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RESONANT TRANSPARENCY OF A THREE-LAYER STRUCTURE CONTAINING THE DENSE PLASMA REGION

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Abstract—A study of electromagnetic wave propagation in dense plasmas when the wave frequency is below the cut-off frequency is presented. A three-layer symmetric structure consisting of dense plasma nested between two boundary layers is studied analytically and numerically. The permittivity of the dense plasma is negative, while the permittivity of each boundary layer is greater than 1. It is shown that total transmission of an electromagnetic wave can be achieved if an adequate incidence angle, dielectric permittivity of the boundary layers and corresponding boundary layer widths are chosen. It is found that plasma transparency is due to resonance between the evanescent waves in the dense plasma region and the standing waves in the boundary layers. Resonance conditions are derived analytically and the relationship between the corresponding parameters of the problem are studied numerically.

1. INTRODUCTION

Electromagnetic wave propagation in dense plasmas is a fundamental problem relevant for many applications of space [1–3] and laboratory plasmas [4–6]. A particular problem occurs when the electromagnetic wave has the frequency below the electron plasma frequency, so that the wave is reflected from the plasma. This phenomenon is

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used in various applications, including plasma density diagnostic. It presents, however, a major problem for radio communications through dense plasmas which is created around a vehicle at re-entry, or during hypersonic flight [7–10]. Characterization of reflected and absorbed electromagnetic radiation is also of great interest for radar applications [11–13]. Various numerical methods have been employed to calculate the reflection, absorption, and transmission in different situations [12, 14, 15]. In the present paper, in order to gain a better understanding of the theory, we investigate the propagation of the electromagnetic waves in a one-dimensional configuration which, in part, can be treated analytically. We emphasize a new regime of translumination of dense plasma [16] via resonance of evanescent and propagating modes.

Our goal is to investigate the signal transmission through a three-layer structure, assuming a sharp interface between the layers. By itself, the dense plasma layer is opaque to electromagnetic waves with frequencies below the plasma frequency ($\omega < \omega_{pe}$). It was shown in [17] that transparency can be achieved by including on each side of the dense plasma with negative permittivity ($\varepsilon < 0$), a boundary layer of rarefied plasma with permittivity $0 < \varepsilon < 1$. In that case, transparency is due to resonance of evanescent waves in the dense plasma layer and the boundary layers. In the present paper, we consider a layer of dense plasma nested between two boundary layers of a material with a dielectric permittivity $\varepsilon > 1$. Such a configuration may occur, for example, in microwave plasma reactors [18]. We show that in this case, the whole structure becomes transparent to the incident wave if the plasma density, the dielectric permittivity of the boundary layers and the width of the boundary layers are chosen appropriately. Employing the impedance method [17], we derive the resonance condition for absolute transmission, which shows that the achieved transparency to electromagnetic waves is a result of a specific resonance involving the evanescent waves in the middle plasma region and the propagating waves in the boundary layers. Although we have considered only symmetric structures, the phenomena we have found exist also for asymmetric configurations.

Recently, manipulation and amplification of evanescent waves became an important tool for the development of various plasmonics devices [19]. Evanescent waves can be amplified in a medium with negative permittivity thus providing energy transport through opaque materials [20–23]. Typically, amplification is achieved by creating conditions for resonant excitation of surface modes [17, 21, 22, 24–26]. The nonlinear interactions may also lead to anomalous plasma transparency [27]. In the configuration we present here, we have found another situation when the surface modes are absent, but there is a specific resonance between the propagating waves and evanescent modes. Our results could be considered somewhat similar to an inverted Fabry-Perot resonator [28, 29]. However, in a Fabry-Perot resonator, a standing wave is formed by propagating electromagnetic waves which are reflected by the end mirrors, which is not the case in the configuration we consider. We note also that reflectionless transmission for special plasma density profiles may also occur in non-stationary regimes [30, 31].

The paper is organized as follows. In Section 2, we formulate the problem and present the basic equation. In Section 3, we derive the resonant conditions for a three-layer structure. In Section 4, we discuss the results.

