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Transmission of electromagnetic waves in the semiconductor plasma

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Abstract

This research investigated the formation of surface waves on a cold semiconductor plasma structure and the way electromagnetic waves pass in the presence of a magnetic field. The main mechanism of the passage of electromagnetic waves through dense plasma was analyzed, ignoring collisions, attenuation, and the effects of the reflection coefficient of electromagnetic waves. The cold semiconductor plasma is opaque to the passage of electromagnetic waves, and only under special conditions of resonance stimulation of surface waves, this plasma can act like a transparent object against these waves. After considering the specific structure of the plasma and defining the basic relations, it will be shown that the passage of the electromagnetic wave through it occurs due to the excitation of the plasma surface states. It was deduced from the relationships that the intensities are maximum at the boundaries, on the plasma surfaces, which indicates the creation of surface states. The wave transmission inside the desired magnetic semiconductor plasma layer occurs due to these surface states. On the other hand, for waves with a lower inclination angle, the amount of electromagnetic wave passing through this material increases. This means that in lower angles, the turbid plasma becomes a transparent medium that can function by transmitting high-wavelength energy through it. It is emphasized that only the normal state was analyzed in this research. Since surface waves can be excited on both sides of the plasma, this structure can be very efficient for fabricating super-lenses, and the introduced structure facilitates the passage of conventional electromagnetic waves through dense semiconductor plasma. In this particular case, it was observed that the external magnetic field does not affect the wave propagation because there is no effect of the magnetic field on the relationships.

Keywords: Semiconductor plasma, cold plasma, electromagnetic waves, QHD model, quantum plasma
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1 Introduction

Much attention has been paid to quasi-materials with graded refractive index in recent years. The electric and magnetic permeability coefficients in these materials are negative ($\epsilon < 0, \mu < 0$). These functional structures are used in invisible coatings, optical concentrators, nano traps, and especially super-lenses [1, 2]. So far, much experimental and theoretical research has been done to understand the mechanism governing the interaction between electromagnetic

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waves and such an environment. These synthetic materials usually contain rows of metal films and unexpectedly ultimately transmit electromagnetic waves at resonant frequencies. By exploiting this unique property and the unusual transmission of light through such materials, new hopes have been created for making ideal lenses with sub-wavelength magnification [3]. Also, due to the unusual property of light transmission, such materials have found many applications in various fields of science, such as optics, Non-linear optics, photo electronics, sub-wave lithography, etc [4, 5, 6, 7, 8]. A plasma with a density higher than the critical limit can also be considered, in which the equivalent electric conductivity coefficient of the plasma is defined as $\epsilon = 1 - ({\omega_{\rho\alpha}}^2)/\omega^2$, which we will have for $\omega < \omega_{\rho\alpha}$ and $\epsilon < 0$. This type of plasma has essential and diverse applications in various theoretical and laboratory fields [9].

In general, there are two mechanisms of absorption of electromagnetic waves in plasma: collisional absorption and resonant absorption. In the collisional absorption mechanism, the energy of the incident wave is converted into kinetic energy and then into heat due to the collision between ion and electron [10]. However, in the resonant absorption mechanism, the linear transformation in the nonlinear plasma causes the resonant excitation of electrostatic waves in the plasma, which ultimately causes the production of high-energy electrons. Another absorption mechanism is considered here, which, according to many researchers, is the main cause of the emission of electromagnetic waves from quasi-materials, especially plasma [11, 12, 13]. The unusual passage of light through the plasma is the result of the excitation of surface modes; these surface modes are called plasmons. The same can be seen in metals. In fact, the free electrons of the metal, which act like a plasma environment, play the main role in the resonant excitation of these surface plasmons. Damped waves are needed for proper excitation of these surface modes [14]. Therefore, it is necessary that the emission waves first pass through a dielectric medium and then enter the plasma medium. Then, under intensified conditions, the excitation of surface modes will cause the wave to pass through the plasma [15, 16, 17, 18, 19].

Excited plasmons in magnetized plasma have already been investigated in the framework of fluid mechanics and theoretically. In addition, the dispersion relation of electrostatic surface wave propagation in a magnetized plasma layer has been studied in kinetic theory. Also, the excitation of surface modes on a magnetized plasma has been investigated. In this research, it was investigated how the electromagnetic wave passes through a semiconductor plasma [20]. The three-dimensional oscillations of the electromagnetic wave range that propagates in the heterogeneous plasma environment can be seen in the nonlinear interactions of laser radiation on the plasma and the heating of the ionosphere at radio frequency [21]. In addition, the wave amplitude in semiconductor plasma undergoes large spatial fluctuations caused by the zero and infinite refractive index. In these cases, the geometrical optics approximation is inefficient, and exact methods must investigate the wave behavior before the wave amplitude is included in the nonlinear theory [22, 23, 24].

