OPTICAL BISTABILITY

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A brief general review of the subject of optical bistability (OB) is given. 'Dispersive' OB is described to illustrate the general principles underlying the many types of OB and the history and development of the subject are outlined. Links are made between OB and other branches of physics and mathematics, and the prospects and limits for OB in all-optical switching are discussed.

1. INTRODUCTION

Optical bistability (OB) is the existence of two stable states for one given set of optical input conditions. The concept is simple but the subject is broad. Although it is only 12 years since OB was proposed[1] and six since it was first observed,[2] the subject ranges through topics in nonequilibrium phase transitions to potential applications in all-optical communications.

This breadth sets a difficult task for a reviewer, all the more so in a limited space, but I will try to indicate the development of the subject (section 3), the physical concepts involved and the relationship to other branches of physics (section 4), and some of the device potential (section 5). No aspect of the subject can be treated in any depth, especially theoretical methods, and the examples explained in greater detail are chosen as much for their didactic and heuristic value as for their importance in the subject.

Before discussing OB in general, I will describe in section 2 how OB arises from elementary considerations in one simple system. This will illustrate many of the basic ideas.

2. DISPERSIVE OPTICAL BISTABILITY

The properties of the well-known Fabry-Perot resonator are illustrated in figure 1. An optical length $\ell = nd$ (n-refractive index, d-mechanical length) separates two parallel partially-reflecting mirrors. The transmission $T = I_{output}/I_{input}$ depends upon the 'tuning' of the resonator (I is intensity, power per unit area). The 'on-resonance' condition is $nd = m\lambda/2$ (m-integer, λ-light wavelength). On resonance, the intensity inside, I_{inside}, is larger than I_{input} by the usual resonant 'magnification,' and T is high. The output intensity I_{output} is simply related to I_{inside} through mirror reflectivities i.e. $I_{output} = B\, I_{inside}$ (B-constant) or

$$T = B\, I_{inside}/I_{input} \tag{1}$$

If for some microscopic physical reason the refractive index (or equivalently the velocity of light) of the medium inside the resonator depends on intensity (e.g. $n = n_o + n_2 I_{inside}$, n_2 - nonlinear refraction constant) then the resonator tuning is intensity-dependent and the periodic transmission function T sketched in figure 1 can be written

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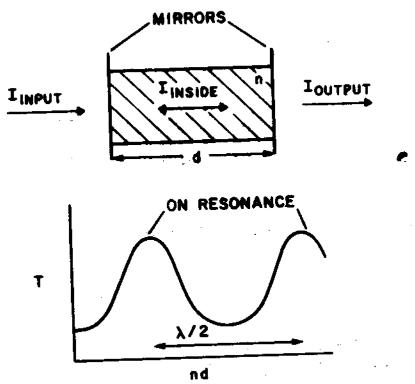


Figure 1 The (linear) Fabry-Perot resonator.

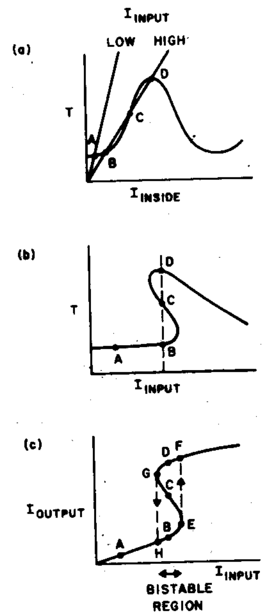


Figure 2 The nonlinear Fabry-Perot resonator and optical bistability (not to scale).

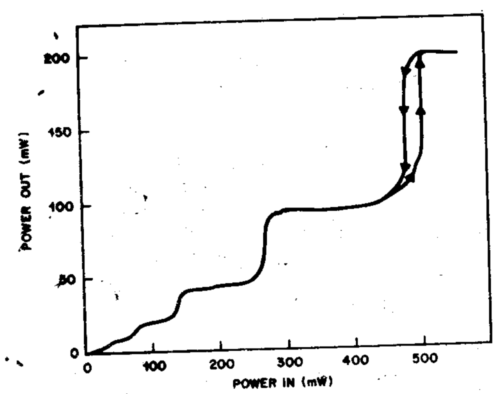


Figure 3 Optical bistability in a cooled InSb crystal,[5] thickness 0.5mm. Input power from a CO laser, beam size 0.2mm diameter, wavelength ~5.3 μm.

$$T = \frac{A}{1 + F \sin^2\left[\frac{2\pi d}{\lambda}\left[n_o + n_2 I_{inside}\right]\right]} \tag{2}$$

by simple substitution in the standard Fabry-Perot equation.[3,4] (A and F are constants). Note that now the 'tuning' of the resonator depends on I_{inside} and I_{inside} depends on the 'tuning' of the resonator. Formally solving equations (1) and (2) simultaneously to eliminate I_{inside} gives T (or equivalently, I_{output}) in terms of I_{input}. Analytically this is difficult but graphically it is simple (see figure 2).

