

ULTRA-HIGH DENSITY OPTICAL DATA STORAGE

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Abstract

We have developed a novel, polymer-based material suitable for shrinkage-free thick holography. It can be produced in arbitrary shapes and sizes, with optical quality surfaces and very low scattering noise. A combination of spatial and angular multiplexing in this material can be used to produce a holographic CD-ROM with a storage capacity of one terabyte in the near future. We have demonstrated storage and recall of 1920 frames of a video in a small sample of this material. The storage capacity of holography can be enhanced further by adding spectral multiplexing. In a crystal of Pr:YSO, we have demonstrated spectral multiplexing in two frequency dimensions, at temperatures greater than 10 K. This approach will enable us to achieve a storage capacity exceeding a petabit per cubic cm, using commercially available lasers and closed-cycle cryostats.

Key Words

210.2860 Holographic and volume memories; 090.7330 Volume holographic gratings; 210.4810 Optical storage-recording materials; 020.1670 Coherent optical effects.

1. Introduction:

The capacity of digital data storage devices tends to dictate the scope of applications computers can be used for. As such, the demand is strong for storage techniques with ever-increasing volumes of memory. In recent years, efforts have been underway to develop data storage units using holography. In this paper, we discuss recent developments in our group at MIT towards developing ultra-high capacity holographic memory devices. In section 2, we describe the recent progress we have made towards the development of a one terabyte capacity CD-

ROM using a novel, polymer-based material we have developed for thick holography. In section 3, we present results from our efforts towards realizing a cryogenic RAM with a capacity approaching a petabits per cubic centimeter, by mutiplexing volume holography with two-photon spectral hole-burning in a crystal of Pr:YSO.

2. Terabyte CD-ROM Using Holographic Storage in a Polymer.

The ability to store a large number of holograms in a single recording material is important for the implementation of optical neural networks, optical interconnects, and holographic computing elements. Recently, a strong effort has been undertaken by several groups to develop high volume data storage devices using holograms.

In volume holography, any information is encoded only in the spatial structure of the optical fields. As such, the fundamental storage capacity in such a system is limited to $\sim V/\lambda^3$, where V is the volume, and λ is the wavelength of light. In practice, this limit is difficult to achieve; various techniques, including angle multiplexing, wavelength multiplexing, orthogonal phase encoding, and fractal-space multiplexing, or a combination thereof have been employed to improve the storage density, although still well below the limit^{1,2}.

For volume holography, a thickness of between 0.5 and 1 cm provides optimum storage density, due to constraints imposed by optical access requirements. Data storage using holograms of such thickness have so far only been performed in photorefractive crystals. However, polymeric systems generally have several distinct advantages over photorefractive systems. These include much lower cost, lack of constraint in shape, higher diffraction efficiency, simplicity of fixing, a wide spectral bandwidth, and lower refractive index (1.6, compared to 2.2

for typical photorefractives) which implies a larger field of view,

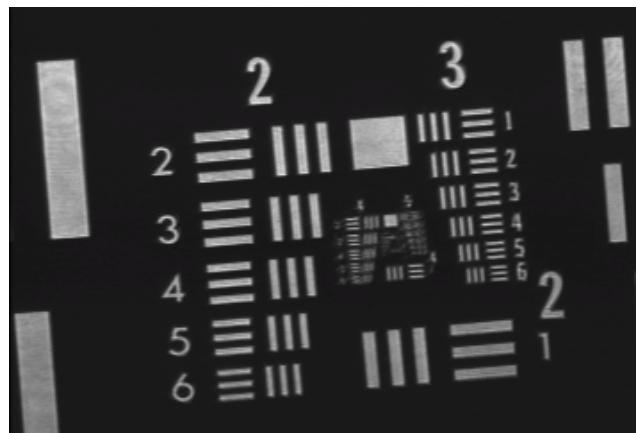
However, to date, only thin (100 μm or less) holograms have been successfully used to demonstrate storage in photopolymeric structures. This is due to a host of problems in creating thick holograms of good quality. These problems span issues such as differential shrinkage, non-uniformity of active elements through the substrate, difficulty in embedding materials into substrates, and lack of high quality optical surfaces. As a result, the full potential of holographic data storage in photopolymers is limited by the useful thickness. For example, the storage achievable in a 100 μm hologram is theoretically two orders of magnitude smaller than what can be achieved in a 1 cm thick hologram. Even within the current limits due to optical accessing architectures, it should be possible to store as much as 10^{12} bytes in a 1 cm thick disc with a diameter of 15 cm.

