4-2 Image Storage Techniques using Photorefractive Effect

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Optical image storage techniques using the photorefractive effect are presented. In these techniques, the random reference multiplexing scheme is introduced to the holographic recording process in order to increase the storage capacity. The common feature of our techniques is the use of a bundle of multimode fibers placed in the optical path of reference wave. This approach can automatically impose quasi-random patterns on the wavefront when the reference wave penetrates the fiber bundle. As a proof-of-principle, experiments of recording holograms are performed with a $LiNbO_3$ crystal. The results show that the use of fiber bundle enables us to build a simple and compact optical setup keeping the capacity of hologram multiplexing.

Keywords
Photorefractive, Hologram multiplexing, Optical memory, Fiber bundle

1 Introduction

Optical holographic data storage using the photorefractive effect has been extensively studied. Several schemes for hologram multiplexing have been examined and successfully improved the storage capacity [1]-[7]. Recently, an optical fiber has been employed in optical setups as a device to impose a quasi-random phase distribution [8]-[10]. Among the methods for hologram multiplexing, the wavelength multiplexing scheme uses the sensitive dependence of random patterns on the wavelength of light input into a fiber [8]. In the spatial multiplexing scheme, cross-talks between recorded holograms are effectively suppressed due to little correlation of a randomly blurred wavefront with its spatially shifted pattern [9]. Furthermore, in the angular multiplexing scheme, the feature of little correlation between the random wavefront and its angularly altered pattern is also utilized to separate holograms [10].

As well as the increase of storage capacity, to build a simple and compact setup is another interest. For this purpose, a single multimode fiber has been replaced by a bundle of fibers to steer the reference beam without any lenses or mirrors[11][12]. In our first attempt, the recording medium is mounted on a linear stage and moved along a direction perpendicular to the axis of the fiber bundle. Thus the random reference multiplexing is combined with the spatial shift multiplexing to enhance the hologram selectivity of the system [12].

Since the use of a linear stage requires excessive space around it for the stage's movement, we have explored another method which is more suitable for a compact setup. In stead of the linear movement of a recording medium, we have decided to use a wedged prism mounted on a rotary stage. In this stage, the prism is rotated around the axis parallel to the bundle's axis, which controls the propagation angle of light to conically illuminate the input surface of the fiber bundle [13]. We here exploit the dependence of random patterns out of the fiber bundle on the propagation angles of light exposing the bundle.

When we look at the way to use a fiber bundle, the bundle has been placed in the optical setups as a fixed device together with some active devices. Since the most direct approach for simple setups must be reduction of elements integrated in the optical system, we employ the fiber bundle as an active device and eliminate other moving parts. Here, we concentrate on a fact that by changing the propagation angle of a beam illuminating the input surface of a fixed fiber bundle, we can make the wavefront out of the bundle to form a different pattern. Similar effects can be observed by rotating the fiber bundle exposed to a beam of fixed propagation angle [14]. This reinterpretation in the use of the fiber bundle contributes to achieve more compact optical setups.

In this work, we present these approaches with experimentally measured results and show the optical setups simplified but keeping the capacity of hologram multiplexing.

2 Spatial shift of recoding medium

In the following experiments, holograms are stored in a $LiNbO_3$ crystal by the light at the wavelength of 532 nm. For this wavelength, the principle refractive indices of the crystal are known to be 2.32 for ordinary rays and 2.23 for extraordinary rays [15]. Although the extraordinary polarization shows larger diffraction efficiency than the ordinary polarization does, the use of the ordinary polarization makes the hologram selectivity of the system sensitive due to the larger refractive index of the crystal. The ordinary polarization also allows us to set the propagation directions of the object and the reference beams to be orthogonal on a plane containing the crystal's optical axis. This layout brings an advantage in reading holograms that the reference beam hardly overlaps with the reproduced images. Therefore, we apply the ordinary polarization for hologram multiplexing throughout our experiments.

