Optical Bistability:

An Undergraduate Experiment

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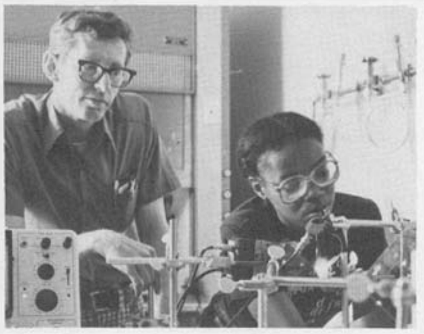
An apparatus for student use is described that utilizes only commercially available components and that can be used as several different optical devices: optical memory, optical limiter, and optical ac amplifier. This simple setup is a close analog of the optical bistable devices being developed for possible optical signal-processing applications.

INTRODUCTION

The phenomenon of optical bistability (OB) is interesting both in the physical systems involved and in light of potentially exciting applications.[1-16] For a recent review of OB, see *Optics News*, Summer 1979.[1] OB occurs in an optical system in which there is a region of input intensities for which the output intensity has two stable values for a given input intensity. The two values represent high and low transmitting levels or states. With the system are associated two input intensities at which the system rapidly transforms from one state to the other. This is referred to as switching, and the appropriate input values are called the switch-up and switch-down input intensities. If the input is varied periodically, the transmission is seen to trace out a hysteresis loop. One model that describes this phenomenon in a nonlinear Fabry-Perot resonator (FP) is mathematically analogous to a first-order phase transition.



Greene adjusts a photomultiplier tube as her mentor Gibbs looks on.

Any such system is potentially an optical three-port device through which the transmission of a light beam is controlled by a weaker light beam. It is easy to demonstrate this in the experiment described below. In fact, the process has recently been achieved in tiny semiconductor étalons, first in a 5-μm GaAs device[15] and then in a 500-μm InSb device,[16] rendering OB a potential asset to optical signal processing.

Venkatesan, Gibbs, McCall, and Passner examine a GaAs optical bistable étalon.

Optical hystereses in cavities containing gain media (i.e., lasing media) are not considered within the present discussion even though some of them were proposed and observed earlier.[17] The analysis[17,18] of a FP containing a nonlinear gain medium is similar to that for a nonlinear absorptive and dispersive medium, but the physical consequences and practical implications are quite different.

Initially, the consideration of OB resulted from the study of FP resonators containing nonlinear absorbers. The possibility of OB's occurring in such a system was independently recognized by three groups.[2-4] Some clues to obtaining OB (Refs. 3,5) and a clear demonstration of the effect in Na (Refs. 6,7) soon followed. The behavior of a FP resonator containing a medium with a light-intensity-dependent index of refraction has been studied in detail.[7-10] Such systems are all optical and are termed *intrinsic*, i.e., the nonlinear response of the intracavity medium is directly proportional to the light intensity. More recently, nonintrinsic, or *hybrid*, OB systems have been constructed that introduce the essential nonlinearity using electrical feedback to an electro-optical device, with or without a FP.[11-14] Thus the study of OB has covered the span of perhaps 10 years, and, in light of this activity, it seems timely that OB take a place in the study of physical optics. The demonstration of this OB experiment at the 1979 annual meeting of the Optical Society of America in Rochester stimulated the invitation to make the details generally available through this article.

THEORY

Suppose that one considers an electro-optical device whose transmission $T(V)$ has a nonlinear dependence on the applied voltage V. Then, by definition,

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$$I_T/I_I = T(V), \tag{1}$$

where I_I is the intensity incident on the device and I_T is the intensity transmitted by the device; in the present device $T(V) = \sin^2(bV^2)$ (Ref. 14) is the approximate functional form of the transmission. The constant b is related to the half-wave voltage V_T by $bV_T{}^2 = \pi/2$. If the transmitted signal is converted to a voltage that is (amplified and) fed back across the device, then

$$V = V_B + \alpha I_T, \tag{3}$$

where V_B is a bias voltage independent of I_T and α is a constant indicating the strength of the feedback. Combining Eqs. (1)-(3), one has

