INCREASE OF STORAGE CAPACITY BY OPTICAL ENCRYPTION TECHNIQUE IN HOLOGRAPHIC MEMORY

Osamu MATOBA, Xiaodi TAN, Tsutomu SHIMURA, and Kazuo KURODA

Institute of Industrial Science, University of Tokyo,
Komaba 4-6-1, Meguro-ku, Tokyo 153-8505, Japan
Telephone: +81-3-5452-6137, Fax: +81-3-5452-6159
E-mail: matoba@iis.u-tokyo.ac.jp

Abstract

A storage capacity in an encrypted holographic memory system is evaluated. In the encrypted holographic memory system, input binary images are encrypted into white-noise-like images by a key code and then are stored as holograms in a recording medium by using angular multiplexing. Even when in angular multiplexing, the angle separation between adjacent images is enough small to cause the cross-talk between adjacent images, the original binary image can be recovered by using a corresponding correct key code whereas the other reconstructed images are still white-noise-like images because of the incorrect keys. Therefore, the capacity of the proposed system can be increased after binalization of the reconstructed image. We present numerical results to confirm that the capacity of the proposed system can be larger than that of the conventional holographic memory system.

1. Introduction

There is a growing demand for the storage and the communication of huge data as computers and the network have been developing rapidly. Holographic memories [1] have inherently a large storage capacity with a fast access to two-dimensional data. 10 Gbit/s data transfer rate have been implemented. Furthermore, optical security techniques [2] are easily applied to the holographic memory system for the data security [3].

In this paper a storage capacity in an angular-multiplexed secure holographic memory system is evaluated. The storage capacity is calculated by multiplying the number of bits per frame by the number of stored frames using angular multiplexing. The number of bits per frame is determined by the display device such as spatial light modulators. The number of angular multiplexing is limited mainly by the cross-talk between adjacent images. In a secure memory system by using double random phase encryption, we show that the number of angular multiplexing can be increased. In the double random encryption technique, input binary images are encrypted into white-noise-like images by using two random phase masks. When the angle separation between adjacent images is enough small, the interpage cross-talk is occurred. In the encrypted memory system, however, superimposed white-noise-like images from adjacent stored data can be eliminated by thresholding. Numerical evaluation is presented to confirm that the capacity of the proposed encrypted memory system can be increased.

2. Secure Holographic Memory System

A secure holographic memory system using double random phase encryption [3] is shown in Fig. 1. Let ith object image, $o_i(x, y)$, denote the two-dimensional binary image to be encrypted, where (x, y) denote spatial coordinates (see Fig. 1). This binary image is multiplied by a random phase mask, $m_i(x, y) = \exp[-j2\pi h_i(x, y)]$, at the input plane. The input data is Fourier transformed by a Fourier transform lens and then is multiplied by another random phase mask, $M_i(\xi, \eta) = \exp[-j2\pi H_i(\xi, \eta)]$, at the Fourier plane. Here (ξ, η) denotes the Fourier plane coordinates. The

two masks, $h_i(x, y)$ and $H_i(\xi, \eta)$, are randomly distributed in the interval [0,1] and statistically independent of each other. After another Fourier-transform, the encrypted data, $e_i(x,y)$ can be obtained as

$$e_i(x,y) = o_i(x,y) m_i(x,y) \otimes F\{M_i(\xi,\eta)\}, \qquad (1)$$

where $\otimes$ denotes convolution and $F\{\bullet\}$ denotes the Fourier transform operation. These encrypted data become white-noise-like data because of the convolution of two random functions.

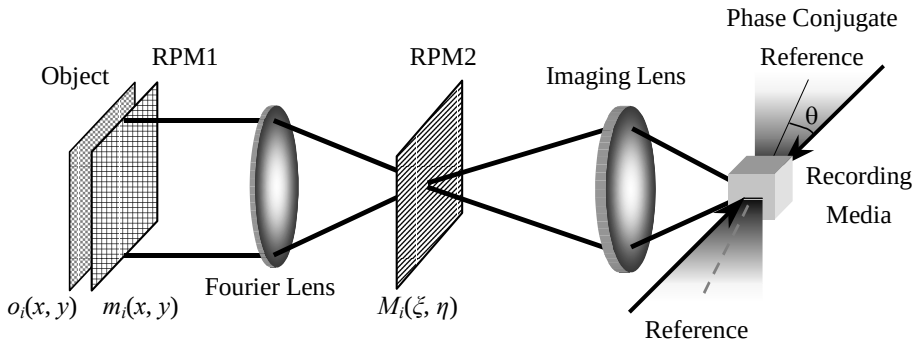

Figure 1 Schematic diagram of the secure holographic memory system using double random phase encryption. RPM's denote random phase masks.

