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# PROPERTIES OF OMNIDIRECTIONAL PHOTONIC BAND GAPS IN FIBONACCI QUASI-PERIODIC ONE-DIMENSIONAL SUPERCONDUCTOR PHOTONIC CRYSTALS

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**Abstract**—In this paper, the properties of the omnidirectional photonic band gap (OBG) realized by one-dimensional (1D) Fibonacci quasi-periodic structure which is composed of superconductor and isotropic dielectric have been theoretically investigated by the transfer matrix method (TMM). From the numerical results, it has been shown that this OBG is insensitive to the incident angle and the polarization of electromagnetic wave (EM wave), and the frequency range and central frequency of OBG cease to change with increasing Fibonacci order, but vary with the ambient temperature of system, the thickness of the superconductor, and dielectric layer, respectively. The bandwidth of OBG can be notably enlarged with increasing the superconductor thickness. Moreover, the frequency range of OBG can be narrowed with increasing the thickness of dielectric layer and ambient temperature. The damping coefficient of superconductor layers has no effect on the frequency range of OBG under low-temperature conditions. It is shown that Fibonacci quasi-periodic 1D superconductor dielectric photonic crystals (SDPCs) have a superior feature in the enhancement frequency range of OBG. This kind of OBG has potential applications in filters, microcavities, and fibers, etc.

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## 1. INTRODUCTION

In the past few years, the propagation of electromagnetic waves (EM waves) in periodic dielectric structures in one, two, three spatial directions has received much attention on the experimental and theoretical investigations since pioneering works of Yablonovitch [1] and John [2]. This kind of periodic dielectric structures is called photonic crystals (PCs), and can generate spectral regions named photonic band gaps (PBGs), which is similar to the electronic band gaps in a semiconductor. The propagation of EM waves with frequency located in the PBG is strongly forbidden in PCs. The earlier studies have been demonstrated [3–5] that a PBG can be formed as a result of the interference of multiple Bragg scattering in a periodic dielectric structure. If EM wave incident at any angle with any polarization cannot propagate in PCs, the total OBG can be achieved. The larger OBGs have been widely used in various modern applications, such as omnidirectional high reflector [6], all-dielectric coaxial waveguide [7], and omnidirectional mirror fiber [8]. The multilayer periodic structure has been always applied in enhancement the OBGs as described in most works [9–11] but the researchers pay more attention on the disordered dielectric structures in recently. Within the intermediate regime between complete order and disorder, quasi-periodic structures following a deterministic sequence also display characteristic spectral properties not present in either of these extreme cases. The most common quasi-periodic structure is Fibonacci sequence [12–15]. Fibonacci sequence multilayer present a discrete Fourier spectrum characterized by self-similar Bragg peak. The Fibonacci sequence also has been extended to the investigation of the total OBGs of 1D PCs [16, 17]. Some researchers have attempted to introduce negative-index materials to 1D PCs with a Fibonacci sequence basis [18–20], the OBG can be obtained. Such OBG also be called the zero-$\widetilde{n}$ gap or single negative gap, but is insensitive to lattice parameter changed in contrast with the behavior exhibited by Bragg gap. Therefore, the dispersive or dissipative medium is used to form tunable PCs, such as semiconductor [21], metal [22], plasma [23] and superconductor [24].

To date, the investigations of SDPCs have attracted the attention of many researchers. If the superconductor is introduced in the PCs, the frequency ranges of PBGs can be in the infrared/optical frequencies (terahertz region) [25–27]. Lee et al. [28] studied the transmission characteristics at visible light range in 1D SDPCs have been analyzed based on the finite element method using COMSOL RF module. They found that the cutoff frequency or PBGs can be manipulated through the thicknesses of the superconductor and dielectric layers as well as the ambient temperature of system. Aly et al. [29] have theoretically investigated that the properties of transmission at terahertz region in a 1D superconducting metallo-dielectric superlattice have been analyzed based on TMM using two-fluid model. They found there is a cutoff frequency in such a bilayer periodic structure, and the cutoff frequency is strongly dependent on thicknesses of the superconductor and dielectric layers, and the temperature as well. In temperature-dependent transmittance, strong oscillations can be seen at higher temperature. Wu and Gao [30] have theoretically calculated the transmittance of Fibonacci quasi-periodic 1D PCs containing superconducting material by TMM. They found that the shift of cutoff frequency becomes more noticeable by adjusting the thickness of superconductor layer than that of the dielectric one, and the cutoff frequency is very sensitive as the ambient temperature of system is close to vicinity of the critical temperature of superconductor. Lin et al. [31] used the 1D SDPCs to form the multichanneled transmission filter in the presence of evanescent wave. Li et al. [32] have systematically investigated the properties of PBGs for 1D SDPCs by TMM. They found that the width of PBGs is more sensitive to the thicknesses of superconductor layers, and damp coefficient does not affect the PBG under low-temperature conditions.

