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Tunable Defect Mode in One-Dimensional Ternary Nanophotonic Crystal with Mirror Symmetry

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Abstract: In this paper, the properties of the defect mode in the photonic band gap of one-dimensional ternary photonic crystals containing high temperature superconductor layer (SPCs) have been theoretically investigated. We considered the quasi-periodic layered structures by choosing two order of ternary Thue-Morse structures with mirror symmetry. We investigated the transmission spectra of these structures by using the transfer matrix method and two-fluid model. It is found that the location of defect mode and the range of photonic band gap can be changed by the incident angle. So that, the defect mode blue-shifted and disappeared by increasing the incidence angle. We observed an omnidirectional photonic band gap for the TE polarization that its range is from 456nm to 520nm. Also, the defect mode can be tuned by the temperature. As a result, the width of defect mode can be decreased by increasing the temperature, especially in the vicinity of the critical temperature of superconductor layer. This kind of SPCs has potential applications in filters, sensors and so on.

Key words: Defect mode, Nanophotonic crystal, Superconductor.

1. INTRODUCTION

Photonic crystals (PCs) are firstly proposed in 1987 by Yablonovitch and John [1-2]. They are ordered nanostructures in which mediums with different dielectric constants were arranged periodically. PCs have attracted a lot of attention in the recent years due to their remarkable features and the possibility to be used in several applications. One of these important features is the photonic band gaps ((PBGs). In these regions, electromagnetic fields cannot propagate in such structures in a given range of frequencies [3].

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Compared to 2D and 3D structures, the 1D layered structures are simpler to fabricate and easier to deal with from a mathematical point of view. The various layered structures of the 1DPCs have been studied as the periodic and quasi-periodic layered structures such as Cantor, Thue-Morse and the Fibonacci structures [4-7]. Intense efforts have been directed towards studying PC composed of conventional materials like dielectrics and metals. Nevertheless, unconventional constituents for PC such as magnetic materials, ferroelectric materials and negative index materials have also been studied. In addition, quasi-periodic PC containing superconductors also attracted much attention recently [8-11]. Superconductor-dielectric photonic crystals (SDPCs) are formed when some of constitutive materials of PCs are superconductor. These layered structures first investigated by Raymond Oai and Auyeing [12].

The use of superconducting material in the photonic crystals has two main advantages compared with the usual metal-dielectric photonic crystals. First, with the damping of electromagnetic waves in metals, several potentially useful properties of metal-dielectric photonic crystals will be suppressed. The metallic loss issue can be remedied by using a superconductor in place of the metal. In fact, the metallic loss can be greatly reduced and be negligibly small when metal becomes a superconductor [9]. Second, the wave properties of a SDPC can be tunable. Since the response to an electromagnetic wave is mainly dependent on the London penetration depth which is a function of the temperature and the external magnetic field as well [13].

In this work, we design a quasi-periodic layered structure consisting of high temperature superconductor. We study its optical properties by using the transfer matrix method (TMM). We introduce the defect mode of this defect less structure. This article is arranged as follows. Sec. 2 contains the suggested structure and the obtained transfer matrix for introduced structure. Sec. 3 presents the results and discussion. Sec. 4 summarizes the conclusions.

2. THEORETICAL MODEL AND NUMERICAL METHOD

We assume that the 1D ternary Thue-Morse SDPC structure in each cell following the Thue–Mores sequence. The Thue–Mores sequence can be generated by the rule $S_n = S_{n-1}\tilde{S}_{n-1}$ for level $n \geq 1$; here, n represents the Thue–Mores order and $\tilde{S}_{n-1}$ is the complement of S_{n-1}. Starting from one layer $S_0 = \{A\}$, one obtains $S_1 = \{AB\}$, $S_2 = \{ABBA\}$, $S_3 = \{ABBABAAB\}$ and so forth, with each step giving a sequence of generation number increased by one. However, the 1D ternary Thue–Mores SDPCs can be generated by starting from double layers $S_0 = \{AB\}$, one btains $S_1 = \{ABS\}$, $S_2 = \{ABSSAB\}$,

$S_3=\{ABSSABBSABABBS\}$, etc. We consider order two of ternary Thue-Morse structure as $TMS_1=\{ABSSAB\}$ and mirror of this structure as $TMS_2=\{\mathrm{BASSBA}\}$. So, we choose symmetric structure as $(TMS_1)^N(TMS_2)^N$ composed of two kinds of dielectric layers (A and B) and superconductor layers where N is the number of period. This structure is assumed to be the free space with $n=1$, as shown in Fig. 1. Here d_A, d_B and d_S are the thicknesses of layer A, layer B and Superconductor layer, respectively. The refractive indices for two dielectric layers are n_A and n_B.

