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HOLOGRAPHIC STORAGE

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INTRODUCTION

Holographic data storage is a potential next–generation storage technology that offers both high storage density and fast readout rate. In this article, I discuss the physical origin of these attractive technology features, and the components and engineering required to realize them. The strengths and weaknesses of available write–once and read–writeable storage media are discussed, including the crucial issue of achieving non–volatile readout from read–write media. Systems issues such as the major noise sources and avenues for defeating or finessing them are detailed, including the potentials and pitfalls of phase–conjugate readout and holographic storage on spinning media. The unique opportunities offered by using massively parallel optical correlation to instantaneously search through digital databases are then presented. I conclude by describing the current state of holographic storage research and development efforts in the context of ongoing improvements to established storage technologies.

HOLOGRAPHY AND DATA STORAGE

At first glance, holographic storage might seem to be a redundant title for a research field. Since a hologram allows one to store a copy of an optical wavefront for later replay, holography itself is already intimately concerned with storage. The subtopic of holographic data storage thus refers specifically to the use of holography to store and retrieve digital data. To do this, digital data must be imposed onto an optical wavefront, stored holographically with high volumetric density, and then extracted from the retrieved optical wavefront with excellent data fidelity.

A hologram preserves both the phase and amplitude of an optical wavefront of interest—called the object beam—by recording the optical interference pattern between it and a second coherent optical beam (the reference beam). Figure 1(a) shows this process. The reference beam is designed to be simple to reproduce at a later stage. (A common reference beam is a plane wave: a light beam that propagates without converging or diverging.) These interference fringes are recorded if the two beams have been overlapped within a suitable photosensitive media, such as a photopolymer (1–4) or inorganic crystal (5–7), or photographic film (8)). The bright and dark variations of the interference pattern create chemical and/or physical changes in the media, preserving a replica of the interference pattern as a change in absorption, refractive index or thickness. When the recording is illuminated by a readout beam similar to the original reference beam, some of the light is diffracted to "reconstruct" a weak copy of the object beam (Figure 1(b)) (9). If the object beam originally came from a 3–D object, then the reconstructed hologram makes the 3–D object reappear (9).

Although holography was conceived in the late 1940s, it was not considered a potential storage technology until the development of the laser in the 1960s. The resulting rapid development of holography for displaying 3–D images led researchers to realize that holograms could also store data at a volumetric density of as much as $1/\lambda^3$ (10–12). In contrast to conventional data storage, where each bit of data is assigned to a particular location within the storage volume or upon the storage surface, holographic storage distributes data throughout a volume in a delocalized way. Data are transferred to and from the storage material as 2–D images composed of thousands of pixels, with each pixel representing a single bit of information. No one location in the crystal is responsible for storing that one bit; each is distributed throughout the associated recorded interference fringes. The direction and spacing of those particular fringes ensures that light arrives at a particular photodetector (within the large detector array) only when a particular readout beam is incident. The $1/\lambda^3$ theoretical density limit can thus be intuitively understood as a crosstalk limit forced by diffraction. Given that each reconstructed object beam must pass through an aperture A to reach a detector array, then two sets of fringes that differ in direction by less than $\lambda/\sqrt{A}$ will be indistinguishable due to diffraction. Given that the contributions of the fringe spacings will be integrated over a thickness of L, two sets of fringes that differ in spacing by less than λ/L cannot be individually reconstructed. So roughly L/λ data pages of A/λ^2 pixels each can be holographically stored within a volume $V = AL$. While this simple argument ignores the role of the bulk index of refraction (as well as real–world media and noise issues), $1/\lambda^3$ would be impressive density performance, corresponding (for green light) to the storage of 1 Terabyte of data in a cubic centimeter.

Since each data page is retrieved by an array of photodetectors in parallel, rather than bit-by-bit, the holographic scheme promises fast readout rates as well as high density (13–18). If a thousand holograms, each containing a million pixels, could be retrieved every second, for instance, then the output data rate would reach 1 Gigabit per second. Despite this attractive potential and fairly impressive early progress (19–30), however, research into holographic data storage all but died out in the mid-1970s. This loss of interest came about because suitable devices for the input and output of large pixelated 2–D data pages were just not available.

In the early 1990s, interest in volume-holographic data storage was rekindled (14, 15, 31–38) by the availability of devices that could display and detect 2–D pages, including charge coupled devices (CCD), complementary metal-oxide semiconductor (CMOS) detector chips and small liquid-crystal panels. The wide availability of these devices was made possible by the commercial success of hand-held camcorders, digital cameras, and video projectors. With these components in hand, holographic-storage researchers have begun to demonstrate the potential of their technology in the laboratory (39–61). By using the volume of the media, researchers have experimentally demonstrated that data can be stored at equivalent areal densities of nearly 400 bits/sq. micron (54). (For comparison, a single–layer of a DVD disk stores data at ~ 4.7 bits/sq. micron (62).) A readout rate of 10 Gigabit per second has also been achieved in the laboratory (52, 53).

Holographic Multiplexing

If a hologram is recorded in a thin material—as on many credit cards—the readout beam can differ in angle or wavelength from the reference beam used for recording the image. The scene will still appear. However, if the hologram is recorded in a thick material, the reconstructed object beam will only appear when the readout beam is nearly identical to the original reference beam.

For any readout beam, some of the incident optical power is diffracted by the recorded hologram to create a diffracted wavefront. In a thick hologram, this diffracted wavefront accumulates energy from throughout the thickness of the storage material. The Bragg condition applies when the diffracted wavefront is momentum matched to the readout beam and grating. For holographic media that record an exact copy of the interference fringes, this occurs when the readout beam is identical in wavelength and incidence angle to the original recording beam. Away from this condition, the discrepancy between the wavefront that would be momentum–matched (to the readout light and the grating) and the wavefront that can actually propagate (the closest solution of the wave equation) represents a phase error. Thus the wavefront diffracted by the front portion of the hologram, after propagating through most of the thick material, finds itself out–of–phase with the wavefront diffracted by the rear portions of the hologram. The integration of this phase error over the thickness of the volume hologram creates Bragg selectivity: the hologram "disappears" as the angle or wavelength is tuned away from the Bragg condition.

