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Photonic States in Superconductor-Dielectric Semi-Infinite Structures

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Resumen

Con base en la teoría de la respuesta lineal, se discuten las propiedades colectivas electromagnéticas de un cristal fotónico semi-infinito que contacta con el vacío. El crstal fotónico consiste en una serie alternada de capas superconductor-dieléctrico de diferentes espesores. Se consideran la estructura de la banda fotónica del sistema en bloque, además de los modos localizados que surgen debido al rompimiento de la simetría traslacional. Se demuestra que, a medida que aumenta la magnitud de la componente en el plano del vector de onda, la frecuencia del modo localizado más bajo crece, mientras que la del modo más alto- decrece. Por otro lado, para un valor dado la magnitud de la componente en el plano del vector de onda, aparecen modos adicionales en la brecha de la banda, de tal forma que si la capa superconductora está en contacto con el vacío, hay un modo en la brecha superconductora que existe para valores del vector de onda por encima de cierto valor crítico no nulo. Los resultados se ilustran con curvas de dispersión del sistema en bloque y para los modos localizados.

Palabras claves: Cristales fotónicos, brecha de banda fotónica, materiales superconductores, materiales ópticos, rompimiento de simetría.

Abstract

On the basis of the linear response theory, we consider the collective electromagnetic properties of a semi-infinite photonic crystal which is contacting with vacuum. The photonic crystal system consists of alter-nating superconductor-dielectric slabs of different thicknesses. The bulk photonic band structure and the corresponding localized modes, arizing due to the broken translational symmery, are considered. It is shown that, as well as the magnitude of the in-plane wave vector rises, the frequency of the lowest local-ized mode increases, as well as the highest-frequency localized mode decreases. On the other hand, for a fixed in plane wave vector there appear additional modes in the band gap, in such a way that if the superconductor layer contacts with vacuum, there is a mode in the superconductor gap which exists for in-plane wave vectors above a critical non zero value. The results are illustrated with dispersion curves of the bulk and localized modes.

Key Words: Photonic crystals, photonic band gap, superconductor materials, optic materials, broken symmetry.

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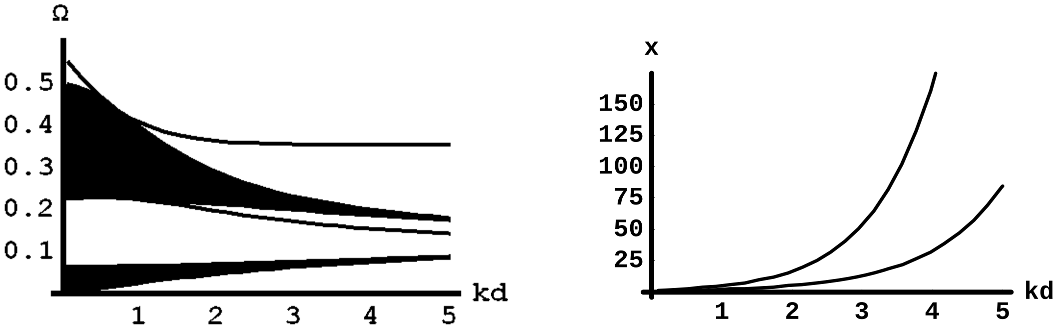
1. Introducción

Photonic crystals [1] have inspired during last years a wealth of potential telecommunication applications (waveguides, channel drop filters, and omni directional reflectors). Special attention has been devoted to modes arising in such systems; for the case of a photonic crystal consisting in a binary system of polar rods immersed in a homogeneous dielectric medium the collective modeswere considered [2]. In the particular case of photonic crystals containing superconductor slabs [3, 4] a low-frequency plasma gap exists associated to the non-zero density of superconductor carriers, and there is a photon-superelectron hybrid mode around the polariton gap.



