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Spectral properties of all superconducting photonic crystals comprising pair of high-high, low-low or high-low temperature superconductors

Mehdi Zamani*

Faculty of Physics, Shahid Bahonar University of Kerman, Kerman, Iran

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ABSTRACT

In this paper, optical properties of reflection- and transmission-type 1-D all superconducting photonic crystals (SPCs) consisting of high-high, low-low or high-low temperature superconductor materials have been studied in visible light region. In this way, the influence of temperature and incident angle of light wave on the PBGs and transmittance resonance-peaks for both TE and TM waves have theoretically investigated. The results show different behaviors for introduced high-high, low-low and high-low SPCs in visible region.

1. Introduction

Superconducting photonic crystals (SPCs) are formed when the constitutive materials of photonic crystals (PCs) are superconductor, or even only a defect layer is superconductor. SPCs are capable to provide unique optical characteristics by exploiting properties of band gaps and defects. A 1-D SPC structure can be created by inserting a superconductor layer into a dielectric photonic band gap (PBG) structure. Because of PBG, certain wavelengths are forcefully reflected from such structures, whereas the existence of a defect layer creates a transmission resonance within the gap that will be able to propagate inside the structure [1,2].

An important advantage of the superconducting photonic crystals is that their PBGs are tunable, because the permittivity and optical properties of a superconductor can be tuned by temperature. Therefore, they have a great opportunity for application in tunable photonic crystals [3–6].

The most earlier works in the field of SPCs have used superconductors in dielectric PCs as defect layers [7–11], or have focused on the PBG characteristics of structures constructed of alternating dielectric and superconductor materials [12–18]. There are few works which have investigated characteristics of pure SPCs made only by superconductors [19,20].

In this paper, we have investigated the optical properties of all superconducting photonic crystals containing high-high-, low-low- and high-low-T_c superconducting materials. In this way, the influence of structural formula, temperature and incident angle of light wave on the PBGs characteristics of reflection-type and transmittance resonance-peaks properties of transmission-type all SPCs for both TE and TM waves have theoretically investigated. Since, the optical properties of a PC structure depend on the form of structural formula of the SPC, constructive materials and thicknesses of layers, therefore, to have the best comparison between all SPCs comprising high-high-, low-low- or high-low-T_c superconductors, we have selected the same structural formula and the same thicknesses for the constructive layers. In addition, we investigated the influence of temperature and angle of incidence on the performance of all SPCs. Regarding obtained results, we can propose operational SPC-based devices such as thermally tunable optical filters.

2. Theory

Superconductivity is characterized by two distinctive properties: perfect electrical conductivity and perfect diamagnetism inside the superconductor [21]. This situation is establishing by a persistent supercurrent on its surface which exactly cancels the applied field inside the superconductor. This surface current flows in a very thin layer of thickness which is called the London magnetic-field penetration depth. In other word, according to the equation $H(x) = H_0 e^{-x/\lambda_L}$, London penetration depth is the distance that for it magnetic field gets to $1/e$ amplitude of magnetic-field just outside the superconductor (H_0). In conventional superconductors, temperature dependence of λ_L is given by

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

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* Tel.: +98 34 33257258; fax: +98 34 33222034.
E-mail address: m-zamani@uk.ac.ir, zamaniphotonics@gmail.com

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in which $\lambda_L(0)$ is the London penetration depth at zero temperature ($T = 0$), T_c is critical temperature of superconducting material. Furthermore, the exponent of p takes the amounts of 2 and 4 for high ($T_c > 77K$) and low ($T_c < 77K$) temperature superconductors, respectively. The refractive index of the superconducting material is described by the Gorter-Casmir two-fluid model in the absence of an external magnetic field [9]. For the lossless superconductors, the refractive index can be expressed by:

$$n_s = \sqrt{\epsilon(\omega, T)} = \sqrt{1 - [\frac{c}{\omega \lambda_L(T)}]^2}, \tag{2}$$

in which λ_L(T) is the London penetration depth, ω is frequency and c is the speed of electromagnetic wave in vacuum. We can rewrite the refractive index as below:

$$n_s = \sqrt{1 - \left[\frac{\lambda}{2\pi\, \lambda_L(T)}\right]^2}, \tag{3}$$

so that λ is the wavelength of electromagnetic wave.

To establish proper Superconducting photonic crystal structures, we have used a transfer matrix method (TMM). To explain this method, we consider a beam of light impinging on top of the multilayer from the medium *i*. If P_m is the electric field at the bottom surface of the *m*th layer, then a relation between electric field in medium *i*, P_i, and that in final medium, P_f, can be given by

$$\begin{aligned} A_i P_i &= A_1 D_1 P_1 = A_1 D_1 A_1^{-1} A_1 P_1 \\ &= A_1 D_1 A_1^{-1} A_2\, D_2\, P_2 \\ &= \prod_{m=1}^{N} (A_m\, D_m\, A_m^{-1}) A_f\, P_f\ . \end{aligned} \tag{4}$$

