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The Electrodynamic Properties of Structures with Thin Superconducting Film in Mixed State

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1. Introduction

Thin superconducting films are used in many areas of microwave technics. The discovery of high temperature superconductors in 1986 (Bednorz & Muller, 1986) was a powerful incentive to application of superconductors in science and engineering. High-temperature superconductors have a lot of necessary microwave properties, for example: low insertion loss, wide frequency band, low noise, high sensibility, low power loss and high reliability. High-temperature superconductors have significant potential for applications in various devices in microelectronics because of the ability to carry large amount of current by high temperature (Zhao et al., 2002). The widely applicable high-temperature superconductor $YBa_2Cu_3O_7$ with critical temperature $T_c=90$ K keeps the superconductivity above the boiling point of nitrogen. One of the applications of high-temperature superconductors is the passive microwave device because of it extremely small resistance and low insertion loss. In recent years new techniques have been developed for production of superconducting layered systems. The superconducting films are indispensable for manufacture of resonators and filters with the technical parameters that significantly surpass the traditional materials. The progress in microsystem technologies and nanotechnologies enables the fabrication of thin superconducting films with thickness about several atomic layers (Koster et al., 2008), (Chiang, 2004). Due to new technologies scientists produce a thin film which exhibits a nanometer-thick region of superconductivity (Gozar et al., 2008).

The thin superconducting films are more attractive for scientists and engineers than the bulk superconducting ceramics. The thin films allow to solve a problem of heat think. The application of thin films increases with the growth of critical current density J_c. Nowadays it is known a large number of superconducting materials with critical temperature above 77 K. But despite of the bundle of different high-temperature superconducting compounds, only three of group have been widely used in thin film form: $YBa_2Cu_3O_7$, $Bi_vSr_wCa_xCu_yO_z$, $Tl_vBa_wCa_xCu_yO_z$ (Phillips, 1995). $YBa_2Cu_3O_7$ has critical temperature $T_c=90$ K (Wu et al., 1987) and critical current density $J_c=5 \cdot 10^{10}$ A/m^2 at 77 K (Yang et al., 1991), (Schauer et al., 1990). The critical temperature of $Bi_vSr_wCa_xCu_yO_z$ films T_c is 110 K (Gunji et al., 2005), that makes these films more attractive than $YBa_2Cu_3O_7$. But single-phase films with necessary phase with $T_c=110$ K have not been grown successfully (Phillips, 1995). Also the $Bi_vSr_wCa_xCu_yO_z$ films have lower critical current density than $YBa_2Cu_3O_7$. The $Tl_vBa_wCa_xCu_yO_z$ films with $T_c=125$ K and critical current density above 10^{10} A/m^2 and $HgBa_2Ca_2Cu_3O_{8.5+x}$ films with $T_c=135$ K are attractive for application in microwave devices (Itozaki et al., 1989), (Schilling et al., 1993).

Now thin high-temperature superconducting films can find application in active and passive microelectronic devices (Hohenwarter et al., 1999), (Hein, 1999), (Kwak et al., 2005). The superconductors based on complex oxide ceramic are the type-II superconductors. It means that the magnetic field can penetrate in the thickness of superconducting film in the form of Abrikosov vortex lattice (Abrikosov, 2004). If we transmit the electrical current along the superconducting film, the Abricosov vortex lattice will come in the movement under the influence of Lorentz force. The presence of moving vortex lattice in the film leads to additional dissipation of energy and increase of losses (Artemov et al., 1997). But we can observe the amplification of electromagnetic waves by the interaction with moving Abrikosov vortex lattice. The mechanism of this amplification is the same as in a traveling-wave tube and backward-wave-tube (Gilmour, 1994). The amplification will be possible if the velocity of electromagnetic wave becomes comparable to the velocity of moving vortex lattice. Due to the energy of moving Abricosov vortex lattice the electromagnetic waves amplification can be observed in thin high-temperature superconducting film on the ferromagnetic substrate (Popkov, 1989), in structures superconductor – dielectric and superconductor – semiconductor (Glushchenko & Golovkina, 1998 a), (Golovkina, 2009 a). The moving vortex structure can generate and amplify the ultrasonic waves (Gutliansky, 2005). Thus, the thin superconducting films can be successfully used in both passive and active structures.

2. Thin superconducting film in planar structure

2.1 The method of surface current

The calculation of electromagnetic waves characteristics after the interaction with thin films is possible by various methods. These methods match the fields outside and inside of thin film. The method of two-sided boundary conditions belongs to this methods (Kurushin et al., 1975), (Kurushin & Nefedov, 1983). The calculation of electromagnetic waves characteristics with help of this method is rigorous. The thin film is considered as a layer of final thickness with complex dielectric permeability. The method of two-sided boundary conditions can be used with any parameters of the film. However, this method is rather difficult. From the point of view of optimization of calculations the approximate methods are more preferable. The method of surface current can be applied for research of electrodynamic parameters of thin superconducting films when the thin film is considered as a current carrying surface. In the framework of this method the influence of thin resistive film can be considered by introduction of special boundary conditions for tangential components of electric and magnetic field (Veselov & Rajevsky, 1988).

The HTSC are the type-II superconductors. If we place the type-II superconductor in the magnetic film $B_{c1}<B<B_{c2}$, where B_{c1} and B_{c2} are first and second critical fields for superconductor respectively, the superconductor will pass in the mixed state (Schmidt, 2002). In the mixed state the superconductor has small resistance which value is on some orders less than resistance of pure metals. Let us consider the thin superconducting film in resistive state. The tangential components of electric field will be continuous, if the following conditions are satisfied (Veselov & Rajevsky, 1988)

$$\Delta\sqrt{\frac{\mu\omega(\sigma^2+\varepsilon^2\omega^2+\varepsilon\omega\sqrt{\varepsilon^2\omega^2+\sigma^2})}{2(\varepsilon\omega+\sqrt{\varepsilon^2\omega^2+\sigma^2})}}<<1\,,\tag{1}$$

where Δ is the thickness, σ - conductivity of film, ε is permittivity and μ is permeability of superconductor, ω is the angular frequency of applied electromagnetic wave. If the inequality $\sigma \gg \varepsilon \omega$ is carried out, the condition (1) can be written in the form

$$\Delta\sqrt{\mu\omega\sigma/2} = \Delta/d \ll 1 \qquad (2)$$

where d is skin depth of superconducting material. In the following consideration the condition (2) is carried out in all cases.

And now let's consider the magnetic field. If the condition (1) and (2) are satisfied, the boundary conditions for tangential components will be given by

$$H_x^I - H_x^{II} = j_z \ , \qquad (3)$$

$$H_z^I - H_z^{II} = -j_x \ , \qquad (4)$$

where j is current density.

Thus if condition $\sigma \gg \varepsilon \omega$ is satisfied, the tangential components of electric field will be continuous and the boundary conditions for tangential components of magnetic field will be written in the form (3-4). This condition is satisfied for superconducting films for microwave and in some cases for infrared and optical range.