$$I_I' = I_T' \sin^{-2}[\tfrac{\pi}{2}(V_B' + I_T')]^2 \tag{4}$$

with $I_I' = \alpha I_I/V_T$, $I_T' = \alpha I_T/V_T$, $V_B' = V_B/V_T$. Equation (4) is plotted in Fig. 1 for $V_B' = 0.33$. When viewed as I_T' versus I_I', the S-shaped curve is clearly multivalued. Stability analysis shows that only the values with positive slope are stable in steady state. As the input intensity is increased from zero, the output I_T' remains low following the lower branch until I_I' (UP) is reached. At that input, the transmission switches from a 10% off value to an 82% on value. The transmission remains on the upper branch so long as the input does not fall below I_I' (DOWN). Figure 1 is closely analogous to the hysteresis curves obtained for a Fabry-Perot étalon containing a nonlinear medium.[1-8]

It has been emphasized that a bistable device can be constructed from *any* optical material or system whose transmission is a nonlinear function $T(V)$ of an applied voltage V.[14] For example, $T(V)$ for the ferroelectric lanthanum-modified lead zirconate titanate (PLZT) crystal used here is not given exactly by Eq. (2); the experimental data are shown in Fig. 2. Since $T(V)$ is not expressible as a simple function, direct calculation of I_I' versus I_T', such as was done above, is no longer possible. But the calculation can be performed graphically.[8,14] On the graph of $T(V)$, also plot the straight lines $(V - V_B)/V_0 = I_T/I_I \equiv T(V)$ whose slopes decrease with increased input intensity since $V_0 = \alpha I_I$. For a given input intensity, $T(V)$ must obviously satisfy both the $T(V)$ curve and the $T(V)$ straight line; i.e., the intersections of a line and the curve give the possible values for $T(V)$ at that input. For example, Fig. 3 shows an experimental $T(V)$ and two straight lines labeled UP and DOWN that correspond to the switching values of the input. Using the intersection values, now plot $T(V)$ versus I_I as in Fig. 1. The bistable region of Fig. 1 corresponds to the range of input intensities for which there are three intersections of a line with the experimental $T(V)$ curve. More generally, if $(dT/dV) > T/V$, then I_T is a multivalued function of I_I for the appropriate bias voltage, and OB can be obtained.[19] Experimentally, one usually varies I_I back and forth between zero and a maximum and then increases the feedback gain and adjusts V_B until OB is observed.

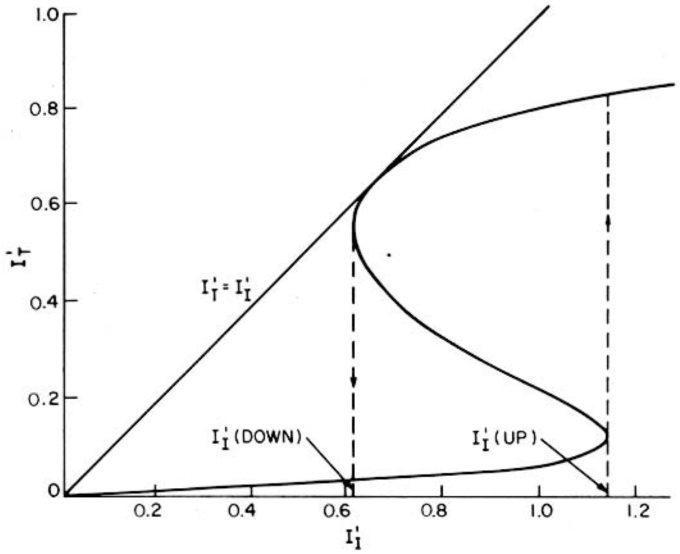

Fig. 1. Plot of the transmission of a hypothetical PLZT crystal between crossed polarizers with feedback [see Eq. (4)].

