

Terahertz wave polarization splitter using full band-gap photonic crystals

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Abstract Manipulation of terahertz wave polarization state exhibits tremendous potential in developing application of terahertz science and technology. A terahertz polarization beam splitter based on three linear defect photonic crystal waveguides is designed and numerically demonstrated. Both plane wave expansion method and finite-difference time-domain method are used to calculate and analyze the characteristics of the proposed device. The simulation results show that the designed polarization beam splitter can split TE and TM polarized mode into different propagation directions with high efficiency in the frequency range from 1.225THz to 1.260THz. Especially, the extinction ratios for both TE and TM modes are larger than 20dB.

Keywords terahertz wave · terahertz polarization beam splitter · TM polarization · TE polarization

1 Introduction

Photonic crystals are periodic structures belonging to a new artificial material, and they have been proven both theoretically and experimentally to be an effective way to perfectly transmit and flexible control electromagnetic wave. Terahertz photonic crystals lead to a great convenience in fabrication of photonic crystal-based terahertz functional devices due to their size larger than those of optical-frequency photonic crystals. Up to now, several photonic crystal-based terahertz devices have been reported, such as switches, modulators, lens, and filters [1–6]. However, with rapid development and diversified applications of terahertz science and technology, it requires for a large number and high-performance terahertz wave functional components [7, 8]. Among the terahertz wave functional devices required, manipulation of terahertz wave polarization state exhibits tremendous potential in developing application of terahertz science and technology. As a kind of manipulation devices, the development of terahertz wave power splitter is still lagging behind [9–11]. Furthermore, long size conventional waveguide terahertz polarization beam splitters impose limitations on the achievable density of integration circuits. We know that a compact high-efficiency polarization splitter

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must separate TM and TE polarized terahertz wave after a short propagation distance with low loss in the device. Fortunately, photonic crystal provides an attractive way for creating a low loss terahertz waveguide for separating both TM and TE polarization states.

In this letter, we propose a novel terahertz polarization splitter by using photonic crystals with three linear defect waveguides. In the proposed scheme, the terahertz wave polarization splitter is designed to separate the TE and TM polarization based on self-imaging principle [12, 13]. Both the plane wave expansion method and finite-difference time-domain method are used to analyze and simulate the characteristics of the proposed device. In our model, TM and TE polarized modes are fed into the same input waveguides, and then separated into different waveguide output ports. Both the polarization extinction ratios of TM and TE polarized terahertz wave are larger than 20dB. This enables the polarization beam splitter to be used in terahertz wave system and terahertz wave integrated circuit fields.

2 Device structure and working principle analysis

The designed terahertz wave polarization beam splitter is illustrated in Fig. 1. As shown in this figure, a two dimension planar photonic crystal structure consists of a hexagonal lattice array of air holes in a high index material (Ge with refractive index $n_{\text{Ge}}=4$) substrate is considered. Here, the Ge is chosen as substrate because its absorption is low enough to be negligible over the entire bandwidth of the terahertz wave radiation region [14]. All of the air holes have radius of $0.48a$ (a is the lattice constant of the structure). The device is comprised of three linear defect photonic crystal waveguides, which are realized by removing three rows of air holes from the perfect photonic crystal. Three linear defect regions are embedded into the photonic crystal to separate the TE- and TM-polarized wave. By using plane wave expansion method, we can calculate both TE and TM polarization band-gap diagrams for the perfect photonic crystal, as shown in Fig. 2. The shaded region with black sloping lines is the photonic band gap for TE polarization modes and the shaded region with red sloping lines is the photonic band gap for TM polarization modes. From the figure, one sees that there has an absolute photonic band-gap for both TM and TE polarization within the normalized frequency range from $0.389(a/\lambda)$ to $0.486(a/\lambda)$.

