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Photonic band structures in one-dimensional photonic crystals containing Dirac materials

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ABSTRACT

We have investigated the band structures of one-dimensional photonic crystals (1DPCs) composed of Dirac materials and ordinary dielectric media. It is found that there exist an omnidirectional passing band and a kind of special band, which result from the interaction of the evanescent and propagating waves. Due to the interface effect and strong dispersion, the electromagnetic fields inside the special bands are strongly enhanced. It is also shown that the properties of these bands are invariant upon the lattice constant but sensitive to the resonant conditions.

1. Introduction

Photonic crystals (PCs) have intrigued considerable attention in several decades due to unique electromagnetic properties and wide potential applications [1–3]. It is well known that the essential property of PCs is the photonic band gap (PBG) which is the result of the interference of Bragg scattering in periodical structures. Conventional Bragg gaps vary with respect to the lattice constant, the incident angle, and polarization, and defect modes are highly localized in defect layers. In the last decade, two new types of gaps, the zero-averaged refractive index gaps [4–6] and the effective zero-phase gaps [7–10], are realized in the PCs with left-handed metamaterials [11] and single-negative meta-materials [12,13], respectively. These gaps are also recognized as omnidirectional gap, which is insensitive to the change of scale length and lattice disorder. Up to now, the PCs based on the PBGs have provided various methods to manipulate photons more effectively and flexibly.

On the other hand, many recent investigations show the existence of the double-conical band structures for photons according to the analogy between electronic band structures in graphene and photonic band structures in two-dimensional PCs [14–20]. The touching point in double-conical band structures is called as Dirac point (DP), and near the DP, the dispersion is linear [21]. Recently, one finds that the DP with a double-cone structure for optical fields is realizable in negative–zero–positive index metamaterials (NZPIMs) [22], and several novel optical transport properties near the DP are also demonstrated, such as Zitterbewegung effect [23–26], optical nonlocality [27], tunable transmission gaps, Bragg-like reflections, and negative or positive GH shifts [28–30].

Motivated by these studies, here our aim is to investigate the band structures of 1DPCs containing Dirac media (which refer to the bulk materials possessing a DP). We find that there are two kinds of passing bands (an omnidirectional narrow passing band and a special band) which result from the interaction of the evanescent and propagating waves. Due to the interface effect, the electromagnetic fields inside the special bands are strongly enhanced. The properties of the special bands are sensitive to the resonant conditions but invariant upon the lattice constant.

The whole paper is organized as follows. In Section 2, it presents the theoretical model and formula on the wave propagating in the 1DPCs. In Section 3, the properties of the photonic bands and gaps, the transmission and the electromagnetic fields inside the 1DPCs containing Dirac materials are analyzed. Last, a summary is given in Section 4.

2. Theoretical model and formula

For simplicity, consider a 1DPC of the structure $(AB)^N$ with N the number of the period, as shown in Fig. 1. Assume that the layers A with thickness d_A are made of NZPIMs, whose relative permittivity and permeability satisfy the Drude model as follows,

$$\varepsilon_A = a - \omega_{ep}^2/(\omega^2 + i\gamma_e\omega), \quad (1)$$

$$\mu_A = b - \omega_{mp}^2/(\omega^2 + i\gamma_m\omega), \quad (2)$$

where ω_{ep} and ω_{mp} are the controllable electronic and magnetic plasma frequencies, respectively, and γ_e and γ_m stand for the corresponding damping rates (relating to the absorption). In

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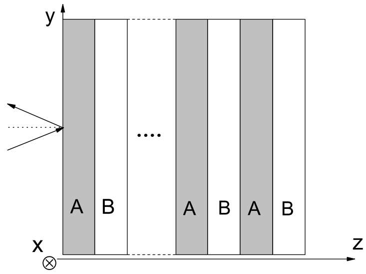

Fig. 1. Schematic representation of a periodic structure $(AB)^N$, where A denotes NZPIMs and B denotes the vacuum or dielectric media.

