Superconductor-Dielectric Photonic Band Gap in Ultraviolet Radiation

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Abstract: Optical properties of a high-temperature superconductor/dielectric (HTcScD) in the UV operation range are theoretically investigated. We have obtained and performed the calculations of optical reflectance and transmittance spectra. The calculated wavelength-dependent reflectance and transmittance for the structure superconductor/dielectric shows that the threshold wavelength is significance by the angle of incidence and the polarization of waves. The variance of the intensity and the bandwidth of the transmission and reflection are strongly dependent on the different thicknesses, different temperatures, and different incident angles as well as we obtained the different band gaps dependent on the thickness of layers. Also we have examined the influence of the increased of the number of periods on the transmittance and reflectance spectra as well as on the band gap positions.

Keywords: HTcScD, Photonic band gap, Transmission, Reflection, Photonic crystals.

1. INTRODUCTION

During the last two decades, huge attention has been concentrated on the theoretical and experimental investigation of photonic crystals (PCs) or photonic band gap materials (PBGs), due to the broad applications of PCs [1-5]. PCs can be obtained as periodic one-, two-, and three dimensional structures, composed of two different materials or more with different refractive indices with the period comparable with the wavelength of the incident electromagnetic wave [6-11] The difference in the refractive indices of the PC components leads to the appearance of photonic band gaps in the spectra of normal electromagnetic waves, *i.e*. forbidden regimes where electromagnetic waves cannot propagate through the photonic structure. The damping of electromagnetic waves in metals tends to suffer the performance of the periodic structure. Such loss issue in metals can be treated by utilization of superconductor instead. In fact, the metallic loss can be reduced and negligibly small when metals are replaced with superconductors [12]. Researchers found that dielectric losses were substantially reduced in the superconductor materials relative to similar structures made out of normal metals. The dielectric losses of such a superconductor nanomaterial [12] were found to be reduced by a factor of 6 when the SC state was penetrated. In fact, there are not numerous authors have studied the optical properties of superconductor metal/ dielectric multilayers. It is possible that the results have been used to design a high reflection mirrors, beam splitters, and band pass filters [13]. In our work we have investigated the optical properties of 1D HTcScD multilayer and the influence of a dielectric thickness layers on the spectra of the transmittance and reflectance.

2. THEORETICAL TREATMENT

The considered structure is $(AB)^N$ as shown in Figure **1** where N is the number of periods, layer A is a high-temperature superconductor material and the second layer B is a dielectric material. The superconductor is strongly sensitive to temperature and external magnetic fields [14]. We use the two-fluid model to describe the electromagnetic response of a typical superconductor without an additional magnetic field [14]. In the model, the electrons in the superconductor occupy one of two states. We consider the superconductor in the London approximation [15,16], *i.e*, assuming that the London penetration depth λ_o of the bulk superconductor is much greater than the coherence length ξ. Where

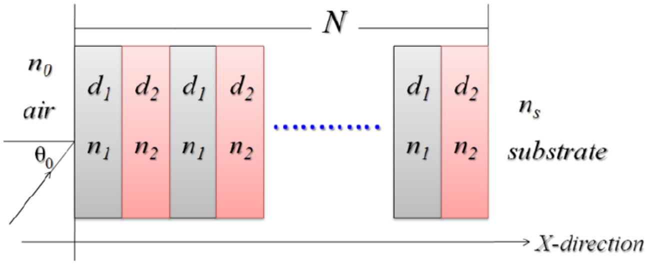

Figure 1: Schematic diagram of 1D-binary structure; the thicknesses of its constituent materials are denoted by d_1 and d_2, respectively, and the corresponding refractive indices are separately indicated by n_0, n_1, n_2, and n_s, where n_0 is the index of the air and n_s is the index of substrate.

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$$\lambda(0) = [m\,c^2 / (4\pi\, n\, e^2)]^{1/2} >> \xi; \tag{1}$$

$$\xi = \frac{\hbar v_F}{\pi\,\Delta}; \tag{2}$$

where n is the electron density; m and e are the mass and the charge of an electron , respectively; Δ is the superconducting gap; and v_F is the Fermi velocity.From Gorter–Casimir model we have:

$$\varepsilon(\omega) = 1 - \alpha(\omega_p^2 / \omega^2) - (1-\alpha)(\omega_p^2 / (\omega(\omega + i\gamma))) \;, \tag{3}$$

which is the frequency $\hbar\omega \prec 2\Delta$ and the plasma frequency is :

