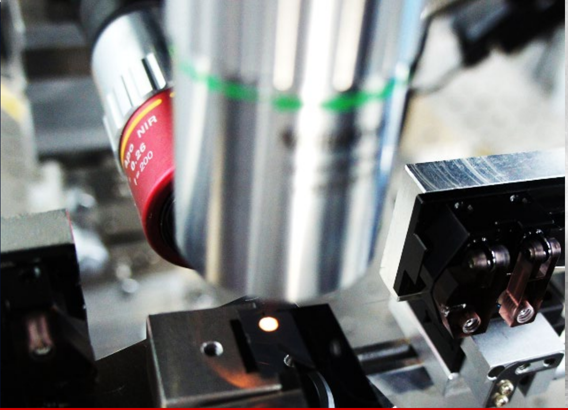
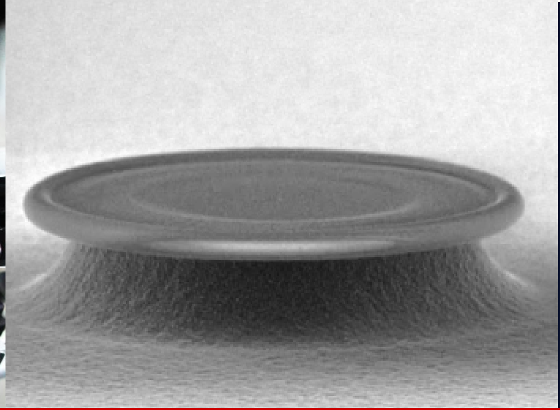
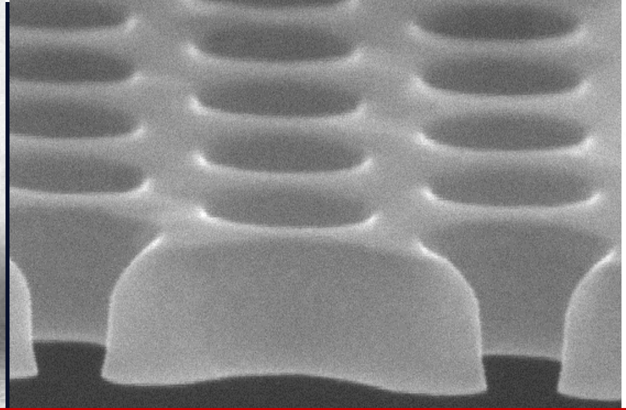
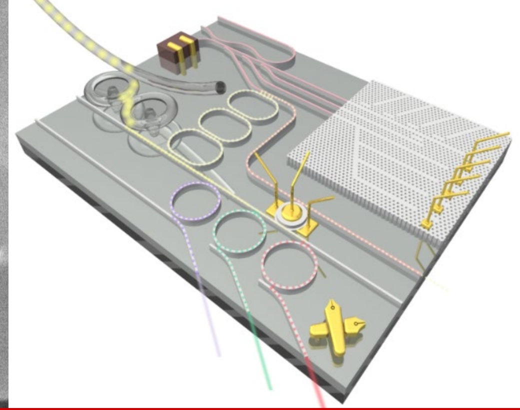





3. June, 2019 14:00-14:45

Optical Nanofiber Applications (ONNA 2019)

# Efficient coupling of whispering-gallery-mode silica toroid microcavity to planer silicon platform

Takasumi Tanabe

Electronics and Electrical Engineering, Keio University, Japan

takasumi@elec.keio.ac.jp

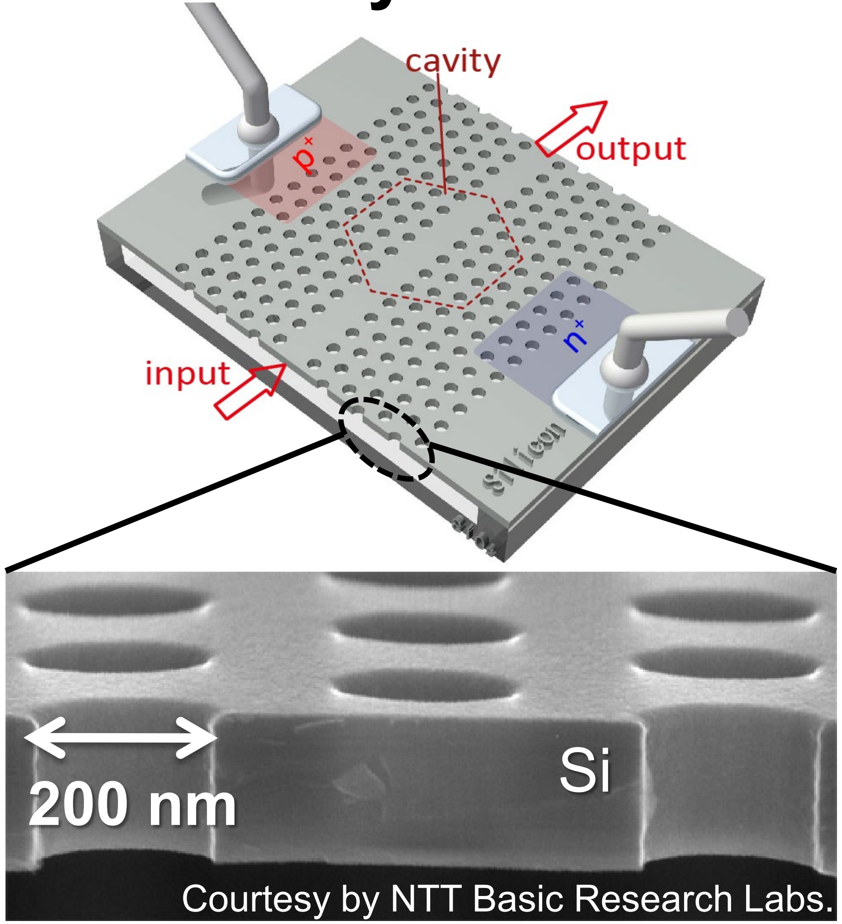


OIST Seaside House, Onna, Okinawa, Japan

# Key device: high Q microcavities

**Microcavity = a device that can cage photons**

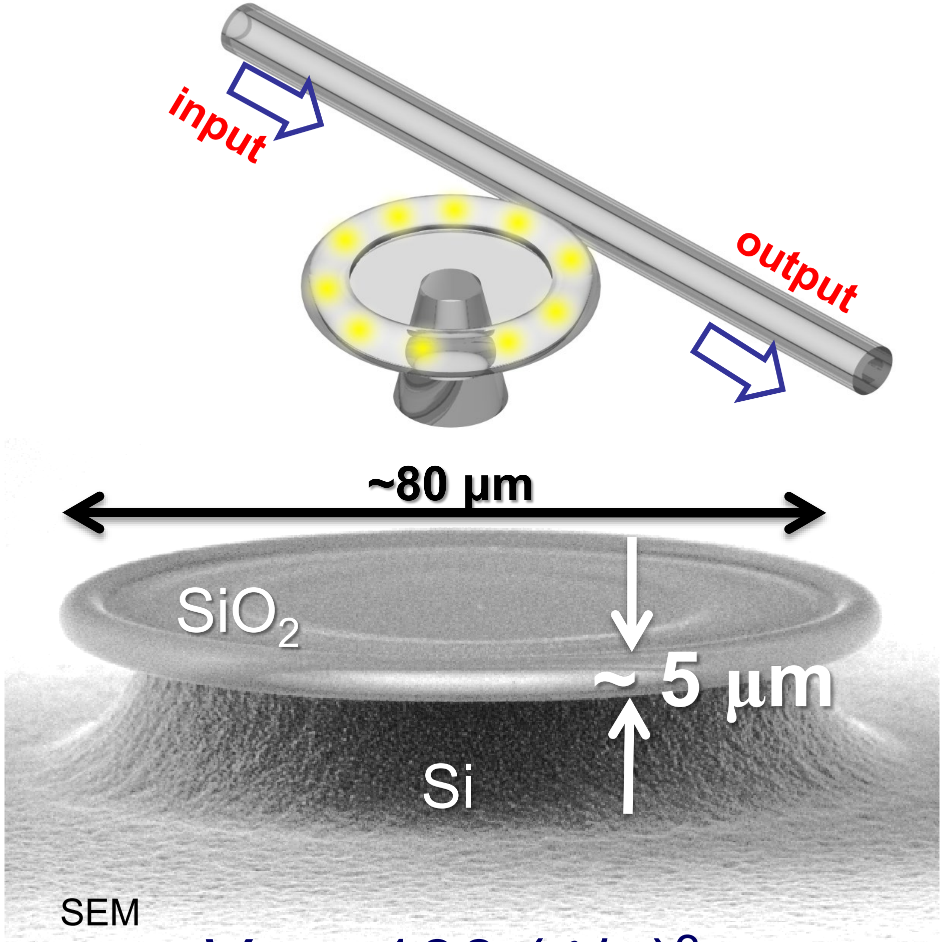
### ▶Photonic crystal nanocavity




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

$Q = 10^6$

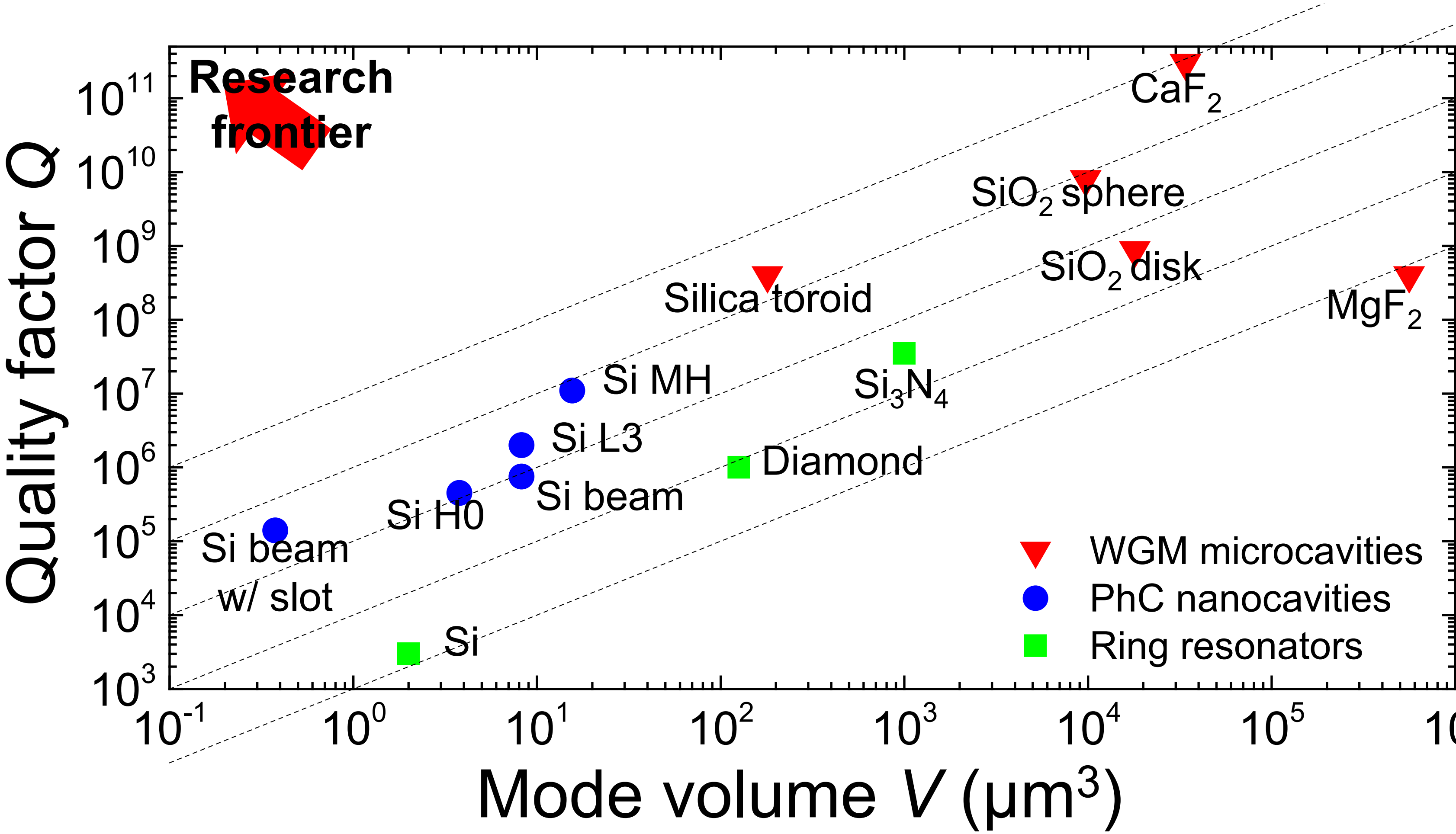
### ▶WGM microcavity




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

$Q = 10^8$

# High Q microcavities




[1] OE **25**, 1769-77 (2017)
[2] APL **104**, 241101 (2014)
[3] APL **105**, 101101 (2014)
[4] APL **94**, 121106 (2009)
[5] OE **21**, 32468-83 (2013)
[6] OE **18**, 18235-42 (2010)
[7] Optica **4**, 619-24 (2017)
[8] NP **8**, 369–74 (2014)
[9] NP **6**, 369–73 (2012)
[10] APL **85**, 6113 (2004)
[11] OE **15**, 6768-73 (2007)
[12] OE **23**, 7713-21 (2015)
[13] OL**23**, 247–9 (1998).

◆Q-factor

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

◆Photon density

$$\propto Q / V$$

# Outline

1. High-Q mode on Si chip w/ tapered fiber

   T. Tetsumoto, *et al*., Opt. Express **23**, 16256 (2015).
   Y. Ooka, *et al*., Sci. Rep. **5**, 11312 (2015).

2. Efficient coupling of WGM w/ Si chip

   Y. Zhuang, *et al., CLEO/Europe,* CK-5.2, Munich, 23-27 June (2019).
   Y. Zhuang, *et al.,* (in preparation)

3. Coupling of WGMs for optical buffering

   W. Yoshiki, *et al.,* Sci. Rep. **7**, 28758 (2017).

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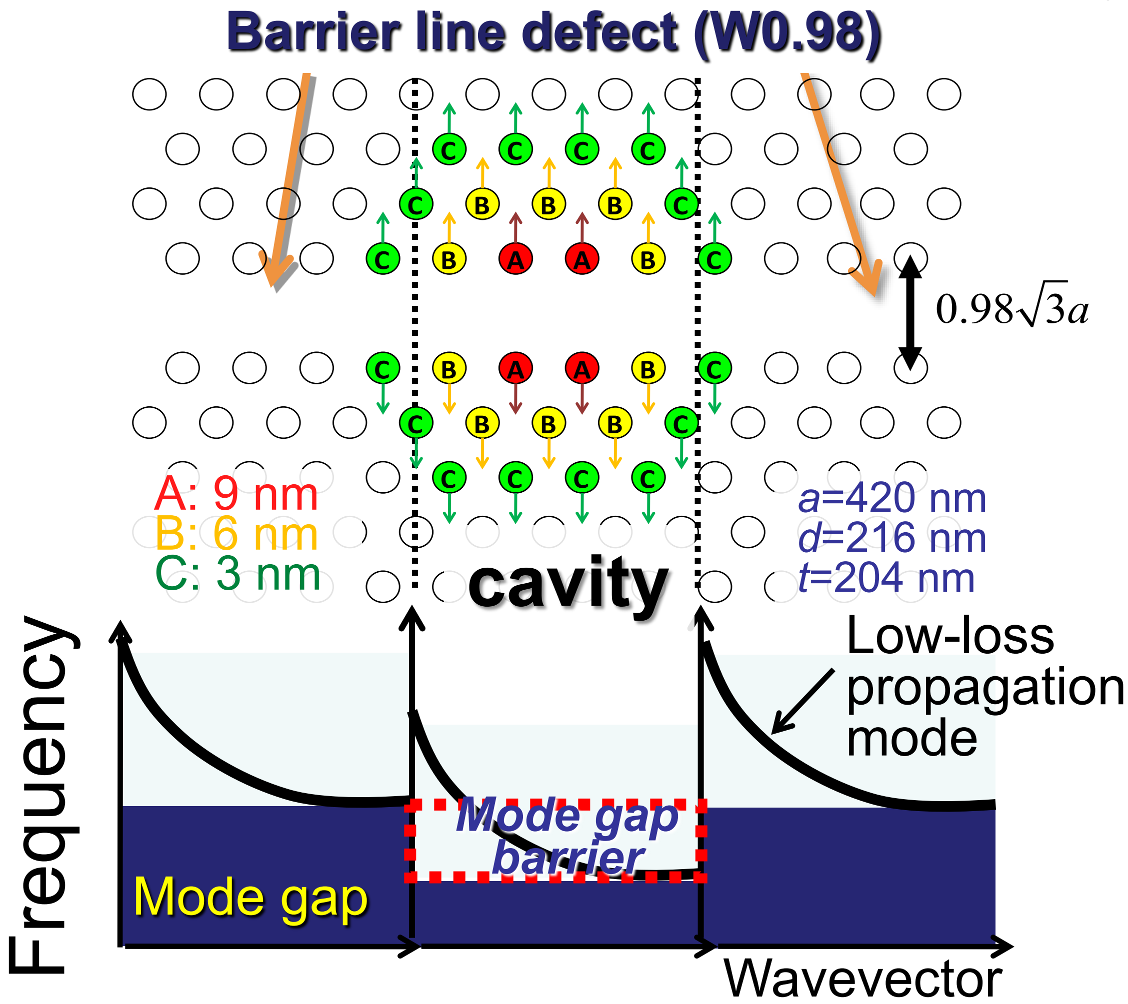
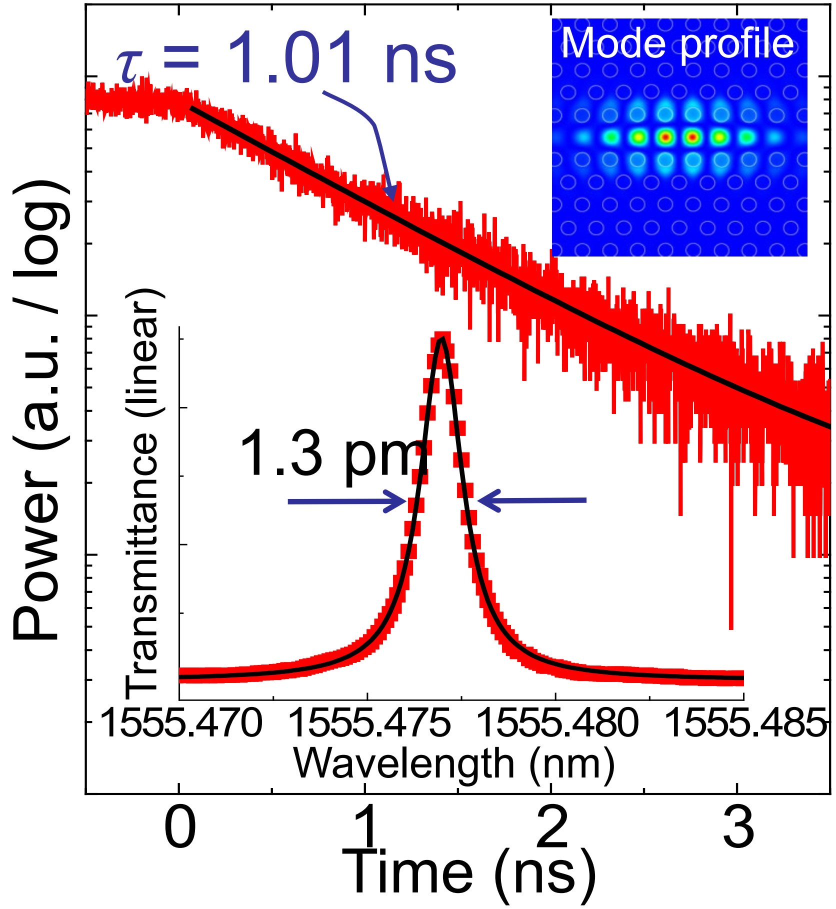
# Ultrahigh-Q w/ mode-gap confined width-modulated line-defect PhC nanoacvity

