Optical Data Storage: Mass Memories for Future Computers?

Computers have become a ubiquitous if unseen feature of life in most industrial countries, and dependence on this technology seems certain to increase. A key element in this success has been the ability to store large amounts of information in forms that are electronically accessible. Still larger memories will be needed in the future to handle the masses of scientific and commercial data that are foreseen. Optical techniques, in particular the holographic storage of information with lasers, may make possible very large, high-speed memories. Although optical memories are still in an early stage of development and commercial success is far from certain, their potential is stimulating considerable research in the United States and in other countries.

Just what the potential for optical memories might ultimately be was the subject of spirited debate at a recent scientific meeting (*1*) in Aspen, Colorado, that included representatives of virtually all the firms that are actively developing this technology, including some in Europe and Japan. Industrial research laboratories guard their commercially significant projects closely, and it is a measure of the state of the art in optical memories that many companies were willing to describe their work. Government research contracts, rather than commercial sales, seem to be the immediate goal of many of the firms represented. Nonetheless, not all of the development efforts of which word circulated at the meeting were presented to the formal sessions, nor were the sessions sparsely attended, despite the attractions of the nearby ski slopes. If the dominant commercial interests in the computer business do not yet believe that optical memories represent the technology of the future, neither are they ready to rule out this possibility.

At present, most computerized information is stored magnetically, by means of magnetic cores in central computer memories and on auxilliary magnetic disks and tapes. But core memory is beginning to be displaced by transistor memories as the sophistication of integrated circuits increases and their cost continues to drop. The future seems to belong to integrated circuits, despite the fact that electrical storage of information is not permanent (for example, the information is lost if the computer loses its power supply).

Central memories capable of random and electronic access rarely contain more than 10^7 bits of information. Mechanically driven disks and tapes are used to store larger amounts of information (so-called peripheral memories). Mechanically driven devices are inherently slow, however, and even the 10^9 bits that can be stored on a magnetic disk memory may not be large enough for many future applications. Bulk memories with capacities between 10^9 and 10^{12} bits seem to be the goal toward which researchers on optical memories are moving.

As conceived by most investigators, an optical memory for use with computers would store digital information in the form of holograms (Fig. 1). A laser beam is passed through a large array of light valves, each of which transmits or blocks the light according to the electronic information (a binary "zero" or "one") previously fed to the valve. The resulting pattern of darkness and light, which constitutes a "page" or block of information containing as many as 10^5 bits, is holographically stored by focusing both the pattern and a reference beam from the same laser onto a light-sensitive material. Only a small area (about 1 millimeter square) is needed to store the hologram, so that theoretically as many as 10^5 pages of information could be packed side by side onto a storage surface smaller than 1 meter square in size.

To retrieve information, the laser beam is directed to the desired hologram, projecting an image of the page of binary data onto an array of photosensors that can reconvert the light into electronic signals. With some designs, a less intense laser beam is used for reading than for writing, so as not to erase the stored information. Because a single operation (deflecting the laser beam to one location on the storage plate) can transfer a whole page of data (thousands of bits) at once, a holographic memory has an advantage over conventional memories that must transfer information a bit at a time. Holographic memories may also be more reliable, because they would have no moving parts and because defects in the storage material would not lead to errors as long as an entire hologram is not destroyed (light reaching any part of a hologram will reconstruct its full content). The density with which information can be stored is also high, in theory limited only by diffraction—essentially, by the wavelength of the light used.

As promising as the conceptual design of an optical memory may be, none of the requisite components has yet been fully developed. The means of deflecting the laser beam, the light valves that "compose" a page of data prior to storage, the storage medium, the photodedectors, and the insufficient intensity of the laser beam itself remain unsolved problems, despite encouraging progress in the last few years. Nonetheless, several prototype memories have been built which, while far from practical devices, do operate.