It is important to note that Bragg selectivity due to angle change only applies for angle changes within the plane formed by reference and object. Angle changes out of this plane maintain the Bragg condition to first order. Consider the following thought experiment: take a cylinder laid on its side with a plane wave hologram written inside (grating planes parallel to the circular top face, or equivalently, grating vector along the cylindrical axis). Assume a bulk index of 1.0 so that externally incident plane waves remain collimated inside the cylinder. If a reference beam is incident at the Bragg condition, nothing changes as the cylinder is rotated around its axis. Equivalently, the hologram continues to reconstruct if the cylinder remains stationary and the reference beam rotates around it, so long as the angle between the reference beam and cylinder axis remains constant. (Changes in this angle would exhibit Bragg selectivity.) The reconstructed object beam will also rotate around, remaining in the plane formed by the grating vector and readout beam. This illustrates grating degeneracy: one grating serves to couple all pairs of reference/object beams that are identical under cylindrical rotation about the grating vector. This has been shown to imply that a volume hologram cannot use an arbitrary 2–D page as a reference beam to store arbitrary 2–D pages (83–85).

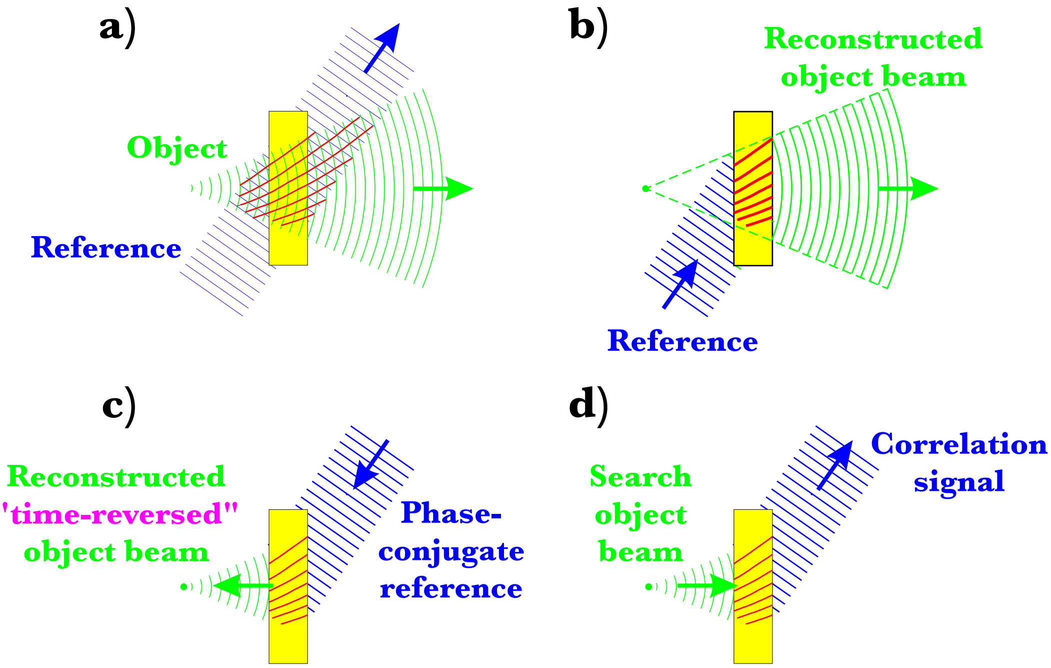

Figure 1: **How to record and read data using holograms:** (a) Holographic storage of a single data bit. The spherical wave from a single pixel interferes with a coherent plane wave in the reference beam. The resulting interference pattern changes the refractive properties of the photosensitive medium. (b) The hologram is read out using the original reference beam, which is diffracted by the stored interference pattern to reconstruct the original spherical wavefront. An image of this beam can be formed on a single detector pixel, resulting in the retrieval of a single bit. (c) The hologram can also be read out by illuminating it with a counter-propagating (or "phase-conjugate") reference beam, which reconstructs a phase-conjugate copy of the original object beam. This beam returns to its original point of origin, where the bit value can be read without requiring a high-quality imaging system (42, 63–74). (d) A third way to retrieve data involves illuminating it with a diverging object beam, which reconstructs the original plane wave reference beam. This beam can be focused onto a detector and provides an optical measurement of the correlation between the stored data and the illuminating object beam (9, 75). This technique can allow one to search the stored data according to its content, rather than according to its address (76–82). (After Reference (17)).

As the material becomes thicker, accessing a stored volume hologram requires tight tolerances on the stability and repeatability of the wavelength and the angle provided by the laser and readout optics. However, Bragg selectivity also opens up a tremendous opportunity: a small storage volume can now store multiple superimposed holograms, each distributed throughout the entire volume yet selectively accessible with its original reference beam. Several different techniques (86) have been developed to define a set of suitable reference beams. We have already implied that tuning the incidence angle (12, 22, 31, 32, 35, 87) or wavelength (88–92) will multiplex holograms. The former has been used much more than the latter, simply because rotating a mirror through large angles is easier to implement than rapidly– and widely–tunable lasers.

Instead of recording one hologram per incidence angle, it is possible to use all the incidence angles for each hologram, imposing a unique phase phase on each of these beamlets individually. The number of holograms that can be superimposed depends on the number of orthogonal phase–codes. Such phase–code multiplexing (93–102) is widely investigated because spatial light modulators could be used to rapidly apply these phases without mechanical motion. One issue is the requirement for low phase error (both random and deterministic (103–105)) in these devices; another is the impact of grating degeneracy on any phase–codes arranged in a 2–D pattern, a consideration that is unfortunately often overlooked.

Another improvement upon angle multiplexing actually exploits this grating degeneracy. Although holographic data pages do not disappear when changing the incidence angle out–of–plane, they are displaced on the detector array as the diffracted beam moves to remain in the plane formed by the incident beam and the grating vector. Once the data page slides completely off the detector array, the same Bragg angle can be used to store a second hologram. This is referred to as fractal—multiplexing, because one backs off from $(A/\lambda)^2$ pixels per page to some fractal dimension (say, $(A/\lambda)^{2-x}$), allowing an increase in the number of stored pages to $(L/\lambda) \times (A/\lambda)^x$ (83–85). Using a combination of angle and fractal multiplexing, as many as 10,000 holograms have been stored in a 1 cm^3 volume (106, 107). Techniques analogous to angle and fractal multiplexing, called shift and peristrophic multiplexing, have been developed for multiplexing holograms in thin disks and are described later.

Storing and Retrieving Digital Data

So multiple volume holograms can be superimposed within a small volume and independently reconstructed when desired. But to use volume holography as a storage technology, digital data must be imprinted onto the object beam for recording and then retrieved from the reconstructed object beam during readout (Figure 2).

The device for putting data into the system is called a spatial light modulator (SLM)—a planar array consisting of thousands of pixels. Each pixel is an independent microscopic shutter that can either block or pass light using liquid-crystal or micro-mirror technology. Liquid crystal panels and micro-mirror arrays with 1280×1024 pixels are commercially available due to the success of computer-driven projection displays. The pixels in both types of devices can be refreshed over 1000 times per second, allowing the holographic storage system to reach an input data rate of 1 Gbit per second—assuming that laser power and material sensitivities would permit.

