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OPTICAL BISTABILITY WITH SURFACE PLASMONS

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ABSTRACT

We theoretically examine bistable operation in reflection with simultaneous excitation of the surface plasmon mode at the interface with a nonlinear Kerr medium. Bistability may occur for an incident power an order of magnitude below that reported previously for a grazing incidence geometry.

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Optical bistability in reflection is a topic which is of considerable recent interest. The theory of hystersis reflection by the boundary of a nonlinear medium at grazing angle incidence was first calculated by Kaplan[1]. Smith <u>et</u> <u>al</u>.[2] have demonstrated optical bistability in reflection at the boundary between a linear glass medium and CS_2, a nonlinear (Kerr effect) medium. By operating at grazing incidence near the critical angle for total internal reflection, the authors used the intensity dependent index of refraction of the nonlinear medium to change the reflectivity of the system by 20% between the total reflection and transmission modes. In this paper we examine optical bistability in reflection near the angle for surface plasmon excitation.

The surface plasmon mode is an evanescent transverse magnetic (TM) electromagnetic wave which propagates along an interface between a medium with a negative dielectric constant such as a metal and a medium with a positive dielectric constant. The wave vector of the mode, k_p parallel to the interface is given by $k_p = \frac{\omega}{c}\left(\frac{\epsilon_a\epsilon_b}{\epsilon_a+\epsilon_b}\right)^{1/2}$ where ω is the angular frequency and ϵ_a and ϵ_b are the dielectric constants of the two media. Surface plasmon waves may be directly coupled with only evanescent waves from a high index prism at the angle of incidence for surface plasmon excitation, θ_p, such that $k_p = \frac{\omega}{c} n \sin\theta_p$ where n is the index of refraction of the prism. The reflectivity at θ_p is characterized by attenuated total reflection due to resonant absorption by the metal film[3].

Consider an interface between a metal and a Kerr nonlinear medium with a positive intensity dependent index of refraction. The surface plasmon mode is excited in the Kretschmann configuration shown in Fig. 1 with the incident angle, θ_i, greater than θ_p. As the incident power increases [redacted] the effective θ_p approaches θ_i and the evanescent field in the nonlinear medium increases resonantly producing a positive feedback effect which switches the reflectance from total to attenuated reflection. Now as the incident power is decreased a point will be reached at which the field in the nonlinear medium will not be able to maintain the surface plasmon mode and the resulting feedback will switch the reflectance back to the total internal reflection value. Over a limited range of incident power bistable operation is possible since the system has two stable modes, total internal reflection (TIR) and attenutated total reflection (ATR).

We analyze the Kretschmann configuration shown in Fig. 1 where we assume a p-polarized plane wave is incident through the hypotenuse face of a high index prism onto a thin evaporated metal film which is in optical contact with the Kerr nonlinear medium. The dielectric constant of the nonlinear medium ε_t may be written $\varepsilon_t = \varepsilon_t^0 + \alpha|E_t|^2$ where ε_t^0 is the dielectric constant of the nonlinear medium at zero intensity, α is the nonlinear coefficient which is connected to the optical Kerr constant n_2 via the relation $n_2 = \frac{4\pi}{c\,\varepsilon_t^0}\alpha$, and E_t is the amplitude of the transmitted electric field in the nonlinear medium. In order that the solution to the boundary value problem reduce to the standard Fresnel equations, we assume that the wave in the nonlinear medium may be treated as a plane wave. Although Kaplan[1] showed that the wave in the nonlinear medium must be described by hyperbolic functions his solution for the nonlinear reflectance at a single interface is in fact derived from the Fresnel equations which are then approximated for glancing angles of incidence. The validity of the Fresnel equations to calculate the nonlinear reflectance has been independently demonstrated by the present authors.

The ratios, r and t, of the reflected field amplitude E_r and the transmitted field amplitude E_t, respectively, to the incident field amplitude E_i may now be written formally as

$$r \equiv \frac{E_r}{E_i} = \frac{r_{12} + r_{23}\, e^{i2kd}}{1 + r_{12}\, r_{23}\, e^{i2kd}}, \qquad (1)$$

and

$$t \equiv \frac{E_t}{E_i} = \frac{t_{12}\, t_{23}\, e^{i2kd}}{1 + r_{12}\, r_{23}\, e^{i2kd}} . \qquad (2)$$

Here $r_{\ell j}$ and $t_{\ell j}$ are the p-polarized Fresnel reflection and transmission amplitude factors[4] between the ℓ^{th} and j^{th} medium, k is the complex component of the wave vector in the metal film normal to the interface, and d is the thickness of the film. In addition Snell's Law gives $\epsilon_i^{1/2} \sin\theta_i = \epsilon_t^{1/2} \sin\theta_t$. Because ϵ_t is not constant but is a function of $|E_t|^2$, Eqs. (1), (2), and Snell's Law form a set of nonlinear coupled equations that cannot generally be analytically solved. Kaplan's method of solution is valid only near grazing angles of incidence. We note that we can easily obtain equations for E_r and E_i as explicit functions of E_t by writing $E_i = \frac{1}{t} E_t$, and $E_r = \frac{r}{t} E_t$. The motivation for rewriting the above equations is that for a given value of E_t, ϵ_t is determined, from which the Fresnel coefficients r and t may be calculated; thus a unique value of E_i and E_r are determined. It is convenient to introduce the following dimensionless optical intensities:

