A Polarization Diversity Two-Dimensional Photonic-Crystal Device

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(Invited Paper)

***Abstract*—2-D photonic crystals (2-D PCs) are expected to enable ultrasmall and highly functional photonic devices to be developed. However, 2-D PCs have a large polarization dependency, which can be an important issue depending on the type of application. To address this matter, we propose a method to realize a polarization diversity operation in a PC. Initially, an ultrasmall PC polarization converter that utilizes 45° tilted airholes is considered. A polarization-independent add–drop filter using this polarization converter is then described, and the operation is experimentally demonstrated.**

***Index Terms*—Photonic crystal, polarization converter, polarization diversity.**

I. Introduction

2-D PHOTONIC crystals (2-D PCs) [1]–[12] are currently the focus of much interest because they have the potential to be a platform for ultrasmall optical devices. Recently, 2-D PC nanocavities with modal volumes as small as a cubic wavelength and experimental quality (Q) factors $>2.5 \times 10^6$ have been achieved [9], [10]. It is predicted that nanocavities will be applied to various areas of physics and engineering, such as ultracompact filters [2]–[6], the slowing and/or stopping of light [12]–[14], ultimate nanolasers [15]–[17], and quantum information processing [18], [19].

However, an important issue associated with 2-D PCs is polarization dependence. For example, a triangular lattice 2-D PC with cylindrical airholes has a photonic band gap (PBG) only for the transverse electric (TE)-like mode and not for the transverse magnetic (TM)-like mode. Two methods have been suggested to overcome this issue: utilizing a PC with a PBG for both TE and TM polarizations [20] and employing polarization diversity [21]–[23]. Although a triangular lattice PC with triangular airholes has already been proposed and demonstrated to have a PBG for both TE and TM polarizations [20], there are still several barriers to overcoming the polarization dependence. In this paper, we focus on the polarization diversity for polarization-independent PC-based devices.

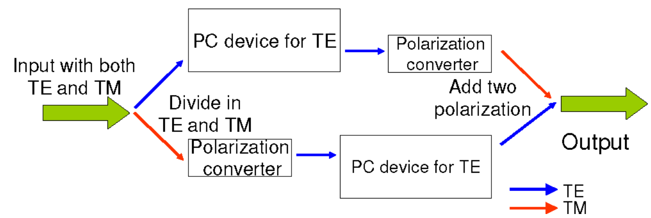

Fig. 1. Basic concept of polarization diversity operation.

The basic concept of the polarization diversity method is shown in Fig. 1. The input with both TE and TM components is divided into TE and TM separately by a polarization beam splitter. The TE component enters into a PC-based device that can operate for only TE polarization, and its output is converted into TM by a polarization converter [24]. Meanwhile, the TM component is converted into TE by the other polarization converter, and it enters into the other PC-based device for TE polarization. The two outputs are combined by a polarization beam splitter.

This type of polarization diversity method has been proposed and demonstrated in wire waveguide-based structures [22], [23]. However, in these structures, the device size is typically larger than that for PC-based structures. Moreover, to integrate the wire waveguide-based polarization diversity system into a PC-based device, the connection between PC-based nanostructures and wire waveguide-based structures remains a difficult issue. Therefore, realization of the polarization diversity operation in a monolithic PC-based structure is expected for ultrasmall and highly functional photonic devices.

In the current paper, we initially propose a polarization converter that can connect within a PC waveguide monolithically. We then discuss a polarization-independent optical add–drop filter based on a PC using a proposed polarization converter as an example of a polarization diversity operation. In Section II, we consider a polarization converter that can be integrated into a 2-D PC. In Section III, we demonstrate a polarization diversity operation of a PC add–drop filter using the proposed polarization converter, which can work for both TE and TM polarizations. Finally, in Section IV, we summarize the work.

