Tunable omnidirectional band gap properties of 1D plasma annular periodic multilayer structure based on an improved Fibonacci topological structure

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Abstract
In this paper, the characteristics of the omnidirectional band gap (OOG) for one-dimensional plasma cylindrical photonic crystals based on an improved Fibonacci topological structure are researched. The influences of the azimuthal mode number (m), incident angle (θ), plasma thickness (d_p), and plasma frequency (ω_p) on the OOG are discussed. These conclusions are drawn that m has a strong ability to regulate the OOG. As m increased, the OOG will be broadened. The θ has a similar ability in adjusting the photonic band gap (PBG), a larger θ will get a wider PBG. When θ = 85°, the TM wave achieves the PBG in the range of 0–3 (2πc/d). So the ultra-wide PBG can be got by the large θ. Contrary to m, d_p has an inverse relationship with the bandwidth of the OOG. As d_p increases, the bandwidth of the OOG will be decreased. Fortunately, the frequency range of the OOG can be controlled by d_p. But ω_p cannot regulate the bandwidth of the OOG. Increasing m and reducing d_p appropriately can obtain a lower frequency and wider OOG. This feature is very beneficial to designing devices such as waveguides, filters, and antenna substrates. In addition, an interesting phenomenon can be found when m = 2, an extra high reflection zone can be inspired in the TM wave. It provides a theoretical support for designing the narrowband filters without introducing any physical defect layers in the structure.

Keywords Plasma cylindrical photonic crystals · Fibonacci · Quasi-periodic structure · Omnidirectional band gap · Transfer matrix method

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1 Introduction

Photonic crystals (PCs) (Nair and Vijaya 2010; Pitruzzello and Krauss 2018; Yip et al. 2011) are a kind of synthetic material, which are formed by the periodic distribution of different mediums in space. When the electromagnetic waves through the periodic medium, the Bragg scattering is inspired (Anusha and Sharan 2018; Dou et al. 2019), so the PCs can produce the photonic band gaps (PBGs) that similar to the electronic band gaps in the semiconductor. The electromagnetic wave with a particular frequency will is reflected in the PBGs. Thanks to the interesting properties of the PBGs, the PCs can be used to manufacture the reflectors (Liles et al. 2016) and band-pass filters (Qiang et al. 2011). However, the features of the PBGs (Ji-jiang and Gao 2015; Tolmachev et al. 2005) are affected by their topological structures in the conventional PCs. As a result, their PBGs are immutable. For the sake of overcoming the defect, on the one hand, a large number of special materials are introduced in the design of the PCs. On the other hand, the reasonable design structure and parameter optimization.

