Two-dimensional photonic crystal polarizer

Chun Zhang, Jun Wan, Feng Qiao

Surface Physics Laboratory (National Key Lab), Fudan University, Shanghai 200433, People’s Republic of China

Jian Zi

International Center for Materials Physics, Shenyang 110015, People’s Republic of China

and

Surface Physics Laboratory (National Key Lab), Fudan University, Shanghai 200433, People’s Republic of China

(May 9, 2018)

Abstract

A novel polarizer made from two-dimensional photonic bandgap materials was demonstrated theoretically. This polarizer is fundamentally different from the conventional ones. It can function in a wide frequency range with high performance and the size can be made very compact, which renders it usefully as a micropolarizer in microoptics.
Since the pioneering work of Yablonovitch [1] and John [2], photonic bandgap (PBG) materials have generated considerable attention [3–6] from many different research fields. PBG materials are periodically modulated dielectric composites that have stop bands for electromagnetic (EM) waves over a certain range of frequencies because of multiple Bragg scattering [1,2], analogous to the electronic band structures in semiconductors. They represent a new class of materials that are capable of uniquely controlling the flow of EM waves or photons [7]. The unique optical properties of photonic crystals render the fabrication of perfect mirrors [8], high efficient antenna [9], thresholdless lasers, novel optical waveguides [10,11], microcavities [12,13] and many other unique optical devices possible [3–7].

Polarizer is one of the basic elements in optics. One of the challenges in microoptics and microstructures optics is the fabrication of clever optical elements and devices, such as refractive, diffractive lenses, gratings, and polarizers, with compact sizes and high performance. In this paper we show that two-dimensional (2D) PBG materials can be used to make polarizer.

Basically, there were three kinds of conventional ways to make polarizers by using the properties of absorption, reflection and refraction. Some materials like polaroid have all of their long organic molecules oriented in the same direction. These molecules absorb radiation of one polarization, thus transmitting the orthogonal polarization. The reflection of light from a surface is polarization and angle dependent. At Brewster’s angle, which is material and wavelength dependent, the reflectance of \( p \)-polarized light becomes zero, and the reflected light is completely \( s \)-polarized. Birefringent crystals, calcite is an example, have different indices of refraction for different polarizations of light. Two rays of orthogonal polarizations entering the crystal will be refracted at different angles and therefore separated spatially on leaving the crystal.

The idea to use 2D PBG materials to make polarizer is basically different from the above mentioned ones. It is based on the special properties of 2D PBG crystals. Any unpolarized light can be decomposed into two components: one with electric field parallel to the periodic plane (TE) and the other one with magnetic filed parallel to the periodic plane (TM). In 2D
PBG crystals, propagations of the TE and TM polarizations can be decoupled [14]. As a consequence, the TE and TM polarizations have their own band structures and PBGs. The typical band structures of a 2D PBG crystal are shown in Fig. 1, from which some general features of propagation of EM waves can be postulated. The transmission of an EM wave is dependent on its frequency and the band structures of the PBG crystal. In the overlapping region of TE and TM bands both TE and TM waves can transmit. In the overlapping region of TE and TM PBGs the propagations of both TE and TH waves are forbidden. In the overlapping region of the TE (TM) bands and TM (TE) PBG, only TE (TM) wave can transmit due to the fact that TM (TE) wave cannot propagate in the region of its PBG. As a result, the outgoing wave will have only one polarization and is perfectly polarized.

For testing purposes, a 2D PBG crystal consisting of dielectric rods arranged in the square lattice, shown in Fig. 2, is used to make polarizer. The lattice constant of the lattice is $a$ and the radius of the rod is $0.25a$. The dielectric constant of rods is $\epsilon = 14.0$. The background is air with $\epsilon_b = 1.0$. The calculated projections of photonic band structures in real space for this 2D square PBG crystal is shown in Fig. 3. The band structures of TE and TM waves are calculated by using the plane wave expansion method. Owing to the introduction of a periodicity in 2D, the wavevector will be limited to $\pi/a$. A large PBG is opened for the TM wave in the reduced frequency range from 0.2 to 0.34 due to the spatially periodic modulation of dielectric constants. From the above discussions, for an incident EM wave with reduced frequency ranging from 0.2 to 0.34, the transmission of the TM component is hence forbidden and that of the TE component is allowable. As a result, the outgoing light will have only TE component. The frequency range from 0.2 to 0.34 is the working window if this structure is used to make polarizer.

The performance of a polarizer is conventionally characterized by the degree of polarization and transmittance. The transmission is calculated by the transfer matrix method [15].

The degree of polarization $P$ is defined by
\[ P = \frac{|I_{\text{TE}} - I_{\text{TM}}|}{I_{\text{TE}} + I_{\text{TM}}} \]  

where \( I_{\text{TE}} \) (\( I_{\text{TM}} \)) is the intensity of the outgoing TE (TM) component. For a natural light, \( P = 0 \) and for a complete polarized light, \( P = 1 \). The transmittance \( T \) of a polarizer is defined here as the ratio of the intensity of the TE wave passing through a polarizer to the incident intensity of the TE wave

\[ T = \frac{I_{\text{TE}}(\text{out})}{I_{\text{TE}}(\text{in})} \]

where in and out stand for the incident and outgoing waves, respectively. For a perfect polarizer, \( T = 1 \) is expected.

