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Three-dimensional optical storage

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ABSTRACT

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1. INTRODUCTION

One of the reasons that computers have become increasingly important in daily life is because they offer unprecedented access to massive amounts of information. The decreasing cost of storing data and the increasing storage capacities of ever smaller devices have been key enablers of this revolution. Current storage needs are being met because improvements in conventional technologies—such as magnetic hard disk drives, optical disks, and semiconductor memories—have been able to keep pace with the demand for greater and faster storage.

However, there is strong evidence that these surface-storage technologies are approaching fundamental limits that may be difficult to overcome, as ever-smaller bits become less thermally stable and harder to access. Exactly when this limit will be reached remains an open question: some experts predict these barriers will be encountered in a few years, while others believe that conventional technologies can continue to improve for at least five more years. In either case, one or more successors to current data storage technologies will be needed in the near future. An intriguing approach for next generation data-storage is to use light to store information throughout the three-dimensional volume of a material. By distributing data within the volume of the recording medium, it should be possible to achieve far greater storage densities than current technologies can offer.

For instance, the surface storage density accessible with focused beams of light (without near–field techniques) is roughly $1/\lambda^2$ [1, 2]. With green light of roughly 0.5 micron wavelength, this should lead to 4 bits/sq. micron or more than 4 Gigabytes (GB) on each side of a 120mm diameter, 1mm thick disk. But by storing data throughout the volume at a density of $1/\lambda^3$, the capacity of the same disk could be increased 2000–fold, to 8 Terabytes (TB). It is interesting to note that the DVD disk standard exceeds this rough estimate of the areal density limit despite using light of slightly longer wavelength. However, no laboratory demonstration of volumetric storage to date has gotten closer than approximately 1% of the $1/\lambda^3$ volumetric density limit [3–5]. The vast unrealized potential of volumetric storage, coupled with the hard limitations encroaching upon surface optical (and magnetic) storage, has fuelled a large number of research efforts.

This article describes and compares two volumetric optical storage approaches that have been proposed and developed in the last decade or so. These are storage of localized bits throughout a volume (accessed either bit–by–bit or in parallel) and volume holographic storage. The article has been condensed from a recent chapter by the same author entitled "Volumetric storage," to which the interested reader is directed for more information and references [6].

In the remainder of this section, I describe the generic features common to both volumetric storage techniques, both to facilitate comparison and to illuminate relevant issues. Each technique is then described in turn, along with its variations, particular storage media and materials requirements, and unique systems issues. In concluding, I compare these volumetric storage techniques and try to give an overview of what each needs to address in order to become a viable next–generation storage technology.

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2. COMMON FEATURES

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, a metric cited in almost every paper promoting some novel volumetric storage technology, is not mentioned here. Why? Because 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 storage technology 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. Or a technique that can record multiple layers in disk media at a layer spacing of 1 micron, but which is subsequently limited to three layers. Areal density is widely used by the established technologies of magnetic and optical storage, because each evolutionary increase in density leads to commensurate increases in capacity for each well–established form factor. However, when unproven alternate storage technologies focus on density instead of achievable capacity, mismatches in background assumptions often lead to overly inflated initial expectations followed inevitably by entrenched (and perhaps undeserved) disenchantment.

Within the black box storage device, volumetric optical storage technologies tend to have several common features. There is always at least one laser, and a way to modulate incoming data onto this laser beam. An optical system delivers the data–bearing beam to the storage material for recording, and carries it away from the storage material to a detector (or detectors) for readout. This is the point at which volumetric storage diverges from surface optical storage: the recording process must add new data to a volume without obliterating other data already recorded, with the obvious constraint that the laser beam must pass along some contiguous path from an edge into and through the volume. In surface optical storage, the laser beam can illuminate only the bit being accessed; in volumetric storage, the laser beam is always partially illuminating other, unrelated bits. Like the recording process, the volumetric readout process must retrieve only the desired bits, with tolerable amounts of crosstalk, and the same constraint about access from the edge of the volume. (One way around this constraint is to sandwich layers of the storage material between waveguides which provide access [7]). Channel electronics then reproduce the original binary data from the analog signal(s) detected by the photodetector(s). At this point, something inside the box must change in order that the next storage/retrieval step applies to a different set of data. This might include moving the material, refocusing, steering, or modulating a laser beam, changing the laser wavelength, or changing the media's properties (with electric or magnetic field, for instance) to allow the laser to selectively address a new data set.

