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Applications of All-Optical Switching and Logic

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Applications of all-optical switching and logic

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In this paper I review the present status of all-optical switching and logic elements. I then discuss their future potential, taking account of limitations imposed by materials, considerations of system architecture, and fundamental physical mechanisms. I conclude by describing two areas in which all-optical signal-processing systems are likely to have a major impact.

1. Introduction

One of the major driving forces behind the current interest in optical bistability and all-optical switching and logic is certainly the hope that important device applications will arise. How realistic are these hopes, and how close are we to these applications? In this paper I summarize the present status of research in these areas, and offer some speculations on the future potential of photonic switching and logic.

2. Present status: overview

There are at present a large variety of bistable optical devices that have been demonstrated. Although many are based on the nonlinear Fabry–Perot resonator, a number of non-resonant devices, including the nonlinear interface and the self-focusing bistable device, have also been studied (Bowden 1983). At this meeting we have heard of new ideas for devices based on bistability due to increasing absorption (D. A. B. Miller, H. Haug & S. Schmitt-Rink, M. Dagenais), self-induced electro-optic effect (SEED) (D. A. B. Miller), radiation pressure (P. Meystre & H. Walther), and novel guided-wave structures (G. I. Stegeman & H. G. Winful).

A wide range of optical materials has been used. Most materials have limitations based on wavelength and power requirements. At this meeting, we have heard of novel results from the use of multiple quantum well (m.q.w.) material (D. A. B. Miller; H. M. Gibbs), and exciton effects in semiconductors (R. Levy *et al.*; H. M. Gibbs; M. Dagenais; D. A. B. Miller).

Clearly, photonic devices are still in the active research stage. There are few current practical applications. There are, however, many exciting prospects.

3. Prospects

A number of recent developments have increased the interest in digital optical signal-processing devices and techniques. Laser technology has now advanced to the point that lasers are being used in consumer electronics. Optical fibre communication systems are being widely installed. Integrated optics spectrum analysers are being marketed.

At this meeting, we have already heard some ideas for optical computing (A. C. Huang), and optical switching and logic (A. C. Walker *et al.*; H. A. Haus). Later in this paper I shall touch on some possibilities for optical parallel processing and mode-locking of semiconductor lasers. Can we make some general statements about future applications?

Figure 1 shows a 'plot' of switching time benchmarks for a variety of mechanisms and devices. The longest time point is the cycle time of the fastest currently available electronic computer: the CRAY-2. The fastest time point is a visible optical cycle. Note that all time points below *ca.* 10 ps are optical. I shall comment further on the potential of photonic devices for ultrafast switching later in this paper.

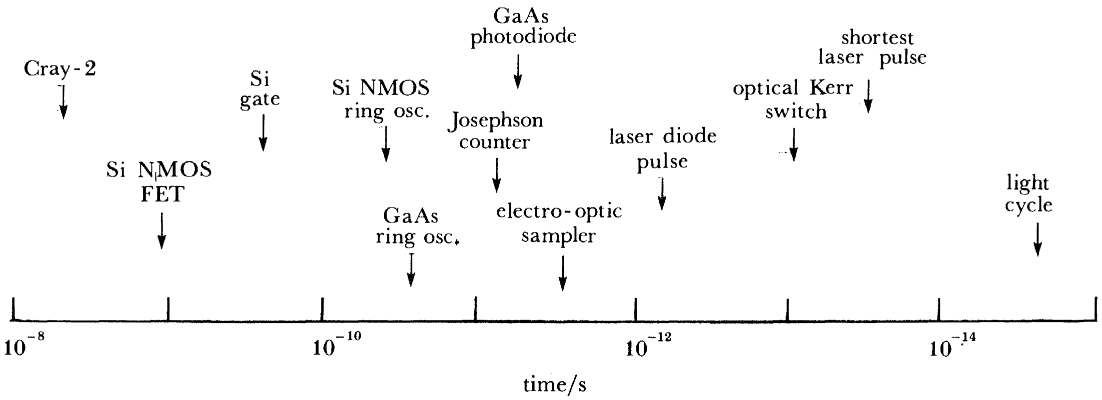

FIGURE 1. 'Time line' showing time benchmarks that are pertinent for several switching and signal-processing technologies.

