Optical bistability that is due to mutual self-action of counterpropagating beams of light

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A new kind of optical bistability is discussed that is based on mutual self-action of light beams in a nonlinear medium. In particular, fundamentally new devices are proposed that use two counterpropagating incident beams and no reflection feedback. Self-focusing (or self-defocusing) and self-bending provide bistability with positive or negative nonlinearity.

In this Letter we discuss a fundamentally new class of optical bistable devices that are based on the mutual self-focusing (or self-defocusing, or self-bending) of counterpropagating light beams interacting with each other. In particular, for the first time to our knowledge, we propose intrinsic (i.e., all-optical) bistable devices that include *no reflection feedback*, in contrast with all known intrinsic systems (e.g., conventional nonlinear Fabry–Perot resonators[1] and even a single, nonlinear interface studied theoretically in Ref. 2 and experimentally in Ref. 3). In general, the proposed device requires only a sample of nonlinear material (whose refractive index depends on the intensity of light) and two light beams incident from opposite sides (Fig. 1). This device provides probably the simplest known opportunity to obtain optical bistability. The required feedback is caused by the mutual influence of the beams, each of which affects the other by changing the average nonlinear component of refractive index.

The parameters of the hysteresis in the proposed devices could be considerably enhanced by employing an aperture or diaphragm (shown in Fig. 1a by a dashed line) or a set of diaphragms whose radii are of the order of the focal spot size or self-channel radius ρ_{ch} (or slightly larger). Suppose that the thickness of the nonlinear layer, 2L, is much larger than the Fresnel zone D of the incident beam, the radius of incident beam ρ_{in} is of the same order as ρ_{ch}, and the critical power of self-channeling for a single incidence is P_{cr}. It is then obvious that the self-channel, once it is established by both counterpropagating beams of the same power of the order of P_{cr}, could then be maintained by significantly lower power. This results in hysteretic behavior, i.e., bistability, a qualitative picture of which is shown in Fig. 2. After the device is switched into the self-trapping regime, a major portion of the light should propagate along the mutual axis and leave the sample, passing through the diaphragm, so that the upper branch of the hysteretic curve in Fig. 2a should be close to the straight line, $P_{out}/P_{cr} \sim 1$.

These systems can demonstrate a number of desirable characteristics. In particular, they allow one (1) to work without any mirrors, (2) to work with broadband sources, (3) to avoid resonant frequency tuning, (4) to get a fast switching response in the picosecond range because of the absence of a high-finesse resonator (5) to use more than one input and one output, and (6) to get a wide variety of controlled parameters of the system (e.g., two different incident powers).

In the last-mentioned case, one of the beams can be of constant power (slightly less than P_{cr}) while the power of the other beam can be driven by an external source. This device can perform as an optical transistor, amplifying a small variation of the driving signal because of the large response in output angle distribution of the forward beam with a constant input power. This system can be considered an *asymmetrical* one.

On the other hand, one can achieve bistability by simultaneous, equal driving of power of both beams. A particular realization of this *symmetrical* configuration is a device using a mirror set in the central plane (see Fig. 1b) and a single input beam while the backward beam is provided by the reflection from the mirror. Such a reflection system was proposed and experi-

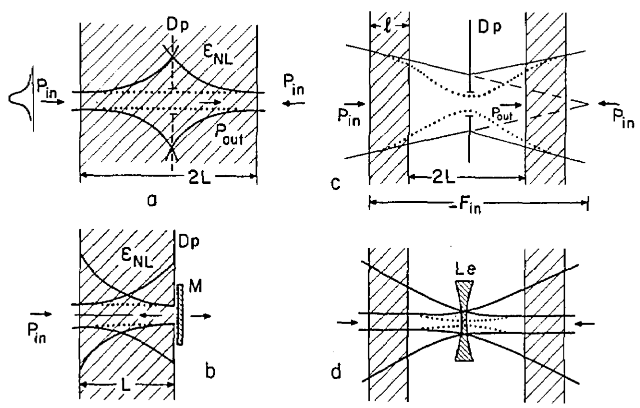

Fig. 1. Various configurations realizing optical bistability from mutual self-focusing (or self-defocusing) of counterpropagated beams. M, mirror; Dp, diaphragm; Le, lens. The solid lines show the spatial behavior of the low-power beams; the dotted lines correspond to the behavior of high-power beams after their switch into a high-transmittance state of the system.