Recently, we have produced high optical quality samples of a holographic substrate called PDA (polymer with diffusion amplification), with high writing efficiency (about a factor of 100 better than lithium niobate), very low scattering, and a large index modulation capacity. Briefly, this material consists of a quinone based dye, embedded in polymethylmethacrylate (PMMA). This medium uses the novel principle of diffusion amplification of holograms on polymeric recording media. Photoexposure of this system results in writing of two out-of-phase periodic structures that partially compensate each other. One of these is formed by a concentration distribution of chromatophore groups combined into macromolecules, while the other is formed by free molecules. As a result of diffusion of the free molecules, the corresponding grating degrades, and the resulting grating is amplified *without additional processing*. The surviving grating is stored in macromolecules that do not diffuse³.

We have demonstrated storage and recall of ten orientations of the Air Force resolution chart, written 5 mrad apart, in a sample about 3 mm thick⁴. Figure 1 shows one of these images, comparing the original to the reconstruction. Note that the reconstructed image is virtually identical to the original, indicating a very low bit error rate.

Following this encouraging result, we have stored and recalled digitized frames of a skating video clip of more than two minutes in duration. The video was sampled at about 15 frames per second, and digitized into a 256 bits X 256 bits image, compatible with the SLM from Displaytech, Inc., of Boulder, CO. These frames were divided into 16 subgroups, each containing 128 frames. Images in a single subgroup were recorded in a single spatial location (4mm X 4mm), using angular multiplexing at 1.7 mrad (0.1 degree) apart. The architecture used is

ORIGINAL IMAGE #1



RECONSTRUCTED IMAGE #1

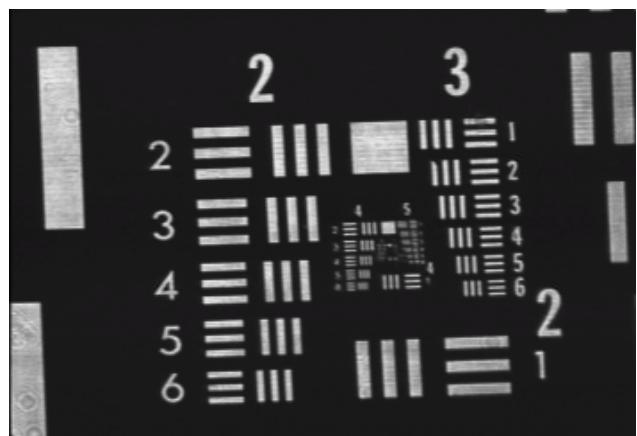


Figure 1. Comparison of the original with the holographic reconstruction of one of the ten images stored in a thick PDA sample 5 mrad apart.

similar to what is shown in figure 2, with the exception that SLM/CAM is replaced by an SLM alone, there was no cat's eye mirror for readout, and the angular multiplexing was done in one dimension only. The 16 different spatial locations were selected by moving the medium around horizontally and vertically. After the images were written and developed, a ccd camera was used to read out the images. The results from this experiment, meant primarily to test the basic features of our architecture, are very preliminary. For high fidelity reproduction of the images, we have to include pixel matching, data thresholding, and error correction coding/decoding. This video can be viewed at our website: <http://qop.mit.edu>.

Currently we are developing a PDA-based Holographic CD-ROM (HCD) with a storage capacity of 1 terabyte. The memory system will be developed with a built-in I/O peripheral system compatible with desktop computers. Such a memory unit will be cost-effective compared to existing alternatives (such as 2000

conventional CD-ROMs). Commercial application of the HCD includes archival storage, video delivery systems, and associative memory based search engines.

