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An introduction to optically bistable devices and photonic logic

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The physical principles of the phenomenon of optical bistability are described and it is shown that a family of devices or 'optical circuit elements' can be realized including memories, logic gates and amplifiers. The current range of materials employed and of properties demonstrated is reviewed: it is concluded that with the present state of knowledge a primitive optical computer could be demonstrated and that other signal-processessing devices are likely to emerge.

INTRODUCTION

The earliest ideas of 'optical bistability' relate to laser systems themselves and can be traced back nearly 20 years; as devices, the size and power consumption of such systems appear impracticable and this Discussion Meeting concentrates on small 'passive' devices made possible by recent discoveries of giant optical nonlinearities. An exception is made by consideration of such effects in semiconductor diode lasers for comparison as optical processing elements.

Szöke *et al.* (1969) proposed that a saturable absorber inside a Fabry–Perot optical resonator could exhibit two bistable states of transmission for the same input intensity. The simple idea is that at high intensities the induced transparency allows constructive interference at resonant wavelengths and, owing to the large internal field in this situation, the system can be held 'on' to lower incident intensities than those required to induce the transparency. The experiments quoted were, however, inconclusive and it was not until 1976 that Gibbs *et al.* (1976) demonstrated optical bistability with sodium vapour in an interferometer. They deduced that the effect was caused by nonlinear refraction rather than saturable absorption. The physics and mathematics underlying optical bistability has attracted much theoretical interest; a review was given by Abraham & Smith (1982), citing 250 papers, around 80% of which are theoretical.

All observations of bistability reported so far have involved a combination of *nonlinearity* and *feedback*. We shall find that both these concepts can have quite varied manifestations.

Nonlinearities

If we begin with intensity-dependent refraction and absorption we can simply express linear effects in intensity I by:

$$n(I) = n_0 + n_2 I, \tag{1}$$

where the nonlinear refractive index, n_2, can conveniently be measured in square centimetres per kilowatt, for refraction and to relate the absorption coefficient $\alpha(I)$ to linear absorption α_0,

$$\alpha(I) = \alpha_0 - \alpha_2 I. \tag{2}$$

Both n_2 and α_2 can be described by the conventional expansion of polarization P_i in powers of the electric field:

$$P_i = \chi^{(1)}_{ij} E_j(\omega_1) + \chi^{(2)}_{ijk} E_j(\omega_1) E_k(\omega_2) + \chi^{(3)}_{ijkl} E_j(\omega_1) E_k(\omega_2) E_l(\omega_3). \tag{3}$$

In the early nonlinear optical experiments it was assumed, consistent with experiment, that high laser powers (in the megawatt region) and intensities (of order gigawatts per square centimetre) were necessary to give electric fields (*ca.* 10^7 V cm^{-1}) comparable with atomic fields in order for second- and third-order polarization to be significant. We are concerned here with third-order polarization for intensity-dependent effects proportional to $\langle E(\omega)\rangle^2$, with $\omega_1 = \omega_2 = \omega_3 = \omega$. Values of $\chi^{(3)}$ reported before 1976 varied from 10^{-8} to 10^{-11} e.s.u.† as reviewed by Wherrett (1983, and this symposium).

In 1976, nonlinear refraction was explicitly observed at milliwatt powers at wavelengths near the absorption edge of a narrow gap semiconductor in our laboratory (Miller *et al.* 1978). Retrospectively, the effect could be recognized in earlier work on the spatial distortion of modes of the spin-flip Raman laser (see, for example, Scragg & Smith 1975; Ironside 1977).