The data are read using an array of detector pixels, such as a CCD camera or CMOS sensor array. The object beam often passes through a set of lenses that image the SLM pixel pattern onto the output pixel array, as shown in Figure 2. To maximize the storage density, the hologram is usually recorded where the object beam is tightly focused, near the back focal plane of the first lens. When the hologram is reconstructed by the reference beam, a weak copy of the original object beam continues along the imaging path to the camera, where the optical output can be detected and converted to digital data.

It would seem that the optimal place to record the hologram would be right at the back focal plane. However, this is often avoided. To explain, it is useful to describe the action of the first lens in terms of Fourier transforms. A Fourier transform takes an input $f(x)$ and produces an output $F(u)$ through a transform kernel of form $\exp(-j2\pi ux)$. It turns out that since the terms of $\exp(-j \ldots x^2)$ introduced by free–space Fresnel diffraction are exactly canceled by the quadratic phase terms that define a simple lens, the optical field amplitude appearing at the back focal plane of any lens is the Fourier transform of the field amplitude at its front focal plane. In Figure 2, the intensity seen at a storage material placed exactly at this Fourier plane will be (the square of) the Fourier transform of the SLM input. If, as is typical, the SLM imposes a binary pattern, then half of the power will be focussed to a sharp peak, corresponding to the DC value of the Fourier transform. Since such a high intensity often exceeds the regime where most holographic media respond linearly, holograms stored here will have severely distorted reconstructions.

There are two families of solutions to this problem. The first is to add something to the object beam that changes the Fourier spectrum of the object beam without affecting the transmitted image (108–113). Although it would best to do this with a single SLM capable of imposing phase and amplitude (114–116), in practice it's been necessary to introduce a pixelated random phase–mask (116–120) or axicon (117) into the object beam. An axicon avoids the careful lateral alignment that a pixelated phase–mask requires, but both must be placed in an exact image plane of the SLM (i.e., more lenses are required) (117). The second solution is to simply give up some of the potential areal density, storing holograms near but not exactly at the Fourier plane (31, 35, 54, 87).

To access holographically-stored data, the correct reference beam must first be directed to the appropriate spot within the storage media. With mechanical access (i.e., a spinning disk), getting to the right spot is slow (long latency), but reading data out can be quick (firing a pulsed laser when the disk is in the right position). Non–mechanical access leads to possibility for lower latency (fast beamsteerers such as acousto–optic deflectors (15, 36, 38, 40, 47, 49, 60) or liquid–crystal beam–steerers (121, 122). Readout with either a CW laser or a pulsed

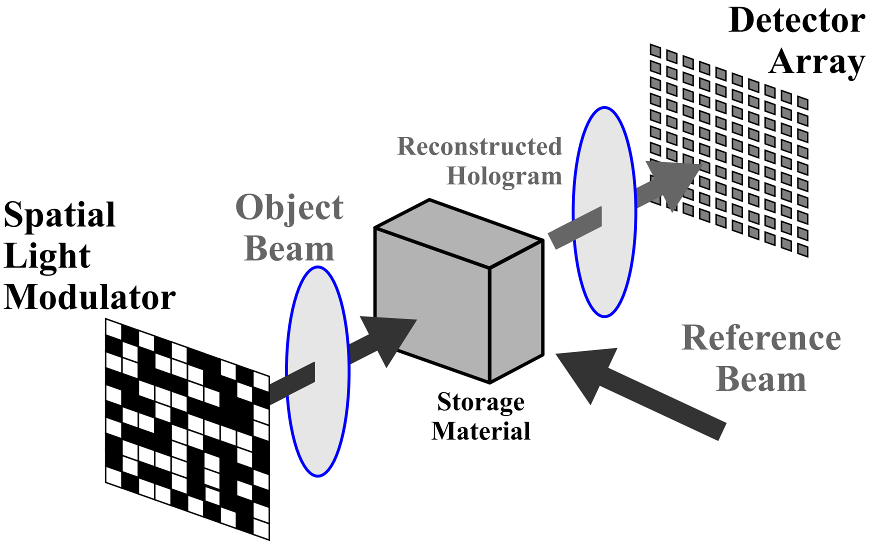

Figure 2: Data are imprinted onto the object beam by shining the light through a pixelated input device called a spatial light modulator. A pair of lenses image the data through the storage material onto a pixelated detector array, such as a charge-coupled device (CCD). A reference beam intersects the object beam in the storage material, allowing the holograms to be stored and retrieved later. (After Reference (17)).

laser of insufficient energy per pulse forces the beam to dwell on the hologram, reconstructing it continuously until a sufficient number of photons accumulate to differentiate bright and dark pixels. A frequently mentioned goal is an integration time of about 1 millisecond, which implies that 1000 pages of data can be retrieved per second. If there are 1 million pixels per data page and each pixel stores one bit then the readout rate is 1 Gigabit per second. This goal requires high laser power (at least 1 W), a storage material capable of high diffraction efficiencies, and a detector with a million pixels that can be read out at high frame rates.

Frame rates of 1 kHz have been demonstrated in such “megapixel” CCDs (58), but these are not yet commercially available. Low-noise megapixel CMOS detector arrays that can support 500 frames per second have also been demonstrated (123). Even with these requirements, faster readout and lower latency could be reached by steering the reference beam angle non-mechanically, by using a pulsed laser, and by electronically reading only the desired portion of the detector array. Both the capacity and the readout rate are maximized when each detector pixel is matched to a single pixel on the SLM, but for large pixel arrays this requires careful optical design and alignment (39, 49–51, 54, 87, 124).

MEDIA

Media for holographic storage has long been one of the primary focus points for researchers. There are two major classes of holographic storage media: write–once media, typically to be used as thin (0.2–2 mm) disks and accessed through disk rotation or translation (50, 51, 56, 125–131); and read–write media, typically kept stationary and accessed by beam–steering (14, 15, 32, 35, 36, 38, 40, 47, 49, 106, 107, 132).

