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

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Key device: high $Q$ microcavities

Microcavity = a device that can cage photons

- Photonic crystal nanocavity
- WGM microcavity

$V = 1.5 \left( \frac{\lambda}{n} \right)^3$
$Q = 10^6$

$V = >100 \left( \frac{\lambda}{n} \right)^3$
$Q = 10^8$

Courtesy by NTT Basic Research Labs.
1. Background & motivation

High Q microcavities

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

\[ \propto \frac{Q}{V} \]

Research frontier

Silica toroid

Si MH

Si L3

Si beam

Si H0

Si beam

Si beam w/ slot

Si3N4

Diamond

SiO2 sphere

CaF2

SiO2 disk

MgF2

WGM microcavities

PhC nanocavities

Ring resonators

References:

Outline

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

2. Efficient coupling of WGM w/ Si chip
   Y. Zhuang, et al., (in preparation)

3. Coupling of WGMs for optical buffering
Outline

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

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

**Width-modulated line-defect cavity**

Barrier line defect (W0.98)

- A: 9 nm
- B: 6 nm
- C: 3 nm
- a = 420 nm
- d = 216 nm
- t = 204 nm

- Mode gap
- Low-loss propagation mode

**Ring-down & spectrum**

\[ Q = 1.2 \times 10^6 \quad V \cong 0.13 \mu m^3 \]

\[ \tau = 1.01 \text{ ns} \]

Mode profile

Power (a.u. / log)

- 1.3 pm

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

Dispersion diagram of 2D PhC waveguides

Mode gap is at higher frequency for narrow width
PhC nanocavity fabrication

Width-modulated line defect cavity

Max amount of shift : 9 nm

Q = 2.2 × 10^5

Numerical

Q = 7.1 × 10^6 \quad V = 2.4 (\lambda/n)^3

Experimental

Q = 2.2 × 10^5
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

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

Optical signal processing

Quantum optics


Waveguide + waveguide = high Q cavity?
Principle of cavity formation

Effective refractive index change results in formation of modegap cavity.

Numerical calculation

**Design**
- Silica fiber (r = 500 nm)
- Radius of curvature 125 μm
- PhC waveguide

**Result**
- Profile of Ey field in xy plane
- Profile of Ey field in zx plane

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

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


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

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**Nanofiber**

- Diameter: ~800 nm
- Transmittance loss: Typically -10 dB, Best -1 dB

**PhC waveguide (W0.98)**
- Lattice constant 420 nm
- Hole diameter 253 nm
- Slab thickness 210 nm

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Experimental results

Transmission spectrum

$$Q_{load} = 5.1 \times 10^5$$ (CE 39%)
Measurement of Q and CE of FCPC

Maximization of Q

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

Maximization of CE

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

\[ Q_{load}^{-1} = Q_{coup}^{-1} + Q_{int}^{-1} \]

Depends on fiber radius
Depends on fiber contact condition

Measured Q

Localization on Si chip w/ tapered fiber
Resonant wavelength tuning

Method

Nanofiber
PhC waveguide
xyz Stage

Moves 100 nm downwards

Fixed

Cavity length is shortened ⇒ Blue shift of resonant wavelength


Tuning sensitivity

\[
\text{Tuning sensitivity} = \frac{\text{Wavelength shift}}{\text{Stage shift}} = 0.27 \text{ pm/nm}
\]
Fiber coupled PhC nanocavity (FCPC)

✓ 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%

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Coupling of WGM w/ silicon PhC waveguide

\[ V = 1.5 \left( \frac{\lambda}{n} \right)^3 \]
\[ Q = 10^6 \]

\[ V = >100 \left( \frac{\lambda}{n} \right)^3 \]
\[ Q = 10^8 \]

Courtesy by NTT Basic Research Labs.
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

*Operating principal: Optical Kerr effect*

 Coupling of WGM w/ silicon PhC waveguide
Sample preparation

Fabrication procedure

1. Resist application
2. Dicing
3. Resist removal
4. XeF$_2$ etching
5. CO$_2$ laser reflow

Silica disk

SiO$_2$

Si
Sample preparation

Fabrication procedure

1. Resist application
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Fabricated structure

Diameter 55 μm

FSR : ~10 nm
Sample preparation

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Fabricated structure

Silica disk $\text{SiO}_2$

1. Resist application
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5. CO$_2$ laser reflow

Edge of the substrate

Diameter 55 μm

$Q_{load} = 1.0 \times 10^6$
Experimental setup and results

Experimental setup

TLS: Tunable laser source
ML: Microlens
OM: Optical microresonator
PWM: Powermeter
DAQ: Data acquisition

Coupling of WGM w/ silicon PhC waveguide
Result: Transmission spectrum

![Graph showing transmission spectrum with wavelength in nm and transmittance in arbitrary units. The graph indicates a sharp drop in transmittance around 1525 nm for the 'w/o a toroid' condition.]
Result: Transmission spectrum