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II. Proposal and Demonstration of PC-Based Polarization Converter

We discuss a polarization converter, which is a key component for realizing polarization diversity. The principle of a polarization converter is typically based on a half-wave plate, which has birefringent characteristics. As well as a conventional half-wave plate, a ridge waveguide-based polarization converter with an asymmetric cross section [25] has also been proposed and has structural birefringence. However, this type of converter can be as 100 μm–1 mm in length, making it difficult to integrate into ultrasmall photonic devices based on 2-D PCs. Moreover, the connection loss due to the large spot size discrepancy between the PC waveguide (diameter: 1 μm) and the ridge waveguide (diameter: 10 μm) is also considered to be an important issue. We therefore propose an ultrasmall polarization converter that can be connected with a PC waveguide monolithically.

In order to discuss the principle of a polarization converter, we must first consider a half-wave plate. A half-wave plate has two principle axes with different wavenumbers, which can be called axis A and axis B. When a linear polarized input with polarization at an angle of θ arrives, it is divided into the two principle axes. When the length of the half-wave plate satisfies

$$d = \frac{(2n+1)\pi}{|k_A - k_B|} \tag{1}$$

where k_A and k_B represent the wavenumber of the principle axes A and B, respectively, and n is an integer, the light is reconstructed into linear polarization with an angle of $-\theta$. Thus, the polarization rotates at 2θ. If θ is set to 45°, then 90° rotation of the polarization can be achieved. Even in a case where $\theta <$ 45°, multiple operation leads to a 90° rotation.

Next, we apply this principle to a PC-based system. Theoretically, in a W1 waveguide introduced into a triangular lattice 2-D PC slab, both TE and TM polarizations can propagate without loss. Although the PC does not have a PBG for the TM mode, theoretically perfect confinement for the TM mode can be realized by total reflection. Moreover, the wavenumber of the TE and TM modes differs, which means that this waveguide has structural birefringence. Here, we propose a polarization conversion devise (Fig. 2) that can convert between TE and TM waveguide modes and can connect with a PC waveguide monolithically. The nearest neighbor airholes are tilted in the x–z plane at an angle of 45°. Conversion units with right-tilted airholes (denoted as R) and with left-tilted regions (denoted as L) are formed periodically. In these (R, L) units, the structure is asymmetric in both the vertical and horizontal directions. Therefore, two waveguide modes denoted as TE′ and TM′ exist, which are not orthogonal to the TE and TM modes in waveguides with vertical airholes (denoted as V). The propagation mode is thus divided into TE′ and TM′ modes at the region of interface between the V region and the R or L region. Moreover, polarization conversion will be realized when the length of the R or L region d satisfies

$$d = \frac{(2n+1)\pi}{|k_{\mathrm{TE}'} - k_{\mathrm{TM}'}|} \tag{2}$$

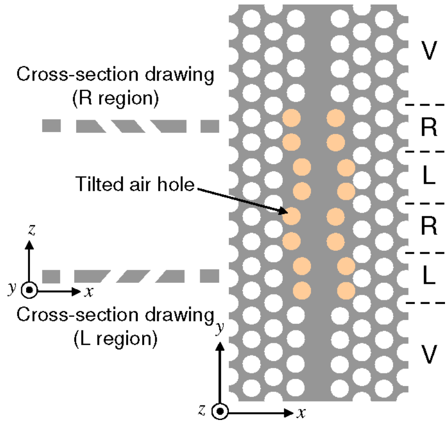

Fig. 2. Schematic of proposed polarization mode converter based on a 2-D PC structure. The nearest neighbor airholes are tilted in the x–z plane at an angle of 45°. Conversion units with right-tilted airholes (denoted as R) and with left-tilted regions (denoted as L) are formed periodically.

where $k_{\mathrm{TE}'}$ and $k_{\mathrm{TM}'}$ represent the wavenumber of the TE′-like and TM′-like modes, respectively, and n is an integer.

In the system with structural birefringence proposed here, the propagation mode cannot be defined as simple linear polarization, because the mode has an electromagnetic component for various directions. Therefore, the polarization angle difference cannot be defined simply from the angle of the electrical vector. However, the relative angle between the TE, TM modes in the V region and the TE′, TM′ modes in the R or L region can be defined from the coupling efficiency from the TE and TM modes in the V region to the TE′ and TM′ modes in the R or L region, or vice versa. We use a 3-D finite domain-time difference (FDTD) calculation to estimate this coupling efficiency. When the angle of the tilted airhole is 45°, the relative angle between the TE and TE′ modes is estimated to be 9°–11°, and that between the TE and TM′ modes is estimated to be 79°–81°. Therefore, when the length of the R or L region satisfies (2), the polarization rotates 18°–22°, and the serial connection of four or five units leads to 90° polarization rotation.