Write–once read-many

A material that permanently stores volume holograms must generally support some irreversible photochemical reaction, triggered by the bright regions of the optical interference pattern, that can lead to changes in index of refraction or absorption. For example, a photopolymer material (as its name would suggest) polymerizes in response to optical illumination: material diffuses from darker to brighter regions so that short monomer chains can bind together to form long molecular chains (2, 3, 133–156). Because this diffusion process can be phototriggered, sensitivities can be made high enough to support holographic recording with single short pulses (52, 53, 149, 153, 154). However, the high sensitivity means that some of the media volume may be inadvertently affected by partial exposure as nearby spots are recorded. In contrast to photopolymers, the illuminated molecules in a so-called direct-write or photochromic material undergo a local change in their absorption or index of refraction, driven by photochemistry or photo-induced molecular reconfiguration. Examples include photoaddressable polymers (157–162), and binding of absorbers to polymer hosts (such as phenanthraquinone (PQ) to polymethylmethacrylate (PMMA) (163–168)).

Both types of materials are inexpensive to make in bulk, but both can have problems reproducing the object beam faithfully. Photopolymers tend to shrink during recording, distorting the reconstructed pixelated images (140, 143, 148, 169–171). Direct–write media respond both to the rapid variations of the interference pattern encoded with data and to long-range brightness variations across the illuminated spot. Such effects also distort the reconstructed data pages. These problems can be minimized by careful system design, such as signal–processing techniques that can compensate for shifted and distorted data pages (172, 173), and optical-illumination systems that deliver beams with extremely uniform brightness (174).

One advantage of a photopolymer is that any unpolymerized monomer left after recording can be polymerized with homogeneous illumination after recording without adversely affecting the stored holograms. In contrast, a direct-write material requires a separate chemical or optical step after the hologram-recording process to deplete the remaining absorbers. Otherwise, the uniform illumination of the readout beam will induce further photochemical reactions throughout the media. Thus the small amount of unreacted absorbers at the recorded bright fringes will be quickly consumed, and subsequent photoreaction at the recorded dark fringes reduces the contrast of the recorded index (or absorption) pattern and erases the stored holograms. (This is akin to the washed–out pictures that result when exposed camera film is accidentally opened in direct sunlight before developing). One way around this problem is to use a thermal diffusion process to homogeneously redistribute unexposed absorbers immediately after the holographic recording (163–168, 175), at which point they can no longer "fill in" the hologram. More useful in a practical system would be optical development, in which exposure with a second wavelength removes the residual photosensitivity at the original writing wavelength. As with photographic film, both photopolymer and direct–write write-once media must be protected from ambient light before use, and both tend to lose their effectiveness as they age.

Although problems with shrinkage, scattering and dynamic range remain, recent developments in these write-once materials have overcome previous difficulties with poor optical quality and excessive absorption and led to fairly thick samples (0.5–1 mm). Together with recently developed multiplexing techniques that use "peristrophic" beam rotation (125,176,177), spherical (128,130,178–181) or randomly speckled (52,53,182–186) reference beams to increase the number of holograms that can be superimposed in thin media, these developments have brought "write-once/read-many" holographic storage systems to the stage where several commercialization efforts are underway.

Read–write

In contrast to the organic WORM media, most erasable holographic materials tend to be inorganic photorefractive crystals doped with transition metals or rare-earth ions (5, 187–195). These crystals are often available in centimeter-thick samples and include lithium niobate (196–199), strontium barium niobate (200–203), and barium titanate (204–207), doped with iron, cerium, manganese or other dopants.

These materials react to an optical interference pattern by transporting and trapping electrons. In an ensemble sense, electrons photoexcited at the bright fringes diffuse or drift (are pushed by an electric field) and are retrapped at a dark fringe. By using noncentrosymmetric crystals exhibiting a linear electro–optic effect, the resulting spatial modulation of electric field leads to a corresponding local change in index of refraction (5, 192). The trapped charge can be rearranged by later illumination, so it is possible to erase recorded holograms and replace them with new ones. This would seem to enable a read-write storage device, where small blocks of data are written, read, and erased with equal facility. However, the recording rates of photorefractive materials are typically 5–50 times slower than the achievable readout rate at any given laser power. In addition, erasing individual holograms from a small storage volume without affecting the other superimposed holograms is quite involved (27, 208–219).

As a result, a holographic storage system built with photorefractive crystals is not a "read-write" system so much as an "erasable write-once, read-many" system. Such a storage device would record data slowly and in large blocks (100- 1000MB), but could then provide very rapid access to any small data block (0.1- 1MB). These large blocks of data could then be erased and replaced as desired.

Before discussing the important issue of volatility in photorefractive crystals, we describe some alternative read–write holographic storage media. These include photorefractive polymers (177, 220–222, 222–243), bacteriorhodopsin (244–260), and the DX–center in semiconductor materials (261–268). These materials are difficult to obtain in the thicknesses that would be required for competitive capacities, and also have their own idiosyncrasies. While photorefractive polymers can achieve large index changes very rapidly and provide many avenues for tuning through constituent substitutions, they require large voltages to create the orientational analogue of the electro–optic effect and tend to have fairly short dark lifetimes (seconds to minutes) (177, 220–222, 222–243) Bacteriorhodopsin can be tuned by genetic and chemical modifications (246, 250, 258, 260) and does not require an external electric field. However, volatility and dynamic range are serious issues (255, 260, 269), and the required operating wavelengths tend to be tightly tied to the protein's innate photocycle (246, 260, 269). Essentially, bacteriorhodopsin acts much like a write–once, direct–write saturable material, where readout "fills in" the holograms. By completing the photocycle with a second wavelength, holograms are erased and new ones can be written in the photosensitive molecules reset to their initial state. Finally, at low temperatures (< 150 K), the persistent photoconductivity exhibited by the "DX" center in semiconductors offers an opportunity for writing strong phase–holograms (261–268). Photoexcited electrons persist in the conduction band without decaying, leading to large index changes (261). This DX–center material also acts as a saturable material. Here, raising the temperature erases the holograms, since the photoelectrons now have enough thermal energy to make it back to the original ground state (261).

Non–volatile read–write storage

Unfortunately, the ability of a photorefractive material to erase through charge re-excitation also results in the undesired erasure of stored holograms during any subsequent optical exposure. This means that holograms erase while other holograms are being recorded, and worse yet, while any of the holograms superimposed within that same volume are being read out. In addition, there is gradual erasure in the dark through thermal excitation (192, 270).

These erasure effects can be counteracted during recording by carefully scheduled the sequence of exposures, to ensure that the final diffraction efficiencies will be equal (75, 107, 271–276). The first holograms are recorded to somewhat higher diffraction efficiencies with longer exposures, so that as subsequent holograms are recorded and these first ones decay, all final diffraction efficiencies are equal (274). As a result of the recording schedule, the effect of erasure is mitigated at some small cost in effective recording rate. (Recording schedules are also used in write-once media, to compensate for changes in sensitivity as a function of recording exposure (138, 140, 142, 277). This can include any pre-exposure required before the material begins to change its index of refraction.)

