Materials Chemistry and Physics 171 (2016) 91–96

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Temperature-dependent optical properties of defect mode in dielectric photonic crystal heterostructure containing a superconducting layer

Ji-Jiang Wu*, Jin-Xia Gao

School of Science, Shandong University of Technology, Zibo 255049, PR China

HIGHLIGHTS

- Effects of temperature on the defect mode of PCH are numerically analyzed.
- Thermal-expansion effect and thermal-optical effect are simultaneously considered.
- Low temperature sensor with high sensitivity can be designed based on the PCH.

ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
30 September 2015
Accepted 1 December 2015
Available online 23 December 2015

Keywords:
Multilayers
Superconductors
Thin films
Dielectric properties
Optical properties

ABSTRACT

The temperature dependence of the defect mode in a one-dimensional dielectric photonic crystal heterostructure (PCH) with a superconductor defect was theoretically investigated by simultaneously considering thermal-expansion effect and thermal-optical effect. For comparison, four structures are discussed. It is found that a dielectric PCH with a superconductor defect has very high temperature sensitivity. The average change in the central wavelength of the defect mode is 7.313 nm/K in the range of temperature variation from 10 K to 90 K. The structure may be used as a low temperature sensor.

1. Introduction

A periodic structure that exhibit photonic band gaps (PBGs) with a certain range of optical waves inhibited to propagate is the so-called photonic crystal (PC). PC has attracted attentions since decades ago. With recent advances in nanoscale fabrication techniques, a variety of new devices can be designed and produced based on PC, such as PC waveguides, PC lasers, and PC optical switch. In recent years, the tunable PC had become a hot study focus with respect to the research and the application. Many kinds of materials have been used to construct tunable PC, such as liquid-crystal [1], semiconductor [2], and magnetic fluid [3]. Among a variety of PCs containing tunable materials, the superconducting PC has attracted widespread interest in recent years [4–6]. An important advantage of the superconducting PC is that its PBG is tunable because the permittivity of a superconductor can be tuned by the system temperature and the external magnetic field.

On superconducting PC, much attention primarily focuses on the properties of photonic band structures. As an important component of the superconducting PCs, the superconductor has also been used as a defect layer or part of a pair defect in a dielectric–dielectric PC or a metamaterial-dielectric PC. Hu et al. [7] have theoretically analyzed the effects of superconducting film on the defect mode in a dielectric PC heterostructure. Their calculation results are shown that the defect mode will be blue-shifted as the thickness of superconducting defect layer or the incidence angle increases. Srivastava [8] analyzed the defect mode properties in a one-dimensional dielectric–dielectric PC containing a high and low temperature superconductor as a defect layer at different temperatures below the superconducting transition temperature (T_c). Lyubchanskii et al. [9,10] first considered a complex defect (with a superconducting film and a dielectric layer) in a

---

[*] Corresponding author.
E-mail address: w9513110@163.com (J.-J. Wu).

http://dx.doi.org/10.1016/j.matchemphys.2015.12.003

dielectric–dielectric PC. Becerra O. et al. [11] had studied the transmission coefficient and dispersion relation for a 1D PC of alternating dielectric-metamaterials slabs with a dielectric–superconductor pair defect. J. Barvestani et al. [12,13] focused on the defect mode properties of two-dimensional dielectric–dielectric PC containing superconducting defect.

One of the important features of superconducting materials is that its permittivity can be tuned by the system temperature and the external magnetic field. Currently the influence of temperature on the transmission spectra of superconducting PC has been extensively investigated [8,9,14]. However, the thermo-optical effect and thermal-expansion effect of the materials which construct PCs have been ignored in these studies when the temperature changes. In this work, we consider a dielectric PC heterostructure with a superconducting defect layer. In Ref. [10], Dadoenkova et al. have given a detailed study on the influence of the thickness of superconducting defect layer and the angles of incidence on the defect mode properties. After the study of Dadoenkova et al., Hu et al. have theoretically investigated a more simple structure [7]. But the effect of temperature on the defect mode in this PC heterostructure has not been investigated in their papers. Here, characteristics of defective mode for this PC heterostructure are studied at different temperature by simultaneously considering thermal-expansion effect and thermal-optical effect.