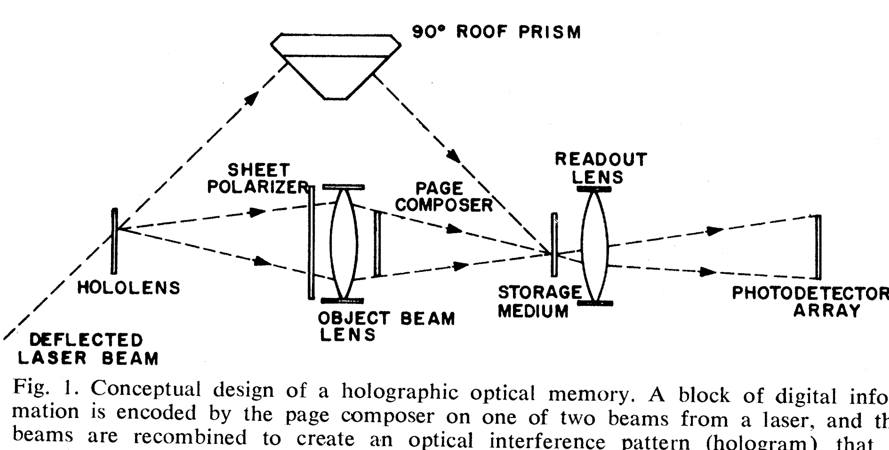

Fig. 1. Conceptual design of a holographic optical memory. A block of digital information is encoded by the page composer on one of two beams from a laser, and the beams are recombined to create an optical interference pattern (hologram) that is stored on a light sensitive medium. Information is retrieved by passing a laser beam through the storage medium and onto a photodetector array, where the holographic image is converted to electronic signals. [Source: R. D. Lohman, RCA Laboratories]

A group headed by P. Waterworth of the Plessey Company, Ltd., laboratory in Caswell, Towcester, Northants, England, has built a prototype of an optical memory from which data could be read by a computer, but into which no data can be written. Such a read-only memory, Waterworth envisions, would be suitable for storing the systems programs and other basic operating instructions that are repetitively used by a computer and that occupy unproductive space in the central memory; updated versions of the holographic memory plate would be produced separately. The memory is designed to have a capacity of about 10^8 bits, any of which could be read within 1 microsecond. The prototype that Waterworth and his co-workers actually built is much smaller but it demonstrated that a given hologram could be read within 200 nanoseconds. More difficulty was encountered with the system for recording the holograms, particularly, in constructing the large array of light valves in the page composer. Nonetheless, Waterworth estimates that use of the full-sized memory would improve the efficiency of a computer by 30 percent. Unfortunately, the computer manufacturers approached by the company expressed no interest in such a device on the grounds that its incorporation into a computer system would require substantial rearrangement of the existing techniques for storing data, and the project has consequently been shelved.

A similar but slower read-only prototype has been built by a Japanese company. According to H. Takahashi of Fujitsu, Ltd., in Kawasaki, experiments indicate that the speed with which data can be read out from their prototype is limited by the photodetectors used to 10 to 100 microseconds, and construction of large photodetector arrays is proving difficult.

Read-only memories have limited applications. Some observers believe, as the Plessey experience would seem to indicate, that read-only memories will have little commercial acceptance for use with computers.

The prototype of a more flexible memory that can both record and retrieve data has been demonstrated by RCA Laboratories in Princeton, New Jersey (Fig. 2). A similar prototype memory is being developed for the National Aeronautics and Space Administration by Harris-Intertype Corp. in Ann Arbor, Michigan. According to R. D. Lohman of RCA, their memory is designed to have a capacity of 10^6 bits organized into 1024 pages of 1024 bits each. An array of liquid crystals is used for the light valves in the page composer, and the holograms are stored on a thermoplastic material. To erase previously stored information, heat is applied to the thermoplastic at the selected location. Although the prototype is full-sized, not all of the electronics have been incorporated, so that only 48 test locations are actually used in trial runs. The memory performs as expected, Lohman says, reading and writing on demand without errors. Because the thermoplastic storage medium requires considerable time to heat and then to cool during each recording cycle, however, the memory is much too slow for practical use. The liquid crystals used as light valves are also too slow for real applications. Thus, Lohman believes, the prototype demonstrates that an operational optical memory can be successfully built, but that there is yet a long way to go to develop a commercial device.