(a) (b)

Fig.1 (*a*) Bulk (shadow regions) and localizaed (continuos lines) modes arising in a semiinfinite insulator-superconductor photonic crystal for the case when the superconductor slab contats with vacuum. *(b)* Behavior of the characteristic parameter *x*. Numerical calculations were performed for Λ=0.5; d_1= 0.2*d*; d_1=1- d_1; ε' = 1; ε_2 := 15;

In recent papers [5, 6] it was shown that, for a given lattice period, when the superconducting slab occupies a major percentage of the unitary cell of the photonic crystal, the number of bands in a fixed range of frequencies diminishes, the intervals of forbidden frequencies decrease and the respective allowed bands present a strong dependence with the wave quasivector. Additionally, as well as the London penetration length decreases, the bands become less dispersive, which indicates that the superconductor slabs are relevant in the coupling of neighbour unit cells.

Most calculations in photonic crystals assume that the system is periodic. Nevertheless, a broken traslational symmetry implies the possibility of the appearance of localized modes with frequencies inside the band gaps and electromagnetic fields decaying exponentially away fron the spatial region where the traslation symmetry is broken. For this reason, in the present communication we consider the collective electromagnetic properties of a semi-infinite photonic crystal which is contacting with vacuum. The surface waves arising in this case have been proposed as a way to inject light into a photonic waveguide [7, 8].

2. Model and general relations

The system under consideration is modeled as a semi-infinite (z>0) superconductor-dielectric multilayer structure contacting with a semi-infinite (z>0) medium with dielectric permittivity ε'. The unit cell of thickness *d* of the multilayered system consists of a superconducting slab of thickness d_1 (with relative dielectric permittivity ε_1 defined below) and a dielectric slab of thickness d_2 (with relative dielectric permittivity ε_2). The superconductor slabs can be characterized by a relative dielectric permittivity of the form $\varepsilon_1(\omega)=1-[c/(\omega\lambda_L)]^2$, λ_L being the temperature dependent London penetration depth given by $\lambda_L(T)=\lambda_0[1-(T/T_c)^4]^{1/2}$, where $\lambda_0=[mc^2/4\pi ne^2]^{1/2}$ and n is the density of superconductor carriers.

To find the bulk and the surface states we must solve the Maxwell equations with the bondary conditions of continuity of the tangential components of the electric and magnetic intensity fields and by assuming a dacaying amplitude of the relevant fields of the form exp(-αz).

Because of the homogeneity and isotropy of the system in the layer planes, the solutions can be assumed to have the form of free waves with frequency ω and wave vector $\mathbf{k}$=(k,0,0). After a long calculation, we obtain the following relations for the *p*-polarized modes:

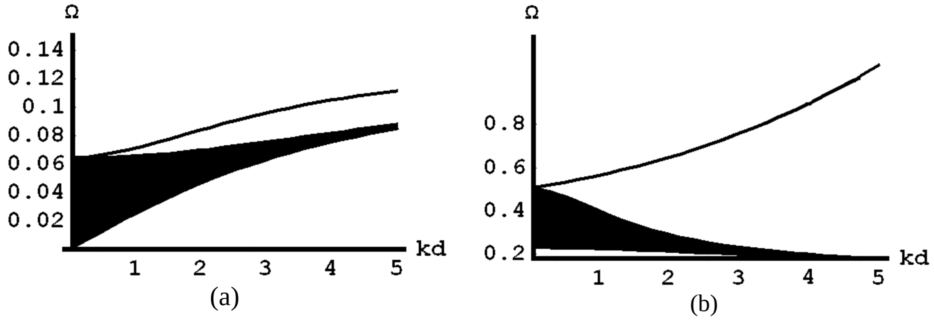
$$\frac{1}{2}\left(x+\frac{1}{x}\right)=\cosh(\kappa_1 d_1)\cosh(\kappa_2 d_2)+\frac{1}{2}\left[\frac{\kappa_2\varepsilon_1}{\kappa_1\varepsilon_2}+\frac{\kappa_1\varepsilon_2}{\kappa_2\varepsilon_1}\right]\sinh(\kappa_1 d_1)\sinh(\kappa_2 d_2) \qquad (1)$$

