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

Coupled cavity system w/ PhC nanocavities

**Advantage**
- Complex functions achievable
  i.e. optical buffer, optical memory

**Disadvantage**
- Requires advanced fabrication technique

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Cavity-QED


Optical signal processing


Optical buffer


Dynamic control of coupling

Nanofiber assisted reconfigurable PhC nanocavity

Fiber coupled PhC nanocavity (FCPC)

- Is reconfigurable
- $Q = 5.1 \times 10^5$, 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).

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

**Setup**

- **TLD**
- **VOA**
- **PC**
- **PM**
- **xyz Stage**

**PhC waveguide**
- Fabricated with 248nm KrF stepper exposure
- Lattice constant: 420 nm,
- Air hole diameter: 253 nm,
- Slab thickness: 210 nm

**Nanofiber**
- Insertion loss of nanofiber: Typically 10dB,
  **Best 1dB**
  - about 800nm

**On-resonance**
- **Nanofiber**
- **PhC waveguide**

**Off-resonance**
Measurement of $Q$ and CE of FCPC

Maximization of $Q$

- $Q_{load} = 6.7 \times 10^5$
- $Q_{int} = 6.8 \times 10^5$
- $Q_{coup} = 3.9 \times 10^7$

Measured $Q$

$Q_{load}^{-1} = Q_{coup}^{-1} + Q_{int}^{-1}$
- Depends on fiber radius
- Depends on fiber contact condition

Maximization of CE

- $Q_{load} = 6.1 \times 10^3$
- $Q_{int} = 1.1 \times 10^4$
- $Q_{coup} = 1.3 \times 10^4$

Nanofiber

Output

Transmittance $\lambda$

$Q_{coup}$

$Q_{int}$

$Q_{load}$

Depends on fiber radius

Depends on fiber contact condition
**Resonant wavelength tuning**

**Method**

- Nanofiber
- PhC waveguide

**xyz Stage**

- Moves 100 nm downwards

**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 resonant peaks

Average FSR of 0.24 nm
⇒ It’s too short for FSR of longitudinal mode of single cavity

Multi-coupled cavity system should be formed
Multiple cavity formation

Multi resonant peaks

Average FSR of 0.24 nm ⇒ It’s too short for FSR of longitudinal mode of single cavity

Multi-coupled cavity system should be formed

Surface of PhC waveguide

Infrared image

Multiple bright spots was observed
Resonant wavelength tuning of multi modes

Amount of shifts are different for each modes

Cavity 1

Cavity 2

Cavity 2 is more sensitive for fiber moving
Coupled cavity formation

Cavity 1
\[ Q = 6.5 \times 10^5 \]

Cavity 2
\[ Q = 3.2 \times 10^5 \]
Coupled cavity formation

\[
g/2\pi = 0.94 \text{ GHz}
\]

Cavity 1
\[ Q = 6.5 \times 10^5 \]

Cavity 2
\[ Q = 3.2 \times 10^5 \]
Numerical model of coupled cavity system

Model of coupled cavity

Nanofiber $\beta_w$

Model 1

Cavity 1

$\omega_1$

$\gamma_{1i}$

$\gamma_{1w}$

$s_{in}$

$\gamma_{2i}$

$\gamma_{2w}$

$d$

$s_{out}$

$\omega_2$

Cavity 2

$a$ : Amplitude of light in a cavity

$\gamma$ : decay rate, $\beta$ : 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**

\[ Q_{load}^{-1} = Q_i^{-1} + Q_w^{-1} \]

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

\[ \lambda_2 = 1537.87 - 0031 \times \text{steps nm}, \quad \lambda_1 = 1537.77 - 00051 \times \text{steps nm}, \quad e^{i\beta d} = i, \]
Numerical model of coupled cavity system (w/o PhC waveguide)

Parameters

\[ Q_{load}^{-1} = Q_i^{-1} + Q_w^{-1} \]

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

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

When \( \omega_1 = \omega_2 \)

No splitting
Numerical model of coupled cavity system (w/ PhC waveguide)

Parameters

\[ Q_{load}^{-1} = (Q_{i}^{-1} + Q_{p}^{-1}) + Q_{w}^{-1} \]

\[ Q'_{1i} = 1.4 \times 10^7, \quad Q_{1w} = 3.0 \times 10^7, \quad Q'_{2i} = 6.3 \times 10^5, \quad Q_{2w} = 7.7 \times 10^6 \]

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

\[ Q_{1p} = 7.0 \times 10^5, \quad Q_{2p} = 7.0 \times 10^5 \]
Numerical model of coupled cavity system (w/ PhC waveguide)

Parameters

\[ Q_{\text{load}}^{-1} = (Q'^{-1}_i + Q'^{-1}_p) + Q_w^{-1} \]

\[ Q'_{1i} = 1.4 \times 10^7, \quad Q_{1w} = 3.0 \times 10^7, \quad Q'_{2i} = 6.3 \times 10^5, \quad Q_{2w} = 7.7 \times 10^6 \]

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

\[ Q_{1p} = 7.0 \times 10^5, \quad Q_{2p} = 7.0 \times 10^5 \]

When \( \omega_1 = \omega_2 \)

\( g/2\pi = 0.51 \text{ GHz} \)
Summary

✓ Properties of fiber coupled PhC nanocavity
  ➢ Obtained a highest Q of \(6.7 \times 10^5\)
  ➢ 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 \(g/2\pi = 0.94\) GHz \((g \approx \gamma)\)

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