

# High density holographic storage in thin films

Allen Pu, Kevin Curtis and Demetri Psaltis

California Institute of Technology,  
Department of Electrical Engineering  
MS 116-81, Pasadena, CA 91125.

## ABSTRACT

We have recently developed a new method of multiplexing volume holograms which we call peristrophic multiplexing. The method involves rotating the material, or equivalently, the recording beams. Peristrophic multiplexing can be combined with other multiplexing methods to increase the storage density of holographic storage systems such as holographic 3-D disks. Peristrophic multiplexing has been experimentally demonstrated using DuPont's HRF-150 photopolymer film. A total of 295 holograms were multiplexed at a single location in a 38  $\mu\text{m}$  thick photopolymer disk by combining peristrophic multiplexing with conventional angle multiplexing. Application of this new multiplexing method toward a 3-D holographic disk is discussed.

## 1. INTRODUCTION

Various spatially multiplexed holographic architectures have been demonstrated<sup>1, 2, 3</sup>. Recently, thin film materials have been developed that are inexpensive, easy to use and which have a relatively large dynamic range, making them good candidates for high density data storage. An example of this material is DuPont's HRF-150-38 photopolymer film<sup>4, 5</sup>. The density of a holographic storage system is limited by two parameters - system bandwidth (either temporal or spatial frequency) and material dynamic range. Because of their relatively large dynamic range and limited thickness, the storage density of DuPont's films is limited primarily by the required system bandwidth. This paper describes a method of multiplexing holograms that alleviates the bandwidth-limited density problem, and therefore increases the storage density of thin films.

## 2. PERISTROPHIC MULTIPLEXING

Peristrophic multiplexing<sup>6</sup> is a solution to this bandwidth-limited capacity problem. With this method, the hologram is physically rotated about an axis of rotation perpendicular to the film's surface every time a new hologram is stored (as shown in Figure 1). Alternatively, the recording beams can be non-mechanically rotated to achieve the same effect. The rotation shifts the reconstructed image off the detector while simultaneously the stored hologram becomes non-Bragg matched. Both effects allow for additional holograms to be stored at the same location. For image pixel sizes larger than  $\sim 2$  microns, using a typical setup for the HRF-150-38 photopolymer, the reconstructed image will shift off the detector first. This process repeats until a rotation angle of  $180^\circ$  is reached, at which point further holograms would be degenerate with the initial holograms.

We experimentally demonstrated peristrophic multiplexing using a setup that is similar to Figure 1, except a second rotation stage was added to rotate the film around the y-axis as well as around the film's normal. This made it possible to combine peristrophic and angle multiplexing. The film was located a significant distance from the Fourier plane, in order to provide a more uniform signal beam. For each peristrophic position, multiple holograms were stored using standard angle multiplexing by rotating the medium around the y-axis. A spatial light modulator (SLM) was used to present images (high resolution cartoons) to the system. The reference and signal beams were initially incident at  $\pm 30^\circ$  from the film's normal. The film was rotated in-plane by  $3^\circ$  between each set of angle multiplexed holograms which allowed the other holograms to be spatially filtered out at the detector plane. Each angle

multiplexed hologram was also separated by  $3^\circ$ . 295 holograms were stored in the  $38\ \mu\text{m}$  thick polymer film by peristrophic multiplexing 59 times and storing 5 angle multiplexed holograms at each peristrophic rotation. The diffraction efficiency for these 295 holograms is shown in Figure 2. The average diffraction efficiency is better than  $10^{-6}$ , with most of the variation due to the input cartoon scenes.

Our previous results on multiplexing holograms in DuPont films<sup>5</sup> were limited to  $\sim 10$  holograms due to the angular bandwidth limit. Thus, peristrophic multiplexing allowed for more than an order of magnitude increase in the storage capacity of the DuPont photopolymer and changed the limiting factor from the angular bandwidth of the optical system to the dynamic range of the material.