Figure 2 shows an extrapolation of a plot of the capacity of experimental optical fibre communications systems as a function of year. If the present trend towards higher-capacity systems continues, there will soon be a severe incompatibility between the bit-rate capacity and the limits imposed by the electronics used for switching and signal handling. Clearly there is a need for fast, high-capacity optical systems to 'push back' the boundary between the optical

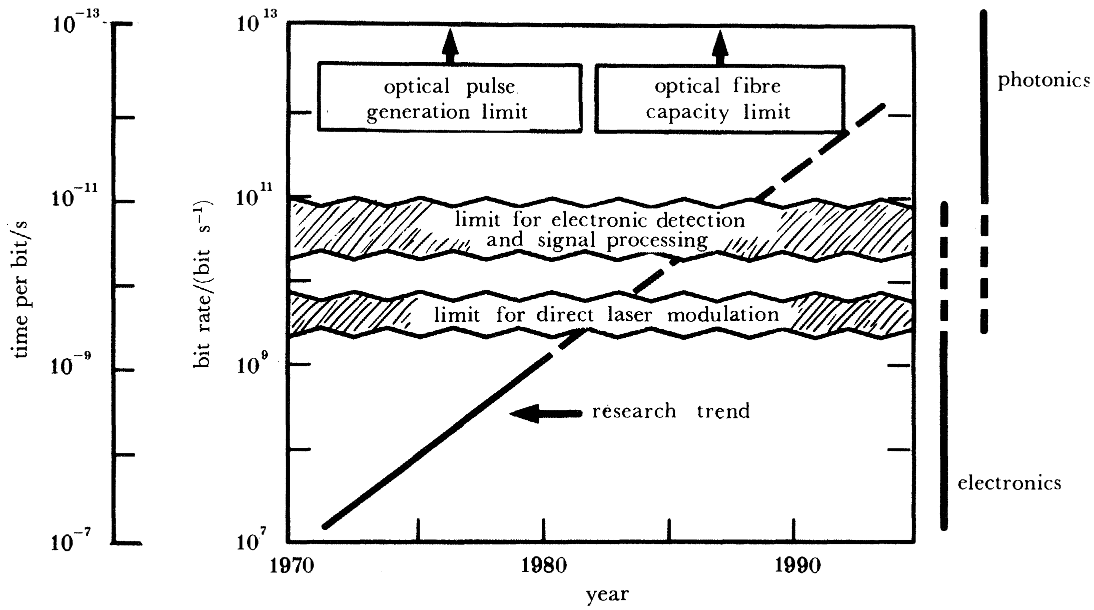

FIGURE 2. An extrapolation of current progress in optical communications systems capacity over the next decade.

(transmission) part of the system and the electronic (signal processing and switching) part. To focus more precisely on the role that optical signal-processing elements can play, it is necessary to examine their fundamental limitations.

4. Towards fundamental limits

Much work has already been done in the search for materials with the right combination of properties for photonic switching applications. In general we can state that the ideal material should have a large optical nonlinearity at the wavelength of interest, fast response time, high resistance to optical damage, and adequate transparency. In addition, because in many systems there will be an interface with electronics, it would be desirable to use a semiconductor optical material that would facilitate the fabrication of the optics–electronics interface. So far, multiple quantum well (m.q.w.) material comes the closest to meeting all these requirements.

It is important to design systems that can take advantage of the special properties of optical switching devices. A. C. Huang (this symposium) has described novel designs for optical computers based on this philosophy. The high degree of parallelism possible with optical devices (see §5) permits computer and switching system architectures very different from those currently used for electronic systems.

