Holographic 3D disks using shift multiplexing

George Barbastathis†, Allen Pu†, Michael Levene‡, and Demetri Psaltis†

† Department of Electrical Engineering
‡ Department of Computation and Neural Systems
California Institute of Technology, MS 116–81, Pasadena, CA 91125
e-mail: {george,allenpu,levene,psaltis}@sunoptics.caltech.edu

ABSTRACT

Holographic techniques and materials have matured sufficiently to allow high capacity in practical systems. We demonstrate a holographic memory with storage density of 10 bits/μm^2. Novel techniques, such as shift multiplexing, can be used to attain even higher capacity with simpler implementation.

Keywords: holographic storage, holographic 3D disks, angle multiplexing, peristrophic multiplexing, shift multiplexing, surface storage density.

1 INTRODUCTION

A holographic 3D disk[1,2] consists of a disk–shaped holographic medium and a recording/ read–out head. The head moves in the radial direction while the disk rotates to allow access to any location on its surface. Methods for storing multiple holograms at each location using a plane wave reference include angle,[3] wavelength,[4,5] phase–code[6] and peristrophic[7] multiplexing. The maximum number of holograms that can be stored over the same location is determined by the Bragg selectivity,[8,2] the geometry, the apertures of the optics, and the dynamic range of the holographic material.

An angle multiplexed disk is shown in Fig. 1. The multiplexing mechanism consists of a beam steerer implemented by a mirror and an imaging system that allows the reference beam to illuminate the disk surface at a range of angles. The beam steerer is incorporated in the disk head along with the spatial light modulator (SLM), CCD camera (used to capture the reconstructions), and passive optical components.

The surface density of conventional optical memories (approximately 1 bit/μm^2) is determined primarily by the size of the illuminating spot. The density of optical CD's will likely increase by an order of magnitude by the end of the decade through the use of shorter wavelength lasers, super-resolution methods,[9] and 3D stacks of recording media.[10] Holographic storage technology will become competitive if the density yielded by holographic disks can exceed the projected density of conventional media by a comfortable margin. To a first approximation, the density of a holographic disk is given by:

$$D_{\mathrm{3D}} = M \times D_{\mathrm{2D}} \tag{1}$$

where D_{3D} and D_{2D} are the surface densities achievable with a 3-D and 2-D medium, respectively, and M is the

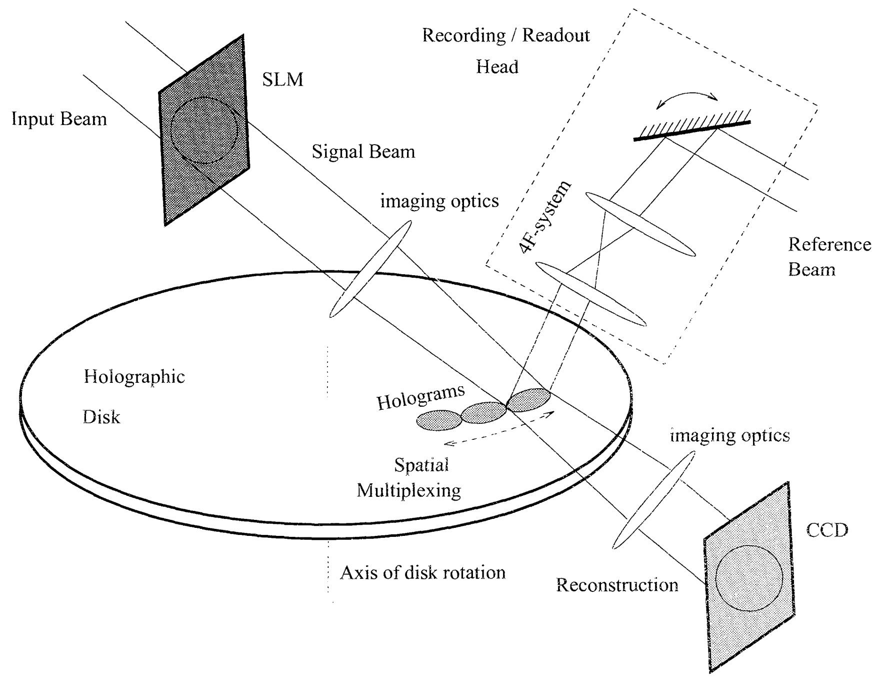

Figure 1: Holographic 3D Disk with Angle Multiplexing.

number of multiplexed holograms.