2. FORMULATION OF THE PROBLEM AND BASIC EQUATIONS

Consider the one-dimensional symmetric three-layer problem depicted in Fig. 1 where a dense plasma layer of negative permittivity is nested between two boundary layers of equal width with permittivity greater than 1. To the right and left, the structure is bounded by a semi-infinite vacuum (air) region. Assume that parameters of the medium vary in the z direction, and that the interface between any two layers is located at $z = a_j$, $j = 1, 2, 3, 4$. An incident electromagnetic wave with the frequency ω is propagating to the right. Most of the wave is reflected or absorbed by the plasma. The question is under what conditions can the wave be transmitted through all three layers.

We here consider only a plasma profile represented by a step-function, such that each layer is homogeneous, i.e., the plasma density in each layer is constant, but may vary from layer to layer. We assume that there is no plasma flow along the z-axis. Moreover, we assume that the frequency of the incident wave is sufficiently weak so that the ions remain immobile in the rf field, and thus, the current of the system is given by the electron conduction current. Furthermore, we assume that the transmitted electromagnetic wave is of the form

$$\mathbf{E}=(0, E_y(z), E_z(z))\exp(iky-i\omega t) \text{ and } \mathbf{H}=(H_x(z), 0, 0)\exp(iky-i\omega t) \quad (1)$$

where $k = \sin(\theta)\omega/c$ with c being the speed of light. Note that the wave propagates at some angle θ with respect to the z-axis.

For simplicity, we consider a cold, collisionless, non-magnetized plasma with permeability $\mu = 1$. According to the Maxwell equations, the electromagnetic wave propagation in the whole three-layer system

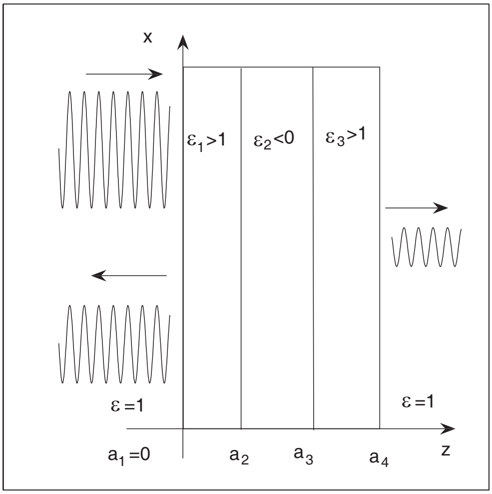

Figure 1. Schematic representation of electromagnetic wave propagation through a three-layer medium.

is governed by the following wave equation

$$\varepsilon \frac{d}{dz}\left(\frac{1}{\varepsilon}\frac{dH_x}{dz}\right) - \gamma^2(\varepsilon, \theta)H_x = 0 \tag{2}$$

with

$$\gamma^2(\varepsilon, \theta) = k^2(\theta) - \varepsilon\frac{\omega^2}{c^2} \tag{3}$$

where

$$\varepsilon(z) = 1 - \frac{\omega_{pe}^2(z)}{\omega^2} \tag{4}$$

is the dielectric permittivity of the system and

$$\omega_{pe}(z) = \left(\frac{e^2 n(z)}{\varepsilon_0 m}\right)^{1/2} \tag{5}$$

is the electron plasma frequency. Here e is the electron charge, m is the electron mass, n is the plasma density and ε_0 is the permittivity of the free space. Note that ε is a step function. In in each layer j, it is constant, and we will denote it by ε_j. Assume that $\varepsilon_2 < 0$, while $\varepsilon_1 = \varepsilon_3 > 1$.

Equation (2) can be solved analytically in each region, yielding a magnetic field of the form

$$H_x(z) = H_0(\exp(\alpha z) + \Gamma \exp(-\alpha z)) \tag{6}$$

where $\alpha^2 = \gamma^2(\varepsilon_j, \theta)$, H_0 is the amplitude of the incidence wave, and Γ is the reflection coefficient. In order to compute the reflection coefficient of the incidence electromagnetic wave, we use the impedance approach [17]. The local wave impedance is defined as the continuous function

$$Z = -\frac{E_y}{H_x} \tag{7}$$

where, from the Maxwell equations,

$$E_y = \frac{i}{\omega\varepsilon_0\varepsilon}\frac{dH_x}{dz} \tag{8}$$

Hence,

$$Z = Z_{ch}\frac{1 - \Gamma\exp(-2\alpha z)}{1 + \Gamma\exp(-2\alpha z)} \tag{9}$$

