Compact Holographic Storage by Using a Fiber Bundle to Guide the Reference Beam

Jiasen ZHANG, Shin YOSHIKADO, and Tadashi ARUGA

Communications Research Laboratory
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795

(Received March 28, 2003)

We propose a compact volume holographic storage system, in which a fiber bundle is used to guide the reference beam. For demonstrating the system, phase-coded multiplexing is implemented by changing the incident direction of the reference beam upon the fiber bundle. Shift multiplexing is also performed by moving the medium. Because no lens or complicated phase modulation system is necessary in the reference arm, the holographic storage system can become more compact. Multiple images are stored in a crystal using the phase coded and shift multiplexing techniques.

Key Words: Optical holographic storage, Phase coded multiplexing, Shift multiplexing

1. Introduction

Optical holographic storage using photorefractive crystal has been intensively studied for several decades due to its potential for high storage densities and fast readout.[1] There are several methods, such as spatial multiplexing,[2,3] angular multiplexing,[4] wavelength multiplexing,[5,6] phase encoding,[7,8] and shift multiplexing,[9,10] to store multiple holograms within a storage medium. Among these methods, angular multiplexing is probably the most common, in which the reference beam is incident upon the crystal at difference angle to record each hologram. The most suitable method for the implementation of a holographic three-dimensional disk[11] may be the shift multiplexing method because simply rotating the disk can implement shift multiplexing and access different locations on the disk surface. In order to be competitive, however, these optical systems need to reduce their volume to become compact.

In this paper, we demonstrate phase coding and shift multiplexing using a fiber bundle to guide the reference beam onto the storage medium. Phase coding is implemented by changing the incident direction of the reference beam upon the fiber bundle using a wedge prism. The beam rotates in a circle when we rotate the prism in a similar circle about an axis perpendicular to its face. Because the output beam from the fiber bundle has no definite direction, we can shift the medium to realize shift multiplexing. No lens or complicated phase modulation system is necessary in the reference arm; the holographic storage system can become simpler and more compact. The obtained signal-to-noise ratio is high. Multiple images are stored in a crystal by using the phase coded and shift multiplexing techniques. The method can be applied in a holographic three-dimensional disk system as an alternative approach of the two-dimensional methods of optical storage, such as CD, DVD, and Magneto-optic disks.

2. Experimental setup

In the experiment, we used the 90° geometry[12] and the schematic diagram of the experimental setup is shown in Fig. 1. An linearly s-polarized laser beam from a cw frequency doubled Nd:YVO_4 laser operating at 532 nm was divided into two beams by a beam splitter. In the reference arm the laser beam was incident upon the input face of a fiber bundle after it passed through a wedge prism, which was mounted on a rotation stage. The wedge prism could rotate in a range of 360° about an axis perpendicular to its face with a resolution of 0.00025°. Thus, the incident direction of the reference beam could be changed by rotating the wedge prism. The fiber bundle used in the experiment was a commercial one (Nippon P.I. Co., Ltd., PLG-1-500S-6) with a diameter of 6 mm. The fiber bundle, which was a bundle of glass fibers with a diameter of 50 μm, was an incoherent bundle, which means that the arrangement of the fibers of the input face dose not corresponding to that of the output face. The transmittance of the laser beam through the fiber bundle was ~ 61 %. The output reference beam from the fiber bundle was incident upon a $LiNbO_3$:Fe crystal (1 cm × 1 cm × 1 cm, c-axis at 45° in the horizontal plane, 0.015 % Fe-doped). Because the polarization of the output laser beam became random after it passed through the fiber bundle, a polarizing filter was used to polarize the reference beam to linearly s-polarization. In the object arm, the object beam was a plane wave that was expanded by a beam expander (BE). It was modulated by a spatial light modulator (SLM) before it was incident upon the crystal. The distance between the SLM and the crystal was about 10 mm. The output signal was monitored by a power meter or a CCD camera. The crystal was mounted on a linear stage, which could shift the crystal along the z-axis shown in Fig. 1 with a resolution of 0.05 μm.