The more crucial issue is erasure of the the stored holograms during readout. With some photorefractive crystals, stored holograms can be "fixed" —made semi-permanent and resistant to erasure during readout—by separate thermal (21, 23, 28, 278–299) or electronic (201–203, 300–305) processes. Unfortunately, these fixing processes affect all the stored holograms within a volume simultaneously, only preserve a fraction of the original grating strength, and tend to be slow and cumbersome. For instance, it's not clear how to thermally fix holograms in one sub–volume while not affecting holograms in any of the neighboring sub–volumes.

Another proposed solution to the volatility problem is periodic copying and refreshing of the pixelated data pages (208–219, 306–313) Here the data pages are read out periodically and rewritten into the memory. Most of the experimentally demonstrated schemes have involved methods to reinforce the original hologram, but copying the data page into a separate storage location should also work. The problems with all of these is loss of data fidelity in all the copying and re–copying, and the performance loss represented by having the system inaccessible to user–generated read and write commands during the refresh operations.

A third approach to non–volatile holographic storage is to read the hologram with a wavelength different than that used for recording (44, 314–327). The idea is that if the absorption at this new readout wavelength is much lower, the erasure will take place much more slowly. The systems problem with this is that not all of the spatial frequencies in the hologram will be Bragg–matched simultaneously, and there will be a tradeoff between how much of the page will be visible, whether the pixels in the page will land where they're supposed to, and how hard one can push towards the theoretical density limit of $1/\lambda^3$ (44, 323–325, 327). These systems issues grow worse as the ratio between the two wavelengths grows larger; but given the broad absorption spectra in these crystals, significant changes in absorption require large (∼50%) changes in wavelength.

A fourth method for achieving non-volatile storage in photorefractive materials is by recording at a wavelength of light which is only absorbed by the crystal in the presence of an additional "gating" beam of different wavelength (7, 328–358). This additional beam is present only during recording and is switched off while the information is read out, allowing the data to be retrieved without erasure. The recorded interference fringes thus remain Bragg–matched to the readout wavelength, and both readout and diffracted wavefronts experience low absorption losses.

Conventional photorefractive materials can be optimized for this gated, two-color recording process by changing the way in which they are fabricated or by adding multiple dopants. For instance, the two-color response of lithium niobate can be enhanced by changing the ratio of lithium to niobium in the compound (336, 338), or by doping it with both manganese and iron atoms (337, 339–341, 346, 359, 360). Gated, two-color photorefractive materials have received much attention recently, leading to improvements in both the sensitivity and dynamic range of the materials (increasing both the speed with which data can be written and the capacity) (7, 336–350, 353, 354, 358). Further improvements, however, will be needed before prototypes can be built.

SYSTEMS ISSUES

Noise vs. coding and signal processing

The previous section concluded with a list of possible solutions to counteract undesirable erasure in photorefractive read–write holographic storage media. However, the seemingly intuitively obvious solution of simply reducing the readout power was not included on this list. Why? Because limiting the readout power has a strong negative impact on the attainable system performance specifications. It might be a good solution to the media problem, but it doesn't make for a good systems solution. In this section, we discuss the systems issues of holographic storage, including why reducing readout power to attain partial non–volatility is ultimately self–defeating.

In its simplest incarnation, a storage device is a black box which takes in user data at some point in time, and which delivers that same data at a later time. Desirable features might include capacity, input and output data rates, latency (the delay between asking for and receiving a desired bit or block of data), cost, system volume, and power consumption. Other defining characteristics might include removability of the storage media, and the ability to erase and rewrite data. High fidelity data retrieval, or conversely, a low probability of data loss through either random errors or catastrophic failure, is an absolute must. The particular bit error rate, as seen by the user (e.g., the user–BER), that is demanded might depend on the intended application of the storage device—the data in the device may be protected by subsequent archival storage, or the device may *be* the archival storage. Whether the black box is a write–once read–many (WORM) or a read–write storage device, the requirement of high fidelity retrieval (at any point in the future) incorporates a desire for long storage lifetime. Note that density at the media is not listed: the only point in acquiring high density is if it can then lead to high capacity—high density in and of itself is insufficient. Picture a holographic storage device that achieves a density of $1/\lambda^3$ at the media, but which requires a roomful of peripheral equipment for each cubic millimeter of media.

In holographic storage, the achievable readout rate and capacity are tightly tied to the readout signal strength. In addition to the diffraction–related crosstalk issues discussed in the introduction, the other basic noise trade-off in volume holography is between the finite dynamic range of the recording material and the fixed noise floor of the system. For instance, the electronic detection process at the camera tends to contribute the same amount of noise no matter how bright the hologram. However, as the number of holograms superimposed in the same volume (within the same 'stack' of holograms) increases, the amount of power diffracted into each hologram reconstruction and the resulting signal–to–noise ratio (SNR) decreases. The same reasoning applies for increases in the readout rate.

Even if all other noise sources are negligible, then there will be a certain hologram strength at which the SNR is inadequate for error–free detection. The number of detected electrons per pixel can be written as

$$n_{electrons} \propto M/\#^2 \, P_{readout} \, \frac{t_{readout}}{M^2 \, N_{pixels}}, \tag{1}$$

where M is the number of multiplexed holograms, N_{pixels} the number of pixels per hologram, $t_{readout}$ the integration time of the camera, $P_{readout}$ the power in the readout beam, and $M/\#$ is a material/system constant (274). The storage capacity is MN_{pixel} and the readout rate is $N_{pixel}/t_{readout}$. (Storage density is MN_{pixel} divided by the volume or area of each hologram 'stack'.) An increase in either capacity or readout rate leads to a decrease in the number of signal electrons (361). As this signal strength approaches the number of noise electrons, the raw–BER of the system will rise.

If sufficiently strong error–correction coding (ECC) is present, then even a relatively high raw–BER can be corrected down to acceptably low user–BER. For instance, the error–correction coding found in CD audio systems can deliver a user–BER of 10^{-12} even when the raw–BER exceeds 10^{-3} (362,363). The cost of this is a reduction in capacity, as some of the pixels of each data page are set aside to encode redundant ECC data. The stronger the ECC, the larger this overhead. If the raw–BER exceeds the level which the ECC can tolerate, then the user–BER of the storage system will not meet the promised specifications.

