Numerical Analysis of Sharply Bent Waveguide with Microcavity Constructed by Air-bridge Type Two-dimensional Photonic Crystal Slab

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***Abstract*—An efficient sharply bent waveguide with a microcavity constructed by an air-bridge type two-dimensional photonic crystal slab has analyzed. The method of solution is the three-dimensional finite difference time domain (FD-TD) method. An input and an output waveguides are connected by a microcavity. The radius and position of six air-holes surrounding the microcavity are modified to lower the resonant frequency into the photonic band gap. We have confirmed that the optical power is transmitted efficiently into the output waveguide due to resonant tunneling caused by the microcavity.**

I. Introduction

In order to accelerate processing speed in a microprocessor, there is a demand for increased interconnect speed within a chip. It is forecasted that intra-chip interconnection by metal wire becomes bottleneck because it has many serious electromagnetic problems such as cross talk, clock skew, and so on. One of the key solutions to the problem is an on-chip optical network system based on silicon photonics [1]–[3] which offers high density integration of optical and electronic functions upon a single silicon substrate. The intra-chip optical network with photonic crystal waveguide devices is one of the candidates for that because the sizes of the photonic crystal waveguide devices are on the order of the wavelength of the light [4]–[8]. In order to integrate highly the optical components, there is a demand to develop a highly efficient bent waveguide because a Fabry-Pérot resonance, which is caused by slight reflection from the bent, degrades the wavelength characteristics of the system. We propose an efficient sharply bent waveguide constructed by a two-dimensional photonic crystal. The bent waveguide has a microcavity making a resonant tunneling [7], [9], which is coupled to an input and an output waveguides. We analyze characteristics of the bent waveguide using the finite-difference time-domain (FD-TD) method. We show that the optical power is transmitted efficiently into the output waveguide due to resonant tunneling caused by the microcavity.

II. Formulation of problems

We consider an air-bridge type two-dimensional photonic crystal slab waveguides constructed on a silicon-on-insulator (SOI) substrate as shown in Fig. 1(a). A two-dimensional photonic crystal is formed in the silicon layer and the oxide layer under the silicon layer is removed. The optical light is confined by a photonic band gap and a difference in refractive index in the horizontal and the vertical direction, respectively. The method of solution is the three-dimensional

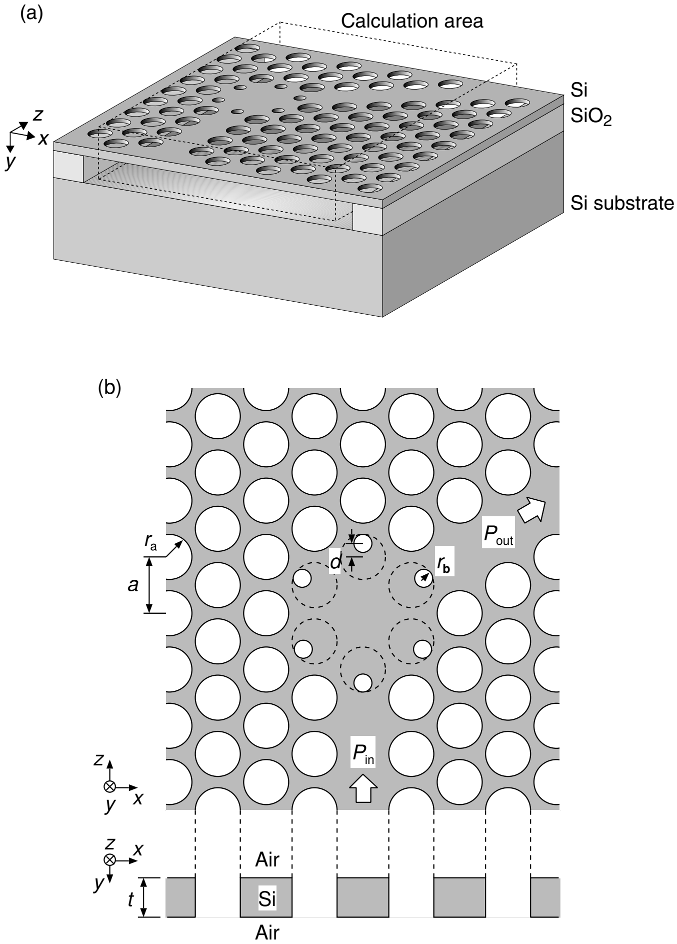

Fig. 1. Bent waveguide constructed by an air-bridge type two-dimensional photonic crystal slab with a microcavity. (a) Schematic structure, (b) top and cross-sectional view.

