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Multichannel Narrowband Tunable Filters Based on Multilayer Structures Made of Yttrium Barium Copper Oxide and Strontium Titanate Layers

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Abstract—The purpose of this paper is to theoretically investigate the properties of electromagnetic wave propagating in both one-dimensional periodic and quasiperiodic photonic crystals consisting of high-temperature yttrium barium copper oxide and strontium titanate dielectric nano-scale materials. By using the transfer matrix method, angle-, polarization- and thickness-dependences of created PBGs are explored individually for periodic and quasiperiodic structures, and some interesting features are presented in the results section. Such supposed structures can be used as very compact polarization sensitive splitters and defect-free multichannel narrowband tunable filters.

1. INTRODUCTION

Recently, not only periodic structures [1–5] but also quasi-periodic systems are significant structures of PCs. Quasiperiodic structures have shown significant and interesting physical properties; there are structures that behave much like disordered ones, but they are constructed according to a deterministic procedure. They possess the properties of both periodic and random structures and have some distinct features not found in traditional media. Among various quasiperiodic structures, the Fibonacci binary quasiperiodic structure has been the subject of extensive efforts in the last two decades. In contrast with the fully disordered localized case, in Fibonacci systems critically localized states decay more weakly than exponentially and have a rich self-similar structure [6]. In recent years, the study on the Fibonacci sequence has been extended to the total omnidirectional photonic band gap of 1D PCs. Abdelaziz et al. [7] used a deformed Fibonacci quasiperiodic structure to broad the range of the omnidirectional photonic band gap for one-dimensional photonic crystals. Studies of some other aspects of wave propagation in the Fibonacci quasiperiodic structures carried out in [8–11] have considerably improved our understanding of wave transport in the Fibonacci quasiperiodic structures.

For a long time, intense efforts had been devoted to studying photonic structures containing layers of dielectrics, metals and magnetic and ferroelectric materials. Another group of materials for photonic multilayers are superconductors. Superconductors have no resistance to the passage of electrical current below a certain critical temperature [12]. Photonic structures composed of superconductors materials start to attract research interest due to lower dielectric losses, lower dispersions, and wider bandwidths of superconductors than normal metals. Takeda et al. calculated PBSs of two-dimensional (2D) photonic crystals composed of copper oxide high-temperature superconductors (HTSCs). They found that those photonic crystals exhibited tunability by temperature and external magnetic field [13]. Feng et al. studied tunable negative refractions in 2D photonic crystals with superconductor components. They found that the refractive angle could be scanned from positive to negative based on the dependence of the superconductor permittivity on temperature [14]. Pei et al. proposed a tunable Mach-Zehnder

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interferometer with a 2D photonic crystal using copper oxide HTSCs [15]. Some other authors reported other features of PCs containing superconductor layers [16, 17].

In this paper, based on the transfer matrix method (TMM) and two-fluid model [18], we intend to investigate the effect of different parameters on photonic transmission spectra of both 1D periodic and quasiperiodic structures containing nano-scale high-temperature superconductor (HTSCs) layers.

2. MODEL AND NUMERICAL METHODS

In the present communication, we report some properties of photonic transmission spectra of both 1D periodic and quasiperiodic structures. Here, the supposed structures are composed of nano-scale $YBa_2Cu_3O_7$ (YBCO) high-temperature superconductor (HTSc) and strontium titanate dielectric layers (see Fig. 1).