2. Theoretical model and numerical method

The dielectric PC heterostructure considered by Hu et al. [7] can be expressed as $(\mathrm{HL})^N\mathrm{S}(\mathrm{LH})^N$, where H and L stand for the different dielectric layers with high and low refractive n_H and n_L, respectively, layer S is the superconducting defect layer and N is the stack number. For comparison, the other three structures have also discussed in following section, namely $(\mathrm{HL})^N(\mathrm{LH})^N$, $(\mathrm{LH})^N(\mathrm{HL})^N$, and $(\mathrm{LH})^N\mathrm{S}(\mathrm{HL})^N$. In our calculation, the material parameters of the dielectric material are taken from Ref. [15]. We assume the layer H of the thickness d_H to be $\mathrm{Bi_4Ge_3O_{12}}$ (BGO). The layer L of the thickness d_L is $\mathrm{SiO_2}$. The period of the structure is $D = d_H + d_L$. The defect layer S is assumed as superconductor $\mathrm{YaBa_2Cu_3O_7}$ (YBCO) with thickness d_S. The medium surrounding the dielectric PC heterostructure is a vacuum.

The electromagnetic response of the superconductor in our structure can be well described by the two-fluid model together with the London local electrodynamics. Here we suppose the superconductor material is nonmagnetic. That is the relative permeability of superconductor material $\mu_s = 1$. With some approximations, the complex conductivity of a lossless superconductor can be written as [7,8]

$$\sigma = -i\frac{1}{\omega\mu_0\lambda_L^2} \tag{1}$$

where the temperature-dependent London penetration depth is given by

$$\lambda_L(T) = \frac{\lambda_0}{\sqrt{1-f(T)}} \tag{2}$$

where the Gorter–Casimir expression for $f(T)$ is

$$f(T) = \left(\frac{T}{T_c}\right)^4 \tag{3}$$

where λ_0 is the London penetration length at temperature $T = 0$, and T_c is the critical temperature of a superconductor. With (1), the relative permittivity can be expressed as

$$\varepsilon_s = 1 - \frac{1}{\omega^2\mu_0\varepsilon_0\lambda_L^2} \tag{4}$$

It can be seen clearly that the relative permittivity of the superconductor is dependent on the frequency and the temperature as well.

It is well known that the thickness and refractive index of medium can be changed due to the thermal-expansion effect and thermo-optical effect. In certain temperature range, the thermal-expansion effect can be described as

$$d(T) = d_0(1 + \alpha\Delta T) \tag{5}$$

where α is the thermal-expansion coefficient, and ΔT is the temperature deviation. d and d_0 are the thickness of each layer under the actual and room temperature, respectively. According to the thermo-optical effect, the relation between the temperature and the refractive index can be written as

$$n(T) = n_0(1 + \beta\Delta T) \tag{6}$$

where β is the thermo-optic coefficient. n and n_0 are the index of refraction of each layer under the actual and room temperature, respectively.

Our calculation is based on the transfer matrix method (TMM), which is one of the most effective methods to analyze the transmission properties of the PC. Let an incident electromagnetic wave from vacuum have an angle θ of incidence upon the PC structure. For the transverse electric (TE) wave, the electric field $\boldsymbol{E}$ is assumed to be in the y-direction, if the dielectric layers are in the x-y plane, and the z-direction is normal to the interface of each layer. In general, the electric and magnetic fields at any positions z and $z + \varDelta z$ in the same layer can be related via a transfer matrix

$$M_j(\Delta z, \omega) = \begin{pmatrix} \cos\left(k_z^j\Delta z\right) & i\dfrac{1}{q_j}\sin\left(k_z^j\Delta z\right) \\ iq_j\sin\left(k_z^j\Delta z\right) & \cos\left(k_z^j\Delta z\right) \end{pmatrix} \tag{7}$$

where $k_z^j = \omega/c\sqrt{\varepsilon_j}\sqrt{\mu_j}\sqrt{1-(\sin^2\theta/\varepsilon_j\mu_j)}$ is the z component of the wave vector k_j in the jth layer, and $q_j = \sqrt{\varepsilon_j}/\sqrt{\mu_j}\sqrt{1-(\sin^2\theta/\varepsilon_j\mu_j)}$. Then the transmission coefficient $t(\omega)$ can be obtained from the transfer matrix method

$$t(\omega) = \frac{2\cos\theta}{(m_{11}+m_{22})\cos\theta + i(m_{12}\cos^2\theta - m_{21})} \tag{8}$$

Here $m_{ij}(\omega)$ $(i,\ j = 1,\ 2)$ is the matrix element of$X_N(\omega) = \prod_{j=1}^{N} M_j(d_j,\omega)$ which represents the total transfer matrix connecting the fields at the incident end and the exit end. The treatment for a TM wave is similar to that for a TE wave. If $t(\omega)$is determined, the transmittance can be calculated by:

$$T = t \cdot t^* \tag{9}$$

3. Numerical results and discussion

In the following calculations, the superconductor material is taken as YBCO and its critical transition temperature and London penetration depth at zero temperature is $T_c = 92$ K and $\lambda_0 = 140$ nm,