2.2 The boundary conditions for thin type-II superconducting film in mixed state

Let us consider the thin type-II superconducting film with thickness $t \ll \lambda$, where λ is a microwave penetration depth.
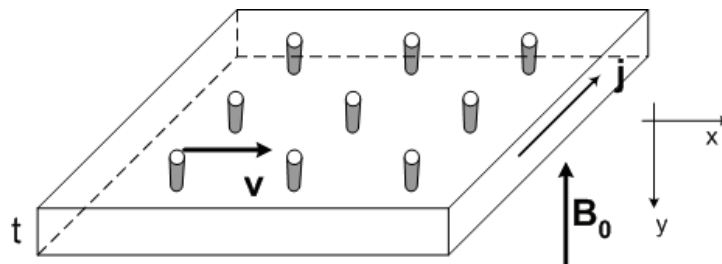

Fig. 1. Geometry of the problem

We let the interfaces of the film lie parallel to the x-z plane, while the y axis points into the structure. A static magnetic field B_{y0} is applied antiparallel the y axis, perpendicular to the interfaces of the film. The value of magnetic field does not exceed the second critical field for a superconductor. The magnetic field penetrate into the thickness of the film in the form of Abrikosov vortex lattice. Under the impact of transport current directed perpendicularly to magnetic field B_{y0} along the 0z axis, the flux-line lattice in the superconductor film starts to move along the 0x axis. Let's consider the propagation in the given structure p-polarized wave being incident with angle θ in the x0y plane. It can be assumed that $\partial/\partial z=0$.

The presence of a thin superconductor layer with the thickness of $t \ll l$ is reasonable to be accounted by introduction of a special boundary condition because of a small amount of thickness. Let's consider the superconductor layer at the boundary y=0. At the inertia-free approximation and without account of elasticity of fluxon lattice (the presence of elastic forces in the fluxon lattice at its deformation results in non-linear relation of the wave to the

lattice, that is insignificant at the given linear approximation) the boundary condition is written in the following way (Popkov, 1989):

$$\frac{\partial B_y}{\partial t}(y=t) + \frac{j_{z0}\Phi_0}{\eta} \frac{\partial B_y}{\partial t}(y=t) = \frac{B_{y0}\Phi_0}{\eta\, t} \frac{\partial}{\partial x}[H_x(y=t) - H_x(y=0)], \qquad (5)$$

where j_{z0} is the current density in the superconducting film and η is the vortex viscosity. The method of account of thin superconducting film in the form of boundary condition enables to reduce the complexity of computations and makes it possible to understand the mechanism of interaction of electromagnetic wave and thin superconducting film.

3. The periodic structures with thin superconducting film

3.1 Dispersion relation for one-dimensional periodic structure superconductor – dielectric

Let's consider the infinite one-dimensional periodic structure shown in Fig. 2 (Glushchenko & Golovkina, 1998 b). The structure consists of alternating dielectric layers with thickness d_1 and type-II superconductor layers with thickness $t \ll \lambda$. An external magnetic field B_{y0} is applied antiparallel the y axis, perpendicular to the interfaces of the layers. The flux-line lattice in the superconductor layers moves along the 0x axis with the velocity v. Let's consider the propagation in the given structure p-polarized wave being incident with angle θ in the x0y plane.
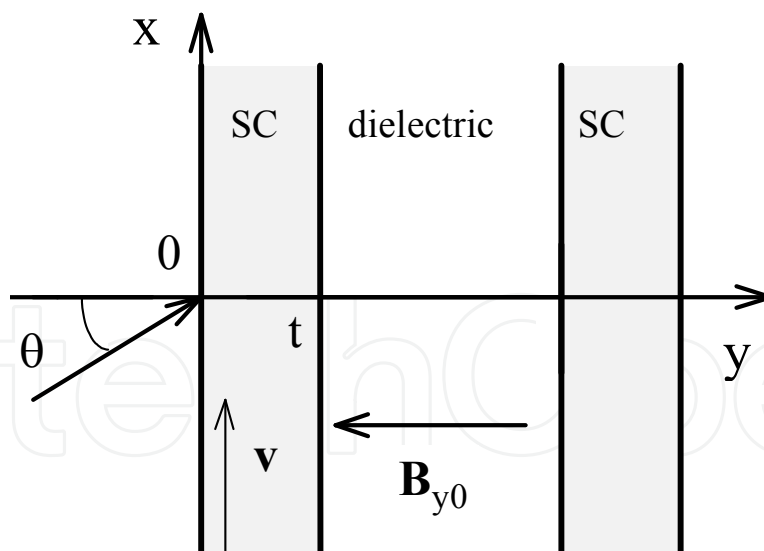

Fig. 2. Periodic structure superconductor (SC) – dielectric

Let's write the boundary condition (5) in the form of matrix M_s, binding fields at the boundaries y=0 and y=t:

$$\begin{pmatrix} E_z(t) \\ H_x(t) \end{pmatrix} = M_s \begin{pmatrix} E_z(0) \\ H_x(0) \end{pmatrix}, \qquad (6)$$

$$
M_s = \begin{pmatrix} 1 & 0 \\ \dfrac{t}{B_{y0}}(\dfrac{\eta}{\Phi_0} - \dfrac{j_{z0}\,k_x}{\omega}) & 1 \end{pmatrix}, \tag{7}
$$

where k_x is the projection of the passing wave vector onto the 0x axis and ω is the angular frequency of the passing wave.

Using matrix method we found dispersion relation for H-wave:

$$
\cos Kd = \cos k_y d_1 + \dfrac{i\,\omega\,\mu_0\,t}{2\,k_y B_{y0}}(\dfrac{\eta}{\Phi_0} - \dfrac{j_{z0}\,k_x}{\omega})\,\sin k_y d_1, \tag{8}
$$

where $K=K'-iK''$ is the Bloch wave number and k_y is the projection of passing wave vector onto the 0y axis. The imaginary pert of Bloch wave number K'' acts as coefficient of attenuation.

The interaction of electromagnetic wave with thin superconducting film leads to emergence of the imaginary unit in the dispersion equation. The presence of imaginary part of the Bloch wave number indicates that electromagnetic wave will damp exponentially while passing into the periodic system even if the dielectric layers are lossless (Golovkina, 2009 b). However, when one of the conditions

$$
\sin k_y\,d_1 = 0\,, \tag{9}
$$

$$
\dfrac{\eta}{\Phi_0} - \dfrac{j_{z0}\,k_x}{\omega} = 0 \tag{10}
$$

is executed, the Bloch wave vector becomes purely real and electromagnetic wave may penetrate into the periodic structure (Golovkina, 2009 a).

The implementation of condition (9) depends on the relation between the parameters of layers and the frequency of electromagnetic wave, while the implementation of condition (10) depends on parameters of superconducting film only, namely on current density j_{z0}.

Still, we are able to manage the attenuation and propagation of electromagnetic waves by changing the value of transport current density j_{z0}. Moreover, the electromagnetic wave can implement the amplification in such structure (Golovkina, 2009 b).