## Width-modulated line-defect cavity




## Ring-down & spectrum

$Q = 1.2\times10^{6}$ $V \cong 0.13\ \mu m^{3}$

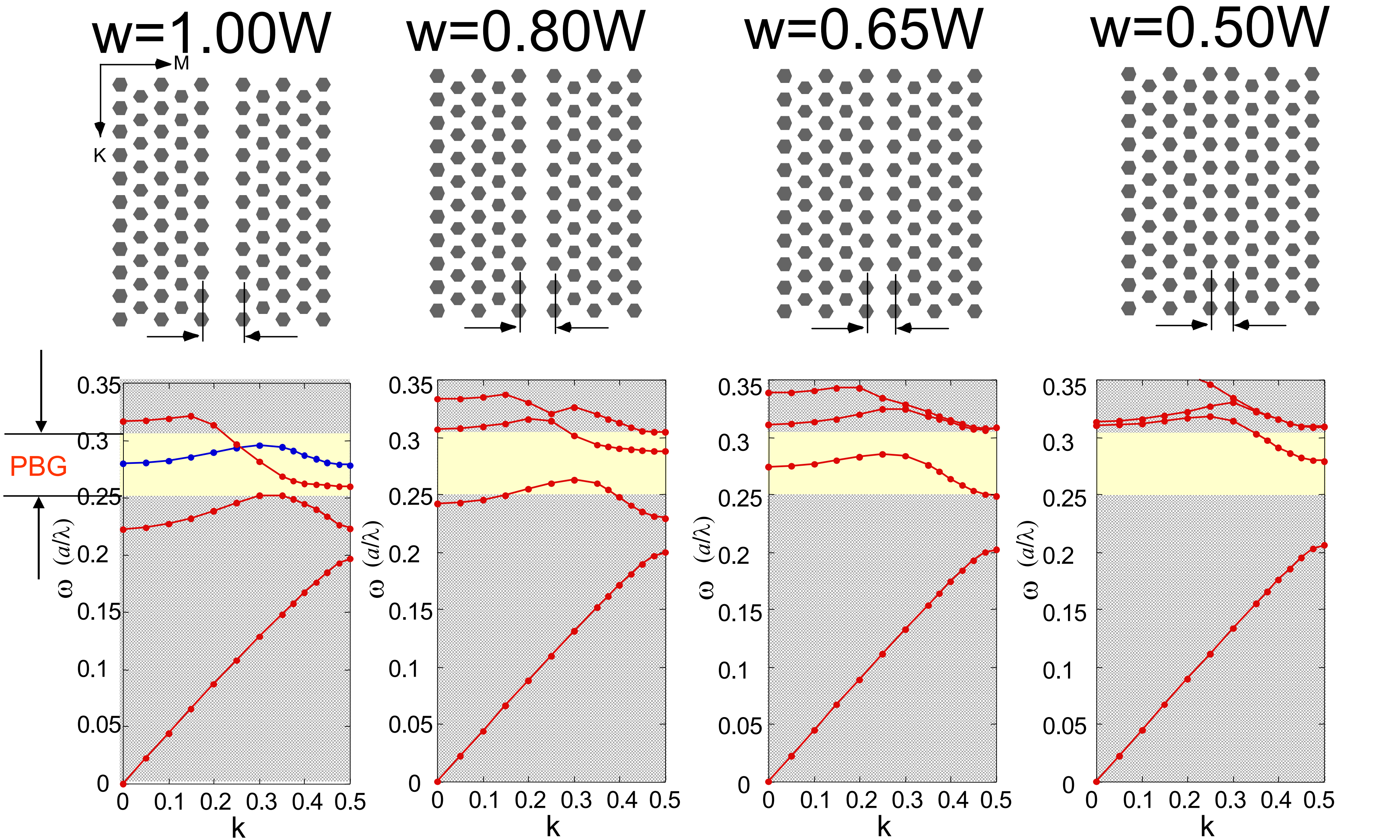



▶**Extremely high-*Q* achieved w/ mode-gap PhC nanocavity**



T. Tanabe *et al.*, Nature Photon. **1,** 49 (2007).

# Dispersion diagram of 2D PhC waveguides

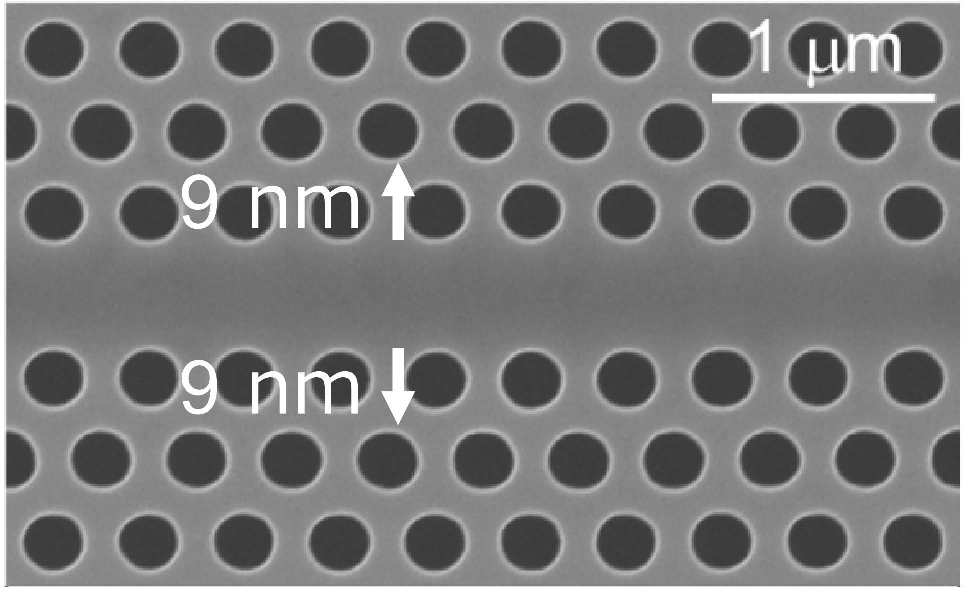



►**Mode gap is at higher frequency for narrow width**

# Fabrication w/ CMOS process

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

▶PhC nanocavity fabrication

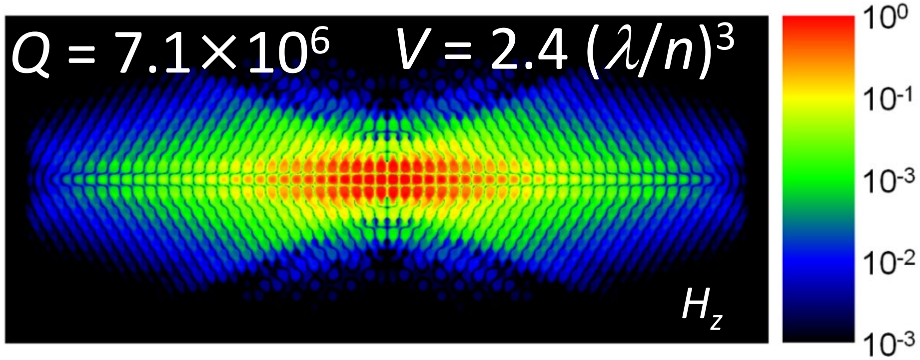



Width-modulated line defect cavity

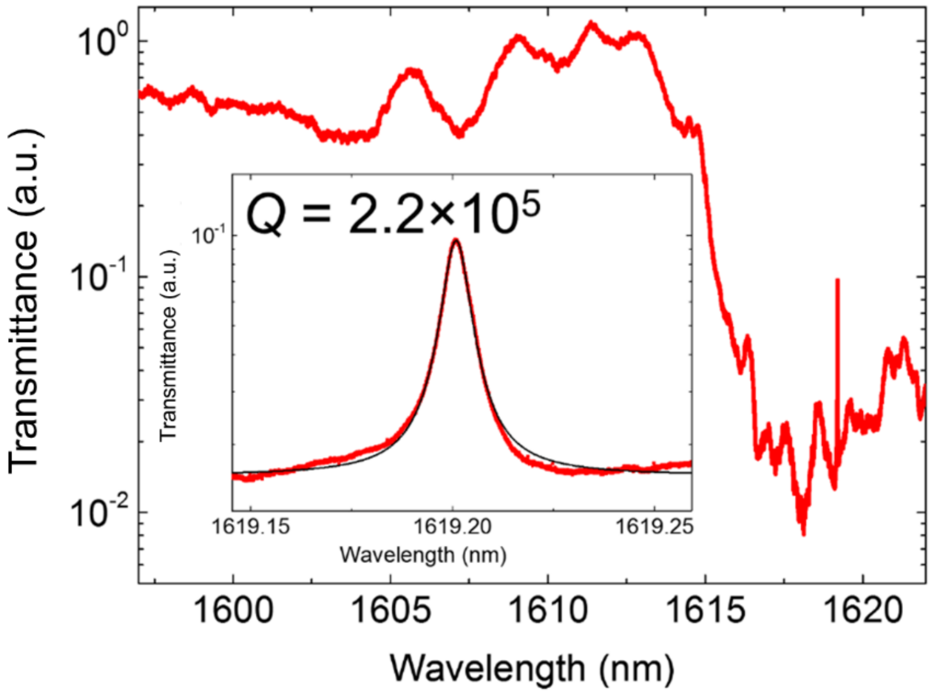
Max amount of shift : 9 nm

$Q = 2.2\times10^5$

▶Numerical




▶Experimental



# Reconfigurable nanocavity

## Photonic crystal (PhC) nanocavity

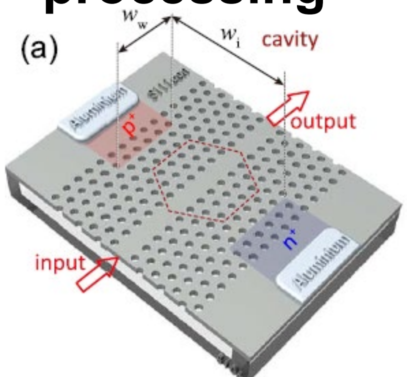
**Advantages**

- ✓ High *Q* & extremely small *V*
- ✓ Suitable for integration

**Disadvantages**

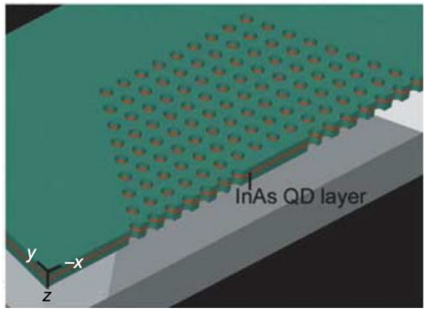
- ✓ Coupling to fiber is poor
- ✓ Collection efficiency is low

**Optical signal processing**




T. Tanabe, *et al.*, Appl. Phys. Lett. **96**, 101103 (2010).

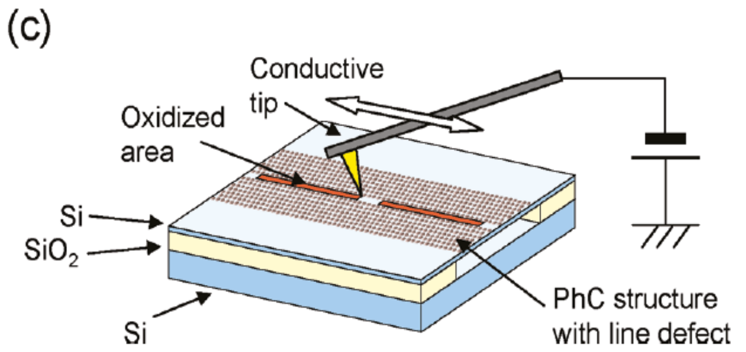
**Quantum optics**




T. Yoshie, *et al.*, Nature **432**, 200-203 (2004).

## Post-formation of PhC

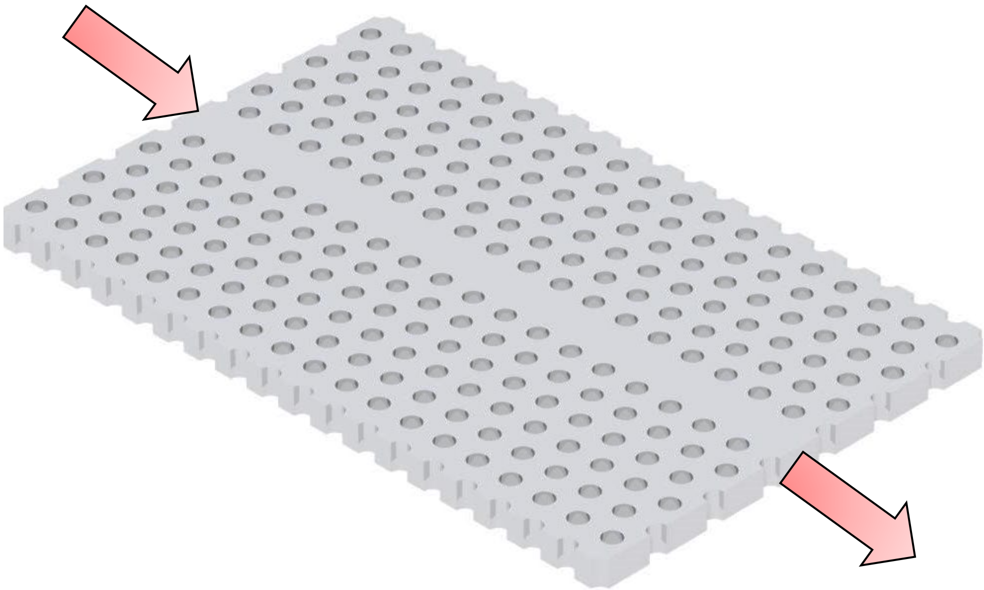
- ✓ Controlability of resonant wavelength & position
- ✓ High Q cavity (> $10^6$)
- ✓ Relocation of the cavity not possible




A. Yokoo, *et al.*, Nano lett. **11**, 3634-42 (2011).

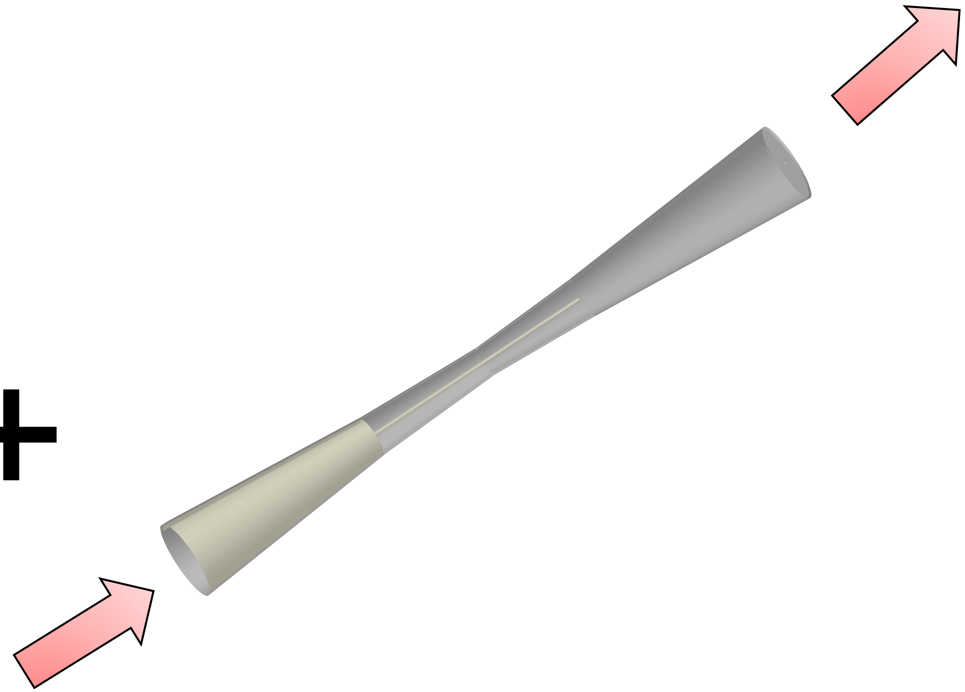
# Waveguide + waveguide = high Q cavity ?

▶**Photonic crystal waveguide**



+

▶**Nano taper waveguide**

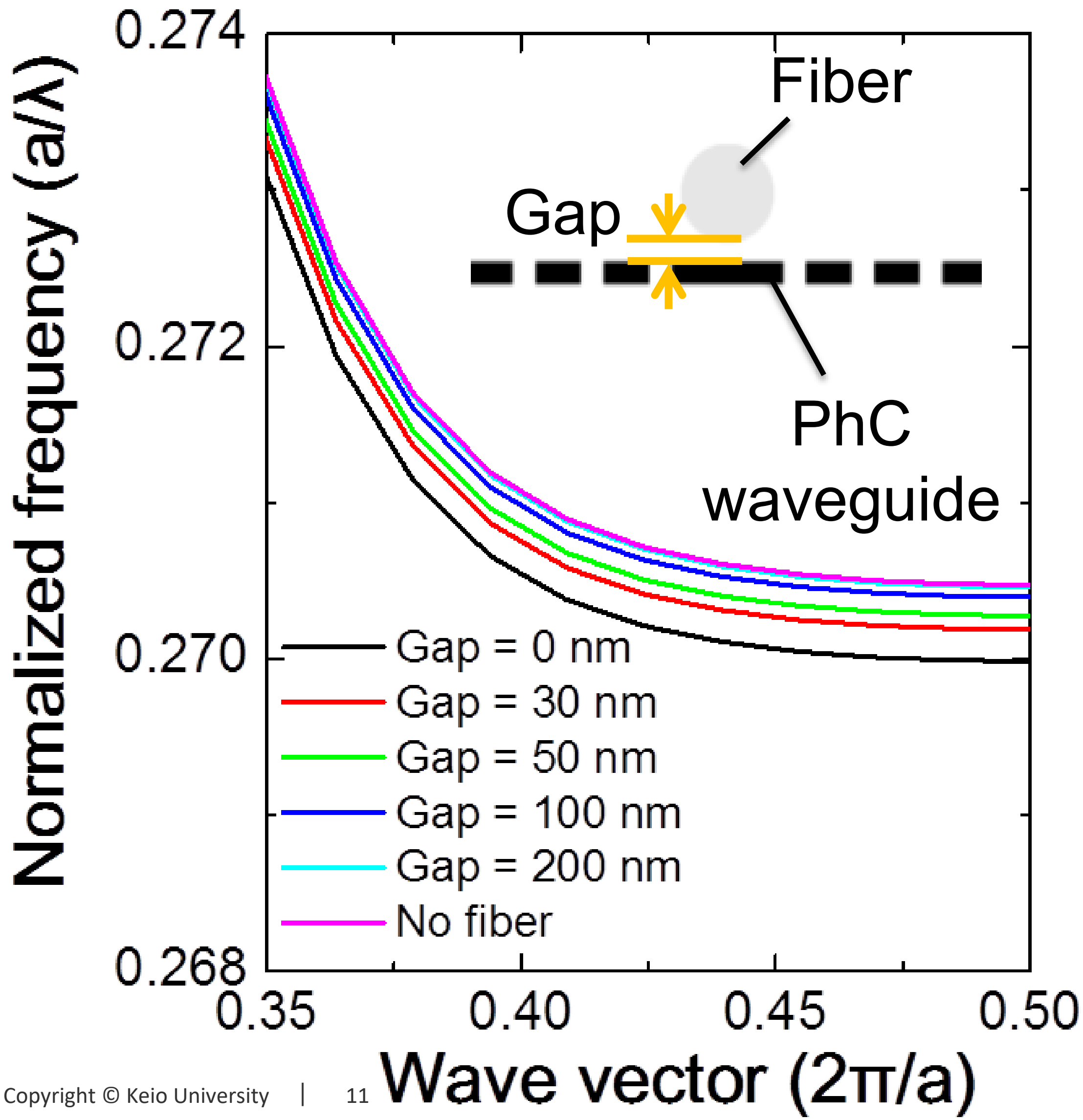


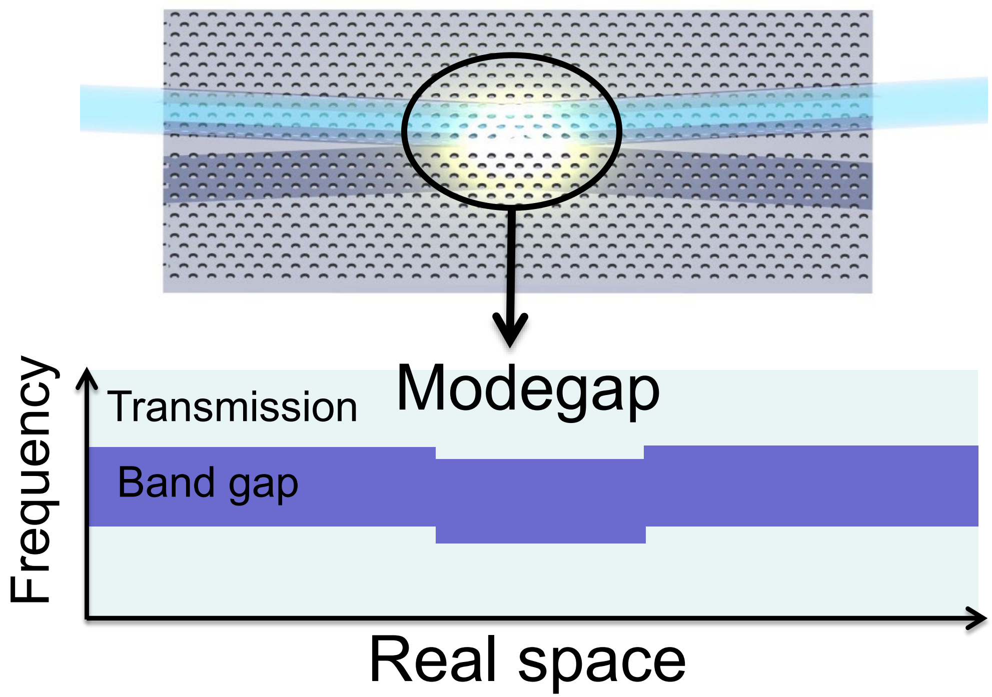
Cavity ?

# Principle of cavity formation

## Cavity formation model

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

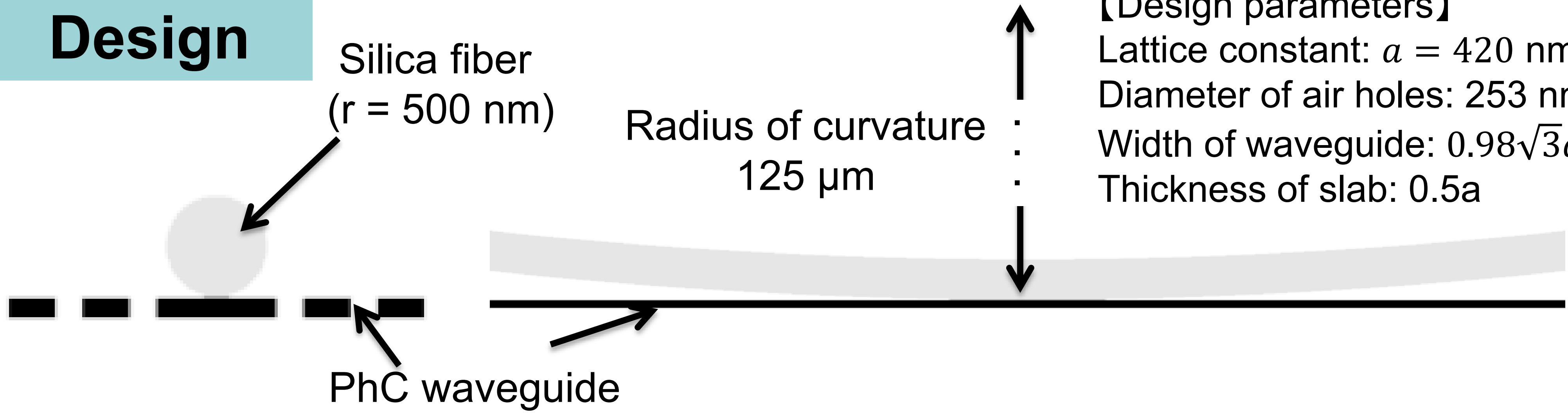



**Effective refractive index change results in formation of modegap cavity**

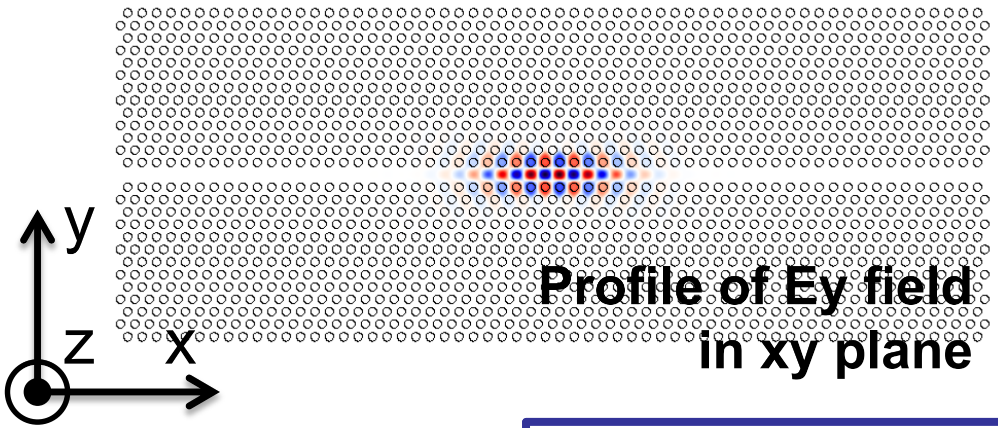
# Numerical calculation

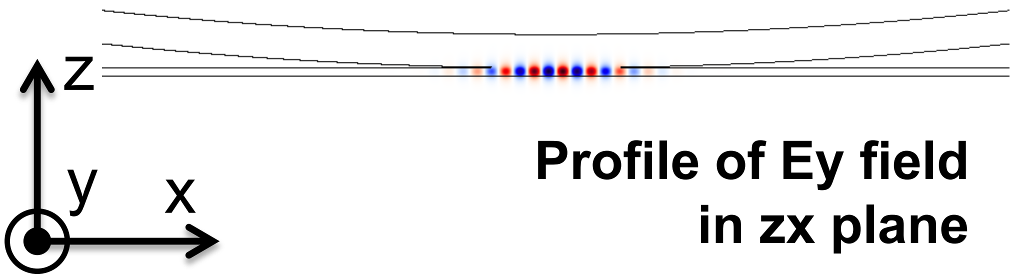
## Design




【Design parameters】
Lattice constant: $a = 420$ nm
Diameter of air holes: 253 nm
Width of waveguide: $0.98\sqrt{3}a$
Thickness of slab: 0.5a

