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Excitation of Josephson plasma waves in a layered high-temperature superconductor slab embedded in a high refractive index dielectric

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The nonlocal optical response of a layered high-temperature superconductor slab embedded in a dielectric medium is theoretically studied. It is assumed that the layers inside the high-temperature superconductor are parallel to the slab surfaces. We calculate its p-polarization optical spectra by using an average permittivity tensor which depends on both the frequency and the wave vector of the electromagnetic wave. Consequently, additional electromagnetic modes just above the characteristic Josephson plasma frequency, being in the terahertz range, are generated. It is shown that the p-polarization reflectivity spectra for a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) superconductor slab, embedded in high refractive index dielectric, exhibit prominent dips breaking the total internal reflection. For very small superconductor slab thicknesses, the optical spectra resonances are associated with Fabry–Perot resonances of the short-wavelength electromagnetic modes. In contrast, the long-wavelength electromagnetic modes, having anomalous dispersion relation, are excited at relatively-large slab thicknesses and manifest themselves as strong resonances in both absorption and transmissivity spectra, suppressing the specular reflectivity.

Keywords: layered superconductors, cuprate superconductors, metamaterials, spatial dispersion, thin films.

1. Introduction

For more than two decades, the optical properties of layered high-temperature superconductors have attracted the attention of scientists because of their intriguing behavior in the terahertz (THz) frequency range and the excitation of Josephson plasma waves. Such layered superconductors are commonly modeled as periodic systems with intrinsic Josephson junctions in the unit cell [1–7]. However, as was shown in the works [4–6,8], in the long-wavelength, their optical properties are well described by using an average nonlocal permittivity tensor, $\vec{\varepsilon}_{\rm av}$, which depends on both the frequency ω and the wave vector $k_z^{(s)}$ of the electromagnetic wave. The nonlocality of the layered high-temperature superconductor is originated by the induction of charge in the superconducting layers, which is responsible for the so-called capacitive interlayer coupling [6]. According to Refs. 4–6, 8, the nonlocal optical response of layered superconductors is relevant at frequencies near the frequency Josephson plasma frequency ω_p, being in the THz range.

If the dynamical breaking of charge neutrality in the layered superconductor is neglected, the average permittivity tensor is independent of the wave vector and the superconductor becomes a local anisotropic medium. Within the local approach, several optical properties of layered high-temperature superconductors have been studied and explained (see, for example, [8–13] and references therein). In particular, it has been established [8] that a layered superconductor behaves as a hyperbolic metamaterial at $\omega > \omega_p$ since the local permittivity components, parallel and perpendicular to the superconducting planes, have different signs. Therefore, the layered high-temperature superconductors are included in the class of natural single-phase hyperbolic metamaterials [15,16].

The dispersion relations of surface and waveguide Josephson plasma waves in a superconducting slab embedded in a dielectric medium, have been studied in Refs. 9, 11, 13, and 14 using a local permittivity tensor. In Ref(s). 9 ([11,13,14]), it was assumed that the superconducting layers are parallel (orthogonal) to the slab surface and the electromagnetic waves have transverse-magnetic (TM) polarization. As follows from such studies, the structure of the eigenspectrum is determined by the ratio between the dielectric constants of the surrounding medium and the insulator separating the superconducting layers, respectively ε_d and ε. Besides, it was shown that the predicted waves can be detected by applying the attenuated-total-reflection (ATR) technique [9,13,14]. Interestingly, for certain parameters of the heterostructure, the excitation of the waveguide modes in the layered high-temperature superconductor is accompanied by the total suppression of specular reflection.

In our previous works [10,17], we have studied the far-infrared reflectivity and transmissivity of a layered high-temperature superconductor slab, embedded in vacuum and having superconducting planes parallel to its surfaces. The optical response of the hyperbolic negative-index superconductor was modeled by using both a local permittivity tensor [10] and a nonlocal one [17]. In the local case, the optical spectra exhibit Fabry–Perot resonances, which are associated with the quantization of the wave vector for TM electromagnetic modes and observed in the passband of the anomalous dispersion. As was shown there, the quantized modes turn out to be quasi-longitudinal because of the strong anisotropy of the far-infrared optical response of the layered superconductor. According to our more-recent work [17], the superconductor nonlocality leads to the generation of additional electromagnetic modes just above the Josephson plasma frequency ω_p. Indeed, the calculated therein p-polarization optical spectra for a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) superconductor slab show very narrow resonances associated with the quantization of the wave vectors of both long-wavelength electromagnetic modes, having anomalous dispersion, and short-wavelength additional (nonlocal) modes with normal dispersion.

In the present work, we shall calculate and analyze the TM optical spectra of a nonlocal layered high-temperature superconductor slab, which is embedded in a dielectric medium, having a dielectric constant ε_d larger than the permittivity ε of the insulating layers in the superconductor ($\varepsilon_d > \varepsilon$). Such a situation is of interest because the total internal reflection (TIR) for TM modes could be frustrated by the hyperbolicity of the layered high-temperature superconductor as it occurs in artificial normal-metal/dielectric hyperbolic metamaterials [18]. Moreover, the phenomenon, which is now called hyperbolicity-frustrated total internal reflection (HF-TIR), should be altered by the excitation of additional electromagnetic modes inside the layered-superconductor metamaterial.

