Design of a Compact Photonic-Crystal-Based Polarizing Beam Splitter

Tao Liu, Armis R. Zakharian, Mahmoud Fallahi, Jerome V. Moloney, and Masud Mansuripur

***Abstract*—A compact polarizing beam splitter based on a photonic crystal (PC) directional coupler with a triangular lattice of air holes is designed and simulated. In the employed PC structure, transverse-electric (TE) light is confined with the photonic bandgap effect, while transverse-magnetic (TM) light is guided through an index-like effect. Due to the different guiding mechanisms, TM and TE light have strikingly different beat lengths, which is utilized to separate the two polarizations in a directional coupler no longer than 24.2 μm. The two-dimensional finite-difference time-domain method of computation is used to evaluate the device performance. The extinction ratios are found to be around 20 dB for both TE and TM polarized light.**

***Index Terms*—Optical waveguides, photonic crystals (PCs), polarizing beam splitters (PBSs).**

I. Introduction

A POLARIZING beam splitter (PBS) is an important functional device in optical integrated circuits. A conventional PBS is usually made in the form of an asymmetric Y-branch [1], a Mach–Zehnder interferometer [2], or a multimode interference device [3]. These conventional waveguide PBSs have one common disadvantage: They require relatively long waveguide structures (on the order of millimeters), which imposes limitations on the achievable density of integration.

To reduce the device size, a compact PBS based on a hybrid photonic crystal (PC)/conventional waveguide structure has been proposed [4]. In this design, the light is guided in conventional optical waveguides, while a PC structure acts as a grating to transmit or reflect the light of differing polarizations. Considering the advantages of PC optical circuits, a PBS based on all-PC structures provides the flexibility of easy integration with other PC-based devices and would, therefore, be more attractive. This letter presents the design and numerical analysis of an all-PC-based PBS.

There are two requirements to realize a compact high-efficiency PBS. First, both transverse-magnetic (TM) and transverse-electric (TE) polarized light must propagate with low loss in the device. Second, the difference between the propagating properties of TM and TE light must be large enough to ensure that the two polarizations can be separated after a short propagation distance. The first requirement might be satisfied by creating the device in a PC with a complete photonic bandgap (PBG) for both polarizations, e.g., a triangular lattice of air holes in a high-index medium with a sufficiently large air-filling factor. However, large air holes are detrimental to waveguiding and lead to losses out of the plane [5]. On the other hand, the size of the PBG, which is defined as the gap-to-midgap ratio, is very narrow for the TM polarization (relative to TE), and that gap could disappear altogether due to fabrication inaccuracies. Furthermore, the difference between TM and TE propagation properties will not be substantial if both polarization states are guided through a similar PBG effect, which would violate the second requirement for a compact PBS.

Fortunately, the PBG effect is not the only mechanism to confine the light in a PC waveguide structure. It has been shown theoretically and experimentally that the light can also be guided through the index contrast in a PC waveguide if the average index in the guiding region is higher than that in the surrounding area [6], [7]. This provides an attractive way for creating a low-loss PC-based waveguide for both polarization states, namely, the PBG effect to confine the TE light, and the index-like effect to confine and guide the TM light. A waveguide of this kind can be realized by removing a row of air holes along the Γ-K direction in a triangular lattice PC that has a PBG for the TE light only. In the defect region (i.e., the missing air holes), the average index is higher than that in the surrounding region. As a result, while the TE light is being guided through the PBG effect, it might be possible to confine the TM light through the aforementioned index contrast effect. In this way, the first requirement for realizing a compact PBS will be satisfied. Since the TE light and the TM light are now guided by two different mechanisms, we can reasonably expect to find an appreciable difference between the TM and TE propagating properties, so that this difference can be used to separate the two polarization states of the input beam. We use a PC directional coupler to implement the functionality of polarization separation. A PBS based on a conventional directional coupler has been fabricated in the past, with a reported length of 9 mm [8]. We show in this letter that polarization separation can be achieved by a PC-based directional coupler over a distance of only 24.2 μm.

II. Design and Analysis

Since most two-dimensional PCs are generally realized in conventional heterostructure slab waveguides, we use the effective refractive index mechanism to confine the light in the third

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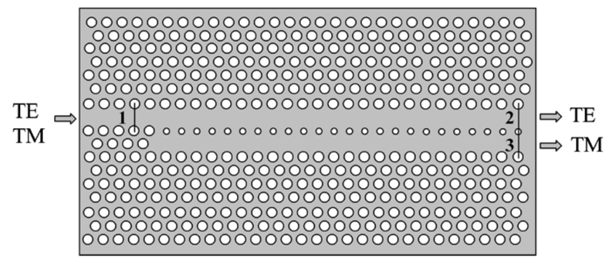

