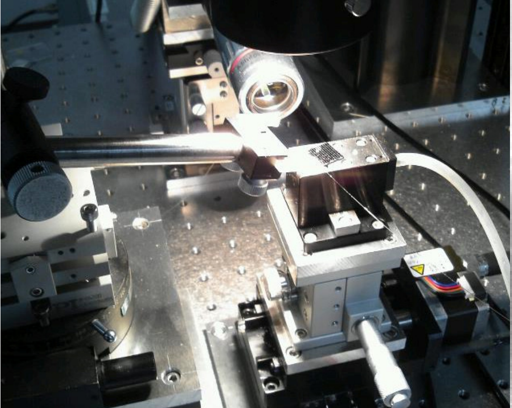
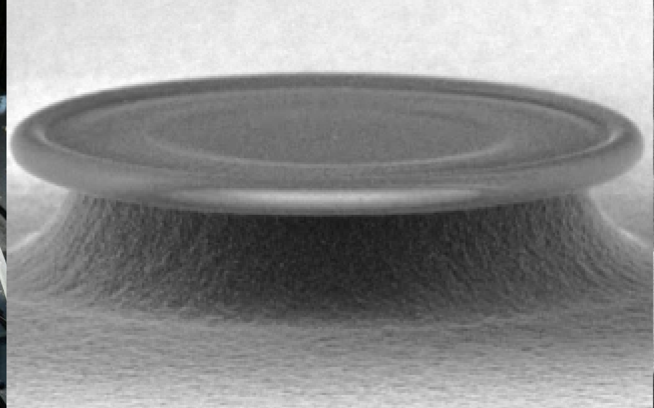
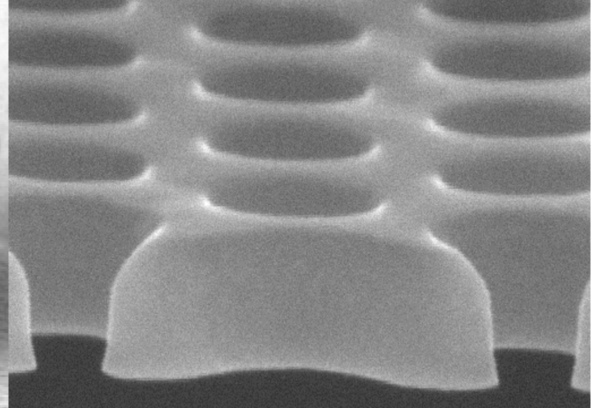
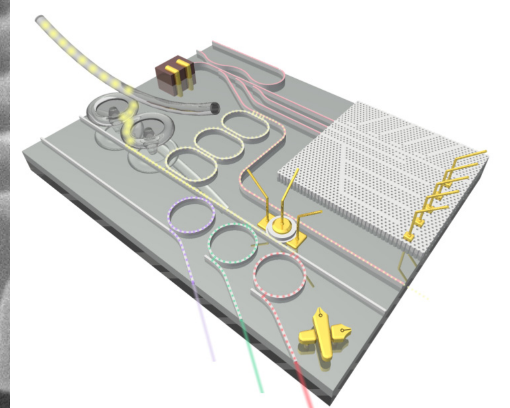





SPIE Photonics West 2016

9756-54

# Fiber-coupled photonic crystal nanocavity for reconfigurable formation of coupled cavity system

*Department of Electronics and Electrical Engineering, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi Kohoku, Yokohama 223-8522, Japan*
*email: takasumi@elec.keio.ac.jp

Tomohiro Tetsumoto, Yuta Ooka, Takasumi Tanabe

# Background

## Photonic crystal (PhC) nanocavity

Advantage

✓ High *Q* & extremely small *V*

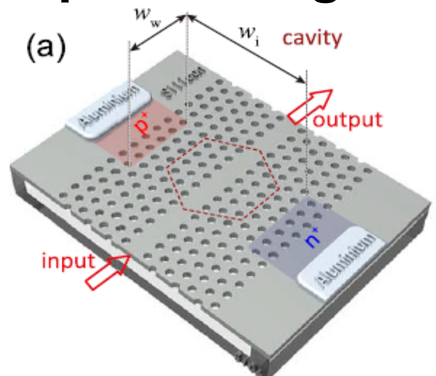
⇒Useful for nonlinear experiments

Disadvantages

✓ Coupling to fiber is poor

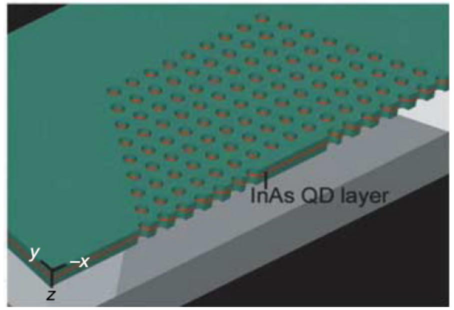
✓ Collection efficiency is low

### Optical signal processing




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

### Cavity-QED




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

## Coupled cavity system w/ PhC nanocavities

Advantage

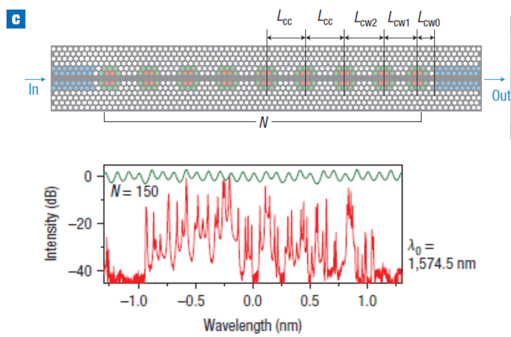
✓ Complex functions achievable

i. e. optical buffer, optical memory

Disadvantage

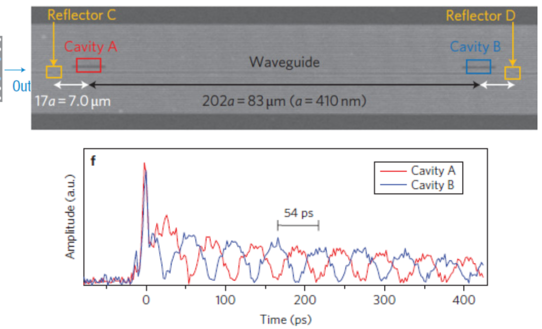
✓ Requires advanced fabrication technique

### Optical buffer




M. Notomi, *et al.*, Nat. Photon. **2**, 741-747 (2010).

### Dynamic control of coupling

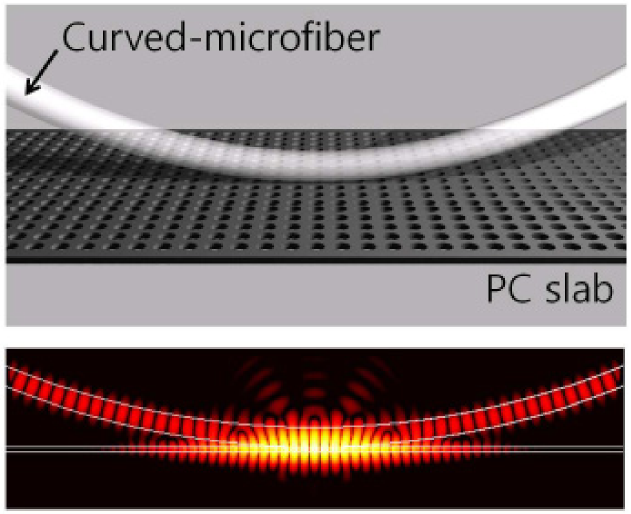



Y. Sato, *et al.*, Nat. Photon. **6**, 56-61 (2012).

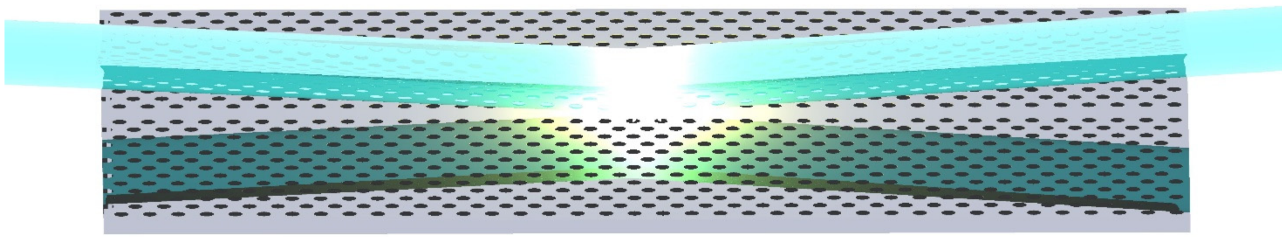
# Nanofiber assisted reconfigurable PhC nanocavity

## Fiber coupled PhC nanocavity (FCPC)

- ✓ **Is 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% (higher recorded value)




Ju-Young Kim, *et al.*, Optics Express **17**, 13009 (2007).