For the parameters chosen in figure 2, at low incident intensities the two 'curves' intersect (figure 2(a)) only once at low I_{input} giving one steady-state solution (at point A) but at higher intensities three solutions are possible (points B, C and D). These multiple intersections are crucial for bistability. Repeating this procedure for every I_{input} yields the solution for T in terms of I_{input} in figure 2(b) or for I_{output} in terms of I_{input} in figure 2(c). Increasing I_{input} from zero, I_{output} will follow the lower part of the curve until point E. If I_{input} is increased further, the system must 'jump' discontinuously to the upper 'branch' to point F. Now on decreasing I_{input},I_{output} remains on the upper branch until point G when it jumps to the lower branch at point H. Thus the system may be bistable within the region indicated on figure 2(c). This bistability is called 'refractive' or *'dispersive'*, dispersion being the spectral variation of refractive index.

This kind of OB can be explained more directly. Suppose the cavity is initially 'off resonance.' Increasing I_{input} will also increase I_{inside}. The resonator therefore moves towards resonance, increasing I_{inside} further by resonant 'magnification' and establishing a regenerative process leading to a 'switching' into an approximately on-resonance state. Once there, the system can be held 'on' with lower I_{input} due to the resonant 'magnification' of I_{inside}, giving the bistability.

Figure 3[5] shows an experimental result taken using only a cooled crystal of the semiconductor InSb; the natural reflectivity (36%) of the crystal faces makes resonator mirrors. In this particularly simple observation, the resonator is very 'weak', and bistability is not seen until the resonator is 'nonlinearly tuned' through several resonator peaks.

Dispersive OB illustrates two basic points about OB

(1) some microscopic nonlinear optical effect is required (here nonlinear refraction)

(2) the alteration which the nonlinear medium makes on the optical field (here in 'optical phase') is macroscopically 'fed back' (here by multiple reflections from the resonator mirrors) to alter the field inside the nonlinear medium further.

The presence of hysteresis *and* switching is also characteristic of OB.

3. HISTORY AND DEVELOPMENT OF OPTICAL BISTABILITY

The first type of OB to be proposed[1] also used a Fabry-Perot resonator but relied on nonlinear optical absorption as the microscopic nonlinearity (*'absorptive'* OB).

Now the resonator is always tuned 'on' resonance. Increasing I_{input} increases I_{inside} and the optical absorption starts to 'saturate' (i.e. reduce progressively to a low value), giving an improvement in resonator 'quality' thus 'magnifying' I_{inside} further; this gives a regenerative process which can lead to switching and bistability.

Early attempts to measure this were unsuccessful[6] because it is difficult to find a material which saturates to a sufficiently low loss. After some further theoretical analysis[7] a further attempt was made and bistability observed,[2] but although absorptive OB was observed the OB actually arose more readily from the 'dispersive' mechanism[2] due to the nonlinear refraction also present in the material (Sodium vapour). Shortly after this observation an analytic solution[8] was found for OB for a special case of absorptive bistability using 'two-level' atomic

Type of Optical Bistability	*Proposed*	*Demonstrated*
(1) Absorptive Resonator	a (1969)	b (1975)
(2) Nonlinear Interface	c (1975),d (1976)	e (1979)
(3) Dispersive Resonator	b (1975),f (1976)	b (1975)
(4) Parametric Oscillator	g (1977)	-
(5) Polarization Modulation	h (1978)	h* (1978)
(6) Directional Coupler	i (1978)	i* (1978)
(7) Harmonic Generation	j (1979)	-
(8) Two-Beam Interferometer	k (1979)	k* (1979)
(9) Degenerate Four-Wave Mixing	l (1980)	-
(10) Small Volume Atomic	m (1981)	-
(11) Self-Focusing	n (1981)	n (1981)

* - demonstrated in a hybrid system only

Table 1 References (a)-1, (b)-2, (c)-14, (d)-15, (e)-16, (f)-3, (g)-17, (h)-18, (i)-19, (j)-20, (k)-21, (l)-22, (m)-23, (n)-24

vapour. Such a situation is empirically difficult to realize (although some very recent experiments have approximated these conditions[9,10]), but this analytic solution has stimulated a large amount of theoretical work[11] (see section 4).