The generic 2D PBG polarizer consists of eight layers of dielectric rods along the \( y \) direction. The incident light is also along the \( y \) direction. To check the performance of the polarizer, we display the calculated degree of polarization \( P \) and transmittance \( T \) in Fig. [4]. Within the range of the reduced frequency from 0.2 to 0.34 the degree of polarization \( P \) is almost 1, indicated that this polarizer is excellent in this frequency range. The transmittance of this polarizer is also very large.

This kind of polarizer possesses the other virtues. Because of the scale invariance of PBG materials, only by adjusting the spatial period \( a \), we can make the polarizer adaptable for the desired range of frequency and at the mean time the degree of polarization \( P \) and the transmittance \( T \) are the same. For example, for \( a = 1 \mu m \), the working frequency window is 6 to 10 THz; for \( a = 10 \mu m \), the window is 0.6 to 1 THz; for \( a = 1 \text{ mm} \), the windows is 60 to 100 GHz. The gap to midgap frequency ratio is rather larger, close to 50 %.

The miniaturization of a polarizer is rather difficult to achieve in the conventional polarizers. The 2D PBG polarizer proposed here, however, can be made with rather small size, which may have potential use in microoptics. By adjusting the period parameter \( a \), we could obtain a polarizer working in the desired frequency range. There features are absent in the conventional polarizers.

We demonstrate in this paper the possibility to make polarizer from 2D PBG materials. The example given here is the square lattice consisting of 2D dielectric rods. It can be easily
realized in the range of millimeter waves and microwaves. It should be noted the air rod structures with dielectric background may be more amiable to realize in the optical and IR wavelengths.

**Acknowledgments:** We thank W. Lu and H. Chen for interesting discussions. This work was supported by the National Natural Science Fundation of China under Contract No. 69625609.
REFERENCES

a) To whom all correspondence should be addressed. Email address: jzi@fudan.edu.cn.

b) Mailing address.

[1] E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1997).

[2] S. John, Phys. Rev. Lett. 58, 2486 (1987).

[3] J. Opt. Soc. Am. B 10 (2) (1993), special issue on PBG materials, ed. by C.M. Bowden, J.P. Dowling, and H.O. Everitt.

[4] Photonic Band Gaps and Localization, ed. by C.M. Soukoulis (Plenum, New York, 1993).

[5] J. Mod. Opt. 41 (2) (1994), special issue on PBG materials, ed. by G. Kurizki and J.W. Haus.

[6] Photonic Bandgap Materials, ed. by C.M. Soukoulis (Kluwer, Dordrecht, 1996).

[7] J.D. Joannopoulos, R.D. Meade, and J.N. Winn, Photonic crystals (Princeston Univ. Press, Princetson, 1995).

[8] Y. Fink, J.N. Winn, S. Fan, C. Chen, J. Michel, J.D. Joannopolous, and E.L. Thomas, Science 282, 1679 (1998).

[9] E.R. Brown, C.D. Parker, and E.J. Yablonovitch, J. Opt. Sco. Am. B 10, 404 (1993).

[10] A. Mekis, J.C. Chen, I. Kurland, S. Fan, P.R. Villeneuve, and J.D. Joannopolous, Phys. Rev. Lett. 77, 3787 (1996).

[11] S.-Y. Lin, E. Chow, V. Hietala, P.R. Villeneuve, and J.D. Joannopoulos, Science 282, 274 (1998).

[12] S.L. McCall, P.M. Paltzman, R. Dalichaouch, D. Simth, and S. Schultz, Phys. Rev. Lett. 67, 2017 (1991).
[13] J.S. Foresi, P.R. Villeneuve, J. Ferrera, E.R. Thoen, G. Steinmeyer, S. Fan, J.D. Joannopolous, L.C. Kimerling, H.I. Smith, and E.P. Ippen, Nature 390, 143 (1997).

[14] In three dimensions, there is no decoupling of the two polarizations.

[15] J.B. Pendry and A. MacKinnon, Phys. Rev. Lett. 69, 2772 (1992).
FIGURES

FIG. 1. Typical photonic band structures of a 2D PBG crystal. The TE and TM waves are decoupled in 2D PBG crystals. The hatched areas stand for the photonic bands. Between bands there exists PBGs.

FIG. 2. Schematic top view of a 2D PBG crystal.

FIG. 3. Calculated band structures of the 2D PBG crystal. The frequency $\omega$ is in the units of $c/2\pi a$, where $a$ is the period and $c$ is the speed of light in vacuum. The frequency can be tuned by adjusting the parameter $a$.

FIG. 4. Calculated degree of polarization (a) and transmittance (b) of the 2D PBG polarizer.
Both TE and TM can transmit

TM can transmit

TE and TM cannot transmit

TE can transmit

Both TE and TM can transmit

Fig. 1

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Fig. 2

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