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On the Physical Limits of Digital Optical Switching and Logic Elements

By P. W. SMITH

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In this paper we identify and discuss some fundamental physical mechanisms that will provide limits on the speed, power dissipation, and size of optical switching elements. Illustrative examples are drawn primarily from the field of bistable optical devices. We compare the limits for optical switching elements with those for other switching technologies, and present a discussion of some potential applications of optical switching devices. Although thermal effects will preclude their wide application in general-purpose computers, the potential speed and bandwidth capability of optical devices, and their capability for parallel processing of information, should lead to a number of significant applications for specific operations in communication and computing fields.

I. INTRODUCTION

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 fiber communication systems are being widely installed. Integrated-optics spectrum analyzers have been developed.

In the research stage it has been shown that optical fibers can be used to transmit information at rates approaching 1 THz.[1,2] This rate is much beyond the capabilities of any presently known electronic light detector. Thus, to utilize this information-handling capacity, some form of optical signal processing will have to be performed before the light signals are converted to electronic ones.

Low-power integrated-optics light switches[3] and low-energy integrated-optical bistable devices[4] capable of performing optical logic have been demonstrated. It is tempting to propose that such digital optical switching elements be used to construct high-speed computers as well as repeaters and terminal equipment for optical communications systems. To examine these possibilities we need to understand: (*i*) What are realistic possibilities for speed, power dissipation, and size for optical switching elements? and (*ii*) What are the fundamental limits imposed by the physics of the nonlinear interactions, and by the available optical materials?

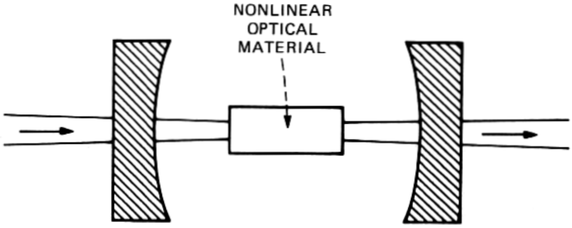
Previous studies of these optical device limits have been made by several authors. The pioneering work of Keyes[5] examined several nonlinear optical processes and concluded that thermal considerations imposed severe limits on the use of optical logic elements. A similar assessment was made by Landauer.[6] A more optimistic conclusion was reached by Fork,[7] who suggested that by using suitable interactions and resonant structures, competitive optical elements could be realized. Recently Kogelnik[8] has examined the role of integrated-optics devices and has concluded that they may well be most useful in performing functions that cannot be provided by other technologies.

In this paper we will attempt to provide a perspective on the ultimate limits of optical switching elements, and the areas in which one might expect optical signal processing to offer a significant advantage over other technologies.

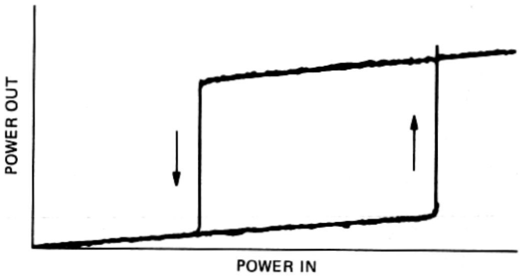
II. BISTABLE OPTICAL DEVICES

In this paper we will draw examples from the field of bistable optical devices. This is to some extent due to a bias of the author, as he has worked on these devices for several years. However, in many respects, bistable optical devices are the most basic binary optical systems, and they have a demonstrated capability for low-energy latching operation. In addition, these devices are extremely versatile and can function as optical limiters, differential amplifiers, and optical logic elements. Their transmission can also be controlled by another optical beam creating an "optical triode."

A generic bistable optical device is shown in Fig. 1. It consists of a Fabry-Perot resonator containing a nonlinear optical material. This nonlinearity can be either a saturable absorption (an absorption that decreases with increasing light intensity), or a nonlinear refractive index (a refractive index that increases or decreases with increasing light intensity). The bistability arises from the simultaneous requirements that the intensity of light inside the resonator, and thus the transmitted light intensity, depends on the resonator tuning (or the loss in the resonator), and the resonator tuning (or the loss in the resonator) depends on the intensity of light in the resonator. The resonator transmission exhibits optical hysteresis, as shown in Fig. 1b.



(a)



(b)

Fig. 1—(a) A generic bistable optical device. (b) Typical output power characteristic for a bistable optical device.

Optical bistability has been demonstrated using both intrinsic devices, which use materials with an intrinsic optical nonlinearity, and hybrid devices, which use a detector and an electrooptic modulator to create an artificial nonlinear medium.

Many types of bistable optical devices have been developed and studied. Small, integrated-optics hybrid devices have been operated with less than a picojoule of optical energy.[9] Two-dimensional arrays of bistable elements using a liquid-crystal light valve have been demonstrated for image-processing applications.[10] Nonresonant devices have been developed that use no Fabry-Perot resonator and thus have a broad frequency response and can switch very rapidly with a suitably fast-responding nonlinear material.[11,12]

III. SPEED AND POWER LIMITATIONS

In this section we will discuss the fundamental physical mechanisms that limit the performance of these devices. Although we will specifically consider bistable optical devices, the results will be generally applicable to any passive digital optical switching elements.

