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Multiplexing methods of volume holograms using fiber speckle patterns

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The method of using fiber speckle patterns can be applied to the multiplexing of volume holograms. Fiber speckle patterns enable various multiplexing techniques such as shift, angular, and mode-scrambling methods. Hybrid methods involving more than one multiplexing technique are also possible. Some images are stored and retrieved with one or two of multiplexing methods, and the experimental results are discussed.

I. INTRODUCTION

The photorefractive volume hologram is one of the candidates for mass data storage systems. The multiplexing technique of holograms is a key to the holographic data storage system. Many methods for hologram multiplexing have been suggested[1] such as angular multiplexing, wavelength multiplexing, or phase code multiplexing[2]. Recently, a multiplexing method using fiber speckle patterns was proposed by the authors[3,4], where a random-phased speckle wavefront plays the role of the address. Because a speckle pattern has little correlation with other speckles, the method using speckle patterns has also been used for a sensor system[5]. An optical fiber can produce a quasi-random phase code with a simple setup[3,6]. Different random-phase information can be obtained by shifting a fiber speckle pattern spatially or angularly, or by changing speckle patterns with mode scrambling.

In this paper, we extend our previous initial work[3,7,8] on hologram storage using fiber speckle patterns to the feasibility test for various multiplexing schemes. Volume hologram using the fiber speckle allows with a simple setup various multiplexing methods such as angular multiplexing, shift multiplexing, and mode- scrambling multiplexing. These methods for a two-dimensional image storage system are investigated in this paper. Each image is stored with a reference beam with different speckle information. The experimental results are presented and discussed in the following sections.

II. ANGULAR MULTIPLEXING

In the conventional method of angular multiplexing using a plane wave reference beam, the angular deviation of the reference(probe) wave from the writing angle induces the phase mismatch in reading a hologram. Here in the method using speckle patterns from a multimode fiber, complex phase due to speckles enhances the sensitivity to the angular deviation.

The experimental setup for probing angular selectivity is shown in Fig. 1. An iron-doped lithium niobate crystal($\sim 1cm^3$) was used as a photorefractive medium, and a He-Ne laser was used as a light source. The optical wave from the multimode fiber, which is 9cm long, was used as the reference beam. The object beam was expanded to a plane wave with a width of 1cm and passed through a film mask which was used as a spatial light modulator(SLM). Images on the SLM were 0.5cm wide. The object beam interfered with the reference beam in a photorefractive crystal with an angle of 30^o and formed a volume hologram. In reading the hologram, the reading angle was varied by rotating the crystal to test the angular selectivity. Also a test experiment for angular selectivity was performed for comparison. In this case, the fiber and coupling components in the reference arm of Fig. 1 were replaced with a beam expander. The diffraction intensity variation with respect to the angular deviation is plotted

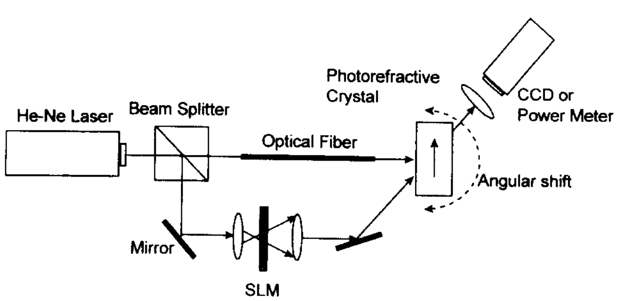

FIG. 1. Experimental setup for angular multiplexing using fiber speckles for the image storage system.

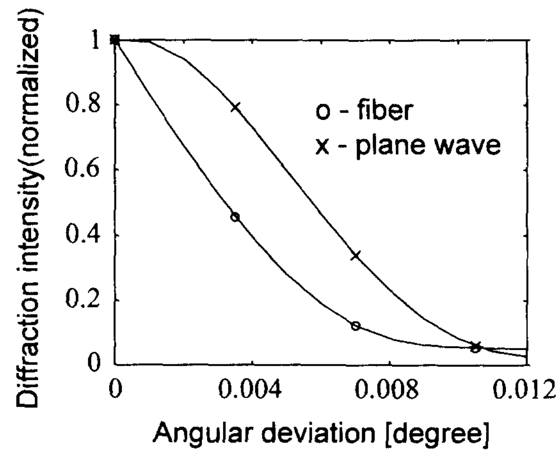

FIG. 2. Diffraction intensity (normalized to its maximum) with respect to angular deviation. o; fiber speckle referencing, x; plane wave referencing.