In this situation, the matrix A_m is the medium boundary matrix. The other matrix, D_m, is the medium propagation matrix which relates the components of the electric field at the two surfaces of the *m*th layer. If we rewrite Eq. (4) as:

$$P_i = A_i^{-1} \prod_{m=1}^{N} (A_m\, D_m\, A_m^{-1}) A_f P_f \equiv M P_f\ , \tag{5}$$

then, the total transfer matrix can be write as

$$M = A_i^{-1} \prod_{m=1}^{N} (A_m\, D_m\, A_m^{-1}) A_f \equiv \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \tag{6}$$

Having this transfer matrix, the optical properties (transmittance, *T*, and reflectance, *R*) can be acquired as below:

$$T = \left|\frac{1}{M_{11}}\right|^2, \quad and \quad R = \left|\frac{M_{21}}{M_{11}}\right|^2. \tag{7}$$

3. Numerical computation and results

The superconducting materials used here for construction of all SPC structures are $HgBa_2Ca_2Cu_3O_{10}$ and $YBa_2Cu_3O_7$ as high-T_c temperature superconductors accompanied by Rb_3C_{60} and K_3C_{60} as low-T_c temperature superconductors. $HgBa_2Ca_2Cu_3O_{10}$ has a critical temperature as $T_c = 135$ K accompanied by a London penetration depth at zero temperature as $\lambda_L(0)$=177 nm [21], while $YBa_2Cu_3O_7$ has a critical temperature and a zero London penetration depth as T_c=93 K and $\lambda_L(0)$=145 nm, respectively [21]. On the other hand, the low temperature superconductor materials Rb_3C_{60} and K_3C_{60} have critical temperatures as $T_c = 30$ K and $T_c = 19.5$ K, respectively, and zero London penetration depths as $\lambda_L(0) = 480$ nm and $\lambda_L(0)$=420 nm, respectively [21]. All of the mentioned properties of utilized superconductor materials have illustrated in Table 1. Hereafter, we denote $HgBa_2Ca_2Cu_3O_{10}$, $YBa_2Cu_3O_7$, Rb_3C_{60} and K_3C_{60} layers as H_1, H_2, L_1, and L_2, respectively; so that H and L indicate high- and low-T_c, respectively.

Table 1
Characteristics of the utilized superconductor materials.

Superconductor material	T_c (K)	$\lambda_L(0)$ (nm)
$HgBa_2Ca_2Cu_3O_{10}$	135	177
$YBa_2Cu_3O_7$	93	145
Rb_3C_{60}	30	480
K_3C_{60}	19.5	420

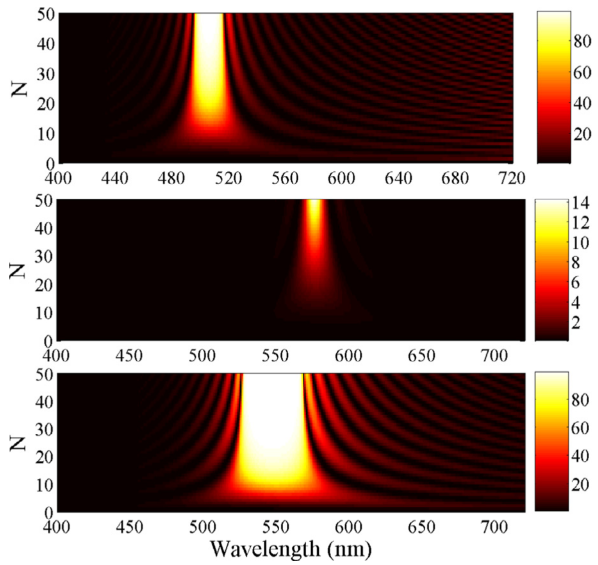

Fig. 1. (Color online) The reflectance spectra of the SPC structures of S_{HH}^R (up), S_{LL}^R (middle) and S_{HL}^R (down) as functions of wavelength and stacking number of *N* at temperature $T = 10$ K and for the case of normal incidence.

To have a good comparison between the high-high-, low-low- and high-low-T_c all SPC structures, we select the same thicknesses for the constructive layers as below:

$$\begin{aligned} d &= \frac{(\lambda_c/4)}{\sqrt{1 - [\frac{\lambda_c}{2\pi\lambda_0}]^2}} \\ &\approx 146.37\ \text{nm}, \end{aligned} \tag{8}$$

in which λ_c is the central wavelength in visible range (560 nm) and λ_0 is the average of zero London penetration depths and is equal to 305.50 nm.

3.1. Reflection-mode

In order to investigate the properties of photonic band gap of all superconducting photonic crystals in the visible region, we choose the structures as follows:

$$S_{HH}^R = (H_2/H_1)^N,$$

$$S_{LL}^R = (L_2/L_1)^N,$$

$$S_{HL}^R = (L_2/H_1)^N.$$

According to above statements, the dependence of the reflectance (PBG) on the wavelength and stacking number *N* for the case of normal incidence at temperature $T = 10$ K has plotted in Fig. 1. The direction of light landing on multilayer structures is in the direction of periodicity of layers. Therefore, normal incidence is the direction perpendicular to the surface of each layer at the point of incidence, or in which a wave-front is parallel to interfaces of layers. As can be seen