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Switching of reflection of light at nonlinear interfaces

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Abstract

The reflection of light at the interface between linear and nonlinear media can provide fundamentally novel nonlinear effects such as nonlinear switching from total internal reflection to partial transmission, bleaching of the interface, and bistability. The nonlinear interface is the simplest switching and bistable optical device. Unlike bistable Fabry-Perot resonators, it allows one to use broadband sources of light and remove resonant restrictions on frequency tuning, and offers potentials to attain high operating speed. Experimental demonstration of those effects shows good agreement with some of the predictions of plane-wave theory. Some of the experimental results as well as computer simulation, however, show a new feature of the phenomenon which requires further exploration.

Introduction

In the past 13 years an optical bistability (OB) arose as a very promising field in nonlinear optics.[1] Elements based on OB can be utilized to perform optically controlled memory and logic operations in high-speed optical processing systems. At the present time the known OB devices are comprised of a Fabry-Perot resonator filled with a nonlinear material which was first proposed in Ref. 2 and first observed in Ref. 3. Use of the Fabry-Perot resonator causes these devices to be strongly selective to the frequency of an incident radiation.

Over the past few years a novel nonlinear optic phenomenon was theoretically proposed[4,5] and experimentally observed[6,7] which can provide fast switching and optical bistability, and which does not have any resonators or cavities, i.e., it is free from restrictions imposed by the use of nonlinear Fabry-Perot resonators. This phenomenon consists in self-action of light at the nonlinear interface (i.e., interface between linear and nonlinear media). In the most studied configuration, light is incident from the linear medium (with susceptibility ε_o) onto the plane surface of the nonlinear medium (Fig. 1) whose susceptibility ε_{NL}

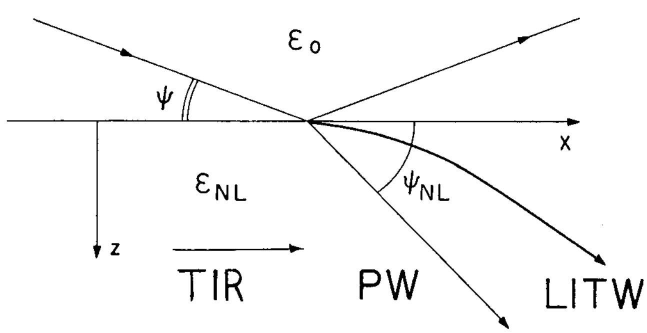

Figure 1. Wave diagram of the nonlinear interface. Ray traces in nonlinear media: 1) travelling plane wave (PW), 2) longitudinally inhomogeneous travelling wave (LITW), 3) total internal reflection (TIR).

depends on the intensity of light. In the case of Kerr-nonlinearity, this dependence is as

$$\varepsilon_{NL} = \varepsilon_o + \Delta\varepsilon_L + \varepsilon_2 |E|^2 \quad (\Delta\varepsilon_L = \text{const}, \ \varepsilon_2 = \text{const}) \tag{1}$$

The competition between the difference of linear susceptibilities $\Delta\varepsilon_L$, forming the interface, and the nonlinear component $\varepsilon_2|E|^2$ can cause a variety of effects. Even if the nonlinear component is small (as is usual for optical nonlinearities), this competition can result in a strong change of reflectivity of the interface during action of the laser pulse, provided that the grazing angle of incidence ψ (see Fig. 1) is sufficiently small. The theory[4] predicted that for plane-wave incidence, reflectivity of the interface should be strongly dependent on the intensity of the incident light; under some conditions it should even become bistable (i.e., demonstrate hysteretic behavior). As intensity of the incident field is increased, the penetrated (or evanescent) field in the nonlinear medium will change the total index difference at the interface, such that, at some critical intensity, an abrupt switching from total internal reflection (TIR) to partial transmission can occur in the case in which $\varepsilon_2 > 0$.

