# Y-type polarization beam splitter based on polarization-selective defects within crystal waveguides in a square-lattice photonic crystal with solid rods

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We propose a Y-type polarization beam splitter based on internal polarization-selective defects within crystal waveguides in a two-dimensional square-lattice photonic crystal with solid rods. When the nonpolarized light launches from the input port, different polarizations will be separated and can only transmit through their own channel. It is demonstrated by finite element method that the proposed structure can achieve good performance for both the transverse electric and transverse magnetic polarizations in a wide range of wavelength, with the polarization extinction ratio more than 25 dB, the degree of polarization nearly 1, and the insert loss less than 0.5 dB, respectively.

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Photonic crystals (PCs)[1,2], a type of new artificial materials with periodic structures, have attracted much attention due to their unique properties, such as photonic band gaps (PBGs), light localization, negative refraction, self-collimation, lossless to waves, and size of wavelength dimensions[3,4]. Because of these interesting properties, PC structures are highly sensitive to the polarization of light, which provides good opportunities to build high-performance polarization control devices, such as polarization beam splitters (PBSs)[5–9]. PBSs are such devices that can split light into two orthogonal polarization states (transverse electric (TE) and transverse magnetic (TM) polarizations), which are believed to be one of the most important devices in integrated optical circuits for optical communication. PBSs are also important for optical logic devices based on polarization logic.

Recently, several types of PBSs based on two-dimensional (2D) PCs have been proposed, such as PBSs based on a self-collimating PC structure[5], PBSs based on self-imaging effect[6], and PBSs constructed by long-range coupling PC waveguides[7]. Although these proposed structures have advantages over traditional ones, they have deficiencies such as large scale, not easy to couple, and large insertion loss, which restrict the application of these PBSs structure in integrated optical circuit.

In this letter, a Y-type PBS has been proposed based on internal polarization-selective defects within crystal waveguides in a 2D square-lattice PC with solid rods. It is demonstrated by finite element method that the proposed structure can achieve great polarization extinction ratio (PER), large degree of polarization (DOP), and high efficiency or low insert loss (IL) in a wide range of wavelength. In addition, this structure is small in size. More important, the square-lattice and Y-type PC waveguide that are compact in size make it easier to combine multiple optical devices into an integrated system.

The schematic of the PBS structure is shown in Fig. 1. The structure is based on a 2D square-lattice PC formed by the background rods consisting of anisotropic tellurium material. Two lines of background rods are removed to form the Y-type PBS, with three linear waveguides connected via a Y-shaped junction. As can be seen from Fig. 1, port 1 indicates the input waveguide. Ports 2 and 3 indicate TE and TM output waveguides with different polarization-selective defects

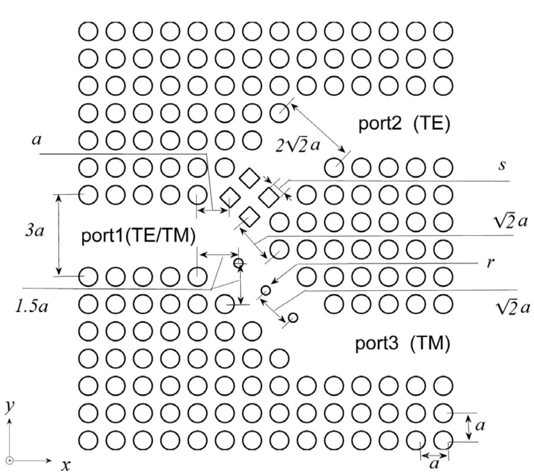


Fig. 1. Schematic of the PBS structure.

 

to filter respective polarizations. For the TE channel, 2×2 arrays of square rods (TE defects) are set rotated anticlockwise 45° around the *X*-direction. For the TM channel, 3×1 arrays of circular rods (TM defects) are placed rotated clockwise 45° around the *X*-direction. The lattice constant, the radius of background rods, the length of TE defects, and the radius of TM defects are assumed to be $a$, $r_T$, $s$, and $r$, respectively. And the other necessary structure parameters are as shown in (Fig. 1).

