УДК 533.9

DISPERSION OF THE SURFACE MAGNETOPLASMONS

S.V. Ivko[1], I.B. Denysenko[1], A.I. Smolyakov[2], N.A. Azarenkov[1]
[1]Department of Physics and Technology, V.N. Karazin Kharkov National University, Kharkov, Ukraine
[2]Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Canada
E-mail: sergey-ivko@yandex.ua

We study the dispersion properties and transmission of a *p*-polarized electro-magnetic wave in a two-layer plasma structure in presence of an external magnetic field. The conditions for resonance transmission are found. The anomalous transparency is attributed to excitation of surface waves at plasma-plasma interface. The dispersion relation for the surface mode at plasma-plasma interface in magnetic field is studied and compared with that for a plasma-vacuum system.

PACS: 52.40.Db, 52.25.Os, 52.35.Hr

1. INTRODUCTION

The materials with negative dielectric permittivity $\varepsilon < 0$ and magnetic permeability $\mu < 0$ (metamaterials) have attracted much attention in recent years. The increased interest to such media has been driven by their potential applications in various branches of science and technology. Such materials have much promises for subwavelength optics, particularly, for imaging systems without the diffraction limit [1], the so called superlense. Manipulation of light at the subwavelength scale also opens the possibilities for all optical computer components which would combine advantages of wide band photonics and nanoscale electronics [2].

Various remarkable properties in metamaterials are based on the amplification of evanescent waves due to surface mode resonances. In this paper, we study transparency of a structure consisting of two plasma layers of different electron densities. It was found earlier [3] that at absence of magnetic field a *p*-polarized electromagnetic wave obliquely incident at a layer with smaller density can be totally transmitted through the two-layer plasma structure. The transparency of the structure occurs as a result of surface mode excitation. The surface wave at the plasma-plasma interface amplifies the transmitted wave, which is evanescent in plasma. In this paper, we study the influence of an external magnetic field on transparency of the two-layer structure. Voigt geometry is considered.

2. TRANSPARENCY OF TWO-LAYER PLASMA STRUCTURE

Consider a two-layer plasma structure surrounded by vacuum (Fig.1). The structure is immersed in an external magnetic field $\vec{H}$ directed along *z*-axis. It is assumed that the density of the first slab Pl1 is small ($0 < \varepsilon_{10} < 1$, where ε_{10} is the dielectric permittivity of the first layer at absence of magnetic field), while the second layer Pl2 is dense with $\varepsilon_{20} < 0$ (here ε_{20} is the dielectric permittivity of the second layer at $H = 0$). A *p*-polarized electromagnetic wave with wave vector $\vec{k}$ is obliquely incident at the first slab. The wave vector has two non-zero components, *x*-component k_x and *y*-component k_y. In the vacuum region V1, the wave consists of the incident ($k_x > 0$) and reflected ($k_x < 0$) waves. The transmitted wave propagates into the semi-infinite vacuum region V2. In the plasma regions Pl1 and Pl2, the waves are assumed to be non-propagating (evanescent) in *x*-direction.

In a constant magnetic field the dielectric permittivity tensor of a plasma slab has the following non-zero components

$$\varepsilon_{11} = \varepsilon_{22} \equiv \varepsilon = 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2},$$

$$\varepsilon_{12} = -\varepsilon_{21} \equiv ig = \frac{i\omega_c\omega_p^2}{\omega\left(\omega^2 - \omega_c^2\right)},$$

$$\varepsilon_{33} = 1 - \frac{\omega_p^2}{\omega^2},$$

where ω, ω_p and ω_c are the wave, plasma and cyclotron frequencies, respectively.

The expressions for components of electro-magnetic field of the wave in different plasma and vacuum regions may be obtained from Maxwell's equations. Obtaining the components, we assumed that the plasma is collisionless and ions are immobile (the wave frequency is assumed to be large).