The explanation of this enormous (10^9) decrease in required power lies in the near resonance between the triply degenerate frequency (ω) of the three field components $E_j(\omega), E_k(-\omega), E_l(\omega)$ and the frequency difference between initial and various intermediate states, corresponding (say) to a semiconductor energy gap or a two-level resonance such as an exciton. All energy denominators in a quantum mechanical calculation then resonate together. In a real system some damping is present to broaden the resonance. Away from resonance, $\chi^{(3)}$ can be separated into real and imaginary parts so that $\mathrm{Re}\,\chi^{(3)}$ leads to a description of nonlinear refraction n_2, and $\mathrm{Im}\,\chi^{(3)}$ gives the intensity dependence of absorption $\alpha(I)$; near resonance the influence of both effects will be present simultaneously. The presence of absorption allows *real excitation* of the system: redistribution of the electron population will temporarily change the properties of the material. The nonlinearity is thus said to be 'active', persisting for a characteristic population lifetime τ_r (varying from microseconds to picoseconds), and can also be said to be 'dynamic'. Just as linear refraction and absorption are related by the Kramers–Kronig relation, the same integral can be used to calculate the nonlinear refraction from the change in absorption induced by population redistribution if the relaxation processes are fast compared with the measurement time. This method has been successfully used to predict the magnitude and sign of 'active' effects in semiconductors (Miller *et al.* 1981). For band edge effects in small-gap materials it is sometimes known as the 'dynamic Moss–Burstein effect' and explains both the resonance behaviour and magnitude of n_2 near (a few tens of reciprocal centimetres) the band edge with values of n_2 of order 0.1–1 cm^2 kW^{-1}. Since a device can be switched with an increment $\Delta n \approx 10^{-3}$, power densities of order watts per square centimetre can be used in practice. This nine orders of magnitude improvement in power requirement clearly opens the way to micrometre dimension devices based on nonlinear optics in which light controls light.

Although the theory outlined above gives a simple explanation of the new effects, it is as yet imperfectly understood, particularly in the absorption mechanisms responsible for carrier

† 1 e.s.u. = 1 cm^3 erg^{-1} ≡ 1.4×10^{-8} m^2 V^{-2}.

excitation. Excitation from band tail or line wing is assumed with a photon energy deficit to be supplied by further carrier interaction. In the absence of theory, a measured α_{eff} has been used (Miller *et al.* 1981), giving the results shown in figure 1, showing good agreement with experiment.

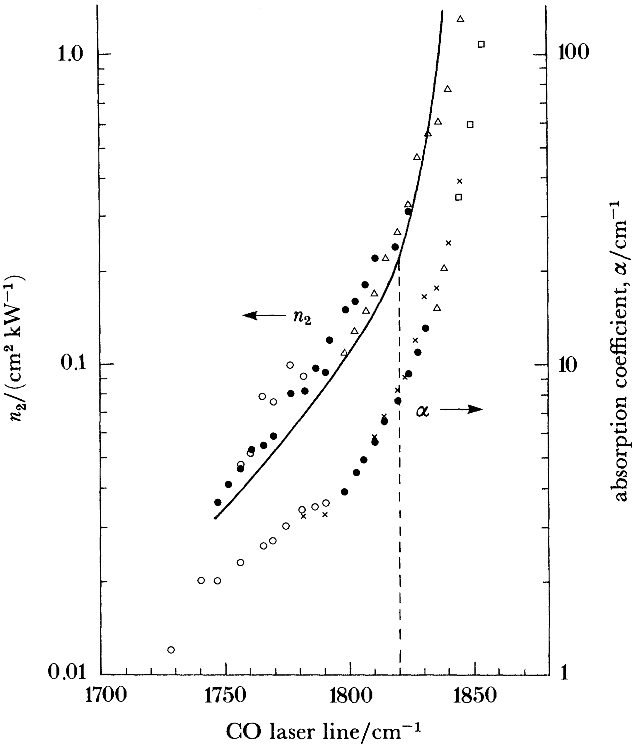

FIGURE 1. Experimentally measured absorption and n_2 as a function of frequency for InSb near 77 K. The n_2 curve is theoretical. (From Miller *et al.* (1981), with additional absorption data.)

