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Physica C 432 (2005) 133–139
PHYSICA C
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Photonic band structure for a superconductor-dielectric superlattice

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Received 20 June 2005; accepted 21 July 2005
Available online 12 September 2005

Abstract

The photonic band structure in the transversal electric mode for a one-dimensional superconductor-dielectric superlattice is theoretically calculated. By using the Abeles theory for a stratified medium, we first calculate the transmittance spectrum from which all the possible bands can be directly seen. Then we calculate the real photonic band structure based on the transcendental equation derived from the transfer matrix method and Bloch theorem. The band structure is shown to be strongly consistent with the transmittance spectrum. We finally study the three lowest band gaps as a function of penetration of superconductor, permittivity of dielectric, and angle of incidence, respectively. The optical properties in a superconductor-dielectric superlattice thus are well disclosed.

PACS: 42.70.Qs; 74.25.Ge; 74.20.De

Keywords: Superconducting film; Photonic crystal; Band structure; Superlattice

1. Introduction

It is well known that photonic crystals have photonic band gaps (PBGs) in the photonic dispersion relation. In the PBGs, optical waves with certain frequencies are not allowed to propagate through the crystal [1,2]. The PBGs are analogous to the electronic band gaps in a solid and their physical origin can be ascribed to the Bragg diffraction in a periodic multilayer structure. A simple 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–dielectric photonic crystal shows that the PBG between the first and second bands

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doi:10.1016/j.physc.2005.07.019

widens considerably as the difference in dielectric permittivity is increased [3]. In addition, no low-frequency band gap below the first (lowest) band can be found. In a metallic photonic made of a normal metal and a dielectric, it is however found that a low-frequency (or metallicity) gap may exist. Contrary to a PBG, this metallicity gap which does not depend on the periodicity, is of the order of the plasma frequency and thus is regarded as a modified effective plasma frequency [4–6].

On the other hand, studies of photonic crystals consisting of a superconducting material and a dielectric have also been reported recently [7–9]. The electromagnetic properties of Abrkosov vortex lattice as a photonic crystal were investigated by changing the Ginzburg–Landau parameter and static magnetic field [7]. In addition to a low-frequency band gap below the first band, they also obtained the PBGs for a superconductor in the presence of vortices. In fact, the issue of a superconducting photonic crystal was first investigated by a group in Singapore [8,9]. They considered a one-dimensional superconductor-dielectric superlattcie. By making use of the transfer matrix method accompanied by the Bloch theorem [10], a low-frequency band gap was seen for both transversal magnetic (TM) and transversal electric (TE) modes. This band gap was found to be about one third of the threshold frequency of a bulk superconducting material. The physical information from this work for TE mode however is quite limited because only the first band is given. As for the other higher bands in addition to the possible PBGs cannot be obtained there. In other words, a full band structure for this one-dimensional superconducting photonic crystal remains unavailable thus far.

A full band structure is a basic and important means for understanding the fundamental physics about electromagnetic wave propagation characteristics in a photonic crystal. This information is not only of fundamental but also of technical use for a superconducting material. Motivated by this, in this paper we shall extend the work of Ref. [8]. We would like to present the full photonic band structure for TE mode in a superconductor-dielectric photonic crystal. Firstly, we use the Abeles theory for a stratified media to calculate the frequency-dependent transmittance [11]. From the transmittance spectrum, we can clearly learn the locations of all possible pass bands and stop bands. With these in hand, one is able to calculate the band structure from the transcendental equation based on the transfer matrix method together with the Bloch theorem. Then a comparison between the transmittance spectrum and full band structure will be made.

The format of this work is as follows: Section 2 describes the theoretical approaches to be used in the calculation. The calculated transmittance spectrum and band structure will be given in Section 3. Discussion on the PGBs will also be made in Section 3. A summary will be addressed in Section 4.

2. Theory

A one-dimensional nonmagnetic superconductor-dielectric photonic crystal will be modeled as a periodic superconductor-dielectric multilayer structure with a large number of periods, $N \gg 1$. Such an N-period superlattice is shown in Fig. 1, where $a = a_2 + a_3$ is the spatial periodicity, where a_2 is the thickness of the superconducting layer and a_3 denotes the thickness of the dielectric layer. We consider that a TE wave is incident at an angle θ_1 from the top medium which is taken to be free space with a refractive index, $n_1 = 1$. The index of refraction of the lossless dielectric is given by $n_3 = \sqrt{\varepsilon_{r3}}$, where ε_{r3} is its relative permittivity. For the superconductor, the index of refraction can be described on the basis of the conventional two-fluid model [11]. According to the two-fluid model the electromagnetic response of a superconductor can be described in terms of the complex conductivity, $\sigma = \sigma_1 - j\sigma_2$, where the real part, σ_1, indicating the loss, is contributed by the normal electrons, whereas the imaginary part, σ_2, is due to the superelectrons. The imaginary part is expressed as [12]

$$\sigma_2 = \frac{1}{\omega\mu_0\lambda_L^2}, \tag{1}$$

where the temperature-dependent penetration depth is given by