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Analysis on Coupling between 2D Photonic Crystal Waveguide and External Waveguide

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1. Introduction

Photonic crystals are expected to offer various promising optical devices because they can arbitrarily control the propagation and/or emission of light. Three-dimensional photonic crystals should be used in order to realize a complete bandgap and to control the light efficiently[1]. However, two-dimensional photonic crystal slabs also attract much attention because of their easiness in fabrication processes. By introducing point and/or line defects, we can construct very compact optical devices and circuitts. In order to utilize such photonic crystal circuits for actual application, it is important to connect them to optical fibers. However, because core size of a single mode optical fiber is much larger than that of the photonic crystal (PC) waveguide, it is difficult to connect the PC waveguide directly to the optical fiber. Thus we should introduce, for example, a wire waveguide between the PC waveguide and the optical fiber to obtain efficient coupling. Since the coupling between fiber and wire has been studied as a spot size converter by using tapered waveguide[2, 3], we can use the knowledge about that. On the other hand, the coupling between the PC waveguide and the wire waveguide is still an important issue and should be studied in detail. Although some numerical analyses were performed for similar structures [4–6], these were two-dimensional with infinite height. Since the diffraction or scattering losses in the vertical direction might be serious in two-dimensional slab structure, three-dimensional analysis is desirable. Thus we analyzed the coupling of light in the slab structure by means of 3D finite difference time domain (FDTD) method.

2. Calculation and Discussion

In this paper, we used hexagonal lattice of air holes in a slab with finite thickness as a photonic crystal. For the photonic crystal, we assumed that the radius of an air hole $r = 0.29a$, the thickness of the slab $d = 0.6a$, and the refractive index of the slab $n = 3.4$ as assumed in previous paper [7, 8]. Here a is the lattice constant and assumed to be 420nm. The bandgap exists in the normalized frequency range $f = 0.256 \sim 0.320(c/a)$. The external wire waveguide is attached to the PC waveguide as shown in Fig. 1.

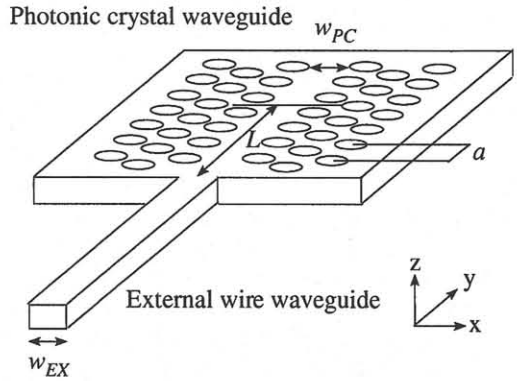

FIG. 1: Schematic image of analyzed system. w_{PC} and w_{EX} are the widths of the PC waveguide and the external wire waveguide, respectively. L is the guiding length from the connecting point to the position where the transmitted power is evaluated. The power of incident light is evaluated at a distance $7.5a$ to the connecting point.

We investigated the transmission properties by varying parameter such as the width of the wire waveguide w_{EX} to optimize the structure of connection. It is expected that the coupling of two waveguides becomes better when the modes propagating in the external wire match that of the PC waveguide. In order to investigate the property of light propagating in the wire, we calculated the dispersion relation and compared it with that of the PC waveguide. The calculation was performed in the same way as used in the previous paper[7, 8]. Figure 2(a) shows the dispersion relations of the two waveguides. The modes in the wire are folded at the wave vector 0.5 in units of $2\pi/a$. In this case we assumed that $w_{PC} = 1.152a$ and $w_{EX} = 0.974a$, where w_{PC} denotes the width of the PC waveguide. Note that the PC waveguide is air-bridge type with no clad and the external wire is on SiO_2 clad. The refractive index of SiO_2 is assumed to be $n_s = 1.46$. By using the SiO_2 clad we can obtain single mode guiding in the wire. Due to the symmetric structure of the system in the x direc-

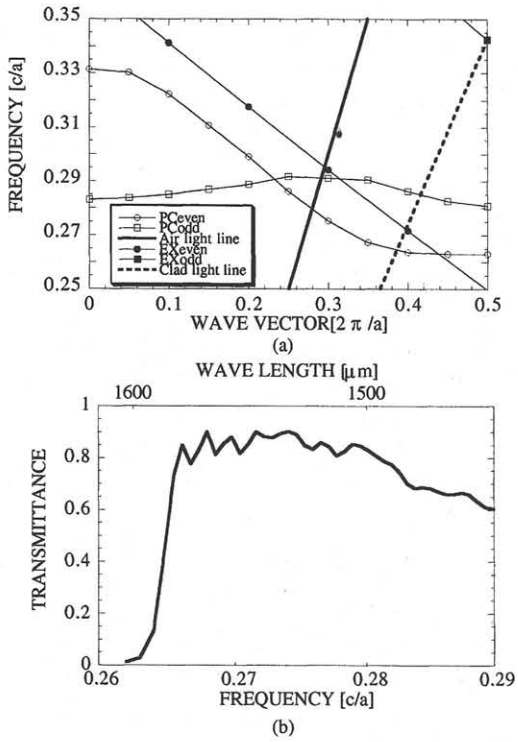

FIG. 2: (a)Dispersion relations of both the wire waveguide on SiO_2 clad and the PC waveguide. The width of the wire $w_{EX} = 0.974a$ and the width of the PC waveguide $w_{PC} = 1.152a$. (b)Transmission spectra for $L = 15a$.

tion, the guided mode can have even or odd symmetry in the x direction. Since group velocity of the even mode in the PC waveguide is not small in a frequency region $0.27 \sim 0.28$, which corresponds to the wavelength region $1.5 \sim 1.55\mu$m, we can use this mode for wave guiding in the optical communication. It is found that dispersion curves for even modes are similar to each other in two waveguides.

In our calculation, we used a pulse source excited in the wire waveguide. Taking the Fourier transform of the fields and integrating Poynting's vector over a surface at a distance of L from the connecting point, we obtained the spectrum of transmitted power into the PC waveguide. When we calculated the incident power, we used a reference composed of only wire waveguide in order to avoid the effect of reflection from the connecting point. In actual calculation, we assumed that the whole length of the PC waveguide was $45a$, and the length of the external wire was $15a$. The number of layers of air holes by the side of the PC waveguide was 13. Mur's absorbing boundary condition of the second order was used for outer boundary in all directions.

Figure 2(b) shows the transmission spectrum for $w_{EX} = 0.974a$ and $w_{PC} = 1.152a$. Here we assume that the wire on SiO_2 clad is attached to the air-bridge type PC slab with no clad. The transmittance becomes about 80% in the frequency region from 0.27 to 0.28 and then it decreases gradually for $f > 0.28$. The reason why the transmittance decreases for $f > 0.28$ is as follows. The frequency of 0.28 corresponds to the cross point of the air light line and dispersion curve for even mode in the PC waveguide. Since the diffraction losses become large in the PC waveguide for $f > 0.28$, the transmitted power into the PC waveguide escapes in the vertical direction.

3.Conclusion

We analyzed the coupling between the external wire waveguide and the PC waveguide by means of 3D FDTD method for the first time. We obtained single mode guiding in both two waveguides by putting the SiO_2 clad below the external wire. We investigated the transmission properties of light at the connecting point when the dispersion relations were similar to each other in two waveguides. The transmittance of the power from the external wire into the PC waveguide was as large as 80% in the 3D system, although it was found that the loss due to scattering or diffraction in the vertical direction is not negligible.

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