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A Comparative Study of a Defective Superconductor/ Semiconductor-Dielectric Photonic Crystal

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Abstract**—**Temperature-dependent tunable photonic crystals have attracted widespread interest in recent years. In this research, transmission characteristics of a one-dimensional photonic crystal structure with a single defect have been studied. Here, we assume two different defect layers: InSb as a semiconducting layer and $HgBa_2Ca_2Cu_3O_{10}$ as a high-temperature superconducting layer. Both the defect layers have temperature-dependent refractive indexes. Two different types of dielectric materials (Si as a high-refractive index dielectric and MgF_2 as a low-refractive index dielectric) are used to construct the asymmetric structures $(Si/MgF_2)^N InSb(Si/MgF_2)^N$ named S.I, and $(Si/MgF_2)^N HgBa_2Ca_2Cu_3O_{10}(Si/MgF_2)^N$ named S.II. It is found that in response to the temperature changes, transmission peaks within the photonic band gap of the S.II structure, in contrast to S.I, show a small wavelength shift. Furthermore, the results show that under the same conditions, S.I structure generates an extra defect mode in the transmission spectra. Besides high efficiency transmission property of S.II structure, it can be concluded that the semiconductor-dielectric photonic crystals are more sensitive to temperature variation than superconductor types.

Keywords**—**Defect modes, photonic crystals, semiconductor, superconductor, transmission.

I. INTRODUCTION

PHOTONIC crystals (PCs) that consist of alternating layers of materials with different dielectric constants, are capable of controlling the frequency ranges in which wave propagates. They have numerous applications such as: filters, optical switches, waveguides, cavities, and temperature sensors [1]-[3]. The concept of PCs is introduced by Yablonovitch [4] and John [5] in 1987. These structures, in particular, photonic band gap (PBG) materials have undergone rapid development in the past three decades. In the case of one-dimensional PC structure, the range of these stop bands depends on a number of parameters such as refractive indices of materials, thickness of the layers, temperature, and angle of incidence. On the other hand, production of the 1d-PCs at any wavelength scale is more feasible, and their analytical and numerical calculations are simple.

There are many ways to make a PBG of the PC structure tunable: By introducing a defect in the lattice, by the system temperature (T-tuning) [6], [7] and also by the external electric (E-tuning) [8], [9] and magnetic (M-tuning) [10] fields. A defective photonic crystal (DPC) structure (or doped PC) can be achieved by changing the thickness of the layer [11], inserting another material into the structure [12], or completely removing of the layer [13]. Doped PC structures are more useful for the sensor application. The defect mode can be clearly identified within the PBGs and in the transmittance spectrum. Besides traditional dielectric PCs, great efforts have been made to study other types of PCs such as metallic PCs [14], plasma PCs [15] and superconducting PCs [16]. Among a variety of PCs composed of nontraditional materials, the superconducting PCs have attracted much attention in recent years because of the temperature-dependent London perturbation length in the superconducting materials [17].

In the present work, we study transmission characteristics of a one-dimensional DPC, embedded in air, with an asymmetric structure $(HL)^N D(HL)^N$, in which H and L are high and low index layers, respectively, D is the defect layer, and N is the number of periods (as illustrated in Fig. 1). We assume two different defects in the host PC $(HL)^N$: once InSb as a semiconducting layer and once $HgBa_2Ca_2Cu_3O_{10}$ as a high-temperature superconducting layer. The T-tuning arises from InSb and $HgBa_2Ca_2Cu_3O_{10}$ because their permittivity is strongly dependent on the temperature. We are going to investigate the defect modes in the ultraviolet and visible region (350-550 nm).

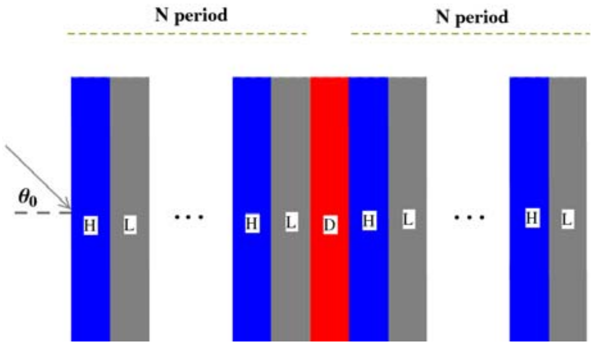

Fig. 1 Structure of an asymmetric DPC

II. THEORY

We consider a one-dimensional DPC as shown in Fig. 1. In this study, layers H, L, and D represent high-refractive index dielectric (Si) with thickness d_H, low-refractive index dielectric (MgF_2) with thickness d_L, defect layer (semiconductor or superconductor) with thickness d_D, respectively. Here, InSb is used for the semiconductor layer and $HgBa_2Ca_2Cu_3O_{10}$ is used for the superconductor layer. The refractive indexes of layers H (n_H) and L (n_L) are assumed to be independent of temperature but the refractive index of