$$\omega_p = \sqrt{4\pi\, n\, e^2 / \varepsilon\, m} \;, \tag{4}$$

where m is the electron effective mass, γ is the phenomenological attenuation coefficient describing the relaxation of normal component, and α is the superconducting component fraction,

$$\alpha(T \prec T_c) = 1 - (T / T_c)^4 . \tag{5}$$

The London penetration depth is: $\lambda_L(T) = \lambda_o / \sqrt{\alpha}$. When the temperature is above 0.8 times the critical temperature, the London penetration depth increases rapidly and approaches infinity as the temperature is close to T_C [14]. Adjusting the temperature of superconductors can control the refractive indices of superconductors as well as the photonic band structures of PCs composed of superconductors. We consider that a TE wave is incident at an angle θ_1 from the top medium which is taken to be free space with a refractive index, $n_1 = 1$. The index of refraction of the lossless dielectric is given by $n_3 = \sqrt{\varepsilon_{r3}}$, where ε_{r3} is its relative permittivity. For the superconductor, the index of refraction, n_2 , can be described on the basis of the conventional two-fluid model [17-19]. We have designed our system as a periodic superconductor-dielectric multilayer structure where $d = d_2 + d_3$ is the spatial periodicity, where d_2 is the thickness of the superconducting layer, and d_3 denotes the thickness of the dielectric layer.According to TMM, the total transfer matrix for this binary PC takes the form [8-11,20]

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \left(M_A M_B\right)^N \tag{6}$$

where the transfer matrix M_i in the individual layer i ($i = A, B$) is given by,

$$M_i = \begin{pmatrix} \cos(K_{iz} d_i) & j q_i^{-1} \sin(K_{iz} d_i) \\ j q_i \sin(K_{iz} d_i) & \cos(K_{iz} d_i) \end{pmatrix} \tag{7}$$

The transmittance is given by[20]

$$T = \left|2P \div ((M_{11} + M_{12}P)P + M_{21} + M_{22}P)\right|^2 \tag{8}$$

$$P = \sqrt{K_0^2 - K_x^2} \div K_0 = \cos(\theta_0) \tag{9}$$

3. RESULTS AND DISCUSSION

For numerical simulation, referring our system, HTcSc (YBaCuO) with T_c =92.2K and $\lambda(0)$ =200nm is taken as first layer whereas SiO2 with n_3 =1.46180 and the glass substrate with n_ℓ =1.52083 are taken as the second and final layers, respectively. The thicknesses of the corresponding layers are set to be d_1 =40nm, d_2 =100(Figure **3a**), 170nm (Figure **3b**), 205nm (Figure **3c**) with the number of periods N =20, and operating temperature T =7.7K are adopted for simulation. The refractive index (n_R) together with the extinction coefficient (n_E) of the HTcSC (YBaCuO) with a T_c =92.2K are plotted as a function of the wavelength in Figure **2a**. It is clearly observed the value of real part of n_R is from 0 0.935 to 0.992 but the value of n_E closed zero. Such material with extremely low index of refraction retains some special features of interests. Figure **2a** shows the variation wavelength (nm). Optical constants of the HTcSc have been calculated using Essential Macleod. The real part of refractive index of the HTcSc has larger value than the imaginary part. Figure **2b** shows the optical constant of SiO2 versus wavelength has been calculated using Essential Macleod. The real part of refractive index of the SiO2 has larger value than the imaginary part except some electromagnetic waves ranges. The optical properties of HTcScDPCs are very clear in our results Figure **3**. We have studied the transmittance and reflectance spectra with different thickness layers; d_2 = 100 nm (Figure **3a**), d_2 =170(Figure **3b**), and d_2 = 205nm (Figure **3c**), and we have showed two clear photonic band gaps (Figure **3a**); the first is between 185 and 208nm and the second is between 349 and 405nm. In (Figure **3b**) where is the thickness of dielectric layers is 170 nm, we have obtained three band gaps; the first one is formed between 156 and 165nm, the second appeared between 195 and 210nm and the third one is formed between 280 and 307nm. That mean the dielectric thickness is significance parameter in our structure. In Figure **3c** we have obtained four band gaps with d_2 =205nm; the first between 150 and