### 3. RECORDING SCHEDULE

With the dramatic increase in the number of holograms that can be stored at a single location by using peristrophic multiplexing, the optimal utilization of the available dynamic range of the photopolymer becomes more important. Figure 3(a) shows the cumulative grating strength as a function of exposure energy for DuPont's HRF-150-38 photopolymer. From the figure, it can be seen that the photopolymer is fairly insensitive for the first  $6\ \text{mJ}/\text{cm}^2$ . The cumulative grating strength then grows quasi-linearly with exposure energy and eventually saturates. To multiplex uniform diffraction efficiency holograms at the same location, it is necessary to divide the available grating strength equally among the holograms. We can fit Figure 3(a) to a mathematical model and extract the necessary recording schedule for equal grating strength holograms, given the desired number of holograms. Figure 3(b) shows the recording schedule computed for 50 holograms, with a  $6\ \text{mJ}/\text{cm}^2$  pre-exposure to sensitize the material. Figure 3(c) shows the diffraction efficiency as a function of hologram number that results by using the recording schedule shown in Figure 3(b). From the figure, it can be seen that the grating strength is uniformly distributed among the 50 holograms.

In applications such as holographic data storage, it is important to have uniform diffraction efficiency holograms to improve the overall signal-to-noise ratio. The method described above can be used to determine the required recording schedule for such applications.

### 4. 3-D HOLOGRAPHIC DISK

To take advantage of the higher storage density offered by peristrophic multiplexing, a 3-D holographic disk can be constructed as shown in Figure 4. The information to be recorded is presented by a spatial light modulator which modulates the signal beam. The reference beam then interferes with the signal beam and the information is recorded throughout the volume of the storage medium where the two beams overlap. The surface density is increased by using angle multiplexing to record multiple holograms in the same volume. To further increase the storage density, the reference beam is also rotated about the signal beam to implement peristrophic multiplexing. The storage capacity of the entire system is expanded by rotating the storage medium to record at non-overlapping regions on the disk (spatial multiplexing). Theoretical prediction of the surface density<sup>2</sup> is around  $20\ \text{bits}/\mu\text{m}^2$  and  $50\ \text{bits}/\mu\text{m}^2$  for  $38\ \mu\text{m}$  and  $100\ \mu\text{m}$  thick photopolymers, respectively. This translates into a system capacity of 200 Gbits per 5.25 inch 3-D holographic disk using  $38\ \mu\text{m}$  thick photopolymer.

### 5. ACKNOWLEDGMENTS

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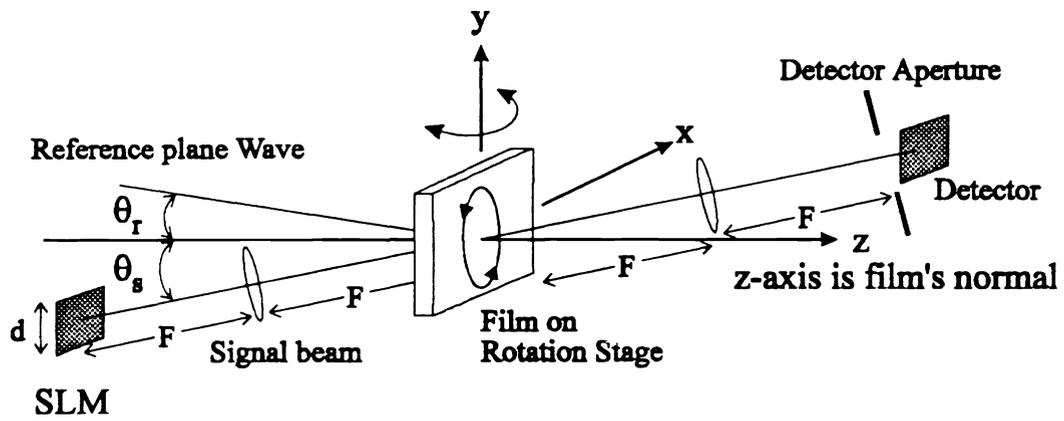


Figure 1. Setup for peristrophic multiplexing.