We propose a method to increase the total number of frames in angular multiplexed recording by reducing the effect of the interpage cross-talk. The idea to improve the storage capacity is described in Fig. 2. When the angular separation between adjacent images is smaller than the angle where the diffraction efficiency of off-Bragg light becomes a minimum value, the interpage cross-talk is the dominant noise and then all the stored frames are superimposed coherently with their diffraction efficiencies derived from the Bragg mismatch. In a conventional holographic memory system without double random phase encryption, this interpage cross-talk results in the bit error at the reconstruction process as shown in Fig. 2(a). However, double random phase encryption can encode the original binary data into a stationary white-noise-like image. When each original data frame is encoded by respective random phase masks, the correct phase mask can reconstruct a corresponding original frame together with white-noise-like frames reconstructed by incorrect masks as shown in Fig. 2(b). After the binarization of reconstructed image, original binary frame can be recovered even when the interpage cross-talk is occurred.

3. Numerical Evaluation of Storage Capacity

In a volume holographic storage, the noise-to-signal ratio due to the interpage cross-talk has been analyzed [4]. In a digital data storage system, bit error rate is the most important issue for the practical implementation. We numerically evaluate the bit error rate in holographic digital data storage systems with and without double random phase encryption when the angular separation between adjacent images is smaller than the Bragg separation angle.

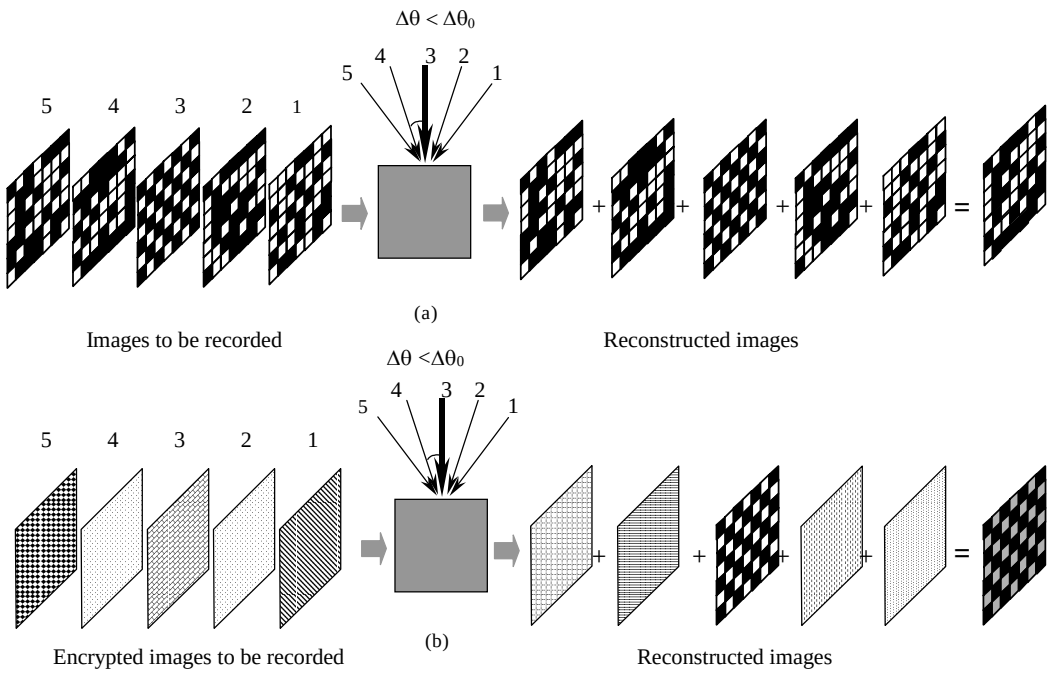

Figure 2 Concept to improve the storage capacity in the holographic memory system using double random phase encryption. (a) the conventional holographic memory and (b) the secure holographic memory using double random phase encryption.

To derive the diffraction efficiency of off-Bragg light, we use the result of the coupled mode theory proposed by Kogelnik [5]. The number of pixels of original binary frame is $(512/p) \times (512/p)$ pixles where each pixel consists of $p \times p$ cells. In this paper we use p = 1, 2, 4, 8, 16. This redundancy in the input data allows us to reconstruct the original binary data by thresholding even when the interpage cross-talk is occurred. The random phase masks in the input and the Fourier planes with 512×512 pixels and each pixel consists of 1×1 cell. The arrays of input data and two random-phase masks are randomly generated. In the reconstruction, all the images are superimposed coherently according to the diffraction efficiency of off-Bragg light which is calculated from the Kogelnik's analysis. After calculation of the intensity at each cell, we calculated the energy of each pixel of the reconstructed image. The threshold value is the average of the energy of the pixels. By the comparison the input and the output binary data, the bit error rate is calculated. We show you an example of the results when p = 8. Figure 3 shows the bite error rate as a function of the angle separation of $\Delta\theta$. These results were averaged over 10 different trials. We use the following values in the calculation: the thickness of the recording medium of 4 mm, the refractive-index change of 4.4×10^{-5}, the wavelength of light of 0.5 μm, and the angle between the object and reference beams of 90º. The bit error rate was calculated as follows. The bit error rate is defined here as the number of error bits divided by the total number of bits in the original data. From Fig. 3, angle separations in holographic memories with and without double random phase encryption are 3.04×10^{-5} rad and 8.48×10^{-5} rad when the bit error rate is 1×10^{-3}. This result shows that the storage capacity of the holographic storage with double random phase encryption is 2.79 times larger than that of the system without double random phase encryption.

