Achieving Tunable Mode Splitter and Omnidirectional Absorber by Semiconductor Photonic Crystal

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Abstract— The properties of one-dimensional (1D) photonic crystals (PCs) composed of the semiconductor (GaAs) and dielectric layers are theoretically investigated by the transfer matrix method (TMM). Due to the Voigt effect, the dielectric constant of the semiconductor could be modified in different modes and frequency ranges. If the frequency range of the incident wave is larger than the plasma frequency, TE and TM modes of the incident wave will be absorbed in a wide incident angle. TM wave will be absorbed but TE wave will be reflected while the frequency range is less than the plasma frequency. By varying the external magnetic field, the absorption of semiconductor can be tuned. The proposed PCs have a reconfigurable application to design a tunable omnidirectional absorber and mode splitter at same time.

1. INTRODUCTION

Photonic crystals (PCs) are artificial materials with a periodic arrangement of refractive index which become a new research focus recently [1, 2]. A perfect absorber utilizing the electromagnetic (EM) response-tailorable ability of metamaterial has been widely explored since it was first proposed by Landy et al. [3]. A broadband omnidirectional absorption in heterostructures with a highly absorptive metallic film and a dielectric Bragg reflector is realized [4]. A mode splitter which can separate the two orthogonal modes of light, is one of the most important components in modern optical communication systems [5]. Various mode splitters have been reported. The fabrication of the mode splitter based on an asymmetrical Y-junction structure [6] or Mach-Zehnder interferometer [7] requires complex processes such as photobleaching and poling. Recently, PCs containing the semiconductor as one of the constituents also have been the focuses of researchers' interests. It is shown that, in semiconductor-based PCs, there are two magneto-optical effects: Faraday and Voigt effects after introducing the external magnetic. Therefore, PBGs of such semiconductor-based PCs will be tuned correspondingly [8], which have important applications in the mode splitter. They found that the dielectric constant of semiconductor is modified differently in different frequency ranges. But limited work had been conducted on investigating a tunable omnidirectional absorber and TE-TM modes splitter based on the similar semiconductor PCs.

The purpose of this paper is to explore the EM wave absorption properties in a PC made of semiconductor and dielectric layers. The semiconductor will be considered to operate near the plasma frequency. The EM waves propagating through the proposed structure are simulated by the transfer matrix method (TMM) [9]. If the frequency range is larger than the plasma frequency, a tunable omnidirectional absorber is obtained. When the frequency range is less than the plasma frequency, TM wave is absorbed. Therefore, only TE wave can be reflected by PCs in wide-range. Due to the Voigt effect of semiconductor, the frequency range that TE and TM waves are splitted can be tuned by adjusting the intensity of the external magnetic field. The proposed tunable omnidirectional mode splitter has some important potential practical applications.

2. THEORETICAL MODEL

Let us consider a finite binary semiconductor-based PC denoted as $(AB)^N$ where layer A is the dielectric, layer B is the semiconductor, and N is the number of periods. The thickness of the layer $A(B)$ is $d_A(d_B)$. The refractive index of the layer $A(B)$ is $n_A(n_B)$. The relative permittivity and permeability layers A and B are ε_i and μ_i ($i = A$, B), respectively. The PC is assumed to be immersed in air. The incident angle of the incident wave is defined as θ.

The Voigt effect is a well-known magneto-optical effect of the semiconductor that should be considered, when the propagation direction of EM waves is perpendicular to the external magnetic direction. If the electric field of the incident waves is parallel to the external magnetic field, the permittivity will be unchanged by the external magnetic field. The relative permittivity can be expressed as [10]

$$\varepsilon_{\|}(\omega)=\varepsilon_0\left(1-\frac{\omega_p^2}{\omega^2+i\omega/\tau}\right) \tag{1}$$

where ε_0 is the static dielectric constant, where τ is the scattering time and ω_p is the screened plasma frequency. The plasma frequency depends on the densities n and effective masses m^* of the free carriers and can be written as [11]

$$\omega_P^2=\sum_i \frac{4\pi n_i e^2}{m_i^*\varepsilon_0} \tag{2}$$

where i is the relevant conducting or valence band of free electrons and holes an e is the charge. For the electric field of the incident waves which is perpendicular to the external magnetic field, the permittivity will be changed if the external magnetic field is modified. The permittivity is given by [12]