The switching speed of a bistable optical device is limited by the buildup time of the resonator, and by the response time of the nonlinear medium. In principle, the resonator response time can be made negligible by reducing the length of the resonator, or by using a nonresonant configuration. The ultimate limit is set by the response time of the nonlinearity. Materials exhibiting strong electronic nonlinearities are known with response times of $<10^{-14}$ seconds. To operate a device with such a short response time, however, requires high light powers.

The switching power and switching speed of a bistable optical device are not independent. For example, if the response time of a given device is dominated by the resonator buildup time, the response time can be reduced by a factor of two by halving the length of the resonator. However, as only half the length of nonlinear material is now available, twice the switching power must be used to reach the switching threshold.

R. W. Keyes[5] has discussed several physical processes that limit the switching power and speed of optical devices. For any (nonreversible) switching operation, it can be shown that a minimum energy of the order of kT must be dissipated (k is Boltzman's constant and T is the absolute temperature). Quantum mechanical considerations lead to the assertion that a switching operation must dissipate at least h/τ of energy (h is Planck's constant and τ is the switching time). These limits are shown in Fig. 2, which is a plot of the power required for a switching operation as a function of switching time, i.e., the time for which this power must be applied. The frequency label on the horizontal axis is appropriate if switching is being done repetitively so that a switching time limit implies a limit on the data rate.

Keyes has discussed the limitations imposed by the heat dissipated in a switching element. For continuous operation, this heat sets an upper limit on the achievable switching rate (a higher rate would result in an unacceptable temperature rise in the device). The region affected by such thermal considerations is also shown in Fig. 2, assuming a value of heat transfer coefficient (100 W/cm^2) that is appropriate for liquid-cooled elements and a maximum acceptable temperature rise of 20°C. In many cases a lower temperature rise may be required because of the rapid refractive index change with temperature exhibited by most optical materials. It is important to note that a switching device can operate in this "thermal transfer" region provided that it is operated at less than the maximum repetition rate, or that not all of the switching power is dissipated in the device.

Keyes considered the case of an optical switching device that operates by absorbing light that saturates an atomic transition and changes the optical properties of the material. To achieve appreciable saturation, the condition

$$\sigma I > hc/\lambda\tau_D \tag{1}$$

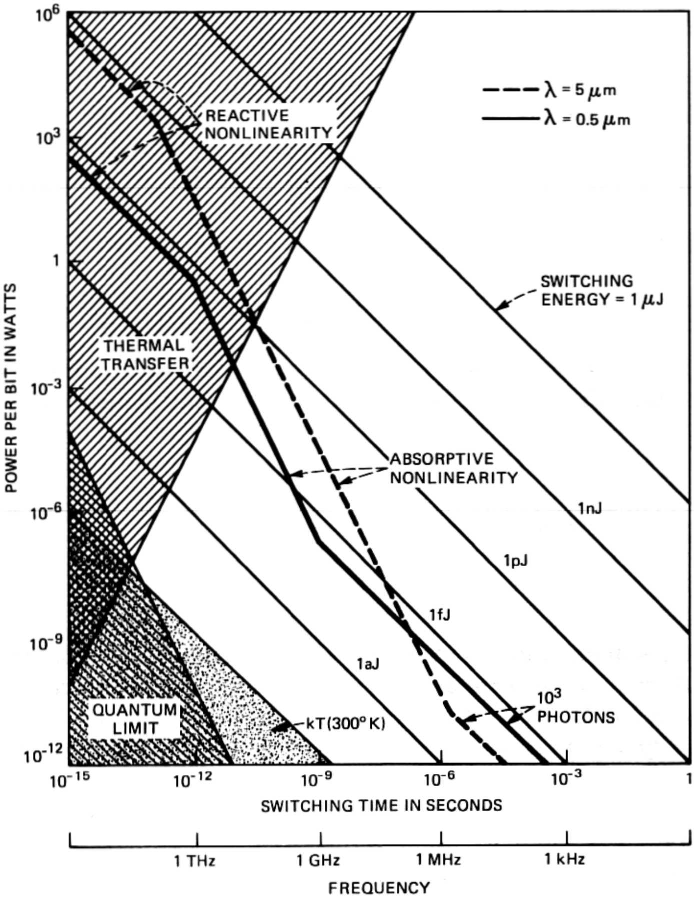


Fig. 2—Limitations on optical switching devices. The frequency scale (at bottom) applies for repetitive switching. The heavy lines indicate limits on optical switching devices for the case of $\lambda = 0.5\ \mu m$ (solid lines) and $\lambda = 5\ \mu m$ (dashed lines).

must be satisfied. Here, σ is the peak absorption cross section of the transition, I is the light intensity, h is Planck's constant, c is the velocity of light, λ is the wavelength of the light, and τ_D is the decay time of the transition. From the expression for the Einstein stimulated emission coefficient, we can write

$$\sigma = \frac{4\pi^2 |\mu|^2 T_2}{3\epsilon_0 h\lambda}, \tag{2}$$

where $|\mu|$ is the dipole moment of the transition, T_2 is the inverse line width of the transition, and ϵ_0 is the vacuum permittivity.

