Design of Polarization Beam Splitter in Two-Dimensional Triangular Photonic Crystals *

CHEN Xi-Yao(陈曦曜)[1], YAO Pei-Jun(姚培军)[1], CHEN Bo(陈博)[1], LI Feng(李锋)[1], ZHANG Jiang-Ying(章江英)[1], XIE Jian-Ping(谢建平)[1], MING Hai(明海)[1**], Shanhui Fan[2***]

[1]*Department of Physics, University of Science and Technology of China, Hefei 230026*

[2]*Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA*

(Received 2 April 2004)

A design of a polarization beam splitter (PBS) in two-dimensional triangular photonic crystals is proposed and numerically demonstrated, for the first time to our knowledge. The principle of the model is based on the polarization dependence of the photonic band gaps in photonic crystals; the polarization extinction ratios for transverse-magnetic and transverse-electric modes are 11.5 dB and 46.7 dB at the centre of its operating frequency range, respectively. When the central wavelength is tuned at 1550 nm, the possible operation wavelength range of this structure can be as large as 28.5 nm, which almost covers the whole C band in modern optical communication systems. Furthermore, due to its small size and only one kind of material being involved, the PBS structure may have practical applications in the integrated optics field.

PACS: 42. 70. Qs, 42. 79. Ci

For more than a decade, photonic crystals (PCs) have attracted much attention from both fundamental and practical viewpoints, because novel concepts such as photonic band gaps (PBGs) have been predicted, and various new applications of PCs have been proposed.[1−3] In particular, waveguides are very important for light propagation in arbitrary directions and for applications in optical circuits.[4] Therefore, great effort has been devoted to the study of PC waveguides. PCs possess PBGs in which light with a certain frequency cannot propagate. However, the existence of linear defect causes dispersion relation in PBGs. Light that satisfies the dispersion relation decays beyond linear defects and can exist only in linear defects. That is, guided modes can exist due to the dispersion relation, and the linear defect becomes a waveguide. On the other hand, if a point defect is introduced in an otherwise perfect PC, a resonant cavity can be created where localized modes may be found at frequencies within the PBG. By combining linear defects and resonant cavities, many optical devices that function such as their conventional counterparts can be realized in PCs.

As two-dimensional (2D) PCs are easier to fabricate than 3D PCs, optical components in 2D PCs have become one of hotspots in the optics research field for several years. A variety of optical devices in 2D PCs, such as optical filters,[5] beam splitters[6,7] and couplers,[8,9] channel demultiplexers[10,11]/multiplexers,[12] and switches,[13] have been presented theoretically and investigated experimentally. Among them, a polarization beam splitter (PBS) in a 2D PC was presented recently by Solli *et al.*[7] The mechanism involves a polarization interference between TE and TM modes that results from the birefringence of a bulk 2D PC. In fact, it functions as a polarization interference filter. Since it involves two extra polarizers between which the PC is sandwiched, there should be big intrinsic insertion loss introduced by the first polarizer. In addition, it cannot output TE and TM waves simultaneously in time and separately in space.

In this Letter, we present a novel design of a PBS in a 2D PC using a completely different physical mechanism. Because the dispersion relations of guide modes are different between TE and TM modes in PCs, we can create an integrated PBS by combining two output PC waveguides in which the guided modes within a certain frequency range are permitted for one polarization but forbidden for the other, with an input PC waveguide in which both TE and TM can propagate. In our model, TE and TM modes are fed into the same input waveguides, and then separated into the two output waveguides. To our knowledge, this is the first design of an integrated PBS in PC structures.

We consider a triangular lattice of air holes made in a GaAs substrate with dielectric constant $\varepsilon = 11.4$. The structure is assumed bidimensional, i.e. the air holes are infinitely long. The ratio between the hole radius and the lattice constant is $r/a = 0.45$. The volume fraction of GaAs is only 0.2654 in this perfect PC. The PC has a complete PBG in the region

* Supported by the Natural Science Major Project Foundation of the Education Office of Anhui Province of China under Grant No 2004kj364zd.

