Materials for Optical Information Processing

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Summary. The goal for optical information processing is to use the unique characteristics of light which are not readily achieved with electronic devices, namely, ultrahigh speed (picoseconds), a high degree of parallelism (image processing), and conductor-free interconnection. The requirements of the nonlinear materials to perform such functions, using all-optical interactions, are discussed and the limitations of the nonlinear mechanisms are outlined.

In recent years there has been a resurgence of activity in optical information-processing devices which make use of effects such as optical bistability, photorefractive effects and numerous electro-optical, acousto-optical, and all-optical processing schemes in integrated optics. In parallel, theoretical studies have been made of novel architectures for information processing which capitalize on the unique capabilities of optics. In this article, the various requirements of the nonlinear optical materials used as the processing medium are discussed and the fundamental materials limitations pointed out. The article will be restricted to the requirements for all-optical processing in which light interacts with light. Many important and nearer term applications of optics will involve the switching of light beams with externally applied fields in an electro-optic material or with sound waves in an acousto-optic material, but these are beyond the scope of this article.

Since the material requirements depend critically on how the optical processing is to be performed, we first give a brief outline of where and how optics might prove useful in a world where electronic processing has already reached an advanced state of technology.

Current Situation in Electronic Processing

The development of computers from the beginning has been dominated by one method of processing, with arithmetic and logic functions performed in a central processing unit (CPU) and programs stored in a separate memory (random-access memory; RAM). These machines evaluate a problem sequentially (serial processing). A difficulty with such a design is that the communication channel between the CPU and RAM limits the computer speed and performance. This is the Von Neumann bottleneck. To eliminate the bottleneck, researchers are working on parallel processing, trying to intermingle memory and processing functions so that several operations are carried out simultaneously rather than sequentially. In practice, current supercomputers all incorporate some degree of parallelism—typically fewer than 100 parallel channels. Current supercomputers offer bit rates of $\sim 10^{10}$ bits per second and future machines with up to 10^{12} bits per second seem feasible. The next generation of machines will require considerable rethinking of conventional computer architectures, and there is an increasing trend to optimize machines for specific application rather than for general-purpose computing.

It is possible that in future generations of machines, optical processing will play a role. The potential of optics for information processing and memory has been realized for many years (*1*). A diffraction-limited optical image can contain $\sim 10^8$ bits of information per square centimeter. Large amounts of information can be processed simultaneously in relatively small volumes, completely free of interference from other electromagnetic waves. Wireless interconnection with noninterfering beams greatly facilitates the design of three-dimensional architectures. Certain functions can be performed with simple linear optics—for instance, performing a Fourier transform with a lens. For any more general processing function, an optical nonlinearity is required.

Nonlinear Interactions of Light

In all-optical processing one light beam is used to control a second signal beam. Since, unlike electrons, photons do not directly interact with each other, an optical medium is required in which an optical property, the refractive index n or absorption α, is changed by the propagation of a light beam in the medium. A nonlinear refractive index n_2 can be defined by

$$n = n_l + n_2 I \qquad (1)$$

and a nonlinear absorption coefficient α_2 by

$$\alpha = \alpha_1 + \alpha_2 I \qquad (2)$$

In such a medium, the presence of one light beam affects the propagation of a second light beam. The optical absorption changes by an amount $\Delta\alpha = \alpha_2 I$ in the presence of light of intensity I, and the intensity of the transmitted beam varies. For a change of refractive index $\Delta n = n_2 I$, the phase of the transmitted signal varies. A phase change can be converted to an intensity change by using polarizers, by holographic techniques, or by placing the medium within a Fabry-Perot cavity. Most of the research to date has made primary use of the nonlinear index n_2 rather than α_2. However, recent work with the nonlinear absorption in multilayer semiconductor structures looks promising for optical switching, and this may change the emphasis.

An important point to emphasize at the outset is that the nonlinear index or absorption alone is not a useful measure of the importance of a material for optical processing. A useful basis for comparison of different materials is the optical energy required to process a bit of information. This quantity depends not only on n_2 but also on the wavelength of light in the medium and the response time of the medium, that is, the rate at which the index changes in response to the incoming radiation.

Promise of Optics

During the 1960's, considerable prejudice was developed against the use of optics for computing because of the following problems.

