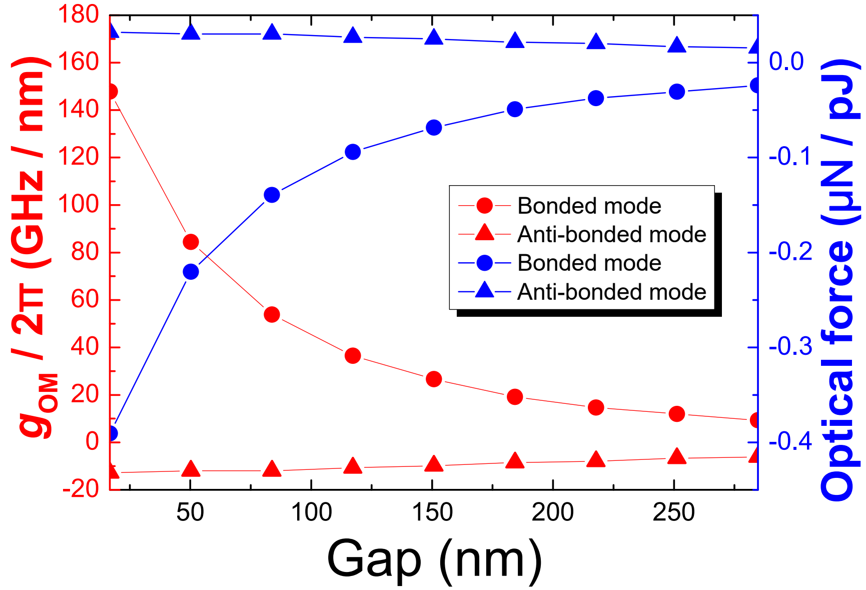
Silica zipper cavity for MOMS switch

T. Tetsumoto and T. Tanabe, AIP Adv. **4**, 077137 (2014).

▶Fabricated zipper

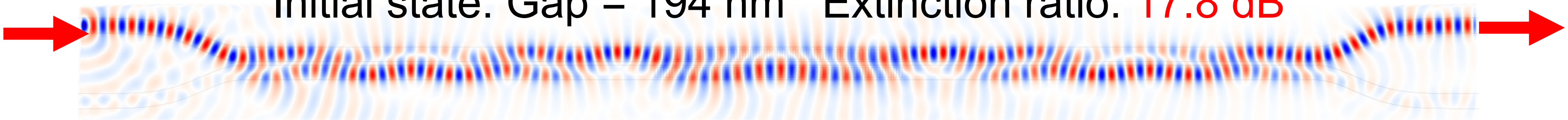


▶Opto-mechanical coupling

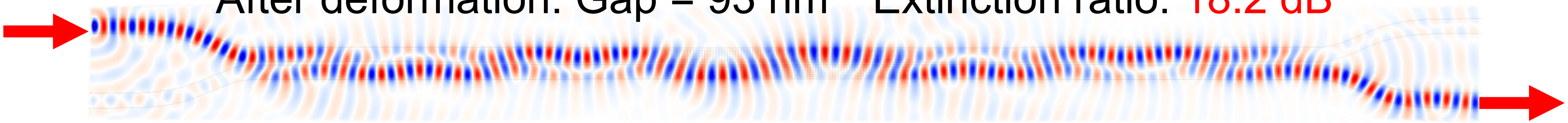


▶Switching demonstration (calc.)

Initial state: Gap = 194 nm Extinction ratio: 17.8 dB



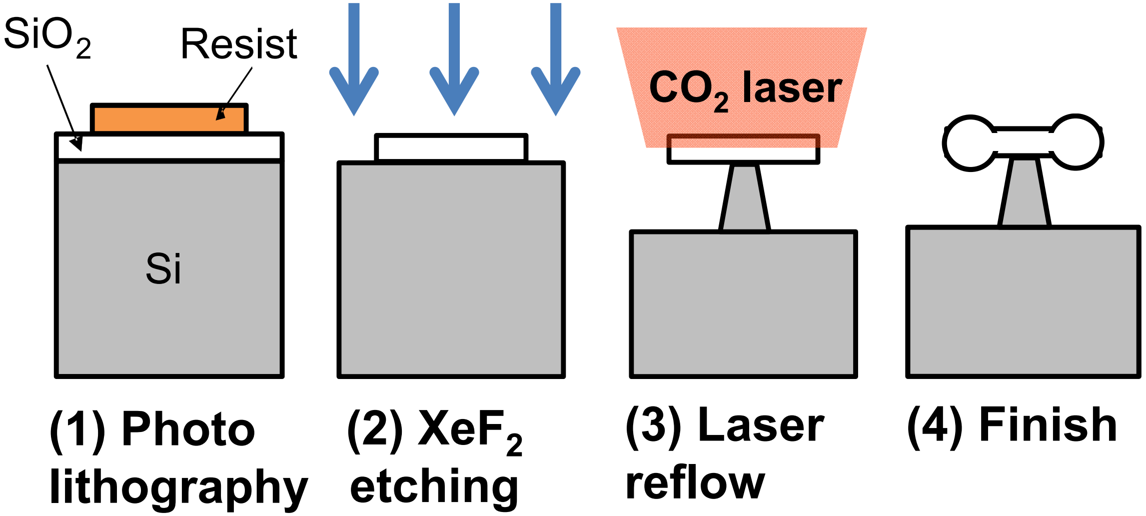
After deformation: Gap = 93 nm Extinction ratio: 18.2 dB



