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Band gap of two-dimensional fiber-air photonic crystals

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ABSTRACT

A two-dimensional photonic crystal (PC) composed of textile fiber and air is initially discussed in this paper. Textile materials are so called soft materials, which are different from the previous PCs composed of rigid materials. The plain wave expansion method is used to calculate band structure of different PCs by altering component properties or structural parameters. Results show that the dielectric constant of textile fibers, fiber filling ratio and lattice arrangement are effective factors which influence PCs' band gap. Yet lattice constant and fiber diameter make inconspicuous influence on the band gap feature.

1. Introduction

Photonic crystals (PCs) which mean periodic structures of materials, have attracted many experimental [1–7] and theoretical [8–12] works in recent years. The most prominent feature of PCs is the existence of photonic band gaps, i.e., the frequency regions in which all optical modes are forbidden to propagate. Since most applications of the PCs rely on this feature, a mount of efforts have been devoted to the creation of photonic band gaps [13].

Mejia-Salazar [14] theoretically study a 2D photonic crystal (PC) comprised by double negative (DNG) metamaterial cylinders, showing that such a system presents a superior light-matter interaction when compared with their single negative (SNG) plasmonic PC counterparts. Nojima [15] attempted to quantitatively determine which process is more responsible for the band-gap formation, Bragg of Mie processes. And further concluded that the dielectric PCs had a greater tolerance than the metallic PCs for the fluctuation of the lattice arrangements, which would undoubtedly facilitate the fabrication of the crystals. Zhang [16] studied the properties of two types of three-dimensional magnetized plasma photonic crystals composed of homogeneous magnetized plasma and dielectric with simple-cubic lattices by a modified plane wave expansion (PWE) method, as the magneto-optical Voigt effects of magnetized plasma are considered.

In this paper, a two-dimensional photonic crystal composed of textile nanofiber and air is initially discussed. The textile nanofiber is soft matter, which comprise two-dimensional photonic crystal, not like the rigid ones that are usually studied in former researches. Textile nanofibers are light in weight, environment friendly and efficient [17]. Plain wave expansion (PWE) method is used to calculate photonic band gaps by altering component properties and structure parameters of PCs.

2. Methods and models

The method used to calculate band structure of two-dimensional fiber-air photonic crystal is plain wave expansion method, which is described in detail in literatures [18,19].

The photonic crystal studied in this article is a two-dimensional system composed of two components, which are textile fiber as rigid frame and air as the matrix. We propose a model as shown in Fig. 1, where *A* represents fiber and *B* is air, *a* is lattice constant, and *d* is the diameter of fiber. Fibers A, which are parallel to the *z*-axis in the cartesian coordinates, arrange in the matrix B by triangular lattice form which is the closest. Then the periodic structure appears on the plain-xoy, which is vertical to the fiber axis.

In this triangular lattice 2D photonic crystal, as shown in Fig. 1, the filling ratio of fibers can be calculated by Eq. (1):

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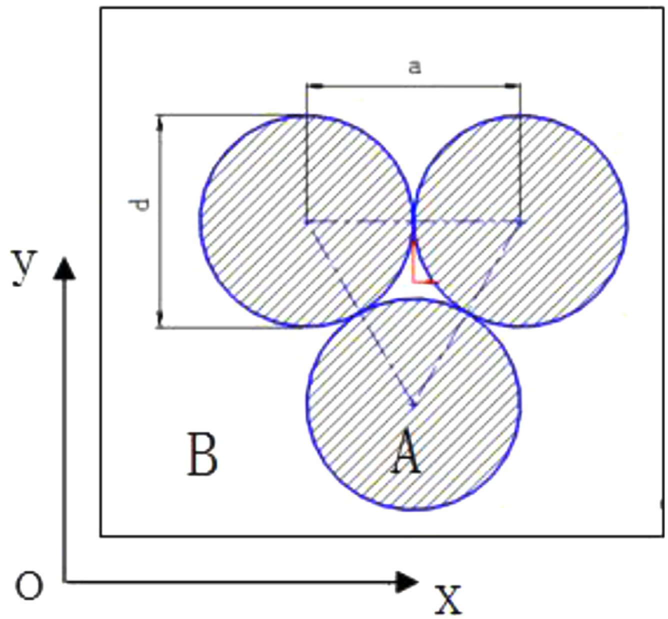

Fig. 1. Transverse cross-section of a triangular lattice 2D photonic crystal.

Table 1
Property parameters of materials.