When the bit error rate is fixed to be 1×10^{-3}, the ratio of the angle separations without and with double random phase encryption is calculated. This ratio indicates how many times the storage capacity increase by using double random phase encryption. Figure 4 shows the rate of increase in the storage capacity as a function of the pixel size per bit in the input data frame. We

can see that the incremental rate becomes large when the pixel size is large. This means that averaging the energy at each pixel is effective to eliminate the cross-talk noise because the white-noise-like image has high resolution. When the pixel size per bit is 16 × 16 cells in the used calculation, the storage capacity of the holographic storage with double random phase encryption is five times larger than that of the system without double random phase encryption. Note that the storage capacity is almost the same as the theoretical maximum storage capacity, V/λ^3, where V is a volume of the recording media and λ is the wavelength of light. We can see this result when the pixel size is 1 in Fig. 4. The storage capacity is much increased when the input device has low resolution.

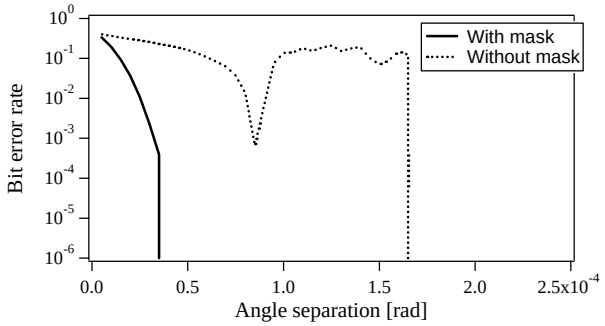

Figure 3 Bit error rate as a function of the angle separation of $\Delta\theta$ when the input pixel size is 8.

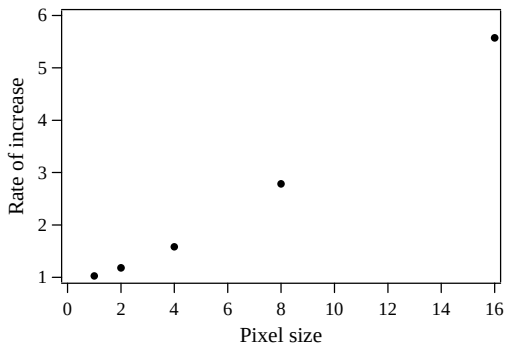

Figure 4 Rate of increase in the storage capacity as a function of the pixel size.

4. Conclusions

A method that can improve the storage capacity of an angular multiplexed holographic storage system using double random phase encryption has been analyzed numerically. In this system, all the input binary images are converted into stationary white-noise-like images by use of different sets of two random phase masks and then are stored as holograms. When the angle separation between adjacent stored images is smaller than the Bragg separation angle, the cross-talk between the adjacent images is occurred in the readout process. In the encrypted memory system, however, the original image can be reconstructed by the correct phase mask together with white-noise-like images from all other stored images because of the incorrect phase masks. The superimposed white-noise-like images can be eliminated by thresholding. Numerical results showed that the storage capacity in the angle-multiplexed holograms can be increased by using double random phase encryption.

References

1. H. Coufal, D. Psaltis, and G. Sincerbox eds., *Holographic Data Storage* (Springer-Verlag, Berlin, 2000).
2. P. Réfrégier and B. Javidi, “Optical image encryption based on input plane and Fourier plane random encoding,” Opt. Lett. **20**, 767-769(1995).
3. O. Matoba and B. Javidi, “Encrypted optical storage with angular multiplexing,” Appl. Opt. **38**, 7288-7293(1999).
4. C. Gu, J. Hong, I. McMichael, R. Saxena, and F.H. Mok, “Cross-talk-limited storage capacity of volume holographic memory,” J. Opt. Soc. Am., A **9**, 1978-1983(1992).
5. H. W. Kogelnik, “Coupled wave theory for think hologram gratings”, Bell Syst. Tech. J. **48**, 2909-2947(1969).