## Result



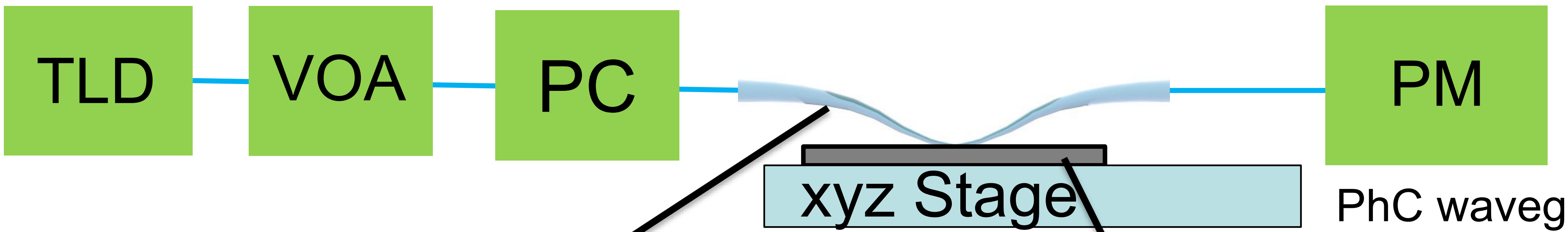




$$Q = 1.4 \times 10^7, V = 1.9(\lambda/n)^3$$
was obtained

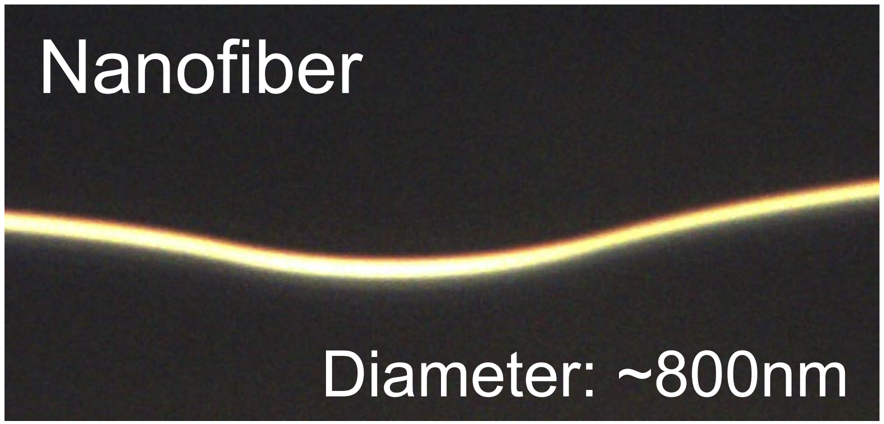
# Experimental setup

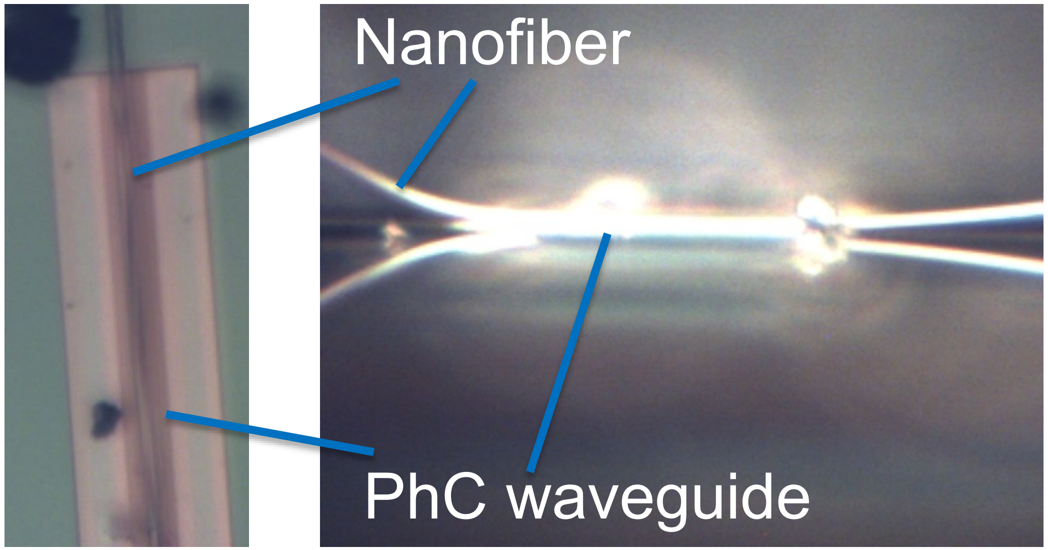
T. Tetsumoto, *et al.*, Opt. Express **23**, 16256 (2015).

TLD: Tunable Laser Diode, VOA: Variable Optical Attenuator,
PC: Polarization Controller, PM: Power Monitor




PhC waveguide (W0.98)
Lattice constant 420 nm,
Hole diameter 253 nm
Slab thickness210 nm

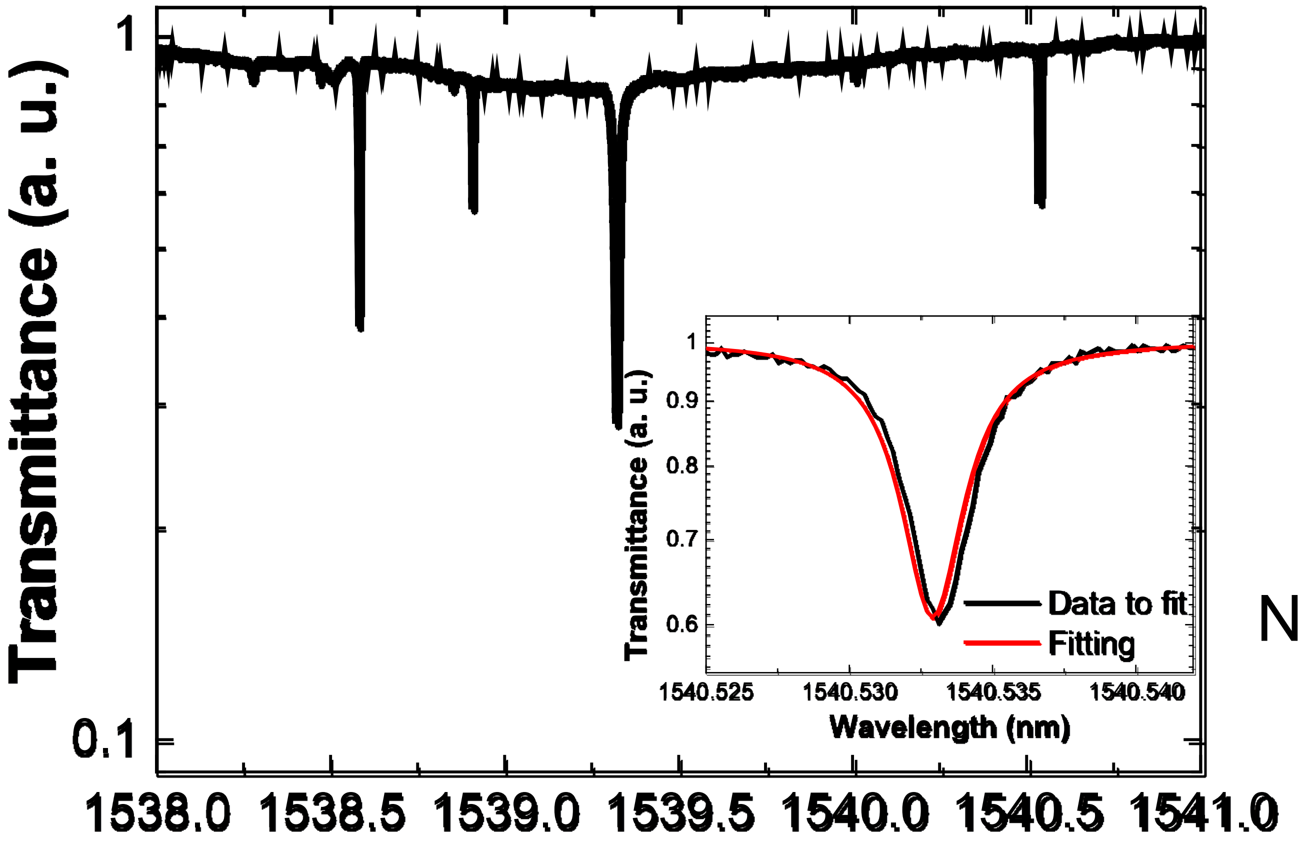



**Transmittance loss:** Typically -10dB, **Best -1dB**

# Experimental results

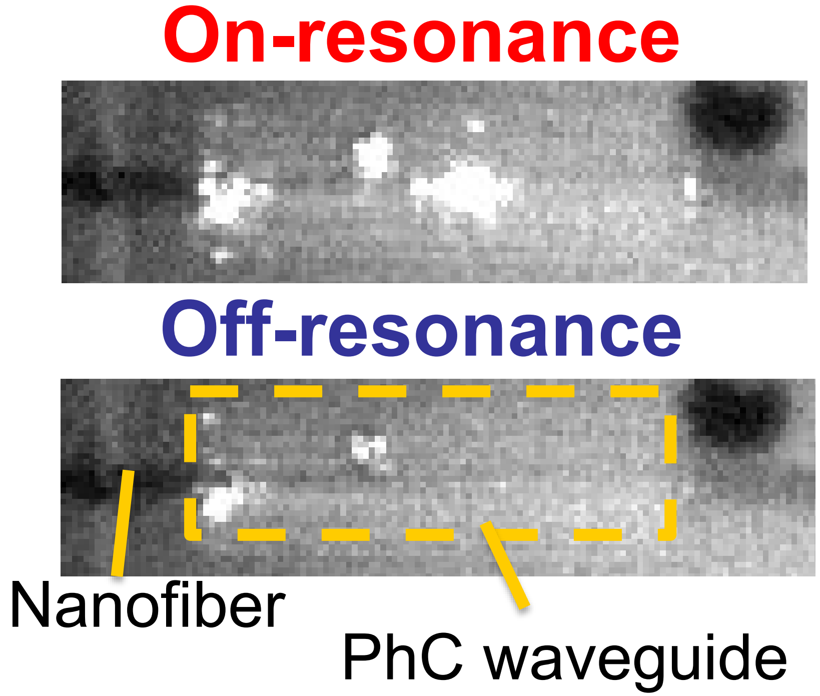
## Transmission spectrum




$$Q_{load} = 5.1 \times 10^5$$

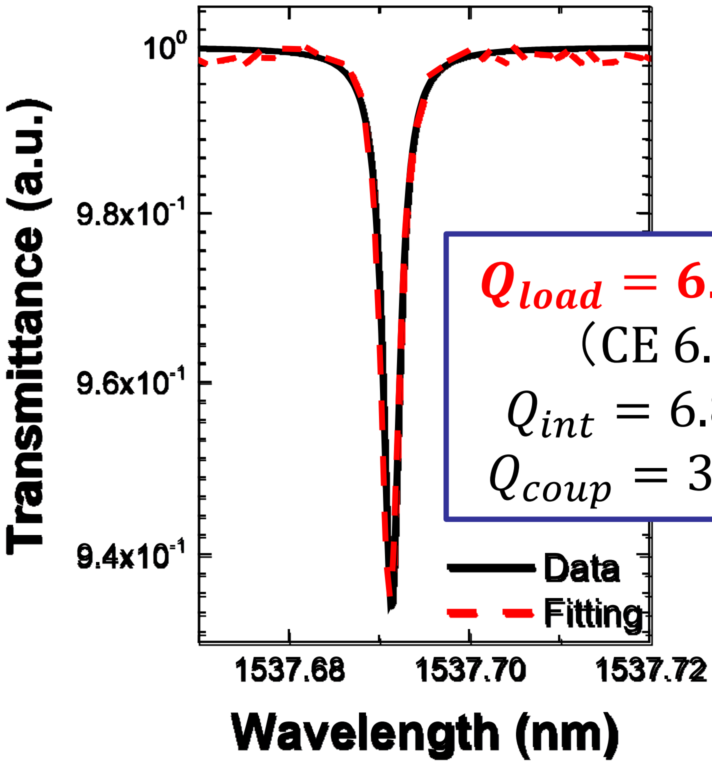
**(CE 39%)**

## Infrared red image



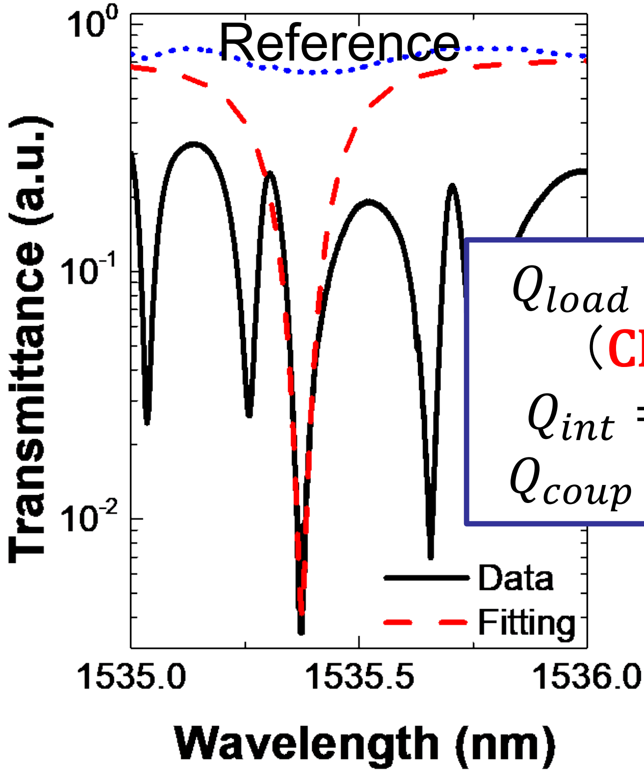
# Measurement of *Q* and CE of FCPC

## Maximization of *Q*




$Q_{load} = 6.7 \times 10^5$
(CE 6.6%)
$Q_{int} = 6.8 \times 10^5$
$Q_{coup} = 3.9 \times 10^7$

## Maximization of CE



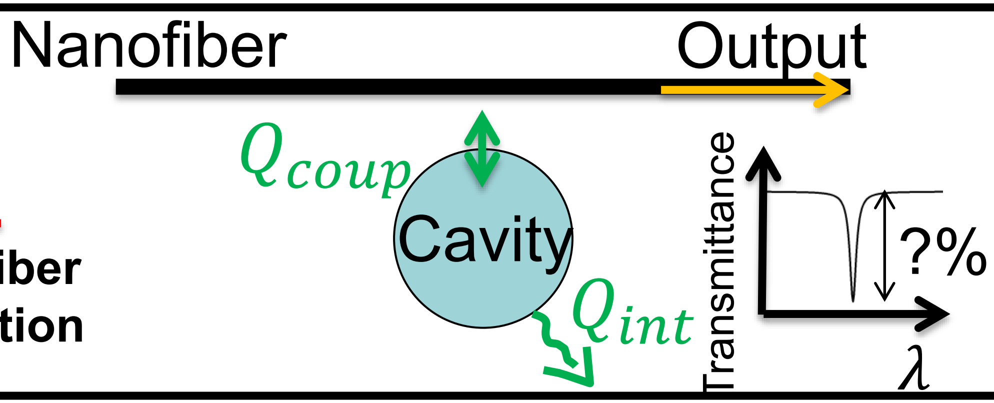

$Q_{load} = 6.1 \times 10^3$
(CE 99.6%)
$Q_{int} = 1.1 \times 10^4$
$Q_{coup} = 1.3 \times 10^4$

## Measured *Q*

$$Q_{load}^{-1} = Q_{coup}^{-1} + Q_{int}^{-1}$$

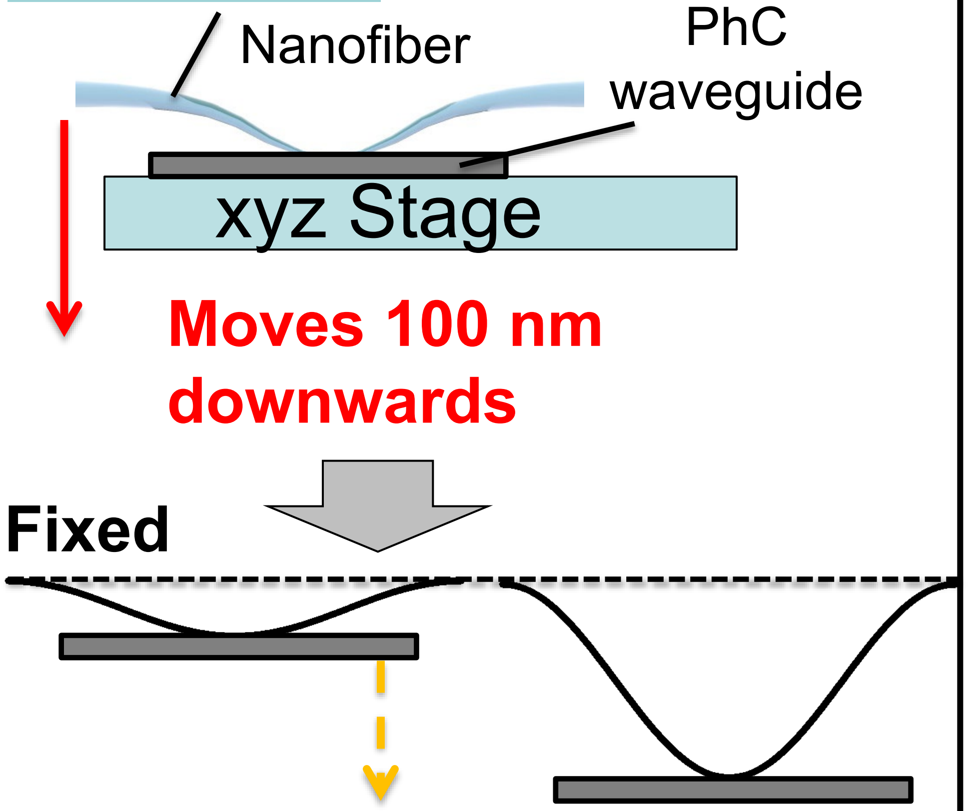
$Q_{coup}^{-1}$: **Depends on fiber radius**

$Q_{int}^{-1}$: **Depends on fiber contact condition**



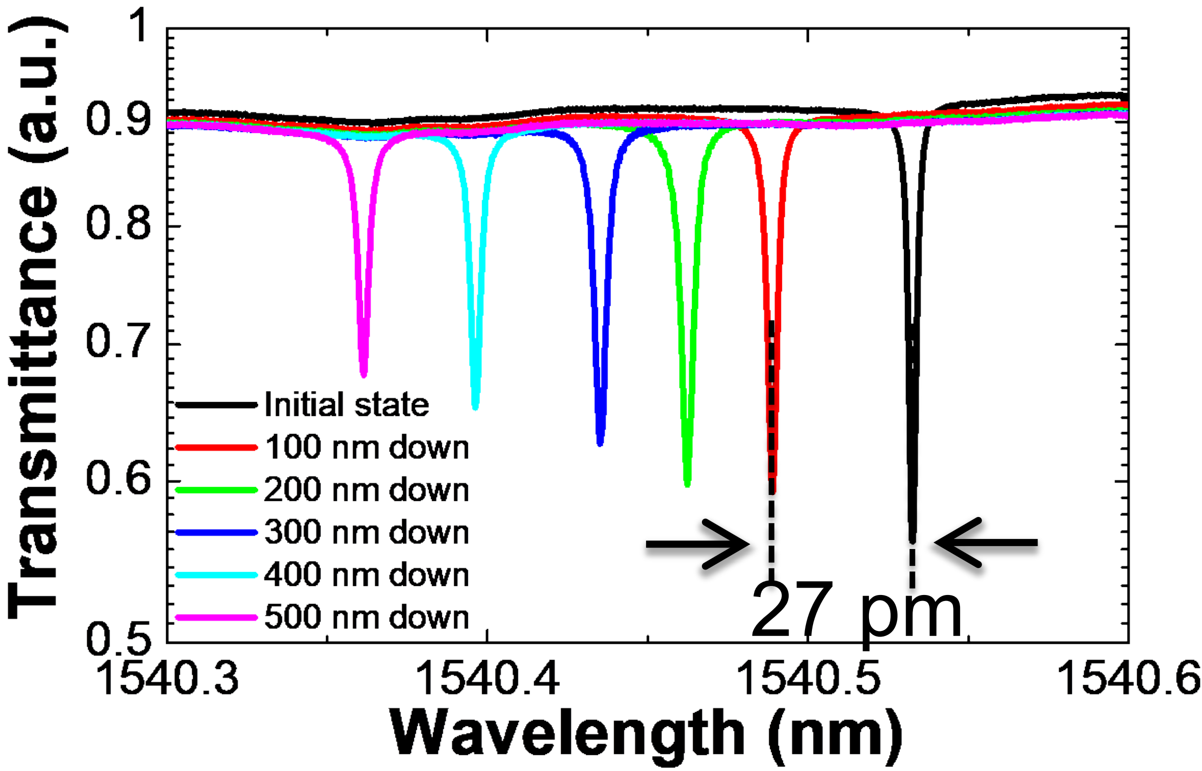
# Resonant wavelength tuning

## Method




**Cavity length is shortened**
**⇒Blue shift of resonant wavelength**

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



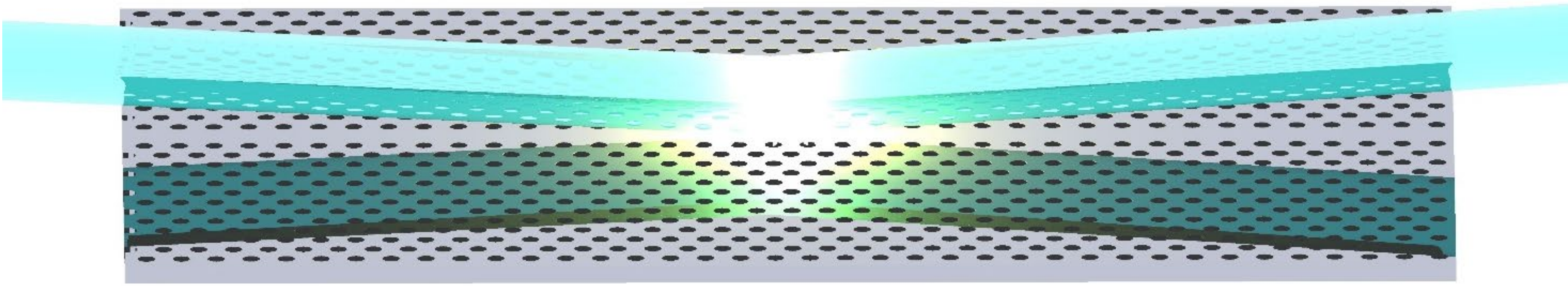

### Tuning sensitivity

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

# Nanofiber assisted reconfigurable PhC nanocavity

## Fiber coupled PhC nanocavity (FCPC)

- ✓ **Reconfigurable**
- ✓ $\boldsymbol{Q = 5.1 \times 10^5}$, coupling efficiency (CE) of 39% (Highest value for reconfigurable PhC nanocavity)
- ✓ $Q = 6.1 \times 10^3$, CE of 99.6%