All the works mentioned above focused on the PBG characteristics of 1D SDPCs composed of alternating superconductor and dielectric material until Dai et al. [33] used the superconductor to design the omnidirectional reflector. There are few works which are concentrated on the enhancement of OBGs in 1D SDPCs with quasi-periodic structures. In this paper, the OBG in 1D SDPCs with a Fibonacci basis is investigated by TMM, and it is found that such OBG is insensitive to the incident angle and the polarization of EM wave. The reflectance is used to analyze the effects the thickness of superconductor layer, the thickness of dielectric, the ambient temperature of system and the damping coefficient of superconductor layers on the properties of OBG, respectively. The results show that the frequency ranges and central frequencies of OBG cease to change with increasing Fibonacci order, but vary with the thickness of superconductor layer, the thickness of dielectric layer, and the ambient temperature of system, respectively. In contrast to the conventional dielectric PCs, the frequency range of OBG is notably enlarged. This paper is organized as follows: A physical model and transfer matrix formulas for both the TE wave case and TM wave case are introduced in Section 2. In Section 3, the enhancement of OBG frequency range in Fibonacci quasi-periodic structure 1D SDPCs is studied. Then, the dependences of OBG frequency range on the ambient temperature of system, the damping coefficient of superconductor layer, the thickness of the superconductor, and dielectric layer are investigated, respectively. Finally, conclusions are given in Section 4.

## 2. THEORETICAL MODEL AND NUMERICAL METHOD

Schematic view of oblique indent EM wave in Fibonacci quasi-periodic structure 1D SDPCs composed of dielectric layers and superconductor layers is plotted in Fig. 1. We consider 1D periodic layered structure in each cell following the Fibonacci sequence. The Fibonacci sequence can be generated by the rule $S_{n+1} = S_{n-1}S_n$ for level $n \geq 1$, with the first two chains as $S_0 = \{A\}$ and $S_1 = \{S\}$. In this paper, layers $A$ and $S$ represent dielectric with thickness of $d_A$, and superconductor with thickness of $d_P$, respectively. For the $n$th generation of the considered Fibonacci sequence, the sequence can be expressed as $F_n = (S_n)^N$, in which $N$ is the number of periods. As an example, the fourth sequence of $F_4$ is $F_4 = \{ASSAS\}$ as depicted in Fig. 1. Here, we use $\varepsilon_a$ and $\varepsilon_s$ to describe the relative permittivity for dielectric A and superconductor, respectively. As we known the superconductor is a kind of frequency dependence dielectric. In order to define the properties of superconductor, the Gorter-Casimir two-fluid model [29–31] is adopted to describe the electromagnetic response of the superconductor layer with the absence of external magnetic field. The effective relative dielectric function of the superconductor is

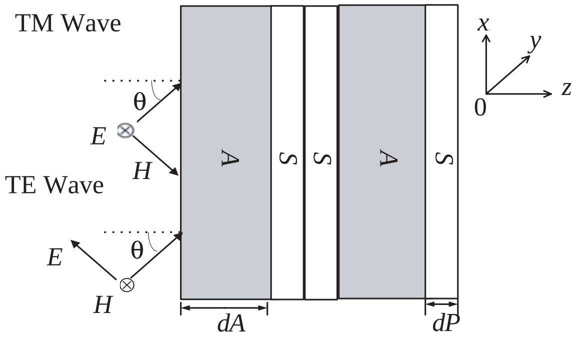



**Figure 1.** Schematic diagram of 4th order Fibonacci quasi-periodic 1D SDPCs consisting of dielectric ($A$) and superconductor ($S$) under any incidence angle ($\theta$) for TE and TM waves.