At any incident angle, the PBGs can be generated in the arbitrary polarization mode (the measurement of the parameters of TE and TM waves (Ilkhechi et al. 2015a, b, 2016a, b; Najibi Ilkhechi and Koozegar Kaleji 2016; Ilkhechi and Kaleji 2017), which are called the omnidirectional band gaps (OBGs) (Feng et al. 2020; Kumar et al. 2011; Chavez-Castillo et al. 2020; Zhao et al. 2017). The OBG has broad application prospects, it is the design principle of many devices, such as waveguides (Xue et al. 2017), omnidirectional filters (Singh et al. 2016), and antenna substrates (Naderi Dehnavi et al. 2017). For those devices, better performance can be obtained by a wider OBG. It has been confirmed that the bandwidth of the OBG can be broadened by changing or make further efforts to break the periodicity of PC topology. Last several years, the quasi-periodic structure (QPS) (Sreejith and Mathew 2017; Xiao and Chen 2015; Zhang et al. 2015) has attracted more attention in the PCs design. Owing to the QPS not only retains the basic physical properties of the period but also its structure is suitable for generating more complicated PBGs, providing the possibility of realizing the ultra-wideband OBG compared with the periodic structure. Therefore, the PCs with the QPS are formed alternately by the dielectric, and plasma can improve the performance of PBGs (Zhang et al. 2012, 2013). In 2016, Srivastava et al. studied the optical properties of the high-temperature superconducting cylindrical PCs (HTSCPCs), they found a superpolariton gap for the higher-order azimuthal mode number in the TM wave (Srivastava and Aghajamali 2016). In 2009, Chen et al. researched the wave characteristics of the single-negative materials cylindrical photonic crystals (CPCs) discovered that the TE wave also produced the additional high reflection bands, and the PBGs had a strong dependence on the initial radius (Chen et al. 2009). In 2013, Hu et al. derived the reflection and transmission formulas of the CPCs under the H-polarization (Hu et al. 2013). In 2013, Aly et al. found that the number of PBG can be controlled by changing the thickness of the dielectric layer when investigated the HTSCPCs (Aly et al. 2013). However, nobody has researched on the OBG characteristics of the CPCs. Therefore, it is necessary to study the OBG characteristics of the CPCs. Moreover, the OBG research work in the previous, many researchers used the layered PCs (Ma et al. 2020) (Ma et al. 2020 mainly studies the polarization splitting and OBG of layered PCs based on the improved Thue-Morse sequence). In this paper, the one-dimensional (1D) plasma CPCs (PCPCs) with an improved Fibonacci topological (IFT) structure is presented, whose attributes of the OBGs are studied. The CPCs in the modern lasers system of vertical emission (Chen et al. 2012), producing the complete band gaps, improving the constraint of transverse
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propagation (Rüdiger and Tobia 2006), optical communication, and optoelectronics (Chen et al. 2009) have potential application. Consequently, researching the CPCs is essential. It is worth emphasizing that our paper is based on the theoretical proposal of 1D PCs under ideal conditions. However, from the manufacturing point of view, the proposed 1D plasma PCPCs that are based on an IFT structure can be fabricated with the etching methods (Renilkumar et al. 2011) that are widely used in the fabrication of PCs.

In the present paper, an 1D PCPCs based on the IFT structure is studied, which is constituted by the plasma and dielectric materials alternately distributed in space. Compared with the metal-dielectric PCs, the wave traits of the plasma PCs can be adjusted. Since the wave characteristics of the plasma depend on the plasma frequency, incident wave frequency and collision frequency. In the procedure of researching the reflection spectra discover that the reflection properties of the PCPCs based on the IFT depend on the azimuthal mode number and other parameters. For the TM wave, an additional high reflection band can be stimulated when the azimuthal mode number is 2. The extra high reflection band can be used to produce the narrow band, which provides a practicable method to devise the narrow band transmission filter without introducing any defect layer to break the periodicity of construction (Hu et al. 2013; Chena et al. 2009). In addition, it can be concluded that a larger azimuthal mode number can obtain a wider OBG. Incident angle and azimuthal mode number have strong ability to regulate the PBGs. And the ultra-wide PBG can be acquired at the large incident angle. In this article, the influences of different azimuthal mode number on the reflection characteristics of the PCPCs based on the IFT is studied, and then the incidence angle, plasma thickness, plasma frequency and other parameters will be discussed (simulation software: Matlab 2019a).

2 Simulation model and calculation method

The Fibonacci 0-level \((L)\) sequence can be expressed as \((A\ B\ A\ B\ ...\)\), the 1-\(L\) sequence can be written as \((A\ B\ A\ B\ A\ B\ ...\)\), the 2-\(L\) sequence can be marked as \((A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ ...\)\), and the 3-\(L\) sequence can be replaced by \((A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ ...\)\). The Fibonacci 2-\(L\) sequence \((A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ A\ B\ ...\)\) is used in this paper, and the A and P dielectric layers are used to replace the A media layers in the construction. So the IFT architecture is \((A\ P\ B\ A - P\ A\ B\ A\ B\ A\ P\ B\ A\ B\ A\ P\ B\ A\ B\ A\ P\ B\ A\ ...\)\). The model of the 1D PCPCs with IFT structure is shown in Fig. 1. Figure 2 furnishes the cross-sectional view of the 1D PCPCs based on the IFT structure. The electromagnetic waves incident from the free space. The model background is the air, so \(n_f = n_0 = 1\), and the starting radius is set \(d (\rho_0 = d)\), \(d\) is the normalization constant. The ordinary dielectric layers are represented by A and B, and the P indicates the plasma layer. The thicknesses are described by \(d_A\), \(d_B\), and \(d_P\), where \(d_A = d_B = 0.08d\), and \(d_P = 0.2d\). In the following calculations, the frequency region is normalized by \(2\pi c/d\), where \(c\) is the speed of light in the vacuum. The dielectric constant is \(\varepsilon_i\) \((i = A, B\ or P)\), where \(\varepsilon_A = 4\), \(\varepsilon_B = 1\), and \(\varepsilon_p\) of the plasma can be expressed as (Li et al. 2011):