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layer D (n_D) is temperature dependent. We should note that we have neglected the thermal-expansion of the material layers in our calculation. Due to thermo-optical effect, the temperature dependence of index of refraction of the semiconductor layer is given by

$$n_{semi-con.}(T) = n_0(1+\gamma T), \tag{1}$$

where $n_0 = 4.418$ is the refractive index of InSb at room temperature, γ is the thermo-optic coefficient ($\gamma = 560\times10^{-6}K^{-1}$), and T indicates the temperature deviation (in the Kelvin scale). For the lossless superconductor, the refractive index can be expressed by

$$n_{super-con.}(T) = \sqrt{1-\left[\frac{\lambda}{2\pi\lambda_L(T)}\right]^2}, \tag{2}$$

where λ is the wavelength of electromagnetic wave, and $\lambda_L(T)$ is the London penetration depth

$$\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1-(T/T_c)^p}}, \tag{3}$$

in which $\lambda_L(0)$ is the London penetration depth at zero temperature ($T=0$), T_c is the critical temperature of the superconducting material, and p depends on the nature of the superconductor ($p=2$ for high-temperature superconductors, i.e. $T_c > 77K$, and $p=4$ for low-temperature superconductors, i.e. $T_c < 77K$).

We employ the transfer matrix method (TMM) to compute the defect modes in the transmission spectra. According to TMM, for light incident from air ($n_0 = 1$) on the multilayer at an angle (θ_0), transfer matrix for each layer can be written as

$$M_l = \begin{bmatrix} Cos\beta_l & \frac{1}{jp_l}Sin\beta_l \\ -jp_l Sin\beta_l & Cos\beta_l \end{bmatrix}, \tag{4}$$

where l indicates either H, L or D layer, $p_l = n_l\cos\left[\arcsin\left(\sin\theta_0/n_l\right)\right]$ (for TE waves) and the phase β_l is

$$\beta_l = \frac{2\pi d_l n_l\sqrt{1-\left(\frac{n_0\sin\theta_0}{n_l}\right)^2}}{\lambda}. \tag{5}$$

For the entire structure of $(HL)^N D(HL)^N$, the total transfer matrix is given by

$$M = (M_H M_L)^N M_D (M_H M_L)^N = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}. \tag{6}$$

Having the transfer matrix of the medium, and neglecting the absorption loss, the optical properties (transmittance “T”, and reflectance “R”) can be acquired as below

$$T = \left|\frac{1}{m_{11}}\right|^2, \text{ and } R = 1-T. \tag{7}$$

III. Numerical Computation and Results

A. Defect Free PC

Let us first consider the defect free PC of $(HL)^{2N}$, in which H=Si with n_H=3.5 and L=MgF_2 with n_L=1.35. The transmission spectra of wavelength dependent of this ideal PC are plotted in Fig. 2. It can be seen that there exists a PBG in the range 345-550 nm.

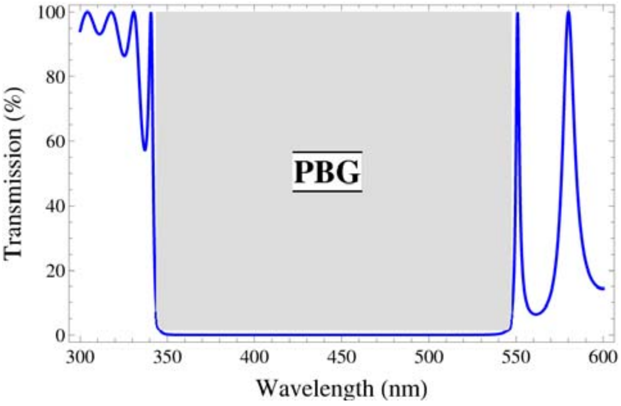

Fig. 2 Calculated transmittance spectrum of $(HL)^{2N}$ structure for normal incidence. Here d_H=42.8 nm, d_L=40.1 nm, and N=6 are used

The size of PBG is $\Delta = 205nm$ and the center wavelength is $\lambda_c = 447.5nm$.