In this letter, the background rods, the TM defects, and the TE defects are all chosen to be the anisotropic material tellurium[10–12], which had been proven to be more efficient to get the absolute or complete PBG than the traditional isotropic materials[11]. Moreover, the materials of tellurium have a very low loss in the mid-and-far infrared wavelength range[12], which has an important application for military or medical purposes. In practical application, dispersions of the materials are unavoidable. Therefore, the ordinary refractive index $n_o$ and the extraordinary refractive index $n_e$ of tellurium are considered to be dispersive as[12]

$$n_o = \sqrt{\begin{matrix}18.5346 + 4.3289\lambda^2(\lambda^2 - 3.9810)^{-1} \\ +3.7800\lambda^2(\lambda^2 - 11813)^{-1}\end{matrix}}, \quad (1)$$

$$n_e = \sqrt{\begin{matrix}29.5222 + 9.3068\lambda^2(\lambda^2 - 2.5766)^{-1} \\ +9.2350\lambda^2(\lambda^2 - 13521)^{-1}\end{matrix}}, \quad (2)$$

where $\lambda$ is the working wavelength measured in micrometer. Here, the extraordinary axis of the background rods and TM defects are chosen to lie along the *Z*-axis, and the extraordinary axis of the TE defects lies along the *Y*-axis. As a result, for the TE polarization, the electric field is aligned along the *Z*-axis; for the TM polarization, the electric field is lying in the *X*–*Y* plane. Assuming the propagation is in the *X*- direction, the electric field for the TM polarization will be along the *Y*-axis.

In order to investigate the performance of the proposed structure, the DOP, PER, and IL are calculated below and the DOP is defined as

$$\text{DOP} = \left|(I_{\text{TE}} - I_{\text{TM}})/(I_{\text{TE}} + I_{\text{TM}})\right|. \quad (3)$$

The PERs are defined as

$$\text{PER}_{\text{TE}} = 10 \times \log_{10}(I_{\text{TE}}/I_{\text{TM}}), \quad (4)$$

$$\text{PER}_{\text{TM}} = 10 \times \log_{10}(I_{\text{TM}}/I_{\text{TE}}). \quad (5)$$

And the IL for both of the TE and TM polarizations is defined as

$$\text{IL} = 10 \times \log_{10}(P_{\text{IN}}/P_{\text{OUT}}), \quad (6)$$

where $I_{\text{TE}}$ and $I_{\text{TM}}$ are the intensities of the TE-polarized and TM-polarized light of the output port. $P_{\text{IN}}$ and $P_{\text{OUT}}$ are the power flows of the input and output ports respectively.

Firstly, because the complete PBG is essential to keep both of the polarization light confine and transmit inside the PBS structure, the band map of a perfect 2D square-lattice PC consisting of tellurium materials are investigated as shown in Fig. 2(a), where the blue, the red, and the yellow clouds represent the TE, TM, and absolute band gap, respectively. From Fig. 2(a), the largest, complete PBG can be obtained where the radius $r_T$ of tellurium is 0.3431$a$. Then the detail range of band is calculated by fixing $r_T = 0.3431a$ as shown in Fig. 2(b), where the range of complete PBG can be obtained to be

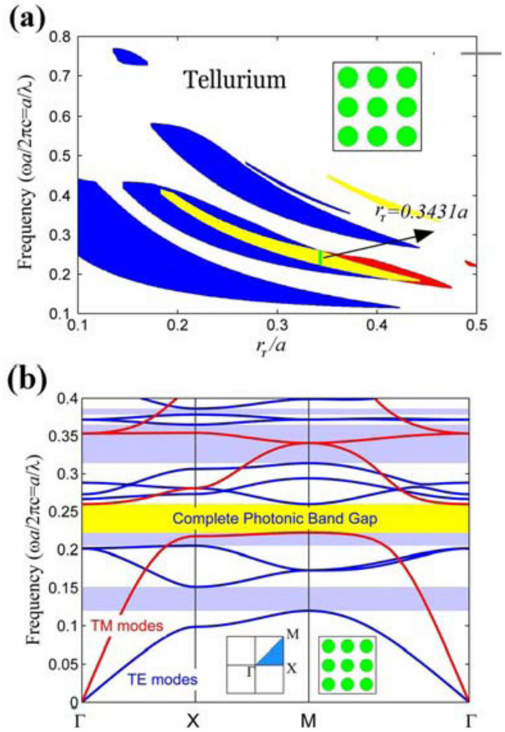


Fig. 2. (a) Band map with the change in $r_T$ for a perfect 2D square-lattice PC, where the blue, the red, and the yellow clouds represent the TE, TM, and absolute band gap, respectively and (b) complete PBG versus the normalized frequency where $r_T = 0.3431a$.