The maximum intensity for a given input power is obtained in a waveguide geometry for which the input power, P, is given by

$$P \sim I\lambda^2 \tag{3}$$

(see Section IV). Combining eqs. 1, 2 and 3 we obtain:

$$P > \frac{3\epsilon_0 h^2 \lambda^2 c}{4\pi^2 |\mu|^2 T_2 \tau_D}. \tag{4}$$

To evaluate eq. 4 we will assume a large dipole moment for an atom given by

$$|\mu| = ea_0, \tag{5}$$

where e is the electronic charge and a_0 is the Bohr radius. We will further take the response time, τ, of the switching element to be

$$\tau = \tau_D \sim T_2. \tag{6}$$

(T_2 cannot be less than τ_D, and a larger T_2 implies a larger switching energy.) With these assumptions we find

$$P > 1.2 \times 10^{-24} \times \frac{\lambda^2}{\tau^2}\, W, \tag{7}$$

where λ is in μm and τ is in seconds. This limit is plotted on Fig. 2 for $\lambda = 0.5\ \mu$m and $\lambda = 5\ \mu$m and labeled "Absorptive Nonlinearity." Two points should be noted. First, Keyes shows that a similar limit should also apply for the case of a second-order nonlinear effect [$\chi^{(2)}$ process] or for the case of a nonlinearity based on self-induced transparency. Second, it has recently been shown that it is possible to find systems in which one can use excitonic resonances[13] to obtain effective dipole moments appreciably greater than ea_0. An example using such a system is described in Section VI.

A different limit is found for the case of a third-order nonlinearity [$\chi^{(3)}$ process]. Let us consider a material exhibiting an optical Kerr effect, i.e., the refractive index has a term proportional to the light intensity. To obtain an appreciable effect, we require a change in phase shift through the medium

$$\Delta\phi > \pi. \tag{8}$$

If the refractive index change is $n_2 I$, where n_2 is the optical Kerr coefficient, then eq. 8 becomes

$$\frac{2\pi n_2 I \ell}{\lambda} > \pi, \tag{9}$$

where ℓ is the length of the element. The delay time is governed by the length

$$\tau = n_0 \ell / c, \tag{10}$$

where n_0 is the (linear) refractive index of the material. Combining eqs. 9, 10, and 3, we obtain

$$P > \frac{n_0 \lambda^3}{2 n_2 c \tau}. \tag{11}$$

Note that the dependence of P on τ is different from that in eq. 7.

How can we estimate n_2? We can argue that the nonlinear refractive-index term should be of the order of unity for light fields of the order of the atomic fields. Thus, we could write

$$n_2 I = n_0 \tag{12}$$

for light fields of the order of e/a_0^2. Now

$$I = \frac{\epsilon_0 n_0 c E^2}{2}, \tag{13}$$

where E is the electric field strength of the light. We combine eqs. 12 and 13 to obtain

$$n_2 = \frac{32\pi^2 \epsilon_0 a_0^4}{c e^2}. \tag{14}$$

From eq. 14 we obtain $n_2 = 2.9 \times 10^{-17}[\mathrm{W/cm^2}]^{-1}$. Much larger electronic nonlinearities are known, however. The polydiacetylene PTS has the largest-known value;[12] it is $n_2 \sim 6 \times 10^{-12}[\mathrm{W/cm^2}]^{-1}$. The reason for this large value is that the electrons are relatively unconfined along the chain axis of the PTS molecules. Thus, effective distances much larger than a_0 are encountered, and as $n_2 \propto a^4$, nonlinearities much larger than our estimate are found. The limits represented by eq. 11 are shown in Fig. 2 for $\lambda = 0.5$ μm and $\lambda = 5$ μm and labeled "Reactive Nonlinearity." They are evaluated using the value of n_2 for PTS.

A third limit shown in Fig. 2 is derived from statistical considerations. A number of photons large compared with unity is necessary to define a switching state. We have somewhat arbitrarily taken 10^3 photons as this statistical limit, i.e.,

$$P\tau = 10^3 hc/\lambda. \tag{15}$$

This limit is also plotted in Fig. 2 for $\lambda = 0.5$ μm and $\lambda = 5$ μm.

A word of caution is in order here. These limits that we have identified are "fuzzy" in that it may not be possible to do as well as these limits, or it may be possible to do somewhat better than these limits would indicate. In general, many kT of energy will be required for stable switching devices. On the other hand, the use of a high-finesse optical resonator will lower the required switching energy. These limits are intended to be used as a guide and an indication of the underlying physical mechanisms.

An optical resonator decreases the required switching power at the expense of a reduction in the bandwidth. A bistable optical device utilizing a lossless material with a refractive nonlinearity has a switching power that varies as

$$P \propto 1/F^2, \tag{16}$$

where F is the finesse of the resonator. In the region where the switching time is limited by the resonator,

$$\tau \propto F \tag{17}$$

so that the switching energy, defined as the product of the switching power and switching time, is given by

$$P\tau \propto 1/F. \tag{18}$$

If the switching time is limited by the response time of nonlinear material, τ will not depend on F, and

$$P\tau \propto 1/F^2. \tag{19}$$

The limits shown in Fig. 2 were computed assuming no resonator, i.e., for $F \sim 1$. We see that with high-finesse resonators, switching energies appreciably below the limits shown in Fig. 2 should be possible. The 10^3 photon limit will still apply, however.