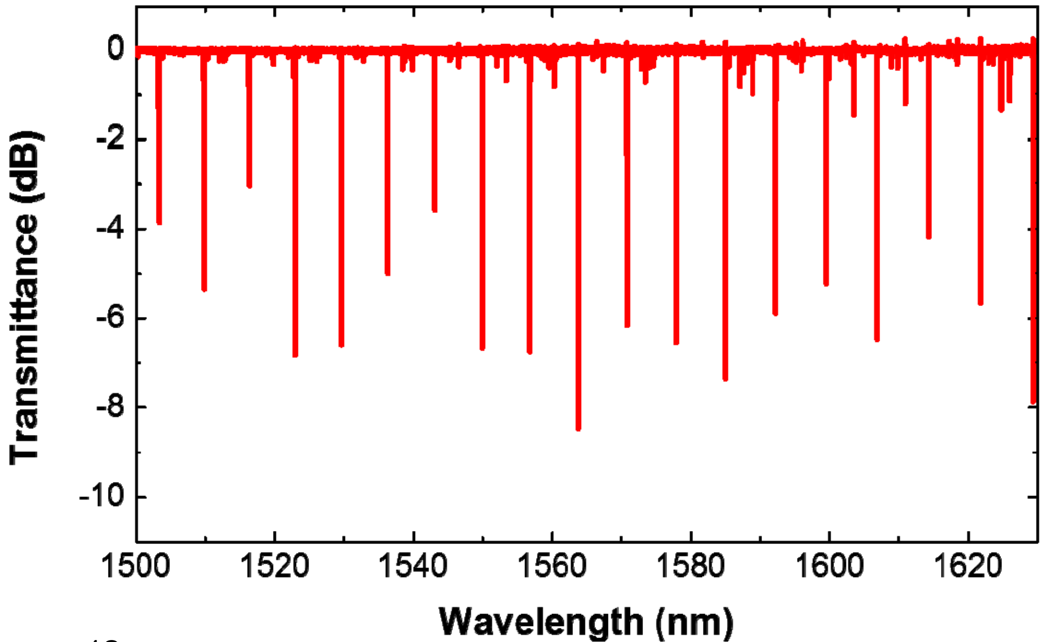
High switching contrast of ≥ 17.8 dB w/ ~100-nm deformation @ 190 mW achieved (calculation)