Equation (1) assumes that the resolution achievable by the optics used in CD's is also available to holographic systems. This is in principle possible, but can be difficult to achieve in practice, since holograms are imaged in the form of pages rather than bit–by–bit. Thus the resolution of the CD lens must be preserved throughout the whole area of the signal imaging lens of Fig. 1. In our experiments we do not yet reach the theoretical upper limit of (1), due to limitations of the available optics.

Limiting factors on the number of holograms M are the volume holographic selectivity, the geometry of the holographic setup, and the dynamic range of the holographic material. The geometrical limitations can be eased by combining two or more multiplexing methods, for example angle and peristrophic. Recently we demonstrated storage density $D_{3D} = 10$ bits/μm^2 in 100 μm thick photopolymer using this method. The results of this experiment together with a discussion of practical issues pertinent to high density holographic storage will be given in Section 2. In Section 3 we will discuss a new storage method, shift multiplexing,[11] that also helps avoiding complications in the geometry and mechanical design of holographic 3D disks.

Once the restrictions arising from the geometry and the resolution have been overcome, the last limitation comes from the available diffraction efficiency η, i.e. the fraction of read–out power diffracted from the hologram and hence available for detection of the information. For most materials, η falls off as $1/M^2$ with M, the number of holograms stored. Therefore M has to be kept low enough for the minimum diffracted power to be detectable. Finally, some noise sources such as cross–talk increase with M. In a practical system, the storage density is maximized by optimizing the optical design while monitoring the signal–to–noise ratio of the reconstructed holograms.

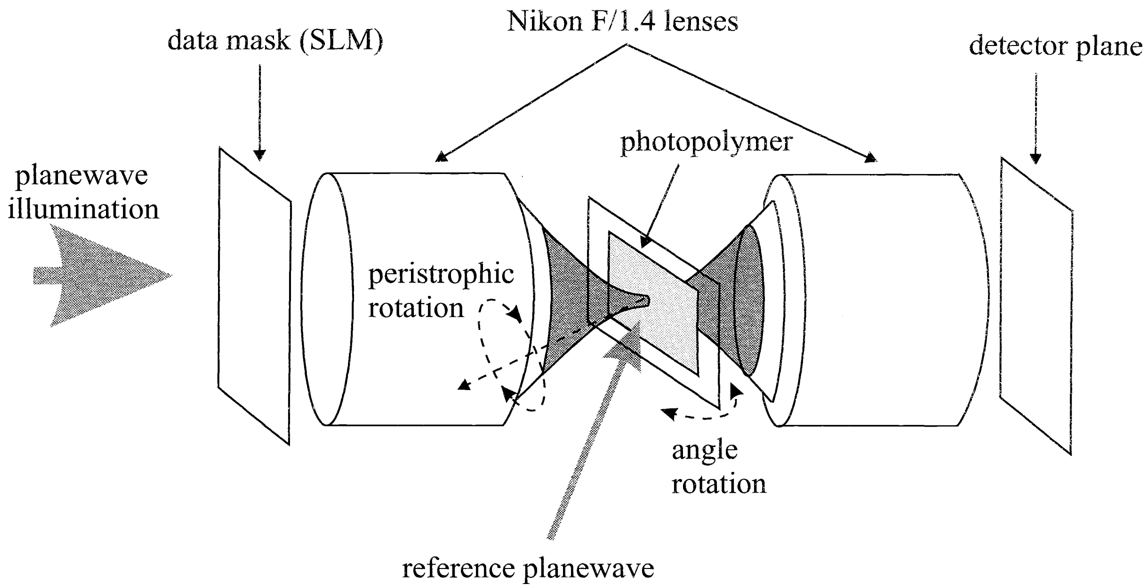

Figure 2: Experimental setup used for the demonstration of 10 bits/μm^2 in photopolymer film.

