High Transparency of Classically Opaque Metallic Films

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It is demonstrated, both theoretically and experimentally, that a classically opaque metallic film can appear highly transparent when the conditions are established for the incident electromagnetic wave to excite coupled surface modes on both sides of the film.

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In previous work[1] we considered a mechanism whereby a normally reflecting overdense plasma layer could become totally transparent to an incident electromagnetic wave. The phenomenon involved the excitation of coupled surface electromagnetic waves on the density (dielectric) discontinuities on either side of the plasma slab, such that the energy in the surface wave was damped by reemission of the incoming electromagnetic wave from the rear surface, thereby rendering the slab transparent. This essentially new phenomenon is an extension of the observations of total absorption in a semi-infinite plasma layer,[2] where surface electromagnetic waves are excited on a density step within the plasma and where the surface wave energy is "dissipated" through irreversible damping of these electromagnetic surface waves. In our case, however, even when irreversible dissipation is absent, the incoming wave can be totally "absorbed" since dissipation of the surface wave energy due to irreversible losses can be replaced by "damping" due to reemission of the incoming wave on the rear surface.

Surface waves can be excited not only on density discontinuities within plasmas but also on interfaces within stratified dielectric media, provided that a suitable dielectric profile can be constructed. Specifically, a multilayer structure combining materials having dielectric constants with opposite signs is required. This naturally leads to the choice of a metal as one dielectric for which, in general, $\mathrm{Re}\epsilon \ll -1$. Furthermore, in order to be able to couple the incident electromagnetic wave to the surface modes, a second restrictive condition must be satisfied, namely, that the coating material in contact with the metal have a positive dielectric constant with a magnitude less than unity (to allow the phase velocity of the surface electromagnetic wave to exceed the speed of light). Normal dielectric materials cannot meet this latter criterion, although some special cases can be found, such as quartz in the region of anomalous dispersion around 8 μm and postassium in the uv.[3] The attenuated-total-reflection technique[4] was developed to overcome this limitation. It involves the addition of a prism coupler, thus forming a structure comprising prism, positive dielectric, and metal, where the incoming electromagnetic wave is normally totally internally reflected at the prism-dielectric boundary. The electromagnetic wave then becomes evanescent within the dielectric layer separating the prism and the metal. Since for total reflection to occur one needs $n_p > n_1$ (n_1 and n_p are the refractive indices of the dielectric and the prism, respectively), then the surface waves with phase velocity $c/n_1 > v_f > c/n_p$ can be excited by an electromagnetic wave which is incident upon the prism-dielectric boundary at some angle θ such that $1 > \sin\theta > n_1/n_p$.

In this paper we study surface-wave–induced transparency of a stratified dielectric medium and provide expressions which define the conditions under which total transparency of a normally reflecting metal layer can be observed. On the basis of these calculations, we have constructed a prototype device which demonstrates the phenomenon and compare its performance with computer predictions. We also suggest some practical applications for the phenomenon.

Theory.—The magnetic component $\mathbf{H} = (0,0,H)$ of the electromagnetic wave which has its electric field vector, $\mathbf{E}$, in the plane of incidence (x,y) is a solution to the well-known wave equation:

$$\frac{d}{dx}\left(\frac{1}{\epsilon}\frac{dH}{dx}\right) + \frac{\omega^2}{c^2}\left(1 - \frac{\sin^2\theta}{\epsilon}\right)H = 0, \qquad (1)$$

where ϵ is the dielectric permittivity of the medium (see Fig. 1), ω is the angular frequency of the radia-

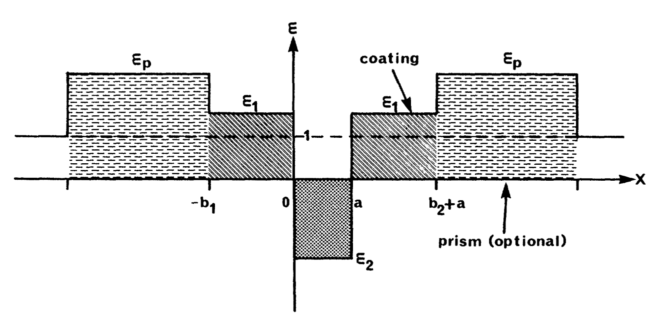

FIG. 1. Schematic showing the spatial distribution of the dielectric permittivity needed to display surface-wave–induced transparency.