\[
\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2 + j\nu_c\omega}.
\]

where \(\omega\) represents the angular frequency of the incident electromagnetic wave, \(\nu_c\) is the collision frequency of the plasma and \(\omega_p\) denotes plasma frequency. The initial parameters are set as \(\nu_c = \pi \times 10^{-5} \times c/d\) Hz, \(\omega_p = 2\pi \times 0.2 \times c/d\) rad/s.
Respectively, supposing the electromagnetic field is related to time $e^{j\omega t}$, and the two Maxwell equations for the passive region can be given below

\begin{equation}
\nabla \times E = -j \omega \mu H. \tag{2}
\end{equation}

\begin{equation}
\nabla \times H = j \omega \varepsilon E. \tag{3}
\end{equation}

There are two kinds of possible waves in cylindrical coordinates of the TE and TM waves. the $E_z$, $H_\theta$, and $H_\rho$ are non-zero and can be represented by the following three equations for the TE wave.

Fig. 1 The top view of the 1D PCPCs based on the IFT structure

Fig. 2 The cross-section view of the medium distribution for the 1D PCPCs periodic multilayer structure based on the IFT. The A and B are common media layers, and the P is plasma layer. The electromagnetic waves incident from the free space
\[ \frac{1}{\rho} \frac{\partial E_z}{\partial \phi} = -j \omega \mu H_\rho, \]  
\[ \frac{\partial E_Z}{\partial \rho} = j \omega \mu H_\phi, \]  
\[ \frac{\partial (\rho H_\phi)}{\partial \rho} - \frac{\partial H_\rho}{\partial \phi} = j \omega \epsilon \rho E_z. \]

From Eq. (4), the equation of \( E_z \) can be obtained by removing \( H_\phi \) and \( H_\rho \)

\[ \rho \frac{\partial}{\partial \rho} \left( \rho \frac{\partial E_z}{\partial \rho} \right) - \rho^2 \frac{1}{\mu} \frac{\partial}{\partial \rho} \frac{\partial E_z}{\partial \rho} + \frac{\partial}{\partial \phi} \left( \frac{\partial E_z}{\partial \phi} \right) + \omega^2 \mu \epsilon \rho^2 E_z = 0. \]

With Eq. (5), the following equation can be acquired by separating the variables

\[ E_z(\rho, \phi) = V(\rho, \phi) = \left[ AJ_m(k\rho) + BY_m(k\rho) \right] e^{j\mu \phi}. \]

where the \( A \) and \( B \) are two constants, \( Y_m \) is the Numann function, \( J_m \) is the Bessel function, \( m \) denotes the azimuthal mode number, and \( k = \omega(e\mu)^{1/2} \cos(\theta) \) is the wave number of the medium, respectively. With Eq. (4), the azimuth part of the magnetic field can be expressed as

\[ H_\phi(\rho, \phi) = U(\rho, \phi) = -j\rho \left[ AJ_m'(k\rho) + BY_m'(k\rho) \right] e^{j\mu \phi}. \]

where \( p = (e/\mu)^{1/2} \cos(\theta) \) is the intrinsic admittance of the medium. In the light of Eqs. (5) and (6) can deduce the single-layer matrix relationship relate to the electric and magnetic fields. For example, for the first matrix can establish the single-layer matrix relation relate to the electric and magnetic fields. The first matrix \( M_1 \) (with refractive index \( n_1 \) and interfaces at \( \rho = \rho_0 \) and \( \rho_1 \) can be written as

\[ \begin{bmatrix} V(\rho_1) \\ U(\rho_1) \end{bmatrix} = M_1 \begin{bmatrix} V(\rho_0) \\ U(\rho_0) \end{bmatrix}. \]

