A new technique for removable media, read-only memories

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INTRODUCTION

New memory systems are often developed as a result of the discovery and exploitation of physical phenomena which exhibit storage properties. As a result of such a "technique-oriented" approach, the structure and performance of the resulting memory system may be dictated by the intrinsic characteristics of the technique and it is possible that the most desirable storage characteristics, from the computer's viewpoint, may not be realized.

An alternative approach, which will be followed in this paper, is to establish a set of performance characteristics from a system's viewpoint and then to identify and examine a technique which can satisfy these guidelines. The objective of such a "system-oriented" approach is to develop memories which increase overall system storage efficiency by optimization of performance characteristics and by specialization of memory structure.

Specifically, the storage requirements of a data processing system are classified into basic functions with the type of information and its associated usage within the system forming the basis for differentiation. Rather than using a general purpose memory to perform all storage functions, a memory unit is designed for a particular function utilizing the specialized nature of the function as a basis for system optimization. Thus, the design procedure begins with an analysis of the class of data involved and uses the characteristics peculiar to this class of data to establish the performance requirements on a storage element and a memory system which will store this data most efficiently. Then, these performance characteristics are used to evaluate possible implementation techniques and if, as is often the case, current techniques fail to satisfy the technical guidelines established then these guidelines serve as an aid in the search for new techniques.

For example, the application of this "system" approach to memory design has resulted in the establishment of technical guidelines for block-oriented,[1] push-down list, and content addressable[2] memories which are associated with those block-oriented, list, and content addressable types of data and storage functions common to data processing systems.

Read-only memory functional requirements

Upon examination of the storage requirements of central processor memory, there is a "read-only" function and a class of "fixed" data which may be identified. The "read-only" function includes the storage of indirect accessing schemes, the implementation of logic functions, the storage of microprogrammed instructions, and related applications. The "fixed" data consist of known information which, by its nature, is relatively permanent and which must be available to the computer on a word basis. Standard subroutines, trigonometric tables, ballistic tables, language translators, and character generators are examples of this type of data and usage.

The primary characteristics of the memory evolve from (1) the specialized read-only function of the memory and the semipermanent nature of the data, and (2) the necessity for direct central processor control of the unit. Thus, the memory must provide nonvolatile storage with nondestructive read-out and the storage must be word-oriented with random access to the word. Following these basic definitions, additional characteristics may be derived.

Removable media

The flexibility of a read-only memory would be extremely limited if there were no provisions for altering the stored data. For example, in circumstances where different tables are required by a program, it would be desirable to have a means of substituting this information without rebuilding the memory. This capability is provided if the memory has the data physically stored on a removable media.

However, associated with the concept of removable media is the problem of media registration. To provide adequate amounts of information for typical applications (without requiring the use of multiple read units), the capacity of a single media must be comparable to that of conventional (read/write) central processor memories. As bit packing densities are increased, correct alignment or registration of the media within the read unit becomes increasingly difficult. The difficulty lies in the coupling of the data on the media to the sense circuits of the read unit.

Tolerances on mechanical positioning of the media during and after insertion can become so critical that manual removal and substitution of the media is impractical. Schemes have been devised which attempt to alleviate the problem, but these schemes are still mechanically limited resulting usually in a restriction on the allowable capacity per media card. In many cases, it is this registration problem and not the storage capability of the media that dictates the overall capacity of the memory.

Read cycle time

Because the read-only memory performs a central processor function, it should provide access at speeds comparable to the primary central processor memory. Since the permanent nature of the storage eliminates the necessity for writing, rewriting, or erasing operations, it is reasonable to expect that the resulting memory organization should be extremely simple and that this simplicity should result in a significant reduction of access times as compared to conventional read-write memories.

Economic considerations

Due to its specialized function, its permanent storage, and the elimination of the write function, the memory should be less expensive than conventional memory types. If the cost per bit for both units is equal, then the particular application must be critically evaluated in terms of the remaining characteristics to determine if the use of a special purpose memory is justified. In fact, if any of the four distinguishing characteristics (i.e., removable media, faster access time, permanent storage, and lower cost per bit) cannot be achieved, then the storage function may be performed more economically, from an engineering viewpoint, by a conventional memory.

Proposed technique

Upon review of current techniques for implementation of the read-only storage concepts developed, the optical-photo methods appear most adaptable to fixed store. Photographic media are quite inexpensive, are capable of extremely high bit densities, and exhibit an inherent write-once, read-only storage capability. The optical read-out techniques, which are used, are nondestructive. On the other hand, such media are highly susceptible to scratches and dust particles; the accessing schemes are generally slow, requiring serial transfer of data; and the registration difficulties limit the overall bit capacity of the memory system below the capability of the media.