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

# Objective & overview

## Motivation

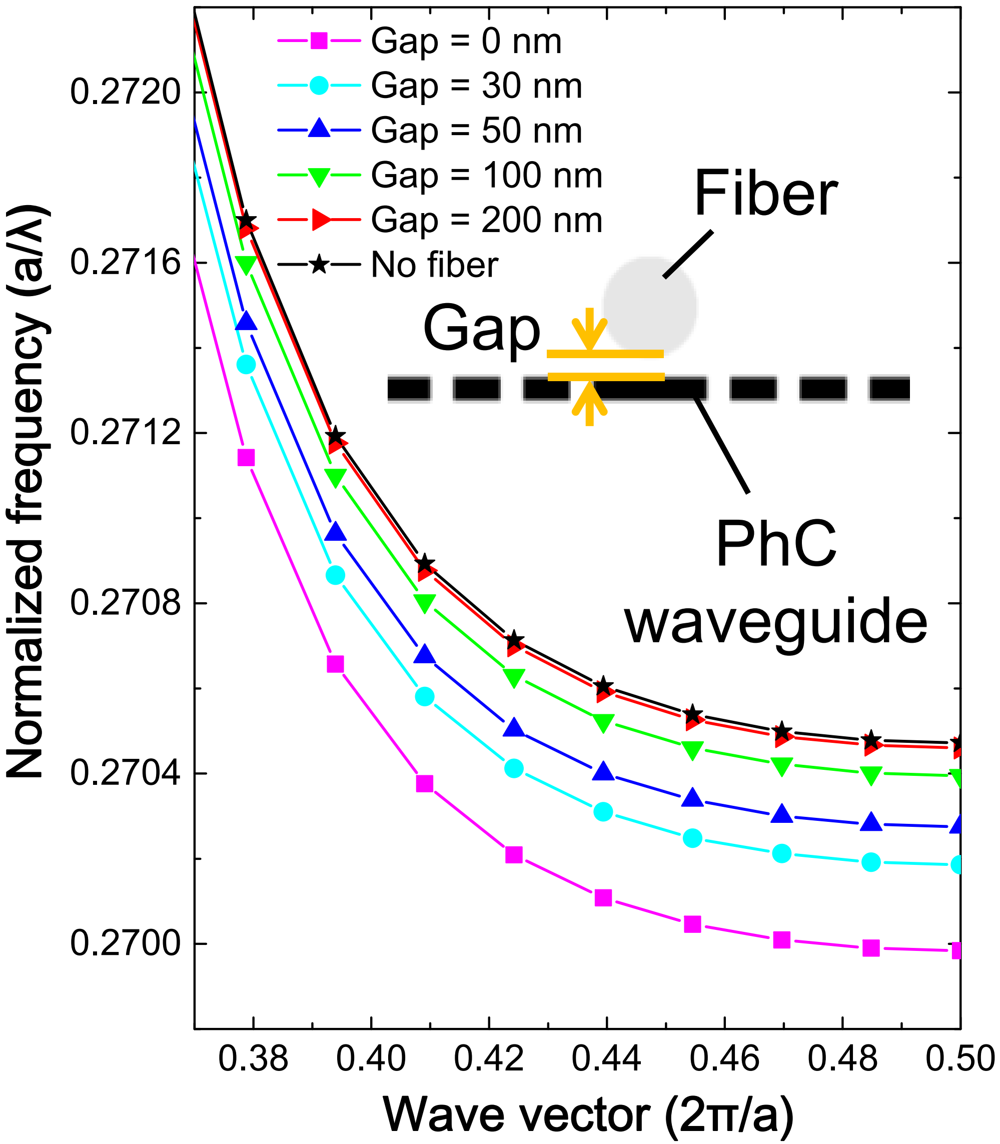
Demonstration of reconfigurable coupled cavity
with high coupling efficiency
using FCPC platform

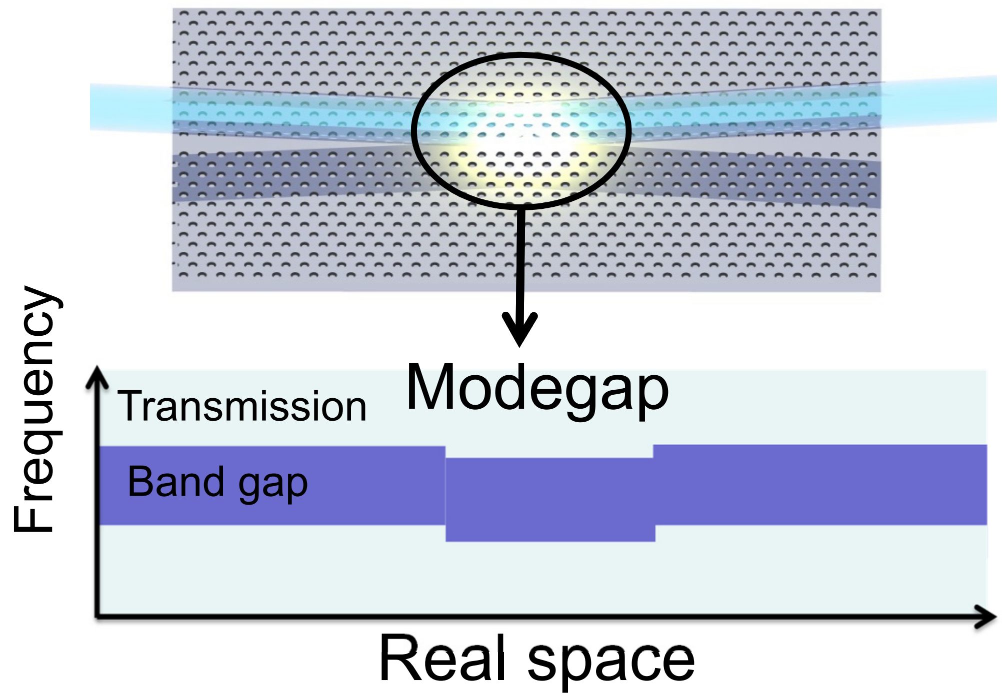
## Overview

- ✓ General properties of FCPC
- ✓ Experimental formation of coupled cavity using FCPC