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1) The minimum size of an optical switching element is $(\lambda/n)^3$, where λ is the wavelength of light.

2) The photon energy $h\nu$ is much larger than the thermal energy kT.

3) Optical nonlinearities are small.

These basic problems imply large switching volumes with accordingly long propagation delay times between switching elements, and high heat dissipation. Detailed evaluations of these limitations were made two decades ago, primarily by researchers at IBM (*1*).

These basic problems have not, of course, changed. However, there have been several developments of importance which have stimulated a new look at the role of optics in information processing.

1) Mode-locked lasers are now readily available which deliver optical pulses of subpicosecond duration—shorter than any electronic pulses available. Such short, intense pulses should permit subpicosecond switching operations.

2) New materials and new nonlinear mechanisms have been discovered which have larger optical nonlinearities.

3) Fiber optics and integrated optics are available which permit the transmission and switching of very high bandwidth ($>>10^{10}$ Hz) communications channels.

4) The limitations of serial electronic processing have become evident and have made the power of optics for large-scale parallel processing increasingly attractive.

Thus, the near-term goal of optical processing is to use the capabilities of optics which are not readily achieved with electronics. This is particularly pertinent for both image processing and fiber-optic communications, where the information is already being carried on optical beams. To achieve this goal, the development of appropriate materials is essential. The important material parameters for all applications are:

1) The optical quality of the material and its resistance to optical damage.

2) The material response time—that is, the speed with which n or α can be changed by a control pulse and the speed with which the material recovers so that it can respond to a second control pulse.

3) The magnitude of the nonlinearity—that is, the energy required in the control pulse to change α or n by the required amount.

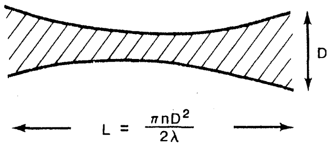

Fig. 1. Cross section of a focused optical beam showing the effect of diffraction.

Optical Quality and Damage

In optical processing, as in many other technologies, the quality of materials is of primary importance for device performance. In the case of optical materials inhomogeneities give rise to spatial variations of the refractive index or absorption which result in distortion of the optical beams to be processed. Such distortion gives rise to problems with the signal-to-noise ratio in a device. As a rule, the larger the nonlinearity of a material the more serious the problems of inhomogeneity become. This is because the optical inhomogeneities are themselves due to strains or local fields acting via the optical nonlinearity. Many of the materials in which simple optical-processing functions have been demonstrated are in the early stages of development as far as optical quality is concerned, and considerable improvement will be required. Extrapolating current results to new materials systems must be done with caution because the problems of crystal growth, particularly in thin-film form for integrated optics, can be severe. Unfortunately, lithium niobate, the only electro-optic material for which an advanced optical waveguide technology has been developed, does not have a sufficiently high nonlinear index to be practical for all-optical processing.

Because of the small optical nonlinearities, high optical intensities are usually necessary for fast serial optical switching. An upper limit to the intensity of light that can propagate in a material is determined by the optical damage threshold of the material. In practical materials, optical damage is difficult to quantify because it depends on many factors. The various common mechanisms for catastrophic damage in nominally transparent materials include local melting or fracture at absorbing inclusions, multiphoton absorption, self-focusing, and avalanche breakdown (*2*). The problem of inclusions, while often a limiting factor in practice, is not fundamental and can in principle be avoided by improved material preparation. Two-photon absorption can for practical purposes be avoided if the photon energy to be processed is less than half of the optical band gap of the material, while three-photon and higher order processes are generally unimportant. Self-focusing and avalanche breakdown are, however, fundamental limitations. Self-focusing has its origin in the same nonlinear index which is necessary for optical processing. If n_2 is positive, the nonlinear index acts as a lens and focuses the light, which in turn increases the local intensity, leading to breakdown. The critical power P_{cr} for such breakdown occurs when self-focusing overcomes the defocusing effect of diffraction

$$P_{cr} \sim \lambda^2/100n_2 \qquad (3)$$

The critical power decreases as the nonlinear index increases. This effect limits the use of positive-n_2 materials to configurations with guided optical waves.