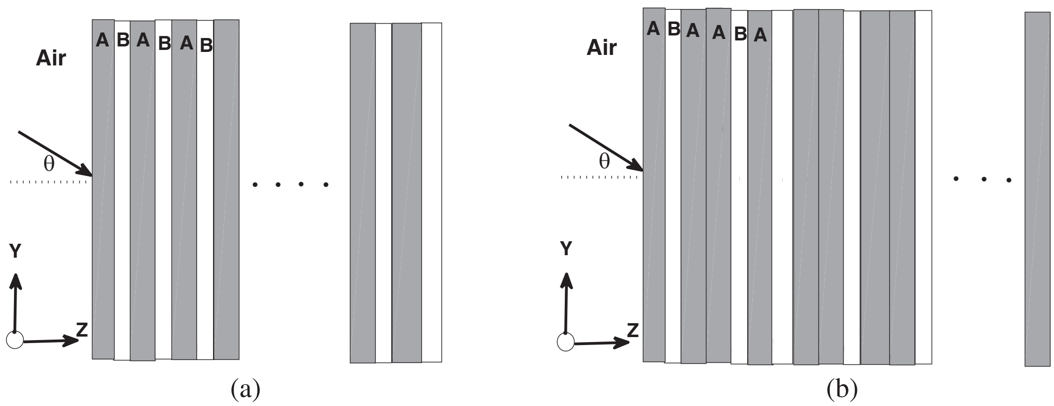


Figure 1. Schematic diagram of the (a) 1D periodic and (b) Fibonacci quasiperiodic structures consisting of superconductor (A) and strontium titanate (B) layers.

In order to define the properties of the superconductor, the Gorter-Casimir two-fluid model is adopted to describe the electromagnetic response of the superconducting layer in the absence of an external magnetic field. Normally, the conductivity in superconductors is complex. With some approximations in [18], the complex conductivity of a superconductor approximates to

$$\sigma(\omega) \approx -i\frac{e^2 n_s}{m\omega} \tag{1}$$

where e and m are the charge and mass of electron, respectively; n_s is the density of superconductor electron; ω is the frequency of external electromagnetic wave. By combining the definition of the London penetration depth λ_L and the Gorter-Casimir result, the London penetration depth can be expressed as

$$\lambda_L(T) = \left(\frac{m}{\mu_0 n_s e^2}\right)^{1/2} = \lambda_L(0)\left\{1-\left(\frac{T}{T_c}\right)^q\right\}^{-1/2} \tag{2}$$

where T and T_c are the temperatures of sample and phase transformation, respectively; $\lambda_L(T)$ and $\lambda_L(0)$ are the London penetration depths at temperature T and zero temperature, respectively; μ_0 is the magnetic susceptibility in a vacuum. For high temperature superconductors ($T_c > 77\,\mathrm{K}$), $q = 2$ and for low temperature superconductors ($T_c < 77\,\mathrm{K}$) $q = 4$ [18]. Thus, the conductivity of a superconductor can be written as follows:

$$\sigma(\omega) \approx -i\left(\frac{1}{\mu_0\omega\lambda_L(0)^2}\right)\left\{1-\left(\frac{T}{T_c}\right)^q\right\} \tag{3}$$

Then, the dielectric response function is

$$\epsilon(\omega) = 1 - \frac{c^2}{\omega^2\lambda_L(0)^2}\left\{1-\left(\frac{T}{T_c}\right)^q\right\} \tag{4}$$

where c is the velocity of light in vacuum. Defining a plasma frequency ω_p,

$$\omega_p^2 = \frac{c^2}{\lambda_L(0)^2}\left\{1 - \left(\frac{T}{T_c}\right)^q\right\} \tag{5}$$

Thus, the dielectric function of the superconductor is similar to that of metal in free-electron form, but the latter is independent of temperature.

In this paper, for calculation of transmission spectra of both supposed periodic and quasiperiodic structures, theoretical model based on the transfer matrix method (TMM) has been used. For this purpose, we assume that a plane wave is incident from air with angle θ onto a fractal multilayer structure, as shown in Fig. 1. For TE polarization, the electric field E is assumed in the x direction (the layers are in the x-y plane), and the z direction is normal to the interface of each layer. In general, the electric and magnetic fields at any two positions z and $z + \Delta z$ in the same layer can be related via a transfer matrix [7]

$$M_j(\Delta z, \omega) = \begin{pmatrix} \cos(k_z^j \Delta z) & \frac{i}{q_j}\sin(k_z^j \Delta z) \\ i q_j \sin(k_z^j \Delta z) & \cos(k_z^j \Delta z) \end{pmatrix}, \tag{6}$$

where $k_z^j = (\omega/c)\sqrt{\epsilon_j}\sqrt{\mu_j}\sqrt{1 - \sin^2\theta/\epsilon_j\mu_j}$ is the component of the wave vector along the z axis, and c indicates the speed of light in vacuum, $q_j = \sqrt{\epsilon_j}/\sqrt{\mu_j}\sqrt{1 - \sin^2\theta/\epsilon_j\mu_j}$ for TE polarization, and $j = A, B$.