While the constant noise floor is usually of primary importance, any additional noise sources will use up part of the SNR budget. This additional noise means that more signal will be required to maintain the minimum tolerable SNR, or equivalently, to stay below the maximum tolerable raw–BER. To provide this added signal, the system designer must either get more performance from the components (media, laser, detector array, etc.), or sacrifice some of the system performance (by reducing either the number of holograms, the number of pixels per hologram, or the readout speed). Noise sources in holographic storage can include:

- *Changes in the readout conditions.* This can occur, for instance, when the recording alters the properties of the recording material, causing unwanted changes in the reference beam path between the time the hologram is recorded and the time it is reconstructed (171, 364–366). Often, the reference beam angle or wavelength can be tuned to optimize the diffraction efficiency and partially compensate for this effect (364).

- *The detector array doesn't line up with the array of pixels in the reconstructed hologram.* This includes errors in camera registration, rotation, focus, tilt and the magnification of the image.

- *The detector is receiving undesired light,* either from light scattering off the storage material (including unintentionally recorded noise gratings (367–369)), crosstalk from other stored holograms (inter–page crosstalk (170,370–390)), or crosstalk between neighboring pixels of the same hologram (inter–pixel crosstalk (114, 115, 391–393). Note that while crosstalk contributions scale with the strength of the holograms, the scattering depends only on readout power and the optical quality of the components (including the media). Inter–page crosstalk tends to build up as many reference beams, closely–spaced in angle or wavelength, are used within the same stack. One source of inter-pixel crosstalk is diffraction–induced low–pass filtering of the pixelated data page (392). The system then has a broad point-spread-function, and the sharply-defined input SLM pixels become blurred at the output detector array. This occurs when an aperture is introduced to increase density by reducing the size of each stack within the material (54, 393).

- *There are brightness variations across the detected image.* This can be a problem if a single threshold is used across the image to separate the pixels into bright and dark and assign binary values. These fluctuations can be caused by the SLM, the optical imaging, or the collimation and beam quality of the laser beams themselves. Such variations tend to be deterministic—they don't vary much from hologram to hologram.

Given these many noise sources and the need to read back holograms and make bright–vs–dark distinctions with high fidelity, how can the system designer maximize the desirable qualities of the system such as capacity and readout rate? These sorts of coding and signal processing considerations have received much attention in holographic storage. In part this is due to the relative maturity of holographic storage (at least as an experimental technology), in part because the two–dimensional nature of the data channel appeals to coding and signal processing professionals, and in part because holographic storage had no closely–related established technology from which it could readily borrow systems techniques.

Approaches for improving the performance of holographic storage systems by combating noise include:

1. From Equation 1, one can increase capacity or readout rate by increasing $P_{readout}$ (buying a bigger laser) by increasing $M/\#$ (getting a better storage material) (346, 394), or by reducing the noise floor due to detector electronics or optical scatter.
2. Pre-process at the spatial light modulator to either increase signal values (395) or reduce the deterministic variations which are reducing the SNR (393).
3. Post-process at the detector array in order to remove the blur from the known point-spread-function, with varying degrees of feedback or sequence estimation (391, 396–403). (Although deterministic variations can also be smoothed out with post–processing, this is best done during pre–processing. In essence, pre–processing knows for sure which pixels are ON and OFF; post–processing doesn't.)
4. Post-process at the detector array in order to compensate shifts of the data pixels, either globally (misregistration) or locally (optical distortion, magnification error, shrinkage) (172, 173, 391).
5. Use a low–pass modulation code which avoids pixel combinations which are prone to inter–pixel crosstalk (114, 392, 404), or modulation codes which encode data while turning ON fewer than half the SLM pixels (thus requiring less diffracted optical power per page) (405, 406).
6. Use a decision scheme which produces fewer errors from the same SNR, either with adaptive thresholding (407), or by encoding at the SLM with a balanced modulation code (87), or by a hybrid of both (408, 409).
7. Use interleaving (410) and strong error–correction (411–413) to produce the same target user-BER from a more error–prone stream of raw binary data.
8. Optimize the physical dimensions of the input and output pixel arrays and of the aperture at the hologram, in order to maximize the storage density (392, 414).
9. Apodize the input beam to make the illumination of the SLM uniform (174, 415), or apodize the reference beam to control the shape of the Bragg selectivity and reduce inter–page crosstalk (387, 416, 417).
10. Arrange the recording exposures so that the BERs of the first- and last-written holograms are equal, reflecting any differences in the noise environment experienced by each (418).
11. Use more than one ‘gray’ level per pixel, so that each pixel represents more than one bit of information (408, 419, 420).

Phase–conjugate readout for read–write systems

Recent experimental demonstrations of holographic data storage have concentrated on pushing high density and fast readout. High areal density can be achieved in holographic data storage by carefully balancing inter-pixel crosstalk (introduced by the small aperture through which each data page is focused) against the loss of signal associated with recording multiple holograms. An equivalent areal density of 394 bits/μm^2 (80× larger than single–layer DVD) was recently demonstrated (54). (The equivalent volumetric density was 1.1% of $1/\lambda^3$). Fast readout rate is attained by reading out large data pages in rapid succession. An optical readout rate of 10 Gbits/sec at moderate density ($\sim$10 bits/μm^2) was recently demonstrated, and a full system readout rate of 1

Gbit/sec shown (including the camera and decoding hardware) (52, 53, 186). Both of the demonstrations reached these specifications by combining large 'megapel' data pages of 1024×1024 pixels with the short focal length optics needed for high density.

However, extending read-write holographic storage to high capacity without sacrificing fast access means that this same high density must be achieved at many storage locations without moving the storage media. The correspondingly greater demands on optical imaging performance limit the capacity achievable by simply designing better lenses to commercially uninteresting values. However, several researchers have long proposed bypassing these imaging constraints with phase-conjugate readout (42, 63–73).

Once a hologram is recorded, the wavefront reconstructed by a phase-conjugate readout beam will retrace the path of the incoming object beam in reverse, canceling out any accumulated phase errors from lens aberrations or material imperfections. This allows data pages to be retrieved with high fidelity using image confinement in fiber–type media (63–71), an inexpensive lens, or even without imaging lenses for an extremely compact system (42, 72, 73). However, many pairs of phase-conjugate reference beams are needed to read the many different holograms recorded within the same volume – and maintaining these beams over long periods of time would be impossible from a practical point of view.

One solution to this problem is to separate the phase-conjugation and hologram storage processes into two successive steps with a 'buffer' hologram (74). Holograms can then easily be multiplexed at a large number of separate storage locations using only one SLM and one detector array. With gated, two–color media, the long–term storage material does not absorb the information–bearing beam until the gating light is present (74). With the phase–conjugate readout, total internal reflection could be used to confine the image–bearing beam within a small cross–section without sacrificing the ability to retrieve this image at the detector array (63–71, 74). Such a system only requires a single pair of phase-conjugate beams, generated either by carefully alignment or with a self–pumped phase-conjugate mirror (74).