Optical and Material Specifications for HCD

In order to determine the details of the architecture, it is useful to consider first the constraints imposed by optics, detectors and the holographic material. For the optical system, we note that the hologram will be written in the image plane, and assume that the minimum resolvable spot size will be 4 microns, a goal easily achievable for the write wavelength of 514 nm and the read wavelength of 516 nm. For the detector array, the integration time will be about 1 ms, during which at least 100 photons will be detected per pixel. Assuming the shot noise limit (with the detector assembly Peltier-cooled), this will correspond to a minimum signal to noise ratio of about 10. For the holographic material, the maximum number of holograms at a single spatial location is determined by the $M_{\#}$ and the noise floor established by the scattering caused by surface and volume inhomogeneities. Consider first the role of the $M_{\#}$, which determines the index modulation capacity, and is defined as the maximum number of 100% efficient sinusoidal gratings that can be written at a given spatial location. If the number of multiplexed holograms in one location is M , then the efficiency of each hologram is given by

$$\eta = \left(\frac{M_{\#}}{M} \right)^2$$

The minimum efficiency is constrained by the fractional intensity of random scattering, η_s . For our material, we have observed a scattering level of 3×10^{-6} , and an $M_{\#}$ of 6 in a 3 mm thick sample, as mentioned above. With a combination of anti-reflection coating and variations in dye concentration as well as sample thickness, we expect to reduce η_s to be below 10^{-6} along with an $M_{\#}$ of 8. For these numbers, we find the maximum number of holograms at a single spatial location to be at least 8,000.

Architecture for Recording. The holographic substrate will be a 5 mm thick disk, with a diameter of 15 cm. It will be segmented into about 1000 square zones, each 4mmX4mm in size, corresponding to a fill factor of about 90%. For each zone, we will use two dimensional angle multiplexing, using galvo-mounted mirrors. Consider, for concreteness, the horizontal plane. The image beam will be incident at a 30 degree angle to the normal of the disk. The reference beam will be centered at a 60 degree angle with respect to the image beam. Around this center position, the reference beam will be scanned, using two (M_3 and M_4 in figure 2) scanning mirrors (to avoid translational shifts), over an angular span of ± 23 degrees (about ± 400 mrad), at a step size of about 1 mrad (larger

than the Bragg selectivity, to avoid cross talk). This corresponds to about 800 different Bragg selected holograms. We will multiplex this further by a factor of 10 by tilting the reference beam in the vertical direction, using a third scanning mirror (M_2 in figure 2). The total number of holograms written at one position will be 8000. The number of bits in a single page will be 1024X1024, so that the net storage capacity will be 1 terabyte.

The beam expander (BE) and the lens assembly for imaging are constructed to minimize aberrations, and guarantee a minimum image resolution of 4 μm . To transfer the data from the SLM to the interference plane, the image is reduced by about a factor of 2, since the SLM pixel size is about 7.6 μm . The waveplates and polarizers are oriented to maximize the image contrast.

A set of microcontrollers (such as the Motorola M68HC11) in master-slave configurations will control the operation of the whole system. A memory buffer of about 100 megabyte (corresponding to 800 memory pages) will be used to hold the data temporarily before each horizontal angular scan. The microcontroller system will regulate the I/O handshake with the mainframe computer. It will also control the radial and angular positioning of the memory disk, and scan the galvo-mounted mirrors, through a set of D/A converters and latches. The built-in A/D converters (each capable of monitoring up to eight channels) will be used to provide feedback stabilization of the galvos, with a bandwidth of up to 16 kHz. The microcontroller system will also regulate the shutters, and allow for user interruption in-between each page in case of unexpected troubles. Electronically controlled attenuators will be used to maintain the laser intensity at the desired level. The whole operation will be carried out on a vibration isolated optical table.

An Argon laser from Coherent, Inc., @ 514 nm, with a single-frequency, single-mode power exceeding 5 Watts, will be used for writing the holograms. The beam will be expanded initially to a size of 3.5 cm (1/e) diameter, in order to ensure good uniformity over the approximately 8 mm X 8 mm area. For a sensitivity of 1 J/cm² necessary to write a single hologram with 100% efficiency, the exposure time needed for each page would be about 1 msec.

Prior to writing, the 1 terabyte of data will first be encoded with the Reed-Solomon error correction algorithm. The level of overhead to be used is determined by the raw bit error rate (BER). For example, a overhead of 6 bits for every 9 bits of useful information can detect and correct for up to 3 random errors for each group of contiguous 60 bits of information stored, corresponding to a raw BER of about 5%. In our system, however, the raw BER is not expected to be any higher than 10^{-4} , so that much lower overhead, of the order of 1%, would be enough.