Next, in order to estimate the length of the R or L region d satisfying (1), we calculate the dispersion relation of the waveguide by the 3-D FDTD method. The calculated results for the V region are shown in Fig. 3, in which the propagation modes are not folded into the first Brillouin zone in order to analyze the modes propagating for the same direction. Even in the L and R regions, the dispersion relation is similar to that in the V region except for the anticrossing region. In the frequency range of 0.264–0.278c/a, the wavenumber difference between the TE and TM modes propagating in the same direction is estimated to be $\sim$0.25 $\times$ $2\pi/a$, where c and a denote the velocity of light in vacuum and the lattice constant of PC, respectively. In the case of the TE′ and TM′ modes in the L or R region, the wavenumber difference is also $\sim$0.25 $\times$ $2\pi/a$. Therefore, from (2), the length of each L or R region d should satisfy

$$d = 2a,\ 6a,\ 10a \ldots. \tag{3}$$

To reduce the length of the polarization converter, d should be equal to $2a$. Moreover, the dispersions of these two modes

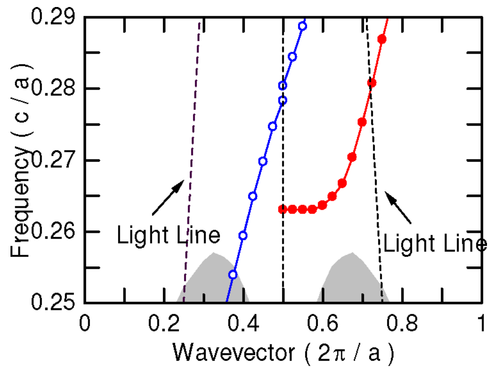

Fig. 3. Calculated band diagram of the W1 waveguide using the 3-D FDTD method. The results for the V region are shown; however, even in the L and R regions, the dispersion relation is similar to the V region except for the anticrossing region. The propagation modes are not folded into the first Brillouin Zone in order to analyze the modes propagating for the same direction.

are parallel in this wide frequency range. Therefore, wide frequency range polarization conversion is expected by utilizing the condition shown in (3).

To confirm these predictions, we used a 3-D FDTD calculation to evaluate the characteristics of the proposed polarization converter. Here, the lattice constant of the PC is 420 nm, the length of each L and R region is set to $2a$, and the sum of the number of L and R regions is set to 4. The TE waveguide modes are excited selectively, and the transmitting light through the polarization converter is calculated. Fig. 4(a) shows the output TM power normalized by the total transmitted power. More than 80% of the transmitted light is converted into TM polarization in a wavelength range of 1515–1575 nm. Fig. 4(b) shows the calculated net loss through the polarization converter (total transmitted power over input power). The loss through the converter is as small as 1–2 dB.

In order to demonstrate the polarization converter experimentally, a silicon (Si) PC-based polarization converter is used. This comprises a Si-on-insulator (SOI) substrate with a top Si layer with a thickness of 250 nm and an Si dioxide (SiO_2) layer with a thickness of 3000 nm just below the Si layer. Initially, vertical airholes are formed in the top Si layer using electron-beam (EB) lithography and an inductively coupled plasma (ICP) etching technique. Then, the tilted airholes are formed by a focused ion beam (FIB) technique [26] by tilting the substrate during the fabrication. Finally, the edge of the sample is cleaved and the SiO2 layer is removed using hydrofluoric acid to form an air-bridge structure. A scanning electron microscopy (SEM) image of the fabricated sample is shown in Fig. 5(a). The nearest neighbor airholes to the waveguide are, indeed, tilted in the x–z plane. The length of each conversion unit and the number of steps are set to $2a$ and 4, respectively. The estimated airhole radii and the length of the PC waveguide are 110 nm and 200 μm, respectively.