FIG. 3. Images read from the angularly multiplexed volume holograms.

in Fig. 2. For the test using the fiber speckle referencing, the speckle pattern was fixed and only the angle of the crystal was changed. The angular selectivity in the method using the speckle pattern is better than that using the plane wave. This is because the reference beam with speckles has a complex wavefront. This improvement in selectivity enables holograms to be multiplexed more closely, and can enhance data storage density.

Some image data were multiplexed with angular multiplexing using a speckle pattern. The angular spacing of multiplexed holograms shown in Fig. 3 was 0.028^{o}. Some ghost images are shown around retrieved images, but are negligible in their intensities. In this experimental setup, the angular multiplexing requires a mechanical moving part. This shortcoming can be removed by adopting acousto-optic deflectors[9,10] for steering a collimated fiber speckle beam. This can enable fast access for the storage system.

III. SHIFT MULTIPLEXING

A speckle pattern shifted by a distance larger than the lateral correlation length becomes uncorrelated with the original pattern. This property can be applied to shift multiplexing. The shift multiplexing can involve just one speckle pattern which is shifted for multiplexing within the photorefractive crystal. Even if the holograms written by the shift multiplexing partially overlap in the storage medium, they can be separately retrieved if the spatial shifts are larger than the lateral correlation length of the speckles. As shown in Ref. 3, the fiber speckle has good spatial selectivity, which is an advantage in high density multiplexing. The spatial movement is two-dimensional, hence the shift multiplexing is a two- dimensional addressing method. This method requires a mechanical moving part, hence the method using a disk-type hologram medium is suitable for the storage system [11,12]. This arrangement uses two-dimensional shift movement for storing and retrieving holograms.

IV. MODE-SCRAMBLING MULTIPLEXING

General phase code multiplexing uses orthogonal phase planes[2]. In the proposed method of mode-scrambling multiplexing using a multimode optical fiber, each hologram is stored and retrieved with a different speckle pattern generated by mode scrambling of the multimode fiber. Two examples of the speckle patterns are shown in Fig. 4. The two speckles have their unique patterns, which come from different mode combinations. The number of obtainable speckle patterns is dependent on the mode scrambler. In our experimental setup, only a few patters were available for multiplexing holograms. This can be increased by improving the mode scrambler. However, due to the restricted number of orthogonal patterns, mode-scrambling multiplexing could be better if used as a hybrid method in combination with other multiplexing techniques.

Generally, a speckle pattern coming from a multimode fiber consists of the superposition of many modes in the fiber. These modes have arbitrary field amplitudes and phases. A speckle pattern from a fiber is changed or transformed to another speckle pattern by variation of surrounding conditions of the fiber, such as stress, temperature, etc., or by giving some deformation to the fiber. This is because the variation of these fiber conditions changes field amplitudes and phases of the modes in the fiber, which produces a different speckle pattern in superposition.

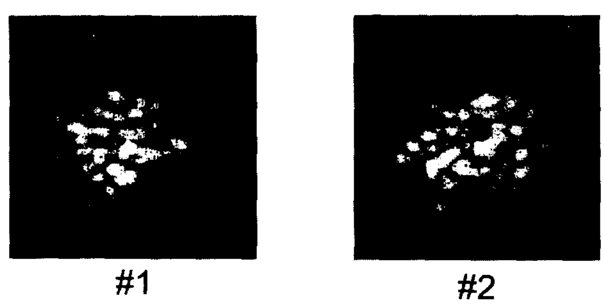

FIG. 4. Example of speckle patterns from a multimode fiber obtained by mode scrambling.