where

$$Z_{ch} = -\frac{i\alpha}{\omega\varepsilon_0\varepsilon} \tag{10}$$

is the characteristic impedance. Note that the characteristic impedance is exactly the impedance of the incidence wave. In particular, in the vacuum regions, $z < 0$ and $z > a_4$, we find $\alpha = i\omega\cos(\theta)/c$ and

$$Z_{ch} = Z_0 = \frac{\cos(\theta)}{c\varepsilon_0} \tag{11}$$

In what follows, we will denote by Z the impedance normalized to the vacuum impedance (i.e., $Z \to Z/Z_0$).

Consider first the characteristic impedance in each region, normalized to the vacuum impedance. In the boundary layers (i.e., $a_1 \le z \le a_2$ and $a_3 \le z \le a_4$), we find that $\alpha = ik_z$ where

$$k_z = \frac{\omega}{c}\sqrt{\varepsilon_1 - \sin^2(\theta)} \tag{12}$$

with $\varepsilon_1 > \sin^2(\theta)$, and the electromagnetic wave (6) is propagating. The normalized characteristic impedance of each boundary layer is then

$$Z_1 = Z_3 = \frac{Z_{ch}}{Z_0} = \frac{k_z}{\omega\varepsilon_0\varepsilon_1 Z_0} = \frac{\sqrt{\varepsilon_1 - \sin^2(\theta)}}{\varepsilon_1\cos(\theta)} \tag{13}$$

In the dense plasma region, $a_2 \le z \le a_3$, for $\omega < \omega_{pe}$, it follows that $\alpha = -\gamma$ where

$$\gamma = \frac{\omega}{c}\sqrt{\sin^2(\theta) - \varepsilon_2} \tag{14}$$

is real. In this case, the incident wave becomes evanescent in the plasma layer and decays rapidly. Thus, the characteristic impedance of the dense plasma layer is

$$Z_2 = \frac{Z_{ch}}{Z_0} = \frac{i\gamma}{\omega\varepsilon_0\varepsilon_2 Z_0} = \frac{i\sqrt{\sin^2(\theta) - \varepsilon_2}}{\varepsilon_2 \cos(\theta)} \tag{15}$$

Assume that in the vacuum region where $z > a_4$, $\Gamma = 0$. Then, $Z = 1$ is constant in the whole region, and in particular, $Z(a_4) = 1$.

We can now compute the normalized local impedance at each interface. Consider one of the layers $a_j \le z \le a_{j+1}$, $j = 1, 2, 3$ and let $l_j = a_{j+1} - a_j$. Then, $Z_{in} = Z(a_j)$ is the input impedance and $Z_L = Z(a_{j+1})$ is the load impedance. From Equation (9), we find

$$Z_{in} = Z_j \frac{Z_L + Z_j \tanh(-\alpha l_j)}{Z_j + Z_L \tanh(-\alpha l_j)} \tag{16}$$

In particular, with $l_1 = l_3$,

$$Z(a_3) = Z_1 \frac{1 + Z_1 L_1}{Z_1 + L_1} \tag{17}$$

$$Z(a_2) = Z_2 \frac{Z(a_3) + Z_2 L_2}{Z_2 + Z(a_3) L_2} \tag{18}$$

$$Z(0) = Z_1 \frac{Z(a_2) + Z_1 L_1}{Z_1 + Z(a_2) L_1} \tag{19}$$

where

$$L_1 = \tanh(-ik_z l_1) = -i \tan(k_z l_1) \tag{20}$$

and

$$L_2 = \tanh(\gamma l_2) \tag{21}$$

For the semi-infinite vacuum region $z < 0$, we find from (9) the relationship between the reflection coefficient Γ and the normalize impedance at $z = 0$:

$$\Gamma = \frac{1 - Z(0)}{1 + Z(0)} \tag{22}$$

Thus, full transparency of the medium is then achieved if $\Gamma = 0$. In this case, the impedance at $z = 0$ is precisely the vacuum impedance, i.e., $Z(0) = 1$. Using this and Equations (17)–(19), we find the following condition for absolute transparency:

$$L_2 L_1^2 \left(Z_1^4 - Z_2^2\right) + 2L_1 Z_1 Z_2 \left(Z_1^2 - 1\right) + L_2 Z_1^2 \left(Z_2^2 - 1\right) = 0 \tag{23}$$

which is a quadratic equation in L_1. Once L_1 is found, the corresponding resonant boundary layer width l_1 can be obtained from Equation (20).