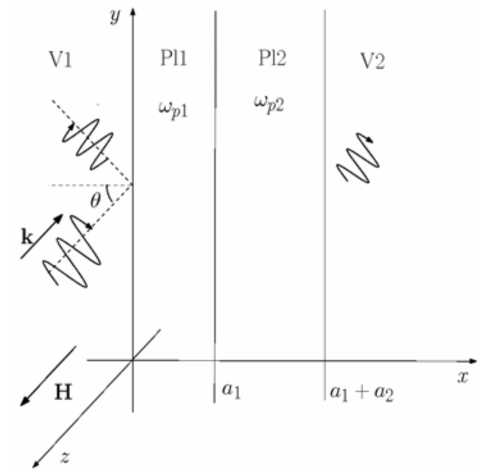

Fig.1. Schematic representation of propagation of electromagnetic wave through the two-layer structure

Assuming that the tangential components of electric and magnetic field of the wave are continuous at interfaces and neglecting reflected wave in the vacuum region V1, one can obtain the condition of the absolute transmission

$$\frac{\psi_1^2-\xi_1^2-ik_x\left(\psi_1+\xi_1\coth\varphi_1\right)}{\psi_1-\xi_1\coth\varphi_1-ik_x}=\frac{\psi_2^2-\xi_2^2-ik_x\left(\psi_2-\xi_2\coth\varphi_2\right)}{\psi_2+\xi_2\coth\varphi_2-ik_x}, \tag{1}$$

where $\xi=\kappa\varepsilon/[k(\varepsilon^2-g^2)]$, $\psi=k_y g/[k(\varepsilon^2-g^2)]$, $\varphi=\kappa a$, a is a layer thickness, $k_x=\cos\theta$ is the normalized *x*-component of the wave vector, θ is the incidence angle, $\kappa=\sqrt{k_y^2-k^2\left(\varepsilon^2-g^2\right)/\varepsilon}$ is the decay constant, $k=\omega/c$, and c is the speed of light. Indexes 1 and 2 in Eq. (1) correspond to the parameters of the slabs Pl1 and Pl2, respectively.

Note that the resonance transmission condition (1) depends on the layer widths, while the condition at $H=0$ is independent on a_1 and a_2 [3].

The equation (1) is equivalent to the set of two real transcendental equations (for its real and imaginary parts), those in general case may be solved only numerically. An analytical solution of Eq. (1) is possible only for the limits of thin ($\varphi \ll 1$) and thick ($\varphi \gg 1$) layers. If the layer is thin, the equation (1) reduces to the set of the following two equations

$$\frac{k_x^2+\xi_1^2-\psi_1^2}{\xi_1}\varphi_1+\frac{k_x^2+\xi_2^2-\psi_2^2}{\xi_2}\varphi_2=0$$

and

$$\frac{\psi_1}{\xi_1}\varphi_1+\frac{\psi_2}{\xi_2}\varphi_2=0 .$$

In the case $\varphi \gg 1$, Eq. (1) transforms to the following equation

$$\left(\psi_1+\xi_1\right)-\left(\psi_2-\xi_2\right)=-2\xi_1\frac{\psi_1+\xi_1+ik_x}{\psi_1-\xi_1+ik_x}e^{-\varphi_1}-2\xi_2\frac{\psi_2-\xi_2+ik_x}{\psi_2+\xi_2+ik_x}e^{-\varphi_2}. \tag{2}$$

3. DISPERSION PROPERTIES OF SURFACE WAVES AT PLASMA-PLASMA AND PLASMA-VACUUM INTERFACES

In zero approximation, neglecting the right-hand side of Eq. (2), we obtain the equation which coincides with the dispersion relation for the surface waves at interface between two semi-infinite plasmas:

$$\psi_1+\xi_1=\psi_2-\xi_2 . \tag{3}$$

The equation (3) may be presented in the form

$$\frac{k_y g_1+\varepsilon_1\kappa_1}{\varepsilon_1^2-g_1^2}=\frac{k_y g_2-\varepsilon_2\kappa_2}{\varepsilon_2^2-g_2^2} . \tag{4}$$

Eq. (4) may be solved analytically only in some limiting cases. Therefore, we found its solution numerically. In Fig.2, the dispersion dependencies for waves with $k_y<0$ and $k_y>0$ are shown. The curves were obtained for $\omega_c/\omega_{p2}=0.125$ and $\omega_{p1}/\omega_{p2}=0.25$.