Avalanche breakdown at optical frequencies is exactly analogous to dielectric breakdown at low frequencies: electrons are accelerated in the electric field of the light wave until they have sufficient energy to undergo an ionizing collision and create another electron-hole pair. The buildup of electron density N goes as

$$N = N_0 \exp[\eta(E)\tau_p] \qquad (4)$$

where τ_p is the duration of the optical pulse, $\eta(E)$ is the avalanche ionization coefficient, and N_0 is the initial density of electrons. This effect decreases in importance with decreasing optical pulse length because of the time required to build up a plasma of sufficient energy to destroy the material. In the case of NaCl, where the effect has been well characterized (*2*), an intensity of about 100 W/μm^2 is required for avalanche breakdown with pulses 1 nsec in duration, but about 10^5 W/μm^2 is required with pulses 1 psec in duration. Thus the pulse energy required for breakdown is approximately constant over this range. Qualitatively, similar behavior is expected for other materials, scaled by the avalanche ionization coefficient according to Eq. 4. For most nonlinear optical materials of interest $\eta(E)$ is not known. The alkali halides are known to have particularly high dielectric strength and such high intensities (while more than adequate for serial optical processing) are not likely to be achieved in nonlinear optical materials.

The above considerations show the importance of measuring fundamental materials parameters which affect the scaling of experimental results to high intensities and small volumes. Once all these parameters are understood, considerable development of material of high optical quality must be undertaken.

Material Response Time

For serial processing, the main potential advantage of optics is ultrahigh speed. Since picosecond optical pulses are available, it is desirable to have materials which respond on a picosecond time scale. The peak intensity of such an optical pulse can be very high even though the pulse energy is low. To avoid excessive transit time delays, such processing would be done in a pipeline mode, that is, with several optical pulses propagating in a transmission line simultaneously. A serial processor capable of processing 10^{12} bits per second would appear to be a reasonable first goal, in view of the potential of competing electronic technology. The only nonlinear mechanism that is known to respond on a picosecond or shorter time scale is the nonresonant electronic Kerr effect. This effect arises in transparent materials because of the nonlinear polarizability of a material due to the instantaneous action of the electric field of the light on its valence electrons. As will be seen below, nonresonant electronic Kerr nonlinearities are very weak, and high optical intensities are required to produce a significant index change. Nonresonant Kerr effects can also be observed in transparent liquids containing anisotropic molecules which are partially aligned in the optical field, but the response time of the medium is increased to 10^{-10} to 10^{-12} second because of the time required to reorient the molecules. It is feasible that materials having resonant nonlinear optical effects which involve optical absorption may be developed with picosecond response times and much larger nonlinearities, but these have not yet been demonstrated. Thus, picosecond optical processing is marginal with present phenomena and materials.

The response time requirement of materials can be greatly relaxed if one turns to parallel processing. For the same throughput of a processor, the required material response time is increased by the number of parallel channels, that is,

Maximum bit rate
= (number of parallel channels)
× (material response time)

For diffraction-limited optics with $\sim 10^8$ bit/cm^2 a simple argument suggests that a material response time of $\sim 10^{-4}$ second would be adequate for a rate of 10^{12} bits per second with a 1-cm^2 nonlinear element. In most situations one would probably not wish to have 10^8 parallel channels (10^6 seems a more reasonable goal), but the example shows that material response times much slower than a picosecond and even on the microsecond time scale may be important for parallel processors. Long response times may even perform some memory functions. A much broader range of materials are available for optical processing on longer time scales. All of these effects involve absorption of the incident light:

1) The resonant Kerr effect with $10^{-12} < \tau < 10^{-3}$ second,

2) The photorefractive effect with $10^{-10} < \tau < 10^{+8}$ seconds, and

3) Electroabsorption with $10^{-10} < \tau < 10^{-4}$ second,

where τ is the material response time. These ranges must be regarded as estimates based on currently available information. In the following sections, these various mechanisms for nonlinear index and absorption changes are discussed in more detail.

Table 1. Magnitude of the nonresonant nonlinear index n_2 for a variety of transparent materials (*13*). The intensity I necessary to create a phase change of π for an optical interaction length L in the material is shown only for comparison of different materials. It should not be deduced that this material will support the optical intensities listed.

