Fano Resonance Properties in (K$_3$C$_{60}$ / HgBa$_2$Ca$_2$Cu$_3$O$_{10}$) 1D photonic crystal

Arafa H Aly$^{1, *}$, D. Mohamed$^1$, N. S. Abd El-Gawaad$^2$, Z. S. Matar$^3$, Y. Trabelsi$^{4, 5}$ and M. A. Mohaseb$^{1, 3}$

$^1$ TH-PPM group, Physics Department, Beni-Suef university, Beni Suef, Egypt
$^2$ Faculty of Science, King Khalid University, Abha, Saudi Arabia
$^3$ Umm-Al-Qura University, faculty of applied science, department of Physics, Mecca, Saudi Arabia.
$^4$ College of Arts and Sciences in Muhail Asir, Physics Department, King Khalid University, Abha, Saudi Arabia.
$^5$ University of Tunis El Manar, National Engineering School of Tunis, Photovoltaic and Semiconductor Materials Laboratory, 1002, Tunis, Tunisia.

E-mail: arafa.hussien@science.bsu.edu.eg

Abstract

The Fano resonance and Electromagnetic induced reflectance (EIR) properties in one-dimensional superconductor photonic crystals (SPCs) have been investigated theoretically by Transfer Matrix Method (TMM). The periodic structure consists of alternating of pair superconductor materials are made of (K$_3$C$_{60}$ / HgBa$_2$Ca$_2$Cu$_3$O$_{10}$) one-dimensional photonic crystal. The SPCs is enclosed by dielectric cap layer at different induced fields. To exam the efficiency of the reported structure, different parameters are used for analysis such as layers thicknesses, temperature, angle of incidence and the dielectric constant, dielectric cap layer on the EIR and Fano line shape. The investigation results exhibits tunable Fano resonances and EIR resonance peaks accompanied by asymmetrical line shape very sensitive to dielectric cap layer, constituent materials and dependence incidence angle. This will be useful reference for different applications of photonic topological states in the integrated photonic devices and information processing chips.

1. Introduction

Photonic crystals (PCs) are the objects of various theoretical and experimental researches due to their ability to control the flow of electromagnetic waves (EMWs). Such microstructures open a promising application in modern optics [1–9] such as optical filter [10, 11], laser LEDs [12], optical microcavities [13], modulators [14], and sensors [15,16].

In the past decades, the superconductor have introduced in photonic crystals due to their advantages and ability to reduce the damped EMWs instead of metal or normal materials. These new superconducting PCs provide an enlarged reflection bands can be tuned by the temperature of superconductor [17-22]. So, the response of system is mainly dependent on the London penetration depth, which is a function of the temperature and the external magnetic field as well [23-28]. Furthermore, the transmittance spectrum of considered superconducting PCs gives an asymmetric line-shape called Fano resonance and a quantum destructive interference phenomenon called electromagnetic induced reflectance (EIR) [29].
The Fano resonance appears in PCs result on interference between a continuum band of state and a discrete quantum state and shows a sharp change of intensity light [29-30]. These Fano resonances given by superconducting PCs are originated of interesting applications in optical switching, sensing and filtering [31, 32]. However, the tunable electromagnetically induced reflectance (EIR) is used specially for metamaterial and plasmonics [33].

In this paper, we predict and demonstrate the generated electromagnetic induced reflectance resonance (EIR) and Fano resonance of the stacked (K$_3$C$_60$/HgBa$_2$Ca$_2$Cu$_3$O$_{10}$/dielectric cap layer) on glass substrate. We have using two-fluid model and transfer matrix method to characterize and determine the photometric spectrum through the multilayered stacks.

2. Theoretical Models

In this part, we present the theoretical model of the proposed one dimensional superconductor PCs in the form of (AB)$^N$ terminated by dielectric cap layer. Here, layer A and layer B are set to be a superconductor with thickness $d_1$ and $d_2$, respectively repeated for N periods. Figure (1) display the schematic diagram of the proposed periodic 1D superconducting PC structure consists of two superconductor materials. The first one is for (K$_3$C$_60$) and the second layer is from (HgBa$_2$Ca$_2$Cu$_3$O$_{10}$).

