VOL. 11, NO. 2 DECEMBER 2000

SPIE's International Technical Group Newsletter

Holography

CROP photopolymers for hologram recording

Holographic photopolymers are systems of organic molecules that rely on photoinitiated polymerization to record volume phase holograms. Characteristics such as good light sensitivity, real-time image development, large dynamic range, good optical properties, format flexibility, good image stability, and relatively low cost, make photopolymers promising materials for write-once, read-many times (WORM) holographic data storage applications.

Vinyl monomers that polymerize through a free radical mechanism, such as acrylate esters, are used in most photopolymer systems. Unfortunately volume shrinkage during hologram recording is a serious problem for many free-radical-based photopolymer systems. Each time a monomer adds to a growing polymer chain, the volume of the system decreases as a covalent chemical bond replaces a non-bonded contact. In severe cases, volume shrinkage distorts the recorded interference pattern and prevents accurate recovery of the stored data. Polaroid Corporation recently developed a holographic recording system that exhibits significantly less shrinkage than conventional photopolymers.[1]

The Polaroid photopolymer uses monomers that polymerize using a cationic ringopening (CROP) mechanism to replace more conventional free-radical monomers. Shrinkage during hologram recording for CROP monomers is partially compensated by a volume increase produced by the ring-opening polymerization mechanism. Aprilis Inc., an independent startup, was founded in 1999 to commercialize the Polaroid CROP photopolymer technology.

Hologram recording with a CROP photopolymer

Results of recording plane-wave transmission gratings in 100µm-thick samples of the Polaroid CROP photopolymer system are presented in Figure 1. The sample was exposed with an argon laser at λ=514.5nm and with an irradiance of 9.3mW/cm². There is an initial, or threshold, exposure of approximately 6mJ/cm² that does not produce detectable holographic activity. After the threshold is exceeded, the diffraction efficiency rises rapidly with additional exposure and then saturates at a value above 95%. The relatively high value obtained for the diffraction efficiency strongly suggests a volume-phase mechanism, in which the holographic interference pattern is recorded as an image-wise variation of refractive index throughout the entire volume of the photopolymer. Accordingly, we apply Kogelnik's coupled wave theory[2] and obtain a value for the refractive index modulation, δn, of ~0.004.

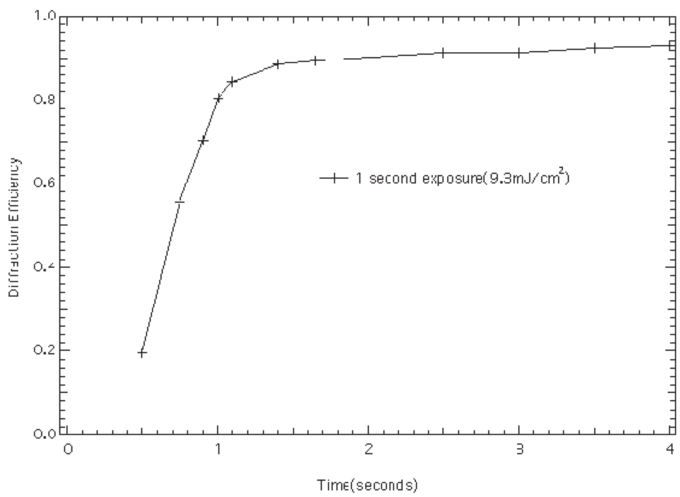


Figure 1. The recording response of a 50µm-thick CROP photopolymer formulation. The real-time growth in diffraction efficiency, determined by a He:Ne laser probe beam, is plotted as a function of time for a 1s exposure at a write irradiance of 9.3mW/cm².

Shrinkage

High capacity data storage demands near-perfect fidelity of the reconstructed image. The original image, therefore, should be recorded faithfully and must be free of distortions produced by hologram shrinkage. Shrinkage in CROP photopolymer holograms have been analyzed by Waldman, Li, and Horner.[3]

Their results reveal that the shrinkage of CROP photopolymer recording materials can be controlled by using an appropriate pre-imaging, incoherent-light exposure. The observed shrinkage for one 200µm-thick CROP formulation, for example, was ~0.20% for a pre-imaging exposure of 80mJ/cm², and ~0.10% for

continues on p. 7

Newsletter now available on-line

Technical Group members are being offered the option of receiving the Holography Newsletter in an electronic format. An e-mail notice is being sent to all group members advising you of the web site location for this issue and asking you to choose between the electronic or printed version for future issues. If you have not yet received this e-mail message, then SPIE does not have your correct e-mail address in our database. To receive future issues of this newsletter in the electronic format please send your e-mail address to spie-membership@spie.org with the word HOLOGRAPHY in the subject line of the message and the words "Electronic version" in the body of the message.

If you prefer to continue to receive the newsletter in the printed format, but want to send your correct e-mail address for our database, include the words "Print version preferred" in the body of your message.

High-density and high-capacity holographic data storage

By superimposing multiple data pages within a small region of an appropriate material, holographic data storage has the potential for both high volumetric and high areal density.[1,2] Achieving high areal density is a balancing act between interpixel crosstalk (introduced by the small aperture through which each data page is focussed), and the loss of signal associated with recording multiple holograms. At IBM Almaden, we have recently demonstrated an areal density 80 times larger than that of DVD on a holographic storage test platform called DEMON II. This platform, shown in Figure 1, combines large, "megapel" data pages (of 1024×1024 pixels) with the short focal length optics needed for high density. A novel apodizer uses aspheric optics to create a uniform, "flat-top" beam for illuminating the large nematic-liquid-crystal reflective spatial light modulator (SLM).[3]

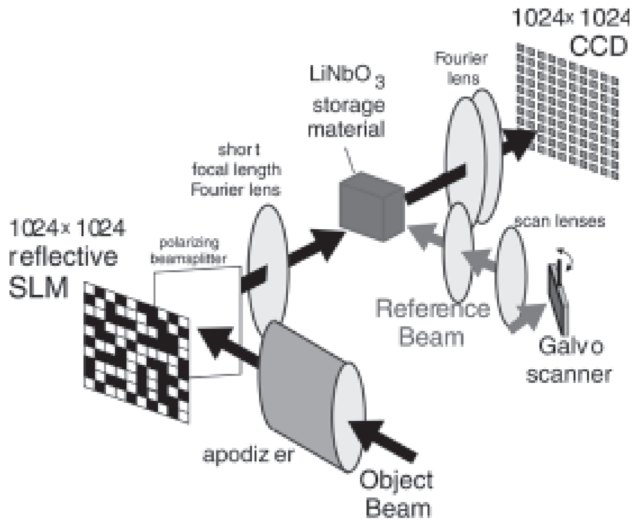


Figure 1. Salient features of the DEMON2 holographic storage platform. An apodizer provides uniform illumination over a reflective SLM of 1024×1024 pixels, which is then imaged to a matched CCD array, through a small aperture, using short focal length optics.

In one experiment, one thousand volume holographic data pages, each containing one million pixels, were angle-multiplexed in a common volume of iron-doped lithium niobate. Given the effective transverse aperture of 1.6×1.6mm^2, the demonstrated areal density (in channel bits) was 394pixels/µm^2 (254Gpixels/in^2).[4] For comparison, a CD has a density of 0.7bit/µm^2, a DVD disk 4.5bit/µm^2, and the magnetic disk in the 1GB IBM MicroDrive has a density of 23bit/µm^2. Retrieved data pages were post-processed with a novel algorithm to compensate both global page misregistration and the local pixel offsets of optical distortion (see accompanying article on p. 4 or Ref. 5). These processed data pages were then decoded with a strong 8-bits-from-12-pixels modulation code.[2] The worst-case raw-BER before error correction was 1.1×10^{-3}, sufficient to deliver a user-BER of 1×10^{-12}. Given the 5.5mm hologram thickness, this result corresponds to 1.1% of the well-known theoretical volumetric density limit of $1/\lambda^3$.

The success of the DEMON II platform is due jointly to excellent imaging fidelity (most of the pixellated data arrives at the right detectors) and tight focussing of the object beam (holograms can be stored using very little volume). These two features were made possible by optical design: minimizing the optical aberrations, particularly distortion, of an optical system with very short focal length. To scale fast-access holographic storage to high capacity, however, this same high density must be achieved at many storage locations, and without moving the storage media. The correspondingly greater demands on optical imaging performance soon limit the capacity achievable along this path to commercially uninteresting values. However, several researchers have long proposed bypassing these imaging constraints with phase-conjugate readout.[6,7]

Once a hologram is recorded, the wavefront reconstructed by a phase-conjugate readout beam will retrace the path of the incoming object beam in reverse, cancelling-out any accumulated phase errors from lens aberrations or material imperfections. This allows data pages to be retrieved with high fidelity using an inexpensive lens, or even without imaging lenses for an extremely compact system. However, two uncertainties prevented earlier work from proceeding. First, researchers were worried that imperfections in producing the phase-conjugate reference beam would introduce errors in each retrieved data page. If the phase-conjugate reference beam is simply carefully aligned, even minor differences between the two beams will distort the reconstructed data pages. However, an extremely accurate phase-conjugate beam can be produced by a self-pumped phase-conjugate mirror in a material such as barium titanate. Recently, we showed that the reference beam produced by a phase-conjugate mirror could retrieve pages containing one million pixels onto a camera with very few bit errors, providing at least one potential solution to this first uncertainty.[2]

The second concern was that many pairs of phase-conjugate reference beams would be needed to read the many different holograms recorded within the same volume—and maintaining these beams over long periods of time would be impossible from a practical point of view. This problem also kept researchers from using the phase-conjugate mirror, since the barium titanate crystal takes several seconds to respond when the input beam changes.