The first storey matrix \( M_1 \) can be expressed as

\[ M_1 = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}. \]

The elements of \( M_1 \) can be specifically expressed as (Chen et al. 2009; Chena et al. 2009)

\[ m_{11} = \frac{\pi}{2} k_1 \rho_0 \left[ Y_m'(k_1 \rho_0) J_m(k_1 \rho_1) - J_m'(k_1 \rho_0) Y_m(k_1 \rho_1) \right], \]
\[ m_{12} = j \frac{\pi}{2} k_1 \rho_0 \left[ J_m(k_1 \rho_0) Y_m(k_1 \rho_1) - Y_m(k_1 \rho_0) J_m(k_1 \rho_1) \right], \]
\[ m_{21} = -j \frac{\pi}{2} k_1 \rho_1 \left[ Y_m'(k_1 \rho_0) J_m(k_1 \rho_1) - J_m'(k_1 \rho_0) Y_m(k_1 \rho_1) \right], \]
\[ m_{22} = \frac{\pi}{2} k_1 \rho_0 \left[ J_m(k_1 \rho_0) Y_m'(k_1 \rho_1) - Y_m(k_1 \rho_0) J_m'(k_1 \rho_1) \right]. \]
where $p = (\varepsilon_1/\mu_1)^{1/2}\cos(\theta_1)$. It can be seen from the formula that the size of matrix elements is related to the radius of the two interfaces. For layer $i$, its transfer matrix $M_i$ can be replaced by

$$p_0 \rightarrow p_{i-1}, \quad p_1 \rightarrow p_i, \quad k_1 \rightarrow k_i = \omega\sqrt{\mu_1\varepsilon_1}\cos(\theta_1), \quad p_1 \rightarrow p_i = \sqrt{\varepsilon_i/\mu_i}\cos(\theta_i).$$

For the 1D PCPCs based on IFT structure with the period is $N$, the total matrices have $8N$. Thus, the total matrix $M$ can be expressed by

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = M_{8N} \cdots M_3 M_2 M_1.$$  

The transmission matrix of the 1D PCPCs with IFT structure is related to the half meridian. Therefore, its must be calculated one by one.

$$C_{m1}^{1,2} = H_{m1}^{1,2}(k_1 p_i) / H_{m1}^{1,2}(k_1 p_i), \quad l = 0, f.$$  

Among them $H_{m1}^1$ and $H_{m1}^2$ are the first Hankel function and the second kind of Hankel function, respectively. For the starting medium and the last medium $p = (\varepsilon_0/\mu_0)^{1/2}\cos(\theta_0)$ and $p = (\varepsilon_f/\mu_f)^{1/2}\cos(\theta_f)$. The results for the TM wave are also obtainable by simply replacing $\varepsilon \leftrightarrow \mu, \quad j \leftrightarrow -j$ and $p = \sqrt{\mu_i/\varepsilon_i}\cos(\theta_i)$ in the formulas of the TE wave.

The reflectivity $R$ and transmissivity $T$ are expressed as follows

$$R = rd \times rd^* = |rd|^2.$$  

$$T = td \times td^* = |td|^2.$$  

For the TE wave:

$$rd = \frac{(M'_{12} + j\rho_0 C_{m0}^2 M'_{11}) - j\rho_f C_{nf}^2 (M''_{22} + j\rho_0 C_{m0}^2 M''_{12})}{(-j\rho_0 C_{m0}^1 M'_1 - M'_2) - j\rho_f C_{nf}^2 (-j\rho_0 C_{m0}^1 M''_{12} - M''_{22})}.$$  

$$td = \frac{4\sqrt{\varepsilon_0/\mu_0}}{\pi K \rho_0 H_{m1}^2 (k_0 \rho_0) H_{m1}^1 (k_0 \rho_0) [(-j\rho_0 C_{m0}^1 M'_1 - M'_2) - j\rho_f C_{nf}^2 (-j\rho_0 C_{m0}^1 M''_{12} - M''_{22})]}.$$  

