Milster has pulled together a series of articles that explore the status, potential, and future of three viable optical data storage systems.

Researchers and technologists are fascinated by the possibility of storing both analog and digital information in features no larger than one micron in diameter. The use of light to store and retrieve information from these small features defines the field of optical data storage, which has been around for some time. The first technical meetings on the subject occurred nearly 25 years ago, but until the advent of the compact disc (CD), the potential of optical data storage was not familiar to the public. Now, CD audio and computer peripherals are commonplace. However, CD technology is not the only form of optical data storage, nor is the CD the limit in performance for disc-based systems.

The following articles describe the status, potential, and future of three types of optical data storage: holographic storage, compact discs type systems, and near-field technology. Each type is distinct, with its own characteristic advantages and disadvantages. What consumers will see as entertainment or computer products in the near future will be largely determined by the success or failure of these technologies.

There are many questions left to answer that are beyond the scope of these articles. For example, what is a storage solution for high-definition television (HDTV)? Will it be optical tape? How far can we take near-field technology? Will we see optical technologies integrated with more traditional magnetic technologies? Can we use incoherent short-wavelength sources, such as mercury lamps, to further improve resolution?

As has been observed in optical lithography, the predicted "roadblocks" to storage technology are broken down with new approaches to familiar problems. The full potential of optical data storage technology has not been reached, and this technology remains an exciting field for research and development.

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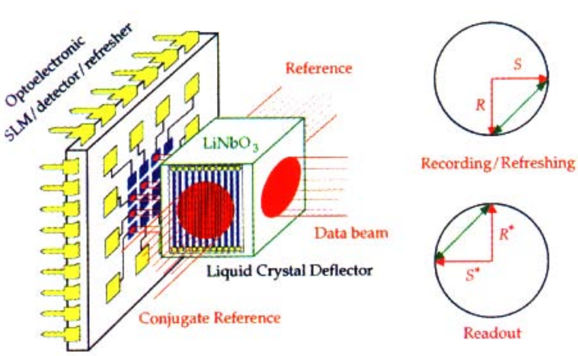
Holographic Memories

Holographic memories, first investigated in the late-1960s and early-70s, have made a remarkable comeback in the 1990s. Research in academia and industry (primarily in the U.S.) has resulted in a number of impressive laboratory demonstrations, showing that holographic memories have the storage density, read-out speed, and fidelity required for competitive commercial products.[1] The missing piece of the puzzle is a suitable recording material; the materials used in laboratory demonstrations [iron doped lithium niobate ($LiNbO_3$) and photopolymer films] are not suitable for products in their present form. Fortunately, system demonstrations of holographic memories have sparked interest in materials and progress is being made. There is a window of opportunity in the next few years to produce holographic memories that are competitive with the projected alternative memory technologies (optical CDs, magnetic storage, and semiconductor memories). Whether we can seize this opportunity and introduce holographic memory products depends primarily on whether recording materials are developed in time.



Holographic Memories Figure 1. Compact holographic memory using phase conjugate read-out.

Rewritable holographic memories are typically demonstrated with photorefractive crystals. Such memories have high storage density due to 3-D recording, fast read-out rate due to the parallel retrieval of entire pages, and potentially faster random access than magnetic discs. More than 1,000 holograms can be superimposed at one location, each hologram containing 1 Mb of data. So, approximately 1 Gb is stored in a crystal with a volume approximately equal to 1 cm^2. In a recent demonstration, phase conjugate read-out was used to construct a lensless system whose overall volume is approximately four times the crystal volume (see Fig. 1). The maximum read-out rate that has been demonstrated is 1,000 holograms/sec corresponding to an impressive 1 Gb/sec read-out rate with each hologram storing 1 Mb. The demonstration of fast read-out is important because rewritable holographic memory products can find a place in the marketplace only if they can be made faster than magnetic discs and at the same time cheaper than dynamic random access memory (DRAM). The lack of a suitable recording material is now the primary obstacle preventing us from pursuing the development of such products. The most serious shortcoming of photorefractives is volatility: holograms decay when they are read-out. Several solu-

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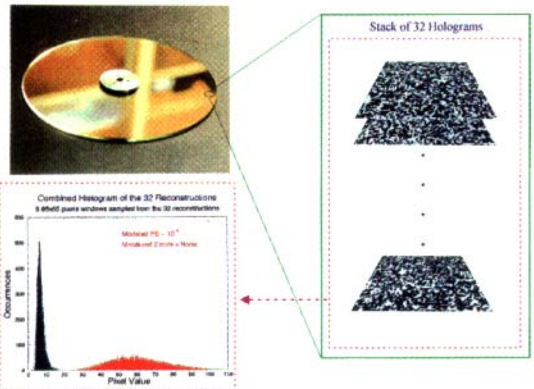
tions to this problem are being investigated but none of the reported solutions are sufficiently mature for commercial applications.