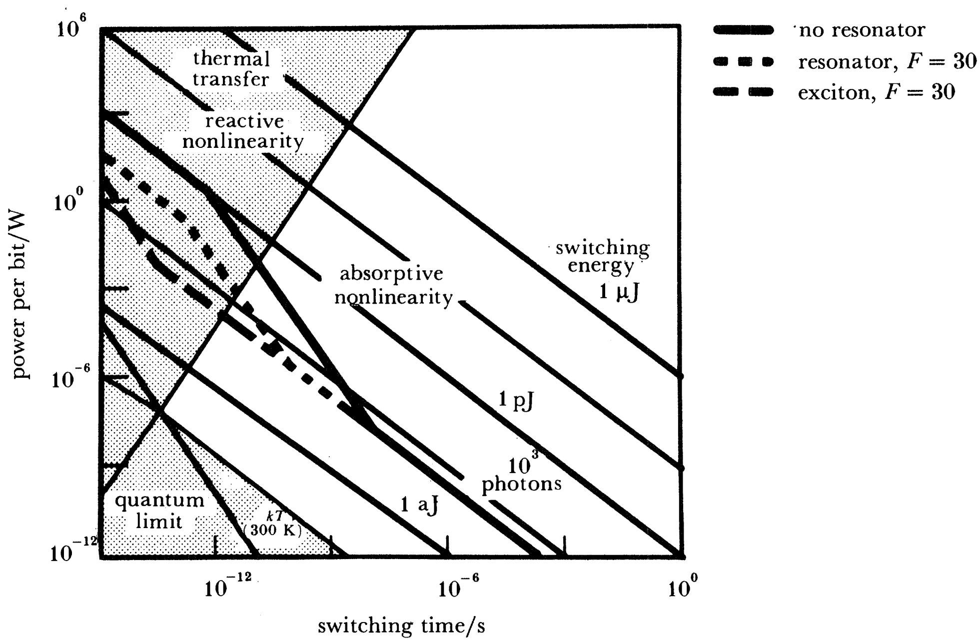

Figure 3. Limits for optical switching devices, with λ set to 0.85 μm. The ordinate is the power that must be applied for a switching operation, and the abscissa is the length of time that the power must be applied. The lines at 45° are lines of constant switching energy.

Figure 3 shows some fundamental limits for optical switching devices (Smith 1982). Certain general considerations will apply to all switching elements. Many years ago, J. von Neumann pointed out from thermodynamic arguments that a single (non-reversible) 'yes–no' switching operation must dissipate a minimum of about kT of energy (here k is Boltzmann's constant and T is the absolute temperature). Quantum mechanical considerations lead to the assertion that a quantum switching operation must use at least h/τ of energy, where h is Planck's constant

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and τ is the switching time. Because these mechanisms represent a 'noise' level for the signal of interest, we should expect that a practical device would require a signal level of many times the kT or $h\nu$ limits.

Keyes (1970) at I.B.M. has examined in depth the physical limits on a number of different types of switching devices (see also Keyes 1975). He shows that for a repetitive operation the heat dissipated per switching operation sets an upper limit to the achievable switching rate (a higher rate would result in an unacceptable temperature rise in the device). The region affected by this consideration is also shown in figure 1 and is labelled 'thermal transfer'. (Note that this area represents power *dissipated* per switching operation. The actual power used may be higher if it is not absorbed in the switching element.) A higher power can also be used if the device is operated at less than the maximum repetition rate.

If an optical switching device operates by absorbing light and saturating an optical transition in some material, certain general relations between power absorbed and switching time can be derived. It can be shown that, for the case where the response time, τ, of the switching element is taken to be the shortest time compatible with the material response, the switching power can be represented by the line labelled 'absorptive nonlinearity'.

A similar argument can be made for a material exhibiting an optical Kerr effect, i.e. the refractive index has a term proportional to the light intensity. For a material with the largest-known value of electronic nonlinearity, the polydiacetylene PTS ($n_2 = 6 \times 10^{-12}$ cm^2 W^{-1}), we obtain the limits shown by the line labelled 'reactive nonlinearity'.

A third type of limit is imposed by statistical considerations. To have reliable switching, the noise associated with 'on' and 'off' states must be sufficiently low. This noise will depend on the number of light photons, or number of absorbing atoms, involved in the switching operation. I have somewhat arbitrarily selected 10^3 photons as the number necessary for low-noise operation, and this limit is also plotted in figure 3.

These limits have been derived without any assumptions about the use of an optical resonator. If we assume a resonator with a finesse of 30, the optical limits are reduced as shown by the dotted line in figure 3. Note that the limit of 10^3 photons will still apply. I have also shown in figure 1 the limits appropriate for a device using the recently investigated room-temperature excitonic nonlinearity in GaAs-GaAlAs m.q.w. material. For this excitonic resonance, the effective oscillator strength is much larger than an atomic oscillator strength. Recent measurements have demonstrated an effective value of $|\mu|^2 \approx 50(ea_0)^2$, where e is the electronic charge and a_0 is the Bohr radius. The broken line in figure 3 shows the limits for an optical switching element with a resonator finesse of 30 making use of such an excitonic nonlinearity.

In figure 4 I show how the limits on optical devices compare with those on semiconductor electronic switching devices and Josephson switching devices. In the 10^{-7} to 10^{-11} s region, the limits for optical devices are slightly below the best current semiconductor device performance. At switching speeds of 10^{-12} to 10^{-14} s, however, optical devices appear to have no competition. This unique capability for subpicosecond switching is one of the most exciting aspects of this new technology.

The switching power required in this short-time region puts the operating point within the 'thermal transfer' region discussed earlier. For this reason it does not appear feasible to design a *general purpose* high-speed, digital optical computer. However, for many applications these thermal limits will not present severe problems.