# Principle of cavity formation



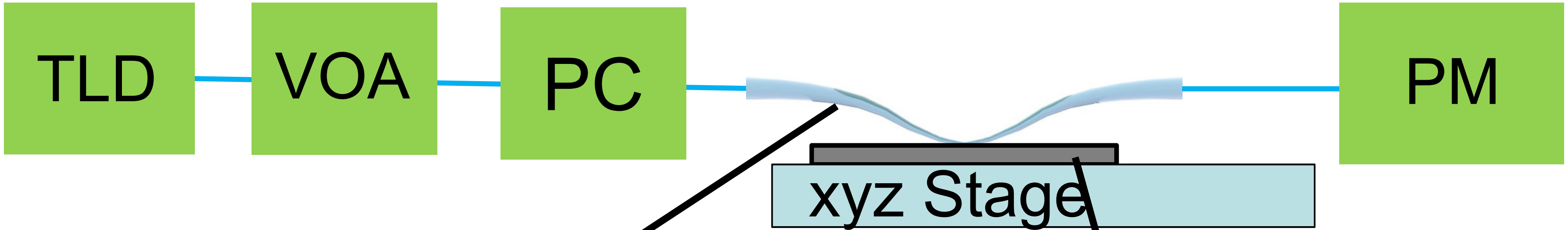



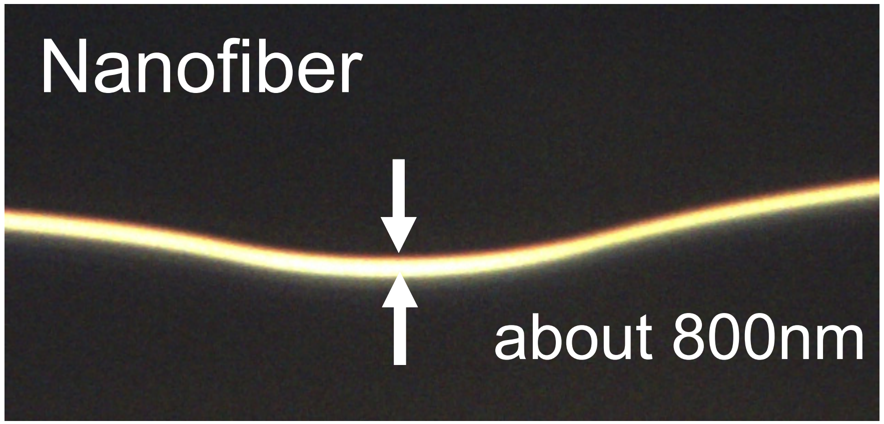

**Effective refractive index change results in formation of modegap cavity**

# Experiment

## Setup

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

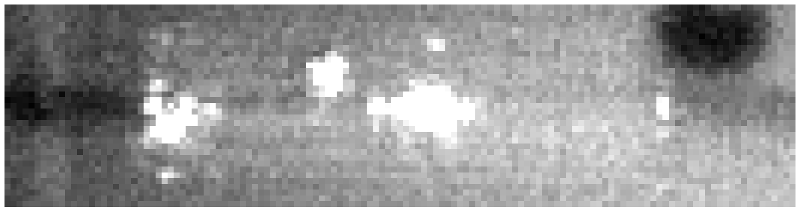


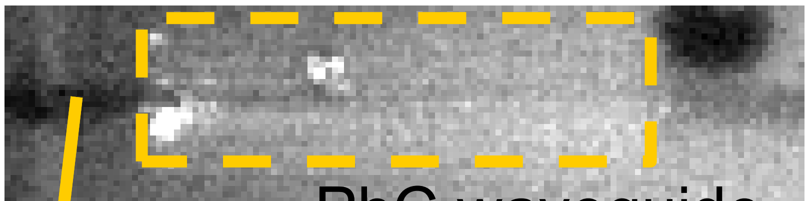

**Insertion loss of nanofiber:**
Typically 10dB,
**Best 1dB**

**PhC waveguide(w0.98)**
**Fabricated with 248nm KrF stepper exposure**
**Lattice constant: 420 nm,**
**Air hole diameter: 253 nm,**
**Slab thickness: 210 nm**

**On-resonance**



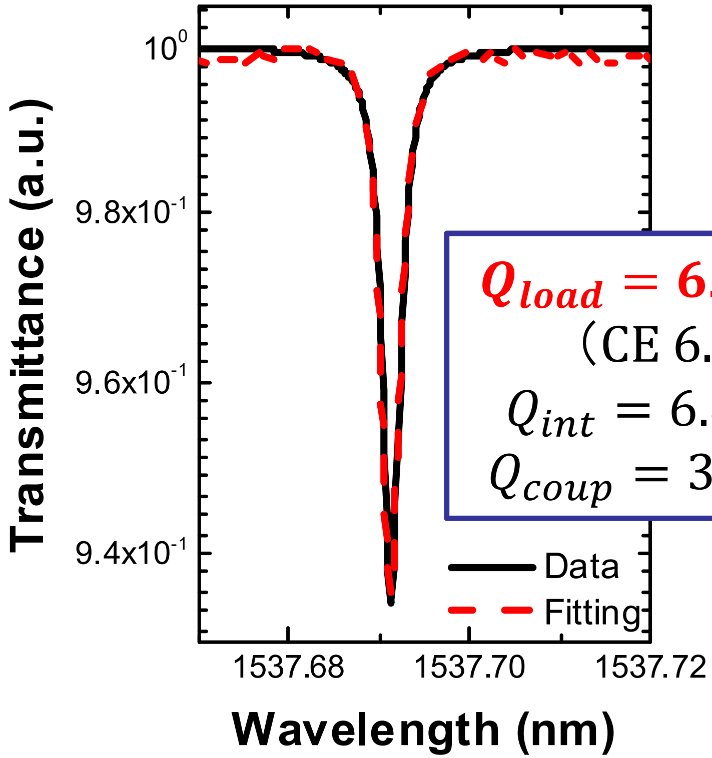
**Off-resonance**



Nanofiber PhC waveguide

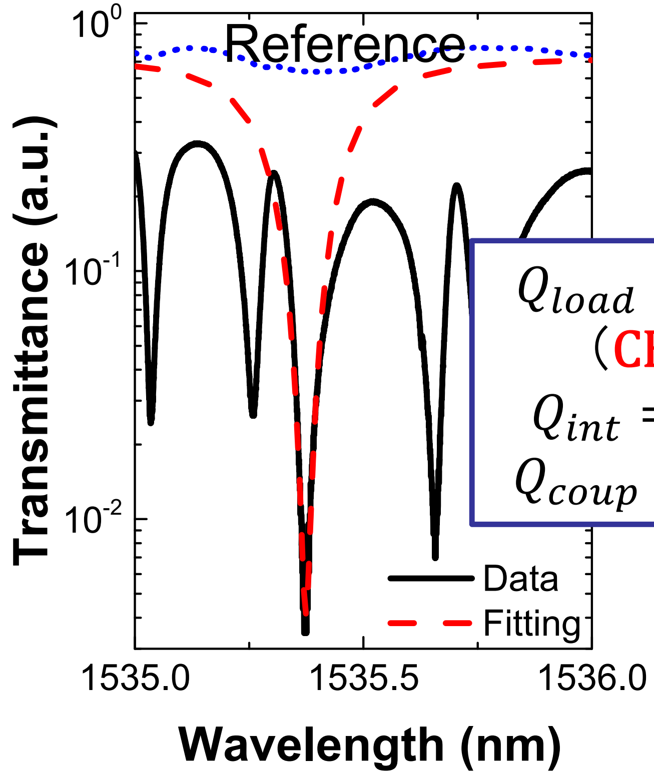
# Measurement of $Q$ and CE of FCPC

## 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

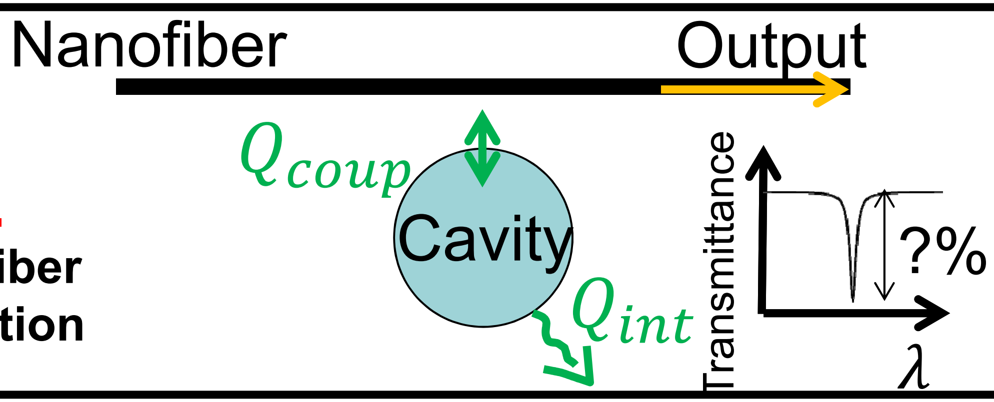



$Q_{load} = 6.1 \times 10^3$ (CE 99.6%)
$Q_{int} = 1.1 \times 10^4$
$Q_{coup} = 1.3 \times 10^4$

## Measured $Q$

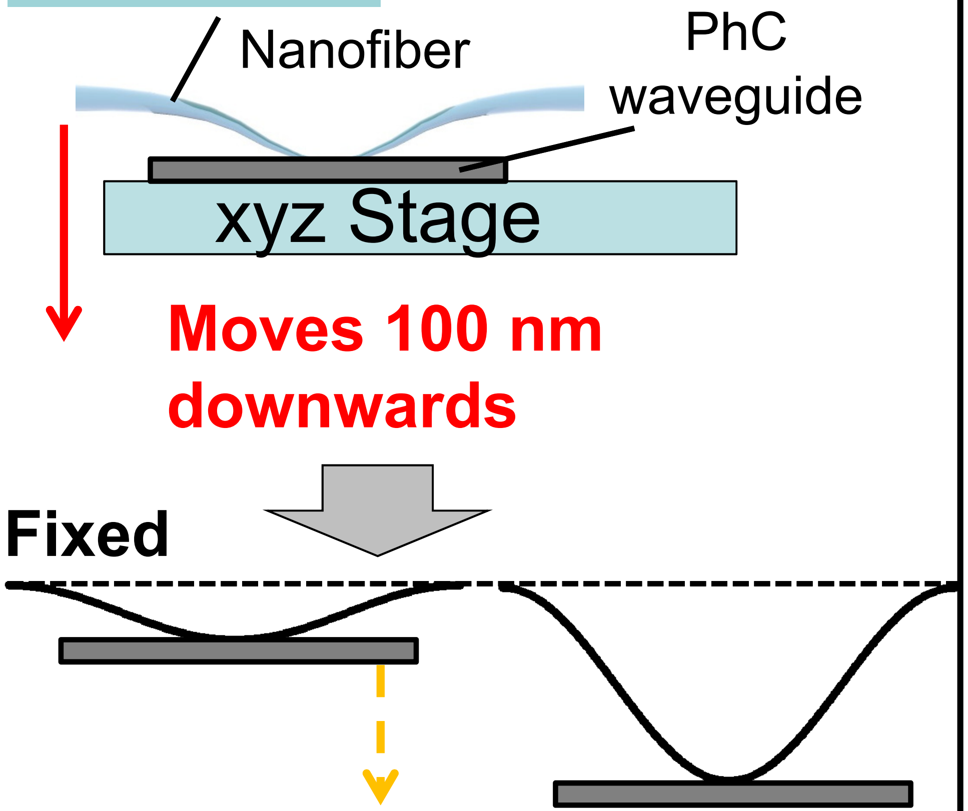
$$Q_{load}^{-1} = Q_{coup}^{-1} + Q_{int}^{-1}$$