This paper has been organized as follows: The formalism, based on the use of a nonlocal average permittivity tensor, for calculating the TM optical spectra of the embedded layered superconductor slab, is described in Sec. 2. Section 3 contains our analysis of the calculated dispersion relation of TM modes and the reflectivity spectra for a Bi2212 superconductor slab. Besides, the effect of the layered-superconductor nonlocality upon the HF-TIR is here studied. The obtained optical spectra for the high-temperature superconductor metamaterial are compared with those observed in artificial hyperbolic metamaterials. Finally, there is a section of Conclusions (Sec. 4).

2. Theoretical formalism

2.1. Formulation of the problem

Let us consider a layered high-temperature superconductor slab, embedded in a dielectric and occupying the space $0 \le z \le d$ (see, Fig. 1). The superconducting layers are assumed to be parallel to the $x-y$ plane, i.e., to the superconductor surfaces at $z = 0$ and $z = d$. It is also assumed that a monochromatic electromagnetic plane wave with p-polarization is incident on the front surface (at $z = 0$) of the superconductor slab. According to the geometry, the magnetic field of the incident wave can be expressed as

$$H_i = (0, H_i, 0)\exp(ik_x x + ik_z z - i\omega t), \quad (1)$$

where $k_x = k\sqrt{\varepsilon_d}\sin\theta$ and $k_z = k\sqrt{\varepsilon_d}\cos\theta$ denote the components of the incident wave vector $\mathbf{k}_i$, $k = \omega/c$, c is the velocity of light in vacuum, ε_d is the scalar permittivity of the dielectric medium, and θ is the incidence angle. The magnetic component of the reflected p-polarized electromagnetic wave is written as

$$\mathbf{H}_r = (0, H_r, 0)\exp(ik_x x - ik_z z - i\omega t), \qquad z \le 0. \quad (2)$$

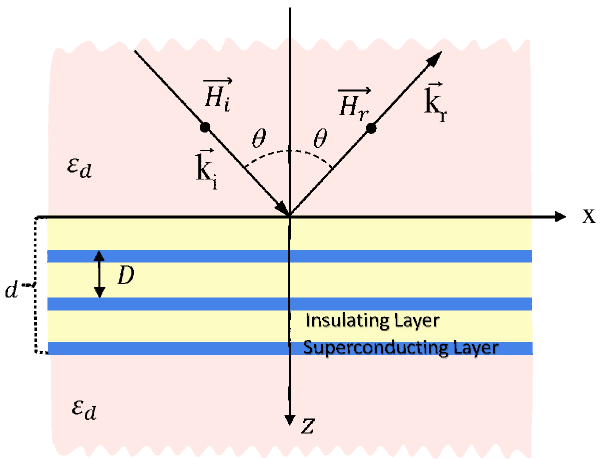

Fig. 1. Scheme of a high-temperature layered superconducting slab embedded in a dielectric medium. $\mathbf{k}_i$ and $\mathbf{k}_r$ are respectively the wave vectors of the incident and reflected light.

Hence, the total magnetic field $\mathbf{H}^{(u)}$ in the upper dielectric space ($z \le 0$) is simply given by

$$\mathbf{H}^{(u)} = \mathbf{H}_i + \mathbf{H}_r, \qquad z \le 0. \tag{3}$$

The magnetic field of the transmitted electromagnetic wave into the lower dielectric space ($z \ge d$) is written as

$$\mathbf{H}^{(t)} = (0, H_t, 0)\exp(ik_x x + ik_z(z-d) - i\omega t), \quad z \ge d. \tag{4}$$

In order to calculate the electromagnetic field inside the layered superconductor slab, we shall model the material equation, relating the displacement vector **D** and the electric field **E**,

$$\mathbf{D} = \vec{\epsilon}_{\rm av}\mathbf{E}, \tag{5}$$

by applying the nonlocal average permittivity tensor $\vec{\epsilon}_{\rm av}$ derived in the works [5,8]. Accordingly, the principal values of $\vec{\epsilon}_{\rm av}$ are functions of the wave number $k_z^{(s)}$ and frequency ω as

$$\varepsilon_x(\omega) = \varepsilon_y(\omega) = \varepsilon\left(1 - \frac{\gamma^2\omega_p^2}{\omega^2}\right) + \frac{i4\pi\sigma_x}{\omega}, \tag{6}$$

$$\varepsilon_z(\omega, k_z^{(s)}) = \varepsilon\left[1 - \frac{\omega_p^2\left(1 + 2\alpha(1 - \cos(k_z^{(s)}D))\right)}{\tilde{\omega}^2}\right], \tag{7}$$

$$\tilde{\omega} = \frac{\omega}{\sqrt{1 - i4\pi\sigma_z \dfrac{\omega}{\omega_p^2\varepsilon}}}, \tag{8}$$

where $\gamma = \lambda_\perp / \lambda_\parallel$ symbolizes the anisotropy parameter given by the ratio between the transverse ($\lambda_\perp$) and parallel ($\lambda_\parallel$) magnetic-field penetration depths, and D is the period of the array of insulating and superconducting layers (Fig. 1). The Josephson plasma frequency ω_p is defined by [5,6]:

$$\omega_p = c / (\lambda_\perp \sqrt{\varepsilon}). \tag{9}$$

Moreover, σ_z and σ_x are the averaged transverse and in-plane quasi-particle conductivities, respectively, and α is the nonlocality (capacitive coupling) parameter.