The first experimental observation of the new phenomenon was made in Ref. 6,7, which demonstrated hysteretic behavior of reflection by $CS_2 (\varepsilon_2 > 0)$. This experiment confirmed the theoretical prediction[4] of an absolute threshold for the onset of nonlinear switching from TIR into the transmission regime. Under some conditions, good agreement with plane-wave theory was also observed during the entire cycle of switching. However, some of the experimental results show some discrepancy with plane-wave theory. Computer simulations with Gaussian beam incidence demonstrated contradictory results. Some of them[8] endorse the existence of bistability for the Gaussian beam, while others[9] dispute it. Some results suggest excitation of the nonlinear surface wave.[10,11,6] However, the most recent computer simulation,[12] which was stimulated by some general consideration[13] based on the theory of solitons, shows that the surface wave does not exist under conditions considered in Ref. 6, 10,11, and only an abrupt switch from TIR to partial transmission should occur with nonlinear channels formed by penetrating radiation.

To avoid the problem related to the limited size of the laser beam, some practical hybrid bistable devices were proposed[14] which are electro-optical analogs of the nonlinear interface. In such a device, the electro-optical crystal forming one medium at the interface is electronically driven by a signal from the detector, which receives the light reflected from the interface. Bistable operation of this device has recently been demonstrated in an experiment[15] in the cw regime.

Wave equations and boundary conditions

Let a plane wave with amplitude E_{in} be incident from a linear medium with susceptibility ε_o at the glancing angle ψ (Fig. 1) onto the boundary of a nonlinear medium with susceptibility ε_{NL}, Eq. (1). For the reasons described in the Introduction, the most dramatic nonlinear effects at the interface can be observed only under conditions:[4]

$$1 \gg |\Delta\varepsilon_L| \sim |\Delta\varepsilon_{NL}|; \qquad 1 \gg \psi \sim \left(\frac{\Delta\varepsilon}{\varepsilon_o}\right)^{1/2} \tag{2}$$

which amount to $\psi \sim 1°$ at $|\Delta\varepsilon_{NL}| \sim 10^{-4}$. The wave equation for the complex amplitude of field E in a nonlinear medium in the one-dimensional case can be written as

$$\frac{d^2E}{dz^2} + k_o^2 E\left[\frac{\varepsilon_{NL}(|E|^2)}{\varepsilon_o} - \cos^2\psi\right] = 0; \quad k_o = \frac{\omega\sqrt{\varepsilon_o}}{c} \tag{3}$$

where the z axis is perpendicular to the boundary. Solution of this equation is to obey generalized boundary conditions:[4,5]

$$i\,\frac{d\,E(0)}{dz} + k_o \sin\psi \left[2E_{in} - E(0)\right] = 0 \tag{4}$$

and reflection coefficient r can be obtained as $r = \frac{E(0)}{E_{in}} - 1$. (Inadequate definition[16] of the boundary conditions could result in missing some substantial feature of the phenomenon.) Field E in a nonlinear medium can be represented in the form:

$$E = u(z)\exp\left[ik_o\int_0^z \xi(z)dz + i\phi + ik_o x\cos\psi\right]; \quad (\phi = \text{const}) \tag{5}$$

where u(z) and $\xi(z)$ are real; ξ is the angle formed by the rays and the x axis at a given point z. For plane waves (PW) u and ξ are constant, and for evanescent waves, when TIR occurs, $\xi = 0$. In general, u and ξ are not constant. In the semi-infinite nonlinear medium, the solution (5) of Eq. (3) is to obey radiation conditions in infinity ($z \to \infty$):

$$u \to \text{const} \equiv u_\infty \gtrless 0, \quad \xi \to \text{const} \equiv \xi_\infty \gtrless 0, \tag{6}$$

in essence, the Sommerfeld radiation condition (the absence of the backward traveling wave).