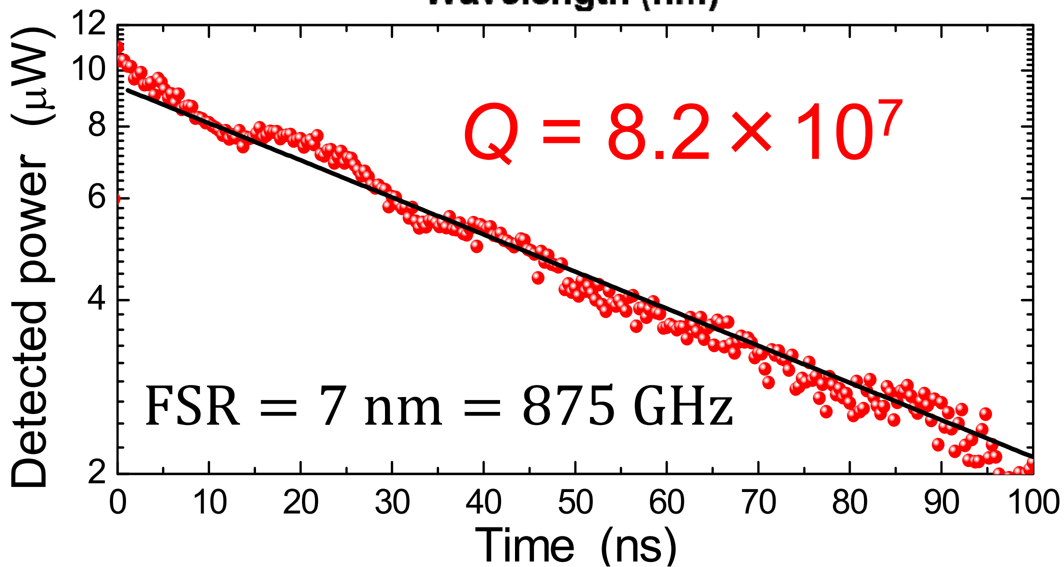
Ultra-high *Q* toroidal microcavity

▶Fabrication

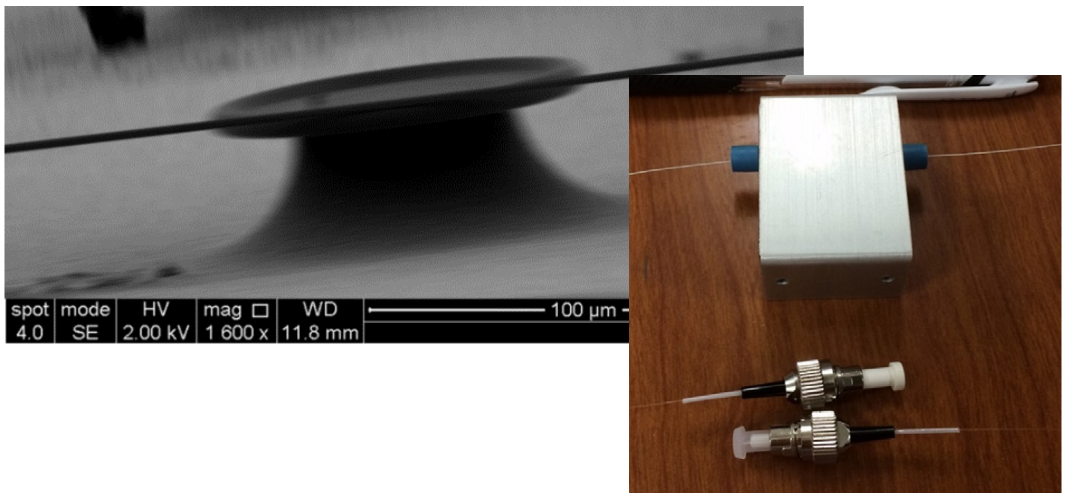


▶Spectrum & photon lifetime



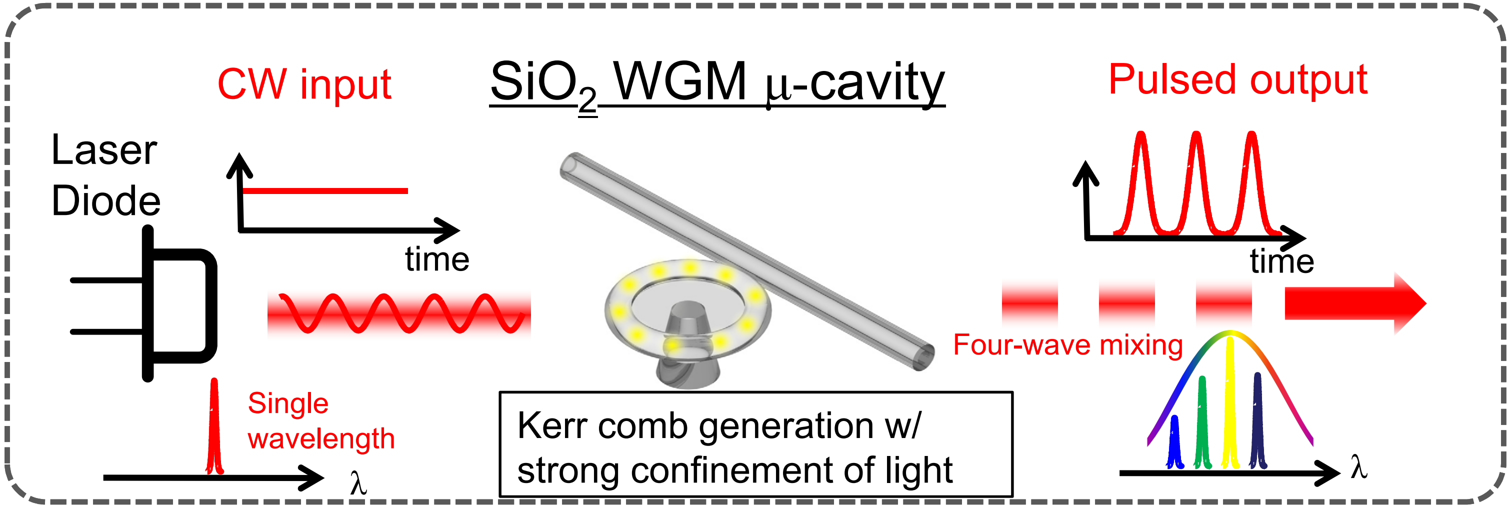


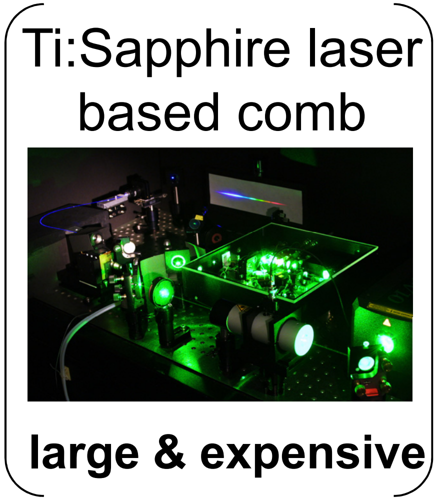
▶Packaging

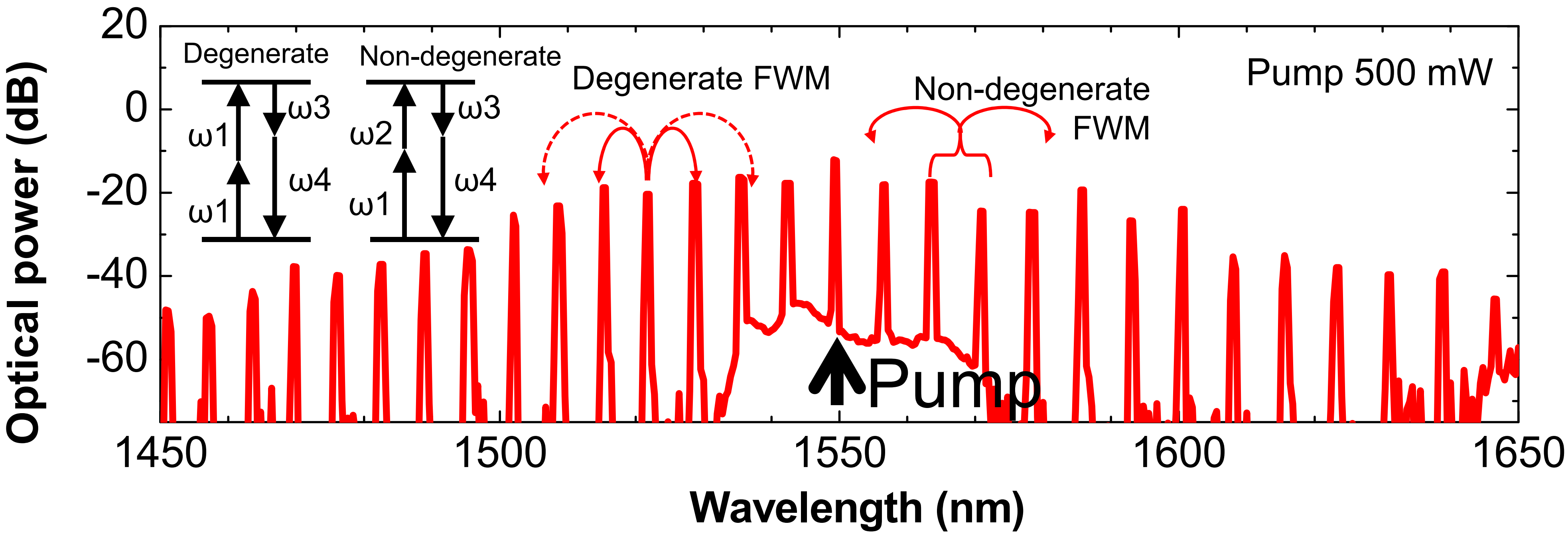


Kerr comb in microcavity system

