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Omnidirectional narrow bandpass filters based on one-dimensional superconductor–dielectric photonic crystal heterostructors

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ABSTRACT

By using transfer matrix method, narrow passbands of TE wave from one-dimensional superconductor–dielectric photonic crystal heterostructures are presented. Various superconductor within the two-fluid model are considered. Results show that by selecting proper width for superconductor and dielectric layers and proper materials selection, single narrow passband in visible region can be obtained. Behavior of these passbands versus the temperature of superconductors, external magnetic field and incident angle are considered. We have shown that it is possible to obtain omnidirectional passbands with examining temperature, the dilation factor of the half part of a heterostructure and the other parameters of the heterostrutures. These tunable narrow passband may be useful in designing of narrow band filters or multichannel filters.

1. Introduction

Photonic crystals (PhCs), are spatially periodic structures, can generate photonic band gap (PBG), where propagation of electromagnetic waves along the direction of periodicity is restricted for a few spectra [1,2]. With the proper design of the periodicity and specific selection of constituting materials, the PhCs can act as a perfect optical waveguide or insulator. One-dimensional (1D) PhC, periodic stack of two or more different layers, has many applications such as omnidirectional mirrors, optical diodes, solar panels, filters, etc. [3–6]. An optical filter is a device, which has the property of adding or dropping a given wavelength channels from the multi-wavelength network.

It is proven that by introducing a defect into a regular photonic structure the periodicity is broken and this leads to the appearance of localized modes in the PBG. This feature can be employed to design optical filters. On the other hand, bandpass filters (BPF) can be realized in a heterostructure of two different PhCs by making the first transmitted peak near the PBG edge of one PhCs coincide with of the other PhC. Polarization BPFs are BPFs for a given polarization and prohibit the propagation of the other. These filters have potential applications in photonic and optoelectronics. Recently, some 1D PhC heterostructures are proposed as a filter with narrow frequency and sharp angular filtering [4,7–10]. However, once the PhC has been fabricated, optical properties of PhCs are immutable and remain unaltered. Therefore, employing of tunable elements in the PhCs gives us the possibility to tune the optical properties with considerable flexibility, leading to novel applications. In general, permittivity's of tunable materials such as ferroelectrics [11,12], liquid crystals [13,14], ferromagnetic [15,16], semiconductors [17–19] and superconductors [8,20–25] in the PhCs can be changed by some external agents like as electric fields, magnetic fields or temperature. Recently, superconducting PhCs have attracted much attention and have two important advances compared with metallic and dielectric PhCs [20–25]. First, as mentioned above, the optical properties of superconducting PhCs can be tuned externally, because the permittivity of superconducting materials is depend on the London penetration depth, which is strongly influenced by temperature and externally magnetic fields. Second, losses can be greatly reduced using a superconductor in place of a metal.

In this work, by the aid of transfer matrix method (TMM), transmission properties of a 1D PhC heterostructure containing of alternative layers of superconductor and dielectric layers are considered. We examined various dilation factors of second sub PhC (subPhC), temperatures and magnetic strength to obtain omnidirectional passband. The reminder of this paper is structured as follows: in the next section we give a brief formalism of transfer matrix method which is used to obtain the numerical results. Section 3 is devoted to numerical results and discussion for filtering. Section 4 concludes with brief comments.

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2. Theoretical model and formalism

A schematic representation of the designed superconductor–dielectric PhC structure is shown in Fig. 1, in which superconductor and dielectric layers are denoted by s and d letters, respectively. Each unit cell is composed of two layers of superconductor and dielectric, which are stacked along the z-axis direction. For the first subPhC the lattice constant is $a = d_1 + d_2$, where $d_1(d_2)$is the thickness of dielectric (superconductor) layers. For the second subPhC same materials are used and the only difference between these subPhCs is the thickness of the layers. More exactly, the thickness of second subPhC is dilated by factor f respect to first PhC one. Therefore, our used 1D PhC heterostructure can be considered as $(AB)^N(CD)^N = (AB)^N(fAfB)^N$in which $A(B)$ is the superconductor (dielectric) layers of the first PhC and $C(D)$ is the superconductor (dielectric) layers of the second PhC.

To obtain the BPF frequencies we have employed transfer matrix method (TMM) and Bloch's theorem. Let a wave be incident from the vacuum at an angle θ onto the PhC heterostructure. For the transverse electric (TE) wave/transverse magnetic (TM) wave, the electric/magnetic field is along with the x direction where the PhC layers are in the x-y plane. The electric and the magnetic fields of one layer can be related via a transfer matrix (see [10] and [11] for further details):

$$M_j = \begin{pmatrix} \cos\delta_j & -\dfrac{i}{\eta_j}\sin\delta_j \\ -i\sin\delta_j & \cos\delta_j \end{pmatrix}, \tag{1}$$

where$\delta_j = \omega/c\sqrt{\varepsilon_j}\,d_j\sqrt{1-(\sin^2\theta/\varepsilon_j)}$,
$\eta_j = \sqrt{\varepsilon_j}\sqrt{1-(\sin^2\theta/\varepsilon_j)}\left(\eta_j = \sqrt{1-(\sin^2\theta/\varepsilon_j)}/\sqrt{\varepsilon_j}\right)$ for the TE (TM) wave and c is the light speed in the vacuum($j = A, B$).