$$f = \omega a/2\pi c = a/\lambda = 0.2368 \sim 0.2569, \lambda = 3.893a \sim 4.223a. \quad (7)$$

In the design of such PBS, we need s large complete PBG as much as possible to enhance the stability and efficiency of the structure. So the radius of tellurium $r_T$ is selected to be 0.3431$a$ in the following calculation. In addition, when the lattice constant $a$ is selected to be 1 $\mu$m, the range of operation wavelength will be from 3.893 to 4.223 $\mu$m, which is located in the mid-infrared band that the loss of tellurium can be ignored[12].

In order to optimize the parameters of the polarization-selective defects, the middle wavelength of the complete PBG 4.05$a$ is assumed to be the working wavelength. Then we investigate the variations in PERs and DOPs by changing the length $s$ of TE defect and the radius $r$ of TM defect (Fig. 3), where the red and blue lines represent the PERs and DOPs of the TE and TM output, respectively. From Fig. 3, for the TE channel, when the length $s$ of the TE defects is 0.5401$a$, the PER is more than 30 dB, and the DOP is nearly 1; for the TM channel, when the radius $r$ of the TM defects is

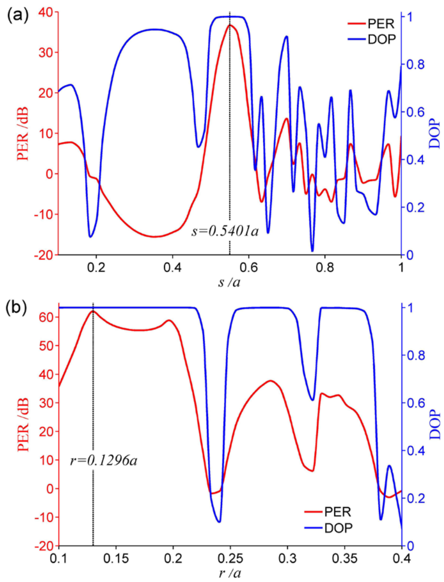


Fig. 3. PERs and DOPs versus (a) $s$ for the TE polarization and (b) $r$ for the TM polarization, where the red and blue lines represent the PER and DOP of the TE and TM output, respectively.

$0.1296a$, the PER can reach a high value greater than 60 dB, and the DOP is also approximately 1. At these defects parameters, different defects will only open for the selected polarization but will close for the others.

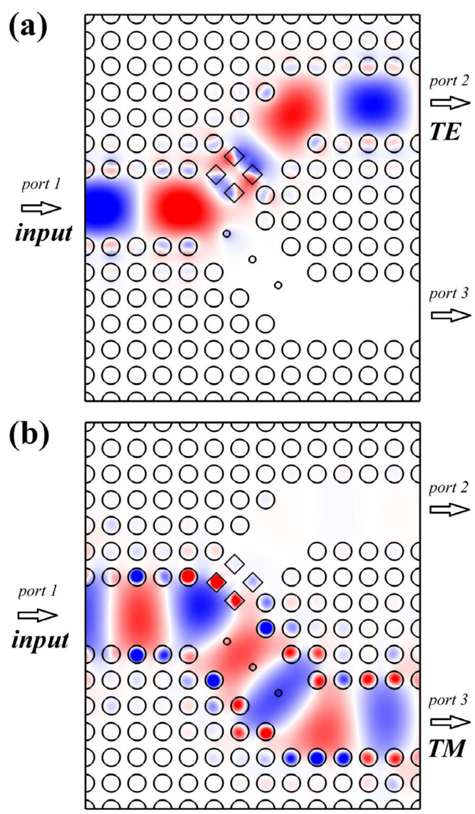


Fig. 4. Field distributions of PBS for (a) TE wave out from port 2 and (b) TM wave out from port 3.