Using the average permittivity components (6) and (7) and solving Maxwell equations, the magnetic field inside the superconductor slab can be expressed as a linear superposition of four TM plane electromagnetic waves:

$$\mathbf{H}^{(s)} = (0, H_y^{(s)}(z), 0)\exp(ik_x x - i\omega t), \tag{10}$$

where

$$H_y^{(s)}(z) = \sum_{j=1}^{4} A_j e^{ik_z^{(j)}z}. \tag{11}$$

Here A_j and $k_z^{(j)}$ ($j = 1, 2, 3, 4$) are, respectively, the amplitudes and wave vectors of the plane waves. The explicit dispersion relation $k_z^{(j)}(\omega)$ for such electromagnetic waves is found by solving the characteristic equation:

$$\frac{\left(k_z^{(s)}\right)^2}{\varepsilon_x(\omega)} + \frac{k_x^2}{\varepsilon_z\left(\omega, k_z^{(s)}\right)} = \frac{\omega^2}{c^2}. \tag{12}$$

As was shown in Refs. 5 and 17, Eq. (12) leads to a bi-quadratic algebraic equation for $k_z^{(s)}$, having four solutions:

$$k_z^{(j)}, \qquad j = 1, 2, 3, 4, \tag{13}$$

where $k_z^{(1)} = -k_z^{(3)}$ and $k_z^{(2)} = -k_z^{(4)}$. Also, it is assumed that

$$\operatorname{Im} k_z^{(1)} > 0 \ \text{ and } \ \operatorname{Im} k_z^{(2)} > 0.$$

Consequently, the first and second ($j = 1, 2$) electromagnetic modes decay in the positive direction of the z axis, whereas the third and fourth modes ($j = 3, 4$) decay in the opposite direction.

Using Eq. (11) and Faraday law, the x and z components of the electric field inside the superconductor slab can be straightforwardly calculated. We get

$$E_x^{(s)}(z) = \frac{c}{\omega\varepsilon_x}\sum_{j=1}^{4} A_j k_z^{(j)} e^{ik_z^{(j)}z}, \tag{14}$$

$$E_z^{(s)}(z) = -\frac{ck_x}{\omega}\sum_{j=1}^{4} \frac{A_j}{\varepsilon_z(\omega, k_z^{(j)})} e^{ik_z^{(j)}z}. \tag{15}$$

2.2. Boundary conditions

The amplitudes of the electromagnetic waves in the dielectric medium (H_r and H_t in Eqs. (2) and (4)), as well as in the superconductor slab (A_j, $j = 1, 2, 3, 4$, in Eq. (11)) are calculated by using Maxwell boundary conditions: the continuity of the tangential components of the electric and magnetic fields at the front and rear slab surfaces:

$$E_x^{(u)}(0) = E_x^{(s)}(0), \qquad E_x^{(s)}(d) = E_x^{(t)}(d),$$
$$H_y^{(u)}(0) = H_y^{(s)}(0), \qquad H_y^{(s)}(d) = H_y^{(t)}(d). \tag{16}$$

Besides the four equations in (16), it is necessary to derive two additional boundary conditions (ABC) for calculating all the amplitudes. Here we shall apply the ABC related with the fact that the surface Josephson junctions have only one neighboring junction and, therefore, the average of the polarization component, parallel to the growth direction of the layered superconductor, just outside the slab should be equal to the polarization of the external medium [5,17].

For the anisotropic layered superconductor having a nonlocal dielectric response, the polarization vector in the anisotropic layered superconductor can be written in the form:

$$\mathbf{P}^{(s)} = \left(P_x^{(s)}(z),\ 0,\ P_z^{(s)}(z)\right)\exp(ik_x x - i\omega t), \tag{17}$$

Here, the polarization x- and z-components are given by

$$P_x^{(s)}(z) = \chi_x E_x^{(s)}(z), \tag{18}$$

where $\chi_x = (\varepsilon_x - 1)/4\pi$, $E_x^{(s)}(z)$ has the form (14) and

$$P_z^{(s)}(z) = \sum_{j=1}^{4} \chi_{e,z}\left(k_z^{(j)}\right) E_z^{(s)}\left(k_z^{(j)}\right) e^{ik_z^{(j)}z}, \quad (19)$$

with $\chi_z(k_z^{(j)}) = (\varepsilon_z(k_z^{(j)}) - 1)/4\pi$ and

$$E_z^{(s)}(k_z^{(j)}) = -\frac{ck_x}{\omega} \frac{A_j}{\varepsilon_z(\omega, k_z^{(j)})}. \quad (20)$$