When the medium is lossless and the imaginary part in dispersion relation is absent, the dispersion relation allows to find the stop bands for electromagnetic wave. If the condition $|cosKd|<1$ fulfils, than the Bloch wave number K will be real and electromagnetic wave will propagate into the periodic structure. This is the pass band. If the condition $|cosKd|>1$ fulfils, than the Bloch wave number will be complex and the electromagnetic wave will attenuate at the propagating through the layers. This is the stop band. The dispersion characteristics for the pass band calculated on the base of the condition $|cosKd|<1$ are presented in Fig. 3. These characteristics are plotted for the first Brillouin zone. We can see that the attenuation coefficient K'' decreases by the growth of magnetic field. But this method of definition of pass band is unacceptable when there is the active medium in considered structure. Even if there are the losses in the periodic structure and the imaginary unit is presents in the dispersion relation we should draw the graph in the whole Brillouin zone, including the parts on which the condition $|cosKd|>1$ is executed. Then the stop band will correspond to the big values of attenuation coefficient K''.
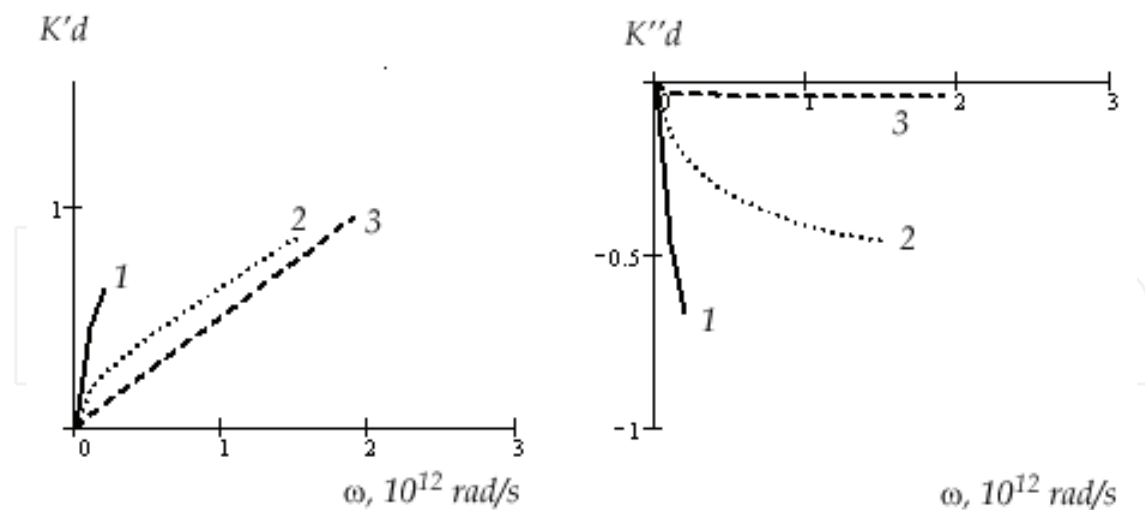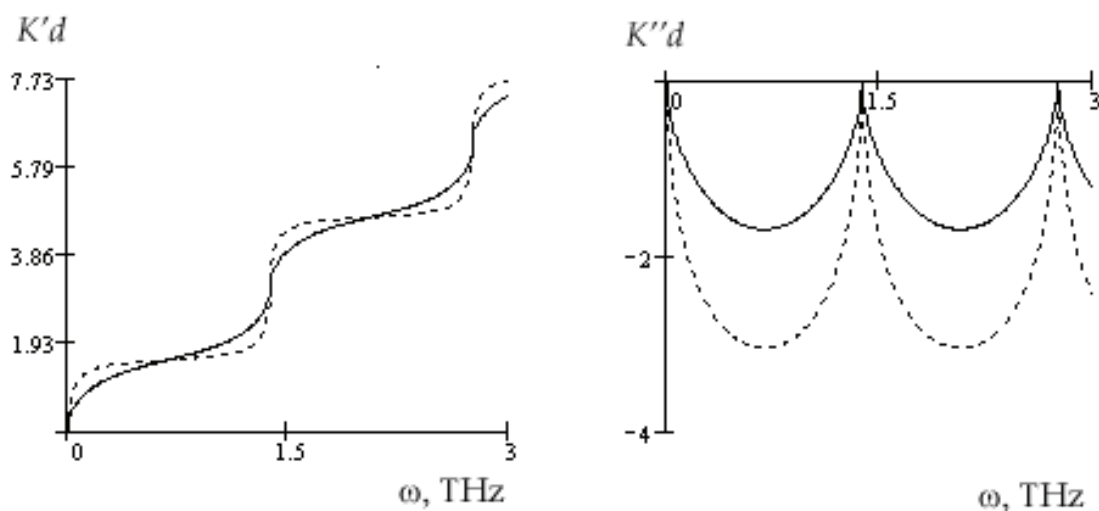
Fig. 3. The real and imaginary part of dispersion characteristic for one-dimensional periodic structure superconductor - dielectric for different values of external magnetic field B. Curve 1: B=0.05 T, curve 2 :B=0.4 T, curve 3: B=5 T. Parameters: d_1=6 µm, t=70 nm, j_{z0}=10^9 A/m^2, η=10^{-8} N·s/m^2, θ=0.1

Fig. 4. The real and imaginary part of dispersion characteristic for one-dimensional periodic structure superconductor – dielectric. Curve 1: t=20 nm, curve 2: t=80 nm. Parameters: d_1=100 µm, j_{z0}=10^8 A/m^2, η=10^{-8} N·s/m^2, B_{y0}=1 T, θ=1.1

The dispersion characteristics for whole Brillouin zone are presented in the Fig. 4. We can't see the stop band in the explicit form in these figures. The band edge can be found from the condition of the big values of attenuation coefficient. This definition of band edge contains an element of indeterminacy. The required attenuation coefficient can accept various values depending on application. For the purposes of our study we must investigate the dynamics of change of the attenuation coefficient K''. If the structure contains an active element (the thin superconducting layer with moving vortex structure for example) the attenuation coefficient K'' can change its sign. And the positive values of K'' indicate that the electromagnetic wave amplifies at the expense of energy reserved in the active element.

3.2 Larkin-Ovchinnikov state

We have considered the superconductor for the case of linear dependence of its characteristics. The differential resistance of superconductor is given by following expression (Schmidt, 2002)

$$\rho_f = \frac{\Phi_0 B}{\eta},$$

(11)

where η is the vortex viscosity depending of temperature T and magnetic field B. This case corresponds to the linear part of voltage-current characteristic of superconductor. Such linear part of voltage-current characteristic exists only in the narrow area of currents exceeding a critical current. With further increase of the transport current in the thin superconducting film the nonlinear area containing jumps of voltage of voltage-current characteristic appears. The theory of Larkin-Ovchinnikov gives the explanation of these phenomena (Larkin & Ovchinnikov, 1975).

Let's suppose, that there is the good heat sink in thin superconducting film, the lattice is in the thermal equilibrum with thermostat and the relaxation time, determined by interelectronic collisions one order greater than the time of electron-phonon interaction. That means that the time of a power relaxation is big. Theory of Larkin-Ovchinnikov gives the following basic expressions (Dmitrenko, 1996):

$$\eta(v) = \eta(0)\ \frac{1}{1+(v/v^*)^2}\ ,$$

(12)

$$v^{*2} = \frac{D\sqrt{14\zeta(3)}\sqrt{1-T/T_c}}{\pi\ \tau_\varepsilon}\ ,$$

(13)

$$D = \frac{1}{3}v_F l\ ,$$

(14)

$$\eta(0) = 0,45\ \frac{\sigma_n T_c}{D}\ \sqrt{1-T/T_c}\ .$$

(15)

Here v^* is the critical velocity corresponding to the maximum of viscous friction, D is the diffusion coefficient, v_F is the Fermi velocity, l is the free electrons length, τ_ε is the electron relaxation time, σ_n is the conductivity of superconductor in normal state, $\zeta(3)$ is Riemann zeta-function for 3. This expressions are valid near the critical temperature T_c for small magnetic field $B/B_{c2}<0.4$.