One of the initial difficulties in OB was finding convenient nonlinear materials. A further important step was taken with the demonstration of *'hybrid'* OB[12] in which nonlinear optical behavior is synthesized using electrical detection and feedback applied to an electrooptic material. Many such hybrid systems have now been demonstrated[13]; these have proved useful in investigating various aspects of OB (including transient behavior and 'optical chaos' which will be discussed below) and in demonstrating new methods of OB.

Although the absorptive and dispersive resonator OB so far discussed have received the most attention overall, a large number of different types of OB has now been demonstrated and/or proposed, and I have summarized these in table 1; there are also many variants of some of these types. Common to all these types is the presence of both microscopic nonlinearity and macroscopic feedback and the existence of both hysteresis and switching. The graphical solution methods discussed above can also be applied to many of these. Note that resonators are not always required (e.g. numbers 2, 5, 6, 8, 9, 10, 11) and some methods may work with incoherent rather than laser illumination (e.g. numbers 2, 5, 11).

The majority of types of OB rely on nonlinear refraction as the microscopic nonlinearity (2, 3, 6, 8, 9, 11 and, as a special case, also 5). Numbers 1 and 10 utilize nonlinear absorption and numbers 4 and 7 use other frequency mixing nonlinearities. Nonlinear refraction can arise through either of two kinds of optical nonlinearity: (a) 'reactive' (or 'passive') nonlinearities which generally require high intensities but absorb no energy in the steady state; (b) 'absorbing' (or 'active') nonlinearities which often require low intensities but continually absorb energy. Saturating absorption is an example of type (b) while frequency mixing processes are the most common application of type (a). Nonlinear refraction can arise from either kind of nonlinearity. 'Absorbing' nonlinear refraction is well-known in atomic vapours and has recently been discovered in semiconductors near their bandgap energies. Dispersive OB using all-optical ('intrinsic') nonlinearities has now been observed using 'absorbing' nonlinearities in atomic vapours Sodium[2] and Rubidium[25,26], in Ruby,[27] in semiconductors InSb[5] and GaAs[28] and with 'refractive' nonlinearities in Kerr liquids.[29]

4. PHYSICAL PHENOMENA IN OB

The generality of OB suggests a more general physical and mathematical basis and I will try to demonstrate some of these connections in this section.

The steady state OB curve (figure 2c) is strongly reminiscent of the Van der Waals equation of state in thermodynamics (take incident field as 'pressure' and transmitted field as 'density') near its (first order) phase transition. However the OB system is not in thermal equilibrium as it is continuously driven by the energy of the input field. As such it is an example of a first order phase transition far from equilibrium. Such nonequilibrium systems are of considerable current theoretical interest and the example of OB (especially absorptive OB) has received a lot of theoretical attention.

One elementary consequence of the first order phase transition analogy is 'critical slowing down.' This has been both predicted(30) and observed(31) in OB. Consider the mechanical analogy of a ball moving in the potentials shown in figure 4(a) and the bistability curve in figure 4(b). At input intensity 1, in the lower state the 'ball' is stable in its potential well at A. Increasing the input intensity to the critical point 2 initially leaves the ball at point B because there is no slope to drive it into the 'upper' state (the potential well on the right). Thus the transition of the ball is 'critically slowed-down.' Increasing the input intensity to point 3 gives the necessary slope to drive the ball to C (thus avoiding the slowing down).

By making various approximations (e.g. using only a single 'mean' spatial distribution of optical field(8)) the OB system can be described by differential equations, the mechanical analogy can consequently be made rigorous and the 'potential' defined. (I will discuss a case where this is not valid below ('chaos')). The existence of a 'potential' and only a finite number of control parameters allows the use of catastrophe theory to illustrate the bistability(32,33) (see figure 5). OB corresponds to a 'cusp' catastrophe with consequently only two independent parameters, u and v, (functions of e.g. mirror reflectivities, resonator length, strength of nonlinearity, input power) determining the behavior of the output (simply related to the variable x in figure 5). Whether a particular variation of parameters gives bistability depends on whether the resultant trajectory in the (u,v) plane crosses the cusp region.

