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HAL Id: jpa-00209790
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Submitted on 1 Jan 1984

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Optical bistability from surface plasmon excitation through a nonlinear medium

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(Reçu le 29 juin 1983, révisé le 10 octobre, accepté le 17 novembre 1983)

1. Introduction.

Much interest has been devoted to optical bistability during the last years. As long as integrated optics is not considered, most of the bistable devices consist of a Fabry-Perot resonator containing either a medium exhibiting intrinsic nonlinear properties, or an electro optic material. In the first case, the feedback which is necessary for bistable operation comes from the nonlinear medium itself and the device is known as an intrinsic one [1, 2, 3]. In the second case, it is a hybrid system in which feedback is driven through an electronic loop [4, 5]. The response time for the latter is generally limited by the electronic feedback circuit. For an intrinsic device, the limits come from either the transient associated with the high-Q Fabry-Perot resonator, or the response time of the nonlinear medium. The potentially fastest devices are intrinsic systems, without Fabry-Perot cavity and using a nonlinear medium with a very short time constant. Some experiments were performed in this way, using reflection near critical incidence on a nonlinear interface [5]. Excitation of surface plasmons by attenuated total reflection can also be considered to get optical bistability. This has been theoretically investigated, within a configuration in which plasmons propagate along the interface between a metal and a nonlinear medium [7]. However, an experimental demonstration requires high nonlinearities, and a sharp plasmon resonance. The numerical estimation given in reference 7 concerns a plasmon wave propagating along a silver-CS₂ interface. Such an experimental configuration cannot be used in practice as silver must be protected from the chemical attack of CS₂ by a dielectric coating, which changes the plasmon characteristics and cancels the expected advantage of field enhancement in the nonlinear medium, associated with the surface wave. We demonstrate that the experiment can however be performed with these materials, if CS₂ is considered as the medium through which the incident light propagates. The silver layer can then be protected by a silicon oxide layer [8] without altering the surface plasmon properties, as the wave propagates along the interface between the silver layer and the external linear medium. Optical bistability has been observed in this way [8, 9] using thermally induced nonlinearities in CS₂. We investigate here the properties of the same device using the nonlinearities associated with the optical Kerr effect in order to develop a fast intrinsic bistable optical device.

2. Surface plasmons and optical bistability.

A surface plasmon wave can propagate along the interface between a metal and a dielectric material in a frequency and wave vector range for which no propagation is possible in both media. A classical way to excite such a wave is to use the Kretchmann configuration which is represented in figure 1. A thin metal
film is sandwiched between two dielectric media whose refractive indices are \( n_1 \) and \( n_2 \) respectively. Assuming \( n_2 > n_1 \), when a TM-polarized light beam is incident in the medium 2 with an incidence angle \( \theta \) larger than the critical one, it is totally reflected. The surface plasmon wave can then be excited across the metal layer through the evanescent wave. This method is well known as Attenuated Total Reflection (ATR).

For a given light frequency \( \omega \), the excitation coupling is maximum when the wave vector component parallel to the interface \( k_{\parallel} = \frac{\omega}{c} n_2 \sin \theta \) fulfills the plasmon dispersion relation. This is adjusted by tuning the incidence angle, and a deep reflectivity minimum is observed when the surface plasmon is resonantly excited.

Let us now consider that the material in which the incident beam propagates has nonlinear optical properties, i.e. its refractive index \( n_2 \) is a function of light intensity. Assuming that the medium 2 remains homogeneous, the reflectivity minima are to be observed at different incidence angles \( \theta \) as \( n_2 \) varies. Simultaneously, for a given incidence \( \theta \), the intensity reflection coefficient is a function of the refractive index \( n_2 \). Such curves \( R(n_2) \) are plotted in figure 2 for various values of \( \theta \).

The refractive index \( n_2 \) of a cubic nonlinear material depends on the total electric field in the medium.

Within the ATR configuration, it can be expressed as:

\[
\begin{align*}
    n_2 &= n_2^{(0)} + K |E_i + E_r|^2 \\
    n_2 &= n_2^{(0)} + n_2^{(2)} I_i (1 + R(n_2))
\end{align*}
\]

where \( E_i \) and \( E_r \) are the electric fields of the incident and reflected beams and \( K \) a constant. The superposition of the incident and reflected beams induces interference phenomena and the refractive index in the nonlinear medium should vary periodically along a direction perpendicular to the interface. However, for an incidence angle \( \theta = 45^\circ \) as the beams have a TM polarization, the incident and reflected electric fields are orthogonal and the variations of \( n_2 \) can be written in the following form:

\[
    n_2 = n_2^{(0)} + K|E_i|^2 + |E_r|^2
\]

or

\[
    n_2 = n_2^{(0)} + n_2^{(2)} I_i (1 + R(n_2))
\]

where \( I_i \) is the incident intensity.