FD-TD method. The computational zone is surrounded by the perfectly matched layers (PMLs) [10] which is used as the absorbing boundary condition. Taking impedance matching condition at the interface between the computational region and the PMLs region in the x-z plane into account, we use the same waveguide structure in the PMLs region as that of the computational region, but the electric and the magnetic conductivity are assigned to the dielectric material whose values satisfy the distortion-less condition [10]. The photonic crystal used here is composed of circular air-holes with radius r_a in silicon having a triangular array with lattice constant a. The relative permittivity of silicon ε_a is 11.9 for infrared light. The waveguide is created by removing one row of air-holes. The microcavity is formed by removing one air-hole and modifying the radius r_b and the position of six air-holes surrounding the microcavity [11] as shown in Fig. 1(b). The displacement of the position for the six air-holes is determined by $d = r_a - r_b$. In order to excite transverse electric (TE)-like polarized mode (E^x mode), y components of magnetic field H_y is excited because the photonic crystal employed here exhibits a wide photonic band gap for the polarization with the electric field parallel to the x-z plane.

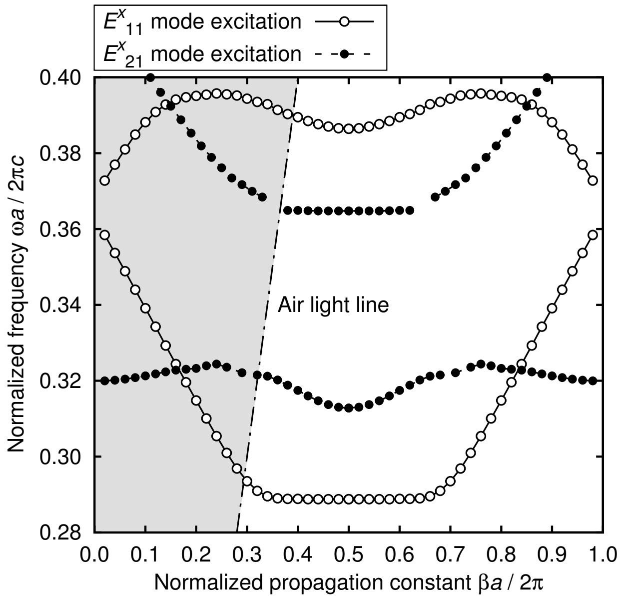

Fig. 2. Dispersion relation of the air-bridge type two-dimensional photonic crystal waveguide slab for TE-like mode (E^x mode). The radius of air-hole and thickness of slab are $r_a/a = 0.36$ and $t/a = 0.5$, respectively.

III. Numerical Results

First, we calculate dispersion relation of the straight photonic crystal waveguide. Fig. 2 shows the result for TE-like mode (E^x mode). The radius of the air-hole and the thickness of the slab are $r_a/a = 0.36$ and $t/a = 0.5$, respectively. There are space harmonic modes due to the periodic boundary of the waveguide layer. Their forward and backward propagating waves couple each other and make a stop-band at the wavenumber satisfying the Bragg condition. The waveguide operates in the single mode regime at the stop band of higher order mode. The dashed line in the figure denotes the light line of the air which is the cladding layer in the y direction. The modes below and above the light line corresponds to the guided and the leaky modes for the slab, respectively. In the single mode regime, the forward propagating waves of the E^x_{11} mode is in the guided mode region for the slab, while backward one of that lies in the leakey mode region which denotes dark region in the figure. Therefore E^x_{11} mode in the waveguide propagates with a slight attenuation.

Next, we analyze the resonant modes in the unloaded microcavity as shown in Fig. 3(a). The radius r_a of the air-hole and the thickness t of the slab are the same as for Fig. 2. The radius and position of six air-holes surrounding the microcavity are modified to lower the resonant frequency into the photonic band gap. Fig. 3(b) shows magnetic field intensity $|H_y|$ in the x-z plane of resonant mode in the unloaded microcavity. The radius and displacement of the position of the air-holes surrounding the microcavity are $r_b/a = 0.16$ and $d/a = 0.2$, respectively. The higher order resonant modes can be excited by modifying the radius and the position of the nearest-neighbor air-holes. The magnetic field distributions in the wavenumber-space for the resonant modes are shown in Fig. 3(c). The white circle in the figure denotes wavenumber in the air at the resonant frequency for the modes, which corresponds to the air light line. The results show that the resonant modes exhibit very little radiation into the air because there is very few leaky wave inside the circle. Fig. 3(d) shows resonant frequency for the resonant modes as a function of air-hole radius r_b. The resonant frequency can be controlled by changing radius r_b.

