Total transmission of electromagnetic waves through slabs of plasmas and plasma-like media upon the excitation of surface waves

R. R. Ramazashvili
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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The phenomenon of total transmission of electromagnetic waves through slabs of dense plasma and metals due to the excitation of surface waves can be exploited to develop polarizers and spectral filters working at a fixed frequency.

An inhomogeneous slab of plasma with a supercritical density at the maximum may turn out to be totally transparent for an incident *p*-polarized wave if dissipative processes are ignored and if there is an abrupt change in the density from a subcritical to a supercritical value.[1] It was also shown in Ref. 1 that this "brightening" of a dense slab is made possible by a resonant excitation at discontinuities of surface waves, which effect a transport of the energy of the incident wave through the opaque region of the slab. The possibility of a total brightening was proved in Ref. 1 only for a spatially symmetric slab (Fig. 1), but it was pointed out that there may also be a reflectionless transmission of waves through an asymmetric slab, as illustrated in Fig. 2. It was concluded in Ref. 2 that there can also be a complete brightening of a symmetric plasma slab, as shown in Fig. 1. The experiment of Ref. 3 models the transmission of electromagnetic waves through a symmetric plasma slab by means of a three-layer insulator-metal-insulator system which is placed between two prisms with a large refractive index. The spatial distribution of the dielectric constant in this sys-

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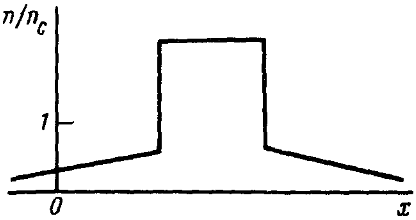

FIG. 1. Profile of the density of the plasma slab, $n(x)$ (n_c is the critical density).

tem is of the same nature as that for the slab in Fig. 1. It was found that there can be an up to 70% transmission of p-polarized radiation through the system, while an s-polarized wave essentially does not penetrate through the slab at all. (Similar results had been found earlier in an experimental study[4] of a three-layer optical polarizer. The idea of developing a polarizer of this type was proposed in Ref. 5.) It was asserted in Refs. 2 and 3 that a necessary condition for total wave transmission is a spatial symmetry of this system. Below we use the simple example of a two-layer system to show that a total transmission of p-polarized waves is also possible in the case of an asymmetric system.

We assume that two layers, of thickness l_1 and l_2 and dielectric constants ϵ_1 and ϵ_2, respectively, in contact with each other, are positioned between two prisms with a dielectric constant ϵ_p. We assume that the prisms fill a half-space. The reflection coefficient (the ratio of the amplitudes of the reflected and incident waves) for a p-polarized wave, which is incident obliquely on the two-layer system, is written as follows:

$$\begin{aligned}R = \{ &(g_1+g_2)[(g_p - ig_1)(g_2 - ig_p) + (g_p + ig_1)(g_2 + ig_p)\exp(-2\kappa_1 l_1' - 2\kappa_2 l_2')] \\ &+(g_1 - g_2)[(g_p + ig_1)(g_2 - ig_p)\exp(-2\kappa_1 l_1') + (g_p - ig_1)(g_2 + ig_n)\exp(-2\kappa_2 l_2')] \} \\ &/ \{ (g_1 + g_2)[(g_p + ig_1)(g_2 - ig_p) + (g_p - ig_1)(g_2 + ig_p)\exp(-2\kappa_1 l_1' - 2\kappa_2 l_2'] \\ &+ (g_1 - g_2)[(g_p - ig_1)(g_2 - ig_p)\exp(-2\kappa_1 l_1') + (g_p + ig_1)(g_2 + ig_p)\exp(-2\kappa_2 l_2')]\}.\end{aligned} \tag{1}$$

Here ω and $k_{\parallel} = k \sin\theta$ are the frequency and the component of the wave vector parallel to the slabs, θ is the angle of incidence of the wave on the first slab, and

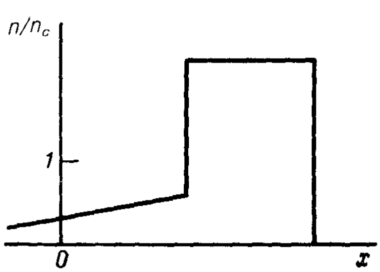

FIG. 2.