IV. SIZE LIMITATIONS

To obtain the largest light intensity for a given input power, it is usually desirable to focus the input light. The light can be focussed to a cross-sectional area of $\sim\lambda^2$, but will diffract rapidly if not confined by some waveguiding structure. For this reason the lowest-power switching devices are likely to be those in which the light is guided in an optical dielectric waveguide with cross-sectional dimensions of $\sim\lambda$. (Kogelnik[8] has pointed out that with a smaller dielectric waveguide, the guided mode will extend beyond the waveguide walls so that the minimum light-beam cross section will always be of the order of λ. Light can be confined to smaller cross sections using metallic waveguides, but in this case large absorption losses will result.)

The minimum length of the waveguide (i.e., the device) will depend on the strength of the optical nonlinearity and on the finesse of the optical resonator. In many cases the linear absorption loss of the nonlinear medium will determine the resonator dimensions. Miller[14] has shown that for a high-finesse waveguide resonator containing a material with a nonlinear refractive index and a linear absorption loss, the lowest switching power will occur for a length of resonator such that

$$1 - R = A, \tag{20}$$

where R is the reflectivity of each of the resonator mirrors, and A is the absorption loss per pass through the nonlinear medium. If we write $A = \alpha \ell$, where ℓ is the length of the medium and α is the absorption coefficient, this condition requires

$$\alpha \ell = \pi / 2F \tag{21}$$

or

$$\ell = \pi / 2\alpha F. \tag{22}$$

Thus, the length of a device that is optimized for minimum switching power will be determined by the absorption coefficient and the finesse of the resonator. If the nonlinearity is caused by the absorption of light, then compact, fast, and efficient elements will require a large value of α. Under optimized conditions the switching power, P, varies as

$$P \propto 1/F. \tag{23}$$

The optimum length of the device varies with R so that the resonator response time, τ, is independent of F. Thus, in this case we find the switching energy

$$P\tau \propto 1/F. \tag{24}$$

In Table I, we show recent results from the literature on bistable optical devices. We have taken the switching time to be the "recovery time" of the device, i.e., the time constant for the return to equilibrium in the absence of a driving signal. It is important to note that in many cases a device can be switched on (or off) much more rapidly by the application of a short, intense driving pulse. The data in Table I shows a wide range of switching powers and speeds. As might be expected, the fastest devices require the highest switching powers. The lowest

Table I—Experiments: recent results

	Switching Power (watts)	Switching Time (seconds)	Switching Energy (joules)
Bistable Fabry-Perot resonators			
CS_2	3×10^{5}	5×10^{-10}	1.5×10^{-4}
Na vapor	10^{-2}	10^{-5}	10^{-7}
GaAs	2×10^{-1}	4×10^{-8}	8×10^{-9}
InSb	10^{-2}	$<5 \times 10^{-7}$	$<5 \times 10^{-9}$
Hybrid bistable Fabry-Perot resonator			
$LiNbO_3$	10^{-5}	5×10^{-8}	5×10^{-13}
Bistable liquid-crystal matrix			
Hughes liquid crystal light valve	5×10^{-7}	4×10^{-2}	2×10^{-8}
Nonlinear interface			
Glass—CS_2	2×10^{5}	2×10^{-12}	4×10^{-7}

reported switching energy is for a hybrid, integrated-optical bistable device. This low energy is possible because of the very large effective nonlinearity created by the electrooptic modulator with electrical feedback. Although for some applications long switching times or large switching powers are acceptable, in general one wishes to minimize each of these parameters. How much could we improve present bistable devices by shrinking device dimensions to provide shorter transit times and higher light intensities for a given input power?

We have extrapolated current experimental results to λ^2/n^2 cross-section waveguide devices with a length adjusted for minimum switching energy. We have assumed a finesse of 30 for the Fabry-Perot resonator and have considered the response time to be the undriven recovery time of the device. The results are shown in Fig. 3. It is interesting to note that with known devices and materials it should be possible to approach rather closely the fundamental limits for optical