Storage capacity then depends on the product of volumetric density (many data sets per unit volume), the accessible volume under each modulator/detector pair, and the number of user bits per data set. Recording rate depends on how long it takes to selectively address the desired data set, and the dwell time of the laser required to store the data. Similarly, readout rate and latency depend on the speed of selective addressing, and the dwell time of the laser required to retrieve the data. The channel electronics add to the latency, but not to the readout rate (unless the electronics are the rate–limiting step). If the storage media is physically moved to selectively address, this often tends to dominate the readout rate and latency. If the storage media is a continuously spinning disk, then the laser often needs to be pulsed (decreasing dwell time) and the latency (the delay to a random data set) can significantly exceed the inverse of the burst readout rate (delay to the next sequentially–placed data set).

In many cases, cost considerations can be broken down into two parts: the cost of the system, and the incremental cost of removable media. The former tends to be dominated by components (laser, modulator, detector, spindles, beam–steerers, optics); the latter usually by finishing costs (cutting, polishing, anti–reflection coatings) rather than by raw material cost. (Of course, since commercialized volumetric storage products are as yet few and far–between, these thoughts are perhaps somewhat speculative). Power consumption budgets also tend to be dominated by peripherals (cryogenics or temperature control if required, spindle, high-voltage modulators) rather than by the detection/modulation electronics or even the laser. Big, inefficient lasers are usually much more painful in terms of cost and size rather than in terms of electrical power consumption.

All of these external factors (capacity, input/output rates and latency, cost, power, and size) are intimately interlinked together, and coupled to the internal consideration of retrieval fidelity. Cost, power, and size can be amortized over large capacity, but large capacity inevitably strains fidelity. Increasing the capacity also affects the speed with which different data sets can be selectively addressed. Media cost couples with media performance (influencing capacity and speed) and media quality (influencing data fidelity). Data fidelity can be addressed with error–correction coding, but only at the cost of additional complexity in channel electronics (both cost, latency, and potential readout rate problems) and reduced capacity (more redundancy means less user data). Judging from the experience of magnetic storage, the only certainty is that no black box will be built with an excessive margin of safety in data fidelity. In general, performance specifications are increased at the cost of fidelity until one reaches the smallest tolerable margin that still satisfies the user–BER constraint.

Stepping back from system design considerations to consider application issues, one finds another tangled web. If some of the features of the ideal black box must be sacrificed during system design, this will have an effect on the eventual market size. For instance, if the stored data doesn't really last forever, or if the recording and readout rates are not comparable, the number of applications that could find a use for the storage device is reduced. Also, people are understandably reluctant to entrust their valuable data to unproven technologies, so finding an initial market may depend on significantly exceeding the performance specifications of competing established storage technologies. In turn, the size of the initial and eventual markets feeds back to the cost and availability of components (particularly those which are not already in wide commercial use through other established technologies), which in turn affect the marketing prospects.

Now that the features and issues of volumetric storage have been introduced in the abstract, the remainder of the chapter turns to specific proposed implementations, beginning with "multilayer" optical storage.

3. 3–D STORAGE OF LOCALIZED BITS

The most straightforward version of volumetric optical storage is the intuitive extension from surface optical storage: localized bits stored not only on the surface but throughout the volume. In relation to the abstract black–box, the modulator is usually the laser itself, and the selective addressing of data–sets is done by focusing the laser beam. Researchers have been exploring several variants of bit–localized storage, which can be roughly grouped into proposals which read one bit at a time, and those which can read multiple bits in parallel. With the former, the laser focuses to single voxels, and reads data out to a single photodetector (or differentially using a few detectors); with the latter, the laser selects a small set of contiguous voxels, and then reads data out to a photodetector array (a CCD or CMOS camera).

4. BIT–SERIAL STORAGE

Extending the CD concept to multiple layers can be done without changing much of the readout hardware [8, 9]. The focus servo becomes responsible for changing between layers of different depth, in addition to its primary task of locking onto a layer once one is chosen. Crosstalk from other layers (and the possibility of confusion for the focus servo) is minimized by separating layers by a fairly large distance as shown in Figure 1 (this spacing is ~ 55 microns for DVD–ROM [9]). This ensures that when the converging (diverging) beam passes through the nearest neighboring layers, the large spot size covers enough data bits that the loss in transmission due to reflecting pits (and the out-of-focus crosstalk signal in reflection) remains roughly constant [8]. If the layers are moved closer together, more crosstalk reaches the detector, and the smaller pool of illuminated data bits means that the statistical variation of random ON and OFF bits can become a significant noise source.