In all cases the nonlinear refractive index, n_2, is proportional to the equilibrium carrier density generated by the incident intensity, I, from

$$n_2 \propto N = (I/\hbar\omega)\,\alpha_{\text{eff}}\,\tau_r.$$

However, the carrier density, N, can be generated arbitrarily quickly by rapidly applying a sufficiently high intensity I, i.e. more quickly than the carrier life time, τ_r. Thus the nonlinearity, and hence a required Δn, can be 'switched on' as rapidly as desired by the application of sufficient intensity. This proves to be useful in activating all-optical logic gates and memories. However, to 'switch off' the nonlinearity and hence the device, removal of the field leaves the material to relax within its characteristic lifetime, τ_r. At this level of argument there is a direct linear trade-off between magnitude of nonlinearity and switching speed. The smaller 'passive' nonlinearities are of course fast, probably substantially sub-picosecond, and therefore unnecessarily fast for devices limited by transit times dependent on their physical size. There exists considerable scope for 'engineering' τ_r to an optimum value by using well-known semiconductor procedures such as doping, use of surface recombination and sweep out.

Feedback

The simplest way to understand the effect of feedback is to consider the internal field in a nonlinear Fabry–Perot resonator. An interferometer of optical thickness nL shows peaks of transmission as a function of wavelength when

$$\tfrac{1}{2}M\lambda = n(I)\,L = (n_0 + n_2\,I_{\text{int}})\,L, \tag{3}$$

where I_{int} is the intensity inside the resonator and M is an integer. Consider an initial detuning from resonance of $\delta\lambda$ (figure 2*a*). As the incident intensity I_{i} increases, the optical thickness changes as the *internal* intensity I_{int} rises, through the term $n_2\,I_{\text{int}}\,L$ in (3). The transmission peak (figure 2*a*) thus moves towards resonance, increasing the transmission $T(\lambda)$ and thus giving a nonlinear characteristic (figure 2*b*). However, the internal intensity I_{int} is related to the 'incident' intensity I_{i} by

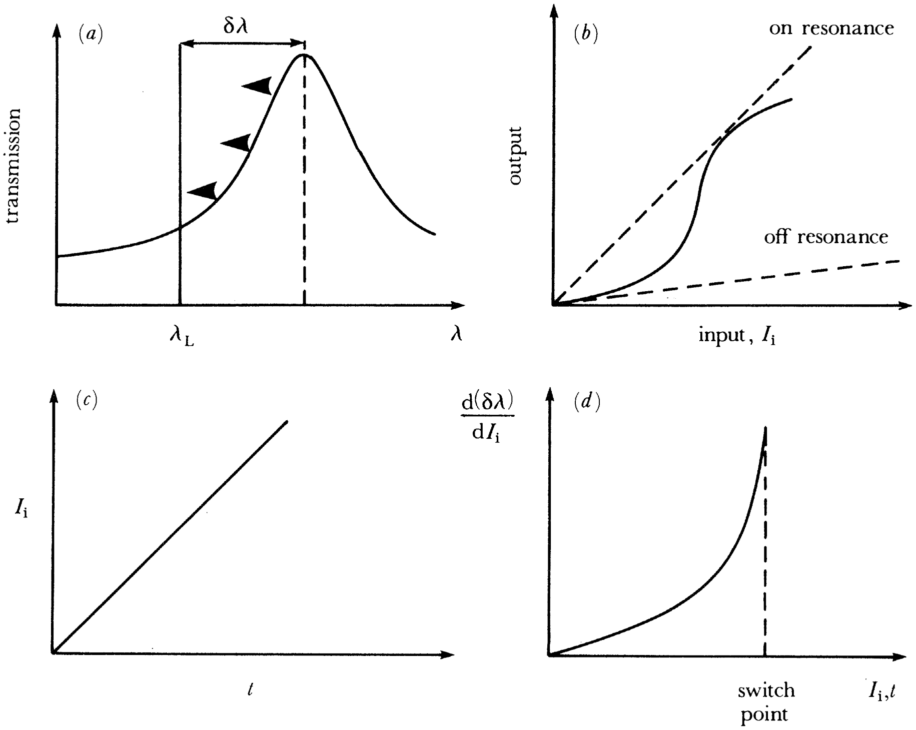

FIGURE 2. A typical Fabry–Perot characteristic (*a*) and the evolution of nonlinear transmission to switching behaviour (*b*–*d*). (See text.)

