Optical bistability and hysteresis with a photorefractive self-pumped phase conjugate mirror

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Bistability and hysteresis have been observed in a photorefractive passive phase conjugate mirror. A threshold basis for the effect is presented and the results of an experimental demonstration of the device are given.

The large effective optical nonlinearities available in photorefractive crystals such as barium titanate, strontium barium niobate, and lithium niobate make them very convenient vehicles for demonstrating novel nonlinear application. The last few years have seen many new devices including ring resonators[1] and passive phase conjugate mirrors.[1-5] In this letter, we report the observation of bistability in a device using a photorefractive phase conjugate mirror, a result with potential impact on the fields of optical memory, switching devices, and pattern recognition.

At the heart of the device [Fig. 1(a)] is a semilinear passive phase conjugate mirror[6] (PPCM) which comprises an appropriately oriented single domain crystal of barium titanate and an auxiliary curved mirror M_2. Beam A_4 from an argon ion laser at 514.5 nm passes through the crystal and induces photorefractive index gratings which support oscillation beams A_1 and A_2 between the crystal mirror M_2. These oscillation beams pump the crystal as a phase conjugate mirror for the input beam A_4. While much of beam A_4 is diffracted into the oscillation beams, some is transmitted through the crystal to mirror M_1 which reflects it back to the crystal where it interferes with the operation of the PPCM by partially erasing the gratings. As the reflectivity of mirror M_1 is varied by means of a variable beam splitter (VBS) the reflectivity of the PPCM also varies. Our observation of bistability rests on the relationship of the reflectivity of M_1 to the phase conjugate reflectivity.

The quarter-wave plate shown in the figure, while not essential to the operation of the device, was used to ensure that the light fed back to the crystal from M_1 could not take advantage of the large electro-optic coefficient r_{42} to write its own gratings; it was to be merely an erase beam. In the absence of the quarter-wave plate mirror M_1 was tilted slightly so that the erase beam would not be mixed with the phase conjugate reflection at detector D_1. With the quarter-wave plate in place a polarizer P_2 was used to prevent such mixing. The bistable behavior can be explained as follows.

The plane wave theory of the semilinear PPCM involves a coupling constant γ, characteristic of the electro-optic and charge transport properties of the crystal.[5] The phase conjugate reflectivity is given by

$$R = \left(\frac{M_2^{1/2} \pm [a^2(1+M_2) - 1]^{1/2}}{M_2 + 2 \mp M_2^{1/2}[a^2(1+M_2) - 1]^{1/2}} \right)^2, \tag{1}$$

where a is related to the coupling constant γ by

$$\tanh(-\gamma l a/2) = a \tag{2}$$

and M_2 is the reflectivity of the PPCM's external cavity mirror M_2.

The threshold coupling strength above which it is possible for the semilinear PPCM to operate is given by[5]

$$(\gamma l)_t = (1+M_2)^{1/2} \ln\left(\frac{(1+M_2)^{1/2} - 1}{(1+M_2)^{1/2} + 1} \right), \tag{3}$$

where l is the interaction length in the crystal.

The fanning effect, interpreted as two beam coupling amplification of scattered light, may also be described in terms of this coupling constant and the fraction s of the incident intensity $I_{\rm in}$ scattered by the crystal into the fanning direction. If s is assumed small, then the intensity I_f of light leaving the crystal as amplified scattering may be expressed as

$$I_f = I_{\rm in}/(1 + e^{\gamma l}/s). \tag{4}$$

In reality, the fanning light is generated in a wide solid angle. Since the coupling constant γ depends on the direction of the