In summary, using the technique described above, we can compute the reflection coefficient and study the relationship between the absolute transparency of a three-layer structure and the corresponding plasma parameters. In the following section, we will illustrate those ideas, using some specific examples.

3. TRANSPARENCY OF SYMMETRIC THREE-LAYER STRUCTURES

In this section, we analyze the conditions for resonant transparency of a three-layer structure. Suppose that the incidence frequency is $\omega/(2\pi) = 1\,\text{GHz}$, and that the width of the dense plasma layer with negative permittivity is $l_2 = 0.02\,\text{m}$. As mentioned above, the resonant boundary layer width can be obtained from Equation (20), after first solving the quadratic Equation (23) for L_1. According to (20), L_1 must be imaginary. Moreover, the function L_1 is periodic in l_1 and the period is $p = \pi/k_z$. Therefore, one obtains an infinite number of positive values for l_1 for a given L_1. Indeed,

$$l_1 = l_0 + \frac{\pi}{k_z} n \tag{24}$$

for $n = 0, 1, 2, 3 \dots$ where

$$l_0 = \frac{1}{k_z} \arctan(iL_1) \tag{25}$$

We will refer to l_0 as the fundamental boundary layer width. Note that $l_0 > 0$ if $\text{Im}(L_1) < 0$, and it follows from (23) that $Z_1 < 1$.

Solving Equation (23), we find that L_1 is imaginary, only if the discriminant D is not positive, i.e.,

$$D = \frac{Z_1^2 Z_2^2 \left(Z_1^2 - 1\right)^2}{L_2^2 \left(Z_1^4 - Z_2^2\right)^2} + \frac{Z_1^2 \left(1 - Z_2^2\right)}{\left(Z_1^4 - Z_2^2\right)} \leq 0 \tag{26}$$

or equivalently,

$$\left(Z_1^2 - 1\right)^2 - L_2^2 \left(Z_1^4 - Z_2^2\right) \left(1 - \frac{1}{Z_2^2}\right) \geq 0 \tag{27}$$

Thus, for a given incidence angle, resonant transparency can be achieved only if one chooses the boundary layer permittivity in such a way that condition (27) is satisfied. Note that since $0 < L_2 < 1$ and $0 < (Z_1^2 - 1)^2 < 1$ condition (27) can be satisfied only if $|\text{Im}(Z_2)|$ is sufficiently large. According to (15), $|\text{Im}(Z_2)|$ is decreasing as $\varepsilon_2 < 0$ is decreasing. Thus, for sufficiently dense plasma $\omega_{pe} \gg \omega$, condition (27) can never be satisfied, and absolute transparency cannot be achieved, no matter how the boundary layer permittivity is chosen. This can also be seen by representing (27) in the following form

$$\left(\frac{\varepsilon_1-\sin^2(\theta)}{\varepsilon_1^2\cos^2(\theta)}-1\right)^2 -L_2^2\left(\frac{\left(\varepsilon_1-\sin^2(\theta)\right)^2}{\varepsilon_1^4\cos^4(\theta)}+\frac{\sin^2(\theta)-\varepsilon_2}{\varepsilon_2^2\cos^2(\theta)}\right)\left(1+\frac{\varepsilon_2^2\cos^2(\theta)}{\sin^2(\theta)-\varepsilon_2}\right)\geq 0 \quad (28)$$

Indeed, for sufficiently large $|\varepsilon_2|$, inequality (28) cannot be satisfied and absolute transparency cannot be achieved. It is obvious from (28) that the conditions for achieving absolute transparency depend on the choice of the incident angle and the plasma density. This illustrated in the Tables 1–4 where one can see the changes for different incident angles in the fundamental boundary width l_0 (in meters), the minimal boundary layer permittivity $\varepsilon_1^{\min}$ and the period p for the resonant boundary layer width as the plasma density increases.