The geometry of the reference beam is shown in Fig. 2. α is the deviation angle of the wedge prism. θ is the rotation angle of the prism about an axis perpendicular to its face. If the opti-

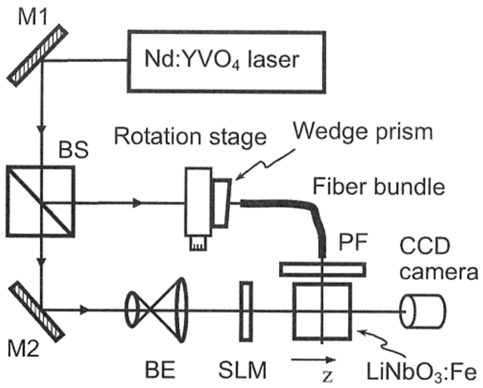

Fig. 1 Schematic diagram of the experimental setup of the holographic storage system. BE, beam expander; M1, M2, mirrors; BS, beam splitter; PF, polarizing filter; SLM, spatial light modulator.

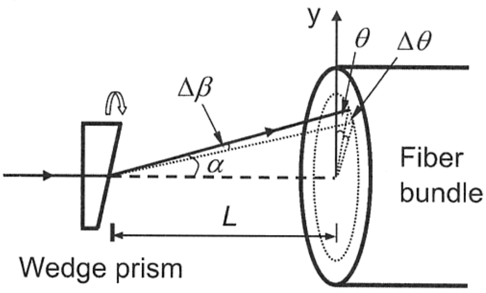

Fig. 2 Geometry of the reference beam.

cal axis is parallel to the axis of the fiber bundle and the prism, the incident angle of the reference beam upon the fiber bundle should be kept to α. In the experiment, we did not adjust exactly the system to be such a situation. L is the distance between the prism and the fiber bundle. When we rotate the prism from θ to $\theta + \Delta\theta$, the change of the incident direction upon the fiber bundle is $\Delta\beta$. When $\Delta\theta$ is small, $\Delta\beta$ can be described as

$$\Delta\beta = \Delta\theta \cdot \sin\alpha \text{ or } \Delta\theta = \Delta\beta / \sin\alpha. \quad (1)$$

3. Experimental results and discussion

3.1 Phase coded multiplexing

The phase of the reference beam can be modulated by changing the direction of the incident beam upon the fiber bundle. Thus, we can implement phase coded multiplexing by rotating the wedge prism. Here, the crystal is not shifted. In order to determine the angular selectivity $\Delta\theta_{min}$ (or $\Delta\beta_{min}$), which is the minimal separation required between holograms, we measured the diffraction efficiency with respect to the angular deviation $\Delta\theta$. Two wedge prisms, whose deviation angles were 8° (the wedge angle was 15.3°) and 4° (the wedge angle was 7.9°), respectively, were used in the experiment. The distance between the prism and the fiber bundle was set to be $L \approx 10$ mm. The experimental results are shown in Fig. 3 for the two prisms. When $\Delta\theta \geq 0.15°$ and 0.3° for $\alpha = 8°$ and $\alpha = 4°$, respectively, the signal-to-noise ratios are better than 200, which is the reciprocal of the normalized intensity. Thus, we set the minimal separations $\Delta\theta_{min}$ 0.15° and 0.3 for $\alpha = 8°$ and $\alpha = 4°$, respectively. These angles respond to a change of the incident direction $\Delta\beta_{min} = 0.02°$ according to Eq. (1). In the method, β can change in a range of 0° ~ 360°, as a result, the accessible angular scanning range (S_A)

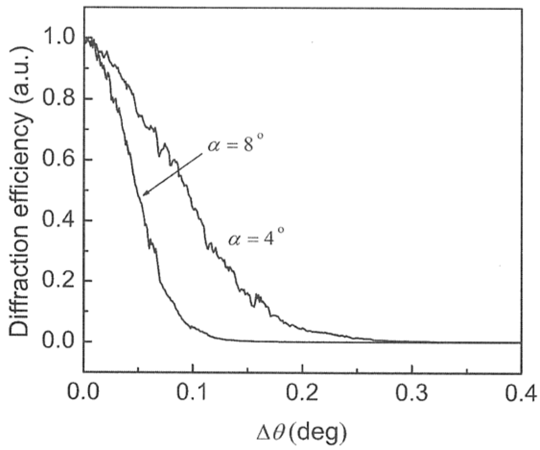

Fig. 3 Diffraction efficiencies versus the angular deviation $\Delta\theta$ using the wedge prisms of $\alpha = 8°$ and $\alpha = 4°$, respectively.

for the prism was 360°.

We stored 100 images in the crystal using phase coded multiplexing and the wedge prism with a deviation angle of 8°. The angular separations between successive holograms were set to be $\Delta\theta = 0.15°$. The recording time for each image was 6 seconds. Nine reconstructed images are shown in Fig. 4. There is no apparent cross talk in the reconstructed images. Sometimes interference patterns appear in the output images, which rise from the interference between the output beam and its specular reflection beam on the surfaces of the crystal. This problem can be solved by using antireflection coatings to the crystal.