Through a plane wave expansion method, we can obtain the TM polarization dispersion curves of the guided modes for input waveguide with linear defect in Fig. 3. From the Fig. 3(a), one can see that there is only one guided mode within the photonic band gap. The dispersion curves of the three parallel single-mode photonic crystal waveguides are shown in Fig. 3(b), where the inset is the super-cell used for calculation. In the Fig. 3(b), the one single guided mode is split into two super-modes. It can be seen from Fig. 3(b) that there are two TM polarization modes in the three parallel photonic crystal linear defect waveguides structure indicated in Fig. 3(b) super-cell. For TM mode, a single guided mode is split into two super-modes in the three parallel photonic crystal linear defect waveguides structure region, which are marked 0th and 1st, respectively. According to the self imaging principle, when the incident electromagnetic wave is symmetric, only even

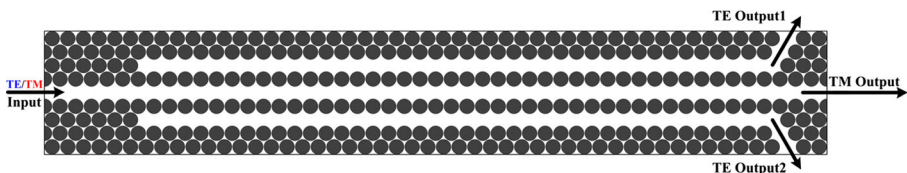


Fig. 1 Configuration of the proposed terahertz wave polarization beam splitter

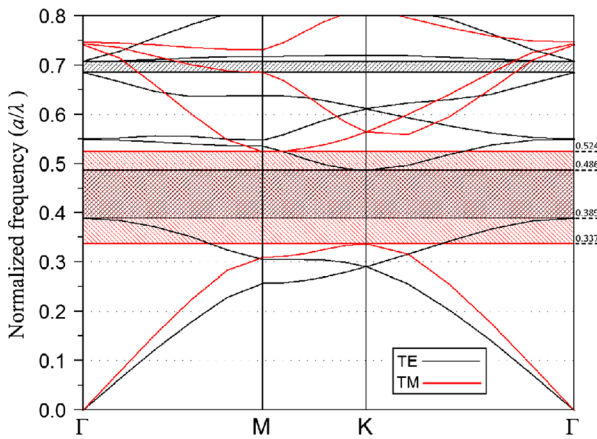


Fig. 2 Band gap diagrams of the perfect photonic crystal

mode such as the 0th mode can be excited. So TM mode transmits through the center linear defect photonic crystal waveguide and finally is collected by the output1 port. Similarly, TE polarization dispersion curves of guided modes for input waveguide with linear defect are shown in Fig. 4. From the Fig. 4(a), it can be noted that there is also only one guided mode within the photonic band gap. The dispersion curves of the three parallel single-mode photonic crystal waveguides are shown in Fig. 4(b), where the inset is the super-cell used for calculation. In the Fig. 4(b), one guided mode of the input waveguide splits into three super-modes, which are marked 0th, 1st, and 2nd, respectively. According to Fig. 4(c), one can see that 0th and 2nd modes are even symmetric, but 1st mode is odd symmetric. Therefore, when the incident electromagnetic wave is symmetric, only two even modes such as the 0th mode and the 2nd mode can be excited. These two modes can be regarded as the defect modes in the photonic crystal with a line defect. The two modes can couple from one photonic crystal waveguide to the other in the structure with a coupling length. Thus, the two modes are taken into account in calculating the coupling length of