Now, let us apply the procedure proposed in Refs. 5 and 17 for determining the ABCs by averaging the polarization z-component over the width ($= D \ll d$) of imaginary Josephson junctions just outside the slab and equating it to the polarization in the dielectric medium. Finally, we get

$$P_z^{(s)}(0) - \frac{1}{2} D \frac{\partial P_z^{(s)}}{\partial z}(0) = \chi_d E_z^{(u)}(0), \quad (21)$$

$$P_z^{(s)}(d) + \frac{1}{2} D \frac{\partial P_z^{(s)}}{\partial z}(d) = \chi_d E_z^{(t)}(d), \quad (22)$$

where $\chi_d = (\varepsilon_d - 1)/4\pi$ is the susceptibility of the dielectric. If the external medium is vacuum ($\varepsilon_d = 1$), the right hand sides of Eqs. (21) and (22) vanish and the ABCs go over into those derived in Ref. 17. The new ABCs belong to the class of generalized ABCs [19]. Using Maxwell boundary conditions (16) and the ABCs given by Eqs. (21) and (22), one can numerically calculate the p-polarization reflectivity ($R_p = |H_r/H_i|^2$) and transmissivity ($T_p = |H_t/H_i|^2$) spectra for the layered superconductor slab embedded in a dielectric medium.

3. Results and discussion

3.1. Excitation of short-wavelength modes

Let us apply the above described theoretical formalism to calculate and analyze p-polarization optical spectra of a Bi2212 superconductor slab embedded in a high refractive index dielectric ε_d, being larger than that (ε) of the insulating layers. The calculated p-polarization reflectivity R_p, transmissivity T_p and absorption $A_p = 1 - R_p - T_p$ as functions of both frequency ω and incidence angle θ are respectively shown in panels (a), (b) and (c) of Fig. 2. The superconductor parameters used in the calculations are [8]: $\omega_p = 10^{12}$ rad/s, $\gamma = 500$, $\varepsilon = 12.0$. Other parameters are: the nonlocality parameter $\alpha = 0.05$, which corresponds to the regime of strong nonlocality [17], a very small superconductor slab thickness $d = 0.1\delta$, where δ is the smallest of the penetration depths for the anisotropic superconductor ($\delta = \lambda_\parallel = c/(\gamma\omega_p\sqrt{\varepsilon}) = 173.20$ nm), and the lattice constant $D = 15.35$ Å of the layered structure. In the calculations, we have used realistic values for both in-plane ($\sigma_x = 3.6\cdot 10^4 \omega_p$ [8,20–22]) and transverse ($\sigma_z = 1.8\cdot 10^{-3}\omega_p$ [8,22,23]) conductivities. The external dielectric medium is assumed to be Ge with $\varepsilon_d = 16$.

As is seen in Fig. 2, the reflectivity considerably decreases at angles $\theta \gtrsim 70^\circ$. Comparing it with the transmissivity

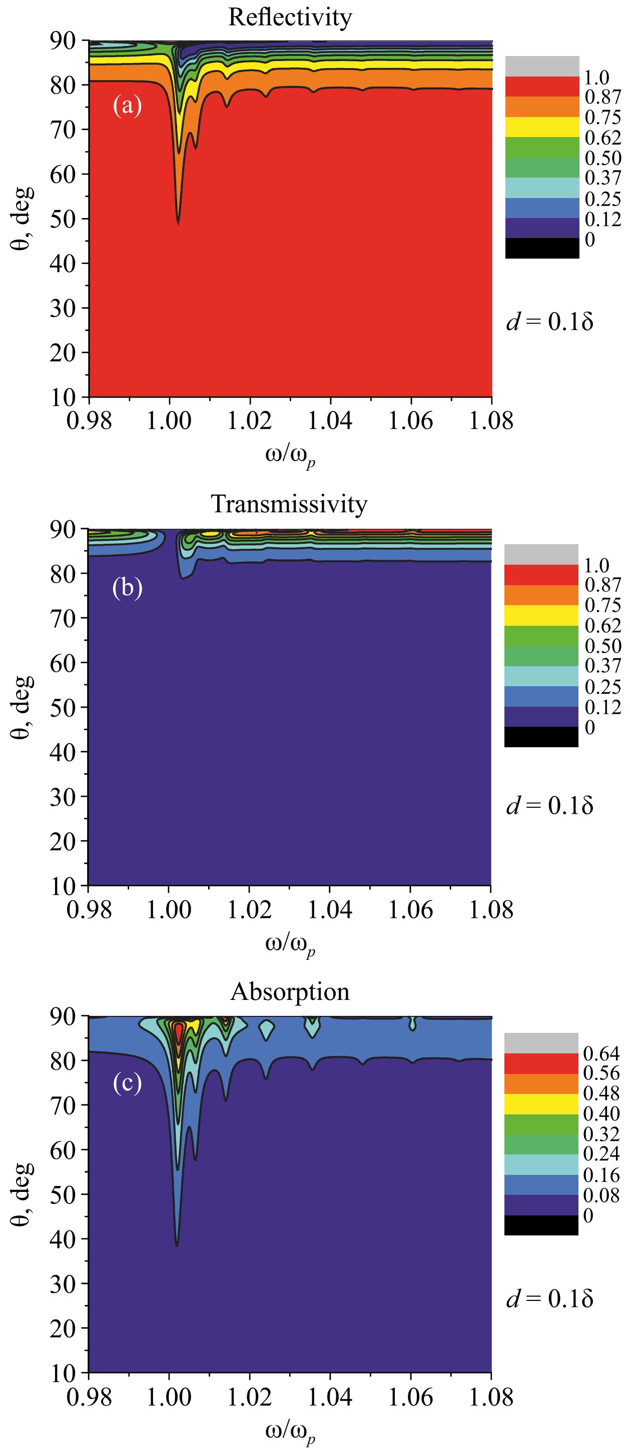

Fig. 2. (Color online) Dependence of the p-polarization reflectivity (a), transmissivity (b) and absorption (c) spectra for a Bi2212 superconductor slab of thickness $d = 0.1\delta$ on frequency ω and incidence angle θ.

