Plasmon resonance at the interface dielectric - nanocomposite material with superconducting inclusions

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Abstract. This article theoretically considers surface plasmon resonance in composite structures. The features of the surface plasmon resonance arising at the interface with media containing nanoparticles from a high-temperature superconductor are investigated. The dielectric constant of spherical superconducting inclusions is considered taking into account Gorter-Casimir two-fluid model. The temperature dependence of the electrodynamic parameters of the superconductor is taken into account. The two-fluid model, the dependence of the concentration of non-superconducting electrons in a superconductor is often used as the fourth power of temperature \( n_s \sim T^4 \). In this work, a phenomenological model is used, according to which the electron concentration of non-superconducting electrons in a superconductor is determined by the formula \( n_s \sim T^\gamma \) with \( \gamma = 1.3 \pm 2 \). This model is in good agreement with experimental data for high-temperature ceramic superconductors. The dispersion characteristics of surface plasmons arising in a planar structure with a thin nanocomposite superconductor layer are investigated. It is shown that the dispersion characteristics depend significantly on temperature.

1. Introduction
Plasmonics is one of the most modern scientific directions with great potential for practical use [1]. Materials in which surface plasmon resonance can be observed are increasingly used to create various optoelectronic devices [2]. Surface plasmon resonance occurs at the interface between two media with positive and negative dielectric permittivity [3]. A special place among plasmon materials is occupied by media with inclusions of nanoparticles of various shapes [4]. One of the important features of nanoplasmonic materials is the dependence of the resonance frequency on the size of nanoparticles, their concentration, and other parameters [5]. Surface plasmons can arise at various interfaces: metal – dielectric [6], metal – semiconductor [7], semiconductor – dielectric [8], metamaterial – dielectric [9], superconductor – dielectric [10]. Surface plasmons arising at the interface with a superconductor have a number of distinctive features. First of all, this is a small attenuation in superconductors at low temperatures. Another important feature is the strong temperature dependence of the properties of the superconductor. This dependence is especially pronounced at temperatures close to the critical temperature [11]. Plasmonic devices based on high-temperature superconductors (HTSC) are used to create supersensitive photon detectors [12], sensors [13], waveguides [14], amplifiers [15]. Most high-temperature superconductors are complex ceramic compounds with an inhomogeneous composition. Therefore, the fabrication of HTSC nanoparticles with a radius of less than 10 nm is a complicated process. However, according to the latest data, HTSC nanoparticles have a higher critical temperature,
which increases their attraction for practical use [16]. This article investigates the properties of surface plasmons arising at the plane boundary of a dielectric and a composite medium containing spherical HTSC nanoparticles.

2. Methods

Let us consider the propagation of surface plasmons in a structure that contains a thin layer of a superconducting nanocomposite located between two nonmagnetic dielectrics (figure 1). The thickness of the superconducting nanocomposite is \(d\), dielectric constants of dielectrics are \(\varepsilon_{d1}\) and \(\varepsilon_{d2}\) respectively. The superconducting nanocomposite consists of dielectric matrix with dielectric constant \(\varepsilon_{d}\), containing spherical inclusions from HTSC with dielectric constant \(\varepsilon_{s}\) (figure 2). We will assume that the dielectric constant \(\varepsilon_{d}\) does not change in the investigated frequency range.

The electrodynamic properties of superconductors are described by a two-fluid model. In this case, electrons in a superconductor are divided into two types. The first type is superconducting electrons that move without dissipation. The second type is ordinary non-superconducting electrons, which have losses. Each type of electron moves independently of the other. The dielectric permittivity of superconductor in accordance with the two-fluid model is described by the following formula [17]

\[
\varepsilon_s = \varepsilon_r - \frac{1}{\omega^2 \lambda_L(T) \varepsilon_0 \mu_0} - \frac{\sigma_n \nu}{\omega \varepsilon_0 (\omega - i \nu)},
\]

where \(\varepsilon_r\) is lattice dielectric constant, \(\omega\) is angular frequency, \(\varepsilon_0\) is vacuum permittivity, \(\mu_0\) is vacuum permeability, \(\sigma_n\) is the conductivity of normal carriers, \(\nu = 1/\tau\) is collision frequency, \(\tau\) is relaxation time and \(\lambda_L\) is London depth of penetration of a magnetic field into a superconductor.