To solve this problem, we have demonstrated—and are currently scaling up—a novel architecture that allows phase-conjugation and multiplexed holographic storage to co-exist.[8] This technique involves separating the phase-conjugation and hologram storage processes into two successive steps by using a "buffer" hologram (Figure 2). Holograms can then easily be multiplexed at a large number of separate storage locations using only one SLM and one detector array. In addition, since such a system only contains a single pair of phase-conjugate beams, it never needs to wait for the phase-conjugate mirror to respond.

We anticipate that the successful use of phase-conjugation in holographic storage will enable compact and affordable high-capacity systems, with only a moderate increase in the overall system complexity. However, such systems still await a recording material that supports both read-write access and nonvolatile storage.[1,2]

Geoffrey W. Burr, Hans Coufal, John A. Hoffnagle, C. Michael Jefferson, Mark Jurich, Roger M. Macfarlane, and **Robert M. Shelby**
IBM Almaden Research Center
650 Harry Road
San Jose, CA 95120
Tel: 408/927-1512
Fax: 408/927-2100
E-mail: burr@almaden.ibm.com

continued on p. 8

Holographic data storage in disk-shaped recording media by combined use of peristrophic, angular, and spatial multiplexing

Holographic memories attract attention because they can perform three-dimensional data storage and parallel data retrieval.[1] To store numerous pages of data holographically, various multiplexing techniques have been invented. Among these, angular, peristrophic,[2] and spatial multiplexing techniques are the most commonly used in holographic data storage experiments. We studied a simple and cost-effective way to combine these three multiplexing techniques to allow the recording of as many holograms as possible, especially where the storage medium is shaped like a disk.

Our system is schematically depicted in Figure 1. The two lenses (L_1 and L_4) are used to make the reference beam converge to a fixed point at the recording medium. The signal beam containing binary data presented by the spatial light modulator (SLM) is incident on the recording medium through L_2 to record Fourier plane holograms.

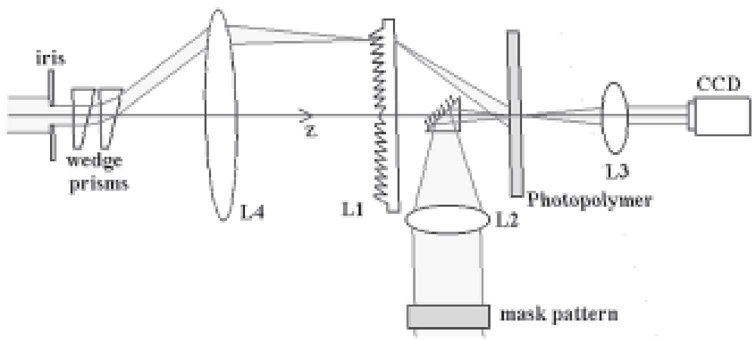


Figure 1. Schematic diagram of holographic storage set-up.

For peristrophic multiplexing, the two wedge prisms are simultaneously rotated around the *z*-axis in order to rotate the reference beam conically, while the relative phase of the wedge prisms is kept at a constant value. For angle multiplexing, the relative phase of the wedge prisms should be changed so that a different apex angle of the reference beam cone can be obtained. Then, the hologram recording with peristrophic multiplexing is repeated again. Finally, spatial multiplexing is obtained by shifting the recording medium in the *(x, y)* plane. After the hologram recording is complete, the stored data is read out with a charge-coupled device (CCD).

To obtain high area storage density S_{2D}, a small *f* number (ratio of focal length to diameter) of L_1 denoted by $F/\#_1$ should be used. However, it is difficult to get a lens with a small *f* number and a low level of distortion. Because the role of L_1 is simply to redirect the reference beam toward the fixed recording point at the recording medium, the lens distortion of L_1 is not as critically important as that of L_2. Therefore, a Fresnel lens with both a small *f* number and low groove density was used for L_1. Such a lens can be easily fabricated with a thin material. The Fresnel lens is positioned near the focal plane of L_4 so that the reference beam can pass through only one of the circular grooves that play the role of prisms.

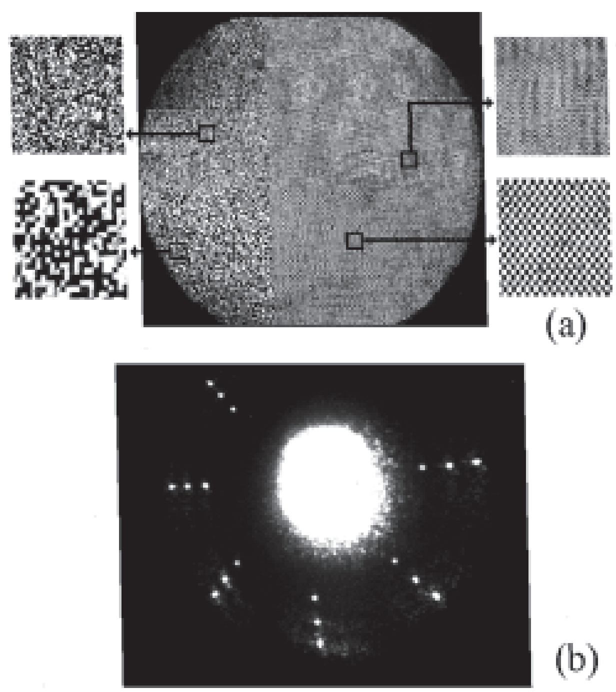


Figure 2. Results of holographic storage experiments. (a) The reconstructed image when only one pattern was stored. When this pattern (signal beam) was repeatedly recorded at one location with 18 different reference beams, it was possible to read out the reference beams simultaneously by illuminating the signal beam alone. (b) The 18 reference beams reconstructed.

The areal storage density S_{2D} is a strong function of $F/\#_1$, $F/\#_2$, and the medium thickness *d*. A simple analysis of our system shows that, regardless of *d*, there exists the optimal value of $F/\#_2$ that makes S_{2D} maximal for a given $F/\#_1$.[3] From this analysis and the fact that it is difficult to get a lens with a small *f* number but still with a low level of distortion, a good practical choice is that $F/\#_2 = 2F/\#_1$. When d=0.1mm (or 0.038mm), for example, we can expect maximally S_{2D}=28 (or 11) bits/μm² if $F/\#_1$=0.5 and $F/\#_2$=1.0, while S_{2D}=13 (or 5) bits/μm² if $F/\#_1$=0.65 and $F/\#_2$=1.3.

We also performed preliminary data storage experiments with DuPont photopolymers whose thickness is 0.038mm. The recording wavelength was 514.5nm. The deflection angle of the two identical wedge prisms was 4°. Instead of the SLM, we used a glass mask containing binary images whose pixel size is either 0.04×0.04mm, or 0.1×0.1mm, or both. A Fresnel lens available in our laboratory was used for L_1. (The diameter of L_1=5cm, $F/\#_1$=0.65, and groove density = 5mm.) Nikon standard camera lenses with *f* numbers of 1.4 were used for L_2 and L_3. We multiplexed up to 18 holograms per location with above experimental parameters (see Figure 2). The estimated area storage density S_{2D} was approximately 2 bits/μm². (The number of pixels per page was 2.5×10^5 and the actual area of the hologram was approximately 2.25mm².) The raw bit error rate we estimated was approximately 10^{-3}. We believe that it was the performance of the available recording medium that limited the areal storage density achievable in these

continued on p. 8

Post-processing to correct for optical distortion and material shrinkage in holographic data storage

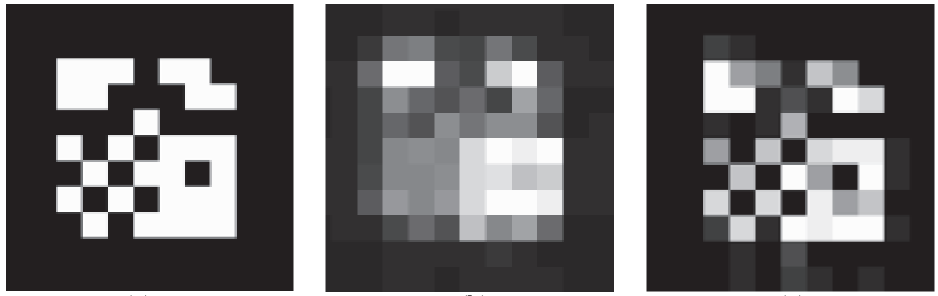
The high density and fast readout offered by volume holographic data storage are due in large part to the arrangement of data into large pixellated pages.[1] But to retrieve any stored data, the pixel array imposed by the input spatial light modulator (SLM) must be accurately delivered to the array of detector pixels. Displacement of individual pixel images from their target detector pixels (because of magnification error, misalignment, optical distortion, or material shrinkage[2]) quickly leads to uncorrectable levels of error.