For the TM wave:

$$rd = \frac{(M'_{12} - j\rho_0 C_{m0}^2 M'_{11}) + j\rho_f C_{nf}^2 (M''_{22} - j\rho_0 C_{m0}^2 M''_{12})}{(j\rho_0 C_{m0}^1 M'_1 - M'_2) + j\rho_f C_{nf}^2 (j\rho_0 C_{m0}^1 M''_{12} - M''_{22})}.$$
\[
\begin{align*}
td &= \frac{4\sqrt{\mu_0/\varepsilon_0}}{\pi K_\rho_0 H^2_m (k_0\rho_0) H^1_m (k_0\rho_0) [(jp_0 C^1_{m0} M'_{11} - M'_{21}) + jp_f C^2_{m2} (jp_0 C^2_{m0} M'_{12} - M'_{22})]}.
\end{align*}
\]

where \( M'_{11}, M'_{12}, M'_{21}, M'_{22} \) are the matrix elements of the inverse matrix of \( M \), \( K = \omega(\varepsilon_0\mu_0)^{1/2} \) is used to indicate the free-space wave number.

### 3 Results and discussion

According to the above-mentioned parameters, and the period is 3, the values of \( L \) are 0, 1, 2, and 3 of the Fibonacci sequence reflection curves can be simulated as shown in Fig. 3. For the TE wave, the bandwidth of the PBG is more or less the same in the \( L \) are 0, 1 and 2, and whose bandwidths are 1.3673 \((2\pi c/d)\). But as the \( L \) increases, the rectangularity of the PBG will be better. When \( L=3 \), the PBG is destroyed, three narrowband modes are inspired in the PBG, making the architecture of the PBG becomes more complicated. For the TM wave, as the \( L \) changes, the transform of the PBG is similar to the TE wave. The difference is a narrowband mode is excited around 0.4 \((2\pi c/d)\) when \( L \) are 0, 1, and 2. Besides, the PBG bandwidth of the TM wave is small 0.0451 \((2\pi c/d)\) than the TE wave, so the bandwidth of the OBG will be determined by the TM wave. In order to understand better the characteristics of the PBG and OBG. Compared with \( L=1 \) and 2, the rectangularity of the PBG will be better at \( L=2 \), so choose \( L=2 \) for the discussion of the parameters. For the sake of increase the selectivity, the period is set to 5.

Figure 4 shows the reflection spectra of the TE and TM waves of the 1D PCPCs based on the IFT structure with the different \( m \). In Fig. 4a, the reflectivity of the TE wave will be decreased suddenly only when the frequencies are 1.1493 \((2\pi c/d)\) and 2.5467 \((2\pi c/d)\), the TE and TM waves almost overlap in other regions. It can be obtained that the two reflection spectra are almost the same, which certificates that the geometric difference of the cylinder curved interface has almost the same effect on the optical properties of the TE and TM waves when \( m=0 \). However, with the increase of \( m \), there is a significant difference between the TE and TM waves in the non-reflection region. When \( m=6 \), the TE and TM waves form a larger PBG in 0–2.5754 \((2\pi c/d)\), so the two polarized waves have a reunified pace. Surprisingly, when \( m=2 \), an extra ultra-high reflection band (blue area)
appears in the TM wave, and the bandwidth is \(0.1505 \, (2\pi c/d)\). In the case of \(m=4\), the extra high reflection band overlaps with the PBG of the front, so it disappears. Figure 4 strongly and forcefully illustrates that the bandwidth of PBG in the high-frequency region hardly alters with the changes of \(m\). On the contrary, the duration of the PBG in the low-frequency region is amplified and moved to the direction of high-frequency with the value of \(m\) is enlarged. As expected in Fig. 4, the bandwidth of the PBG in the high-frequency region is not affected by increasing \(m\) and the bandwidth is \(1.376 \, (2\pi c/d)\). But the bandwidth of PBG in the low-frequency region is enlarged when \(m\) is magnified. While \(m=6\), it connects with the PBG in the high-frequency region to form a larger PBG. So, the PBG will be broadened when \(m\) is amplified. In order to intuitively see what change of the PBG and OBG with \(m\) is transformed, Fig. 5 is plotted.