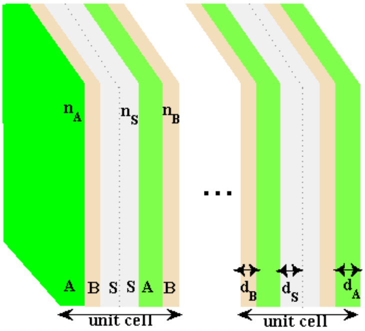

Fig. 1. The schematic structure of symmetric nanophotonic crystal.

For the transverse electric (TE) wave, the electric field is assumed to be in the y-direction. The layers of structure are in the x-y plane and the z-direction is normal to the interface of each layer. According to transfer matrix method (TMM), the electric and magnetic fields at any positions z and $z+\Delta z$ in the same layer can be related via a transfer matrix [14]:

$$m_j=\begin{bmatrix}\cos(\mathrm{k}_z{}^j\,\Delta \mathrm{z}) & \dfrac{1}{iq_j}\sin(\mathrm{k}_z{}^j\,\Delta \mathrm{z})\\ iq_j\sin(\mathrm{k}_z{}^j\,\Delta \mathrm{z}) & \cos(\mathrm{k}_z{}^j\,\Delta \mathrm{z})\end{bmatrix},\quad j=A,\mathrm{B},\mathrm{S} \tag{1}$$

where $k_z{}^j=(\omega/c)\sqrt{\varepsilon_j\mu_j}\sqrt{1-(\sin^2\theta/\varepsilon_j\mu_j)}$ is the z component of the wave vector in the layer and $q_j=(\sqrt{\varepsilon_j}/\sqrt{\mu_j})\sqrt{1-(\sin^2\theta/\varepsilon_j\mu_j)}$. By using the transfer matrix method (TMM), the total transfer matrix M for studied layered structure is obtained to be [14]

$$M_{total}=\prod_{i=1}^{N}(m_Am_Bm_Sm_Sm_Am_B)_i\prod_{j=1}^{N}(m_Bm_Am_Sm_Sm_Bm_A)_j \tag{2}$$

which m_A, m_B and m_S are the transfer matrix for A, B and superconductor layers, respectively. The transmission coefficient of the considered structure is given by

$$t(\omega,r)=\frac{2}{(M_{22}+M_{11})-i(M_{12}+M_{21})} \tag{3}$$

The transmittance is related by

$$T(\omega,r)=\left|t(\omega,r)\right|^2 . \tag{4}$$

The electromagnetic response of the superconductor in our structure can be well described by the two-fluid model together with the London local electrodynamics [9]. Here, we suppose the superconductor material is nonmagnetic. The frequency and temperature dependent refractive index of a superconductor is $n_s(\omega,\mathrm{T})=\sqrt{\varepsilon_s(\omega,\mathrm{T})}$. For a lossless superconductor the relative permittivity can be expressed as [12]

$$\varepsilon_S=1-\frac{\omega_{th}{}^2}{\omega^2} \tag{5}$$

ω_{th} is the threshold frequency of the superconductor where it is given by using the Gorter-Casimir result [15]

$$\omega_{th}=\frac{c}{\lambda_0}\sqrt{(1-(\frac{T}{T_C})^p)} \tag{6}$$

furthermore, p=2 and p=4 for high ($Tc > 77K$) and low ($Tc < 77K$) temperature superconductors, respectively [16-17].