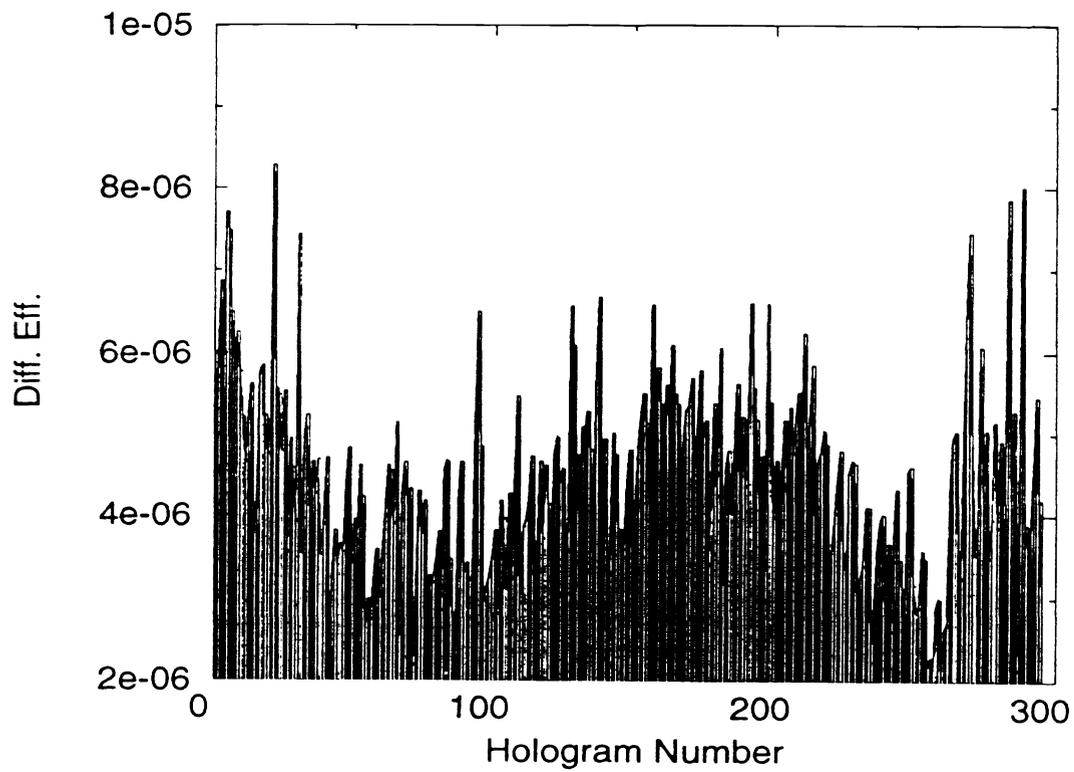


Figure 2. Diffraction efficiency of 295 holograms.

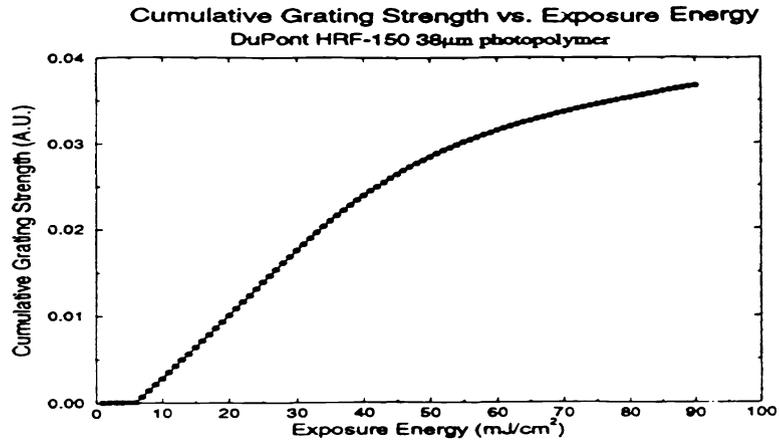


Figure 3(a). Cumulative grating strength as a function of exposure energy.

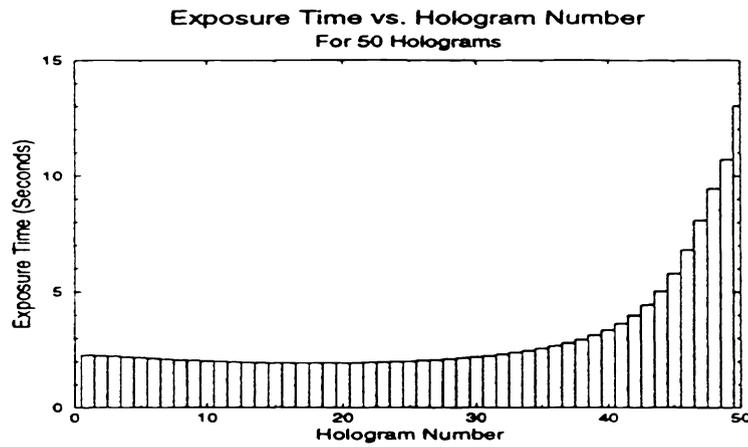


Figure 3(b). Exposure schedule for 50 holograms (Total incident power  $\sim 500 \mu\text{W}/\text{cm}^2$ ).