Material	λ (μm)	n_2 ($\times 10^{14}$ cm^2/W)	I (MW/cm^2)	L (cm)
CS_2	0.69	8	45	20
PTS	1.32	530	30	1
2-Methyl-4-nitroaniline	1.32	170	90	1
GaAs	10	100	900	1
InSb	10	5000	18	1
Silica	1.0	0.06	1500	1
$LiNbO_3$	1.0	~2.5	4500	1

Magnitude of Nonlinearity

Because the change of refractive index Δn or absorption $\Delta\alpha$ is proportional to the intensity of the control beam, the smaller the area corresponding to a single bit, the less optical energy is required for a switching operation. There is a penalty, however, for decreasing the focal spot size. This penalty is due to diffraction as shown in Fig. 1. The confocal parameter (the effective interaction length L of the beams in the material) decreases in proportion to the area of the focal spot, that is,

$$L = \frac{\pi n D^2}{2\lambda} \qquad (5)$$

where D is the diameter of the beam waist at the focus and λ is the wavelength of light. For a 1-μm^2 spot size and $n = 1$, the interaction length is only 3 μm. This distance is too short to achieve adequate phase change ϕ ($= \pi \Delta n L/\lambda$) for most situations. For $\phi \sim \pi$ the required index change is $\Delta n \sim 0.3$! Either the focal spot must be increased with correspondingly increased energy requirements, or a guided wave structure (for serial processors) or holographic techniques (for parallel processors) which overcome the effects of diffraction must be used. With the latter techniques, phase changes of π are achievable with $\sim$1-μm^2 bit cross sections and long interaction lengths.

As mentioned above, the most useful parameter for comparing the magnitude of the nonlinearity of materials is the energy required to switch or process a bit of information. For changes of refractive index, the transmission (neglecting reflection losses) of a material between crossed polarizers is

$$T = e^{-\alpha d} \sin^2\phi \qquad (6)$$

or the diffraction efficiency of a thick phase hologram is

$$\eta_p = e^{-\alpha d} \sin^2\phi/2 \qquad (7)$$

where α is the optical absorption coefficient and d is the optical path length in the material. Thus, a phase change of $\phi = \pi$ gives maximum contrast for the processing operation, that is, the change of diffracted power between the control beam on and off ($\phi = \pi/2$ for maximum transmission in Eq. 6). Values of $\phi << \pi$ can be tolerated in many situations, the minimum value being determined by the tolerable signal-to-noise level, which is directly related to the bit error rate.

Similar considerations are true for changes of the absorption coefficient. In this case the transmission

$$T = e^{-\alpha d} \qquad (8)$$

A high contrast here implies a large change of absorption $\Delta\alpha/\alpha$.

Nonlinear absorption has not attracted a great deal of attention for holographic processing because the maximum diffraction efficiency of a thick absorption hologram is only 3.7 percent, compared with close to 100 percent for thick phase holograms.

For the mechanisms involving nonlinear refraction, it is possible to make some general estimates of the minimum energy required for a phase change of π for each class of nonlinearity.

Nonresonant Kerr effect. The electronic Kerr effect is the fastest of all mechanisms for optical processing. Because of the high speed, it responds to

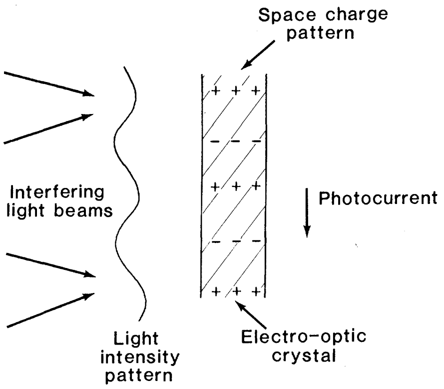

Fig. 2. Two-wave mixing for holographic processing, using the photorefractive effect.

