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Experimental demonstration of holographic storage with discrete random phase-code multiplexing

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We studied experimentally a discrete random phase-code multiplexing technique for holographic data storage, which we believe can overcome some disadvantages of conventional random phase-code multiplexing adopting either a diffusion plate or a multimode fiber. Experimental demonstration is presented to show the potential usefulness and some characteristics of the discrete random phase-code multiplexing technique.

I. INTRODUCTION

Holographic memories attract attention because of potentially high storage density and parallel data retrieval. To store numerous pages of data holographically, various multiplexing techniques such as angular multiplexing, rotational multiplexing, shift (spatial) multiplexing, orthogonal phase-code multiplexing, wavelength multiplexing, etc., were invented [1-7]. Among these techniques, angular multiplexing is commonly used, in which a reference beam that is angularly distinct from any other by at least the Bragg separation angle is used. If the beam direction is controlled by a mechanical method, angular multiplexing has a limitation in the accuracy and the speed of the beam steering. If a beam controller such as an acousto-optics device is used for fast access of the reference beam, the system becomes complex and its cost becomes high.

An alternative technique that can avoid the above drawbacks is phase-code multiplexing. In this technique, the phase distribution of the reference beam is varied to obtain a set of the orthogonal reference beams. There are two kinds of phase-code multiplexing. One is random phase-code multiplexing and the other is deterministic phase-code multiplexing.

In random phase-code multiplexing, the phase distribution of the reference beam is randomized by passing it through an element such as a diffusion plate or a piece of multimode fiber, and then mutually orthogonal random phase distributions are generated by physically changing the element [8,9]. Instead of a simple plane wave, if a beam with a complex phase distribution is used for the reference beam in either angle multiplexing or shift multiplexing, their selectivities become enhanced [9]. Thus the storage density of the medium can be increased. In fact, to obtain the statistically orthogonal reference beams in this method, the phase distribution of each reference beam must be sufficiently complex. In the case of a multimode fiber, for example, statistically orthogonal reference beams can be expected only when the number of modes supported by the fiber is very large in general. If the number of modes increases to guarantee the orthogonality of the reference beams, however, the phase distribution of the beam coming out of the multimode fiber becomes more sensitive to environment perturbations such as temperature changes, mechanical impacts, vibrations, etc. In addition, control of the phase in a predictable way is very difficult even if the number of modes is relatively small. In particular, if the phase-randomizing element (either the diffusion plate or the multimode fiber) used for hologram recording is damaged, it is difficult to reconstruct the stored holograms because the same random phase distributions used for data storage cannot be generated again.

On the other hand, in deterministic phase-code multiplexing, a set of orthogonal reference beams are generated by changing the phase distribution of each pixel in the reference beam to be either 0 or π with a spatial phase modulator [6,7]. In previous studies of deterministic phase-code multiplexing, the spatially separated pixels of the phase modulator are used. This is to make the angle between any pair of reference beam components be larger than the Bragg selectivity angle of the recording medium when the reference components are converged to the recording medium by a lens. In this case, crosstalk noise can be reduced. Therefore, the number of orthogonal reference beams that can be generated is limited because a part of the pixels in the phase modulator should be used.

In this paper, unlike conventional deterministic phase-code multiplexing, all the pixels of the SLM without any pixel sampling are used for phase modulation. Therefore, the number of orthogonal reference beams that can be generated is as many as the number of pixels in the SLM. Our method has a similarity with conventional random phase-code multiplexing in that the whole phase distribution is used without any pixel sampling, and also has a similarity with conventional deterministic phase-code multiplexing in that only discrete phase shifts, 0 and π, are used. Thus we call our method discrete random phase-code multiplexing. Like conventional random phase-code multiplexing, our method can also enhance the angular or shift selectivity if it is used in combination with angular of shift multiplexing. An experimental demonstration was performed to show the feasibility of the discrete random phase-code multiplexing technique, and the crosstalk characteristic was examined.

