Optik - International Journal for Light and Electron Optics 170 (2018) 384–390

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

# Dependence of the transmittance spectrum on temperature and thickness of superconducting defects coupled in dielectric one-dimensional photonic crystals

Francis Segovia-Chaves[a,b,*], Herbert Vinck-Posada[a]

[a] *Departamento de Física, Universidad Nacional de Colombia, AA 055051 Bogotá, Colombia*
[b] *Programa de Física, Universidad Surcolombiana, AA 385 Neiva, Colombia*

ARTICLE INFO

*Keywords:*
Photonic crystal
Temperature
Superconductor
Defect mode
Transfer-matrix method

ABSTRACT

In this work by using the transfer matrix method we calculate the transmittance spectrum in a dielectric one-dimensional photonic crystal, composed of alternating layers of $Bi_4Ge_3O_{12}$ and $SiO_2$, with one and two superconducting defects of high critical temperature $HgBa_2Ca_2Cu_3\ O_{8+\delta}$. We found the presence of defective modes within the photonic band gap, where the position of the modes changes to shorter frequencies as the temperature and thickness of the superconducting layer increase. In addition, we found that the number of defects within the PBG depends on the thickness of the superconducting layer, and by increasing the separation of the defects the coupling decreases.

## 1. Introduction

Photonic crystals (PC) were first described simultaneous and independently in 1987 by Yablonovitch E. [1] and John S. [2], with works on the inhibition of spontaneous emission and localization of light, respectively. The PCs are artificial structures with spatial periodicity of the dielectric constant, with defined ranges of frequency for which the propagation of light is forbidden or allowed [3]. The frequency bands where the propagation of light is not allowed are called photonic band gaps (PBG) [4], and the main technological applications of PCs are based on the existence of PBG [5–10]. The tuning of the PBG opens a new perspective in scientific research and technological applications. In essence, to obtain a tunable PBG, the dielectric constant or the magnetic permeability of one of the constituent materials must depend on some external parameters, such as the applied electric or magnetic field, the temperature and the hydrostatic pressure, applying mechanical force and stress, etc., which can modify the structure of these systems and, consequently, the optical response function of the PC [11–15]. Among the constituent materials of the PCs used to tune the PBG we have the semiconductors, metals, superconductors, metamaterials, ferrites and liquid crystals. However, superconducting materials have an advantage over other materials. For frequencies smaller than the superconductor gap, the scattering of the incident light due to the imaginary part of the dielectric function is much smaller than for the metallic particles [16].

The insertion of defects (geometric or compositional) in the PC that break the spatial periodicity of the crystal, gives rise to the presence of electromagnetic modes within the PBG. These modes are similar to the impurity states in the electronic band gap of a doped semiconductor [17]. PCs with defects allow the confinement of light of great interest in solid state and quantum optics, the construction of waveguides with quality factors greater than those of fiber optic, optical filters, optical switches, resonant cavities and Fabry Perot resonators [18–21]. The interaction between the constituents of the PCs like the coupling of the electromagnetic modes

* Corresponding at: Grupo de óptica e información cuántica, Universidad Nacional de Colombia. Programa de Física, Universidad Surcolombiana.
*E-mail address:* francis.segoviac@gmail.com (F. Segovia-Chaves).

https://doi.org/10.1016/j.ijleo.2018.05.109
Received 8 April 2018; Accepted 24 May 2018