T. Tetsumoto, *et al*., Opt. Express **23**, 16256-16263 (2015).

# Outline

1. High-Q mode on Si chip w/ tapered fiber

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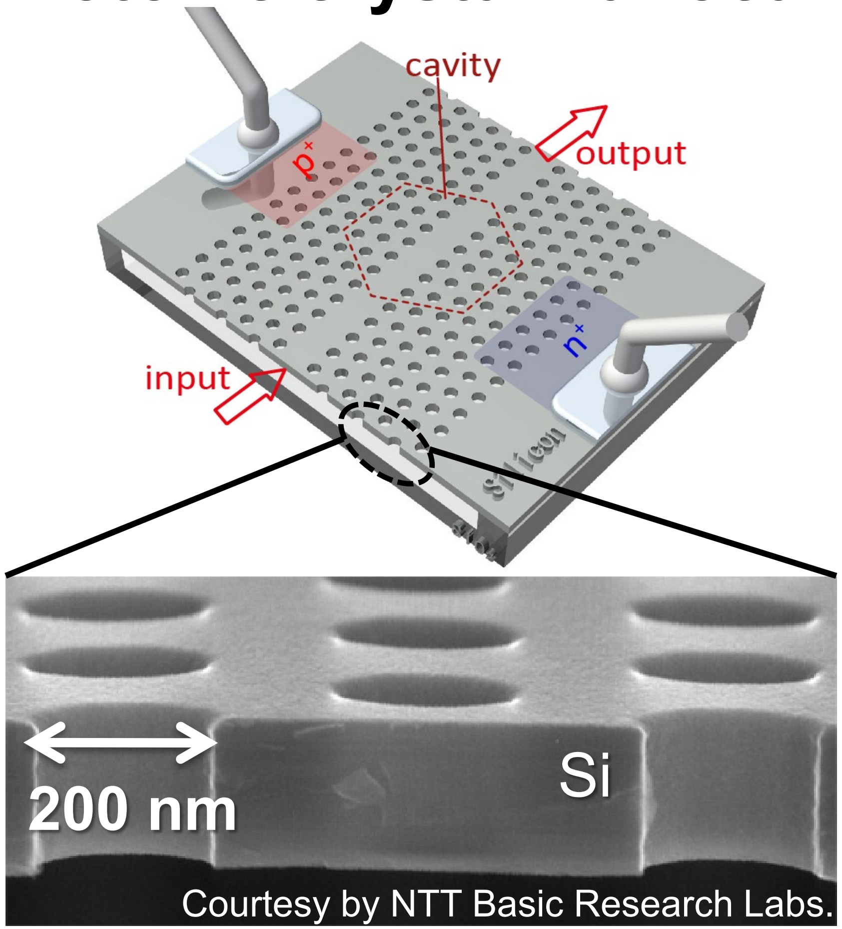
3. Coupling of WGMs for optical buffering

   W. Yoshiki, *et al*., Sci. Rep. **7**, 28758 (2017).

# Key device: high Q microcavities

**Microcavity = a device that can cage photons**

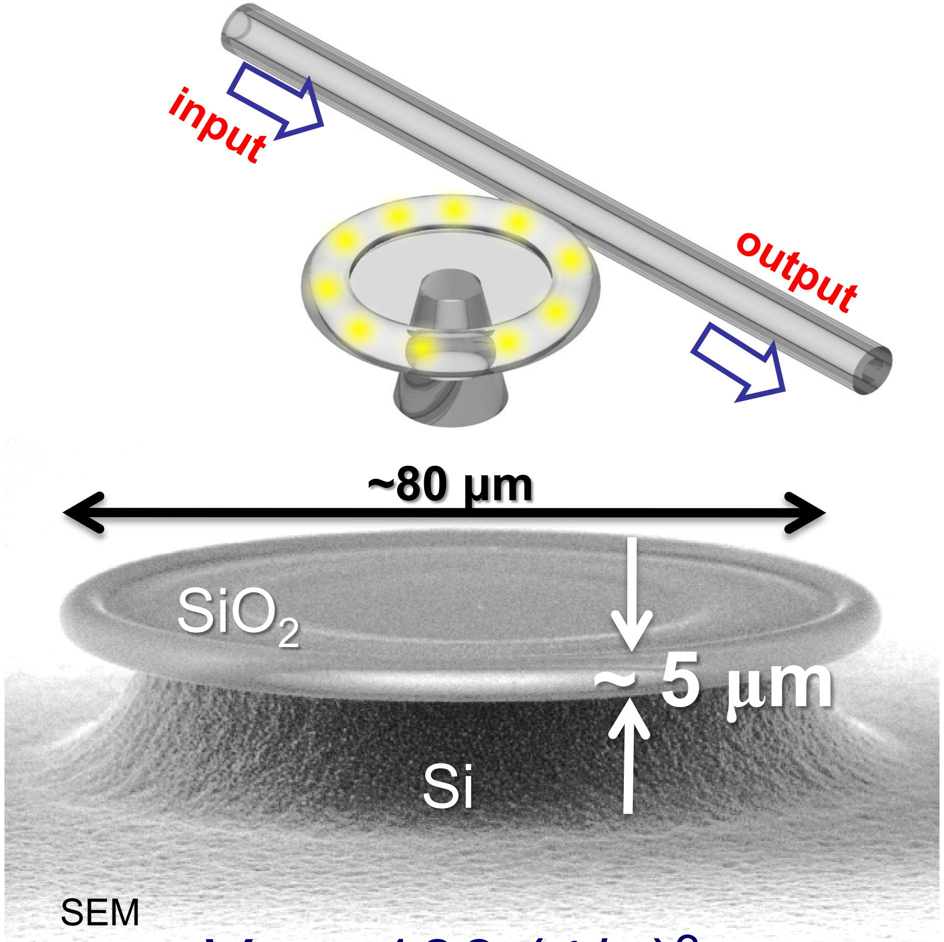
## ▶Photonic crystal nanocavity




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

$Q = 10^6$

## ▶WGM microcavity




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

$Q = 10^8$

# Hybrid system consisting of two different cavities

**Silica toroid microcavity**

Ultra-high *Q* (Long storage time)

Operating principal: Optical Kerr effect

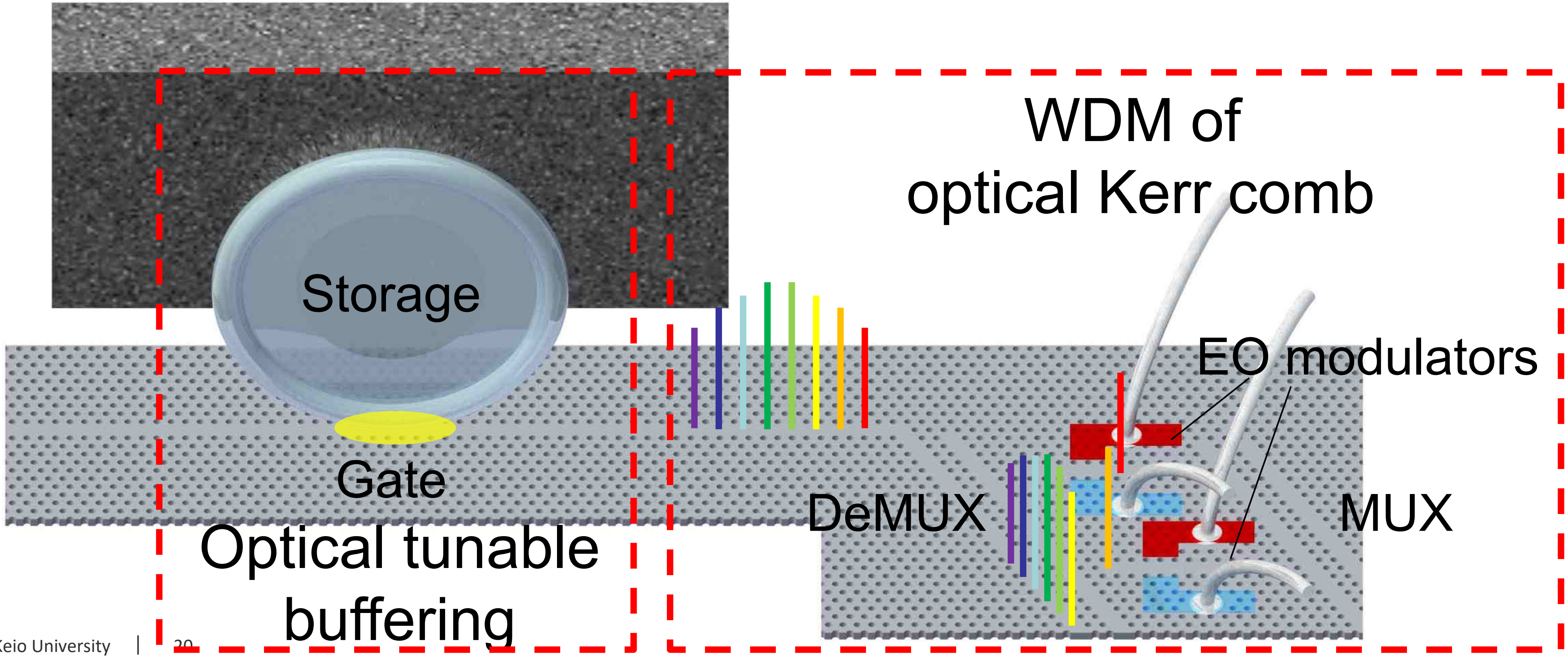
- Frequency Kerr comb
- Low power optical switch
- Optical buffer

**Si Photonic crystal nanocavity**

Ultra-small *V* (Quick response)

Operating principal: Carrier plasma effect

- Fast optical switching
- Photodetection
- EO modulation



# Sample preparation

## Fabrication procedure

Silica disk

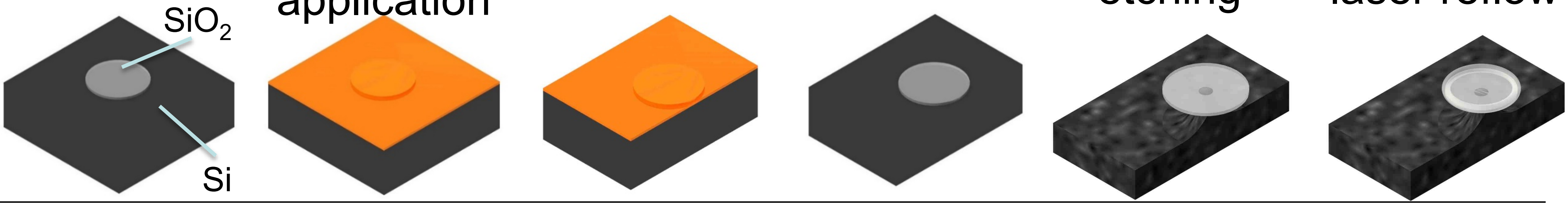
1. Resist application

2. Dicing

3. Resist removal

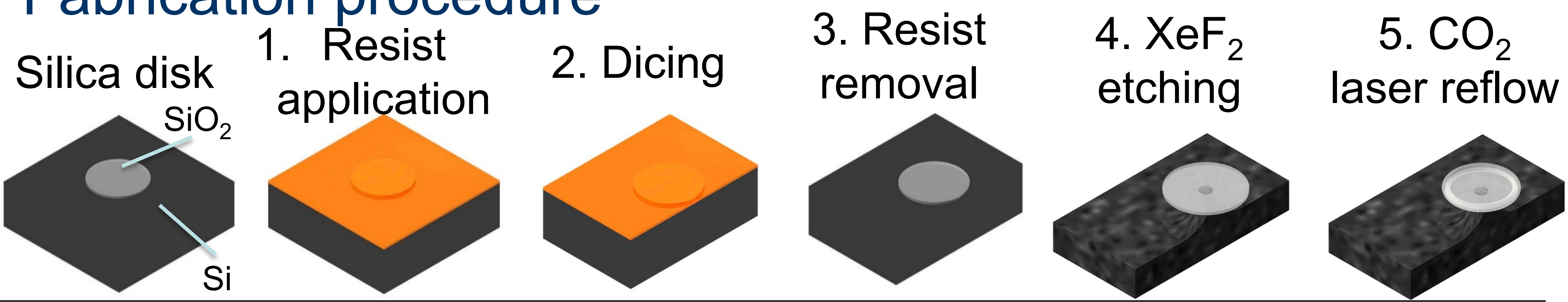
4. $XeF_2$ etching

5. $CO_2$ laser reflow

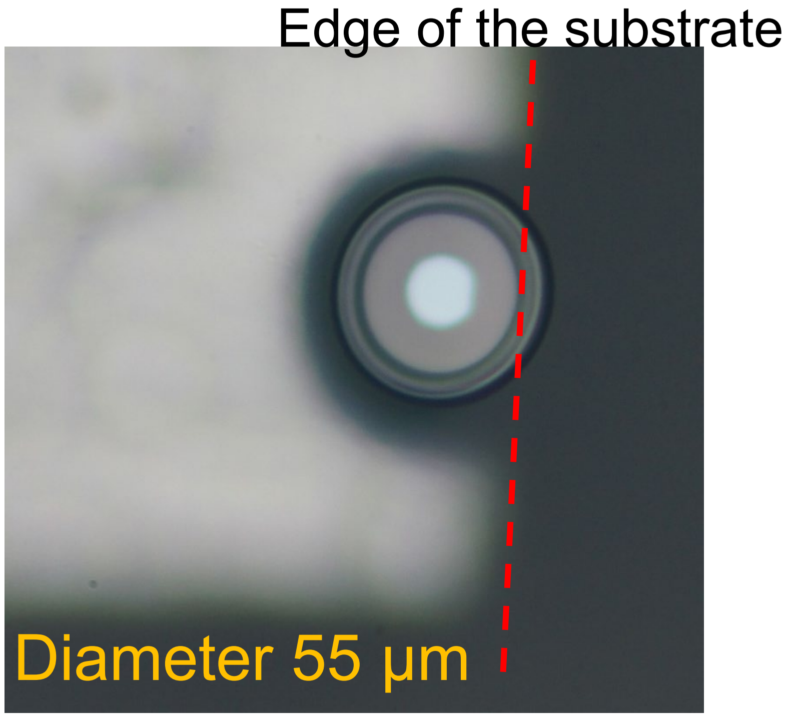


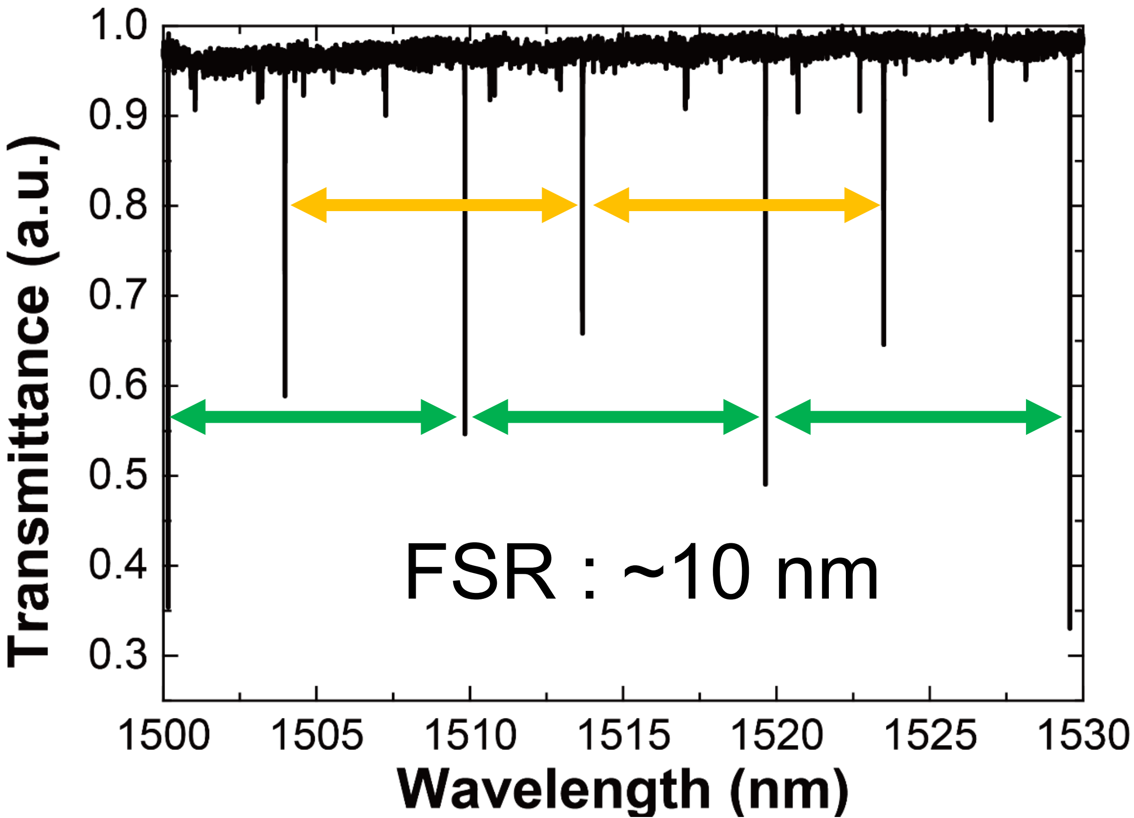
# Sample preparation

## Fabrication procedure




## Fabricated structure



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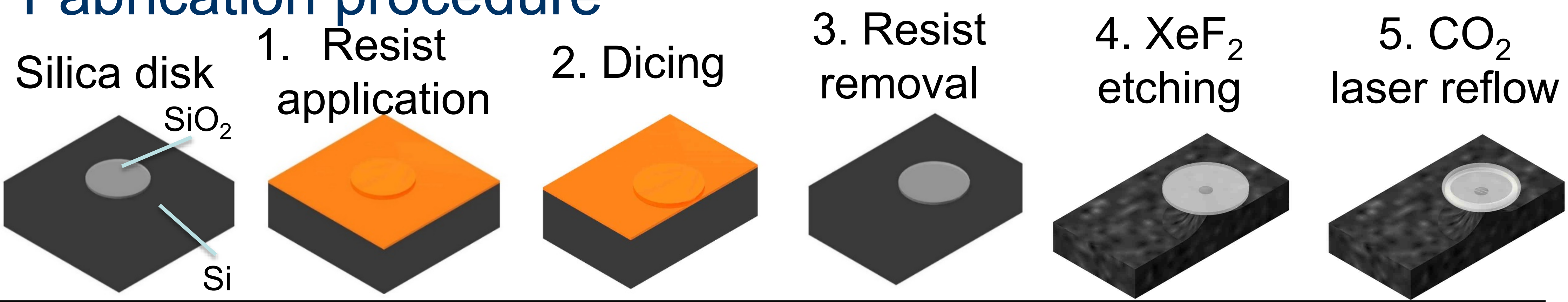
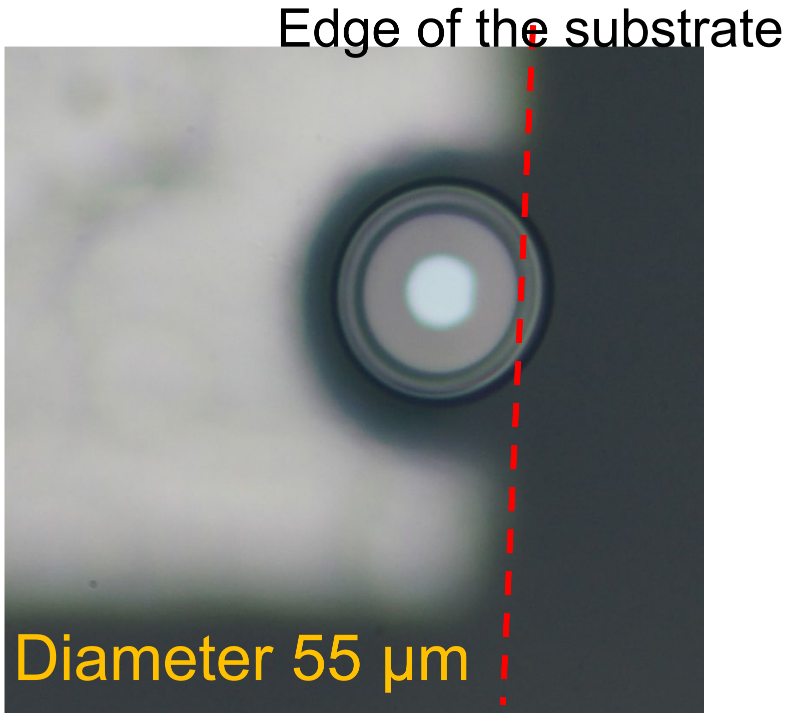
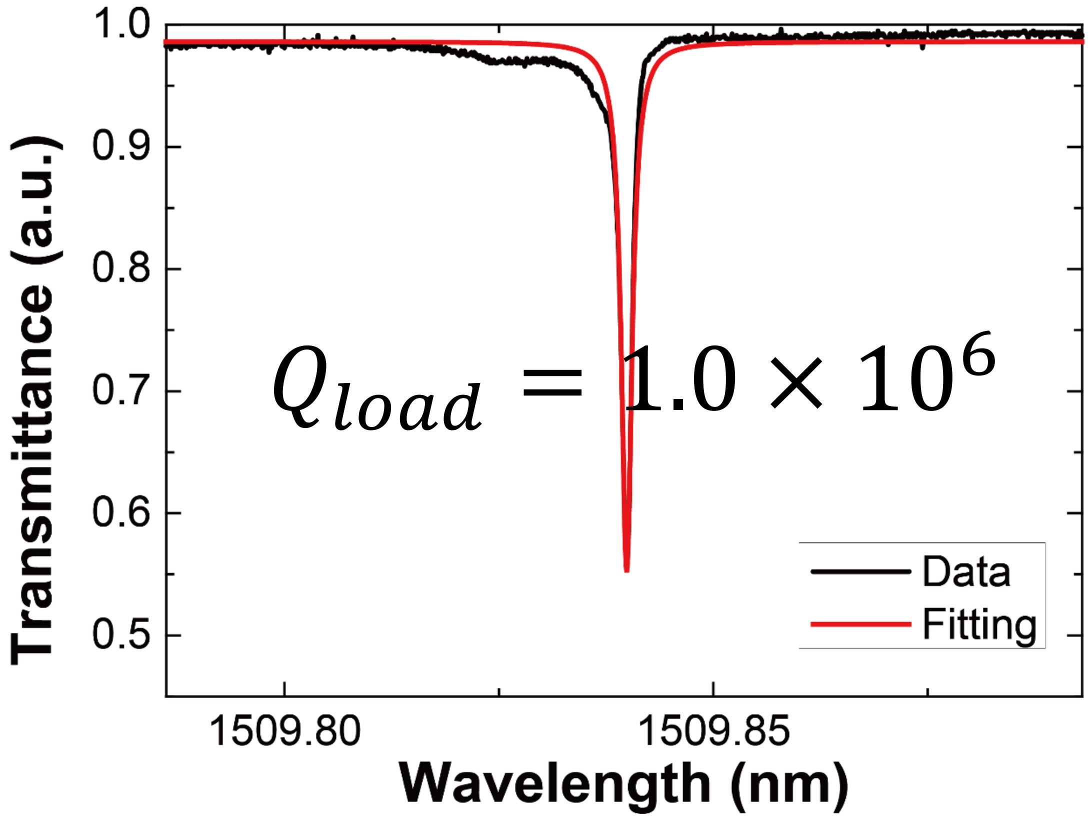