Plane-wave theory in the case of "positive" nonlinearity[4]

One can show that in the case of Kerr-nonlinearity with $\varepsilon_2 > 0$, only two kinds of one-dimensional wave regimes can exist:

1) homogeneous plane wave (PW), $u(z)$ = const, which corresponds to the transmission regime ($|r|<1$) and
2) evanescent wave (EW), $\xi = 0$, which corresponds to TIR ($|r| = 1$).

Both of them are nonlinear analogs of corresponding linear waves, but differ now from those by dependence on the incident light intensity. Using Eq. (3)-(5) with u and ξ constant for the transition regime under conditions (2), it is easy to obtain "Snell's nonlinear formula" for transmission angle ξ, or "Fresnel's nonlinear formula" for the reflection coefficient r, (see Fig. 2)

$$4r\psi^2 + \frac{\Delta\varepsilon_L}{\varepsilon_o}(1+r)^2 + \frac{\varepsilon_2}{\varepsilon_o}|E_{in}^2|(1+r)^4 = 0, \tag{7}$$

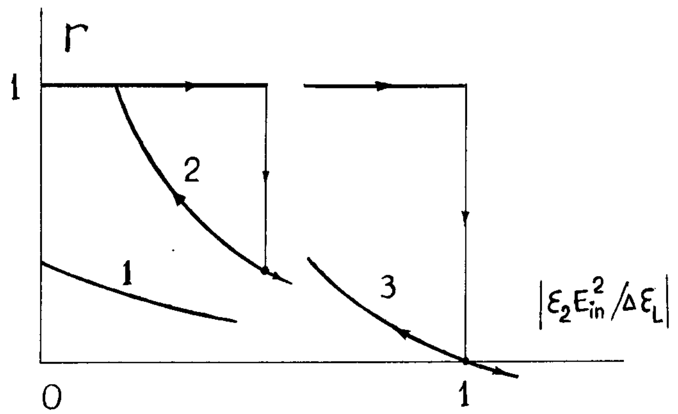

Figure 2. Reflectivity r vs. incident intensity of light $|E_{in}|^2$ at various angles ψ in the case of $\Delta\varepsilon_L < 0$ and $\varepsilon_2 > 0$. Curves: 1) $\psi > \psi_{cr}$; 2) $1 > \psi/\psi_{cr} > 2^{-1/2}$ (hysteresis); 3) $\psi = {}_{cr}\cdot 2^{-3/2}$ (nonlinear bleaching).

If linear mismatch is negative ($\Delta\varepsilon_L < 0$) and $\psi < \psi_{cr}$, where $\psi_{cr} = (|\Delta\varepsilon_L|/\varepsilon_o)^{\frac{1}{2}}$ is the critical angle of linear TIR, then nonlinear TIR can be excited. The profile of wave intensity now is not exponential; integration of Eq. (3) for $\varepsilon_2 > 0$ yields that evanescent field has "self-channel" amplitude shape well known in the soliton theory of two-dimensional self-focusing:

$$u = \left(\frac{2\varepsilon o}{\varepsilon_2}\right)^{\frac{1}{2}} \frac{\gamma}{\cosh(k_o\gamma z + c)}; \quad \gamma = \left(\psi_{cr}^2 - \psi^2\right)^{\frac{1}{2}} \tag{8}$$

where c is determined from boundary conditions (4) and can have from one to four values (for different ψ and E_{in}) that provide multistability and the feasibility of hysteretic jumps (see Fig. 2). The threshold incident intensity $|E_1|^2$ at which a switching from non-linear TIR into partial transmission occurs, is given by

$$\left|\frac{\varepsilon_2 E_1^2}{\Delta\varepsilon_L}\right| = \begin{cases} \frac{1}{2}\left[1-\left(\psi/\psi_{cr}\right)^2\right]; & 2^{-\frac{1}{2}} \lessdot \psi/\psi_{cr} < 1 \\ \frac{1}{8}\left(\psi_{cr}/\psi\right)^2; & \psi < \psi_{cr}\cdot 2^{-\frac{1}{2}} \end{cases} \tag{9}$$