B. Defective PC

Now, we introduce a defect layer in two different ways. In the first case, we take InSb semiconductor, while in the second case $HgBa_2Ca_2Cu_3O_{10}$ high-temperature superconductor is taken as a defect layer. Figs. 3 and 4 show the transmission spectra for DPC structures having the form $(HL)^N$InSb$(HL)^N$ (S.I) and $(HL)^N HgBa_2Ca_2Cu_3O_{10}(HL)^N$ (S.II), respectively. The high-temperature superconductor material $HgBa_2Ca_2Cu_3O_{10}$ with thickness (d_H+d_L), has critical temperature as $T_c = 135K$, and zero London penetration depth as $\lambda_L(0) = 177nm$. Hereafter, we use the same initial parameters in order to compare the transmittance spectrum of S.I and S.II structures.

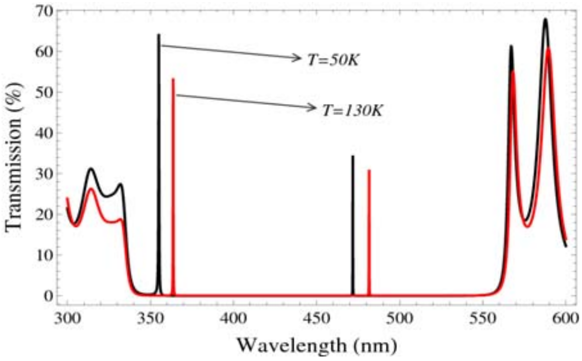

Fig. 3 Calculated transmittance spectrum of structure S.I for normal incidence

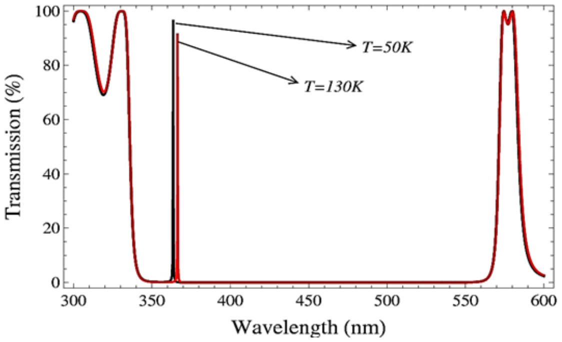

Fig. 4 Calculated transmittance spectrum of structure S.II for normal incidence

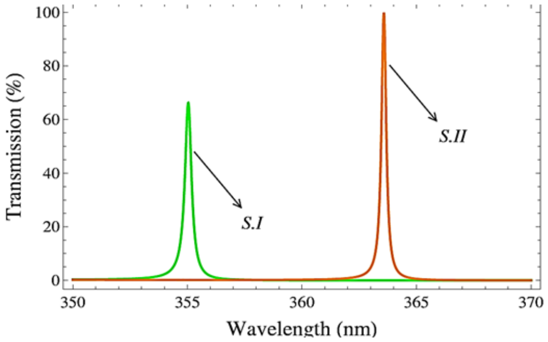

Fig. 5 Comparison of calculated transmittance spectrum of DPCs S.I and S.II at T=50K for normal incidence

Now, defect modes within the PBG for structures S.I and S.II can be clearly seen in Figs. 3 and 4. If the temperature of the defect layer changes, by keeping other parameters fixed, this causes a shift in the position of the defect mode in the transmission spectra. For both structures, the shift is towards longer wavelengths as the temperature increases. Comparing the transmission peaks, we find that the structure S.I has relatively larger shift $(\sim 9nm)$ than structure S.II. Also, in comparison with the structure S.II, the number of transmission (defect) modes in the DPC structure containing InSb is increased.

As shown in Fig. 5, the transmission peaks for the structures S.I and S.II at a fixed temperature of 50 K have been compared with each other. The maximum transmittance cannot be attained for the structure S.I, indicating the loss effect in InSb.

While for the structure S.II, the peak height attains a maximum of unit transmittance.

C. Effect of the Defect Layer Thickness

Figs. 6 and 7 show the simulated transmission spectra of the S.I and S.II structures, respectively, with the increased thickness of the defect layer, i.e. $d_D = 2(d_H + d_L)$. One can see that when the thickness is increased, then the number of transmission peaks for the structure S.I increases and becomes three. This new transmission peak lies at wavelength 530 nm and 540 nm for $T = 50K$ and $T = 130K$, respectively.