In general phase encoding method, usually the reference beam is modulated by a complicated phase spatial light modula-

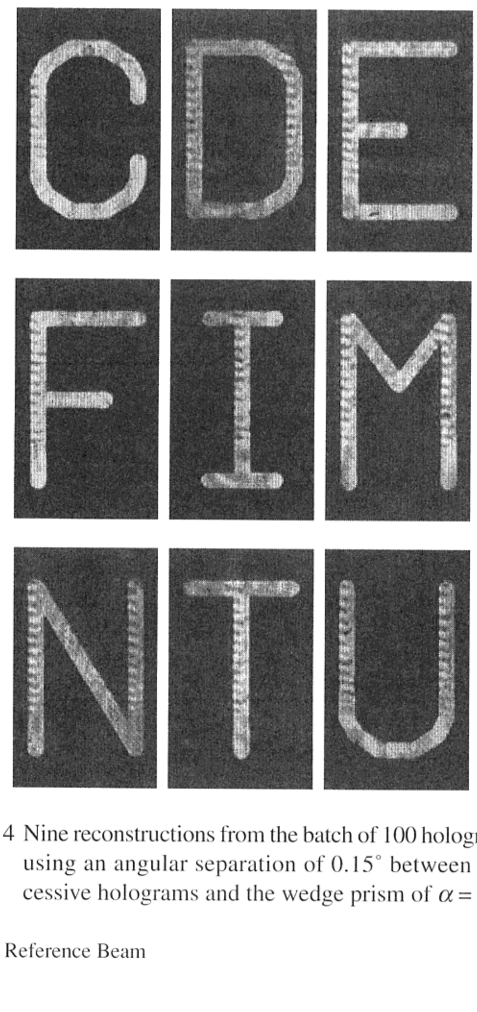

Fig. 4 Nine reconstructions from the batch of 100 holograms using an angular separation of 0.15° between successive holograms and the wedge prism of $\alpha = 8°$.

tor.[13-16] In this paper, we used a fiber bundle to guide the reference beam and the phase of the reference beam was modulated by changing the direction of the laser beam upon the fiber bundle using a wedge prism. The distinctive feature of this method is simplicity. In the experiment, a commercial fiber bundle with a length of 50 cm was used. By using a short fiber bundle, the system can become compact. In the method, the accessible angular scanning range S_A of the prism is 360°. For a prism with a deviation angle of 8°, the geometric storage bandwidth, B_A, which is defined as the ratio of S_A to $\Delta\theta_{min}$, is 2400. The diameter of the incident beam upon the fiber bundle was 1.4 mm in full width at half maximum. Two ways can increase the selectivity: (1) using a reference beam with a larger diameter; (2) using a wedge prism with a larger deviation angle. In order to increase the storage capacity of the system further, we can change the position of the crystal to store images at multiple locations.

3.2 Shift multiplexing

In the reference arm, the laser beam scattered from the fiber bundle. Thus, the reference beam was a diverged laser beam. We can consider this condition as shift multiplexing using a reference beam that is an overlap of many spherical waves.[9] So that, we can use the fiber bundle to guide the reference beam to implement shift multiplexing by shifting the medium along z-axis. We expected that this method have a better selectivity and a higher signal-to-noise ratio than using a spherical wave referencing. Here we define L' as the distance between the output face of the fiber bundle and crystal.

When we performed shift multiplexing, we did not change the direction of the reference beam upon the fiber bundle. First, we measured the diffraction efficiency with respect to the shift distance of the crystal for L' = 12 mm, 22 mm, and 32 mm, respectively. We used a uniform object beam and the reference beam to write a grating at the original position. Then, we used the reference beam to read the grating. The intensity of the diffraction beam was measured while moving the crystal about its original position. The experimental results are shown in Fig. 5. When the shift distance equals 2.4 μm, the signal-to-noise ratio is about 300 for L' = 12 mm. Because of the asymmetry of the fiber bundle, no period has been found, which appeared in the case of a reference beam that is composed of multiple plane waves because of the periodicity of the array.[9]

We stored 100 images in the crystal with a spatial separation of 3 μm and L' = 22 mm. Here we used a uniform exposure time of 6 second for all holograms because of the lack of a computer control system. Some of the reconstructed images are shown in Fig. 6. No evident cross talk has been found.