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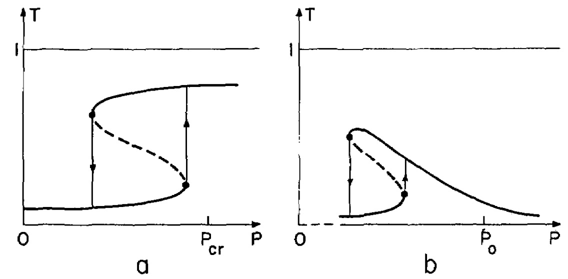

Fig. 2. Hysteresis of transmittivity $T = P_{out}/P_{in}$ in the cases of a, self-trapping and b, external self-action.

mentally demonstrated in Ref. 4; it utilizes self-trapping in sodium vapor in the cw regime,[5] where large nonlinearity is caused by resonant interaction[6] at the D_1 (or D_2) line. However, if one uses fast-response nonlinear materials, such as glasses or liquids (e.g., CS_2), one has to deal with uncontrolled catastrophic collapse (i.e., nontrapping) of the light beam above a self-focusing threshold. Moreover, bistability that is due to self-trapping allows one to employ only self-focusing materials, whereas other materials exist that possess a large self-defocusing nonlinearity [e.g., InSb (Ref. 7)].

To solve these problems (i.e., to employ self-defocusing and to avoid a catastrophic collapse of the beam inside the nonlinear material), the so-called external focusing (or defocusing) system was proposed by us,[8] in which a focal spot of the beam is set outside the nonlinear layer of thickness l. This layer then acts as a nonlinear lens whose focal length is intensity dependent[9,10] (see Figs. 1c and 1d). When a self-focusing medium is used, the initial location $|F_{in}|$ of the focal spot of the incident beam should be set behind a diaphragm, i.e., $|F_{in}| > L + l/n$ (as is shown in Fig. 1c), where L is half of the distance between two layers, so that only a small portion of the incident power reaches an opposite layer (lower branch of Fig. 2b). Then, following the action of strong light, the focal spot moves toward the diaphragm, which creates a strong feedback, and at some intensity almost all the incident power passes through the diaphragm (if the diameter of the diaphragm is of the same order as a focused spot size; see Fig. 2b). In the case of a self-defocusing medium, the initial focus of the incident beam should be located in front of the diaphragm ($|F_{in}| < L + l/n$). This system can also perform either in a two-beam regime or in a single-incident-beam regime. In the latter case, the mirror should be set immediately behind the diaphragm.

The external configuration can utilize linear lenses as well (see Fig. 1d). This provides an opportunity to work without diaphragms and to employ only narrow parallel beams. The switch appears when linear and nonlinear lenses almost cancel each other, so one should use a defocusing lens for the focusing medium and vice versa.

It is obvious that the phenomenon described can even be used in resonators if desired. The system could be constructed as a Fabry–Perot resonator (filled with nonlinear material) with sufficiently small, semitransparent mirrors so the Fresnel zone (i.e., the diffractional length) is smaller than the resonator length. (Here, only one incident beam might be used.) For weak input power, such a system will show no resonant action at all, whereas, for a strong signal that forms a nonlinear channel (smaller than a mirror size), this system will act as a resonator of good finesse, which leads to hysteresis. Such a configuration can be described as an interferometer with strongly nonlinear diffractional losses, as opposed to existing resonator devices[1] (consideration of self-focusing in resonators[11] usually assumes large-size reflectors, so such losses are negligible).

Let us consider the basic features of the theory of the proposed systems. By representing a total complex field E of the two beams, counterpropagating along axis z, as

$$E = E_1 \exp(ikz) + E_2 \exp(-ikz), \qquad (1)$$

where E_j are slow functions of spatial coordinates, one can write a conventional parabolic equation for each beam:

$$2ik\partial E_j/\partial z + \Delta_\perp E_j + k^2 E_j \epsilon_0^{-1} \Delta\epsilon_j^{NL}(|E_1^2|, \quad |E_2^2|) = 0, \qquad j = 1, 2, \qquad (2)$$

where, in the case of a cylindrical beam, $\Delta_\perp = \partial^2/\partial r^2 + r^{-1}\partial/\partial r$ (r is radial coordinate). If one is dealing with a cubic nonlinearity, $\Delta\epsilon^{NL} = \epsilon_2|E|^2$, it turns out that the nonlinear factors in Eq. (2) have different magnitudes for opposite directions of propagation[11]:

$$\Delta\epsilon_1^{NL} = \epsilon_2(|E_1|^2 + 2|E_2|^2), \qquad \Delta\epsilon_2^{NL} = \epsilon_2(|E_2|^2 + 2|E_1|^2). \qquad (3)$$

The development of the correct theory for the self-trapping configuration involves difficult problems. This is caused by a non-Gaussian distribution of light intensity at cross section and by the necessity to consider the highest terms of nonlinearity (e.g., saturation) to compute spatially oscillating noncollapsing trapping above the threshold of self-focusing.

