CONTROLLED ANOMALOUS TRANSMISSION THROUGH PLASMA LAYERS

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We study propagation of a p-polarized electromagnetic wave through a two-layer plasma structure in an external magnetic field perpendicular to the incidence plane. It is shown that normally opaque plasma layer can be made absolutely transparent. The conditions for resonant transmission are obtained and analyzed. The influence of the external magnetic field on resonant transmission is studied. We show that one can control electromagnetic radiation transmitted through the plasma structure by altering the magnetic field.

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1. INTRODUCTION

Tunneling of particles and electromagnetic waves through potential barriers has been widely studied in physics. In optics, the light tunneling in the experiment with frustrated total internal reflection occurs due to penetration of the decaying field of the evanescent wave inside the barrier. The transmission through the barrier can be increased by amplifying the evanescent wave. One of the amplification methods is interference with a resonant surface mode excited on density discontinuities.

Resonant structures exploiting this principle are well-known. The resonant transmission of a p-polarized electromagnetic wave through a symmetrical three-layer structure composed of a media with negative dielectric permittivity, that was placed between layers with positive permittivity, was demonstrated both theoretically and experimentally [1]. Lately [2,3], it was shown that symmetry of the system is not a necessary condition, and total brightening of an asymmetric two-layer system is also possible. It was suggested that the total transparency was due to a surface mode excitation at the interface between layers. The surface waves with phase velocity exceeding the speed of light couple with the incident electromagnetic wave and transmit energy through the opaque layer.

Recently, structures, that can resonantly transmit evanescent waves, attracted much interest. It was shown by Pendry [4], that amplification of evanescent spectrum of the incident light can be used to create a subwavelength optical imaging system without the diffraction limit (superlens). 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 [5].

In this paper we study propagation of a p-polarized electromagnetic wave through a two-layer plasma structure in an external magnetic field perpendicular to the incidence plane. We find the conditions when total transparency occurs. It is shown that transparency of the system can be controlled by changing the magnetic field.

2. TRANSMISSION THROUGH A 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 $H = 0$). Consider propagation of a *p*-polarized (with field components E_x, E_y, H_z) electromagnetic wave with the wave vector $\vec{k} = k_x\vec{e}_x + k_y\vec{e}_y$ through the structure. The wave propagating from the half-infinite vacuum region V1 is obliquely incident at the plasma layer Pl1. In the vacuum region V1, there are the incident ($k_x > 0$) and reflected ($k_x < 0$) waves. The transmitted wave propagates into the half-infinite vacuum region V2. In the plasma regions Pl1 and Pl2, which have widths a_1 and a_2, the waves are assumed to be non-propagating (evanescent) in *x*-direction.

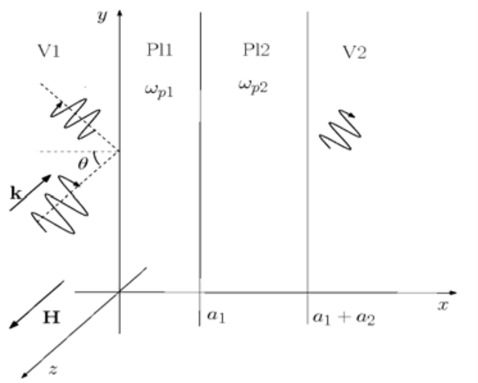

Fig. 1. Schematic representation of propagation of the electromagnetic wave through the two-layer structure

We assume that ions in plasma are motionless and electron collision frequencies are much smaller than the wave frequency. Thus, the components of the dielectric permittivity tensor of plasma in magnetic field has the following form

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2},$$

$$g = \frac{\omega_c \omega_p^2}{\omega\left(\omega^2 - \omega_c^2\right)},$$

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

From Maxwell's equations we obtain the expressions for components of electromagnetic field of the wave

$$E_x(x) = -\frac{1}{k_0(\varepsilon^2 - g^2)}\left(k_y \varepsilon H_z + g\frac{dH_z}{dx}\right), \quad (1)$$

$$E_y(x) = -\frac{i}{k_0(\varepsilon^2 - g^2)}\left(k_y g H_z + \varepsilon\frac{dH_z}{dx}\right), \quad (2)$$

$$\frac{d^2 H_z}{dx^2} + \kappa^2 H_z = 0, \quad (3)$$

where $\kappa^2 = k_y^2 - (\varepsilon^2 - g^2)k_0^2/\varepsilon$, $k_0 = \omega/c$, c is the speed of light. The equations (1) - (3) are valid for both plasma and vacuum regions. For the vacuum regions, $\varepsilon = 1$ and $g = 0$.

