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Total absorption of electromagnetic radiation in a dense inhomogeneous plasma

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It is demonstrated that a p-polarized electromagnetic wave incident obliquely on a layer of inhomogeneous nontransparent plasma, whose density has a steep rise in the vicinity of the plasma resonance, can be totally absorbed. The effect occurs when the damping of the so-called leaking waves is fully compensated by the radiation inflow.

Recently, laser-produced plasma experiments[1] revealed a steepening of plasma density profile near the resonant point. This effect was theoretically predicted by Gildenburg and Fraiman,[2] who evaluated a stationary deformation of the plasma resonance region induced by the ponderomotive force of a longitudinal high-frequency field. A similar situation was obtained also in numerical simulations of intense laser radiation interacting with a plasma.[3] In connection with the considered density profile modification, an appreciably increased absorption of the obliquely incident radiation was observed.[4] Therefore, a detailed qualitative analysis of such an enhanced absorption now becomes necessary.

Using the linear theory to explain this absorption phenomenon, it turns out that a crucial role is played by the so-called leaking waves[5] existing in plasmas with such a density profile. They appear to be eigenmodes if the distance between the quasiclassical reflection point and the resonance region is sufficiently large. The main characteristics of these waves is their damping arising from energy loss due to radiation ("leaking") into the transparent region. This energy leaking, however, can be reversed by radiation inflow. On the other hand, the leaking waves could also be dissipated through standard irreversible processes like the linear wave transformation, collisions, etc. Consequently, it becomes possible to construct a self-consistent system of the external radiation source and the absorbing dense medium with all irreversible dissipative processes completely compensated by the energy inflow. In other words, a total (100%) absorption could be achieved by resonant excitation of leaking waves.

To demonstrate the explained effect explicitly, we shall consider a collisionless plasma whose density is assumed weakly inhomogeneous everywhere except in the vicinity of the resonant point x_c $[\epsilon(x_c)=0]$, where it steeply increases from n_1 $[\epsilon(n_1)\equiv\epsilon_1]$ to n_2 $[\epsilon(n_2)\equiv\epsilon_2]$ over a narrow transition layer of the length a $(k_\parallel a \ll 1)$.

The magnetic field behavior of a p-polarized wave in an inhomogeneous plasma can be described by the well-known equation

$$\frac{\partial^2 B}{\partial x^2}-\frac{\partial \ln\epsilon(\omega,x)}{\partial x}\frac{\partial B}{\partial x}-\mathcal{K}^2(x)B=0\,, \tag{1}$$

where

$$\mathcal{K}^2(x)=k_\parallel^2-(\omega^2/c^2)\epsilon(\omega,x)\,,$$

$$\epsilon(\omega,x)=1-\omega_{pe}^2(x)/\omega^2\,,$$

and $k_\parallel$ is the wave-vector component parallel to the transition layer.

This equation can be solved by the method of geometrical optics in the region of weak inhomogeneity (the corona region) and by successive approximations in the transition layer where $k_\parallel a$ is small. By matching the solutions, the following expression for the reflection coefficient was obtained:

$$R=\frac{(g_+-b^2g)^2+(g_-b^2-g)^2}{(g_++b^2g)^2+(g_-b^2+g)^2}\,, \tag{2}$$

where

$$g_\pm=\frac{\mathcal{K}_1}{\epsilon_1}\pm\frac{\mathcal{K}_2}{\epsilon_2}\,,\quad b=\frac{1}{\sqrt{2}}\exp\left(-\int_0^D\mathcal{K}(x)\,dx\right),$$

$$g=\frac{\omega^2}{c^2}\sin^2\theta\left|\operatorname{Im}\int_D^{D+a}\frac{dx}{\epsilon(\tilde\omega,x)}\right|$$

$$\equiv\frac{\omega^2}{c^2}(\sin^2\theta)\pi l\,,$$

$$\tilde\omega=\omega+i\Delta\,,$$

$$\mathcal{K}_{1,2}^2=(\omega^2/c^2)(\sin^2\theta-\epsilon_{1,2})\,.$$

Here θ is the angle of incidence of the incoming radiation; the quasiclassical reflection point $x=0$