Consider first the incidence angle $\theta = 0$. Let $\omega_{pe}/\omega = 2.5$. Then, $\varepsilon_2 = -5.25$ and condition (28) is satisfied for $\varepsilon_1 \geq 6.926$. In particular, choosing $\varepsilon_1 = 6.926$ yields a unique solution L_1 of (23) of multiplicity 2 (i.e., $D = 0$ in (26)) and a corresponding fundamental boundary layer width $l_0 = 0.0133$ m. For $\varepsilon_1 > 6.926$, we find two imaginary solutions of (23) (i.e., $D < 0$) and two corresponding fundamental boundary layer widths. Fig. 2 shows the dependance

Table 1.

$\theta = 0$			
ω_{pe}/ω	$\varepsilon_1^{\min}$	l_0	p
2.5	6.926	0.0133	0.0569
3	10.93	0.0104	0.0453
4	28.16	0.0058	0.0282
5	91.12	0.0024	0.0157
6	–	–	–

Table 2.

$\theta = \pi/6$			
ω_{pe}/ω	$\varepsilon_1^{\min}$	l_0	p
2.5	10.32	0.0097	0.0472
4	47.7	0.0036	0.0218
5	–	–	–

Table 3.

$\theta = \pi/4$			
ω_{pe}/ω	$\varepsilon_1^{\min}$	l_0	p
2.5	23.5	0.0048	0.0312
3	–	–	–

Table 4.

$\theta = \pi/3$			
ω_{pe}/ω	$\varepsilon_1^{\min}$	l_0	p
2.5	–	–	–

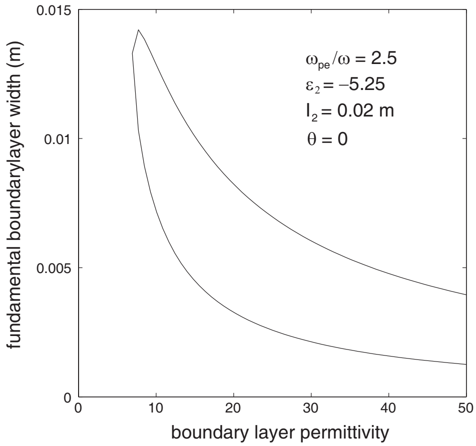

Figure 2. Fundamental boundary layer width versus boundary layer permittivity.

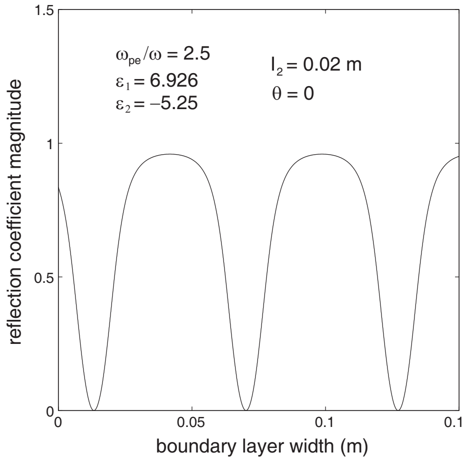

Figure 3. Periodicity of the reflection coefficient magnitude with respect to the boundary layer width.

of the fundamental boundary layer width on the boundary layer permittivity for the above choice of plasma parameters. Note that the fundamental boundary layer width is comparable in size to the dense plasma layer and is decreasing as ε_1 is increasing. Fig. 3 shows the reflection coefficient as a function of the boundary layer width for $\varepsilon_1 = 6.926$. As expected, absolute transmission occurs periodically with the period $p = \pi/k_z = 0.0569$. Fig. 4 shows the reflection coefficient as a function of the boundary layer width for $\varepsilon_1 = 8$. One can clearly see absolute transparency at the two fundamental boundary layer width which repeats periodically. Fig. 5 shows the magnetic wave field during resonance when 100% of the incident wave is transmitted. The boundary layers prevent the rapid decay of the wave amplitude in the plasma region.