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

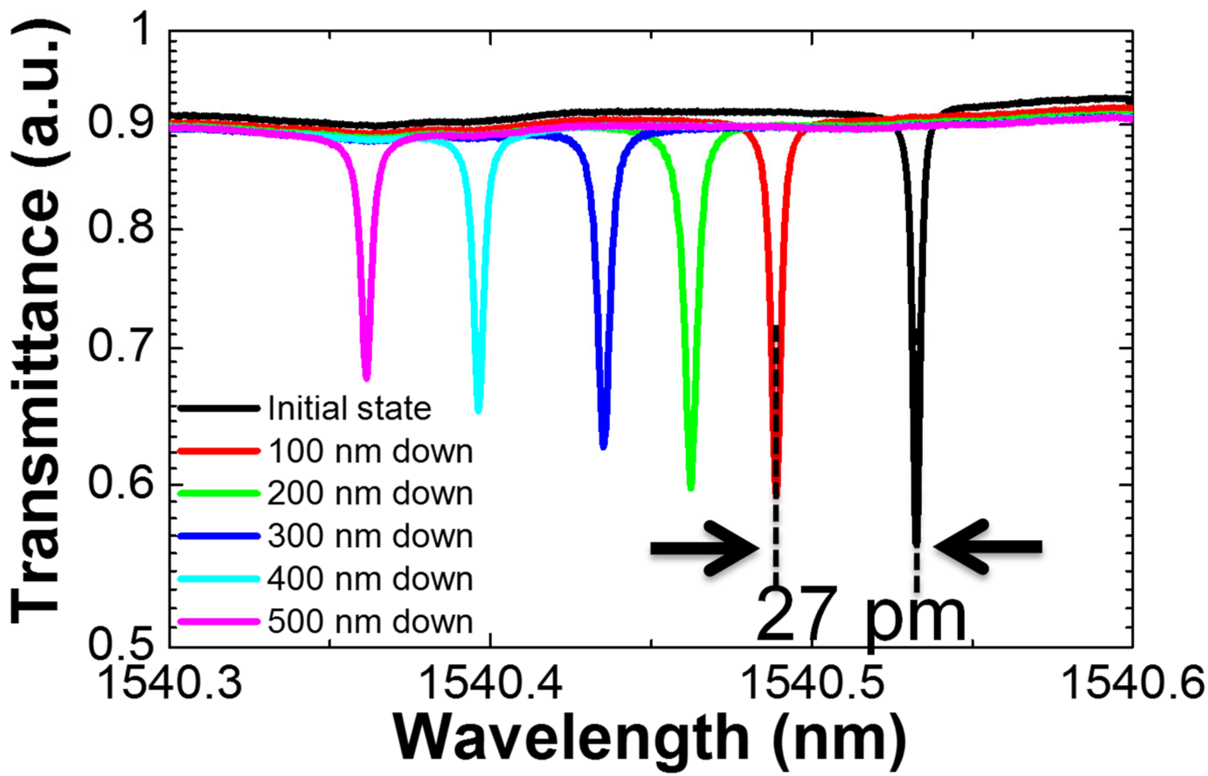


# Resonant wavelength tuning

## Method




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

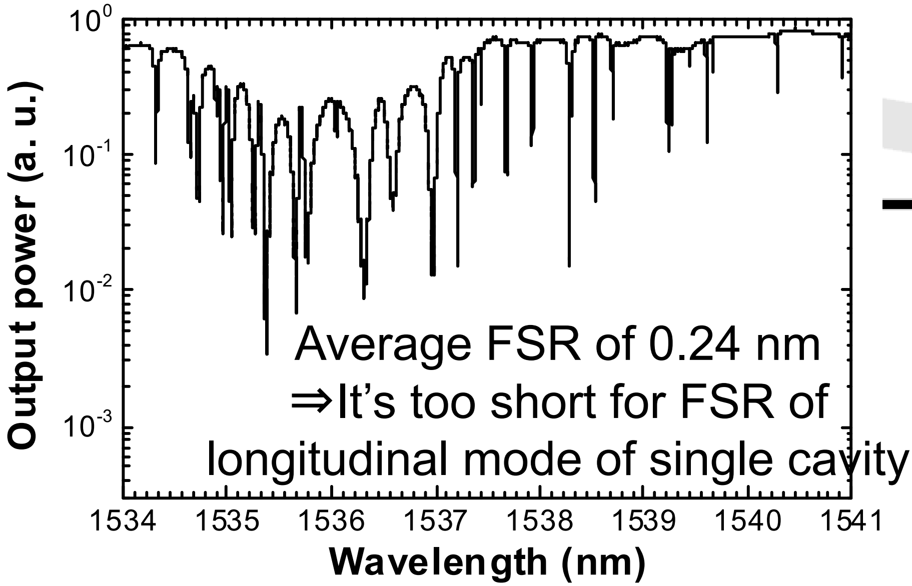


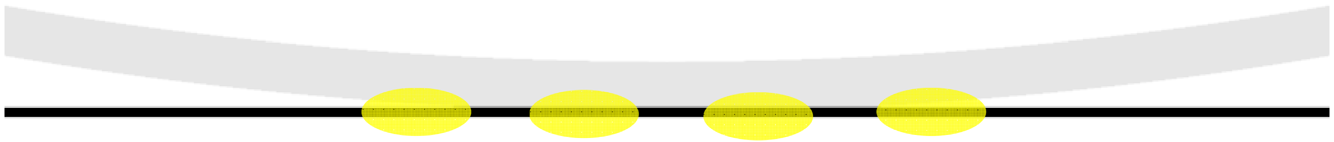

### Tuning sensitivity

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

# Multiple cavity formation

**Multi resonat peaks**

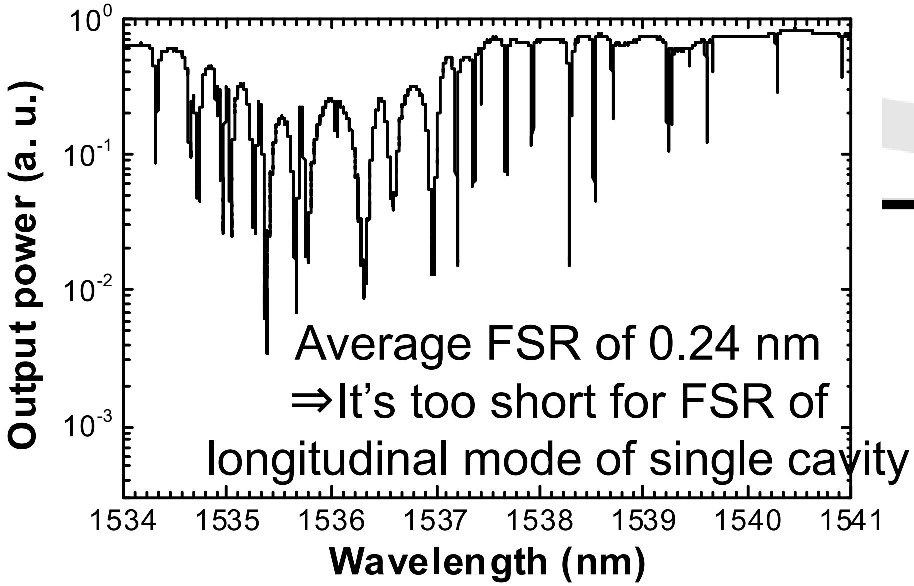


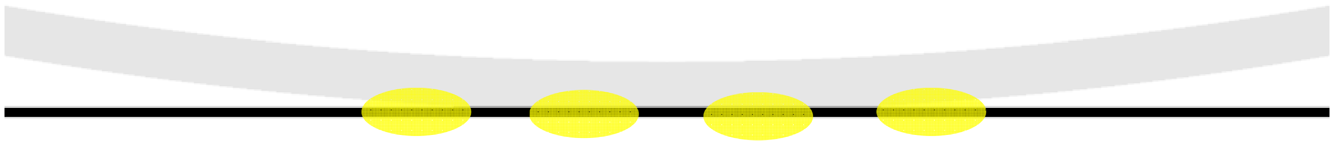



Multi-coupled cavity system
should be formed

# Multiple cavity formation

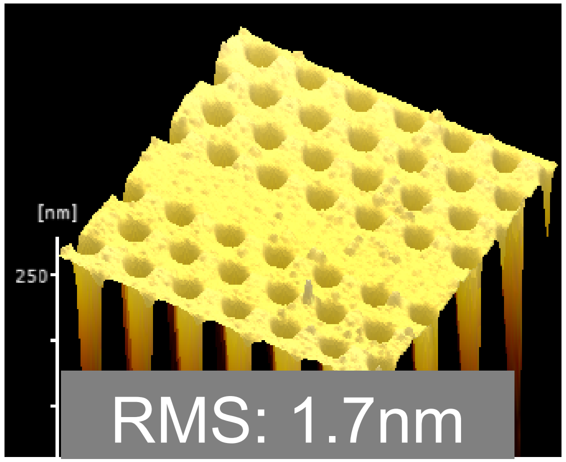
## Multi resonat peaks

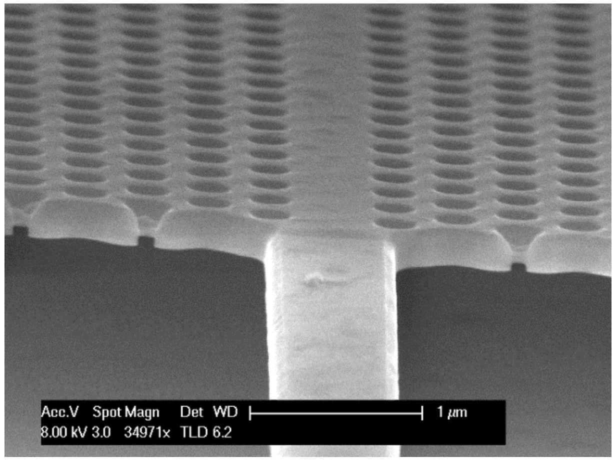


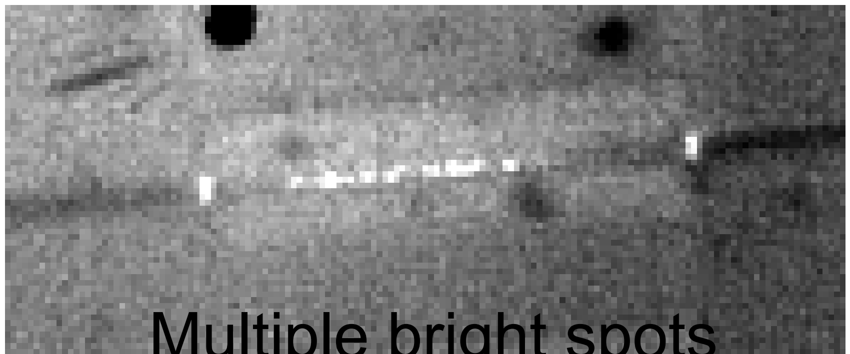
Multi-coupled cavity system
should be formed