For 1D PhC heterostructure the electric and the magnetic fields of the first and the last layers can be associated by transfer matrix

$$\begin{aligned} \begin{pmatrix} E_1 \\ H_1 \end{pmatrix} &= M_1M_2\ldots M_n\begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix} \\ &= (M_AM_B)^N(M_CM_D)^N\begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix} \\ &= M\begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix} \\ &= \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}\begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix}, \end{aligned} \tag{2}$$

where, m_{ij} are the matrix elements connecting electromagnetic fields at the incident end and those at exit end. The transmittance is $T = tt_*$ where t is the transmission coefficient that is given by

$$t = \frac{2\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} + m_{21} + m_{22}\eta_0}, \tag{3}$$

Here, $\eta_0 = \eta_{n+1} = \sqrt{1-\sin^2\theta}$ for the vacuum at the input and output. For an infinite periodic structure, we can use Bloch's theorem by knowing that the two components of electromagnetic fields beside on period should be fulfilled

$$\begin{pmatrix} E_{n+2} \\ H_{n+2} \end{pmatrix} = e^{iK_Ba}\begin{pmatrix} E_n \\ H_n \end{pmatrix}, \tag{4}$$

Table 1
Our used superconductors with their critical temperature and zero-temperature London penetration depth.

	Materials name	T_c (K)	$\lambda_L(0)$	ε_{sc}	p
1	$Bi_{1.85}Pb_{0.35}Sr_2Ca_2Cu_{3.1}O_y$	107 [20]	λ_L(5 K) = 23 μm	12	1
2	$Bi_2Sr_2CaCu_2O_{8+\delta}$	85 [20]	–	10	1
3	Nb	9.2 [26]	83.4 nm	1	4
4	NbN	16 [8]	200 nm	1	4
5	K_3C_{60}	19.5[8]	480 nm	1	4
6	$YBa_2Cu_3O_7$	93 [8]	145 nm	1	2
7	$HgBa_2Ca_2Cu_3O_{10}$	135 [8]	177 nm	1	2

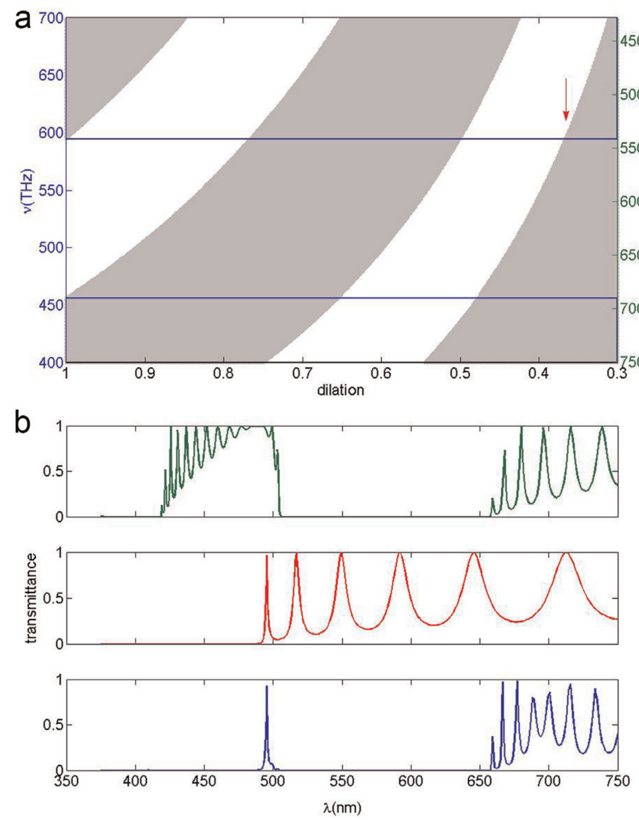

Fig. 2. (a) TE projected band structure of the second subPhC as a function of its dilation factor. The shaded and white areas are show the passbands and bandgaps of the second subPhC, respectively. The horizontal solid lines correspond to band edges of first subPhC (in which no dilation exist, f=1). (b) Transmittance of structures which is depicted in Fig. 1 for a given dilation factor. upper panel: PhC1 without any dilation, middle panel: PhC2 with a fixed dilation and lower panel: the whole heterostructure versus wavelength. The dilation factor is $f = 0.355$ in panels a and b which is depicted by an arrow in part a. fourth SC of Table 1 and Si materials are used for computations for SC and dielectric layers, typically.

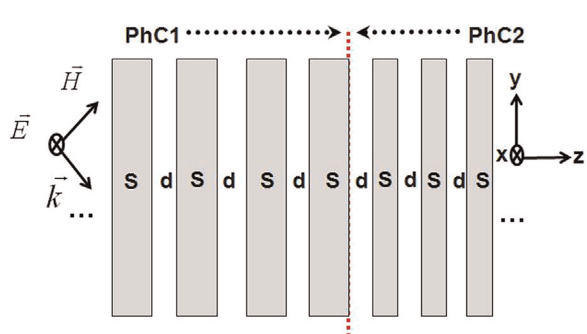

Fig. 1. Schematic representation of selected heterostructure. The vertical dotted line indicates the interface of the subPhCs.