Note that surface waves at plasma-vacuum interface are always slow ($v_{ph}<c$, where v_{ph} is the wave phase velocity). It is connected with the fact that dielectric permittivity larger than unity doesn't allow surface modes with phase velocities greater than the speed of light. In plasmas with $\varepsilon<1$, propagation of fast waves ($v_{ph}>c$) is possible. Thus, in the plasma slabs Pl1 and Pl2 the surface modes can couple to incident electromagnetic waves, which are evanescent in the plasmas.

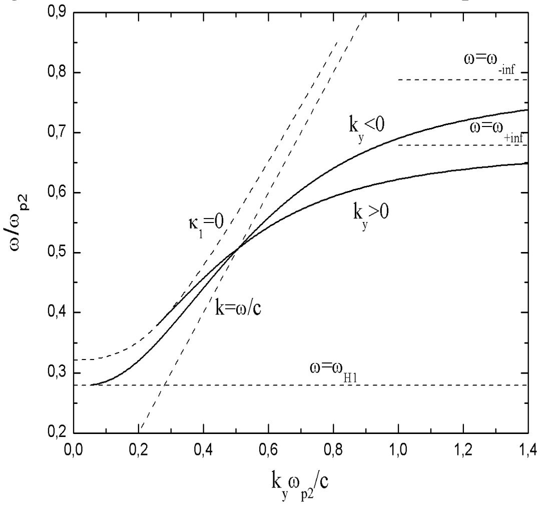

Fig.2. Dispersion of the surface waves at plasma-plasma interface. The curves were obtained for $\omega_{p1}/\omega_{p2}=0.25$ and $\omega_c/\omega_{p2}=0.125$

The waves in magnetized plasmas are non-reciprocal, i.e. dependent on the sign of k_y. We term the wave with $k_y>0$ a positive branch and the wave with $k_y<0$ a negative branch. The positive and negative branches exist in different frequency ranges (Fig.2).

To find the upper limit of the frequency range, we let $k_y \gg k$, that gives us

$$g_1\mp\varepsilon_1=g_2\pm\varepsilon_2 , \tag{5}$$

$$2-\frac{\omega_{p1}^2}{\left(\omega\mp\omega_c\right)\omega}-\frac{\omega_{p2}^2}{\left(\omega\pm\omega_c\right)\omega}=0 . \tag{6}$$

Here, the upper sign is for the positive and lower for the negative branch, correspondingly.

In the case of weak magnetic field ($\omega_c \ll \omega_p$), Eq. (6) has the following solution:

$$\omega_{\pm\inf}=\omega_{\inf}^{(0)}\pm\frac{\omega_c}{2}\cdot\frac{\omega_{p1}^2-\omega_{p2}^2}{\omega_{p2}^2+\omega_{p1}^2},$$

where $\omega_{\inf}^{(0)}=\sqrt{\left(\omega_{p1}^2+\omega_{p2}^2\right)/2}$ is the asymptotic frequency (at $k_y \gg k$) for the case of non-magnetized plasma. For the surface waves at plasma-vacuum interface ($\omega_{p1}=0$) the equation (6) is quadratic. It has solutions

$$\omega_{\pm\inf}^{(v)} = \frac{1}{2}\left(\sqrt{2\omega_p^2 + \omega_c^2} \mp \omega_c\right).$$

Thus, at large k_y the wave frequency is close to $\omega_{\pm\inf}^{(v)}$ (Fig.3).

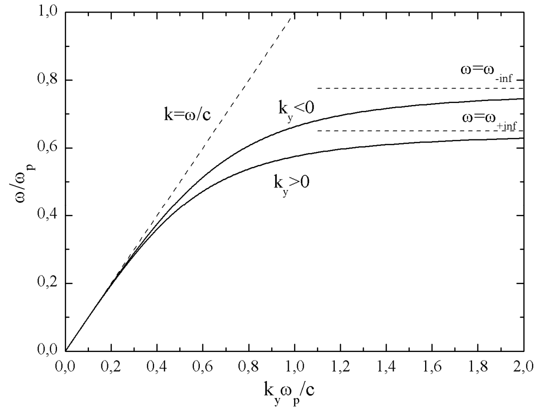

Fig.3. Dispersion of the surface wave at plasma-vacuum interface. The curves were obtained for $\omega_c / \omega_p = 0.125$

We can also find a partial solution of Eq. (3), if we request

$$\psi_1 - \psi_2 = 0\,, \quad (7)$$

$$\xi_1 + \xi_2 = 0\,. \quad (8)$$

The partial solution of the system (7), (8) is

$$k_y = k\,,$$

$$\omega_1^2 = \frac{\omega_c^2}{2} + \sqrt{\frac{\omega_c^4}{4} + \omega_{p1}^2\omega_{p2}^2}\,.$$

The frequency ω_1 corresponds to the upper frequency limit for the fast waves.