2 HOLOGRAPHIC STORAGE IN PHOTOPOLYMERS

Photopolymer films are promising materials for holographic read–only memories. We used DuPont's HRF–150–100 photopolymer[12] for demonstration of high storage density. This material has thickness $L = 100$ μm, which limits the number of Bragg resolvable gratings that can be recorded. Compared to photorefractive materials, also popular in holographic storage experiments, the photopolymer lacks an axis of preference for the grating direction (this adds flexibility in the storage geometry), it does not have erasure effects (so that holograms can be retrieved long after storage with minimal degradation), and has excellent optical quality.

A diagram of the experimental setup used to demonstrate 10 bits/μm^2 is shown in Figure 2. A glass mask of a random binary bit pattern served as the input SLM. The center-to-center spacing of the pixels was 45 microns and the fill factor was 100%. Nikon F/# 1.4, 4 cm aperture camera lenses were used for imaging. A total of 590,000 pixels fit in the apertures of the two Nikon lenses and a sharp image of the entire field was obtained at the CCD plane. The holograms were recorded with a plane reference beam approximately .5 mm past the Fourier transform plane. At that position, the diameter of the signal beam was 1.5 mm and its spatial uniformity was much better than at the exact Fourier plane.

The diffraction efficiency of a hologram as a function of the incidence angle of the reference beam is a sinc function[8,2] centered at the angle at which the hologram was recorded. For the 100 μm thick recording medium, the angular separation to the first null of the sinc function was approximately .7° in our setup. In order to minimize cross–talk between holograms, we used angular separation of 2.5°. This allowed 8 angular locations to fit in the optics we used. Angle multiplexing was achieved by rotating the film instead of changing the reference beam angle.

Peristrophic multiplexing[7] was used together with angular multiplexing in order to multiplex even more holograms on the same location. Specifically, sets of 8 angularly multiplexed holograms were recorded at 4 different peristrophic positions. Each peristrophic position corresponds to a different rotational angle of the

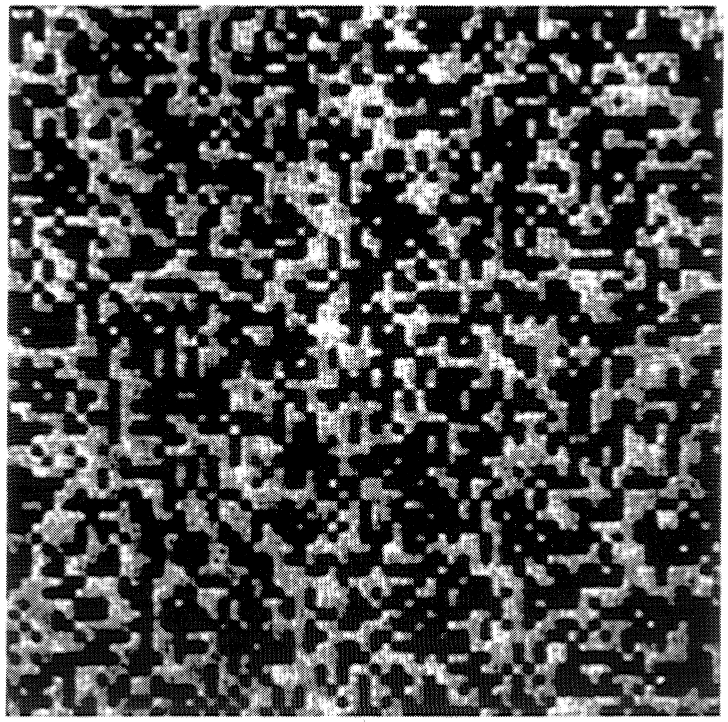

Figure 3: Sample reconstruction from the 10 bits/μm^2 experiment.