A second proposed solution to phase–conjugate readout is to attain high capacity from multiple compact modules, each created by attaching an SLM, a detector array, and the storage media directly to a pair of beamsplitters (42). The phase–conjugate readout allows the whole system to remain extremely compact, and density can be further augmented by increasing the page size. It has been shown that phase–conjugate readout can retrieve pages with pixel pitches as small as 1μm (421). This approach has the advantage that the object beam need not be confined with total internal reflection because it is never allowed to propagate far from the SLM. But it does require inexpensive components, since the capacity per set of components is relatively low. Both the compact and buffer–enable phase–conjugate systems still require a low–power and convenient method for supplying thousands of unique reference beams to hundreds or thousands of spatial locations, using either micro–mechanical mirrors, liquid–crystal beam steerers, individually addressable lasers, or wavelength–tunable lasers.

The successful use of phase-conjugation in holographic storage should enable compact and affordable high-capacity systems, with only a moderate increase in the overall system complexity. Obviously, such systems still await a recording material that supports both read-write access and nonvolatile storage (337–339). Even so, there remain other serious issues that must be addressed before commercialization. Thermal stability must be good, lest the interference patterns change spacing and orientation as the media expands or contracts with temperature. Good mechanical and laser stability are also required (the media and interference fringes must not move during exposures, and motion afterwards can cause the reconstructed optical signals to veer off their assigned detector pixels). Fortunately, the stability during recording will become easier to attain as exposure times decrease through improvements in material sensitivity and increases in available laser power.

Despite all of the techniques for removing and suppressing volatility, it is unlikely that any read–write holographic storage material will be truly non–volatile: most likely the data will slowly fade over several months or years due to thermal effects (slow excitation from electron traps, diffusion of compensating ions) or through residual absorption. So while blocks of read–write media may be removable from the read/write head (which enables something like a petabyte "jukebox"), the media will probably need to remain within the jukebox so that data can be periodically refreshed.

Write–once systems using spinning disks

In contrast to read–write holographic systems, progress in write–once materials research (especially photopolymers (2, 3, 422)) has brought write–once systems to the stage where people are working on prototypes. Now the long–held conventional wisdom that the only thing between researchers and products was the material will finally be challenged.

Beyond the problems of perfecting the media (in characteristics such as dynamic range, scatter, sensitivity, shelf–life before and after recording, and thermal expansion properties) are the systems engineering issues of building robust holographic data storage devices around a spinning disk format. What makes this even trickier is that the obvious application areas (low–cost data archiving, possible next–generation distribution format for data and multimedia) call for inexpensive and robust disk readers (as well as cheap media). The first systems problem is the interplay between high rotation speed (needed for low latency) and the need for a high–power, compact pulsed laser to read and write with single pulses. And then there are the difficulties of getting the pulse to the right spot (tracking, focusing, synchronizing pulses to disk rotation), and getting the reconstructed data page to the detector array (compensating for tracking, tilt, disk jitter). Zhou et. al. have demonstrated tracking for low density holographic disks (51, 131). They showed both tracking and tilt compensation: the former by measuring the data page rotation to synchronize the beam shutter (on a CW laser), and the latter by tuning the reference beam angle so that data pages landed squarely on the pixelated detector array (51, 131).

To get high density, the reference beam must cover a wide spread of incidence angles, so good antireflection coatings may be needed to keep power from being lost in Fresnel reflections (and this increases media cost). To get the best density while suppressing aberrations in the imaging system, the object beam should probably enter the holographic disk media at normal incidence. As this must be done with short–working–distance optical system, the delivery of writing and reading beams around these imaging optics (without increasing the scatter into them) is further complicated. Although a read–only transmission–geometry head can avoid passing the reference beam past input optics, transmission geometry implies that the read head is split into two parts on either side of the rotating disk (and both sides must be aligned).

Several novel multiplexing methods have been developed to allow holograms to be superimposed very densely, even in thin disks. High density can be reached with "peristrophic"–multiplexing, at the cost of a fairly complicated read head that rotates the reference beam around the normal to the disk surface (125, 176, 177). In contrast, by using either a spherical (128, 130, 178–181) or a randomly speckled (52, 53, 182–186) reference beam, the motion of the spinning disk can allow the reference beam to selectively reconstruct stored holograms with an extremely simple read heads. If this "shift" multiplexing is done with a spherical reference beam, then holograms can be packed densely along one line (i.e., along the track), but only sparsely along the orthogonal direction (tracks must be widely–spaced) (128, 130, 178). Speckle–shift, or correlation, multiplexing using a random phase plate or diffuser (52, 53, 182–186) can allow dense packing in both radial and along–track dimensions, but this advantage does not come for free. Essentially, the size of the random speckles determines the disk motion needed to make each hologram disappear through destructive interference (182, 183). This should be small to maximize density, but not as small as the innate disk wobble and jitter of an inexpensive disk and spindle. On the other hand, the destructive interference depends on the number of random speckles that are spatially integrated as the reconstructed hologram transits the thickness of the disk. So while smaller speckle lead to better inter–page crosstalk SNR, they also make the readout conditions so selective that holograms might not be reliably found with inexpensive components. Another consideration is any noise from gratings and index changes recorded into the highly sensitive WORM recording media by the speckle pattern itself.

These systems difficulties do not prevent one from building systems that can write and read holograms on spinning disks—several working demonstrations have been shown (50, 51, 56, 131, 186). For instance, Orlov et. al., working at Stanford on the final systems demonstrator for the DARPA–sponsored HDSS (Holographic Data Storage Systems) program, built a system capable of 10 Gbit/second optical readout, and 1 Gbit/second end-to-end electronic readout, at greater than DVD areal densities on a disk spinning at >300 RPM (52, 53, 186). The spindle was so accurate that holograms could be incrementally recorded over several rotations (i.e., the accuracy and repeatability were at interferometric levels) (186). However, any commercial product will need to use much smaller and cheaper components, without sacrificing the high density, the fast readout rate, and the ability to robustly write and read holograms on the fly.

An alternate approach to wavelength–multiplexing is to use micro–holograms (423–430). Here each micro–hologram occupies a few square microns of surface area, and can either extend throughout the thickness of the disk or exist in one of several thick layers. Multiple bits of data are written at each microhologram by means of reflection gratings, which can be read out by active wavelength multiplexing (laser light scanned across the appropriate spectral band) (425–427), wavelength multiplexing (white light in, colored light out containing data) (428, 430, 431) or by angle–multiplexing (425). The beams are confined either by the focussed beam itself within a thin film (425), or by a micro–fiber within the material (428).