To overcome these problems and to retain the advantages of photographic emulsions, it is proposed to use holographic storage of binary information.[3] Holography, a new form of photographic recording, can introduce a unique type of redundant storage. For example, Leith[4] reports that diffused illumination holograms have an immunity to dust and scratches, and that particles have little effect in producing erroneous signals as in previous photographic memories. Also certain types of holograms act as a complete imaging system since they do not require lenses to project real images. This capability may indirectly ease registration tolerances and permit storage capabilities superior to other optical techniques.

It is intended that a hologram of a binary data array would constitute the card-like removable media. Upon insertion into the memory read unit, the hologram would continuously focus a real image of the data onto a photodetector matrix. Such an arrangement can permit electronic random access to the information within the array while eliminating the stringent optical requirements on the detectors involved.

Basic holographic principles

Holography, or imaging by wavefront reconstruction, is a two-step imaging process developed by Gabor.[5] The technique is based upon the illumination of objects by coherent light and the ability of such light to sustain a time invariant intensity distribution on a photographic plate. Although recent contributions have increased the complexity of the field, the underlying concepts remain the same.

General theory of holography

Construction: Figure 1 depicts the construction phase of the holographic process. Illumination of the target with temporally and spatially coherent light generates two fields at the photographic plane z_p. One field has not been altered by the object while

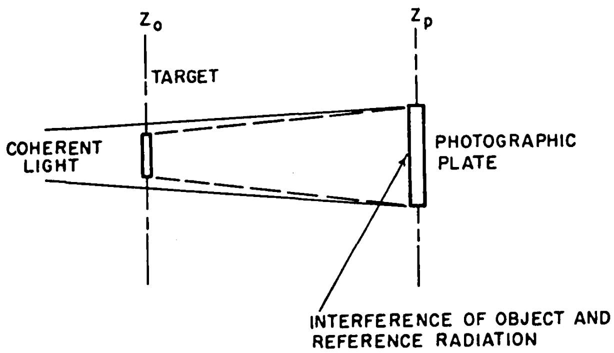

Figure 1 – Holographic construction

a second field results from object scattering. The total scalar field at the plate may be written as

$$E\ \exp(j\phi) = \exp(j\phi_r - j\omega t)[E_r + E_d\exp(j\phi_d - j\phi_r)] \quad (1)$$

where

$$E_d(x,y)\ \exp\ [j\phi_d(x,y) - j\omega t]$$
$$\text{and } E_r(x,y)\ \exp\ [j\phi_r(x,y) - j\omega t]$$

represent the modified and unmodified light respectively. The resultant power density (intensity) of the total field is equivalent to the square of the absolute value of the wave, or

$$I = [E\ \exp(j\phi)] \cdot [E\ \exp(j\phi)]^*$$

where * indicates the complex conjugate. Substituting Equation (1), one obtains

$$I = |E_d|^2 + |E_r|^2 + 2E_rE_d\cos(\phi_d - \phi_r). \quad (2)$$

Because photographic emulsions are sensitive to incident optical power, they will record this expression. Note that the time factor $\exp(j\omega t)$ has been eliminated, thereby making the power distribution fixed or stationary relative to time. Such a condition is maintained due to the coherent property of the light. Further, this expression exhibits information about the scattered phase ϕ_d as well as the scattered amplitude. The first and second terms of Equation (2) may be considered as D.C. components which contain little information but act as a bias level for the signal. The final term, representing the signal, expresses the modifications of light due to object scattering as the relative phase and amplitude variations with respect to the unmodified or reference light. The variations are functions of the spatial coordinates in the photographic plane but are invariant in time.

Through the ordinary photographic recording process, the energy distribution incident upon the plate during exposure is converted into a proportional value of real amplitude transmission t_n where t_n, in this case, is a function of Equation (2).