Our discrete random phase-code multiplexing can be achieved by use of either a phase SLM or an amplitude SLM [10]. The principle of phase modulation with an amplitude SLM is as follows: The polarizer attached on the front surface of the SLM should be removed, while the polarizer on the back surface called the analyzer should not. Suppose the polarization angle of the linearly polarized input beam is θ as shown in Fig. 1. It is assumed that the polarization direction of the beam after passing through the turned-on (ON) pixels of the SLM rotates by an angle of α, while through the turned-off (OFF) pixels it is maintained. The Jones vector of the input beam $\mathbf{V}_{\rm IN}$ can be represented by

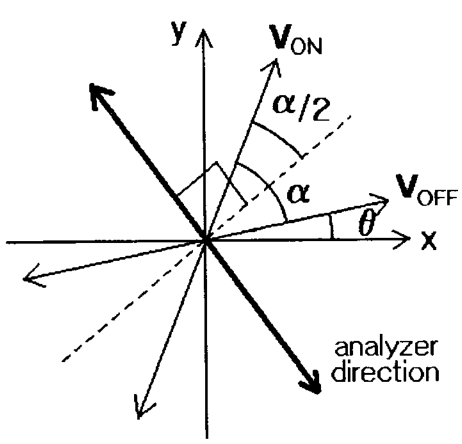

FIG. 1. Beam polarization directions and analyzer direction for 0 and π phase modulation.

$$\mathbf{V}_{\rm IN} = \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} Ae^{j\phi} \equiv \mathbf{V}_{\rm OFF} \tag{1}$$

where the input beam is assumed to be a plane wave whose amplitude is A and phase ϕ, and $j = \sqrt{-1}$. A common phase delay due to the SLM is neglected and thus we set $\mathbf{V}_{\rm IN} \equiv \mathbf{V}_{\rm OFF}$, where $\mathbf{V}_{\rm OFF}$ is the Jones vector of the beam after the OFF pixels but before the analyzer. However, the Jones vector after ON pixels $\mathbf{V}_{\rm ON}$ becomes

$$\begin{aligned} \mathbf{V}_{\rm ON} &= \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} Ae^{j\phi} \\ &= \begin{bmatrix} \cos(\theta+\alpha) \\ \sin(\theta+\alpha) \end{bmatrix} Ae^{j\phi}. \end{aligned} \tag{2}$$

If the analyzer direction is perpendicular to the angle $\theta + \alpha/2$ as shown in Fig. 1, the Jones matrix of the analyzer $\mathbf{M}$ becomes

$$\mathbf{M} = \frac{1}{2} \begin{bmatrix} 1-\cos(\alpha+2\theta) & -\sin(\alpha+2\theta) \\ -\sin(\alpha+2\theta) & 1+\cos(\alpha+2\theta) \end{bmatrix} \tag{3}$$

where the absorption loss of the analyzer itself is assumed to be negligible. The Jones vectors of the output beams through this analyzer become

$$\begin{aligned} \mathbf{V}_{\rm out,OFF} &= \mathbf{M}\mathbf{V}_{\rm OFF} = \frac{1}{2} \begin{bmatrix} \cos\theta - \cos(\alpha+\theta) \\ \sin\theta - \sin(\alpha+\theta) \end{bmatrix} Ae^{j\phi} \\ \mathbf{V}_{\rm out,ON} &= \mathbf{M}\mathbf{V}_{\rm ON} = \frac{1}{2} \begin{bmatrix} \cos(\alpha+\theta) - \cos\theta \\ \sin(\alpha+\theta) - \sin\theta \end{bmatrix} Ae^{j\phi} \\ &= -\mathbf{V}_{\rm out,OFF} = e^{j\pi}\mathbf{V}_{\rm out,OFF}. \end{aligned} \tag{4}$$

Thus we can see the phase difference between the ON and OFF pixels is π. In our experiment, because the direction of the analyzer attached on the back surface of the SLM is fixed, the polarization direction of the input beam θ is controlled with a half-wave plate to get 0 and π phase shift.

To obtain the orthogonal phase-coded reference beams in our experiments, an orthogonal set of Hadamard codes [11] were generated to drive the SLM. The Hadamard code of order N=768 was used. After the N orthogonal Hadamard codes $h_1, h_2, ..., h_N$ were obtained as shown in Fig. 2(a), the positions of their pixels in each code vector were arbitrarily shuffled in a consistent manner for all the code vectors. And then, by properly juxtaposing the h codes in a two-dimensional (2-D) plane, orthogonal code vector with more than N pixels, $H_1, H_2, ..., H_N$, were composed. Note that it is not easy to calculate the Hadamard codes of large N directly, because it requires a long computation time and a high memory capacity in computers. In addition, when the Hadamard codes are rearranged in a 2-D array, periodic patterns frequently emerge. Our method of orthogonal code generation removes these problems. All the H codes we obtained

