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Physics Letters A 369 (2007) 524–527
PHYSICS LETTERS A
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# Dispersion-based all photonic crystals polarization beam splitter

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Received 24 January 2007; received in revised form 26 March 2007; accepted 4 May 2007

Available online 17 May 2007

Communicated by R. Wu

**Abstract**

We present the design and simulation of an ultra-compact high-efficient polarization beam splitter (PBS) based on the material engineering by combining photonic crystal dispersion properties and photonic band gap in this Letter. The PBS consists of two periodic structures: a polarization-independent self-collimation (PIS) structure and a splitting region. The PIS structure served as a virtual wave-guide in which the TE- and TM-polarized light can diffractionless propagate simultaneously; the splitting structure can be used to reflect TE-polarized light because it is within the photonic band gap, but TM-polarized light is transmitted across the splitting structure because it lies in the photonic band. The splitting properties of the PBS have been numerically studied using the finite difference time domain (FDTD) method. It has been shown a 90° separating angle and efficiency of more than 85% for TE- and TM-polarized light over a wide frequency range 0.268–0.278$(c/a)$ can be obtained. The size of PBS is only 9.0 μm × 9.0 μm at optical communication wavelength $\lambda = 1.55$ μm. These features of the proposed PBS make it a promising candidate in optical communication application.


*PACS:* 42.70.Qs; 42.79.Fm; 42.25.Ja; 42.79.Ag

*Keywords:* Photonic crystals; Self-collimation; Polarization beam splitter

## 1. Introduction

Polarization beam splitters (PBS), which can separate the two orthogonal polarizations of light into different propagation directions, are very important in optical communication, optical recording and integrated optical circuits. Since the size of PBS based on conventional multi-layer dielectric or ridge waveguide is on the order of millimeters, it is less competitive to use it in high-integrated optical circuits. In order to find high efficient ultra-compact photonic components, people have paid more attention to photonic crystals (PCs) that are artificially designed to control the propagation of light at optical wavelength scale [1,2]. Recently, several types of PBS based on PCs have been reported [3–10]. However, most of the PBSs are only concerned with the splitting structure [3–5]. If they are applied to optical circuits, extra waveguides have to be added to guide the input and output light. This will enlarge the size of PBS, reduce their efficiency, and make them less attractive. S. Kim et al. proposed a hybrid structure consisting of conventional waveguide and PCs, which uses the waveguide to confine the propagation of light [8]. Researchers have also proposed two kinds of all-PCs PBSs by introducing line defect [9,10]. However these designs can separate the polarized light within a small splitting distance and only act as a polarizer.

PCs display strong dispersion and anisotropy due to complicated photonic bands, which can lead to many interesting phenomena such as superprism effects [11], self-collimation [12–18] and negative refraction [19]. Self-collimation effect can effectively freeze the spatial width of a light beam inside PCs without using waveguides or nonlinear optical materials. In this Letter, we demonstrate a new kind of compact hybrid all-PCs PBS, it consists of two kinds of periodic structures: A polarization-independent self-collimation (PIS) structure [20,21] and a splitting structure [22]. The PIS structure is served as a virtual waveguide to route the flow of TE- and TM-polarized light simultaneously, the splitting struc-

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0375-9601/$ – see front matter 
doi:10.1016/j.physleta.2007.05.035

ture is used to separate these two orthogonal polarized lights. The splitting properties of the PBS have been numerically simulated by using the finite difference time domain (FDTD) method, the results show that the PBS has many advantages, such as high splitting efficiency, small size and large splitting angle.

## 2. Design of the PBS

The PBS of our design for exploiting the various dispersion properties of PCs is shown in Fig. 1. It consists of two parts: a PIS structure and a polarization splitting structure. Both of these PCs structures consist of square lattice of air holes with different radii introduced into a high index material ($n = 3.5$). The PIS structure, whose air-hole radius is $R = 0.33a$, serves as a virtual waveguide to guide the propagation of light, where $a$ is the lattice constant. The splitting structure consists of six rows of air holes aligning along $\langle 11\rangle$ direction with a radius of $R' = 1.2R$. While TE- and TM-polarized light (TE-polarized light has the electric field and TM-polarized light has the magnetic field perpendicular to the axis of the air holes) reaches the interface of these two structures, the orthogonal polarizations of light will be separated: TM-polarized light is along the same direction as the incident wave, the propagation direction of TE-polarized light is perpendicular to the incident light.