The boundary condition (5) for the superconductor in Larkin-Ovchinnikov state can be written in the following form (Glushchenko & Golovkina, 2007)

$$\frac{2\Phi_0}{\eta(0)\,v^{*2}}\frac{\partial B_y}{\partial t} + \left(\frac{1}{j_z}\pm\sqrt{\frac{1}{j_z^2}-\frac{4\Phi_0^2}{\eta(0)^2\,v^{*2}}}\right)\frac{\partial B_y}{\partial x} =$$
$$= \frac{B_{y0}}{t}\left(\frac{1}{j_z}\pm\sqrt{\frac{1}{j_z^2}-\frac{4\Phi_0^2}{\eta(0)^2\,v^{*2}}}\right)\frac{\partial}{\partial x}[H_x(y=0)-H_x(y=t)]$$

(16)

The dispersion relation for H-wave is given by

$$\cos Kd = \cos k_y d_1 + C \sin k_y d_1 \quad , \tag{17}$$

$$C = \frac{i\omega\mu_0 \, t \, j_z^{\,2}}{2 \, k_y B_{y0}} \sqrt{1 - \frac{4\Phi_0^{\,2} j_z^{\,2}}{\eta(0)^2 v^{*2}}} \left[\frac{2\Phi_0}{\eta(0)v^{*2}} \left(\sqrt{1 - \frac{4\Phi_0^{\,2} j_z^{\,2}}{\eta(0)^2 v^{*2}}} \pm 1 \right)^{-1} \mp \frac{k_x}{\omega \, j_z} \right] , \tag{18}$$

The top sign corresponds to a wave propagating in a positive direction of the y axis, bottom corresponds to a wave propagating in the opposite direction along the motion of vortex structure.

The dependence of vortex viscosity from magnetic field, temperature and vortex velocity leads to the origination of new control methods, which could operate on parameters of electromagnetic waves. Let's compare the structure dielectric - superconductor in linear case with the structure dielectric - superconductor in Larkin-Ovchinnikov state. If the structure with superconductor in Larkin-Ovchinnikov state has the same parameters as the structure with superconductor in linear case, then the imaginary part of Bloch wave number will be less for superconductor in Larkin-Ovchinnikov state (see Fig. 5). Therefore structure with superconductor in Larkin-Ovchinnikov state demonstrates small attenuation in addition to new control methods.
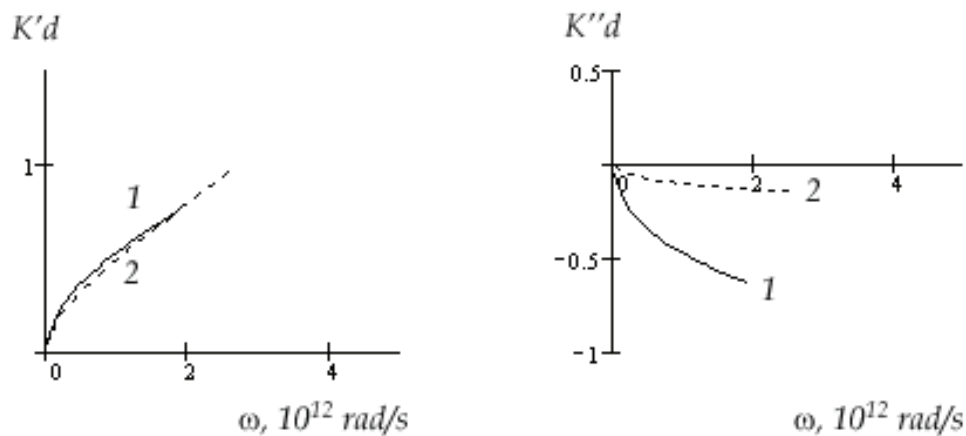

Fig. 5. The dispersion characteristics of periodic structure superconductor – dielectric. Curve 1 : superconductor in linear case, curve 2: superconductor in Larkin-Ovchinnikov state. Parameters: d_1=6 μm, t=70 nm, η=10^{-8} N·s/m², B_{y0}=5 T, θ=0.5, v*=1750 m/s

Let us consider the expression (17). The imaginary part of Bloch wave number K equals zero if C=0. That corresponds to two values of transport current density:

$$j_{z1} = \frac{\eta(0) \, v^*}{2\Phi_0} \quad at \quad v = v^* , \tag{19}$$

$$j_{z2} = \frac{\omega\eta(0)}{k_x\Phi_0[1 + \omega^2 / (v^{*2}k_x^{\,2})]} \quad . \tag{20}$$

The calculated under the formula (20) transport current density j_{z2} is frequency-independent for structure superconductor - dielectric.

The value of the j_{z1} depends only on parameters of superconductor; the value of the j_{z2} depends on parameters of superconductor and dielectric. For epitaxial films $YBa_2Cu_3O_7$ on substrate MgO the velocity reaches the value $v^*=2000$ m/s in magnetic field $B_y=1$ T at the temperature $T=79.65$ K (Dmitrenko, 1996). For this parameters the transport current density j_{z1} reaches the value $j_{z1}=4.8 \cdot 10^9$ A/m^2 for viscosity coefficient $\eta=10^{-8}$ N·s/m^2. At these parameters of superconducting film the transport current density j_{z2} varies with the angle θ from $2 \cdot 10^5$ A/m^2 for big θ to $2 \cdot 10^5$ A/m^2 for $\theta=0.01$ (Glushchenko & Golovkina, 2007). Thus if the superconductor is found in the Larkin-Ovchinnikov state the amplification electromagnetic wave could be observed at the lower values of transport current density.
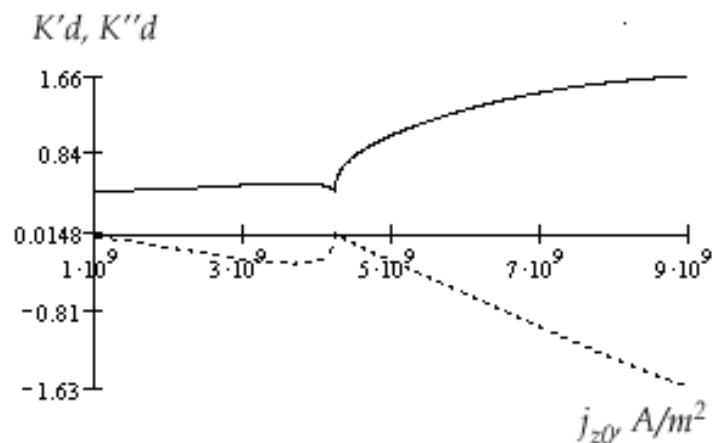

Fig. 6. The normalized Bloch wave number $K'd$ (solid line) and attenuation coefficient $K''d$ (dotted line) versus transport current density. The case of opposite direction of electromagnetic wave and vortex structure, $\omega=10^9$ rad/s
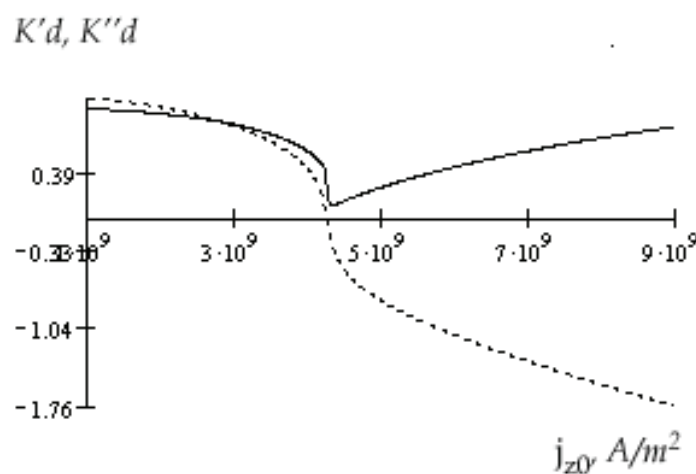

