DISPERSION PROPERTIES OF SURFACE WAVES AT PLANAR STRUCTURES 'METAL – DIELECTRIC – MAGNETIZED PLASMA'

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This report is devoted to the investigation of the dispersion properties and field spatial structure of potential surface waves (SWs) that propagate along interfaces metal – dielectric – magnetized plasma of a finite pressure. The external steady magnetic field is directed perpendicularly to the interfaces of mediums. Plasma is considered in the hydrodynamic approach as warm collision medium. The influence of finite metal conductivity, dielectric parameters, electron collision frequency and external magnetic field value on properties of the SW is investigated. The influence of the mentioned above parameters on frequency region of SW existence and spatial wave field structure is studied.
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1. INTRODUCTION

The plasma-metal waveguides are widely applied in plasma, semiconductor electronics, gas discharges and plasma technologies [1]. This explains the intensive theoretical and experimental researches of wave processes in them [1-4]. The feature of such structures is the existence and propagation of surface waves in them. The linear theory of SW in the Voigt geometry (the magnetic field is parallel to the plasma surface and perpendicular to the wavevector) and in the Faraday geometry (when the field is parallel both to the surface and to the wavevector) is developed enough completely [3-5]. But in practice often there are waveguide structures, in which the magnetic field is perpendicular to the interfaces of mediums [6-7]. They are typical for HF and UHF discharges, magnetrons, Penning sources, magneto-discharge pumps, Hall sensors, fusion devices (divertor, limiter) etc.

The properties of potential SW that propagates at interface of perfect conducting metal and collisionless plasma of a finite pressure at the presence of exterior magnetic field that is normal to the interface was studied earlier in [7]. However, as a rule, between plasma and metal there is a dielectric interlayer (oxide film on metal, plasma sputtering, transition plasma layer, which in first approximation it is possible to consider as a vacuum, and so on). At the same time the account of a finite value of metal conductivity and plasma electron collision frequency can result in modification of dispersion properties, attenuation and spatial structure of SW field. This report is devoted to the research of these problems.

2. DISPERSION RELATION

Let us consider the SWs that propagate in a planar waveguide structure 'metal - dielectric – plasma' along interfaces of mediums in direction of axis y. Plasma is assumed as nonisothermal medium ($T_e >> T_i$, where T_e, T_i are the electron and ion temperature respectively) and occupies a half-space $x > 0$. In a plane $x = 0$ it bounds with a thin dielectric interlayer by permittivity ε_d and thickness a. In the region $x < -a$ there is a metal described by conductivity σ. An external steady magnetic field is directed along axis x perpendicularly to the medium interfaces.

The set of equations describing SW propagation in the considered waveguide structure consists of the Maxwell equations and quasihydrodynamics ones. The solutions of this set will be searched in form: $\exp[i(k_2 y - \omega t)]$, where k_2 is a wavenumber and ω is a frequency of the SW.

To derive the dispersion relation it is necessary to use the boundary conditions, which consist of a continuity of tangential components of electrical and magnetic SW fields at the medium interfaces. Besides as the electron thermal motion in plasma was taken into account, it is necessary to realize one more condition. The normal component of plasma electron velocity is zero on the plasma - dielectric interface ($x = 0$).

Thus, applying the mentioned above boundary conditions, it is possible to derive the following dispersion equation:

$$1 + k_2^2 r_{de}^2 - r_{de}^2(\lambda_1^2 + \lambda_1\lambda_2 + \lambda_2^2) = - (\lambda_1 + \lambda_2)(1+\eta)[\varepsilon_d k_2 (1-\eta)]^{-1}\lambda_1\lambda_2 r_{de}^2, \quad (1)$$

where $r_{de} = V_{Te}/\omega_{pe}$ is electron Debye radius, V_{Te}, ω_{pe} are electron thermal velocity and plasma frequency respectively. The parameters $\lambda_{1,2}$ describe the spatial distribution of SW field in plasma region

