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Optical bistability due to increasing absorption

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It is shown theoretically that optical bistability will exist in a material whose optical absorption is more than linearly proportional to the degree to which the material is excited. No cavity or external feedback is required. The underlying principle of this bistability appears to be a generalization of several previous independent discussions of mirrorless bistabilities in specific physical systems. This bistability and associated differential gain are demonstrated experimentally using a thermal nonlinearity in a GaAs/GaAlAs multiple-quantum-well semiconductor. Theory and experiment show good agreement.

Optical bistability (OB) had recently received much attention both as a model physical system and for practical applications. Many different methods of obtaining OB have been proposed.[1] Most require a microscopic optical nonlinearity combined with macroscopic optical feedback. Recently, however, several authors have independently discussed OB without mirrors or other external feedback both theoretically[2–4] and experimentally[3,5] in diverse, specific physical systems [relativistic electrons,[2] amorphous $GeSe_2$,[3] dense two-level atoms,[4] and CdS (Ref. 5)]. We believe that all these OB's result from the same underlying class, although a detailed comparison is beyond the scope of this Letter.

In this Letter we derive the general theory of this OB, deducing a simple criterion for its existence. We also demonstrate the OB in an experiment in which other causes of OB can be specifically excluded and compare this with theory.

The principle is as follows. We have a medium whose optical absorption A depends on the degree N to which the medium is excited. We presume that we know the precise functional form of A against N, although at the moment we write this condition in its most general form:

$$A = A(N). \tag{1}$$

[In the demonstration below, for example, N is temperature rise and $A(N)$ is measured in a separate experiment.] If light of power P is shone into the medium, a total power AP is absorbed. If we assume for simplicity that in the steady state N is directly proportional to the absorbed power (i.e., *all* absorption contributes equally and linearly to N), then

$$N = \eta AP, \tag{2}$$

where η is a constant.

Solving Eqs. (1) and (2) simultaneously to eliminate N gives A as a function of P. The output power $P_r = \rho(1 - A)P$ is then known as a function of the input power (ρ accounts for reflection and scattering losses). This theory is a simple generalization of that in Ref. 3. Using a graphical method (see Fig. 1), we plot $T \equiv \rho(1 - A)$ against N from Eq. (1) and T against N for various P from Eq. (2), the latter being a set of straight lines as in Fig. 1(1). The intersections give the solutions. The bistable switching is clearly seen.

The regenerative action underlying the switching is as follows. Increasing the power P increases the excitation N. Increasing N increases A; this further increases the absorbed power and hence further increases N and hence A. Under the correct condition this feedback process can become regenerative, leading to switching. Note that A *must* depend on N and not merely on P; otherwise there is no regenerative action. This rules out all nonlinear absorption rigorously expandable in powers of the electric field (such as two-photon absorption) with constant coefficients. The nonlinearity must be dynamic,[6] that is, the optical properties are a function of the real state of excitation of the material.

The borderline condition for bistability is that the straight line be tangent to the curve, i.e., $dA(N)/dN > A/N$, for bistability. Solving this expression gives

$$\frac{A(N_2)}{N_2} > \frac{A(N_1)}{N_1}, \tag{3}$$

where $A(N_2) > A(N_1)$ and $N_2 > N_1$, i.e., bistability may exist if, over some range of N, A is more than linearly proportional to N.

To demonstrate this principle we use a direct-band-gap semiconductor material, operating at photon energies just below the band-gap energy. Any optical absorption will heat up the semiconductor and, in our case, reduce the band-gap energy and increase the absorption. We use a GaAs/GaAlAs multiple-quantum-well structure semiconductor as it has a particularly abrupt band-edge absorption[7] at room temperature and

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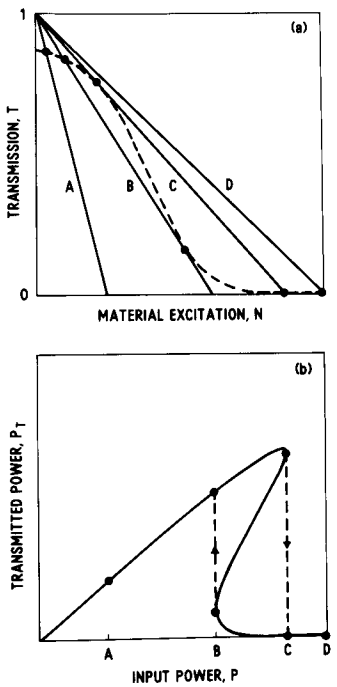