and absorption spectra, such a reflectivity decrease is mainly connected to the increase of absorption just above the Josephson plasma frequency (panel (c)), and to the enhancement of the transmissivity at higher frequencies. To explain such a behavior, we present the frequency dependence of the optical spectra (R_p, T_p, and A_p) for the same super-

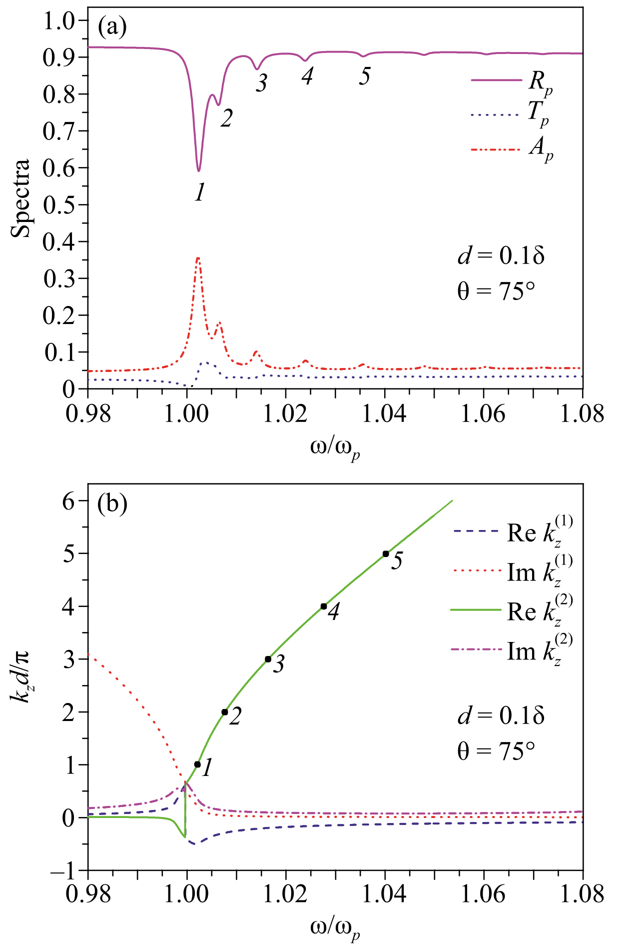

Fig. 3. (Color online) (a) p-polarization reflectivity (R_p), transmissivity (T_p) and absorption (A_p) spectra for a Bi2212 superconductor slab of thickness $d = 0.1\delta$ at $\theta = 75^\circ$. (b) Dispersion relation $k_z^{(s)}(\omega)$ for p-polarized modes in a Bi2212 superconductor.

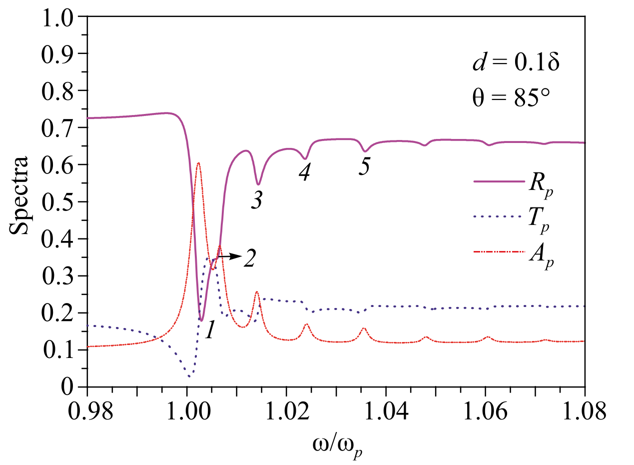

Fig. 4. (Color online) p-polarization reflectivity (R_p), transmissivity (T_p) and absorption (A_p) spectra for a Bi2212 superconductor slab of thickness $d = 0.1\delta$ at $\theta = 85^\circ$.

conductor slab, but at the angle of incidence $\theta = 75^\circ$ (Fig. 3(a)), as well as the dispersion relation curves of the TM electromagnetic waves (panel (b)). Note that the optical spectra exhibit a rich resonance structure which is due to the

