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The design of optical diodes

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In this paper, the optical diodes have been designed by one-dimensional function photonic crystals (FPCs), which the refractive indexes of media A and B are not constant, but it is the functions of space coordinate. By calculation the transmissivity and electric field distribution, we found the positive incident light can pass the function photonic crystals, but the negative incident light can not pass through it, the function photonic crystals (FPCs) can be made into optical diodes.

Keywords: function Photonic crystals; transmissivity; electric field distribution; Optical diode

1. Introduction

Electrical diodes are basic electronic devices and essential building blocks of modern electronics. Such as p-n junction diodes and Schottky diodes. But they have too many limitations. So we want to overcome the limitations posed by electronic devices, and to satisfy the need for optical elements in integrated photonic circuits, Asymmetric light transmission is essential for fabricating such an all-optics based system. Optical diodes enable asymmetric transmission or one-way transmission of light. So, numerous optical diodes have been manufactured using the magneto-optic effect, the acousto-optic effect, photonic crystals, second harmonic generators, the thermo-optic effect, dynamically modulated ring resonator structures or absorbing multilayer systems, [1-7] in the past.

Various optical diodes and optical triodes have been put forward nowadays, such as nonreciprocal reflection-transmission in anisotropic media, ring resonators, graded dissipative media and left-handed materials [8-11]. A great deal of attention has been paid to periodic or quasi-periodic systems: photonic band-gaps with a linear index variation [12,13], photonic crystals with defects [14,15], nanoparticles [16], and quadratic waveguides with quasi-phase matching [17].

There has been rapidly growing interest in optical-diode phenomenon, we can employ magneto-optical materials, [18,19] nonlinear media, [20] or spatial-temporal modulations of refractive indices [21,22]. All the three approaches could implement an ideal optical diodes that can transmit and block any spatial mode in the opposite two directions. It's characterized by cheap, don't need require large magnetic fields and it can be used to miniaturized optical circuits straightforward [23,24].

An important feature of the photonic crystal is that there are allowed and forbidden ranges of frequencies, and the forbidden frequency range known as photonic band gap (PBG). In Refs. [25-30], we have proposed the FPCs, which the medium refractive index is the function of space position, which can be realized by the electro-optic effect or the Kerr effect. On the basis, we have designed optical diodes using one-dimensional FPCs $(AB)^N$, which the refractive indexes of media A and B are not constant, but the functions of space coordinate, such as $n_a(x) = n_a(0) + \frac{n_a(a)-n_a(0)}{a}x$, and $n_b(x) = n_b(0) + \frac{n_b(b)-n_b(0)}{b}x$. We calculate the transmissivity and electric field distribution of the negative incident and reverse incident of light in one-dimensional FPCs respectively. By calculating, we found the positive incident light can pass the function photonic crystals, this is the characteristic of optical diodes. The function photonic crystals (FPCs) can be made into optical diodes. In Ref. [30], we have designed the optical triode with the one-dimensional FPCs. For the convention photonic crystals, the refractive indexes of media A and B are constant, because its transmissivity and electric field distribution are the same for the positive incident and negative incident, it can not be made into optical diodes.

2. The transfer matrix and transmissivity of one-dimensional function photonic crystals (FPCs)

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In Refs. [25-30], we have given the transfer matrices of media A and B , they are

$$M_B = \begin{pmatrix} \cos \delta_b & -\frac{i \sin \delta_b}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_b(b) \cos \theta_i^I} \\ -in_b(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^I \sin \delta_b & \frac{n_b(0) \cos \theta_t^I \cos \delta_b}{n_b(b) \cos \theta_i^I} \end{pmatrix}, \quad (1)$$

$$M_A = \begin{pmatrix} \cos \delta_a & -\frac{i \sin \delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_a(a) \cos \theta_i^{II}} \\ -in_a(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^{II} \sin \delta_a & \frac{n_a(0) \cos \theta_t^{II} \cos \delta_a}{n_a(a) \cos \theta_i^{II}} \end{pmatrix}, \quad (2)$$

where

$$\delta_b = \frac{\omega}{c} n_b(b) (\cos \theta_i^I b + \sin \theta_i^I \int_0^b \frac{dz}{\sqrt{\frac{n_b^2(z)}{n_0^2 \sin^2 \theta_i^0} - 1}}), \quad (3)$$

$$\delta_a = \frac{\omega}{c} n_a(a) (\cos \theta_i^{II} \cdot a + \sin \theta_i^{II} \int_0^a \frac{dz}{\sqrt{\frac{n_a^2(z)}{n_0^2 \sin^2 \theta_i^0} - 1}}),$$

and

$$\sin \theta_i^{II} = \frac{n_0}{n_a(a)} \sin \theta_i^0, \quad (4)$$

$$\cos \theta_i^{II} = \sqrt{1 - \frac{n_0^2}{n_a^2(a)} \sin^2 \theta_i^0}. \quad (5)$$

$$\sin \theta_t^I = \frac{n_0}{n(0)} \sin \theta_i^0, \cos \theta_t^I = \sqrt{1 - \frac{n_0^2}{n^2(0)} \sin^2 \theta_i^0}, \quad (6)$$

$$\cos \theta_t^{II} = \sqrt{1 - \frac{n_0^2}{n_a^2(0)} \sin^2 \theta_i^0}, \quad (7)$$

