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Plasmon resonance coupling in cold overdense dissipative plasma

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Abstract

It has been shown that the overdense plasma in the resonance conditions can be totally transparent to the incident electromagnetic waves, due to the excitation of the surface modes or plasmons. This scenario requires excitation of a single surface mode which is provided by placing a dielectric layer in front of the incident wave. Here, it is shown that this procedure would be complete and more efficient by arranging the conditions to excite coupled surface modes, namely by placing two dielectrics on both sides of the plasma layer. The results show that in this case, the overdense plasma slab could poses high transmittance in spite of the presence of the dissipative effects. In addition, in this case, the resonance conditions can be achieved more easily and efficiently, and can be used for wider range of the overdense plasma widths.

Keywords: Surface waves, Overdense plasma, Left-handed materials, Plasmons, Dissipative effects

Introduction

An overdense plasma layer normally reflects the electromagnetic waves [1,2]. However, some procedures were made wherein this plasma becomes totally transparent to the incident electromagnetic waves [3-8]. This anomalous transmission can be seen also in perforated metallic films [9,10]. Enormous efforts were made to find out an explanation to these phenomena and to achieve the possible and extraordinary application of overdense plasma layers in many areas of physical science; for example, see [11-14].

The mechanism of the passing of the wave through this material resembles that of the left-handed materials (LHM). LHM are materials with a negative index, originally proposed by Veselgo in 1960 [1]. These materials do not occur in any known natural materials, but artificial structures with these properties were designed and made. The materials with negative index have extraordinary properties that make them suitable applicants for a number of potential applications such as the prefect lens, wave guides in physics, and engineering [3-6].

The main procedure of this anomalous wave transmission involves the excitation of surface modes or plasmons on the plasma surface [3,5]. The surface wave in fact causes the transmission of the electromagnetic energy through the plasma slab and makes it totally transparent. However, in order to excite the surface modes, it is firstly needed to place a diffracting layer in front of the plasma layer to transform the incident propagating wave into evanescent wave. Then, this evanescent wave causes the excitation of the plasmons.

In the previous work, we examined a mechanism of the total transmission of the electromagnetic waves through a warm overdense plasma slab [8]. The procedure requires placing two dielectric layers on both sides of the plasma slab. This sandwich-like structure leads to the instantaneous excitation of the coupled surface waves on both sides of the overdense plasma slab. Then, by exciting these coupled plasmons, the energy of the incident wave transmits through the structure. However, in reference [7], it has been shown that in order to have wave transmission through the plasma, it is not necessary to consider a structure whereby coupled surface modes excite on both sides of the plasma layer. They considered only one dielectric layer, which is supposed to be placed in front of the plasma layer; they also showed that the total transparency occurred for the considered structure.

This work is devoted to present a comparison between the results of these two mechanisms. To this end, we

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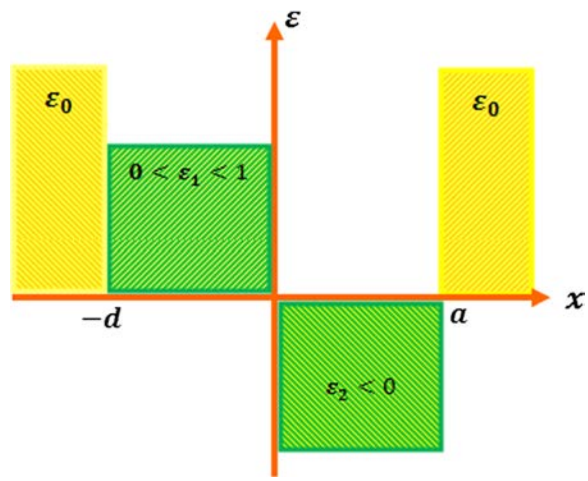

Figure 1 Schematic showing the spatial distribution of the dielectric permittivity required to excite *single* plasmon waves.

study and derive the transmission rate for a cold overdense plasma layer for the two structures separately. Specifically, we focus on the case of the plasma with collisional effects. In this case, we observe that the mechanism involving the excitation of coupled surface waves is preferred. This mechanism has advantages of being better, and its resonance conditions can be achieved easily. In addition, for wider range of the overdense plasma widths, resonance transmission can be produced. Moreover, in the presence of the collisional effects, the overdense plasma slab shows high transmittance especially due to the excitation of coupled surface plasmons.