the instantaneous intensity of an optical pulse. It is now well established, both theoretically and experimentally, that the nonlinear index n_2 is proportional to the density of bonds in the material and the orientation of the bonds with respect to the optical field, and depends critically on the degree of delocalization of electrons in the bond. Materials with the highest known values of n_2 are highly conjugated long-chain molecules such as polymerized diacetylenes whose monomers have alternating single and triple bonds: R–C≡C–C≡C–R, where R is an organic functional group (*3*). These solids have semiconductor character in the direction of the polymer chains and insulator character perpendicular to it. The components of the nonlinear polarizability of the polymer are some three orders of magnitude larger than those of the monomers. A limit to the degree of delocalization of the electrons is dictated by the required optical transparency of the material. The electronic absorption edge E_g shifts to longer wavelengths with increasing delocalization, that is, $n_2 \propto E_g^{-6}$. The polydiacetylene PTS [bis(*p*-toluene sulfonate)] probably represents the limiting case for operation at infrared wavelengths near 1.0 μm. As seen in Table 1, the nonlinear index of this solid is huge compared with that of inorganic solids such as SiO_2 and $LiNbO_3$. At present, it is difficult to grow crystals of any polymeric material with sufficient quality for optical device applications, and techniques for the growth of waveguiding thin films will be required. A compromise may be found with nitroanilines, which more readily grow in single-crystal form. Also listed in Table 1 are examples of semiconducting materials which have larger nonlinear refractive indices at wavelengths in the infrared within the band gap of the material. In *n*-type InSb the nonlinearity is a free-electron effect due to the nonparabolicity of the conduction band. In GaAs, the effect is due to bound electrons. It is seen in Table 1 that InSb has a particularly large nonlinear index n_2 at a wavelength of 10 μm. However, the diffraction-limited bit size at 10 μm is some 50 times larger than at 1.3 μm, so that PTS requires less power per bit for processing than InSb. Another factor is that detectors are less sensitive at the longer wavelength. Semiconductors have the advantage of being available as large crystals with good optical quality.

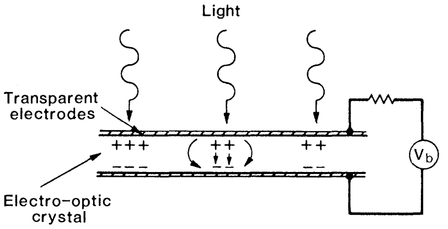

Fig. 3. Image storage due to charge transfer in an electro-optic material.

Table 2. Magnitude of the resonant nonlinear index n_2 for a variety of absorbing materials (*13*). As in Table 1, the intensities indicated have been normalized to give a phase change π. The nonlinearities may saturate at intensities lower than those indicated.

Material	λ (μm)	n_2 (cm²/W)	τ (sec)	*I* (MW/cm²)	*L* (cm)
Sodium vapor	0.59	5×10^{-11}	10^{-9}	0.2	6
CdS exciton (77 K)	0.49	1.6×10^{-6}	2×10^{-9}	3	10^{-5}
InSb	5.3	6×10^{-5}	3×10^{-7}	2×10^{-4}	5×10^{-2}
GaAs (300 K)	0.87	2×10^{-5}	2×10^{-8}	4×10^{-2}	10^{-4}
GaAs (QW)*	0.85	4×10^{-3}	2×10^{-8}	4×10^{-3}	10^{-4}

*QW, quantum well multilayer structure.

Table 3. Comparison of the parameters of various photorefractive materials.

Material	Useful wave-length range (μm)	Drift length (μm) E = 2 kV/cm	Dark τ_d (sec)	$n_i^3 r_{ij}$ (pm/V)	$n_i^3 r_{ij}/\varepsilon_j$ (pm/V)
InP (*14*)	0.85–1.3	3	10^{-4}	52	4.1
GaAs (*14, 15*)	0.8 –1.8	3	10^{-4}	43	3.3
$LiNbO_3$ (*6*)	0.4 –0.7	$\leq 10^{-4}$	300	320	11
$Bi_{12}SiO_{20}$ (*16*)	0.4 –0.7	3	10^5	82	1.8
$Sr_{0.6}Ba_{0.4}Nb_2O_6$ (*17*)	0.4 –0.6		10^2	2,460	4.0
$BaTiO_3$ (*18*)	0.4 –0.9	0.1	10^2	11,300	4.9
$KNbO_3$ (*19*)	0.4 –0.7	0.3	10^{-3}	690	14

In contrast to the electronic Kerr effect, the molecular rotation Kerr effect depends on the orientation of molecules in the electric field of the light. This effect has not been seriously considered for optical-processing applications because the known nonlinear susceptibilities are smaller than those obtained with the electronic effect and the effect is slower because viscous forces hinder the molecular rotation. Furthermore, it is not clear that an integrated optics technology based on a liquid active medium is viable. For comparison, the nonlinear index n_2 of CS_2 is listed in Table 1. Carbon disulfide has one of the largest values of n_2 in the visible spectrum using molecular rotation.