![Figure 1: A Schematic diagram of the proposed 1D superconducting PC](image)

The Gorter Casimir two fluid model is adopted to describes the electromagnetic response of the superconductor materials [18]. By adopting some approximations the relative permittivity of superconductor can be written as:

$$\varepsilon_s(\omega)=1-\frac{c^2}{\omega^2\lambda_L^2}$$  \hspace{1cm} (1)

Where, $c$ and $\lambda_L$ denote the velocity of light in vacuum and the temperature dependent London penetration depth [18] noted as follows:

$$\lambda_L=\frac{\lambda_0}{\sqrt{(1-(\frac{\omega}{\omega_T})^q)}}$$  \hspace{1cm} (2)
With $\lambda_0$ represent the London penetration depth where $T = 0$ K. Here T and Tc are the operating and the critical temperature of the superconducting materials. With $q$ takes 2 for High Tc superconductivity and 4 for low Tc superconductivity. The interaction between the incident EMWs and each interface layer through the periodic heterostructure is described using the following matrix [18]:

$$M_j = \begin{pmatrix}
    \cos(k_j \delta_j) & -(i/p_j) \sin(k_j \delta_j) \\
    -(i/p_j) \sin(k_j \delta_j) & \cos(k_j \delta_j)
\end{pmatrix} \quad (3)$$

Where, $M_j$ is the characterized matrix of the $j$th layer. With $\delta_j$ represents the phase variation at $j$th layer. For both TE and TM modes, $\delta_j = d_j n_j \cos \theta_j$. Whereas, $p_j = n_j \cos \theta_j$ for TE mode and $p_j = \cos \theta_j / n_j$ for TM mode. $\theta_j$ is the angle of incidence.

The interaction between all stratified layers and incident EMWs is described using the following matrix [18]:

$$M = \begin{pmatrix}
    m_{11} & m_{12} \\
    m_{21} & m_{22}
\end{pmatrix} = (M_A M_B)^N \quad (4)$$

With N is the period of periodic superconducting layers. Thus, the transmittance values are given by the elements of transfer matrix as [18]:

$$t = \frac{2p_0}{(M_{11} + M_{12} p_f) p_0 + (M_{21} + M_{22} p_f)} \quad (5)$$

With \( p_{0, f} = \sqrt{\frac{\varepsilon_0 n_{0, f}}{\mu_0} / \cos \theta_{0, f}} \).

Then, the transmittance can be expressed as [18]:

$$T = \frac{p_f}{p_0} |t|^2 \quad (6)$$

3. Results and discussion

In this section, the numerical results of the proposed periodic 1D PCs with superconductor photonic heterostructure have been studied in the visible and near infrared (IR) wavelength range. The structure consists of the pair superconductor layers of $K_3C_60$ [34] with \( d_1 = 70 \text{ nm}, \quad T_c = 19.5 \text{ K}, \quad \lambda_0 = 420 \text{ nm} \) and $HgBa_2Ca_2Cu_3O_{10}$ [35] with \( d_2 = 10 \text{ nm}, \quad T_c = 135 \text{ K}, \quad \lambda_0 = 177 \text{ nm} \), respectively. Where, $d_1$, $d_2$, $T_c$ and $\lambda_0$ are the thicknesses, the critical temperature and the London penetration depth of consider superconductor. Let us consider the proposed 1D superconducting PC that are delimited by dielectric cap layered with \([n_3 = 2.5, \ d_3 = 20 \text{ nm}]\) and surrounded by air and glass substrate.

Figure 2 shows the dependence of the reflectance on the normalized frequency of the periodic superconducting PC consisting of the pair superconductor layers ($K_3C_60 / HgBa_2Ca_2Cu_3O_{10}$). It is obvious that the proposed heterostructure exhibit a spectrum with two symmetric narrow reflectance peaks. The first one called Fano resonance and the second peak with two side bands form a broad up ward reflectance valley called the EIR that
took place at 1.11 and 1.55 normalized frequencies. Furthermore, the amplitude of the Fano resonance of the pair superconductor is reach to 80%. However, the EIR reach to 50% of reflection. The given Fano resonance and EIR are due to the destructive interference of a discrete state with a continuum one. The proposed structures can serve as optical switching and light modulator.

Figure 2: Dependence of the reflectance on the normalized frequency of the periodic superconducting PC consisting of the pair superconductor layers (K3C60 / HgBa2Ca2Cu3O10).