tion, c is the speed of light, and θ is the angle of incidence measured relative to the normal to the surface of the layered medium at the interface $x=-b_1$. The solution of Eq. (1), for the case when the spatial distribution of dielectric permittivities is as shown in Fig. 1, leads to the following expressions for the reflectivity, R, and transmission coefficient, T:

$$R=-\frac{\alpha(1-\alpha_0^2)(\beta_1+\beta_2)+[1-\alpha^2\alpha_0^2+(\alpha^2-\alpha_0^2)\beta_1\beta_2+\alpha_0(1-\alpha^2)(\beta_1-\beta_2)]\tanh\kappa_2 a}{\alpha[(1+\alpha_0^2)(\beta_1+\beta_2)-2\alpha_0(1+\beta_1\beta_2)]+[1+\alpha^2\alpha_0^2+(\alpha^2+\alpha_0^2)\beta_1\beta_2-\alpha_0(1+\alpha^2)(\beta_1+\beta_2)]\tanh\kappa_2 a},$$

$$T=\frac{e^{\kappa_1 b_1}}{e^{\kappa_1 b_2}}\,\frac{1+e^{-2\kappa_1 b_1}}{1+e^{-2\kappa_1 b_2}}\,\frac{1+\alpha_0\beta_1+R(1-\alpha_0\beta_1)}{[1-\alpha_0\beta_2+\alpha(\beta_2-\alpha_0)\tanh\kappa_2 a]\cosh\kappa_2 a},$$

where

$$\alpha=\frac{\epsilon_2\kappa_1}{\kappa_2\epsilon_1},\quad \kappa_{1,2}=\frac{\omega}{c}(\epsilon_p\sin^2\theta-\epsilon_{1,2})^{1/2},$$

$$\alpha_0=\frac{i\epsilon_1}{\epsilon_p^{1/2}\kappa_1}\,\frac{\omega}{c}(1-\sin^2\theta)^{1/2},\quad \beta_{1,2}=\frac{1-e^{-2\kappa_1 b_{1,2}}}{1+e^{-2\kappa_1 b_{1,2}}}.$$

The maximum transmission (which is 100% in the case when irreversible dissipation is absent, i.e., when ϵ_1, ϵ_2, and ϵ_p are all real quantities) occurs when $R=0$.[5] This latter condition is equivalent to a dispersion equation for two coupled surface waves propagating along the boundaries $x=0$ and a (see Ref. 1). This dispersion relationship has a solution only if $\alpha<0$, i.e., when the real parts of ϵ_1 and ϵ_2 have opposite signs. Since the wave must be evanescent in the regions $-b_1<x<0$ and $a<x<b_2+a$, then for $\epsilon_p=1$ (i.e., with the prisms absent), the real part of ϵ_1 must be within the interval $0<\mathrm{Re}\epsilon_1<1$.

In practice, to increase the range of coating materials that can be used, the prisms are included and the relation $0<\mathrm{Re}\epsilon_1<1$ is then replaced by the condition $n_p>n_1$, where n_p and n_1 are the refractive indices of the prism and the material on either side of the central layer, respectively. In this case, provided that $1>\sin\theta>n_1/n_p$, the wave is evanescent in the regions $-b_1<x<0$ and $a<x<b_2+a$, even when $\mathrm{Re}\epsilon_1>1$.

For a typical situation where the middle layer (see Fig. 1) is a metal foil for which $|\epsilon_2|>>\epsilon_p>1$, the dispersion relation gives the angular position of the transmission peak as follows:

$$\theta_{\max}=\arcsin\left(\frac{\epsilon_1\epsilon_2(\eta^2\epsilon_2-\epsilon_1)}{\epsilon_p(\eta^2\epsilon_2^2-\epsilon_1^2)}\right)^{1/2},$$

where

$$\eta=\eta_\pm=-(\tanh\xi)^{-1}\pm[(\tanh\xi)^{-2}-1]^{1/2},$$

and

$$\xi=(\omega/c)a|\epsilon_2|^{1/2}.$$

In general, there are two transmission peaks which correspond respectively to the two cases $\eta=\eta_-$ and $\eta=\eta_+$ (see Sarid[6]). Their presence or absence is determined by the obvious extra condition $\theta_{\max}<90°$, which implies that a critical value for η exists, given by

$$\eta_c=\frac{\epsilon_1(1-\epsilon_2/\epsilon_p)^{1/2}}{\epsilon_2(1-\epsilon_1/\epsilon_p)^{1/2}}.$$