This kind of description involving a 'potential' can also serve as a basis for analyses involving statistical mechanics (through, for example, a one-dimensional Fokker-Planck equation(34)) where the potential describes some generalized 'free energy.' Such schemes offer a basis for investigating the effects of fluctuations on OB systems, ranging from quantum mechanical field fluctuations to simple noise in the incident laser beam(35). One immediate qualitative consequence is that neither 'stable' state is actually 'stable' as a sufficiently large fluctuation will eventually switch the system to the other state; in this aspect it is no different from any other 'bistable' system. Also one 'stable' state is more stable than the other, at any given incident intensity in the bistable region because one 'potential well' will be deeper than the other (i.e. only one of the two possible states is 'globally' stable, the other having only 'local' stability(36)).

In looking at the transient behavior of any OB system, because we deal with both microscopic nonlinearity and macroscopic feedback we automatically acquire at least two characteristic response times, a material 'relaxation' time constant, τ_M, and a feedback time constant, τ_F. The transient behavior depends on which is larger. In Table 2 I have set out the regimes for the most studied systems of absorptive and dispersive resonator OB together with some of the predicted time-dependent effects expected in each. In resonator systems the resonator 'round trip' time τ_{RT} is also relevant, although τ_{RT} is usually $\ll \tau_F$ because several 'round trips' are required to establish the overall feedback.

With the possible exception of critical slowing down which is probably a general phenomenon, the phenomena listed in table 2 are mostly restricted to the regimes listed. The situation in

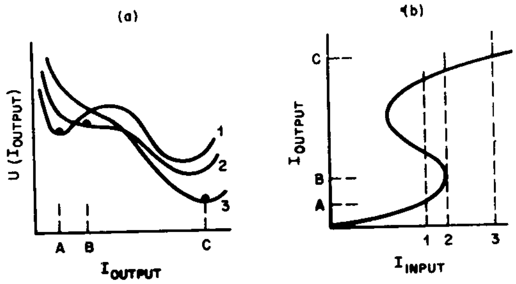
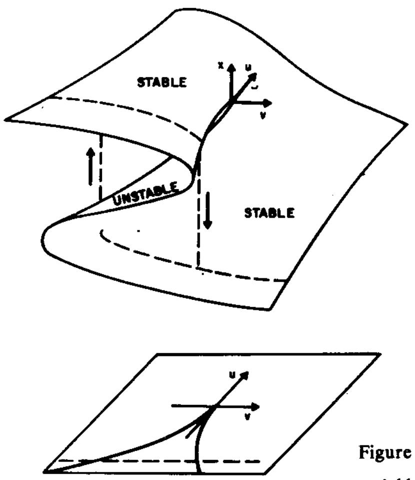


Figure 4 Potential diagram for critical slowing-down.



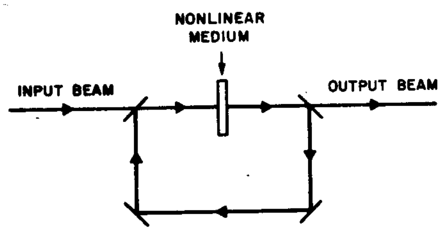


Figure 6 Ring resonator. The light is reflected by the mirrors in a 'ring'. Input and output mirrors are partially transmitting.

Figure 5 Cusp catastrophe[33]. Control variables u and v, response x.

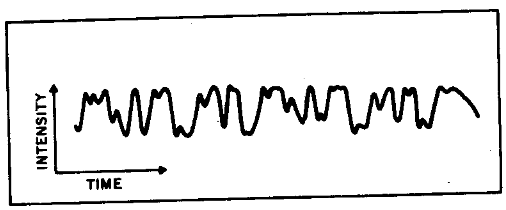


Figure 7 Chaotic output[42] obtained in parts of the bistability cycle with a hybrid system.

