How to Write Good Books

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Abstract: We introduce two novel techniques enabling media-efficient recording allowing for more pages per book and decreasing the disk space needed by each book. We present explanations and experimental results including our latest density results.

1. Introduction

Storing holographic information at high bit densities requires that a recording architecture be optimized in order to take full advantage of the limited media dynamic range. It is important to maximize the volumetric bit density (number of bits per unit volume). When the SLM dimensions are fixed, e.g. 1280x1024 pixels for our test system, maximizing the volumetric bit density is done by minimizing the volume exposed by a page. This is done by increasing the numerical aperture of the data beam's focusing lens and also by recording as close to the Fourier plane as possible. Because we use phase conjugation, we have been able to use a numerical aperture of 0.65, which is much higher than typical image based systems. Focusing into the media is complicated by the fact that the Fourier plane contains a DC signal that is as much as 10^5-10^6 times greater in intensity than the data. The media cannot record such a huge dynamic range signal, so techniques have been developed to apply a random phase function to the data with a phase mask in such a way that the DC signal is dramatically decreased[1]. In this paper, we present a novel technique that utilizes a moving non-pixel matched phase mask that allows us to focus the data beam into the media and therefore maximize the bit density while minimizing the amount of required media dynamic range.

While a phase mask decreases the effect of the DC signal, there can be residual DC or other intensity non-uniformities at or near the Fourier plane that lead to a non-uniform media usage. This non-uniform media usage can also be seen from book to book when there is a partial overlap of a page or book onto the bedia with different exposure history. Skip sorting[2] books is one method that is commonly used to record books in a uniform way so that index walls or intensity spikes don't build up inside the book. Another complimentary technique is proposed in this paper called "short-stacking" that utilizes small media movements within a book so that the index variations within a book don't build up and cause unwanted noise.

2. Dynamic Phase mask

The first technique utilizes a moving analog phase mask that is imaged onto the SLM to provide enough DC suppression so that recording can be done with the focus (Fourier plane) of the object beam inside the media (see Figure 1). There are several methods for being able to achieve true Fourier Plane recording, the best of which is a SLM that modulates both amplitude and phase. However, such a device is not yet commercially available. Imaging a pixel matched phase mask is another potential solution, however, this requires positional manufacturing tolerances of about ±0.5um to match the phase mask to the SLM, and this is unattainable in a commercial product.

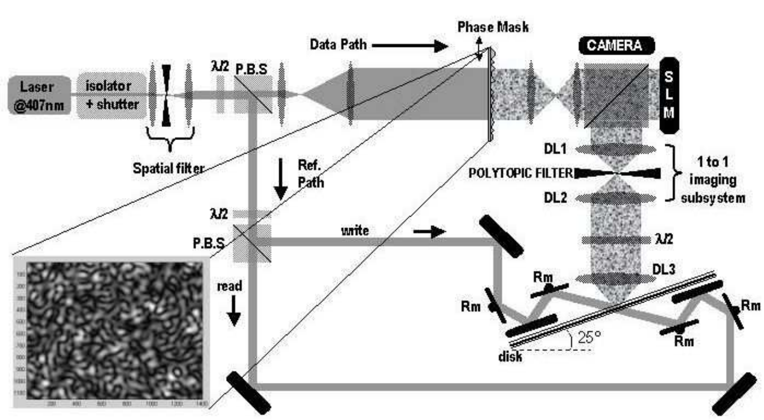

Figure 1:System layout of Polytopic Phase Conjugate Geometry with a moving phase mask imaged onto the SLM