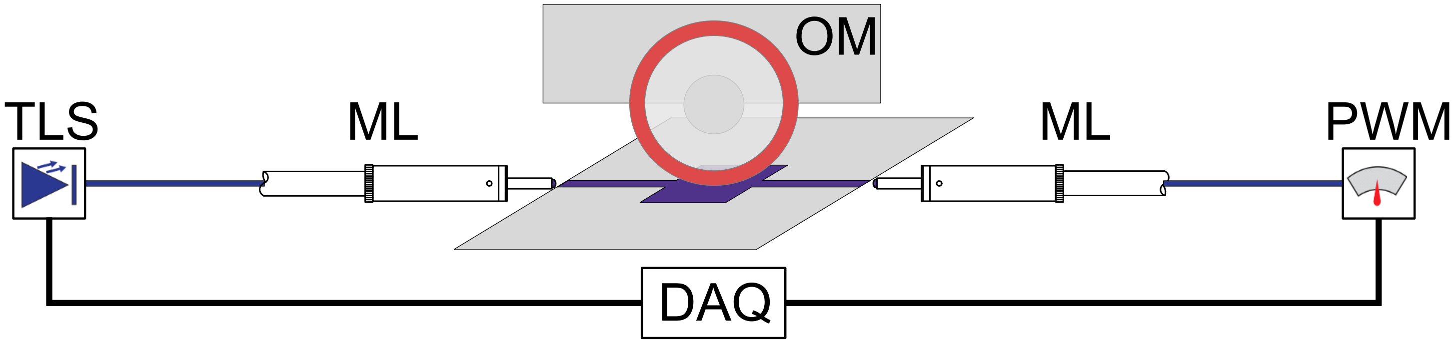

## Fabricated structure



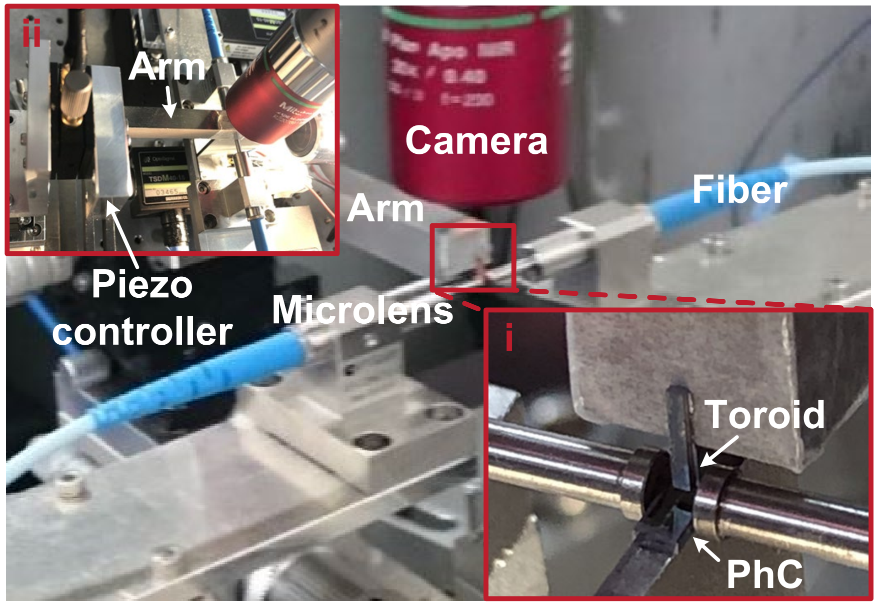
# Experimental setup

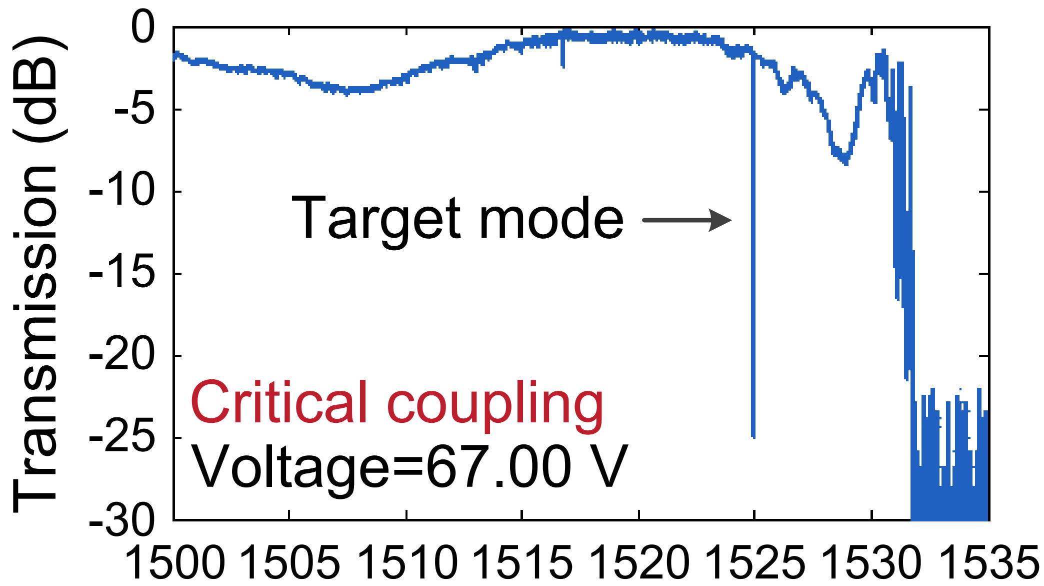
## ☐ Experimental setup and results



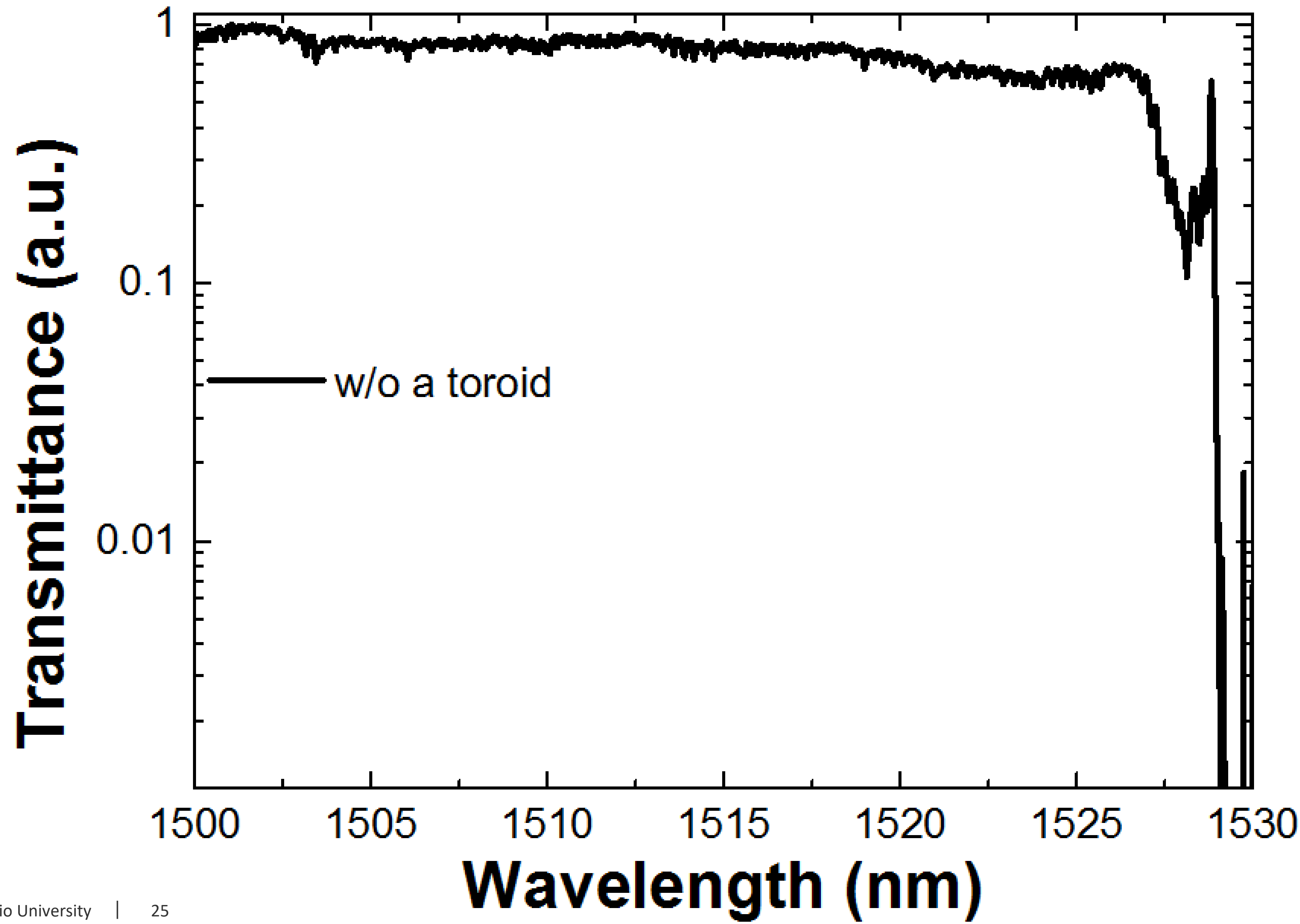

TLS: Tunable laser source
ML: Microlens
OM: Opitcal microresonator
PWM: Powermeter
DAQ: Data acquation

Experimental setup



# Result: Transmission spectrum



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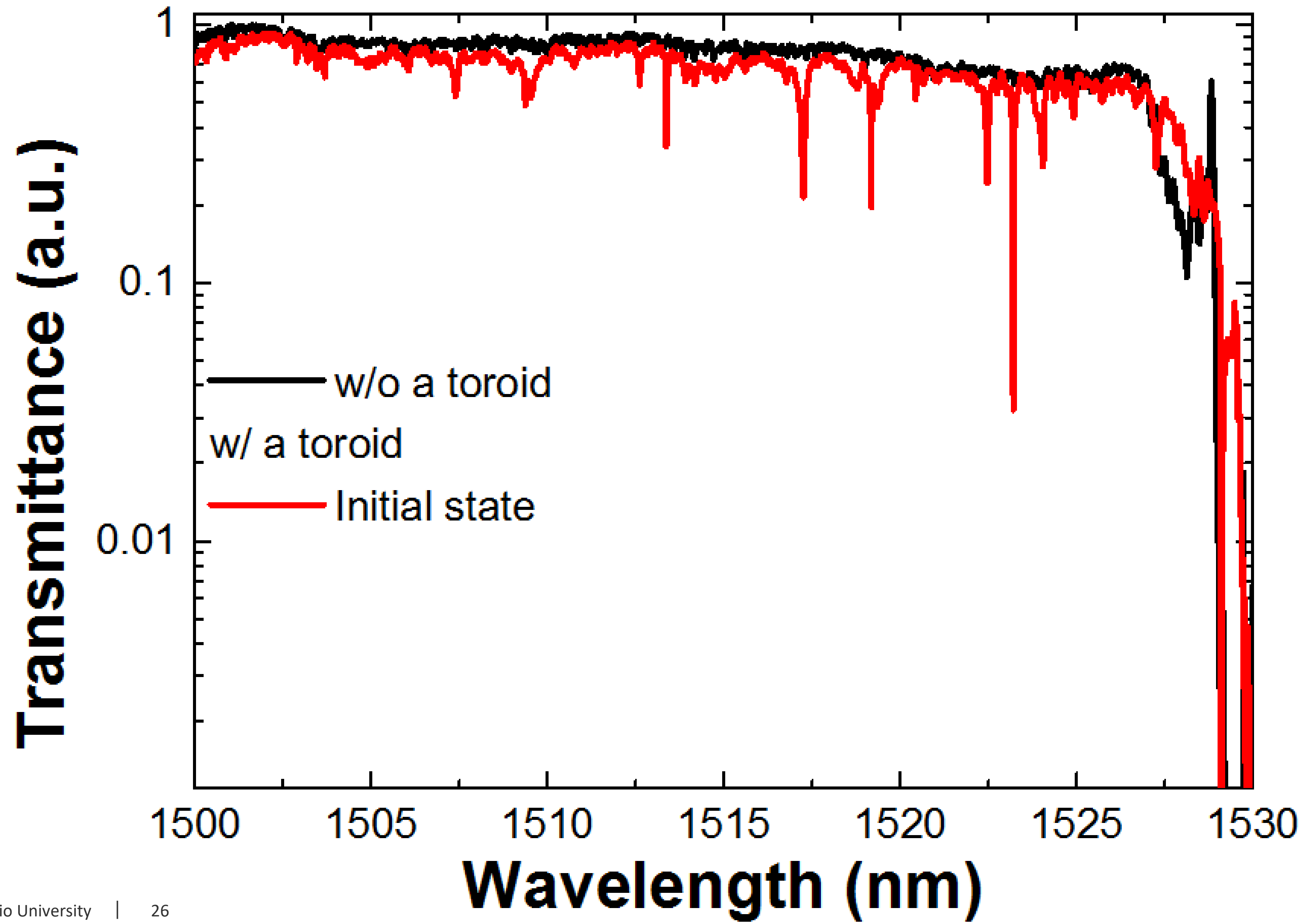
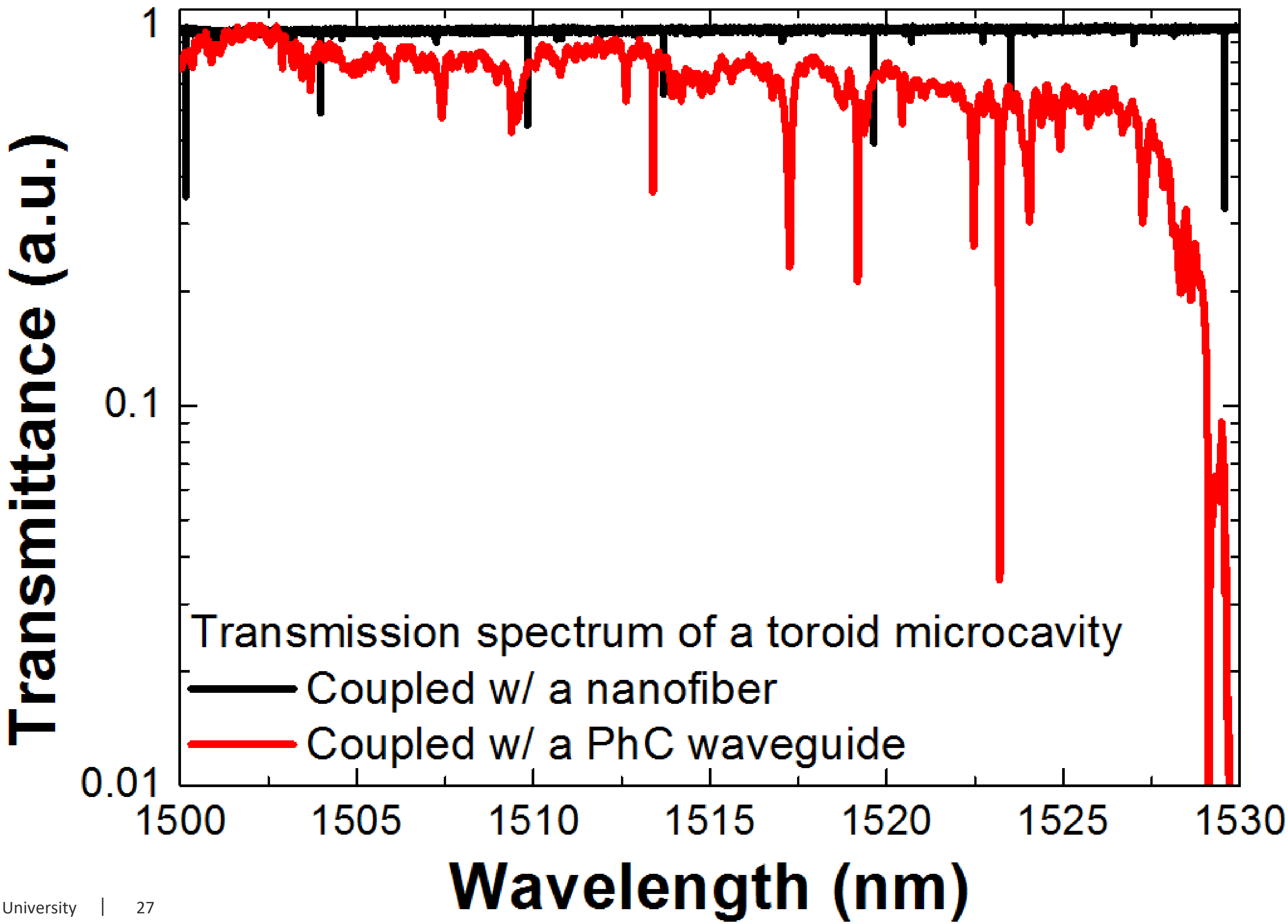
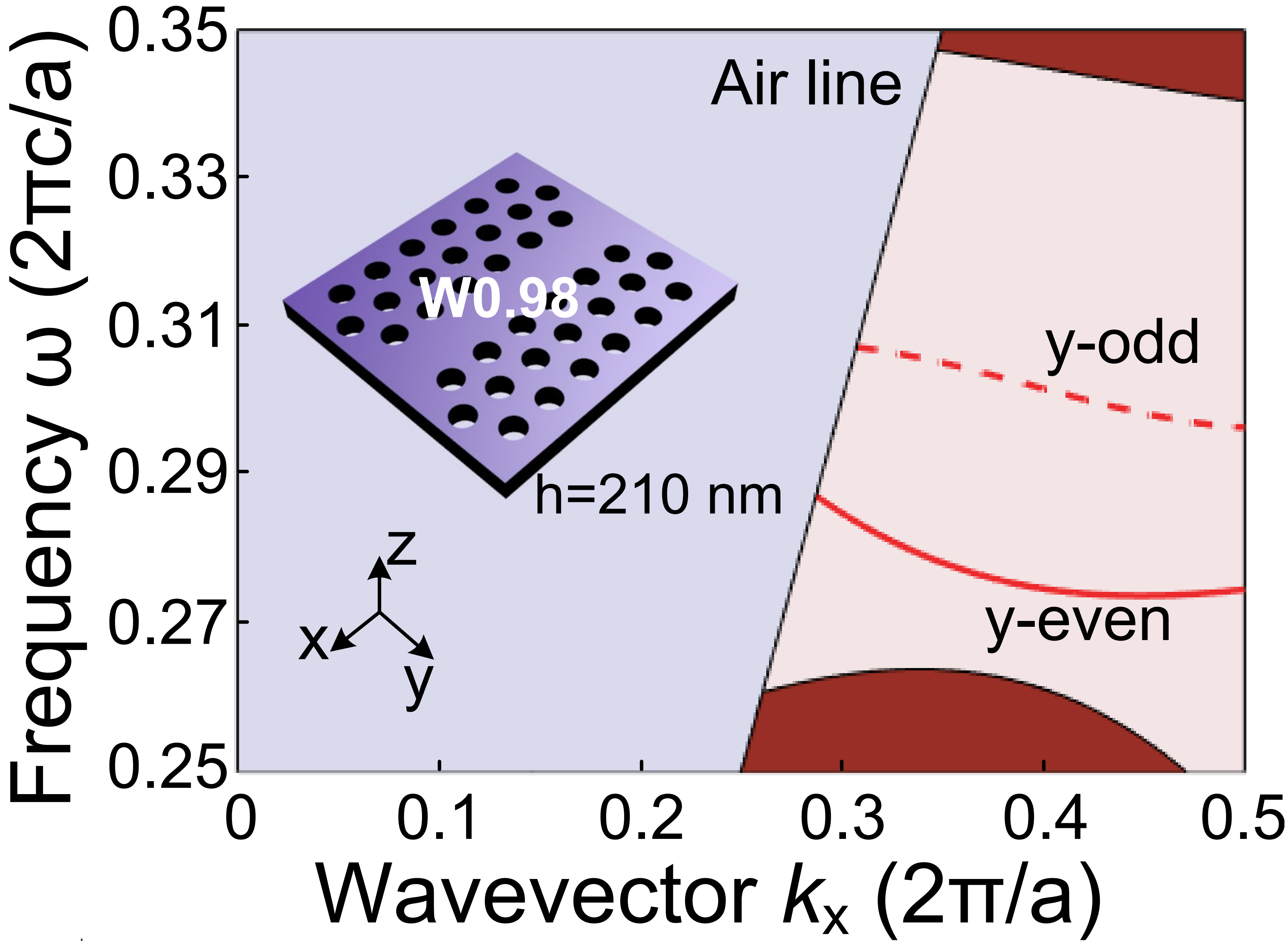