$$I_{\text{int}} = T(\lambda)\,\frac{(1+R)}{(1-R)}\,I_{\text{i}}, \tag{4}$$

so that I_{int} increases as $T(\lambda)$ rises, giving positive feedback to the nonlinear shift in optical thickness. In fact, then, the peak in figure 2*a* moves increasingly quickly toward the laser wavelength λ_{L}. If a linear intensity ramp (with time) is used to address the device, the rate can be expressed either as a function of incident intensity or time (figure 2*c*) and is given by

$$\frac{\mathrm{d}(\delta\lambda)}{\mathrm{d}I_{\text{i}}} = T(\lambda)\bigg/\left(\frac{T_{\max}}{2n_2L} - I_{\text{i}}\frac{\mathrm{d}T}{\mathrm{d}\lambda}\right). \tag{5}$$

The two terms in the denominator of the right-hand-side of (5) represent the nonlinear shift and feedback respectively. When the feedback, changing with I_i and $dT/d\lambda$, becomes large enough this denominator approaches zero and the rate of approach of the moving resonant wavelength to the pump wavelength diverges and becomes infinite. At this point the device switches suddenly on to resonance. The large internal field being now established, reduction in I_i leaves the resonator in its upper state and hysteretic, i.e. memory behaviour is seen. The simplest plane-wave theory is obtained by simultaneous solution of (4) for $T(\lambda)$ with the standard Airy formula describing figure 2*a*,

$$T(\lambda) = 1/(1+F\sin^2\theta), \tag{6}$$

where $F = 4R/(1-R)^2$ and $\theta = 2\pi nL/\lambda$.

The input–output characteristic may appear as in figure 2*b*, but varies according to choice of initial detuning, $\delta\lambda$. An experimental example is given in figure 3 for an InSb resonator activated by a CO laser at 1819 cm^{-1}. It can be seen that either a memory function, a region of differential gain or simply a nonlinear modulator can be obtained according to the device desired. The control of the characteristic depends upon choice of feedback characteristic and initial detuning. This leads to the family of optical circuit elements.