3. RESULTS AND DISCUSSION

In this work, we intend to assume two multilayers: (i) 1D periodic structure, and (ii) 1D quasiperiodic structure consisting of high temperature superconductor (HTSc) and strontium titanate ($SrTiO_3$) dielectric materials. For the first multilayer, we consider a 1D bilayer periodic structure $(AB)^m$, where A and B indicate two different materials, and m is the period number. For the second one, a 1D quasiperiodic structure based on the Fibonacci sequence is assumed. The two-component Fibonacci structure can be made by juxtaposing two building blocks A and B in such a way that the certain stage of the superlattice is given by the recursive rule $S_N = \{S_{N-1}, S_{N-2}\}$ for $N \geq 2$ with $S_0 = \{B\}$ and $S_1 = \{A\}$. The number of layers is given by F_N, where F_N is the Fibonacci number obtained from recursive relation $F_N = F_{N-1} + F_{N-2}$, with $F_0 = F_1 = 1$. The all A-type layers are selected to be YBCO. In the following numerical calculations, the material parameters of YBCO layer are taken on the order of typical system of $YBa_2Cu_3O_7$ (YBCO), that is, $T_c = 92\,\mathrm{K}$, $\lambda_0 = 200\,\mathrm{nm}$ and operating temperature $T = 4.2\,\mathrm{K}$. Also, Layer B is a dielectric of $SrTiO_3$ because this dielectric material is widely used as a substrate for YBCO materials. We choose the structure parameters of both layers as follows: $n_A = \sqrt{\epsilon(\omega)}$, $d_A = 25\,\mathrm{nm}$, $n_B = 2.437$, $d_B = 45\,\mathrm{nm}$. The medium surrounding the supposed structures is vacuum. The Fibonacci order is 7 as FS_7.

Firstly, for TE polarization the transmission spectra of both 1D periodic $(AB)^{10}$ (Fig. 2) and FS_7 quasiperiodic (Fig. 3) structures are depicted at three different incident angles as 0°, 30° and 60°. For periodic structure, from Fig. 2 it is seen that there are two PBGs for each assumed incident angle, which are located at the following ranges as: for 0° (Fig. 2(a)) 1st gap 117.3–154.6 nm, 2nd gap 217–330.5 nm, for 30° (Fig. 2(b)) 1st gap 112.5–151 nm, 2nd gap 209–325 nm, and for 60° (Fig. 2(c)) 1st gap 102.5–143.2 nm, 2nd gap 192.5–307 nm. On the other hand, for FS_7 quasiperiodic structure, it is found that two broad PBGs for TE wave. For incident angle 0° (Fig. 3(a)), the 1st PBG is from 123.4 nm to 165.4 nm, while the 2nd PBG is from 216 nm to 370 nm. In the case of incident angle 30° (Fig. 3(b)), the 1st PBG is from 116.3 nm to 160.7 nm, while the 2nd PBG is from 204.4 nm to 358.4 nm. Also, at incident angle 60° (Fig. 3(c)), the 1st PBG is from 103.6 nm to 152.8 nm, while the 2nd PBG is from 189 nm to 343 nm. By analyzing Figs. 2 and 3, we can conclude that there are some common features: firstly, the transmission spectra in both structures depend on the incident angle; secondly, the band edges of PBGs in both are sensitive to incident angle. The left (λ_L), right (λ_R) and central (λ_c) wavelengths of PBGs shift to lower wavelengths (red-shift) by increasing incident angle; thirdly, ($\Delta\lambda$) of PBGs become smaller at lower wavelengths. Moreover, there is one prime difference between the two supposed multilayers. That is, using quasiperiodic structure instead of periodic one reveals that the bandwidths of PBGs are wider than those in the periodic structure.