** Email: minghai@ustc.edu.cn

*** Email: shanhui@stanford.edu

$0.412 < \omega a/2\pi c < 0.448$, in which either TE or TM modes cannot propagate. The PBS we put forward is composed of three linear waveguides in the PC mentioned above. As shown in Fig. 1, they are connected via a Y-shaped junction and the separation angles between them are 120°. L_1 indicates the input waveguide. L_2 and L_3 indicate TE and TM output waveguides, respectively. Each of them is formed by decreasing the radii of air holes in a row along the ΓK direction. The radii of defect holes constituting L_1, L_2 and L_3 are $0.34a$, $0.37a$ and $0.40a$, respectively.

Guided modes along the waveguides can exist in the PBGs of the perfect PC Due to the introduction of linear defects. The dispersion relations along L_2,

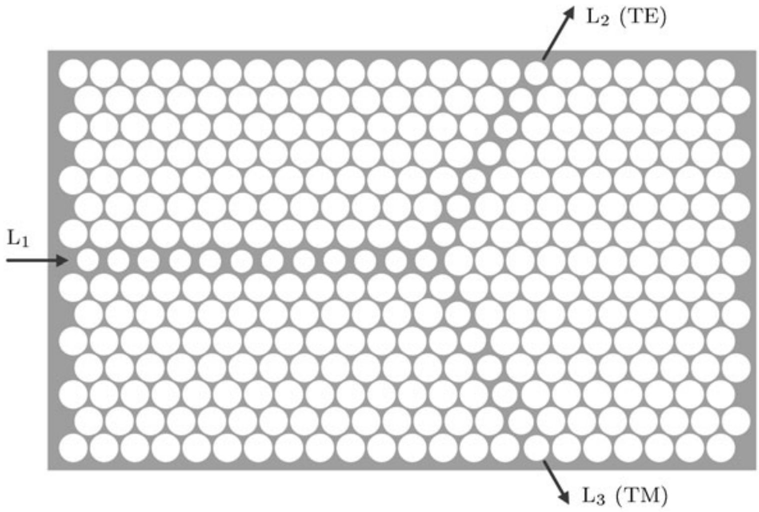

Fig. 1. Structure of a polarization beam splitter in a two-dimensional photonic crystal with a triangular lattice composed of air holes in the GaAs background. Dark regions indicate GaAs. The radii of air holes in three linear waveguides L_1, L_2 and L_3 are $0.34a$, $0.37a$ and $0.40a$, respectively.

