Optical bistability based on self-focusing

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We experimentally demonstrate a fundamentally new type of intrinsic optical bistability that requires no resonant optical cavity. Operation is based on mutual self-focusing of counterpropagating laser beams in a nonlinear medium.

We propose and experimentally demonstrate a fundamentally new type of optical bistability.[1] The operation of this new class of devices is based on self-focusing of light; the feedback required for bistability is provided by an apertured retroreflector. These devices exhibit intrinsic bistability (the feedback is optical) and are related to nonlinear waveguide devices proposed earlier.[2]

Self-focusing occurs when a light beam having a *nonuniform* spatial profile (such as a Gaussian laser beam) and sufficient intensity propagates through a nonlinear medium having an intensity-dependent index of refraction.[3] Previously proposed devices that exhibited intrinsic bistability are operable in principle with light beams having uniform intensity profiles. More importantly, the new class of devices further differs from previous intrinsic devices in that the earlier devices have all required resonant optical cavities[4]; no such cavity is required for this new class of devices. In principle, eliminating the resonant cavity removes restrictions on tuning of the light frequency and offers the potential for broad-bandwidth operation.

The basic principles on which the new class of devices operates can be understood from a simplified discussion based on the schematic diagram of Fig. 1. A laser beam of power P_{in}, assumed to have a Gaussian intensity profile, is focused onto the input face of a medium having an intensity-dependent index of refraction. For self-focusing to be possible the refractive index must increase with increasing light intensity. A measure of the strength of this nonlinearity is called the critical power, P_{cr}.[3] When $P_{in} = P_{cr}$, the input laser beam passes through the medium with no change in spot size, as shown by the dashed lines; this situation is referred to as self-trapping. For $P_{in} < P_{cr}$, the laser beam diverges less rapidly than it would in the absence of the nonlinearity, and for $P_{in} > P_{cr}$, the beam converges. For $P_{in} \ll P_{cr}$, there is essentially no self-focusing; the input focal spot size is chosen such that, for these conditions, the laser beam diverges appreciably in passing through the nonlinear medium, as shown by the solid lines. The optical field at the output face of the nonlinear medium is imaged by the lens L onto the partially transmitting mirror M, which is aligned normal to the laser beam to provide optical feedback. Immediately in front of the mirror is an appropriately sized aperture. The aperture size is adjusted to satisfy two criteria. First, it must be small enough that in the absence of self-focusing the fraction of the incident light fed back into the nonlinear medium by the mirror is small. Second, it is large enough that under self-trapping conditions essentially all the light passes through the aperture and is reflected back upon itself by the mirror. This strong feedback reinforces the self-focusing in the nonlinear medium, and it allows self-trapping to be maintained even when the input power is subsequently reduced below P_{cr}. This is the mechanism that gives rise to the optical bistability (hysteresis). Devices working on the same basic principles can take other forms. For instance, the aperture and mirror could be combined and deposited on the exit face of the nonlinear medium to minimize device length and the optical transit time. It is also possible to envisage devices[5] that operate in the external self-focusing (or defocusing) limit.[3] In this limit, the nonlinear medium acts as a thin lens having a power-dependent focal length; bistability should be possible using either focusing or defocusing media.

Our experimental demonstration of these principles utilized atomic sodium vapor as the nonlinear medium. Although it not a suitable medium for a practical device, sodium vapor has the virtue of having a large nonlinear

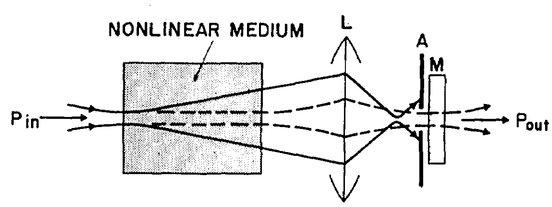

Fig. 1. Schematic diagram of the new bistable optical device. The lens L images the optical field on the exit face of the nonlinear medium onto the partially transmitting mirror M. The aperture A causes feedback to depend on the laser beam spot size at the exit face of the medium. The situations corresponding to normal propagation and self-trapping are shown by the solid and dashed lines, respectively.

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index for frequencies near its resonance transitions.[6] Also important for our application is the fact that the nonlinearity saturates at reasonable intensity levels, so that catastrophic self-focusing does not occur.[7] These factors have allowed steady-state self-focusing and self-trapping to be observed in sodium vapor using cw dye lasers.[8] The sodium vapor was contained in a 20-cm-long heated cell constructed of Pyrex. The input laser beam was obtained from a single-mode cw ring dye laser (Spectra-Physics Model 380A). The transverse mode of the laser was TEM_{00} (Gaussian mode), and its focal spot size (e^{-1} field radius) on the input face of the vapor cell was approximately 80 μm; the corresponding confocal parameter of the laser beam was about 6.8 cm, so that in the absence of self-focusing the spot size on the exit face of the cell was about 480 μm. A linear polarizer and a quarter-wave plate situated between the laser and the vapor cell were used as an isolator; thus circularly polarized light was incident onto the cell. A 16-cm focal-length lens imaged the optical field at the exit face of the cell, with unity magnification, onto a flat mirror having a reflectance of 94%. An aperture was placed several millimeters in front of the mirror; aperture diameters between 100 and 200 μm were used.