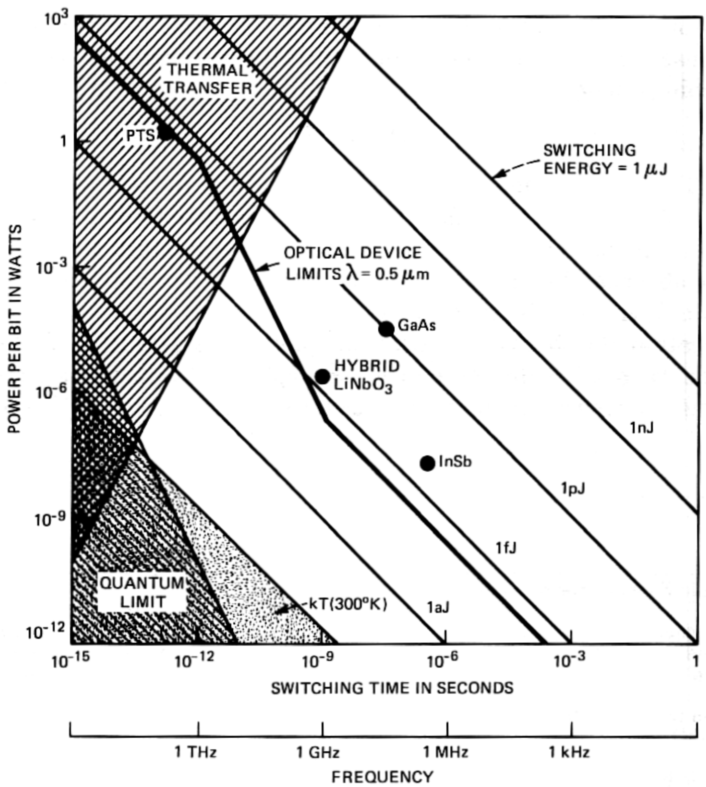


Fig. 3—The points represent performance limits extrapolated from current experimental values for waveguide Fabry-Perot resonators containing the polydiacetylene PTS, the semiconductor GaAs, the semiconductor InSb, and a hybrid device using the electrooptic crystal $LiNbO_3$.

devices; however, as we see in Table I, present laboratory devices are not yet developed to the point where they are close to these limits.

V. COMPARISON WITH OTHER SWITCHING TECHNOLOGIES

How do these projected results and limits that we have derived compare with those for other switching technologies? In Fig. 4 we show how the limits for bistable optical devices compare with the best reported values for two well-established switching technologies—semiconductor electronic devices, and Josephson devices. It is also interesting to see how these devices compare with a biological switching device—a neuron.

It is clear that in the 10^{-6} through 10^{-11} second region, one cannot hope to switch with substantially less power than that required for semiconductor electronic devices, and appreciably lower switching powers are possible with Josephson technology. In the 10^{-12} through 10^{-14} second region, however, optical devices appear to have no com-

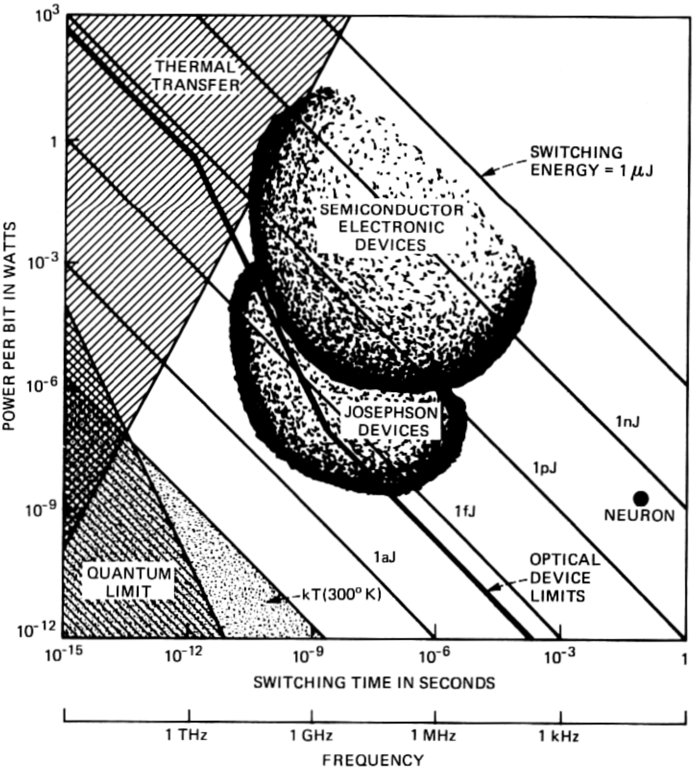


Fig. 4—A comparison with the operating range of two other switching technologies: semiconductor electronic devices, and Josephson devices. The operating point for a biological "switch"—a neuron—is also shown for comparison.

petition. This unique capability for sub-picosecond switching is one of the most exciting aspects of optical switching technology.

The switching power required in this short-time region puts the operating point well within the "thermal transfer" region discussed earlier. For this reason, it does not appear feasible to design a high-speed, general-purpose digital optical computer. However, for many applications these thermal limits may not present severe problems. Two points are worth noting. First, devices using a reactive nonlinearity do not depend on the absorption of the incident light. Thus, most of the switching power is transmitted by the device and the power dissipated is much less than the power required for switching. Second, for some applications, fast switching operations are required at relatively low duty cycles. In both cases the temperature rise in the switching elements will be much lower than the maximum value used in computing the "thermal transfer" region boundary.

There are many other factors that relate to the choice of a switching technology that cannot be 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 Fig. 4 in which other technologies show a switching-energy advantage.