Let us consider the temperature dependence of superconductor parameters. The temperature dependence of the concentration of superconducting electrons \(n_s\) and non-superconducting electrons \(n_n\) is written in the following form [17]

\[
n_s(t) = n_0(1 - t'), \quad n_n(t) = n_0 t',
\]

where \(n_0\) is total concentration of electrons in the superconductor, \(t = T/T_c\), \(T\) is temperature, \(T_c\) is critical temperature for the superconductor, \(\gamma\) is exponent.

For conventional low-temperature superconductors, good agreement with experimental data gives the value \(\gamma = 4\) [17]. However, as shown in [16], the situation is more complicated for high-temperature superconductors. The value of \(\gamma\) in essentially depends on the type of the HTSC. So, according to [1],

\[
\varepsilon_s = \varepsilon_r - \frac{1}{\omega^2 \lambda_L(T) \varepsilon_0 \mu_0} - \frac{\sigma_n \nu}{\omega \varepsilon_0 (\omega - i \nu)},
\]
for yttrium ceramics $YBa_2Cu_3O_7$ according to Bardeen–Cooper–Schrieffer theory the parameter $\gamma$ takes values from 1.3 to 2.08. In this case, the temperature dependence of $\lambda_\varepsilon$ has the following form

$$\lambda_\varepsilon(t) = \lambda_\varepsilon(0) \cdot \left(1-t^\gamma\right)^{-1/\gamma},$$

(3)

where $\lambda_\varepsilon(0)$ is the London penetration depth for $T=0$. In accordance with [17], $\lambda_\varepsilon(0)$ takes values from 134.8 nm to 261.7 nm for $YBa_2Cu_3O_7$, and the critical temperature $T_c = 90K$.

Within the framework of phenomenological model [17], the conductivity of normal carriers depends on temperature as follows

$$\sigma_n(t) = \sigma_n(1) \left[t^\gamma + \alpha(1-t^\gamma)\right],$$

(4)

where $\sigma_n(1)$ is the conductivity at $t=1$, $\alpha$ is a phenomenological parameter. For $YBa_2Cu_3O_7$ parameter $\alpha = 1.2 \cdot 10^6 \, (\Omega \cdot m)^{-1}$, the relaxation time $\tau = 3.57 \cdot 10^{-14} \, s^{-1}$.

Let us consider the electrodynamic parameters of a nanocomposite with superconducting inclusions. Considering the size of the inclusions to be small (much less than the length of the electromagnetic wave), the medium can be regarded as homogeneous. Then the effective dielectric constant of the composite medium containing spherical inclusions from HTSC with volume fraction of the inclusions $f$, in accordance with the Maxwell Garnett formula, has the form [16]

$$\varepsilon_{\text{eff}} = \varepsilon_s + 3\varepsilon_i \cdot \frac{\varepsilon_d - \varepsilon_s}{\varepsilon_d + 2\varepsilon_s} \cdot \frac{f}{1-f} \cdot \frac{\varepsilon_d - \varepsilon_i}{\varepsilon_d + 2\varepsilon_i},$$

(5)

Figure 3. Frequency dependence of the real part $\varepsilon'_{\text{eff}}$ for different temperatures $t$ for the value of the volume fraction $f=0.35$. Curve 1: $t=0.7$, curve 2: $t=0.8$, curve 3: $t=0.95$.

Figure 4. Temperature dependence of the real part $\varepsilon'_{\text{eff}}$ for different values $f$ at $\omega = 1.2 \cdot 10^{15} \, s^{-1}$. Curve 1: $f=0.1$, curve 2: $f=0.2$, curve 3: $f=0.3$, curve 4: $f=0.4$. 