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



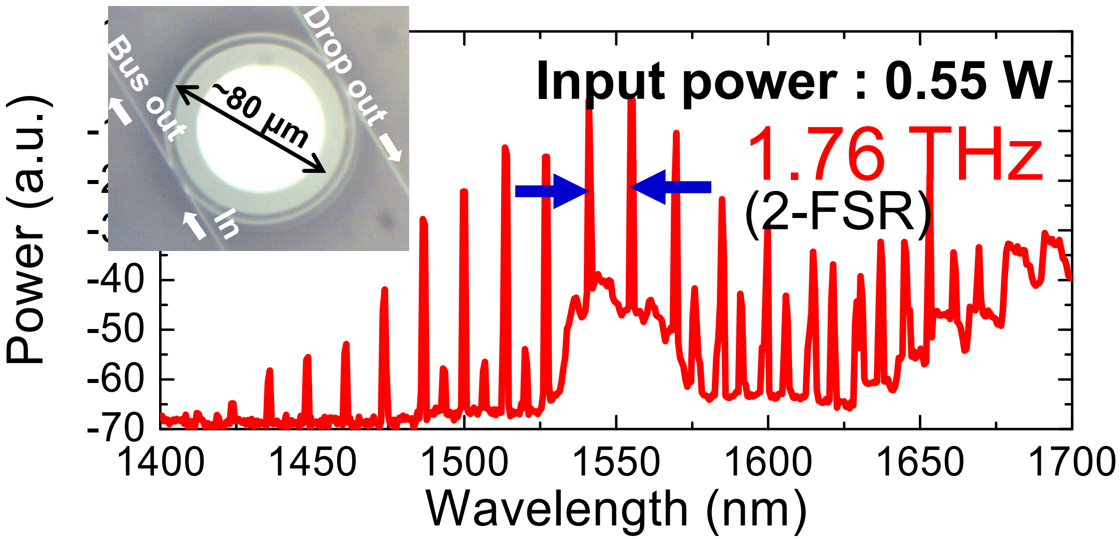


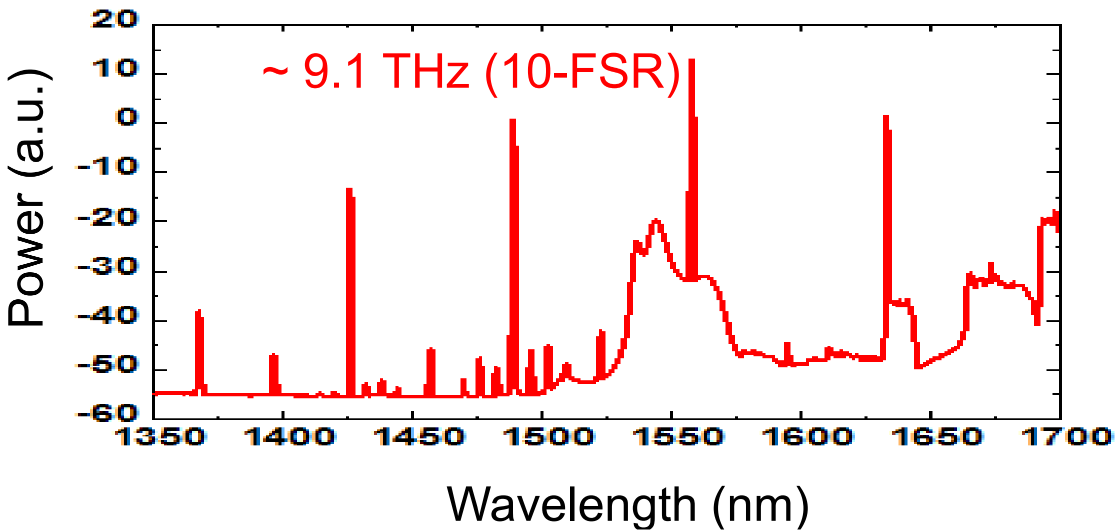


Ultrahigh repetition rate pulse generation

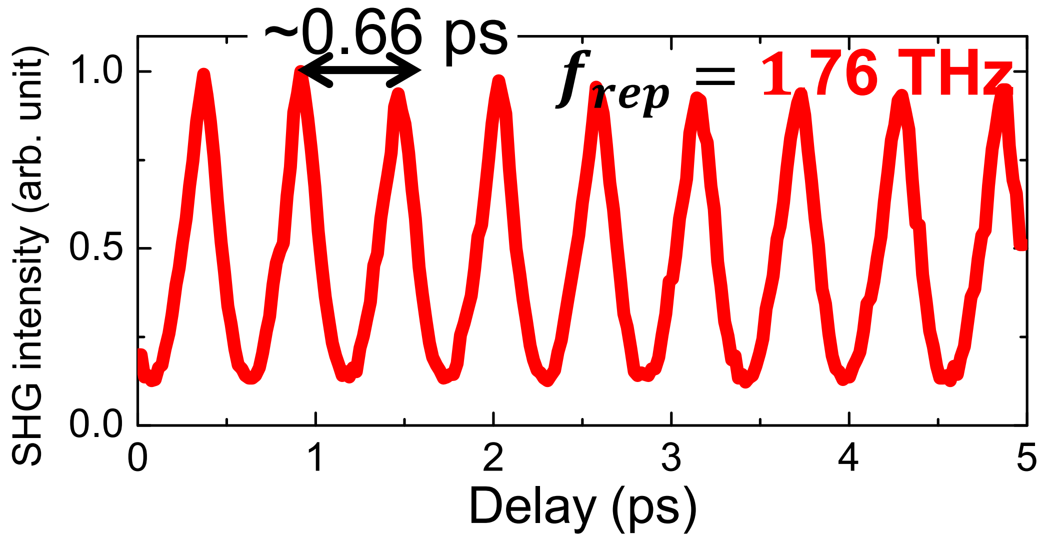
T. Kato, *et al*. Jpn. J. Appl. Phys. **55**, 072201 (2016). (editor's pick)