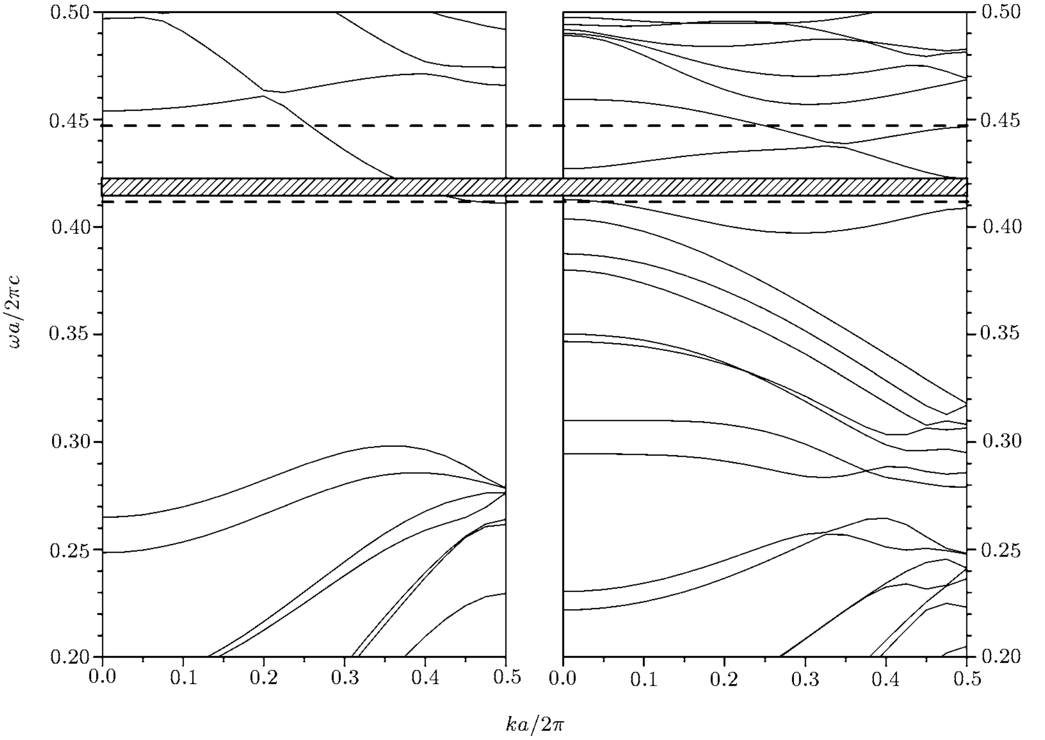

Fig. 2. Dispersion relations of guided modes along L_2 consisting of circular air holes with the radius of $0.37a$. The normalized frequency range of 0.413–0.422 indicated with oblique lines is a PBG for TM modes, in which TE modes can propagate. The region of between the two dashed lines corresponds to the complete PBG of the perfect crystals.

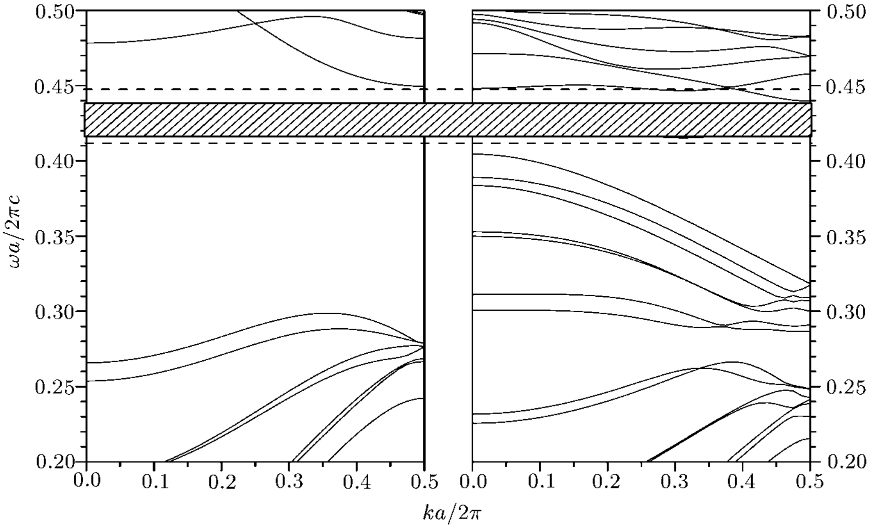

Fig. 3. Dispersion relations of guided modes in L_3 consisting of circular air holes with the radius of $0.40a$. In the normalized frequency range of 0.415–0.438 indicated by oblique lines, no TE guided mode can exist but TM modes can travel.