VI. ILLUSTRATIVE EXAMPLES

We have shown that because of thermal problems associated with the high packing densities required for rapid operation, optical switching elements are unlikely to be used as building blocks for a general-purpose computer. For certain specific applications, such as the integrated-optical spectrum analyzer recently developed for microwave signal processing, and optical computers for picture processing and pattern recognition,[15–17] special-purpose optical computers have already demonstrated their usefulness. We should also point out that fast optical switching devices are opening up a new time region for scientific studies, and picosecond spectroscopy is rapidly becoming an important field of research.[18]

In this section we will consider a few specific applications of optical switching elements, and see where an extrapolation of current technology might lead. In many cases nonlinear materials with a suitable combination of properties are not currently available. The materials we have chosen for these examples illustrate the wide range of properties that can be obtained.

6.1 Low-energy optical switch

The lowest "switch-off" energy currently demonstrated is 0.5 pJ for a hybrid bistable device (see Table I). Extrapolation of this figure with a $LiNbO_3$ device with minimum waveguide dimensions and assuming current detector technology, we find 1 fJ operation should be possible. A similar limit is found by extrapolating current figures for InSb devices at 5 μm wavelength. These figures might be reduced still further by using optical resonant structures related to those currently being employed for surface-enhanced Raman studies. (See, for example, Ref. 19.)

6.2 High-speed optical switch

The highest-speed operation will be obtained with a device utilizing a nonlinear material with an electronic nonlinearity. Such nonlinearities are believed to have response times in the range of 10^{-14} seconds. For minimum device response time, a nonresonant configuration should be used. A suitable configuration might be the self-focussing, bistable optical switch described in Ref. 20. By focusing the input to a spot size on the order of the wavelength of the light at the nonlinear material, adequate discrimination between "on" and "off" states could be obtained with a device length of 20 wavelengths. For a device using as nonlinear material the polydiacetylene PTS[12] and light of 1 μm wavelength, the response time would be 0.1 ps and the peak pulse switching power would be 100 W. This power is low enough that it might be reached with a mode-locked semiconductor laser diode.

6.3 4 x 4 optical switching network

If picosecond speed is not required, an optical distribution network could be formed with integrated optics technology on a $LiNbO_3$ substrate, as demonstrated by Schmidt and Buhl.[21] This example is somewhat different from the others we have given, in that electrical signals are used to control the distribution of the optical signals. Kogelnik[8] has addressed the question of the limits for the stepped $\Delta\beta$ couplers that comprise the switching units. He shows that the limiting electrical energy, E_{SW}, needed for one switch of the optical path is given by

$$E_{SW} \cdot \tau = 100 \text{ pJ} \times \text{ps}, \tag{25}$$

where τ is the transit time through the device. A directional coupler switch with a switching time of 110 ps and a transit time of 3 ps has already been demonstrated.[22] Switching times of 30 ps should be possible with 1 μm electrode gaps.[22] $LiNbO_3$ waveguides suffer severe problems at optical power levels higher than ~100 μW in the visible range. Much higher power levels are possible, however, if near infrared light is used.

6.4 Image amplifier

An optical image amplifier could be made using an array of bistable elements, as shown in Fig. 5a. Each element in the array is a self-focussing bistable element similar to that described in Ref. 20. A typical output characteristic for each element is shown in Fig. 5b. It can be seen that a weak input signal (I_S) produces a strong modulated signal at the output when the input light level corresponds to the

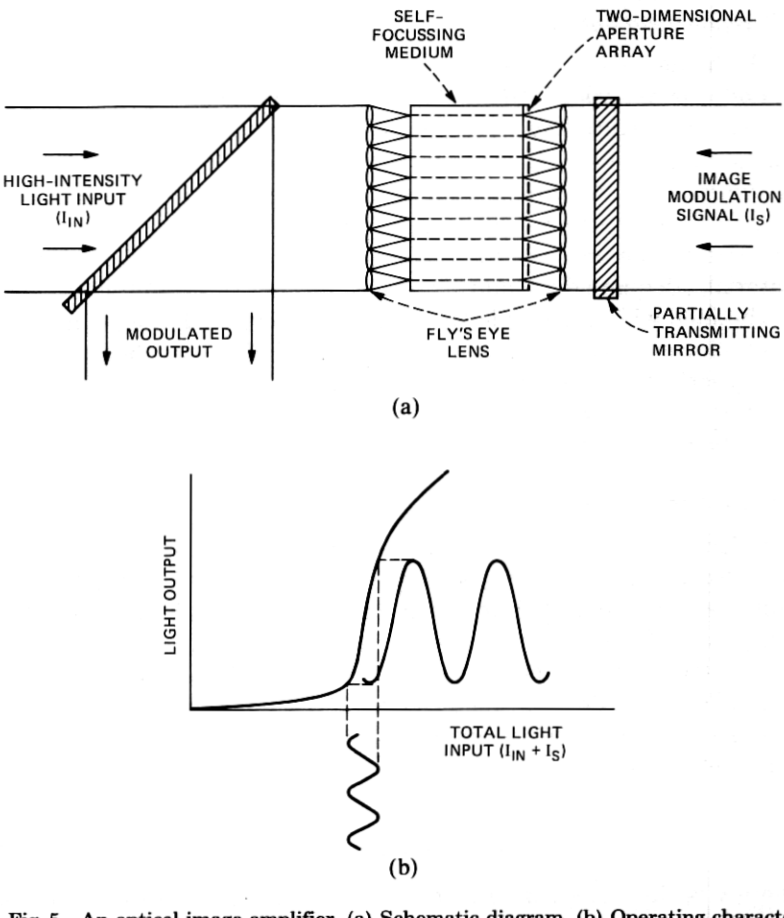


Fig. 5—An optical image amplifier. (a) Schematic diagram. (b) Operating characteristic of each element.