In this research, electromagnetic wave transmission from the semiconductor plasma layer was investigated. First, the governing equations of the cold semiconductor plasma environment were derived in the general state and the general shape of the density of the plasma structure was introduced. Then, by selecting the normal mode, the data was analyzed. In this case, $E_z \neq 0$, and other electric field components are zero. In this particular case, the effect of the external magnetic field on the equations is not seen. Finally, in the same normal state, the shape of the wave function was checked for vertical descent and inclined descent to the desired structure.

2 Basic equations of electromagnetic waves in cold semiconductor plasma

The semiconductor plasma environment consists of electrons and holes and the modified Euler equation of this environment includes electromagnetic, quantum, and thermal aspects. In this equation, the forces affecting the motion include Lorentz forces, classical pressure gradient, quantum Bohm, and exchange-correlation potential [25]. To investigate the passage of the electromagnetic wave inside the cold semiconductor plasma, we consider the following linearized fluid Maxwell equations:

$$\nabla \times E = -\partial B/\partial t \tag{2.1}$$

$$\nabla \times B = \mu_0 \epsilon_0 \frac{\partial E}{\partial t} - 4\pi \sum_{\alpha=e,h} q_\alpha (n_{h0} V_{hx} - n_{e0} V_{ex}) \tag{2.2}$$

$$m_\alpha n_{i\alpha} \frac{\partial V_{i\alpha}}{\partial t} = q_\alpha n_{i\alpha}(E + V_{i\alpha} \times B_0) - \frac{1}{3} V_{Fi\alpha}^2 m_\alpha \nabla n_{i\alpha} - \frac{\hbar^2}{4m_\alpha} \nabla \left[\frac{1}{\sqrt{n_{i\alpha}}} \nabla^2 \sqrt{n_{i\alpha}} \right] - 2^{4/3} q_\alpha^2 \sqrt[3]{\frac{3}{\pi}} \sqrt[3]{n_{i\alpha}} \nabla n_{i\alpha} \tag{2.3}$$

In these equations, α refers to holes (h) and electrons (e). $n_{i\alpha}$, m_α , and q_α respectively equilibrium density, mass and charge of α-th plasma component. The terms of equation 3 include Lorentz force due to electrostatic potential, the force due to Fermi pressure ($P_\alpha = \left(\frac{m_\alpha V_{Fi\alpha}^2}{3n_{i0}^2}\right) n_{i\alpha}^3$, where $V_{Fi\alpha}^2 = \frac{2K_B T_{F\alpha}}{m_\alpha}$, quantum forces due to Boehm potential ($V_{q\alpha} = -\frac{\hbar^2}{2m_\alpha}\nabla^2\sqrt{n_{i\alpha}}/\sqrt{n_{i\alpha}}$, and $\mu_\alpha = \frac{e\hbar}{2m_\alpha}$, and exchange-correlation potential [26]. To linearize the equations, the range of oscillations was assumed to be small, and to analyze the dispersion of the system, the first-order disturbance coefficients related to $\exp(i(k_y y + k_z z - \omega t))$ was used. It is assumed that the plasma is exposed to an external magnetic field $B0$, and with the Fourier transform, the disturbed magnetic field is obtained from equation 2.1, as $B_0 = -(\frac{kE}{\omega})\hat{z}$. Using space and time derivatives, we have:

$$\nabla \times \nabla \times E = \nabla \times \left(-\frac{\partial B}{\partial t}\right) \Rightarrow \nabla(\nabla.E) - \nabla^2 E = \nabla \times \left(-\frac{\partial B}{\partial t}\right) \tag{2.4}$$

$$\nabla \times \left(\frac{\partial B}{\partial t}\right) = \mu_0\epsilon_0 \frac{\partial^2 E}{\partial t^2} - \frac{\partial}{\partial t}\left(4\pi \sum_{\alpha=e,h} q_\alpha \left(n_{h0}V_{hx} - n_{e0}V_{ex}\right)\right) \tag{2.5}$$