## Surface of PhC waveguide



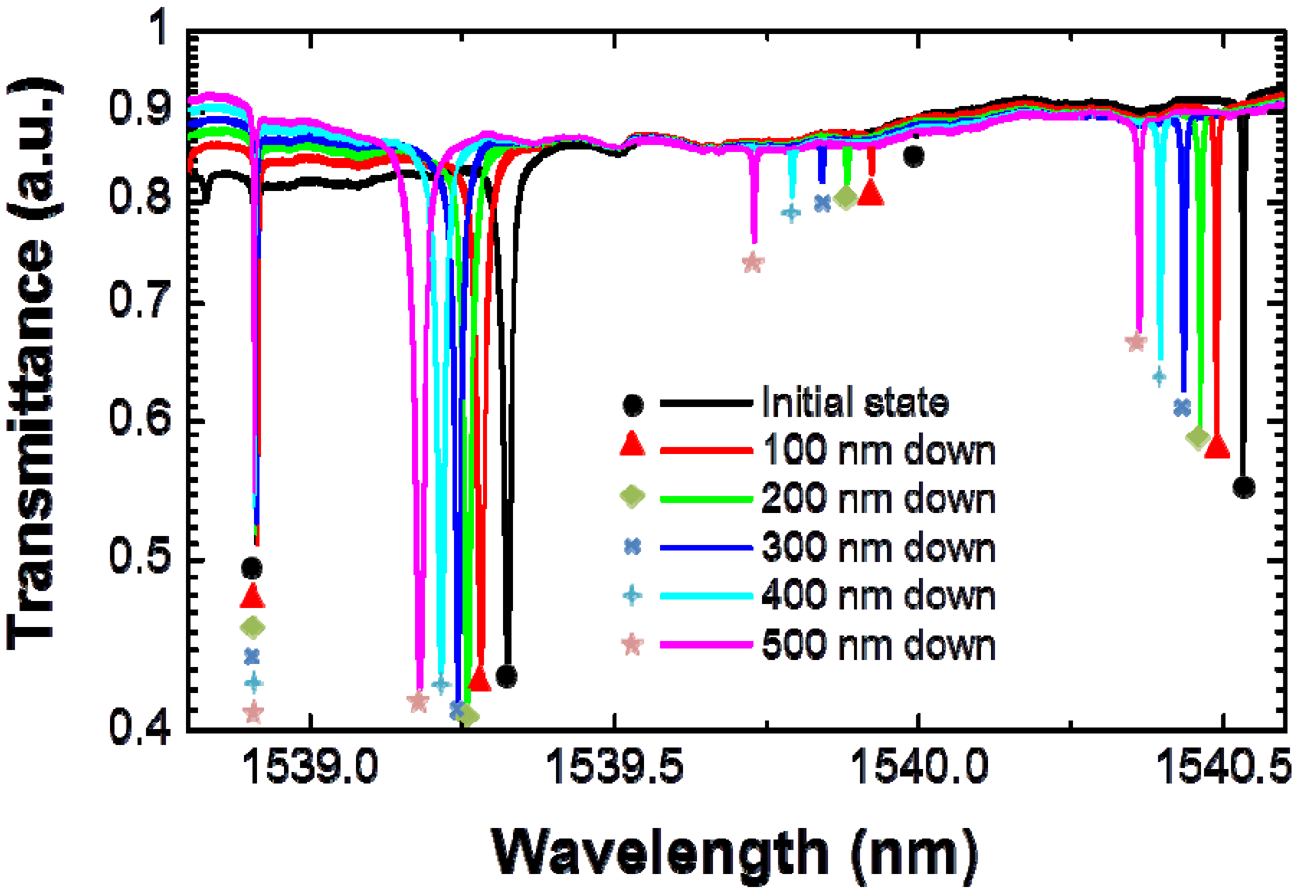



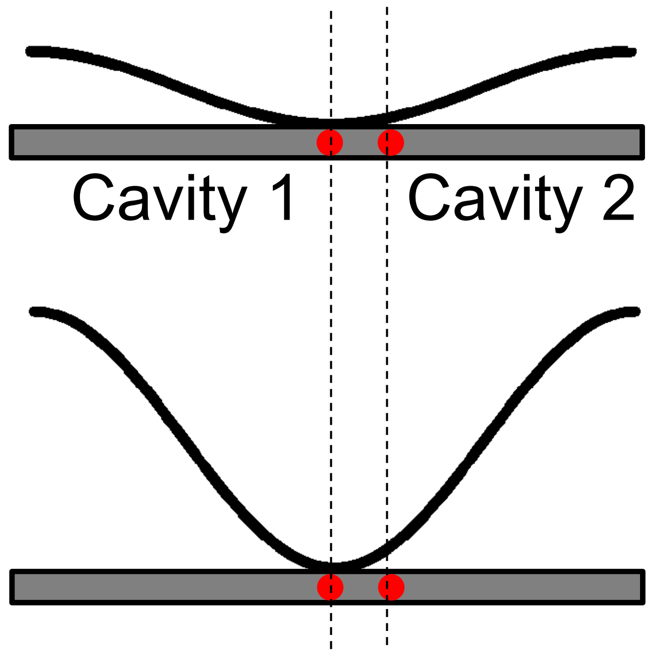

## Infrared image



Multiple bright spots
was observed

# Resonant wavelength tuning of multi modes

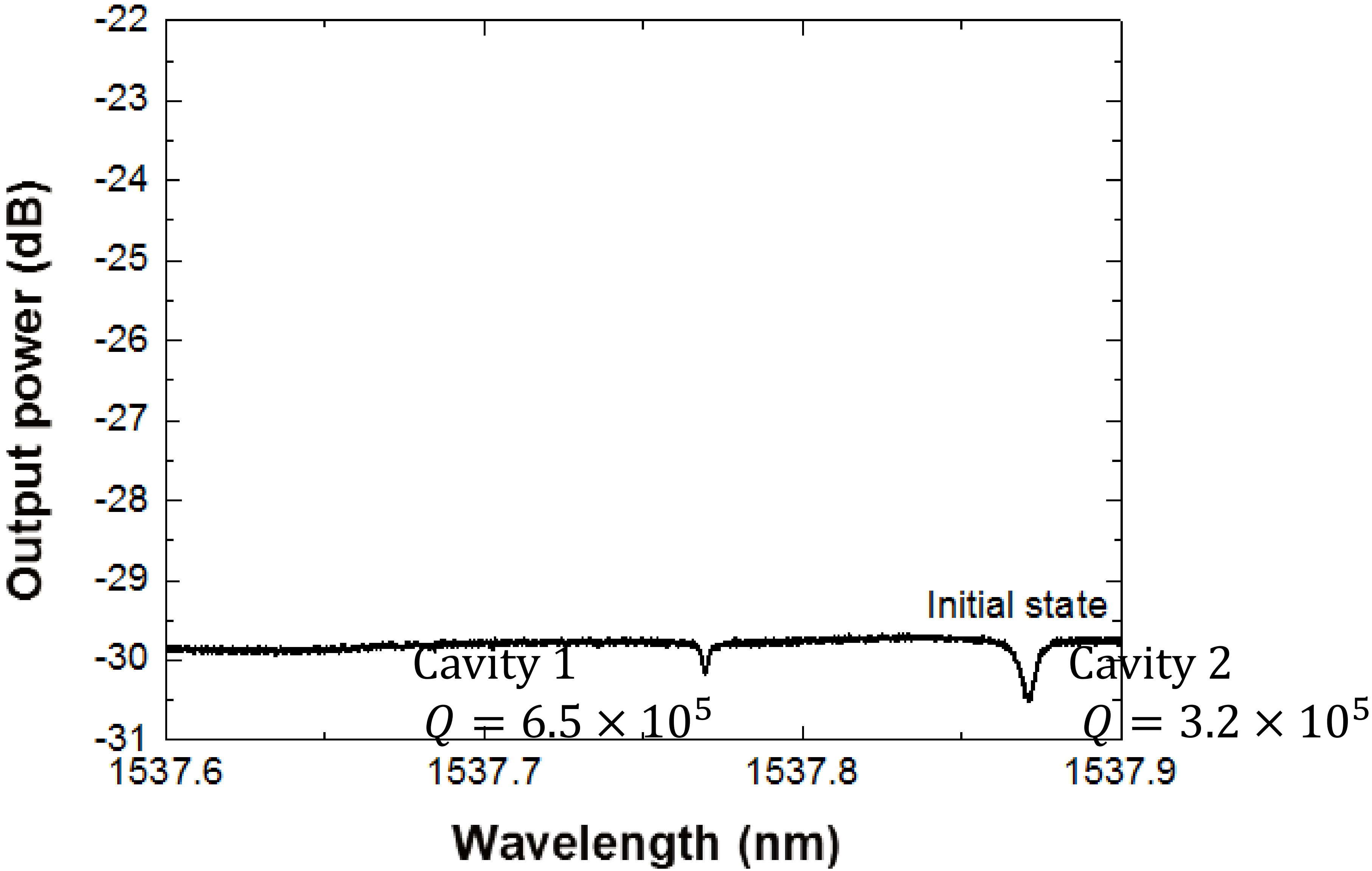


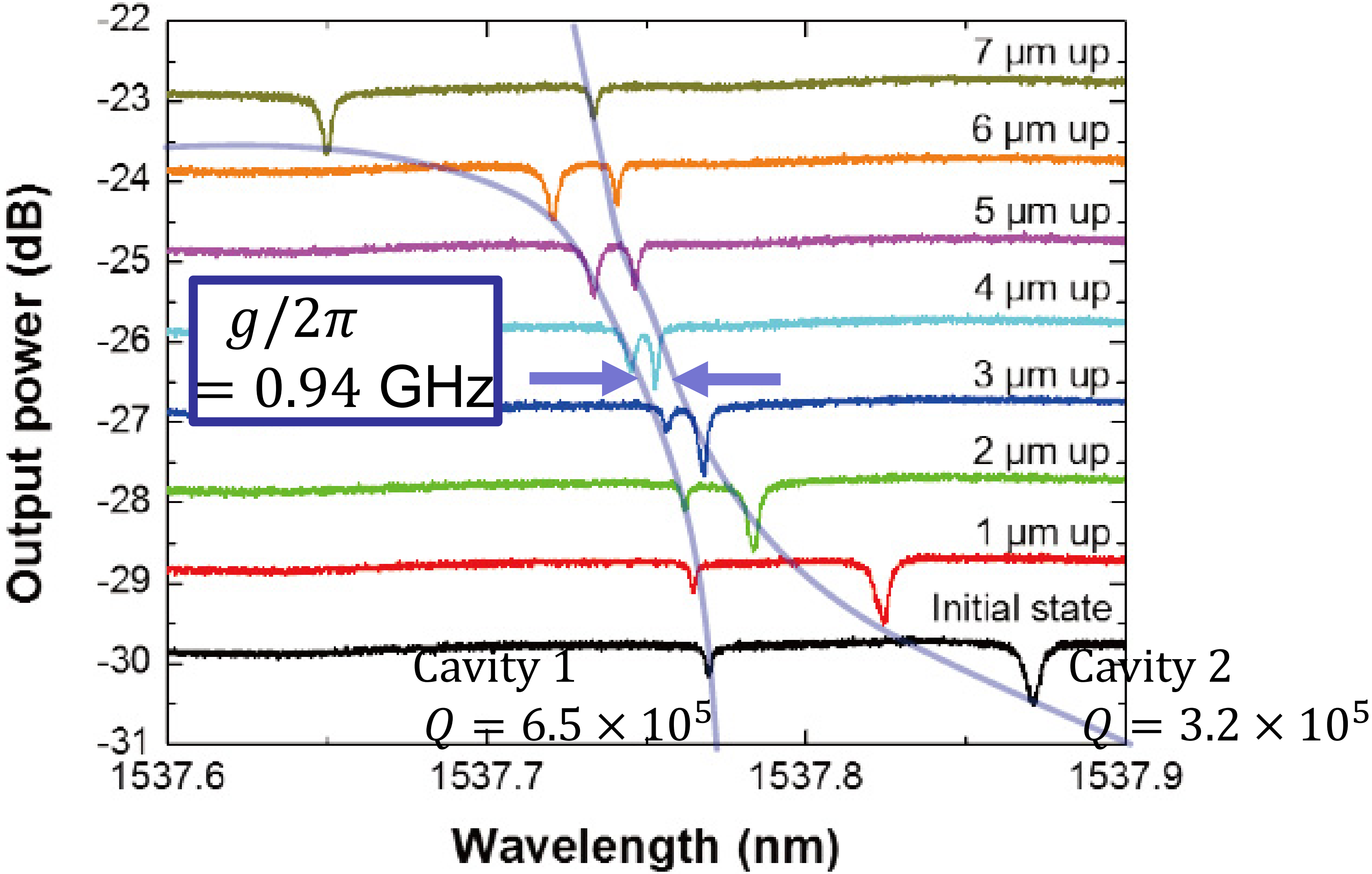