During the writing stage, the shutters S1 and S2 will be open, and S3 closed. 800 data pages from a mainframe

computer (with a memory bank large enough to store the 1 terabyte of information to be stored) will be loaded into the memory buffer of the SLM driver. The firmware in the SLM driver, in synchronization with the rest of the scanning and positioning control system, will upload each page of data in the SLM, and the data page will be recorded in the hologram at the proper horizontal angle of the reference beam. As stated above, each page will be written in a msec. Once the 800 pages of data are recorded via angle multiplexing, the horizontal angle galvos will be reset to the starting position, and the vertical angle galvo will be updated to the next (vertical) angle. After the next 800 pages are loaded, the horizontal angle scanning sequence will resume. Once the ten vertical angles have been multiplexed, the R-θ stage (see figure 2), will be moved electro-mechanically to choose the next spatial location. Without undue interruption, the whole writing process would take less than 3 hours. It should be possible to run a few of these setups in parallel, increasing the throughput.

After the holograms have been written, the material will be processed and fixed in-situ, so as not to affect the alignment. The read-out will be performed by closing shutter 1, and opening shutters 2 and 3. The reference beam will pass through the holograms, and be reflected by the read-out mirror, M5. This can be either a cat's eye reflector (using a long focal length lens, and a flat mirror located at its focal plane), or a phase conjugator (e.g., an acetylene cell, which acts as a self-phase conjugator, as used in the Infinity YAG laser from Coherent, Inc.). The reflected beam, which will trace-back the path of the original reference beam, will produce the desired image at the camera, which is colocated with the SLM. This geometry will ensure very accurate pixel registration. The slight shift in the position of the camera pixels with respect to the SLM pixels can be compensated for by mounting the SLM on an electro-mechanically controlled XY stage.

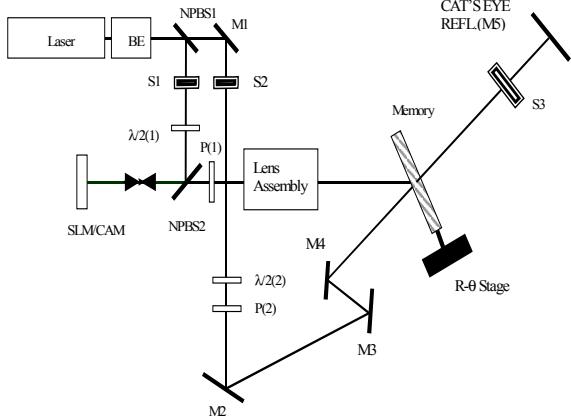


Figure 2. The basic schematic of the read-write architecture.

Note that this has to be done only once, since all the images will have the same shift. The data accumulated from the detectors will first be digitized via thresholding with a firmware, then stored in the SLM/CAM memory buffer. After 800 pages have been read, the data will be uploaded into the main-frame computer, processed by the error correction decoding software, and compared to the original data bank. Following the industry standard, no more than 1 bit-error per 1 terabits will be tolerated for HCD's developed for digital computer applications. In the case of video-delivery systems or image-correlation applications, the file allocation tables will be held to the same standard. However, the tolerance level can be relaxed for the data fields containing image information.

Architecture for Readout. As discussed earlier, the HCD can have a range of potential applications. As such, different read-out architectures would be necessary for different end users. Here, we discuss explicitly the readout scheme for digital computers. In this case, the readout will be performed using a 35 mW solid state laser (or a 100 mW semiconductor laser) @ around 516 nm. These lasers have just become available commercially. While the solid state ones are expensive, the semiconductor lasers are expected to be very inexpensive.

Consider first the issue of simply retrieving the data from the memory unit. As before, the whole read-out system will be controlled by one or more microcontrollers, which will also monitor the I/O protocol with the host computer. On each spatial location, there will a single page of data used for *alignment*, to be used whenever deemed necessary in order to reduce the error-creep as the read-out system jumps around from location to location.

The optical memory will be implemented as a PCI bus add-on memory unit. An optical cache controller will regulate the data addressing, data synchronization, and the scan control. When the computer requests data, it will provide the address of the page containing the data, in the form of the appropriate coordinates (such as R , θ , horizontal angle, and vertical angle), to the read-out system. The system will first move to the proper spatial location (R, θ), and then select the requested horizontal and vertical angles. Once a page of data (digitized via thresholding) is valid at the detector array, it will be accessed in chunks of 128 bits. The 128 bits of data is then split into four identical parallel channels, each 32 bits wide. In each channel, the data is first processed through a logic board for error correction, which produces the corrected data stream (recall that during the recording, the data is encoded through a Reed-Solomon error correction algorithm). The corrected data is then stored in an SRAM with a size of 64KX32. Once the corrected data is valid in the SRAMs, the data is then available to the PCI Bus Interface. With four channels, the net capacity of the optical cache is 64KX128 bits, or about 1 megabyte. Such

an interface can be used to connect the HCD to an *existing* personal computer.