$$U_i \equiv \frac{\alpha}{\epsilon_t^0} |E_i|^2,$$

$$U_r \equiv \frac{\alpha}{\epsilon_t^0} |E_r|^2, \text{ and}$$

$$U_t \equiv \frac{\alpha}{\epsilon_t^0} |E_t|^2. \qquad (3)$$

Note that U_t may be interpreted as the fractional change in the dielectric constant of the nonlinear medium. When the expressions for the Fresnel coefficients r and t of Eqs. (1) and (2) are substituted into Eq. (3) there results

$$U_i = \frac{1}{4} U_t \left| \sqrt{\frac{\epsilon_i \epsilon_t^0}{\epsilon_m}} \left[\frac{\epsilon_m}{\epsilon_i} \cos(kd) - i \sin(kd) \sec\theta_i \sqrt{\frac{\epsilon_m}{\epsilon_i} - \sin^2\theta_i}\right] \sqrt{1+U_t} \right.$$
$$\left. + \left[\cos(kd) \sec\theta_i - i \frac{\epsilon_m}{\epsilon_i} \sin(kd) \left(\frac{\epsilon_m}{\epsilon_i} - \sin^2\theta_i\right)^{-1/2}\right] \sqrt{1 - \frac{\epsilon_i}{\epsilon_t^0} \left(\frac{\sin^2\theta_i}{1 + U_t}\right)} \right|^2 , \qquad (4)$$

and

$$U_r = \frac{1}{4} U_t \left| \sqrt{\frac{\epsilon_i \epsilon_t^o}{\epsilon_m}} \left[\frac{\epsilon_m}{\epsilon_i} \cos(kd) + i \sin(kd) \sec\theta_i \sqrt{\frac{\epsilon_m}{\epsilon_i} - \sin^2\theta_i}\right] \sqrt{1+U_t} \right.$$

$$\left. - \left[\cos(kd) \sec\theta_i + i \frac{\epsilon_m}{\epsilon_i} \sin(kd) \left(\frac{\epsilon_m}{\epsilon_i} - \sin^2\theta_i\right)^{-1/2}\right] \sqrt{1 - \frac{\epsilon_i}{\epsilon_t^o} \left(\frac{\sin^2\theta_i}{1 + U_t}\right)} \right|^2 . \quad (5)$$

The notation follows that given previously where subscripts i, t, and m refer to quantities defined in the incident prism, the nonlinear dielectric, and the metal film respectively. Unfortunately these expressions are too complicated to permit analytic demonstration of the bistable nature of the solution as can in fact be done for the single boundary nonlinear reflectance problem(5). Finally the reflectance R is determined from $R = \frac{U_r}{U_i}$.

The reflectance is calculated as follows. Values of U_t are assumed for a given incident angle θ_i close to the plasmon angle θ_p. Equations (4) and (5) are used to produce graphs of U_i and U_r versus U_t. If bistability is to occur it is necessary that a given value of U_i correspond to multiple values of U_t; however, each value of U_t produces a unique value of U_r. This procedure may lead to multiple values of the reflectance for a single value of U_i. Two of these values are due to the fact that for a limited range of U_i the boundary can be either in a (TIR) or (ATR) state. The state of the boundary is determined by the previous value of U_i; i.e., the reflectance exhibits hysteresis.

The result of a typical calculation is illustrated in Fig. 2, where we plot reflectance R versus dimensionless incident intensity U_i. The glass prism and positive Kerr medium have linear dielectric constants $\epsilon_i = 3.6$ and $\epsilon_t^o = 2.25$. The silver film thickness is 625 Å and $\epsilon_{Ag} = -57.8 + i0.6$ at 1.06μ where the absorption of the silver is near a minimum[6]. We set the initial angle offset $\theta_i - \theta_p = 0.14°$ so that at zero incident power the system is in the TIR mode. As the input power increases the surface plasmon resonance is approached and the amplitude of the resonant evanescent field in the nonlinear medium increases which causes the operating point on the reflectivity curve to move from TIR below θ_p to ATR slightly above θ_p. The critical dimensionless incident intensity needed to achieve this switching action is designated U_c. Further increases in incident power move the operating point further from θ_p and thus increase the reflectivity. Now, as the input power is decreased θ_p decreases and the operating point moves toward a minimum ATR value. Although the incident power is decreasing the enhancement of the field in the nonlinear medium due to the surface plasmon resonance maintains the operating point on the ATR curve. Finally as the incident intensity is further decreased, the field in the non-linear medium can no longer maintain the surface plasmon and the operating point now switches from the minimum of the ATR curve at the surface plasmon resonance to the TIR off resonance. The arrows on the long dashed lines indicate the direction around the hysteresis loop at the switching points and the short dashed line represents a solution to the nonlinear boundary value problem which is not stable.

The most important experimental quantity is the critical switching intensity, U_c, needed to achieve bistable operation. In Fig. (3) we show U_c as a function of the initial angular offset from the plasmon angle with all other numerical parameters the same as in Fig. (2). The switching intensity increases rapidly with the angular offset since more optical power is required to move the positive intensity dependent θ_p to θ_i. For the case of a negative nonlinear medium the reflectance results are very similar to those shown in Fig. (2), but in this case the initial angular offset is negative as shown in Fig. (3). The switching intensity also increases with absorption in the metal; however, the rate of increase is not very rapid since for a factor of ten increase in $\mathrm{Im}(\epsilon_m)$ U_c changes by less than a factor of two[5]. This result is significant since surface roughness effects can be approximated to lowest order by increasing the bulk absorptive dielectric function[7].