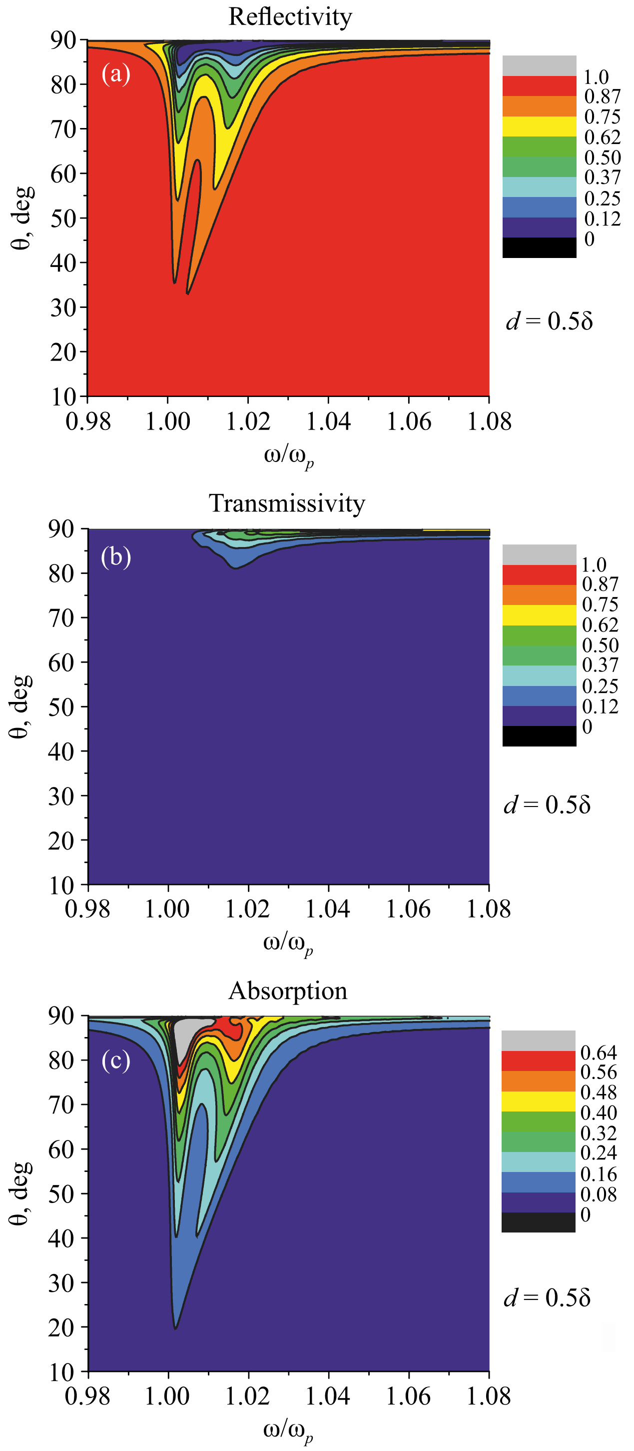

Fig. 5. (Color online) Dependence of the p-polarization reflectivity (a), transmissivity (b) and absorption (c) spectra for a Bi2212 superconductor slab of thickness $d = 0.5\delta$ on frequency ω and incidence angle θ.

excitation of quantized short-wavelength electromagnetic waves, whose wave vector satisfies the Fabry–Perot condition $\mathrm{Re}\, k_z^{(2)} d = n\pi$ ($n = 1, 2, \ldots$ and $0 < \mathrm{Im}\, k_z^{(2)} \ll \Re k_z^{(2)}$) in the thin superconductor slab.

In Fig. 4 we show p-polarization optical spectra (reflectivity, transmissivity and absorption) for a superconductor slab as that considered in Figs. 2 and 3, calculated with $\theta = 85^\circ$. Evidently, the overall decrease of the reflectivity is correlated with the enhancement of both absorption and transmissivity. Unlike the resonances observed in optical spectra for very thin layered superconductor slabs embedded in vacuum [17], the predicted here resonances for the case when the external medium has a high refractive index $\sqrt{\varepsilon_d} > \sqrt{\varepsilon}$ are well discernible.

3.2. Excitation of long-wavelength modes

We have also calculated p-polarization reflectivity R_p, transmissivity T_p and absorption $A_p = 1 - R_p - T_p$ for a Bi2212 superconductor slab of thickness $d = 0.5\delta$ as functions of both frequency ω and incidence angle θ (panels (a), (b) and (c) of Fig. 5, respectively). As is seen, the reflectivity is practically suppressed at incidence angles $\theta \gtrsim 70^\circ$, whereas the absorption and transmissivity are enhanced just above the Josephson plasma frequency ω_p.

Figure 6(a) presents the frequency dependence of p-polarization reflectivity, transmissivity and absorption spectra for the same superconductor slab as in Fig. 2 at the angle of incidence $\theta = 75^\circ$. The panel (b) of Fig. 6 exhibits the dispersion relation curves of the electromagnetic modes in