The organization of this paper is as follows: In the 'Constructive equations' section, the governing equations and their solutions in the plasma medium are introduced. In the 'Single plasmon excitation' section, the transmission of the electromagnetic waves through an overdense plasma layer via a mechanism involving a single plasmon excitation is studied, that is, a plasma layer is placed adjacent to a dielectric layer. The next section is devoted to the study of the wave transmission using a mechanism which deals with the simultaneous excitation of the coupled plasmons on both sides of the overcritical plasma layer. In this case, the overcritical plasma layer is supposed to be placed between two dielectrics. This section also contains some comparisons between two mechanisms. Finally, the concluding remarks are presented.

Constructive equations

In order to investigate the transmission of the electromagnetic waves through the overdense collisional plasma, we consider multilayer of dielectrics and the plasma. The governing linearized set of the electromagnetic field equations in these medium is given as follows:

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

$$\nabla \times \boldsymbol{B} + \frac{4\pi n_0 e}{c}\tilde{V} - \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} \tag{2}$$

$$\frac{\partial \tilde{V}}{\partial t} + \frac{e}{m}\boldsymbol{E} + \nu\tilde{V} = 0. \tag{3}$$

In these equations, it is supposed that the ions are motionless. $\tilde{V}$ stands for the linear electron velocity. The parameter ν is the collision frequency. Since the medium discontinuities are supposed to be placed at the x axis, all the field quantities shall be considered to vary such as $\psi(x)\exp(ik_y y - i\omega t)$. In this way, the z and y axes are supposed to be along the interfaces.

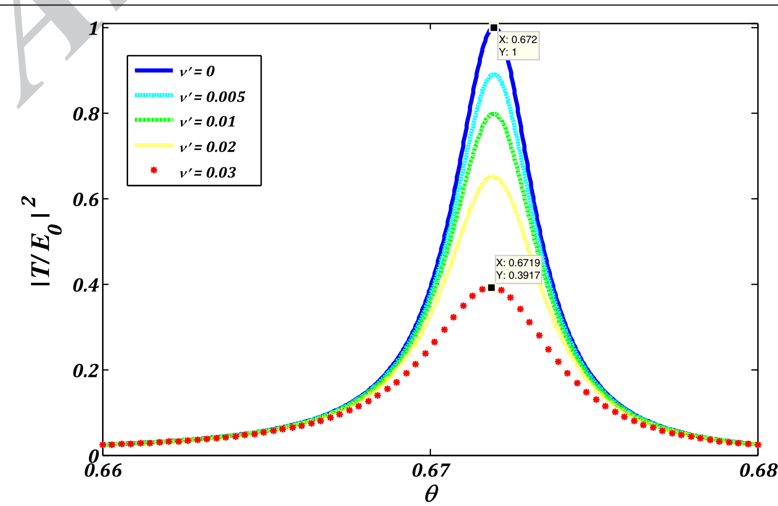

Figure 2 The transmission curve $|T/E_0|^2$ as a function of the incident angle θ. For four different values of the losing factor $\acute{\nu}$.

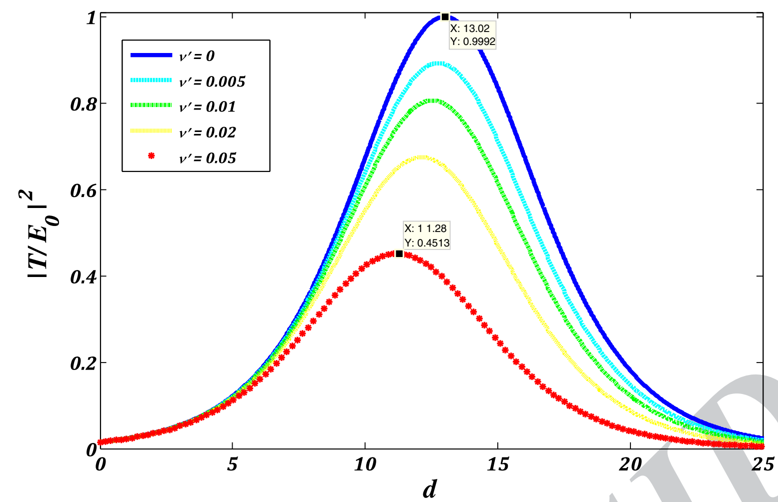

Figure 3 The transmission curve $|T/E_0|^2$ as a function of the dielectric width *d*. For four different values of the losing factor $\acute{v}$.

