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Omni directional reflectance properties of superconductor-dielectric photonic crystal

G.N. Pandey [a,*], Khem B. Thapa [b], S.P. Ojha [c]

[a] Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Noida, U.P., India
[b] Department of Physics, UIET, Chhatrapati Shahu Ji Maharaj University, Kanpur, U.P., India
[c] IIMT, Greater Noida, U.P., India

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ABSTRACT

The omnidirectional reflection properties in one dimensional superconductor-dielectric photonic crystal have been studied theoretically. In this present communication, the superconductor-dielectric photonic crystal in one dimension having alternate regions of superconductor-dielectric. The reflectance behaviors from these periodic multilayered structures are calculated for different angles of incidence. The reflectance and band structure is obtained by solving a Maxwell's equation using a translational matrix method. The study of reflectance bands of such superconductor-dielectric photonic crystal show that it can be used as broad band reflector.

1. Introduction

A good amount of work has been reported on the computation of the band structures of electromagnetic propagation is one-, two- and three-dimensional dielectric periodic structure since it was shows [1,9] that these periodic structures can be designed to produce the required band structures. The band structures were explored mainly fabricated from dielectric materials [2–4] typically used in the semiconductor technology. Dielectric periodic structure can be designed to mold the light propagation in integrated semiconductor optoelectronics where electronic and optical signals coexist and transform between each other.

It has already been proposed that Photonic Crystals (PCs) constructed with ferroelectric or ferromagnetic materials could be tuned by means of an external electric or magnetic field [5,6]. Recently, it was proposed that photonic crystal of the inverse opal type doped with a liquid crystal [7] and photonic crystals made of semiconductor constituents are suitable to constitute tunable photonic crystal [8].

One-dimensional photonic crystal is, in general, made of alternating layers of material with different permittivities, forming a superlattice with infinite periods. The band structure for a dielectric photonic crystal show that the photonic band gap (PBG) between the first and second bands widens considerably as the difference in dielectric permittively is increased [9]. In addition, no low frequency band gap below the first (lowest) and can be found. In a metallic photonic mode of a normal metal and a dielectric, it is however found that a low frequency (or metallicity) gap may exist [10–12]. The wide range of materials that can be used to make PCs provides vast avenues in the design and applications of novel PCs devices for integration into the semiconductor optoelectronic system.

Yaw [13] has submitted his thesis in 2002 on transmission properties of a high critical temperature Superconductor-dielectric multilayer photonic band gap structure. He has demonstrated that superconductivity can be rapidly quenched (transition temperature on the order of 10^{-9} s.) with an incident electromagnetic field above some 'critical' intensity and the superconductivity is restored.

On the other hand, the study of photonic band gap consisting of a superconducting material and a dielectric has been reported [14–19]. The gap size is characterized by polarization, penetration depth, and highly dependent on temperature at the vicinity of superconducting transition temperature. The analysis shows that the property of thin photonic crystals may have application in optical region if extremely low relaxation time superconductor is used.

The photonic crystals is to incorporate a superconductor constituent [16] because photonic band structures in PCs determine the optical routine of light transmitting in them, it is also possible to obtain tunable negative refraction in PCs by modifying the band structures. Feng et al. [20] have been described tunable negative refraction in the lowest band of a 2D PC, incorporating in the superconductor constituents. Ricci et al. [21] has

* Corresponding author at: Department of Applied Physics, Amity Institute of Applied Science, Amity University, Sector-125, Express Highway, Noida, U.P., India.
E-mail address: girijeshpandey_itbhu@rediffmail.com (G.N. Pandey).

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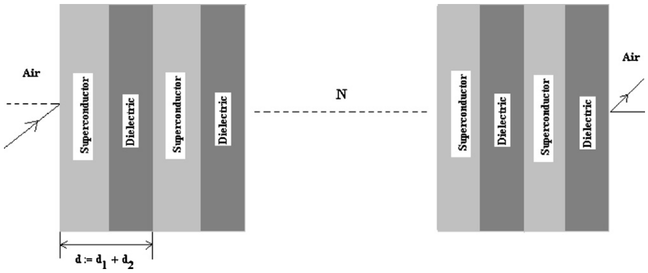

Fig. 1. Schematic presentation of superconductor/dielectric periodic structure.

examined experimentally the properties of a low loss super conducting materials and Peminov et al. [22] have realized experimentally of negative refraction in ferromagnetic superconductor superlattices at millimeter wave. In fact, the issue of a super conducting photonic crystal was first investigated by a group in Singapore [15]. They have considered one-dimensional superconductor/dielectric superlattices, by making use of the transfer matrix method and accompanied by the Bloch theorem [23]. Recently, Wu et al. [18] has been theoretically calculated the full band structure in the TE mode for a one-dimensional superconductor dielectric super lattice.

In this present communication, we have studied the optical properties of PCs with super conducting constituent using the TMM method for a stratified medium; we first calculate the dispersion and transmittance spectrum of superconductor-dielectric periodic structure based on the transcendental equation derived from TMM and Bloch theorem. The reflectance and transmittance at different incidence angle and temperature, this study show the filtering properties in superconductor-dielectric photonic band gap material.