The following relationship is obtained from the combination of equations 2.4 and 2.5

$$\nabla\left(\nabla.E\right) - \nabla^2 E = \nabla \times \left(-\frac{\partial B}{\partial t}\right) = \mu_0\epsilon_0 \frac{\partial^2 E}{\partial t^2} - \frac{\partial}{\partial t}\left(4\pi \sum_{\alpha=e,h} q_\alpha \left(n_{h0}V_{hx} - n_{e0}V_{ex}\right)\right) \tag{2.6}$$

$$\nabla\left(\nabla.E\right) - \nabla^2 E - \frac{\omega^2}{c^2}\vec{E} = \frac{i\omega}{\epsilon_0 c^2}\left(4\pi \sum_{\alpha=e,h} q_\alpha \left(n_{h0}V_{hx} - n_{e0}V_{ex}\right)\right) \tag{2.7}$$

Plasma dimensions are assumed in the y and z directions, the refractive index changes along the x-axis, so k_z and k_y follow Snell's law and are not functions of x and are considered constant. In simplifying the equations, non-collision plasma was assumed ($V = 0$). The speed of electric charge carriers was considered as $\vec{V} = (V_x, V_y, 0)$ and the magnetic field inside the plasma was uniform and as ($\vec{B_0} = B_0\hat{z}$. In this case, according to equation 2.3, the velocity vector is removed from equation 2.7, and this equation becomes the following three equations in different directions:

$$\left[k_y^2 + k_z^2 + \frac{\omega^2}{c^2}\left(\frac{\omega_{\rho\alpha}^2}{\omega^2 - \omega_c^2} - 1\right)\right] E_x + ik_y\frac{\partial E_y}{\partial x} - i\frac{\omega\omega_c}{c^2}\left(\frac{\omega_{\rho\alpha}^2}{\omega^2 - \omega_c^2}\right) E_y + ik_z\frac{\partial E_z}{\partial x} = 0 \tag{2.8}$$

$$k_y\frac{\partial E_x}{\partial x} + i\frac{\omega\omega_c}{c^2}\left(\frac{\omega_{\rho\alpha}^2}{\omega^2 - \omega_c^2}\right) E_x - \frac{\partial^2 E_y}{\partial x^2} + \left[k_z^2 + \frac{\omega^2}{c^2}\left(\frac{\omega_{\rho\alpha}^2}{\omega^2 - \omega_c^2} - 1\right)\right] E_y - k_z k_y E_z = 0 \tag{2.9}$$

$$k_z\frac{\partial E_x}{\partial x} - k_z k_y E_y - \frac{\partial^2 E_z}{\partial x^2} + + \left(k_y^2 + \frac{\omega_{\rho\alpha}^2 - \omega^2}{c^2}\right) E_z = 0 \tag{2.10}$$

Where $\omega_c^2 = (q_\alpha^2 B_0^2)/(m_\alpha^2)$ and $\omega^2 = (q_\alpha^2 n_{\alpha 0})/(\epsilon_0 m_\alpha)$ are the Cyclotron and the plasma frequency respectively. Now, by analyzing the wave equations (equations 2.8 to 2.10), we can study the wave behavior in the plasma environment.

3 Vertical propagation of the electromagnetic wave, normal mode

In this case, we assume the wave enters vertically to the plasma layer $\vec{k} = (k_x, 0, 0)$. In this case, relation 2.10 becomes independent from two relations 2.8 and 2.9, and becomes as follows:

$$\frac{\partial^2 E_z}{\partial x^2} - \frac{\omega^2}{c^2}\left(\frac{\omega_{\rho\alpha}^2 - \omega^2}{c^2}\right) E_z = 0 \tag{3.1}$$

This wave equation is also true for a non-magnetic plasma and the E_z component can be calculated. The expression in the parentheses in the above relation is equivalent to the electrical conductivity coefficient. The other two components of the electric field (E_x, E_y) can be obtained using relations 2.8 and 2.9 as follows:

$$E_x = i\alpha(x)E_y \tag{3.2}$$

$$\frac{\partial^2 E_y}{\partial x^2} + \beta(x)E_y = 0 \tag{3.3}$$

Here $\alpha(x) = \frac{\omega_c}{\omega}\left(\frac{\omega_{\rho\alpha}^2}{\omega_{\rho\alpha}^2 - \omega^2 + \omega_c^2}\right)$, and $\beta(x) = \left[\frac{\omega^2}{c^2} - \frac{\omega_{\rho\alpha}^2}{c^2}\left(\frac{\omega^2 - \omega_{\rho\alpha}^2}{\omega^2 - \omega_{\rho\alpha}^2 - \omega_c^2}\right)\right]$ are the electrical permittivity coefficient and the generalized permittivity coefficient, both of these coefficients are a function of x. The $\beta(x)$ obtained here is similar to the anomalous mode in a uniform plasma. In this research, the normal mode was investigated $\vec{E} = (0, 0, E_z)$, and the wave equations are reduced to the average of 11, so we will have a linear mode in which the electrons will not have cyclotron motions.