**Cavity 2 is more sensitive for fiber moving**

Amount of shifts are different for each modes

# Coupled cavity formation

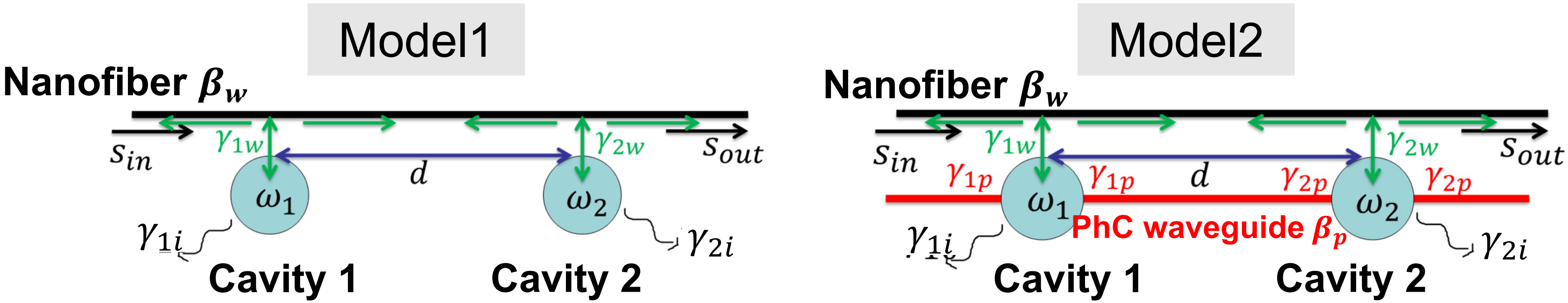


# Coupled cavity formation



# Numerical model of coupled cavity system

## Model of coupled cavity




$a$ : Amplitude of light in a cavity $\gamma$: decay rate, $s_{in}$: amplitude of input light
$\beta$: propagation constant