An equi-frequency contours (EFCs) analysis is adopted to illustrate the propagation direction of TE- and TM-polarized light in this device. The EFCs of the PIS structure, which are obtained by using a plane wave expansion method, are shown in Fig. 2. In PCs, the group velocity vector is defined by $\vec{v}_g = \nabla_k \omega(k)$, where $k$ is the Bloch wave-vector. From its definition, the group velocity vector is perpendicular to the EFC in the direction along which $\omega(k)$ is increasing [23,24]. It can be proved that the energy velocity vector is equal to the group velocity vector in PCs [23]. Thus, the refracted wave has the same direction as the group velocity. Fig. 2(a) and (b) are the EFCs at the normalized frequency $f = 0.26(c/a)$ for TE- and TM-polarized light, respectively, their EFCs are squares with rounded corners and centered at $\Gamma$ point of the first Brillouin zone. The flat regions of the EFCs imply that the PIS structure is capable of self-collimating along $\langle 10\rangle$ direction for TE- and TM-polarized light simultaneously. Therefore, the PIS structure can act as a virtual waveguide to route the flow of two polarizations without a traditional waveguide or line defect in the PCs structure.

In order to achieve the separation of two orthogonal polarized light, we introduce a splitting structure into the PIS region as discussed in the previous section, i.e., we change the radii of six rows air-holes along $\langle 11\rangle$ direction. It is interesting to note that as the radius of air holes increases to $R' = 1.2R$, a photonic band gap (PBG) appears for TE-polarized light, while TM polarization still remains within the allowed band (shown in Fig. 3). As the incident light reaches the splitting structure via the PIS region, TE-polarized light will be reflected to the orthogonal direction of incident light, while TM-polarized light maintains the same direction after it transmits the splitting structure. The separating angle is up to 90°, which is larger than most of the reported results [4–6].

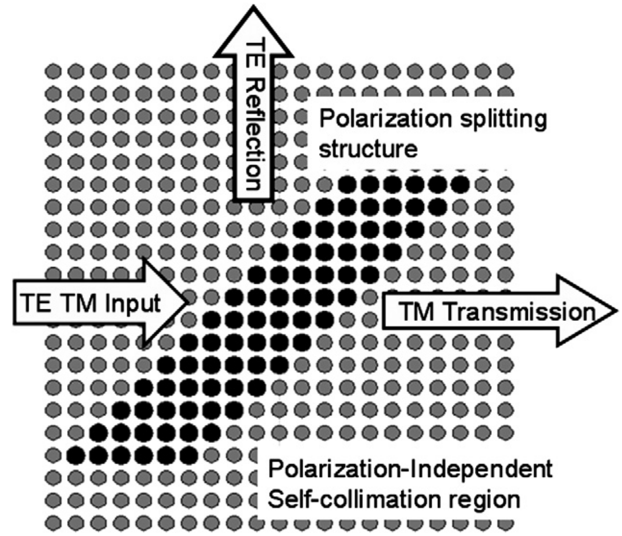


Fig. 1. Polarization beam splitter structure. The grey and black regions represent non-channel PIS structure and polarization splitting structure, respectively; the marked arrows indicate the propagation direction of TE- and TM-polarized light.