Signal processing techniques developed for the conventional 1D channels found in storage and communication systems can be extended to two dimensions[3-4] to alleviate pixel blur in holographic storage systems. (This pixel blur is introduced by optical aberrations or by diffraction from the spatial bandlimiting introduced to maximize areal density[5]). Unfortunately, the linear channel model assumed by most of these techniques does not match the physical detection process in holographic data storage, nor are these algorithms capable of adapting when the entire page drifts out of perfect alignment. At IBM Almaden, we have recently derived an algorithm that can compensate for both optical distortion and misalignment, correcting a moderate pixel blur in the presence of a significant pixel offset.[6]

The algorithm comes directly from the detection physics. Consider the readout signal received at a detector pixel when the incoming data page is shifted such that two SLM pixel images are contributing (the correct SLM pixel, and one neighbor). In the simplest 1D case, we can decompose this detected signal r_2 into linear contributions from the two SLM pixel intensities p_1, p_2 and a nonlinear factor through their constructive interference, as:

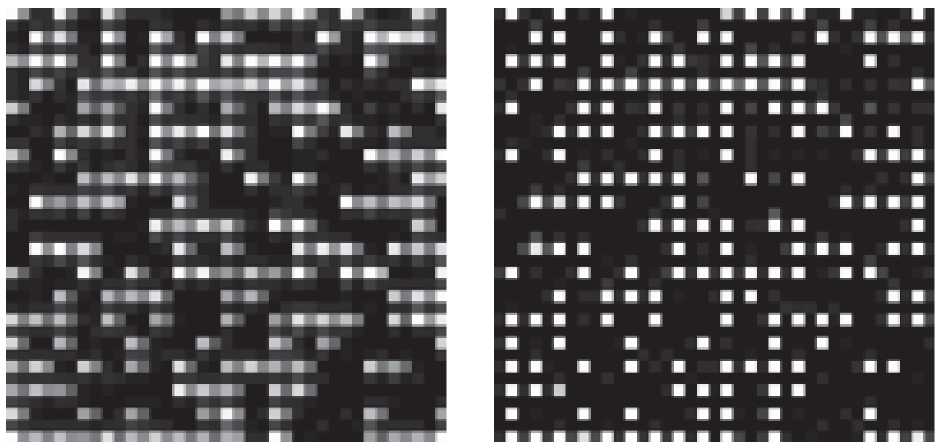
$$r_2 = p_2 H_{00}(s) + 2\sqrt{(p_1 p_2)}\, H_{01}(s) + p_1 H_{11}(s)$$

The weights $H_{00}(s)$, $H_{11}(s)$ and $H_{01}(s)$ represent the normalized signal integrated by the detector pixel from the correct SLM pixel alone, the signal from the neighboring SLM pixel alone, and the additional contribution when both SLM pixels are present, respectively. This equation can be inverted to iteratively solve for each pixel's correct value from the just-processed neighbor pixel and the received data signal. At each pixel, we take the measured signal r, subtract the portion that belonged to the previous pixel, subtract a further portion due to interference, and then add in the missing signal that should have been here but which actually fell into the next pixel. It turns out that in our DEMON2 system,[7] the 2D data page can be processed by using this simple 1D algorithm repeatedly, first on all the rows, and then on the columns.[6]



(a) (b) (c)

Figure 1. A 9×9 pixel pattern is imaged from SLM to CCD: (a) under perfect conditions; (b) with half-a-pixel offset in both x and y; (c) after post-processing with the shift-compensation algorithm.



(a) (b)

Figure 2. A portion of a 512×512 data page, stored in Aprilis photopolymer and received by a 4:1 oversampling detector, is shown: (a) before and (b) after applying the shift-compensation algorithm.

In Figure 1(a), we show a small 9×9 pixel block as it should ideally be received. Figure 1(b) shows the same pattern imaged through DEMON2 when the SLM is shifted a half-pixel in both *x* and *y*. The DEMON2 platform pixel-matches megapel pages through an aperture of 1.36 D_N (1.7×1.7mm^2 aperture, f=30mm, l=532nm, SLM d=12.8μm). In Figure 1(c), we show this data after post-processing with the shift-compensation algorithm: the original pixel pattern is recovered. To process each block of pixels, the algorithm combines the dynamic global shifts, as measured by dedicated fiducial marks, with the static local baseline offsets taken from a lookup table. Assuming that 1×10^{-3} is the maximum acceptable raw bit-error-rate (BER) that can be corrected by error-correction codes,[8] the shift-compensation algorithm increases the position tolerance of the DEMON2 tester from ±16% to ±40% of the pixel pitch.

In addition to local pixel shifts due to optical distortion, shrinkage of photopolymer-type media during recording can lead to magnification and distortion of holographic data pages that would otherwise be imaged perfectly. These media exhibit both transverse shrinkage (the thin polymer film gets thinner) and lateral expansion (material pushes out towards the sheet boundaries). Cationic ring-opening polymer (CROP) media can reduce this effect greatly, producing only ~0.5% transverse shrinkage and ~0.01% lateral expansion.[3] At the cost of some diffraction efficiency, stored holograms can be read out such that only the smaller lateral expansion leads to pixel shifts.

continued on p. 8

Bulk photopolymer with negligible shrinkage for holographic memory

Holographic data storage systems have been proposed and demonstrated that have high storage capacity and data rate, good image quality, and low bit-error rate.[1] However, a lack of suitable storage materials has obstructed progress in this technology. Crucial characteristics for a good holographic material include high sensitivity to optical exposure, large dynamic range, easy fabrication in large area or volume with high optical quality (for low scattering), and dimensional stability. Among them, the latter is the most important factor in determining the usable material thickness, and thus the storage capacity of volume holographic memory.[2] Typical photopolymer materials exhibit noticeable dimensional change, which results in the detuning of the volume holographic grating. The useable material thickness is limited to a few hundred microns. Here, we present a technique for synthesizing photopolymers with high optical quality, large dynamic range, and negligible dimensional shrinkage.[3-4]

Typical photopolymer materials consist of a photopolymerizable monomer, a photo-initiator, and a sensitizer in a polymer binder. During optical exposure, incident photons initiate a chain reaction of polymerization of monomer molecules, which causes a change of the refractive index to form a phase hologram. Because a large number of monomer molecules are involved in the formation of the hologram, the material exhibits significant dimensional change (usually, shrinkage). Our strategy, to alleviate this problem, is to separate the photo-chemical reaction from the polymerization of the host monomer molecules. Our photopolymer sample consists of two components: poly(methyl methacrylate) (PMMA), the host matrix, which was made from the chain reaction of thermal-polymerization of MMA monomers and a small amount of azobisisobutyronitrile (AIBN, ~0.5%); and phenathrenequinone (PQ), the dopant molecules with the photosensitive elements that cause the refractive index change (up to 0.7%) .

During the material preparation, most of the monomer MMA molecules have been polymerized to form the host polymer matrix. Thermal gravimetric analysis shows that ~10% of the MMA in our samples were un-reacted and left as the residual monomers. These un-reacted monomer molecules, together with photo-sensitizers, are uniformly distributed in the host polymer matrix. This process is known as pre-polymerization. During the holographic recording, under illumination, the photosensitive PQ molecules absorb photons and become radicals such that they bond with the residual monomer molecules on a one-to-one basis. This chemical reaction occurs in the bright region. Due to the molecule density difference, free PQ and MMA molecules diffuse from the dark into the bright regions.

Since the structural change of the PQ molecules, induced by the bonding of PQ and MMA molecules, can induce a strong refractive index change, a strong difference between the refractive index in the dark region and that in the bright region is consequently created. However, because the residual monomers and photosensitizers involved in the formation of the hologram are only a small fraction of the compositions, the host polymer matrix structure can be maintained during the optical recording. As a result, the dimensional shrinkage and the bulk refractive index change induced by the recording light are minimized. Figure 1 shows a picture of our polymer bulk samples. The dimensions of the blocks could be in the range from 1×1 to 2.5×2.5cm^2 with a thickness of 1-25mm.