From the results, we analyze the bent waveguide with microcavity. Fig. 4 shows the normalized optical power transmission spectra of the bent waveguide for some air-hole radius r_b. The radius r_a of the air-hole and the thickness t of the slab are the same as for Fig. 2. The power flow in the waveguide is defined by

$$P(\omega) = \int_s \frac{1}{2}\mathrm{Re}\Big[\big\{\boldsymbol{E}(\omega) \times \boldsymbol{H}^*(\omega)\big\} \cdot \boldsymbol{u}\Big] ds \qquad (1)$$

where s means the cross section perpendicular to the propagation direction, $\boldsymbol{E}(\omega)$ and $\boldsymbol{H}(\omega)$ are the Fourier transformed electric and magnetic field, respectively, $*$ denotes the complex conjugate, and $\boldsymbol{u}$ is the unit vector in the propagation direction. We can see that over 90 percent of the optical power is transmitted at the resonant frequency and it can be controlled by changing the radius and position of the nearest-neighbor air-holes. The distribution of magnetic field intensity $|H_y|$ in the x-z plane of the bent waveguide at the resonant frequency is shown in Fig. 5. The air-hole radius r_b/a and incident frequency $\omega a/2\pi c$ are 0.16 and 0.335, respectively. It is confirmed that the hexapole resonance mode is excited in the microcavity. There is no standing wave pattern in the input waveguide which means that there is little reflected wave from the microcavity. Therefore it may be that the optical power loss is caused by radiation into the air cladding in the y direction.