represented as follows [32]:

$$\varepsilon_{\mathrm{S}}(\omega) = \varepsilon_c \left[1 - \frac{\omega_{sp}^2}{\omega^2} - \frac{\omega_{np}^2}{\omega(\omega + j\gamma)}\right] \tag{1}$$

with

$$\omega_{sp} = \sqrt{\frac{n_s e^2}{m\varepsilon_0\varepsilon_c}}, \quad \omega_{np} = \sqrt{\frac{n_n e^2}{m\varepsilon_0\varepsilon_c}}, \tag{2}$$

where $\varepsilon_c$ is the dielectric constant of the crystal, $\omega_{np}$ and $\omega_{sp}$ are the plasma frequencies of the normal conducting electrons and the superconducting electrons, respectively. $\gamma$ is the damping term of normal conducting electrons. $n_s$ and $n_n$ are densities of superconducting electrons and normal conducting electrons, respectively. $e$ and $m$ are the charge and mass of the electron. We can rewrite Eq. (2) in the form by using the Gorter-Casimir result [32]:

$$\omega_{sp} = \frac{c}{\lambda_0\sqrt{\varepsilon_c}}\sqrt{\left(1 - \left(\frac{T}{T_c}\right)^4\right)}, \quad \omega_{np} = \frac{c}{\lambda_0\sqrt{\varepsilon_c}}\left(\frac{T}{T_c}\right)^2 \tag{3}$$

where $\lambda_0$ is the London penetration length at temperature $T = 0$, and $T_c$ is the critical temperature of a superconductor. $\omega$ is electromagnetic wave frequency, and $c$ is the light speed in vacuum. Substituting Eq. (3) into Eq. (1), the temperature dependent dielectric function of the superconductor can be expressed as

$$\varepsilon_s(\omega) = \varepsilon_c - \frac{c^2}{\omega^2\lambda_0^2}\left[1 - \left(\frac{T_c}{T}\right)^4\right] - \frac{c^2}{\omega(\omega + j\gamma)\lambda_0^2}\left(\frac{T_c}{T}\right)^4 \tag{4}$$

If the damping term $\gamma$ is very small, the third term on the right-hand side of Eq. (4) cannot be neglected [32].

The EM wave is incident from the vacuum to the $n$th order Fibonacci multilayer with incident angle $\theta$. For the transverse electric (TE) wave, the electric field $\mathbf{E}$ is polarized along the $y$ direction. Suppose wave vectors $\mathbf{K}(\omega)$ lie in $xz$ plane. In order to calculate the reflectance for a Fibonacci multilayered structure, the TMM is used [31]. According to this method, we can set up the characteristic corresponding to the electric and magnetic fields at any two positions in the adjacent layer which is given as

$$M_k = \begin{pmatrix} \cos\beta_l & \frac{j}{p_l}\sin\beta_l \\ jp_l\sin\beta_l & \cos\beta_l \end{pmatrix} \tag{5}$$

where $\beta_l = k_0 n_l d_l \cos\theta_l$ and $p_l = \frac{n_l}{Z_0}\cos\theta_l$ (TE wave), $p_l = \frac{1}{Z_0 n_l}\cos\theta_l$ (TM wave) with $l = A, S$ and impedance of vacuum $Z_0 = \sqrt{\mu_0}/\sqrt{\varepsilon_0}$.

Here $d_l$ is the thickness of periodic length of the $d_A$, $d_B$ and $d_P$ with refractive indices $n_A$, $n_B$ and $n_s$, respectively. Thus, the transfer matrices $\mathbf{M}_j$ are $\mathbf{M}_2 = \mathbf{M}_A\mathbf{M}_S$, $\mathbf{M}_3 = \mathbf{M}_S\mathbf{M}_A\mathbf{M}_S$, and $\mathbf{M}_4 = \mathbf{M}_A\mathbf{M}_S\mathbf{M}_S\mathbf{M}_A\mathbf{M}_S$ for $S_2$, $S_3$, and $S_4$, respectively. If the order of the Fibonacci sequence is $N$, the total transfer matrix of the $N$th order Fibonacci sequence $\mathbf{M}_N$ can be deduced from the following recursion relations:

$$\mathbf{M}_N = \mathbf{M}_{N-2}\mathbf{M}_{N-1} \quad (N \geq 2) \tag{6}$$

So, the total translation matrix $\mathbf{M}$ is obtained to be

$$\mathbf{M} = \prod_{k=1}^{N} \mathbf{M}_k = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \tag{7}$$

The reflection coefficients of the considered structure are given by

$$r = \frac{(M_{11} + M_{12}p_s)p_0 - (M_{21} + M_{22}p_s)}{(M_{11} + M_{12}p_s)p_0 + (M_{21} + M_{22}p_s)} \tag{8}$$