Resonant nonlinearities. The nonresonant effects discussed above depend on the response of a transparent material to the electric field of the light beam. As the frequency of light approaches an electronic resonance, some of the optical power is absorbed by the medium, causing a redistribution of the population among the energy levels. As a result, the dispersion associated with the absorption line is changed, giving rise to an intensity-dependent index of refraction. For light beams of constant intensity *I*, a nonlinear index n_2 can still be defined according to Eq. 1. However, the change of refractive index persists for the duration of the electron in the excited state. Thus, for a resonant nonlinearity the change of refractive index is integrated over the excited state lifetime τ. If the optical pulse length τ_p is short compared with τ, then the change of refractive index Δ*n* depends on the absorbed energy $\alpha\int_0^{\tau_p} I\,dt$ and not the instantaneous intensity *I*. In terms of the density of absorbed photons *N*, we can write the index change

$$\Delta n = \sigma N \tag{9}$$

The proportionality constant σ is simply related to the nonlinear index n_2 by

$$n_2 = \sigma(\alpha\tau/h\nu) \tag{10}$$

Table 4. Minimum energy per bit for a phase change of π estimated for each of the nonlinear mechanisms.

Material	Nonlinear mechanism	λ (μm)	τ (sec)	Energy (pJ/bit)
PTS	Nonresonant Kerr	1.3	10^{-14}	$0.2\tau_p \times 10^{12}$
GaAs (QW)	Resonant Kerr	0.85	2×10^{-8}	1
InSb	Resonant Kerr	5.3	3×10^{-7}	10
$Bi_{12}SiO_{20}$	Photorefractive	0.6	10^5 (dark) $\sim 10^{-2}$ (light)	1
InP	Photorefractive	0.85–1.3	10^{-4}–10^{-6}	1

where $h\nu$ is the photon energy. The proportionality constant σ varies from about 10^{-22} cm^{-3} in photochromic molecules to about 6×10^{-17} cm^{-3} at the band edge of InSb.

Because of the integrating effect of the excited state, resonant nonlinearities become energetically more favorable than nonresonant effects for longer pulses and lower intensities. The largest effects are achieved for very sharp absorption lines having a high oscillator strength such as those found in alkali vapors or at exciton absorption lines in semiconductors. Several examples are shown in Table 2. Values of n_2 are given since the absorption coefficient α is not known in all cases for calculation of σ.

The closer the optical frequency is to the optical absorption, the greater is the change of refractive index for a given incident intensity. The maximum crystal length is limited by the absorption length, and in practice it is necessary to move away from the center of the absorption line to achieve sufficiently large phase shifts. As before, the nonlinear index is proportional to the density of oscillators. It would seem that excitons provide the highest density of oscillators possible since excitons can be created up to a density comparable to the inverse cube of the exciton diameter—the point at which the excitons begin to overlap (*4*). Generally, exciton absorption lines are well defined only at low temperatures. However, it was recently observed that thin GaAs-GaAlAs multilayer heterostructures exhibit sharp exciton absorption lines even at room temperature. This is due to the increased confinement and binding energy of the exciton within the thin layer structure. When light at a wavelength just below the exciton peak was used an extremely large nonlinear index n_2 was observed: a significant phase change ($\sim 10^{-2}$ radian) was observed in a film only 1 μm thick. A value of $\sigma = 4 \times 10^{-19}$ cm^{-3} (Eq. 9) for this material was achieved (*4*), which is the largest value obtained in the wavelength range near 1 μm for a resonant nonlinearity.

The nonlinear behavior of such materials varies rapidly with optical wavelength because of the sharpness of the absorption peak. Thus, it is essential that both the optical wavelength and the temperature of the materials be precisely controlled.