The relationship between PBG and \(m\) is given in Fig. 5a when \(\theta=60^\circ\), while Fig. 5b shows the relevance between OBG and \(m\). In Fig. 5a, when \(m\) turns from 0 to 20, the PBG bandwidths of both TE and TM waves are significantly broadened. So \(m\) has a strong ability to regulate the PBG of the TE and TM waves. Figure 4d proves that almost all TE and TM waves form PBGs below \(2.5396 \, (2\pi c/d)\) at \(m=6\). While \(m=13\), the TE and TM waves form a bigger PBG between 0 \((2\pi c/d)\) and 3 \((2\pi c/d)\). The changing trend of the TE and TM waves are roughly the same, as shown in Fig. 5. For the first OBG (brown area), with the value of \(m\) enlarged, the upper edge of the TM wave is moved slowly to the high-frequency direction. However, the lower edge is moved to the low-frequency direction, so the bandwidth of the first OBG is increased. For the second OBG (blue area), with the magnification of \(m\), the upper edge is rapidly moved to the high-frequency direction. In the case of \(m=10\), the first OBG overlaps with the second OBG to form a comparatively large OBG. At \(m=20\), the bandwidth of the OBG is enlarged to \(2.77 \, (2\pi c/d)\). Compared with 0.3
(2\pi c/d) (Ma et al. 2020) and 0.19 (2\pi c/d) (Zhao et al. 2017), the OBG has an advantage in bandwidth. In summary, a larger \( m \) can obtain a larger PBG, and increasing the value of \( m \) is beneficial to expand the bandwidths of the OBGs.

Figure 6 shows the reflection curves of the TE and TM waves when \( \theta \) are 0°, 30°, 60°, and 85°. As plotted in Fig. 6a, if \( \theta = 0^\circ \) (normal incidence), the frequency range of PBG

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**Fig. 5** Testimony of the relationship between \( R \) and \( m \) when \( \theta = 60^\circ \). \( \textbf{a} \) The top view of \( R \) with the different \( m \), and \( \textbf{b} \) the diagram of the OBG at different \( m \)

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**Fig. 6** The reflection curves of the TM and TE waves for 1D PCPCs based on the IFT structure with the different \( \theta \) when \( m = 2 \). \( \textbf{a} \) \( \theta = 0^\circ \), \( \textbf{b} \) \( \theta = 30^\circ \), \( \textbf{c} \) \( \theta = 60^\circ \), and \( \textbf{d} \) \( \theta = 85^\circ \)
in the high frequency area is 0.9701–1.4288 \((2\pi c/d)\) and the bandwidth is 0.4587 \((2\pi c/d)\). The bandwidth of PBG in the low-frequency range is 0.1245 \((2\pi c/d)\), and the frequency range is 0–0.1245 \((2\pi c/d)\). At \(\theta=60^\circ\) (see Fig. 6c), the frequency range of PBG in the high-frequency region is 1.1923–2.5398 \((2\pi c/d)\), and the bandwidth is 1.3473 \((2\pi c/d)\). The PBG in the low-frequency region is 0–0.1603 \((2\pi c/d)\) and the bandwidth is 0.1603 \((2\pi c/d)\). Available from the above data, when \(\theta\) is enlarged from 0° to 60°, the bandwidth of high-frequency region PBG is amplified 0.8886 \((2\pi c/d)\), the starting point of the PBG is moved to high-frequency direction 0.2222 \((2\pi c/d)\) and the bandwidth of low-frequency region PBG is magnified 0.0358 \((2\pi c/d)\). It can be concluded that the bandwidth of the PBG increases with the enlarging of \(\theta\) and moves to the high-frequency direction. From Fig. 6, we can see that the TM wave produces an extra high reflection band (the blue areas) in the low-frequency region. As mentioned in Fig. 6b, the starting frequency of the PBG is 0.2248 \((2\pi c/d)\) and width is 0.072 \((2\pi c/d)\) when \(\theta=30^\circ\). In Fig. 6d, at \(\theta=85^\circ\), 0.9558 \((2\pi c/d)\) is the starting position and the bandwidth of the PBG is 0.2652 \((2\pi c/d)\). Therefore, a larger \(\theta\) can get a larger PBG and the location is moved to the high-frequency region with \(\theta\) is amplified.