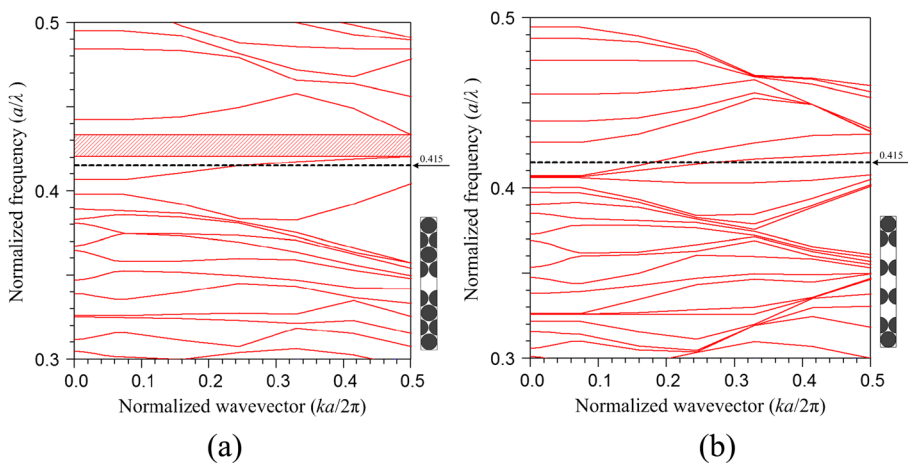


Fig. 3 (a) TM polarization dispersion curve for input waveguide with one single mode, (b) TM polarization dispersion curves for three parallel photonic crystal linear defect waveguides. The super-cells are inserted in each figure

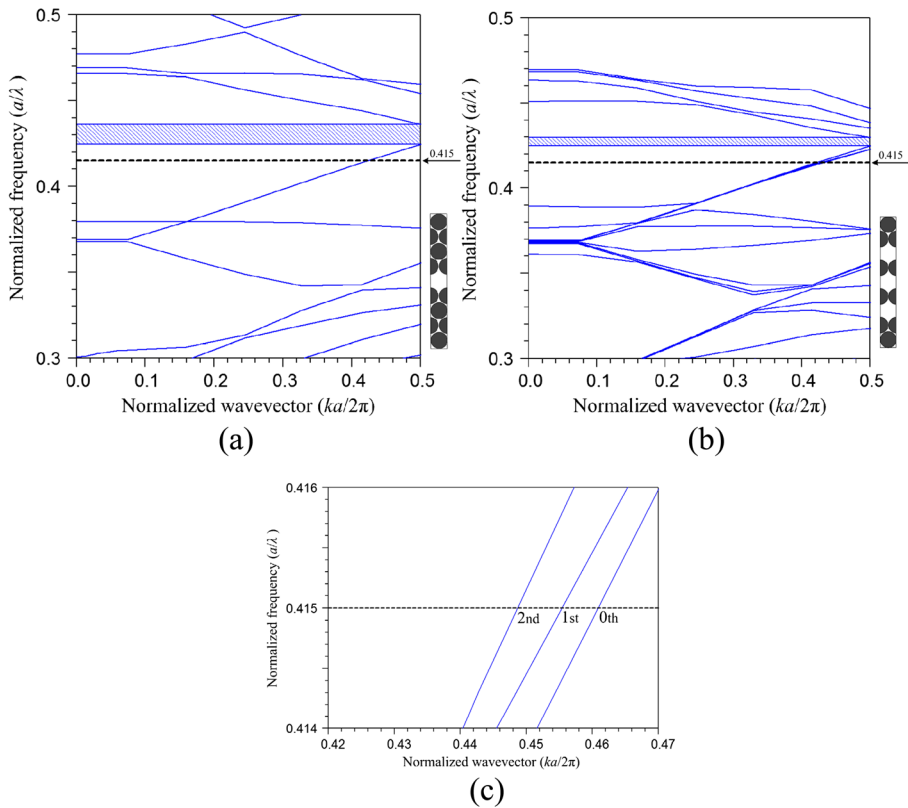


Fig. 4 (a) TE polarization dispersion curve for input waveguide with one single mode, (b) TE polarization dispersion curves for three parallel single-mode photonic crystal waveguides, (c) Local amplification of the TE polarization dispersion curves for three parallel single-mode photonic crystal waveguides. The super-cells are inserted in each figure

$$L_t = \frac{(2k - 1)\pi}{\beta_0 - \beta_2}, k = 1, 2, 3, \dots \tag{1}$$

where β_0 and β_2 are of 0th and 2nd propagation constants, respectively.