In our first approach, we attend the shift multiplexing scheme under the influence of randomly blurred referencing. The experimen-

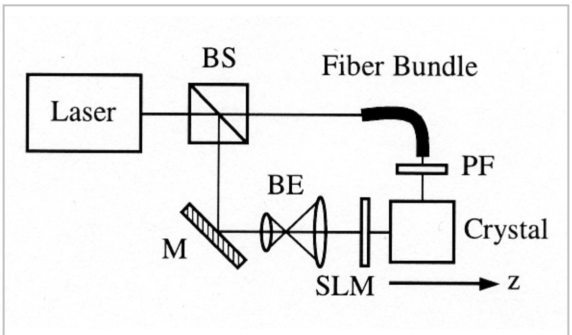

Fig.1 Experimental setup

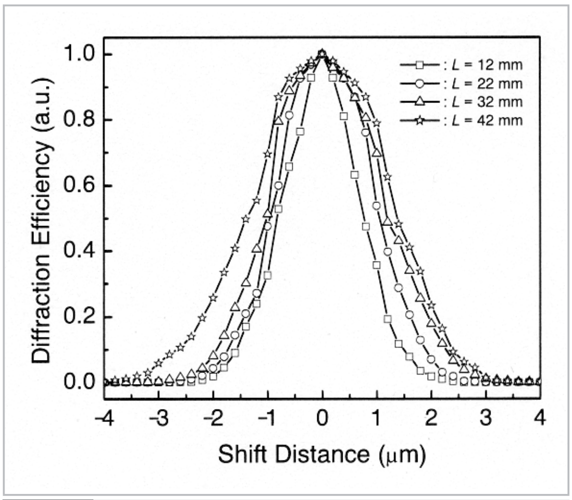

Fig.2 Diffraction efficiency of a single hologram

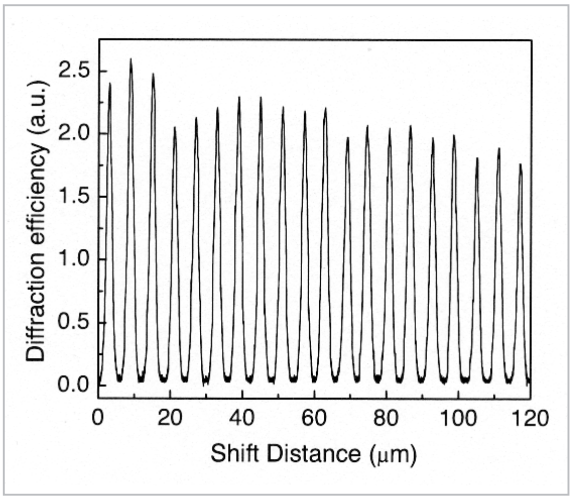

Fig.3 Diffraction efficiency of serial holograms

tal setup is shown in Fig.1, where BS is a beam splitter, M is a mirror, BE is a beam expander, SLM is a spatial light modulator and PF is polarization filter. We use a cubic 45 deg.-cut $LiNbO_3$:Fe crystal of the side length of 1 cm. The light source is a frequency-doubled Nd:YVO_4 laser at the wavelength of 532 nm. The fiber bundle is commercially available, and its length is 50 cm, the diameter is 6 mm, and the power transmittance is about 60 %. The crystal is mounted on a linear stage which is moved along the z-direction with the resolution of 0.05 μm to record holograms.

To estimate the amount of spatial shift required in the hologram multiplexing, we measured the diffraction efficiency as a function of the shift distance. The result is shown in Fig.2, where the distance between the bundle's output surface and the input surface of the crystal is given as L. According to Fig.2, we can consider that the hologram multiplexing is well performed with 2 μm shift when L=12 mm, and 3 μm shift if L=22 mm. For the further confirmation, we set L=22 mm and measure the diffraction efficiency of serial holograms as shown in Fig .3, where the exposure time for all holograms is 6 sec. The separation of each hologram is clearly observed. Thus, the hologram multiplexing can be performed by the spatial shift of the recording medium.

3 Conical illumination by wedged prism

In stead of using the linear stage, a wedged prism is mounted on a rotary stage and put in front of the input surface of the fiber bundle as shown in Fig.4. The wedged prism manipulates the incident angle of the reference wave onto the fiber bundle and changes the output wavefront. Since a wavefront blurred by the fiber bundle at a certain incident angle has little correlation with that obtained at another angle, we can employ the random referencing scheme for hologram multiplexing.