Reconstruction: The effect of this transmission can be seen in the reconstruction phase during which the negative is illuminated by a coherent beam, expressed as $E_c\exp(j\phi_c - j\omega t)$. The negative itself becomes an object scattering the incident illumination in proportion to the real amplitude transmission such that the transmitted field becomes

$$E_{trans} = E_c\exp(j\phi_c - j\omega t) \cdot t_n.$$

Substituting for t_n, its equivalent expression in terms of the original object field, one obtains a final value for the transmitted wave,

$$\begin{aligned} E_{trans} &= k_nE_cE_r\exp(j\phi_c - j\omega t) \cdot [E_r + E_d\exp j(\phi_d j\phi_r)] \\ &+ k_nE_cE_r\exp(j\phi_c - j\omega t) \cdot \frac{Ed^2}{E_r} \\ &+ k_nE_cE_r\exp(j\phi_c - j\omega t) \cdot [E_d\exp(-j\phi_d + j\phi_r)]. \end{aligned}$$

where k_n is a constant of the photographic process. Comparing this equation with Equation (1), one can see the direct resemblance of the first term of the reconstructed wave to the original signal. It differs by a multiplier and a constant phase shift. The second term has little significance and may be considered as noise. The third term is critical, however, and is characteristic of the holographic process. It is generated by the modulating action of the emulsion and is therefore characteristic of all holograms. That is, because the emulsion acts essentially as a square law device, recording the product of the field and its complex conjugate, this final term will be produced in all holograms. It is frequently called the conjugate or twin image of the signal, for it contains the same amplitude as the signal but has opposite phase shifts relative to the background.

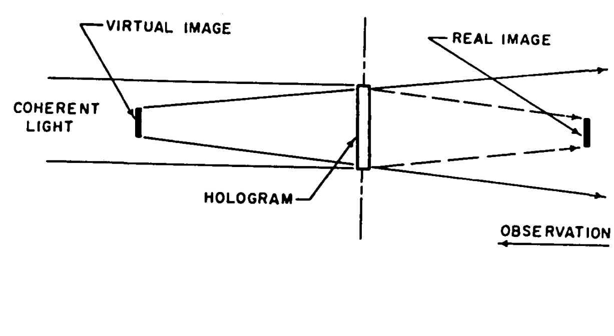

Figure 2 – Holographic reconstruction

When the hologram is viewed as in Figure 2, the signal term seems to diverge from an object behind the hologram plane, thereby appearing as a virtual image. This signal is a replica of the field that would be produced if the object were in place. The conjugate term represents a real image whose rays converge to a plane in front of the hologram plate. When constructed in this manner, these real and virtual images are superimposed acting as mutual noise. The effect of such noise on the original signal is a major problem with Gabor's original technique, but such effects can be reduced by special construction methods, e.g., masking.[5]

The second term in Equation (3) acts as background noise for both the real and virtual images. Its effect may be reduced by controlling the reference light amplitude during the construction phase.[5]

Hologram storage characteristics

General discussion

The system characteristics for the memory have been established previously. The distinguishing memory characteristics of high speed, large capacity, permanent store, and low cost are the major factors in determining system feasibility. The additional factors of expandability, small size, low power consumption, and high environmental resistance are included to insure compatibility of the memory with the remainder of the computer system.

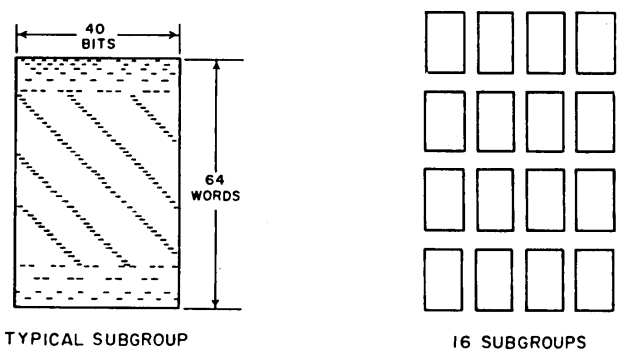

Figure 3 — Data array configuration

A diffused illumination, twin-beam hologram is to be constructed of a binary data array which consists of 1024 words of bit length 40. A possible configuration for the array may resemble Figure 3 which illustrates the placement of the data into sixteen subgroups each containing 64 computer words. The dimensions of the final array and bit configuration depend upon the capability of the holographic process and the physical limitations imposed by the read unit.

During reconstruction, the read unit would allow a real image of this array to be continually focused onto an optical read matrix, which consists of a photodetector for each bit location. Access may then be accomplished randomly by electronic selection and sensing of the individual detectors.