In the following we use wave impedance to match boundary conditions. The local wave impedance is defined as

$$Z(x) = \frac{E_y(x)}{H_z(x)}.$$

In the first vacuum region V1, the local impedance for the electromagnetic wave is

$$Z_{v1}(x) = Z_v \frac{\exp(ik_x x) - \Gamma_v \exp(-ik_x x)}{\exp(ik_x x) + \Gamma_v \exp(-ik_x x)}, \quad (4)$$

where $Z_v = k_x / k_0$ is the characteristic impedance of the vacuum region, Γ_v is the reflection coefficient of the wave incident from the half-infinite vacuum region onto the plasma-vacuum interface. It follows from (4) that

$$\Gamma_v = \frac{Z_v - Z_{v1}(0)}{Z_v + Z_{v1}(0)}, \quad (5)$$

where $Z_{v1}(0)$ is the impedance at plasma-vacuum interface.

In the plasma regions, the wave field is evanescent and the impedance takes the form

$$Z(x) = -i\psi + i\xi \frac{\exp(-\kappa x) - \Gamma \exp(\kappa x)}{\exp(-\kappa x) + \Gamma \exp(\kappa x)},$$

where $\xi = \kappa\varepsilon / [k_0(\varepsilon^2 - g^2)]$, $\psi = k_y g / [k_0(\varepsilon^2 - g^2)]$.

The wave impedance in the second vacuum region Z_{v2} is spatially independent

$$Z_{v2} = Z_v.$$

Since tangential components of the electric and magnetic fields are continuous at $x = 0$, a_1, $a_1 + a_2$, the impedances are also continues at the interfaces. We match impedance at each interface

$$Z_{v1}(0) = Z_1(0), \quad (6)$$

$$Z_1(a_1) = Z_2(a_1), \quad (7)$$

$$Z_2(a_1 + a_2) = Z_v, \quad (8)$$

where the indexes 1 and 2 correspond to the plasma regions Pl1 and Pl2, respectively.

Using the boundary conditions (6) - (8), we calculate impedance at the first plasma-vacuum interface $Z_{v1}(0)$. Then, using the obtained $Z_{v1}(0)$, we get the reflection coefficient Γ_v. The transmission coefficient T is defined as

$$T = 1 - \Gamma_v^2, \quad (9)$$

where

$$\Gamma_v = \frac{Z_v - Z_1(0)}{Z_v + Z_1(0)}, \quad (10)$$

$$Z_1(0) = -i\psi_1 + i\xi_1 \frac{(Z_2(a_1) + i\psi_1) + i\xi_1 L_1}{i\xi_1 + (Z_2(a_1) + i\psi_1)}, \quad (11)$$

$$Z_2(a_1) = -i\psi_2 + i\xi_2 \frac{(Z_v + i\psi_2) + i\xi_2 L_2}{i\xi_2 + (Z_v + i\psi_2)}, \quad (12)$$

$L_l = \tanh(\kappa_l a_l)$ and $l = 1,2$.

3. CONDITIONS FOR THE TOTAL TRANSPARENCY

From (10) it follows that the total transparency ($\Gamma_v = 0$) occurs only if $Z_v = Z_1(0)$. Using the relation, from (11) - (12) we find the condition for the total transparency

$$\psi_1 - \xi_1 \frac{Z_v + i(\psi_1 - \xi_1 L_1)}{i\xi_1 - (Z_v - \psi_1 L_1)} = \psi_2 - \xi_2 \frac{Z_v + i(\psi_2 + \xi_2 L_2)}{i\xi_2 + (Z_v + \psi_2 L_2)}. \quad (13)$$

The equation (13) 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. If the layers are thick ($L_{1,2} \approx 1$), we obtain the equation which coincides with the dispersion relation for the surface waves at interface between two semi-infinite plasmas:

$$\psi_1 + \xi_1 = \psi_2 - \xi_2.$$

Note that at plasma-plasma interface, propagation of fast ($v_{ph} > c$, where v_{ph} is the wave phase velocity) and slow ($v_{ph} < c$) surface waves is possible. At plasma-vacuum and plasma dielectric interfaces, the surface waves are always slow [6,7]. Thus, in the plasma slabs Pl1 and Pl2 the surface modes can couple to incident electromagnetic waves, which are evanescent in the plasmas. Since for the incident waves we have $k_y < k_0$, the resonant transmission is possible only in the frequency range, where the surface waves are fast. Dispersion of waves in magnetized plasmas depends on 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.

For the both branches transition from slow mode to fast mode occurs at frequency

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

The branches start from the frequency determined by the inequality $\kappa^2 > 0$. In particular, the negative branch starts at the hybrid frequency $\omega_{H1} = \sqrt{\omega_{p1}^2 + \omega_c^2}$, which is smaller than the onset frequency for the positive branch. Below ω_{H1} the Voigt dielectric constant $\varepsilon_{V1} = (\varepsilon_1^2 - g_1^2)/\varepsilon_1$ is large and positive, and, as a result, $\kappa_1^2 < 0$ for a finite propagation vector, i.e. the surface wave doesn't exist.