Here $p_0$ and $p_s$ are the first and last mediums of the structure, which given as $p_0 = n_0 \cos\theta_0/\mathrm{Z}_0$, $p_s = n_s \cos\theta_s/\mathrm{Z}_0$ (TE wave) and $p_0 = \cos\theta_0/(n_0\mathrm{Z}_0)$, $p_s = \cos\theta_s/n_s\mathrm{Z}_0$ (TM wave). In our case we have taken $n_0 = n_s = 1$ for the vacuum. The reflectance is related by

$$R = |r|^2 \tag{9}$$

## 3. RESULTS AND DISCUSSIONS

In this section, we investigate the properties of OBG for Fibonacci quasi-periodic 1D SDPCs in the terahertz region, and subsequently study how the OBG frequency range relation of Fibonacci quasi-periodic 1D SDPCs vary with thickness of superconductor, dielectric, the ambient temperature of system and the damping coefficient of superconductor layer, respectively. We choose the structure parameters as follows: $\varepsilon_A = 4$, $\mu_A = 1$, $d_A = 400\,\mathrm{nm}$, respectively. The superconductor layer is taken to be $T_c = 9.2\,\mathrm{K}$, $\lambda_0 = 83.4\,\mathrm{nm}$, and $\gamma = 1 \times 10^5\,\mathrm{Hz}$, respectively [32]. Assumed the thickness of superconductor layer $d_P = 30\,\mathrm{nm}$, the ambient temperature of system $T = 4.2\,\mathrm{K}$, and $\varepsilon_c = 1$, respectively. The Fibonacci order is 10. Here, we only focus in the band gap in the frequency domain 0–250 THz.

### 3.1. Introduced the Superconductor Layer to Enhance the OBG with Fibonacci sequence

Firstly, we discuss the OBG of 1D dielectric PCs consisting of alternate dielectric $A$ and air. Assumed the thickness of air layer is 30 nm. We plot the influence of the PBG on the frequency and incident angle for TM polarization in the Fig. 2(a). The red areas correspond to the Bragg gaps or high-reflectance ranges (reflectance greater 0.99). It can be seen from Fig. 2(a) that there do not exist OBG obviously for 1D dielectric PCs, and the Bragg gap of TM polarization is closed at an incident angle between 54° and 74° due to Brewster's angle [34]. In order to avoid the Brewster's window, we replace the air layers with superconductor layers, and are arranged with a Fibonacci basis to form a new quasi-periodic structure SDPCs. For comparison, we also plot the dependence of the PBG on the frequency and incident angle for TM polarization of the 1D SDPCs in the Fig. 2(b). As shown in Fig. 2(b), there is a Bragg gap obviously of TM polarization, and the Bragg gap is opened at an incident angle between 54° and 74°. The dependence of photonic band structure of Fibonacci quasi-periodic 1D SDPCs on the incident angle and angular frequency for both polarizations is plotted in Fig. 3(a). The area between two white lines is the total OBG. Reflectance spectra of Fibonacci quasi-periodic 1D SDPCs at various incident angles is also plotted in Fig. 3(b). The gray areas correspond to PBGs. We can see clearly from Fig. 3 that there exists OBG obviously. The frequency range of OBG runs from 191 to 223.5 THz, and the frequency width is 32.5 THz. From Fig. 3(a), we can clearly see that the OBG is insensitive to the incident angle for TM polarization but is sensitive for TE polarization. The upper edges of the OBG shift upward to higher frequencies with increasing incident angle for both polarizations. It also can be seen that the lower

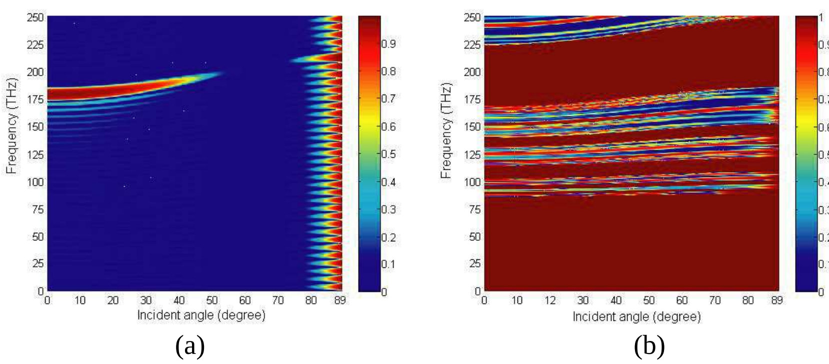
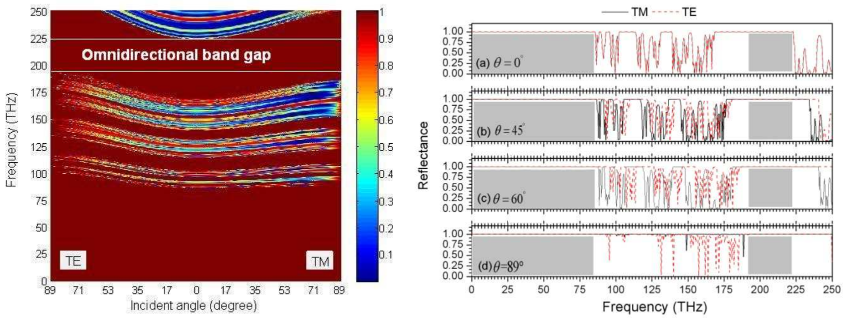