On the other hand, for the external configuration (Figs. 1c and 1d), one can obtain analytical results in a straightforward way by using a Gaussian-beam approximation, assuming that the radii of the beams (as well as their Gaussian profiles[12]) change very little while the beams pass through each nonlinear layer. In particular, this assumption is valid if the following conditions are satisfied: $l < L < D, D = k\rho_{in}^2$. By using Eq. (2) and following the calculation[10] that provides the diffractional theory of nonlinear lenses, one can obtain the formula for each nonlinear lens:

$$\left(F_{out} + \frac{l}{n}\right)^{-1} + F_{in}^{-1} = \left(F_0 + \frac{l}{n}\right)^{-1}\left(1 + \frac{l}{nF_{in}}\right)^{-1}, \qquad (4)$$

where $n = \sqrt{\epsilon_0}$, F_{in} is the radius of curvature of the phase front of the wave at the incident plane ($F_{in} < 0$ for a convergent beam), F_{out} is the radius of curvature at the back-wall plane ($F_{out} > 0$ for convergent beam), and F_0 is the nonlinear focal length of the layer. In geometrical optics, F_{in} and F_{out} correspond to the object

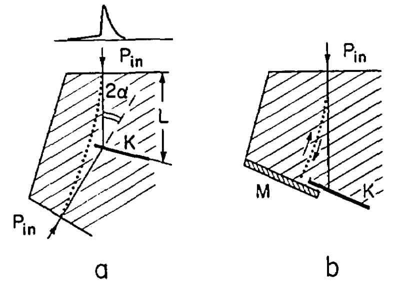

Fig. 3. Configurations realizing bistability from mutual self-bending of the light beams. M, mirror; K, knife edge.

and image positions, respectively. In the case of a single beam, Eq. (4) is valid for an arbitrary thickness of layer.[10] Supposing that $F_0 \sim L$ (which corresponds to the strongest feedback) and taking into consideration Eq. (3), one can determine that under the above-mentioned conditions the value of F_0 with respect to the incident beam is

$$(F_0^{-1})_j \approx \frac{4\epsilon_2 l}{c\epsilon_0}\left[\left(\frac{P_{in}}{\rho_{in}^4}\right)_j + 2\left(\frac{P_{out}}{\rho_{out}^4}\right)_{3-j}\right], \qquad j = 1, 2, \quad (5)$$

where P_{in} is the total power of the incident beam and ρ_{in} is its radius [i.e., the intensity is proportional to $\exp(-r^2/\rho_{in}^2)$], whereas P_{out} and ρ_{out} are the corresponding values for the backward beam transmitted through the diaphragm and emerging from the system. Now by performing conventional calculations for propagation of beams in the linear space between the layers (as well as their diffraction at the diaphragm), considering the only case in which both of the beams possess the same parameters at their planes of incidence (and are driven simultaneously, which refers to the symmetrical configuration), one can obtain the required formula for behavior of the system:

$$\frac{P_0}{P_{in}} = \left\{1 + \frac{2T}{[(1+a^2)T + a^2]^2}\right\} \times \left[\frac{1}{A \pm \mu(T^{-1} - 1 - a^2)^{1/2}} - \frac{l}{nL}\right], \quad (6)$$

where $T = P_{out}/P_{in}$ is a transmittance of the system, and

$$P_0 = \frac{c\rho_{in}^4\epsilon_0}{4lL\epsilon_2}, \qquad \mu = d/\rho_{in},$$

$$a = L/kd\rho_{in}, \qquad A = 1 + \frac{L + l/n}{F_{in}}.$$

Here d is the radius of the diaphragm and P_0 defines some scale power. Formula (6) is valid only if $\rho_{out} \gtrsim \rho_{in}$; this is always so if $a \geqslant 1$. If $a = 1$, then the critical condition for hysteresis to appear (Fig. 2b) is $|\mu/A| < 1/16$. In the case in which $\rho_{in} = 0.4$ mm and $F_{in} = \infty$, $L < 10$ cm and $d < 0.025$ mm. For $\epsilon_2 > 0$ (self-focusing), it is necessary to set $A > 0$, whereas for $\epsilon_2 < 0$ (self-defocusing, i.e., $P_0 < 0$), it should be $A < 0$. The same formula (6) is valid for the reflection configuration as well, if the mirror is set directly behind the diaphragm (T then corresponds to the reflectivity of the system).

Optical bistability could result also from the self-bending of the light beam.[8] Self-bending[13] consists of an angular deflection of the whole trajectory of a beam whose intensity profile possesses an asymmetrical shape (Fig. 3). By using self-bending, optical bistability can be achieved either by employing two beams whose initial axes are slightly tilted (see Fig. 3a) or by employing one beam with a mirror set outside the initial axis (Fig. 3b). For both of these configurations the threshold power for hysteresis (Fig. 2) might be estimated in geometric-optical approximation[13] as

$$P_{SB} \sim 2\alpha n^3 c\rho_{in}^3/\pi|\epsilon_2|L, \quad (7)$$

where α is a half-angle of the initial tilt. This formula is valid under the condition that $2\rho_{in}/\alpha < L < k\rho_{in}^2$. If $|\epsilon_2| \sim 10^{-2}$ esu (Ref. 7), $L = 1$ cm, $\rho_{in} = 0.05$ mm, and $\alpha = 2°$, then formula (7) yields $P_{SB} \sim 1$ mW.

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