1402 OPTICS LETTERS / Vol. 29, No. 12 / June 15, 2004

# Polytopic multiplexing

**Ken Anderson and Kevin Curtis**

*InPhase Technologies, 2000 Pike Road, Longmont, Colorado 80501*

Received February 19, 2004

Polytopic multiplexing is a new method of overlapping holograms that, when combined with other multiplexing techniques, can increase the capacity of a volume holographic data storage system by more than a factor of 10. This is because the method makes possible the effective utilization of thick media. An experimental demonstration of this technique is also presented. © 2004 Optical Society of America

*OCIS codes:* 210.2860, 090.4220, 090.7330, 070.6020, 210.4680.

Recent advances in holographic storage materials have made possible the development of commercial volume holographic storage devices.[1] In the past, media performance factors such as dynamic range ($M\#$), shrinkage, poor optical quality, and insufficient thickness limited the demonstration of a practical device well before the system performance limitations could be reached. Although many multiplexing techniques, such as the angle, wavelength, correlation,[2] shift,[3] and peristrophic[4] techniques, have been presented through the years, no one method or combination of methods offers a robust implementation and very high density simultaneously. Here we present a new method, polytopic multiplexing,[5] that makes possible a significant increase in storage capacity. We present the theoretical implications and an experimental demonstration of this technique.

Angle multiplexing, for example, is a simple method that provides many advantages with regard to speed, media interchangeability, and environmental robustness. Unfortunately, angle multiplexing has a limited achievable capacity[6] of ~200 Gbytes for a 5.25-in. disk recorded with 407-nm light. This limitation arises from the fact that gains from increasing the media thickness are eventually negated by the increase in surface area on the media occupied by a single book of multiplexed holograms. The larger area of a book results in fewer books that can be placed within a given media area.

Volume holographic system densities are limited mainly by three factors. The geometric limit relates to the size of the holograms and the geometric limits on multiplexing a number of holograms in volume of material. Cross-talk noise can be another important consideration. As holograms are made smaller there is more intrapage cross-talk noise generated, and as more holograms are multiplexed the system will see more interpage cross talk. The other major limitation is the dynamic range of the media. As is well known, the diffraction efficiency of a hologram drops as $1/M^2$, where $M$ is the number of holograms that are multiplexed in the same volume. The diffraction efficiency must be higher than other sources of noise such as scatter for the data in the hologram to be recovered. Polytopic multiplexing directly addresses the geometric limits of a volume holographic system and, for thick media, can improve the dynamic range limitations as well.

Polytopic multiplexing allows for books of multiplexed holograms to overlap in the media. This results in higher achievable geometric densities with smaller books than when the books do not overlap. Reference 7 showed books of angle-multiplexed holograms overlapping, but this was accomplished by limiting the reference angle of each book so that the reference angles were unique for each overlapped book. This significantly decreases the available angles or number of holograms that can be stored in a book, and thus this method does not increase the achievable geometric density of the holographic system. Polytopic multiplexing allows for the books of holograms to overlap without decreasing the usable angular sweep (i.e., the number of holograms) that can be multiplexed in each book.

An example of one particular implementation of polytopic (Greek for "many places") multiplexing is shown in Figs. 1 and 2. Figure 1A shows the traditional angle-multiplexed approach, in which the books are spatially separated. The area of the book is much larger than the signal beam waist as the beam expands in the media and the reference beam sweeps in angle. Figure 1B shows the polytopic-angle

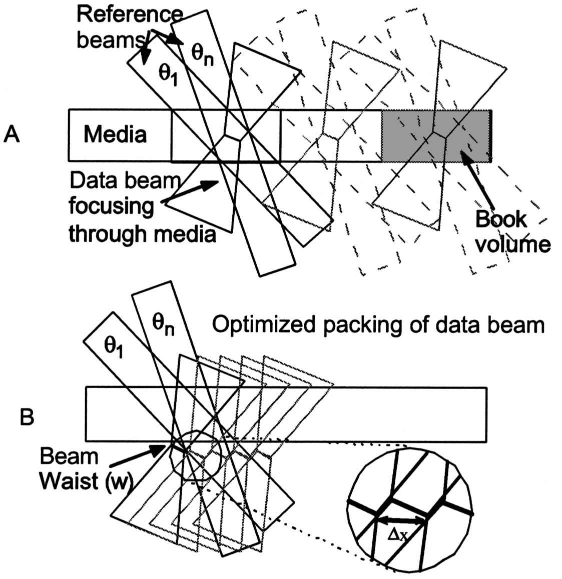

Fig. 1. Illustration of the packing density increase by using polytopic multiplexing, B, over traditional angle multiplexing, A.