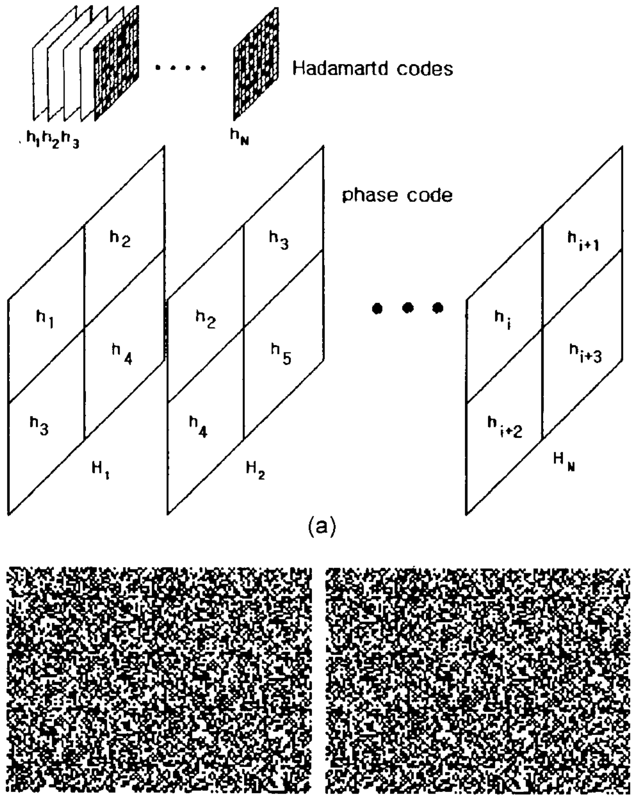

FIG. 2. (a) Generation of orthogonal phase codes to modulate the phase distribution of the reference beam. (b) Two examples of the codes we used.

are mutually orthogonal and look random as shown in Fig. 2(b). An orthogonal set of reference beams with discrete random phases is obtained by displaying the $H_1, H_2, ..., H_N$ codes in the SLM one by one, and then passing a uniform plane wave through it.

Our experimental setup to demonstrate multiple hologram recording with discrete random phase-code multiplexing is shown in Fig. 3. The light source was an Argon-ion laser operating at λ=514 nm and the storage medium was a $BaTiO_3$ crystal. The amplitude SLM with 320 × 240 pixels (Kopin CyberDisplay 320 model) is used for the phase modulator. The beam is expanded by a beam expander (B.E.) and is divided into the signal and the reference beam by a beam splitter (B.S.). In the reference arm, there are a half-wave plate, an SLM and three lenses. The half-wave plate in the reference arm is to control the polarization angle of the input beam θ as mentioned previously. However, a small portion of the input beam that passes through the gaps between the pixels of the SLM is not modulated. Thus the phase-modulated reference beams have a DC component in the Fourier plane. A DC block was positioned between the lenses L_1 and L_2 to remove the DC component that causes the crosstalk noise. L_1, L_2,

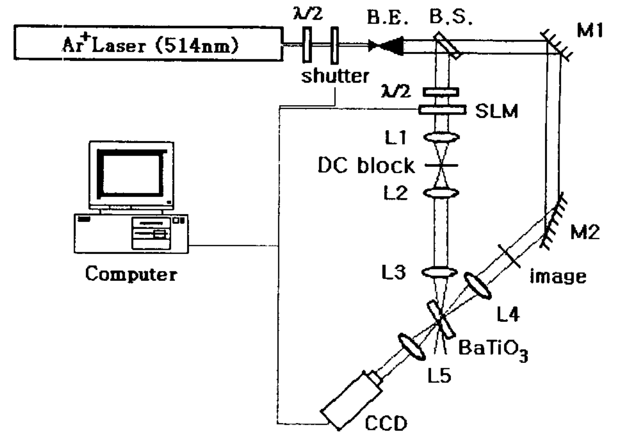

FIG. 3. Holographic recording system with discrete random phase-code multiplexing.

and L_3 form a $6f$-system. The images to be stored were prepared in transparent films.