$$\varepsilon_{\perp}(\omega)=\varepsilon_0\left(1-\frac{(\omega^2+i\frac{\omega}{\tau})\omega_P^2-\omega_P^4}{\left(\omega^2+i\frac{\omega}{\tau}\right)\left(\omega^2-\omega_c^2-\omega_P^2+i\frac{\omega}{\tau}\right)}\right) \tag{3}$$

where ω_c is the cyclotron frequency and it can be expressed as [10]

$$\omega_c=\frac{eB}{m^*c} \tag{4}$$

B denotes the external magnetic field and c is the speed of light in vacuum. For a semiconductor layer, the relative permittivity can be expressed as $\varepsilon_B(\omega)=\varepsilon_{||}(\omega)$ for TE mode and $\varepsilon_B(\omega)=\varepsilon_{\perp}(\omega)$ for TM mode.

3. NUMERIAL RESULTS AND DISSUSSION

In this section, we investigate the properties of the relative permittivity of semiconductor, absorption and mode split of 1D semiconductor-based PC. Without loss of generality, we plot $\omega a/2\pi c$ with the normalization convention $\omega_0 a/2\pi c=1$. With this definition, we choose the parameters as follows: the number of periods $N=4$, $\varepsilon_A=1$, $\mu_A=1$, $d_A=0.03a$. We consider the semiconductor as GaAs. The thickness of the layer B is $d_B=a$. We can define the plasma frequency as $\omega_p=4.16\omega_0$ and the scattering time $\tau=1.2\pi/\omega_0$ [12]. If the external magnetic field is $B=1\,\mathrm{T}$, the cyclotron frequency becomes $\omega_c=0.93\omega_0$. The static dielectric constant is taken to be $\varepsilon_0=12.9$ [12]. The thickness of the GaAs is $d_B=a$.

As shown in Figure 1(a), the absorption band is insensitive to the incident angle. When the incident angle increases, the absorption decreases and the pass band remains the same. As a result, it is convenient to realize an omnidirectional absorber. On the other hand, the absorption for incident wave at large incidence could not be more than 80% in our case. Therefore, we only discussed the band with absorption over 70%, which is an important criteria to evaluate an absorber. Therefore, as shown in Figure 1(a), the omnidirectional absorption band with absorption over 70% is located from $4.57\omega_0$ to $9\omega_0$.

Partial view of Figure 1(a) is shown in Figure 1(b). As is shown in Figures 1(a) and 1(c), it is obviously that when the frequency range is less than the plasma frequency and runs from $3.68\omega_0$ to $4.1\omega_0$, TE wave will be reflected but TM wave is absorbed by PCs in different angles. Thus the proposed structures can be used as omnidirectional mode splitter. As shown in Figure 1(d), if the frequency range covers from $3.68\omega_0$ to $4.1\omega_0$, we can find that the real part of ε_B for TM wave is positive, which can be tuned by the external magnetic. According to the results in Ref. [13], impedance matching for TM wave has been met. But the real part of ε_B for TE wave will not be influenced by the external magnetic and it is negative. Thus, the impedance matching for TE wave has not been met [13]. Therefore, TM wave will be absorbed and TE wave will be reflected in the region ranging from $3.68\omega_0$ to $4.1\omega_0$. These results may be provided theoretical instructions for semiconductor of future mode splitter applications.

In order to study the effect of the external magnetic field on absorption of PCs, the high and low band of absorption as a function of the external magnetic field is shown in Figure 2. It is obviously that if $\omega=4.1\omega_0$, the real part of ε_B for TE wave will be close to zero, which is not