Photorefractive effect. The photorefractive effect depends on the absorption of light in electro-optic crystals, but in this case the absorption bands are typically very broad and wavelength is noncritical. The effect is based on photoexcitation of free carriers, which then diffuse or drift in an externally applied electric field away from the light beam to trapping sites. The resulting redistribution of charge gives rise to space charge fields within the crystal in the illuminated regions. The space charge fields give rise to refractive index changes, through the electro-optic effect, which replicate the incident intensity. The induced index change Δn persists for the duration of the space charge field, which can vary from subnanosecond time scale in semiconductors to years in insulators. The photorefractive effect can produce nonlinear index changes Δn comparable to Kerr effects because the optically induced index change is not just a local (atomic scale) change in polarizability but is due to the displacement of electrons over a distance of micrometers. This large photoinduced dipole gives rise to an amplification of the index change. The material can be viewed as having a built-in optical detector which generates an electric field.

The photorefractive effect was originally discovered (*5*) in $LiNbO_3$ and soon after was found to be generally present in other electro-optic crystals. The material requirements are (i) absorbing centers which give rise to photocarriers, (ii) trapping sites, and (iii) a suitable transport mechanism. The largest nonlinear index changes are observed in materials such as ferroelectric $BaTiO_3$ and $Sr_{1-x}Ba_xNb_2O_5$ (SBN), which have extremely high electro-optic coefficients r_{ij}, but the nature of the absorbing centers and traps in these materials is not known. Such materials are important in applications such as wave front conjugation where large index changes are required. However, it has been shown (*6*) that the index change per absorbed photon (σ in Eq. 9) which is important for optical processing depends primarily on the photocarrier drift or diffusion length and the ratio $n_i^3 r_{ij}/\epsilon_j$, where ϵ_j is the dielectric constant. This ratio is as large in $Bi_{12}SiO_{20}$, InP, GaAs, and CdTe as $BaTiO_3$ and SBN despite considerably smaller electro-optic coefficients. The values of $n_i^3 r_{ij}$ and $n_i^3 r_{ij}/\epsilon_j$ for several photorefractive materials are shown in Table 3.

The relaxation time τ depends only on the dielectric relaxation time of the material; in GaAs and InP this has been varied from the millisecond region to the microsecond region (and perhaps will eventually be varied into the subnanosecond region) by varying the electronic conductivity. In insulators, the relaxation time is considerably longer. The minimum energy per bit for processing via the photorefractive effect is approximately 1 pJ for a 1-μm^2 bit size. This corresponds to a value of σ (Eq. 9) of about 5×10^{-19} cm^{-3}, comparable to the resonant nonlinear index in GaAs multilayer structures. Such materials are well suited to image processing, as outlined earlier.

There is another important aspect of the photorefractive effect in which it is unique among all mechanisms for nonlinear index change: there can be a spatial phase shift between the incident intensity pattern and the induced index which depends on the direction of displacement of the photocarriers. In a holographic two-beam mixing experiment, shown in Fig. 2, this gives rise to transfer of energy from one beam to the other. A weak image beam can, in this way, be amplified by mixing it with an intense pump beam (carrying no information). Amplification factors of up to 100 can be achieved (*7*). Signal regeneration will be essential in any complex optical processing operation. The photorefractive effect thus offers considerable versatility for processing information, particularly since the wavelength of operation is noncritical and beams of one wavelength can be used to control several other wavelengths. The effect has been used both for holographic processing as shown in Fig. 2, where the transverse electro-optic effect is employed, and for real image processing as shown in Fig. 3, where the longitudinal electro-optic effect is used. In the latter case, the minimum bit size is approximately equal to the thickness of the material. In the holographic case, the resolution is determined by the spatial frequency of the hologram. The minimum energy requirements for each mechanism for phase change of π are summarized in Table 4.