$$g_p = \sqrt{\epsilon_p - n_\parallel^2}/\epsilon_p;\ g_{1,2} = \kappa_{1,2}/\epsilon_{1,2};\ \kappa_{1,2} = \sqrt{n_\parallel^2 - \epsilon_{1,2}};$$
$$n_\parallel^2 = k_\parallel^2 c^2/\omega^2;\ l'_{1,2} = \omega l_{1,2}/c. \tag{2}$$

The condition $R = 0$ is equivalent to the two equations

$$g_1 + g_2 = 0 \quad \text{and} \quad \kappa_1 l_1 = \kappa_2 l_2 . \tag{3}$$

If the first of these conditions is to be satisfied, we must have $\epsilon_1\epsilon_2 < 0$. From this condition we find a dispersion relation for surface waves at the interface between two media with dielectric constants[6] ϵ_1 and ϵ_2:

$$n_\parallel^2 = \epsilon_1\epsilon_2/(\epsilon_1 + \epsilon_2). \tag{4}$$

The second condition means that the effective thicknesses of the slabs are equal. This condition guarantees that the incident and transmitted radiation fluxes are equal, since under this condition an intensification of the field in one slab is offset by an attenuation of the field in the other.

The particular features of the brightening conditions depend on the specific dispersion properties of the slabs. We consider the two following cases:

1. The first medium is an insulator with $\epsilon_1 = \text{const} > 0$, while the second medium is plasma-like with $\epsilon_2 = 1 - \omega_p^2/\omega^2$. From the brightening conditions and the equation $k^2 = \omega^2\epsilon_p/c^2$ we find

$$\omega^2 = \omega_p^2 l_2/(l_2 + \epsilon_1 l_1);\ k_\parallel^2 = \frac{\omega_p^2}{c^2}\,\frac{\epsilon_1 l_2 l_1}{(l_1 - l_2)(l_1\epsilon_1 + l_2)};\ \sin^2\theta = \epsilon_1 l_1/\left[\epsilon_p(l_1 - l_2)\right]. \tag{5}$$

A necessary condition for the satisfaction of this second equation is

$$\epsilon_p > \epsilon_1 l_1/(l_1 - l_2). \tag{6}$$

2. Both slabs are plasma-like:

$$\epsilon_1 = 1 - \omega_{p1}^2/\omega^2;\ \epsilon_2 = 1 - \omega_{p2}^2/\omega^2;\ \omega_{p2}^2 > \omega_{p1}^2 . \tag{7}$$

In this case the conditions for total brightening give us

$$\omega^2 = \frac{l_1\omega_{p1}^2 + l_2\omega_{p2}^2}{l_1 + l_2};\ k_\parallel^2 = \frac{l_1 l_2}{l_1^2 - l_2^2}\,\frac{\omega_{p2}^2 - \omega_{p1}^2}{c^2};$$
$$\sin^2\theta = \frac{l_1 l_2}{(l_1 - l_2)\epsilon_p}\,\frac{\omega_{p2}^2 - \omega_{p1}^2}{l_1\omega_{p1}^2 + l_2\omega_{p2}^2}. \tag{8}$$

Here the following inequality must hold:

$$\epsilon_p > \frac{l_1 l_2}{l_1 - l_2}\,\frac{\omega_{p2}^2 - \omega_{p1}^2}{l_1\omega_{p1}^2 + l_2\omega_{p2}^2} . \tag{9}$$

For the given parameters of the slabs, we have thus unambiguously determined those values of the frequency and angle of incidence of the wave for which the two-slab system is completely transparent. We have thus proved the possibility of a total brightening of an asymmetric system.

It is simple to see that a slight inhomogeneity of a plasma slab (Fig. 2) does not prevent a reflectionless transmission of p-polarized waves through a dense plasma.

There is an important distinction between symmetric and asymmetric systems: In a symmetric system, the incident and transmitted radiation fluxes are automatically equal in the reflectionless case by virtue of the geometry of the problem, and the equation $R = 0$ simply gives us a relationship between ω and $k_{\parallel}$ of the transmitted wave.[1] An asymmetric system, in contrast, transmits a wave only for certain unambiguously determined values of the frequency and the angle of incidence. This result means that a two-slab system can be used to develop spectral filters with a rigidly fixed passband. The relative width of the passband of such a filter is determined by the quantity $\exp(-2\kappa_1 l'_1)$, and it may be quite small if the layers are sufficiently thick. We note, however, that the passband cannot be so small that it is comparable to the imaginary parts of the dielectric constants, which we have ignored.

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Translated by Dave Parsons