High Density Holographic Data Storage

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Abstract

The demand for increases in the capacity and speed of data storage tests the limits of conventional technologies and drives the search for new approaches. Optical holography has long held the promise of storage densities and data transfer rates far greater than those of traditional magnetic and optical systems. In the past, its realization has been frustrated by the lack of availability of suitable system components, the complexity of holographic multiplexing strategies, and perhaps most importantly, the absence of recording materials that satisfied the stringent requirements of holographic data storage. Here we report on the design and development of a high-performance photopolymer recording medium and on advances in the design of a holographic storage system that have enabled demonstrations of storage densities as high as 31.5 channel Gbits/in^2. We believe these results will provide the foundation for a practically realizable, high capacity storage system with fast transfer rates and low-cost, removable recording media.

1. Introduction: How Holographic Data Storage Works

The compelling features of volume holography, rapid transfer rates and ultrahigh storage densities, arise from two basic properties: (i) the writing and reading of bits of data occur in a parallel, page-wise fashion, unlike the serial read-write processes of most storage technologies; (ii) the three-dimensional nature of holography enables the storage of many of these pages of data within the same volume of a recording medium, thereby enabling densities far beyond the diffraction limit of conventional optical technologies.

In holographic storage, light from a coherent laser source is split into two beams, signal (data-carrying) and reference beams. These two beams are spatially overlapped through the volume of a photosensitive storage medium producing an optical interference pattern that is imaged within the medium. This process records information contained in the phase and amplitude of the two beams. The optical interference pattern typically induces modulations in the refractive index of the recording material yielding diffractive volume gratings. A schematic of a typical holographic storage system is shown in Figure 1.

The reference beam is used during readout to diffract off of the recorded grating and reconstruct the information that was contained in the signal beam. The readout of data depends sensitively upon the characteristics of the reference beam. By varying the reference beam, for example by changing its angle of incidence or wavelength, different holograms can be recorded in the same volume of material and read out by applying a reference beam identical to that used during writing. The number of holograms that can be overlapped or multiplexed within a volume typically depends on the thickness of the material – the thicker the material, the higher the selectivity of the material and therefore the greater the number of holograms that can be multiplexed.

Information to be stored is digitized with appropriate error correction and channel modulation. The digital data are arranged into pages or large arrays of bits. The 0's and 1's of the data pages are translated into pixels of a spatial light modulator that either block or transmit light. The light of the signal beam traversing through the modulator is therefore encoded with the "checkerboard" pattern of the data page. Each of the pages of data is recorded as the signal and reference beams interfere through the volume of the storage material. When the appropriate reference beam diffracts off of stored volume gratings within the material, it recreates the array of bits which is projected onto a pixelated detector that reads the data in parallel. The recovered data pages are then processed using the channel and error correction codes to reconstruct the original information.