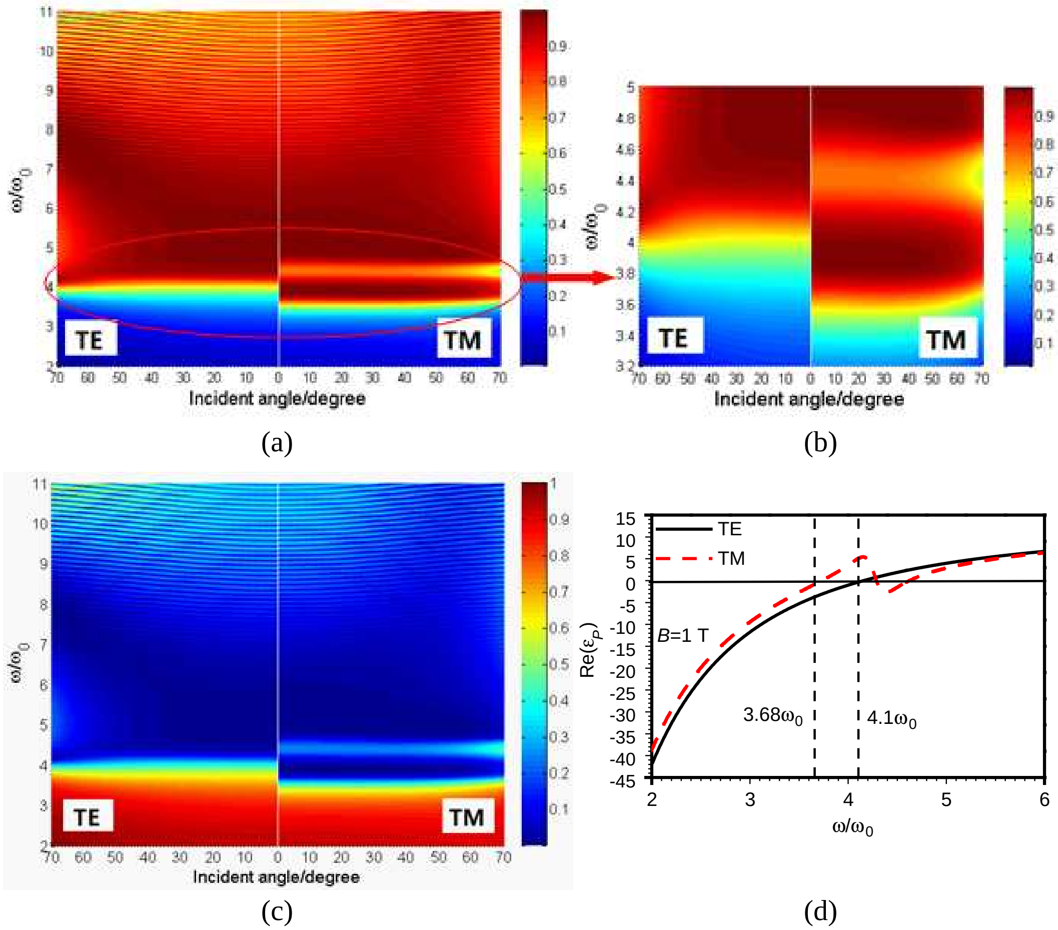

Figure 1: (a) Absorbance of PCs in terms of angular frequency and incident angle for TE wave and TM wave. (b) Partial view of Figure 1(a). (c) Reflectance of PCs in terms of angular frequency and incident angle for TE wave and TM wave. (d) The real parts of the dielectric permittivity of the GaAs as $B = 1\,\text{T}$.

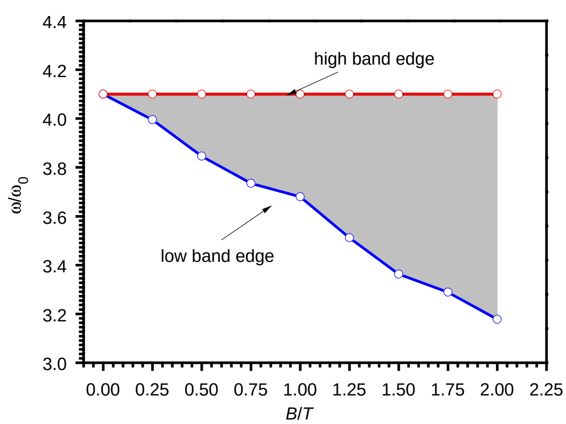

Figure 2: The high and low band edges as a function of the external magnetic field if $d_A = 0.03l$, $d_B = l$.

influenced by the external magnetic field B. Thus, the high band edge is equal to $4.1\omega_0$ which is less than the plasma frequency, and it's not changed as B increased. Meantime, the low band edge will decreased obviously with increasing B. When $B = 0\,\text{T}$, the real parts of ε_B for TE and TM waves are equal. Thus the low band edge is equal to the high band edge, so the bandwidth of mode splitter is zero. If B is increased to $2\,\text{T}$, the real part of ε_B for TM wave will be positive and it's negative for TE wave as the frequency ranging from $3.32\omega_0$ to $4.1\omega_0$. Thus, the impedance matching for TE wave has not been met, but the impedance matching for TM wave has been met. Therefore, the frequency range of the mode splitter will be $3.32\omega_0 \sim 4.1\omega_0$. As mentioned above, we can get a conclusion that the bandwidth of mode splitter is broadened as B is increased.