As more layers are added, then the reflectance and transmission of each layer needs to be adjusted so that the signals from each layer are equally detectable. (In the DVD–ROM, this is done by using a gold coating on the top layer and aluminum on the bottom [10].) The signal-to-noise ratio is reduced not only by the lower average signal level, but also by the scattering of the reflected beam as it passes through higher layers on its way back to the detector. As the number of layers increases and the bottom layers move relatively deep into the substrate, a tradeoff emerges between high numerical aperture (needed for tight focusing more than depth of focus since the disk is layered already) and the working distance between the lens and disk surface. Spherical aberration, usually

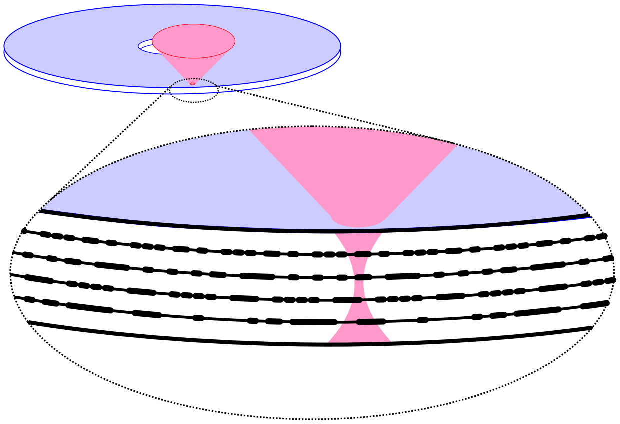

Figure 1. A pre–fabricated disk with multiple layers is accessed from one surface for bit–localized volumetric optical storage.

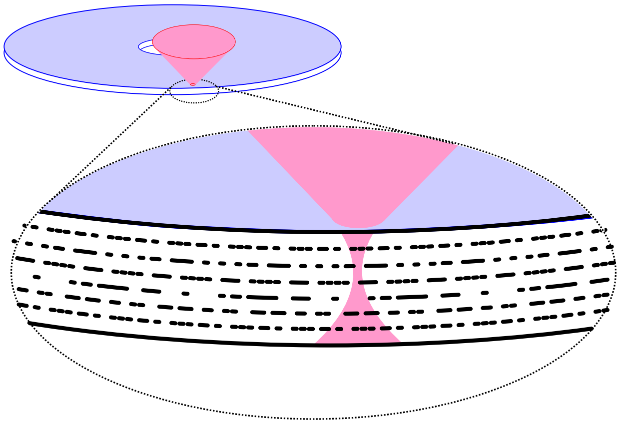

Figure 2. Bits are localized within a initially homogeneous block of media by careful focusing and either confocal imaging, nonlinear material response, or both.

corrected for in the optics, now varies from layer to layer. Without adaptive correction for each layer, this rapidly limits the number of accessible layers: since only one layer can be exactly corrected for (probably in the middle of the disk), the spot-size is maximum at either the top or bottom layers [11]. Birefringence of the substrate should also become more problematic as the optical path lengths inside the material increase. Despite these difficulties, early researchers working on multilayer optical storage believed that the number of layers could be increased to 20 simply by increasing the read power [8]. For read–write disks, more thought is involved because the read power must remain below the write threshold, and the absorption and recording characteristics as well as the reflectivity of the written state must be individually tuned for each layer. However, by choosing the transmissivity of each layer carefully, a design point of 20 writable layers with a 100mW laser was found [8]. (Note that the media design for just a two layer recordable disk is already quite involved [12,13]).

An additional and important real–world consideration to extending a next–generation–DVD standard beyond two layers is the difficulty of fabricating prerecorded disks with more than two read layers. Currently, while DVD disks can contain as many as four layers, only two layers are read from any surface (i.e., the four–layer disk must be flipped over in a standard one–head drive). So in fabrication, each half of the disk is fabricated with injection molding and is then glued to another half to produce the final disk. If a second data layer is needed on either half, then a 55 micron (±15 micron) thick layer of UV curable polymer is laid down and the bottom layer stamped into this [10,13]. Apparently, one of the main headaches is gluing the substrates together without warping the resulting disk, since commercial DVD drives do not contain a tilt servo to compensate for warped disks [10]. Other problems include registering the layers (with same center of rotation) so that a read/write head that is tracking on one layer can move to another and still know which track it will be on, and keeping the layer thicknesses uniform so that the focus servo can always distinguish between layers.