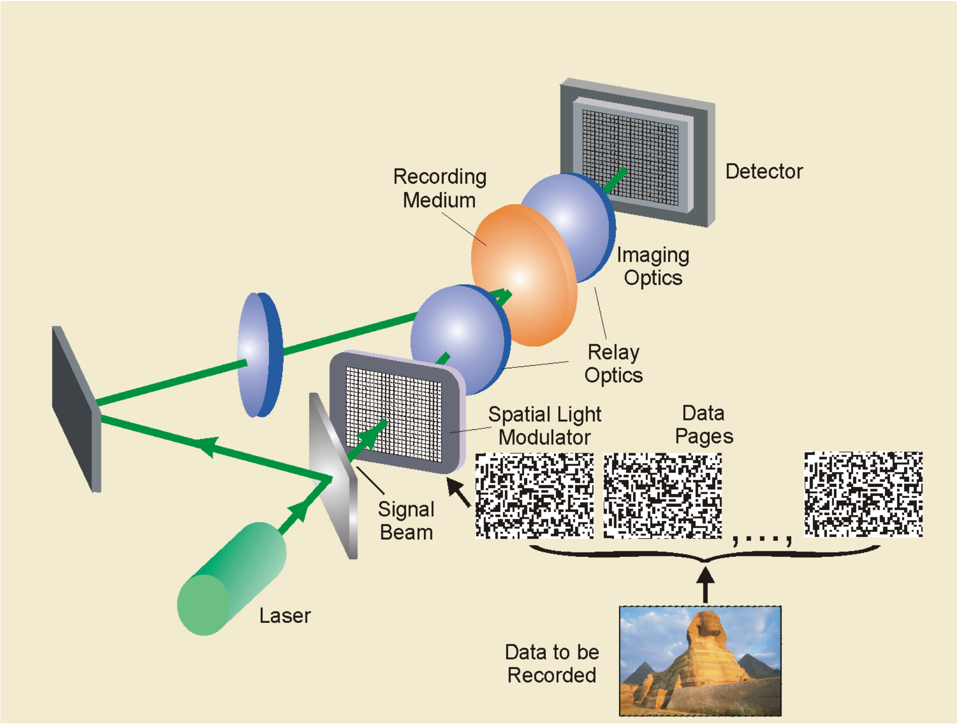


Figure 1. Schematic of a holographic storage system. Light from the source laser is split between the reference and signal arm. The signal arm is encoded with the data to be stored. The signal and reference arms overlap in the recording medium to produce diffractive gratings that are readout by the reference arm. The readout data is imaged onto a pixelated detector.

2. Holographic Recording Media – Photopolymer Materials

One of the major challenges in the area of holographic data storage has been the development of suitable storage materials. Holographic media must satisfy stringent criteria, including high dynamic range, high photosensitivity, dimensional stability, optical clarity and flatness, nondestructive readout, millimeter thickness, and environmental and thermal stability.

While many materials have been considered as media for holographic storage, most suffer from disadvantages that preclude their use in practical systems. Lithium niobate, the traditional choice for holography, exhibits the dimensional stability required for digital data storage, yet suffers from low dynamic range and poor photosensitivity and typically exhibits volatile readout. More recently, photorefractive polymers have shown promise as holographic media, but require the application of electric fields which become prohibitively large for thick media. Photochromic materials can be used for rewritable applications but are characterized by low photosensitivity and limited dynamic range.

Photopolymer materials are attractive candidates for write-once-read-many (WORM) times data storage applications because they can be designed to have large modulations in their refractive index and high photosensitivity, record permanent holograms, and be easily processed. Most of the currently available holographic photopolymers, however, have been optimized for display applications. Typically, these materials can be used only as thin ($\leq$100-200 μm) layers and often exhibit significant dimensional and bulk refractive index changes due to the polymerization of the photosensitive species that occurs during recording.

To better meet the needs of holographic data storage, we designed a new type of polymer system that is composed of two independently polymerizable and compatible chemical systems: low refractive index matrix precursors and high refractive index photopolymerizable monomers [1]. The matrix of our media is formed by an *in-situ* polymerization to yield a cross-linked network in the presence of the photopolymerizable monomers, which remain dissolved and unreacted. Recording of holograms occurs through a spatial pattern of polymerization of the photosensitive species that mimics the optical interference pattern generated during writing – polymerization is induced in the light intensity maxima of the interference pattern while no polymerization occurs in the nulls. The concentration gradient that results from this patterned polymerization leads to diffusion of the unpolymerized species which creates a refractive index modulation that is determined by the difference between the refractive indices of the photosensitive component and the matrix. The most important aspects of this strategy which yield high performance holographic storage media are (i) preforming the matrix *in-situ* which allows media to be shaped into the required thick and flat formats, (ii) the creation of a cross-linked matrix as a support structure for stable holographic gratings, (iii) the choice of compatible matrix and monomer systems to yield media with good optical clarity and low levels of light scattering, and (iv) the design of independent matrix and monomer systems so as to avoid cross reactions that dilute the refractive index contrast. The fourth point ensures that the low refractive index of the "background" matrix is not detrimentally raised by the premature polymerization of the high refractive index monomer. Media with high refractive index contrast can be fabricated using small amounts of the high index monomer thereby minimizing the photopolymerization-induced dimensional and bulk refractive index changes that occur during recording.