In the experiment, the intensities of the reference and the signal beams were 40 nW/cm^2 and 30 nW/cm^2, respectively. The recording time constant and the erasure time constant of the crystal were 400 seconds and 140 seconds, respectively. This means that it is difficult to record many holograms because of the fast erasure effect in our crystal. We found that it was almost impossible to multiplex more than ten holograms in our crystal with angle multiplexing. Thus, ten orthogonal discrete random phase-codes were generated as explained previously in Fig. 2(a) to store ten holograms.

When the ten holograms were recorded with an equal exposure time (120 seconds), their measured diffracted beam powers are shown in Fig. 4(a). In fact, the diffracted intensities of the first six patterns were close to the background crosstalk noise level (0.06 nW/cm^2) in our experiment. When these six patterns were reconstructed, they looked like faint scattered noise patterns. To obtain equal diffracted beam powers (i.e.,

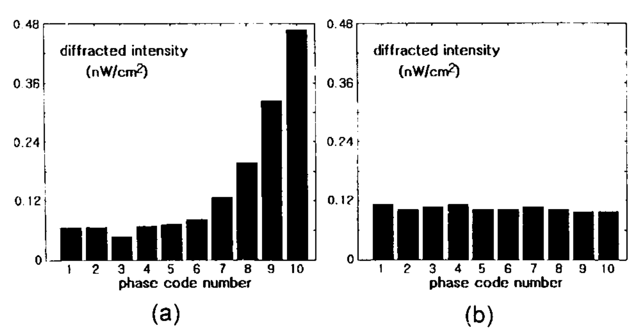

FIG. 4. (a) The diffracted beam powers of 10 multiplexed holograms for equal exposure time. (b) The diffracted beam powers of 10 multiplexed holograms for scheduled exposure time.

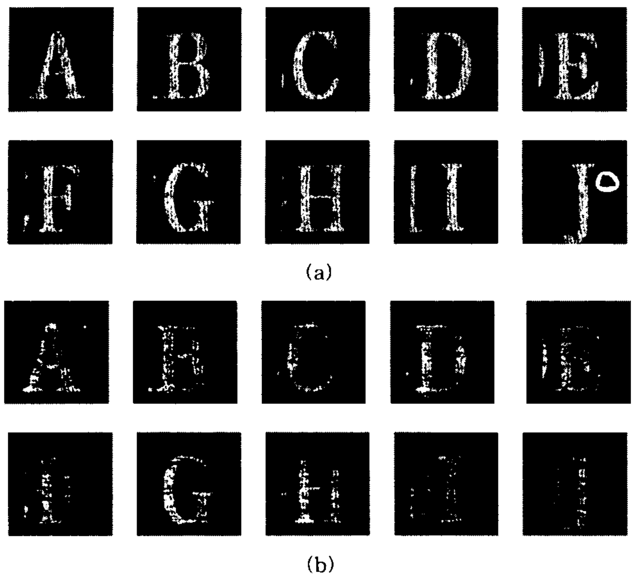

FIG. 5. (a) Ten original images to be stored. (b) Reconstructed images when scheduled exposure time was used.

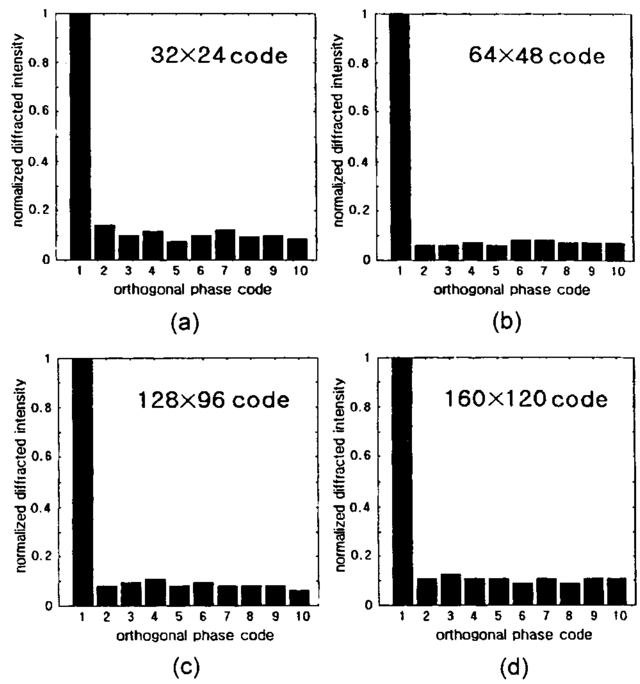

FIG. 7. Normalized crosstalk beam powers as the number of pixels used to get orthogonal phase-codes was varied. Only 'A' was stored in this experiment and it was read out by the ten orthogonal reference beams. (a) When 32×24 pixels were used. (b) When 64×48 pixels were used. (c) When 128×96 pixels were used. (d) When 160×120 pixels were used.

equal diffraction efficiencies) for the ten holograms, we used a method of scheduled-time recording [12]. In this case, the result is shown in Fig. 4(b). Fig. 5 shows the ten original images to be stored and the ten reconstructed images.

