Proposal for a Compact Resonant-Coupling-Type Polarization Splitter Based on Photonic Crystal Waveguide With Absolute Photonic Bandgap

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***Abstract*—We propose a resonant-coupling-type polarization splitter based on a photonic crystal structure with absolute photonic bandgap. The scalar finite-element method was used to calculate resonant frequencies of the cavity and frequency dependences of the polarization splitter. This device supports single-mode operation for both transverse-electric and transverse-magnetic waves. We show that miniaturization of the proposed polarization splitter can be realized by utilizing resonant coupling.**

***Index Terms*—Absolute photonic bandgap (PBG), finite-element method (FEM), photonic crystal (PC) waveguide, polarization splitter.**

I. Introduction

In photonic crystal (PC) waveguides, it is possible to guide lightwave without radiation losses by utilizing the photonic bandgap (PBG) effect, even if PC waveguides are bent tightly [1]–[3]. Therefore, PC structures have been used as key materials for miniaturization and integration of photonic devices. In recent years, extensive investigations of PC applications such as the splitter, optical switch, or isolator have been carried out [4]–[6]. Furthermore, in two-dimensional PCs, the ability to realize absolute PBGs, which forbid both transverse-electric (TE) and transverse-magnetic (TM) wave propagation, by reducing structural symmetry has been reported [7], [8]. By using PCs which possess absolute PBGs, PC waveguides have the possibility that both TE and TM modes can be supported and it is expected that the applicability of PC devices will be further extended. For example, suppression of in-plane radiation losses can be realized in PC-based polarization splitters or polarization converters.

Previously, we proposed a compound-type PC of honeycomb and triangular lattices which possess absolute PBG [8]. Also, we reported a PC waveguide in which single-mode operation is realized, and demonstrated that one can use the PC directional coupler as a polarization splitter [8]. The polarization splitter reported in [8] has a length of $21a$ (a is the lattice constant of the proposed PC). On the other hand, in order to miniaturize the PC device, it is known that utilizing the resonant coupling through microcavities is effective and the wavelength filters based on microcavities have been already reported [2], [9]. It is expected that the microcavity in the PC with absolute PBG has strong polarization dependence and that the compact polarization spitter based on the microcavity can be realized.

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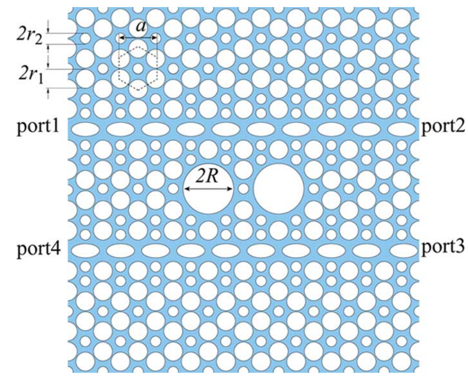

Fig. 1. Structure of resonant-coupling-type polarization splitter.

Although other types of PC-based polarization splitters have also been reported [10]–[12], the light confinement of these structures is not based on the PBG effect. Whereas the waveguide in [8] can confine lightwave by the PBG effect, therefore, it seems to be easier to construct integrated lightwave circuits using PBG-based waveguides.

In this letter, we propose a compact polarization splitter with microcavities. First, in order to determine the microcavity size for the design frequency, we calculate the microcavity size dependence of resonant frequencies by scalar finite-element method (FEM). Then, it is shown that the polarization splitter can be realized at the design frequency. In order to calculate propagation properties of the splitter, the scalar FEM with perfectly matched layer [13] is used.

II. Resonant-Coupling-Type Polarization Splitter

Fig. 1 shows the structure of a resonant-coupling-type polarization splitter based on the PC waveguide with the microcavity proposed here. The hexagonal region surrounded by a dotted line indicates a unit cell of the PC proposed in [8], where the background refractive index is 3.4, a is lattice constant, and radii of air holes, r_1 and r_2 are $0.27a$ and $0.15a$, respectively. In the waveguide region, elliptical air holes are introduced, where the major and minor axes of the air hole are $0.4a$ and $0.2a$, respectively. In these structural parameters, absolute PBG exists between $a/\lambda = 0.550$ and 0.584 [8], and single-mode operation for both TE and TM modes is realized between $a/\lambda = 0.557$ and 0.569 [8]. Fig. 1 shows the proposed polarization splitter which consists of two parallel PC waveguides coupled by double microcavities with radius R. In the following section,

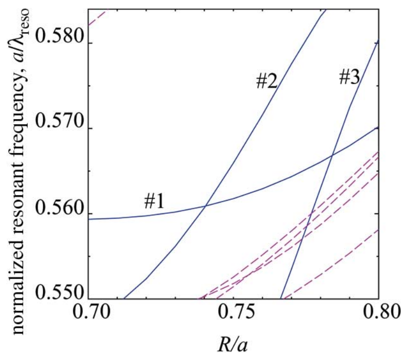

Fig. 2. Resonant frequency of the single cavity for TM wave.

