High speed holographic data storage at 500 Gbit/in.^{2}

By Ken Anderson, Edeline Fotheringham, Adrian Hill, Bradley Sissom, and Kevin Curtis

A holographic system is presented, along with experimental results that demonstrate data densities of 500 Gbit/in.^{2} with a write user rate of 23 MBytes/s and a read user rate of 13 MBytes/s.

Holographic storage has long promised high density and fast transfer rate storage. Simultaneously achieving high write transfer rate, read transfer rate and high data density has been difficult due to both system and media limitations. Density must be shown over large enough areas of media to completely eliminate overlap issues in order for the density to translate into high capacities[1]. For high numerical aperture (N.A.) systems with media thicker than several hundred microns this typically requires storing thousands of holograms. High density and fast write times both contribute to lower diffraction efficiency, which conflicts with fast readout rates without using expensive and unpractical lasers. For the first time, a practical holographic storage system with a commercially realizable photopolymer media will be described that achieves all three parameters simultaneously.

The combination of angle and polytopic multiplexing[2] with a phase conjugate architecture achieves a high-performance compact system. Using InPhase's Tapestry™ blue media with a 1.5 mm thick recording layer, 500 Gb/in.^{2} was demonstrated by multiplexing 6720 holograms in 21 books with 320 pages of data per book. Each data page contains 146,918 bytes of data as well as additional pixels for servo and page ID. Using a Sony laser (52 mW at 407 nm) the average record and readout periods per page were 3.1 ms and 5.4 ms respectively, resulting in 23 MBytes/s user write and 13 MBytes/s user read rates with a channel rate of one half.

System architecture

By using phase conjugate readout as described in reference[3], a high performance system can be achieved. This architecture offers the following advantages: higher N.A. optics can be used because design requirements are relaxed, polytopic and Nyquist filtering of the signal can also be easily implemented, and almost all optics and electronics can be on the same side of the media.

Polytopic multiplexing[2] allows for books to overlap by filtering at the data beam waist.

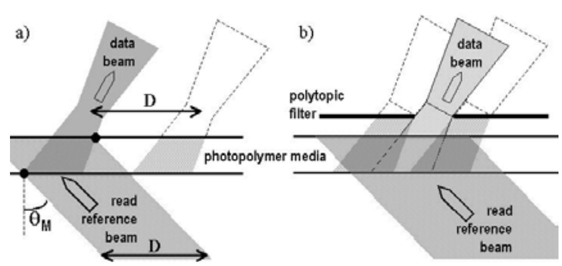

Fig. 1. a) Book spacing without a polytopic filter b) Overlap of books with a polytopic filter.

Figure 1 (a) illustrates the traditional minimum book spacing D in the recording media to avoid simultaneous readout of holograms in neighboring books. This distance D depends on the largest incident angle of the reference beam θ_M needed to cover the data beam and increases with media thickness. With a polytopic filter in place (Fig. 1 (b)), neighboring data beams are spatially distinct only in the region of their waists. This configuration leaves no volume in the media without data although it introduces overlap complexity in the writing stage. The size of the filter is solely determined by the signal's spatial bandwidth. In practice, this filter is relayed into the media with lenses.[2,3] Using lenses with higher numerical aperture reduces the imaged size of the polytopic filter. This in turn reduces the minimum book spacing, thus increasing the achievable density.

Layout of holograms

Photopolymer materials' photosensitivities decrease with M# consumption. Partially overlapping holograms can write stronger gratings in less exposed media resulting in variable diffraction efficiency across the page, which results in a loss of decodability. One solution,[4] consists of recording data in layers of non-overlapping books of holograms so that every book "sees" a uniform consumption of the M# everywhere in the media. Each layer of books is shifted from previous ones by at least one polytopic dimension in the plane of the media.

Accurate demonstrations of bit densities must show writing and recovery of at least one book overlapped by all the neighboring books that *can* overlap it in the media.[1] For better density and readout speed, all holograms are recorded at the same diffraction efficiency. The holograms in the different layers are recorded with fixed intensity and varying exposure times. The schedule is specific to the media chemistry, the number of holograms per book and the number of layers.