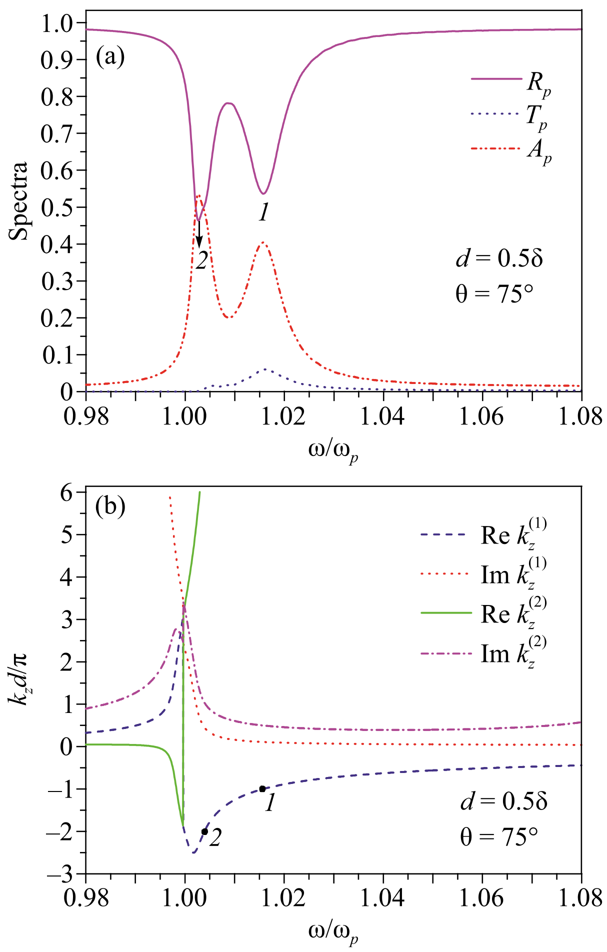

Fig. 6. (Color online) (a) p-polarization reflectivity (R_p), transmissivity (T_p) and absorption (A_p) spectra for a Bi2212 superconductor slab of thickness $d = 0.5\delta$ at $\theta = 75^\circ$. (b) Dispersion relation $k_z^{(s)}(\omega)$ for p-polarized modes in a Bi2212 superconductor.

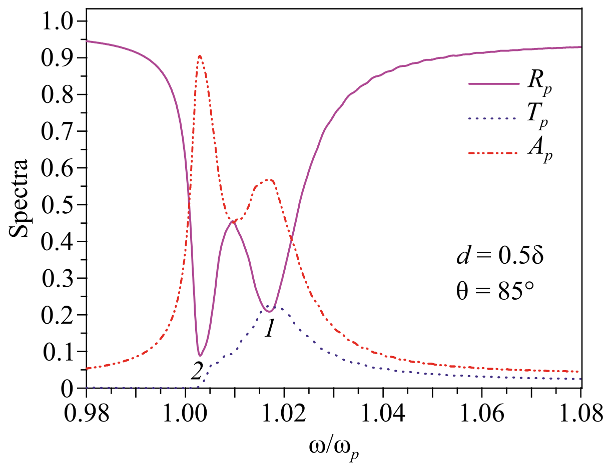

Fig. 7. (Color online) p-polarization reflectivity, transmissivity and absorption spectra for a Bi2212 superconductor slab of thickness $d = 0.5\delta$ at $\theta = 85^\circ$.

the superconductor slab. According to these results, the resonances associated with the short-wavelength modes are smoothed out because of their coalescence. In contrast, the resonances associated with long-wavelength electromagnetic waves emerge in the optical spectra at frequencies where the Fabry–Perot condition $|\mathrm{Re}\, k_z^{(1)}|\, d = n\pi$ $(n = 1, 2, \ldots$ and $0 < \mathrm{Im}\, k_z^{(1)} \ll |\mathrm{Re}\, k_z^{(1)}|)$ is fulfilled. It should be noted that the dispersion relation for these modes is anomalous (i.e., the phase velocity ω / k_z is opposite to the group velocity $\partial\omega / \partial k_z$).

In Fig. 7 we show p-polarization optical spectra for a superconductor slab embedded in Ge as that of Fig. 6, but calculated with an incidence angle $\theta = 85^\circ$. As is seen, the resonances associated with the quantized long-wavelength modes are even more pronounced at $\theta = 85^\circ$. These results allow us to conclude that the quantization of long-wavelength modes in a layered superconductor slab, embedded in a high refractive index dielectric, are more clearly observed in comparison with the case of superconducting samples being in vacuum [17].

3.3. Breaking of the total internal reflection

The numerical results presented in this section can be qualitatively interpreted within the local approach [5,9,10,17], according to which, the dispersion relation of the TM electromagnetic modes in a layered superconductor is given by

$$k_z = \frac{\omega}{c}\sqrt{\varepsilon_x (1 - \varepsilon_d \sin^2\theta / \varepsilon_z)}, \tag{23}$$