Another avenue through which holographic memories might enter the market is as successors to CDs and DVDs. A holographic 3-D disc (see Fig. 2) is constructed by laminating a layer of holographic recording medium onto a transparent disc substrate. The storage density that can be achieved on a single stored hologram is roughly equal to the density that can be achieved using surface recording. When multiple holograms are superimposed at one location, the surface density increases proportionally and discs with very high storage density (>100 bits/μm^2) can be realized.



Holographic Memories Figure 2. Holographic discs realize high surface density by storing multiple pages of data at each location.

Holographic discs have been made using photopolymer materials. Unlike photorefractive materials, these photopolymers are not rewritable. Therefore, holographic discs are usually intended as ROM devices. The majority of the experimental demonstrations have been carried out with a polymer material that is available commercially from Dupont. This material has an excellent diffraction efficiency and good sensitivity, but it is only available in a relatively small thickness (100 μm or less), thereby limiting the surface density of the disc to only 10 bits/μm^2, comparable to the effective surface density of DVDs.[2] For holographic discs to be competitive, their surface density should be 100 bits/μm^2, requiring an increase in the film thickness to 1 mm. Such density has been demonstrated experimentally in a 1-mm thick disc made with iron doped $LiNbO_3$. A polymer film of that thickness has not yet been reported but several promising materials are currently being tested.

The availability of recording materials will dictate if and when holographic memory products will be introduced in the next few years. The development of new photorefractive materials takes too long to have an impact in the short term. Improvements in the use of existing materials such as $LiNbO_3$ are still the best bet for photorefractives, while photopolymers offer a promising solution for write-once or read only memory (ROM) systems in the near term.

References

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2. D. Psaltis and A. Pu, "High density recording in photoploymer-based holographic 3-D discs," Appl. Opt. **35** (14), 2389–2398 (1996).

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Compact Discs

With an installed base of over 100 million CD read-only memory (CD-ROM) readers and over half a billion CD audio players, the CD is easily the most successful family of optical storage systems, and in fact, one of the most successful consumer electronic products of all time. Approximately 90% of all personal computers shipped today contain a CD-ROM reader. This large installed base, plus the low cost of the disc ($.005/MB for a "one-off" recorded CD, less for a mass replicated CD) makes CD the ideal format for distributing or sharing digital data.

The first member of the family, CD-digital audio (CD-DA), was introduced by Sony and Philips in the Fall of 1982 as a method of conveniently and inexpensively distributing high fidelity audio in a digital format. As Nicholas Negroponte, founding director of the MIT Media Lab, has said "bits are bits." The digital audio format was quickly expanded to include digital data (CD-ROM) in 1984, video (CD-V), interactive games and multimedia (CD-I) in 1987, and still images (Photo CD) in 1990.

How they're written

Initially, the CD family consisted only of ROM discs. Information is first laser-recorded in photoresist on a high-quality disc substrate, which is a process called mastering. The photoresist is then developed and coated with a metal layer. The coated substrate is called a stamper and it is has protrusions where the photoresist was exposed by the laser.

The stamper is used as one face of a mold that is injected with molten polycarbonate plastic. The plastic solidifies to create the 120-mm diameter, 1.2-mm thick disc substrate, which now contains depressions where the photoresist was exposed. These depressions or "pits" form a continuous spiral with a pitch of 1.6 μm. The pits are approximately 0.5-μm wide and vary in length from 0.833 μm to 3.054 μm in 9 discrete steps. The side of the substrate with the pits is coated with aluminum or an aluminum alloy. The reflective layer is protected by a coating, which is generally a UV cured acrylate (see Fig. 1, page 37).

How they're read

During reading, light from a laser is focused through the substrate onto the reflective layer, forming a spot with full width at half maximum intensity (FWHM) of FWHM $\cong 2.35 \times 0.25\lambda/NA$, where λ is the wavelength of the laser and NA is the numerical aperture of the focusing lens. In the CD, system $\lambda = 780$ nm and $NA = 0.45$, so FWHM $\cong$ 1μm.

Since discs consist of transparent plastic and an aluminum alloy reflector, the reflectivity of the pits and the surrounding region (the "land") is the same; interference effects, not reflectivity variations, form the basis for