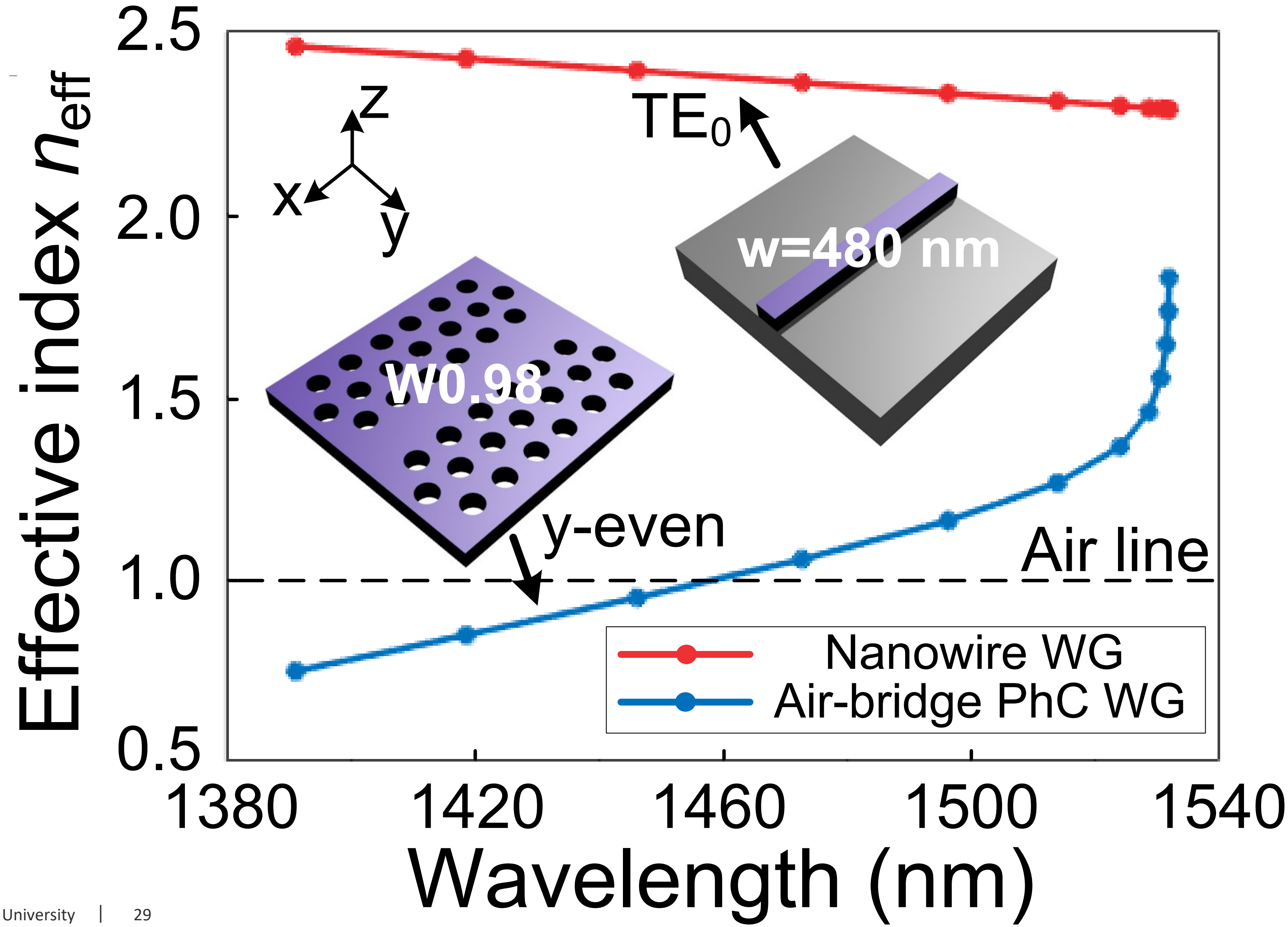
# Nanofiber vs. PhC waveguide



# Dispersion of a PhC waveguide (W0.98)

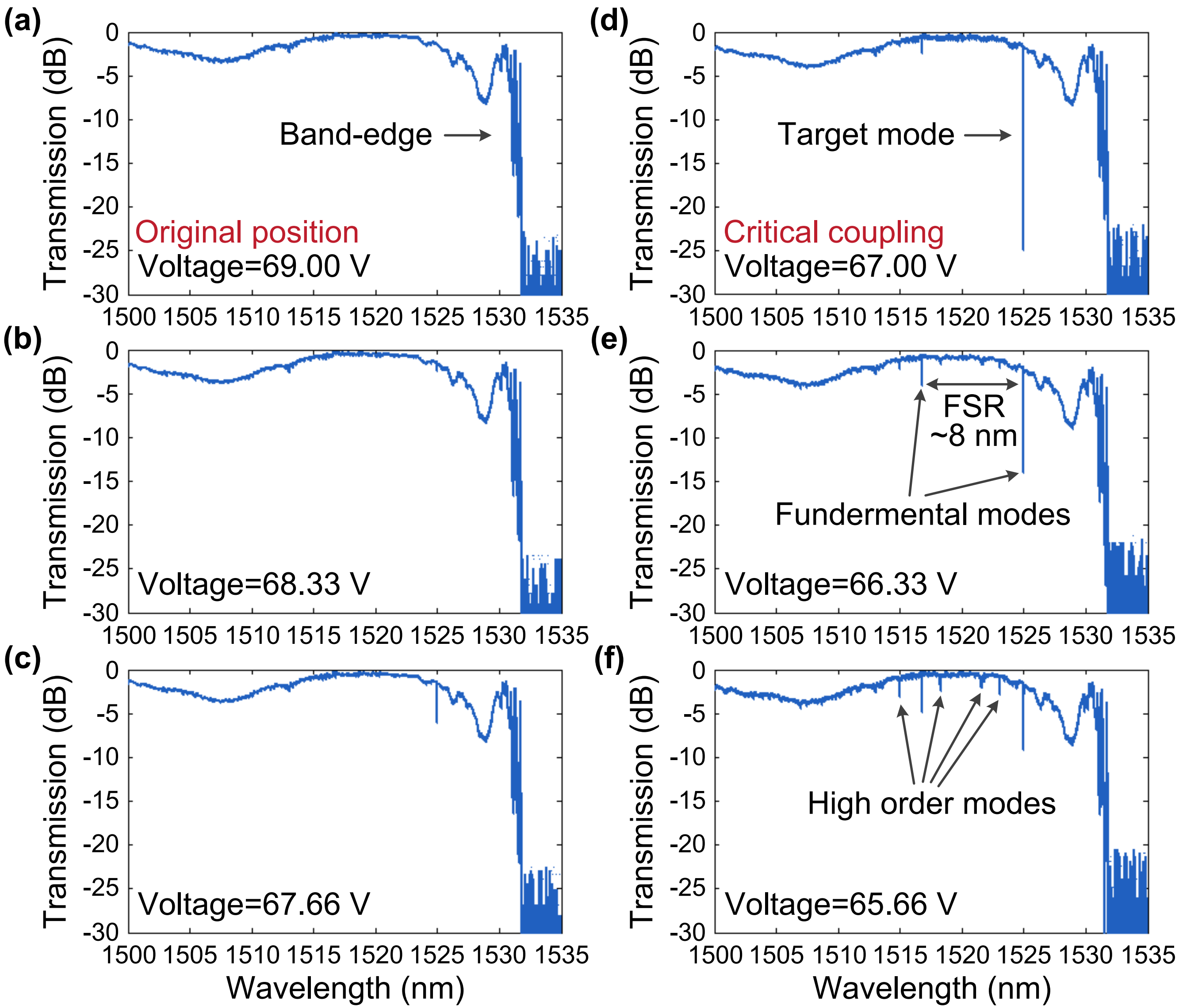


# Effective index of waveguide

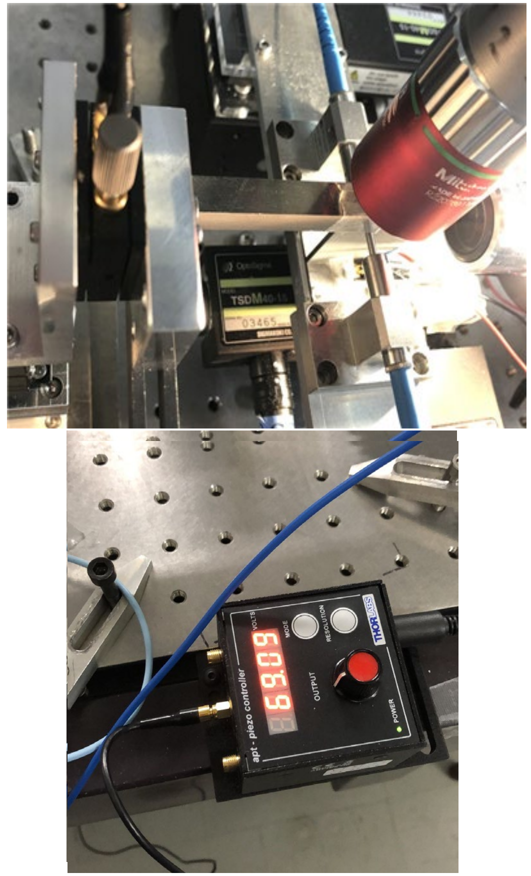


# Dip depth (coupling) at different distances

## ☐ Transmission spectrum vs voltage

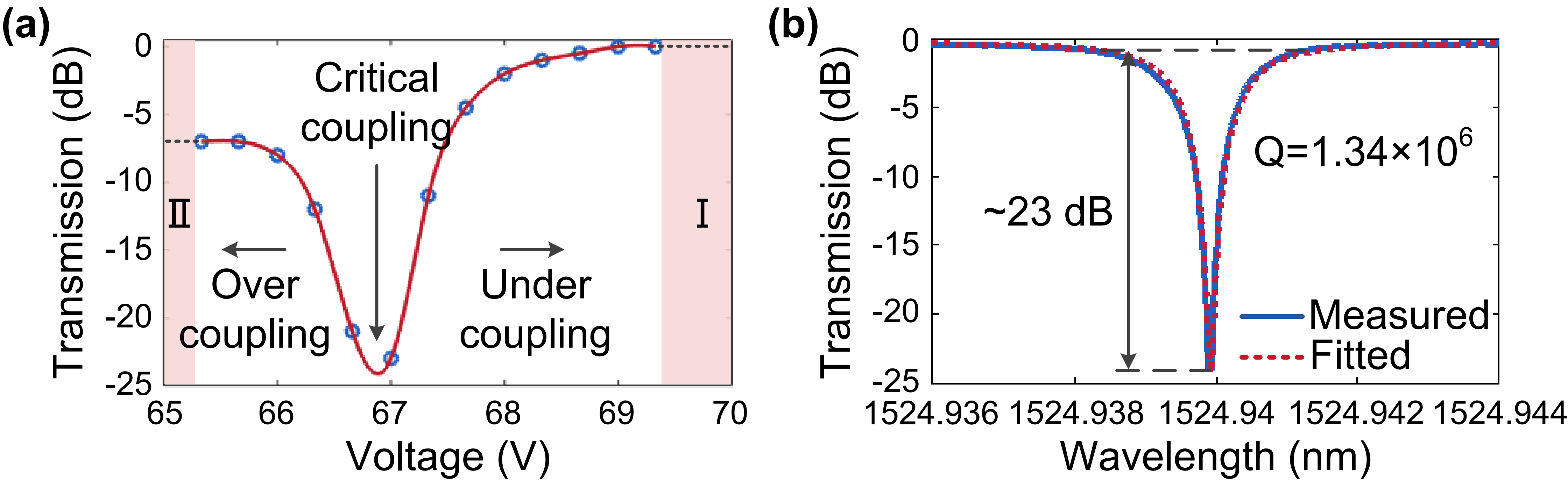



Piezo controller



333 nm/V

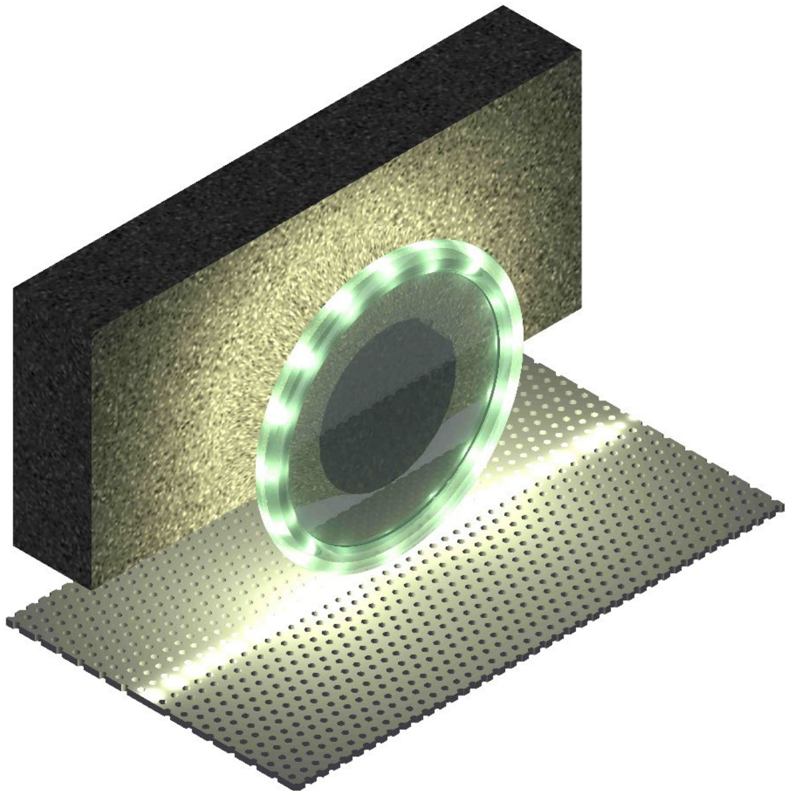
# Dip depth (coupling) at different distances

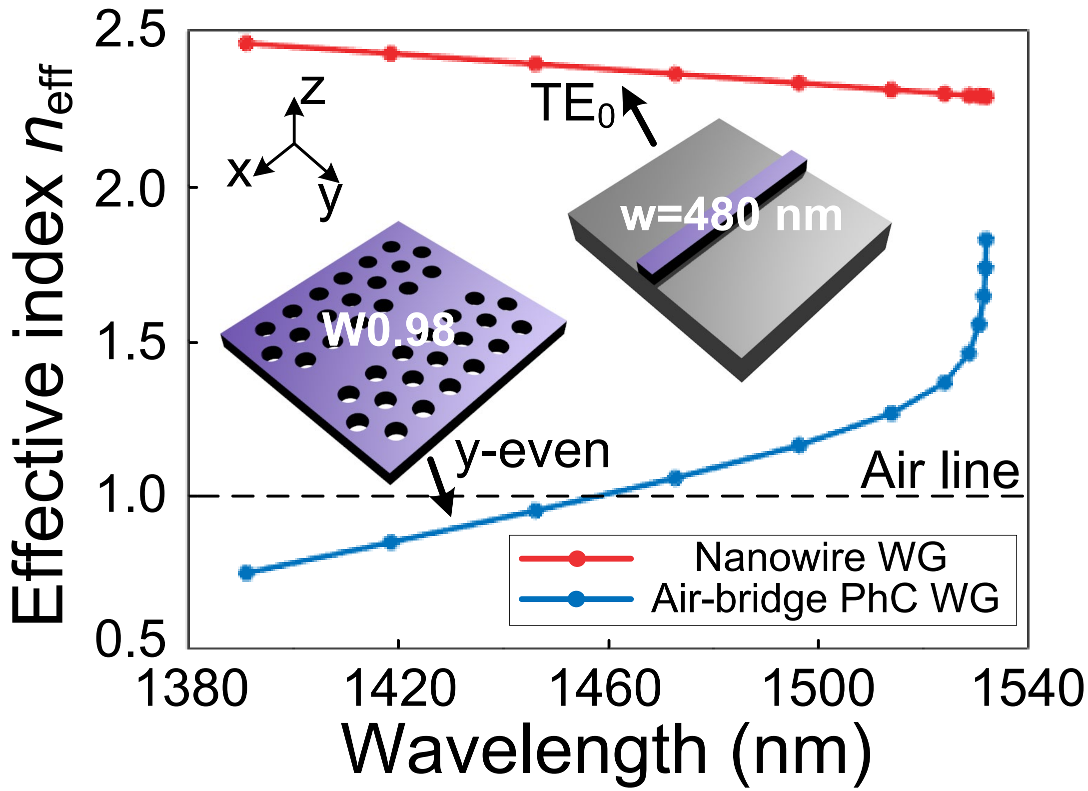



(0.33 μm/V)

# Summary

Achieved extremely efficient coupling between silica (n=1.4) WGM microcavity with silicon (n=3.4) photonic crystal waveguide






■ High coupling efficiency: 99.5% (~23 dB)

# Outline

## 1. High-Q mode on Si chip w/ tapered fiber

T. Tetsumoto, *et al*., Opt. Express **23**, 16256 (2015).
Y. Ooka, *et al*., Sci. Rep. **5**, 11312 (2015).

## 2. Efficient coupling of WGM w/ Si chip

Y. Zhuang, *et al., CLEO/Europe,* CK-5.2, Munich, 23-27 June (2019).
Y. Zhuang, *et al.* (in preparation)

## 3. Coupling of WGMs for optical buffering

W. Yoshiki, *et al.,* Sci. Rep. **7**, 28758 (2017).

# Hybrid system consisting of two different cavities

**Silica toroid microcavity**

Ultra-high *Q* (Long storage time)

Operating principal: Optical Kerr effect

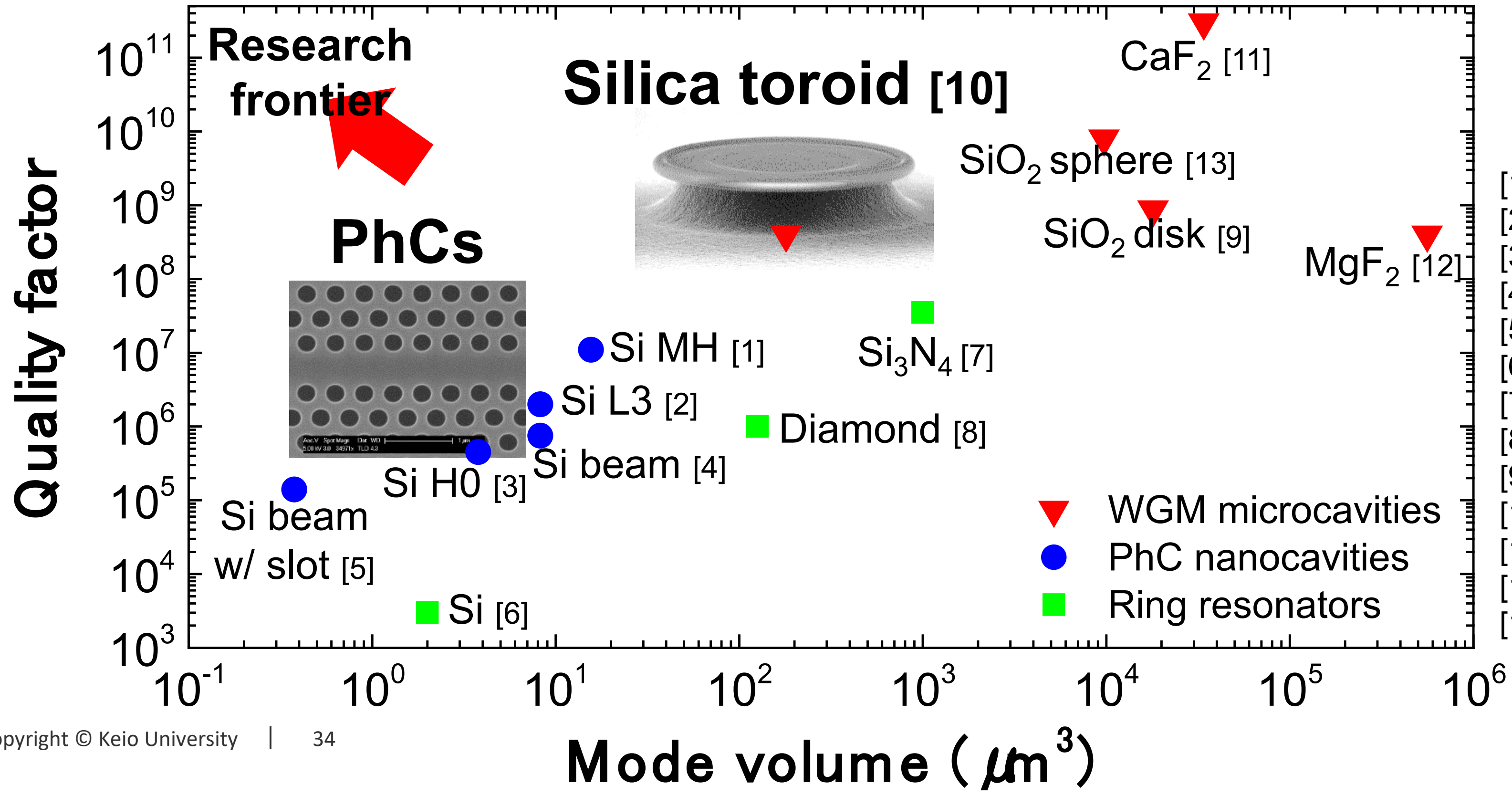
- Frequency Kerr comb
- Low power optical switch
- Optical buffer

**Si Photonic crystal nanocavity**

Ultra-small *V* (Quick response)

Operating principal: Carrier plasma effect

- Fast optical switching
- Photodetection
- EO modulation




[1] Opt. Express **25**, 1769-77 (2017)
[2] Appl. Phys. Lett. **104**, 241101 (2014)
[3] Appl. Phys. Lett. **105**, 101101 (2014)
[4] Appl. Phys. Lett. **94**, 121106 (2009)
[5] Opt. Express **21**, 32468-83 (2013)
[6] Opt. Express **18**, 18235-42 (2010)
[7] Optica **4**, 619-24 (2017)
[8] Nat. Photon. **8**, 369–74 (2014)
[9] Nat. Photon. **6**, 369–73 (2012)
[10] Appl. Phys. Lett. **85**, 6113 (2004)
[11] Opt. Express **15**, 6768-73 (2007)
[12] Opt. Express **23**, 7713-21 (2015)
[13] Opt. Lett. **23**, 247–9 (1998).

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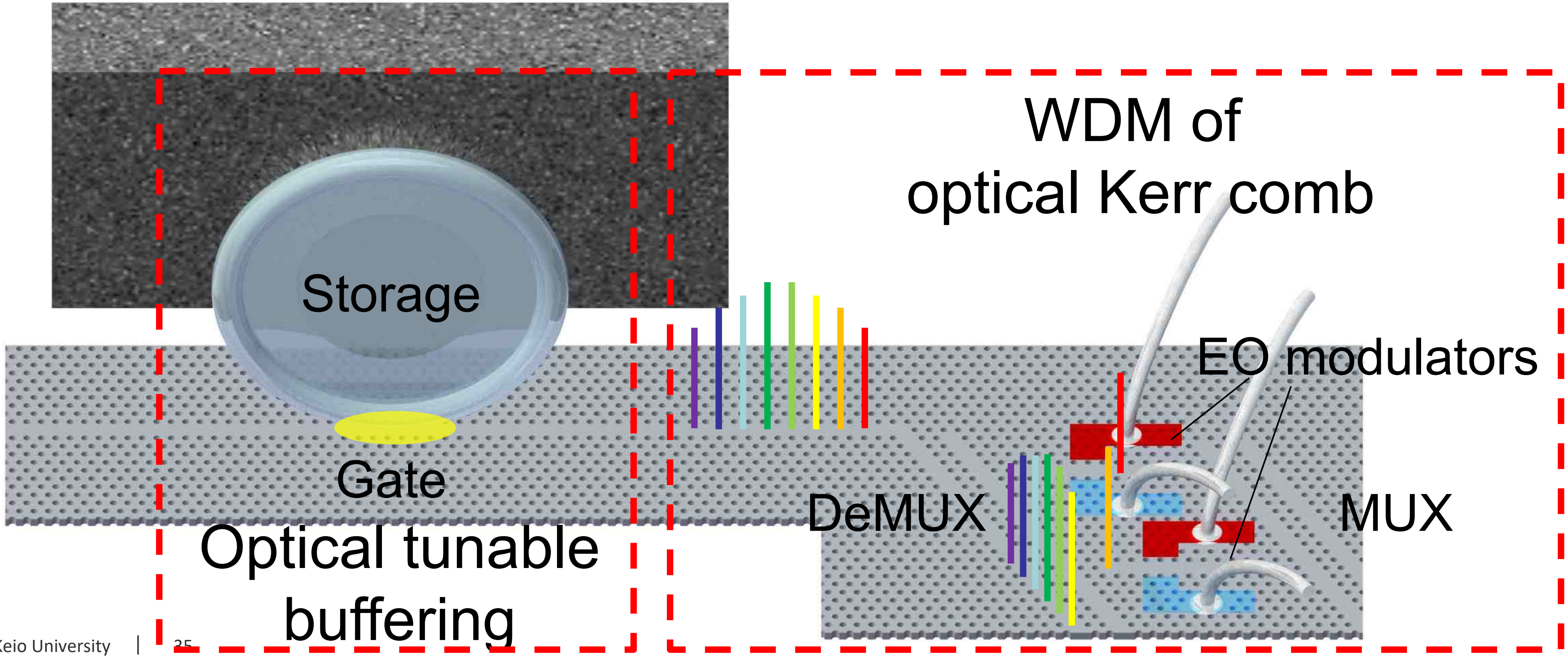
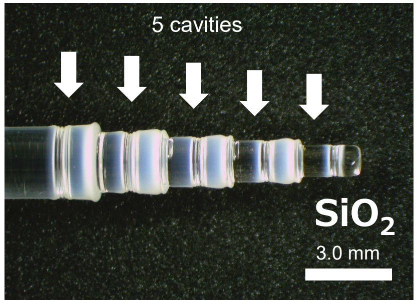


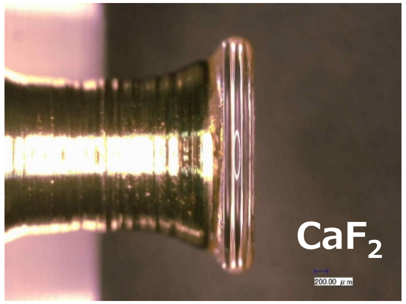

 

# Whispering gallery mode cavity

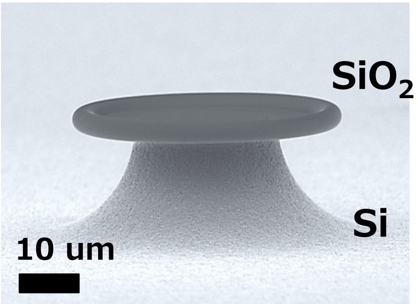
## Whispering gallery mode cavities



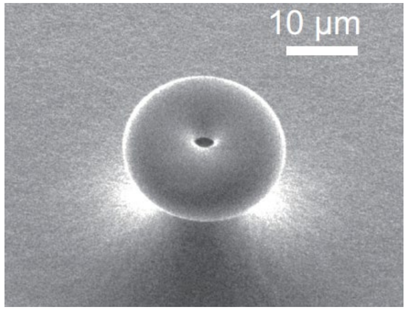

**Silica rod** ($Q$>$10^8$)




**$CaF_2$ disk** ($Q$>$10^{10}$)

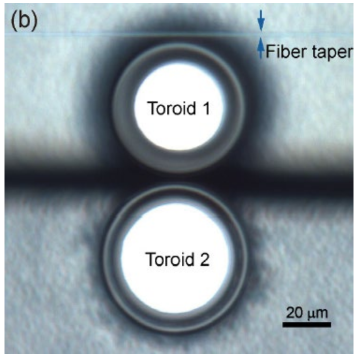



**Silica toroid** ($Q$>$10^8$)

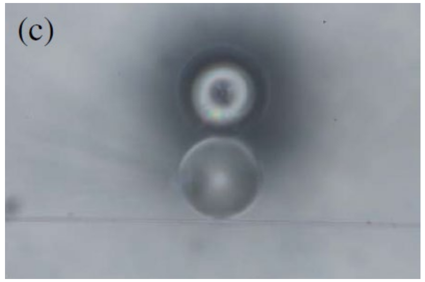



**Silica sphere** ($Q$>$10^8$)

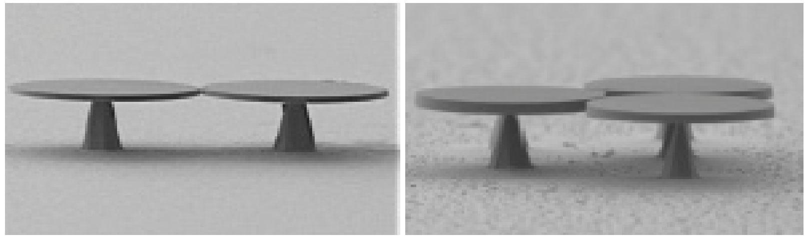
CRIT




C. Zheng *et al.*, Opt. Express 20, 18319–18325 (2012).




B. Peng *et al.*, Opt. Lett. 37, 3435-3437 (2012).



C. Schmidt *et al.*, Phys. Rev. A 85, 033827 (2012).

## Tuning methods

- Thermo-optic tuning
  (e.g. Armani et al., Appl. Phys. Lett. 22, 5439- (2004))
- Pressure tuning
  (e.g. Ilchenko et al., Opt. Commun. 145, 68- (1998))

**Slow response > 1 μs**

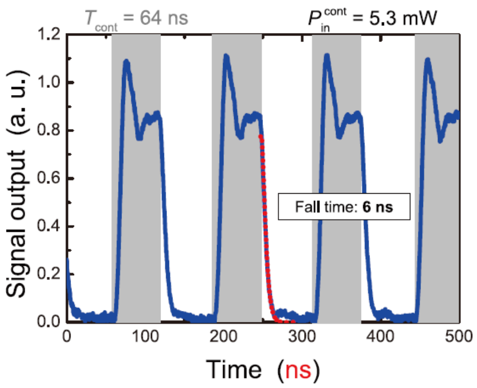
# Objective

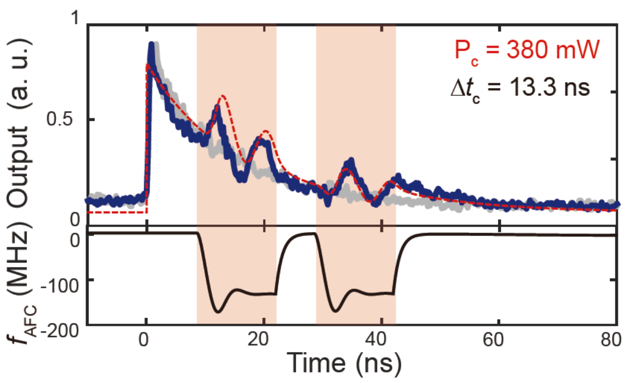
## To achieve all-optical tunable buffering using the Kerr effect in coupled ultra-high-$Q$ silica toroid microcavities

### ● Kerr effect

- Changes refractive index **instantaneously**.
- Employed for **all-optical switching** and **frequency conversion**.