The OBG of the 1D PCPCs based on the IFT structure is shown in Fig. 7, which is the region between the white lines. In Fig. 7, the OBG frequency ranges of the TE and TM waves are 0–0.1625 \((2\pi c/d)\) and 1.1900–1.4690 \((2\pi c/d)\), and their bandwidths are 0.1625 \((2\pi c/d)\) and 0.2790 \((2\pi c/d)\). Besides, the OBGs of both polarized waves shift to the higher frequency area when \(\theta\) is increased.

Figure 8 provides the relationship between the reflection spectra of 1D PCPCs based on the IFT structure with the different \(d_p\) when \(\theta=60^\circ\). As \(d_p\) accumulates from 0.01d to 0.35d, the frequency range of the main PBG is shifted from 1.7923–3.1300 \((2\pi c/d)\) to 0.9312–1.9846 \((2\pi c/d)\), the bandwidth is abated from 1.3377 \((2\pi c/d)\) to 1.0534 \((2\pi c/d)\). Therefore, with the accumulation of \(d_p\), the frequency of the main PBG is reduced and the bandwidth is decreased. As shown in Fig. 8, the new PBGs are excited by enlarging \(d_p\). So, the number of PBG can be controlled by changing \(d_p\). In Fig. 8b, the main PBG is fused with the PBG in front cause the main PBG is increased temporarily. In the low-frequency region of the TM wave, an additional high reflection band (the blue areas) is produced, which is confirmed by Fig. 8. The width increases from 0.0418 \((2\pi c/d)\) to 0.125 \((2\pi c/d)\).
because of the enlargement of $d_p$. Thus, it can be concluded that with $d_p$ amplifies, the ultrahigh reflection band is magnified slowly.

To clearly observe the OBG phenomena of the TM and TE waves, the reflectivity spectrograms of two polarized waves with the different $d_p$ are given in Fig. 9. Figure 9a shows that $d_p$ has a strong adjustment ability on the PBGs of the TE and TM waves when $\theta=60^\circ$,
but has no contribution to the PBG broadening. It only acts on the selection of the PBG excitation frequency. In Fig. 9, the PBG bandwidths of the TE and TM waves increase slowly with the $d_p$ aggrandized, the maximum value appears in near 0.1$d$, and then they are decreased with the increase of $d_p$. In Fig. 9b, there are two OBGs of the TE and TM waves in the frequency range of 0–3 ($2\pi c/d$). The first OBG (the blue area) have the same transform trend as the PBG. In the case of $d_p = 0.45d$, the first OBG is diminished to 0 ($2\pi c/d$). For the second OBG (the brown area), when $d_p$ is in the range of 0.01d–0.05d, the TE wave bandwidth is close to 0.1 ($2\pi c/d$), while the remaining bandwidth is around 0.2 ($2\pi c/d$). The second OBG bandwidth of the TM wave is almost unchanged, and it is around 0.2 ($2\pi c/d$). In summary, increasing the $d_p$ has little effect on the expansion of the OBG, while the PBG and OBG can be moved to the low-frequency region by magnifying $d_p$. This feature can be used to reduce the operating frequency of the device.