To examine the holographic storage performance of our polymer samples, we performed a multiple-exposure experiment on a polymer cube by using a 90°-geometry recording setup. This particular geometry provides the most critical Bragg selectivity, so that the material shrinkage can be easily examined and the storage capacity can be maximized. A 1×1×1cm^3 polymer cube was used in the experiment. A chess-board pattern is used as our input pattern, displayed on a liquid crystal television with resolution of 320×240 pixels. The sample was located at near the Fourier plane of the LCTV. Two hundred and fifty Fresnel holograms were recorded in a single location. The exposure time of each was determined by a suitable schedule that was designed to

continued on p. 10

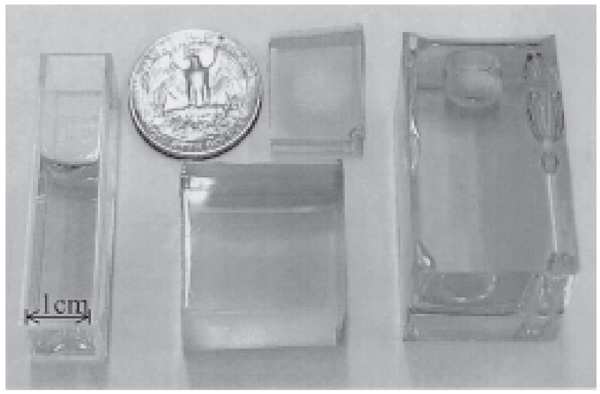


Figure 1. Bulk polymer samples.

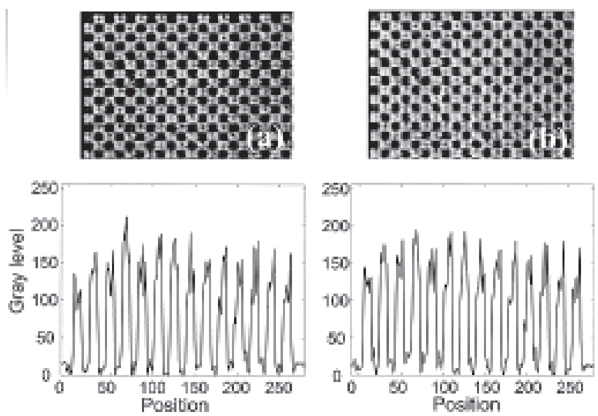


Figure 2. The experimental results for multiple hologram storage. The upper row shows the original transmitted image and one of the reconstructed images. The lower row is the sketch of the gray-level distribution along an arbitrary horizontal line on each image.

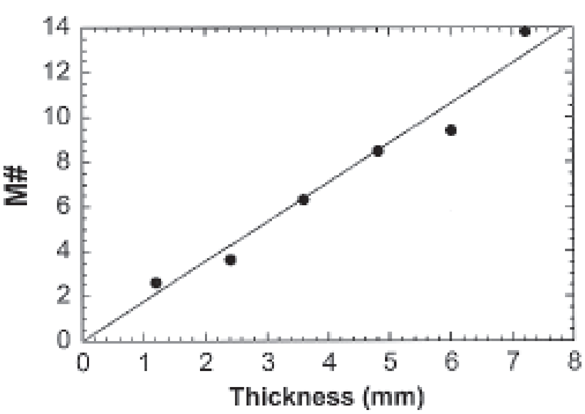


Figure 3. The M/# of our photopolymer as a function of the sample thickness.

Optically programmable gate array

Holographic memory modules possess an inherently high degree of parallelism, since the data is handled in page format. Such parallelism results in a large communication bandwidth between the memory and either the array of photodetectors (during a readout cycle), or the SLM (upon recording). The use of optical memories in information processing systems makes it necessary to consider the interface between the two main components: the holographic module, and the silicon circuitry that processes the data retrieved from the memory and stores computational results. This is something we are currently studying in Professor Demetri Psaltis' Optical Information Processing Lab at the California Institute of Technology.

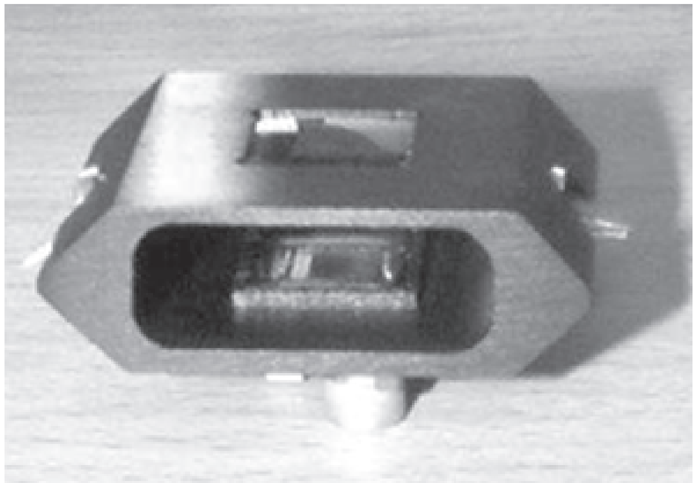


Figure 1. Mechanical design of the OPGA module.

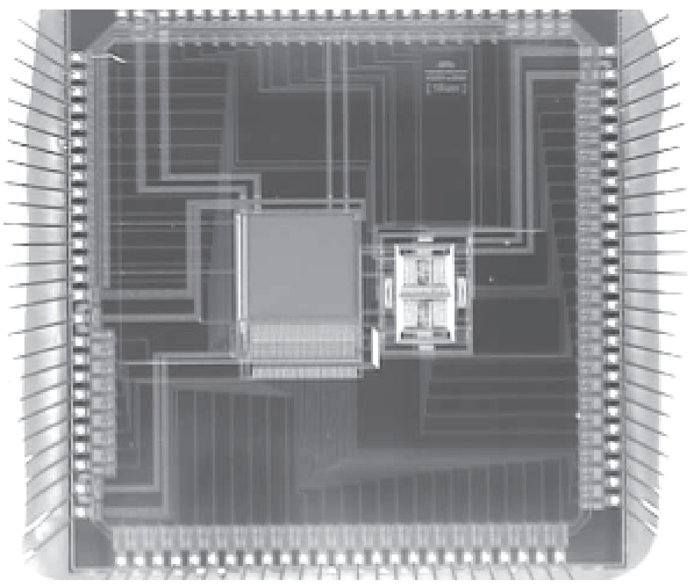


Figure 2. The OPGA chip combines an array of photodetectors (left), and logic blocks (right).

Traditionally, holographic systems have not addressed this issue: so even though the information could be delivered very quickly to and from the optical memory, this parallelism was lost in the communication between the optoelectronic chips and the processor. Thus, a bottleneck was created. A direct interface between memory and processor could be much more effective, on the other hand, as parallelism would always be preserved. Slow inter-chip communication is avoided in such a system by simply integrating, on the same silicon die, the logic circuitry and the photodetectors. However, the question is now to identify which computing devices have enough hardware parallelism to exchange data efficiently with the optical memory.

A good candidate to meet this requirement is the Field Programmable Gate Array (FPGA). A typical FPGA consists of a large array of configurable logic blocks—each able to implement a simple logic operation—and a mesh of programmable interconnects. FPGAs are very versatile since the user can define the functionality of the chip by specifying a configuration bitstream. By interfacing an optical memory with an optoelectronic version of an FPGA, the configuration data can be downloaded into the chip in parallel as a single page and decrease the configuration time to microseconds rather than milliseconds as in current FPGAs. The Optically Programmable Gate Array[1,2] (OPGA) is then a device where the computation is still performed by programmable logic blocks and interconnects—as in the conventional FPGA—but where the configuration data is brought into the chip optically.

The OPGA is basically the integration of three main components or technologies: an array of vertical cavity surface-emitting lasers (VCSELs), used to readout the holograms; the optical memory that contains the set of configuration contexts in the form of holograms; and the optoelectronic chip.

Our technique to multiplex the holograms in the memory combines both spatial and shift multiplexing. Upon recording, a lens focuses the beam that illuminates the SLM down to a small spot on the recording medium. By changing the angle of incidence of the beam on the lens, the signal spot focuses on a different location in the material that is partially overlapping with the previous ones. The pages of data are recorded in these partially overlapping circles, spanning a stripe on the optical material. To achieve Bragg-mismatch among holograms, the reference beam needs to be shifted accordingly to illuminate the corresponding signal spot.

In the recording setup, a laser diode can be used instead of the VCSEL array. The reference beam is focused by a lens that is mounted on a mechanical scanner. This is used to translate the beam to match the position of each one of the VCSELs in the array. The OPGA reader module (see Figure 1) becomes very compact due to the reflection recording geometry and phase-conjugate readout, which makes the use of any extra optical components unnecessary.