Now, we investigated the influence of incident angle on the resonance properties of the periodic superconducting PC. Reflectance spectra versus incident angles for TE waves are shown in Figure 3. As the incident angle increases, both Fano resonance and EIR shift toward the longer frequencies for the proposed structure. This behavior is due to the two coupled oscillator modes that consider the EIR resonance as a special case of Fano resonance happened when the frequencies of strongly and weakly damped oscillators matched [33, 34].

Figure 3: Reflectance spectra versus normalized frequency of the periodic superconducting PC for different incident angles.
Now, we discuss the influence of operating temperature on both Fano and EIR resonances. Figure 4 shows the dependence of the reflectance on the normalized frequency of the periodic superconducting PC for different values of operating temperature. Here the temperatures are set to be 2, 10, 15 and 20 K, respectively. It is obvious that the proposed structures both Fano and EIR peaks have a slowly increase of its amplitude of Fano resonance and the EIR resonance.

![Figure 4: Reflectance spectra versus normalized frequency of the periodic superconducting PC at different values of the temperature.](image)

We study the effect of change in thickness of the superconductor with thicknesses $d_1$ of the periodic superconducting PC. In Figure 5, we have plotted the frequency-dependent reflectance for the superconducting PC in TE wave at different thicknesses $d_1 = 70$ nm, 90 nm, 100 nm and 150 nm respectively. By increasing the thickness $d_1$, the obtained Fano resonance of the periodic superconducting PCs shifted to lower normalized frequency region. Wherein, the EIR with symmetrical line shape shifted towards the high normalized frequency region accompanied by new Fano resonance peaks. It is obvious that from the spectrum the number of Fano resonance peaks depends on set thickness and can serve as multi-optical switching. It constitute an advantages of macroscopic opto-electronic switching in which the damped of oscillation within this behavior is reduced.

The dependence of the reflectance for the TE polarized EMWs on the Fano resonance and EIR for the normal incidence angle is illustrated in Figure 6, for some refractive index of dielectric cap layer: 1.3, 1.6, 2 and 2.5. By increasing the refractive index of dielectric cap layer, the reflectance exhibit a spectra in which position and amplitude of Fano resonance peak and the EIR decrease progressively for an increase of refractive index of its dielectric cap layer. This decrease in peak height means an incomplete resonance at the defect mode. For the refractive index of substrate layer, $n_s=2.5$, the Fano resonance of the proposed superconducting PC become
symmetrical line shape. In this case, such dielectric cap layer is very important to calibrate the proposed structure by adjusting the characteristics of Fano resonance and EIR peaks.

**Figure 5:** Reflectance spectra versus normalized frequency of the periodic superconducting PC at different values of thicknesses $d_1$ (nm).

**Figure 6:** Reflectance spectra versus normalized frequency of the periodic superconducting PC at different values of refractive index of consider dielectric cap layer.

In Figure 7, the resonance properties are depicted as functions of normalized frequency for different thicknesses of dielectric cap layer $d_c$ (nm). By increasing the $d_c$, the reflectance exhibits a spectrum in which the Fano resonance in the periodic superconducting PCs present two asymmetric resonance peaks. However, the position
of given EIR peaks shifted to the lower normalized frequency region when we increase the thickness of dielectric cap layer. It should be noted that its peak of EIR become with asymmetric shape line from dc=8nm due to the increase of the phase shift in the two coupled oscillator mode.

Figure 7: Reflectance spectra versus normalized frequency of the periodic superconducting PC at different values of thicknesses of dielectric cap layer dc (nm).

Conclusion:

A theoretical study of Fano resonance and EIR properties in periodic 1D superconducting PCs consisting of (K3C60 / HgBa2Ca2Cu3O10) superconducting materials are investigated. The suggested structure exhibits a tunable Fano resonances and EIR resonance peak accompanied by asymmetrical line shape very sensitive to thickness and refractive index of dielectric cap layer, constituent materials, dependence incidence angle and temperature. Furthermore, the obtained spectra are tunable by adjusting the value of the optical parameters. As a result, a good response with maximum peaks of reflection is given by the proposed structure. Finally, the structure will be helpful in the field of optical communication and it can be used as optical switch.

4. References

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