Information capacity

The digital information capacity of photographic emulsions has been shown to be extremely large.[6] Future photographic systems are predicted which have storage densities greater than those of contemporary storage techniques by a factor of 10^6, and this recording potential is surpassed only by genetic memories.[6] Analysis of emulsions on the basis of data capacity has been given extensive treatment in literature.[7] It has been demonstrated, to a first order approximation, that the information capacity in bits per unit area is equivalent to the square of the emulsions's resolving power. Numerically, then, Kodak 649-F plates (estimated to have a resolving capability of 2000 lines per millimeter) have an upper limit of 4×10^6 bits per square millimeter capacity.[7] Of course, attainment of such capacity depends upon the techniques of processing the data.

In terms of a one-to-one storage technique, a larger memory (4096 words) contains approximately 160,000 bits. If it is assumed that only 30% of 21-square inch media area is devoted to data, the bit packing density is only 40 bits per square millimeter. Obviously, this value imposes a modest demand upon the plate resolution.

Image Intensity: During reconstruction, it is desirable to transmit maximum light energy into the real image in order to maximize the electrical signal, improve signal-to-noise ratio, and compensate, to some degree, the variations in detector characteristics. With the holograms considered, there are several parameters that can be controlled to vary the real image intensity. The most obvious parameter is the output power of the reconstruction light source. It must be remembered, however, that since the outputs of present continuous wave lasers are proportional to the physical size of the device, there is a definite size limitation imposed by the memory on applicable lasers. Work on semiconductor lasers may prove useful in eliminating such a limitation. Secondly, it was noted that the image intensity is directly proportional to the amount of hologram area illuminated. Thus, a larger illuminating area seems advantageous. Thirdly, it may be shown by Equation (2),

$$I = |E_d|^2 + |E_r|^2 + 2E_rE_d\cos(\phi_d - \phi_r),$$

which relates the signal and bias levels, that a maximum signal is obtained by making the modulation index, $\frac{2E_rE_d}{(E_d^2+E_r^2)}$, equal to unity. This may be done by controlling the object and reference beam levels with filters. With this index set at unity, the exposures may be controlled to permit operation of the photographic process in a linear region of the Hurter-Driffield[5] curve, thereby producing low plate densities after development. A low density plate transmits and, therefore, diffracts more of the incident light into the real image.

Resolution: Armstrong[8] demonstrates that the size of the hologram plate constitutes a finite aperture for Fresnel-hologram imaging systems. Mathematically this may be seen by extending the Fresnel process equation into two dimensions and integrating over the finite limits specified by the dimensions of the photographic plate. Upon performing the integration, it is found that the reduction in resolution is proportional to the constriction of aperture area. Thus, the introduction of particles or scratches decreases the resolution by reducing the effective aperture area below that of the plate. It may be stated that the resolution loss varies as the ratio of aperture sizes before and after the inclusion of a particle. This indicates that with half the hologram destroyed or blocked half the original resolution is obtainable.

Further, since the image intensity (assuming constant illumination) is dependent upon the illuminated area of the hologram, a reduction in the effective hologram area reduces the image power. This may be seen if one considers each hologram point as a lens which focuses into its own image. The total intensity of the image then is a function of the number of lenses or the illuminated area of the hologram. The amount of light diffracted into the image depends upon the source intensity and the area effecting the diffraction.

This variation of resolution and intensity as a function of plate aperture is not a characteristic of ordinary photographs. If half a photograph is destroyed, only half the image is visible, but the resolution and intensity of the remaining half has not been changed. On the other hand, if only a portion of a diffused illumination hologram is used, the entire image can be retrieved, but the intensity and resolution of this image is proportionally reduced. In digital storage applications, this effect may not be critical because half an image may be more necessary than half the resolution. The memory, for example, may tolerate reduction of resolution (assuming the initial value was adequate) but cannot tolerate the loss of any part of the image.

Registration effects

The coupling problem associated with most optical read memories may be divided into two major areas. First, there is the difficulty of converting the light signals into corresponding electrical outputs. This conversion becomes a function of the image intensity, and of the optical sensitivity and speed of the photodetectors. Second, there are problems in the registration, or alignment, of the media and the light signals with respect to the detectors. These problems are related to the bit size and the mechanical limitations imposed by the removable media requirement. The registration problem is not peculiar to photographic memories but stems from the high bit density and the removable media criteria. The difficulty can generally be traced to the storage scheme which, for most memories, is on a one-to-one basis. Each data bit, then, is allocated a physical position in the memory. The media placement must register each bit location onto a corresponding sensor location.