160nm, the second between 177 and 189nm, the third between 225 and 246, and the fourth obtained between 330 and 358nm. Also, we have examined the influence of the number of periods on our structure as shown in Figure **4**; we have designed our structure with three different numbers of periods, 20, 40, and 60. Although we have used different numbers of periods we got the same spectra, the same PBGs positions, there is no influence on the spectra or the PBGs positions. The results of HTcSc photonic crystals may be have a potential application in the near future in the optical devices. Finally, (Figure **5**) examined the reflectance and transmittance spectra with the variance of incident angles of s-pol and p-pol when the incident angle changes from 0-90 ^{o} and d_1, d_2, T are 40nm, 100nm, 7.7 ^oK as θ vary from 0 ^{o} to 90 ^{o}, respectively. Optical properties of a high-temperature superconductor/ dielectric (HTcScD) in the UV operation range are theoretically investigated. Investigations are performed through the calculations of optical reflectance and transmittance spectra. The calculated wavelength-dependent reflectance and transmittance for the structure superconductor/dielectric shows that the threshold wavelength is strongly influenced by the angle of incidence and the polarization of waves.

4. CONCLUSIONS

By using transfer matrix method and two-fluid model for a superconductor, we have calculated the

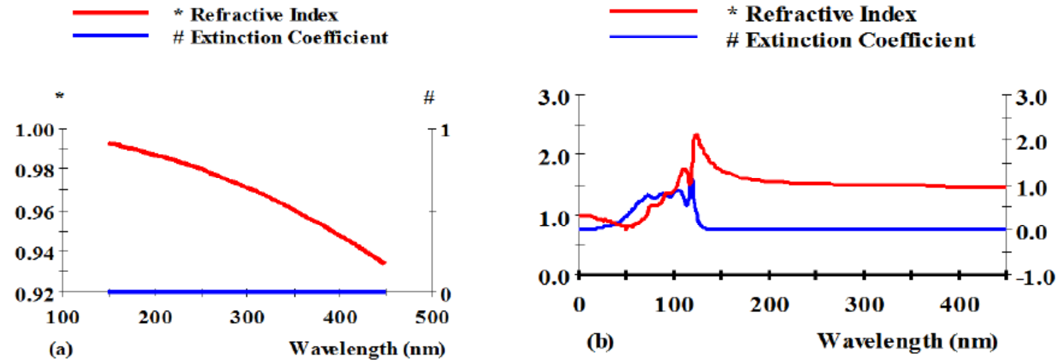

Figure 2: Plot of refractive index, n_R and the extinction coefficient, n_E of **a**) HTcSc at 92.2 K; and **b**) The refractive index of SiO2.