Thus, if starting from TIR at the low incident intensity and gradually increasing the intensity, the interface is switched from TIR into partial transmission. In the reverse process, when the incident intensity is decreased, switching from transmission to TIR occurs at smaller intensity $|E_2|^2$:

$$\left|\frac{\varepsilon_2 E_2^2}{\Delta\varepsilon_L}\right| = \frac{1}{4}\left[1-\left(\psi/\psi_{cr}\right)^2\right] < \left|\frac{\varepsilon_2 E_1^2}{\Delta\varepsilon_L}\right| \tag{10}$$

One interesting feature of nonlinear reflection is nonlinear bleaching of the interface. It is seen from Eq. (7) that at some incident intensity $|E_{b\ell}^2| = -\Delta\varepsilon_L/\varepsilon_2$ there is no reflection at all ($r = 0$) for any glancing angle ψ. This phenomenon is not the nonlinear analog of the Brewster bleaching (since it does not depend on either the angle or polarization of incident light), but is just due to the fact that the field equalizes the susceptibilities of the two media and makes the boundary completely transparent. In this case, the jump from total reflection to the total transmission takes place at $\psi = \psi_{cr}/2\sqrt{2}$ (see curve 3 in Fig.2). For CS_2, where $n_2 \sim 10^{-11}$ cgs esu, we have $E_{b\ell} \sim 1.8 \times 10^6$ v/cm at $\Delta\varepsilon_L \sim 10^3$, in which case $\psi \simeq 0.54°$.

Experiment at nonlinear interface[6,7]

The first experiments[6,7] were aimed at observing hysteretic switching of reflection at the nonlinear interface, predicted by the theory.[4] In this experiment, the CS_2 was employed as a nonlinear medium with "positive" nonlinearity ($\varepsilon_2 > 0$), and the glass was used as a linear medium. The temperature regulation of the cell served to arrange a fine control of the difference $\Delta\varepsilon_L$ between both susceptibilities required by relationship (2).

Experiments were performed with the apparatus shown in Fig. 3. The input pulse was generated by a mode-locked traveling-wave ruby laser. Internal Fabry-Perot mode selection was employed so that the laser output consisted of a train of ≈ 1-ns pulses. The absence of internal structure in these pulses was verified with a streak camera. A single pulse was selected from this train and directed onto the setup shown in Fig. 3.

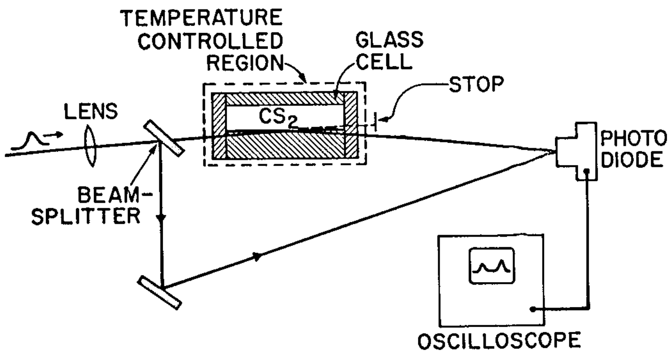

Figure 3. Experimental setup.

A portion of the beam was sampled and directed with an optical delay of ≈6 ns onto a fast photodiode. The remainder of the beam was focused into the glass cell containing CS_2. The glass was chosen to have an index of refraction close to that of CS_2 at room temperature. The entire cell was placed in a temperature-controlled holder and the temperature was adjusted so that for the 694.3 nm wavelength of the ruby laser, the index difference $\Delta \simeq 10^{-3}$. This corresponds to $\psi_{cr} \simeq 2.0°$ in the glass cell.

The reflected beam was monitored by the same photodiode used to monitor the incident pulse, and the diode output was displayed on a fast oscilloscope. The detector-oscilloscope combination had a measured response time of 320 ps.