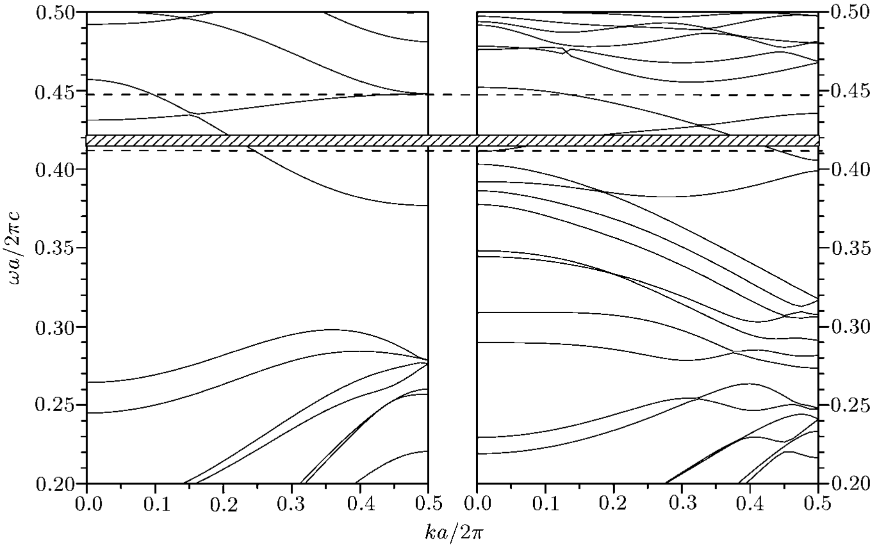

Fig. 4. Dispersion relations of guided modes in L_1 consisting of circular air holes with the radius of $0.34a$. In the normalized frequency range of 0.415–0.422 indicated by oblique lines, both TE and TM modes can exist.

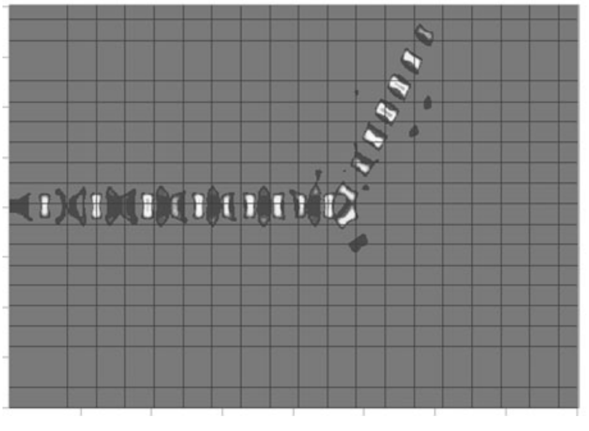

Fig. 5. Snapshot of magnetic field distribution in the PBS for TE guided mode at the operation frequency $\omega = 0.418 \times 2\pi c/a$.

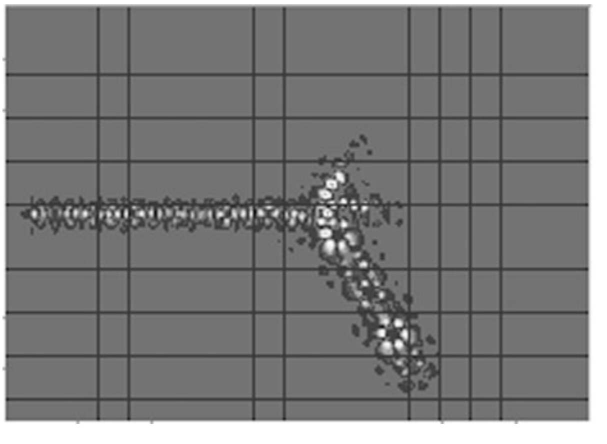

Fig. 6. Snapshot of electric field distribution in the PBS for TM guided mode at the operation frequency $\omega = 0.418 \times 2\pi c/a$.

L_3 and L_1 are shown in Figs. 2–4, respectively. For waveguide L_2, there is a PBG in the region of $0.413 < \omega a/2\pi c < 0.422$ for TM modes. However, TE modes with even parity can propagate in this frequency range. On the other hand, there is a spectral range of $0.415 < \omega a/2\pi c < 0.438$ for waveguide L_3 in which no TE guided mode exists but TM modes with even parity can travel. Therefore, in the range of $0.415 < \omega a/2\pi c < 0.422$, the TE modes are permitted in L_2 only and TM modes in L_3 only. In addition, both the TE and TM modes exist in waveguide L_1, as can be seen in Fig. 4. Therefore, in the frequency range of 0.415–0.422, incident TE modes propagate from L_1 to L_2 while TM modes propagate from L_1 to L_3.