The two peaks are then present if the relevant values of η, being either η_- or η_+, are such that $|\eta|>\eta_c$. The η_- peak corresponds to an asymmetric spatial distribution of E_x, while the η_+ peak is associated with a symmetric E_x distribution. Since the symmetric mode carries more of its energy in the dissipative metallic film, it is more heavily damped than the asymmetric mode. While this could be an advantage when high absorption is required, as in the case of experiments demonstrating surface-wave–induced absorption,[2] it is a disadvantage in our case where high transmission is sought, and hence the η_+ peak is observed only when very thin metallic films are used. The characteristic spatial distribution of the modulus of the field, as well as the Poynting vector, corresponding to a pair of coupled surface waves is shown in Fig. 2 for a prism-MgF_2-Ag-MgF_2-prism structure and an optimum angle of incidence. Note that the field actually grows in the MgF_2 layer and reaches a value far in excess of that in vacuum at the boundary with the metal. This simply reflects the fact that the surface wave is localized on that boundary, but also illustrates graphically the way in which the surface wave facilitates the coupling between the incident and transmitted waves.

Experiment.—A prototype surface-wave coupler was constructed by evaporation of MgF_2 ($n=1.38$) and silver films onto the base of a borosilicate-crown-glass isoceles prism ($n=1.515$) with an apex angle of 25°. Silver was chosen as the central layer because it has a small index of refraction ($n\simeq 0.066$) and a relatively large extinction coefficient ($k\simeq 4.0$) in the visible region of the spectrum, which normally results in its having good reflectivity for the incident wave but low dissipation ($nk<1$) for the surface waves. For the longer-wavelength region ($0.5\ \mu\mathrm{m}<\lambda<1.5\ \mu\mathrm{m}$) gold has similar favorable properties, while aluminium would also be useful in the uv and blue spectral regions.

The films were deposited with use of a standard radiant-heater evaporation rig onto the cold substrate with the relative thickness being controlled to about

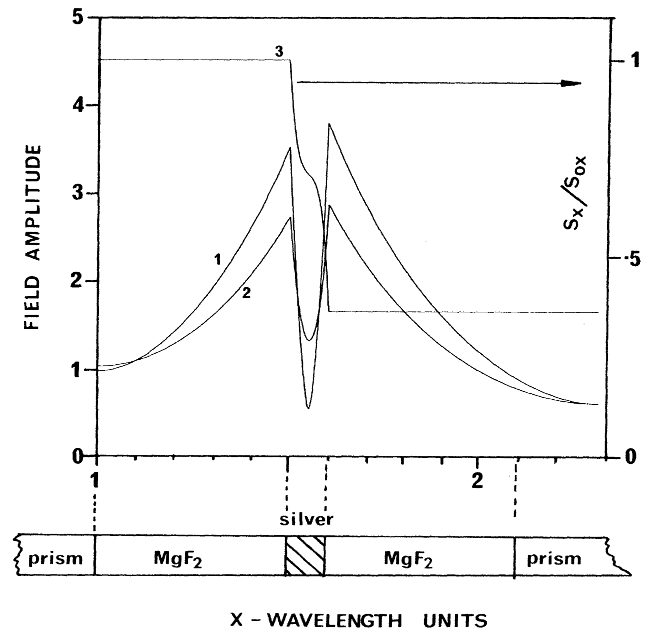

FIG. 2. The spatial distribution of electromagnetic field associated with a pair of coupled surface waves and the corresponding distribution of the Poynting vector S. The curves correspond to a prism-MgF_2-Ag-MgF_2-prism structure with $a=0.1\lambda$, $b_1=b_3=0.5\lambda$, $\epsilon_p=2.295$, $\lambda=6328$ Å, and the optimum angle of incidence, $\theta=\theta_{max}=74.7°$. Curve 1, $|E_y/E_{0y}|$; curve 2, $|H/H_0|$; and curve 3, S_x/S_{0x}. E_{0y}, H_0, and S_0 correspond to the incident wave.

50 Å. A simple device using nominally 3000-Å MgF_2 layers sandwiching a 600-Å Ag layer was constructed. To provide the symmetry required to obtain transmission, an identical glass prism was placed in close contact with the films with use of ethyl salicylate as an index-matching fluid ($n \simeq 1.52$). The complete structure was placed in a rotating mount, and its transmission as a function of angle and polarization for He-Ne laser radiation ($\lambda = 6328$ Å) was determined.