Now, we turn to investigate the TM wave case for both periodic (Fig. 4) and quasiperiodic (Fig. 5) structures. The transmission spectra, with the same wavelength ranges, structure parameters and incident angles as those in Figs. 2 and 3, are shown in Figs. 4 and 5. As clear from Fig. 4 that for periodic structure, there exist only two complete gaps at range of 117.3–154.6 nm and 217–330.5 nm for normal incident (Fig. 4(a)), while for oblique incidence three PBGs are opened. At 30°, three PBGs are located in 114.5–136.5, 179.5–203 and 211.7–339.7 nm, respectively (Fig. 4(b)), and those for 60° are 101.8–109, 144–202 and 204.2–351 nm, respectively (Fig. 4(c)). Similar to Fig. 4, in the case of FS_7 quasiperiodic structure, it is evident from Fig. 5 that there exist three PBGs. At 30°, they span from

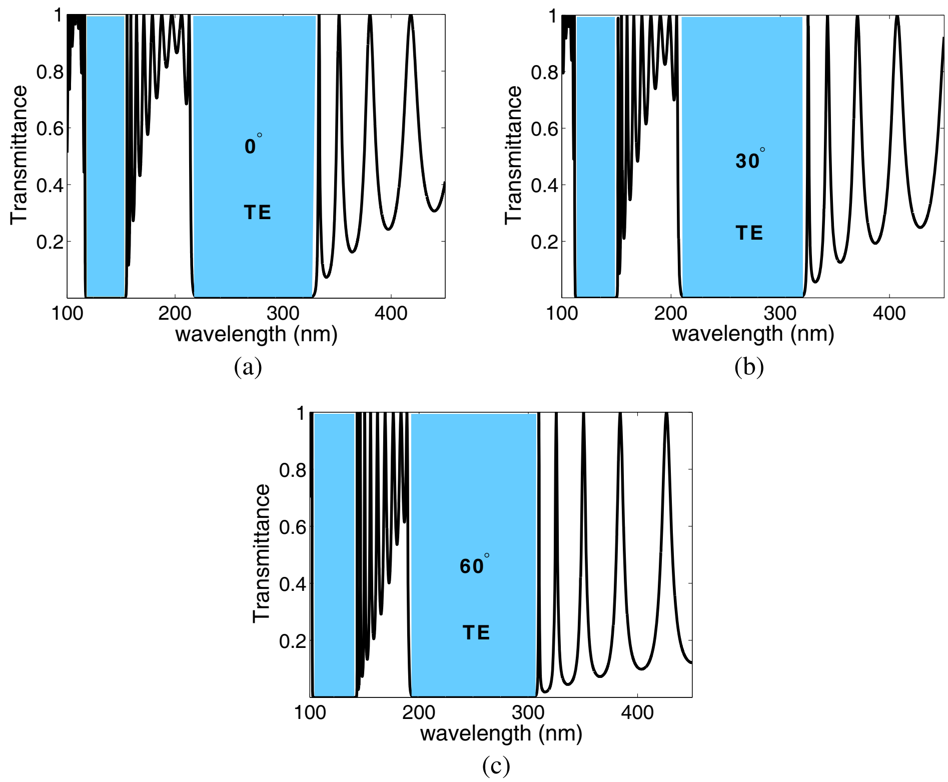
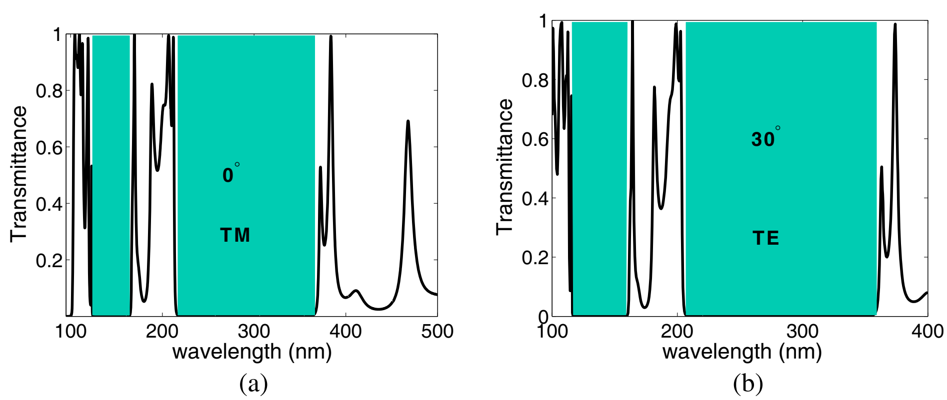


Figure 2. The transmission spectra of $(AB)^{10}$ periodic structure composed of high-temperature ($YBa_2Cu_3O_7$) superconductor and strontium titanate ($SrTiO_3$) dielectric layers for TE polarization at different incident angles as (a) 0°, (b) 30° and (c) 60°. Structure parameters are $n_A = \sqrt{\epsilon(\omega)}$, $d_A = 25\,\text{nm}$, $n_B = 2.437$, $d_B = 45\,\text{nm}$.