Electroabsorption. Another recent discovery is the use of electroabsorption to produce a nonlinear absorption change in GaAs multilayer heterostructures (*8*). As with the photorefractive effect, the effect used is hybrid; photocarriers resulting from optical absorption change the field inside the material and hence the absorption through the large electroabsorptive effect discovered in these heterostructures. This electroabsorption results from a shift of the sharp exciton line. In the first of these so-called self electro-optic devices (SEED's), the heterostructure is biased through a series resistor. Photocurrent resulting from optical absorption gives a voltage drop across the resistor, changing the field across the heterostructure and hence its optical absorption. In analogy with the photorefractive effect, the effective material response time is the resistive-capacitive time constant of the series resistor and the intrinsic capacitance of the heterostructure. An important aspect of this result is that only very thin samples (~ 1 μm) are necessary. The first results demonstrate that an on-off contrast ratio of 2:1 in transmission can be achieved with only 4 fJ/μm^2 of optical energy, and an additional 16 fJ/μm^2 of electrical energy from the bias circuit. Although only single devices have been demonstrated, the technology is promising for parallel arrays. It is likely that a bit size of a few square micrometers is achievable. Furthermore, higher contrast is in principle achievable with some penalty in sensitivity. It is not clear at this time how to make a comparison of this with the energy to create refractive index changes in Table 4, which are normalized to induced phase changes of π for maximum contrast. However, this approach opens up new possibilities for materials and new flexibility for parallel optical processing with energies in the subpicojoule range.

Source Limitations

It is clear from Table 4 that the energy requirements of presently known materials for optical processing, whether serial or parallel, is ~ 1 pJ per bit for a phase change $\phi \sim \pi$. This can be decreased significantly if the nonlinear medium is placed in a Fabry-Perot cavity, but with increased system complexity. It is also likely that adequate contrast can be achieved with phase changes considerably less than π in many processing operations, thereby reducing the energy required per switching event. Thus, for a single injection laser source of ~ 10 mW power, a bit rate of 10^{10} per second is achievable. To achieve 10^{12} bits per second, a laser diode array having 100 injection lasers is required. An important point here is that with simple optical sources, the available source power limits the simultaneous use of high speed and a high degree of parallelism. The material response time should be tailored to the requirements of the system: a material which is too fast does not make optimum use of available energy.

Thermal Limitations

Most of the nonlinearities discussed involve optical absorption in the nonlinear medium. Even in the more sensitive nonresonant Kerr media (such as PTS) the optical absorption is significant since the largest nonlinearities are achieved in the materials having a smaller band gap. From the discussion above, it is clear that for resonant nonlinearities for a phase change of π about 1 pJ or between 1 and 10^{-4} J/cm^3 of optical energy is dissipated. The larger figure corresponds to the shortest optical interaction length of an unguided wave (~ 1 μm). The smaller figure corresponds to a 1-cm-long optical waveguide. The adiabatic temperature rise of a switching volume can be as high as 1°C per switching event in the worst case. Thus, the repetition rate between pulses must be kept sufficiently small compared with the thermal relaxation time of the device to prevent temperature rises large enough to cause thermally induced index or absorption changes. Such considerations critically limit the performance of serial processing systems (*1*), but they do not seriously affect architectures having a high degree of parallelism because of the increased volume used for processing.

Application

A variety of problems confront the application of optics for computing with serial architectures. Certainly, elementary logic functions can be demonstrated in primitive form, but the appropriate combination of material properties required for high-speed serial processing has not yet been developed. Because of the fast material response needed for a serial processor, the choice of materials is severely limited. This, coupled with other complexities of serial optical computing (interconnection, heat dissipation, and so on), puts serial optical processing some distance in the future. In the meantime, some specialized applications may emerge which make use of the high-speed potential of all-optical serial switching at low duty cycles.

Because the materials requirements for high-speed parallel processing are less demanding, more progress is being made in this area than in serial processing. Materials with resonant nonlinearities and photorefractive materials are already available with characteristics suitable for prototype demonstrations of the power of parallel processing. These include applications such as real-time interferometry (*9*), convolution and correlation (*10*), image amplification (*7*), and wave front conjugation (*11*). In all these cases, the information to be processed is already in image form. Photorefractive materials are best suited to holographic processing, while resonant exciton nonlinearities in semiconductor multilayer structures are best suited to direct image processing. A potentially much wider range of applications exists in processing information that is transmitted serially down fibers and converted into parallel streams by means of laser arrays or liquid crystal light valve arrays. Such applications include numerical computation such as matrix algebra (*12*). This potential continues to provide the motivation for fundamental work in new materials and mechanisms for nonlinear optical processing.

References and Notes

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