W. Yoshiki, & T. Tanabe Opt. Express 22, 24332-24341(2014).
W. Yoshiki, T. Tanabe et al., Opt. Lett., 41, 5482-5485 (2016).

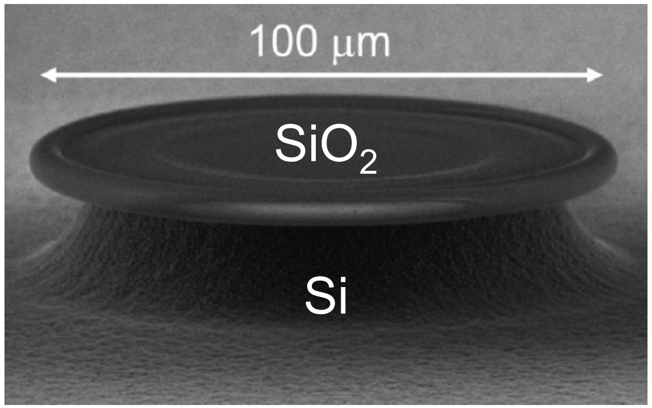



### ● Silica toroid microcavity

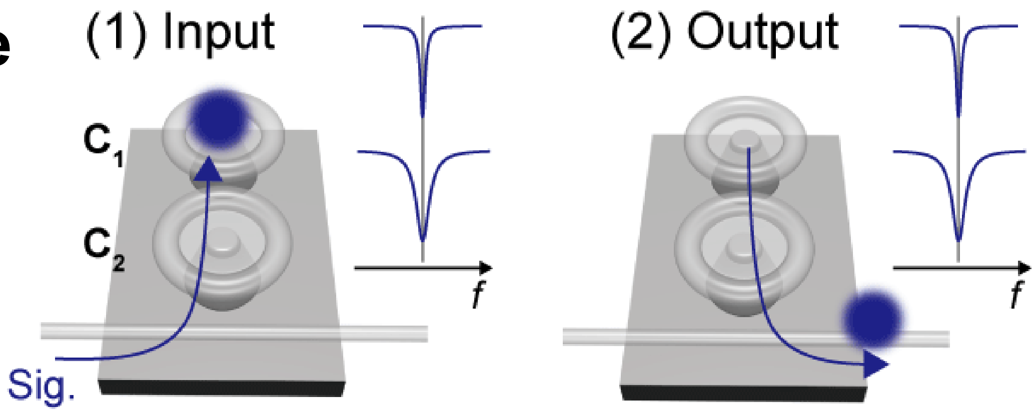
- Ultra-high $Q$ factor (~4 x $10^8$)
- Small mode volume (~ 200 μ$m^3$)
- On-chip fabrication

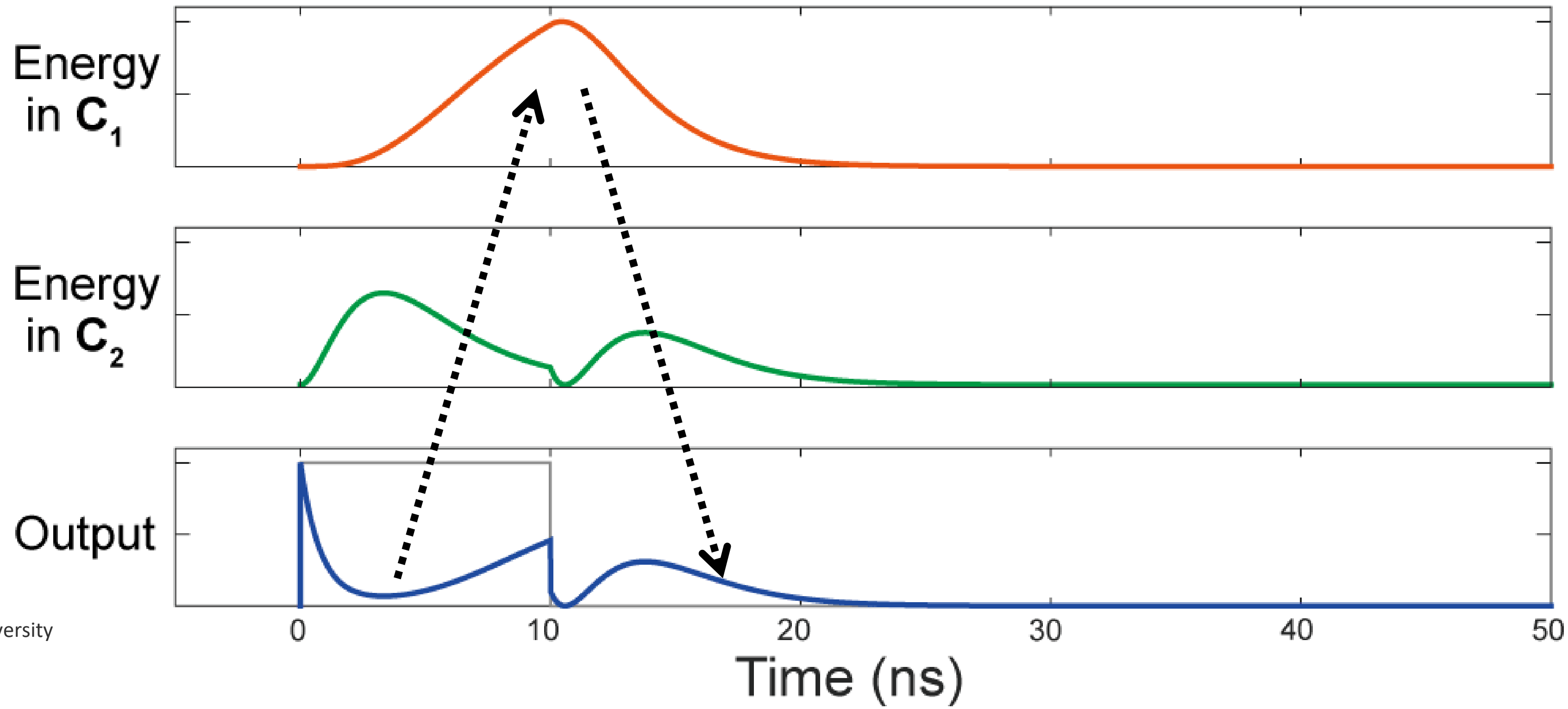
T. Kippenberg et al., Appl. Phys. Lett. **85**, 6113 (2004).



# Introduction: All-optical "tunable" buffering

## ● Principle



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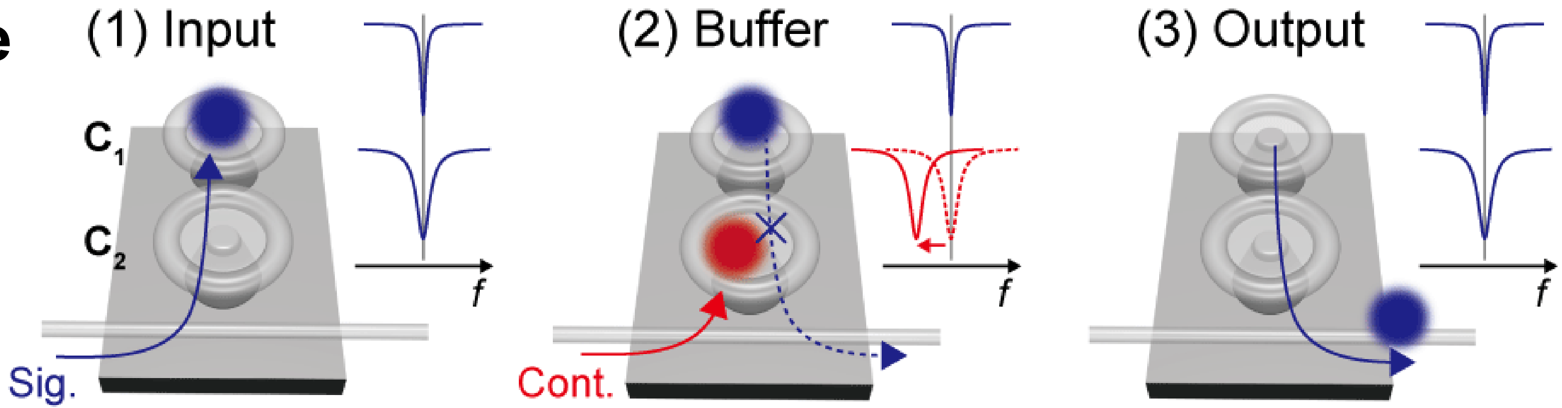
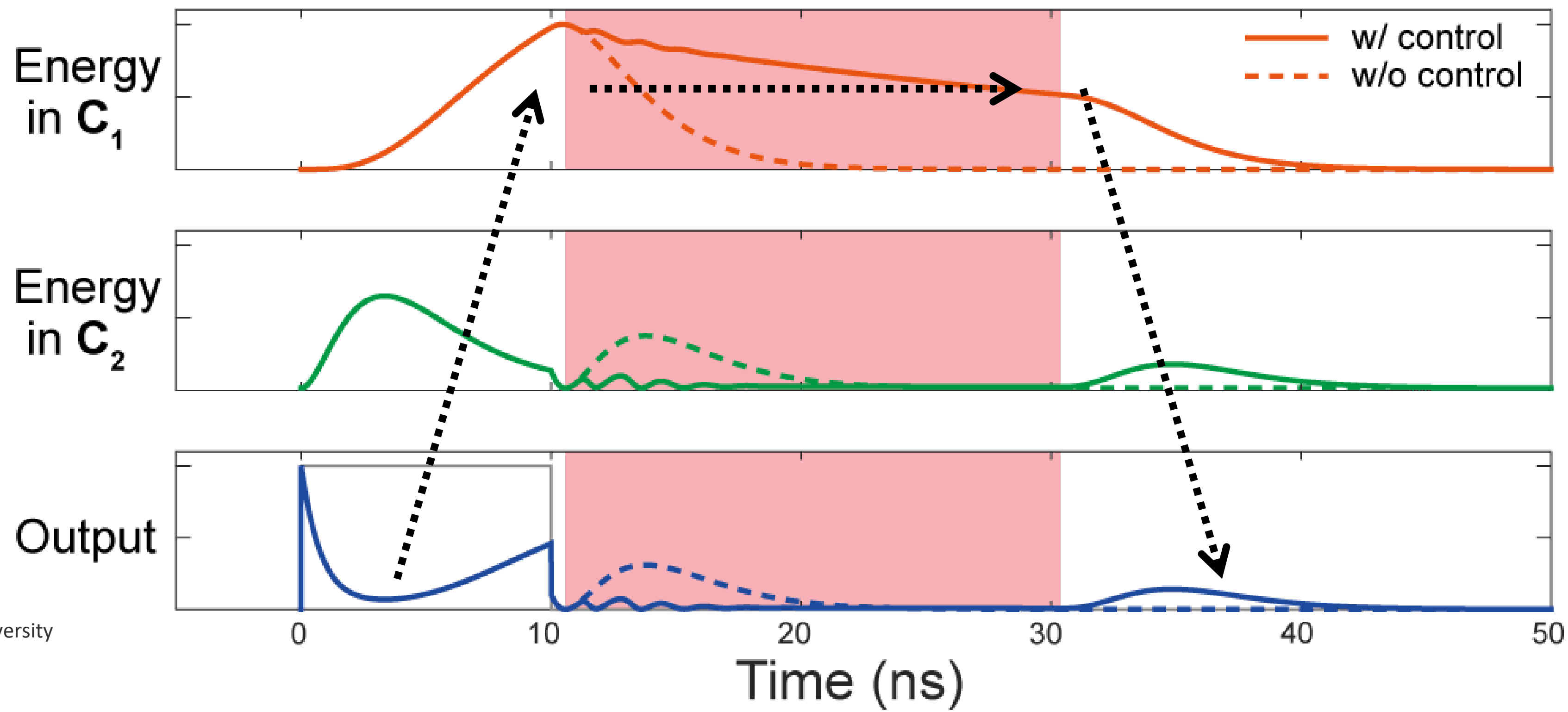
## Principle