To briefly demonstrate the superiority of hologram registration, consider a possible random-access photographic memory which uses bit-by-bit storage. The media is a photographic picture of a data array which consists of appropriate transparent and opaque areas. This array is focused by a lens system onto an associated photosensor matrix. The positioning of the media with respect to the lens system must permit focusing of a single bit such that the movement or displacement of the media does not result in a movement or displacement of the image more than a fraction of the bit size. Therefore, the mechanical holders for the media must maintain placement to within a bit size, assuming a direct relationship exists between media and image positions. Numerically, assume that the memory specifications require 1024 words of 40 bits each to be stored on a 21-square inch media. This demands a maximum bit length of .0224 inch. Positioning accuracies should be well within one quarter of this size, allowing a .0056-inch positioning tolerance of the media in the media plane. This one-quarter derating factor must reflect the resolution available, diffraction effects, lens distortion, and photodetector characteristics. It may be that this value is too large and greater mechanical accuracies are necessary.

Now consider the holographic reconstruction process depicted in Figure 4. A diffused, twin-beam, Fresnel hologram is used to generate a magnified real image at a finite distance from the plate. A normal incident beam will, in the case illustrated, produce a diffracted, first-order, magnified image. It is evident that a transverse shift of the hologram by a distance d across the beam will cause the real image to move the same lateral distance d. Therefore, even with magnification, there is a unity factor between the positioning of the media and the image.

Although the Fresnel holograms seem to offer an improvement over conventional photographic tech-

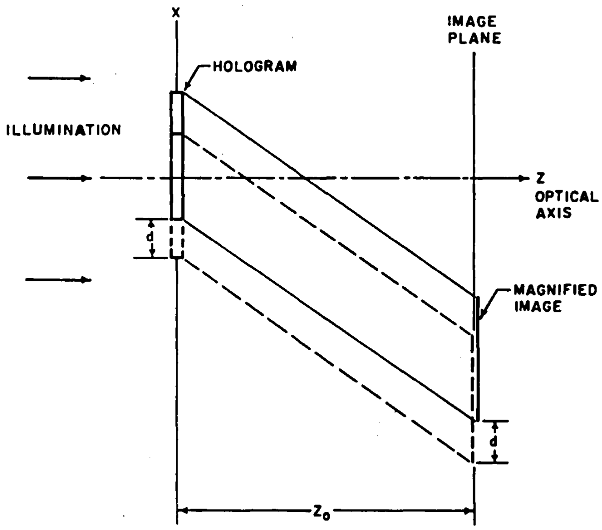

Figure 4 – Lateral shift of plate, Fresnel hologram

niques, an attempt was made to determine a more optimum condition for image registration. In this respect, Fraunhofer holograms appear to offer significant advantages. Figure 5 shows the Fraunhofer construction of an object composed of an infinite number of line sources. Because each source is placed at the

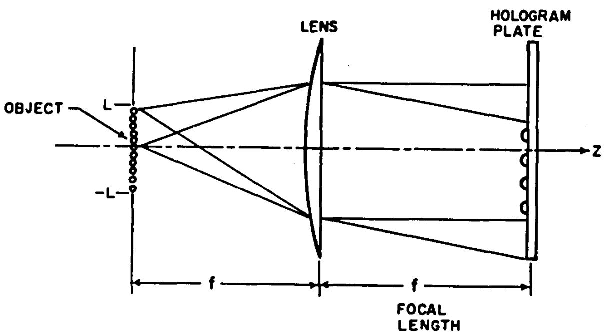

Figure 5 – Construction of object at infinity

focal plane of the lens, it will generate, in conjunction with the lens, a plane wave emanating at a predictable angle. Each source then creates a corresponding plane wave across the plate. The addition of a reference beam produces a sinusoidal intensity distribution on the plate for each source. Interference between source components is not considered. Because the distribution for a single source is similar over the entire plate in one linear dimension, illumination of any section during reconstruction will produce the same result. That is, employing a reconstruction beam whose illuminating area is less than the plate area causes plane waves to be emitted and, therefore, an image to be produced whose angular position does not depend on the hologram's linear displacement in one dimension, but which is a function of the incident beam position. As the hologram is moved across the beam, the angular position of the image does not vary (cf Figure 6). However, unlike the Fresnel type of hologram, a lens is required to produce a reconstructed image at a finite distance. Figures 7 and 8 illustrate the characteristics of diffused illumination Fraunhofer reconstructions with respect to image registration. Although the preceding discussion does not consider all of the possible displacements of the hologram and the resulting effects on the reconstructed image, it does serve to illustrate some of the more significant advantages of the technique.