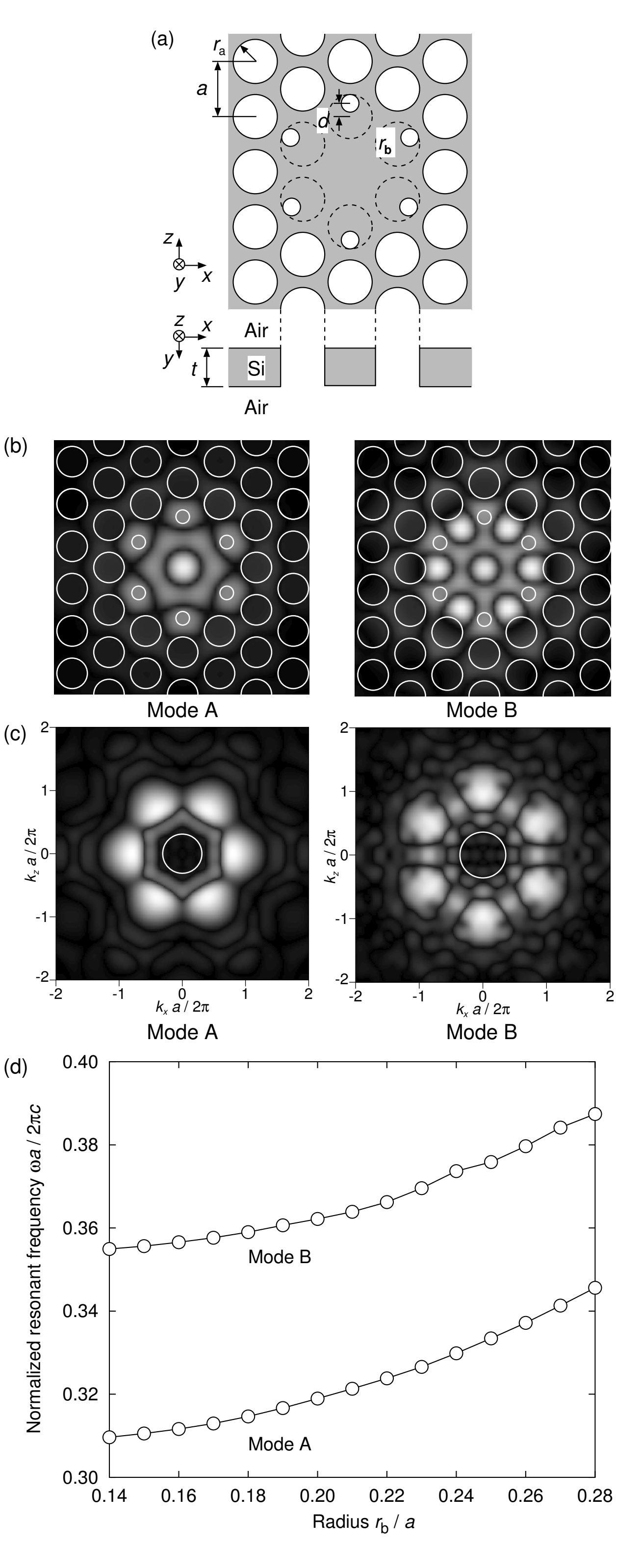

Fig. 3. (a) Structure of the unloaded microcavity, (b) Magnetic field intensity $|H_y|$ of the resonant mode in the unloaded microcavity with the air-hole radius of $r_b/a = 0.16$, (c) Magnetic field intensity $|H_y|$ in the wavenumber-space for the resonant modes, and (d) Resonant frequency as a function of air-hole radius r_b. The radius of air-hole and thickness of slab are $r_a/a = 0.36$ and $t/a = 0.5$, respectively.

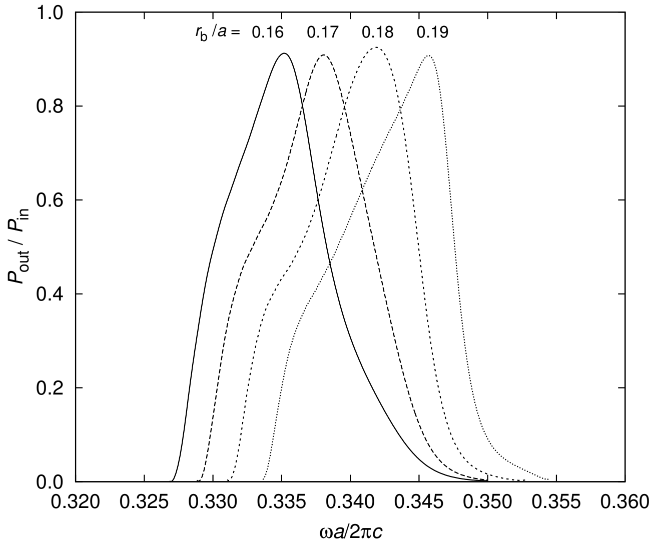

Fig. 4. Optical power transmission spectra as a function of radius r_b of six air-holes surrounding the microcavity. The radius of air-hole and thickness of slab are $r_a/a = 0.36$ and $t/a = 0.5$, respectively.

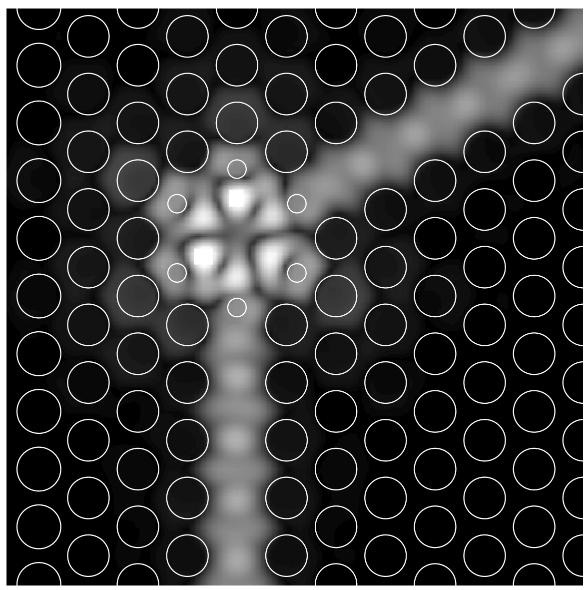

Fig. 5. Magnetic field intensity $|H_y|$ of the bent waveguide at the resonant frequency $\omega a/2\pi c = 0.335$. The radius of six air-holes surrounding the microcavity is $r_b/a = 0.16$.

The mode profile in the output waveguide shows the same transverse one as that of the input waveguide. In other words, the mode conversion does not occur and the eigenmode profile is kept even if the light propagates through the microcavity.

IV. Conclusion

We have analyzed an efficient sharply bent waveguide with a microcavity constructed by an air-bridge type two-dimensional photonic crystal slab. The numerical results show that the optical power is transmitted efficiently into the output waveguide due to resonant tunneling caused by the microcavity. We have shown that the transmission bands can be controlled by changing radius and position of six air-holes surrounding the microcavity.

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