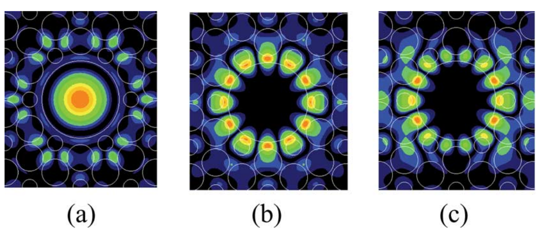

Fig. 3. Field distributions of TM cavity modes at $R = 0.77a$. (a), (b), and (c) correspond to the modes #1, #2, and #3 in Fig. 2, respectively.

although Fig. 1 shows the splitter with a double cavity (coupled cavity), we also consider the case of a single cavity similarly. The device size of proposed structure with double microcavities, $4a \times 6\sqrt{3}a$, is much smaller than that in [8], $21a \times 5\sqrt{3}a$.

III. Numerical Results

In this section, we carry out FEM calculation [13] in order to investigate characteristics of the polarization splitter. At first, we have to determine the value of radius of cavity R. It is expected that strong coupling between the microcavities and the waveguides occurs around the resonant frequency of the microcavity [2], [9]. Fig. 2 shows resonant frequency of a single microcavity for TM wave as a function of R. On the other hand, for TE wave, there are no cavity modes within the considered frequency range. Here, we choose $R = 0.77a$, so that resonant frequency of a localized mode labeled #1 in Fig. 2 lies near the center of the single-mode region of the PC waveguide. Fig. 3 shows the field distributions of three localized modes at $R = 0.77a$. Fig. 3(a) shows the cavity mode (#1 in Fig. 2), and we can see that the field localizes in the center of the cavity strongly. Fig. 3(b) and (c) shows some of the other cavity modes (#2 and #3 in Fig. 2, respectively). In contrast to Fig. 3(a), each of fields localizes around the cavity, like whispering gallery modes (WGMs).

Next, we consider the polarization splitter with a single cavity. The structure is the same as the one shown in Fig. 1 except for having only a single cavity. Fig. 4 shows frequency properties of the transmitted power into Ports 2 and 3 in the case of a single cavity. For TE wave, an incident wave is transmitted to Port 2 efficiently (more than 95%), and TM incident wave is transmitted to Port 3 efficiently around $a/\lambda = 0.564$, which corresponds to the resonant frequency of the microcavity. On the other hand, splitting efficiency is degraded away from the resonant frequency of the microcavity. Around $a/\lambda = 0.561$, the normalized output power is dramatically changed. It seems that the cause of this result is the existence of another cavity mode. Fig. 5 shows propagating fields for both TE and TM waves at $a/\lambda = 0.564$, and for the TM wave at $a/\lambda = 0.561$. We can see that at $a/\lambda = 0.564$, TE and TM waves are separated and transmitted to Ports 2 and 3, respectively. On the other hand, in Fig. 5(c), a WGM-like mode affects the resonant coupling. In the frequency range of Fig. 4, because of absolute PBG-effect and single-mode operation, there are no radiation losses and higher mode beatings.

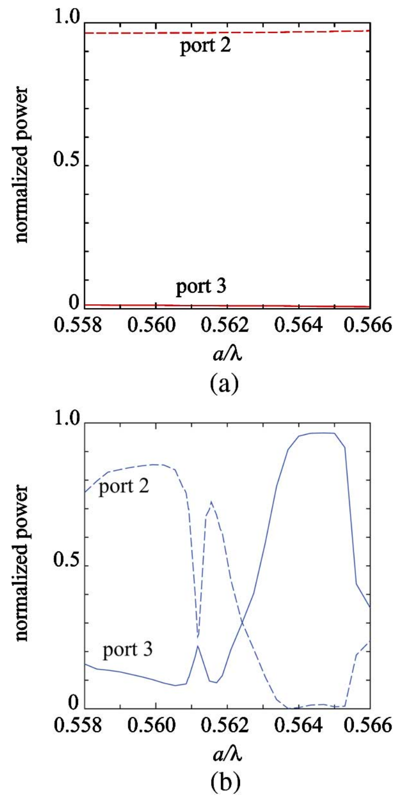

Fig. 4. Frequency dependences of transmitted power of the polarization splitter with single cavity. (a) For TE wave and (b) for TM wave.