2. Theory

A one-dimensional non-magnetic of refractive index $n_1 = \sqrt{\varepsilon_1}$ and $n_2 = \sqrt{\varepsilon_2}$ photonic crystal will be modeled as a periodic dielectric (ε_1) and dielectric (ε_2) multilayer structure with a period of $d = d_1 + d_2$. The schematic diagram of the dielectric-superconductor materials is shown in Fig. 1.where d is the spatial periodicity with d_1 and d_2 are the thickness of the refractive indices n_1 and n_2 respectively. The refractive index profile of the structure given by

$$n(x) = \begin{cases} n_d, & d_2 < x < d \\ n_s, & 0 < x < d_2 \end{cases} \quad (1)$$

with $n(x) = n(x + d)$ where, n_d, n_s are the refractive indices of the dielectric and superconductor materials, $d = d_1 + d_2$ is the period of the lattice with a and b being the width of the dielectric and superconductor materials respectively.

The electric field $E(x)$ within each homogeneous layer is a combination of right-traveling waves and left-traveling waves and so it can be expressed as the sum of an incident plane wave and reflected plane wave. Thus, the electric field in the mth unit cell can be written as

$$E(x) = \begin{cases} a_m e^{-ik_1(x-md)} + b_m e^{ik_2(x-md)}; & (md - d_1) < x < md \\ c_m e^{-ik_2(x-md+d_1)} + d_m e^{ik_2(x-md+d_1)}; & (m-1)d < x < (md - d_1) \end{cases} \quad (2)$$

where

$$k_1 = \left[\left(\frac{\omega}{c}\, n_1\right)^2 - \beta^2\right]^{1/2} = \frac{n_d\,\omega}{c} \cos\ \theta_1, \quad k_2 = \left[\left(\frac{\omega}{c}\, n_2\right)^2 - \beta^2\right]^{1/2} = \frac{n_s\,\omega}{c} \cos\ \theta_2 \quad (3)$$

For the superconductor, the index of refraction can be described on the basis of the conventional two fluid models [15–17]. The complex conductivity of a superconductor can be expressed as

$$\sigma(\omega) = \frac{-i\,e^2\,n_s}{m\,\omega} \quad (4)$$

where $\sigma(\omega)$ is the conductivity of the superconductor, e and m are the charge and mass of electron, respectively, n_s is the density of electron and ω is the frequency of external electromagnetic wave. The approximation condition can be found in Ref. [15]. The conductivity can be expressed in term of London-penetration depths λ_L, since

$$\lambda_L^2 = \frac{m}{\mu_0\, n_s\, e^2} \quad (5a)$$

So that

$$\sigma(\omega) \approx -\frac{i}{\mu_0\,\omega\,\lambda_L^2} \quad (5b)$$

From the Gorter–Casimir result [15], $n_s/n_n = (T_c/t)^4 - 1$ and the London-penetration depth, we obtain

$$\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1 - (T/T_c)^4}} \quad (6)$$

where the conductivity Eq. (5b) is temperature dependent. In the superconductor layer with no external source current and charge the Maxwell's equation becomes

$$\vec{\nabla}\cdot\vec{E} = 0, \quad \vec{\nabla}\cdot\vec{B} = 0, \quad \vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \quad \text{and}$$
$$\vec{\nabla}\times\vec{B} = \mu_0\left[\sigma\vec{E} + \varepsilon_0\frac{\partial\vec{E}}{\partial t}\right] \quad (7)$$

Taking the curl if the last of Eq. (7) and using the convention $e^{-i(\omega t + \vec{k}\cdot\vec{r})}$, we have

$$\vec{\nabla}\times\vec{\nabla}\times\vec{B} = \left[\frac{\omega^2}{c^2} - i\ \omega\,\mu_0\,\sigma(\omega)\right]\vec{B}$$
$$\text{or}\quad \vec{\nabla}^2\vec{B} + k_1^2\vec{B} = 0 \quad (8)$$

By substituting Eq. (5), we have

$$k_1^2 = \left(\frac{\omega^2}{c^2} - \frac{1}{\lambda_L^2}\right) \quad (9)$$

Then, from snell's law, the length of the tangential wave vector k_{1x} (parallel to the dielectric superconductor interface) is conserved. That is $k_{1y} = (\omega/c)\sin\theta = \beta$, where θ is the angle of incident (relative to normal of interface) of the electromagnetic wave as vacuum. Then, we have the frequency dependent normal vector,

$$k_{1x} = \sqrt{\frac{\omega^2}{c^2}\quad \cos^2\theta - \frac{1}{\lambda_L^2}} = \frac{\omega}{c} n_1(\omega) \quad (10)$$

where $n_1(\omega) = \sqrt{\cos^2\theta - \frac{c^2}{\omega^2}\quad \frac{1}{\lambda_L^2}}$