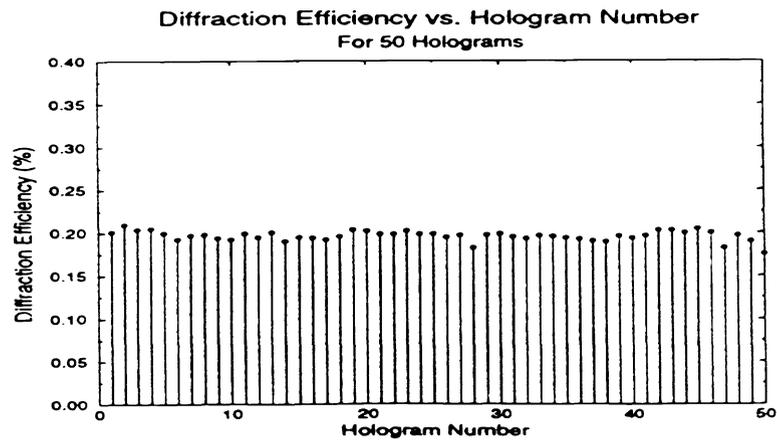


Figure 3(c). Diffraction efficiency of 50 holograms recorded with a schedule.

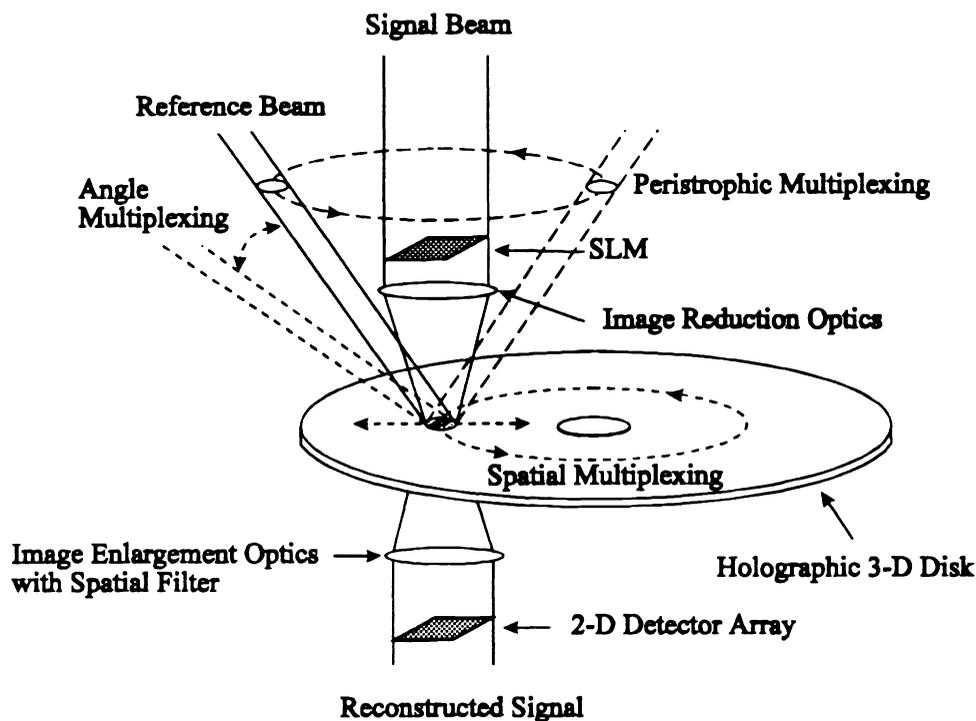


Figure 4. 3-D holographic disk system using both angle and peristrophic multiplexing.

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