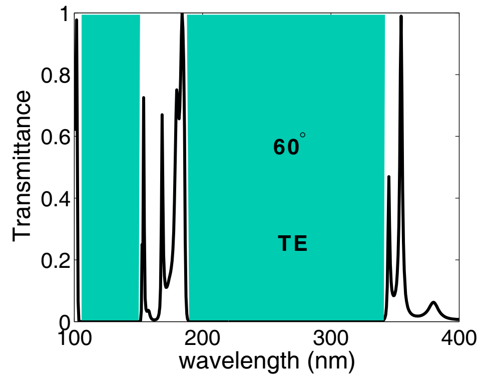


Figure 3. The same as Fig. 2 but for FS_7 quasiperiodic structure.

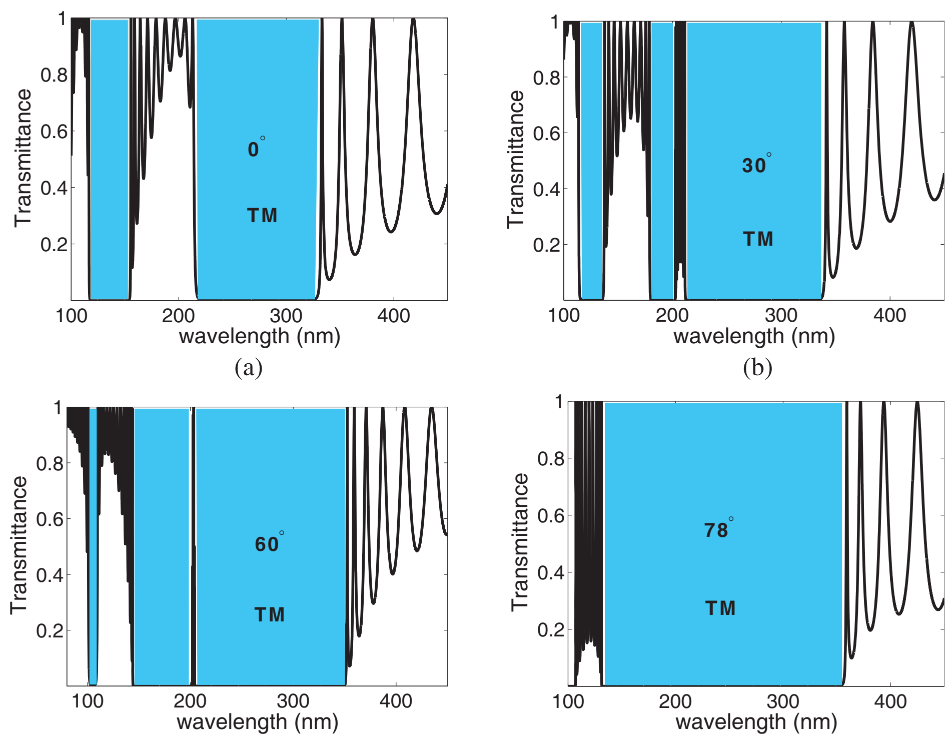


Figure 4. The TM wave transmission spectra of $(AB)^{10}$ periodic structure composed of high-temperature ($YBa_2Cu_3O_7$) superconductor and strontium titanate ($SrTiO_3$) dielectric layers at different incident angles as (a) 0°, (b) 30° and (c) 60°. Structure parameters are $n_A = \sqrt{\epsilon(\omega)}$, $d_A = 25\,\text{nm}$, $n_B = 2.437$, $d_B = 45\,\text{nm}$.