Let us consider the electric and magnetic field components as $\boldsymbol{E} = (E_x, E_y, 0)$ and $\boldsymbol{B} = (0, 0, B)$ and the electron velocity as $\tilde{\boldsymbol{V}} = (\tilde{V}_x, \tilde{V}_y, 0)$. Applying these assumptions, the field equations (1 to 3) take on the following form:

$$\varepsilon\frac{d}{dx}\left(\frac{1}{\varepsilon}\frac{dB_z}{dx}\right) - \alpha^2 B_z = 0, \tag{4}$$

where

$$\alpha^2 = k_y^2 - \frac{\omega^2}{c^2}\varepsilon \tag{5}$$

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\nu}. \tag{6}$$

The plasma frequency is $\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m}}$. The field equation (4) also can be written as

$$\varepsilon\frac{d}{d\varepsilon}\left(\frac{1}{\varepsilon}\frac{dB_z}{dx}\right) + i\frac{\omega^2}{c^2}\left(\sin^2\theta - \varepsilon\right)B_z = 0, \tag{7}$$

where k_y in (5) is replaced by $k_y = k_0 \sin\theta$ with $k_0 = \frac{\omega}{c}$. Equation (7) has the following general solution:

$$B_z = A_1 e^{ikx} + A_2 e^{-ikx}, \tag{8}$$

where $k = k_0\sqrt{\varepsilon - \sin^2\theta}$.

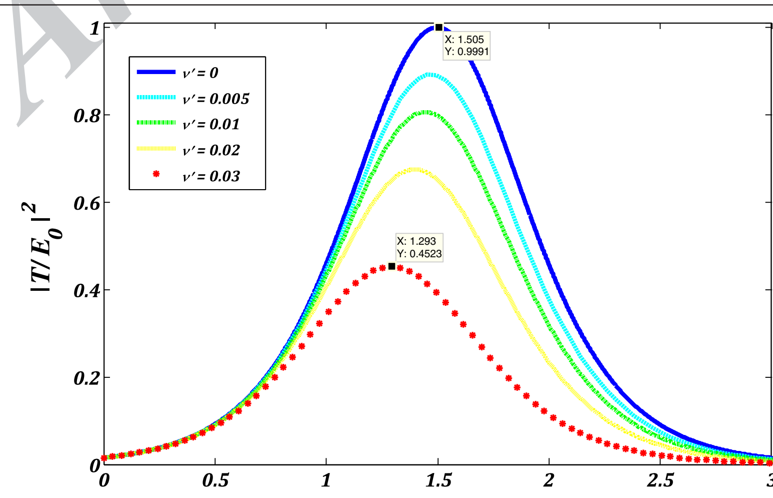

Figure 4 The transmission curve as a function of the overdense plasma width *a*. For four different values of the losing factor $\acute{v}$.