Fig. 1. Diagram of the proposed PBS based on a PC directional coupler. The effective refractive index of the host material is 3.32; the period of the triangular lattice of air holes is $a = 0.457$ μm; the radius of the lattice holes is $r_0 = 0.147$ μm; while the radius of the smaller holes that separate the two guides in the coupler region is $r_1 = 0.118$ μm. The lengths of the input guide and the directional coupler are $15a$ and $53a$, respectively. The top waveguide is referred to as the direct channel, while the bottom guide is called the adjacent channel. Also, shown are three line detectors used in the FDTD simulations: 1) to monitor the power input into the directional coupler, 2) to monitor the power in the direct channel, and 3) to monitor the power in the adjacent channel.

dimension [9] in our finite-difference time-domain (FDTD) simulations [10]. In a high-index-contrast heterostructure, e.g., the SiO_2–Si–SiO_2 system ($n_c = 3.6, n_s = 1.5$), the effective indexes for the TM and TE polarizations are very different, which makes it difficult for the TM and TE transmission bands to overlap. However, in a low-index-contrast structure, e.g., a Ga(Al)As laser-like heterostructure, the effective indexes for the two polarizations are fairly close to each other. In the latter case, we found it relatively easy to get the TM and TE high-transmission bands to overlap. We, thus, consider a two-dimensional PC in a Ga(Al)As laser-like heterostructure corresponding to the carefully studied case of GaAs samples in [11] with the effective refractive index of 3.32 for both polarizations.

The proposed PC-based PBS in a triangular lattice of air holes is shown in Fig. 1. The single-channel waveguide on the left-hand side (along the Γ-K direction) is used as the input guide to couple the light into the directional coupler. The coupler consists of two parallel waveguides (i.e., defects in the lattice) separated by a single row of smaller air holes (as compared to the lattice air holes). In this design, the $\boldsymbol{E}$-field of the TM light and the $\boldsymbol{H}$-field of the TE light are normal to the plane of periodicity. In order to find suitable structural parameters, including the PC period and the radius of the air holes, we began with a large air-filling factor that would give a large TE bandgap. The transmission efficiency was then calculated for both TE and TM light. If we failed to achieve low-loss transmission bands for TM and TE light in such a way that they would overlap over some range of frequencies, the air-filling factor would be reduced until the overlap was found. Further reduction of the air-filling factor would gradually close the TE bandgap, which is not desired for the device performance. The selected period of the triangular lattice is $a = 0.457$ μm, the radius of the regular air holes is $r_0 = 0.147$ μm, and the radius of the small air holes (separating the two guides in the coupler region) is $r_1 = 0.118$ μm. By using small air holes to separate the channels, one can improve the coupling strength for TM light, and therefore, reduce its beat length and the device size. (In our case, the beat length for TM light is shortened from $192a$ to $106a$ when the hole radius is reduced from $r_0 = 0.147$ μm to $r_1 = 0.118$ μm.) The coupling strength for TE light around the working point does not change much with the reduction of the coupling holes; this point will be discussed later on.

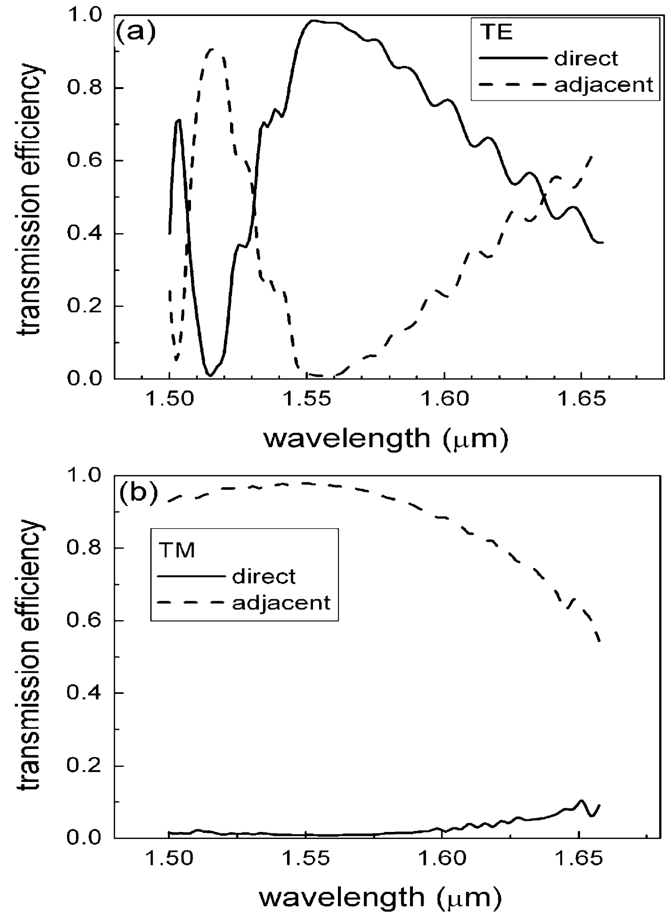

Fig. 2. Computed transmission efficiency for the direct channel and the adjacent channel for (a) TE light and (b) TM light.