The amount of crosstalk noise was examined experimentally in our system. First, after a few holograms were recorded, the diffracted beam powers were measured when they were read out with all ten orthogonal discrete random phase-codes that we used. The results are shown in Fig. 6. Here, we can see the absolute power of the crosstalk noise does not increase as the number of multiplexed holograms increases. Of course, even if the crosstalk noise is constant, it limits the maximal number of holograms that can be multiplexed because the diffraction efficiency decreases as the number of multiplexed holograms increases. In addition, the crosstalk noise was measured as the SLM pixel size to represent one bit value of the codes was varied. The number of pixels is inversely proportional to their size, because the total size of the SLM is finite and fixed, and the whole panel of the SLM was used for the phase modulation. These results are shown in Fig. 7, which can be viewed as optical correlation values between

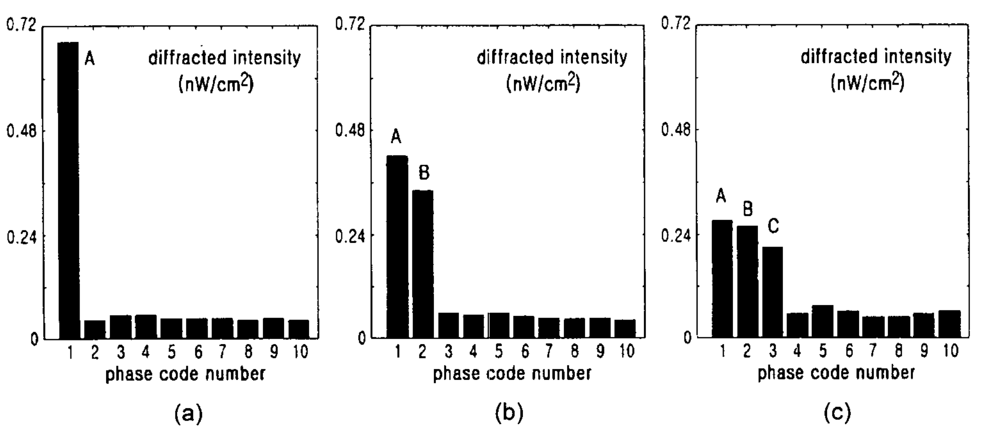

FIG. 6. Beam powers of the crosstalk noise. (a) The readout outputs by the ten orthogonal phase-code reference beams only when 'A' was stored. (b) When 'A' and 'B' were stored. (c) When 'A', 'B' and 'C' were stored.

the first phase-coded reference beam used to record 'A' pattern and others, including itself for autocorrelation. The orthogonal phase-coded reference beams with four different pixel sizes (and thus pixel numbers) were prepared and the same experiments were repeated for each pixel size. The diffracted beam powers were normalized in each experiment. From these experiments we can see the pixel size does not affect the crosstalk noise significantly in our experimental parameter ranges.

Under the same experimental conditions, we also performed the experiment to store the 10 patterns with angle multiplexing for comparison purposes. Even in the angle multiplexing experiment, a similar level of crosstalk noise was present at the output charge-coupled device (CCD) plane, when the reference beams were distinct from each other by the first Bragg separation angle. Thus the background crosstalk noise (approximately 0.06 nW/cm^2) we can see in Fig. 4 and 6 seems to be caused by other reasons, such as beam fanning and scattering noise amplified toward the signal beam direction especially when the grating is present in the crystal.

In summary, the possibility of discrete random phase-code multiplexing is experimentally demonstrated by recording multiple holograms with this multiplexing technique. Discrete random phase-code multiplexing can be used as an alternative method that can overcome the drawbacks of conventional random phase-code multiplexing. To analyze the cause of the crosstalk noise in our method and system in detail, systematic experiments are planned.

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