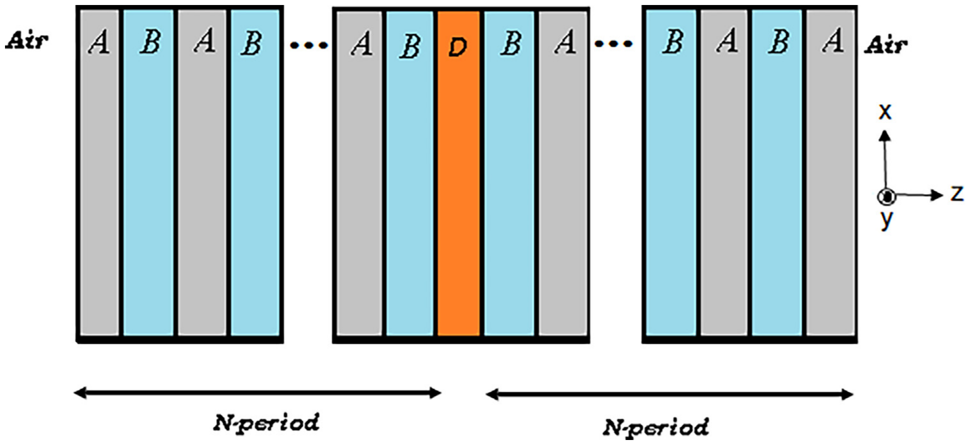


**Fig. 1.** Structure of 1DPC Air/$(AB)^N D(BA)^N$/Air.

associated with the defects in the structure, attracts attention because it provides some important functionalities which cannot be reached with a single defect, as in the waveguides made of coupled defects which are referred to as coupled cavity waveguides and in optical-switches [22,23].

In the present work, we considered a one-dimensional (1DPC) dielectric PC consisting of alternating layers of $Bi_4Ge_3O_{12}$ and $SiO_2$, which contains one and two coupled defects of high critical temperature superconductors. For the superconducting material in the context of the phenomenological model of the two fluids, the effects of dissipation are neglected, and the electromagnetic response can be considered assuming that they are non-magnetic materials with frequency-dependent dielectric constant. For this structure, we are interested in studying the dependence on temperature and the thickness of the superconductor on the transmittance spectrum for the case of normal incidence. We considered the simultaneous thermo-optic and thermal expansion effects for $Bi_4Ge_3O_{12}$ and $SiO_2$. This paper is organized as follows: Section 2, we present the 1DPC structure and the basic equations used for our analysis. In Section 3, the numerical results and we discussed the transmittance spectra of the 1DPC with one and two defects. The conclusions are presented in Section 4.

## 2. Theoretical model

In this work we studied the propagation of electromagnetic waves with normal incidence, over a finite dielectric 1DPC surrounded by air and with an homogeneous pattern in the $xy$ plane and direction of periodicity in $z$, as shown in Fig. 1. The crystal is composed of alternating layers of non-magnetic and isotropic A and B materials, with refractive indices $n_A$, $n_A$ and thicknesses $d_A$, $d_B$, respectively. The defect is given by D with refractive index $n_D$ and thickness $d_s$, the number of periods of layers AB is N.

The monochromatic electric field of frequency $\omega$, linearly polarized and propagating in the plane $(x, z)$ is given by $\mathfrak{D}_0$

$$\overrightarrow{E_j}(x, z) = \overrightarrow{e_y}(\mathfrak{A}_j e^{\mathrm{i}k_{j,z}z} + \mathfrak{B}_j e^{-\mathrm{i}k_{j,z}z})e^{-\mathrm{i}qx} \tag{1}$$

with $k_{j,z} = \sqrt{\left(\frac{\omega}{c}\right)^2 \epsilon_j - q^2}$ the $z$ component of the wave vector, $\epsilon_j$ the dielectric constant in the $j$th layer and $q$ the wave vector along the $x$-axis. The values of $\mathfrak{A}_j$ and $\mathfrak{B}_j$ are determined through the conditions of continuity of the tangential components of the electric and magnetic fields. In the TMM each layer A, B and D of the 1DPC is represented by the matrix [24]:

$$M_j = \mathfrak{D}_j P_j \mathfrak{D}_j^{-1} \quad j = A, B, D \tag{2}$$

with $P_j$ the propagation matrix is given by,

$$P_j = \begin{pmatrix} e^{i\varphi_j} & 0 \\ 0 & e^{-i\varphi_j} \end{pmatrix} \tag{3}$$

where the phase $\varphi_j$ is given by:

$$\varphi_j = k_{j,z} d_j = \frac{2\pi d_j}{\lambda} n_j \tag{4}$$

In Eq. (4) $d_j$ and $n_j = \sqrt{\epsilon_j}$, are the thickness and the refractive index of the $j$th layer, respectively. The dynamic matrix is given by,

$$\mathfrak{D}_j = \begin{pmatrix} 1 & 1 \\ n_j & -n_j \end{pmatrix} \tag{5}$$

The total transfer matrix for the 1DPC Air/$(AB)^N D(BA)^N$/Air, is defined as