In our FDTD simulations, perfectly matched layers [12] were used to terminate the designed PC structure. A pulse source, centered around $\lambda = 1.55$ μm and having a spatial Gaussian shape, was located at the entrance to the input waveguide; this pulse was used to launch the TM or TE light into the device. In Fig. 1, three line detectors, one before the directional coupler and marked as 1, another across the direct channel output (marked as 2), and the third across the adjacent channel output (marked as 3), were used to monitor the input and output power levels. The output power was then divided by the input power to compute the transmission efficiency of the PBS at various wavelengths. Note that Monitor 1 measures the amount of power that is coupled into the directional coupler; reflection from the directional coupler is, thus, excluded from the calculation.

Fig. 2 shows the computed transmission efficiency of the direct and adjacent channels for TE and TM polarized light. In the FDTD simulations, the length of the coupling region was $53a$, where a is the crystal period. Note that the TM high transmission band (>95%) around $\lambda = 1.55$ μm overlaps with the TE transmission band. It can be seen in Fig. 2 that for wavelengths in the vicinity of $\lambda = 1.55$ μm, the TE light remains confined to the direct channel, while almost all the TM light is transferred to the adjacent channel. At $\lambda = 1.554$ μm, 98.3% of the TE light

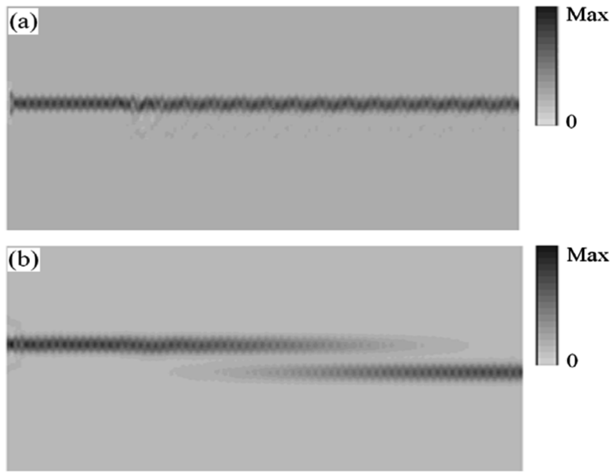

Fig. 3. Simulated Poynting vector distribution along the guide direction for (a) TE light and (b) TM light in the structure shown in Fig. 1. The optical wavelength is 1.554 μm.

remains in the direct channel and 97.6% of the TM light transfers to the adjacent channel. The distributions of the Poynting vector along the guide direction for the TE light and TM light are shown in Fig. 3, where the polarization separation is clearly observed. The operating principle of the PBS is discussed in the next section.

For the directional coupler in the proposed PBS, the two waveguides are decoupled for the TE light [13], [14] in the vicinity of $\lambda = 1.55$ μm. This decoupling makes the beat length of the directional coupler extremely large for the TE light. As a result, the TE light remains in the direct channel after propagating through this short device. A careful examination of the Poynting vector distribution of the TE light in the adjacent channel indicates that the field there is not precisely null [see Fig. 3(a)]. This is mainly caused by the slight mismatch between the modal field profiles of the input waveguide and the directional coupler. However, the fact that TE light level remains more or less constant when propagating along the direct channel indicates that the direct and the adjacent channels are actually decoupled. In contrast, the TM light, for which the two channels are tightly coupled, behaves quite differently. This explains why the TM light can transfer completely to the adjacent channel after propagating a distance of half the beat length in the directional coupler. (The beat length was found numerically to be around $106a$.) The two polarizations are, thus, separated at the output of the directional coupler into two channels: TE light to direct channel and TM light to the adjacent channel. If necessary, a PC sharp bend may be added at the end of the device to further separate the two polarized beams. Sharp bends with a high transmission efficiency in triangular PCs have been extensively studied [15]–[17] and will not be discussed in this letter.

From Fig. 2, it can also be seen that the bandwidth for the TE light is much narrower than that of the TM light. This can be explained by the properties of the odd and even modes' dispersion curves for TE light in the vicinity of $\lambda = 1.55$ μm that is close to the upper band edge. (The dispersion curves are not shown in this letter.) From the decoupling point ($\lambda = 1.55$ μm) to longer wavelengths, the two curves have similar slopes, which causes the slow wavelength routing, as shown in Fig. 2(a). From the decoupling point to shorter wavelengths, however, the slope difference between the two dispersion curves increases dramatically, which explains the rapid wavelength routing in the shorter wavelength regime and hence the small TE bandwidth.

III. Conclusion

We have presented the design of a compact PBS based on a PC directional coupler in a two-dimensional triangular lattice of air holes in a Ga(Al)As laser-like heterostructure. The polarization separation functionality is enabled by the two different guiding mechanisms: PBG effect for the TE light and index-contrast for the TM light, which makes the two channels of the directional coupler decoupled for TE and tightly coupled for TM light. By utilizing this property, a PBS based on a directional coupler as short as 24.2 μm can be realized with the extinction ratios ~20 dB for both TE and TM light.

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