![Graph showing transmission spectrum with wavelength in nm on the x-axis and transmittance in arbitrary units on the y-axis, comparing transmission without a toroid and with a toroid.]
Nanofiber vs. PhC waveguide

Transmission spectrum of a toroid microcavity

- Coupled w/ a nanofiber
- Coupled w/ a PhC waveguide
Dispersion of a PhC waveguide (W0.98)

Frequency $\omega$ ($2\pi c/a$)

Wavevector $k_x$ ($2\pi/a$)

- Air line
- y-odd
- y-even

h = 210 nm

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Effective index of waveguide

- Wavelength (nm)
- Effective index $n_{\text{eff}}$
- Air line
- Nanowire WG
- Air-bridge PhC WG
- $w=480$ nm
- TE$_0$
- y-even
- W$_{0.98}$
Dip depth (coupling) at different distances

Transmission spectrum vs voltage

(a) Transmission spectrum at Voltage=69.00 V
(b) Transmission spectrum at Voltage=68.33 V
(c) Transmission spectrum at Voltage=67.66 V
(d) Target mode
(e) Critical coupling
(f) High order modes

Critical coupling FSR ~8 nm

333 nm/V

Piezo controller
Dip depth (coupling) at different distances

(a) Transmission (dB) vs. Voltage (V)
- Critical coupling
- Over coupling
- Under coupling

(b) Transmission (dB) vs. Wavelength (nm)
- Measured
- Fitted
- Q = 1.34 x 10^6
- ~23 dB

(0.33 µm/V)
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)
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Hybrid system consisting of two different cavities

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**Research frontier**

- **Silica toroid [10]**
- CaF$_2$ [11]
- Si$_3$N$_4$ [7]
- MgF$_2$ [12]
- WGM microcavities
- PhC nanocavities
- Ring resonators

**Mode volume ($\mu m^3$)**

**Quality factor**

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Hybrid system consisting of two different cavities

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Coupling of WGMs for optical buffering
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 \((Q>10^8)\)

- 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 \(\mu\)s
**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.

- **Silica toroid microcavity**
  - Ultra-high $Q$ factor ($\sim 4 \times 10^8$)
  - Small mode volume ($\sim 200 \mu m^3$)
  - On-chip fabrication

Introduction: All-optical “tunable” buffering

**Principle**

1. Input
2. Output

![Diagram showing coupling of WGMs for optical buffering](Image)

- Energy in $C_1$
- Energy in $C_2$
- Output

Time (ns)
Introduction: All-optical “tunable” buffering

Principle

1. Input
2. Buffer
3. Output

Energy in $C_1$

Energy in $C_2$

Output

Time (ns)
Device preparation

- **Silica toroid microcavity on an edge**
  - Shrinkage owing to laser reflow
  - Use of edge silica toroid microcavity

- **Fabrication**
  1. Photolithography
  2. HF etching
  3. Dicing
  4. XeF$_2$ etching
  5. Laser reflow
  6. Completion
Optical modes employed for experiments

- Three modes: $M_1$, $M_2$ (signal) and $M_3$ (control).
- $M_1$: ultra-high $Q$ ($\sim 2.5 \times 10^7$)
- $M_2$ & $M_3$: moderate $Q$ ($\sim 10^6$)
Observation of coupling

Different gap

\[ \frac{\kappa}{2\pi} = 110 \text{ MHz} \]
\[ \frac{\kappa}{2\pi} = 63 \text{ MHz} \]
\[ \frac{\kappa}{2\pi} = 44 \text{ MHz} \]
\[ \frac{\kappa}{2\pi} = 23 \text{ MHz} \]
\[ \frac{\kappa}{2\pi} = 13 \text{ MHz} \]

Different temperature

\[ \delta f = -274 \text{ MHz} \]
\[ \delta f = -164 \text{ MHz} \]
\[ \delta f = -31 \text{ MHz} \]
\[ \delta f = 67 \text{ MHz} \]
\[ \delta f = 189 \text{ MHz} \]
\[ \delta f = 300 \text{ MHz} \]
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**

  ![Graph showing buffering operation](image)

  - Control ON
  - $\tau_{\text{width,c}} = 20 \text{ ns}$
  - $\tau_{\text{width,c}} = 15 \text{ ns}$
  - $\tau_{\text{width,c}} = 10 \text{ ns}$
  - $\tau_{\text{width,c}} = 5 \text{ ns}$
  - No control

  - All-optical tunable buffering / 10-ns pulse buffered for 20 ns
Output efficiency: \(~10\%\) (due to spectral mismatch)

Equivalent light attenuation: \(1.1 \text{ dB/m}\)

State-of-art “fixed” on-chip optical buffer: \(~0.1 \text{ dB/m}\)
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.
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Acknowledgement

The team

Post doc position soon available!