5. BIT LAYERS IN HOMOGENEOUS MEDIA

In contrast with these pre–layered disk schemes, much of the recent scientific literature on localized bit–serial storage has considered the storage of bit layers within initially homogeneous media (Figure 2). Localized–bit volumetric optical data storage has been demonstrated using two–photon fluorescence [14–18], by bleaching two–photon fluorescence [19,20] , by refractive changes in photochromic [21–25], photopolymer [26,27], photorefractive [4,28–32], and photorefractive polymer [33] materials, and by generating micro-explosions in glass through two–photon absorption [34–42]. Exposure times have ranged from seconds for photorefractives down to single 100 femtosecond pulses for glass [39].

With large refractive index changes or 2–photon fluorescence, the written data pattern can be read with an ordinary microscope [34,35,39–42]. Otherwise, a confocal microscope is usually required to read the data with the desired depth selectivity [4,19,20,22,23,26,29,31,33,43–46]. The first confocal experiments were performed with a differential interference contrast microscope (as described above) [26]. For the more widely–used transmission phase–contrast confocal microscope, it turns out that the optical transfer function does not always provide enough spatial frequency coverage to adequately distinguish localized bits, depending on how the bits were recorded [31, 45]. Essentially, such a microscope cannot "see" un-slanted reflection gratings of any grating pitch [47]. Despite this, several early experiments were performed with special annular optics to prepare the readout focus [29, 43], or a split detector to perform differential measurements [48]. A reflection confocal microscope has advantages over the transmission microscope, because the background signal due to scatter and local index inhomogeneities is greatly reduced [23, 46]. Having all the optics located on one side of the sample also reduces complexity, and allows a single adjustment of microscope tube length to compensate for spherical aberration [19]. Although a reflection phase–contrast microscope has problems similar to the transmission version in covering the spatial frequency band, if the numerical aperture (N.A.) is increased sufficiently and the writing and readout wavelengths chosen carefully, localized bits can be selectively detected [31, 45]. Several nice results were obtained this way [4, 23, 31, 46], but unfortunately, the need to have an oil–immersion objective (for N.A.>1.0) limits the general applicability.

Thus research in localized–bit volumetric recording appears to have settled on two–photon processes and fluorescence. This includes one–photon confocal detection of fluorescence changes induced by two–photon absorption [20, 33, 37], and detection with an ordinary microscope of two–photon fluorescence in optically–ablated silica [40–42]. In the former, high intensity CW illumination can also be used to read and write the data [20]; in the latter, the ablated bits can also be detected by their large refractive index change [39]. Since the photoluminescence, whose origins in optically damaged glasses is not yet well understood [41], can be erased by annealing [40], researchers hope to store two bits per voxel through this method. In addition, by sectioning the glass and measuring the exposed voxels with an atomic–force microscope, Glezer and Mazur found the written marks to be significantly smaller than the optical spot size [35], an effect attributed to self–focusing of the sub–picosecond laser pulse.

Tanaka and Kawata considered the achievable volumetric density for localized bit recording and found that it scaled as $(\text{N.A.})^4$ [44]. Factoring in the interplay between high numerical aperture and shorter working distance (i.e., fewer layers), the equivalent areal density of bit–localized volumetric storage (and thus the capacity of a fixed form factor such as a 120mm disk) should scale roughly as $(\text{N.A.})^3$. One of the advantages of recording layers in a homogeneous media is that fabrication issues do not come into play when determining the minimum layer spacing, which should make tighter spacings possible. Thus, the same spherical aberration that would show up for 10 layers at 100 micron layer–spacing would correspond to 200 layers at 5 micron spacing. For media removability, of course, the top layer should still be some distance underneath the surface to avoid problems from surface defects and scratches.

6. BIT–PARALLEL READOUT OF 2–PHOTON FLUORESCENCE

Moving from bit–serial to bit–parallel access is an attractive way to increase the potential data transfer rates. With two–photon fluorescence readout, a data–set containing many bits can be selected and read out in parallel. A number of papers on bit–parallel two–photon memories have been produced, starting from the initial materials work by Parthenopoulos and Rentzepis [49, 50] and subsequent systems efforts of Esener and co–workers [51–53]. In this scheme, the two–photon process is selectively applied to a localized region or spot by applying two beams through orthogonal faces of a cube of material. For bit–serial access, both beams are focused [51]; for bit–parallel access, one beam contains a page of information imaged to a plane within the material while the other beam is a cylindrically focused sheet of light illuminating only this image plane from the side (See Figure 3).