recording medium around the axis perpendicular to the surface of the medium. Using this combined angle/peristrophic method, we stored a total of 32 holograms at a single location. One of the 32 reconstructions is shown in Figure 3. The surface density of each hologram is 590,000 bits $/(\pi \times .75 \times .75 \text{ mm}^2)$ which equals .334 bits/μm^2. Since 32 holograms are superimposed in the same region, the overall surface density is $32 \times .334 = 10.68$ bits/μm^2.

The density of the current system can be further improved by using lower F/# lenses (higher resolution and density per page), reducing the angular separation between holograms, and increasing the range of angles over which holograms can be recorded. In addition, large gains in density are obtained by using thicker recording media, although issues like disk stability and optical quality may be of concern.

Holographic 3D disks are subjected to many sources of noise such as cross–talk between holograms, lens aberrations, scattering from the material and surface imperfections, multiple reflections, noise from the SLM, laser noise, and index aberrations induced by the recording of previous holograms. An additional source of errors in the reconstructions is the shrinkage of the photopolymer material sustained during recording. Shrinkage alters the Bragg matching condition making it difficult to read–out entire holograms. We have studied in detail many of these sources of noise and we minimized them with a proper setup. We sampled 9 different 65×65 pixel windows from the stored holograms and we detected no errors in the reconstructions. The combined histogram from the 9 different sampled windows is shown in Figure 4. It is likely that there were no errors in any of the 32 stored holograms even though we did not check all the stored data. The bit error rate for the system we demonstrated was 10^{-4}, obtained by fitting a χ^2 distribution with 1 degree of freedom to the histogram of Figure 4. It is reasonable to expect further decrease in the error rate by further improving the design of the optical setup.

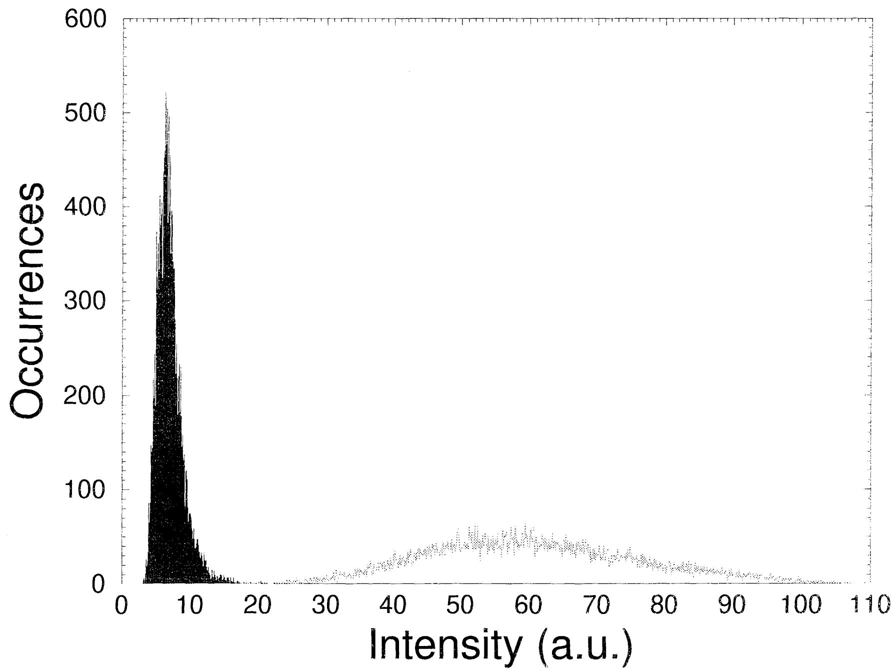

Figure 4: Composite histograms of reconstructed intensities for the dark (black) and bright (gray) pixels. Data are shown for reconstructions of 9 holograms out of 32 from the 10 bits/μm^2 experiment.