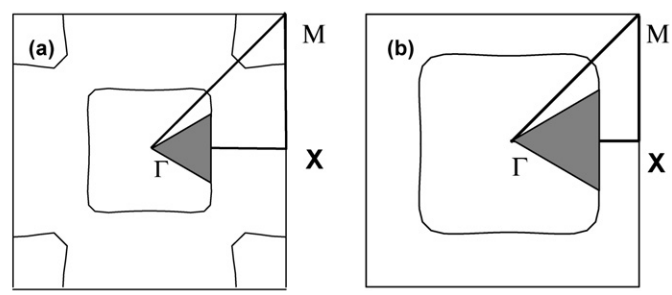


Fig. 2. Equi-frequency contours of TM (a) and TE (b) for frequency $f = 0.26(c/a)$ of the PIS structure. The square with rounded corners centered $\Gamma$-point is the EFC of the second band; the curves centered M-point correspond to the third band of TM-polarized light. The shaded region shows the wide angle that self-collimation can be realized.

## 3. Simulation and analysis

In order to illustrate the propagation and separation for TE- and TM-polarized light in the PBS, we carry out numerical simulations by using the FDTD method with perfectly matched layer boundary conditions. In the simulation, a $6a$ wide continuous Gaussian beam normally incident into the PBS in the $\langle 10\rangle$ direction. The frequency of input light is $f = 0.27(c/a)$. Simulations results are shown in Fig. 4, the polarization beam splitting effect is clearly observed in this structure. In the PIS region, TM- and TE-polarized light are self-collimated without any other external restriction. As the self-collimated light beams reach the splitting structure, the two orthogonal polarizations are separated: TM-polarized light pass through the splitting structure and propagate along the original direction; TE-polarized light is reflected to the vertical direction due to

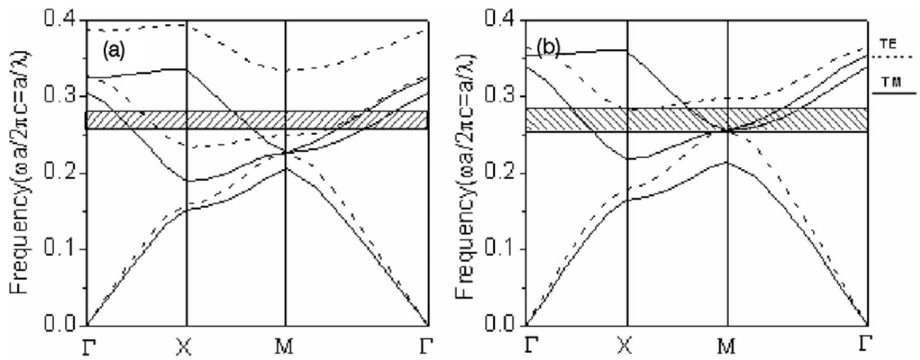


Fig. 3. Band diagrams of the PIS (a) and polarization splitting structure (b). The dot and solid lines represent the polarization bands of TE- and TM-polarized light, respectively. The shaded bar of (a) marks the polarization independent self-collimation frequencies $f = 0.258–0.281(c/a)$. The TE-polarized light band gap (shaded bar of (b)) appears to open at frequency $f = 0.258–0.283(c/a)$.

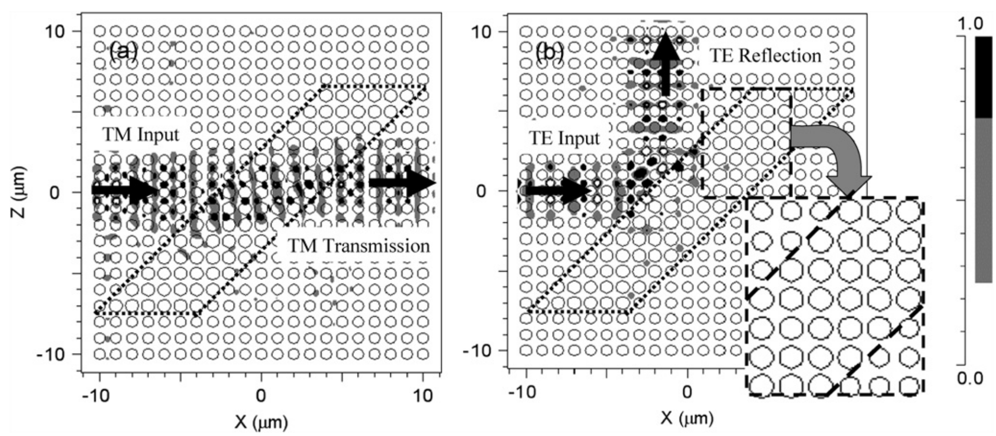


Fig. 4. Steady-state electrical field distribution for TM-polarized light (a) and magnetic field distribution for TE-polarized light (b) at frequency $f = 0.27(c/a)$ calculated using the two-dimensional FDTD method. The inset in (b) shows the enlarged display of the polarization splitting part of the device with the radius $R' = 1.2R$.