4 Oblique propagation of the electromagnetic wave, normal mode

In this case, we assume that the electromagnetic wave enters the semiconducting plasma surface obliquely. The $\vec{k}$ wave vector is located in the xy plane ($\vec{k} = (k_x, k_y, 0)$, and makes a θ° with the x-axis. By selecting the normal mode, the electric field is parallel to $\vec{B_0}$, and in the absence of the magnetic field, this mode is known as the TE mode. Therefore, with the above assumptions, relation 2.10 will change to the following form:

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\omega^2}{c^2}\left(\frac{\omega^2 - \omega_{\rho\alpha}^2}{\omega^2} - sin(\theta)\right)E_z = 0. \tag{4.1}$$

By changing the $\epsilon(x) = \frac{\omega^2}{c^2}\left(\frac{\omega^2 - \omega_{\rho\alpha}^2}{\omega^2} - sin(\theta)\right)$ variable, we will have:

$$\frac{d^2 E_z(\epsilon)}{dx^2} + \epsilon(x)E_z(\epsilon) = 0. \tag{4.2}$$

In this case, the answers are given based on Airy functions of the first and second type. According to the behavior of these functions, we choose Airy functions of the first type. The Airy function of the second types leads to unusual and additive solutions, so we define the acceptable physical solution as follows:

$$E_z(\epsilon) = -Ai(-\epsilon). \tag{4.3}$$

From these relationships, it is deduced that the wave will be maximum at the edges and minimum at the depth of the layer, in other words, surface waves are produced in the wave transition from the semiconductor plasma layer. On the other hand, the larger the angle of incidence, the intensity of the wave distribution function at the edges will decrease. So, the more vertical the entrance angle is, the better the wave transition is.

5 Discussion and Numerical analysis

In a semiconductor plasma, $\omega_\rho > \omega_z$, and a negative transmittance coefficient is obtained ($\epsilon < 0$). In this model, it was assumed that the gradient of permeability coefficient changes with location is linear (Figure 1). We assume that the electromagnetic emission wave enters the semiconductor plasma medium. For simplicity, the vertical wave descent was first investigated and the normal mode was obtained without considering the magnetic effects.

Now we will examine how the electromagnetic wave propagates in such an environment. Knowing the wave function in the determined area, the waveform in the semiconductor plasma was obtained as follows (Figure 2). The horizontal axis indicates the location and the vertical axis indicates the intensity of the wave. As can be seen in the figure, with the reduction of the transmittance coefficient and the increase of the density, the amplitude of the wave decreases and for the minimum value of the transmittance coefficient ($\epsilon(x) = -1$), the wave intensity reaches zero. In fact, at the

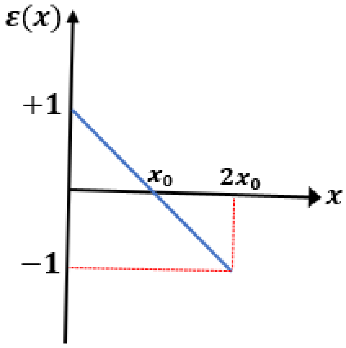

Figure 1: Spatial variations of plasma equivalent electrical conductivity

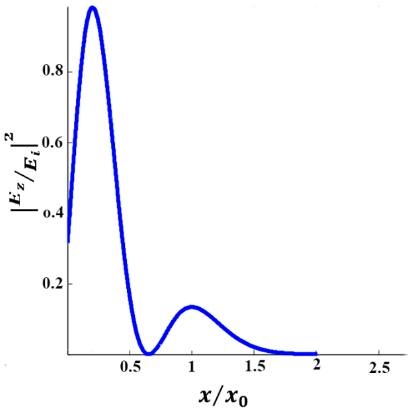

Figure 2: Vertical electromagnetic wave intensity distribution inside semiconductor plasma

$x = 2x_0$ point where the plasma density is the maximum value, the transmittance coefficient, and the minimum wave intensity are measured.