Figure 4a shows the measured incident and reflected pulse shapes for an incident intensity slightly above the threshold for hysteresis. The dashed curve is from the incoherent plane-wave calculations, based on Eq. (7), and was fitted to the data by adjusting the ratio of the peak intensity I to the threshold intensity $I_1 = |E_1{}^2|$, which corresponds to switching from TIR into partial transmission. One can see that experimental and calculated curves fit well. The fit becomes disturbed as the peak input intensity is increased; however, plane-wave theory still predicts accurately the threshold intensity $I_1 = |E_1{}^2|$. It is known that $n_2 = 3 \times 10^{-8}$ $(MW/cm^2)^{-1}$ for CS_2, the theoretical value of $I_1 = 8.1 \times 10^9$ W/cm^2 was computed based on Eq. (9). The experimentally measured value was $I_1 = 7.5 \times 10^9$ W/cm^2, in very good agreement with the theoretical value. Another important fact is that the reverse switch from transmission into TIR always occurs at the "reverse threshold" input intensity $I_2 = |E_2{}^2|$ less than the threshold intensity I_1 at the onset of nonlinear behavior, i.e., $I_2 < I_1$ for all experimental situations. That confirms the fact of hysteretic behavior of the system. In Fig. 4b the same experimental data are shown as in Fig. 4a, but replotted in the form of reflectivity versus input intensity. This form emphasizes the optical hysteresis observed. Moreover, one can see that $I_2 \approx \frac{1}{2} I_1$, which also confirms the prediction of plane-wave theory [see Eq. (9) as compared with Eq. (10)]. Finally, the measured values of threshold intensity I_1, as a function of angle of incidence, ψ, are shown in Fig. 5. We see that the results are again in good agreement with the predictions of plane-wave theory, Eq. (9).

Some of the experimental results show substantial disagreement with plane-wave calculations. For instance, for sufficiently large peak input intensities, the measured reflected

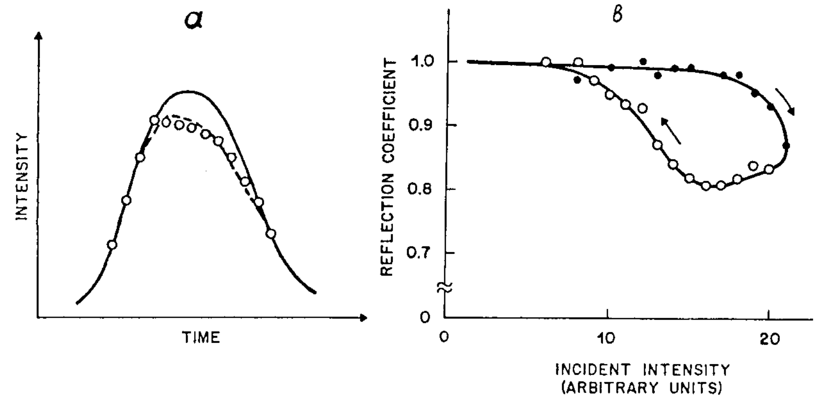

Figure 4. Experimental measurements of incident and reflected pulse shapes for $\psi/\psi_c = 0.707$. (a) The solid curve is the incident pulse, and the dots are the experimental measurements of the reflected pulse. The dashed line is the reflected pulse calculated from an incoherent plane-wave analysis for $I/I_1 = 1.125$ (see text). (b) The experimental data in (a) plotted in a way that demonstrates the optical hysteresis observed.

pulse shapes deviate significantly from those obtained from calculations. It deserves further experimental and theoretical studies, because the nonlinear interfaces are, in some way, the ultimate cavityless nonlinear switching systems.