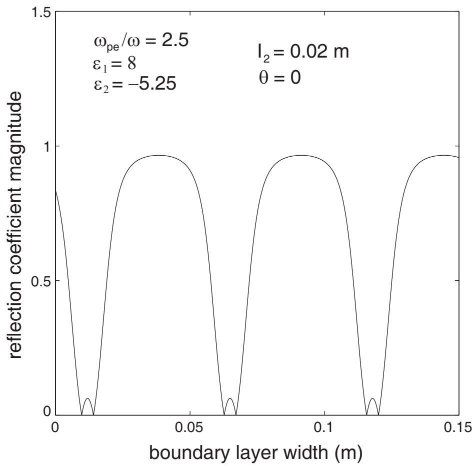

Figure 4. Period doubling in the reflection coefficient magnitude with respect to the boundary layer width.

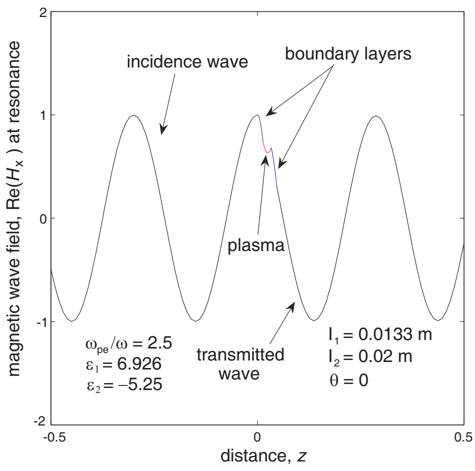

Figure 5. Normalized magnetic wave field $\mathrm{Re}(H_x)$ at resonance

For $\theta = 0$, and $\omega_{pe}/\omega = 3$, we find $\varepsilon_2 = -8$. In that case, condition (23) is satisfied if $\varepsilon_1 \geq 10.93$, and the corresponding fundamental boundary layer width is $l_0 \leq 0.0104\,\text{m}$. Choosing $\varepsilon = 10.93$, absolute transmission occurs at $l_0 = 0.0104\,\text{m}$ and is repeated periodically with respect to the boundary layer width with the period $p = 0.0453$. Note that as the plasma density is increased for $\theta = 0$, ε_1 becomes larger, while the fundamental boundary width and the period become smaller. In fact, for $\omega_{pe}/\omega = 4$, we find $\varepsilon_1 \geq 28.16$, $l_0 \leq 0.0058\,\text{m}$, and $p \leq 0.0282\,\text{m}$. For $\theta = 0$ and $\omega_{pe}/\omega = 5$, we find $\varepsilon_1 \geq 91.12$, $l_1 \leq 0.0024\,\text{m}$, and $p \leq 0.0157$. For $\omega_{pe}/\omega = 6$, condition (23) cannot be satisfied and absolute transparency cannot occur. Qualitatively, Figs. 2–5 do not change as the plasma density is increased.

Changes in the incidence angle will affect the values of parameters needed for (23) to be satisfied (see Tables 1–4). Although qualitatively Figs. 2–4 remain the same, and the characteristic behavior with respect to an increase in the plasma density does not change, the actual value of the boundary layer permittivity and the fundamental boundary layer width which insure transparency changes. For example, if $\theta = \pi/6$ and $\omega_{pe}/\omega = 2.5$ then (23) is satisfied if $\varepsilon_1 \geq 10.32$, which corresponds to the fundamental boundary layer width $l_0 \leq 0.0097\,\text{m}$ and a period $p = 0.0472$. For $\theta = \pi/6$ and $w_{pe}/\omega = 4$, we find $\varepsilon_1 \geq 47.7$, $l_0 = 0.0036\,\text{m}$, and $p = 0.0218\,\text{m}$. For $\omega_{pe}/\omega = 5$ no absolute transmission can occur. For $\theta = \pi/4$ and $\omega_{pe}/\omega = 2.5$, we find $\varepsilon_1 = 23.5$, $l_0 = 0.0048\,\text{m}$, and $p = 0.0312$. There is no resonant transmission for $\omega_{pe}/\omega = 3$. For $\theta = \pi/3$, there is no resonant transmission for $\omega_{pe}/\omega = 2.5$. Thus, if the incidence angle is increased the boundary layer permittivity has to be increased. However, for a sufficiently large incidence angle, transparency cannot be achieved for any choice of ε_1.