Fig. 1. Graphical solution of optical bistability due to hypothetical absorption increasing with increasing excitation. (a) The dashed line is $T = 1 - A(N)$ [Eq. (1)]. Lines A to D correspond to increasing power in Eq. (2). Lines A and D intersect only once with the curve, indicating only one solution for these powers. Lines B and C, each showing two intersections, represent the critical powers for switch-up and switch-down. Any lines between B and C would show three intersections, as required for optical bistability. (b) P_T, the transmitted power, is plotted against P, the incident power, using the above solution method. $\rho, \eta = 1$ for simplicity.

its band-gap energy suits the wavelength range of our laser. The sample consisted of 375 periods of $Ga_{0.7}Al_{03}As$ layers, 8.7 nm thick, alternating with 8.5-nm-thick GaAs layers, with this whole structure sandwiched between ~1.2-μm-thick $Ga_{0.7}Al_{0.3}As$ cap layers, giving a total thickness of ~9 μm. This sample was grown by molecular-beam epitaxy on a GaAs substrate; it was coated with an antireflecting layer of silicon nitride on its top surface to eliminate specifically any cavity effects, and the entire substrate was removed by etching. A piece of the resulting thin sample, ~1.1 mm × ~0.6 mm, was epoxied, on the uncoated side, to the side of a 170-μm-diameter glass fiber near one end of the fiber. The glass fiber, 6 mm long, is used to give a mechanically rigid mounting with low thermal conduction and serves no direct optical purpose. The laser was a krypton-ion-laser-pumped oxazine 750 dye laser.

The solid line in Fig. 2 shows the measured absolute transmission spectrum of this sample, taken with low laser power (≤300 μW). Fabry–Perot fringes are seen in the more transparent region below ~1.46 eV. The depth of these fringes implies ~2.6% remaining reflection on the antireflection-coated surface.

The experimental results in Fig. 3 are the input–output characteristics of this sample for four different laser wavelengths. Clear bistability can be seen on curves (c) and (d). Curve (b) also shows a differential gain of ~2.7 (without any reflection corrections) near 2.2 mW. These curves were taken by slowly scanning a variable neutral-density filter in the laser beam and recording input and output powers measured with silicon detectors. The incoming laser beam was focused to a relatively small spot (25 μm for the measurements in Fig. 3) to avoid epoxy-covered regions on the sample and was incident upon the uncoated side of the sample. No significant changes in behavior were noted for spots from 10 to 100 μm in diameter. This is consistent with the assumption that the whole sample heats uniformly, with the principal temperature drop occurring across the fiber. The stability of both states in the bistable region was checked over half-hour periods. By man-

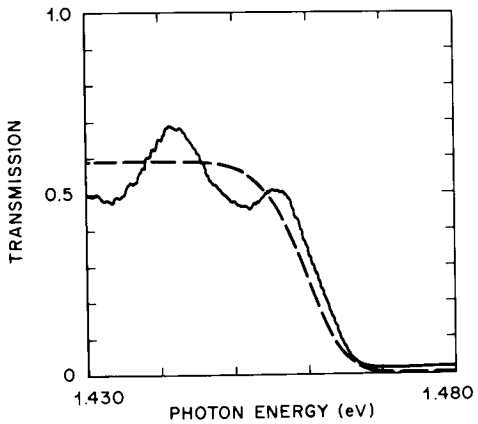

Fig. 2. Solid line, measured low-power optical transmission spectrum of the sample. Dashed line, smoothed analytical function used for theoretical modeling.