3. RESULTS AND DISCUSSIONS

Our simulations and plots have been done with programs written in Matlab. First, we plot the transmission spectra of a 1D ternary Thue-Morse SDPCs $(TMS_1)^N$. Then, we compare it with the transmission spectra of the mirror symmetric structure as $(TMS_1)^N(TMS_2)^N$ in the visible region are shown in Fig. 2. These structures contain nano-scale dielectric layers of A and B and superconductor layer S. Considering that the superconductor material is YBCO (Y123) with critical transformation temperature $T_C=92K$ and London penetration depth at zero temperature $\lambda_0=145nm$ [18]. Its thickness and refractive index were assumed to be $d_S=10nm$ and $n_s=\sqrt{\varepsilon_s}$, respectively. The dielectric materials $Bi_4Ge_3o_{12}$ (BGO) and SiO_2 are quarter-wavelength, that is, $n_Ad_A=n_Bd_B=\lambda_0/4$ (the designed wavelength is assumed to be $500nm$). These dielectric are and nano-scale with the refractive indexes $n_A=2.13$ and $n_B=1.45$, respectively.

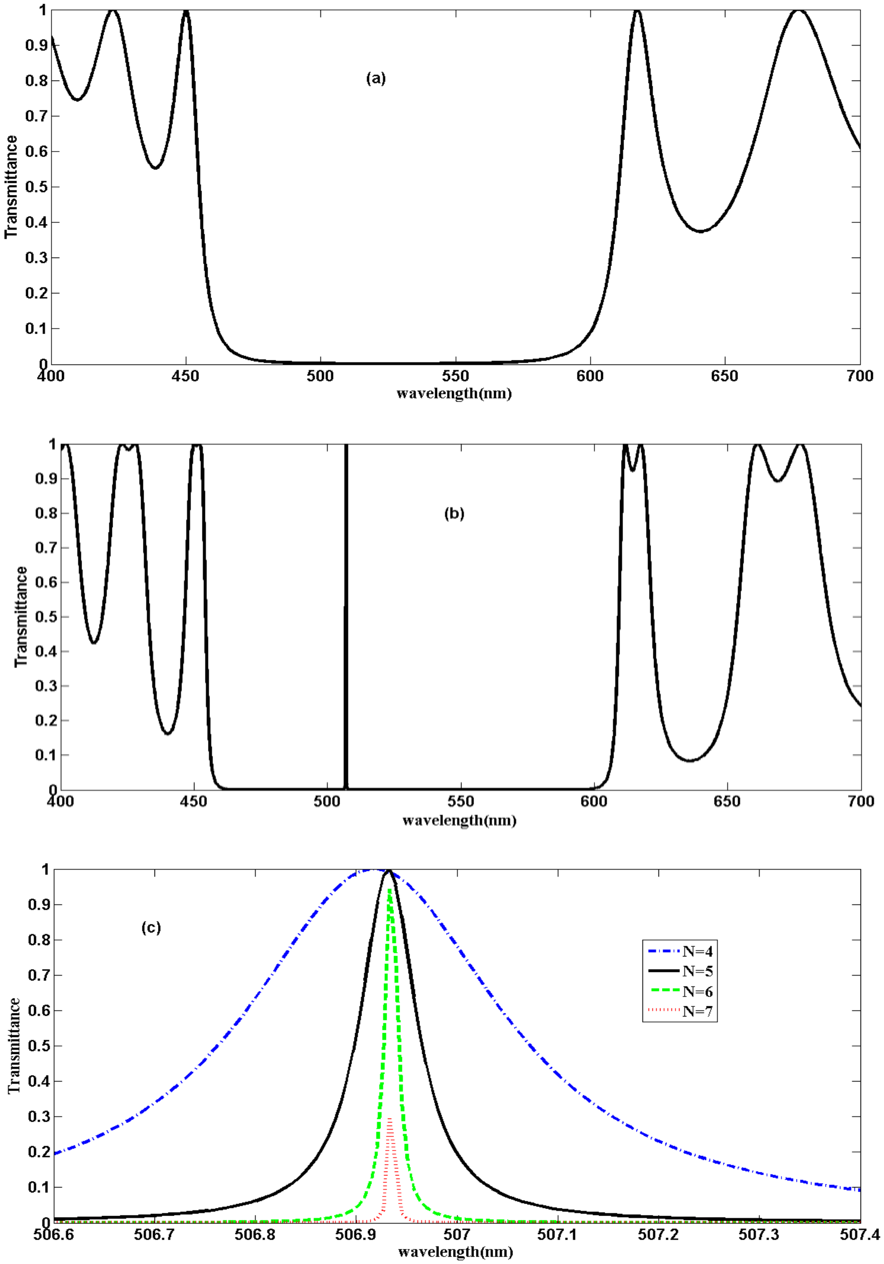

Fig. 2. The transmission spectra (a) of $(TMS_1)^N$ and (b) of $(TMS_1)^N(TMS_2)^N$. (c) The defect Mode of $(TMS_1)^N(TMS_2)^N$ in deferent number of period.