The storage capacity of holography can be enhanced further by adding spectral multiplexing. In a crystal of Pr:YSO, we have demonstrated spectral multiplexing in two frequency dimensions, at temperatures greater than 10 K. This approach will enable us to achieve a storage capacity exceeding a petabit per cubic cm, using commercially available lasers and closed-cycle cryostats. In the following section, we discuss recent results from this effort.

3. Optical Data Storage via Two-Photon Spectral Hole-burning

Optical spectral hole-burning (SHB) materials have been proposed for numerous storage and high-speed processing applications because of their large storage capacity, fast response time, and high photon efficiency⁵⁻⁷. The large storage capacity is achieved by adding a fourth dimension of frequency (or time) to the three spatial dimensions. The maximum storage capacity of the frequency dimension is given by the ratio of inhomogeneous to homogeneous widths of the optical transition, which can be larger than 10^6 in rare earth doped crystals. The response time is determined by the optical inhomogeneous width, which is typically on the order of 4 GHz or larger. The photon efficiency is determined by the write and read efficiencies. The write efficiency can be as large as 50 % since the writing process consists of optical pumping among ground state hyperfine levels. The read efficiency is typically on the order of 1 % but can be enhanced by using inverted populations.

Processing applications of SHB materials include optical correlators (or associative memories), header recognition for wavelength division multiplexing (WDM) systems, and lidar or radar signal processing. These applications make use of the high speed of SHB materials to perform operations such as spatial and time (or frequency) correlations, without the bottleneck of converting optical signals into electronic signals.

The major practical limitation that has prevented SHB material from dominating the memory and processing fields is the requirement for liquid helium. Above 4 K the optical homogeneous width increases rapidly with temperature due to phonon interactions, and this directly affects storage capacity. Recent advances in cryogenics have led to the development of closed cycle coolers that can reach temperatures on the order of 10 K with reasonable economy and reliability. However, at this temperature the homogeneous widths of rare earth doped crystals are already on the order of 20 MHz or larger. For a 4 GHz inhomogeneous width, this translates to a frequency dimension storage capacity of only 2×10^3

which barely justifies the expense of even the closed cycle cooler.

To recover much of the frequency storage capacity at higher temperatures, and also to alleviate laser frequency stability requirements, we have been investigating the use of spin coherences, excited (and probed) by resonant optical Raman interactions⁸⁻¹¹. The advantage to using spin echoes is that spin homogeneous widths are much less sensitive to temperature than optical widths. For example, our experiments in Pr:YSO show no temperature degradation of the spin coherence lifetime up to 6 K.

To illustrate how Raman excited spin coherences can restore the performance of a memory or processing system, consider a specific example of an optical memory. A popular technique for constructing optical memories consists of writing angularly multiplexed holograms of two-dimensional arrays of optical bits (up to 1000 x 1000). The arrays are read in with a spatial light modulator (SLM) and read out by a video camera. Assuming $10 \mu\text{m}^2$ pixels and 3000 angles (3 mm thick sample), this gives a storage capacity of about $3 \times 10^9 \text{ bits/cm}^2$. SHB materials can increase this storage capacity by a factor of $\sim 10^6$ by simply chopping the frequency domain into channels approximately the size of camera (and SLM) bandwidths ($< 1 \text{ MHz}$) and using photon echoes to store as many frames as possible in each channel. The result is a semi-random access memory, since the optical frequency and angular channels can be accessed randomly. As temperature is increased above 4 K, the frequency channel width would have to be broadened to match the optical homogeneous width ($\sim 20 \text{ MHz}$ at 10 K for Pr:YSO), and the photon echoes would need to be replaced by Raman excited spin echoes. As shown above, there are $\sim 2 \times 10^3$ optical frequency channels for Pr:YSO at 10 K. The projected spin echo storage capacity would add an additional factor of 200 for a total of 4×10^5 . Finally, note that the spin inhomogeneous width is about 100 kHz which gives a fast enough response for liquid crystal SLM's.