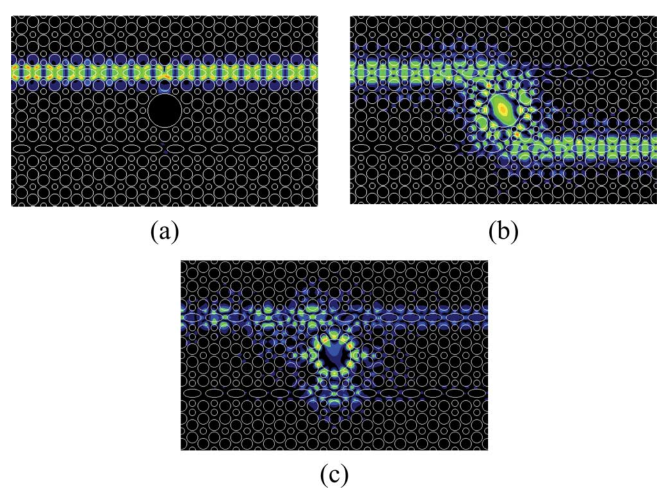

Fig. 5. Propagating fields in the polarization splitter with a single cavity. (a) For TE wave at $a/\lambda = 0.564$, (b) for TM wave at $a/\lambda = 0.564$, and (c) for TM wave at $a/\lambda = 0.561$.

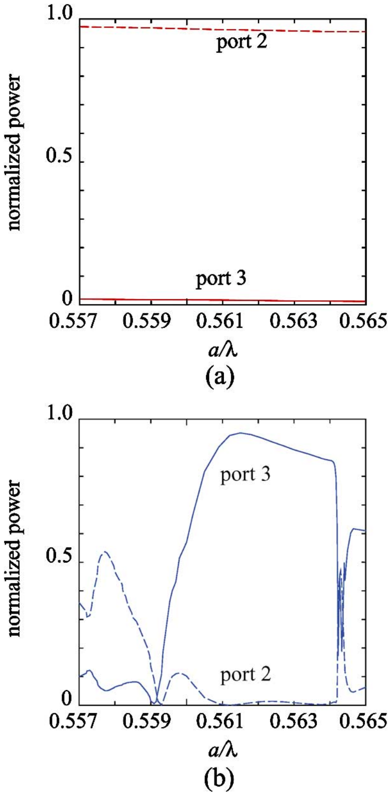

Fig. 6. Frequency dependences of transmitted power of the polarization splitter with the coupled cavity. (a) For TE wave and (b) for TM wave.

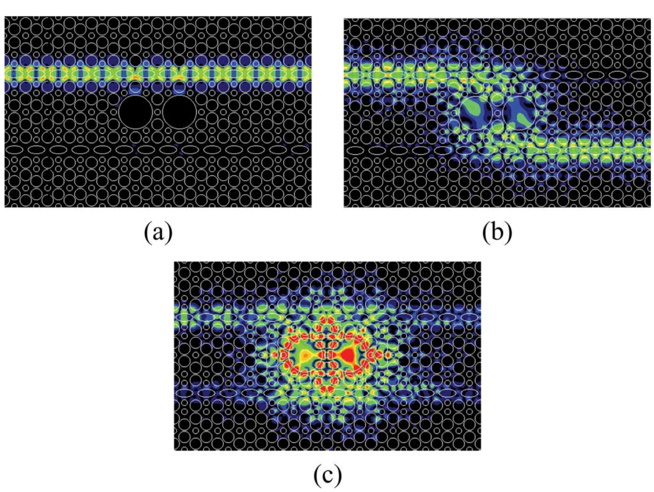

Fig. 7. Propagating fields in the polarization splitter with coupled cavity. (a) For TE wave at $a/\lambda = 0.561$, (b) for TM wave at $a/\lambda = 0.561$, and (c) for TM wave at $a/\lambda = 0.564$.

Finally, in order to expand the operating bandwidth as a polarization splitter, we consider the case of a coupled cavity, as shown in Fig. 1. In the coupled cavity, a resonant frequency of the single cavity is separated to two resonant frequencies (correspond to even and odd modes) around the original resonant frequency, so the operating bandwidth can be expanded. Fig. 6 shows frequency dependences of the transmitted power into Ports 2 and 3. For the TE wave, an incident wave is transmitted to Port 2 efficiently (more than 95%). On the other hand, a TM incident wave is transmitted to Port 3 efficiently around the $a/\lambda = 0.561$, but propagation efficiency is degraded at $a/\lambda = 0.564$. It is considered that another cavity mode of the coupled cavity affects the propagation property. Fig. 7 shows propagating fields for both TE and TM waves at $a/\lambda = 0.561$ and for the TM wave at $a/\lambda = 0.564$. From Fig. 7(a) and (b), we can see that TE and TM waves are separated and transmitted to Ports 2 and 3, respectively. On the other hand, in Fig. 7(c), the WGM-like mode also affects the resonant coupling.

IV. Conclusion

We proposed a resonant-coupling-type polarization splitter based on a PC waveguide with absolute PBG. By utilizing resonant coupling of the microcavity, the length for polarization splitting can be shortened. It has been reported that the PC-coupler-based polarization splitter in [8] can be realized with a length of $21a$. On the other hand, the polarization splitter proposed here has a length of $4a$, which is one-fifth as long as the device length in [8]. Moreover, considering the actual device application, in the structure in [8], bending waveguides are required to separate the upper and lower waveguides, but, in the present structure, not required.

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