where the permittivities components, $\varepsilon_x(\omega)$ and $\varepsilon_z(\omega)$, respectively have the forms (6) and (7) with the capacitive-coupling parameter $\alpha = 0$. In the THz range and neglecting the energy losses, namely the contribution of the averaged in-plane and transverse quasi-particle conductivities to the imaginary parts of permittivity components, ε_x is a negative real quantity $(\varepsilon_x(\omega) < 0)$, whereas $\varepsilon_z(\omega)$ is a real quantity having a zero at $\omega = \omega_p$. The permittivity z-component is positive (negative) above (below) ω_p. Since we have assumed that $\varepsilon_d > \varepsilon$, the factor $(1 - \varepsilon_d \sin^2\theta / \varepsilon_z)$ in Eq. (23) is positive for angles smaller than the critical one $\theta_c = \sqrt{\arcsin(\varepsilon_z / \varepsilon_d)}$ at $\omega > \omega_p$ and, consequently, k_z (23) turns out to be imaginary. For such subcritical incidence angles the p-reflectivity is close to 1 as it is observed in Fig. 5. On the contrary, when $\theta > \theta_c$, the wave number k_z (23) becomes a real one and the reflectivity is suppressed as it is seen in Fig. 5. Such a phenomenon has been predicted for artificial type II hyperbolic metamaterials [18] and called hyperbolicity-frustrated total internal reflection. However, because of the energy losses in the layered superconductor the breaking of the total internal reflection is characterized not only by enhanced transmissivity, but also by a large absorption. For very thin superconductor slabs the nonlocal effects are well manifest [17] and, according to our theoretical predictions (see Fig. 2) the breaking of the total internal reflection is mainly related with the excitation of short-wavelength electromagnetic waves, producing well-discernible resonances in the absorption optical spectrum.

4. Conclusions

We have studied the spatial dispersion effects in a layered high-temperature superconductor slab embedded in a dielectric medium, assuming that the insulating layers inside the high-temperature superconductor are parallel to the slab surfaces. Using an average nonlocal permittivity tensor for describing the optical response of the layered superconductor slab, embedded in a high refractive index dielectric, we have derived a generalized additional boundary condition (ABC), which allows us to calculate the amplitudes of the electromagnetic waves in the structure. In particular, we have calculated and analyzed the p-polarization optical spectra of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconductor slab, embedded in Ge. It was found that for very thin superconductor slabs (with thickness $d \approx 17$ nm) the optical spectra show resonances associated with the excitation of quantized short-wavelength electromagnetic modes only. On the other hand, if the slab thickness is sufficiently larger, such resonances coalesce and are smoothed out. However, in that case new resonances, which are connected to the excitation of quantized long-wavelength waves, having anomalous dispersion, appear. It is established that the manifestation of both short- and long-wavelength quantized Josephson plasma waves is quite strong when the layered superconductor slab is embedded in a high refractive index dielectric, instead of vacuum or air [17].

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Збудження джозефсонівських плазмових хвиль у пластині шаруватого високотемпературного надпровідника, який вбудовано у діелектрик з високим показником заломлення

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Теоретично досліджено нелокальний оптичний відгук пластини шаруватого високотемпературного надпровідника, який вбудовано у діелектричне середовище. Передбачається, що шари всередині високотемпературного надпровідника паралельні поверхням пластини. Розраховано оптичні спектри для *p*-поляризації. Для розрахунків використано усереднений тензор діелектричної проникності, який залежить як від частоти, так і від хвильового вектора електромагнітної хвилі. Внаслідок додатково генеруються електромагнітні моди з частотою трохи вище характерної джозефсонівської плазмової частоти, що належить терагерцовому діапазону. Показано, що для *p*-поляризації спектр відбиття пластини надпровідника $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), вбудованого в діелектрик з високим показником заломлення, демонструє сильне порушення повного внутрішнього відбиття. При дуже малій товщині пластини надпровідника резонанси в оптичних спектрах схожі з резонансами Фабрі–Перо для короткохвильових електромагнітних мод. Навпаки, довгохвильові електромагнітні моди, які мають аномальне дисперсійне співвідношення, збуджуються при відносно великій товщині пластини та проявляються у вигляді сильних резонансів в спектрах як поглинання, так і пропускання, та пригнічують дзеркальну відбивну здатність.

Ключові слова: джозефсонівські плазмові хвилі, високотемпературний надпровідник, діелектрик з високим показником заломлення.

Возбуждение джозефсоновских плазменных волн в пластине слоистого высокотемпературного сверхпроводника, встроенного в диэлектрик с высоким показателем преломления

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Теоретически изучен нелокальный оптический отклик пластины слоистого высокотемпературного сверхпроводника, встроенной в диэлектрик. Предполагается, что слои внутри высокотемпературного сверхпроводника параллельны поверхностям пластины. Рассчитаны оптические спектры для *p*-поляризации. Для расчетов использован усредненный тензор диэлектрической проницаемости, который зависит как от частоты, так и от волнового вектора электромагнитной волны. В результате дополнительно генерируются электромагнитные моды с частотой чуть выше характерной джозефсоновской плазменной частоты, принадлежащей терагерцовому диапазону. Показано, что для *p*-поляризации спектр отражения пластины сверхпроводника $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), встроенного в диэлектрик с высоким показателем преломления, демонстрирует сильное нарушение полного внутреннего отражения. При очень малой толщине пластины сверхпроводника резонансы в оптических спектрах подобны резонансам Фабри–Перо для коротковолновых электромагнитных мод. Напротив, длинноволновые электромагнитные моды, имеющие аномальное дисперсионное соотношение, возбуждаются при относительно большой толщине пластины и проявляются в виде сильных резонансов в спектрах как поглощения, так и пропускания, подавляя зеркальную отражательную способность.

Ключевые слова: джозефсоновские плазменные волны, высокотемпературный сверхпроводник, диэлектрик с высоким показателем преломления.