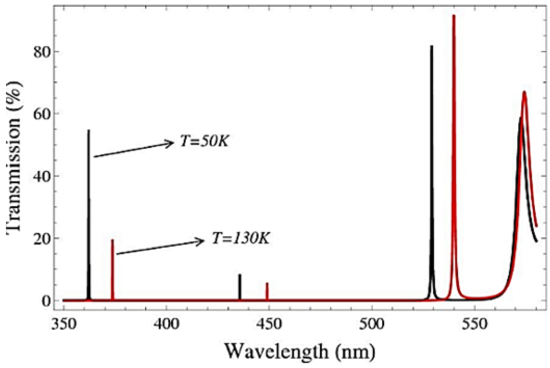

Fig. 6 Calculated transmittance spectrum of structure S.I when the defect layer thickness is doubled and the incidence is normal

But, for the structure S.II, we can only see a large wavelength shift. The wavelength of the defect mode centered at 364 nm (366 nm) has now been shifted to 428 nm (440 nm) corresponding to temperature 50 K (130 K). Therefore, it can be concluded that any change in thickness of the defect layer will cause different changes in the transmission spectra of the structures S.I and S.II.

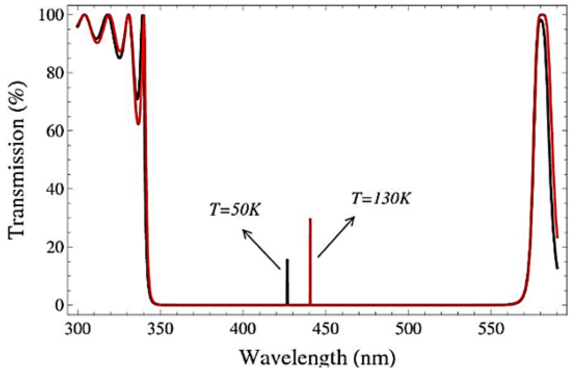

Fig. 7 Calculated transmittance spectrum of structure S.II when the defect layer thickness is doubled and the incidence is normal

D. Effect of the Incident Angle

The angle dependence of the defect modes has been investigated. Figs. 8 and 9 depict the transmittance spectrum of the structures S.I and S.II for an oblique light incidence. The results express that increasing of angle of incidence leads to a blue shift in the position of the transmission peaks for both structures S.I and S.II.

The average central wavelength shift of the defect modes for the structure S.I is about 9.5 nm, while this value is about 33 nm for the structure S.II, indicating that superconductor-based DPCs are more sensitive to the incident angle variation.

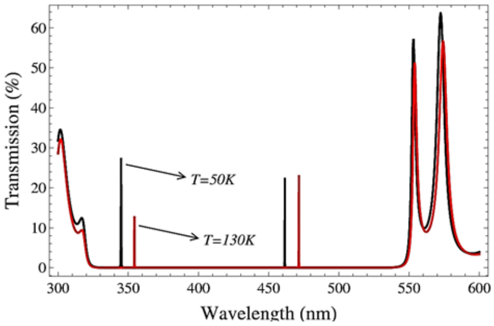

Fig. 8 Calculated transmittance spectrum of structure S.I for $\theta_0 = 45^\circ$ incidence

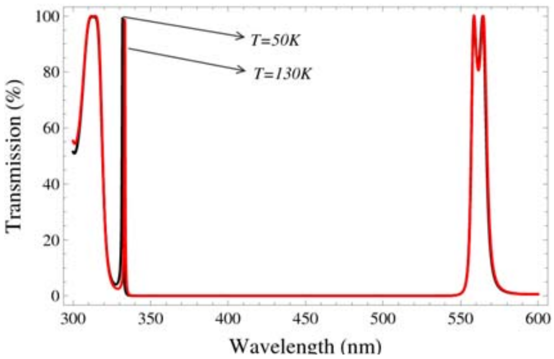

Fig. 9 Calculated transmittance spectrum of structure S.II for $\theta_0 = 45^\circ$ incidence

IV. CONCLUSION

In summary, the study of defect modes in a one-dimensional PC structure having a defect layer has been presented. We investigated the influence of two different materials, namely high-temperature superconductor and semiconductor, as a defect layer, on the transmission spectra of PC structure. It is found that, for both structures S.I and S.II, center of the defect modes depends on the system temperature (also defect layer thickness and incident angle) and shifts towards the longer wavelengths as the temperature increases. But, between these two structures, the semiconductor-based DPC (S.I) has the highest temperature sensitivity. The interesting thing is that tunability of defect modes depends, beside temperature (and other parameters), on the defect layer's material, hence one can get an extra transmission peak without changing the thickness or refractive indexes of alternate layers. This tunable feature of DPCs has many applications and it can be utilized in different optical systems.

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