By using a fiber bundle to steer the reference beam, the system becomes simpler and more compact. In this paper, we used the 90° geometry that the reference beam and the object beam are incident on the crystal from different surface. On the other hand, the two beams can also be incident on the same surface of the medium. In the experiment, a crystal was used as the medium and the storage capacity was limited by its volume. Because there is no period or sidelobe; the signal-to-noise ratio is fairly high; and multiplexing can be implemented by just moving the medium, this method is very suitable for holographic three-dimensional disks[11] supporting 100 Gbytes ~ 1 Tbytes per 120-mm disk with a readout rate of more than 200Mbits/s.[17]

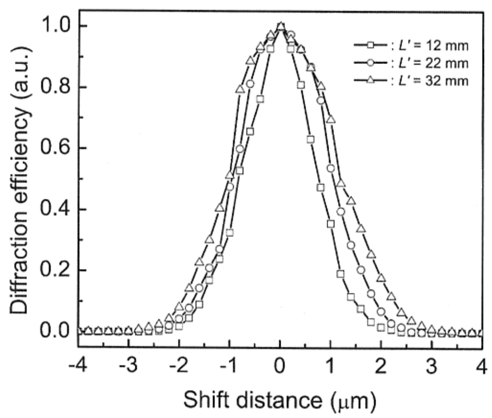

Fig. 5 Diffraction efficiencies versus the shift distance for the distance between the output surface of the fiber bundle and the crystal L' = 12 mm, 22 mm, and 32 mm, respectively.

4. Conclusion

We proposed a more compact holographic storage system comparing with the traditional holographic storage methods using a fiber bundle to guide the reference beam. Phase coded multiplexing was implemented by changing the incident direction of the reference beam upon the fiber bundle using a wedge prism. We also demonstrated shift multiplexing using a fiber bundle to guide the reference beam. The spatial separation was 2.4 μm when the distance between the output surface of the fiber bundle and the crystal was L' = 12 mm. Multiple images were stored in a crystal using the two kinds of multiplexing methods and no evident cross talk has been found. By using a fiber bundle, the system became more compact and simpler compared with the conventional holographic methods. Phase coded multiplexing and shift multiplexing can be implemented at the same time so

Fig. 6 Nine reconstructions from the batch of 100 holograms using shift multiplexing. Here the spatial separation between successive holograms was 3 μm and L' = 22 mm.

the capacity can be increased.

References

1) L. Solymar, D. J. Webb, and A. Grunnet-Jepsen: The Physics and Applications of Photorefractive Materials (Clarendon Press, Oxford, 1996), Chap. 12.
2) W. J. Carson: Appl. Opt. **13** (1974) 896.
3) L. d'Auria, J. P. Huignard, C. Slezak, and E. Spitz: Appl. Opt. **13** (1974) 808.
4) F. H. Mok, M. C. Tackitt, and H. M. Stoll: Opt. Lett. **16** (1991) 605.
5) F. T. S. Yu, S. Wu, A. W. Mayers, and S. Rajan: Opt. Commun. **81** (1991) 343.
6) G. A. Rakuljic, V. Leyva, and A. Yariv: Opt. Lett. **17** (1992) 1471.
7) T. F. Krile, M. O. Hagler, W. D. Redus, and J. F. Walkup: Appl. Opt. **18** (1979) 52.
8) J. E. Ford, Y. Fainman, and S. H. Lee: Opt. Lett. **15** (1990) 1088.
9) D. Pasltis, M. Levene, A. Pu, and G. Barbastathis: Opt. Lett. **20** (1995) 782.
10) J. Zhang, S. Yoshikado, and T. Aruga: Appl. Phys. Lett. **82** (2003) 25.
11) H-Y. S. Li and D. Psaltis: Appl. Opt. **33** (1994) 3764.
12) G. W. Burr, F. H. Mok, and D. Psaltis: Opt. Commun. **117** (1995) 49.
13) C. Denz, G. Pauliat, and G. Rossen: Opt. Commun. **86** (1991) 171.
14) C. Alves, G. Pauliat, and G. Rossen: Opt. Lett. **19** (1994) 1894.
15) C. Denz, K.-O. Müller, T. Heimann, and T. Tschudi: IEEE Journal of Select. Topics in Quantum Electron. **4** (1998) 832.
16) C. C. Chang, K. L. Russell, and G. W. Hu: Appl. Phys. B **72** (2001) 307.
17) D. Psaltis and G. W. Burr: Computer **31** (1998) 52.