In order to determine the angular selectivity in the rotary movement of the wedged prism, we use a motorized rotation stage with the resolution of 0.005 degrees and measure the diffraction efficiency with respect to the rotary angle $\Delta\theta$. The fiber bundle is the same one as used in Fig.1. The measured diffraction efficiency is shown in Fig.5, where two prisms of the deviation angle α of 4 degrees and 8 degrees are used for the estimation. According to Fig.5, we find that the case of α=8 degrees brings steeper decrease in the diffraction efficiency than that of α=4 degrees. Thus, we determine to use the wedge prism of α=8 degrees and perform the hologram multiplexing. The rotary angle $\Delta\theta$ is set to 0.15 degrees to decrease the diffraction efficiency to almost 0.

Figure 6 shows an example of the reproduced image, where no apparent cross-talks are observed. Although some interference patterns appear in the output images, this problem can be solved by using antireflection coatings to the crystal.

4 Rotary movement of fiber bundle

Following concept of the schematic drawings Figs. 7(a) and 7(b), we modify the interpretation on the use of a fiber bundle. In Fig.7(a), a fiber bundle is placed as a fixed device and the input surface is conically illuminated. When the illumination angle of the light is controlled, the quasi-random pattern of the light output from the bundle is changed. Similar result can be obtained by means of the fiber bundle with a rotary movement as shown

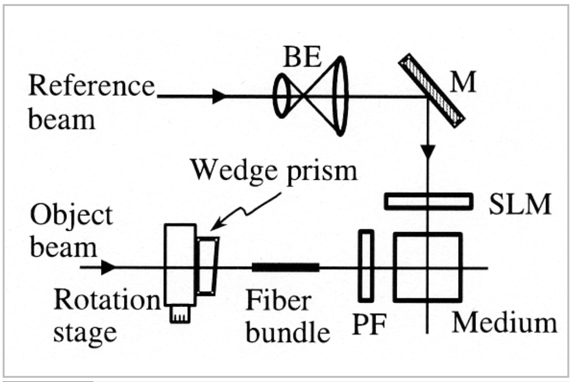

Fig.4 Experimental setup

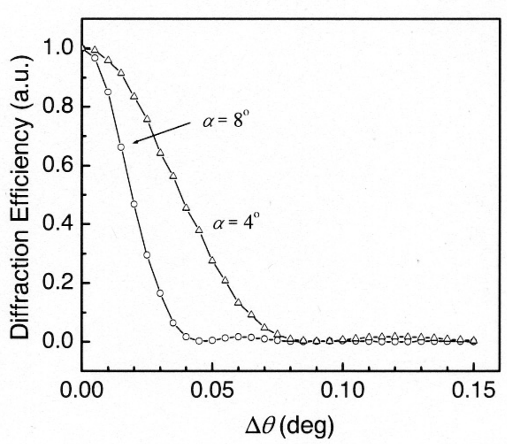

Fig.5 Diffraction efficiencies

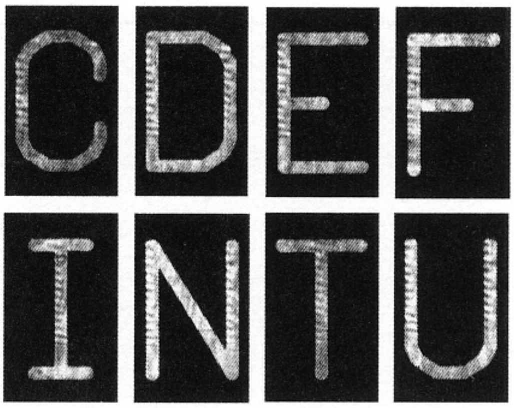

Fig.6 Eight reconstructions from the batch of 100 holograms

in Fig.7(b), where the bundle's input surface is conically illuminated by a light of fixed propagation angle. According to the interpretation, we deliberately give a tilt to the incident angle of the light to the fiber bundle in our experiment.

The experimental setup is shown in Fig.8, where FB is an optical fiber bundle and the rotary movement is depicted with a bold arrow in the inset. The fiber bundle employed in the setup is commercially available and has the numerical aperture of 0.56. The transmittance is 60 % for the light of visible range. For a rotary movement, the bundle is covered with a protective jacket of aluminum around the side of the cylinder and is held in a motorized rotary stage used in the experiment shown in Fig.4. The length is cut to 1 cm and the diameter is also 1 cm in which multimode glass fibers of the diameter 50 μm are tied together, i.e. about 40,000 fibers are contained.