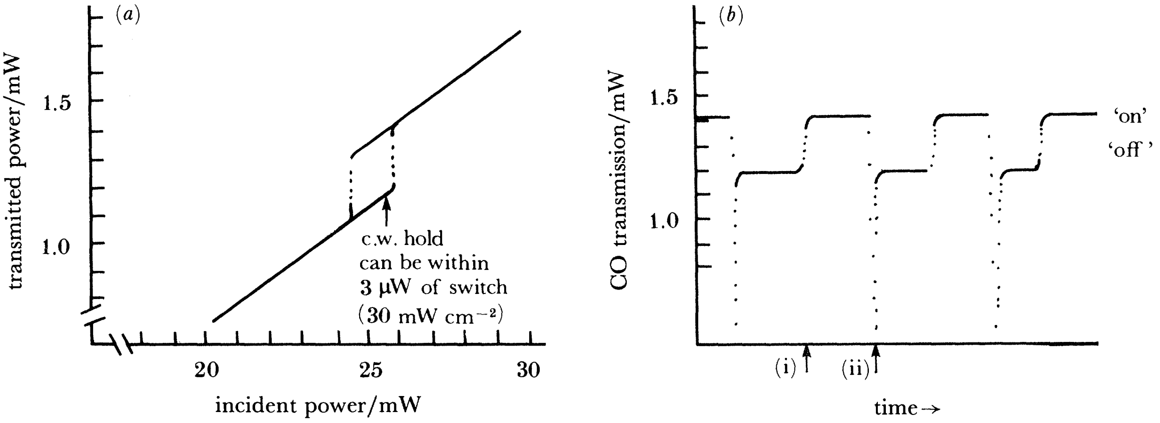

FIGURE 3. (*a*) Input–output characteristic for a 210 μm thick InSb etalon near 77 K, with 1819 cm^{-1} radiation. (Surface reflectivities 36%, spot size *ca.* 0.2 mm.) (*b*) External switching of the above device with the use of 35 ps, 1.06 μm wavelength pulses: (i) 5 nJ Nd:YAG pulse external address; (ii) interrupt.

Other nonlinearities and feedback mechanisms

Nonlinearities other than refraction have been employed for optically bistable devices. These include absorption, electronically simulated nonlinearity and radiation pressure.

Similarly, *feedback* can be contrived externally via electronic circuits, by using various geometries such as focusing or defocusing, by using guided wave configurations with and without distributed gratings, thermal effects via absorption and even, it is suggested, by microscopic internal field modification. So far, however, the 'system function' appears to resemble the refractive example cited here in all reported systems.

One case of note leads to a permanent as opposed to volatile memory and was reported by Hajto & Janossy (1983*a*, *b*). The optical behaviour of self-supporting α-GeSe$_2$ films showed nonlinearity at intensity levels around 50 W cm^{-2} and exhibited hysteresis and bistability without placing the sample in an optical resonator. Whereas above I have considered only electronic effects, Hajto & Janossy invoke thermal effects and photostructural effects – the latter possibly laser-induced reversible microcrystallization of the amorphous material – to explain a variety of intensity-dependent effects.

The thermal effects on absorption are very instructive. The temperature-dependent band tail is assumed described by Urbach's expressions

$$\alpha = \alpha_0 \exp\left[-\{(E_s - h\nu)/kT\}\right]. \tag{7}$$

The temperature rise of an illuminated spot is determined by the heat loss proportional to the difference between 'spot temperature' T, and film temperature, T_f. Thus

$$\tau_0\, \delta T/\delta t = \eta J D(T) - (T - T_f), \tag{8}$$

where τ_0 and η are constants, J is incident laser flux, D is a dissipation coefficient (dissipation/incident flux) that depends on α and thus on T. The stationary value of spot temperature is then given by

$$\eta J D(T) = T - T_f, \tag{9}$$

together with the stability condition

$$\frac{\partial}{\partial T}\left\{D(T) - \frac{T - T_f}{\eta J}\right\} < 0. \tag{10}$$

At certain critical intensities, the increasing absorption causes 'thermal run-away' and rapid switching occurs. A feedback occurs between the value of the absorption coefficient, α, and the temperature rise, which can give 'induced absorption bistability', there being stable and unstable regions in a plot of α_0 against $T - T_f$.

The additional existence of photostructural changes also affecting α gives phenomena showing memory functions that can exist in the absence of the laser beam. In comparison with the electronic effects the photostructural effects are slow (seconds) with thermal effects of intermediate size (milliseconds to microseconds). Corresponding effects in intensity-dependent refractive index will also occur and will be important in resonator-type devices.

Although this survey is incomplete we may conclude that there already exists a rich variety of nonlinear optical and feedback effects requiring fundamental study and giving excellent device prospects.

OPTICAL CIRCUIT ELEMENTS

The principles of nonlinearity and feedback inherent in a bistable optical switch have been shown to have wider application to a whole family of both analogue and digital optical devices equivalent to those currently used in electronic signal processing.