$$\lambda_{1,2}^2 = \frac{1}{2\beta}\left\{\beta(1+\alpha) - \varepsilon_1 \pm \pm\sqrt{\varepsilon_1^2 + \beta(1-\alpha)[\beta(1-\alpha) + 4 - 2\varepsilon_1]}\right\}, \quad (2)$$

where, $\alpha = \omega'^2/(\omega'^2 - \omega_{ce}^2)$, $\beta = k_2^2 V_{Te}^2/(\omega\omega')$, ω_{ce} is electron cyclotron frequency, $\omega' = \omega + i\nu$, ν is electron collision frequency and $\varepsilon_1 = 1 - \omega_{pe}^2/(\omega\omega')$.

In eq. (1) parameter η takes into account the influence of dielectric and metal:

$$\eta \approx -\left(1 + 2(1+i)\varepsilon_d \frac{k}{k_2}\sqrt{\frac{\omega}{8\pi\sigma}}\right)\exp(2k_2 a). \quad (3)$$

2. DISPERSION PROPERTIES OF SWS

As the dispersion equation (1) is complicated, its general solution at finite values of external magnetic field, dielectric thickness, metal conductivity and electron collision frequency can be obtained only numerically. Nevertheless in of some limit cases it is possible to derive the analytical solutions of eq. (1) at a finite magnetic field.

So, for example, in the case of perfect conducting metal ($\sigma \to \infty$), and dielectric absence ($a = 0$) the eq. (1) becomes simpler and its solution for wave number k_2 can be written in following expression:

$$k_2^2 = \frac{1}{2V_{Te}^2}\frac{\omega}{\omega'}\left(\frac{\omega'^2}{\omega_{ce}^2}-1\right)\left\{\omega'^2+\omega_{ce}^2+\frac{\omega'}{\omega}\omega_{pe}^2 - \sqrt{\left(\omega'^2-\omega_{ce}^2+\frac{\omega'}{\omega}\omega_{pe}^2\right)^2+4\frac{\omega'}{\omega}\omega_{ce}^2\omega_{pe}^2}\right\}. \qquad (4)$$

In the case of collisionless plasma ($\nu = 0$) the expression (4) coincides with solution obtained earlier in paper [7].

The numerical analysis of expression (4) has shown that in collisional plasma is possible the existence of the SWs in the frequency region below electron cyclotron frequency. But in this case the waves strongly attenuate.

The magnetic field growth leads to the decrease of $\mathrm{Re}\,k_2$ and increase of spatial attenuation coefficient $\mathrm{Im}\,k_2$. Thus growth of magnetic field leads to more effective spatial attenuation of the SWs.

The strongest influence on SW damping is electron collision frequency one. Its growth results in essential increase of imaginary part of SW wavenumber and in insignificant growth of one's real part.

Analytical solutions of eq. (1) can be derived also in the case of a thin dielectric interlayer ($2k_2 a$, $\lambda_1 a$, $\lambda_2 a << 1$), when the influence of metal and dielectric is rather weak, so the wave number k_2 is possible to present as $k_2 = k_{20} + \delta k_2$. Here k_{20} and $\delta k_2 << k_{20}$ are the value (4), and variation of wavenumber due to influence of thin dielectric and metal. In this case δk_2 given by:

$$\frac{\delta k_2}{k_{20}} = -\frac{\alpha+1}{2\alpha(\alpha-1)}\frac{1}{\varepsilon_d^2}\frac{L^2}{r_{de}^2}\frac{\alpha k_{20}^2-\varepsilon_2/\beta}{2\alpha k_{20}^2-\varepsilon_2/\beta} * \left[1+k_{20}^2 r_{de}^2 + r_{de}^2\sqrt{k_{20}^2(\alpha k_{20}^2-\varepsilon_2/\beta)}\right], \qquad (5)$$

where $L = a + (1+i)\varepsilon_d k k_{20}^{-2}\sqrt{\omega/(8\pi\sigma)}$,

$$\varepsilon_2 = 1 - \omega_{pe}^2\omega'/[\omega(\omega'^2-\omega_{ce}^2)].$$

The analysis of expression (5) shows that, because the considered waves are potential ($k_2 >> k$), a finite value of metal conductivity value weak influences on SWs dispersion and results in insignificant increase of phase velocity and additional damping of SWs. According to (5), this influence is increased with growth of phase velocity and can become essential for non-potential waves.