When $\theta = 60^\circ$, the relationship between $R$ and different $\omega_p$ is revealed in Fig. 10. Figure 10 demonstrates that the bandwidth of the PBG in the high-frequency region of the TE or TM wave is hardly altered with the $\omega_p$ enlarged. At $\omega_p = 0.01$ ($2\pi c/d$), the bandwidth of PBG in the high-frequency region is 1.3616 ($2\pi c/d$), and the width of PBG in the high-frequency region is 1.3902 ($2\pi c/d$) when $\omega_p = 0.35$ ($2\pi c/d$). So $\omega_p$ changes from 0.01d to 0.35d, the bandwidth of PBG in the high-frequency region only changes 0.0286 ($2\pi c/d$). However, in the low-frequency region, the relationship between the PBG and $\omega_p$ have opposite characteristics. The PBG bandwidth is 0.1102 ($2\pi c/d$) at $\omega_p = 0.15$ ($2\pi c/d$). When $\omega_p = 0.35$ ($2\pi c/d$), the width is 0.2607 ($2\pi c/d$), so the bandwidth is widened 0.1505 ($2\pi c/d$). In addition, an added high reflection band (the blue areas) is found in the TM wave.

![Fig. 10](image-url)
wave. Figure 11a certifies this point more strongly. With $\omega_p$ altered, the bandwidth of the high reflection band is barely changed. Its starting point is shifted to the high-frequency direction because of the $\omega_p$ increased. The starting position is 0.2965 ($2\pi c/d$) in the case of $\omega_p = 0.15$ ($2\pi c/d$). While $\omega_p = 0.35$ ($2\pi c/d$), the starting position is 0.6763 ($2\pi c/d$). The $\omega_p$ from 0.15 ($2\pi c/d$) to 0.35 ($2\pi c/d$), the starting position of the PBG is shifted 0.3798 ($2\pi c/d$). For the sake of better understanding, the relationships between the PBG and $\omega_p$ Fig. 11 are given, Fig. 11 also proves the relationship between the OBG and $\omega_p$. As expected in Fig. 11a, the change of $\omega_p$ does not affect the PBG in the high-frequency region, on the contrary, the PBG in the low-frequency region is increased with the increase of $\omega_p$. The conclusion that change of $\omega_p$ is no effect for the bandwidth of the first OBG (the blue area), but the second OBG (the brown area) is enlarged with the $\omega_p$ amplification is proved by Fig. 11. To sum up, it can be concluded that it is effective for widening OBG as the $\omega_p$ is increased, while the frequency range should be controlled well, that only works in the region below 0.5 ($2\pi c/d$).

4 Conclusion

In this paper, bring forward a model of 1D PCPCs with IFT structure and its optical properties is researched. Because the QPS breaks the spatial symmetry of the conventional PCs, it brings more interesting phenomena. In this article, the influences of $m$, $\theta$, $d_p$, and $\omega_p$ on the optical properties of the 1D PCPCs are discussed. From the above discussion, it comes to these conclusions that $m$ has a strong ability to adjust the OBG, and a larger OBG will be acquired by a larger $m$. The $\theta$ has a similar ability in the regulation of the PBG with $m$, and the bandwidth of the PBG is increased as the $\theta$ amplifies. And when $\theta = 85^\circ$ the TM wave obtains an ultra-wide PBG. Contrary to $m$, $d_p$ has an inverse relationship with the OBG. With the $d_p$ is magnified, the OBG will be decreased. Fortunately, the $d_p$ can control the frequency range of the OBG. While $\omega_p$ has the inability to regulate the bandwidth of the OBG. So from the theoretics, increasing $m$ and appropriately reduce $d_p$ can obtain a lower frequency and bandwidth OBG. In addition, there is an unexpected discovery, when $m = 2$, 

Fig. 11 Confirming the truth of the relationship between $\omega_p$ and $R$ when $\theta = 60^\circ$ and $m = 2$. a The top view of $R$ diagram under different $\omega_p$, b the diagram of the OBG at different $\omega_p$.
the TM wave will produce an extra high reflection band. The special performances make the architecture can be used to devise the narrowband transmission filter without inserting any physical defect layer in the construction. These interesting results will contribute to the design of the multifunctional devices integrated with OBG in theory and practical applications.

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