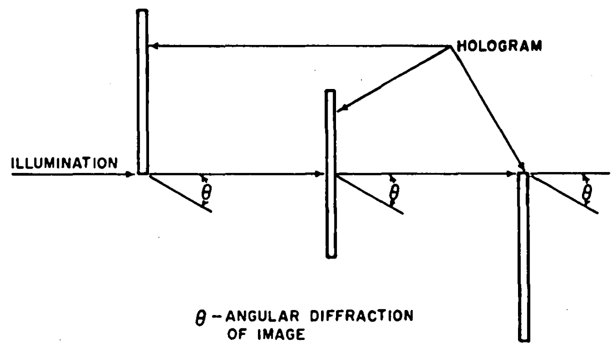

Figure 6 – Reconstruction with image at infinity

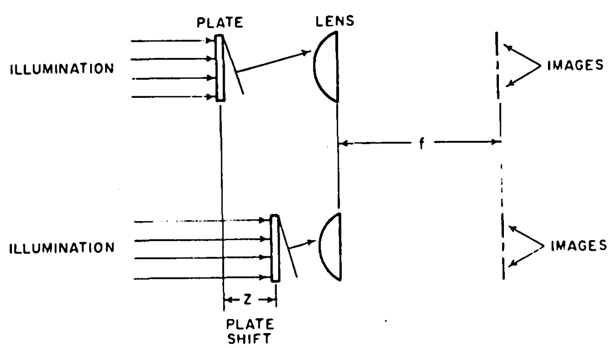

Figure 7 – Z axis displacement, Fraunhofer hologram

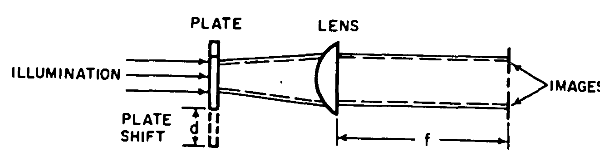

Figure 8 – X or Y axis displacement, Fraunhofer hologram

System design considerations

As previously stated, one approach to the implementation of a removable media, read-only memory by holographic techniques is as follows. The removable media would consist of a hologram of a binary data array. The actual dimensions of the array and the final configuration of the data will depend upon the capability of the holographic process and the physical limitations imposed by the read unit. During reconstruction, the read unit would allow a real image of the array to be continually focused onto an optical read matrix consisting of a photodetector for each bit location. Access may then be accomplished randomly by electronic selection and sensing of the individual detectors. It is proposed to use a laser to provide the coherent illumination.

In the design synthesis, advantage should be taken of the specialized nature of the read only function. For example, effort should be made to decrease access time and to implement the system with a minimal amount of hardware. In this case, the effort will consist of gaining simplicity in the control block and in the remaining circuitry peripheral to the detector matrix. Overall, the memory must provide a word-oriented, random access, nondestructive read capability while being compatible with the remainder of the computer through the processor-memory interface. Figure 9 shows a block diagram of the proposed memory design.