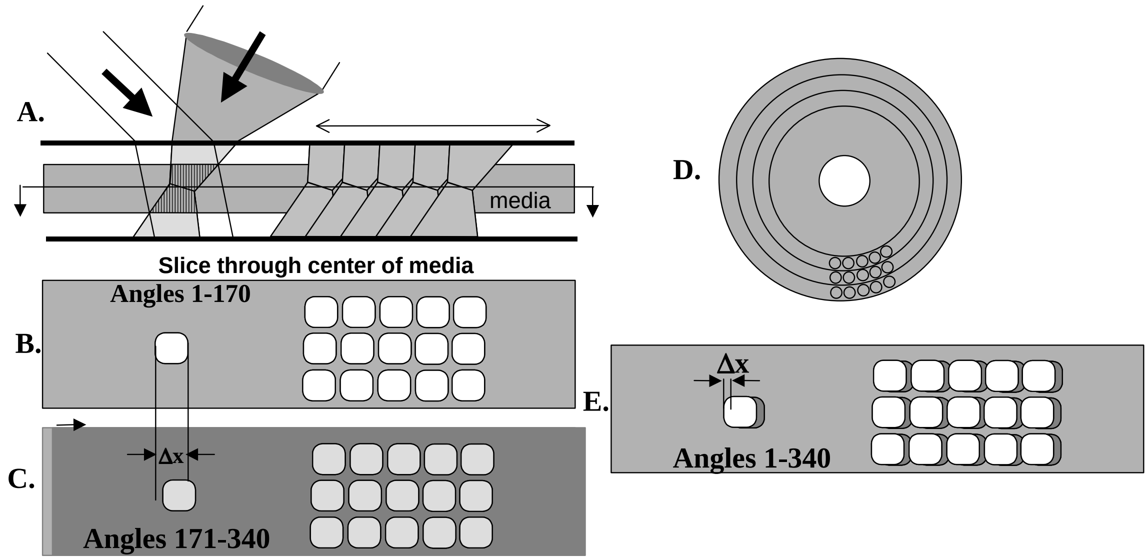

Figure 2: Illustration of Short-Stacking. See text for explanation

We have explored analog phase masks at length. These masks can be imaged onto the SLM without the need to pixel match. However, these phase masks force us to balance between DC suppression and filtering loss through the polytopic filter. This is because a more aggressive phase mask spreads the Fourier plane further and is clipped by the polytopic filter. In addtion, any residual DC signal can cause a non-linear media response that can lead to a low-pass filtering effect in the Fourier plane and therefore a high frequency enhancement in the image plane. This non-linear effect limits the number of pages in a book unless the phase function is changed. When the phase mask is moved during recording, thereby changing the phase function, the media non-linearities are not allowed to buildup from book to book and therefore mitigate any high frequency enhancement.

3. Short Stacking

A second method for decreasing media non-uniform buildup is a method called "short-stacking". Short stacking is similar to skip sorting where the books are layered in such a way that the media index buildup is smoothed out by staggering the order in which books are recorded (like laying bricks). Short stacking takes this idea one step further and splits the book into "short stacks" that contain a fraction of the total pages written in the book. The recording of each short-stack is staggered in such a way that the media index buildup is smoothed out. Figure 2 illustrates the process where two layers of short-stacks each containing 170 holograms are recorded into a disk media (see Figure 2d). Figure 2b shows a slice through the center of the media and the exposed area of the first short-stack layer of a 5x3 grid of books containing the first 170 holograms. Figure 2c shows a media movement (Δx) in the disk tangential direction that is at least a few microns and as much as a polytopic displacement[3] and a second layer of a grid of books being written. Figure 2e shows the two layers superimposed with the slight shift between the layers. As long as the short-stacks from the same layer (i.e. the same set of angles) do not overlap, there will be no cross talk between short-stacks even with large Δx.

4. 350 Gbit/in^2 demonstration

In October, we demonstrated 350Gbit/in^2 using the above two techniques. This is a significant increase from our previously result of 200Gbit/in^2 reported at ODS 2005. This jump is primarily due to the decrease in object beam volume that has allowed us to achieve a much smaller overlap factor between neighboring books. Our previous density demonstrations were all done with the data beam focus being outside of the media and therefore had a very high book overlap factor. Up to this point, we were unable to achieve any significant density with a phase mask due to the media non-uniform buildup that resulted in fine high intensity structures being present in the reconstructed image. This structure was entirely eliminated with the technique of moving the phase mask. As a result, we were able to fully utilize the media M# while keeping a very small book volume.