$$\frac{\varepsilon_2\kappa_2\left[(\kappa_1\varepsilon')^2-(\kappa'\varepsilon_1)^2\right]-\kappa'\varepsilon'\left[(\kappa_1\varepsilon_2)^2-(\kappa_2\varepsilon_1)^2\right]\tanh(\kappa_1 d_1)}{\varepsilon_1\kappa_1\left[(\kappa'\varepsilon_2)^2-(\kappa_2\varepsilon')^2\right]\tanh(\kappa_1 d_1)}=\coth(\kappa_2 d_2) \qquad (2)$$

$$\frac{1}{x}=\cosh(\kappa_1 d_1)\cosh(\kappa_2 d_2)+\frac{\kappa'\varepsilon_2}{\kappa_2\varepsilon'}\sinh(\kappa_1 d_1)\cosh(\kappa_2 d_2)+\frac{\kappa_1\varepsilon_2}{\kappa_2\varepsilon_1}\sinh(\kappa_1 d_1)\sinh(\kappa_2 d_2)-\frac{\kappa_1\varepsilon'}{\kappa'\varepsilon_1}\cosh(\kappa_1 d_1)\sinh(\kappa_2 d_2) \qquad (3)$$

where $\kappa(z)=(k^2-\varepsilon(z)\omega^2/c^2)^{1/2}$ and x= exp(-αz). The localization of the excitation can be characterisized by the magnitude *x*.

3. Results and discussion.



(a)

(b)

Fig.2 Same as in Fig. 1 for low *(a)* and high *(b)* frequency modes arising in the case when the dielectric slab contacts with vacuum.

For the description of the localized modes arising in a semi-infinite 1D photonic crystal, let us introduce the dimensional-less quantities $\Omega=\omega d/(2\pi c)$, $\Lambda=d/(2\pi\lambda_L)$.

The bulk bands of this system for homogeneous (k=0) oscillations were described in [6]. By means of a numerical analysis of relation (2) we have found that in the semi-infinite photonic crystal considered here there are not localized homogeneous modes, because of the relevant role played by the retadation effects. For this reason in the following we will describe the collective excitations in the nonretarded region of spectra.

The bulk spectra of collective excitations consist of a narrow low frequency band (with frequencies in the range $0<\omega<\omega_0$, $\omega_0<1/\lambda_L$) and a wider high-frequency band with frequencies $\omega>1/\lambda_L$, the bands being separated by a band gap. These bulk bands are illustrated by the shadowed regions in Figs. 1(a), 2(a) and 3(a). At the narrow band (correspondly, at the wider band), the lowest (highest) frequencies correspond to out of phase oscillations of the electromagnetic fields at adjacent layers (edge of the mini Brillouin zone). Additionally, the center of the mini Brillouin zone corresponds to the highest (lowest) frequencies of the narrow (wider) band.

In Fig.1(a) we have illustrated the localized modes arising when the traslational symmtry is broken at the superconductor slab. In this case there are two localized modes close to the wider band. The lowest (highest) frequency mode starts at the center (edge) of the mini Brillouin zone of the wider bulk band. The behavior of the corresponding localization parameter x is displayed in Fig. 1*(b)*. It can be seen that of the mode becomes more localized as well as the in plane wave vector increases.

In the case when the traslational symmtry is broken at the insulator slab, the lowest frequency mode starts at the center of the mini Brillouin zone of the narrower band, as is displayed in Fig. 2*(a)*. On the other hand, the behavior of the the high frequency mode for graet values of the in plane wave vector is qualitativaly similar to that displayed in Fig. 1. This means that only the character of lowest frequency mode is affected by the kind of layer wich is breaking the traslational symmetry.

Conclussion.

In summary, in discussing the localizaed modes arising in a semi-infinite dielectric-photonic crystal, we obtained the general relations allowing us to describe the dispersion relations of such modes in the non-retarded region of spectra. The obtained results can be extended to consider additional mechanisms of breking the periodic condition, such as the inclusion of single and several defect layers.

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