3 SHIFT–MULTIPLEXED HOLOGRAPHIC 3D DISKS

3.1 Shift multiplexing

In the previous section we saw that holographic materials such as photopolymers have sufficient dynamic range and optical quality to yield high storage density write–once read–many (WORM) memories. The implementation of a working holographic storage system using the combination of angle and peristrophic multiplexing is straightforward, but it does present some design challenges. One of them is the implementation of the motion of the beams (i.e. of the beam steerer) in a compact and robust fashion. In addition, since spatially multiplexed locations are at least a few millimeters apart, the disk motion must occur in abrupt jumps; this requires very careful motor design in order to avoid drift and subsequent loss of accuracy. Alternatively, continuous disk motion can be implemented but at the cost of using a high power pulsed laser source for read–out.

Shift multiplexing[11] is a new holographic storage method that eliminates some of these problems. Instead of changing the reference beam angle, holograms are superimposed at one location simply by a small relative shift of the recording medium with respect to the readout head. Therefore there is no need for motion inside the disk head; shift occurs as a result of disk rotation, which is implemented naturally by the mechanical motion incorporated in current optical memory systems.

The design of a shift multiplexed holographic disk[13] is shown in Fig. 5. The reference is a spherical wave produced by a high numerical aperture objective lens, coming to a focus distance z' (measured in air) from the

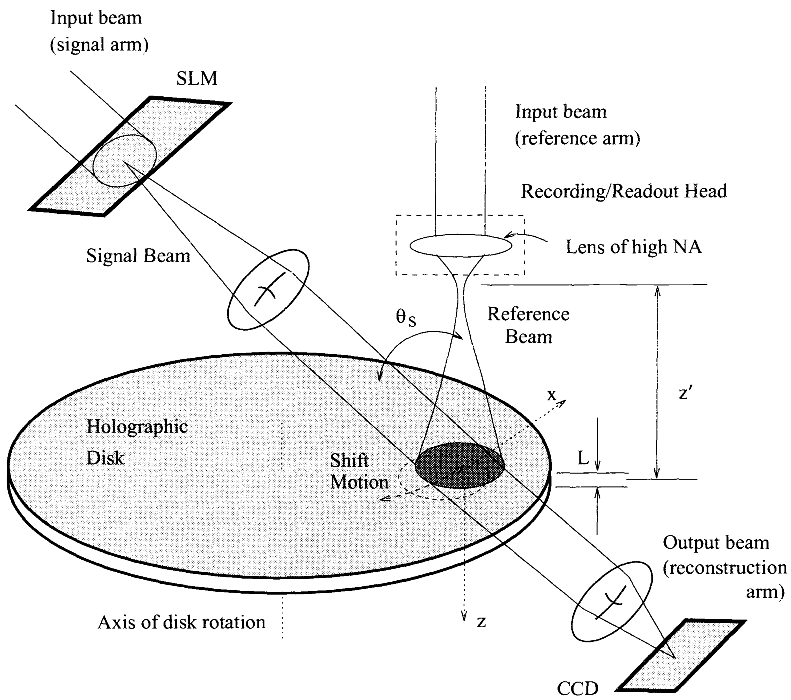

Figure 5: Holographic 3D Disk with Shift Multiplexing.

center of the disk. The CCD camera captures the reconstruction that occurs when the reference exactly coincides with the hologram. Multiplexing is performed utilizing disk rotation only. This is equivalent to a shift of the hologram being reconstructed with respect to the stationary illuminating reference beam. A relative shift of a few microns (i.e. much smaller than hologram lengths, typically a few millimeters) causes the reconstruction to vanish allowing a new hologram to be recorded in the shifted position.