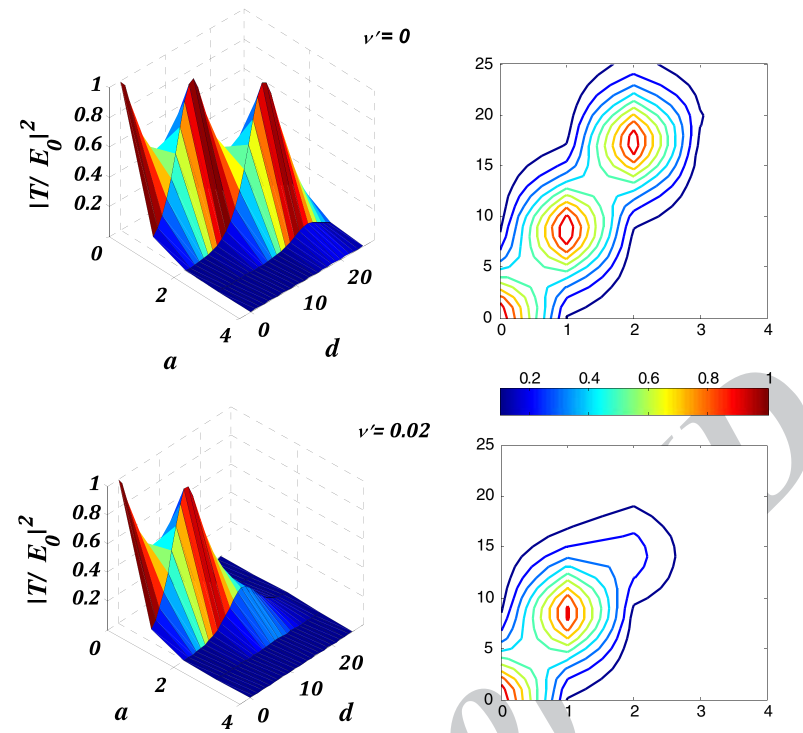

Figure 5 Transmission rate surface as a function of *a* and *d* with and without dissipative effects. At the right are their corresponding contour diagrams which show the maximums of the transition rate for each case.

Single plasmon excitation

In order to study the transmission of electromagnetic waves through the overdense plasma layer, we consider a mechanism involving a single plasmon excitation, namely, the plasma layer in the presence of one dielectric layer. The dielectric layer or equivalently an under critical plasma layer is needed to produce evanescent waves from propagating waves. Then. the evanescent waves will excite surface waves or plasmons, which will lead to the transmission of electromagnetic waves through the overdense plasma layer. Let us consider a structure which is illustrated in Figure 1.

The wave solutions in the different regions of Figure 1 are given in the form of (8) and are considered as follows:

$$\begin{array}{ll} B_z = E_0 e^{ik_0 \cos\theta x} + R e^{-ik_0 \cos\theta x} & x < -d \\ B_z = A_1 e^{ik_1 x} + A_2 e^{-ik_1 x} & d < x < 0 \\ B_z = A_3 e^{ik_2 x} + A_4 e^{-ik_2 x} & 0 < x < a \\ B_z = T e^{ik_0 \cos\theta x} & a < x \end{array}, \qquad (9)$$

with $k_{1,2} = k_0\sqrt{(\varepsilon_{1,2} - \sin^2\theta)}$.

The permittivity ε is given in (6) which can be rewritten as

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}\left(1 + i\frac{\nu}{\omega}\right)^{-1} \cong 1 - \frac{\omega_p^2}{\omega^2}\left(1 - i\frac{\nu}{\omega}\right), \qquad (10)$$
$$\varepsilon \cong \in + i\,\nu'$$

where $\in$ refers to the real part of the permittivity and ν' corresponds to its imaginary part. Here, the losses effects are considered only for the overdense plasma;

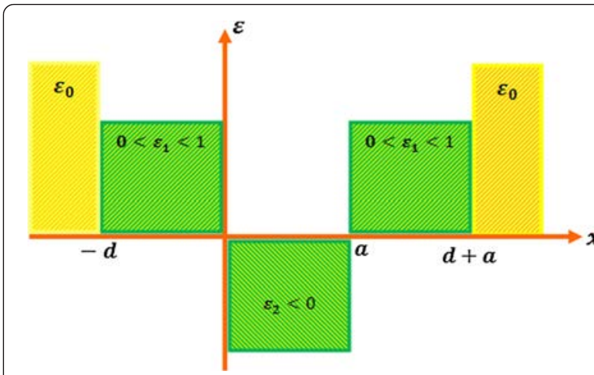

Figure 6 Schematic showing the spatial distribution of the dielectric permittivity required to excite *coupled* plasmon waves.

