Design Considerations for a Semipermanent Optical Memory

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The potential of high-speed optical memories using electro-optic or acousto-optic light deflection for address selection is examined. It is shown that for such memories the total memory capacity decreases as the third power of the addressing rate and that capacities in excess of 10^8 bits are feasible with a random access rate of 10^6 addresses/sec.

A specific semipermanent memory design is then described which uses a laser light source, an acoustic xy light deflector and an array of 10^4 holograms as information storage elements. Each storage element contains 10^4 bits which appear as a pattern on a semiconductor read-out matrix when the storage element is illuminated through the xy deflector. Accordingly, the system has a total capacity of 10^8 bits with an access time of less than 10 μsec.

I. INTRODUCTION

The increased computational capabilities of modern day computers are accompanied by a sharply increased need for a semipermanent memory to store their base programs. The capacity requirements for a given base program memory generally increase as fast or perhaps faster than the computational complexity of the computer increases.

Along with the increased capacity, the next generations of memories must have increased speed capabilities since the speed of the program memory generally controls the overall computer processing speed. Ideally, a program memory should have a random access capability to each instruction or to each group of instructions if the instructions can be suitably grouped.

If individual instructions are accessed in one memory cycle, the speed of the program memory has to match the rate at which the desired instructions have to be made available to the logic or processor frame. If, however, a group of instructions can be obtained in one access operation in the program memory, then the number of groups which must be accessed per unit time is reduced by the number of desired instructions contained within each group. This concept is usually referred to as paging; that is, each access operation within the memory selects a page, or set of instructions, rather than a single instruction. Operations within the memory output circuits then transfer the desired instruction from the accessed page, or pages, to the logic frame.

The twofold requirements of high speed and large capacity for a semipermanent memory suggests a review of the status and the capabilities of optical memories, particularly in view of the progress made in coherent optics within the past few years. The high speed requirements restrict the considerations to systems with access times well below 1 msec which make mechanical motion in the address selection impractical. The flying spot store was the first fully-developed optical memory with a short access time in the order of a few microseconds.[1] Recent publications in the field include studies of electro-optical systems,[2,3,4,5,6,7] holographic systems,[8,9] magneto-optical systems,[5,10,11,12] and ferro-electric optical systems.[13]

With a view towards high speed and high capacity a system using a laser light source and solid-state light deflectors appears particularly promising. This combination permits one to direct highly collimated and coherent light beams to a given address. Two suitable methods for deflecting light are available. They are the digital light deflector[14,15] and the acousto-optic deflector.[2] The high light intensity available from lasers, in conjunction with semiconductor detector arrays, makes it feasible to increase substantially the number of bits stored at each address as is required for page organization.

In order to assess the potential usefulness of such a system, the achievable speed and memory capacity should be examined on as general a basis as possible. Such an assessment is presented in the following section of this paper. To illustrate the potential of optical semipermanent stores this is followed by a description of a specific system which is based entirely on present technology and which has a storage capacity of 10^8 bits, divided into pages of 10^4 bits each with a page access time of less than 10 μsec.

II. STORAGE CAPACITY AND SPEED POTENTIAL

The total number of bits that can be stored in an optical memory of the type discussed here has an upper limit that depends on the speed of the memory. This limit is set by physical limitations in the addressing rate as a function of the total number of addresses and by the number of bits at each address which for a given interrogation rate is limited by the light intensity.

For both methods of light deflection the ultimate limit in the addressing system can be expressed in terms of a number for the capacity speed product CSP $= N_a^{\frac{1}{2}} \nu_a$, where N_a is the total number of addresses and ν_a is the rate (addresses/sec) of random addressing.* At low addressing rates an upper limit on N_a is set by the diffraction limit.

Kurtz[16] discussed the capacity speed product for the electro-optic deflector in the form described by Tabor.[15] For a linear electro-optic material he obtains

$$\text{CSP} = N^{\frac{1}{2}}\nu_a = \frac{6}{100\lambda\epsilon V_\pi^2\left[1 + \dfrac{(S_m - S)}{S_m}\right]} P_d ,$$

where the symbols have the following meaning:

- P_d reactive drive power
- ϵ dielectric constant of the electro-optic material
- V_π reduced half-wave voltage, that is the voltage which for an electrode spacing equal to the length produces half-wave phase retardation.
- λ the wave length of the light
- S_m The length of a module consisting of a polarization switch of length S and a Wollaston prism of length $S_m - S$.