The measured and calculated transmission curves for p-polarized light are shown in Figs. 3 and 4, respectively. Near perfect agreement is obtained if it is assumed that the MgF_2 thickness was 3250 Å rather than 3000 Å as determined by the monitoring system. Such a discrepancy is quite feasible since the quartz-crystal-oscillator film-thickness monitor had to be placed some distance from the substrate in a position where slight under-reading of the actual film thickness would be expected. No transmission ($<0.2\%$) was obtained with use of s-polarized light, in accordance with expectations. The performance of the device was also measured with use of other index-matching liquids. The transmission fell to one-half its maximum value when the refractive-index mismatch was only about 5%.

Both the experimental and computed transmission curves show one major transmission peak corresponding to the solution $\eta=\eta_-$. The other solution, $\eta=\eta_+$, can just be discerned in the form of the transmission plateau at higher angles.

To conclude, it should be noted that the phenomenon described here is purely linear and appears to have a number of practical applications. For example, an interface between two dielectrics at which total internal reflection normally occurs can be made totally transparent by the addition of a metal overcoat and further dielectric layers. Such a situation could be encountered in the use of optical fibers, where by suitably coating the outside of the fiber, it may be possible to couple radiation out through the walls. Further-

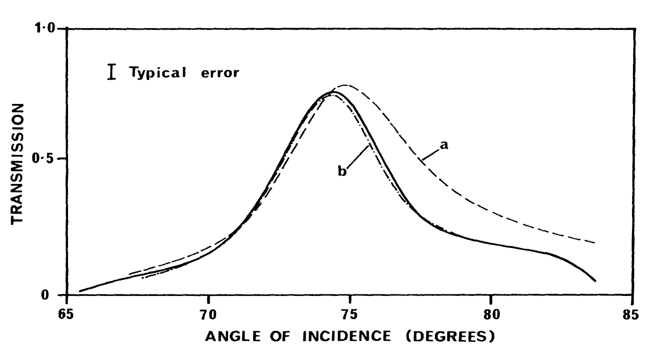

FIG. 3. The measured transmission characteristics of the prototype prism-MgF_2-Ag-MgF_2-prism device for He-Ne laser radiation. The thickness of the Ag and MgF_2 layers was 600 and 3000 Å, respectively. The calculated transmission curves correspond to a thickness of the MgF_2 layer of (a) 3000 Å and (b) 3250 Å.

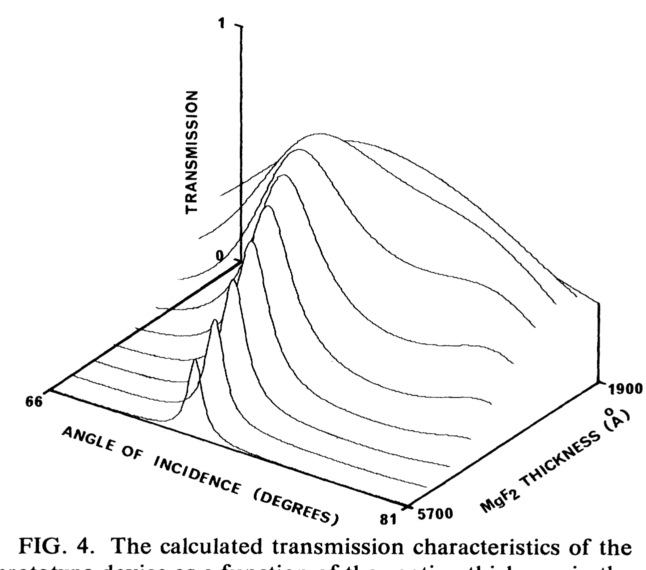

FIG. 4. The calculated transmission characteristics of the prototype device as a function of the coating thickness in the range 1900–5700 Å.

more, the sensitivity of the transmission characteristic to the properties of the incident radiation suggests that the phenomenon may be useful in devices such as polarizers, filters, modulators, and beam splitters.

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[5]Note that R can be identically zero for a symmetric structure ($\beta_1 = \beta_2$) when the numerator of the expression for R is a real quantity. Any asymmetry ($\beta_1 \neq \beta_2$) results in a "leaky" character for the coupled surface waves and, therefore, leads to radiative losses; i.e., R can be $\ll 1$ but not identically zero.

[6]D. Sarid, Phys. Rev. Lett. **47**, 1927 (1981).