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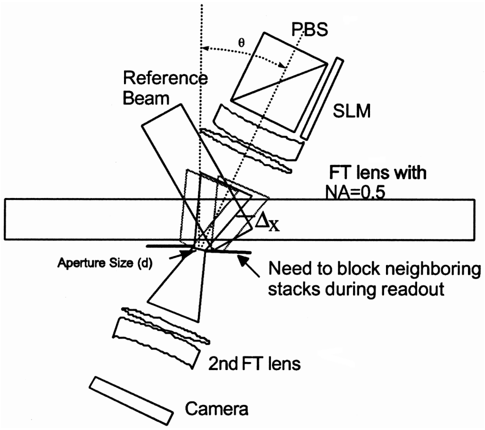

Fig. 2. Illustration of the polytopic multiplexing system.

approach, in which the books (recorded by the signal and the reference beams shown in the figure) overlap in the media. Note that the books overlap in the media, but the signal beams' waists (shown outside the media) do not overlap. Figure 2 illustrates a setup for reading and writing polytopic-angle-multiplexed pages into the media. A laser beam is collimated and sent through a polarizing beam splitter (PBS) and onto a spatial light modulator (SLM), where a binary data pattern is modulated onto the beam. The modulated beam is then focused through a layer of the holographic media by a Fourier transform (FT) lens onto an aperture located on the other side of the media. The beam propagates through a second FT lens and is then imaged onto a camera. As the data beam is focused through the media, a collimated reference beam at a chosen angle interferes with the data beam inside the media, causing the interference pattern to be recorded. Neighboring books of holograms are subsequently recorded by simply moving the media by an amount equal to $\Delta x = d\cos(\theta) + d\sin(\theta)\tan(\theta + \alpha)$, where $d$ is the Fourier plane aperture size, $\theta$ is the data beam center angle, and $\alpha = \sin^{-1}$ (numerical aperture of the FT lens). Moving by $\Delta x$ is required to ensure that the Fourier plane of neighboring holograms does not overlap. On readout with the reference beam, the desired page and several of its neighbors are simultaneously reconstructed. However, the physical aperture blocks holograms from neighboring undesired books as they are reconstructed, and only the page from the desired book is allowed to propagate to the camera and be detected. This allows the books to be separated by the Fourier plane width of the data beam as opposed to the maximum width of the beam at the surface of the media. This can similarly be done for image plane holograms as well with the aperture located at an image plane. The aperture is sized to produce the optimal signal-to-noise ratio performance[8] and density. For FT plane holograms this is usually a bit larger than the Nyquist area, $(\lambda f/\Delta)^2$, of the signal, where $\lambda$ is the wavelength, $f$ is the focal length of the lens, and $\Delta$ is the pixel pitch of the SLM.

The signal beam waist does not have to be outside the media for the polytopic filter to be implemented. Another option is to use an optical relay system to image the aperture into the media. For thick media this is particularly important so that the media's dynamic range ($M\#$) requirement is not dramatically increased. Imaging the aperture can result in usage of the media similar to that obtained with traditional separated angle-multiplexed books.

A comparison of disk user capacity for a 5.25-in. disk for angle multiplexing versus angle plus polytopic multiplexing is shown in Fig. 3. Polytopic multiplexing permits user capacities greater than 1.5 Tbytes for a 2.0-mm-thick 5.25-in. disk (~15% of theoretical geometric capacity). Capacity for the polytopic-angle case is reduced to

$$\text{capacity} = \frac{\Delta^2 MANR}{\alpha^2 \lambda^2 f^2},$$

where $M$ is the number of holograms in a book calculated as in Ref. 6, $A$ is the area of the disk, $N$ is the number of pixels per page, $R$ is the overhead rate, and $\alpha$ is the linear Nyquist scaling dimension, where $\alpha = 1$ represents the Nyquist aperture. Both curves in Fig. 3 are calculated with the analysis from Ref. 6, in which the data beam is normal to the media, $\alpha = 1$, $F/\# = 1$, the reference beam sweep is 30–65° from normal, $R = 1/2$, $N = 1{,}048{,}576$, and $\lambda = 407$ nm. Note that for angle multiplexing alone the capacity saturates at 150 Gbytes with a material thickness of 800 $\mu$m. By making possible the efficient use of thick media, polytopic multiplexing produces a factor-of-10 increase in capacity. Capacity will then be limited by the dynamic range of the media. For example, Fig. 3 also shows an estimate of achievable capacity (aperture relayed inside the media) with a material that has an $M\#$ of 6 per 200 $\mu$m and a system that requires diffraction efficiencies greater than $5 \times 10^{-5}$. This curve approaches an 870-Gbyte user capacity at 2-mm material thickness. A higher $M\#$ (more efficiency) and (or) a more sensitive detector (lower efficiency required) are needed to increase capacity beyond this value.