Alternatively, the reference can be a fan of plane waves converging towards the hologram (array method[11]); then the shift selectivity effect is a result of destructive phase interference. In this paper we will discuss the spherical wave implementation only.

Shift selectivity is a Bragg mismatch effect related to the curvature of the spherical wavefront. Consider the case of a spherical reference wave of angular spread Θ, originating a distance z_0 with respect to the recording material of thickness L (for simplicity we neglect refraction effects in this analysis), as in Fig. 6. A relative shift δ between the hologram and the reference produces an angular deviation, proportional to δ, in the direction of propagation of the reconstruction with respect to the original signal incidence angle θ_S. Therefore the reconstruction gradually becomes Bragg mismatched and eventually vanishes when the shift becomes equal to the shift selectivity

$$\delta = \frac{z_0 \lambda}{L \tan\theta_S} + \frac{1}{2}\frac{\lambda}{\sin\Theta} \tag{2}$$

New holograms can be stored after shifting by δ or its integer multiples $\delta_{\mathrm{m}} = m\delta$. For parameters typical to polymers (refractive index $n = 1.525$), $L = 100\ \mu$m, $\theta_S = 40°$, $z' = 2$ mm, $\Theta = 36.9°$ (numerical aperture 0.6) we obtain $\delta = 21.22\ \mu$m. Photorefractive crystals, such as $LiNbO_3$ (refractive index $n = 2.24$), can have thicknesses up to several centimeters. Using $L = 5$ mm and $z' = 1$ cm yields $\delta = 3.21\ \mu$m.

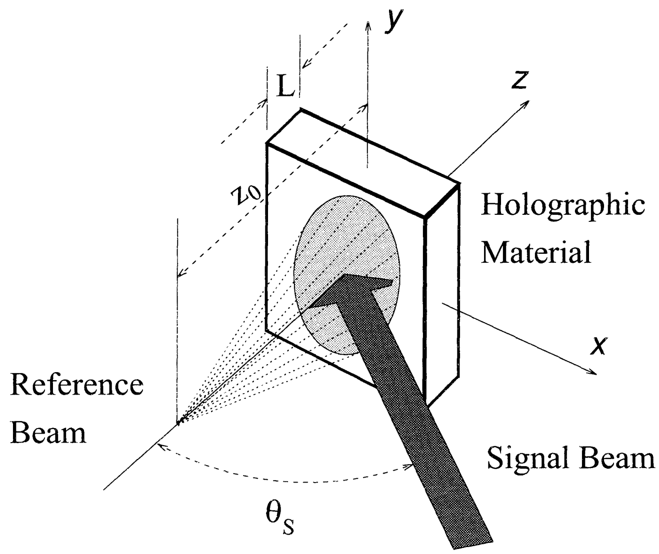

Figure 6: Geometry for Shift Multiplexing using a spherical wave reference.

3.2 Design issues

As in the case of angle and peristrophic multiplexing, issues important for the design of a holographic disk system are the choice of material, the noise performance, and the storage density. Photopolymer has already been used to demonstrate high storage density in a read–only memory (Section 2). On the other hand, photorefractive crystals can be used for rewrittable storage. $LiNbO_3$ has been used for storage of 10,000 angle–multiplexed holograms.[14] Either of these materials can be used for the implementation of shift multiplexed memories.

The noise performance of shift multiplexing along the x direction (Fig. 6) is equivalent to that of angle multiplexing. A theoretical calculation shows that the cross–talk properties are exactly the same for the two methods. Usually crosstalk is quite high if the holograms are separated by δ (one Bragg null), but drops to an acceptable level if 2δ is used instead. In practice, the quality and aperture of the spherical wave are important for shift multiplexing, while for thick media hologram non–uniformity (caused by the intensity variation in the reference beam) may also become a limiting factor.