There are many factors that relate to the choice of a switching technology that cannot be

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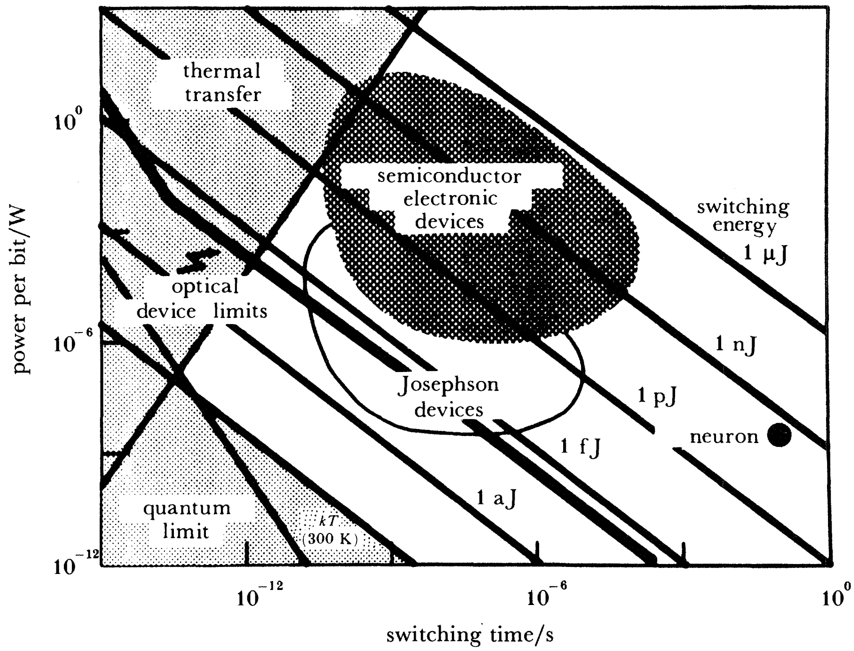

FIGURE 4. Comparison of optical switching device limits with present results for other technologies.

shown on a power–time plot. In many cases it is desirable to perform some signal-processing operation on a light signal, either because the incoming signal is in the form of light or because freedom from electromagnetic interference is desired. Optical switching devices typically operate at room temperature. In many cases, they have extremely large bandwidths and can be adapted for many special functions such as rapid parallel processing of information. For these reasons there will be cases where optical switching systems will be used, even in an area of figure 4 in which other technologies show a switching-energy advantage.

5. PREDICTIONS: TWO AREAS OF MAJOR IMPACT

There are many applications of optical switching devices that can be predicted. I select here two areas that appear to have great promise.

(a) *High-speed switching*

In optical communications systems the characteristics of large bandwidth, high speed and the ability to process signals already in the form of light should be particularly useful. It would be possible, for example, to make an optical multiplexer that would take several optical data streams, each with the maximum data rate compatible with electronic devices, and time-division multiplex them onto a single fibre. At the other end a similar all-optical device could demultiplex to get back to data rates that can be handled with electronic components.

A multiplexer can be made from a number of triggerable switching elements, as shown in figure 5*a*. A trigger pulse with the proper time synchronization is required to multiplex pulses as shown. Each element could be made from a properly designed bistable optical device, as shown in figure 5*b*. This bistable device consists of a suitable nonlinear optical material in a