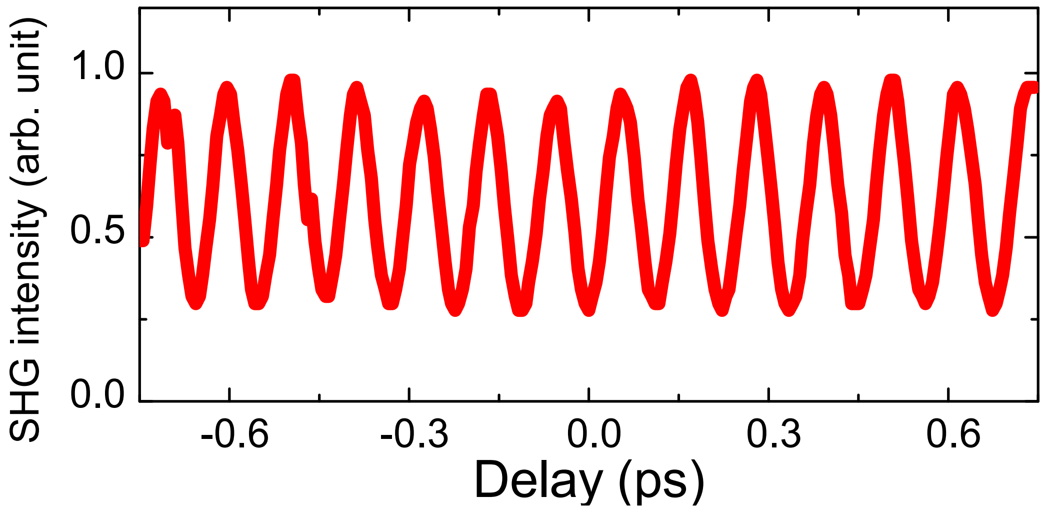
▶Kerr comb generation





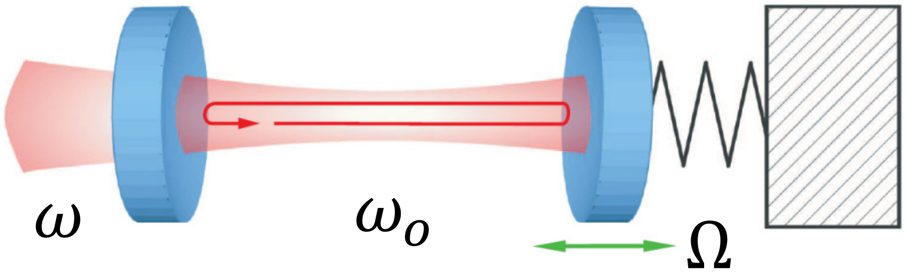
▶SHG autocorrelation trace



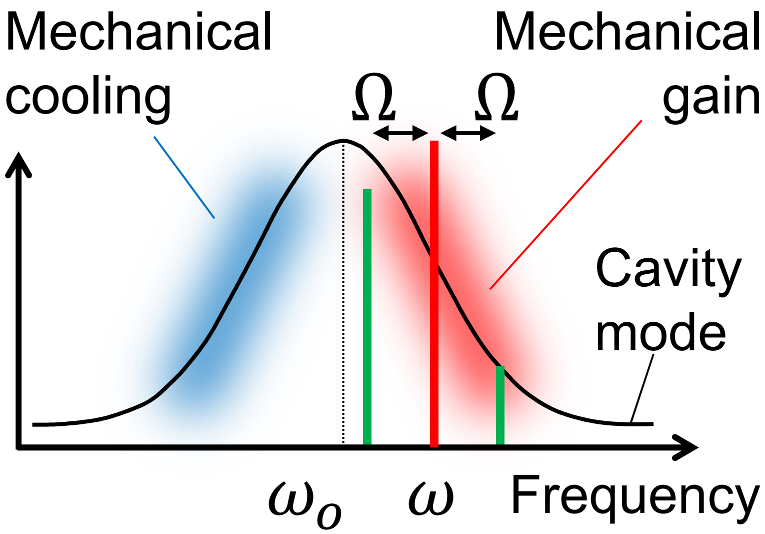


RF noise measurement (effect of cavity opto-mechanics)