Polytopic multiplexing was experimentally demonstrated with a 532-nm laser by recording nine

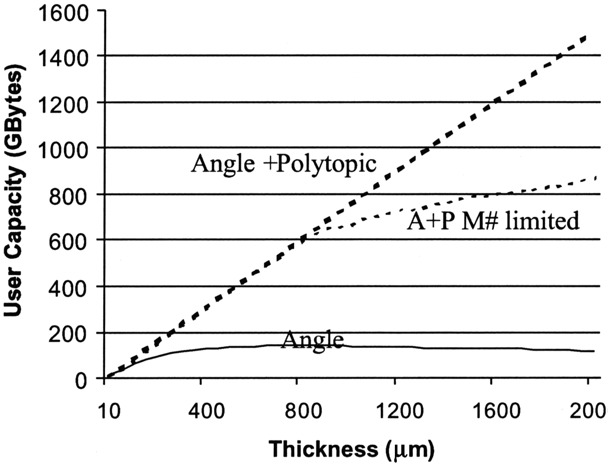

Fig. 3. Comparison of angle and polytopic-angle multiplexing as a function of media thickness.

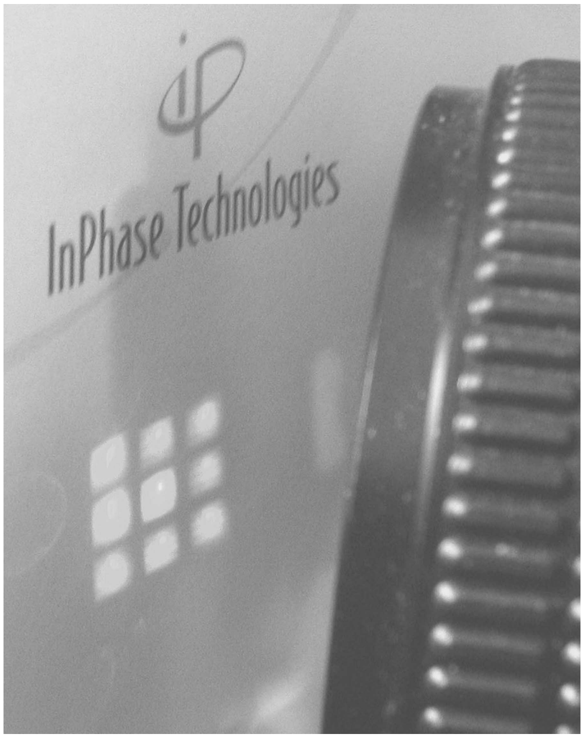

Fig. 4. Picture of the filter plane showing reconstructions from all neighboring books.

overlapping books in a 3 × 3 grid in a 1-mm-thick medium. Each book had ten angle-multiplexed pages with a beam waist area of 1.2 times the Nyquist area (0.9 mm × 1 mm for the system used). The effective overlap factor is 1.8, and thus diffraction efficiency would go as $1/18^2$ versus $1/10^2$ if the books were not overlapping. The object path is 15° from normal ($\theta$), and the recording reference beams are centered at 45° from normal (60° between beams). The SLM's higher orders were filtered out before recording. The reconstructed FT plane holograms were first imaged by a $4F$ system (focal length 18 mm/N.A. 0.5 and 80 mm) to the polytopic filter plane and then another FT lens (focal length 80 mm) transforms the desired reconstruction onto a camera. Figure 4 is a picture of the filter plane when reading out a (1280 × 1024 pixel data page with 12-$\mu$m pixel pitch) hologram from the center book. Holograms from all nine books are reconstructed and are incident upon the filter plane. The aperture in the filter just passes the center reconstruction. Without the aperture, the noise from the undesired reconstructions completely swamps the signal from the desired hologram (signal-to-noise ratio $-25$ dB). With the polytopic aperture in the system, a high-quality reconstruction of the desired page is obtained at the camera (signal-to-noise ratio $>5$ dB).

Polytopic multiplexing significantly enhances the storage capacity of many complementary holographic multiplexing techniques. In this Letter we have presented a polytopic-angle-multiplexed system that increases the system's addressable locations by a factor of 10 over the number of addressable locations for an angle-multiplexed system. In polytopic-angle multiplexing, fewer angle-multiplexed holograms are required for a given capacity and, for thick media, can improve the usage of the media dynamic range.

InPhase gratefully acknowledges the support of the Department of Commerce Advance Technology Program award. K. Curtis's e-mail address is kevincurtis@inphase-tech.com.

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