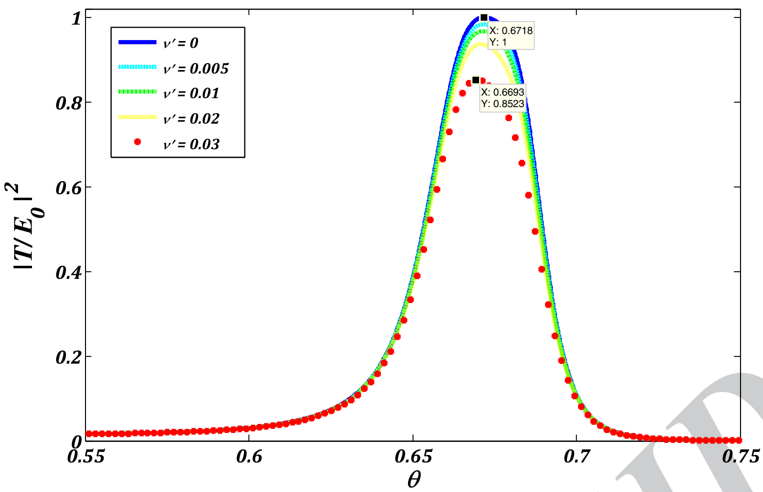

Figure 7 The transmission curve as a function of the incident angle *θ*. For four different values of the losing factor $\acute{\nu}$.

hence, the permittivity of the dielectric layer namely ε_1 is a real positive number, and the permittivity of the overdense plasma layer ε_2 has a negative real part and an imaginary part which corresponds to its losing effects.

Applying the conditions that are the continuity of B_z and $\frac{1}{\epsilon}\frac{dB_z}{dx}$ at the boundaries, one finds six equations; then, the transmission coefficient can be explicitly found in terms of the incident coefficient E_0. Here, this is obtained by using a numerical method. In all cases, it is considered $\epsilon_1 = 0.3428$ and $\epsilon_2 = -2.97$. Also, the width of the dielectric layer d and the plasma width a become dimensionless by a factor k_0. Figures 2, 3, and 4 show the transmission coefficient $|T/E_0|^2$ versus the incident angle θ, the widths d and a, respectively, for the four different values of $\acute{\nu}$. These figures in fact monitor one of the resonant point of the transmission which occurs at $a = 1.50$, $d = 13.0180$, and $\theta = 0.6720$. At this resonant point, the transmission coefficient has its maximum value, namely $|T/E_0|^2 \approx 1$, for the diagram without dissipation, that is, the diagram with solid line; for other cases, the height of this maximum decreases. For example, for $\acute{\nu} = 0.03$, the resonant value of transmission decreases to $|T/E_0|^2 \approx 0.4$.

However, in fact, there are infinite numbers of the resonant points at different values of θ, a, and d. In Figure 5, the numbers of the resonance points in the absence and in the presence of dispersion effects are compared. In this figure, the transmission rate is shown as a function of a and d, where the length steps variation of a and d are 1, and the incident angle is $\theta = 0.6720$. As observed in Figure 5, the transmission rate without dissipation has

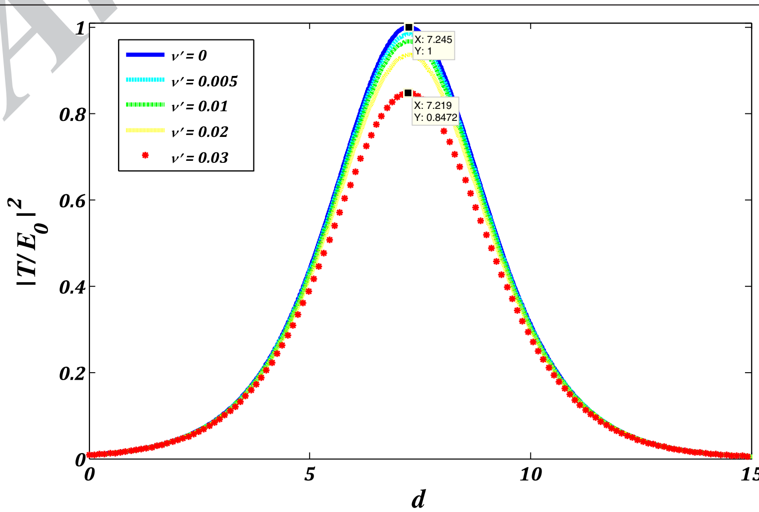

Figure 8 The transmission curve as a function of the dielectric width *d*. For four different values of the losing factor $\acute{\nu}$.