Fig. 7. The normalized Bloch wave number $K'd$ (solid line) and attenuation coefficient $K''d$ (dotted line) versus transport current density. The electromagnetic waves and vortex structure propagate in the same direction, $\omega=10^9$ rad/s

The dependence of Bloch wave number and attenuation coefficient from the transport current density is presented on Fig. 6 and 7. The parameters of superconducting film and dielectric layers are following: thickness of the dielectric layers d_1=6 μm, thickness of the superconducting layers t=50 nm, η=10^{-8} N·s/m², B_{y0}=1 T, θ=0.5, v^*=1750 m/s. The Fig. 6 corresponds to the choice of the top sign in formula (18). The Fig. 7 corresponds to the bottom sign in (18), when the electromagnetic wave propagates along the moving vortex lattice. We can see that the attenuation coefficient K'' changes its sign at transport current density j_z= j_{z1} (see Fig. 7). The amplification of electromagnetic waves could be observed at positive values of attenuation coefficient. Thus we can manage the process of amplification or attenuation by changing the transport current density.

Let us examine the behavior of attenuation coefficient K'' for the case when the electromagnetic waves and vortex structure propagate in the same direction (see Fig. 7, Fig. 8, Fig.9). The parameters of the structure in these figures are the same as in the Fig. 6.
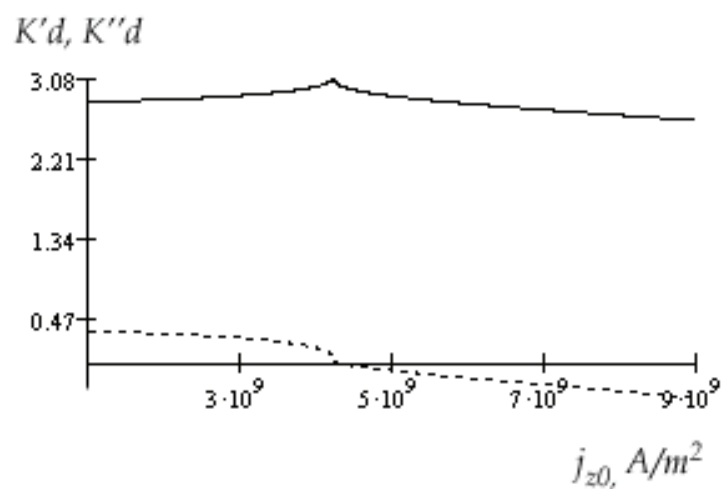

Fig. 8. The normalized Bloch wave number $K'd$ (solid line) and attenuation coefficient $K''d$ (dotted line) versus transport current density, ω=7·10^9 rad/s
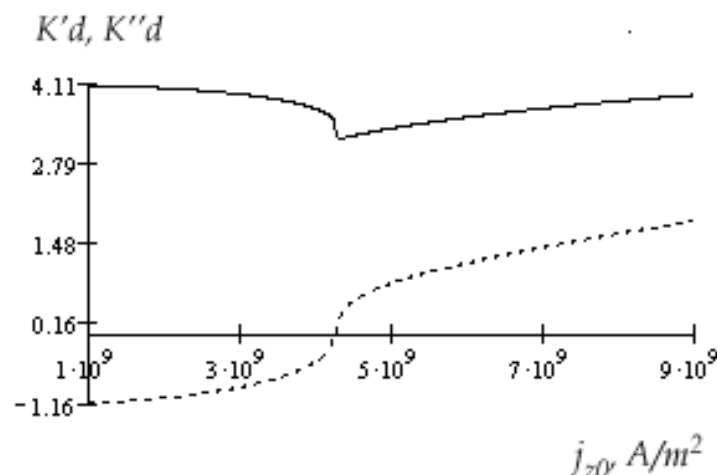

Fig. 9. The normalized Bloch wave number $K'd$ (solid line) and attenuation coefficient $K''d$ (dotted line) versus transport current density, ω=8·10^9 rad/s

The value of attenuation coefficient depends on the angular frequency ω. At the frequency change from $\omega=10^9$ rad/s (Fig. 7) up to $7 \cdot 10^9$ rad/s (Fig. 8) the absolute value of K'' decreases. And at the further growth of angular frequency up to $\omega=8 \cdot 10^9$ rad/s the areas of attenuation and amplification change their places (Fig. 9).

Thus the periodic structure with thin superconducting layers in Larkin-Ovchinnikov state demonstrates the new features in comparison with the superconducting structure in mixed state. Firstly, the amplification becomes possible at lower values of transport current density. Secondly, the coefficient of attenuation K'' can change its sign depending on j_z. Therefore we can manage amplification by means of transport current. Thirdly, the value of attenuation coefficient K'' depends on the angular frequency ω. All these features allow us to design new broadband amplifiers and filters. We can change the parameters of this devices not only by external magnetic field but also by transport current.

3.3 One-dimensional periodic structure superconductor - semiconductor

Let us consider the properties of one-dimensional periodic structure superconductor-semiconductor. There are essential distinctions between the structure superconductor-dielectric and the structure superconductor-semiconductor. The presence of a frequency dispersion of permeability in semiconductor layers leads to the appearance of new types of waves, propagating with various phase velocities. Also under the action of external electric field the free charged particle drift appears in semiconductor. As the result the medium gains active properties with new types of instabilities of electromagnetic waves. It is necessary to consider, that various dissipative processes exert significant influence on the electromagnetic wave propagation. That leads to the increase of attenuation and change of dispersion characteristics.

Let's consider the semiconductor plasma as a set of mobile electrons and holes which exist in a crystal. Let's use the hydrodynamic model in which electronic plasma is described as the charged liquid. The effective permittivity of superconductor can be written in following form:

$$\varepsilon_{eff} = \frac{2\cos^2\theta + \sin^2\theta\left(1+\frac{\varepsilon_\perp}{\varepsilon_\parallel}\right)}{2\left(\frac{\cos^2\theta}{\varepsilon}+\frac{\sin^2\theta}{\varepsilon_\parallel}\right)} \pm \frac{\sqrt{\left[2\cos^2\theta + \sin^2\theta\left(1+\frac{\varepsilon_\perp}{\varepsilon_\parallel}\right)\right]^2 - 4\varepsilon_\perp\left(\frac{\cos^2\theta}{\varepsilon}+\frac{\sin^2\theta}{\varepsilon_\parallel}\right)}}{2\left(\frac{\cos^2\theta}{\varepsilon}+\frac{\sin^2\theta}{\varepsilon_\parallel}\right)}, \quad (21)$$

$$\varepsilon = 1 - \frac{\omega_p^2(\omega-i\nu_e)}{\omega\left[(\omega-i\nu_e)^2-\omega_c^2\right]}, \quad (22)$$

$$\varepsilon_\parallel = 1 - \frac{\omega_p^2}{\omega(\omega-i\nu_e)}, \quad (23)$$