Time Dependent Phenomena in Absorptive and Dispersive OB

Relative *Time scales*	Switching *Time*	Absorptive†	Dispersive‡
			Phase switching g (1979)
$\tau_F >> \tau_M$	$\gtrsim \tau_F$	Critical slowing-down d (1979) Multiple mode self-pulsing (period τ_{RT}) f(1979)	Chaos and oscillations of period 2 τ_{RT} e (1979)
$\tau_F \sim \tau_M$	$\gtrsim \tau_F, \tau_M$		Overshoot switching and pulse frequency division L (1980).
$\tau_F << \tau_M$	$\gtrsim \tau_M$	Discontinuous appearance of Rabi oscillations a (1976) Critical slowing down d (1979)	Double nonlinearity self-pulsing b (1978) Critical slowing down c (1979)

τ_M - material relaxation time; τ_F - resonator feedback time; τ_{RT} - resonator round trip time.
† - all predictions for absorptive OB refer to atomic 'two-level' systems.
‡ - some of the predictions for 'two-level' atomic system absorptive OB may also apply to primarily dispersive OB operating with an atomic system near atomic transition resonance.

Table 2 References (first predictions) (a)-8, (b)-37, (c)-31, (d)-30, (e)-38, (f)-39, (9)-40, (h)-41

absorptive OB for $\tau_M \sim \tau_F$ is unclear at present. Of the predictions in Table 2 for dispersive OB, chaos,[42] overshoot switching and pulse frequency division,[41] double nonlinearity self-pulsing[37] and critical slowing-down[31] have been observed using the closely-related polarization modulation hybrid OB. Double nonlinearity self-pulsing has very recently been observed in intrinsic Fabry-Perot dispersive OB.[43]

There is not space here to discuss the many phenomena in table 2 though some are self-evident. By rapidly changing the phase of the incident optical field the system can be switched (phase-switching). The existence of oscillating or pulsating outputs for steady input fields is a common prediction for many 'OB' systems. Double nonlinearity self-pulsing results from two microscopic nonlinearities of different signs and timescales while multiple mode self-pulsing should result from the 'beating' of cavity modes coupled through a fast absorptive nonlinearity. Of course when such oscillations appear, the 'states' are no longer truly 'stable.'

Rabi oscillations or 'sidebands' are spectral features which arise in dilute atomic systems pumped by strong optical fields. The predicted discontinuous appearance reflects the transition from 'cooperative' atomic behavior at low intensities in a resonator when the atoms 'see' primarily the field from other atoms to 'non-cooperative' behavior in the upper bistable state, when the incident field dominates.

One of the most intriguing of the phenomena in table 2 is optical chaos. The optical 'ring' resonator (see figure 6) is similar to a Fabry-Perot resonator but the light goes in a ring rather than bouncing back and forth. In figure 7 the optical field at the front of the thin nonlinear refractive medium, E(t), is of the form

$$E(t) = E_i + AE(t-\tau_{RT})e^{i\varnothing_{NL}} \tag{3}$$

where E_i is the incident field transmitted into the resonator and $E(t-\tau_{RT})$ is the field one 'round trip' previously which has now propagated through the nonlinear medium acquiring nonlinear phase $\varnothing_{NL}$ (itself dependent on $E(t-\tau_{RT})$). 'A', a complex constant, describes linear loss and phase in propagating round the ring. The normal method of analyzing OB is to approximate equation (3), which is a *difference* equation, by a differential equation in which dE/dt approximates $[E(t) - E(t-\tau_{RT})]/\tau_{RT}$. This method enables the definition of a 'potential' as the differential equation resembles a mechanical dynamical equation, but is not always valid. For example, it is possible to imagine oscillations of period $2\tau_{RT}$, in the difference equation if an increase in $E(t-\tau_{RT})$ results in an increase in $E(t)$ and *vice versa;* these are not predicted by the differential equations. Oscillations at other integer multiples of τ_R are also possible and with several such oscillations running together, the output may appear 'chaotic,' and may ultimately even be truly aperiodic. An experimental result from a hybrid system is shown in figure 7. Such difference equations have been extensively studied mathematically[44] and have found applications as diverse as population dynamics and turbulence in fluid mechanics. Chaos is a common consequence of these simple deterministic equations.

5. DEVICES

The applicability of OB for making all-optical switching and memory devices is obvious. Various related effects are also possible with OB type devices. Increasing the macroscopic feedback in dispersive resonator OB for example leads to 'multistability' when several bistable regions overlap.

In most OB systems reducing the feedback until OB just disappears leaves a strong kink in the input/output characteristic whose slope dI_{output}/dI_{input} may be greater than 1 i.e. showing 'differential gain'[2] and enabling 'optical transistors' (also called 'optical triodes' or 'transphasors'[45]) to be constructed. Other applications of this 'kink' region include limiters, pulse shapers and OR and AND logic gates.