Here, the working frequency point is set to be $0.415(a/\lambda)$, as shown in Fig. 4(c). The lattice constant are assumed to be $a=60\mu\text{m}$, correspondingly the working frequencies are of $f=1.245\text{THz}$. Then, it can be found that the propagation constants of the two excited even modes are of $\beta_0=0.4609(2\pi/a)$ and $\beta_2=0.4487(2\pi/a)$ by using plane wave expansion method. From the equation (1), we know coupling length of the input field appears at position $L_t=40.98a$. Fig. 5 shows the electric field intensity of horizontal spatial distribution of three guided modes for TE polarization, respectively.

3 Simulation and demonstration

We use the finite-difference time-domain method to simulate the terahertz wave propagation in the proposed polarization beam splitter shown in Fig. 6 using the commercial software

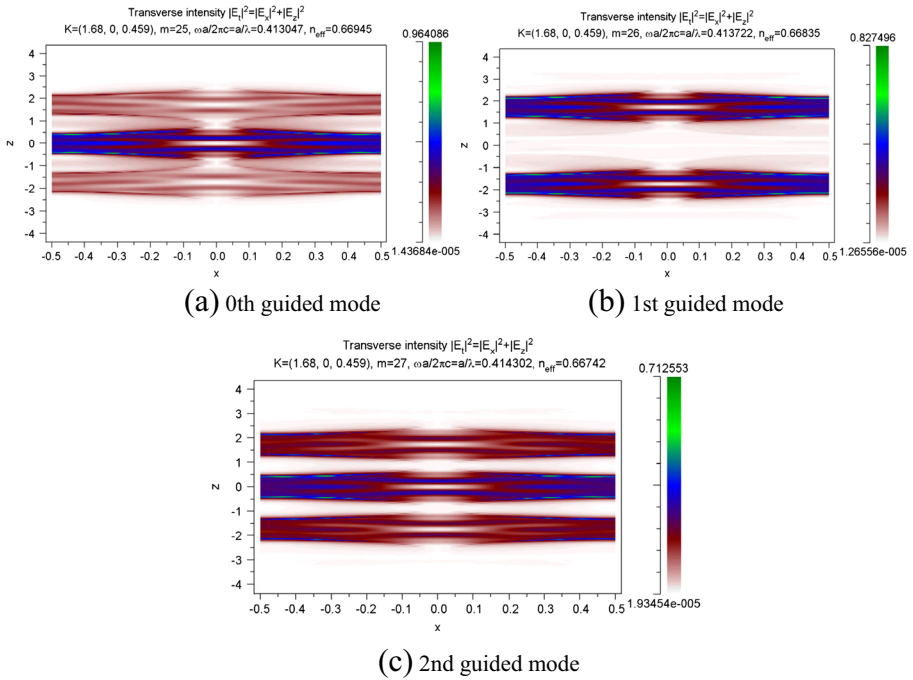


Fig. 5 Electric field intensity of horizontal spatial distribution of three guided modes for TE polarization (a) 0th guided mode (b) 1st guided mode (c) 2nd guided mode