**Figure 2.** Photonic band structure of (a) 1D binary dielectric PCs, and (b) 1D Fibonacci quasi-periodic SDPCS in terms of angular frequency and incidence angle for TM polarization. The background corresponds to Bragg gaps or high-reflectance ranges.




(a) (b)

**Figure 3.** (a) Photonic band structure of 1D Fibonacci quasi-periodic SDPCS in terms of angular frequency and incidence angle. The areas between two white lines are the total OBG, and (b) reflectance spectra of 1D Fibonacci quasi-periodic SDPCS at various incident angles is calculated by TMM. The black solid (red dash dot) curves are for TM (TE) polarization, and the gray areas correspond to the PBGs.

edges of the OBG is insensitive to the increase of the incident angle for both polarizations. As shown in Fig. 3(a), there is an OBG for TE polarization in the display frequency range from 191 to 223.5 THz, and frequency width is 32.5 THz. For TM polarization, frequency region of the OBG runs from 185.5 to 223.5 THz, and bandwidth is 38 THz. Thus, we can know that the TE omnidirectional gap determines the bandwidths of the OBG. This property is obviously different from that of the OBG in Fibonacci structure containing single negative materials, in which the lower or upper band edges of the single negative gap are insensitive to incident angle for both polarizations. The main reason for the different results is because their mechanisms of band formation are different. The band formation originates from EM wave scattering of propagating modes in Fibonacci quasi-periodic 1D SDPCs; while for Fibonacci structures with single negative materials, it comes from tunneling of evanescent modes [20].

### 3.2. Effects of Fibonacci Order on OBG

Secondly, we analyze the dependence of the PBG on the frequency and Fibonacci order ($N \geq 4$) for normal incidence. In Fig. 4, we plot the normal incidence reflection spectra for the different Fibonacci orders as a function of the frequency with $S_5$ (Fig. 4(a)), $S_6$ (Fig. 4(b)), $S_7$ (Fig. 4(c)), and $S_8$ (Fig. 4(d)). It can see from the Fig. 4 that,

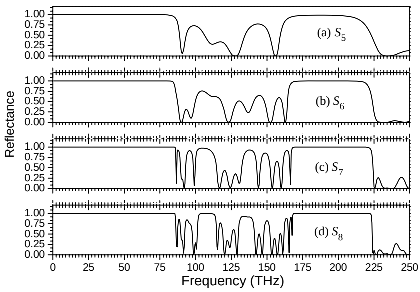



**Figure 4.** Normal incident reflection spectra for the different Fibonacci orders as a function of the frequency with (a) $S_5$, (b) $S_6$, (c) $S_7$, and (d) $S_8$.

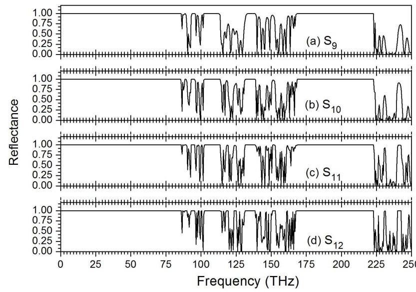



**Figure 5.** Normal incident reflection spectra for the different Fibonacci orders as a function of the frequency with (a) $S_9$, (b) $S_{10}$, (c) $S_{11}$, and (d) $S_{12}$.

with increasing order of Fibonacci sequence, the central frequency of the Bragg gap (195.72 THz) remain invariant, and the edges of the reflectance become much shaper. We also can see from Fig. 4 that, when increasing the Fibonacci order $N$ from 5 to 8, the upper edges of the Bragg gap shift up to higher frequencies, while the lower edges of the Bragg gap shift down to lower frequencies, and the frequency range of Bragg gap becomes larger. If we continue to increase the Fibonacci order, the influence of the PBG on the frequency and Fibonacci order for normal incidence is plotted in Fig. 5. In Fig. 5, the reflection spectra for normal incidence is shown in the cases of Fibonacci structures where $S_9$ (Fig. 5(a)), $S_{10}$ (Fig. 5(b)), $S_{11}$ (Fig. 5 (c)), and $S_{12}$ (Fig. 5 (d)). It is demonstrated that, if increasing the Fibonacci order $N$ from 9 to 12, the upper and lower edges of the Bragg gap remain constants, the frequency region of the Bragg gap which we focus on spans from 168.03 to 223.03 THz, and the frequency width is 55 THz. Therefore, the frequency range and central frequency of the OBG cease to change with increasing Fibonacci order.