our calculation, without loss of generality, we assume $a = b = 1$, $\gamma_e = \gamma_m = \gamma = 10^{-5}$ GHz $\ll \omega_{ep,mp}$, and $\omega_{ep} = \omega_{mp} = \omega_D$. Under these parameters, material A has almost the linear dispersion with a DP at frequency ω_D. The layers B can be the vacuum or dielectric media. For simplicity, here we take the layers B as vacuum with thickness d_B. Let a plane wave be injected from vacuum into the 1DPC at an incident angle θ. From the transfer matrix method [31,32], the electric and magnetic fields between any two positions z and $z + \Delta z$ within the same layer are related via a transfer matrix

$$M_j(\Delta z, \omega) = \begin{pmatrix} \cos[k_z^j \Delta z] & i\frac{1}{q_j}\sin[k_z^j \Delta z] \\ iq_j \sin[k_z^j \Delta z] & \cos[k_z^j \Delta z] \end{pmatrix}, \tag{3}$$

where $k_z^j = \sqrt{k_j^2 - k_y^2}$ ($j = A, B$) is the z component of the wave vector in the jth layer for $k_j^2 > k_y^2$, otherwise $k_z^j = i\sqrt{k_y^2 - k_j^2}$; $k_j = k_0\sqrt{\varepsilon_j}\sqrt{\mu_j}$ is the corresponding wave vector in materials, $q_j = k_z^j/(\mu_j k_0)$ for TE wave and $q_j = k_z^j/(\varepsilon_j k_0)$ for TM wave, $k_0 = \omega/c$ the wave vector in the vacuum, and c is the light speed in vacuum. By using the boundary conditions, the reflection and transmission coefficients for a finite 1DPC can also be obtained from the transfer matrix method [31,33,34]

$$r(\theta,\omega) = \frac{[q_0 x_{22} - q_s x_{11}] - [q_0 q_s x_{12} - x_{21}]}{[q_0 x_{22} + q_s x_{11}] - [q_0 q_s x_{12} + x_{21}]}, \tag{4}$$

$$t(\theta,\omega) = \frac{2q_0}{[q_0 x_{22} + q_s x_{11}] - [q_0 q_s x_{12} + x_{21}]}, \tag{5}$$

where $q_0 = q_s = \cos\theta$ for the vacuum of the space $z < 0$ (before the incident end) and the space $z > L$ (after the exit end), and L is the total length of the 1DPC. In the above, x_{ij} are the matrix elements of the total matrix $X_N(\omega) = \prod_{j=1}^{2N} M_j(d_j, \omega)$, which represents the total transfer matrix for the light fields propagating from the incident to exit ends.

For an infinite periodic structure ($N \to \infty$), based on the Bloch's theorem, the dispersion at any angle of incidence obeys the following relation

$$\begin{aligned}\cos[\beta_z\Lambda] &= \frac{1}{2}\mathrm{Tr}[M_A M_B] \\ &= \cos[k_z^A d_A]\cos[k_z^B d_B] \\ &\quad - \frac{1}{2}\left(\frac{q_A}{q_B} + \frac{q_B}{q_A}\right)\sin[k_z^A d_A]\sin[k_z^B d_B],\end{aligned} \tag{6}$$

where $\Lambda = d_A + d_B$ is the lattice constant of the 1DPC, and $\beta_z\Lambda$ is the reduced phase shift of the propagating fields along the z direction. The condition of the real solution for β_z requires $|\cos\beta_z\Lambda| \leqslant 1$, which corresponds to the pass bands of the 1DPCs. In the following calculation and discussion, we take $\omega_D/2\pi = 10$ GHz, and this corresponds to the wavelength $\lambda_D = 30$ mm in vacuum. In what follows we will demonstrate the properties of the PBGs, transmission spectrum, and the electromagnetic fields in the PCs. Here we only present the result of TE-polarized plane waves, and similar results can be obtained for the TM-polarized plane waves.