$$\varepsilon_\perp = \frac{\omega_p^2\omega_c}{\omega\left[(\omega-i\nu_e)^2-\omega_c^2\right]}, \quad (24)$$

where ν_e is the effective collision frequency, ω_p is the plasma frequency, ω_c is the cyclotron frequency of charge carriers. The dispersion equation for structure superconductor-semiconductor coincides with the dispersion equation for structure superconductor-dielectric (8). The difference is that we can not separate the independent E-and H-waves. In periodic structure with semiconductor layers two elliptically polarized waves can propagate. Each polarization corresponds to one of signs in the equation (21). The frequency dependence of permittivity leads to the appearance of new stop bands and new amplification bands. The presence of an imaginary part at Bloch wave number K indicates that the electromagnetic wave will attenuate exponentially when they pass through the periodic structure. However the Bloch wave number K becomes real when the condition *Im(K)=0* is fulfilled and the electromagnetic wave can penetrate deep into the structure. The amplification is observed if *Im(K)>0*. The equality of *Im(K)* to zero is possible if two condition are fulfilled:

$$\frac{\eta\,\omega}{\Phi_0} - j_{z0}\,k_x = 0 \tag{25}$$

or

$$\sin k_y d_1 = 0 . \tag{26}$$

Taking into account the formulas (21) - (24) we can write the expressions (25) and (26) in the following form

$$\varepsilon_{eff} = \frac{\eta^2 \cdot c^2}{\Phi_0^2\,j_{z0}^2 \sin^2\theta} \tag{27}$$

or

$$\varepsilon_{eff} = \frac{\pi^2 c^2 n^2}{d_1^2 \cos^2\theta\;\omega^2}, n = 0,1,2... \tag{28}$$

The solution of equations (27) and (28) is difficult. To simplify the solution, we consider an extreme case of collisionless plasma (when the effective collision frequency ν_e=0). This yields to the following expression for effective permittivity of semiconductor (Vural& Steele, 1973)

$$\varepsilon_{eff} = 1 - \frac{2\left(y^2 - 1\right)}{2\left(y^2 - 1\right)y^2 - \dfrac{\omega_c^2}{\omega_p^2}y^2\sin^2\theta \pm \sqrt{y^4\dfrac{\omega_c^4}{\omega_p^4}\sin^4\theta + 4\dfrac{\omega_c^2}{\omega_p^2}y^2\left(y^2 - 1\right)\cos^2\theta}}, \tag{29}$$

where y=ω/ω_p. In the expression (29) the top sign "+" in a denominator corresponds to an ordinary wave, and the bottom sign "-" to an extraordinary wave. In the further for the designation of effective permittivity of the extraordinary wave we shall use index 1, and for the ordinary wave - index 2. The effective permittivity of the ordinary wave vanishes when

$$y_{20} = 1 . \tag{30}$$

The effective permittivity of the extraordinary wave vanishes when

$$y_{10} = \sqrt{1 \pm \frac{\omega_{ce}^2}{\omega_{pe}^2}} \, .$$
(31)

As it has been shown in (Golovkina, 2009 a), the solution of equation (27) corresponds to the resonance frequencies of ε_{eff} at value of vortex viscosity $\eta=10^{-8}$ N·s/m^2 and transport current density $j_{z0}=10^{10}$ A/m^2. The solutions of (27) on the frequencies which are not equal to the resonance frequencies of ε_{eff} appear when the vortex viscosity decreases and the transport current density increases (Bespyatykh et al., 1993), (Ye et al., 1995). The appropriate dispersion characteristic is shown in the Fig. 10.

We can see from the Fig. 10 that the imaginary part of Bloch wave number K is equal to zero at the frequencies $\omega_1=0.025\,\omega_p$, $\omega_2=0.15\,\omega_p$ and $\omega_3=0.19\,\omega_p$. These frequencies are the solutions of equation (27). At the frequencies $\omega<\omega_1$ and $\omega_2<\omega<\omega_3$ the electromagnetic wave attenuates, and at the frequencies $\omega_1<\omega<\omega_2$ the electromagnetic wave amplifies.

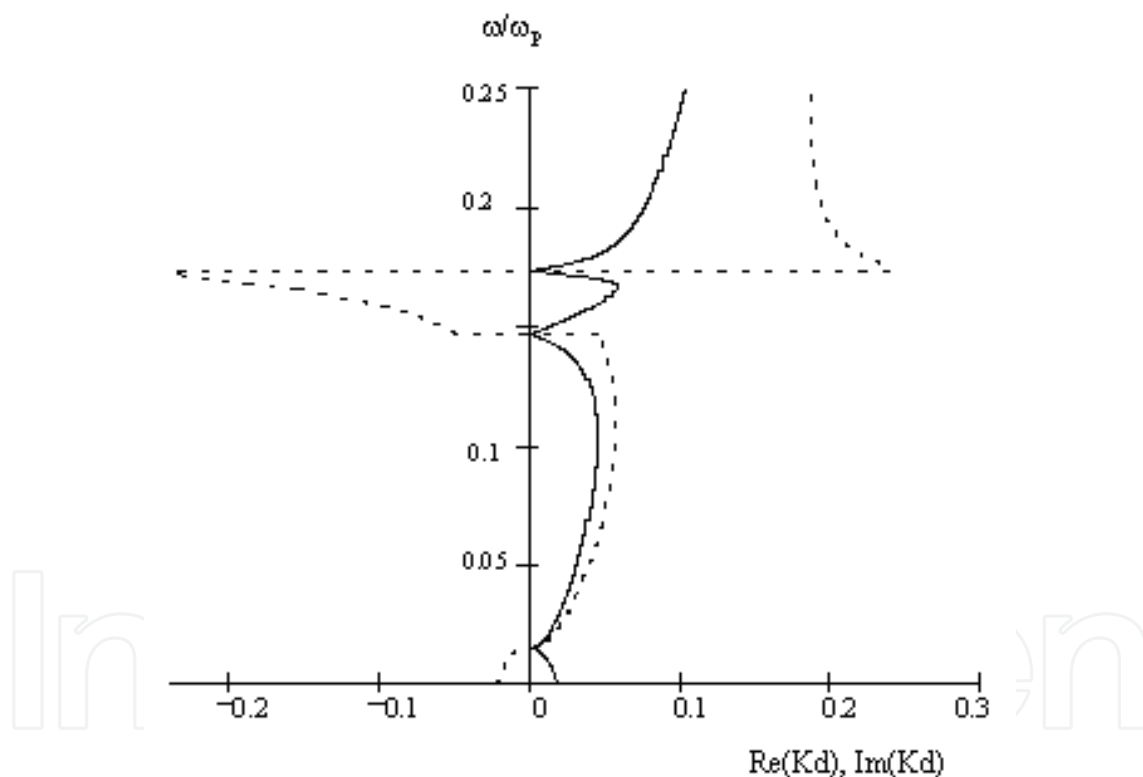Fig. 10. The dispersion characteristics of periodic structure superconductor – semiconductor (the ordinary wave). The solid line: Re(Kd) , the dotted line: Im(Kd). Parameters:
$\omega_p=1.2\cdot10^{12}$ s^{-1}, $\omega_c=10^{12}$ s^{-1}, $\nu_e=10^{10}$ s^{-1}, $d_1=3$ μm, t=60 nm, $\eta=10^{-8}$ N·s/m^2, $j_{z0}=10^{10}$ A/m^2

Thus the amplification of electromagnetic waves can be observed in the periodic structure superconductor - semiconductor as well as in the structure superconductor - dielectric. The amplification realizes at the expense of energy of moving Abikosov vortex lattice. The presence of frequency dispersion in semiconductor layers leads to the appearance of additional stop bands and amplification bands.