### 3.3. Effects of the Thickness of Superconductor Layer on OBG

Next, we discuss the influence of the thickness of superconductor layer on the OBG of Fibonacci quasi-periodic 1D SDPCs. We plot the reflectance of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of the thickness of superconductor layer at normal incidence in Fig. 6. The red regions denote the high-reflectance ranges. It can be seen from Fig. 6 that the edges of the Bragg gap

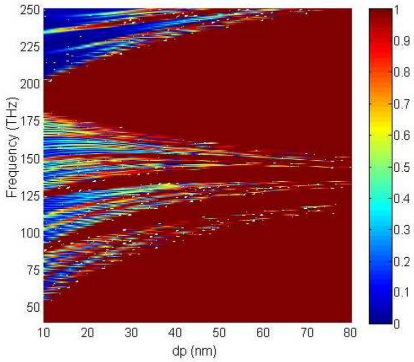



**Figure 6.** Reflection coefficients of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of the superconductor thickness at normal incidence.

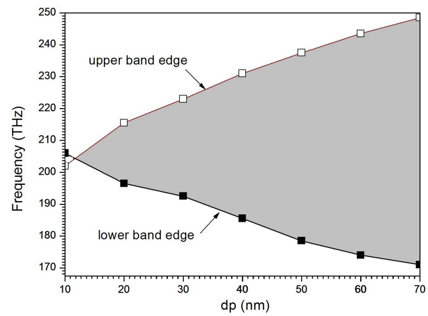



**Figure 7.** The frequency range of the OBG for Fibonacci quasi-periodic 1D SDPCs as a function of the superconductor thickness. The gray area is OBG.

are sensitive to increasing the thickness of superconductor layer, and the frequency shift of the edges is every obvious. The upper edge of the Bragg gap shifts upward to higher frequencies but the lower edge is downward to lower frequencies with increasing the superconductor thickness. Thus, the bandwidth and central frequency of the Bragg gap can be modulated by increasing the thickness of superconductor layer. To take a close look at the dependence of the OBG on the thickness of superconductor layer, we also plot the frequency range of the OBG for Fibonacci quasi-periodic 1D SDPCs as a function of the superconductor thickness in Fig. 7. The gray area is OBG. Form Fig. 7, one can see that the upper edge of the OBG is upward to higher frequencies and the lower edge is downward to lower frequencies with the increasing the thickness of superconductor. The bandwidth of the OBG is broadened, and central frequency of the OBG is increased with increase of the superconductor thickness. As shown in Fig. 7, the frequency range of the OBG runs from 170.87 to 248.33 THz, and the frequency width is 77.46 THz. If the thickness of superconductor layers is less than 11.71 nm, the OBG does not exist. As thickness of superconductor layers is creased from $d_P$ =11.71 nm to $d_P$ =70 nm, here is a increasing of 77.46 THz in bandwidth of the OBG as compared to $d_P$ =11.71 nm. From the aforementioned discussions, the frequency range of the OBG is obviously enlarged with increasing the thickness of superconductor layer. Consequently, the bandwidth of OBG is enlarged.

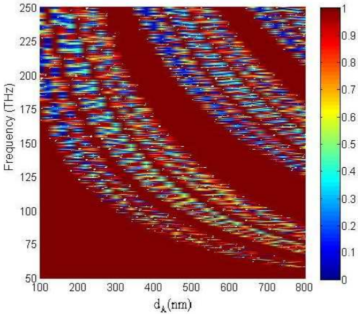



**Figure 8.** Reflection coefficients of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of the thickness of dielectric layer at normal incidence.

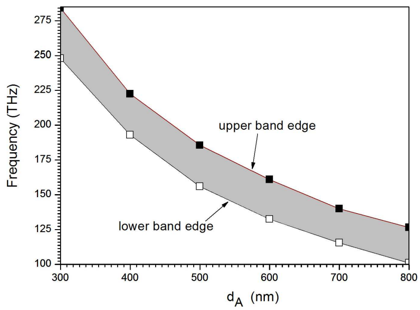



**Figure 9.** The frequency range of OBGs for Fibonacci quasi-periodic 1D SDPCs as a function of thickness of dielectric layer. The gray area is OBG.