In summary, whether transparency of a three-layer structure can be achieved depends on the plasma density and on the incidence angle. For an appropriate choice of those parameters, one can find corresponding values of the boundary layer permittivity when absolute transmission can be achieved. In all cases, the fundamental boundary layer width is quite small. The absolute transmission is periodic with respect to the boundary layer width. Thus, when the plasma density and incidence angle are chosen appropriately, there are infinitely many choices for the boundary layer widths such that transparency can be achieved.

4. DISCUSSION

Alternating layers of materials with negative and positive permittivities are typical structures of many plasmonic designs [19, 24, 25]. Three-layer structures also naturally occurs in bounded plasmas [32]. Plasma boundary layers formed at hypersonic speeds have a more complicated profile with a typical feature of a three-layer structure (sheath-plasma-sheath) [33]. Therefore, studies of three-layer structures are relevant to a variety of space and laboratory plasmas applications.

In the present paper, we presented a study of resonant transmission of electromagnetic waves through a three-layer structure, consisting of dense plasma and two boundary layers, such that the permittivity of the dense plasma is negative, while the permittivity of the boundary layers is greater than 1. For the plasma width, we chose $l_2 = 0.02\,\mathrm{m}$ as a typical example of the plasma layer around a hypersonic vehicle [33].

Transmission of electromagnetic waves through a three-layer medium was studied in [17] in the case when the electromagnetic wave in each of the three layers was evanescent and decayed rapidly. In that regime, the amplification of evanescent waves was triggered by surface wave resonance. In the present paper, as in [17], the plasma permittivity ϵ_2 in the middle region is also negative and the wave in that region is evanescent. In contrast to [17], the waves in the boundary layers are propagating. Thus, no surface mode excitation can occur in the present situation. We have shown that there exists a specific resonance condition, given by Equation (23), at which absolute transparency occurs due to resonance of evanescent modes in the central region and propagating modes in the end regions. Resulting amplification of evanescent modes lead to resonant transmission of the electromagnetic wave through a dense plasma layer.

Studying the relationship between the resonant incidence angle, the boundary layer permittivity and the plasma frequency, we have found that transparency of a three-layer structure can be achieved only for an appropriate choice of those parameters. In particular, for a normal incidence angle, $\theta = 0$, transparency can be achieved for a plasma frequency up to $5 \cdot 10^9\,\mathrm{GHz}$, for $\theta = \pi/6$, transparency is possible for a plasma frequency up to $5 \cdot 10^9\,\mathrm{GHz}$, for $\theta = \pi/4$, transparency is possible for a plasma frequency up to $2.5 \cdot 10^9\,\mathrm{GHz}$, while for $\theta = \pi/3$ there is no resonant transmission for the plasma frequency $2.5 \cdot 10^9\,\mathrm{GHz}$. In all case, when resonant transmission is possible, the permittivity of the boundary layer is quite large. The smallest boundary layer permittivity is $\epsilon_1 \approx 7$ for a normal incidence wave and plasma frequency $2.5 \cdot 10^9\,\mathrm{GHz}$. As the plasma frequency is increasing, the boundary layer permittivity increases drastically.

When the plasma density, the incidence angle and the boundary layer permittivity are chosen appropriately, resonant transmission occurs for infinitely many choice of boundary layer width. The smallest of them is comparable in size with the plasma layer and can be made quite small by increasing the permittivity of the boundary layer. The reflection coefficient is a periodic function of the boundary layer width.

In our study, we have neglected the effects of dissipation. It is worth noting that in the presence of dissipation, the resonance investigated in our work will lead to an increased energy absorption. This is important for a number of laboratory plasma devices [18, 34] and radar applications [35, 36]. These studies are left for future work.

In summary, for a three-layer structure, one can observe total transmission of an electromagnetic wave by inducing a standing wave resonance. For a given plasma density, this can be achieved by choosing an adequate incidence angle, boundary layer permittivity and a corresponding boundary layer width. We expect that the phenomena of resonant transmission in this configuration can be utilized in a number of plasmonic and communications applications.

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