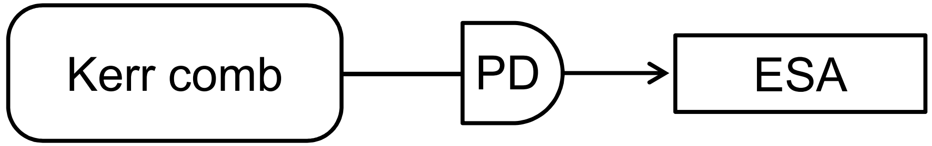
▶Cavity opto-mechanics

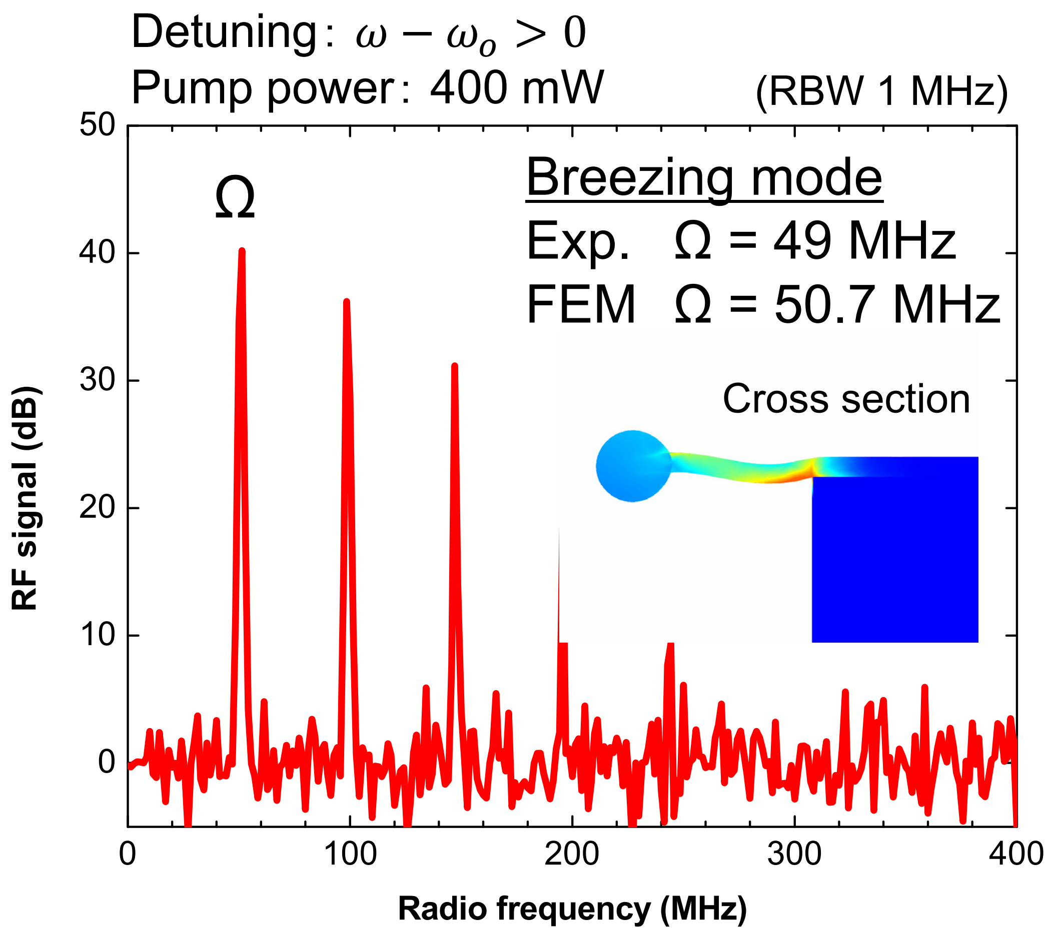


T. Kippenberg & K. Vahala, Opt. Express **15**, 17172 (2007).



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

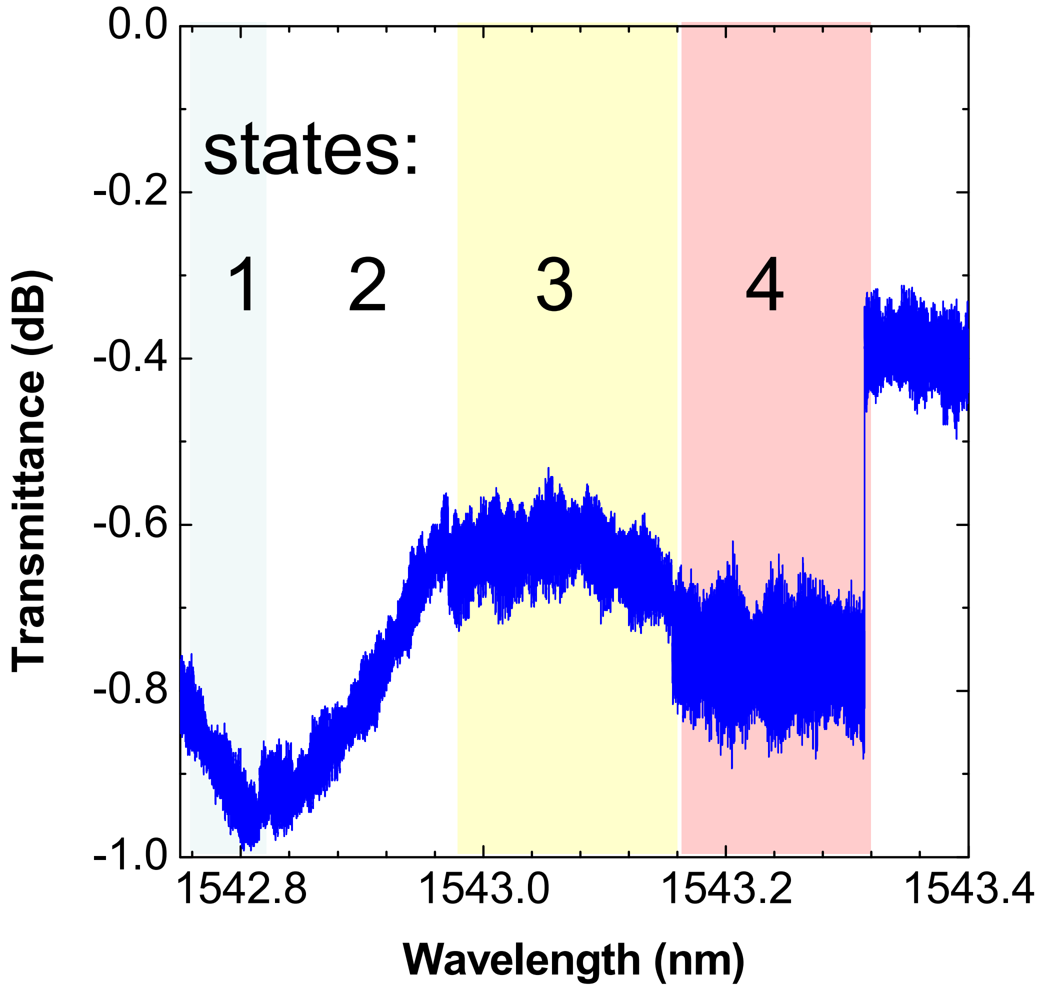