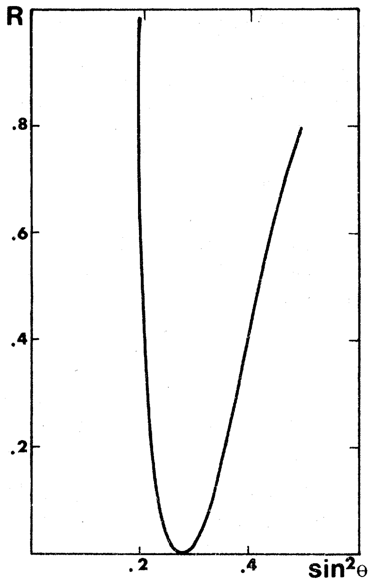

FIG. 1. A particular calculated example showing the dependence of the reflection coefficient R on incident angle θ when $\omega L/c = 10$, $\pi\omega l/c = 3.34$, $\epsilon_1 = 0.2$, and $\epsilon_2 = -1$.

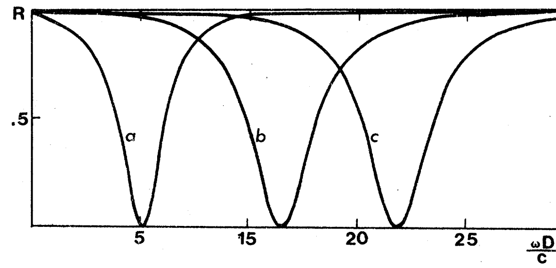

FIG. 2. A set of calculated curves expressing the dependence of the reflection coefficient R on variable $\omega D/c$ for various ratios of collisional frequency to the incident radiation frequency: (a) $\nu/\omega = 0.01$; (b) $\nu/\omega = 0.001$; and (c) $\nu/\omega = 0.0001$, $\epsilon_1 = 0.2$, and $\epsilon_2 = -1$.

is determined from the condition $\mathcal{H}(x=0)=0$; the point $x = D$ is at the beginning of the transition layer (interval $D < x < D+a$), while the quantity g represents the dissipation effect. From the expression (2) we can see that the reflection coefficient vanishes when the following conditions are simultaneously satisfied:

$$g_+ - b^2 g = 0 , \tag{3}$$

$$g_- b^2 - g = 0 . \tag{4}$$

The condition (3) requires a resonance of the incoming radiation with leaking waves,[5] while the condition (4) imposes a necessity that the dissipative damping of leaking waves due to linear transformation in local plasma waves is fully compensated by the radiation inflow.

In the special case of a part-by-part linear density variation Eqs. (3) and (4) for $R = 0$ yield the following angle of incidence and the related density jump:

$$\sin^2\theta = \epsilon_1 + \left(\frac{3c}{4\omega L}\right)^{2/3} \times \ln^{2/3}\left\{\frac{c}{\omega l}\left(\frac{c}{\omega l}\right)^{1/3} \frac{1}{\epsilon_1[\epsilon_1 + (4c/3\omega L)^{2/3}]}\right\} , \tag{5}$$

$$\frac{n_2 - n_1}{n_c} = \epsilon_1 \frac{2\sin^2\theta - \epsilon_1}{\sin^2\theta - \epsilon_1} , \tag{6}$$

where L and l are the respective typical density inhomogeneity scale lengths for regions with small and large density gradient.

A numerical example for such a density distribution was calculated; the obtained results are presented in Fig. 1. From this plot one can determine the interval of incident angles at which the largest amount of the incoming radiation is being absorbed.

It should be remarked that the total absorption can also occur at relatively small angles of incidence, but there exists a minimal value of θ for which R can vanish,

$$\sin^2\theta_{\min} \approx 2(3c/4\omega L)^{2/3} \ln^{2/3}(L/l) , \tag{7}$$

provided that the following conditions are satisfied:

$$\epsilon_1 \approx \left(\frac{3c}{4\omega L}\right)^{2/3} \ln^{2/3}\left(\frac{L}{l}\right)$$

and

$$\frac{n_2 - n_1}{n_c} \approx 3\epsilon_1 . \tag{8}$$

Calculations were also carried out for a collisional plasma with a double-step density profile. Figure 2 shows that the total absorption of incident radiation can occur in this case too if the plasma parameters are chosen properly in full consistency with the physical interpretation given in the present paper. Earlier investigations[6] of the same profile, however, missed this most interesting result of total absorption.

Finally, it is worthwhile to underline that such unique behavior of the reflection coefficient in optically thick dissipative plasmas can also be applied in other fields of physics as a method for a perfect energy radiation input into opaque dissipative media.

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