4. CONCLUSION

In summary, a novel of PCs structure composed of conventional material and semiconductor material is proposed. If the frequency of incident EM wave is larger than the plasma frequency ω_p, due to the impedance matching, the proposed structure can be used to realize an omnidirectional absorber. Due to the Voigt effect, when the frequency range is less than the plasma frequency ω_p, TE and TM waves will be split obviously. The frequency range of the incident wave, whose modes can be split, will be expanded by increasing the external magnetic field B. Therefore, these properties could be applied in an omnidirectional absorber or a number of photonic devices controlling the polarization-dependent propagation of light.

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REFERENCES

1. John, S., "Strong localization of photons in certain disordered dielectric superlattices," *Physical Review Letters*, Vol. 58, No. 23, 2486–2489, 1987.
2. Yablonovitch, E., "Inhibited spontaneous emission in solid-state physics and electronics," *Physical Review Letters*, Vol. 58, No. 20, 2059–2062, 1987.
3. Landy, N. I., S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Physical Review Letters*, Vol. 100, No. 20, 207402, 2008.
4. Gong, Y., X. Liu, H. Lu, L. Wang, and G. Wang, "Perfect absorber supported by optical Tamm states in plasmonic waveguide," *Optics Express*, Vol. 19, No. 19, 18393–18398, 2011.
5. Shi, Y., "A compact polarization beam splitter based on a multimode photonic crystal waveguide with an internal photonic crystal section," *Progress In Electromagnetics Research*, Vol. 103, 393–401, 2010.
6. Hu, M. H., J. Z. Huang, R. Scarmozzino, M. Levy, and R. M. Osgood, Jr., "Tunable Mach-Zehnder polarization splitter using height-tapered Y-branches," *IEEE Photonics Technology Letters*, Vol. 9, No. 6, 773–775, 1997.
7. Soldano, L. B., A. I. de Vreede, M. K. Smit, B. H. Verbeek, E. G. Metaal, and F. H. Green, "Mach-Zehnder interferometer polarization splitter in InGaAsP/InP," *IEEE Photonics Technology Letters*, Vol. 6, No. 3, 1994.
8. Xu, C., D. Han, X. Wang, X. Liu, and J. Zi, "Extrinsic photonic crystals: Photonic band structure calculations of a doped semiconductor under a magnetic field," *Applied Physics Letters*, Vol. 90, No. 6, 061112, 2007.
9. Zhang, H. F., S. B. Liu, X. K. Kong, B. R. Bian, and Y. Dai, "Omnidirectional photonic band gap enlarged by one-dimensional ternary unmagnetized plasma photonic crystals based on a new Fibonacci quasiperiodic structure," *Physics of Plasmas*, Vol. 19, No. 11, 112102, 2012.
10. Feng, L., X. P. Liu, Y. F. Tang, Y. F. Chen, J. Zi, S. N. Zhu, and Y. Y. Zhu, "Tunable negative refraction in a two-dimensional active magneto-optical photonic crystal," *Physical Review B*, Vol. 71, No. 19, 195106, 2005.
11. Kong, X. K., S. B. Liu, H. F. Zhang, S. Y. Wang, B. R. Bian, and Y. Dai, "Tunable bistability in photonic multilayers doped by unmagnetized plasma and coupled nonlinear defects," *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 19, No. 1, 8401407–8401407, 2013.
12. Xu, C., X. Hu, Y. Li, X. Liu, R. Fu, and J. Zi, "Semiconductor-based tunable photonic crystals by means of an external magnetic field," *Physical Review B*, Vol. 68, No. 19, 193201, 2003.
13. Zhou, J., L. Jin, and E. Y. B. Pun, "Tunable multichannel nonreciprocal perfect absorber based on resonant absorption," *Optics Letters*, Vol. 37, No. 13, 2613–2615, 2012.