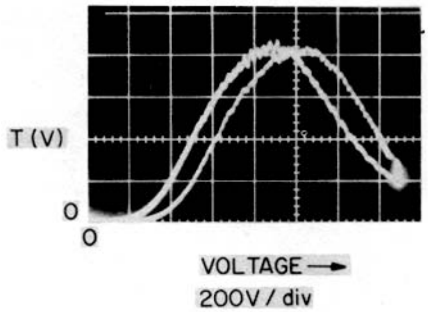

Fig. 2. PLZT transmission curve. The left curve is for increasing V; the right for decreasing. This intrinsic hysteresis could be used for an optical memory if V is proportional to the input I_I because $T(V)$ would reveal whether the present I_I was reached by increasing from zero or decreasing from a maximum. But the characteristics of such a device would differ greatly from the present OB device, in which V is determined by I_T. In particular, without feedback, no switching would occur for an infinitesimal change in input intensity. This PLZT hysteresis is undesirable for this experiment in that it is not needed to observe OB.

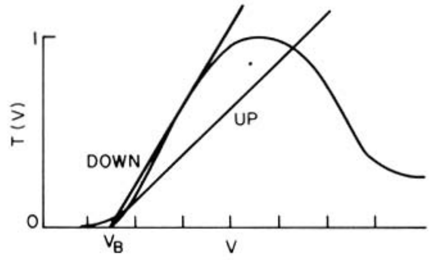

Fig. 3. Graphical determination of transmission with feedback from known dependence of transmission on voltage.

EXPERIMENTAL SETUP

The apparatus is shown in Fig. 4; this setup is essentially identical to that of Ref. 14 except that there the polarization is rotated with a $LiNbO_3$ crystal. Here the nonlinear optical switch is an electroded PLZT ceramic wafer bonded to glass-supported crossed linear polarizers. This switch is made by Motorola under the composition name 9565. The device is easy and safe to handle, especially if mounted on a translator

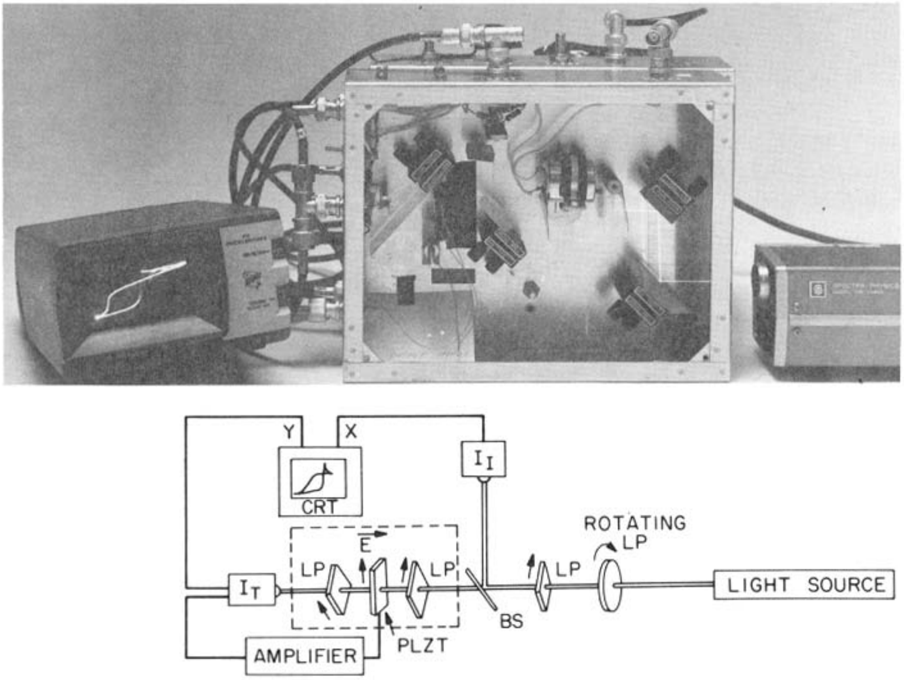

Fig. 4. Simple apparatus for observing optical bistability (top) and its schematic. The light source was a linearly polarized multimode He–Ne laser. LP is a linear polarizer, BS is a beam splitter, and PLZT is a piezoelectric crystal in which an electrical feedback signal modulates the transmission through electric field-dependent index changes. The Motorola 9565 bonded wafer consists of the PLZT and LP's within the dashed box. I_I and I_T are the input- and transmitted-light detectors connected to the oscilloscope CRT.