The presence of thin dielectric interlayer also leads to growth of SW phase velocity. This variation is proportional to square of dielectric thickness and inversely as square of its permittivity. In the case of finite dielectric thickness the dispersion equation (1) can be solved only numerically. The results of numerical investigation of dielectric parameters influence have shown in fig. 4, 5. The dielectric thickness does not influence essential on spatial damping of SWs (fig.1). It is connected with fact that in the given task the energy losses in dielectric were not taken into account. The thickness increase results in a growth of SW phase velocity. However, if the value a exceeds 5-10 Debye radiuses, then the further its growth weakly influences on SWs dispersion. The dependence SW properties on permittivity ε_d is most essential in the region of small frequencies, as penetration depth of SW field in dielectric in this region is rather great. The phase velocity decreases with growth of ε_d (fig.2).

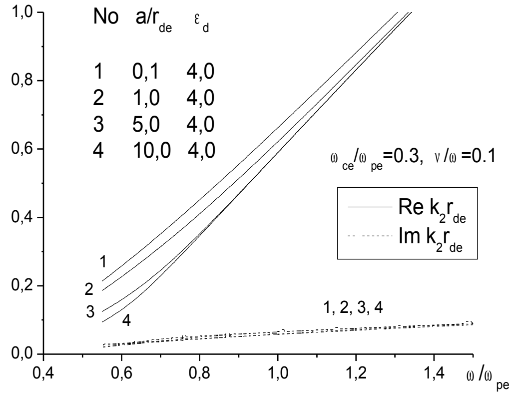


Fig. 1. The influence of dielectric thickness on dispersion of SWs

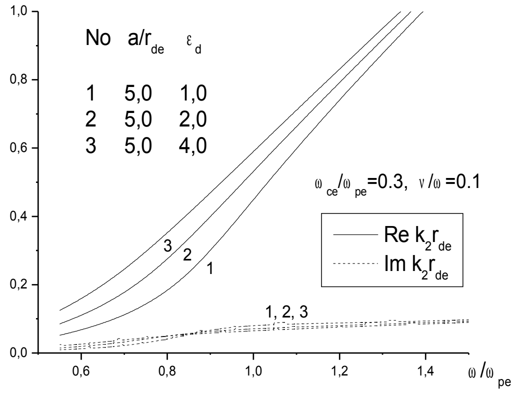


Fig. 2. The dependence of SWs dispersion on dielectric permittivity

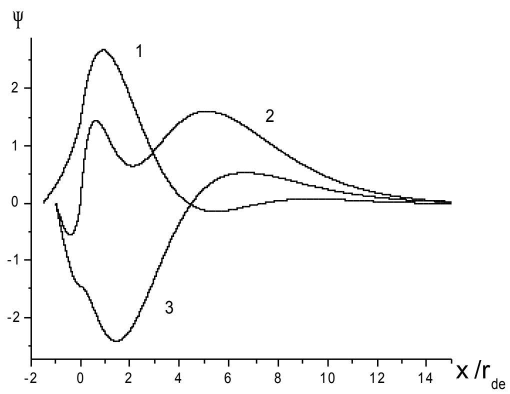
The necessary condition of SWs existence at the interface 'plasma - metal' is a finite value of plasma electron thermal velocity. However, dielectric presence leads to the considered waves can exist and in the case of cold plasma. There is increase of wavelengths in the considered waveguide structure due to the temperature growth.