The OPGA chip,[2] designed in collaboration with Suat Ay from Photobit Inc., combines a 64×32 array of differential Active Pixel Sensors (APS) and the logic array. The latter contains four logic blocks and the switching matrices to fully interconnect the logic blocks: both between themselves and with the I/O buses (see Figure 2). Differential photodetectors have proven to be very robust to the inherent intensity non-uniformity of the reconstructed holograms. In this case, each bit of information required to program the chip is represented by a pair of pixels in the hologram. The differential photodetector must have two photosensitive areas, referred to as left and right pixels, which need to be matched to the pixel pair in the hologram. Logic 1 is then represented by left pixel on and right pixel off and logic 0 by left pixel off and right pixel on. This coding scheme makes it unnecessary to set any threshold for the photodetectors. Since the effect of the global variation of the incident illumination is reduced, the signal-to-noise ratio is in-

continued on p. 10

CROP photopolymers for hologram recording

continued from cover

100mJ/cm^2. These pre-imaging exposures consumed 50% and 75%, respectively, of the total dynamic range of the material. The dynamic range that remains afterwards is still sufficient for multiplex recording of many data holograms

Hologram multiplexing

Multiplexing many holograms in the same volume of recording material is necessary for high-capacity data storage. The number of usable holograms that can be multiplexed in the same sample volume is directly related to the recording material's maximum refractive index modulation, δn. A useful measure of δn is the cumulative grating strength parameter described by Pu, Curtis and Psaltis.[4]

They define the cumulative strength of a series of multiplexed gratings as the sum of the square root of the diffraction efficiency of each co-locationally recorded hologram. Figure 2 shows the growth in cumulative grating strength for 1050 plane-wave holograms recorded sequentially and co-locationally in a 200µm-thick CROP photopolymer formulation. The peristrophic multiplexing procedure of Curtis, Pu, and Psaltis was used in this experiment.[5]

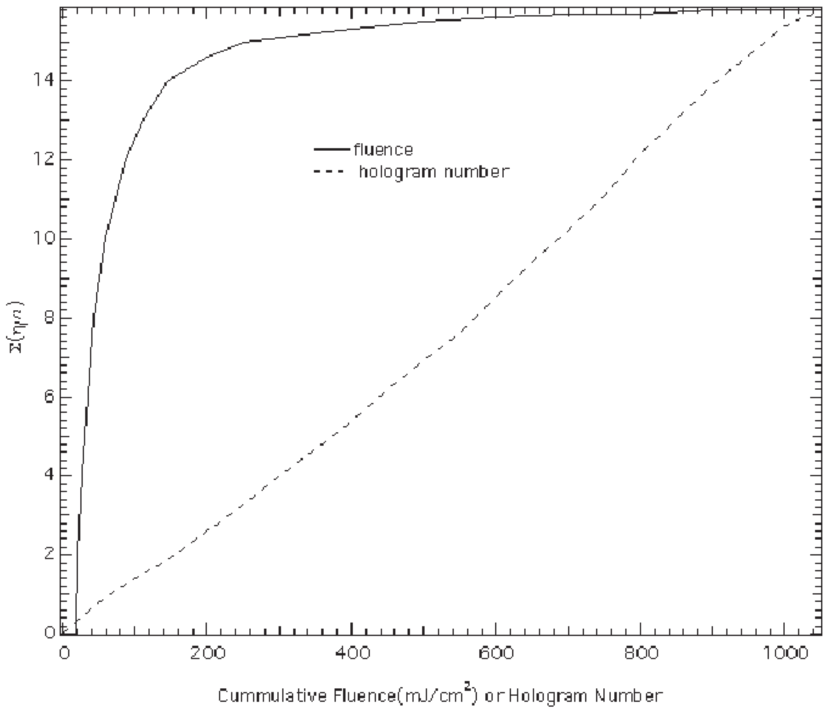


Figure 2. The cumulative grating strength, as defined in the text, is shown both as a function of the number of multiplexed plane-wave holograms, and as a function of the cumulative recording fluence. Peristrophic and angle multiplexing were combined. The recording material was a 200µm-thick CROP formulation. The pre-imaging exposure was 20mJ/cm^2, the recording irradiance was 4.85mW/cm^2, and a calculated exposure schedule was applied for the first 1000 holograms.

Data-page recording

Ingwall, Waldman, and Shelby[6] examined a Polaroid CROP photopolymer formulation using a specially designed and constructed holographic test bed located at the IBM Almaden Research Center.[7]

Multiplexing 70 holograms of 64kbit data pages was carried out in a 200µm-thick sample. The recorded data pages were reconstructed with raw bit-error-rates less than 10^{-4} throughout the multiplex run. More recently Orlov[8] has recorded megapixel (1024×1024) data-page holograms in a Polaroid CROP formulation. He was able to read the data at a rate of 750MB/sec.

Summary

Photopolymer systems have many characteristics that are required or useful for WORM holographic data storage. They can be made sensitive to light throughout the visible and into the near-infrared spectral region. Their high light sensitivity allows hologram recording with nanosecond range exposures and modest laser powers. For many, photopolymer image quality is limited by the shrinkage that accompanies recording. Substitution of cationic ring-opening monomers for the more common free-radical monomers reduces shrinkage significantly, and allows megapixel data pages to be recorded with good image fidelity.

Recording in relatively thick photopolymer samples of 500µm has been achieved and should allow recording data at area densities greater 100bits/µm^2. Both free-radical and CROP photopolymers are relatively inexpensive and can be easily incorporated into practical recording formats such as CD-style disks. Photopolymers are light and heat sensitive before recording and must be stored carefully. Data lifetime is expected to be very good, based on the chemical and physical durability of most fully-exposed photopolymers. For many systems, however, this expectation has not yet been tested.

Richard T. Ingwall and **David Waldman**
Aprilis, Inc.
750 Main Street
Cambridge, MA 02139
http://www.Aprilisinc.com

References

1. D.A. Waldman, R.T. Ingwall, P.K. Dhal, M.G. Horner, E.S. Kolb, H-Y.S. Li, R.A. Minns, and H.G. Schild, *Cationic ring-opening photopolymerization methods for holography*, **Proc. SPIE 2689,** pp. 127-141, 1996.
2. H. Kogelnik, *Coupled Wave Theory for Thick Hologram Gratings*, **Bell Syst. Tech. J. 48,** pp. 2909, 1969.
3. D.A. Waldman, H-Y.S. Li, and M.G. Horner, *Volume Shrinkage in Slant Fringe Gratings of a Cationic Ring-opening Volume Hologram Recording Material*, **J. Imaging Sci. Technol. 41,** 5, pp. 497-514, 1997.
4. A. Pu, K. Curtis, and D. Psaltis, Exposure schedule for multiplexing holograms in photopolymer films, **Opt. Eng. 35** (10), pp. 2824-2829, 1996.
5. K. Curtis, A. Pu, and D. Psaltis, *Method for holographic storage using peristrophic multiplexing*, **Optics Letters 19,** pp. 993-994, 1994.
6. R.T. Ingwall, D.A. Waldman, and R.M. Shelby, **Optical Society of America, Fall Meeting,** Baltimore, 1998.
7. M.-P. Bernal, H. Coufal, R.K. Grygier, J.A. Hoffnagle, C.M. Jefferson, R.M. Macfarlane, R.M. Shelby, G.T. Sincerbox, P. Wimmer, and G. Wittmann, *A precision tester for studies of holographic storage materials and recording physics*, **Applied Optics 35,** pp. 2360-2374, 1996.
8. S. Orlov, presented at **CLEO,** San Francisco, CA, May 8-12, 2000.

High-density, capacity

continued from p. 2

References

1. H.J. Coufal, D. Psaltis, and G. Sincerbox, editors, **Holographic Data Storage,** Springer-Verlag, 2000.
2. J. Ashley, M.-P. Bernal, G.W. Burr, H. Coufal, H. Guenther, J.A. Hoffnagle, C. M. Jefferson, B. Marcus, R.M. Macfarlane, R.M. Shelby, and G.T. Sincerbox, *Holographic data storage,* **IBM Journal of Research and Development 44** (3), pp. 341-368, 2000.
3. J.A. Hoffnagle and C.M. Jefferson, *Design and performance of a refractive optical system that converts a Gaussian to a flattop beam,* **Applied Optics 39** (30), pp. 5488-5499, 2000.
4. G.W. Burr, C.M. Jefferson, H. Coufal, M. Jurich, J.A. Hoffnagle, R.M. Macfarlane, and R.M. Shelby, *Volume holographic data storage at an areal density of 250 Gigapixels/in²,* submitted to **Optics Letters.**
5. G.W. Burr and T. Weiss, *Compensation of pixel misregistration in volume holographic data storage,* submitted to **Optics Letters.**
6. F. Ito, K.-I. Kitayama, and H. Oguri, *Compensation of Fiber Holographic Image Distortion Caused by Intrasignal Photorefractive Coupling by Using a PhaseConjugate Mirror,* **Optics Letters 17** (3), pp. 215-217, 1992.
7. F. Zhao and K. Sayano, *Compact Read-Only Memory with Lensless PhaseConjugate Holograms,* **Optics Letters 21** (16), pp. 1295-1297, 1996.
8. G.W. Burr and I. Leyva, *Multiplexed phase-conjugate holographic data storage using a buffer hologram,* **Optics Letters 25** (7), pp. 499-501, 2000.