For the numerical simulation of the PBS, the finite-difference time-domain (FDTD)[14] method is used. The PC waveguides are terminated with perfectly matched layers (PMLs)[15] in which the original PC structure remains, and the Bloch waves can be absorbed efficiently. Figure 5 shows the magnetic field patten when the waveguides are excited at the entrance of waveguide L_1 with TE-polarized incident light with frequency at $\omega a/2\pi c = 0.418$. Figure 6 shows the electric field patten in the case of the incident light with TM polarization at the same frequency. The simulation completely agrees with our band structure analysis presented above. The incident TE light propagates from L_1 to L_2 almost with no fields in L_3 (Fig. 5). In the case of TM polarization as shown in Fig. 6, however, incident light travels through L_1 and then only into L_3. Thereby a polarization beam splitter in the PC is realized.

In order to investigate the structure quantitatively, we numerically determine the contrast in power flow of the two output waveguides by calculating the flux through the observation line in the FDTD simulations. For TE input, the polarization extinction ratio (PER) between L_2 and L_3 is 46.7 dB. As to TM input, the PER between L_3 and L_2 is 11.5 dB.

According to the scaling law, $0.415 < \omega a/2\pi c < 0.422$ corresponds to $1532.5\,\text{nm} < \lambda < 1561.0\,\text{nm}$ for $a = 648.1\,\text{nm}$. Therefore, the possible operation wavelength range of this structure can be as large as 28.5 nm when the central wavelength is tuned at $\lambda_o = 1550\,\text{nm}$. The size of the PBS structure in Fig. 1 is only $14.3\,\mu\text{m} \times 8.4\,\mu\text{m}$ under the present circumstances and is far more compact than previous design.

In conclusion, we have designed a novel polarization beam splitter in 2D PCs. It can separate an incident beam into two different polarization beams that propagate along different output waveguides. Thereby it can be used not only as a polarizer, but also as a polarization beam splitter. It may have possible applications in optical communication systems due to its potential large operation wavelength range around 1550 nm. Also, it may have an important role in integrated optics.

References

[1] John S 1987 *Phys. Rev. Lett.* **58** 2486
[2] Yablonovitch E 1987 *Phys. Rev. Lett.* **58** 2059
[3] John S and Quang T 1995 *Phys. Rev. Lett.* **74** 3419
[4] Mekis A, Fan S and Joannopoulos J D 1998 *Phys. Rev.* B **58** 4809
[5] Costa R, Melloni A and Martinelli M 2003 *IEEE Photon. Technol. Lett.* **15** 401
[6] Chung K B and Yoon J S 2003 *Opt. Quantum Electron.* **35** 959
[7] Solli D R et al 2003 *J. Appl. Phys.* **93** 9429
[8] Thorhauge M, Frandsen L H and Borel P I 2003 *Opt. Lett.* **28** 1525
[9] A Martinez, F Cuesta and J Marti 2003 *IEEE Photon. Tech.* **15** 694
[10] M Qiu and B Jaskorzynska 2003 *Appl. Phys. Lett.* **83** 1074
[11] Fan S et al 1999 *Phys. Rev.* B **59** 15882
[12] Smajic J, Hafner C and Erni D 2003 *Opt. Express* **11** 566
[13] Takeda H and Yoshino K 2003 *Phys. Rev.* B **67** 037106
[14] Taflove A and Hagness S C 2000 *Computational Electrodynamics: The Finite-Difference Time-Domain Method* 2nd edn (Norwood: Artech House)
[15] Berenger J P 1994 *J. Comput. Phys.* **114** 185