### 3.4. Effects of the Thickness of Dielectric Layer on OBG

In order to investigate the effect of the thickness of dielectric layer on the OBG of Fibonacci quasi-periodic 1D SDPCs, the reflectance of 1D SDPCs versus frequency as a function of the thickness of dielectric layer at normal incidence is plotted in Fig. 8. As shown in Fig. 8, the number of PBGs is sensitive to increasing the thickness of dielectric layer and the more PBGs appear. The edges of the PBGs shift downward to lower frequencies and the frequency ranges of PBGs are changed obviously. The central frequencies of the PBGs also are downward to lower frequencies regions. Thus, we can draw a conclusion that the bandwidths and central frequencies of the PBGs can be modulated, and the number of the PBGs is increased, with increasing the thickness of dielectric layers. To show the dependence of the OBG on the thickness of dielectric layer, Fig. 9 is demonstrated that frequency range of the OBG for Fibonacci quasi-periodic 1D SDPCs as a function of the thickness of dielectric layer. From Fig. 9, we can see that the edges and central frequencies of the OBGs shift downward to lower frequencies, and the frequency range of the OBG are narrowed with increasing the thickness of dielectric layer. The frequency range of the OBG runs from 101.78 to 126.73 THz, and the bandwidth is 24.95 THz, when the thickness of dielectric layer is creased from $d_A = 300\,\text{nm}$ to $d_A = 800\,\text{nm}$. Here is a decreasing of 10.05 THz in bandwidth of the OBG as compared to $d_A = 300\,\text{nm}$. As mentioned above, the frequency range of the OBG is obviously narrowed, central frequency of the OBG is decreased and the number of PBGs is increased with increasing the thickness of dielectric layer. Consequently, the bandwidths of OBGs and the number of PBGs can be modulated by the thickness of the dielectric layer.

### 3.5. Effects of the Ambient Temperature on OBG

In order to study the effect of the ambient temperature on the OBG of Fibonacci quasi-periodic 1D SDPCs, the reflectance of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of the ambient temperature at normal incidence is shown in Fig. 10. As shown in Fig. 10, it is clearly that bandwidths of PBGs are slightly reduced, when the ambient temperature is less than 5 K. If the ambient temperature is larger than 5 K, the frequency shifts of the edges and central frequencies of the PBGs are downward to lower frequencies, and the frequency ranges of PBGs become smaller obviously. Therefore, we can get a conclusion that the bandwidths of PBGs can be enlarged by decreasing ambient temperature. To take a close look at the dependence of the OBG on the ambient temperature, we also plot the frequency range of OBG for Fibonacci quasi-periodic 1D SDPCs as a function of the ambient temperature in Fig. 11. We can see from Fig. 11 that the edges of the OBG are unchanged first then shift to the lower frequencies, but the frequency shift of lower edge of the OBG is small as compared to the upper edge. As shown in Fig. 11, the frequency range of the OBG runs from 187.98 to 191.09 THz, and the frequency range is 3.11 THz, as the ambient temperature is creased from $T = 1$ K to $T = 9$ K. Here is a decreasing of 27.90 THz in frequency range of the OBG as compared to $T$=1K. As mentioned above, the frequency ranges of the OBG can be enlarged by decreasing the ambient temperature. Consequently, Fibonacci quasi-periodic 1D

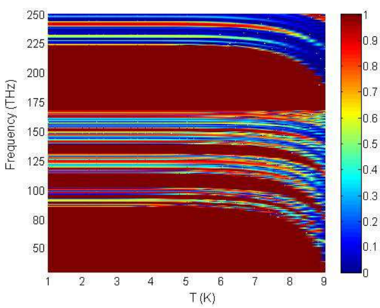



**Figure 10.** Reflection coefficients of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of the ambient temperature.

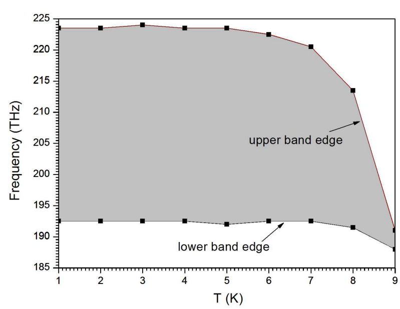



**Figure 11.** The frequency range of OBGs for Fibonacci quasi-periodic 1D SDPCs as a function of the ambient temperature. The gray area is OBG.

SDPCs has potential applications in tunable filters or microcavities, which are controlled by the ambient temperature.