The full density demonstration records one book in the highest-level layer with all of its neighbors in that layer, plus all of the books needed to complete the layers underneath it. Letting b_x and b_y represent the books' largest dimensions in the media, and p_x and p_y represent the projected polytopic filter dimensions in the media (Fig. 2 (a)), the maximum number of recordable uniform layers is $(b_x/p_x)x(b_y/p_y)$. In the experiments the first ratio is 2 and the second ratio is 1, therefore requiring holograms from 2 different layers to show maximum density. The number of books laid down in this experiment is 21. Figure 2b illustrates the layout of the 21 books of holograms in 2 different layers.

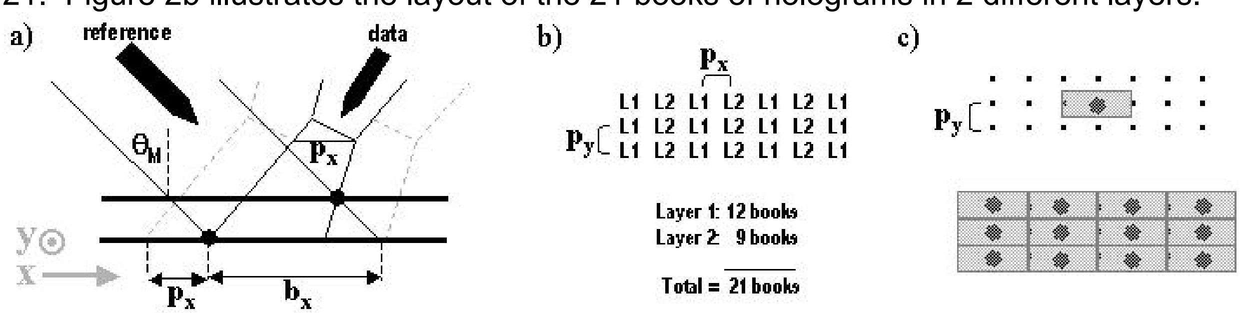

Fig. 2. a) bx is the dimension of a book in the media and px is the projected size of the polytopic filter in the media. b) Spatial positions of the books' centers in the experiment c) Footprint of a book (top) and footprint of all the books in layer 1 (bottom) relative to all the laid down books' centers (small dots).

Experimental setup

Figure 3 shows a schematic of the experimental test bed. A Sony laser provides 52 mW of light at 407 nm. A mechanical shutter controls exposure timing. The beam is spatially filtered, magnified, and split into the data path and the reference path during the recording stage. For readout, all the light flows into the reference path. The expanded data beam illuminates a reflection S.L.M. (1,175, 344 pixels, 16.5 mm diagonal). Lens DL1 and DL2 relay its image with the filtering plane in between. Lens DL3 (NA of 0.6, f=13.8mm) focuses the data beam into the media at a 25-degree incident angle. DL2 and DL3 demagnify the polytopic aperture (x1.16 the Nyquist area) down to 0.49 mm by 0.49 mm. Projecting these dimensions onto the media results in p_x=0.67 mm and p_y=0.49 mm. The media form factor is a 2.9 mm thick disk (two 0.7 mm glass substrates). In the reference paths, two rotating mirrors Rm on both sides of the disk provide the two degrees of freedom necessary to angle and position the reference beam over the data beam.

