Reflection-type holographic disk-type memory using three-dimensional speckle-shift multiplexing

Osamu Matoba

(Graduate School of System Informatics, Kobe University, Rokkodai 1-1, Nada, Kobe 657-8501, Japan)

Abstract: This review presents a reflection-type holographic memory using three-dimensional (3D) speckle-shift multiplexing. First, the schematic of the proposed memory system was described. Then, experimental demonstrations of multiplexing in plane and along the depth direction were presented. The estimated storage capacity of single layer recording was introduced and the maximum storage capacity was discussed. To increase the storage capacity, the multi-layered recording was described. In the multi-layered recording, the storage capacity can be increased by appropriate arrangement of holograms in each layer.

Key words: holographic memory; reflection-type hologram; speckle shift multiplexing

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0 Introduction

The amount of digital data in the world have been increasing rapidly and it is estimated that the total amount of the storage capacity of hard disk drive (HDD), solid state drive (SSD), magnetic tape, and optical disk reaches about 40 ZB in 2020. Most of digital data will be accessed rarely. These data are called as cold data that is categorized in long archival data. Optical disk memory is applied to the cold data storage, but the storage capacity and the data transfer rate are not sufficient to compete with the present archival system using magnetic tape. Holographic data storage is one of the promising candidates of the next-generation optical disk memory [1-2]. There are two major characteristics that are volume recording of two-dimensional (2D) page data and high transfer rate. To increase the storage capacity, there are many configurations of recording schemes such as collinear [3], polytopic [4-5], angular multiplexing [6], wavelength multiplexing, polarization, and shift-multiplexing. However, the storage capacity is not still sufficient to compete with other storage devices. Regarding the data transfer rate, 1 Gbps (1 bps=1 bit/s) was achieved[6].

We have presented a reflection-type holographic memory using speckle-shift multiplexing [7-15]. In the proposed system, a reflection-type hologram is created by the interference pattern between counterpropagating beams. The reflection-type hologram has advantage of short interaction length that leads to three-dimensional multiplexing, especially the multiplexing along the depth direction. The hologram is created by a speckle reference wave modulated by a random phase mask and the speckle-shift multiplexing is applied to increase the storage capacity. In this review paper, we

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Biography: Osamu Matoba, professor, research interests are in holographic applications such as optical memory, 3D display, and digital holography, and artificial control of scattering phenomena. Email:matoba@kobe-u.ac.jp

present the experimental demonstration of the reflection-type holographic memory and then the estimated storage capacity is derived numerically in the single-layer recording. Then, the multi-layer recording is introduced to increase the storage capacity.

1 Reflection-type holographic memory using three-dimensional speckle multiplexing

Figure 1 shows the concept of a reflection-type holographic disk memory using speckle shift multiplexing. A forward propagating signal wave and a backward propagating reference wave can make the interference in the recording medium as a reflection-type hologram. The reference wave is modulated by a random phase mask and then the speckle shift multiplexing is used to record the holograms by rotating the recording medium.

The recording intervals in the transverse plane and along the depth direction are determined by the speckle size in the both directions. The effective size of reflection-type hologram can be small, so we expect the three-dimensional multiplexing to increase the storage capacity. The surface reflection of the medium becomes very large noise. However, it can be reduced by antireflection-coating.