the photonic bandgap. Furthermore, the beam profile is substantially unchanged after the splitting process as it is routed by the self-collimation effect.

We employ a crystal of $21a \times 21a$, which is small enough to be used in integrated optical circuits and also large enough to guide and split the two orthogonal polarized light beams for quantitative analyzing the efficiency of reflection and transmission of TE- and TM-polarized light and the polarization extinction ratios (PERs) of this PBS. In order to obtain the power of the incident, reflected, and transmitted light beam, we integrate the intensity across the beam cross section, we obtain the efficiency of reflection and transmission of TE- and TM-polarized light by normalized with respect to the incident power. The transmission and reflection efficiency of the proposed PBS for TM- and TE-polarized incident light are shown in Fig. 5, which is calculated by using the FDTD method. It can be seen that the reflection and transmission efficiency remains above 85% between the frequencies $0.268–0.278(c/a)$, and it is noteworthy that the reflection efficiency for TE-polarized light is approximately 99% at frequency $f = 0.28(c/a)$. The PER of transmitted beam is defined as $-10\log(T_{te}/T_{tm})$ and the PER of reflected beam is defined as $-10\log(R_{tm}/R_{te})$, respectively. The PERs of transmission and reflection light beams are 23.09 dB and 15.94 dB at frequency $f = 0.27(c/a)$. These advantages make the polarization-splitting device has potential useful in optics communication. For example, the proposed PBS can be used in optical recording and integrated optical circuits. To render the working wavelength at 1.55 μm, the lattice constant and the radius of the air holes should be $a = 405$ nm, $R = 135$ nm and $R' = 162$ nm, respectively. The PBS occupies

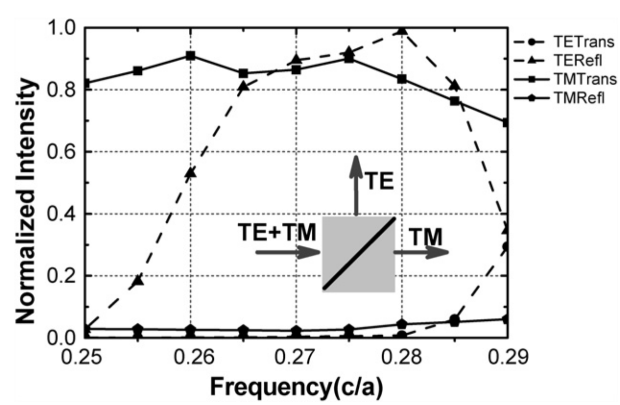


Fig. 5. Reflection efficiency and transmission efficiency versus frequency for TE- and TM-polarized light are shown. Dash line with triangular dots is corresponded to the TE-polarized light and solid line with square dots to the TM-polarized light. Schematic picture depicting the separation of TE- and TM-polarized light by the PBS is shown in the inset of the figure.

an area as small as 9.0 μm × 9.0 μm at optical communication wavelength $\lambda = 1.55$ μm, which is feasible for manufacture of current technologies.

## 4. Conclusion

We have proposed and numerically demonstrated a novel type of an ultra-compact polarization beam splitter based on the dispersion characteristics of photonic crystals. With all photonic crystal design, the PBS does not need waveguide or line defect to route the propagation of light, and it has a large separating angle, high splitting efficiency and high polarization extinction ratios of two orthogonal polarizations. These features of the proposed device make it a promising candidate for integrated elements in all photonic crystal circuits and optical communication application.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 10674177) and the Science Foundation of China University of Mining & Technology (Grant No. 2006B025).

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