for positioning. The bonded wafer has an on-state transmission of 17% and an off-state transmission of 0.032%. The light source is a 1-mW He-Ne linearly polarized multimode laser; almost any source could be used so long as its polarization is linear along a fixed direction and it can be modulated and collimated. Here, the light is modulated by using a linear polarizer mounted on a slow motor.[20] A polarizer is inserted before the glass-slide beam splitter in order that the input detector receive a light flux proportional to that passing through the first polarizer of the PLZT bonded wafer. The detectors are Texas Instruments type TIL81 phototransistors (see Fig. 5).[20] The feedback amplifier can be a Kepco OPS-1000 operated with an internal feedback resistor of 1 MΩ and variable 1-kΩ input resistor to adjust the gain. A variable 100-kΩ resistor between the supply's +6-V terminal and the input null point determines the bias voltage. Or the Kepco amplifier (≈$650) can be replaced by the much less expensive (≈$15 for operational amplifier and transistor) circuit of Fig. 6.[22] Note that *all* the components of this proposed undergraduate experiment are commercially available and are relatively inexpensive. The most expensive components are the amplifier and the PLZT wafer (≈$200). This wafer requires high voltages, but its advantages are its very large aperture and its ready availability (because it is used in welder's goggles). Unelectroded wafers are much cheaper; they can be cut into several crystals and homemade electrodes attached. When waveguide electro-optical devices become readily available and inexpensive, the high-voltage amplifier will no longer be needed.

RESULTS AND DISCUSSION

Figure 7 shows an oscilloscope display of the hysteresis curve, as well as the time dependence of the input and output signals, for the apparatus of Fig. 4. Here, the bias is set at 313 V, and V swings between 313 and 1100 V. Such a trace may be observed over a fairly wide range of bias voltages and amplifier gain. Under good conditions, the ratio of the higher and lower transmitting states may be around 10:1. Switching times, that is, the times for the system to flip from one state to the other, are on the order of a few milliseconds.

That the system is indeed optically bistable is readily demonstrated.[14] Referring to Fig. 7(a), stop the rotating polarizer so that the system is in state A. Briefly shine a flashlight on the output detector to switch the device to a point A′ on the upper part of the curve directly above A. Obstruct the path of the input beam to restore the system to A. Also, by varying the gain and the bias voltage, one may observe the clipper, limiter, and differential gain modes of the system.

It is of interest to consider what causes the switching events associated with bistability. Referring to Fig. 3

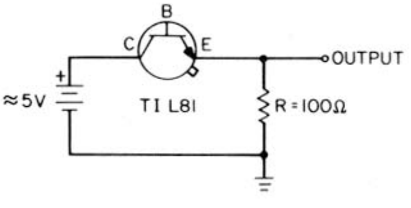

Fig. 5. Phototransistor detector. The case tab indicates the wire connections (top view).

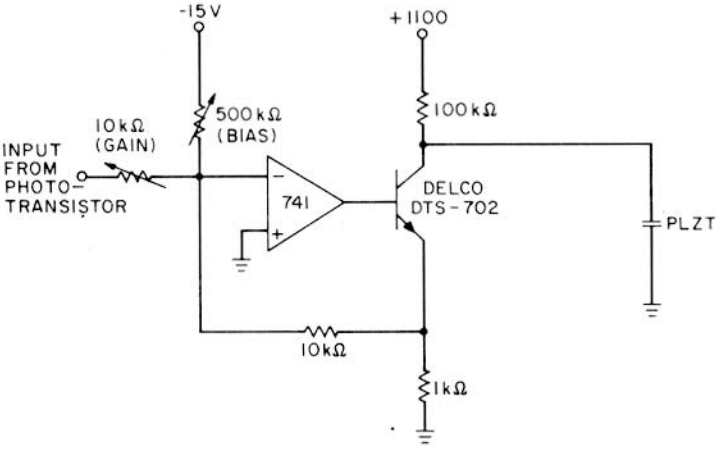

Fig. 6. Inexpensive feedback-amplifier circuit.