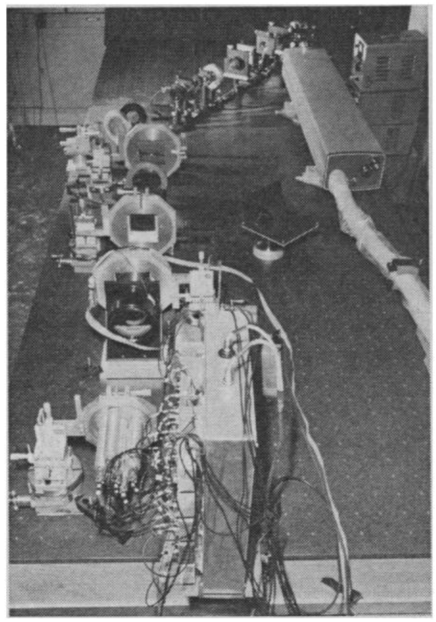

Fig. 2. Prototype optical memory with a capacity of 10^6 bits. [Source: R. D. Lohman, RCA Laboratories]

Optical Constraints

Engineering problems associated with particular components are not the only problem. An analysis by A. Vander Lugt of Harris-Intertype Corp. indicates that the ultimate capacity of an optical memory and the density with which information can be packed on a holographic storage plate are limited by the optical properties of the system as a whole. It is generally agreed that optical memories will require capacities in excess of 10^9 bits—some would say far in excess—to compete with existing memory techniques. Vander Lugt and others find, however, that optical constraints are likely to prohibit this capacity with existing conceptual designs.

One possible way around this obstacle is that proposed by E. Spitz of the Laboratoire Central de Recherches, Thomson-CSF Corporation, in Orsay, France, and others. Spitz suggests using a thick recording medium on which many holograms could be superimposed by rotating one of the incoming laser beams (the reference beam). Thus, in effect, the storage medium becomes a three-dimensional memory rather than a two-dimensional one as in the simpler design. Spitz has experimentally achieved the superposition of ten holograms, and believes that several hundred might eventually be possible. In this way, he estimates, capacities as high as 10^{11} bits might be achieved. Only a few storage materials suitable for three-dimensional recording have been found, however, and difficulties such as how to erase only one hologram at a time have not been overcome.

A second approach to expanding the capacity of optical memories is that proposed by H. Kiemle of the Siemens AG laboratory in Munich, Germany. By using a modular design in which the light from a single laser is split and directed to many different storage plates, each with its own detector array, Kiemle calculates that capacities as high as 10^{11} bits could be achieved. A major problem with this approach is that existing lasers are not of sufficient intensity for even simple designs and known recording materials; if the laser beam is split up among many modules, either much more powerful lasers will be needed or the speed of the memory will be greatly reduced because of longer recording times.

Many of those working on optical memories believe that systems problems can be solved, and efforts toward this end are now being de-emphasized in many laboratories. Instead, more effort is being directed to what most investigators see as the key problem, that of finding suitable materials, especially for the holographic storage medium. The types of storage media under investigation include thermoplastics, amorphous materials such as chalcogenides, ferroelectric materials such as lithium niobate, and magnetic materials such as manganese bismuth. Thin films of MnBi, for example, can be heated with a laser beam to temperatures above the Curie point, wiping out the magnetic information stored at that location. As the heated portion of the film cools, it becomes magnetized in a direction opposite to the surrounding, unheated areas. The optical interference pattern of the hologram thus creates a corresponding magnetic domain pattern. To read, a reference beam is directed onto the film, and the light transmitted or reflected from the film undergoes a phase variation corresponding to the magnetization. Investigators such as D. Chen of the Honeywell, Inc., laboratory in Bloomington, Minnesota, believe that magneto-optic materials, including MnBi, europium oxide, nickel arsenide and similar compounds, may not prove to be good storage media for holograms, because their sensitivity is too low. For nonholographic optical recording, however, these materials appear well suited.

Ferroelectric crystals have been shown to be a more suitable medium for holographic storage. Trapped electrons within the crystal are photo-excited by a laser beam and move around, creating stable ionic patterns corresponding to the holographic interference patterns. The ionic electric field induces variations in the crystal's refractive index, so that light hitting the crystal when information is being read undergoes phase variations to recreate the holographic image. Methods to greatly improve the sensitivity of several different ferroelectric crystals have been found by F. Micheron of Thomson-CSF in Orsay, France, and by D. L. Staebler of RCA Laboratories in Princeton, New Jersey.

A third class of storage materials includes amorphous semiconductors that undergo structural changes when heated with a laser beam. A. W. Smith of the IBM Research Center in Yorktown Heights, New York, has found that amorphous chalcogenide films are a good storage medium for nonholographic optical recording which he believes will find application in archival memories. Information is stored bit by bit in the form of spots of amorphous material on crystalline films or conversely.