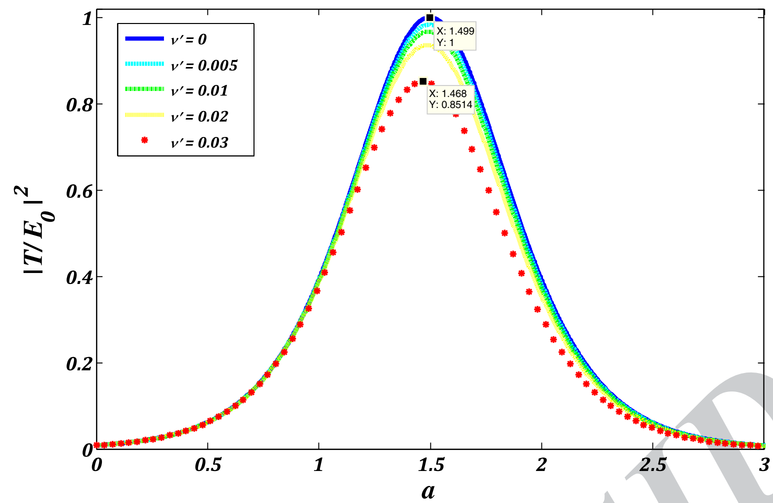

Figure 9 The transmission curve as a function of the overdense plasma width *a*. For four different values of the losing factor $\acute{\nu}$.

two resonant points occurring approximately at a = 2, d = 17, $|T/E_0|^2$ = 0.9617 and at a = 1, d = 9, $|T/E_0|^2$ = 0.9947. But for a dispersive overdense plasma, the numbers of the resonances expectedly decrease, namely for $\acute{\nu} = 0.02$, Figure 6 shows that only one resonance exists, which happened approximately at a = 1, d = 8, $|T/E_0|^2$ = 0.916.

Coupled plasmon excitation

In this case, it is supposed that the transmission of the electromagnetic waves takes place due to the simultaneous excitation of the coupled plasmons on both sides of the overcritical plasma layer. Hence, it is necessary to consider one dielectric layer on each side of the overcritical plasma layer to produce the evanescent waves from

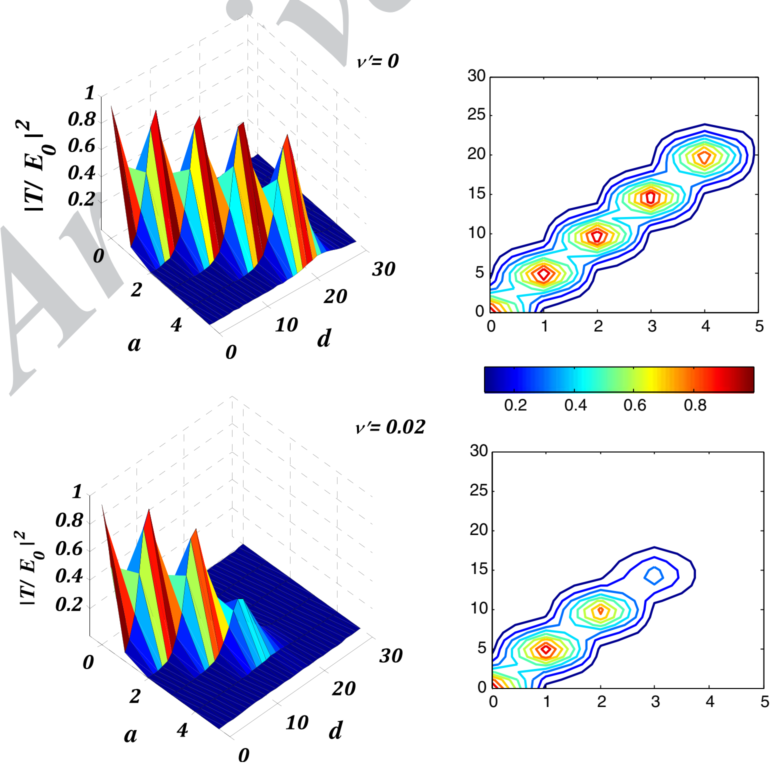

Figure 10 The transmission surface as functions of *a* and *d*, with and without dissipative effects. At the right are their corresponding contour diagrams which show the maximums of the transmission rate in each case.