Surface plasmon resonance is observed at the interface between two media with positive and negative dielectric constant [18]. Figure 3 shows the results of calculating the frequency dependence of the real part of the effective dielectric constant of a nanocomposite with superconducting inclusions. The
frequency dependence is calculated for the following parameters: $\sigma_n(1)=4.3\cdot10^4 \left(\Omega \cdot m\right)^{-1}$, $T_c=90K$,$\tau=3.57\cdot10^{-14} s^{-1}$, $\lambda_L(0)=150nm$, $\gamma=1.5$, $\alpha=10$. Figure 3 shows that the real part of the effective dielectric constant of the composite becomes negative at frequencies exceeding the surface plasmon resonance frequency for the composite. As can be seen from figure 3, this frequency increases with increasing temperature.

The temperature dependence of $\varepsilon_{eff}$ for different values of the volume fraction of inclusions f is shown in figure 4. This calculation was performed for the same parameters as indicated for figure 3. We see from figure 4 that the temperature dependence has a resonant character, and can take negative values at low temperatures. Thus, surface plasmons can exist in the structure under consideration.

Dispersion relations for surface plasmons at the interfaces in the structure shown in figure 1 were obtained in [18]. In the case of equality of the parameters of the dielectrics $\varepsilon_{d1}$ and $\varepsilon_{d2}$, these dispersion relations are divided into relations for symmetric and antisymmetric modes [18]

$$\theta h q_dq_d = -\frac{\varepsilon_{d1} q_d}{\varepsilon_{s} q_d} , \quad c\theta h q_dq_d = -\frac{\varepsilon_{d1} q_d}{\varepsilon_{s} q_d} , \quad (6)$$

where $q_{s,d} = \left(\beta^2 - k_0^2 \varepsilon_{s,d}\right)^{1/2}$ is transverse components of the wave vector of the surface plasmon in the composite with HTSC inclusions and dielectric respectively, $\beta$ is longitudinal wavenumber along the Ox axis, $k_0 = \omega/c$, $c$ is speed of light in vacuum.

3. Discussion

The dispersion characteristics of surface plasmons that can propagate at the interface in the structure composite with HTSC inclusions - dielectric are shown in figure 5.

Figure 5. Dispersion characteristics of surface plasmons at the interface between the dielectric and a composite medium for different temperatures. The case of symmetric modes. Low-frequency surface plasmons (bottom three curves) and high-frequency surface plasmons (top three curves). The thickness of the composite layer with superconducting inclusions d=100 nm, parameter $\alpha=10$, $\gamma=1.5$. Curve 1: $t=0.6$, curve 2: $t=0.8$, curve 3: $t=0.99$.

In figure 3 we see the result of calculating the dispersion characteristics of surface plasmons for symmetric modes for $\sigma_n(1)=1.8\cdot10^4 \left(\Omega \cdot m\right)^{-1}$. Each dispersion characteristic has two branches. The
low-frequency branch has no cutoff and starts at frequency $\omega = 0$. The high frequency branch has a temperature dependent cutoff frequency.

As expected, the dispersion characteristics show a temperature dependence. As the reduced temperature $t$ rises from 0.6 to 0.99, the cutoff frequency increases from $1.6 \times 10^{15}$ s$^{-1}$ to $2.3 \times 10^{15}$ s$^{-1}$. Thus, by changing the temperature, it is possible to control the appearance of surface plasmon resonance. The temperature dependence of the cutoff frequency for high-frequency plasmons can be used to control the number of modes propagated in planar structures. Also, structures with superconducting inclusions can be used to create sensitive sensors with the possibility of temperature change in their parameters.

4. Conclusion

The study carried out in this work has shown that composite media with HTSC inclusions have good prospects for practical application. The characteristics of surface plasmons arising at the interface with such media depend both on the concentration of superconducting inclusions and on temperature. This circumstance makes it possible to control the parameters of surface plasmons.

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