Initially, spirobenzopyran embedded in polymer was used because its desirable photochromic behavior (that is, light can induce a change in the molecule's absorption spectrum) was accessible with the fundamental and second harmonic of Nd:YAG lasers [49–51]. The energy levels are shown in Figure 4 for the unwritten and written forms of the molecule. The orthogonal arrangement of beams is required because of the potential for two–photon absorption by the green beam alone. By using the green light as the cylindrical addressing beam, the two–photon write process is confined to this illuminated 2–D plane. As shown in Figure 4, written layers can be illuminated either by one– or two–photon fluorescence. Using one–photon fluorescence (green addressing beam for readout) offers more efficiency and does not necessarily imply destructive readout [54]. The orthogonal arrangement also provides the opportunity for multi–functional access of database records using the different faces of the storage cube for different database actions [55].

After these initial studies, subsequent materials development then attempted to improve the response of spiropyrans or to find other suitable photochromic materials [52, 56–59]. A list of desired characteristics, adapted from Reference [59], might include:

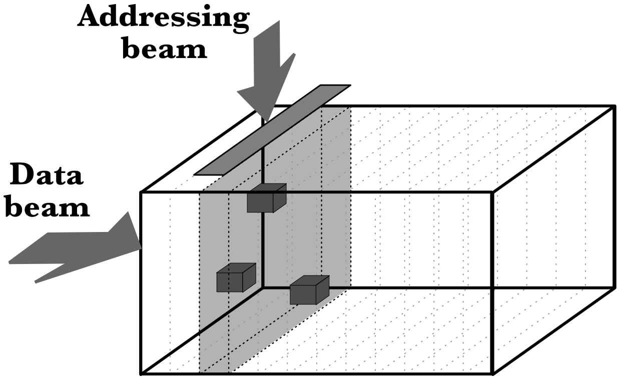

Figure 3. Orthogonal beams used to write and read data in parallel in 3–dimensions using 2–photon fluorescence (After Reference [51]).

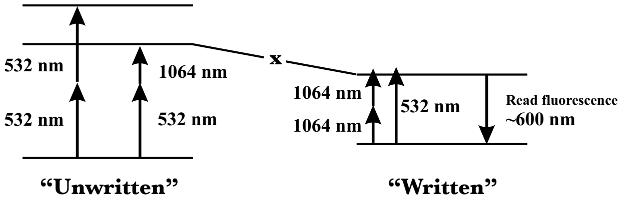

Figure 4. Energy band diagrams for the unwritten and written forms of the fluorescent photochromic material spirobenzopyran (After Reference [51]).

1. a high two–photon absorption cross–section so that incident light is used efficiently to write information, and/or high doping levels to increase the number of molecules per voxel;
2. the written form of the molecule should have a high fluorescence quantum yield, for sufficient readout signal strength. Note that since the fluorescence is emitted in all directions, only the portion captured by the numerical aperture of the readout optics contributes to the detected signal strength (One proposal for improving this is to use 3–D photonic bandgap structures at each voxel in order to generate fluorescence only in the desired direction [17]);
3. both forms (written and unwritten) of the photochromic molecule should be stable at (and even above) room temperature;
4. high fatigue resistance (i.e., few residual products in the photochemical reactions) for $> 10^6$ write–read–erase cycles;
5. a large separation in absorption and emission spectra so that readout signals can be filtered out, and so that the fluorescence signal does not affect either written or unwritten molecules;
6. nondestructive readout (also linked to the spectral separations);
7. and the capability of being fabricated in low–scatter, high–optical quality samples using simple polymer hosts.

In addition to these rewritable photochromics, write–once materials, composed of organic dyes triggered by photoacid generators, have also been developed [60]. For rapid generation of pre–recorded disks, a "stamping" scheme was proposed, using a volume holographic element read with multiple mutually incoherent reference beams to generate the recording optical signals at multiple layers simultaneously [61].