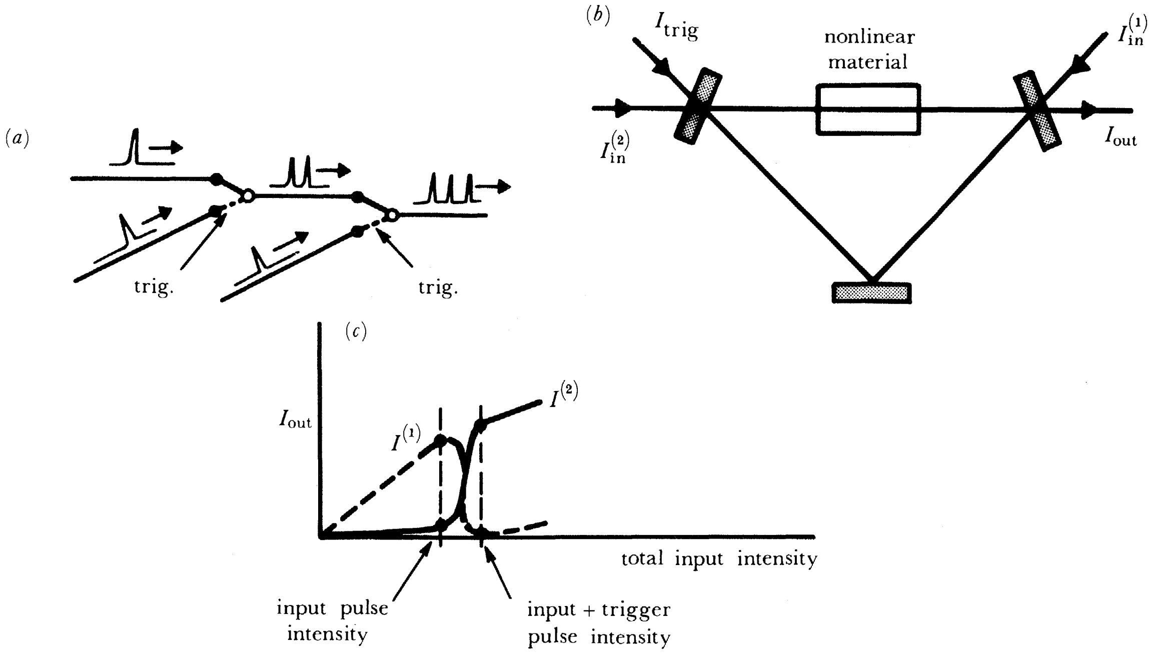

FIGURE 5. Optical time-division multiplexer: (*a*) overall schematic diagram; (*b*) ring triggerable bistable element; (*c*) output characteristic of ring bistable element.

ring resonator. The ring geometry allows separation of the inputs and outputs. However, some polarization selectivity may have to be employed to avoid interference effects between the two input beams $I_{in}^{(1)}$ and $I_{in}^{(2)}$. Let us assume here that pulses in these two beams are never present simultaneously in the element. The output intensity depends on the total input intensity $I_{in}^{(1)} + I_{in}^{(2)} + I_{trig}$, as shown in figure 5*c*. If the input pulses are of intensity slightly less than the critical intensity corresponding to the 'knee' of the curves, the output in the absence of a trigger input will consist solely of $I_{in}^{(1)}$. However, during the time that a small trigger signal, I_{trig}, is present, the output will consist solely of $I_{in}^{(2)}$. Because of the sharp 'knee' in the characteristic curves, only a small I_{trig} is required to accomplish this switching.

In my laboratory we have recently been conducting experiments on the use of m.q.w. material as a saturable absorber for mode-locking semiconductor diode lasers. Stable passively mode-locked pulse trains of 10 ps pulses have already been obtained, and much shorter pulses appear possible.

(*b*) *Parallel processing*

As mentioned earlier in this paper, many optical devices are especially suited for parallel operations such as image processing. As a specific example, consider a 1 cm^2 Fabry–Perot etalon containing GaAs m.q.w. material. Such an etalon has *ca.* 10^7 resolvable spots, and each spot is a bistable element with a (measured) response time of 30 ns. The throughput of this device is 3×10^{14} bit s^{-1}, which corresponds to simultaneous telephone conversations by the entire population of the world! In principle the total optical power required would be only 0.1 W. Clearly this capability is a powerful one, and it will be a challenge for systems designers to develop optical systems that make use of this potential.

6. Conclusions

As one can see by looking at the papers presented at this meeting, the field of optical switching and logic is still in its infancy, and new mechanisms, materials, devices, and systems are currently being invented and studied. In general we can state the following.

(*a*) The strong points of optical switching devices are:

(1) speed: with an electronic nonlinearity or free-carrier generation in semiconductors, subpicosecond switching times are possible;

(2) capability for parallel processing: with a liquid crystal bistable array, image processing has already been demonstrated;

(3) compatibility with optical fibre systems: i.e. the ability to treat directly signals already in the form of light;

(4) bandwidth: with a non-resonant bistable optical device or a nonlinear interface, a large fraction of the visible light bandwidth can be used.

(*b*) The weak points of optical switching devices are:

(1) high power is required for fast switching: this will tend to create thermal problems unless highly transparent materials are used;

(2) materials do not yet exist that have the ideal combination of properties for these devices;

(3) the minimum size of an optical switching element cannot be reduced below a volume of about λ^3;

(4) theoretical and practical problems involved in waveguide and microresonator formation in λ^3 volumes have yet to be overcome.

In the future, it will be important to design systems that can make full use of the capabilities of optical switching devices. Such systems, which exploit the potential speed and bandwidth capability of optical devices and their capability for parallel processing of information, should find significant applications in communication and computing fields.

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