Without feedback from the mirror, strong self-focusing and self-trapping were readily observed with approximately 150 mW of light tuned about 1.2 GHz above the resonant frequency of the $3S_{1/2}(F = 2) \rightarrow 3P_{1/2}$ sodium transition at 5896 Å. The sodium density was approximately 2×10^{12} cm^{-3}. Bistability was observed when the mirror was aligned normal to the laser beam and the input light was amplitude modulated at about 50 Hz with a spinning transmission grating composed of closely spaced fine wires. The input power (P_{in}) and the power passing through the mirror (P_{out}) were monitored as functions of time using photodiodes and a dual-channel digital oscilloscope (Nicolet Explorer II); the signals could also be displayed and recorded as P_{out} versus P_{in}.

A wide variety of behaviors was obtained depending on the precise adjustment of the various parameters. Figure 2 presents data obtained under conditions for which the device exhibited bistability; the laser was tuned about 1.2 GHz above the $3S_{1/2}(F = 2) \rightarrow 3P_{1/2}$ transition. As the input power was increased, upward switching from a low-transmission state to a high-transmission state occurred at an input power of about 130 mW. At switching, the transmission abruptly increased by a factor of 4.1 with a rise time of about 20 μsec. Subsequent reduction of the input power resulted in a downward switch of the same speed at about 95 mW of input power. Optical pumping of the sodium atoms undoubtedly plays a role in the nonlinearity of the medium, and the observed switching time may be more characteristic of optical pumping than of the switching process itself. The dashed lines of Fig. 2 show the calculated low- and high-transmission limits, based on the measurement of 45 mW incident onto the aperture for an input power of 140 mW and no feedback. The high-transmission limit assumes 100% transmission by the aperture. Note that the substantial optical absorption of the sodium vapor is saturated for input powers greater than 60 mW; this indicates that saturation of the absorption is not the dominant mechanism leading to bistability. The upward switch occurs at a power level roughly equal to the level at which self-trapping was observed without feedback. Visual observation of the resonance fluorescence induced by the laser beam shows dramatically that at switching the laser beam abruptly changes from diverging propagation to what appears to be self-trapping. With higher sodium density and a smaller input spot size, several switching levels and several hysteresis loops were obtained, perhaps corresponding to oscillations of the spot size as the laser beam propagated through the self-focusing medium.[7,8]

Data obtained with the device acting as a power limiter are shown in Fig. 3. The various device parameters were roughly the same as those of Fig. 2 except that for 140 mW of input power about 40 mW was incident onto the aperture. The device transmission jumped by a factor of 3.6 at an input power of 110 mW, and for further increases of the input power the output power was essentially clamped to a level of about 1.3 mW. No hysteresis was present. The occurrence of limiting appeared to be associated with small misalignments of the feedback optics.

Under some circumstances the output power as a function of time was noisy. This noise appeared to be a rapid switching back and forth between different transmission states and may be related to predictions of instabilities inherent in certain bistable optical devices.[9]

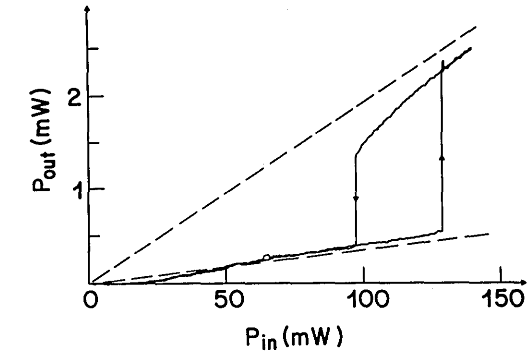

Fig. 2. Experimental curve of P_{out} versus P_{in} with parameters adjusted so that the device exhibits bistable operation. The aperture diameter was 150 μm, and the arrows show the switching directions.

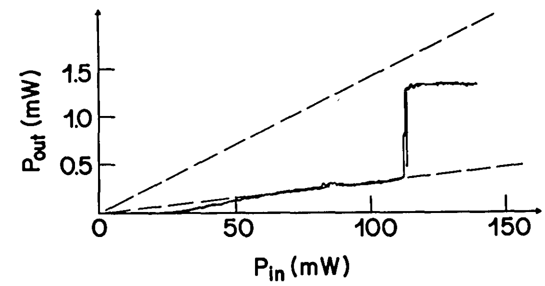

Fig. 3. Experimental curve of P_{out} versus P_{in} obtained with parameters adjusted so that the device operates as a power limiter. The aperture diameter was 150 μm.

Finally we point out that intrinsic bistable devices are of particular interest because of their potential for ultrafast switching.[10] Given a suitable medium having a sufficiently strong nonlinearity, the type of device discussed here would be scalable to short lengths giving the potential for fast response times. Focusing the input laser beam to a spot size of the order of λ, the wavelength of the light, allows one to use device lengths of the order of 50λ with corresponding transit times for the light of about 0.2 psec. However, this would require an induced change in the refractive index of about 0.05,[6] which would be hard to achieve.

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