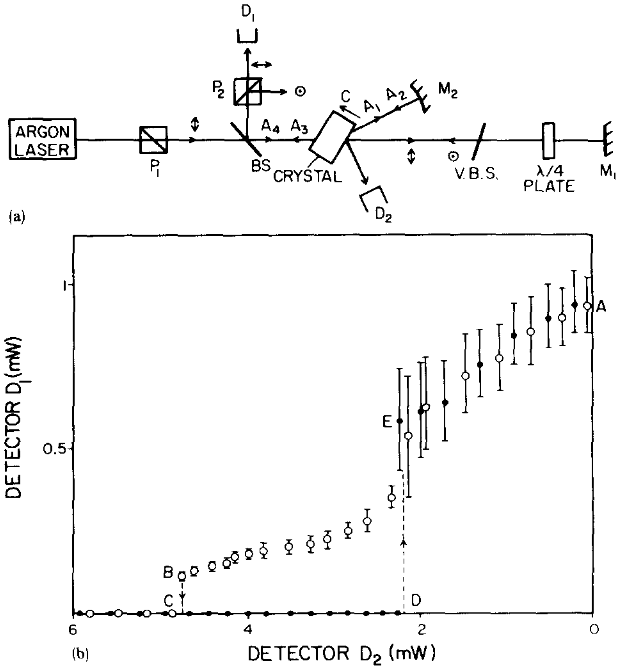

FIG. 1. (a) Experimental arrangement of the optical bistable device. The laser used in all the experiments is an argon ion laser operating at 488-nm wavelength and 2.3-mm beam diameter. The incident laser beam power on the crystal is 340 mW. The crystal is a single domain $BaTiO_3$ crystal with dimension 5×5×4 mm and the c axis is parallel to the 5-mm surface. M_2 is the curved mirror with radius of curvature 5 cm. BS is a beam splitter. P_1 and P_2 are polarizing beam splitters. VBS is the variable beam splitter. M_1 is a mirror. A Pockels cell was used as a quarter-wave plate. (b) Experimental data of phase conjugate output against the transmitted erase beam power. ○ and ● are the points taken when the erase beam is increasing and decreasing, respectively.

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wave vector of the grating it describes, the above description of fanning in terms of a single value of the coupling constant is necessarily approximate.

The oscillation beams A_1 and A_2 are generally confined to a smaller solid angle so that the description of the semilinear mirror in terms of a single coupling constant is more accurate, though still approximate. Also these models assume that the beam intensities are uniform across their phase fronts where in reality the beams are at least approximately Gaussian. These approximations notwithstanding, we can still proceed to qualitative understanding of the operation of the device.

An experimental curve is shown in Fig. 1(b), which was taken by continuously changing the reflectivity of the VBS. At point A the intensity of the erase beam is zero, and we have pure semilinear mirror operation. As the attenuation of the VBS is decreased the intensity I_e of the erase beam rises. This beam does not contribute to the writing of any significant gratings, since it is of ordinary polarization: its effect is to saturate the coupling constant

$$\gamma l = \frac{(\gamma l)_0}{1 + I_e/I_0}, \qquad (5)$$

where I_0 is the total intensity of the beams A_1, A_2, A_3, and A_4 participating in four-wave mixing in the PPCM. As I_e rises the phase conjugate reflectivity drops. When the point B is reached, the coupling strength is driven below threshold, the PPCM stops working and the reflectivity falls to zero at point C. The light in the crystal-M_2 cavity is now just due to fanning, not oscillation. Mirror M_2 reflects this light back to the crystal where it contributes to the saturation of the coupling constant:

$$\gamma l = \frac{(\gamma l)_0}{1 + (I_e + I_f)/I_0}, \qquad (6)$$

where I_0 is now the total intensity of the beams which participate in the fanning.

Now as the intensity of the erase beam is decreased, the fanning light continues to depress the coupling constant and oscillation does not again reappear until the point D when the coupling constant again reaches threshold and jumps with the collapse of the fanning into oscillation to a value well above threshold, corresponding to reflectivity at point E.

On the basis of this explanation it might be expected that with the transitions between fanning and PPCM operation, the erase intensity I_e should also change discontinuously. That such a jump in I_e is not observed experimentally is somewhat surprising, and is the subject of current investigations.

In the experiment, a temporal oscillation of the phase conjugate output with period 8.0 ± 0.5 s was also observed. The period of oscillation was inversely proportional to the input laser power and independent of the feedback erase beam power. After careful observation, we concluded that the mode pattern inside the crystal-curved mirror cavity was changing periodically. This mode hopping effect causes the phase grating inside the crystal to change and consequently the phase conjugate output oscillates.[7]

This device has two distinctive features. (1) Since beams A_1 and A_2, A_3 and A_4 are phase conjugate pairs, any optical aberration along these optical paths can be easily corrected. (2) The "ON" and "OFF" states can be controlled by any incoherent light or even with light of different wavelength as long as it can erase the grating inside the crystal.

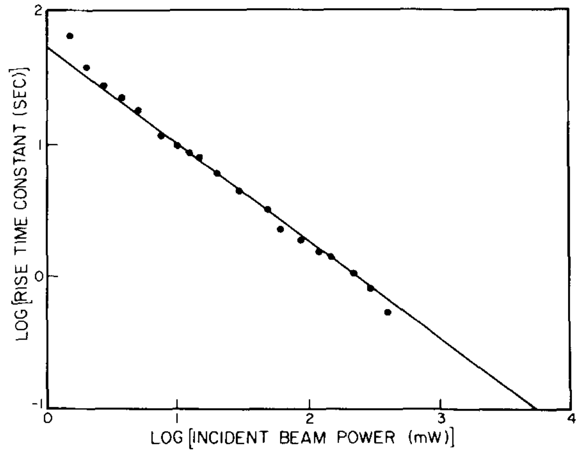

FIG. 2. Experimental plot of rise time constant for oscillation in the device of Fig. 1(a) against the incident beam power in the absence of an erase beam. The slope of the best fit straight line is 0.74. The crystal used in the experiment is a $BaTiO_3$ crystal.