So far, devices able to perform all fundamental logic operations have been demonstrated, for example figure 3*b*. I illustrate in figure 4: (*a*) optical memory, (*b*) AND gates and OR gates that are self-resetting or if configured by initial detuning as in (*a*) can remain latched, (*c*) a transphasor amplifier, enabling the cascading of elements, fan-out and cross-modulation of differing frequencies to be achievable, and (*d*) a power limiter. Using these devices already demonstrated, we may deduce that a further series of devices in figure 5 can be predicted to be practical: (*a*) optically addressable directional optical switches, (*b*) two-dimensional

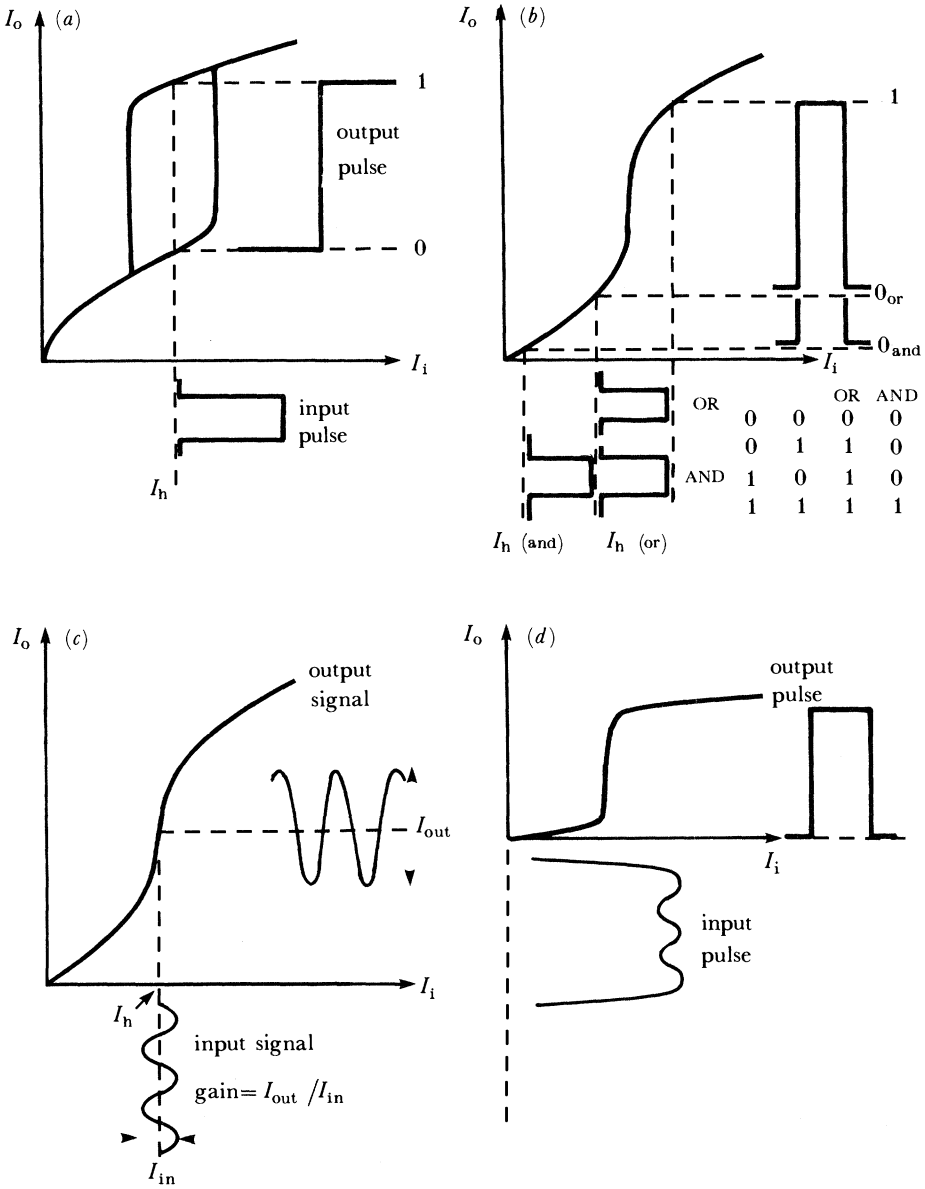

FIGURE 4. Basic optical circuit elements already demonstrated: (*a*) latching switch; (*b*) logic gate; (*c*) transphasor; (*d*) power limiter. I_h is the holding intensity.

parallel-to-series and series-to-parallel convertors, (*c*) array processors that can be externally programmed and can address each other in sequences, and (*d*) the possibility of optically addressable display devices.