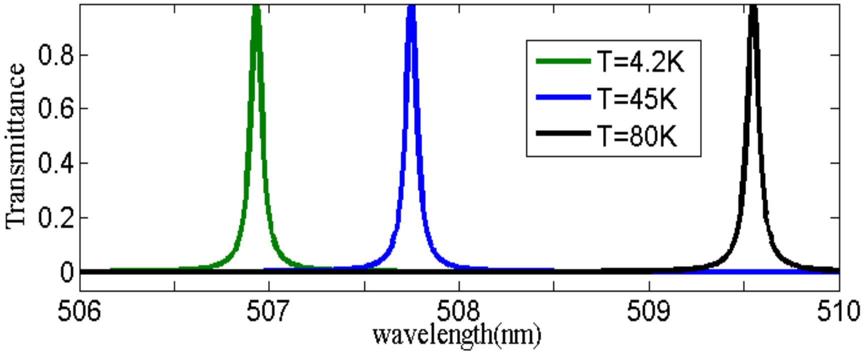

Fig. 3. Wavelength dependent transmission of defect mode at different operating temperatures.

It is obvious from Fig. 2 that the transmittance peak, which we named as defect mode, appears itself within the photonic band gap in the mirror symmetric structure. This property of it can be used to design an optical filter based on ternary Thue-Morse SDPC. In the mirror symmetric structure the defect mode itself appears around wavelength $\lambda = 507nm$ in the transmission spectra as same as defective structure. As shown in part (c) of Fig. 2, we consider that the number of periods to be 5 in the part (a) and (b) of Fig. 2, since the defect mode has complete transmittance and the least broadening around wavelength $\lambda = 507nm$. By increasing the number of periods, the appeared mode around wavelength $\lambda = 507nm$ was narrow while its transmittance decreased. Thus, we decided to choose $N = 5$ in which the defect mode becomes sharper and has a complete transmittance as seen in part (c) of Fig. 2. Also, we tried to tune defect mode of the mirror symmetric structure as a narrow band filter by changing other related parameters.

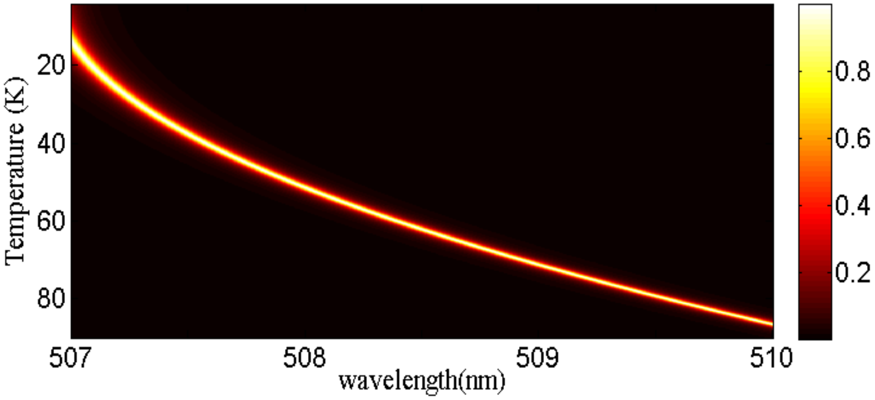

Fig. 4. The variation of the central wavelength of the defect mode with temperature.