For the measurement, TE polarized light is introduced from a wavelength-tunable laser from one facet and a polarizer is set after the other facet in order to measure the conversion characteristics. Fig. 5(b) shows the measured output TM power normalized by the total transmitted power. The normalized TM power ratio is as high as 70%–80% in the wavelength range of 1520–1580 nm, which is consistent with the FDTD calculation results. Fig. 5(c) shows the loss of the polarization converter normalized by the transmittance of a waveguide without a polarization converter fabricated on the same chip. The measured loss is ∼4–6 dB in the wavelength range of 1520–1580 nm. Compared with the calculated results, there is 3–4 dB additional loss in the fabricated sample. One origin of this additional loss is the fabrication accuracy. As shown in Fig. 5(a), the measured radius of the tilted airholes is $0.36a$, which is larger than intended in the design, and the misalignment of the tilted airholes is estimated to be $\sim 0.2a$. Improvement of the fabrication technique would reduce this additional loss.

III. Polarization-Independent Add–Drop Filter Using Polarization Diversity

In Section II, we proposed and demonstrated a polarization converter integrated into a PC. Here, we demonstrate a polarization diversity operation using this polarization converter. We describe a polarization-independent optical add–drop filter [2]–[6] with polarization diversity.

The proposed structure, which is shown in Fig. 6, consists of two waveguides, two polarization converters, two high-Q nanocavities, and four TE barriers layer using a hetero interface. Both TE and TM can propagate in the waveguide, but only TE can resonate in the nanocavity. In the TE barriers, the lattice constant for the direction perpendicular to the waveguide is slightly reduced in order to reflect TE light and to pass TM light [5], [27]. When a TE input is introduced from the input port shown on the lower left-hand side of Fig. 6, it is dropped to the upper waveguide through cavity 1 if the wavelength of the input is the same as the resonant wavelength of the cavity. A drop efficiency of 100% is achieved by including the correct distance between the nanocavity and the TE barrier in the design [6]. The dropped TE input is converted into TM polarization by polarization converter 1 (Fig. 6); it passes through TE barrier 3 and is not dropped by cavity 2, because it has been converted into TM. Therefore, the dropped TE input finally passes to the output port shown on the upper right-hand side of Fig. 5. Meanwhile, when the TM input is introduced, it is not dropped by cavity 1, passes through TE barrier 2 and is converted into TE. The converted light with a wavelength equal to the resonant wavelength of the cavity is dropped to the waveguide with 100% efficiency and passes to the output port. In this scheme, both the TE and TM inputs are dropped to the same port and thus polarization-independent operation is expected.

In order to confirm these qualitative predictions, we use 3-D FDTD calculations. A Si-based PC is assumed, and the airhole radii and slab thickness are set to $0.29a$ and $0.6a$, respectively. W1 waveguides, L3 cavities with six neighbor airhole shifts [7], and the polarization converter discussed in Section II are employed. In the TE-barrier layer, the lattice constant for the direction perpendicular to the waveguide is reduced by a factor of 0.975. We excite the TE and TM selectively with the same frequency as the resonant frequency of the cavities. Fig. 7(a)–(d) shows the calculated vertical component of the magnetic field

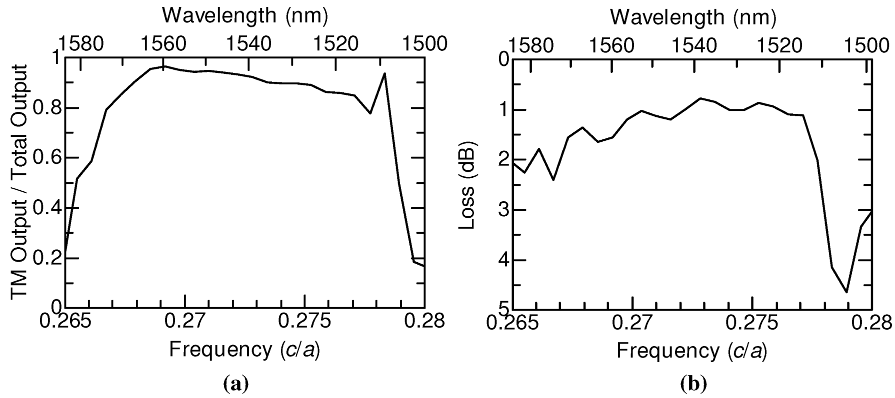

Fig. 4. (a) Calculated output TM power normalized by the total transmitted power when TE is introduced to the proposed polarization converter. (b) Calculated transmittance of the polarization converter.

