BISTABILITY ON A SURFACE IN NONLINEAR DIFFRACTION

V. M. Agranovich, A. I. Voronko, and T. A. Leskova

Institute of Spectroscopy, USSR Academy of Sciences, Troitsk, Moscow r-n, 142092, USSR

ABSTRACT

We discuss the optical phenomena that arise due to the diffraction of a surface polariton (SP) by the impedance step created when a thin film of thickness \( d \) (\( d \ll \lambda \), where \( \lambda \) is the vacuum wavelength of the SP) is applied on a metal surface. The frequency of the excitations in the film is assumed to be in the frequency range of the SP. The theory of SP diffraction by an impedance step has been developed in (1) for the case when the optical nonlinearity of the film may be neglected. On the basis of this linear theory we have succeeded in studying analytically the nonlinear diffraction of SPs by the impedance step produced by applying an optically nonlinear film with a specific form of the nonlinearity on an optically linear substrate (metallic substrate). Namely, in the resonance region \( \omega \approx \omega^0 \), where \( \varepsilon_1(\omega^0) = 0 \), the dielectric constant of the film is assumed to have the form \( \varepsilon_{NL}^0 = a[\omega^0 - \omega(Y)] \), where \( \omega(Y) = \omega^0 - \gamma Y \), \( Y = a\omega^0 N \), \( N \) is the concentration of SPs and \( a \) is the nonlinearity constant, and \( N = U(\omega)/\mu_0 \omega \), where \( U(\omega) \) is the density of the electromagnetic field energy carried by the SP in the film. In the frequency region under discussion \( \omega = \omega^0 \) the existence of surface waves of several kinds is possible, so the expression assumed for \( \varepsilon_{NL}^0 \) corresponds to the disregard of wave interference. To estimate the role of this effect the problem of nonlinear diffraction has been solved numerically for a nonlinearity of the form \( Y = \beta |\mathbf{E}|^2 \), where \( \mathbf{E} \) is the total electric field in the film. The analytical study, as well as the numerical calculations, shows a bistable dependence of the intensity of the transmitted (or diffracted) radiation on the intensity of the incident SP.

1. LINEAR DIFFRACTION OF SURFACE POLARITONS

In the presence of a transition layer or a thin film on a metal surface the spectrum of surface polaritons can change drastically. The effect of a thin film is most prominent when the frequencies of electric-dipole-active excitations in the film fall in the frequency range in which surface polaritons on the metal surface can exist. As was shown
such a resonance leads to the appearance of a gap in the surface polariton spectrum whose width is \( \Delta \sim \sqrt{d/\lambda} \), where \( d \) is the thickness of the film, \( \lambda \) is the vacuum wavelength of the surface polariton, and \( d \ll \lambda \). This splitting was observed in both the infrared region\(^{2} \) and in the spectral region of electronic transitions\(^{3,4} \). Furthermore, additional surface waves appear in the same spectral region\(^{5} \). Their appearance, however, is not connected with the inclusion of spatial dispersion in the substrate or film, but follows from the fact that there are terms in the surface polariton dispersion law that are linear in \( k \). These terms are of the order of \( |k|d \), where \( k \) is the wave vector of the surface polariton. The inclusion of spatial dispersion in the film only increases the number of additional surface waves\(^{6} \).

It is known that in bulk crystal optics with spatial dispersion, the inclusion of additional waves results in appreciable modifications of the Fresnel formulae that determine the amplitudes of the radiation reflected from and transmitted through the crystal boundary. It turns out that analogous effects also occur in the reflection and refraction of surface waves at the boundary between surfaces. However, an important feature of surface polariton refraction is the possibility of the conversion of surface polaritons into bulk radiation, and this makes the mathematical treatment of the problem much more complicated.

A theory of the diffraction of surface polaritons by the impedance step created by applying a thin film on a metal surface was developed\(^{6-9} \). The thin film was assumed to be described by a dielectric constant containing a zero at the frequency \( \omega \). An analytic solution for the diffraction problem was obtained by the Wiener-Hopf technique, and the energy transformation coefficients for surface polaritons impinging on the step either from the region of the clean metal surface or from the region of the metal surface coated with the film were calculated, as well as the energy transformation coefficients for a bulk electromagnetic wave incident onto the step from the vacuum above the surface.

Figure 1 illustrates schematically the process of wave transformation when a surface polariton with a wave vector \( \mathbf{k}(\omega) \) is incident onto the edge of the film from the region of the clean metal surface. The dispersion curve for surface polaritons on the clean metal surface is shown in Fig. 1b, while the dispersion curves for surface polaritons on the metal surface coated with the film in which at the frequency \( \omega \) there is a dipole-active excitation polarized perpendicularly to the plane of the film are shown in Fig. 1c. In this case a gap and an additional surface wave appear in the surface polariton spectrum. Therefore, for frequencies below the gap two transmitted surface waves with wave vectors \( \mathbf{k}_1(\omega) \) and \( \mathbf{k}_2(\omega) \) may propagate in the region \( x > 0 \). When the frequency of the incident surface polariton is far from the resonance frequency most of the incident energy is carried away by the transmitted ordinary surface polariton. As the frequency approaches the gap most of the incident energy is radiated into the vacuum (Fig. 2). For the reverse process, viz. the diffraction of bulk plane waves by the impedance step, the anomaly in the coefficient of specular reflection from the region of the impedance step is of special interest. In Fig. 3 the reflection coefficient is plotted as a function of the frequency for different angles of incidence. It is possible by decreasing the angle of incidence to bring up the dip in the frequency dependence of the reflection coefficient to the natural width which is determined by damping.

We have already pointed out that in the presence of spatial dispersion in the film not two but four surface waves can exist in a certain frequency region (the dispersion curves for surface polaritons