Since the permittivity of superconducting material depends on the system temperature, the defect mode can be tuned by variation in temperature. The change of the operating temperature has an impact on the position of the defect mode. As seen in Fig. 3, in which the mode in wavelength 506.9 nm is shifted to wavelength 509.6 nm with the temperature rise to $80K$ at the vicinity of T_C . Furthermore, it is obvious that the width of the defect peak decreases and becomes narrower by increasing the temperature, especially in the vicinity of T_C as seen in Fig. 4. According to this finding, optical narrow band filters can be achieved using SPCs and the studied structure is suitable for purpose.

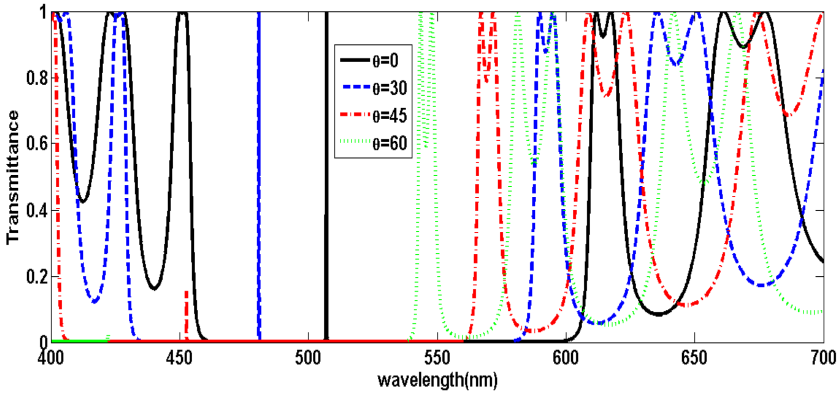

Fig. 5. Wavelength dependent transmission of defect mode at different angle of incident beam.

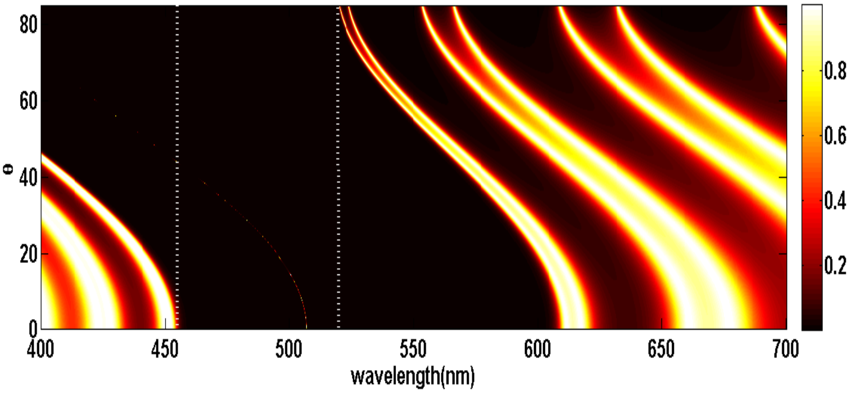

Fig. 6. Color map of the transmittance of the mirror symmetric structure vs. the wavelength and incidence angles.

Figure 5 demonstrates the transmission of defect mode at four angles of incidence, 0, 30^0, 45^0 and 60^0, in the TE polarization. Increasing the incidence angle leads to destroy the defect mode. With the increasing incidence angle, the defect mode disappears and the location of it blue-shifted from 506.9nm to 422nm. In addition, the range of photonic band gap of structure becomes wider. Figure 6 also shows it more clearly. However, we can observe an omnidirectional photonic bang gap for the TE polarization that ranges from 456nm to 520nm.

4. CONCLUSION

We found that a defect mode could appear itself in the transmission spectrum of aperiodic photonic crystals with mirror symmetry as same as the defective layered structure. In addition, we studied the properties of a defect mode introduction by using a two-fluid model the transfer matrix method. The optimum value for the number of periods (i.e. N=5) was obtained by investigating the properties of the defect mode, which was found to become sharper at this number. This study found that the defect mode can be tuned depending on the incidence angle and operating temperature. We observed a red-shift of the defect mode from $\lambda = 506.9nm$ to $\lambda = 509.6nm$ by increasing the operating temperature. In addition to a blue-shift of the defect mode by increasing the incidence angle. The results showed that the existence of an omnidirectional photonic bang gap for the TE polarization in the range from 456nm to 520nm. It seems that these structures to be the best candidate in designing an optical tunable filter and temperature sensors.

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