If the electromagnetic wave descends obliquely to the surface of the semiconductor plasma, the wave vector makes a theta angle with the x-axis, and the wave vector $\vec{k} = (k_x, k_y)$. By choosing the normal mode, the parallel electric field $\vec{B_0}$ is considered. The results of this wave are in good agreement with the results of the perpendicular wave (Figure 3) and similarly, the intensity is maximum at the edge of the semiconductor plasma environment. The intensity is minimal at the depth of the layer, and surface waves are produced in the wave transition from the plasma layer. As seen in Figure 3, the larger the landing angle, the lower and weaker the intensity of the wave function at the edge (the intensity of the wave function at the edge is inversely proportional to the size of the landing degree). It can be concluded that the more vertical the incident angle is, the intensity of the incident wave function reaches zero with a lower slope.

Under near-perpendicular incidence angles, the turbid plasma becomes a transparent medium that can act like an over-lens with high transmission of wave energy through it. Since the passage of the wave is due to the creation of surface waves at the edge of the semiconductor plasma environment, the intensity of the incident wave is maximum. While in the depth of the plasma, where the maximum value density is possible, the wave intensity is minimized. This emphasizes the fact that the creation of surface waves is the main mechanism of electromagnetic wave passage through the semiconducting plasma environment. It should be mentioned that the excitation of the surface wave from both sides of the plasma layer occurs simultaneously. Like springs that are coupled to each other, with the vibration of one of them, the other spring is excited at the same time and starts to vibrate (the damping effect can be seen well). The situation described in this study can occur in the phenomenon of ionospheric heating. The ionosphere as a low ionized plasma can interact with an electromagnetic wave. This interaction may lead to the exchange of energy between the incident wave and the particles forming the ionospheric plasma and its heating. The incident electromagnetic wave to the ionosphere through the minimization of the intensity of the incident wave in the depth of the plasma leads to the phenomenon of heating the ionosphere using electromagnetic waves.

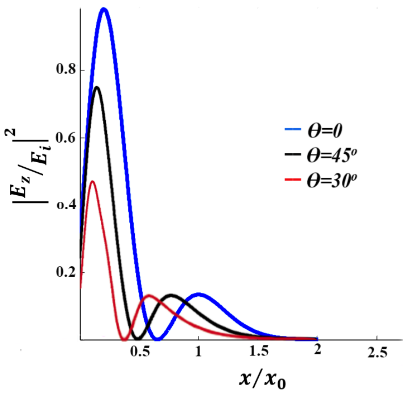

Figure 3: Angular electromagnetic wave intensity distribution inside semiconductor plasma

6 Conclusion

Semiconductor plasma is opaque to the passage of electromagnetic waves, and only under special conditions, this plasma can act like a transparent object to electromagnetic waves. This happens in the conditions of the excitation of surface waves and has been investigated in dense plasma with constant density. Since the plasma environment is not a uniform and homogeneous environment and has a density gradient, the passage of light inside a semiconductor plasma will undergo changes. In this research, this issue has been given special attention. Non-linear optics should be used to examine such materials, which requires knowing their waveforms as well.

In this research, the formation of surface waves on a structure of cold semiconductor plasma was investigated. The plasma was considered magnetized and collision-less. Damping and essential effects of the electromagnetic wave reflection coefficient of the whole structure were ignored. In general, the main mechanism of electromagnetic waves passing through dense plasma is the resonant excitation of surface waves. To investigate the propagation of electromagnetic waves from magnetized semiconductor plasma with variable density, the desired model was introduced and its governing equations were derived. To simplify the relationships, a normal state was assumed. Then the responses were analyzed in two vertical and inclined landing modes and density changes were applied linearly. With these assumptions, the way the wave passes through this plasma was investigated. It was deduced from the relationships that the intensities are maximum at the boundaries, on the plasma surfaces, which indicates the creation of surface states. The wave transmission inside the desired magnetic semiconductor plasma layer occurs due to these surface states. On the other hand, for landings with a lower landing slope angle (landing perpendicular to each other), the amount of electromagnetic wave passing through this material increases. This means that under these angles, the cloudy plasma becomes a transparent medium that can act like a super-lens by transmitting high-wavelength energy. It is emphasized that only the normal state was analyzed in this research. In this particular case, it was observed that the external magnetic field does not affect wave propagation because there is no effect of the magnetic field on the relationships. These results were not far from expected, because in this case, the external magnetic field and the electric field are in the same direction, so the magnetic field does not affect the oscillations of the particles, as if the particles do not see the magnetic field.

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