"knee" in the characteristic curve. Thus, each spatial element behaves as an "optical triode."

One possible nonlinear medium for this application would be a liquid suspension of sub-micron dielectric particles. As shown in Ref. 23, this medium exhibits a large nonlinear coefficient, although it has a slow response time on the order of a second. Such times may be acceptable for certain image-processing operations. If each element of the input image is focussed by the composite lens to a spot size of $\sim\lambda^2$, with an aqueous suspension of quartz particles one would require an input power of 10 mW/resolution element at $\lambda = 0.5\ \mu m$ and 1 mW/resolution element at $\lambda = 5\ \mu m$. Recent calculations[24] indicate that input powers of ~100 μW/resolution element and a response time of ~1 μsec might be possible using suitably doped GaAs as the nonlinear medium. The verification of these ideas must await further experiments.

6.5 Optical time-division multiplexer and demultiplexer

As our final example, let us consider a high-speed optical time-division multiplexer (or demultiplexer) that might be used to multiplex picosecond optical pulses into a high-capacity optical fiber, and demultiplex the signals at the receiver to obtain low enough bit rates to allow handling by optical detectors and subsequent electronic systems.

A multiplexer can be made from a number of triggerable switching elements, as shown in Fig. 6a. 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 Fig. 6b. This bistable device consists of a suitable nonlinear optical material in a 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 Fig. 6c. 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 a similar way, one can perform demultiplexing by using an optical "tap," as shown in Fig. 7a. A similar bistable ring resonator serves as a triggerable "tap," as shown in Fig. 7b; the output characteristics are shown in Fig. 7c.

An appropriate nonlinear material for use in these devices might be

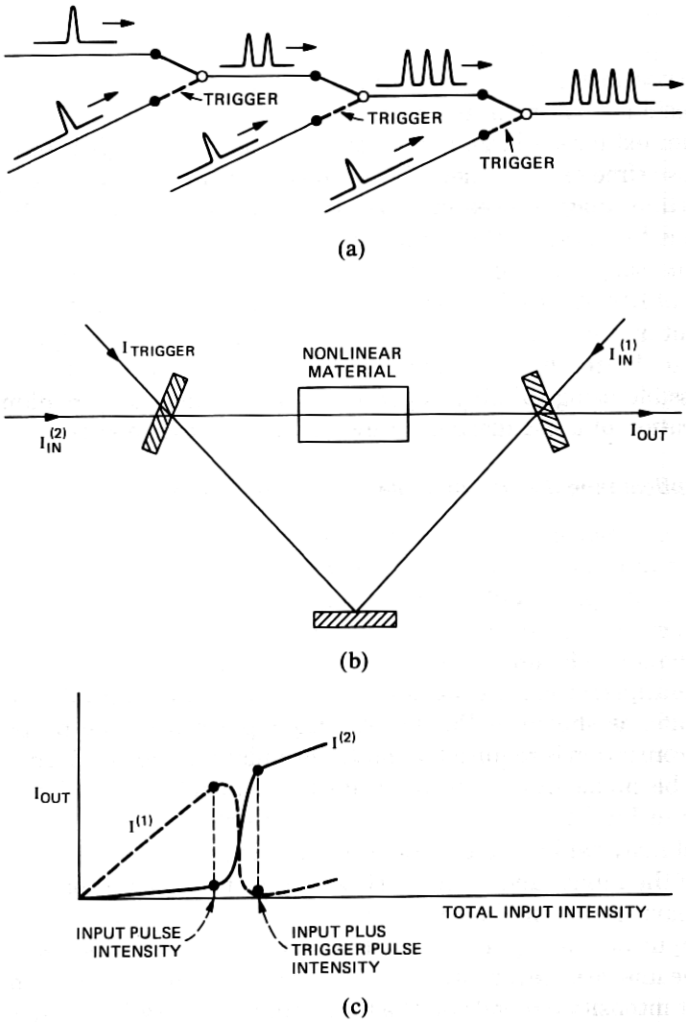


Fig. 6—Optical time-division multiplexer. (a) Overall schematic diagram. (b) Ring triggerable bistable element. (c) Output characteristic of ring bistable element.

the semiconductor CdS. It has recently been shown[13] that large nonlinear effects are found near the biexitonic resonance line. By using light at $\lambda \sim 4836$Å, we will obtain a sufficiently large nonlinearity to allow the device to operate at a pulse power level of about 1 mW with a time response of ~1 ps. This material requires cooling to liquid helium temperatures, however, and the wavelength range over which this operation can be obtained is small (~5Å). A material such as PTS will avoid these difficulties, but will increase the peak power required