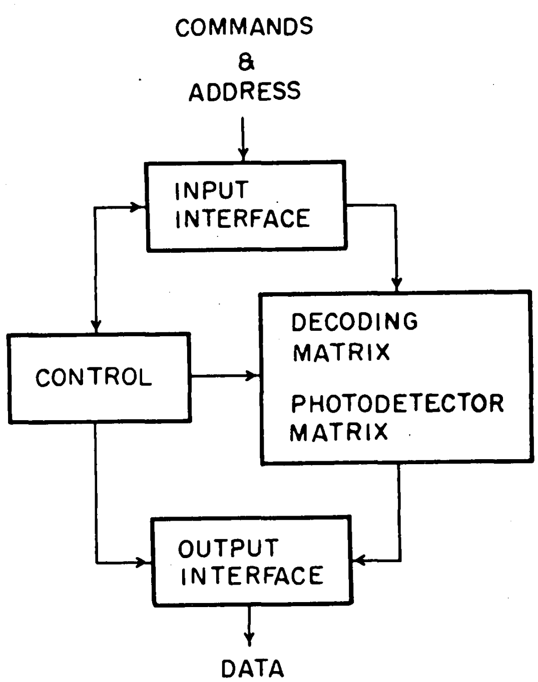

Figure 9 – System organization

Read matrix requirements

The read unit matrix, in conjunction with the control section, must accept the address, decode the address, and place the data into the sense amplifiers. The matrix consists of a 40,960-bit planar array of detectors and associated address-decoding circuitry. Figure 10 shows a simplified matrix which demonstrates the access technique. Here, a diode decoding matrix, driven by the address line drivers, A,$\bar{A}$,B,$\bar{B}$, exhibits a word-oriented, random access, linear select function. The speed of decoding depends upon the diode switching speeds which, in turn, are functions of diode capacitance. Extension of this simple matrix to the full tance. Extension of this simple matrix to the full 1024-word memory would indicate, due to the number of diodes involved, the necessity of address drivers to insure a .1-us access time. Such an expansion would also indicate the 1024 lines connecting the decoding circuitry to the photodetector array and the need for completing these connections during fabrication of the matrix. It may be possible to utilize the photodetectors in the array for address decoding if the proper addressing is included in the image of the hologram.

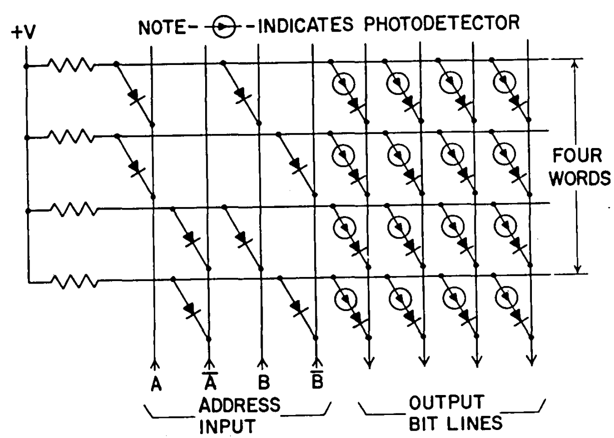

Figure 10 – Simplified read matrix

Each bit location, or cell, contains an electrically fast, highly sensitive photodetector and a high speed isolation diode to prevent crosstalk. The electrical characteristics of both the photodetector and the isolation diode affect the read cycle. To increase the speed, the capacitance per cell should be reduced to the lowest possible value. It is conceivable to use a driver per word line or a driver per element although such additions would increase matrix complexity beyond present day practical realization.

Detector Study: It should be apparent that many of the matrix characteristics depend upon the type photodetector to be used, and, indeed, the photodetector properties may dictate system feasibility. The principal concern is the choice of appropriate detectors and, from those available, which can be fabricated by simple techniques. In choosing the most suitable detector, the main properties that are required are optical sensitivity, electrical response, and ease of fabrication. The sensitivity of each detector must be high due to the relatively low optical power usually concentrated in the hologram real image.

In examining the electrical speed of the detectors, one must differentiate between optical and electrical switching characteristics. To illustrate these differences, consider a photodetector which is maintained at the proper electrical bias. If it is exposed instantaneously to a level of light, the optical response or switching time will be defined as the time required to electrically detect (at the output terminals) the total light change. This time includes the delay through the device and the rise time of the electrical variable, voltage or current. If, on the other hand, light is constantly on the detector, and the electrical bias is applied as a unit step function, the time required to fully sense the state of the detector will be referred to as the electrical switching time.

A survey of several optical detectors, including a discussion of the basic physics of their operation, can be found in the literature.[9,10] The devices which are applicable, especially from the standpoint of fabrication, are photoconductors, photodiodes, and phototransistors. In terms of the distinguishing characteristics dictated by the memory, i.e., sensitivity, speed, and ease of fabrication, all three detector types seem applicable. Because the image of the data array will be continually focused onto the detectors, the electrical switching characteristics are most interesting. From this standpoint, perfect photoconductors act simply as resistors, and therefore the electrical switching response is dependent upon its conductance and the impedances of the pre- and post-circuits. With good circuit design, this response becomes that of the pre- and post-circuits which, in this case, includes the decoding circuitry for the matrix. (Practically, there will be some parasitic capacitance associated with each detector element.)

Experimental results

A number of basic experiments were performed in an attempt to verify the predicted characteristics of holograms with respect to the read-only memory application. The primary areas of interest were the image intensity, image resolution, and registration effects associated with the construction and reconstruction of holograms storage images of two dimensional digital arrays.