Materials	Density (g/cm^3)	Dielectric constant
Polypropylene fiber	0.9	2.2
Polyester fiber	1.38	3.4
Ceramic fiber	2.9	6
Air	0.00129	1

$$\varphi_{tri} = \frac{\left(\frac{\pi d^2}{4}\right)/2}{\frac{\sqrt{3}}{4}a^2} = \frac{\sqrt{3}\,\pi d^2}{6a^2} \tag{1}$$

3. Results and discussions

Three typical fibers involved in this study are polypropylene fiber whose density is the smallest in the textile fibers, ceramic fiber who is the heaviest one, and the polyester fiber which is most popular and has a middle density. All the property parameters of fibers and air that may be concerned in calculation are listed in Table 1.

3.1. Effect of material properties

Properties of components may influence the band gap of PCs, especially the density and dielectric constant. So in this part, we fix the structural parameters of triangular lattice 2D PCs, including lattice constant a, fiber diameter d and fiber filling ratio φ_{tri}, in order to investigate the effect of material properties.

We set lattice constant $a = 10\mu\text{m}$, fiber diameter $d = 8\mu\text{m}$, then the fiber filling ratio is $\varphi_{tri} = = \frac{\sqrt{3}\pi d^2}{6a^2} = 0.58$. Under this case, we calculate the band gap of three different types of fiber-air photonic crystal with triangular lattice.

Results are shown in Fig. 2, in which Fig. 2(a) gives the band gap of polypropylene fiber-air PC; Fig. 2(b) gives the band gap of polyester fiber-air PC; and Fig. 2(c) shows the band gap of ceramic fiber-air PC. The yellow shadow region in each figure represents the band gap where light wave can not propagate. From Fig. 2, we take summary of the band gap distribution in Table 2.

As can be seen in Table 2, the start frequency becomes lower with the larger dielectric constant of fiber, and meanwhile the bandwidth becomes larger.

3.2. Effect of structural parameters

Then, we take polyester fiber-air 2D PC as an example, to investigate the influence on the band gap brought by structural parameters of photonic crystal, including lattice constant a, fiber filling ratio φ_{tri}, lattice arrangements and some other factors.

3.3. Effect of lattice constant a

For polyester fiber-air 2D PC with triangular lattice arrangements, the fiber filling ratio is fixed as $\varphi_{tri} = 0.58$, then different band gap are calculated by altering the lattice constant a.

As the diameter range of common textile fibers is $0.1 - 100\mu\text{m}$, so we select three data sets as $d_1 = 0.8\mu\text{m}$, $d_2 = 4\mu\text{m}$, and $d_3 = 8\mu\text{m}$. According to Eq. (1), the lattice constant is set as $a_1 = 1\mu\text{m}$, $a_2 = 5\mu\text{m}$ and $a_3 = 10\mu\text{m}$. The band gaps of three different PCs are shown in Fig. 3.

Fig. 3(a) indicates the band gap distribution of 2D polyester fiber-air photonic crystal with lattice constant $a_1 = 1\mu\text{m}$; the band gap distribution of 2D polyester fiber-air photonic crystal with lattice constant $a_2 = 5\mu\text{m}$ is displayed in Fig. 3(b); while the band gap distribution of 2D polyester fiber-air with $a_3 = 10\mu\text{m}$ is shown in Fig. 3(c).

The data of band gaps from Fig. 3 are summarized in Table 3. It is obvious that the start frequency, gap width and quantities of band gaps are nearly the same. It can be concluded that lattice constant and fiber diameter make inconspicuous influence on the band gap feature of different PCs with same fiber filling ratio φ_{tri}.

3.4. Effect of fiber filling ratio φ

In this part, the lattice constant of polyester fiber-air 2D PCs with triangle lattice are fixed as $a = 10\mu\text{m}$. By changing the fiber diameter d, the fiber filling ratio is also changing, to study the effect of filling ratio on the band gap properties of photonic crystal.

Fiber diameter is set as $d_1 = 4\mu\text{m}$, $d_2 = 7\mu\text{m}$, $d_3 = 8\mu\text{m}$, $d_4 = 9\mu\text{m}$, correspondingly filling ratio is $\varphi_1 = 0.145$, $\varphi_2 = 0.444$, $\varphi_3 = 0.58$, $\varphi_4 = 0.734$. The band gap properties of four PCs with different fiber filling ratio are shown in Fig. 4.

Compared of the four band gap distribution figures, the start frequency, cut-off frequency and bandwidth are summarized in Table 4. It can be concluded that fiber filling ratio makes great influence on the band gap characteristics. There exist no band gap when $\varphi_1 = 0.145$, maybe this ratio is smaller than the critical ratio that can generate band gap. Above this critical ratio, with the increasing fiber filling ratio, the start frequency becomes higher while the bandwidth gets narrower.