To prepare samples for holographic recording, resins, consisting of the matrix precursors, photopolymerizable monomers, and a visible light sensitive photoinitiator, were dispensed between two optically flat glass slides. The *in-situ* room temperature formation of the matrix allowed routine fabrication of high optical quality media with polymer thicknesses between 200 μm to 1.5 mm. A transmission interferogram of a typical 1 mm thick (polymer thickness) is shown in Fig. 2(a) with a surface plot of the variation in the optical flatness shown in Fig. 2(b); the data show flatness within 500 Å (λ/10) over the three inch diameter sample.

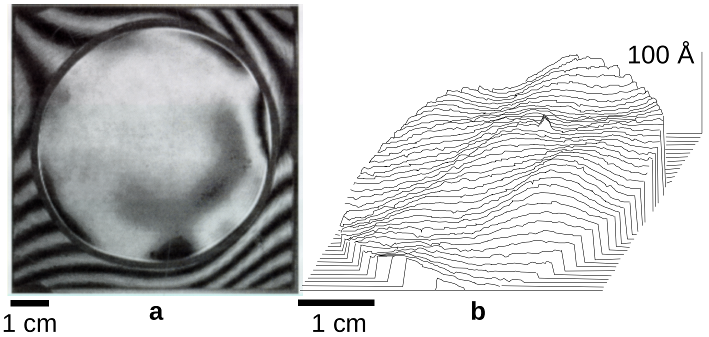


Figure 2(a) Transmission interferogram of a typical 1 mm thick photopolymer medium. **(b)** Surface plot of the variation in the optical thickness of the inner 4 cm of the sample. The optical flatness of the sample varies less than λ/10/cm (~500 A) over the entire area of the medium.

In order to enable simultaneously high densities and rapid recovery rates, a material must have the dynamic range to support large numbers of holograms with sufficiently high diffraction efficiencies. The dynamic range of a medium, which depends both on the magnitude of the modulation in its refractive index and its thickness, is typically characterized by a parameter, M/# [2]. The M/# is defined to be the number of $\sum_{i=1}^{N}\sqrt{\eta_i}$, where N is the maximum number of holograms that can be stored in a volume of the material and η is the diffraction efficiency of each hologram. The M/# of iron-doped lithium niobate is typically 1-1.5 for 1 cm thick crystals. It is commonly believed that M/#'s at least an order of magnitude higher will be required to achieve compelling storage densities and transfer rates. Polymer systems developed at Bell Laboratories have yielded M/#'s as high as 42 in ~1 mm thick formats. The high dynamic range of our polymer media is achieved while controlling the dimensional and bulk refractive index changes that accompany the recording-induced polymerization of the photosensitive species. Recording media must undergo only limited changes in their dimensions and bulk refractive index as these changes can degrade the fidelity of data recovery and ultimately limit the storage density of a material. Our design strategy enables us to optimize the response by minimizing the concentration of the reactive material and simply tuning the refractive index difference between it and the matrix. This approach allows us flexibility in tailoring the media to the particular needs of high density holographic data storage.

In Figure 3(a), we show the M/#'s of a series of 200 μm thick media that were fabricated using the same matrix but writing monomers of varying refractive index and varying size where the concentrations of the monomers were adjusted to yield equivalent levels of recording-induced changes in dimension and bulk refractive index. (Each of the samples underwent changes equivalent to ~0.35% in thickness and ~2.1x10^{-3} in the bulk refractive index for the complete reaction of the photoactive monomers.) Increases in M/# from 2 to 11 were realized while maintaining the same level of effective dimensional stability of the media.

Media with high M/# were obtained by fabricating thick samples of our photopolymer materials. In Figure 3(b), we show how the M/# scales with thickness in media fabricated with a typical writing monomer. Data from three sets of samples are shown, with each set formulated with a different concentration of the monomer and therefore exhibiting different levels of effective dimensional stability. The gains in M/# with increasing thickness are possible because of the low levels of light absorption and light scatter and the high level of effective dimensional stability of the media.