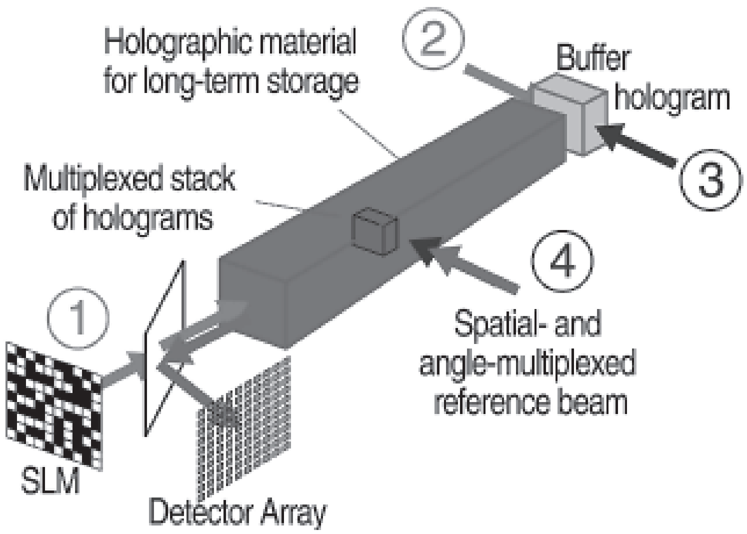


Figure 2. Phase-conjugate holographic storage system using a buffer hologram. A temporary buffer hologram is recorded by an object beam containing the data from the SLM (1) and a reference beam (2). This hologram is illuminated with a phase-conjugate beam (3), reconstructing the phase-conjugate of the original object beam, which is then stored permanently with a spatial- and angle-multiplexed reference beam (4).

Holographic data storage in disk-shaped recording media by combined use of peristrophic, angular, and spatial multiplexing

continued from p. 3

experiments.

Ju-Seog Jang
Division of Electronics, Computers, and Telecommunications
Pukyong National University
599-1 Daeyun-Dong, Nam-Gu
Pusan 608-737, Korea
E-mail: jsjang@jjlab.pknu.ac.kr
Phone: +82 51 620-6475
Fax: +82 51 620-6470

References

1. D. Psaltis and F. Mok, *Holographic memories,* **Sci. Am. 275** (11), pp. 52-58, 1995.
2. K. Curtis, A. Pu, and D. Psaltis, *Method for holographic storage using peristrophic multiplexing,* **Opt. Lett. 19** (13), pp. 993-994, 1994.
3. J.-S. Jang, D.-H. Shin, and Y.-S. Park, *Holographic data storage system by combined use of peristrophic, angular, and spatial multiplexing,* **Opt. Eng. 39** (11), 2000.

Post-processing to correct for optical distortion and material shrinkage in holographic data storage

continued from p. 4

Figure 2(a) shows the effect of approximately 0.01% lateral expansion on a 512×512 data page (as detected by a 4:1 oversampling detector using Aprilis CROP media[1,3] on the PRISM tester[1,2]); Figure 2(b) shows the same data page after post-processing with the shift-compensation algorithm.

We expect that this procedure can help relax—and with further improvement, completely remove—the tight constraints on page registration, optical distortion, and material shrinkage that currently hamper page-oriented holographic data storage systems.

Geoffrey W. Burr, Timo Weiss, and **Robert M. Shelby**
IBM Almaden Research Center
650 Harry Road
San Jose, CA 95120
Tel: 408/927-1512
Fax: 408/927-2100
E-mail: burr@almaden.ibm.com

References

1. H.J. Coufal, D. Psaltis, and G. Sincerbox, editors, **Holographic Data Storage,** Springer-Verlag, 2000.
2. J. Ashley, M.-P. Bernal, G.W. Burr, H. Coufal, H. Guenther, J. A. Hoffnagle, C. M. Jefferson, B. Marcus, R.M. Macfarlane, R.M. Shelby, and G.T. Sincerbox, *Holographic data storage,* **IBM Journal of Research and Development 44** (3), pp. 341-368, 2000.
3. R.M. Shelby, D.A. Waldman, and R.T. Ingwall, *Distortions in pixel-matched holographic data storage due to lateral dimensional change of photopolymer storage media,* **Optics Letters 25** (10), pp. 713-715, 2000.
4. J. Heanue, K. Gurkan, and L. Hesselink. *Signal detection for page-access optical memories with intersymbol interference,* **Applied Optics 35** (14), pp. 2431-2438, 1996.
5. V. Vadde and B.V.K. Vijaya Kumar, *Channel modeling and estimation for intrapage equalization in pixel-matched holographic data storage,* **Applied Optics 38** (20), pp. 4374-4386, 1999.
6. M.-P. Bernal, G.W. Burr, H. Coufal, and M. Quintanilla, *Balancing inter-pixel crosstalk and thermal noise to optimize areal density in holographic storage systems,* **Applied Optics 37** (23), pp. 5377-5385, 1998.
7. G.W. Burr and T. Weiss, *Compensation of pixel misregistration in volume holographic data storage,* submitted to **Optics Letters.**
8. G.W. Burr, C.M. Jefferson, H. Coufal, M. Jurich, J.A. Hoffnagle, R.M. Macfarlane, and R.M. Shelby, *Volume holographic data storage at an areal density of 250 Gigapixels/in²,* submitted to **Optics Letters.**

Photo-addressable polymers for holographic data storage

continued from back cover

like injection molding are accessible.

- Finally, the lateral resolution is very high because the photo-physical processes are purely based on molecular re-orientations.

To summarize, the physical properties of PAP materials, as well as the possibility of tailoring their properties by chemical modifications, make them a promising material for holographic storage applications.

To test the holographic recording features of PAP materials we designed some holographic grating experiments. PAP films with thicknesses ranging from 5 to 200µm exhibit volume phase holograms with large diffraction efficiencies of more than 90%.[6,7] To further demonstrate the feasibility in formats close to the technical requirements, we managed to prepare holographic discs with thicknesses of 1-2mm. This thickness range is necessary in order to write volume holograms with a high Bragg selectivity for angular multiplexing. As mentioned above, we changed the PAP's molecular structure in order to tailor it to the specific laser wavelength (532nm or 568nm). We used injection molding to produce the holographic sample discs. The low Bragg angle of $\Delta\theta \sim 0.2^\circ$ allowed us to write several hundreds of holographic gratings at the same 3×3 mm^2 area of the PAP sample in an angular multiplexing experiment (see Figure 2). The dynamic range of those PAP samples was in planewave experiments in the range of M/# = 2-5.

Holographic recording of two-dimensional data masks has been performed at the Almaden IBM Research Center. The hardware (IBM PRISM tester) is described in detail elsewhere.[1] We stored a 256kbit mask (512×512 pixel) and a megapel mask (1024×1024 pixel) as holograms in a PAP sample. The bit-error rate appeared to be very low: for the 256kbit mask it turned out to be in the range of 1.2×10^{-6}.

The described optical experiments prove that PAP materials have a high potential as photoactive storage media for a future holographic memories. Our current work focusses on a further increase of the light sensitivity by at least one order of magnitude.

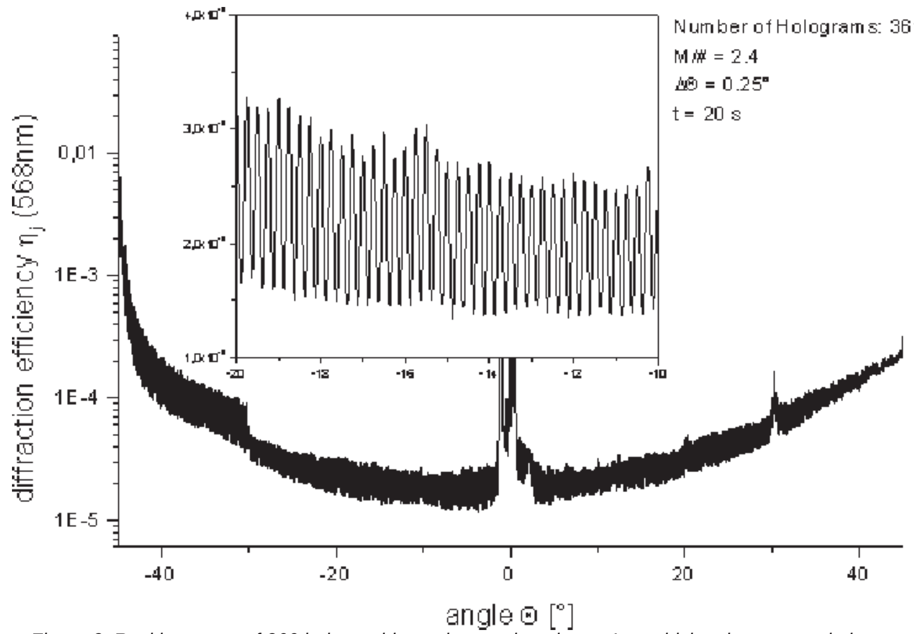


Figure 2. Rocking curve of 360 holographic gratings, written into a 1mm thick polymer sample by angular multiplexing. The sample was rotated by 0.25° between exposures. The illumination parameters for writing one holographic grating were: wavelength, 568nm; intensity, 100mW/cm^2; writing time, 20s.

The photo-addressable polymers were synthesized by Dr. Serguei Kostromine and Dr. H. Berneth (Bayer AG, Central Research Department, 51368 Leverkusen, Germany). Dr. Udo van Stevendaal and Lutz Glabasnia performed the optical screening tests and holographic grating experiments at Bayer. The authors thank the IBM HOST team, especially Dr. Hans Coufal and Dr. Robert Shelby (IBM Research Center, San Jose / California, USA) for performing the holographic experiments.