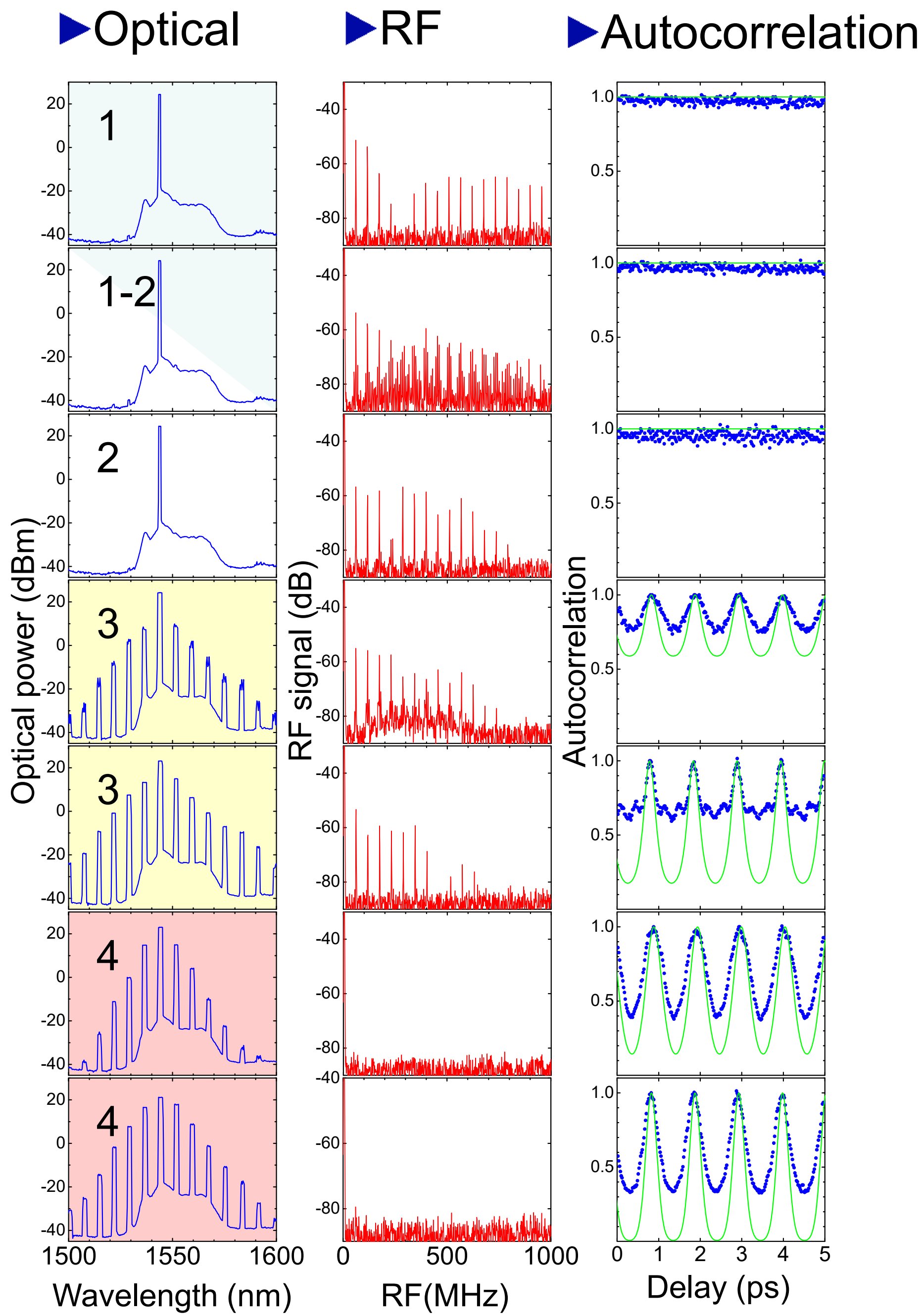


Detuning: $\omega - \omega_o \approx 0, \text{or} < 0$
→ Can we reduce mechanical oscillation?

Wavelength scan with toroid microcavity

▶Transmittance spectrum

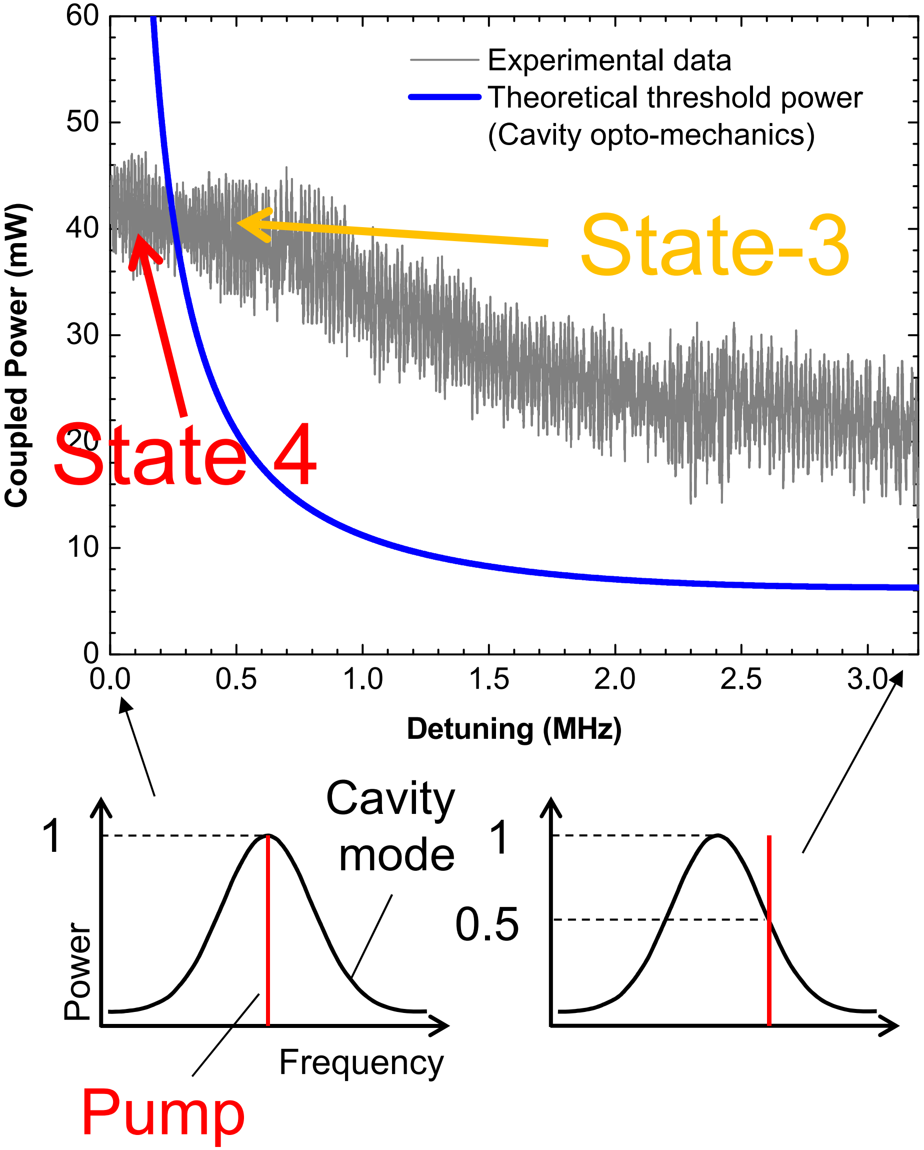




Different states appear
(opto-mechanics?)