V. HYBRID MULTIPLEXING

The hybrid multiplexing is a method which enlarges the multiplexing capacity by adopting several readout mechanisms. Here we demonstrated the hybrid multiplexing using both the shift and the mode-scrambling multiplexing methods at the same time. The experimental setup is shown in Fig. 5. Mode scrambling and spatial shifting methods were used at the same time. The mode scrambling was done by giving deformation to the multimode fiber, and the spatial shift was done by moving the photorefractive crystal as shown in the figure. In this method, an image was stored with a speckle pattern at one spatial position of the reference fiber. Then, another image was stored with a different speckle pattern at the same position, or with the same speckle pattern at a different reference fiber position. The address information was in the speckle pattern and the spatial position of the reference fiber.

In Fig. 6, some images reconstructed from multiplexed holograms using both the shift and the mode-scrambling multiplexing methods are presented. In the shift multiplexing, the optical fiber was shifted by $10\mu m$. Crosstalk-induced ghost images behind reconstructed images were negligible in Fig. 6. The crosstalk appeared because the speckle patterns in this experiment were not fully orthogonal. This crosstalk can be further reduced by increasing the number of modes and ensuring enough phase deviation between the modes.

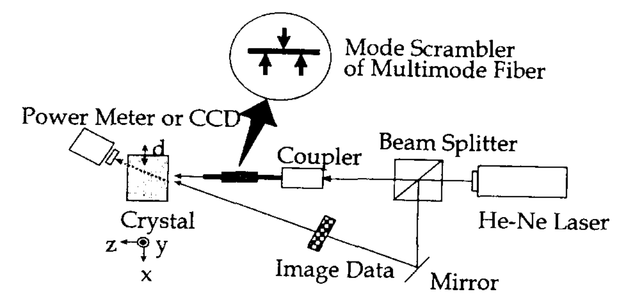

FIG. 5. Experimental setup for the hybrid multiplexing using both the shift and the mode scrambling methods.

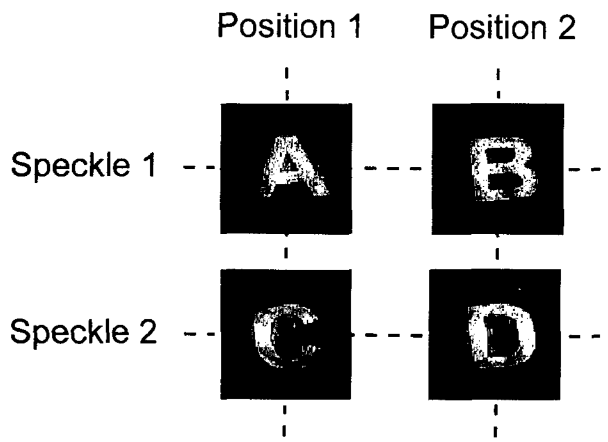

FIG. 6. Images reconstructed from the multiplexed holograms by the hybrid multiplexing method.

VI. DISCUSSIONS

The scheme of using a fiber speckle pattern as a phase code does not entirely eliminate crosstalk, unlike the method of using orthogonal patterns[13]. In case of the mode scramble multiplexing, as the number of modes forming a speckle pattern increases, the crosstalk will decrease. And, if the phase differences between modes become more random, the crosstalk will also decrease. The length of the multimode fiber used in the experiment was 9cm. This short length makes some cladding modes remain through the fiber and hence makes the number of coupled modes larger than that in a normal multimode fiber. But this short length makes it difficult to induce large phase variations of the modes. Hence, there is a trade-off for a good SNR(signal-to-noise ratio). The short fiber length has another advantage of better stability. The fiber is susceptible to external disturbance which makes a speckle pattern unstable. But shortening a fiber reduces disturbances, and enhances the stability. In our experiment, the optical setup showed repeatability and immunity to external disturbances. The effect of temperature variation will be tested in future research.

VII. CONCLUSION

Fiber speckle patterns produce random-phase codes with a simple setup. The various multiplexing methods with fiber speckle patterns, such as angular multiplexing, shift multiplexing, and mode-scrambling multiplexing, have some advantages over the conventional methods in constructing a storage system. These methods can be combined to make a hybrid system. Quantitative analysis on crosstalk noise, which is due to the imperfection in orthogonality between speckle patterns, needs more study.

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