Table 1 Maximum widths of overdense plasma and dielectric layer for the transmission rate over 0.95%

		$\acute{v}=0$	$\acute{v}=0.005$	$\acute{v}=0.01$	$\acute{v}=0.02$	$\acute{v}=0.03$
Single plasmon structure	*a*	2.0600 ± 0.001	1.2730 ± 0.001	1.0820 ± 0.001	0.8880 ± 0.001	0.7740 ± 0.001
	d	17.9200 ± 0.01	10.9700 ± 0.01	9.2900 ± 0.01	7.6200 ± 0.01	6.6100 ± 0.01
Couple plasmon structure	*a*	3.8160 ± 0.001	2.1000 ± 0.001	1.7300 ± 0.001	1.3550 ± 0.001	1.1350 ± 0.001
	d	18.7200 ± 0.01	10.1700 ± 0.01	8.3800 ± 0.01	6.5600 ± 0.01	5.5000 ± 0.01

the propagating waves and vice versa. This structure is illustrated in Figure 6.

The wave solutions are in the form of (9) except for

$$\begin{cases} B_Z = A_5 e^{ik_1x} + A_6 e^{-ik_1x} & a < x < d \\ B_Z = T e^{ik_0 \cos\theta x} & d < x \end{cases}. \quad (11)$$

Using appropriate boundary conditions consisting the continuity of B_z and $\frac{1}{\varepsilon}\frac{dB_z}{dx}$ across interfaces, one finds eight equations for the unknown coefficients. The calculated transmission curves as functions of the incident angle, the dielectric, and the plasma widths are shown in the Figures 7, 8, and 9, respectively. In these calculations, $\in_1 = 0.3428$ and $\in_2 = -2.97$ are considered, and the widths a and d become dimensionless by a factor k_0. These figures contain one of the resonant points of the transmission, which occurs at $a = 1.50$, $d = 7.2470$, and $\theta = 0.6720$. For the overdense plasma without dispersion, the transmission curve reaches to the maximum $|T/E_0|^2 \approx 1$, but this maximum value decreases by the increase of the losing factor $\acute{v}$; so, for $\acute{v} = 0.03$, it is reduced to $|T/E_0|^2 \approx 0.852$.

Figure 10 shows the transmission surface as a function of the overdense plasma width a and the dielectrics width d in the absence and the presence of the dissipative effects, which corresponds to Figure 5. As it is obvious from the figure, the numbers of the resonant points and their heights decrease by the increase of the losing factors. Figure 10 corresponds to the transmission curve without dissipation and contains four resonant points, with the highest at $a = 1$, $d = 5$, $|T/E_0|^2 = 0.9946$, and the lowest at $a = 4$, $d = 20$, $|T/E_0|^2 = 0.8893$. But in the figure below which shows the transmission curve with $v' = 0.02$, the numbers of the resonant reduce to two points occurring at $a = 1$, $d = 5$, $|T/E_0|^2 = 0.9686$ and at $a = 2$, $d = 10$, $|T/E_0|^2 = 0.8283$.

By comparing Figure 10 with Figure 5, it is observed that the numbers of the resonant points in the coupled plasmon mechanism are more than about two times of the single plasmon procedure. Therefore, setting the conditions appropriate for the resonant transmission rate is easier in the coupled plasmon mechanism as compared with the single plasmon procedure.

The Table 1 contains the upper limit widths of the overdense plasma layer a and their appropriate