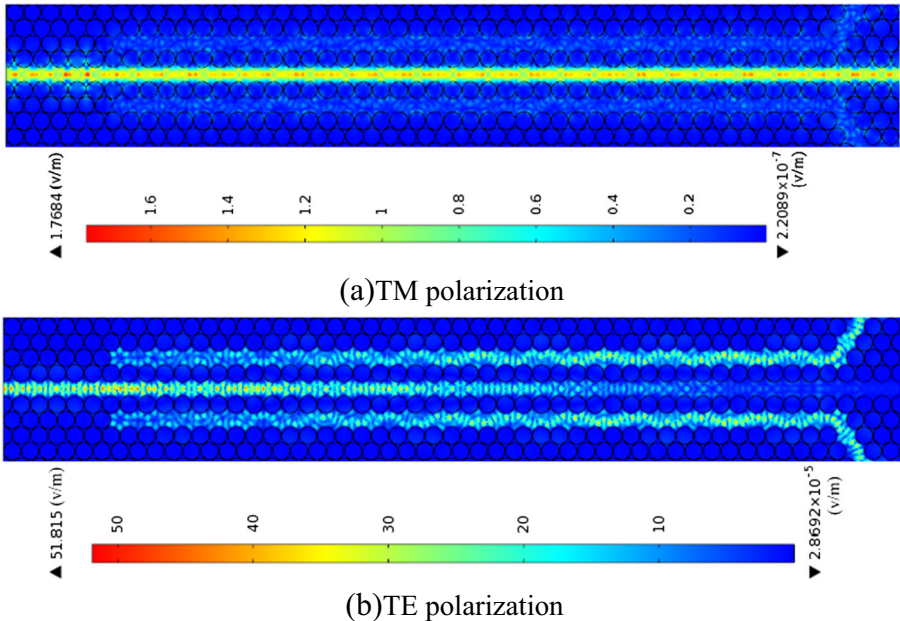


Fig. 6 Steady state electric field distribution at frequency $f=1.245$ THz

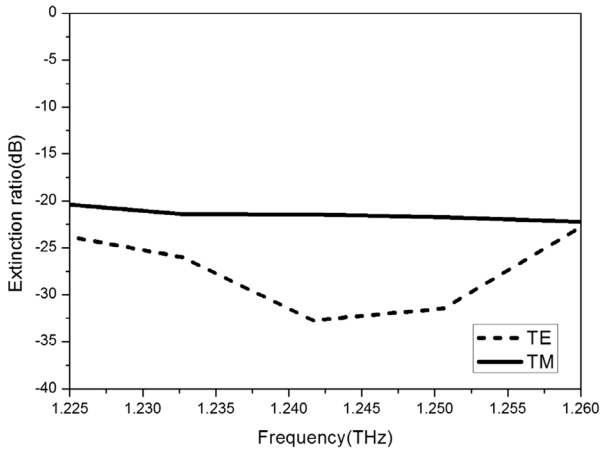


Fig. 7 Polarization extinction ratios of the proposed polarization beam splitter

module, Rsoft FullWave. The perfectly matched layers (PMLs) are located around the structure as the absorbing boundary condition. A pulse source, centered around $f=0.415(a/\lambda)$ (i.e. $f=1.245$ THz) and having a spatial Gaussian shape, was located at the entrance to the input waveguide and this pulse was used to launch the TM or TE polarizations terahertz wave into the device. Fig. 5 shows the steady-state electric field distributions as obtained by finite-difference time-domain method calculations for both TE and TM polarizations at working frequency $f=1.245$ THz. According to Fig. 6 (a), one can see that the input TM polarization transmits through the center linear defect photonic crystal waveguide and finally is collected by the end of TM polarization output port. It is clearly shown in the Fig. 6(b) that TE polarization terahertz wave is successfully collected by TE polarization output1 and output2. Furthermore, the simulated propagation pattern of electric field agrees well with the theoretical calculated length. In order to investigate the structure quantitatively, we have also calculated the extinction ratios for the polarization beam splitter, as shown in Fig. 7. Results of simulations with the two-dimensional finite-difference time-domain method show that 94.6% of TM-polarized terahertz wave can transmit through the photonic crystal structure (with a 20.23dB extinction ratio), whereas 92.5% of TE-polarized terahertz wave propagates through the structure (with a 23.1dB extinction ratio). The dimensions of the presented terahertz wave polarization beam splitter are of $540\mu\text{m}\times 3000\mu\text{m}$. Due to its small size and only one kind of material being involved, the polarization beam splitter structure may have practical applications in the terahertz wave integrated circuit fields.

4 Conclusions

In this paper, we propose a new method for designing terahertz wave polarization beam splitter. The design is based on the self-imaging effect in two-dimensional photonic crystal. The plane wave expansion method is used to obtain the band-gap diagrams. The finite-difference time-domain method is used to simulate the terahertz wave propagation in the proposed structure. The results show that the polarization extinction ratio is larger than 20.23dB for TM-polarized wave and 23.1dB for TE-polarized wave. Numerical simulation results agree well with theoretical expectation. This enables the polarization beam splitter to be used in terahertz wave integrated system.

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