Dr. Rainer Hagen and **Dr. Thomas Bieringer**
Bayer AG
Central Research Department
D-51368 Leverkusen
Germany
Phone: +49 214 30-{28372, 56858}
E-mail: {rainer.hagen.rh,thomas.bieringer.tb}
@bayer-ag.de

References:

1. J. Ashley, M.-P. Bernal, G. W. Burr, and H. Coufal et al., **IBM J. Res. Develop. 44** (3), p. 341, May 2000.
2. S. Xie, A. Natansohn, and P. Rochon, **Chem. Mater. 5,** p. 403, 1995.
3. V. L. Colvin, R. G. Larson, A. L. Harris, and M. L. Schilling, **J. Appl. Phys. 81,** p. 5913, 1997.
4. K. Buse, A. Adibi, and D. Psaltis, **Nature 393** (6686), p. 665, 1998.
5. M. Eich, J. H. Wendorff, B. Reck, and H. Ringsdorf, **Makromol. Chem. Rapid Commun. 8,** p. 59, 1987.
6. S. Hvilsted, F. Andruzzi, and P.S. Ramanujam, **Opt. Lett. 17,** p. 1234, 1992.
7. A. Natansohn, P. Rochon, J. Gosselin, and S. Xie, **Macromolecules 25,** p. 2268, 1992.
8. U. Wiesner, N. Reynolds, C. Boeffel, and H. W. Spiess, **Liq. Cryst. 11,** p. 251, 1992.
9. S. Hvilsted, F. Andruzzi, C. Kulinna, H.W. Siesler, and P.S. Ramanujam, **Macromolecules 28,** p. 2172, 1995.
10. D.Y. Kim, L. Li, J. Kumar, and S.K. Tripathy, **Appl. Phys. Lett. 66,** p. 1166, 1995.
11. V. Shibaev, S. Kostromine, S. Ivanov, L. Lasker, T. Fisher, and J. Stumpe, **Macromol. Symp. '96,** p. 157, 1995.
12. T. Bieringer, R. Wuttke, D. Haarer, U. Geßner, and J. Rübner**, Macromol. Chem. Phys. 196,** p. 1375, 1995.
13. S. J. Zilker, T. Bieringer, D. Haarer, R.S. Stein, and J.W. van Egmond, S.G. Kostromine, **Adv. Mater. 10,** p. 885, 1998.
14. J. Eickmans, T. Bieringer, S. Kostromine, H. Berneth, and R. Thoma, **ISOM, Technical Digest,** p. 184, Tsukuba, Japan, 1998.
15. S. Zilker, M. R. Huber, T. Bieringer, and D. Haarer, **Appl. Phys. B 68,** p. 893, 1999.
16. V. Cimrová, D. Neher, S. Kostromine, and T. Bieringer, **Macromolecules 32**(25), p. 8496, 1999.
17. J. Eickmans, T. Bieringer, S. Kostromine, H. Berneth and R. Thoma, **Japanese J. Appl. Phys. 38,** p. 1835, 1999.

Bulk photopolymer with negligible shrinkage for holographic memory

continued from p. 5

compensate for the saturating effect in typical photopolymers and produce holograms of almost equal diffraction efficiency.

After recording, the data pages contained in the 250 holograms could be reconstructed completely at every recording angle. The diffraction efficiency of each hologram was around 1.5×10^{-4}. The original transmitted image and one of the reconstructed images are shown in the upper row of Figure 2. The plots on the lower row show the gray-level distribution along an arbitrary horizontal line on each image. It is seen that the reconstructed image has almost the same fidelity as the original transmitted image. The result demonstrates that the shrinkage effect is almost negligible in this 1cm-thick sample.

In order to measure the M/#, we have performed a peristrophically multiplexed holographic storage experiment: 355 plane wave holograms were recorded, each with equal exposure energy (~8mJ/cm^2). The diffraction efficiency of each hologram was measured, and the square roots of the measured diffraction efficiencies were summed up to obtain the M/# value. Figure 3 shows the M/# of our photopolymer as a function of the sample thickness. As shown in the figure, the M/# increases linearly with the thickness of the polymer sample. For a 8mm-thick polymer, the M/# is as large as 14. Based on this value, if the diffraction efficiency of each hologram can achieve 4×10^{-6},[1] then the total number of pages that can be recorded at a single spot can be estimated to be 7000. This suggests that our PQ-doped PMMA polymer can be very useful for large capacity holographic data storage.

In summary, we have made a new PQ:PMMA photopolymer. The shrinkage effect in this thick material is so small, and the optical quality of the bulk polymer is so good, that the material should be very attractive for holographic data storage.

Shiuan Huei Lin and **Ken Y. Hsu**
Institute of Electro-Optical Engineering,
National Chiao Tung University
Hsin-Chu, 30050
Taiwan
E-mail: ken@cc.nctu.edu.tw

References:

1. D. Psaltis and G.W. Burr, *Holographic data storage,* **IEEE Computer 52,** pp. 412, 1998.
2. X. Yi, P. Yeh, and C. Gu, *Crosstalk in volume holographic memory,* **Proc. IEEE 87,** pp.1912-1930, 1999.
3. G.J. Steckman, I. Solomatine, G. Zhou, and D. Psaltis, *Characterization of phenanthrenequinone-doped poly(methyl methacrylate) for holographic memory,* **Opt. Lett., Vol. 23**, pp.1310-1312, 1998.
4. S.H. Lin, K.Y. Hsu, W.Z. Chen, and W.T. Whang, *PQ:PMMA photopolymer bulk for volume holographic data storage,* **Opt. Lett., Vol. 25** 7, pp. 451-453, 2000.

Optically programmable gate array

continued from p. 6

creased and therefore the bit-error rate (BER) is improved. From the optics point of view, this type of data representation is simple and does not increase the system cost.

By time multi-plexing the hardware resources, the fast configuration properties of the OPGA allow it to solve problems in pattern recognition and database searching more efficiently.

Jose Mumbru and **George Panotopoulos**
Department of Electrical Engineering
California Institute of Technology
MC 136-93, Pasadena, CA 91125
Phone: 626/395-3888
Fax: 626/568-8437
E-mail: {jmumbru, gpano}
@sunoptics.caltech.edu
http://optics.caltech.edu

References:

1. J. Mumbru, G. Zhou, S. Ay, X. An, G. Panotopoulos, F. Mok, and D. Psaltis, *Optically Reconfigurable Processors,* **SPIE Proc. CR74,** pp. 265-288, June 1999.
2. J. Mumbru, G. Panotopoulos, D. Psaltis, X. An, F. Mok, S. Ay, S. Barna, and E. Fossum, *Optically Programmable Gate Array,* **SPIE Proc. of Optics in Computing 2000,** Vol. 4089, p. 763-771, May 2000.

Calendar

2001

Photonics West
20-26 January
San Jose Convention Center
San Jose, California USA
Including international symposia on:

- **LASE ’01—High-Power Lasers and Applications**
- **OPTOELECTRONICS ’01—Integrated Devices and Applications**
- **BiOS ’01—International Biomedical Optics Symposium**
- **SPIE/IS&T’s EI ’01—Electronic Imaging: Science and Technology.**

Education Program and Short Courses;
Technical Exhibit: 20-21, 23-25 January

Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing
4-8 March
Newport Beach, California USA
Technical Exhibit: 6-7 March

Correlation Optics
10-13 May
Chernivtsi, Ukraine
Sponsored by SPIE/UKRAINE and SPIE/RUS. SPIE to publish Proceedings. Contact: Edmund Akopov, SPIE/RUS, 12 Mokhovaja Str., Moscow, Russia 121019. Phone/fax: 095/202 1079. E-mail: edmund@spierus. msk.su

Complex Adaptive Optics
3-6 June
Hutchinson Island Marriott Beach Resort & Marina
Florida

SID Symposium
3-8 June
San Jose, California USA
Contact: Society for Information Display, 1526 Brookhollow Dr., Ste. 82, Santa Ana, CA 927055421 USA. Phone: (1) 714/545-1526. Fax: (1) 714/545-1547. E-mail: socforinfodisplay@mcimail.com. Web: www.sid.org

For more information contact
SPIE • PO Box 10,
Bellingham, WA 98227-0010
Phone (1) 360/676-3290
Fax (1) 360 647-1445 • E-mail spie@spie.org
Web www.spie.org

Join the Technical Group

...and receive this newsletter

Membership Application

Please Print ☐ Prof. ☐ Dr. ☐ Mr. ☐ Miss ☐ Mrs. ☐ Ms.

First Name, Middle Initial, Last Name ______________________________

Position ____________________ SPIE Member Number ____________________

Business Affiliation ______________________________

Dept./Bldg./Mail Stop/etc. ______________________________

Street Address or P.O. Box ______________________________

City/State ____________________ Zip/Postal Code __________ Country __________

Telephone ____________________ Telefax ____________________

E-mail Address/Network ______________________________

Technical Group Membership fee is $30/year, or $15/year for full SPIE members.