## Coupled mode equations

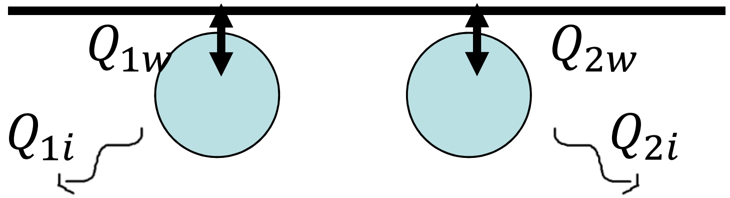
$$\frac{da_1}{dt} = i\omega_1 a_1 - \frac{\gamma_{1i} + 2\gamma_{1w} + 2\gamma_{1p}}{2} a_1 + \sqrt{\gamma_{1w}} s_{in} + e^{i\beta d}\sqrt{\gamma_{2w}\gamma_{1w}} a_2 + e^{i\beta_p d}\sqrt{\gamma_{2p}\gamma_{1p}} a_2$$

$$\frac{da_2}{dt} = i\omega_2 a_2 - \frac{\gamma_{2i} + 2\gamma_{2w} + 2\gamma_{2p}}{2} a_2 + \sqrt{\gamma_{2w}} e^{i\beta d} s_{in} + e^{i\beta d}\sqrt{\gamma_{1w}\gamma_{2w}} a_1 + e^{i\beta_p d}\sqrt{\gamma_{1p}\gamma_{2p}} a_1$$

# Numerical model of coupled cavity system (w/o PhC waveguide)

## Parameters

$Q_{load}^{-1} = Q_i^{-1} + Q_w^{-1}$

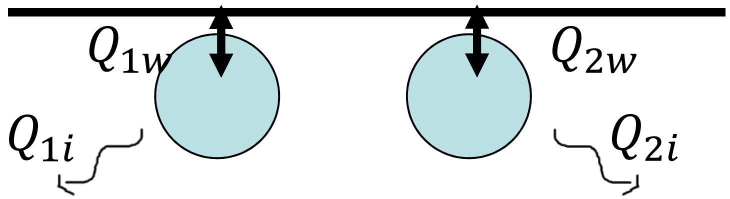



$Q_{1i} = 6.7 \times 10^5$, $Q_{1w} = 3.0 \times 10^7$, $Q_{2i} = 3.3 \times 10^5$, $Q_{2w} = 7.7 \times 10^6$
$\lambda_2 = 1537.87 - 0031 \times \text{steps nm}$, $\lambda_1 = 1537.77 - 00051 \times \text{steps nm}$, $e^{i\beta d} = i$,

# Numerical model of coupled cavity system (w/o PhC waveguide)

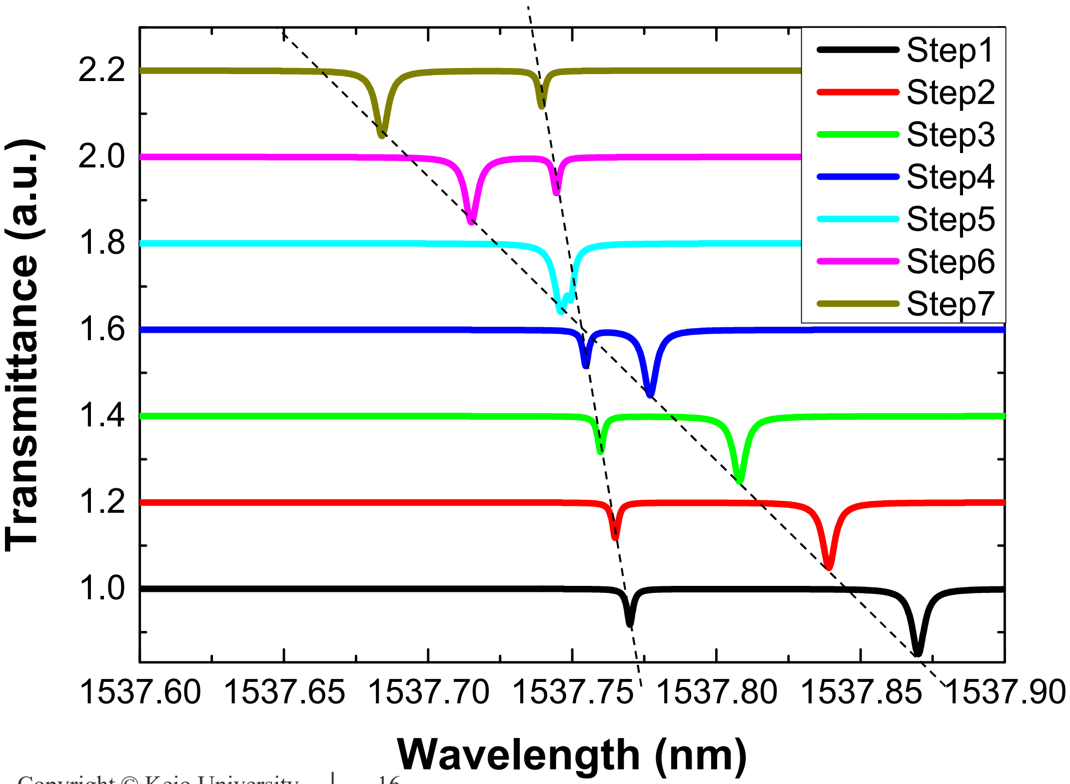
## Parameters

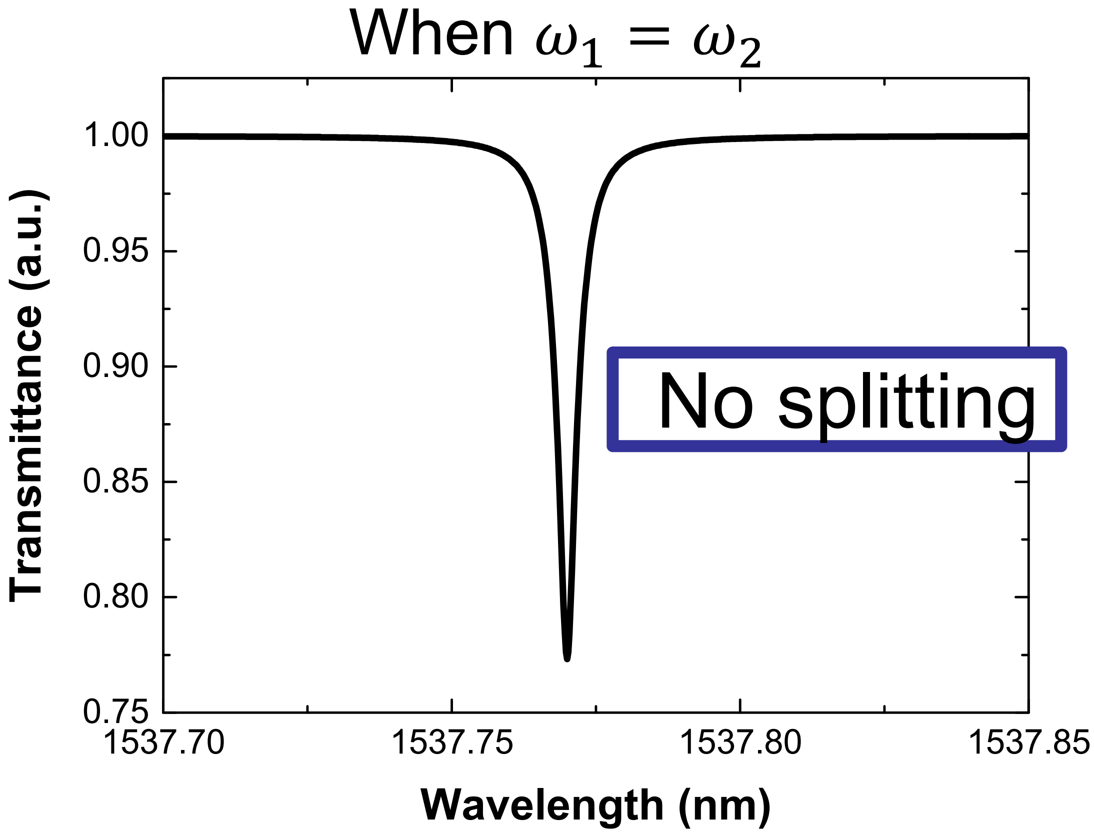
$$Q_{load}^{-1} = Q_i^{-1} + Q_w^{-1}$$




$Q_{1i} = 6.7 \times 10^5$, $Q_{1w} = 3.0 \times 10^7$, $Q_{2i} = 3.3 \times 10^5$, $Q_{2w} = 7.7 \times 10^6$

$\lambda_2 = 1537.87 - 0031 \times \text{steps nm}$, $\lambda_1 = 1537.77 - 00051 \times \text{steps nm}$, $e^{i\beta d} = i$,