In this formula, it is assumed that the smallest angular increment between addresses is given by $5\lambda/d$ with d the width of the aperture. This assumption allows for a $\lambda/4$ wavefront distortion, the aperturing due to the "walkoff",† and a guardband of $1.5\lambda/d$. It should correspond to about −20-dB crosstalk.

Obviously the driver power should be as large as possible. The only inherent limit is given by the heating of the electro-optic material which is a consequence of the finite Q of the crystal. For most linear electro-optic materials, heating does not present a serious problem.

The situation is more complicated for the quadratic electro-optic material KTN. Kurtz derived the capacity speed product for that case and particularly considered the limitations due to heating since

* The treatment of the capacity speed product draws heavily on an unpublished summary of the subject by K. D. Bowers.

† The light entering all but the first module has undergone at least some deflection and thus, "walked off" the optical axis.

the material has to be operated very close to its Curie temperature so that small changes in temperature will cause a large change in the electrical permittivity, hence in the polarization, hence in the electrically induced birefringence.

For the evaluation of specific cases the following assumptions are made:

driver power $P_d = 10\ W$
wave length of light $\lambda = 0.633\mu$
$S_m = 1.2$ S.

The resulting capacity speed products are listed in Table I. For KDP the listed values are for the longitudinal electro-optic effect since in that case it is larger than the transverse electro-optic effect. The values for all other materials are for the transverse electro-optic effect. The value listed for KTN is taken from Kurtz, but adjusted for the higher wavelength.

It can be seen that the highest capacity speed product achievable with presently known materials is on the order of 10^9 sec^{-1}.

The acousto-optic deflection of light has recently been reviewed by Gordon.[2] In this method, light is diffracted on the modulation of the refractive index produced by an acoustic wave. The deflection angle is changed by changing the sound frequency. The range of angular deflection is given by

$$\Delta\theta = (\lambda/v_s)\cdot\Delta f_s ,$$

where v_s is the sound velocity and Δf_s is the range of the acoustic frequencies available.

TABLE I

Material	$\kappa = \epsilon/\epsilon_0$	V_π (10^3 volt)	κV_π^2 (10^8 volt^2)	CSP (10^9 sec^{-1})
Linear electro-optic effect				
KDP[17]	20	8	13	0.07
CuCl[18]	8	7.2	4	0.23
$LiNbO_3$[19,20]	32	2.8	2.5	0.37
$LiTaO_3$[21]	43	2.4	2.5	0.37
ZnTe[22]	10	2.9	0.84	1.1
Quadratic electro-optic effect				
KTN[23]	1400	0.054	0.4	0.8

Since the incident light is apertured to the width d of the deflector, the emerging beam will have an angular spread due to diffraction. In order to have well-resolved output positions an angular separation between neighboring addresses of $4\lambda/d$ is assumed which allows for a $\lambda/4$ wave front distortion and for a guardband of $1.5\lambda/d$. This separation is somewhat less than was assumed in the electro-optic case where an additional allowance had to be made for the "walkoff." The number of resolvable addresses in one coordinate is thus obtained as

$$n = \Delta\theta/(4\lambda/d) = (\Delta f_s/4)\cdot(d/v_s).$$

The quantity d/v_s is the transit time for the acoustic energy across the optical aperture, that is, the time needed to change the frequency in the deflector, or in other words $v_s/d = \nu_a$. If the X deflector is followed by a similar Y deflector and the two are operated simultaneously, the total number of resolvable addresses is

$$N = n^2 = (\Delta f_s/4)^2(d/v_s)^2 = (\Delta f_s/4)^2/\nu_a^2 .$$

Therefore, the capacity speed product is

$$\text{CSP} = N^{\frac{1}{2}}\nu_a = \Delta f_s/4.$$

Considering the present state of the technology it is justified to assume $\Delta f_s = 400$ MHz which gives a capacity speed product of 10^8 sec^{-1}.