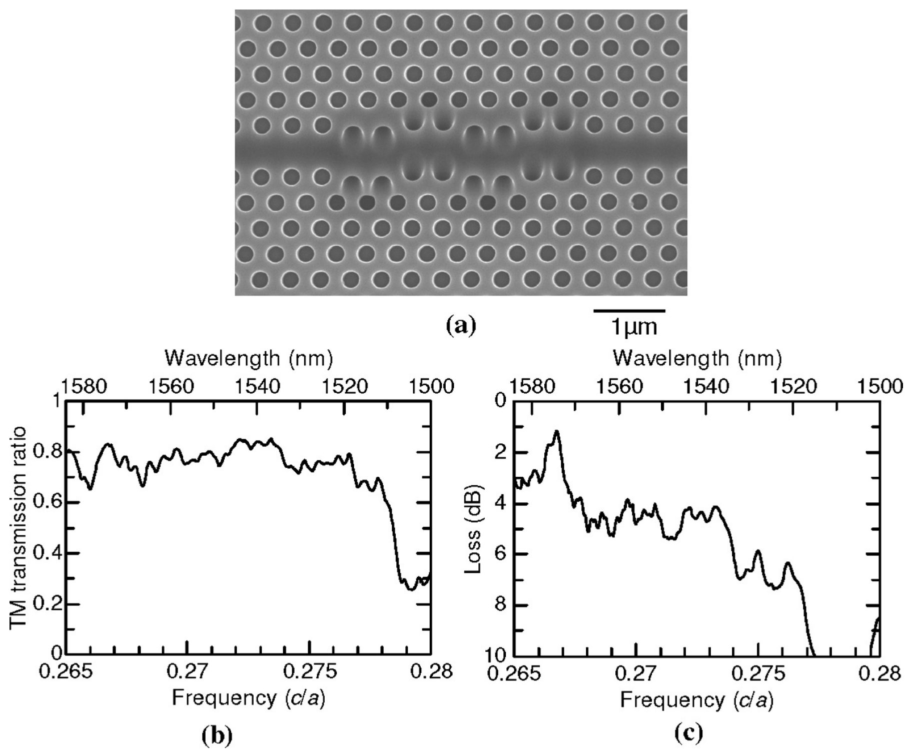

Fig. 5. (a) SEM image of fabricated polarization converter. (b) Measured output TM power normalized by the total transmitted power when TE is introduced to the proposed polarization converter. (c) Measured transmittance of the polarization converter for TE input.

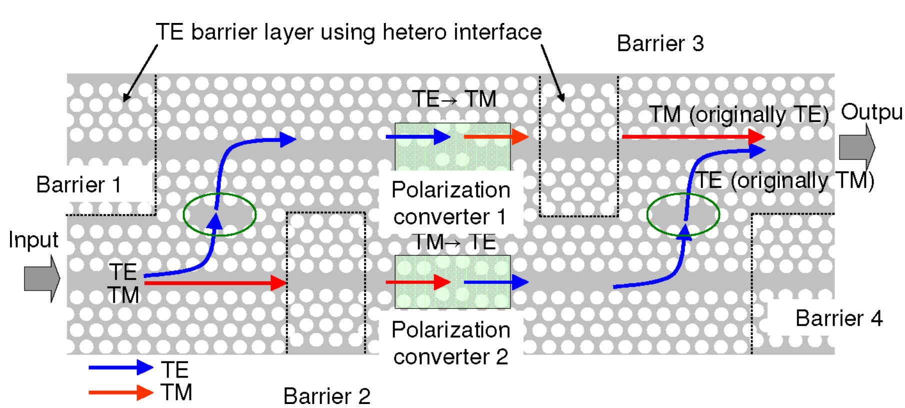

Fig. 6. Schematic of the proposed structure, which consists of two waveguides, two polarization converters, two high-Q nanocavities, and four TE barriers layer using a hetero interface.