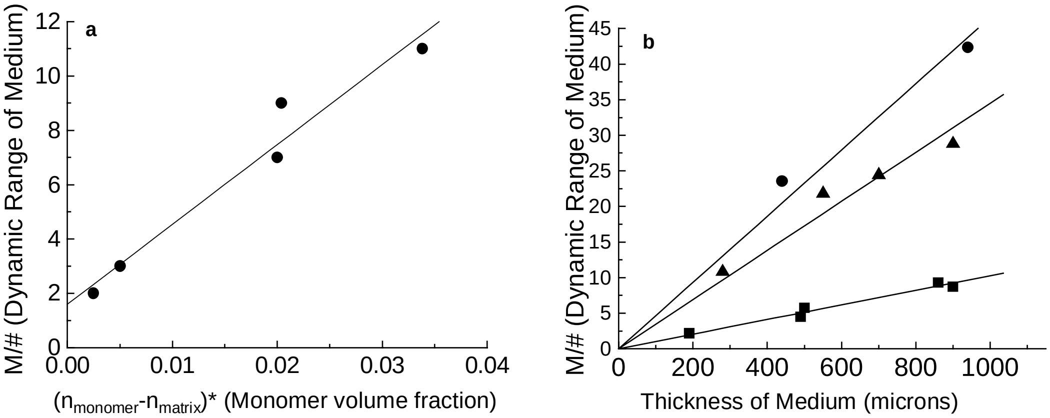
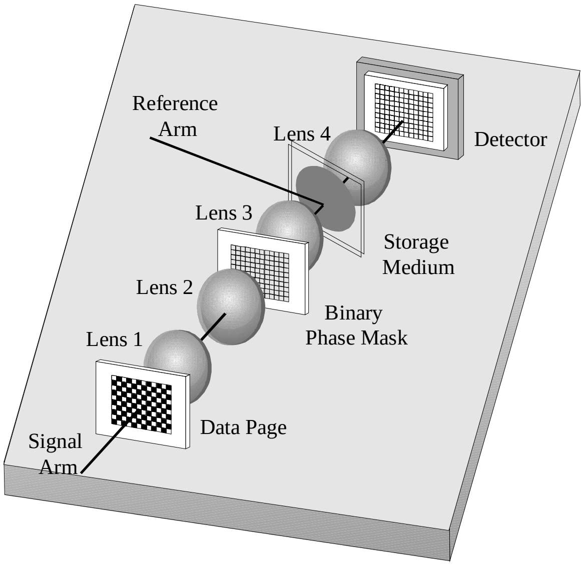


Figure 3(a) M/# versus the product of the difference between refractive indices of the photosensitive monomer and the matrix and the volume fraction of the monomer for five different resins. The molar number of reactive groups of the photoactive monomer in each of the media is adjusted to yield equivalent amounts of recording-induced rotations in the Bragg angle upon recovery. The media are all 200 μm thick. **(b)** M/# versus thickness for photopolymer media fabricated with a typical writing monomer: closed squares (triangles, circles), media exhibit ~0.1% (0.35%, 0.5%) change in thickness upon recording.

The optical quality of the photopolymer media is demonstrated by the "straight-through" image shown in Figure 4. Here, an 800x600 pixel chrome on glass amplitude mask is imaged through the media onto a charge-coupled device detector as shown in Figure 4(a). The transmitted image and image statistics are shown in Figure 4(b).

(a)



(b)