3. SPATIAL STRUCTURE OF SWS

As it was noted above, the dependence of SWs dispersion properties on finite metal conductivity value is weak. It is possible to show that it also weak influences on a spatial field structure SWs. Thus, in the considered task it is possible to consider metal with an adequate accuracy as perfect conducting, neglecting a penetration of wave field into metal.

The spatial field structure in plasma and its type are determined by parameters $\lambda_{1,2}$ (2). It is obvious that at finite values of electron collision frequency the considered waves in all frequency range are generally surface waves

(GSWs). The typical oscillations of potential Ψ at its decrease deep into plasma (fig. 3) are evidence of it. Thus dielectric thickness and its permittivity essential influence on spatial distribution of wave field. So, depending on thickness a, the potential can grow or decrease nearby the plasma interface (fig. 3). The increase of collision frequency result in growth of imaginary part of coefficients λ_1 and λ_2. Thus the spatial scale of oscillations of the potential decreases and can be some electronic Debye radiuses. Thus, before the wave field amplitude essentially will decrease deep into plasma, the potential can make some oscillations (fig. 3).



№	a / r_{de}	ε_d	ν / ω	ω / ω_{pe}	$\omega_{ce} / \omega_{pe}$
1	1.5	2.0	1.0	0.85	0.5
2	1.0	2.0	1.0	1.2	0.5
3	1.0	2.0	0.75	1.2	0.5

Fig. 3. The influence of dielectric parameters, collision and wave frequencies on spatial structure of SW potential

However, in the limit of small collision frequencies values ($\nu << \omega$) it is possible to separate the frequency ranges of existence GSW and SW [7].

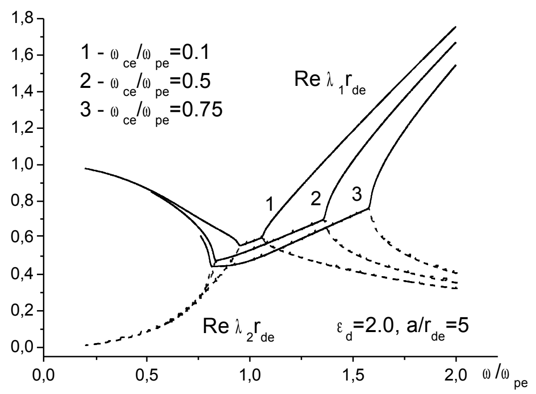


Fig. 4. The influence of magnetic field value on spatial distribution type of wave potential

Numerical investigation has shown that increase of permittivity ε_d or decrease of dielectric thickness a result in expansion of frequency region of existence GSWs.

There is essential influence of external magnetic field value on this region and spatial scales of wave amplitude modification. So, for example, the increase of a parameter $\omega_{ce} / \omega_{pe}$ from value 0.1 till 0.75 leads to expansion of frequency region of GSWs in some times (fig. 4). The continuous and dashed lines correspond to $\mathrm{Re}\lambda_1 r_{de}$ and $\mathrm{Re}\lambda_2 r_{de}$ respectively. Note, that frequency region, where values $\mathrm{Re}\lambda_1 r_{de}$ and $\mathrm{Re}\lambda_2 r_{de}$ coincide, corresponds to propagation of GSWs.

4. CONCLUSIONS

It is shown that as against waveguide structure 'metal - plasma', the presence of a dielectric results in the considered waves can exist and in the case of cold plasma. The influence of a finite value of metal conductivity on dispersion properties of SWs is insignificant. The dielectric thickness decrease and its permittivity increase lead to decrease of the SW phase velocity. These influences are more essential at the small wave frequencies in comparison with plasma one. The wave damping is determined basically by plasma electron collisions. The analytical expressions of influence of dielectric parameters on SW properties in the case of thin dielectric layer are obtained.

It is shown that the dielectric permittivity increase and its thickness decrease result in expansion of the frequency region of the generally surface wave existence. The growth of a magnetic field value leads to essential expansion of this region.

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