The storage density for a shift multiplexed disk is determined from (1) where M is the number of overlapping shift multiplexed holograms, given by the ratio of the page length (measured along the x direction) by the shift selectivity δ. As an example, we use the $L = 100\ \mu$m thick photopolymer with the page configuration used in the experiment of Section 2. We have $\delta = 21.22\ \mu$m, and $M \approx 46$ (using the second Bragg null when multiplexing holograms); because the signal is tilted, D_{2D} drops to 0.256 bits/μm^2, hence $D_{3D} = 46 \times 0.256 = 11.8$ bits/μm^2. The expected diffraction efficiency is $\eta \approx 10^{-2}$, well within the range of comfortable detection. Therefore shift multiplexing would allow us to achieve a slight increase in the density in our current setup without compromising the reliability of the reconstructions.

4 CONCLUSIONS

In conclusion, we have demonstrated a high capacity angle and peristrophic multiplexed holographic disk with parallel readout and low bit error rate. The new method of shift multiplexing is promising for the next generation of holographic disk memories. With this method, the implementation is simpler and more robust, while higher densities can be achieved.

5 ACKNOWLEDGMENTS

This research was supported by the Air Force Office of Scientific Research. We thank Fai H. Mok and Geoffrey W. Burr for helpful discussions, and Yayun Liu for technical assistance.

6 REFERENCES

[1] H.-Y. S. Li and D. Psaltis. "Three dimensional holographic disks". *Appl. Opt.*, 33(17):3764–3774, June 1994.

[2] Hsin-Yu Sidney Li. *"Holographic 3D Disks for optical data storage and artificial neural networks"*. PhD thesis, California Institute of Technology, 1994.

[3] D. L. Staebler, J. J. Amodei, and W. Philips. "Multiple storage of thick holograms in $LiNbO_3$". In *VII International Quantum Electronics Conference*, Montreal, May 1972.

[4] G. A. Rakuljic, V. Levya, and A. Yariv. "Optical data storage by using orthogonal wavelength–multiplexed volume holograms". *Optics Letters*, 17(20):1471–1473, 1992.

[5] S. Yin, H. Zhou, F. Zhao, M. Wen, Y. Zang, J. Zhang, and F. T. S. Yu. "Wavelength–multiplexed holographic storage in a sensitive photorefractive crystal using a visible–light tunable diode–laser". *Optics Communications*, 101(5-6):317–321, 1993.

[6] C. Denz, G. Pauliat, and G. Roosen. "Volume hologram multiplexing using a deterministic phase encoding method". *Optics Communications*, 85:171–176, 1991.

[7] K. Curtis, A. Pu, and D. Psaltis. "Method for holographic storage using peristrophic multiplexing". *Optics Letters*, 19(13):993–994, 1994.

[8] H. Kogelnik. "Coupled wave theory for thick hologram gratings". *Bell System Technical Journal*, 48(9):2909–2947, November 1969.

[9] S. M. Mansfield and G. S. Kino. "Solid immersion microscope". *Appl. Phys. Let.*, 57(24):2615–2616, 1990.

[10] K. A. Rubin, H. J. Rosen, W. W. Tang, W. Imaino, and T. C. Strand. "Multilevel volumetric optical storage". *SPIE Proc. Opt. Data Storage*, 2338, 1994.

[11] D. Psaltis, M. Levene, A.Pu, G. Barbastathis, and K.Curtis. "Holographic storage using shift multiplexing". *Optics Letters*, 20(7):782–784, April 1995.

[12] K. Curtis and D. Psaltis. "Characterization of the Du-Pont photopolymer for 3-dimensional holographic storage". *Applied Optics*, 33(23):5396–5399, 1994.

[13] A.Pu, G.Barbastathis, M.Levene, and D. Psaltis. "Shift-multiplexed holographic 3D disk". In *1995 OSA Spring Topical Meeting on Optical Computing*, Salt Lake City, 1995.

[14] F. H. Mok, G. W. Burr, and D. Psaltis. "Angle and space multiplexed random access memory (HRAM)". *Optical Memory and Neural Networks*, 3(2):119–127, 1994.