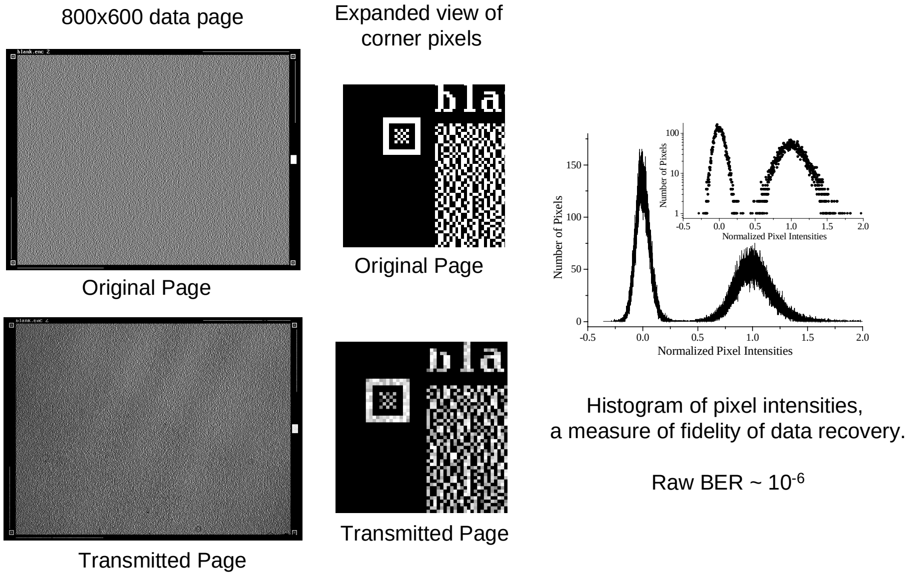


Figure 4(a) Optical system used for digital holographic data storage. A spatial light modulator (the data page), encoded with an array transmitting and opaque pixels, is illuminated with a plane wave. The data page is imaged through lenses 1 and 2 onto a random binary phase mask which serves to randomize the information of the data page at the recording plane. The data page is then Fourier transformed through the storage medium at the recording plane by lens 3 and imaged through lens 4 onto a charge-coupled device detector. For high fidelity data recovery, each pixel of the data page must be precisely mapped through the optical train of the signal arm onto a corresponding pixel of the detector array requiring the storage medium to be of high optical quality. The reference arm is spatially overlapped with the signal arm at the storage medium during the recording process and is used alone to reconstruct the data page during the recovery process. **(b)** Straight-through image of a 480 kbit data page. The intensities were digitized using a Princeton Instruments ST138 CCD camera with 16 bit resolution. The calculated raw bit error rate calculated from a histogram of the pixel intensities is 2.6 x 10^{-6}. (Before calculating the histogram, the intensities of the pixels were normalized so that the local averages of the on and off bits equaled the global averages.) The inset shows the data plotted on a logarithmic scale.

The materials described here represent substantial advances in the development of recording media for holographic data storage. Ongoing work is focused on the temperature sensitivity of the polymer media and the long-term archival life of stored data are also under investigation.

3. New Multiplexing Methods

The methods used to overlap or multiplex holograms determine the complexity and architecture of the recording system. Two recently developed multiplexing methods have led to system designs in which accessing different holograms requires only motion of the media.

Both approaches used a fixed set of optics to create the reference beam. In shift multiplexing, the reference beam consists of a collection of plane waves or a spherical wave [3]. Holograms are multiplexed through spatial translations on the order of microns of the media relative to the reference beam. Large numbers of holograms can therefore be overlapped in essentially the same volume of the media. In correlation multiplexing, a complex reference beam encodes the position of the hologram in the recording medium and again micron-scale translations allow many holograms to be multiplexed [4]. These “fixed optics” methods enable a holographic storage system based on a spinning disk architecture used throughout much of the storage industry. A schematic of a holographic drive based on these fixed optics methods is shown in Figure 5.

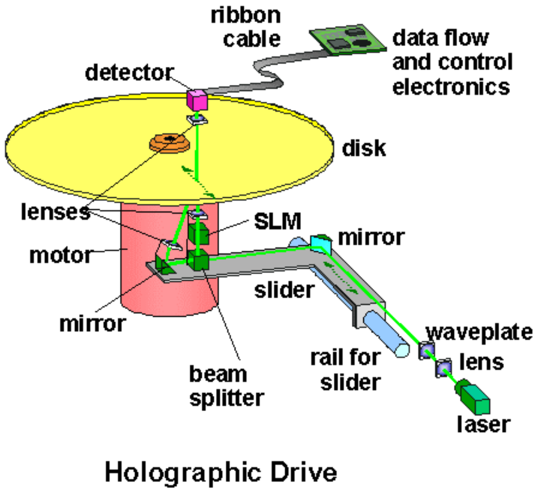


Figure 5. Schematic of a rotating holographic drive based on multiplexing methods that use fixed optics.