Switching devices are often compared through the parameters switching power, speed and energy. Hybrid OB devices have the lowest optical switching energies and powers so far demonstrated in OB ($5\times10^{-13}J$ and $10\ \mu W$) but are ultimately limited by electrical time constants probably to ~ 1ns for a device of low switching energy. A recent development in intrinsic materials has been the discovery of large nonlinear refractive effects (of the 'absorbing' or 'active' type) in semiconductors, for photon energies near to the bandgap: these have been used to demonstrate OB.[5,28,45] Switch-on can be very fast (e.g. picoseconds), but switch-off is determined by recombination times which can be in the region of nanoseconds although there are in principle ways of shortening this time. Such systems have so far been run cooled to 120K or less with powers as low as 8mW and overall switching energies of ~5nJ[45] although in a waveguide of cross section λ^2 (λ = wavelength) (the smallest allowed by diffraction) switching energies $\sim10^{-14} - 10^{-15}J$ may be possible in resonator devices and $\sim 10^{-12} - 10^{-13}$ in non-resonator systems; room temperature operation may yet be possible[45,46]. Similar energy limits apply to hybrid systems. These energies would be more or less independent of switching speed, the main trade off being between power and speed. (Switching energy in resonator systems is generally inversely proportional to resonator 'quality'). 10^{-15}J is about as low an energy as would be practical from a noise point of view, certainly at optical wavelengths as it corresponds to only a few thousand photons. These limits on switching energy are comparable to the best attainable by conventional electronics although Josephson junctions operating at 4K exhibit considerably smaller switching energies. Scaling of ultra high speed reactive nonlinearity devices(47) suggests switching energy limits $\sim$ 3 pJ and speeds $\sim$ 10fs (more than 1000 times faster than any current electronic system). Much work remains to be done in testing these limits and in developing suitable materials for the conditions of practical interest (e.g. room temperature at $\sim 1 \mu m$ wavelength for optical communications), but these scalings are very encouraging for practical applications.

The characteristics of any all-optical device differ from electronic ones in several important aspects. There are no interconnection wires with capacitances. They are immune to most electromagnetic interference. Even quite slow optical devices may still switch optical signals with bandwidths as high as 10^{13} Hz in principle. The absence of wire interconnections makes 2 dimensional processing (image processing) possible; even with slow devices this 'parallel' processing can correspond to very high data rates. Because these devices would work directly with light inputs they may find applications in optical communications technology and other areas where signals occur naturally in the form of light. Such special characteristics will determine the applications in which all-optical devices are most useful.

6. CONCLUSIONS

Although OB is still a comparatively young subject it has acquired a considerable breadth in physical configurations and phenomena while still retaining the unifying concept of microscopic nonlinearity with macroscopic feedback. Its development has been stimulated both by the many interesting physical effects involved and the possibility of practical applications. It represents a new trend in quantum electronics into all optical switching and amplifying external to lasers leading to new nonequilibrium thermodynamic systems and drawing on the fascinating mathematics of 'discontinuity' in catastrophe theory and difference equations.

At the time of writing, several groups are working on extending the understanding of the nonlinear refractive microscopic nonlinearities which appear to be most useful for OB, both in 'absorbing' and 'reactive' materials. There are doubtless also many other configurations capable of exhibiting OB, and none of the systems have so far been tested to anything like their physical limits. Some fundamental theoretical points remain unanswered. Why, for example, do resonator OB systems illuminated with nonuniform beams (as they always are in practice) switch at all? It is also too early to judge the ultimate practical usefulness of OB which may depend as much on technological considerations such as reliability and cost as on physical limits. However the prospect of a completely new switching technology is an exciting possibility, and the diverse physics of OB should remain a fertile area of study in the future.

FURTHER READING

Of necessity the reference list in this short paper is brief and incomplete. For a recent tutorial introduction and discussion especially of device potential see Smith and Tomlinson.(47) A comprehensive selection of recent work is contained in the "Proceedings of the International Conference on Optical Bistability," (1980) (see refs. 9 and 23) and a selection of short reviews is found in the July/August, 1980 edition of Optical Engineering (vol. 19, no. 4). A collection of the most recent papers appears in IEEE Journal of Quantum Electronics Vol. QE17 no. 3 (March, 1981).

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