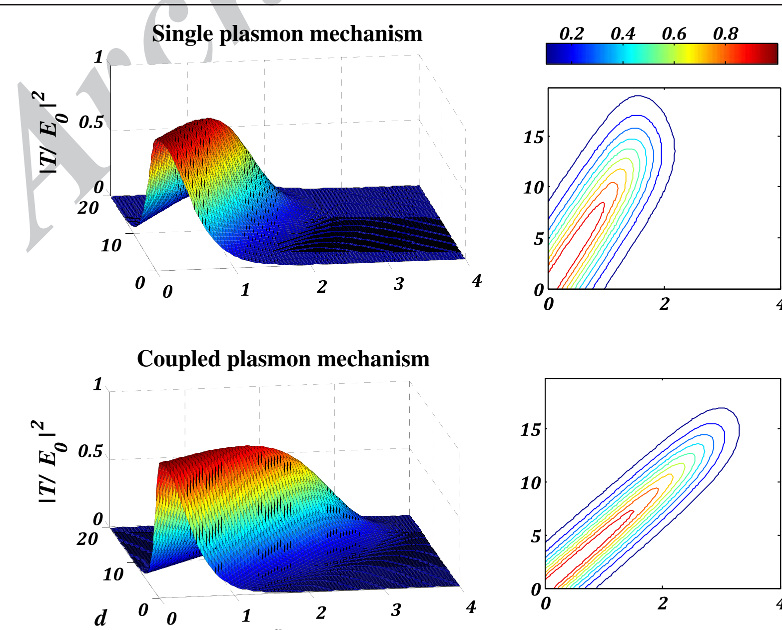

Figure 11 The transmission surface as a function of *a* and *d*. In the case of the single plasmon and the coupled plasmon structures.

dielectric layer d at which the transmission rate is over of 0.95%. These results are obtained for the incident angle θ = 0.6720. As it is observed from Table 1, these upper limits reduce by the increase of the losing factor $\acute{\nu}$. Also, the results shows that for each loosing factor $\acute{\nu}$, the upper limit of a for the case of coupled plasmon structure is greater than that of the single plasmon structure. This fact is one of the advantages of the coupled plasmon structure. This also is illustrated in Figure 11, where the transmission rate is given as a function of a and d for both cases of the single plasmon structure and coupled plasmon structure. In both cases, they are considered θ = 0.6720 and $\acute{\nu} = 0.03$, but the step variation of a and d is supposed to be less than one. This figure emphasizes that the width of the plasma layer in the coupled plasmon mechanism can be longer than that in the single plasmon case. This property makes it possible to construct wider entrance pupil for lens apparatus in the case of coupled plasmon mechanism [15].

Concluding remarks

Here, in order to study the transmission of the electromagnetic waves through an overdense plasma layer with dissipative effects, we considered two different mechanisms. These procedures involved the excitation of the surface plasmons. The first case deals with the excitation of the single surface plasmons, and in its corresponding structure, the overdense plasma is considered to be placed adjacent to an ordinary dielectric layer. However, in the second case, it is supposed that the coupled surface waves are responsible for the wave transmission. In this latest mechanism, the overdense plasma is considered to be placed between the two dielectrics.

In order to make a comparison between the transmissions results of these two mechanisms, their transmission curves were numerically calculated as functions of the incident angle, the width of the dielectrics, and the widths of the overdense plasma layers. It was observed that by the increase of the losing factor of the overdense plasma, the maximum of the transmission rate resonant reduces in both mechanisms, but this reduction in the case of the coupled plasmons, is remarkably lower than that in the single plasmon case. For example, for $\acute{\nu} = 0.03$, the resonant value of the transmission rate in the single plasmon case reduces to $|T/E_0|^2 \approx 0.4$, while in the case of coupled plasmon, it reduces to $|T/E_0|^2 \approx 0.852$. Therefore, the observations confirm that the structure of the coupled plasmons can have very good transmission properties despite the application of losing effects.

Also, it is observed that by the increase of the losing factor, the transmission resonances slightly shift toward the lower values of the dielectric layer and the overdense plasma widths. These shifts specially can be observed for single plasmon mechanism.

Moreover, these investigations indicate that in the coupled plasmon structure, the maximum transmission, in spite of applying of the dissipative effects, can be achieved more easily and efficiently because the number of the transmission resonances is more in the coupled plasmon case compared to that in the single plasmon structure. In addition, the results demonstrated that the resonant transmissions show that the ranges of the overdense plasma layer widths in coupled plasmon mechanism can be more than those in the single plasmon procedure. This property makes it possible to construct wider entrance pupil for lens apparatus in the case of coupled plasmon mechanism [15]. In conclusion, it should be noted that the results obtained here can be generalized to appropriate metallic films instead of the overdense plasma layer and, hence, appear to have a number of practical applications [3].

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The authors had the same and equal participation in any section of the article. All authors read and approved the final manuscript.

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