Absolute band gaps in two-dimensional graphite photonic crystal

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The off-plane propagation of electromagnetic (EM) waves in a two-dimensional (2D) graphite photonic crystal structure was studied using transfer matrix method. Transmission spectra calculations indicate that such a 2D structure has a common band gap from 0.202 to 0.2035 c/a for both H and E polarizations and for all off-plane angles form 0° up to 90°. The presence of such an absolute band gap implies that 2D graphite photonic crystal, which is much easier and more feasible to fabricate, can exhibit some properties of a three-dimensional (3D) photonic crystal.

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It is well known that structures with periodic dielectric constant may give rise to photonic band gaps (PBGs), in which the EM wave propagation is forbidden. Photonic crystals are the significant subjects in recent years since many applications have been proposed. It is easy to obtain a gap for single polarization (E polarization or H polarization). Nevertheless, if the emitted light is slightly or not polarized, it is better to have an absolute PBG, created by overlap of gaps of both E and H polarizations. Generally, the full characteristics of PBG should be best realized in a 3D system that exhibits a complete band gap along all dimensions in space[1]. But the difficulty of fabricating such 3D photonic crystals with PBGs has not been overcome from real application point of view. So it is of a large interest to obtain properties of 3D photonic crystals as many as possible using lower-dimensional structures, significant progress has been achieved now including 3D control of light in a 2D photonic crystal slab[2] and omnidirectional external reflection by a 1D photonic crystal[3,4].

Previous researches have proved that 2D structures can present absolute PBGs for high air filling factor[1]. The graphite structure of dielectric rods in the air background[5,6] and the triangular structure of air holes in the dielectric background have been shown to be the most promising 2D cases[7−9]. To the triangular structure, the dielectric wall between nearest holes must be very thin because of high air filling factor, which causes the difficulty in fabrication. However, the graphite structure of dielectric rods in the air background is a much stable 2D photonic crystal structure even though high air filling factor. In addition, the interest in 2D photonic crystals has been mainly concentrated on the in-plane (plane of periodicity, designated as the XY plane) propagation of EM wave. More realistic configuration should be a constant off-plane incident angle for all frequencies, and thus, different k_Z for different frequencies[10]. So in this paper, the characteristics of off-plane propagation of EM waves in a 2D graphite photonic crystal were investigated using transfer matrix method[11−14], and absolute band gaps are found when the off-plane incidence angle ranging from 0° to 90°.

We start from the wave equation in nonmagnetic and lossless substance,

$$\begin{aligned}\nabla\times\nabla\times\mathbf{E} &= -\nabla^2\mathbf{E}+\nabla(\nabla\cdot\mathbf{E})\\ &= \frac{\varepsilon(\mathbf{r})}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}.\end{aligned} \tag{1}$$

Rewrite it into (k,ω) space,

$$\begin{aligned}&(k\cdot k)\mathbf{E}(k)-k[k\cdot\mathbf{E}(k)]\\ &=\frac{\omega^2}{c^2}\sum_{k'}\varepsilon(k,k')\mathbf{E}(k').\end{aligned} \tag{2}$$

Discretize this equation following the essence of a finite-element method in which space is divided into a set of small cells with coupling between neighboring cells. And on transforming them back into real space, we get the matrix $T(\mathbf{r},\mathbf{r}')$ relating fields on one side of a structure to those on the other, defined as the transfer matrix.

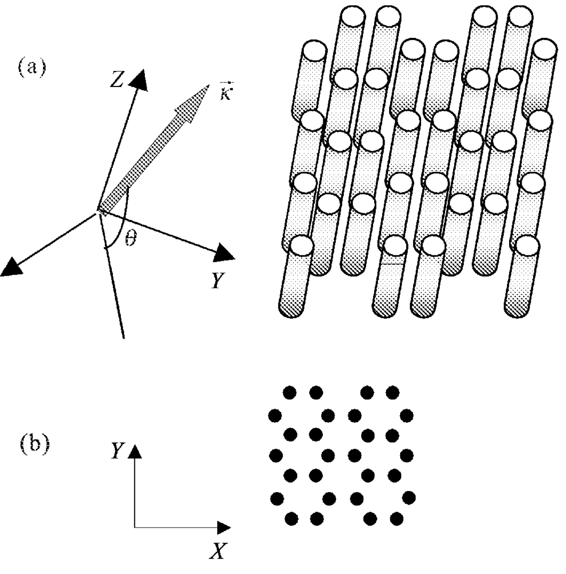

Fig. 1. The 3D schematic and 2D top view of a graphite photonic crystal.