CONTENT–ADDRESSABLE STORAGE

With a conventional memory or data storage device, a user must supply an address at which the desired data is located. In volume holographic data storage, this implies that the data – which were once imprinted on an "object" beam and stored within the volume – can be read out later by illuminating the volume with the correct "addressing" reference beam (Figures 1(a) and 1(b)). However, this hologram can also be illuminated by the object beam (Figure 1(d)), reconstructing all of the angle-multiplexed reference beams that were used to record data pages into the volume. The amount of power diffracted into each "output" beam is proportional to the similarity between the input data page being displayed on the spatial light modulator and the stored data page. The set of output beams can be focused onto a detector array, so that each beam forms its own correlation "peak." The stored pages that match the input page can be identified by setting a threshold on the detected optical signal. If the patterns that make up these pages correspond to the various data fields of a database, and if each stored page represents a data record, then this optical-correlation process can be used to simultaneously compare an entire digital database against the search argument.

This search parallelism gives content-addressable holographic data storage an inherent speed advantage over a conventional serial search. This is particularly true for searches on complex queries through large databases, where an index for every possible search query becomes untenable. For example, it would take a conventional software-based search ∼40 seconds to go through one million records, each containing 1 kilobyte of data, if this Gigabyte of data has to be pulled off a hard drive for each search. Connecting a gigabyte of DRAM to a 1GHz microprocessor could reduce this search time to ∼1 second. In comparison, an appropriately designed holographic system could search the same records in about 1 millisecond. Spatial light modulators capable of 10kHz frame rate (e.g., one search every 100μsec) are also becoming commercially available, although the potential performance speed of such a holographic content–addressable memory depends on having sufficient hologram output power (diffraction efficiency times readout power) as well as on the requisite modulator speed.

The key to the massive parallelism is to arrange multiple storage volumes, which can each store around 1000 holograms, along the path of the data–bearing object beam (432, 433). As the optically–encoded search beam passes through each sub–volume, a small amount of power diffracts from the holograms that are significantly similar to the search information (80, 432, 433). By using one photodetector per hologram, millions of analog similarity metrics could be measured simultaneously. Exact matches to a query (76–82), or records that are just similar to a query (80, 432, 433) could be identified.

However, since the detected analog result of each correlation is subject to random noise, it is possible that database records which sufficiently match the search argument may be overlooked in favor of records that *almost* sufficiently match it. Fortunately, a hybrid system can combine the speed advantage of the holographic content–addressable memory with the digital precision of serial electronics (80, 432, 433). By passing both matching and near–matching records from the holographic front–end to a subsequent electronic processor, the probability of overlooking even one matching record can be made arbitrarily low ($< 10^{-12}$) while retaining much of the speed advantage (80, 434). Given sufficient signal–to–noise ratio and a spatial light modulator of merely 1kHz frame rate, a database of 1 million one–kilobyte records could be searched in less than 0.5% of the time required by a

1 Gigahertz microprocessor connected to 10 Gigabytes of DRAM.

If the ability to search thousands or millions of holograms in parallel can be demonstrated and a suitable non–volatile holographic recording media developed, volume holographic content-addressable data storage could be an attractive method for rapidly searching vast databases with complex queries.

CONCLUSIONS AND OUTLOOK

This chapter has surveyed the background and current status of holographic data storage. As a volumetric storage technology offering parallel data transfer, it offers both the density and readout rates required to be seriously considered as a next–generation data storage technology. We described two forms of holographic data storage: The first, using read–write inorganic crystals, can offer submillisecond access to large (Terabyte) blocks of data while still offering some degree of media removability. The second, using millimeter–thick disks of write–once media, offers high capacity in the conventional spinning–disk format.

The return of holographic storage in the early 1990's was motivated by the advent of the required components: spatial light modulators and detector arrays capable of modulating (detecting) large 2–D pixelated data pages, and high–power single–spatial–mode lasers with moderate to long coherence length and good stability. However, smaller, cheaper, and better components will go a long way to making holographic storage more feasible, especially high–repetition rate, high–average–power, pulsed lasers for spinning disk systems and/or rapidly–tunable lasers in the visible. Supporting components – such as spindles, focus servos, angle–deflectors – must also be developed, and system packaging engineered for robust performance despite strong susceptibility to real–world mechanical vibrations and thermal fluctuations.

Even more important than the laser source, holographic storage will live and die by the performance of the storage media. Write–once media has improved greatly (in thickness, sensitivity, dynamic range, and scatter), but must improve even more for successful commercialization because of the engineering and cost tradeoffs inherent in the spinning–disk format. And new issues will crop up, including the shelf life before and after recording, environmental stability under fairly diverse shelf and operating conditions, and robustness and repeatability in the manufacturing process. Comparatively, development of read–write media still has a long way to go before the simpler engineering and cost tradeoffs inherent in stationary media systems can be exploited. In particular, gated holographic storage in two–color photorefractives, in combination with phase–conjugate readout, offer a path towards truly volumetric storage.

The final pieces to the puzzle are the systems techniques, the tricks that finesse media and component problems, or the balancing of this tradeoff against that to arrive at a design point that satisfies all of the specifications. Sometimes, this is just simply recognizing what are deterministic variations rather than noise; sometimes, one recognizes the advantages of something the media "also" provides (such as the very low absorption that gated materials can have once gating is completed).

While the future of holographic storage is hard to predict, it seems fairly certain that it will be settled soon. The demand for storage is almost certain to continue. But the $1/\lambda^3$ limit – which seemed so outrageously large in the 1970's – is not moving, while most of the competing storage technologies (both experimental and established) are. The DVD standard is now well–established, lending strength to any next–generation optical disk standard (for instance, using blue laser diodes), and making backward–compatibility with DVDs and CDs a requisite drive feature. Magnetic hard disk drives are driving towards 100Gbit/sq.in. and simultaneously decreasing in price; and Flash–RAM and DRAM are similarly improving in density and price, closing the gap between them and magnetic storage that read–write holographic storage has been hoping to fill. The efforts of our second wave of research in the 1990's have produced a mature understanding of what it would take to create viable holographic storage systems. And, for write–once materials, these projects have finally moved from pure and applied research into concerted development efforts. Despite the inherent differences, the future prospects of read–write and content–addressable holographic storage systems are tightly linked to the success, or failure, of these ongoing efforts to commercialize write–once holographic storage systems. The countdown clock—driven by customer requirements and the growing capabilities of competing technologies—is ticking.

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