❑ Holography
Total amount enclosed for Technical Group membership $ __________

❑ **Check enclosed.** Payment in U.S. dollars (by draft on a U.S. bank, or international money order) is required. Do not send currency. Transfers from banks must include a copy of the transfer order.

❑ **Charge to my:** ❑ VISA ❑ MasterCard ❑ American Express ❑ Diners Club ❑ Discover

Account # ____________________ Expiration date ____________________

Signature ______________________________
(required for credit card orders)

This newsletter is printed as a benefit of membership in the **Holography Technical Group.** Technical group membership allows you to communicate and network with colleagues worldwide.

Technical group member benefits include a semi-annual copy of the *Holography* newsletter, SPIE's monthly publication, *OE Magazine*, membership directory, and discounts on SPIE conferences and short courses, books, and other selected publications related to Holography.

SPIE members are invited to join for the reduced fee of $15. If you are not a member of SPIE, the annual membership fee of $30 will cover all technical group membership services. For complete information and an application form, contact SPIE.

Send a copy of this form to:
SPIE • P.O. Box 10
Bellingham, WA 98227-0010 USA
Phone: (1) 360/676-3290
Fax: (1) 360/647-1445
E-mail: spie@spie.org
Anonymous FTP: spie.org

Please send me

☐ Information about full SPIE membership
☐ Information about other SPIE technical groups
☐ FREE technical publications catalog

Reference Code: 2447

HOLOGRAPHYONLINE

New Holography Web Discussion Forum launched

You are invited to participate in SPIE's new online discussion forum on Holography. The **INFO-Holography** mailing list is being "retired" as we move the discussions to the more full-featured web forums. We hope you will participate. To post a message, log in to create a user account. For options see `"subscribe to this forum."`

You'll find our forums well-designed and easy to use, with many helpful features such as automated email notifications, easy-to-follow "threads," and searchability. There is a full FAQ for more details on how to use the forums.

Main link to the new Holography forum: `http://spie.org/app/forums/tech/`

Related questions or suggestions can be sent to `forums@spie.org`.

SPIE The International Society for Optical Engineering

Holography

This newsletter is published semi-annually by SPIE—The International Society for Optical Engineering for its International Technical Group on Holography.

Technical Group Chair	Michael Klug	*Managing Editor*	Linda DeLano
Technical Editor	Sunny Bains	*Advertising Sales*	Roy Overstreet

Articles in this newsletter do not necessarily constitute endorsement or the opinions of the editors or SPIE. Advertising and copy are subject to acceptance by the editors.

SPIE is an international technical society dedicated to advancing engineering, scientific, and commercial applications of optical, photonic, imaging, electronic, and optoelectronic technologies. Its members are engineers, scientists, and users interested in the development and reduction to practice of these technologies. SPIE provides the means for communicating new developments and applications information to the engineering, scientific, and user communities through its publications, symposia, education programs, and online electronic information services.

SPIE—The International Society for Optical Engineering, P.O. Box 10, Bellingham, WA 98227-0010 USA. Phone: (1) 360/676-3290. Fax: (1) 360/647-1445.

European Office: Contact SPIE International Headquarters.

In Japan: c/o O.T.O. Research Corp., Takeuchi Bldg. 1-34-12 Takatanobaba, Shinjuku-ku, Tokyo 160, Japan. Phone: (81 3) 3208-7821. Fax: (81 3) 3200-2889. E-mail: otoresco@gol.com

In Russia/FSU: 12, Mokhovaja str., 121019, Moscow, Russia. Phone/Fax: (095) 202-1079. E-mail: edmund@spierus.msk.su.

Want it published?

Submit work, information, or announcements for publication in future issues of this newsletter by e-mail to Sunny Bains. For full submission information, length and format required, deadline, etc., please go to: **http://www.sunnybains.com/newslet.html.** All materials are subject to approval and may be edited. Please include the name and e-mail address of someone who can answer technical questions. Calendar listings should be sent at least eight months prior to the event.

Photo-addressable polymers for holographic data storage

Thanks to the "information age," the demand for fast data transfer and high storage capacity is rapidly growing. Accordingly, the data-storage technologies must be improved to meet future requirements. One promising new optical technology is based on volume holographic data storage. Recent progress has been made in the development of the hardware for holographic data storage devices, enabled by lower-cost components[1] and new storage materials.[2] Despite the progress reported in recent years, however, there is so far no holographic storage material available that meets all technical requirements. Photopolymers seem to be the most suitable holographic medium for write-once-read-many (WORM) applications.[3] However, in rewritable (R/W) laboratory demonstrations,[4] photorefractive crystals like iron-doped lithium niobate ($LiNbO_3$) are generally used. Here, we present a class of organic materials, so-called photo-addressable polymers[5-10] (PAP), that we actually tailor to meet the requirements for a R/W, volume-holographic, data storage device.

PAP materials are side-chain copolymers functionalized with photoactive azobenzene dye molecules and liquid-crystalline side groups, called chromophores and mesogens, respectively (see Figure 1).[11-17] Light-induced isomerization cycles of the azobenzene molecule lead to a reorientation of its transition dipole into a direction perpendicular to the polarization vector of the actinic light. Starting from an isotropic molecular configuration, irradiation with linearly-polarized light results in an uniaxial re-orientation of the long axis of the chromophores. The task of the mesogens is to follow the re-orientation of the chromophores (co-operative effect) and to stabilize and amplify the new configuration (enhancement effect). As a result of the molecular re-orientation, the material becomes birefringent with an optical axis parallel to the polarization direction.

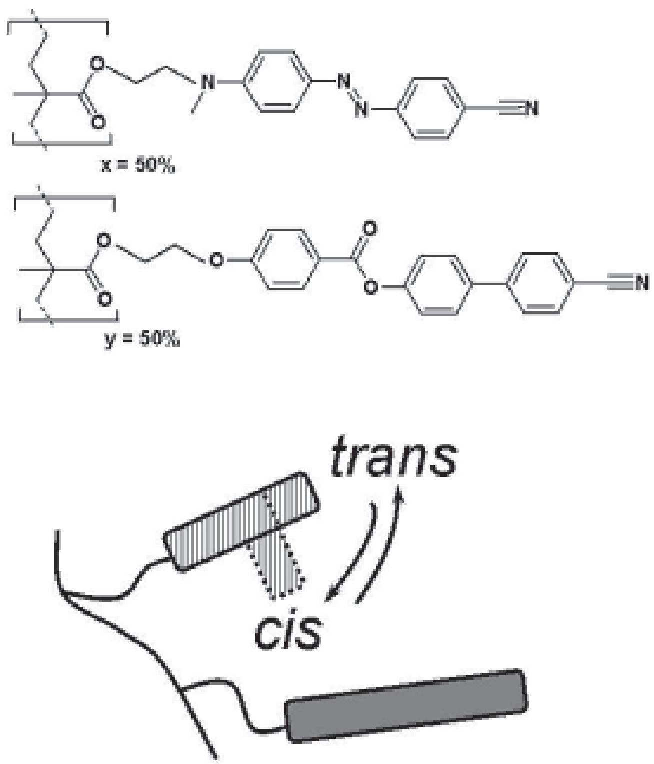


Figure 1. Top: chemical structure of a typical photo-addressable polymer (PAP). The shorter molecule with concentration x is an azobenzene chromophore, the longer molecule with concentration y is a mesogen. Bottom: the chromophore undergoes light-induced isomerization cycles between the trans and the cis state. The mesogen is not photoactive but will follow the chromophore orientation due to steric or dipolar interaction.

PAP materials are optimized with regard to an effective coupling between all sidegroup molecules. This has two consequences:

- PAP materials exhibit very large light-induced birefringence values (Δn). In thin films, Δn can reach values larger than 0.5. This promises high dynamic ranges for PAP storage layers which are basic for holographic multiplexing techniques.
- The temporal and thermal stability is excellent: we measured stable Δn values at temperatures up to 160˚C and storage at room temperature over one year, which underlines the excellent archival properties.

Besides these two features, PAP materials fulfill further main requirements for rewritable storage media, namely:

- The rewritability is guaranteed in principle by the reversible molecular orientation processes: After any change in the polarization direction of the actinic light, the optical axis of the polymer will switch accordingly.
- There was no evidence for any shrinkage of the PAP materials in holographic storage experiments.
- PAP materials are amorphous at operating temperatures. The amorphous phase allows a high optical quality which is a key characteristic for any holographic application. The weighting between chromophore-substituted and mesogen-substituted monomer units is balanced in such a way that the polymers exhibit a (weak) liquid-crystalline phase transition in calorimetric experiments at high temperatures but are frozen-in amorphously below the glass transition temperature T_g (T_g ~ 120˚C).
- Large bulk samples are easy to prepare from these amorphous polymers.

Widely used low-cost preparation methods

continues on p. 9

SPIE Society of Photo-Optical Instrumentation Engineers

P.O. Box 10 • Bellingham, WA 98227-0010 USA

Change Service Requested

DATED MATERIAL

Non-Profit Org.
U.S. Postage Paid
Society of
Photo-Optical
Instrumentation
Engineers