Resonance transparency occurs when the wave frequency ω, y-component of the wave vector k_y and the plasma layer widths a_1 and a_2 are connected by the resonance condition (13). Without magnetic field the resonance condition is independent on sign of k_y , and the structure is totally transparent at the same wave frequency for both $k_y < 0$ and $k_y > 0$ (Fig.2 solid line).

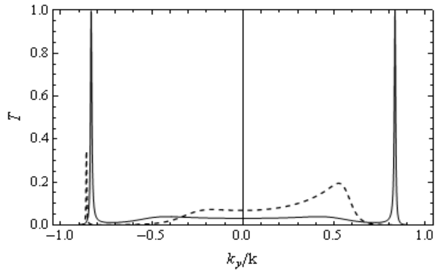

Fig. 2. The transparency coefficient over the normalized wave vector for different values of magnetic field: $\omega_c / \omega_{p2} = 0$ *(solid line),* $\omega_c / \omega_{p2} = 0.2$ *(dashed line) . The dependencies are obtained for* $\omega / \omega_{p2} = 0.67$ *,* $a_1 = 3.71\, c / \omega_{p2}$ *,* $a_2 = 1.34\, c / \omega_{p2}$ *and* $\omega_{p1} / \omega_{p2} = 0.5$

Applying an external magnetic field to the system, which is totally transparent at *H=0*, we decrease the transparency of the system (Fig. 2, dashed line). We can restore the absolute transparency by changing width of a layer, for instance, a_1 . The resonance width a_1 is different for the positive and negative branches (Fig. 3).

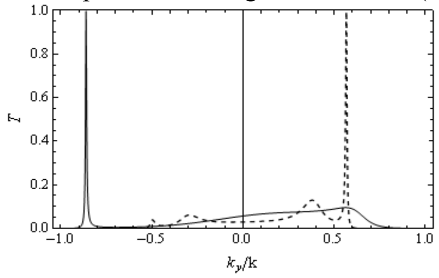

Fig. 3. The transparency coefficient over the normalized wave vector for different widths of the first plasma layer: $a_1 = 2.57\, c / \omega_{p2}$ *(solid line),* $8.7\, c / \omega_{p2}$ *(dashed line). The dependencies are obtained for* $\omega / \omega_{p2} = 0.67$ *,* $a_2 = 1.34\, c / \omega_{p2}$ *,* $\omega_c / \omega_{p2} = 0.2$ *and* $\omega_{p1} / \omega_{p2} = 0.5$

CONCLUSIONS

It has been shown that an overcritical plasma slab (with negative dielectric permittivity) in a magnetic field can be made transparent to a *p*-polarized electromagnetic wave. The condition for total transparency has been obtained. The anomalous transmission is explained by interference between the evanescent field of the incident wave and the field of the resonant mode in the two-layer structure. In the limit of thick layers, the dispersion of the resonant mode coincides with the dispersion of the surface waves at plasma-plasma interface in a magnetic field.

Structures consisting of alternating layers of media with positive and negative permittivity are potential building blocks of various plasmonic devices. Applying a magnetic field to the structure, additional possibility to control transmission of electromagnetic energy through the structure appears. This possibility may be used in constructing various gate devices.

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УПРАВЛЯЕМОЕ АНОМАЛЬНОЕ ПРОХОЖДЕНИЕ ЧЕРЕЗ ПЛАЗМЕННЫЕ СЛОИ

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

Изучается прохождение *p*-поляризованной электромагнитной волны через двухслойную плазменную структуру во внешнем магнитном поле, перпендикулярном плоскости падения. Показано, что непрозрачный плазменный слой может быть сделан абсолютно прозрачным. Условия резонансного прохождения получены и проанализированы. Изучено влияние магнитного поля на резонансное прохождение. Показано, что можно контролировать электромагнитное излучение, прошедшее через плазменную структуру, изменяя магнитное поле.

КЕРОВАНЕ АНОМАЛЬНЕ ПРОХОДЖЕННЯ КРІЗЬ ПЛАЗМОВІ ШАРИ

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

Вивчається проходження *p*-поляризованої електромагнітної хвилі крізь двохшарову плазмову структуру в зовнішньому магнітному полі, перпендикулярному до площини падіння. Показано, що непрозорий плазмовий шар може бути зроблено абсолютно прозорим. Умови резонансного проходження отримано та проаналізовано. Вивчено вплив магнітного поля на резонансне проходження. Показано, що можна керувати проходженням електромагнітного випромінювання через плазмову структуру, змінюючи магнітне поле.