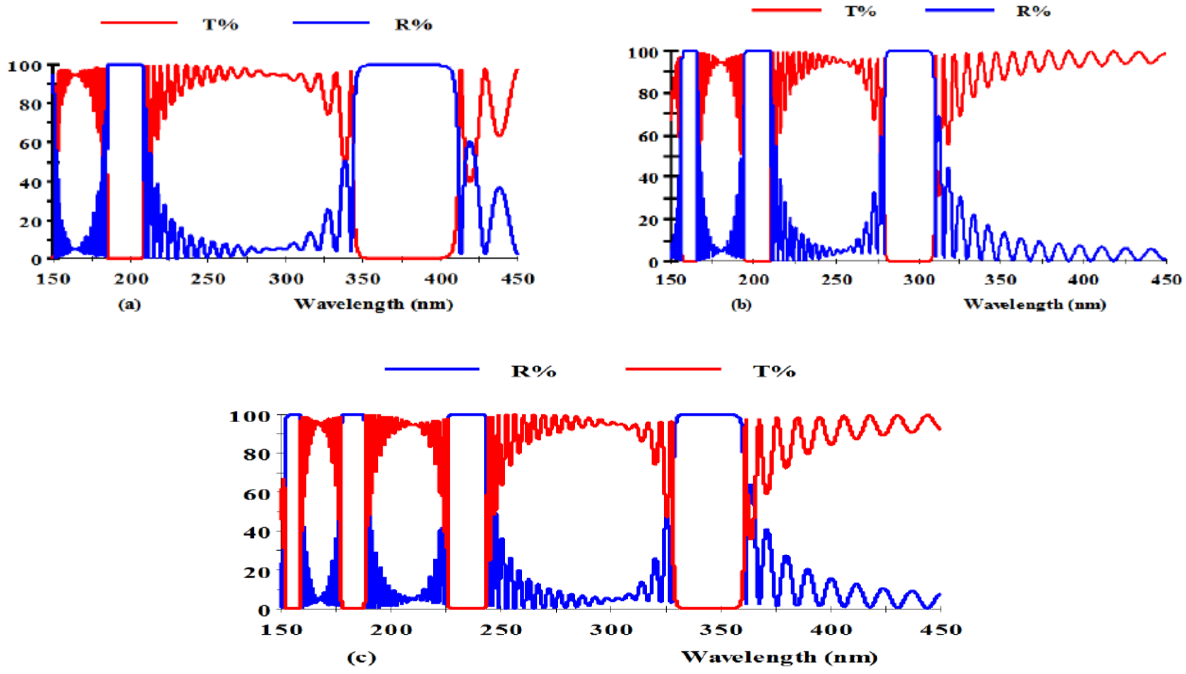

Figure 3: Transmittance (T) and Reflectance (R) spectra; HTcSc/SiO2 multilayer with d_1 =40nm,N=20, $\theta = 0^\circ$ and **a**) d_2 =100nm, **b**) d_2 =170nm, and **c**) d_2 =205nm.

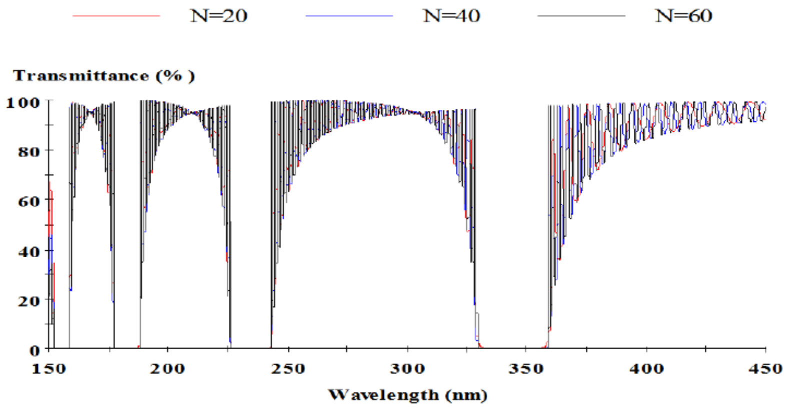

Figure 4: Transmittance (T) spectrum; HTcSc/SiO2 multilayer with d_1 =40nm, $\theta = 0^\circ$ and a) d_2 =205nm with different N=20,40,60.

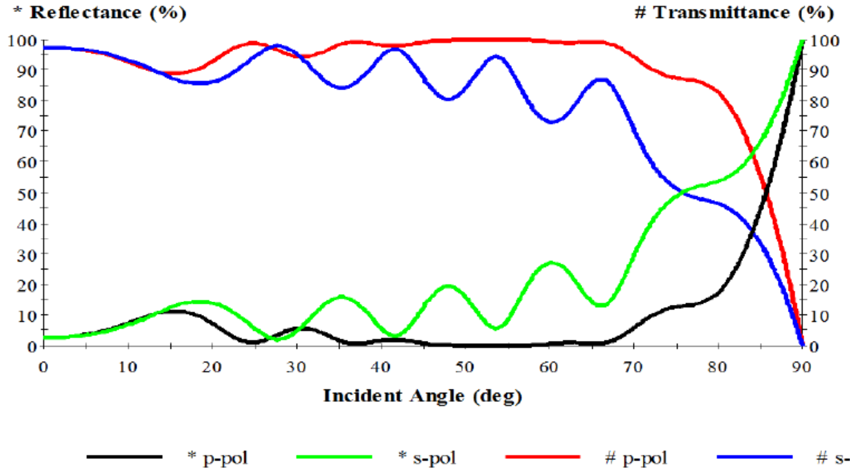

Figure 5: Transmittance and Reflectance spectra against different incidence angles; HTcSc/SiO2 multilayer with d_1 =40nm, d_2 =100, N=20.

transmittance and reflectance spectrum for a one dimensional high Tc superconducting-dielectric multilayers. The band structure shows a multiple-PBG structure, not just the first band as shown previously works [21]. Besides the first band gap, we also have investigated the second, third and fourth PBGs as a function of thickness, angle of incidence, and permittivity of dielectric. The number of band gaps increased with the dielectric thickness increased. Furthermore, we have examined the influence of the number of periods; N=20, 40, 60. Although we have used different numbers of periods we got the same spectra, the same PBGs positions, there is no influence on the spectra or the PBGs positions. The results of HTcSc photonic crystals may be have a potential application in the near future in the optical devices. Also, these results make known more basic information for the electromagnetic response of superconductor and it could be of technical use in superconducting electronics.

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