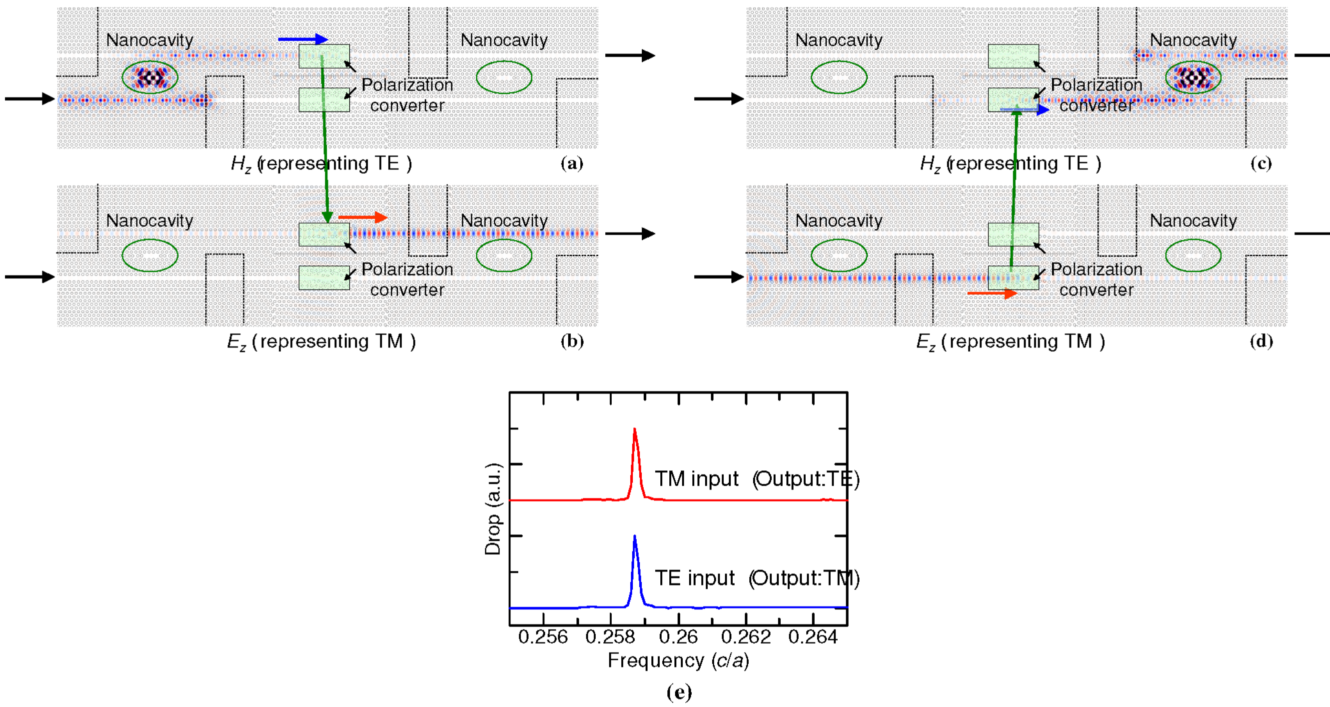

Fig. 7. (a,b) Calculated electromagnetic field when a TE input with the same frequency as the resonant frequency of the cavities is introduced; (a) and (b) represent the H_z and the E_z, respectively. (c,d) Calculated electromagnetic field when a TM input with the same frequency as the resonant frequency of the cavities is introduced; (c) and (d) represent the H_z and the E_z, respectively. (e) Calculated drop spectra of the designed add–drop filter; the blue and red lines indicate the TE and TM inputs, respectively.

(H_z) and the vertical component of the electric field (E_z) on the center plane of the PC slab. H_z and E_z represent the TE and TM components, respectively. Fig. 7(a)–(d) shows that the TE and TM inputs are dropped to the output port via cavity 1 and cavity 2, respectively. Fig. 7(e) shows the calculated drop spectrum. Both the TE input and the TM input with a frequency of 0.2587*c/a* are dropped. These results indicate that a polarization-independent drop operation is realized.