Although the resonant excitation is generally obtained for \( \theta > 45^\circ \), this expression of \( n_2 \) can be considered as a good approximation, and used to discuss in a simplified way the bistable operation of the device. This expression leads to:

\[
    R(n_2) = -1 + \frac{n_2 - n_2^{(0)}}{n_2^{(2)} I_i}.
\]

This equation can be solved graphically for any \( \theta \) value (Fig. 3). Within a given intensity range, several solutions exist and this allows bistability characteristics.

Fig. 2. — Calculated reflection coefficient for a silver layer on a \( \text{SiO}_2 \) substrate versus the refractive index \( n_2 \) of the nonlinear medium (CS\(_2\)) for three values of the incidence angle (\( \lambda = 1.06 \mu\)m). (a) \( \theta = 68^\circ 7' 30'' \); (b) \( \theta = 68^\circ 00' \); (c) \( \theta = 67^\circ 52' 30'' \).

Fig. 3. — Graphical determination of bistability for \( \theta = 68^\circ 00' \).
For low incident intensities, there is a single solution (point A). When the intensity increases, the left part of the curve is described (point B) until point C is reached. At this point the solution switches to point D. When the intensity is lowered, it is the right part of the curve which is followed from D to E before coming back to the lower reflectivity level.

The corresponding curve giving $I_r/I_i$ has been calculated versus $I_i$ and is plotted in figure 4b. It shows bistability characteristics.

When the incidence angle is varied, the position of the reflectivity minimum changes with respect to the value $n_2^{(0)}$. The shape of the curve $I_r/I_i$ versus $I_i$ also varies as it is shown in figure 4. Bistability is not always observed but S-shaped characteristics can be obtained. The incidence angle is the equivalent of a polarization point from an electronic point of view.

This demonstrates the feasibility of bistable operation by tuning a plasmon resonance when the non-linear refractive index variations are induced by the excitation light beam in an ATR configuration.

3. Discussion.

The above considerations were developed within the assumption of plane waves, the refractive index variations being uniform in the whole nonlinear material. A real experiment will set Gaussian beams into action, and the light intensity distribution will be non uniform. The refractive index variation is then more important in the vicinity of the beam axis, and near the interface with the metal layer, where the incident and reflected waves are superposed, i.e. in the space region of interest. Furthermore, the superposition of the two light beams may induce interference phenomena. From numerical simulations, in which Gaussian beams are considered, it can be shown that the total intensity results from a spatial mean value, which is equal to the sum of the incident and reflected intensities on which oscillations along a direction perpendicular to the layer plane are superimposed.

Although the refractive index variations are stratified according to such interference effects, this does not influence the plasmon resonance tuning as the longitudinal wave vector component is conserved. The index variations can then be described by the expression (1).

The plane wave derivation is a good approximation even if the beams are Gaussian, as long as their convergence is small i.e. if the beam angular aperture is small with respect to the plasmon angular linewidth.

The light intensity required to perform such an experiment depends on the nonlinear coefficient which characterizes the refractive index variations, and on the plasmon linewidth. The latter is a function of the metal which is used and becomes narrower as the light wavelength increases. Assuming that a plasmon is excited along a silver layer interface, at a wavelength of 1.06 μm, and that the nonlinear medium is carbon disulfide, a refractive index variation $\Delta n = 10^{-3}$ is necessary to obtain a reflectivity curve shift approximately equal to its linewidth. Under these conditions the incident power is estimated to 35 GW/cm² according to $n_{2}^{(0)} = 2.8 \times 10^{-8}$ (MW/cm²)⁻¹. This value is higher than that given in [7] because, as it was pointed out in the introduction, the field enhancement in the vicinity of the interface cannot be used in practice. However it can be consistent with the output of a pulsed Nd YAG laser.

Acknowledgments.

We gratefully acknowledge D. Riviere who lent us an efficient program for plasmon curve calculation, and W. Carvalho for long and interesting discussions. (Both are with the Institut d'Optique, Université Paris-Sud, Orsay.)
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