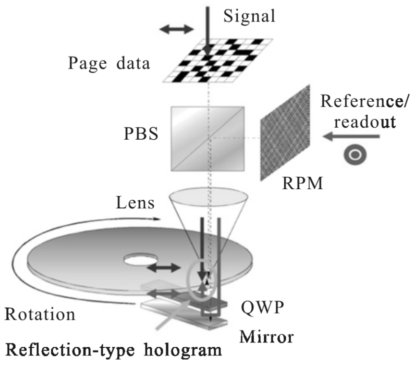


Fig.1 Schematic of holographic memory

2 Experiments

Here, we present the experimental demonstration of the reflection-type holographic memory using a photorefractive Fe-doped $LiNbO_3$ (LN) crystal [9]. Figure 2 shows the optical setup of the experiment. We use a LN crystal with a thickness of 0.5 mm to record the reflection-type holograms. The c-axis of the crystal is parallel to the depth direction. A laser light beam emitted from an Argon-ion laser operated at a wavelength of 514.5 nm is used as a light source. The laser beam is divided into two beams to create the counterpropagating beams after the magnification of beam diameter. In the signal arm, the spatial light modulator (SLM) is used to modulate the binary data page.The numerical aperture (NA) of focusing lenses, L3 and L4, is 0.28. In the reference arm, a random phase mask is used to generate the speckle pattern. A LN crystal is put on a three-dimensionally movable stage.

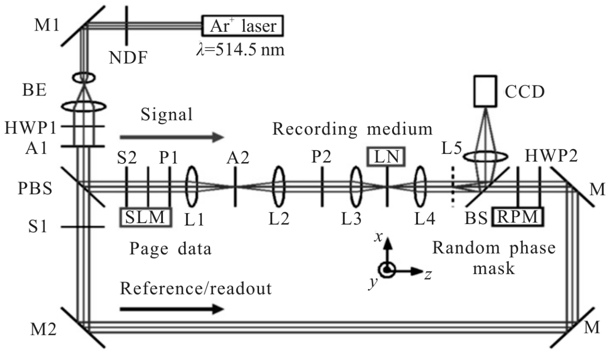
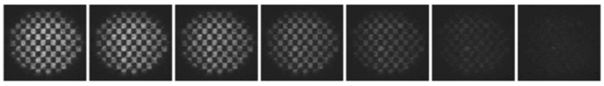
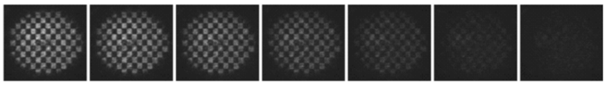


Fig.2 Scheme of experimental setup

Figures 3(a) and (b) show the reconstructed data when the LN crystal is shifted in the transverse plane and along the depth direction, respectively. The reconstructed powers are decreased by both shifts, and are negligible by a shift of 1.2 μm in the transverse plane and that of 12 μm along the depth direction. Therefore, shift selectivitiesare 1.2 μm in the transverse plane and 12 μm along the depth direction. Figure 4 shows the experimental results of shift multiplexing along the depth direction. Three images are recorded at the recording interval of 12 μm. Figures 4(a) and (b) show the original images and the reconstructed images, respectively. Three images are reconstructed well without significant cross-talk noise.



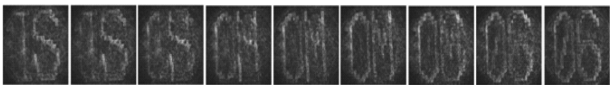
(a) With an interval of 2 μm along the transverse plane



(b) With an interval of 2 μm along the depth direction

Fig.3 Examples of readout images when the recording medium is shifted

(a) Original images



(b) Reconstructed images with the shift interval of 3 μm

Fig.4 Shift multiplexing along the depth direction

3 Estimation of achievable storage capacity

In the holographic memory, the storage capacity can be determined mainly by interpage and intrapage cross-talk noises, dynamic range of the recording medium, imperfectness of the recording beams and the dynamic range of recording medium, detector noise, and so on. One of the important issues is the interpage cross-talk noise due to the hologram multiplexing. In the hologram multiplexing, many data pages are readout simultaneously, but the cross-talk noise should be small. This interpage cross-talk noise causes the bit error. Due to the interpage cross-talk noise, it is difficult to achieve the maximum number of recording of the storage medium.