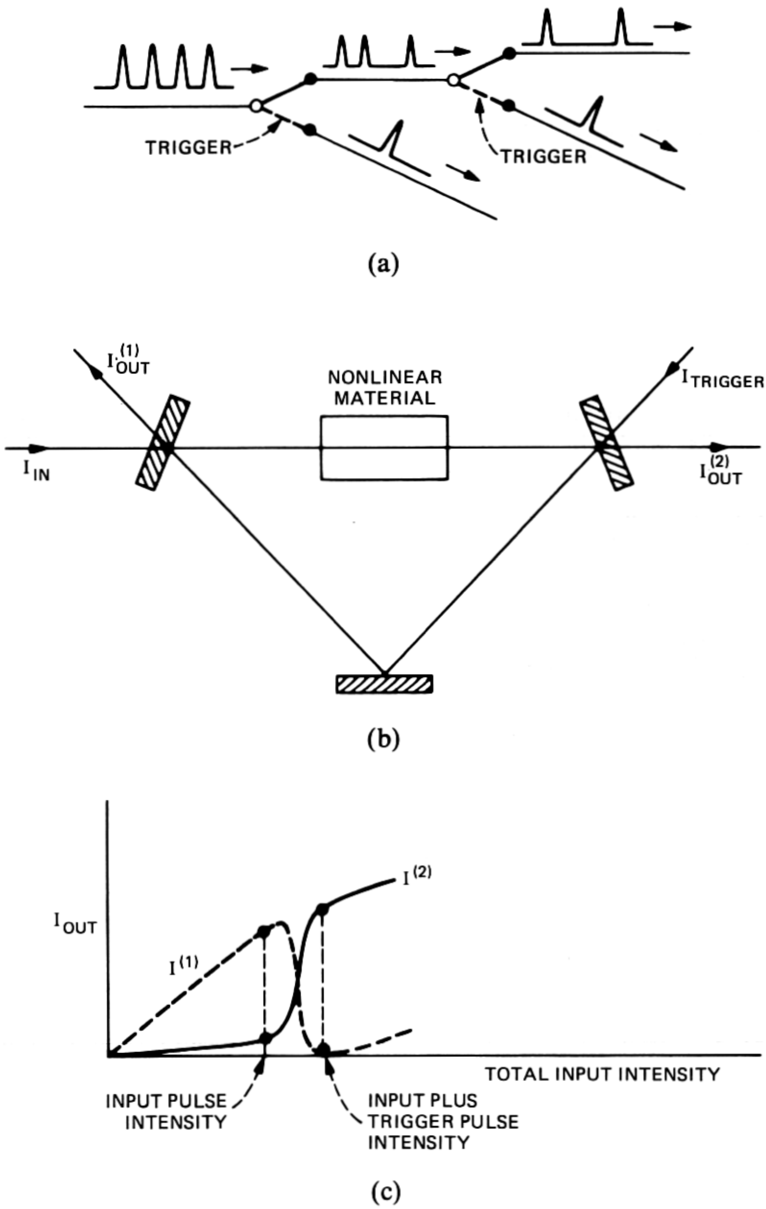


Fig. 7—Optical time-division demultiplexer. (a) Overall schematic diagram. (b) Ring triggerable bistable element. (c) Output characteristic of ring bistable element.

to the 1 W level. As this power is only required for 1 ps, however, the operating energy would still be a very reasonable 1 pJ.

VII. CONCLUSIONS

Having identified the physical limits for optical switching devices and discussed some specific examples, let us try to draw some general conclusions with regard to their future applications. The strong points of optical switching devices are:

(*i*) Speed: With an electronic nonlinearity or free-carrier generation in semiconductors, sub-picosecond switching times are possible.

(*ii*) Bandwidth: With a nonresonant bistable optical device or a nonlinear interface, a large fraction of the visible light bandwidth can be used.

(*iii*) Ability to treat directly signals already in the form of light.

(*iv*) Capability for parallel processing: With a liquid crystal bistable array, image processing has already been demonstrated.[15]

The weak points of optical switching devices are:

(*i*) High power is required for fast switching. This will tend to create thermal problems unless highly transparent materials are used.

(*ii*) Materials do not yet exist that have the ideal combination of properties for these devices.

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

(*iv*) The minimum size of an optical switching element cannot be reduced below a volume of about λ^3 unless lossy metallic structures are used.

The field of digital optical switching is a dynamic one in which rapid progress is being made. New materials and devices are being proposed and studied. Let us close by proposing some areas where future work should be directed.

There is clearly a need for good optical quality, high-nonlinearity materials with low absorption coefficients. The development of such materials will have a great impact on future applications. Techniques must be developed for fabricating optical waveguides and optical resonant structures with dimensions on the order of optical wavelengths. For many applications, the problem of regeneration of signals associated with 'fan out' is important.[7] Some types of bistable lasers may well find use here. Finally, the general problem of the optics—electronics interface (i.e., making optics compatible with electronics)—is one that will require a good deal of attention if the most effective use is to be made of the tremendous potential of digital optical switching.

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