For both deflectors, the maximum number of addresses is limited by the optics of the system in conjunction with the practical limit on the size of the deflector element. This limit is estimated at 10^6 addresses. In the case of the electro-optic deflector this corresponds to an aperture of a few centimeters for the polarization switches, a size which will be difficult to exceed for electro-optic materials of adequate optical quality. On the other hand, in the acoustic case the generally required cylindrical optics makes it difficult to exceed the above limit.

The resulting limitations in the number of addresses versus addressing rate are depicted in Fig. 1 (a) and (b).

If one stores M bits at each address, the laser energy reaching this address has to be distributed over the M bits. In order to detect any one bit, a certain minimum amount of light energy (number of photons) is needed at the detector for any desired signal-to-noise ratio. For a given light power reaching a given address, this sets an upper limit to the number of bits that can be accommodated at each address.

If an ideal photon detector were used, the noise limit would correspond to 1 photon per bit reaching a detector in the time interval which

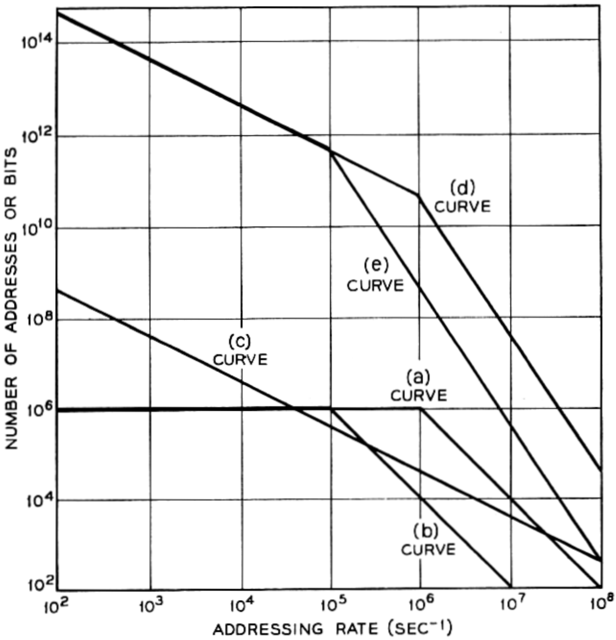

Fig. 1 — Capacity speed limitations in an optical memory. (a) Number of addresses vs addressing rate for the electro-optic deflector, (b) Number of addresses vs addressing rate for the acousto-optic deflector. (c) Number of bits per address vs addressing rate. (d) Number of total bits vs addressing rate for electro-optic deflector. (e) Number of total bits vs addressing rate for acousto-optic deflector.

is consistent with the desired memory cycle time. With a multiplying p-n junction, the noise limit is approximately 10^2 photons per bit and with a non-multiplying junction, the corresponding limit is 10^4 photons.[24] For an adequate signal-to-noise ratio, the number of photons reaching the detector should be 10^2 times the number corresponding to the noise limit.

For an array of photodetectors, non-multiplying junctions offer the greatest economy and flexibility. Thus, a minimum of 10^6 photons per bit should reach the detector in the time in which the read-out is to be performed.

At present, simple, reliable lasers operating in the visible range are available which emit in excess of 100 mW in continuous operation. In the light deflection and the projection onto the photodetectors, a fraction of the light intensity will be unavoidably lost. In a practical optical system it will be very difficult to keep these losses below 10 dB. Accordingly, it can be assumed that 10 mW will be available at the detectors. If one further assumes that the rate at which bits are to be read out from any one detector should equal the addressing rate, an inverse relation between the number of bits that can be paralleled at one address and the bit rate per detector can be determined. Fig. 1(c) gives the resulting relation for a photon energy of 1.5 eV and 10^6 photons per bit.

The product between Fig. 1(c) and Fig.1(a) and (b), respectively, gives the overall limit of the total bit capacity. Fig. 1(d) gives this product for electro-optical deflection while Fig. 1(e) gives it for acousto-optical deflection. These curves indicate that for high addressing rates the resulting limit of the total capacity decreases with the third power of that rate.