The field of the surface mode decays from the interface, i.e. the decay constant κ is a real number. Requiring $\kappa^2 > 0$, we determine the onset frequency. For the wave propagating in positive direction, the frequency is determined by inequality $k_y \geq k\sqrt{\varepsilon_{V1}}$, where $\varepsilon_{V1} = (\varepsilon_1^2 - g_1^2)/\varepsilon_1$ is the Voigt dielectric constant for the plasma slab Pl1. The negative branch starts at the hybrid frequency $\omega_{H1} = \sqrt{\omega_{p1}^2 + \omega_c^2}$ (see Fig.2), which is smaller than the onset frequency for the positive branch. Below ω_{H1} the Voigt dielectric constant ε_{V1} is large and positive, implying that $\kappa_1^2 < 0$ for a finite propagation vector, i.e. no surface magnetoplasmon is allowed.

CONCLUSIONS

In conclusion, we have studied the resonant properties of a two-layer plasma configuration in an external magnetic field. We have found the conditions at which the structure becomes absolutely transparent for an incident *p*-polarized electromagnetic wave. The case when the magnetic field is perpendicular to the wave vector and is parallel to the plasma-vacuum and plasma-plasma interfaces has been considered (Voigt geometry). It has been shown that in the case of infinitely thick layers the condition of anomalous transparency reduces to the dispersion relation for the surface waves at plasma-plasma interface. The dispersion relation has been studied in detail. The unique properties of the plasma-plasma system in magnetic field have been noted. Among them are existence of the fast surface mode and non-reciprocity of the waves. The frequency region, where the surface waves exist, has been found. We have also determined the upper frequency limit for the fast wave, what is important for the problem of resonant transmission.

This work was supported by the NATO Collaborative Linkage Grant CBP.NUKR.CLG.983378.

REFERENCES

1. J.B. Pendry and D.R. Smith, The quest for the superlens // *Sci. Amer.* 2006, v.295, №1, p.60-67.
2. R. Zia, J.A. Schuller, A. Chandran, and M.L. Brongersma. Plasmonics: the next chip-scale technology // *Materials Today*. 2006, v.9, №7-8, p.20-27.
3. E. Fourkal, I. Velchev, C.M. Ma, A. Smolyakov. Evanescent wave interference and the total transparency of a warm high-density plasma slab // *Physics of Plasmas*. 2006, v.13, №9, 092113.

Статья поступила в редакцию 05.07.2010 г.

ДИСПЕРСИЯ ПОВЕРХНОСТНЫХ МАГНЕТОПЛАЗМОНОВ

С.В. Ивко, И.Б. Денисенко, А.И. Смоляков, Н.А. Азаренков

Изучаются дисперсионные свойства и прохождение *p*-поляризованной электромагнитной волны в двухслойной плазменной структуре в присутствии внешнего магнитного поля. Получены условия резонансного прохождения. Аномальная прозрачность объясняется возбуждением поверхностной волны на границе плазма-плазма. Изучается дисперсионное соотношение для поверхностной волны на границе плазма-плазма в магнитном поле, проводится сравнение с дисперсией поверхностных волн в системе плазма-вакуум.

ДИСПЕРСІЯ ПОВЕРХНЕВИХ МАГНЕТОПЛАЗМОНІВ

С.В. Івко, І.Б. Денисенко, А.І. Смоляков, М.О. Азарєнков

Вивчаються дисперсійні властивості та проходження *p*-поляризованої електромагнітної хвилі в двошаровій плазмовій структурі за наявності зовнішнього магнітного поля. Отримано умови резонансного проходження. Аномальна прозорість пояснюється збудженням поверхневої хвилі на межі плазма-плазма. Вивчається дисперсійне співвідношення для поверхневої хвилі на межі плазма-плазма в магнітному полі, проводиться порівняння з дисперсією поверхневих хвиль в системі плазма-вакуум.