In one period, the transfer matrix M is

$$\begin{aligned} M &= M_B \cdot M_A \\ &= \begin{pmatrix} \cos \delta_b & \frac{-i \sin \delta_b}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_b(b) \cos \theta_i^I} \\ -in_b(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^I \sin \delta_b & \frac{n_b(0) \cos \theta_t^I \cos \delta_b}{n_b(b) \cos \theta_i^I} \end{pmatrix} \\ &\quad \begin{pmatrix} \cos \delta_a & \frac{-i \sin \delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_a(a) \cos \theta_i^{II}} \\ -in_a(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^{II} \sin \delta_a & \frac{n_a(0) \cos \theta_t^{II} \cos \delta_a}{n_a(a) \cos \theta_i^{II}} \end{pmatrix}. \end{aligned} \quad (8)$$

The form of the FPCs transfer matrix M is more complex than the conventional PCs. The characteristic equation of FPCs is

FIG. 1: The input and output electric field and magnetic field in the FPCs.

$$\begin{aligned}
 \begin{pmatrix} E_1 \\ H_1 \end{pmatrix} &= M_1 M_2 \cdots M_N \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix} \\
 &= M_b M_a M_b M_a \cdots M_b M_a \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix} \\
 &= M \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix}.
 \end{aligned} \tag{9}$$

Where N is the period number.

With the transfer matrix M , we can obtain the transmission and reflection coefficient t and r , and the transmissivity and reflectivity T and R , they are

$$t = \frac{E_{tN+1}}{E_{0i}} = \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_{N+1} + C + D\eta_{N+1}}, \tag{10}$$

$$r = \frac{E_{0r}}{E_{0i}} = \frac{A\eta_0 + B\eta_0\eta_{N+1} - C - D\eta_0}{A\eta_0 + B\eta_0\eta_{N+1} + C + D\eta_0}, \tag{11}$$

and

$$T = t \cdot t^*, \tag{12}$$

$$R = r \cdot r^*. \tag{13}$$

Where $\eta_0 = \eta_{N+1} = \sqrt{\frac{\epsilon_0}{\mu_0}}$, E_{0i} and E_{0r} are incident and reflection electric fields, and $E_1 = E_{0i} + E_{0r}$.

In the following, we give the electric field of light in the one-dimensional FPCs, it is shown in FIG. 1. The optical diode model is shown in FIG. 2, the light positive incident (red line) and negative incident (blue line) to the FPCs, there is

$$\begin{aligned}
 \begin{pmatrix} E(z) \\ H(z) \end{pmatrix} &= M_2(d_1 + d_2 - z) \cdots M_N(d_N) \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix} \\
 &= \begin{pmatrix} A(z) & B(z) \\ C(z) & D(z) \end{pmatrix} \begin{pmatrix} E_{tN+1} \\ H_{tN+1} \end{pmatrix}.
 \end{aligned} \tag{14}$$

FIG. 2: The light positive incident (red line) and negative incident (blue line) to the FPCs.

where d_1 and d_2 are the thickness of first and second medium, respectively, $E(z)$ and $H(z)$ are the electric field and magnetic field in the second medium, when position z changes we can obtain the electric field and magnetic field in other medium. The E_{tN+1} and H_{tN+1} are the output electric field and magnetic field. From Eqs. (10-14), we get

$$\begin{aligned}
 E(z) &= A(z)E_{tN+1} + B(z)H_{tN+1} \\
 &= A(z)E_{tN+1} + B(z)\sqrt{\frac{\varepsilon_0}{\mu_0}}E_{tN+1} \\
 &= t(A(z) + B(z)\sqrt{\frac{\varepsilon_0}{\mu_0}})E_{0i},
 \end{aligned} \tag{15}$$

and then

$$\left| \frac{E(z)}{E_{0i}} \right|^2 = |t|^2 \cdot |A(z) + B(z)\sqrt{\frac{\varepsilon_0}{\mu_0}}|^2 \tag{16}$$

3. Numerical result

In this section, we report our numerical results of transmissivity and electric field distribution. The refractive indexes of media A and B are the linearity functions as space coordinates, they are

$$n_b(z) = n_b(0) + \frac{n_b(b) - n_b(0)}{b}z, \quad 0 \leq z \leq b, \tag{17}$$

$$n_a(z) = n_a(0) + \frac{n_a(a) - n_a(0)}{a}z, \quad 0 \leq z \leq a, \tag{18}$$

FIG. 3: The line refractive index functions as space coordinates in a period. The FIG. 3 (a) is the refractive indexes function of linear increase for positive incident. The FIG. 3 (b) is the refractive indexes function of linear decrease for negative incident.