The curves permit a general assessment of the potential usefulness of optical memories using present state of the art components. Designing a memory that operates near its physical limits increases the complexity and cost; a memory designed for an addressing rate and capacity which are well removed from these limits can be built much more readily.

For a memory capacity of 10^8 bits or more, the curves of Fig. 1 indicate that, for such a capacity, addressing rates of 10^6 addresses per second are fairly close to the physical limitations. However, if the concept of paging is used and the number of desired instructions per address is a number between 1 and 100, depending on the program design, then a range of addressing rates of 10^4 to 10^6 addresses per second gives a net rate approaching 10^6 instructions per second.

III. DESIGN CONSIDERATIONS FOR SYSTEM USING AN ACOUSTO-OPTIC DEFLECTOR

A system realizing the above concept utilizes a laser light source and an XY-deflector which directs the light to any one address in a matrix of storage elements as depicted in Fig. 2. Each storage element has associated with it an optical system through which the stored information is projected onto a common read-out matrix. Thus, upon illumination of a selected address a real image of an information matrix is generated in the read-out plane. Whether a matrix point receives light or not corresponds to a logical "1" or a logical "0". In the read-out plane a matrix of photodiodes or other light sensitive detectors will convert the light into electrical signals. Therefore, by illuminating

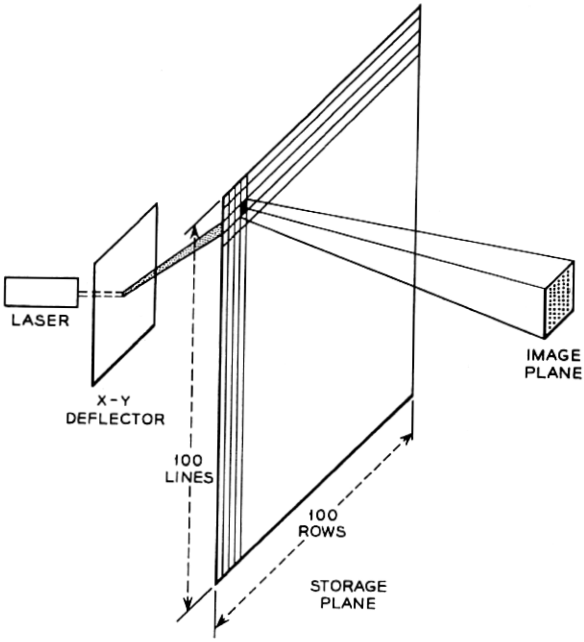

Fig. 2 — Schematic of optical memory system.

any one storage element with laser light, one transfers a large block of information from the storage location to the location of the read-out matrix.

At present, acousto-optic deflection is the most practical method of light deflection. Specifically, an addressing rate of 10^5 addresses per second and a total of 10^4 addresses is well within the range of available technology.[2] By storing 10^4 bits per address a total storage capacity of 10^8 bits is possible. Electro-optic light deflectors may ultimately replace the acousto-optic deflector since, theoretically, the former has a higher capacity speed product. However, due to materials problems the electro-optic light deflector is currently limited to speeds no higher than those achievable with the simpler acousto-optic deflector.

The following more specific considerations are based on the above configuration. It will become clear that the design is sufficiently far from all inherent limitations so that it will be possible to increase both capacity and speed through appropriate refinements within the established technology.

In the most straight forward approach a real image of the information matrix is stored in the storage plane. The projection onto the read-out plane requires a separate lens system associated with each storage location, the resolution of which is dictated by the number of bits stored at each location. It might be possible that such a multi-lens system is realizable with molded plastic fly eye lenses.

To keep the overall size within reasonable limits, the individual real image will be quite small. This would make the system very sensitive to dust particles and alignment.