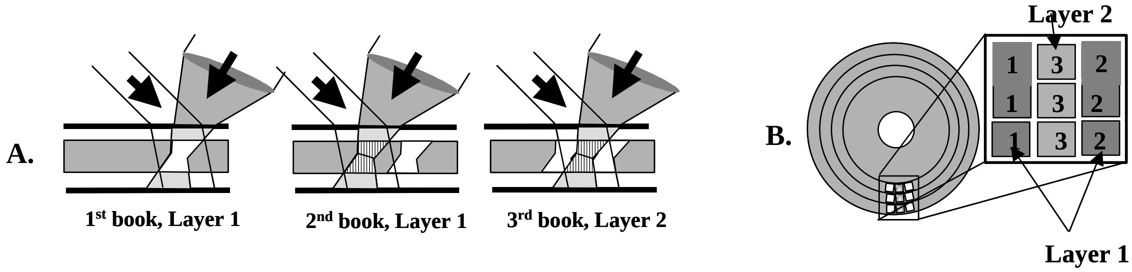

Figure 3: Book recording and layout. See text for description.

Since the book volume was so small, demonstrating density only required a 3 by 3 grid of books. The small grid size required for density is simply due to the fact that the overlap factor was around 1.34 and therefore a book only partially overlapped its immediate neighbors on both sides along the track and not across the track. We wrote three tracks of 3 books each as illustrated in Figure 3. Skip-sorting and short-stacking were used to layer the books for optimal uniformity. Figure 3A illustrates the layering effect in one track and shows the order in which the books were recorded. Figure 3B illustrates the three tracks of the disk that were written for this demonstration. It is important to note that the small book volume has allowed us to move into a regime where we can record high densities and still retain track by track recording with no overlap of books in the radial dimension.

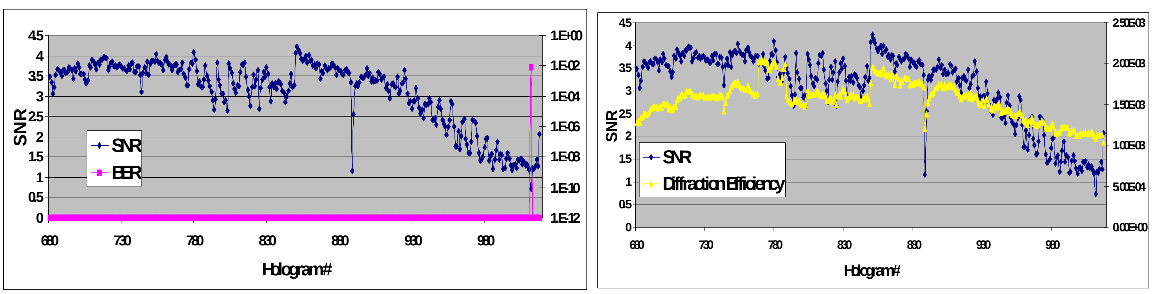

Figure 4: Data from our 350 Gbit/in^2 experimental demonstration. This data is taken from the last book containing two short-stacks of 170 holograms each. Left: Bit Error Rate (BER) and SNR. Right: SNR and Diffraction Efficiency.

The results of a complete hologram recovery of the 3rd book in the track is illustrated in Figure 4. Figure 4a shows SNR and BER as a function of hologram number. Note that there are 340 holograms in each book and 170 holograms in each short-stack (not shown here). There is a slight degradation of SNR towards the end of the book due to a slight scheduling mismatch. This is also seen in Figure 4B from the drop in diffraction efficiency for the last 100 holograms. There were a total of 1020 holograms recorded per track (3060 total holograms written and recovered) with a track width of 900um. The reference beam size used to recover the holograms was 1.1mm x 900um. The average diffraction efficiency was 1.55×10^{-3} and this is a little higher than required. However, we would like to be close to this diffraction efficiencies due to the requirement of high transfer rates with limited available laser power.

6. Conclusions

We have presented two techniques that have enabled recording densities of 350Gbit/in^2: Short stacking and a dynamic Phase Mask. These techniques have essentially allowed us to move the object beam focus into the media, thereby significantly decreasing the volume used for a book and enabling the optimal usage of media dynamic range.

6. References

1. C.B. Burkhardt, Applied Optics, Vol. 9, 695-700 (1970).
2. K.R. Curtis et al., US Patent #6,614,566.
3. K. Anderson and K. Curtis, Optics Letters, Vol. 29, No. 12, 1402 (2004).