Figure 2 shows a plot of the measured rise time t_r of the phase conjugate output as a function of input beam power with no erase beam. The rise time is here defined as the time required for the phase conjugate output to reach 90% of steady state. Except at very high or very low beam power, the data may be described moderately well with a straight line which corresponds to the relationship $t_r I_0^{0.74} =$ constant. Figure 3 illustrates the measured erase time constant t_e against the erase beam power for various input beam powers I_0. The erase time is defined as the time taken for the phase

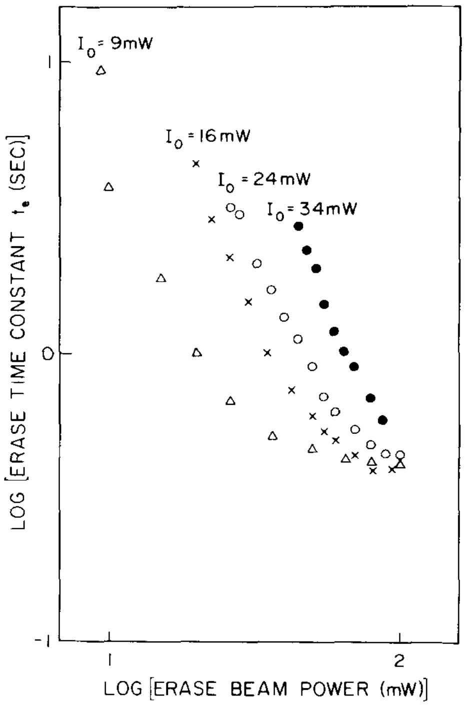

FIG. 3. Experimental plot of the erase time constant against the erase beam power for several incident beam powers.

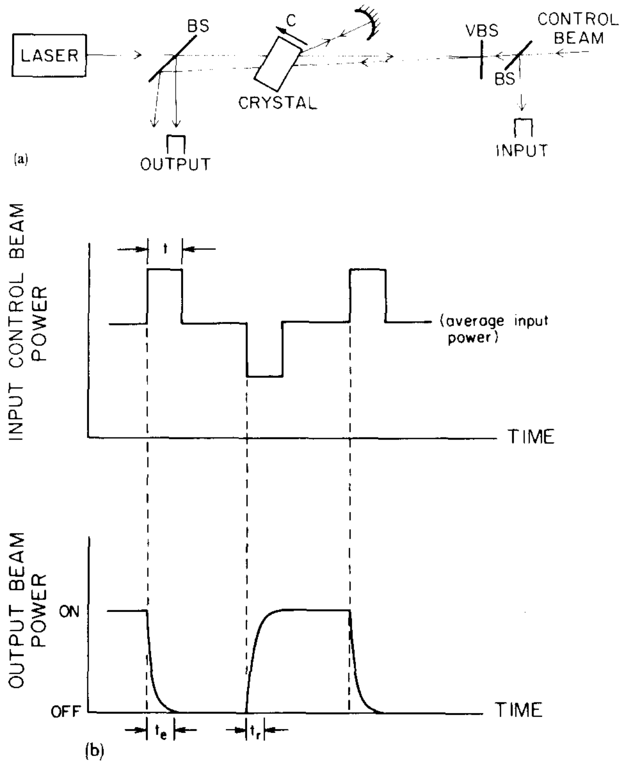

FIG. 4. (a) Proposed experimental arrangement to switch the bistable device in Fig. 1(a). (b) Input/output relationship of the device, where t, t_e, and t_r are the switching pulse width, the erase and the rise time constants of the device, respectively.

conjugate output to reach 10% of its initial value. The curves indicate the time constant is longer for larger I_0 with the same erase beam power. The erase time constant seems to be bounded by a certain low limit even at very high erase beam power, which may be due to a carrier saturation effect in the photorefractive crystal.

Figure 4 illustrates a proposed switching scheme. By adjusting the VBS and the average input power of the control beam to the point where the device will be operated at the hysteresis region of Fig. 1(b). Then the input and output are related in Fig. 4(b).

The bistable behavior reported in this experiment is unrelated to that observed in previous experiments with a Fabry–Perot cavity involving a photorefractive lithium niobate waveguide[8] in which at low optical powers, the change in refractive index in the intracavity medium was found to be intensity dependent, giving rise to standard Fabry–Perot bistability. The mechanism is also quite different from another proposed bistable device[9] in which light fed back to a fanning crystal discourages that fanning.

In summary, we have observed bistability and hysteresis in a photorefractive passive phase conjugate mirror. We have presented a threshold basis for the effect as well as the results of an experimental demonstration of the device.

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[6] The semilinear mirror we described here is slightly different from the "semilinear mirror" in Ref. 2 which is not self-starting. The self-starting behavior of the present semilinear mirror is due to the feedback of the fanning light and overcomes the threshold of oscillation by the use of an external curved mirror.

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