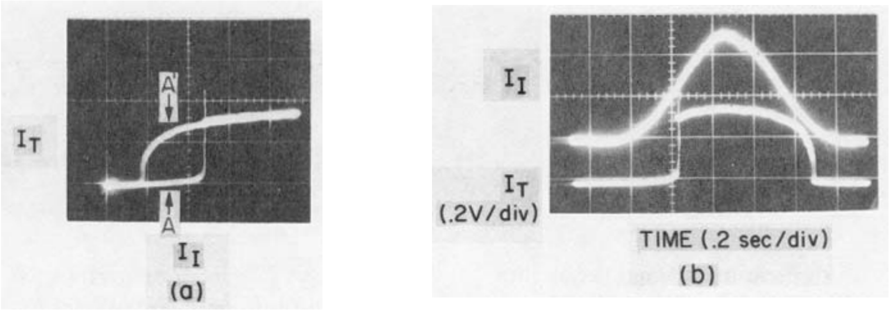

Fig. 7. Optical bistability observed with the apparatus of Fig. 4.

again, at low input intensities, V is low, as are $T(V)$ and $\mathrm{d}T(V)/\mathrm{d}V$; the $(V - V_B)/V_0$ straight line is nearly vertical, i.e., $V \approx V_B$. Here it is important to note that $V = V_B + \alpha I_T$ (i.e., feedback). At sufficiently high I_I, the αI_T term begins to contribute significantly to V, thus increasing $T(V)$ and further increasing I_T. When the $(V - V_B)/V_0$ straight line becomes tangent to the lower knee in $T(V)$, i.e., becomes the UP curve, the device turns on in a runaway manner. The transmission passes through the peak transmission (spikes in Fig. 7) and comes to equilibrium at a lower $T(V)$, so that Eqs. (1) and (3) are satisfied simultaneously. Now, in decreasing the input light, i.e., increasing the slope in Fig. 3 from that of the UP line to that of the DOWN line, the turned-on device requires less input for high transmission than was required to turn it on. Once the input is low enough that $(\mathrm{d}T/\mathrm{d}V) > T/(V - V_B)$, the device rapidly turns off.

In summary, a simple apparatus is described that permits a student to observe optical bistability. This phenomenon is an interesting dynamical process having potential for all-optical data processing and having interesting phase-transition properties.[1]

APPENDIX: ALTERNATIVE APPROACHES

The experiment suggested herein involves readily available components and only a 1-mW He-Ne laser or even an incoherent light source. This experiment is, of course, a hybrid experiment involving both electronics and optics and no cavity. There is a close analogy, however, between this hybrid experiment and the intrinsic experiments involving an intensity-dependent refractive index within a Fabry-Perot interferometer. The analogy can be made even closer by using a PLZT crystal (with no cross polarizers attached, which results in a much more fragile element) within a Fabry-Perot interferometer. Or feedback can be made to a piezoelectric on which one of the Fabry-Perot mirrors is mounted.[13] Hybrid experiments are suggested here because at present it is simpler to supply electrical power than laser power. However, a somewhat higher-power laser (≈20 mW) would enable one to observe intrinsic thermal optical bistability in a color filter.[23] In that case, an intensity-dependent refractive index is induced within a Fabry-Perot cavity by optical absorption, leading to heating and thermal optical path-length changes. As the field of OB develops, undoubtedly low-power intrinsic systems will become easily available.