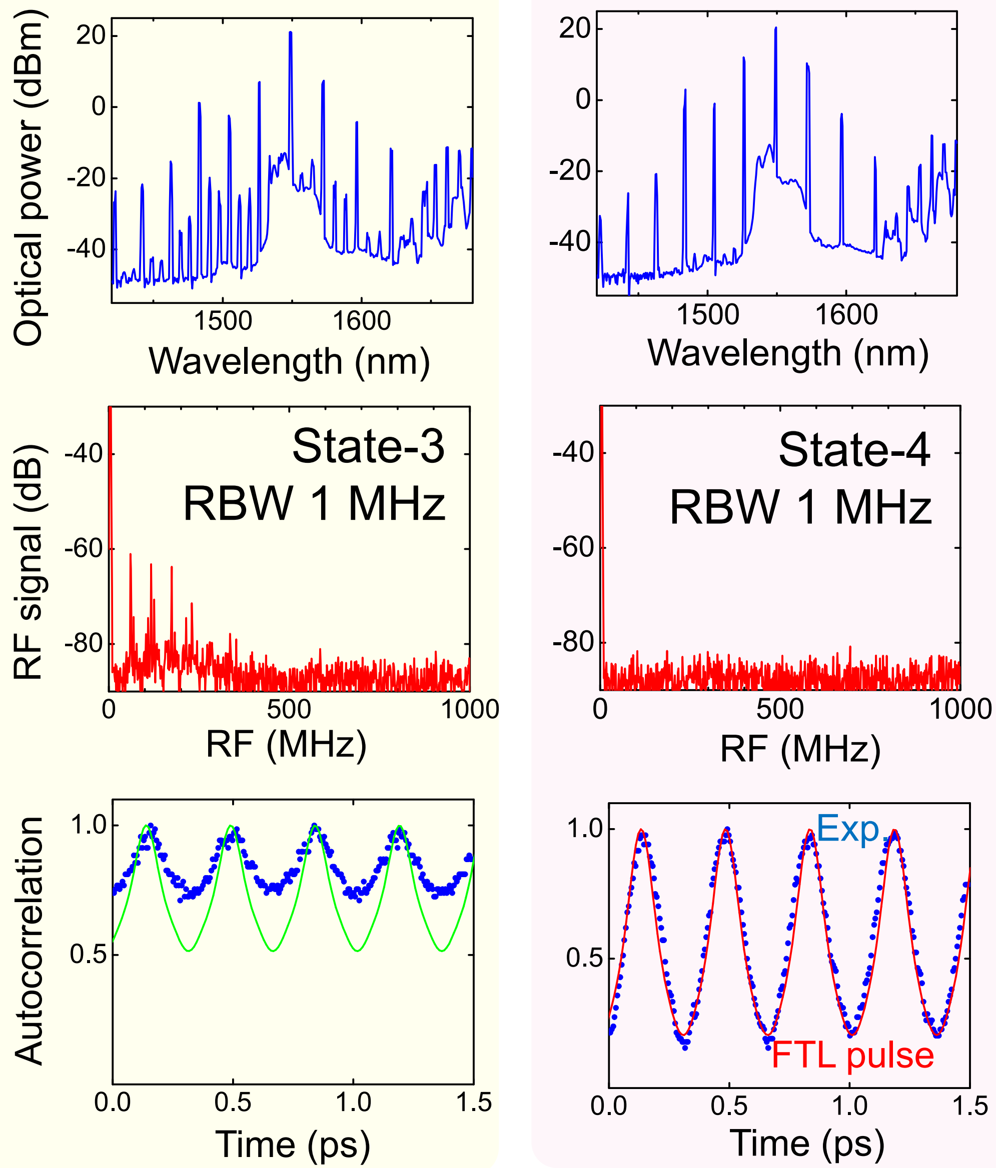
Cavity opto-mechanics & mode-locking

▶Detuning vs. Threshold power



▶State-3 (OM)

▶State-4 (no OM)



Summary

Silicon technologies

1. Ultrahigh Q nanocavity w/ photolithographic Si PhC
2. Electro-optic modulator w/ controlled random PhC
3. 8-ch in-plane DWDM demux demonstration

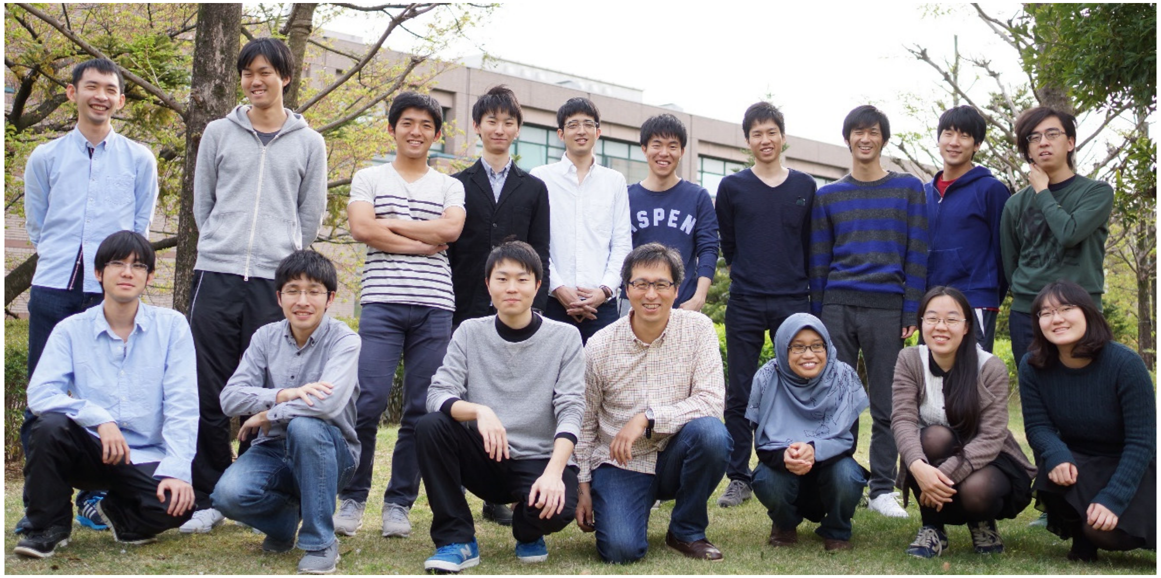
SiO_2 ultrahigh *Q* microcavity technologies

4. Tapered fiber assisted resonance
5. Kerr comb generation in silica WGM microcavity

toward SiO_2 / Si hybrid system

Acknowledgement

▶ The team



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