Some of the systems difficulties with this two–photon parallel–access method stem from the media. The low sensitivity of the two–photon process requires high–power pulsed lasers, which means that any optics with an intermediate focus must be enclosed in vacuum [54], and the optics and the spatial light modulator for imposing pixelated data patterns must have high damage thresholds. Despite the high powers, the media still requires hundreds of recording pulses per data plane [54], or forces serial access during writing.

Other difficulties are inherent to the system: the need to have a sheet of light implies that the effective width of each data layer may be much larger than the wavelength. Marhic pointed out that this tradeoff between density and transfer rate can actually limit the effective areal density to the same $1/\lambda^2$ limit as surface optical storage [62]. Another difficulty is the need to refocus the output detector array onto each data plane to be read [54]. This problem can be solved by arranging the data planes in a "turbofan" arrangement, so that each data plane contains the radius of a spinning cylinder or thick disk [63]. In this way, the disk rotation brings each data plane to exactly the same position relative to an external read head. The readout light enters the surface of the disk illuminating a tilted plane, and the fluorescent signals are detected back through the top of the disk, using anamorphic optics to correct for the change in path length between the disk entrance face and the different points on the data plane [63]. Using such a scheme, twenty–five layers have been recorded and read with a layer spacing of 75 microns [63]. More recently, a system capable of being scaled up to faster readout per channel was designed for four layers each with 16 data bits [64].

7. HOLOGRAPHIC STORAGE

In contrast to localized–bit recording, where each bit of data is assigned to a particular location within the storage volume, holographic storage distributes data throughout a volume in a delocalized way. A hologram is a recording of the optical interference pattern that forms at the intersection of two coherent optical beams (object and reference—Figure 5(a)). The object beam carries the information to be stored, while 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.)

To record a hologram, the reference and object beams are made to overlap in a photosensitive medium, such as a photopolymer [65, 66] or inorganic crystal [65, 67] or even photographic film [68], where the resulting optical interference pattern creates chemical and/or physical changes. As a result, a replica of the interference pattern is stored as a change in absorption, refractive index or thickness. Since the pattern contains information about both the amplitude and the phase of the two light beams, when the recording is illuminated by the readout beam, some of the light is diffracted to "reconstruct" a weak copy of the object beam (Figure 5(b)) [69]. If the object beam originally came from a 3–D object, then the reconstructed hologram makes the 3–D object reappear [69].

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 potentially, holograms could also store data at a volumetric density of $1/\lambda^3$ [70–72].

In holographic storage, data sets 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. However, no one location in the crystal is responsible for storing that one bit; each bit is distributed throughout the recorded interference fringes. Since an entire "page of data" can be retrieved by a photodetector at the same time, rather than bit-by-bit, the holographic scheme promises fast readout rates as well as high density [65, 73–77]. 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 [78–83], however, research into holographic data storage all but died out in the mid-1970s mostly because of the lack of suitable devices for the input and output of pixelated 2–D data pages.

In the early 1990s, interest in volume-holographic data storage was rekindled [74, 75, 84–87] 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 this technology in the laboratory [5, 65, 88–97]. 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 [5]. (For comparison, a single–layer of a DVD disk stores data at ~ 4.7 bits/sq. micron [98].) A readout rate of 10 Gigabit per second has also been achieved in the laboratory [97].

8. HOLOGRAPHIC MULTIPLEXING

If the hologram is recorded in a thin material—such as the security hologram stamped onto 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.

Since the diffracted wavefront accumulates energy from throughout the thickness of the storage material, a small change in either the wavelength or angle of the readout beam generates enough destructive interference to make the reconstructed object beam effectively disappear. 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, destructive interference also opens up a tremendous opportunity: a small storage