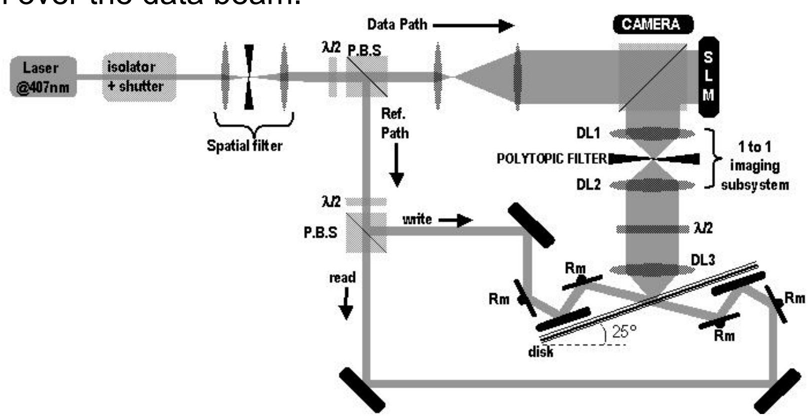

Fig. 3. Schematic of the experimental test bed.

1 Density and transfer rate experimental results

In our experiments, each book contains 320 pages, with a book pitch of 672 μm in x and 700 μm in y. Although the latter number is above p_y the reference beam's dimensions are 2 times the books' pitches in x and 1 time the books' pitches in y, so the layout of Fig. 2 (b) still applies. The layout yields a full raw bit density of 799 b/μm^2=799 Mb/mm^2=515 Gb/in^2 over an area of 8.5 mm^2 (area covered by our second layer). Figure 4 (a) graphs the write exposure times for the holograms in layer 1 and 2. Each step defines a layer. The average write exposure time is 2.7 ms per page corresponding to a raw write transfer rate of 54 MBytes/s. The holograms have an average diffraction efficiency of 3e^{-3} and are all read out with a 5 ms exposure time (Fig. 4c) corresponding to a raw read transfer rate of 29 MBytes/s. Including a 0.5 ms delay between pages accounting for mirror movement and a factor of one half for channel overhead, results in user transfer rates of 23MBytes/s for writing and 13MBytes/s for reading. Figure 4 (b) shows a recovered book from layer 2 with an average SNR of 1.5 dB.

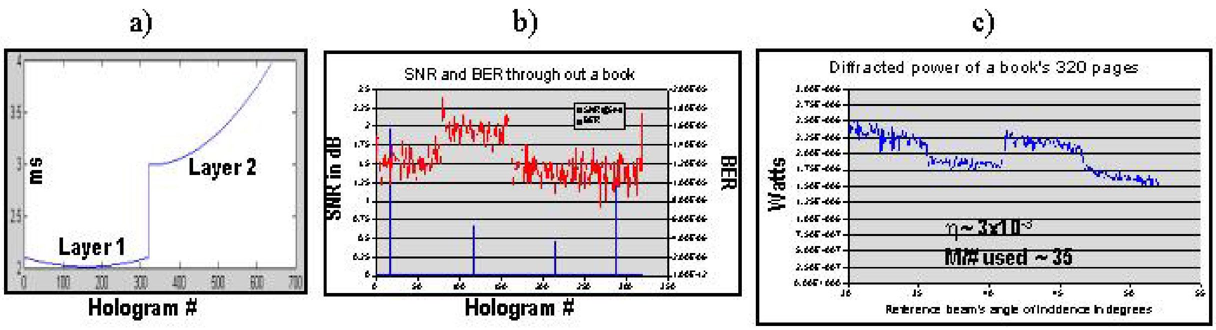

Fig. 4. a) Exposure schedule for holograms in layers 1 & 2. b) SNR and BER of a book in layer 2 (recovered with 5ms read exposure times). c) Diffracted power throughout the same book in layer 2.

2 References

1. Norihiro Tanabe, et al,"Experimental Research on Hologram Number Criterion for evaluation bit error rates of shift multiplexed holograms," ISOM conference, October 14, 2004, Jeju Island, Korea, paper Th-PP-05.

2. K. Anderson and K. Curtis, "Polytopic Multiplexing," Optics Letters, vol.29, **12** (June 15th, 2004).

3. K. Curtis, et al, "High Density Holographic Storage," ISOM conference, October 14, 2004, Jeju Island, Korea, paper Tu-D-01

4. "Process for holography involving skip-sorted hologram storage," U.S. Patent 6,614,566