MATERIALS, WAVELENGTHS AND CONDITIONS OF EXPERIMENTS IN OPTICAL BISTABILITY AND RELATED DEVICES

Table 1 lists chronologically some of the experimental systems that have been used to demonstrate optical bistability. The first two systems are included for historical purposes but it has been assumed that atomic vapour systems are not of practical interest, nor are those

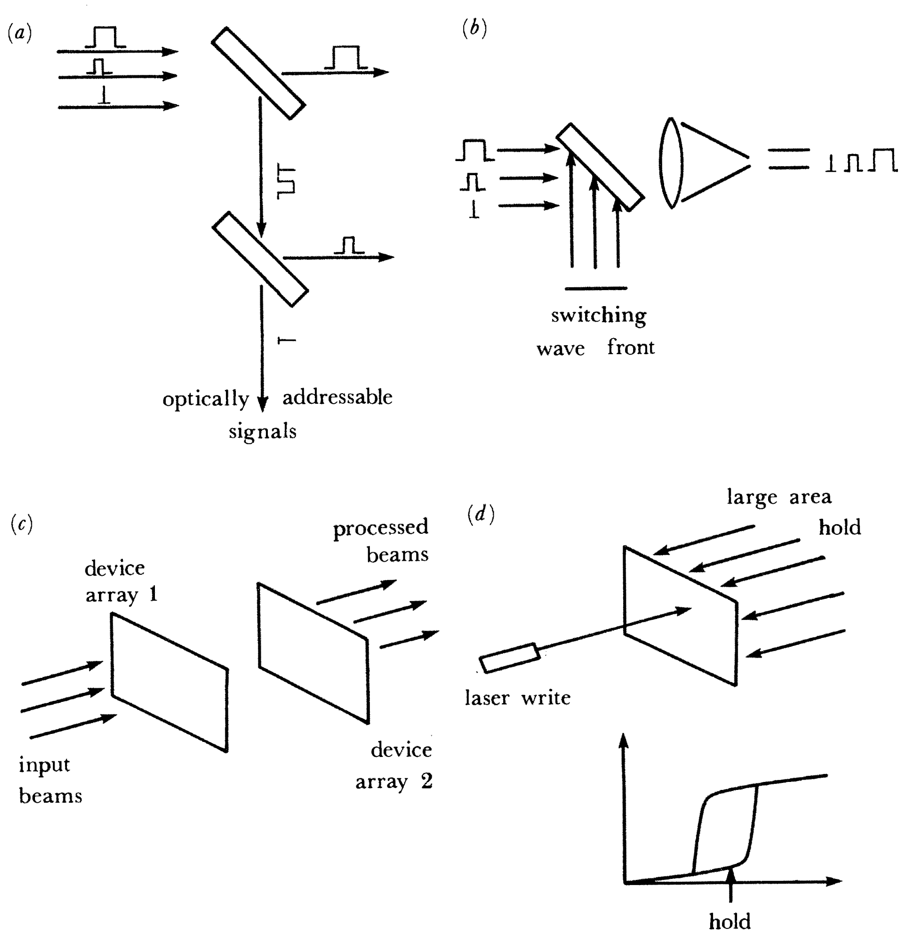

FIGURE 5. Potential devices based on optically bistable elements: (*a*) optically addressing signal; (*b*) parallel-to-series array processing; (*c*) serial array processing; (*d*) display.

systems that require very large laser powers. There is by now a substantial number of examples in solid materials, usually semiconductors. At the time of writing, no one material satisfies such desirable practical specifications as operation in the visible or 'optical fibre' wavelength region with milliwatt powers and at room temperature. Taking the best examples, however, switching on picosecond timescales, operation with milliwatt powers and a variety of wavelengths have been demonstrated experimentally.