4. The structures with thin superconducting film and negative-index material

4.1 Periodic structure with combination of dielectric layer and layer with negative refractive index

In this section we consider the dispersion relations for electromagnetic wave propagation in an infinite periodic structure containing thin superconducting film and combination of two layers - dielectric and negative index material. The negative index materials or metamaterials are artificially structured materials featuring properties that can not be acquired in nature (Engheta & Ziolkowski, 2006). The new materials with negative index of refraction were theoretically predicted in 1968 by Veselago (Veselago, 1967). In these materials both the permittivity and the permeability take on simultaneously negative values at certain frequencies. In metamaterials with the negative refractive index the direction of the Pointing vector is antiparallel to the one of the phase velocity, as contrasted to the case of plane wave propagation in conventional media. The metamaterials with negative index of refraction are demonstrated experimentally first in the beginning of 20 century (Smith et al., 2000), (Shelby et al., 2001). In negative-index materials we can observe many interesting phenomena that do not appear in natural media. To unusual effects in negative-index materials concern the modification of the Snell's law, the reversal Cherenkov effect, the reversal Doppler shift (Jakšić, 2006). The most important effect is that wavevector and Pointing vector in negative-index material are antiparallel. Therefore the phase and group velocities are directed opposite each other. The unusual properties of negative-index materials are demonstrated especially strongly in its combination with usual medium.
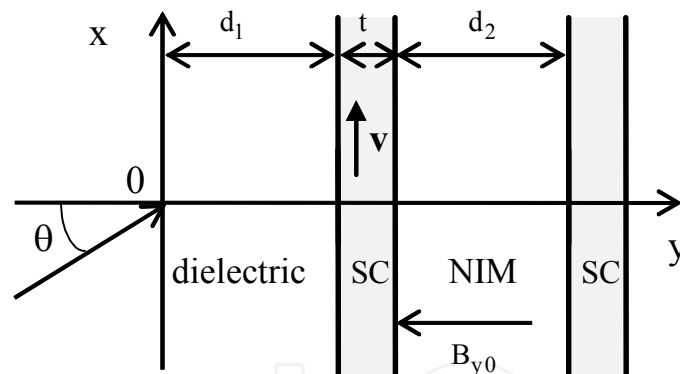

Fig. 11. Geometry of the problem. One-dimensional structure dielectric – superconductor – negative-index material

Let's consider the periodic structure containing the layer of usual dielectric with thickness d_1, the layer of negative-index material with thickness d_2 and the thin superconducting film with thickness t (see Fig. 11). By usage of matrix method we expressed dispersion relation for H-wave for considered structure in the following way (Golovkina, 2009 b):

$$
\cos Kd = \cos k_{y1}d_1 \cos k_{y2}d_2 - \frac{1}{2}\left(\frac{k_{y1}\mu_2}{k_{y2}\mu_1} + \frac{k_{y2}\mu_1}{k_{y1}\mu_2}\right)\sin k_{y1}d_1 \sin k_{y2}d_2 -
$$
$$
-\frac{1}{2}\frac{i\omega\mu_0 t}{B_{y0}}\left(\frac{j_{z0}k_x}{\omega} - \frac{\eta}{\Phi_0}\right)\left(\frac{\mu_1}{k_{y1}}\sin k_{y1}d_1 \cos k_{y2}d_2 + \frac{\mu_2}{k_{y2}}\cos k_{y1}d_1 \sin k_{y2}d_2\right),
$$
(32)

where ε_1 and μ_1 are the permittivity and permeability of usual dielectric ($\varepsilon_1 > 0$, $\mu_1 > 0$), ε_2 and μ_2 are the permittivity and permeability of negative-index material ($\varepsilon_2 < 0$, $\mu_2 < 0$).

The study of dispersion characteristics of electromagnetic wave in considered periodic structure with thin superconducting film and combination of two layers - dielectric and negative-index material has shown that these characteristics don't differ qualitative from the dispersion characteristics of periodic structure without negative index material layer.

The explanation of this fact consists in following. When electromagnetic wave propagates through the infinite one - dimensional periodic structure the phase velocities in dielectric and negative-index material are directed opposite each other (see Fig. 12). But the group velocities are co-directional in projection to axis z. Therefore the presence of negative index material layer in infinite structure does not affect on the resulting group velocity of electromagnetic wave.
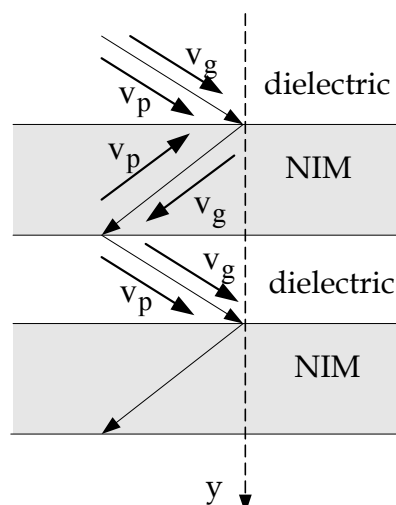

Fig. 12. The directions of phase and group velocities in periodic structure dielectric - negative-index material (NIM)

The important distinctive feature of negative index material (opposite direction of phase and group velocities) can be revealed only in the limited structures. The waveguide structures containing combination of dielectric and negative index material can excite the nondispersive modes and super - slow waves (Nefedov & Tretyakov, 2003), (Golovkina, 2007). Such slow waves can interact efficiently with moving Abrikosov vortex lattice.

4.2 Nonlinear pulses in waveguide with negative index material and thin superconducting film

The electromagnetic wave can amplify at the interaction with moving vortex structure when the velocities of electromagnetic wave and vortex lattice are approximately equal. For implementation of amplify condition it is necessary to slow down the electromagnetic wave. The slow waves can exist in two layered waveguide with negative index material slab (Nefedov & Tretyakov, 2003), in two layered waveguide with negative index material and with resistive film (Golovkina, 2007). The combination of two layers: dielectric and negative index material acts the role of slow-wave structure. The presence in waveguide of dielectric with negative index material can lead to amplification of evanescent electromagnetic waves (Baena et al., 2005). The amplification can be observed also in waveguide with negative-index material and thin superconducting film (Golovkina, 2009 c). If we add thin

superconducting film in waveguide with nonlinear dielectric we can manage the process of electromagnetic waves propagation (Golovkina, 2008).