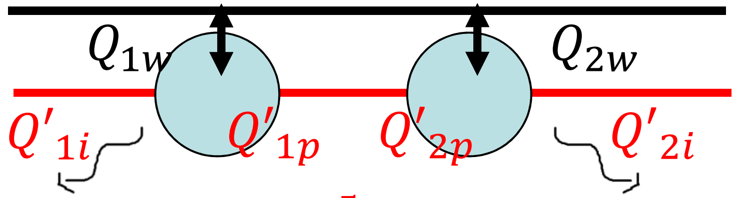


# Numerical model of coupled cavity system (w/ PhC waveguide)

## Parameters

$Q_{load}^{-1} = ({Q'}_i^{-1} + Q_p^{-1}) + Q_w^{-1}$

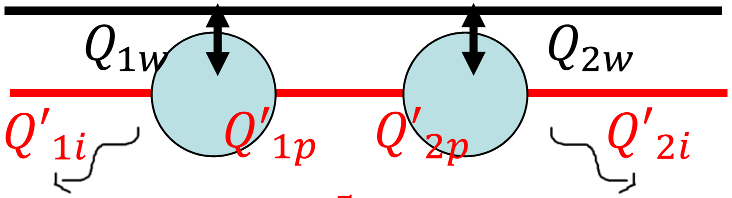



$Q'_{1i} = 1.4 \times 10^7$, $Q_{1w} = 3.0 \times 10^7$, $Q'_{2i} = 6.3 \times 10^5$, $Q_{2w} = 7.7 \times 10^6$
$\lambda_2 = 1537.87 - 0031 \times \text{steps nm}$, $\lambda_1 = 1537.77 - 00051 \times \text{steps nm}$, $e^{i\beta d} = i$, ,
$Q_{1p} = 7.0 \times 10^5$, $Q_{2p} = 7.0 \times 10^5$

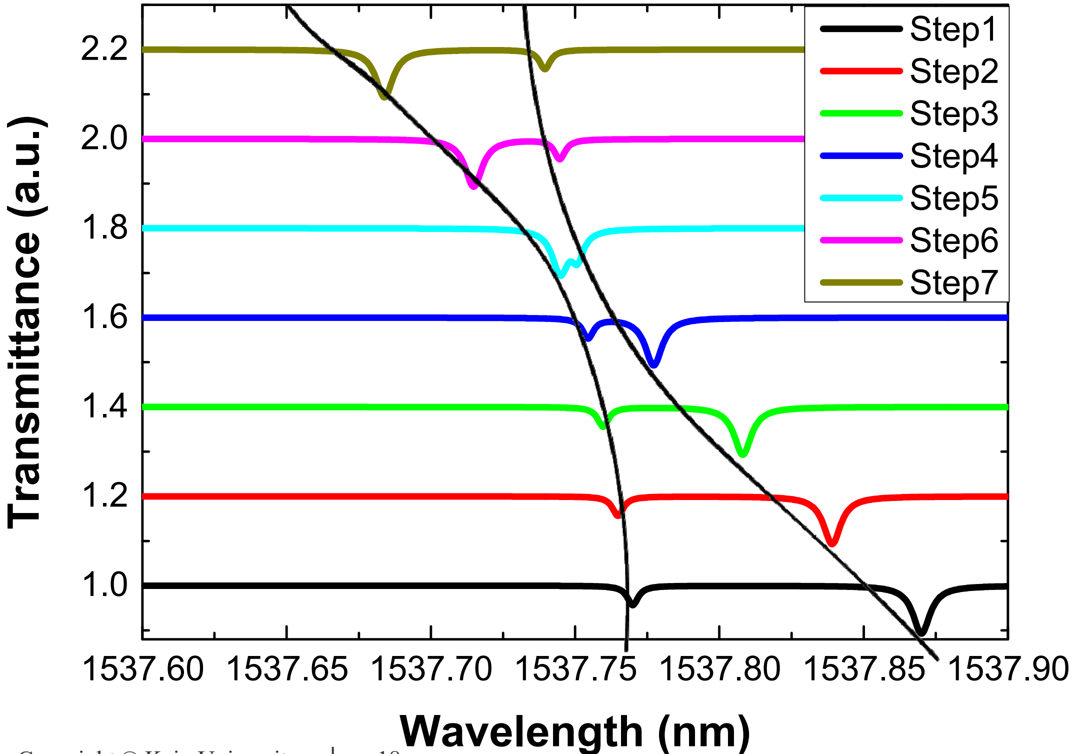
# Numerical model of coupled cavity system (w/ PhC waveguide)

## Parameters

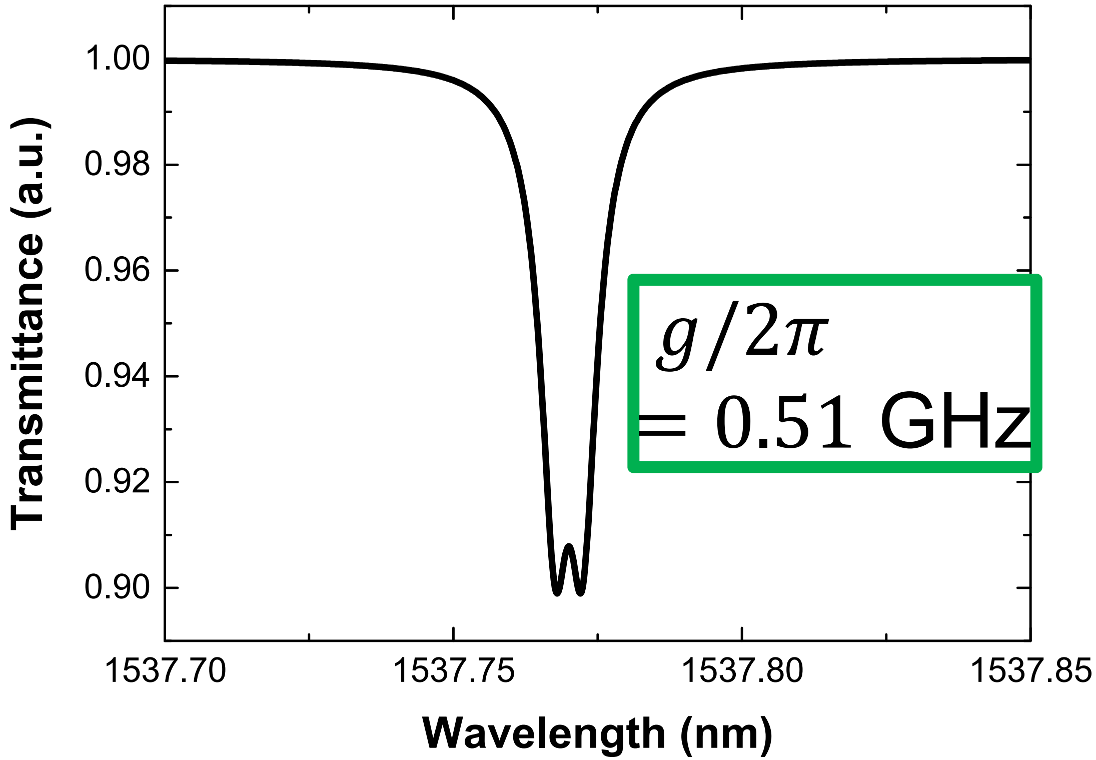
$$Q_{load}^{-1} = ({Q'}_i^{-1} + Q_p^{-1}) + Q_w^{-1}$$




$Q'_{1i} = 1.4 \times 10^7$, $Q_{1w} = 3.0 \times 10^7$, $Q'_{2i} = 6.3 \times 10^5$, $Q_{2w} = 7.7 \times 10^6$
$\lambda_2 = 1537.87 - 0031 \times \text{steps nm}$, $\lambda_1 = 1537.77 - 00051 \times \text{steps nm}$, $e^{i\beta d} = i$, ,
$Q_{1p} = 7.0 \times 10^5$, $Q_{2p} = 7.0 \times 10^5$




When $\omega_1 = \omega_2$



# Summary

- ✓ **Properties of fiber coupled PhC nanocavity**
  - ➢ Obtained a highest Q of $\mathbf{6.7 \times 10^5}$
  - ➢ Controlled CE from 6.6% to **99.6%**
    (Corresponds to $Q_{\text{coup}} = 3.7 \times 10^7$ and $1.3 \times 10^4$)
  - ➢ Demonstrate tuning of resonant wavelength
    (resolution of 0.27 pm/nm)
- ✓ **Coupled cavity formation based on FCPC**
  - ➢ Achieved $\boldsymbol{g/2\pi = 0.94\ \text{GHz}}$ $(\boldsymbol{g \approx \gamma})$

**This work was supported by
the Strategic Information and Communications R&D Promotion Programme
(SCOPE).**