If faster speeds are required, permanent magnets can be used to create a magnetic field variation of 1 kG over the 3 mm thick crystal for an inhomogeneous broadening of 1 MHz. However, this trades spatial storage for time domain storage, since now the 3 mm thick crystal can be viewed as composed of 10 slices of 0.3 mm samples, where the number of slices is given by the ratio of the 1 MHz magnetically induced spin inhomogeneous width to the 100 kHz intrinsic width.

The above example is based on Pr:YSO because it was used for the Raman excited spin echo demonstration experiment to be described next. However, other materials may have advantages. For example, Eu:YSO has more narrow optical transitions at higher temperatures, so that the optical homogeneous width at 10 K would be closer to the spin inhomogeneous width. Ions having larger magnetic interactions and therefore larger spin inhomogeneous widths could also be used to narrow the

gap between spin inhomogeneous and optical homogeneous widths. Of course, such materials will also tend to have shorter spin lifetimes. However, if a non-magnetic host is used (for example CaWO_4), it may be possible to find a material with a sufficiently long lifetime.

Raman Excited Spin Echoes in a Three-level System

Consider a Λ -type three-level optical medium interacting with two Raman resonant frequencies, ω_1 and ω_2 (Figure 3(a)). Ideally, the two ground states are long lived and the excited state is short lived. In this case, after

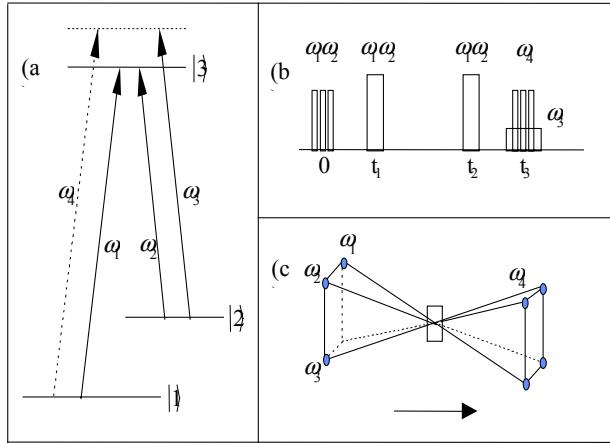


Figure 3. (a) Enhanced NDFWM detection of Raman excited spin coherence. (b) Pulse sequence for Raman excited spin echoes. (c) Background-free detection of Raman excited spin echoes using NDFWM.

few optical pumping cycles, a Raman “dark state” is formed. However, because the Raman resonant fields are not co-propagating, the relative phases of the two ground state contributions to this dark state depend on position. This creates a grating-like structure. Readout of this grating can be accomplished using a single, near resonant probe beam at ω_3 that is Bragg matched to diffract into an output beam at ω_4 via nondegenerate four wave mixing (NDFWM). By tuning the probe beam slightly off-resonance, higher diffraction efficiency can be achieved.

When the long-lived ground states are magnetic sublevels, the Raman dark state is equivalent to a spin coherence excited by an rf field of appropriate phase. The dark state grating is therefore a spin orientation grating that is capable of diffracting light. In a material with an inhomogeneously broadened spin transition, this spin grating can dephase. However, it is possible to re-phase the grating by applying an rf or Raman pulse, just as in spin echoes. Therefore, using Raman resonant light, spin echoes can be optically excited and optically probed by NDFWM. Moreover, high resolution optical holography can be performed using these spin echoes. A representative

pulse sequence for the Raman excited spin echo storage of a stream of binary optical data bits is shown in Figure 3(b). Here, optical data is read in as a series of non-copropagating object and reference beam pulses, containing both ω_1 and ω_2 . The intense write beam is also composed of (plane wave) ω_1 and ω_2 beams. The case shown corresponds