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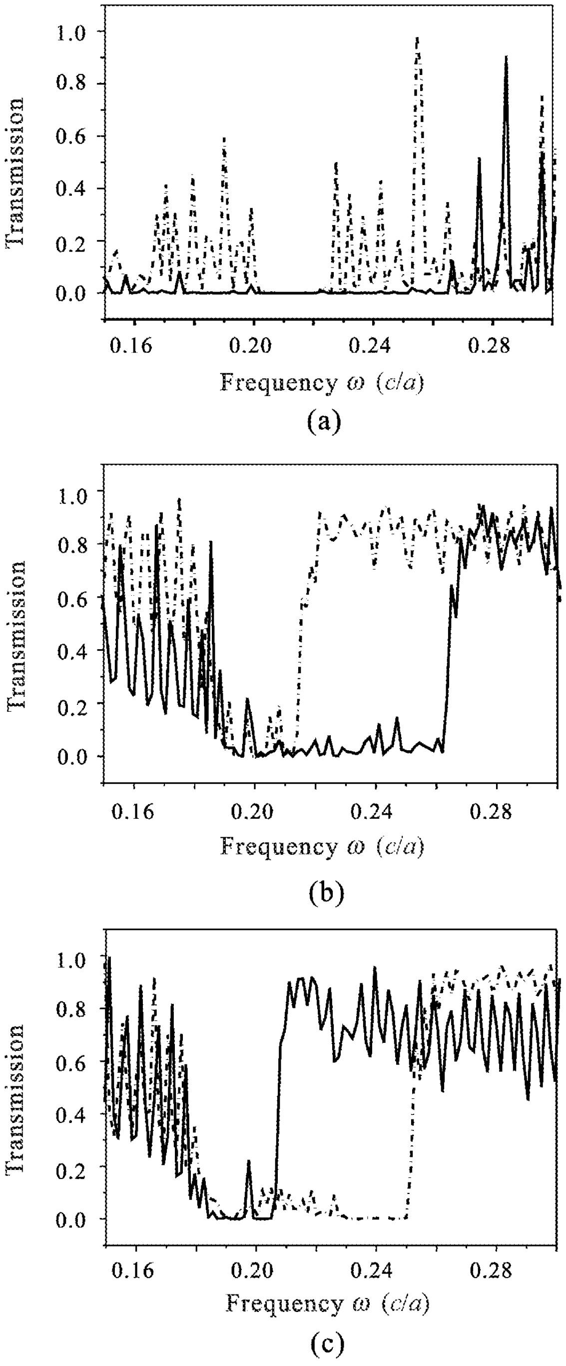
$$\mathbf{V}(\mathbf{r}+\mathbf{d})=\sum_{\mathbf{r}'}T(\mathbf{r},\mathbf{r}')\mathbf{V}(\mathbf{r}'), \qquad (3)$$

where $\mathbf{V}$ is the characteristic vector of EM wave compose by the X, Y components of E and H fields, and $\mathbf{d}$ is the mesh basis along Z axis. The transmission coefficient is gotten as the quotient of outgoing EM wave intensity divided by the ingoing intensity.



(a)

(b)

(c)

Fig. 2. Transmission spectra for a graphite structure of dielectric cylinders in air at different off-plane incidence angles of EM waves. (a) $\theta = 0°$, (b) $\theta = 45°$, (c) $\theta = 90°$. The graphite photonic crystal has a dielectric constant of $\varepsilon = 8.5$ and a filling factor of $f = 35\%$. Dashed lines represent H polarization and solid lines represent E polarization.

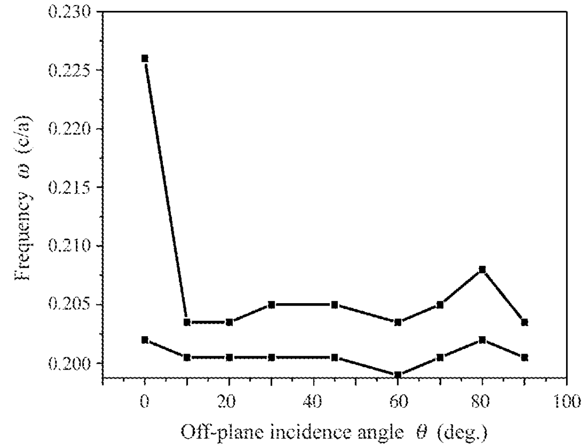


Fig. 3. Dependence of the absolute band edges on the off-plane incidence angles.

The schematic view of 2D graphite photonic crystal is shown in Fig. 1, the dielectric cylinders in air are infinite and an EM wave is incident from air to the crystal at an off-plane angle of θ. In our calculations, the dielectric cylinders have a dielectric constant of $\varepsilon = 8.5$ and a radius of $r = 0.38a$, so the filling factor is $f = 35\%$.

Figure 2 displays the transmission spectra for the graphite photonic crystal of three different incidence angles. Figure 2(a) shows the results for the in-plane propagation ($\theta = 0°$) for both E (solid lines) and H polarization (dashed lines) modes. The overlapped gap of two modes creates an absolute band gap, with frequency ranging from 0.202 to 0.226 c/a (here c is the light speed in vacuum, and a the lattice constant). And at an off-plane angle of $\theta = 45°$, as shown in Fig. 2(b), both polarizations have the band gap from 0.2005 to 0.205 c/a. With θ continuing to increase and reaching 90°, the lower band edge moves to 0.2005 c/a and the upper band edge moves to 0.2035 c/a, as we can see in Fig. 2(c). In spite of the shift of these band edges, we still obtain a common band gap for all off-plane angles up to 90°, the absolute band gap is from 0.202 to 0.2035 c/a.

The dependence of the absolute band edges on the off-plane incidence angles was plotted in Fig. 3, the size of the common band gap is the largest at $\theta = 0°$ and the smallest at $\theta = 90°$. With the increasing of off-plane incidence angle, the absolute band gap range decreases rapidly.

In conclusion, we have investigated the dependence of absolute band gaps in a 2D graphite photonic crystal on the off-plane incidence angles of EM waves, and absolute band gaps are found in such a 2D structure. This simple 2D structure may realize some of the properties of a 3D photonic crystal.

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