### 3.6. Effects of the Damp Coefficient of Superconductor Layer on OBG

Finally, we investigate the effect of the damp coefficient of superconductor layers on the OBGs of Fibonacci quasi-periodic 1D SDPCs. If temperature of superconductor is larger than 4.55 K, the damp coefficient of superconductor layers should be considered [32]. Based on $T = 6\,\mathrm{K}$ for different damp coefficient of superconductor layer, the reflectance of Fibonacci quasi-periodic 1D SDPCs versus frequency at normal incident in Fig. 12. From Figs. 12(a)–(d), one can see that the frequency range of Bragg gap at normal incident is obviously unchanged with increasing damp coefficient of superconductor layer. Fig. 12(a) shows that the bandwidth of the Bragg gap that we focus on is 168.47 and 222.64 THz, as damp coefficient of superconductor layers is null. When damp coefficient of superconductor layer is $\gamma = 1 \times 10^{11}\,\mathrm{Hz}$, the Bragg gap is still unchanged as shown in Fig. 12(d), as compared to Fig. 12(a). To take a close look at the dependence of the OBG on damp coefficient of superconductor layer, we present reflectance of Fibonacci quasi-periodic 1D SDPCs versus frequency as a function of $\lg^{\gamma}$ at $T = 6\,\mathrm{K}$ in Fig. 13.

We can see from Fig. 13 that the edges of the OBG are almost unchanged with increasing $\lg^{\cdot\gamma}$. The frequency range of the OBG spans from 191.31 to 223.07 THz, and the frequency range is 31.76 THz, as the

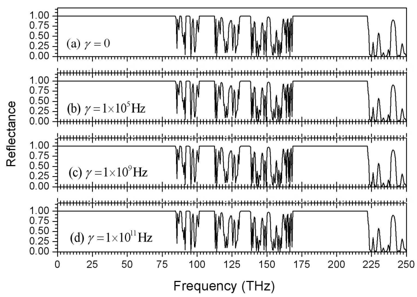



**Figure 12.** Reflectance of Fibonacci quasi-periodic 1D SDPCs versus frequency at normal incidence with different damp coefficient of superconductor layers at $T = 6\,\mathrm{K}$.

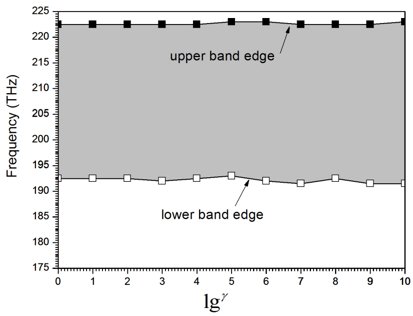



**Figure 13.** The frequency range of OBGs for Fibonacci quasi-periodic 1D SDPCs as a function of $\lg^{\gamma}$ at $T = 6\,\mathrm{K}$. The gray area is OBG.

$\lg^{\gamma}$ is creased from $\lg^{\gamma} = 0$ to $\lg^{\gamma} = 11$ at $T = 6\,\mathrm{K}$. As mentioned above, the frequency range of the OBG can not be changed by increasing the damp coefficient of superconductor layer. Consequently, whether or not the contribution of the normal conducting electrons is considered, the damping coefficient of superconductor layer has no effect on the frequency range of the OBG.

## 4. CONCLUSIONS

In summary, the band structure and OBG of 1D quasi-crystals composed of isotropic dielectric and superconductor, arranged according to a recursion rule of the Fibonacci sequence, have been investigated by TMM. It is shown that this kind of SDPCs has the OBG obviously, which is insensitive to the incident angle and the polarization of EM wave. In contrast to the OBG originating from a zero-$\widetilde{n}$ gap or single negative gap, the OBG originating from the Bragg gap are found in Fibonacci quasi-periodic 1D SDPCs, which originates from EM wave scattering of propagating modes. The numerical results show that the frequency range and central frequency of the OBG cease to change with increasing Fibonacci order, but the bandwidth of the OBG can be notably enlarged by increasing with the thickness of superconductor layer and decreasing with the ambient temperature system. The number of the PBGs can be increased, and their bandwidth can be narrowed by increasing the thickness of dielectric layer. Increasing the thickness of dielectric layer means the frequency range of OBG is narrowed, and changing the damping coefficient of superconductor layer has no effect on the frequency range of the OBG under low-temperature conditions. It also show that Fibonacci quasi-periodic 1D SDPCs has a superior feature in the enhancement of OBG frequency width compared with the conventional 1D dielectric PCs as described in our paper. The OBG has potential applications in filters, microcavities, and fibers, etc.

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