REFERENCES

1. H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Opt. News 5(3), 6 (1979).
2. H. Seidel, U.S. Patent No. 3,610,731 (October 5, 1971).
3. A. Szöke, V. Daneu, J. Goldhar, and N. A. Kurnit, Appl. Phys. Lett. **15**, 376 (1969).
4. S. L. McCall, Phys. Rev. A **9**, 1515 (1974).
5. J. W. Austin and L. G. DeShazer, J. Opt. Soc. Am. **61**, 650 (1971); E. Spiller, J. Opt. Soc. Am. **61**, 699 (1971), J. Appl. Phys. **43**, 1673 (1972).
6. S. L. McCall, H. M. Gibbs, G. G. Churchill, and T. N. C. Venkatesan, Bull. Am. Phys. Soc. **20**, 636 (1975); J. Opt. Soc. Am. **65**, 1184 (1975).
7. H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Phys. Rev. Lett. **36**, 1135 (1976); and U.S. Patents No. 4,012,699 (March 15, 1977) and 4,121,167 (October 17, 1978).
8. F. S. Felber and J. H. Marburger, Appl. Phys. Lett. **28**, 731 (1976).
9. T. N. C. Venkatesan and S. L. McCall, Appl. Phys. Lett. **30**, 282 (1977); T. N. C. Venkatesan, Ph.D. dissertation, (City University of New York, New York, 1977).
10. T. Bischofberger and Y. R. Shen, Phys. Rev. A **19**, 1169 (1979).
11. A. A. Kastal'skii, Sov. Phys. Semicond. **7**, 635 (1973).
12. P. W. Smith and E. H. Turner, Appl. Phys. Lett. **30**, 280 (1977).
13. S. L. McCall, Appl. Phys. Lett. **32**, 284 (1978).
14. E. Garmire, J. H. Marburger, and S. D. Allen, Appl. Phys. Lett. **32**, 320 (1978).
15. H. M. Gibbs, T. N. C. Venkatesan, S. L. McCall, A. Passner, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **34**, 511 (1979); H. M. Gibbs, S. L. McCall, A. Passner, A. C. Gossard, W. Wiegmann, and T. N. C. Venkatesan, IEEE J. Quantum Electron. **QE-15**, 108D (1979); H. M. Gibbs, S. L. McCall, T. N. C. Venkatesan, A. C. Gossard, A. Passner, and W. Wiegmann, Appl. Phys. Lett. **35**, 451 (1979).
16. D. A. B. Miller, S. D. Smith, and A. Johnston, Appl. Phys. Lett. **35**, 658 (1979); D. A. B. Miller and S. D. Smith, Opt. Commun. **31**, 101 (1979).
17. G. J. Lasher, Solid-State Electron. **7**, 707 (1964); W. E. Lamb, Jr., Phys. Rev. **134**, A1429 (1964); R. L. Fork and M. A. Pollack, Phys. Rev. **139**, A1408 (1965); R. L. Fork, W. J. Tomlinson, and L. J. Heilos, Appl. Phys. Lett. **8**, 162 (1966); V. N. Lisitsyn and V. P. Chebotaev, JETP Lett. **7**, 1 (1968); K. H. Levin and C. L. Tang, Appl. Phys. Lett. **34**, 376 (1979).
18. A. P. Kozantsev, S. G. Rautian, and G. I. Surdutovich, Sov. Phys. JETP **27**, 756 (1968); M. B. Spencer and W. E. Lamb, Jr., Phys. Rev. A **5**, 884, 993 (1972).
19. The condition for OB is that Fig. 1 be an S-shaped curve, which requires a region with $\mathrm{d}I_T/\mathrm{d}I_I < 0$. Since $I_I \equiv I_T/T$,
$$\frac{\mathrm{d}I_I}{\mathrm{d}I_T} = \frac{1}{T} - \frac{I_T}{T^2}\frac{\mathrm{d}T}{\mathrm{d}I_T},$$
so that $\mathrm{d}I_I/\mathrm{d}I_T < 0$ requires that $T/I_T < \mathrm{d}T/\mathrm{d}I_T$. Since the feedback voltage is proportional to V, one has $T/V > \mathrm{d}T/\mathrm{d}V$ for OB.
20. Globe Industries, Inc., Dayton, Ohio: 27 V, 0.5 A, 24 RPM, Spec. No. RC15230.
21. *The Optoelectronics Data Book*, 5th ed. (Texas Instruments, Dallas, Tex., 1975) pp. 63–66.
22. For increased portability, use Model E-10 1000-V supply from Emco High Voltage ($50) and Model LOD-Y-152 ±12-V supply from Lambda ($68).
23. S. L. McCall and H. M. Gibbs, J. Opt. Soc. Am. **68**, 1378 (1978); S. L. McCall, H. M. Gibbs, W. Greene, and A. Passner, unpublished.