FIG. 4: The relation between transmissivity and the incident light frequency, red line correspond to positive incident and blue line correspond to negative incident.

FIG. 5: The relationship between the transmittance and the wavelength of positive (red line) and negative (blue line) incident light

The FIG. 3 are the line refractive indexes figures of media B and A , the $n_b(0)$, $n_b(b)$, $n_a(0)$ and $n_a(a)$ are the endpoint values of refractive index. The main parameters are: the thickness of media B and A are $b = 100nm$ and $a = 10nm$. For the positive incident, the endpoints of media B and A are $n_b(0) = 1.25$, $n_b(b) = 1.29$ and $n_a(0) = 2.52$, $n_a(a) = 2.56$, it is shown in FIG. 3 (a). For the negative incident, the endpoints of media A and B are $n_a(0) = 2.56$, $n_a(a) = 2.52$ and $n_b(0) = 1.29$, $n_b(b) = 1.25$, it is shown in FIG. 3(b). The center frequency $\omega_0 = 1.215 \times 10^{15}Hz$, $\lambda_0 = 1.55 \times 10^{-6}nm$ corresponding to center wavelength, and the structure of FPCs is $(BA)^{16}$.

By calculation, we can obtain the transmissivity of the one-dimensional FPCs for the positive and negative incident of light. The positive incident figure (red line) and the negative incident figure (blue line) is shown in FIG. 4. In the range of $\omega/\omega_0 = 7.692 \sim 9.0$, $12.04 \sim 13.98$, $16.64 \sim 18.71$ and $21.29 \sim 23.01$, the positive incident light can pass through the one-dimensional FPCs, but the negative incident light cannot pass through, because the negative incident light is in the forbidden band. So, the one-dimensional FPCs with structure and parameters have the characteristics of optical diodes in the range of frequency above.

Take the frequency range of $16.64 \sim 18.71$ as an example, we give the relationship between the transmissivity and the wavelength of positive incident (red line) and negative incident (blue line), it is shown in FIG. 5. We can find in the wavelength range of $\lambda/\lambda_0 = 0.055 \sim 0.060$, the light can pass through the positive direction but can not pass through from reverse incident, this characteristic enable one-way transmission of light.

In addition, we also calculated the electric field distribution. In the forbidden bands $\omega/\omega_0 = 7.692 \sim 9.0$ and $16.64 \sim 18.71$, we take frequency $\omega/\omega_0 = 8$ and $\omega/\omega_0 = 17.5$, respectively, and obtained the electric field distribution for positive incident (red line) and negative incident (blue line), they are shown in FIG. 6 and FIG. 7. We can find that the positive incident light can pass, but the negative incident light can not pass through, i.e., the light can only be transmitted one way in the one-dimensional FPCs, which can be made into optical diodes.

FIG. 6: The electric field distribution of the positive incident (red line) and negative incident (blue line) with $\omega/\omega_0 = 8$.

FIG. 7: The electric field distribution of the positive incident (red line) and negative incident (blue line) with $\omega/\omega_0 = 17.5$.

4. Conclusion

In summary, We have theoretically investigated the function photonic crystals (FPCs), which the refractive index of medium is the function of space position. We choosed the line refractive index functions for two media A and B . By calculation the transmissivity and electric field distribution, we can find that the positive incident light can pass the function photonic crystals, but the negative incident light can not pass through it, the function photonic crystals (FPCs) can be made into optical diodes.

5. Back matter

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Data availability. No data were generated or analyzed in the presented research.

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Figures

Figure 1

The input and output electric field and magnetic field in the FPCs.

Figure 2

The light positive incident (red line) and negative incident (blue line) to the FPCs.

Figure 3

The line refractive index functions as space coordinates in a period. The FIG. 3 (a) is the refractive indexes function of linear increase for positive incident. The FIG. 3 (b) is the refractive indexes function of linear decrease for negative incident.

Figure 4

The relation between transmissivity and the incident light frequency, red line correspond to positive incident and blue line correspond to negative incident.

Figure 5

The relationship between the transmittance and the wavelength of positive (red line) and negative (blue line) incident light

Figure 6

The electric field distribution of the positive incident (red line) and negative incident (blue line) with $\omega/\omega_0 = 8$.

Figure 7

The electric field distribution of the positive incident (red line) and negative incident (blue line) with $\omega/\omega_0 = 17.5$.