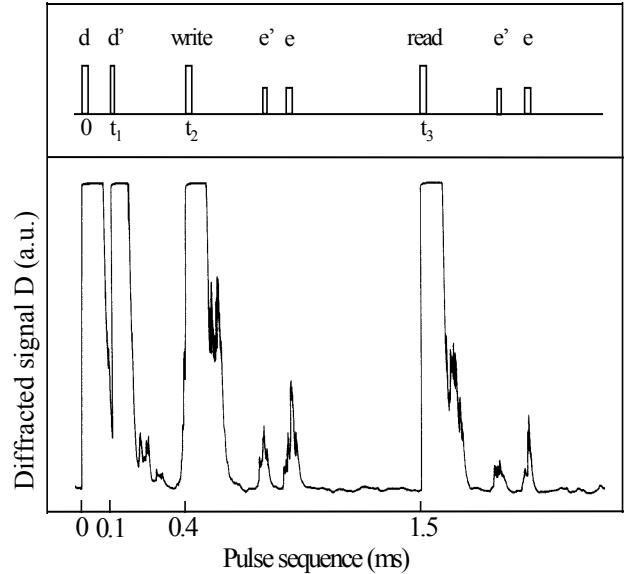


Figure 4. Optical data storage by EIT excited spin echo in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$.

to a stimulated spin echo, so that a read pulse is required. The read pulse is also composed of plane wave ω_1 and ω_2 beams. Finally, to probe the resulting spin echo, a Bragg matched probe beam at ω_3 is applied at the appropriate time to generate the readout beam at ω_4 via NDFWM.

Frequency-selective Time-domain Data Storage using Raman Excited Spin Echoes

Figure 4 shows the storage of two bits of optical data using Raman excited spin echoes in $\text{Pr}:YSO$ at 6 K. As mentioned already, each input pulse is composed of two Raman resonant frequencies, ω_1 and ω_2 (see fig. 3). The laser powers at ω_1 and ω_2 are ~ 30 mW and ~ 2 mW, respectively. To distinguish the data pulses d and d' (see fig. 4) from each other, the pulse widths are adjusted to be 7 μs and 2 μs , respectively. Because the pulse width contributes to pulse area, and both pulses are shorter than the spin inhomogeneous dephasing rate, the resulting echoes are expected to have different amplitudes. This is observed in the echo signals of figure 4. For this data, the write pulse delay time t_2 (400 μs) is chosen to be much longer than the optical T_2 (< 100 μs), so that no optical

coherence survives. Similarly, the read pulse time delay t_3 (1500 μ s) is chosen to be much longer than the spin T_2 (560 μ s) so that no spin coherence survives. Thus, the second set of echoes in figure 4 are stimulated echoes.

The use of stimulated echo for data readout means that the storage time of the data is determined by T_1 , which can be tens of seconds. The fastest writing speed here is determined by the inhomogeneous linewidth of the spin transition, which is about 100 kHz in this case. Of course, much faster writing speed can be achieved by increasing the inhomogeneous broadening via the application of a strong magnetic field gradient, as discussed earlier. The number of optical holes that can be used for multiplexing (over the 4 GHz broad inhomogeneous width of the optical transition) is determined by the effective width of the optical frequency channel, which is determined by laser jitter since the natural linewidth of the optical transition is about 1 kHz. For the data shown here, this width is about 1 MHz. Much narrower width can be achieved by stabilizing the laser. However, for a practical memory device operating at 10 K, it would be easier to use an inexpensive laser system, since the optical linewidth will be more than 1 MHz, as discussed earlier.

In near future, we plan to construct an ODRAM (optical dynamic random access memory) using this technique. While the potential storage capacity of such a device can be several petabits, the actual capacity will be limited somewhat by the state of enabling technologies such as the speed of SLM's, and sensitivity of detectors. For applications such as temporary storage and redirection of data in fiberoptic communication systems, even an ODRAM with a limited capacity can be of great help, by avoiding the bottleneck of exchange the information between the optical and electronic domains.

4. Conclusion

In this paper, we have discussed the status of our current efforts towards developing ultrahigh density optical data storage units. For room temperature applications, we have developed a novel, polymer-based material suitable for shrinkage-free thick holography. It can be produced in arbitrary shapes and sizes, with optical quality surfaces and very low scattering noise. A combination of spatial and angular multiplexing in this material can be used to produce a holographic CD-ROM with a storage capacity of one terabyte in near future. We have demonstrated storage and recall of 1920 frames of a video in a small sample of this material. The storage capacity of holography can be enhanced further by adding spectral multiplexing, possible primarily under cryogenic conditions. In a crystal of Pr:YSO, we have demonstrated spectral multiplexing in two frequency dimensions, at temperatures greater than 10 K. This approach will enable us to achieve a storage capacity exceeding a petabit per cubic cm, using commercially available lasers and closed-cycle cryostats.

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