Figure 5 shows the numerical model to analyze the interpage cross-talk noise[11,16]. The recording medium is divided into many layers to present the volume characteristics. The modulation of the hologram and the propagation of light waves are based on scalar diffraction theory. From Ref.[11], the interpage cross-talk noise is analyzed numerically. When the signal-to-noise ratio (SNR) is set to be larger than 2, the storage capacity is given by

$$\text{Capacity}=a\text{NA}^4\frac{V}{\lambda^3} \tag{1}$$

where a is the constant; NA is a numerical aperture of a focusing lens; V is the volume of the recording medium; λ is a wavelength of light. The storage capacity is proportional to the fourth power of NA. Figure 6 shows the achievable storage capacity by Eq.(1) with three cases. When NA=0.85 and λ is 405 nm, the achievable storage capacity is 2.37 TB in a 5 in disk. This is the theoretical maximum and it is not sufficient. Therefore, we have to increase more the storage capacity. In the following section, we describe the multiple layer recording to increase the storage capacity.

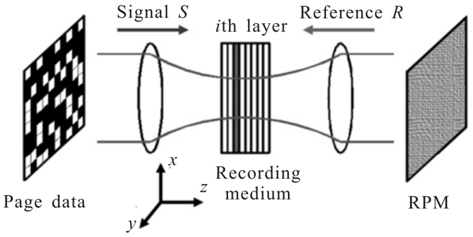


Fig.5 Numerical model to analyze the interpage cross-talk noise

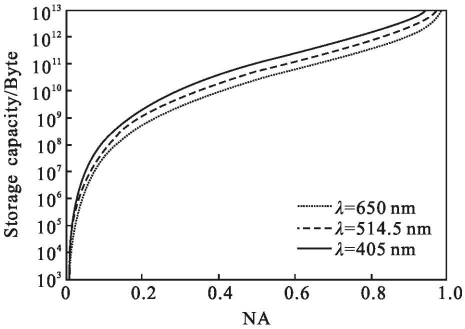


Fig.6 Storage capacity as a function of NA from Eq.(1)

4 Three-dimensional shift multiplexing

Figure 7 shows the single-layer recording and three-layer recording when the thickness of the recording medium is 0.5 mm. The appropriate arrangement of hologram recording, we can increase the number of holograms with high SNR [15]. We use the following parameters in the numerical evaluation. Wavelength of light is 532 nm, effective NA is 0.43, the number of pixels of binary data page is 256×256, bit size is 32 μm×32 μm, size of computational grid is 4 μm×4 μm, the number of computational grid is 4 096×4 096, and the thickness of the recording medium is 0.5 mm. The reason of low NA of 0.43 is due to the 64 GB RAM of the computer. In the future, it is necessary to analyze TB recording by increasing the NA.

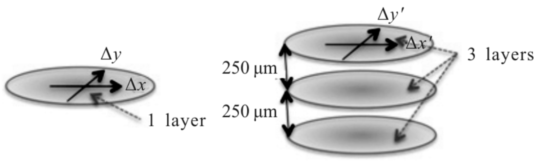


Fig.7 Schematics of a single layer recording and three-layers recording

First, we present the numerical evaluation of the recordable holograms in single layer recording. Figure 8 shows the shift selectivity along the transverse plane and the depth direction. From Figs.8(a) and (b), the shift intervals of 1st nullalong the transverse plane and the depth direction are 0.4 μm and 1.4 μm, respectively.

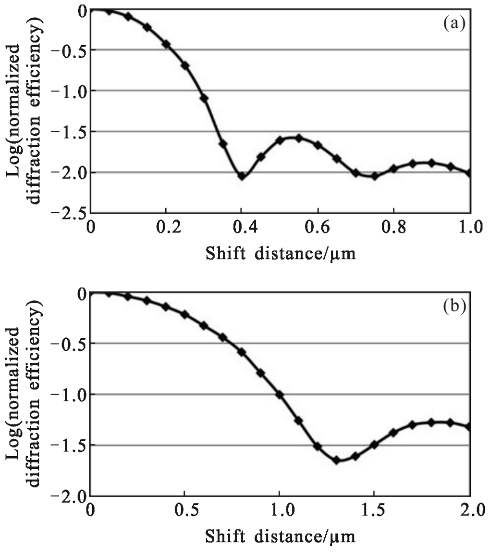


Fig.8 Shift selectivities (a) in the transverse plane and (b) along the depth direction