Since the use of coherent light has already been assumed, it is readily possible to use holograms as optical elements. In that case the lens and the storage function can be combined by preparing a hologram which upon illumination by the deflector generates a real image of an information matrix in the read-out plane. Within each hologram, the information about each bit is spread over the entire area,[25] so that the sensitivity to dust particles is significantly reduced. The presence of dust in that case gives an overall reduction of the signal-to-noise for all bits stored in one hologram. Uniformity of illumination is also not very critical. Furthermore, the exact positioning of the individual hologram is not very critical. The location of the image, however, will depend on the angular orientation of the hologram. With a 100×100 read-out matrix it will be adequate to control the angular positions of the individual holograms to one part in 1,000, a precision which is quite practical.

In the hologram case a positional requirement exists between the laser and the read-out matrix. It can be expected that the alignment of the laser beam with regard to the read-out matrix can be much more readily accomplished than the alignment of the picture in the case where the information is stored as a real image. In particular, with an acoustic deflector that portion of the light which emerges undeflected might be used in a positional servo-mechanism.

In the hologram case the complications lie primarily in the fabrication of the holograms. It appears feasible to store the required 10^8 bits of information on 10^4 individual holograms within an overall size of 2×2 inches.

The laser to be used in such a system should emit light of a wavelength of less than one micron so that silicon devices can be used as photodetectors. It is also desirable that the laser be operable in a pulsed mode.

The best operation would be achieved with a Q-switched solid state laser, since, in such lasers, power can be integrated for up to approximately 10^{-4} seconds and the energy so stored can be released in pulses as short as 10^{-7} seconds.[26] Most solid-state detectors will operate with a minority-carrier lifetime of less than 10^{-6} seconds. In such devices, an optimum signal is obtained if the light pulse is short in comparison to the lifetime. A Q-switched solid-state laser will thus permit an optimum utilization of available laser intensity, since it is capable of integrating power up to the longest cycle times of interest and since it can discharge the energy in a time shorter than, or at worst comparable to, the lifetime in typical semiconductor devices.

In the simplest case the read-out matrix will consist of individual photodiodes located at each matrix point whereby all diodes can be read out simultaneously. For the specific case considered here, this requires 10^4 diodes and 10^4 read-out circuits. These circuits could be bi-stable elements such as flip-flops which are set by the photodiode.

As an alternative to a diode with a flip-flop, a pnpn diode in series with a resistor might also be used as a bi-stable element in the read-out matrix. The light could switch such a device from the low-current high-impedance state to a high-current low-impedance state.

The state of the individual bi-stable circuits could be interrogated through a multicoordinate address selection. Once the elements are set, the interrogation speed is only determined by semiconductor device considerations and it should be readily possible to interrogate "words" within the "page" with access and cycle times well below 100 nsec.

In this organization one is really dealing with a small (10^4 bit) semiconductor memory which is set by the optical system. This small semiconductor memory may be operated as a buffer store which can hold the information of one page for any desired period of time.

In other applications it may be necessary to have more than one page available in a random access high-speed buffer store. This requires that all information be rapidly transferred from the read-out matrix into a buffer store. In this case, the time for which the read-out matrix is to hold the information may become quite short and other methods of temporary information storage may be considered such as holding the information as a voltage on a capacitor. A particularly suitable method might be the use of photo transistors operated in the charge storage mode.[27] In that mode the light-generated charge is stored in a reverse biased junction for times much longer than a lifetime. The information is interrogated by applying a bias pulse to the transistor.

The charge storage mode has the additional advantage in that it can be used to integrate light over fairly long times making it possible to use CW lasers such as HeNe lasers with such detectors. This, however, leads to a somewhat less efficient operation than with a Q-switched solid-state laser since the CW laser will not integrate intensity during the time a new address is established.

IV. CONCLUSIONS

The preceding considerations lead to the conclusion that a semipermanent optical memory utilizing either acousto-optic or electro-optic light deflectors shows potential as a memory with 10^8 or more bits capacity and with page access as short as 1 μsec. Specifically, a memory with 10^8 bits capacity using acousto-optic deflectors can easily have page access times of 10 μsec. Such a memory using holograms as a storage medium and semiconductor devices as read-out elements appears well within the state of the art. Significantly shorter access times for similar capacities will probably require electro-optic deflectors using materials which are not yet available in adequate optical quality.

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