Thermoplastics are used in thin layers sandwiched with a photoconducting layer. An electric field across the layers is modified by light impinging on the photoconductor, and when heated, the thermoplastic deforms slightly to store the optical pattern. Thermoplastics have been used to store holograms, but in

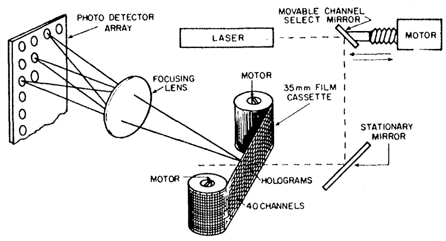

Fig. 3. Holoscan memory used to store credit card numbers. [Source: K. K. Sutherlin, Optical Data Systems, Inc.]

practice do not appear to be ideally suited for this purpose.

Although random access memories for use with computers are the most glamorous application of optical techniques, there is also considerable interest in more mundane designs. A system for permanent recording of archival information developed by E. E. Gray of Precision Instrument Company in Palo Alto, California, for example, does not use holography at all. Instead, a laser is used to record information bit-by-bit by vaporizing spots on a mechanically driven strip of rhodium-coated film. The information does not degrade with time or heavy use, as does magnetic tape. And although the access time to any piece of information is fairly slow, as with any tape system, the data is packed about 27 times more densely than that on a magnetic disk.

Mechanically Driven Memories

Mechanically driven holographic memories may ultimately prove very attractive, too. What is apparently the first commercial application of this concept is the Holoscan system produced by Optical Data Systems, Inc., in Mountain View, California, which is used for credit card verification (Fig. 3). According to K. K. Sutherlin of Optical Data Systems, the unit stores 10^7 bits on a replaceable cassette of 35-mm film. Sutherlin believes that the redundancy of holographic storage is a big advantage for memories used, as his are, under field conditions by untrained sales clerks; he reports that the memory has performed reliably despite dirt and scratches on the film.

For a more general purpose memory of the type describe earlier, many technical problems remain to be solved before commercial application can even be thought of. Perhaps the main question facing researchers, however, is not how to build an optical memory—although that is still unanswered—but rather what role an optical memory would play in a world dominated by fast semiconductor memories and inexpensive mass data storage on magnetic disks. At the Aspen meeting, there was no consensus on this question. E. S. Barrekette of the IBM Research Center in Yorktown Heights, New York, believes that optical memories will have a hard time replacing existing memory technologies because of continuing improvements in the latter and the tenacity with which, in recent decades, dominant technologies have resisted competitors in the computer industry. He stresses that the organization of computers into a hierarchy of memory devices means that relatively slow bulk memories—such as magnetic disks—are tolerable. In consequence, Barrekette believes that optical memories should ideally be very large—10^{12} bits—very cheap, but not necessarily very fast, if they are to be successful.

A contrasting and much more optimistic view, expressed by J. A. Rajchman of RCA Laboratories in Princeton, New Jersey, is that optical memories, because of their ability to transfer large blocks of data in a single operation, may eventually replace the existing hierarchy of memory devices, thus eliminating the complex and space consuming software that controls the hierarchy. He envisions optical memories as the sole on-line storage device in most applications and believes that they can provide the link between the high speed semiconductor memories of the central computer and the mass data storage of archival memories. Consequently, Rajchman believes that optical memories need not be so large—perhaps only 10^{10} bits—but that they should be fast and capable of permanent recording. Still other believe that optical memories may find particular applications outside of the computer business—storing seismic data and other permanent records, for example, or providing increased reliability of storage for frequently used information.

In the pursuit of better way to store large quantities of information, lasers and holographic techniques may ultimately play a major role. But at present, the forecast for optical memories seems to be compounded of conflicting opinions, unfulfilled potential, and hope.—ALLEN L. HAMMOND

Notes and Additional Reading

1. Much of the information on which this article is based was gathered at the meeting on Optical Storage of Digital Data, 19 to 21 March 1973, in Aspen, Colo. The meeting was jointly sponsored by the Optical Society of America, Institute of Electrical and Electrical Engineers, and International Commission for Optics.
2. J. A. Rajchman, *J. Appl. Phys.* **41**, 1376 (1970).