The ability to 'hold' the system on a given part of its characteristic with a continuous wave (c.w.) beam is important for optical logic gates and transphasor amplifiers. In this respect InSb at 77 K is currently unique, enabling, for example, a device to be held within 3 μW of switch point and then externally addressed with short pulses. Figure 3*b* illustrates this system in use as a pulse-addressable optical memory and an AND gate. Use of the device in reflection produces a NOR gate. Two-beam signal amplification or transphasor action was observed in 1979, and recently gain as high as 10^4 has been demonstrated (Smith & Tooley 1984).

The other successful semiconductor so far, GaAs, has a nonlinearity approximately 10^{-3} as large, implying power densities around kilowatts per square centimetre compared with watts per square centimetre for InSb. However, the absorption levels are in general high in GaAs ($\alpha \approx 10^4\ \text{cm}^{-1}$) so that devices have not been operated or 'held' with c.w. beams. Future

Table 1. Optically bistable systems and devices

year	material	typical power	observation	comment	reference
1976	Na atoms	milliwatts	optical bistability	large and slow	1
1978	CS$_2$, etc.	gigawatts, pulsed	o.b.	large and fast	2
1979	InSb	milliwatts, c.w.	o.b. transphasor with gain logic gates incoherent switching	small, fast c.w. + external address 5 μm 77 K	3 4 5 6
1984	InSb	kilowatts, pulsed	optical bistability limiter	10 μm, 300 K 2-photon excitation	7
1979	GaAs	milliwatts, modulated	o.b.	0.8 μm, not very small, 300 K	8
1983	GaAlAs m.q.w.	watts, modulated	o.b.	not c.w.	9
1981	Te	megawatts, pulsed	o.b.	300 K, 10 μm	10
1982	GeSe$_2$	milliwatts, c.w.	o.b., etc.	slow, visible photo-refraction	11
1982	Si	megawatts, pulsed watts	tuning o.b.	300 K, 1.06 μm slow, thermal	12
1983	CdS	megawatts, c.w.	o.b.	5 K, visible	13
1983	CuCl	megawatts, pulsed	o.b.	5 K, visible biexciton	14
1984	InAs	milliwatts	o.b.	3 μm	15
1984	CdHgTe	kilowatts, pulsed	o.b.	12 μm, 2-photon	16

References: 1, Gibbs *et al.* (1976); 2, Bischofberger & Shen (1978); 3, Miller *et al.* (1979); 4, Miller & Smith (1979); 5, Seaton *et al.* (1983); 6, Smith & Tooley (1984); 7, Kar *et al.* (1983); 8, Gibbs *et al.* (1979); 9, Gibbs *et al.* (1982); 10, Staupendahl & Schindler (1982); 11, Hajto & Janossy (1983*a*, *b*); 12, Eichler (1982, 1983); 13, Dagenais & Winful (1984); 14, Grun *et al.* (1984); 15, Poole & Garmire (1984); 16, Miller & Parry (this symposium).

investigation of materials will no doubt be directed to obtaining such operation, since this will be necessary for optical circuits to be built. Other materials of interest include liquid crystals and the molecular gases NH$_3$ and SF$_6$, which may find use in 'optical clock' driving devices.

Conclusions

In recent years the physics of giant refractive and absorptive nonlinearities has progressed sufficiently rapidly to allow the demonstration of a family of optical circuit elements. Although there remains much to be done to make the systems sufficiently practical to constitute a new technology, the capability to demonstrate simple optical signal processing now exists, and a demonstration of a primitive optical computer should be possible.

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