120 up to 144 nm, from 178 up to 205 nm and from 211 up to 375 nm (Fig. 5(b)), while for 60° the three PBGs are 144–201.8, 139–202.2 and 205–385.5 nm, respectively (Fig. 5(c)). At normal incident angle, the transmission spectra of TE and TM polarizations for any photonic structure are the same (Figs. 4(a) and 5(a)). For both supposed periodic and quasiperiodic structures, it can be seen from Figs. 4 and 5 that for TM mode at normal incident angle, there are two broad PBGs, while at oblique incident angles until 77° such as 60°, three broad PBGs are observed. A similar blue-shift of TE mode is also seen for TM wave as θ increases. It can also be found from Figs. 4(d) and 5(d) that for angles of incidence greater than 77°, the second gap for TM-polarized light is eliminated, and we have only

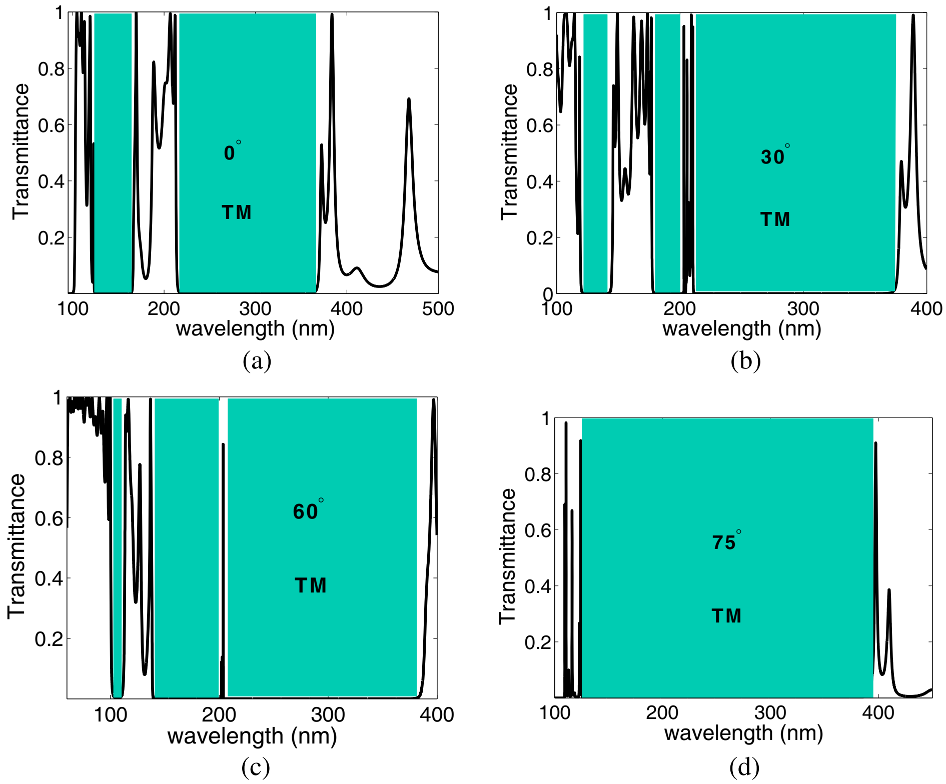


Figure 5. The same as Fig. 4 but for FS_7 quasiperiodic structure.

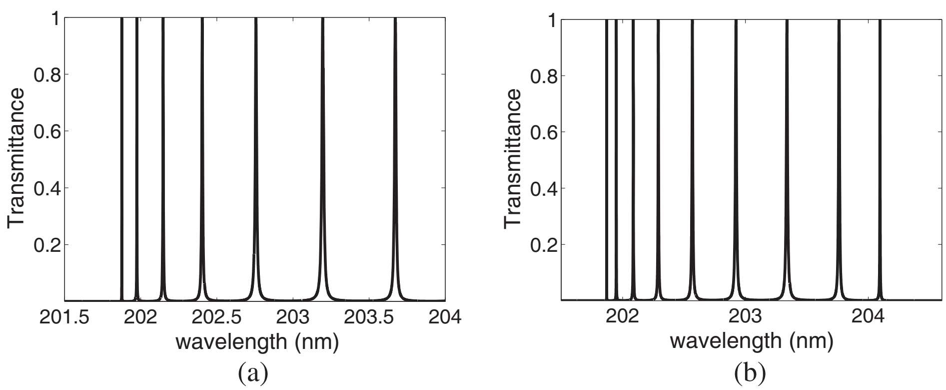


Figure 6. Closely piled together peaks created in the transmission spectra near frequencies $\lambda = \lambda_p$ for periodic structures (a) $(AB)^{10}$ and (b) $(AB)^{11}$.

one complete PBG. By comparing TM transmission curves, it is found that the two structures have similar behaviors except one that bandwidths of Fibonacci structure are larger than those in periodic multilayer.