In the fabricated polarization diversity add–drop filter, the vertical airholes are formed by EB lithography and ICP etching, and the tilted airholes are formed by FIB, as described in Section II. The distance between the nanocavity and the waveguide is set to be five rows, and the lattice constant in the polarization conversion region is set by a factor of 1.025 in order to match the resonant wavelength of the cavities and the band of polarization converter. An SEM image of the fabricated sample with the intended structure is shown in Fig. 8(a) and (b). In the measurement, first TE light from a wavelength tunable laser is introduced, and a TM polarizer is set after the output port to reduce the scattering light. The resulting drop spectra for TE input is shown in Fig. 8(c). Conversely, when TM light is introduced, and TE polarizer is set after the output port, the drop result is shown in Fig. 8(d). The drop operation for both TE and TM cases has a wavelength of 1542.1 nm. These results show the realization of polarization-independent operation by polarization diversity.

We have discussed and demonstrated a polarization-independent add–drop filter. By using this strategy, a polarization-independent photonic device based on PC can be realized by employing the system shown in Fig. 9, which consists of two waveguides, two polarization converters, two high-Q nanocavities, and any two PC-based devices. Recently, 2-D PC nanocavities with experimental Q factors of 2.5×10^6 [9], [10] and theoretical Q factor of $\sim 10^9$ [28] have been achieved. Moreover, dynamic control of PCs in the time domain has been investigated for arbitrary control of photons. On-demand trapping and releasing photons in nanocavities [12], [13] and waveguide [29], [30] has been investigated and demonstrated. By

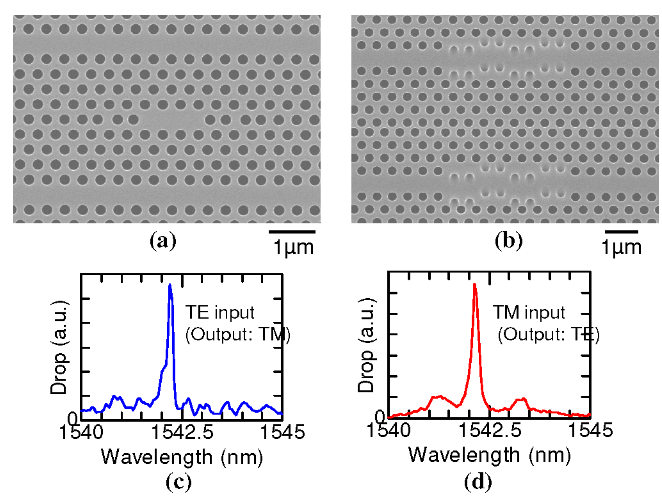

Fig. 8. (a,b) SEM image of fabricated polarization-independent add–drop filter. (c,d) Measured drop spectra for the TE and TM inputs, respectively.

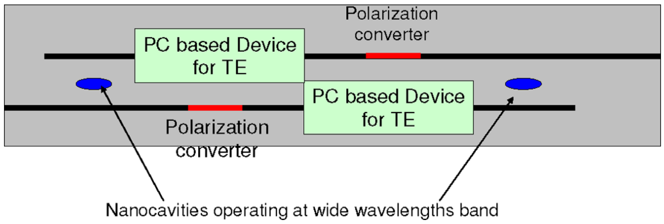

Fig. 9. Schematic image of polarization-independent PC device based on polarization diversity.

combining these techniques with the proposed polarization diversity system shown in Fig. 9, photons can be controlled regardless of their polarization.

IV. Conclusion

In this paper, we propose and investigate a polarization converter integrated into a 2-D PC waveguide, and a polarization diversity operation using this polarization converter. The converter has a bandwidth of 50 nm, and a conversion efficiency of 85%, with a length of $<10\ \mu$m. Moreover, a polarization-independent add–drop filter using polarization diversity is proposed, and its successful operation is shown. These results could help to realize polarization-independent PC-based photonic devises.

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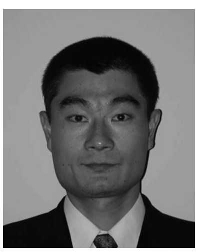

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