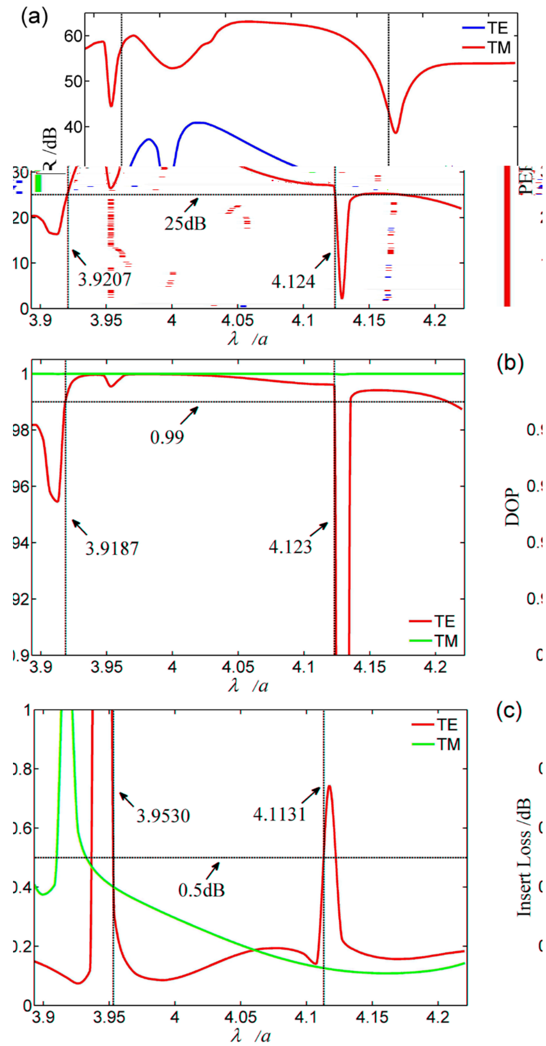


Fig. 5. Wavelength scans on (a) PERs, (b) DOPs, and (c) ILs for the PBS, where the blue and red lines are calculated for the TE and TM polarizations, respectively.

Consequently, different polarizations can only transmit through their own channel while can be blocked by the others. This behavior can be understood as, due to the birefringence characteristic of the anisotropic materials, different polarizations with the component of light parallel or perpendicular to the optical axis can give rise to different effective refractive indices. Therefore, if the area size of the polarization-selective defects is properly selected, it is possible to transmit one polarization and block the others.

In order to figure out how different polarization light propagate inside the PBS, the field distributions are studied as shown in Fig. 4, where the working wavelength is $4.05a$. Figure 4 supports our point. When nonpolarized light launches from port 1, different polarizations can be effectively separated and only transmit through their own channel.

To further characterize the performance of the PBS, a wavelength scan is performed on the PERs, the DOPs, and ILs (Fig. 5), where $s$ and $r$ are selected to be $0.5401a$

and 0.1296$a$, respectively. From Fig. 5, the wavelength range can be obtained from 3.9207$a$ to 4.124$a$ for PER more than 25 dB, from 3.9187$a$ to 4.123$a$ for DOP greater than 0.99, and from 3.9530$a$ to 4.1131$a$ for IL less than 0.5 dB. The common part of these three wavelength range is the stable bandwidth, that is, from 3.9530$a$ to 4.1131$a$. The performance of the PBS is demonstrated to be good in a wide range of wavelength, much better than those proposed in Refs. [5–9].

It should be pointed out that, with the consideration of the dispersion, the scaling law[13] in PCs is invalid. However, the same method for designing such PBS structure can be applied to the other range of operation wavelength.

In conclusion, we propose and demonstrate a Y-type PBS by anisotropic materials in a 2D square-lattice PC that exhibits a complete PBG. The field distributions show that different polarizations will be separated and can only transmit through their own channel in the proposed structure. For both of the polarizations, the PERs, DOPs, ILs are obtained to be more than 25 dB, nearly 1, and less than 0.5 dB, respectively, in a wide range of wavelength. Such structures are useful for designing high-quality and low-loss polarization splitter in integrated optics devices.

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