Finally, for TM transmission spectra at oblique incidence, we focused on the wavelength range from nearly 201 up to 205 nm. Some closely piled together peaks are created in both supposed structures (Figs. 6 and 7). A striking feature of these figures is that the peaks are created only for TM polarization but absent for TE polarization. It is worth remembering that for TM mode by using Maxwell's equations, we can easily conclude that magnetic field is proportional to the permittivity multiplying the derivative of electric field. On the other hand, the permittivity of superconductors depends on the incident frequency (or wavelength), see Equation (4). So, only for TM mode, in the near-zero-permittivity

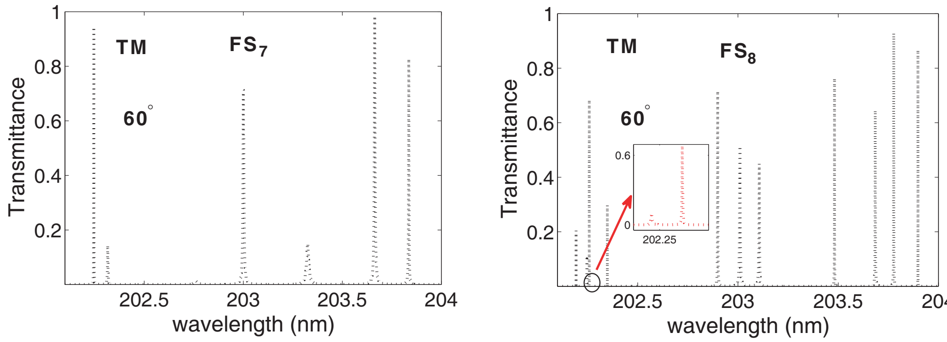


Figure 7. Closely piled together peaks created in the transmission spectra near frequencies $\lambda = \lambda_p$ for (a) FS_7 structure and (b) FS_8 structure.

operation range (nearly 201–205 nm) some closely piled peaks are created. Our numerical results show that the peaks are moved to the higher wavelengths as incident angle and thickness of layers increase. The number of resonant peaks in the transmission spectra for both periodic and quasiperiodic is added by increasing period number and Fibonacci sequence order. In addition, there is a special difference between Figs. 6 and 7. As shown in Fig. 6, number p of resonant peaks is determined uniquely by period number m: $p = m-1$ while there is no relation between the sequence number of the Fibonacci structure and the number of peaks (Fig. 7). It is clear from Fig. 6(a) that for $(AB)^{10}$ there are $p = 9$ peaks in the transmission spectrum, and for $(AB)^{11}$ $p = 10$ peaks appear (Fig. 6(b)), while in the cases of FS_7 and FS_8 quasiperiodic structures 6 and 11 peaks are observed, respectively (Fig. 7). Such supposed structures can be used as multichannel narrowband tunable filters.

4. CONCLUSIONS

To summarize, we individually calculate ultraviolet spectroscopic properties of both 1D periodic and quasiperiodic multilayer structures composed of nano-scale Y-based HTSC with Tc 92 K and strontium titanate materials for both TE and TM polarizations. From the obtained results, some conclusions can be listed as follows:

(1): The band edges of TE nd TM PBGs in both periodic and quasiperiodic structures are sensitive to incident angle. The left, right and central wavelengths of PBGs are shifted (blue-shifted) to the lower wavelengthes by increasing incident angle.

(2): At oblique incident angles, the numbers of PBGs for TE and TM waves are different in both the assumed arrangements.

(3): For angles of incidence greater than 77°, the second gap for TM wave is eliminated.

(4): For oblique incidence, some closely piled together peaks are created. The peaks are observed only for TM polarization but absent for TE polarization.

(5): The number of resonant peaks in the transmission spectra for both periodic and quasiperiodic is added by increasing period number and Fibonacci sequence order.

(6): In the periodic structure, number p of resonant peaks is determined uniquely by period number m as $p = m-1$ while there is no any relation between the sequence number of the Fibonacci structure and the number of peaks.

(7): The bandwidths created in the transmission spectra of quasiperiodic structure are larger than those in periodic structure.

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