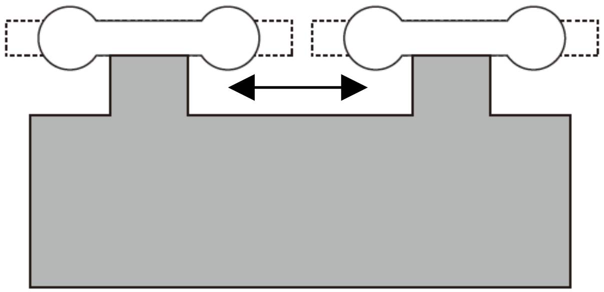


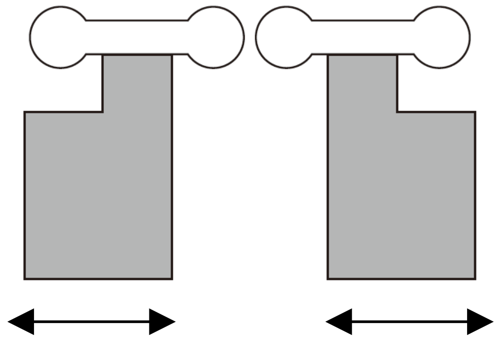
# Device preparation

## ● Silica toroid microcavity on an edge

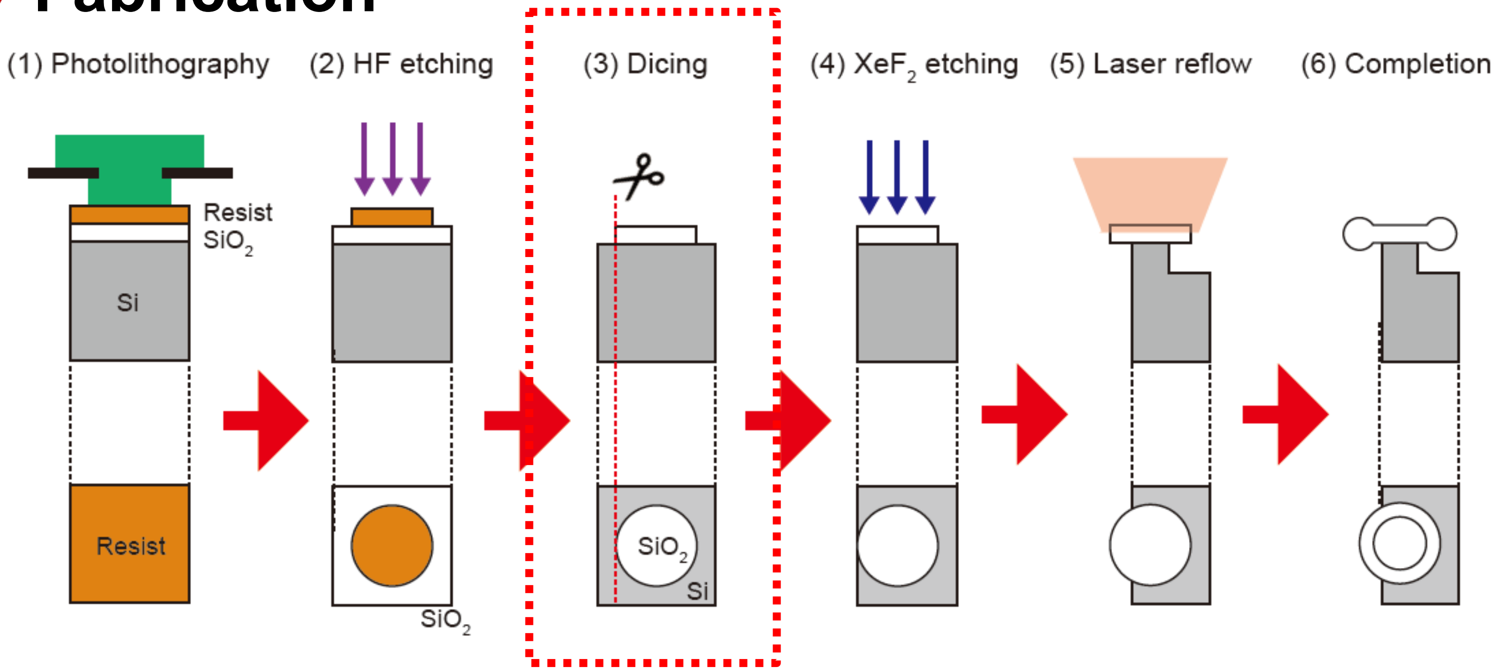
- ■ Shrinkage owing to laser reflow

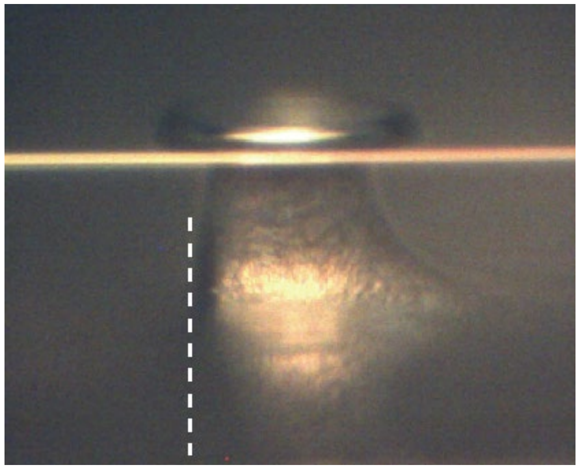


- ■ Use of edge silica toroid microcavity



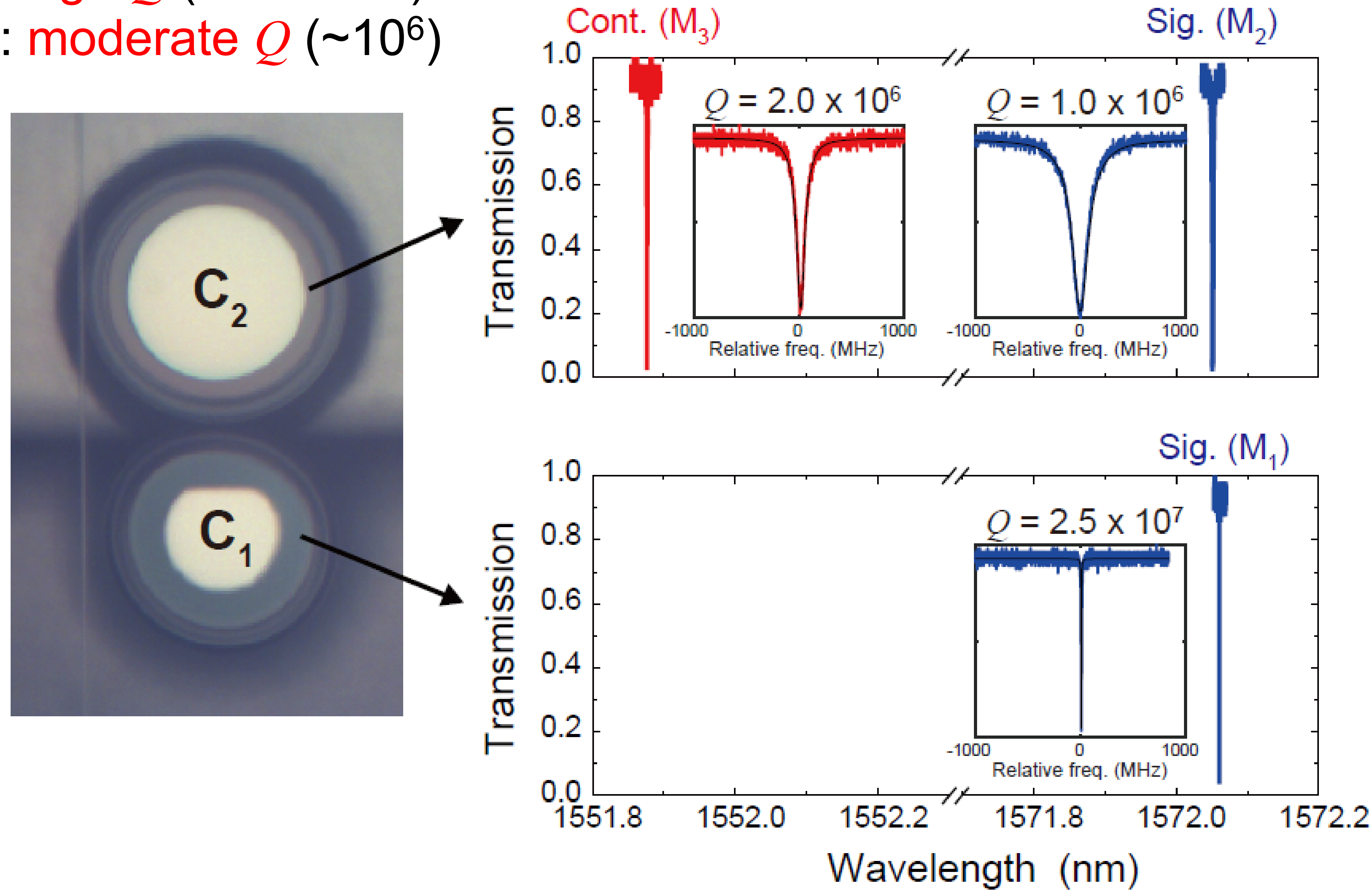
## ● Fabrication



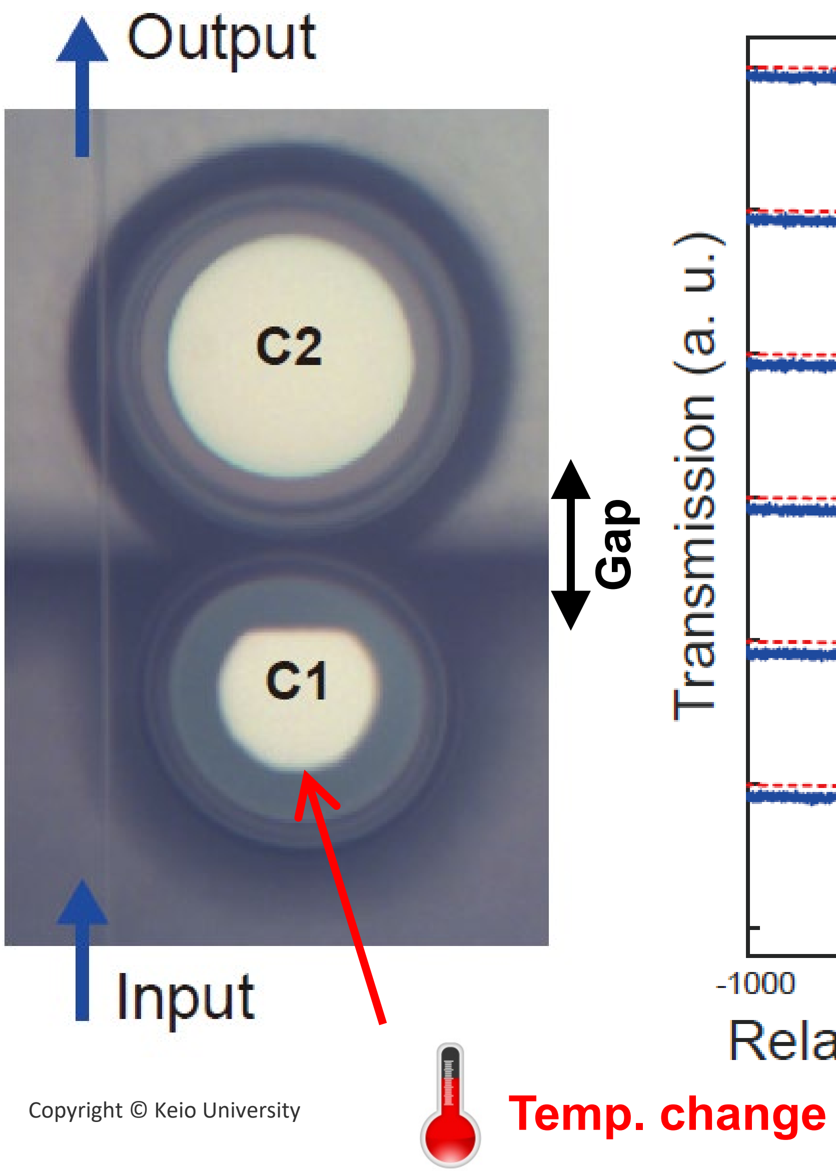



# Optical modes employed for experiments

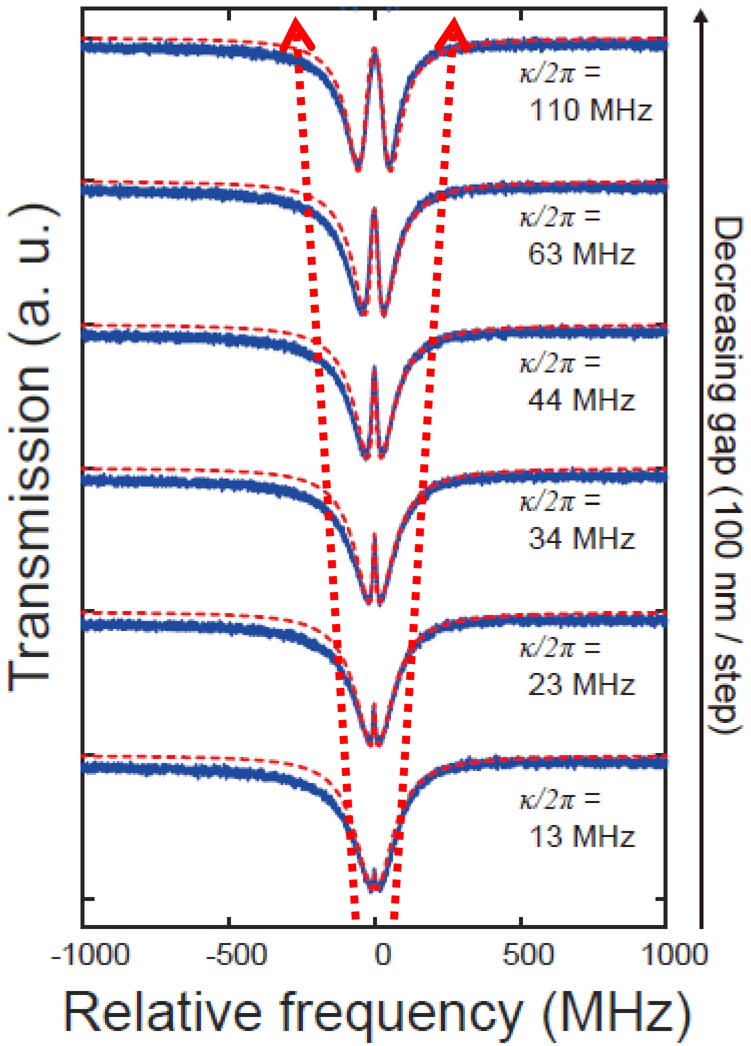
- Three modes: **$M_1$**, **$M_2$** (**signal**) and **$M_3$** (control).
- **$M_1$**: ultra-high $Q$ (~2.5 x$10^7$)
- **$M_2$** & **$M_3$**: moderate $Q$ (~$10^6$)



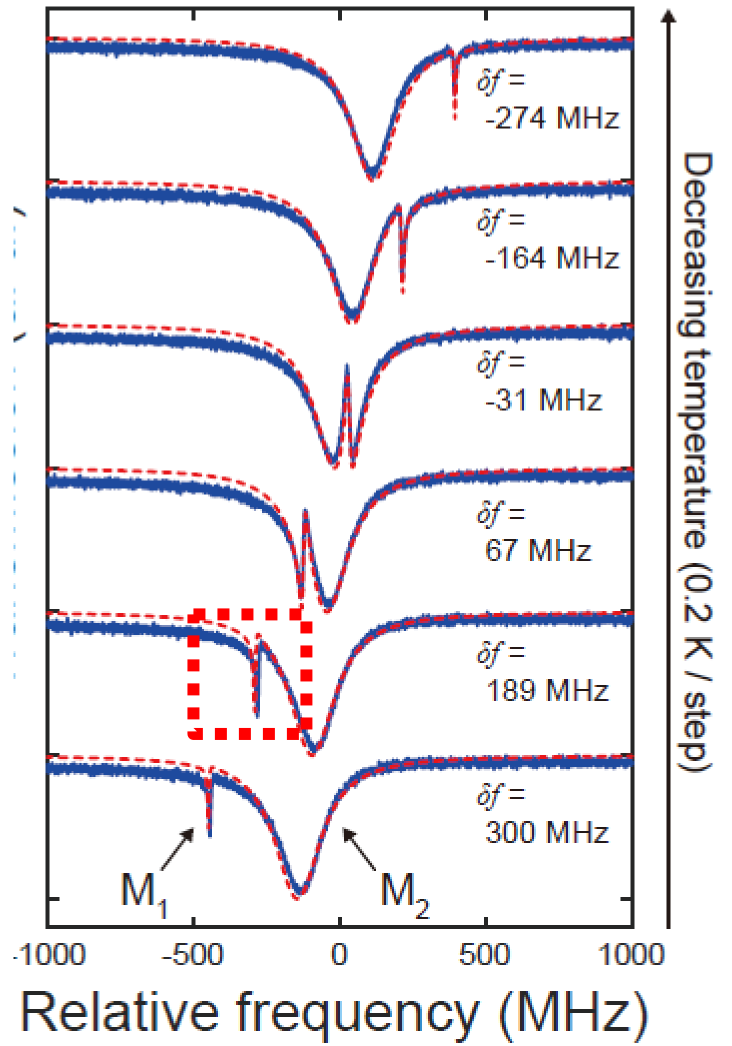
# Observation of coupling



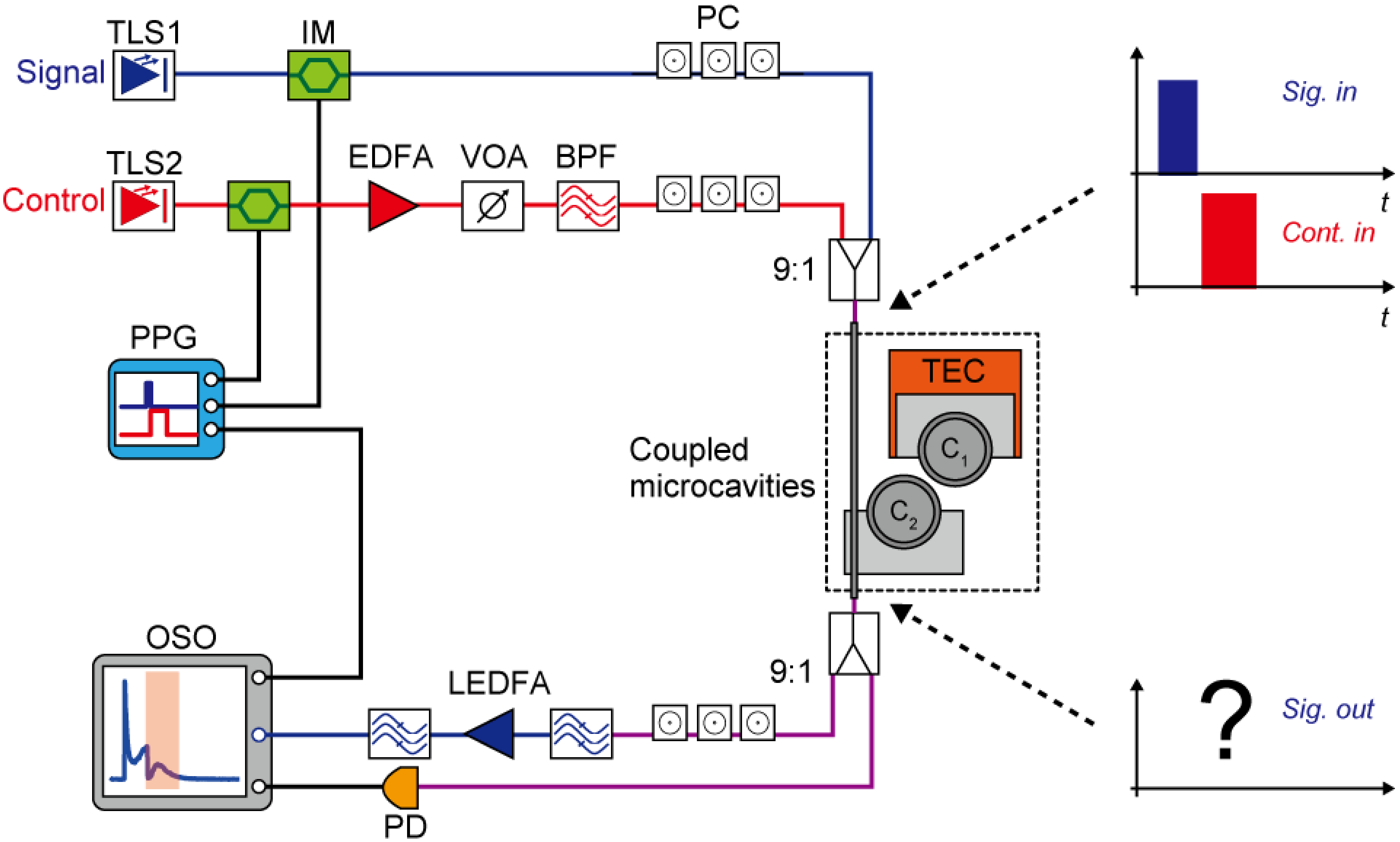

## ● Different gap




## ● Different temperature



# Experimental setup

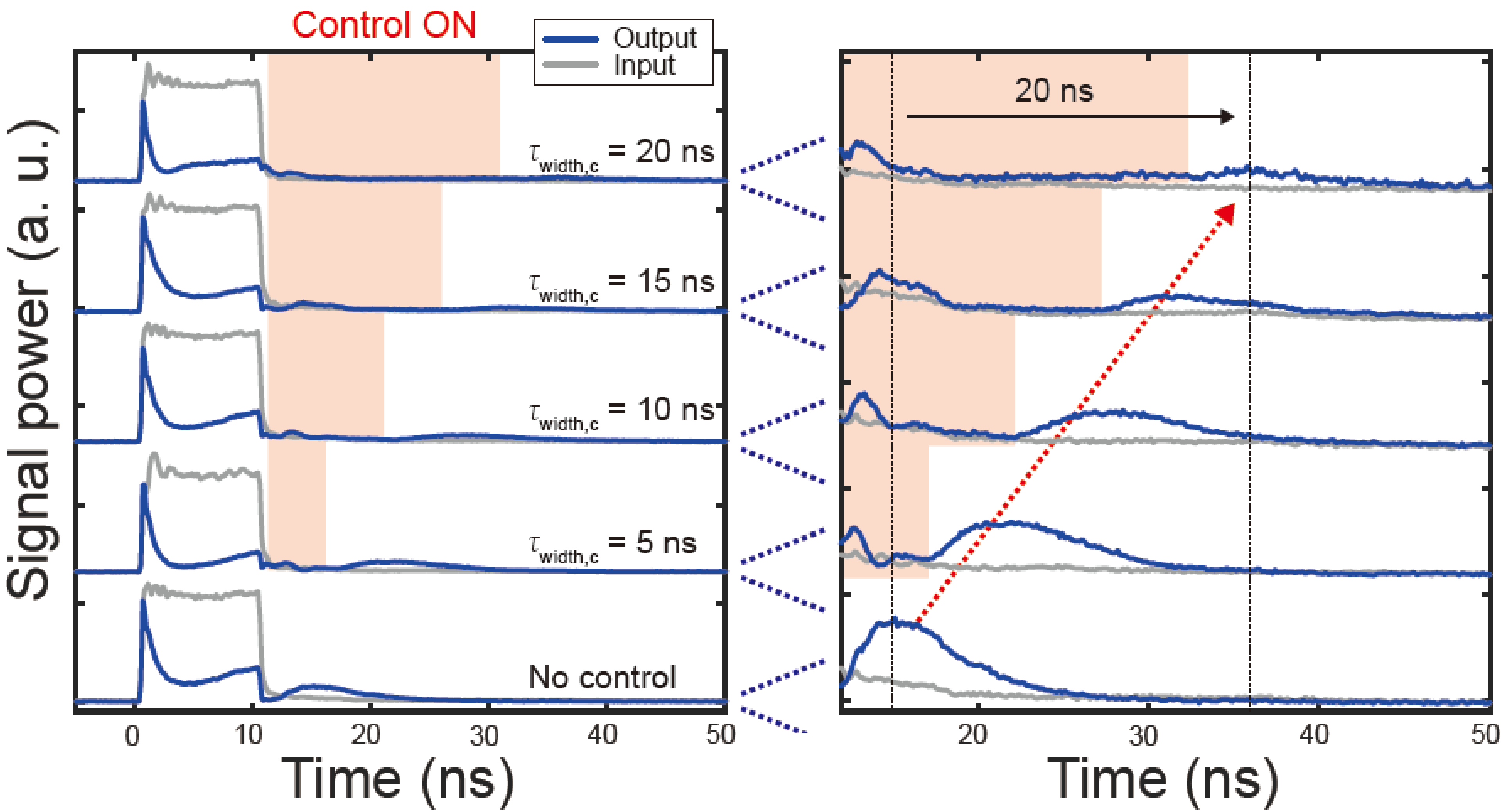





**TLS**: Tunable laser source / **IM**: Intensity modulator / **EDFA**: Erbium-doped fiber amplifier
**VOA**: Variable optical attenuator / **BPF**: Band-pass filter / **PC**: Polarization controller
**PD**: Photodetector / **OSO**: Optical sampling oscilloscope / **PPG**: Pulse pattern generator

# Experimental results (1)

- **Buffering operation**

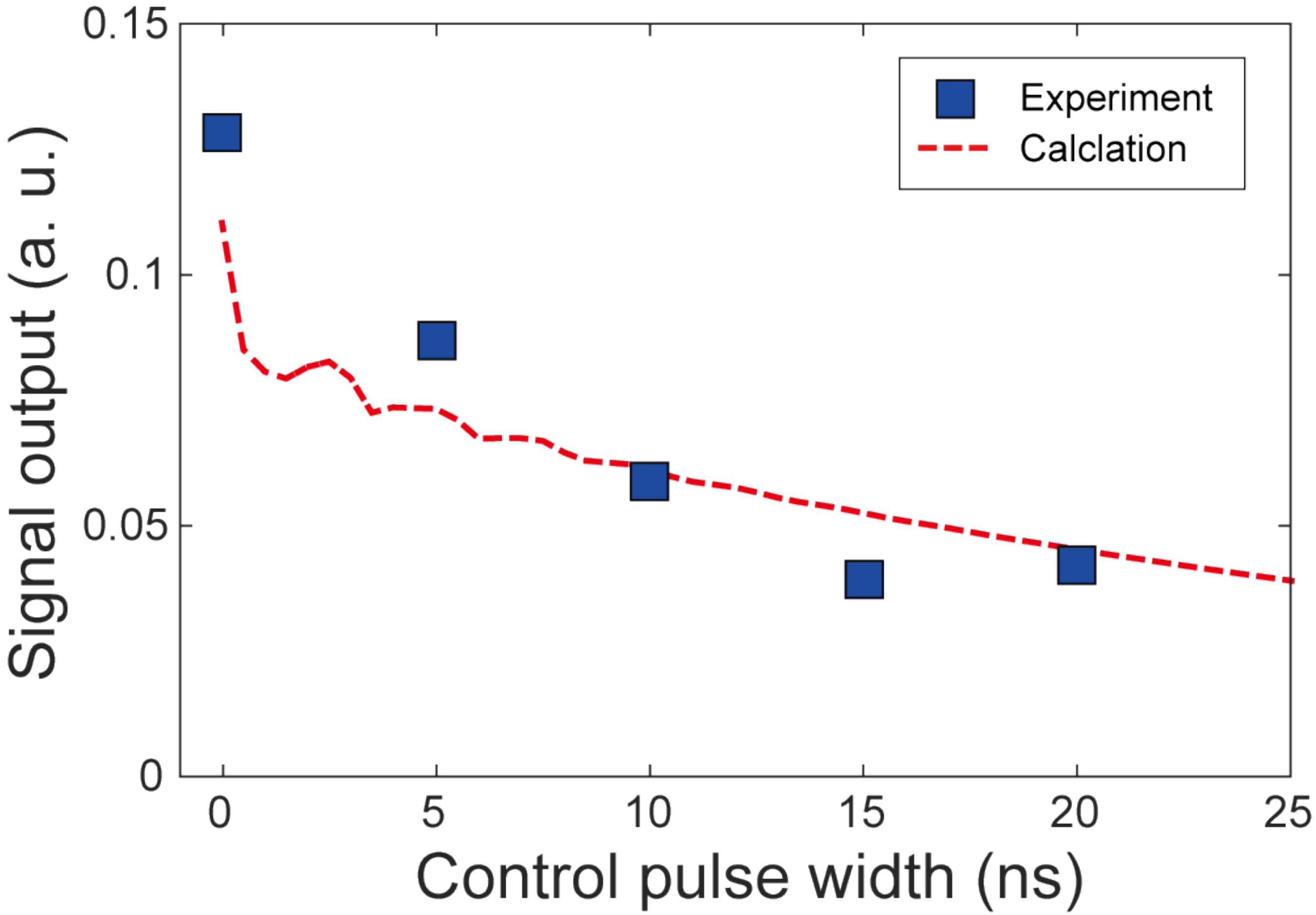


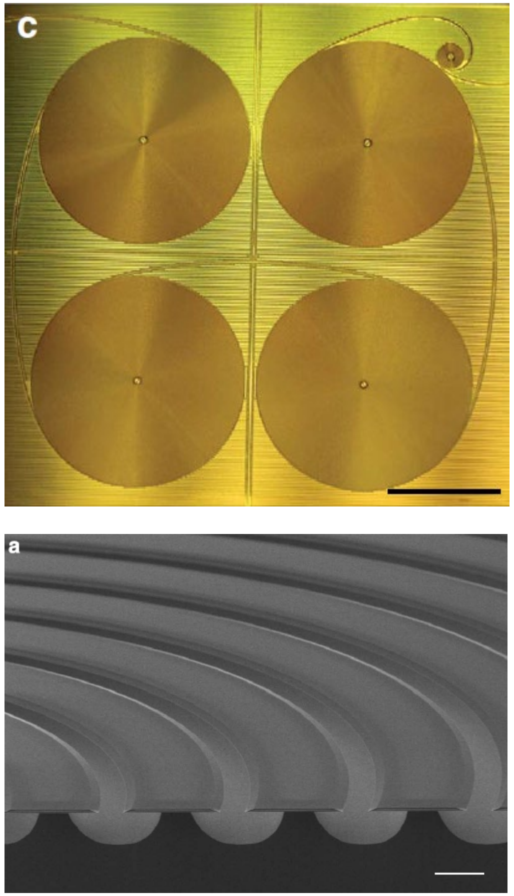



**All-optical tunable buffering / 10-ns pulse buffered for 20 ns**

# Experimental results (2)

## ● Control pulse width vs Signal output



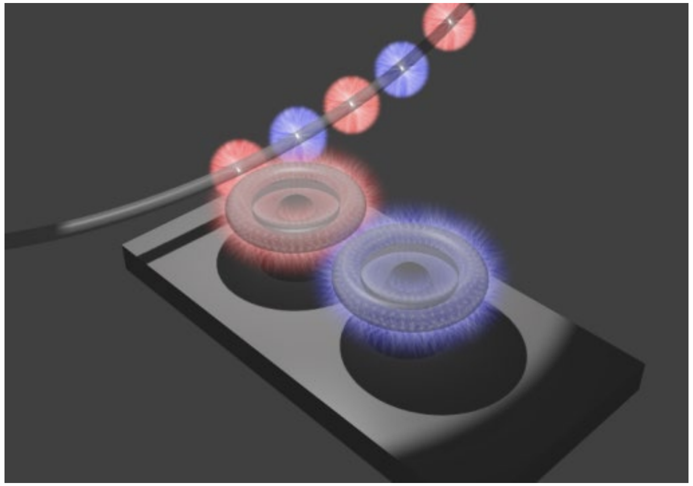

H. Lee et a., Nat. Commun. **3**, 867 (2012).

- Output efficiency: **~10%** (due to spectral mismatch)
- Equivalent light attenuation: **1.1 dB/m**

⟷ State-of-art "fixed" on-chip optical buffer: **~0.1 dB/m**

# Summary

## Achieved all-optical tunable buffering using the Kerr effect in coupled ultra-high-$Q$ silica toroid microcavities



- **First attempt** to dynamically control CMIT w/ ultra-high $Q$ WGM cavities.
- **10-ns signal pulse** can be buffered for **20 ns**.

# Summary

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# Acknowledgement

- The team

**<u>Post doc position soon available!</u>**