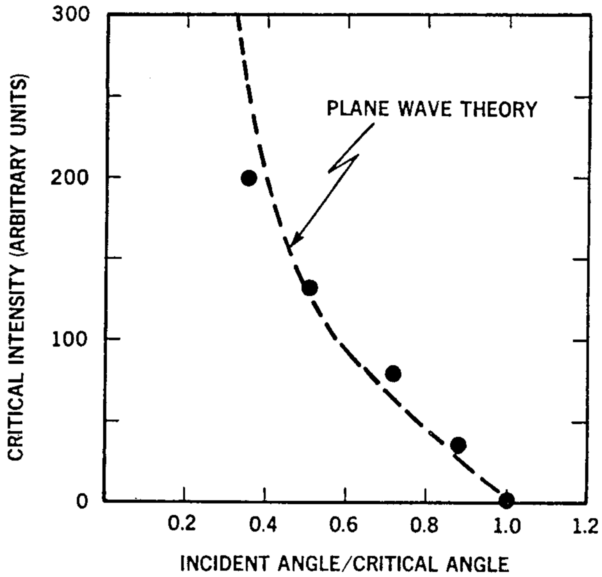

Figure 5. Experimentally measured critical intensity, I, as a function of ψ/ψ_c. The dashed curve shows the critical intensity predicted by plane-wave theory.

"Negative" nonlinearity and longitudinally inhomogeneous traveling waves (LITW)[5]

In a number of materials, nonlinearity can be "negative" [i.e., $\varepsilon_2 < 0$ in Eq. (1)], e.g. in semiconductor InSb.[17] The main peculiarity of this case is the feasibility of excitation of a novel kind of waves: longitudinally inhomogeneous traveling waves (LITW).[5] Being inhomogeneous and non-planar near the interface, such a wave reduces to plane wave sufficiently far from the interface. Excitation of LITW results in novel effects. One of the most interesting of them is self-parallax,[5] i.e., displacement of the refracted rays along the interface. This effect is not the nonlinear analog of the well known Goos-Hänchen displacement of bounded beams under TIR, because in contract to G.-H., self-parallax is valid for unbounded waves, and for the transmission regime, rather than for TIR. It corresponds to the initial "sticking" of the rays (Fig. 1, curve 2). The amplitude profile of LITW u(z) and the ray trace x(z) are given by the formulas

$$u^2 = 2\,\frac{|\varepsilon_2|}{\varepsilon_o}\left[\frac{Q}{3} + \frac{1}{(k_o z + c)^2}\right]; \quad x = z(3/Q)^{\frac{1}{2}} + \ell(1 + z_\ell/z)^{-1}; \; \left(Q \equiv \frac{\Delta\varepsilon_L}{\varepsilon_o} + \sin^2\psi\right), \qquad (11)$$

where c, ℓ, and z_ℓ are constants determined by boundary conditions (4); ℓ is the parallax for $z \to \infty$ and z_ℓ is the characteristic depth for half of the parallax. It was shown in Ref. 5 that under typical conditions the parallax could be very large ($\ell \sim 1$ cm) and arise at a very small depth ($z_\ell \sim 10^{-3}$ cm).

Conclusions

In this paper we have outlined the current state of experimental and theoretical progress towards the understanding of nonlinear interfaces. Many important questions remain to be investigated. Under what conditions does one expect to observe optical bistability? What are the limits on response time imposed by the transient field redistribution in the region of the interface? Much additional theoretical and experimental work will be necessary to fully answer these questions.

We can, however, make some general statements. Nonlinear interface devices may prove to be highly useful and versatile optical signal processing elements. Although the details remain to be studied, we can see in a general way that if the response time of the nonlinearity is sufficiently rapid, field redistribution effects will take place in a time less than the transit time through the device. For waveguide devides proposed in Ref. 7 and based on nonlinear interface effects, the transit time can be $<10^{-13}$ seconds. Nonlinear materials exist with extremely fast intrinsic response times. Recent measurements indicate that the polydiacetylene P.T.S. (which has a response time estimated to be 10^{-14} seconds) has a nonresonant nonlinear coefficient of 150 times that of CS_2. Thus, the potential exists for extremely fast and relatively sensitive nonlinear interface optical signal processing elements.

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