Figure 9 shows the SNRs when the recording intervals in the transverse plane are second null, fourth null, 16th null, and 32th null. From Fig.9, SNR becomes 3, when the number of recorded hologram is 50. In the ideal case, maximum number of data pages can be calculated by the beam width of signal wave and the recording interval. For example, when the recording interval is 0.8 μm that is the second null, the maximum number of recorded holograms is 47 424. However, it decreases 103 when the following condition that SNR is larger than 2, is added. This means that the recorded data cannot be recovered successfully if the number of holograms is larger than 103. Appropriate recording scheme can be applied to increase the number of holograms. If the recording interval becomes large, the interpage cross-talk noise decreases. If we set the condition that SNR is larger than 2, the achievable number of holograms is 185 when the recording interval is 12.8 μm.

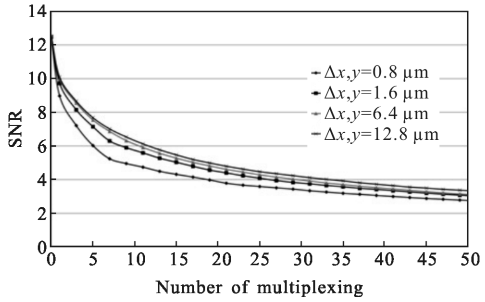


Fig.9 SNRs as a function of number of multiplexing in the cases of five shift intervals in a single layer recording

Next, we consider multi-layer recording. Figure 10 shows the diffraction efficiency when the holograms are recorded in two planes at z=0 and z=250 μm. In the same plane, there is no difference between the recording intervals of 12.8 μm and 18.4 μm. However, the diffraction efficiency becomes 72 % when the recording position is shifted by 250 μm along the depth direction. This means that the cross-talk noise from the other layers becomes smaller than that from the same layer. To increase the total number of recorded holograms, the recording interval in the transverse plane and the number of layers become large. When the number of layers is 3, the maximum number of holograms is 269 when the recording interval in the transeverse plane is 18.4 μm. The achievable number of holograms becomes 1.45 time larger than that in single layer recording.

To increase the number of recorded holograms, we introduce the block coding such as 3:16 code where three pixels among 16 pixels are "1". The number of holograms becomes two times larger than that in single layer recording without block coding. From the simple calculation in a 5 in disk with a thickness of 0.5 mm, the achievable storage capacity is 366 GB/disk when NA is 0.43. By using Eq.(1), the estimated maximum storage capacity becomes 5.45 TB/disk when NA is 0.85. This is twice of the single layer recording. We hope that the storage capacity can be increased by increasing the thickness of the recording medium and the number of layers.

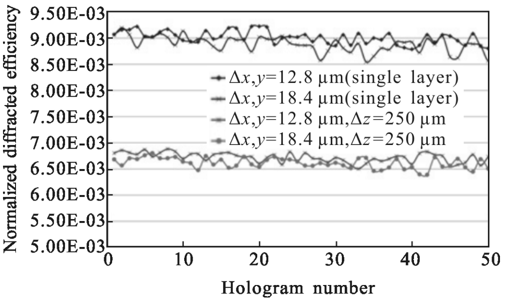


Fig.10 Diffraction efficiencies in plane and along the depth direction

5 Conclusion

We have presented the reflection-type holographic memory using three-dimensional speckle-shift multiplexing. The experimental results and the estimated storage capacity of single layer recording are presented. To increase the storage capacity, the multi-layered recording is described. In the multi-layered recording, the storage capacity is increased by appropriate arrangement of holograms in each layer.

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