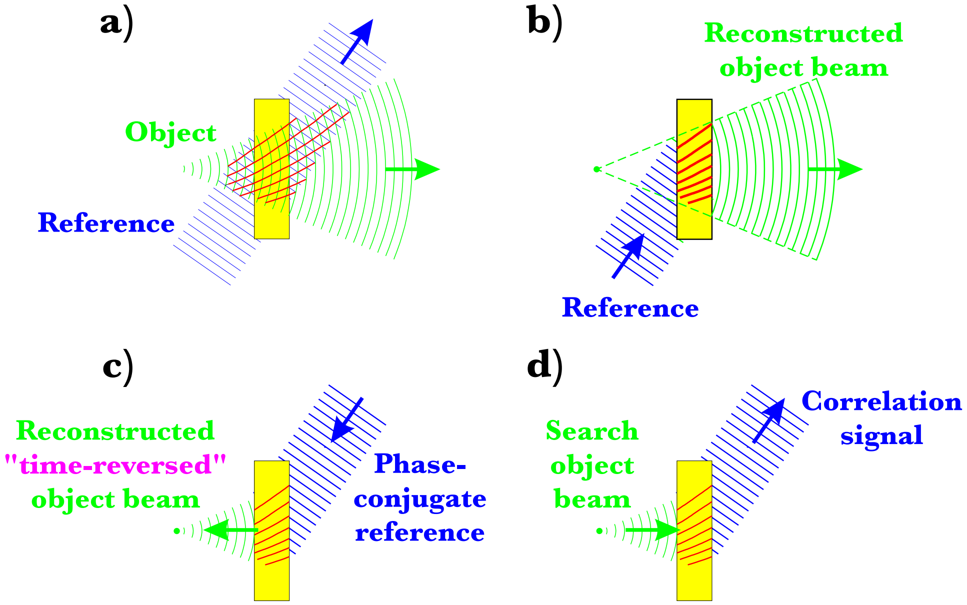

Figure 5. How to record and read data using holograms: (a) Holographic storage of a single data bit. The spherical wave from a single pixel interferes with a coherent plane wave in the reference beam. The resulting interference pattern changes the refractive properties of the photosensitive medium. (b) 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 [90, 99–105]. (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 [69, 106]. This technique can allow one to search the stored data according to its content, rather than according to its address [65, 107–110]. (After Reference [77]).

volume can now store multiple superimposed holograms, each one distributed throughout the entire volume. The destructive interference allows each of these stored holograms to be selectively accessed with its original reference beam. Several different techniques [65] have been developed to define a set of suitable reference beams by, for example, slightly changing the angle [72, 84], wavelength [111, 112] or phase–front [113–115] of the original light beam. Using so-called "angle multiplexing," as many as 10,000 holograms have been stored in a 1 cm^3 volume [116, 117].

9. STORING AND RETRIEVING DIGITAL DATA

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 6).

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 elements 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 the laser power and material sensitivities 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 6. To maximize the storage density, the hologram is usually recorded where the object beam is tightly focused. 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.

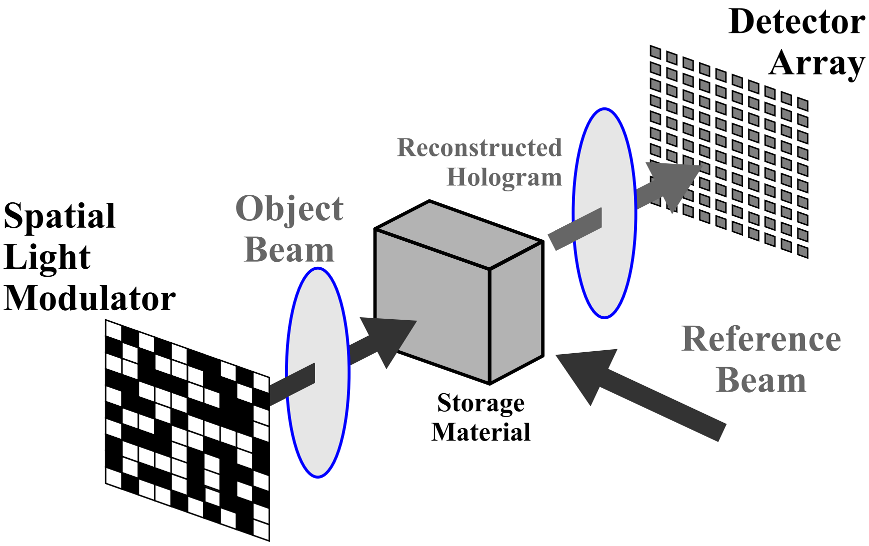

Figure 6. Data are imprinted onto the object beam by shining the light through a pixelated input device called a spatial light modulator. A pair of lenses image the data through the storage material onto a pixelated detector array, such as a charge-coupled device (CCD). A reference beam intersects the object beam in the storage material, allowing the holograms to be stored and retrieved later. (After Reference [77]).

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). While non–mechanical access leads to the possibility for lower latency (fast beamsteerers such as acousto–optic deflectors [65, 75, 87, 89, 94] or liquid–crystal beam–steerers [118]), if this is done with a CW laser then the beam must dwell on the hologram, reconstructing it 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 [65], but these are not yet commercially available. Low-noise megapixel CMOS detector arrays that can support 500 frames per second have also been demonstrated [65]. 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 [5, 88, 94–96, 119, 120].