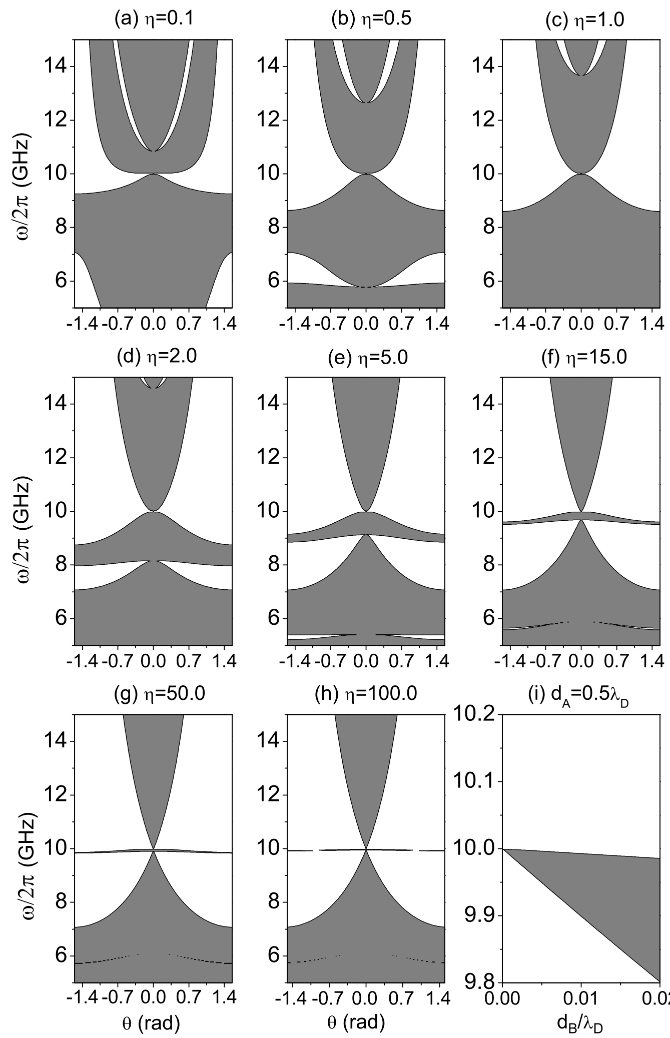

Fig. 2. Dependence of photonic band structures on the ratio of widths $\eta = d_A/d_B$ for the structures $(AB)^N$ with $N \to \infty$ under $\Lambda = 0.5\lambda_D$, the ratio η from (a) to (h) is 0.1, 0.5, 1.0, 2.0, 5.0, 15.0, 50.0, and 100.0. (i) Dependence of photonic band structures on the thickness d_B under $d_A = 0.5\lambda_D$ and $\theta = 10°$. The dark areas are the allowed bands, the white areas correspond to the forbidden gaps. The Dirac frequency of layers A is $\omega_D/2\pi = 10$ GHz.

3. Numerical results and discussions

In this section, we will demonstrate the photonic structures in the 1DPC by using the transfer matrix approach. The approximate band structures, transmission spectrum and electromagnetic fields are also shown to display the physical mechanism and the unique property of special bands. Finally, we will explore the effects of incident angle and lattice constant of photonic crystal on the photonic structures.

Let us first consider the photonic band gaps in the system. Fig. 2 demonstrates the dependence of photonic band structures on the ratio of widths $\eta = d_A/d_B$, for the structures $(AB)^N$ with $N \to \infty$ under $\Lambda = 0.5\lambda_D$. From Fig. 2(a) to Fig. 2(c), as the thickness of layer A increases, a PBG appears near the Dirac frequency ω_D of the bulk material A. This gap opens at the inclined angle (i.e. $\theta \neq 0$). The band edge of the above passing band (above the