The experiments confirmed the predicted registration effects and the application of holographic techniques to the read-only memory problem appears to offer significant advantages in the area of image registration with respect to the detectors. Measurement of the image resolution indicated that the resolution achieved was in the order of 13 lines/mm. However, due to the "granularity" which appears under visual observation of the reconstructed image, it is felt that the measurement was limited by the technique and that the actual resolution exceeds this figure. In addition, the resolution is also a function of the sophistication of the experimental facilities and technique and this value should not be interpreted as a maximum limit. Image intensity requirements are obviously dictated by the sensitivity of the selected photodetectors. To obtain some indication of the adequacy of image intensity for the intended application, as well as the overall feasibility of this approach, a breadboard model was constructed to actually read digital information from a hologram.

The breadboard model as shown in Figure 11, consisted of (1) a main chassis containing address selection switches, sense amplifiers, a four-bit output register and associated indicators, and (2) an auxiliary chassis containing a 4 × 4 array of photoresistors with an associated diode selection matrix. The photodetectors were organized into four words of four-bits each and were located in the auxiliary chassis to facilitate positioning with respect to the reconstructed image. A Neon-Argon gas laser with a power output of 0.6 mW (fundamental mode) was used as a source to reconstruct a hologram of a 16-bit data array. When the photodetector array was illuminated by the reconstructed image of the data array, it was possible to select and read out a four-bit word.

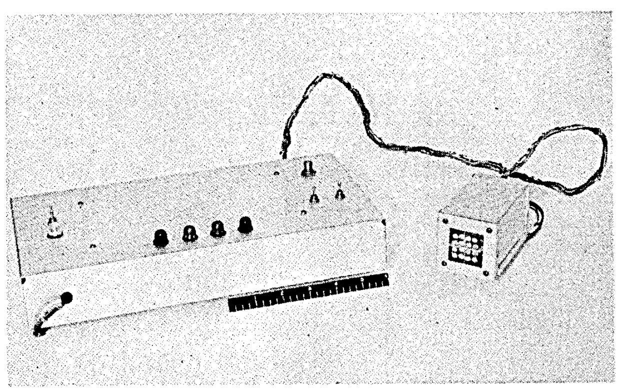

Figure 11 — 16-bit breadboard

Alternate approaches

The proposed approach for implementing a read-only memory using holographic techniques specifies a single reconstruction source and a single photodetector array with sufficient capacity to read the contents of a 1024-word memory. However, the ultimate feasibility of the technique need not depend on the development of such a photodetector array. Alternate configurations are possible which would allow the use of detector arrays with fewer photodetectors without reducing the total storage capacity of the memory.

For example, by using two reconstruction sources and by constructing two different holograms on a single photographic plate (each covering one-half the plate), the number of photodetectors in the array may be reduced by one-half. Each hologram would be associated with one of the reconstruction sources and would be constructed to cause proper imaging on the photodetector array upon illumination by the associated source. Then, access to a desired word would involve the selection and triggering of the proper source in addition to the normal selection in the photodetector array.

Of course, this scheme would require that the optical response of the photodetectors be less than 100 ns since the illumination of the elements in the array is no longer steady-state. This requirement would indicate the use of photodiodes or phototransistors in the photodetector array.

CONCLUSIONS

In general, the results of this study have indicated that holographic techniques are particularly suited to satisfy the functional requirements of read-only memory as specified. For example, holography offers solutions to two key problems associated with the requirement for a single removable media storing up to 160,000 bits. First, the unique redundance inherent in holograms constructed with diffused illumination eliminates the loss of data due to such environmental effects as dust and scratches. Second, the potential freedom from registration effects which can be achieved by proper selection of construction techniques allows the manual insertion and removal of media with high bit packing densities and does not add a requirement for complicated mechanical positioning or complex electrical interconnection in the read unit.

Although the initial construction of a storage media by holographic techniques requires a coherent light source and a fairly stable system, these requirements are within the scope of the system functional requirements, as previously defined. Moreover, the requirements for the reconstruction or reproduction of a storage media are much less stringent and appear to be capable of allowing the development of a read unit which is suitable for operation in a field environment. It has been shown that holograms can be reproduced by contact printing and that holograms can be reconstructed by noncoherent light sources.

Of course, the development of a feasible holographic read-only memory does not depend solely on holography. It is apparent that the ultimate success of this concept also requires the existence of photodetector matrices with sufficient size, sensitivity, and speed for this application, and which, in addition, are capable of economic fabrication. The development of photodetector matrices with the required characteristics appears to be within the state-of-the-art and should present no insurmountable obstacles. Indeed, if a "multiple-source/multiple-hologram" approach is selected, the number of bits required for the photodetector matrix may be small enough to allow practical and economic fabrication of the matrix on a discrete element basis.

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