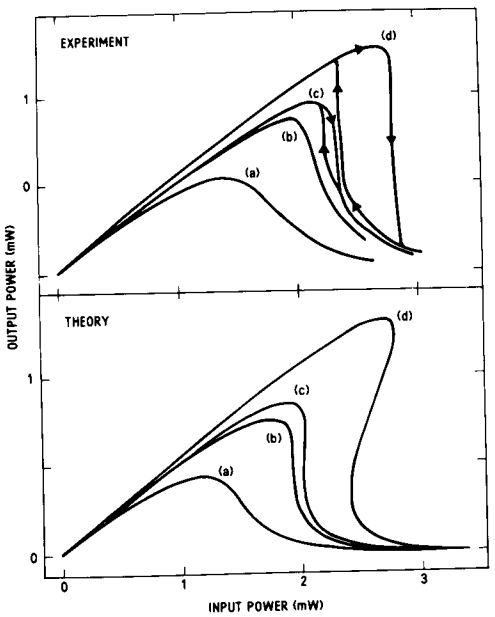

Fig. 3. Experimental input–output characteristics of the sample for four different laser photon energies: (a) 1.4544 eV, (b) 1.4523 eV, (c) 1.4519 eV, (d) 1.4500 eV, and theoretical curves calculated all with the same parameter values according to the semiempirical model discussed in the text. Only two adjustable parameters were used in fitting the whole set of theoretical curves.

ually varying the attenuator slowly, it was possible to observe clear switching on an oscilloscope displaying the output of the silicon detector in the output beam. Ten-to-ninety-percent switching times were as follows: high-to-low transmission 12–16 msec; low-to-high transmission, 200–400 msec under quasi-static power changes and ~40 msec when the power was changed rapidly (~50% in 0.5 sec). Critical slowing down is therefore seen on the low-to-high transition, with more-rapid switching occurring when the system is overdriven, although it was not observed on the high-to-low transition.

To deduce $A(N)$ experimentally, we first approximate the measured transmission $T(\hbar\omega)$ by a smooth function (the dashed line in Fig. 2) to average out the weak remaining Fabry–Perot fringes. (The smooth function, chosen arbitrarily for convenience, was a Gaussian absorption line.) From the known surface reflectivities we then deduce $A(\hbar\omega)$. Finally, we assume that the effect of temperature rise N is simply to shift the whole absorption spectrum in proportion to lower photon energies and hence deduce $A(N)$ from $A(\hbar\omega)$ within a proportionality constant. The final semiempirical $A(N)$ deduced was

$$A(N) = 1 - 0.88 \exp\left[-7.5 \exp \frac{(x + N - 1.4778)^2}{(0.12)^2}\right],$$

where x is the photon energy. Only the parameter 1.4778 (eV) has been adjusted with a ±1-meV range (which corresponds to the reproducibility range of the spectra) to improve the fit of the calculated input–output curves. With a fitted factor of 6.384 meV/mW for the shift of the absorption spectrum with absorbed power, we obtain the family of theoretical curves in Fig. 3; these clearly reproduce the main qualitative features of the experiment with generally good quantitative agreement.

There are various possible reasons for the remaining small discrepancies between theory and experiment: (1) The absorption will not simply shift with temperature; there will also be some broadening. (2) There is some light scattered around the sample. (3) Some electronic nonlinear absorption will exist at the intensities used here[7–9]; the switching speeds rule this out as the main mechanism, and the insensitivity to spot size shows that it makes little contribution.

Conventional absorptive and/or dispersive bistability are directly excluded because of (1) low finesse, (2) high-to-low transmission switching, and (3) observation of bistability with broadband (and hence low coherence) illumination (e.g., 1.444–1.457 eV). Care has been taken to collect all the transmitted light.

In conclusion, we have demonstrated good agreement between the simple general theory and experiment for this class of mirrorless bistability. The main characteristics of this class are as follows: (1) The switching is to lower transmission with increasing input power (and vice versa). (2) The positive feedback that causes the switching is due to the material absorption's increasing as the real degree of excitation of the material is increased. [The degree of excitation takes different forms in different systems (e.g., temperature rise here and in Ref. 3, average kinetic energy,[2] population inversion,[4] and band-gap renormalization[5]), but a higher degree of excitation always corresponds to higher energy of the material.] (3) The nonlinear absorption that gives rise to this bistability *must* depend on the real state of excitation of the material and cannot therefore be described simply as a susceptibility rigorously expandable in powers of the electric field.

Given the general conditions for this bistability, it should be observable in many physical systems; given its absence of cavities and inverting logic operation, it may prove to be of practical interest.

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