Let us consider the wave propagation in two-layered waveguide. On layer of thickness a is a negative-index material ($\varepsilon_1 < 0$, $\mu_1 < 0$) and the other one of thickness b is an usual dielectric ($\varepsilon_2 > 0$, $\mu_2 > 0$) (see Fig. 15). The thin film of type-II superconductor with thickness t and thin film of Kerr nonlinear dielectric with thickness δ are placed in the plane y0z. The thickness of superconductor is $t \ll \lambda$, where λ is magnetic field penetration depth, $\delta \ll \Lambda$, where Λ is wavelength. The transport current in superconductor is directed along the 0y axis.
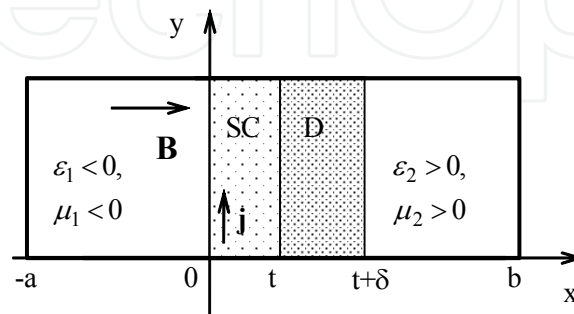

Fig. 13. The geometry of the structure. SC - superconductor, D - dielectric with Kerr-type nonlinearity

Let us consider the H-wave which effectively interacts with flux-line lattice in superconductor. Using boundary conditions for two-layered thin film superconductor - nonlinear dielectric we have received the equation for component $E_y(z,t)$ of the electric intensity and its Fourier transform $E_y(\omega, \beta)$ in the form (Glushchenko & Golovkina, 2006)

$$\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} (2\pi)^{-2} d\omega d\beta R(\omega,\beta) E_y(\omega,\beta) \exp[i(\omega t - \beta z)] = \frac{\partial}{\partial t}(P_N(E_y)) , \qquad (33)$$

where $\mathbf{P} = \alpha_1 \mathbf{E} + \alpha_3 |\mathbf{E}|^2 \mathbf{E} + ...$ is the vector of polarization of Kerr nonlinear dielectric media, $R((\omega, \beta)$ is function of parameters of the film, magnetic field and input impedances of negative index material and usual dielectric. After carrying out the $E_y(\omega, \beta)$ in form of high-frequency pulse with slowly varying complex envelope $e(z, t)$ we obtain from (33) the nonlinear Schrödinger equation (Korn & Korn, 2000). The solution of this equation is represented by lattice of nonlinear pulses or by lattice of dark pulses.

The group velocity of pulses depends on parameters of thin films, on amplitude of pulse and on external magnetic field:

$$v = [\frac{\partial R(\omega = \omega_0, \beta = \beta_0)}{\partial \beta} \left(-\frac{\partial R(\omega = \omega_0, \beta = \beta_0)}{\partial \omega} \right) + i 2\pi \delta k^{-2} \alpha_3 E_s^2 (2k^2 - 1)]^{-1} . \qquad (34)$$

Here E_s is the amplitude of pulse, k is module, α_3 is the coefficient in the nonlinear series expansion of vector of polarization P .

The numerical calculation demonstrates that the group velocity can change the magnitude and the sign by the variation of magnetic field (see Fig. 14). The calculated results offer the opportunity to considered waveguide to operate as an effective control structure at optical, IR and microwave frequencies. It should be noted that each layer of the structure is of the

great importance: thin Kerr nonlinear dielectric produces the soliton-like pulses, thin superconducting film gives the possibility of control, negative index material slab reduces the pulse velocity providing large interaction of pulses with a flux-line lattice in superconductor.
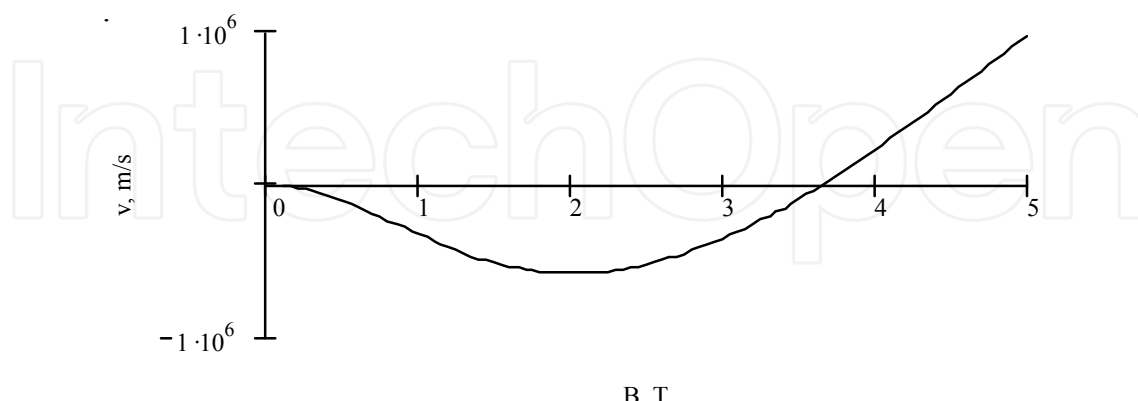

Fig. 14. Magnitude of the pulse velocity as function of external magnetic field. The parameters of the structure are: t=40 nm, $\eta=10^{-8}$ N·s/m^2, $j_{y0}=10^9$ A/m^2, $\omega=20\cdot10^{11}$ rad/s, a=0.025 m, b=0/02 m, $\delta=100$ μm, $E_s=10^3$ V/m, $\alpha_3=10^{-15}$ C·m/V^2

7. Conclusion

In this chapter the propagation of electromagnetic waves in structures with thin high temperature superconducting film is investigated. The interaction of electromagnetic wave with thin superconductor in the mixed state is studied. It is shown, that the presence of the moving magnetic vortex structure in superconductor can lead not only to attenuation, but also to amplification of electromagnetic waves. The condition of amplification consists in equality of velocity of electromagnetic wave and the moving vortex structure. It is shown, that the electromagnetic wave amplification takes place at the expense of energy of Abrikosov vortex lattice. The representation of thin superconducting film in the form of boundary condition has enabled us to understand the mechanism of electromagnetic wave interaction with moving vortex structure. This method allowed us to simplify the numerical calculation.

In this study also the propagation of electromagnetic waves in periodic structures superconductor - dielectric is examined. The peculiarities of periodic structures with thin superconducting film in Larkin-Ovchinnikov state are revealed. The features of periodic structures superconductor - semiconductor are studied. The new pass bands and amplification bands are found. The possibility of the control of processes of attenuation and amplification is shown. The control can be realized by means of change of external magnetic field and transport current density. The dependence of coefficients of attenuation and amplification on the thickness of superconducting film and frequency enables us to make active devices which parameters can vary widely.

The structures with thin superconducting film in mixed state and combination of dielectric layer and negative index material layer are considered. It is shown, that the combination of dielectric and negative index material acts as the slow-wave structure in limited structures. The combination of dielectric and negative index material with thin superconducting film can be used in different devices such as waveguides and resonators as the control section. As the example of such application the waveguide with nonlinear thin film is considered. It

is shown, that the nonlinear film with Kerr like nonlinearity excites the nonlinear soliton-like pulses. And the presence in such waveguide of the control section on the base of thin superconducting film permits to change not only attenuation coefficient, but also the direction of pulse propagation.

The properties of structures with thin high temperature superconducting films in the mixed state open the promissory perspective for their application in modern devices with control of parameters.

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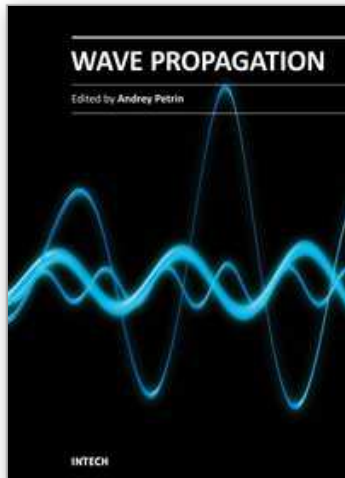
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