10. WRITE–ONCE SYSTEMS USING SPINNING DISKS

This article did not contain room for a complete survey of the write–once and read–write materials that have been used for holographic data storage. See References [6, 65] for more details.

Continued progress in write–once materials research (especially photopolymers [65, 121]) has brought write–once systems to the stage where people are working on prototypes. (See Reference [6] for a more complete review of holographic storage materials). 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 [65, 96]. 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 [65, 96].

To get high density, one must come in with the reference beam from a wide spread of angles, so good antireflection coatings are needed to keep power from being lost in Fresnel reflections (thus increasing media cost). Also for high density and to keep aberrations in the imaging system low, the object beam probably needs to come in normal to the disk through a short–working–distance optical system, further complicating the delivery of writing beams. Although a read–only transmission–geometry head can avoid having to slip the reference beam past the object beam delivery 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 [122, 123]. In contrast, by using either a spherical [124–126] or a randomly speckled [127–129] 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) [124, 125]. Speckle–shift, or correlation, multiplexing using a random phase plate or diffuser [97, 127–129] 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 [127, 128]. 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 over as the reconstructed hologram transits the thickness of the disk. So while smaller speckle leads to better inter–page crosstalk SNR, it also makes the readout conditions so selective that holograms might not be reliably found with inexpensive components.

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 [65, 95–97]. 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 [97]. The spindle was so accurate that holograms could be incrementally recorded over several rotations (i.e., the accuracy and repeatability were at interferometric levels) [97]. 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.

11. CONCLUSIONS AND OUTLOOK

This article has surveyed two main variants of volumetric storage: localized–bit and holographic. Each has shown promise in initial research studies, and each shows the potential to significantly out–perform conventional storage technologies in at least one of the desirable 'black–box' specifications (capacity, input and output data rates, latency, cost, system volume, and power consumption).

Serial storage of localized–bits throughout a multilayered disk offers to increase the capacity of a standard optical disk with moderate changes to the readout optics (and the disk fabrication infrastructure). Parallel readout then can be added to increase readout rate, with the degree of modification to conventional readout systems depending on the degree of parallelism.

Holographic storage, which distributes or delocalizes data throughout a volume with interference fringes, can take two forms. 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 (see References [?, 65] for more details). The second, using millimeter–thick disks of write–once media, offers high capacity in the conventional spinning–disk format.

The hurdles between current research and reliable, competitive products are numerous. All of these techniques are unattractive with current laser technology: each needs smaller, cheaper, and higher–power lasers and especially high–repetition rate, high–average–power, pulsed lasers for spinning disk systems. Holographic storage needs single–spatial–mode lasers with high stability, and would profit greatly from the development of rapidly– and widely–tunable lasers in the visible.

Even more important than the laser source, these storage techniques live and die by the performance of the storage media. An interesting trend is observable in each of these disparate types of volumetric optical storage: each has started with materials that simply responded linearly to illumination, recognized the limitations that this imposed on volumetric selectivity (and on non–volatile readout of read–write storage), and moved to find media which respond either nonlinearly or are gated in some way. With localized–bit storage, these are the two–photon absorption/fluorescence materials; with holographic storage, the gated, two–color photorefractives. The cost of using such a two–photon process is typically a reduction in sensitivity.

Then there are the supporting components, whether these are simply spindles and focus servos; or angle–deflectors, spatial light modulators, and CMOS detector arrays; or high–bandwidth modulators and acousto–optic deflectors. In some cases, like the spatial light modulators and detector arrays, other commercial interests can drive much of the development; in others, the component development may need to be completed by those working on the volumetric storage technology that needs it.

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 photon–gated materials can have once gating is completed).

The future of these volumetric storage technologies is hard to predict: some (or maybe even all!) of the storage methods described here may never progress past the research stage. While the demand for storage is almost certain to continue, the drive to research volumetric optical storage will depend not only on the progress made by its proponents, but also on the progress made in conventional storage and other prospective storage technologies. The vast unrealized potential of volumetric optical storage, the wide variety and maturity of already established techniques, and the almost universal recognition that "Tomorrow, I will need more storage" leads me to suspect that the work reviewed here will not be the final word.

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