4. Demonstrations of High Storage Densities

In early experiments [5], we demonstrated the feasibility of digital storage in thick photopolymer systems by recording and recovering with low bit error rates multiple high capacity (480kbit) digital data pages in media up to 500 μm thick. The results established that (i) polymer media could be fabricated with the high optical quality and low level of light scatter required for high density data storage applications, and (ii) optical components and the media could be integrated to yield a high performance storage system.

More recently, storage densities as high as 31.5 channel Gbits/in^2 have been attained by recording and retrieving >3000 data pages (each of capacity 480 kbit) using shift multiplexing in a 750 μm thick photopolymer medium [6]. Each of the 3000 data pages were fully recovered with signal-to-noise levels above that required for error-free readout. These experiments provide further evidence of the storage capabilities of the photopolymer media. In addition, the data indicate that even greater storage densities are possible with in-house, higher response versions of the materials used here.

5. Prototype Holographic Recording System

The development of practical components for holographic systems has been accomplished largely in fields outside the storage industry. For example, the frequency-doubled, diode-pumped Nd:YAG laser, used in medical, cable TV, and printing industries, is an attractive recording source due to its small size, ruggedness, and low cost. Digital micro-mirror devices appearing in display applications are ideal spatial light modulators with their large numbers of pixels (~ 1 million), fast frame rates (2000 Hz), and high optical contrast. The CMOS active pixel detector arrays emerging in digital photography exhibit the rapid access and data transfer properties required for holography. The volume of these non-storage markets is expected to lead to low-cost, reliable components.

A prototype digital storage system assembled from the components described above and readily available optics is shown in the accompanying photograph in Figure 6. The system occupies an approximately 1x2 foot area and can be considerably reduced in size with the use of custom-designed optics.

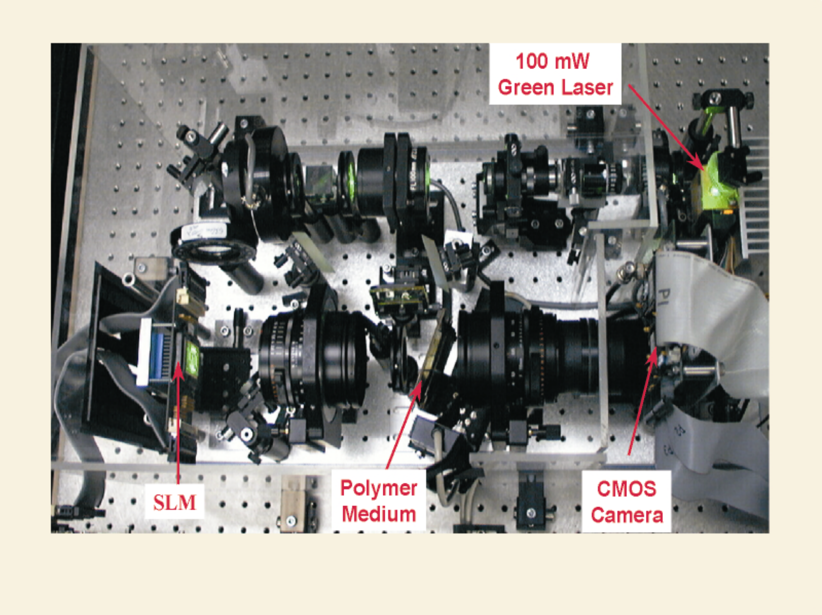


Figure 6. Prototype holographic storage system.

6. Outlook for Holographic Data Storage

The recent commercial availability of optical components such as spatial light modulators, CMOS detectors, and compact visible wavelength lasers has removed many of the obstacles that previously prevented the practical consideration of holographic data storage. We believe the advances in media, recording methods, and the demonstrated densities of >30 channel Gbits/in^2 described here further enhance the prospects for holography to become a realizable, next-generation storage technology.

References

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