The tilt angle of light illuminating the bundle was 4.7 degrees measured from the normal to the bundle's input surface. The polarization of a beam reflected by PBS is ordinary and that passing through PBS is extraordinary. Since the polarization of light passing through the fiber bundle becomes disarrayed, the ordinary polarization can be automatically obtained.

The total power of exposing the crystal is 20 mW and the power ratio of the reference to the signal is 10:1. The hologram multiplexing is performed, where we write an Arabic numeral 1 for 30 seconds at first, turn off the object beam, and rotate the fiber bundle 0.2 degrees. We then turn on the object beam again on which the numeral 2 is imposed and write it for 30 sec. This procedure is repeated until the figure 30 is written. In the process of reading holograms, the recorded holograms are read out in numerical order. Figure 9 shows the images just as monitored by the CCD camera. The measured power of the read out numeral 1 is 0.663 mW before writing the numeral 2 and 0.177 mW at the begging of the reading process, which means 3.7 % and 0.98 % of the incident power of reference beam. Although the decrease of diffraction efficiency is observed due to hologram multiplexing, the recorded holograms are successfully read out with a simple manipulation of rotating the fiber bundle in this experiment.

With respect to the size of optical setups, reduction of the dimension at the part serving a function for hologram multiplexing makes a strong contribution to the compact systems. In our approach, the part is provided by using a fiber bundle of 1 cm length without any other elements such as lenses or moving mirrors. Besides, since the fiber bundle is rotated around an axis parallel to the plane in which optical elements are arranged, we do not need to keep an excessive space for the rotary movement.

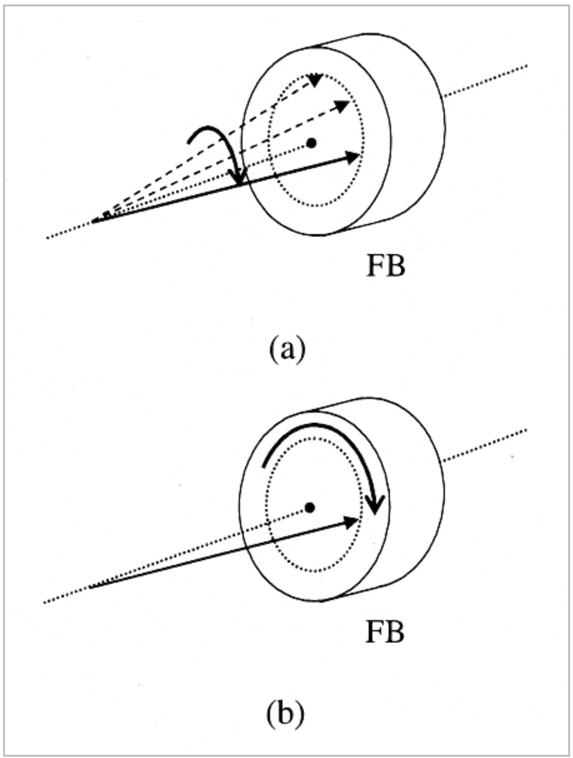

Fig.7 (a) A fixed fiber bundle with conical illumination and (b) a fiber bundle in rotary movement with a fixed illumination angle

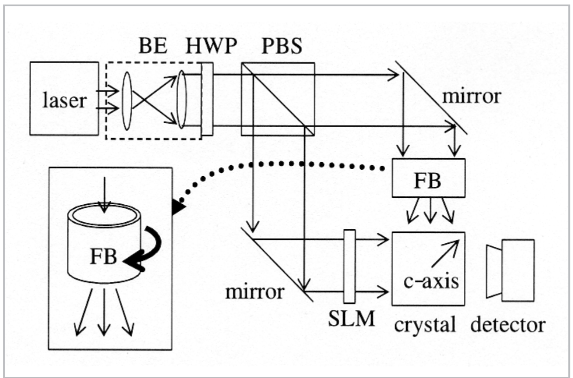

Fig.8 Experimental setup

5 Conclusions

In this work, we have presented optical

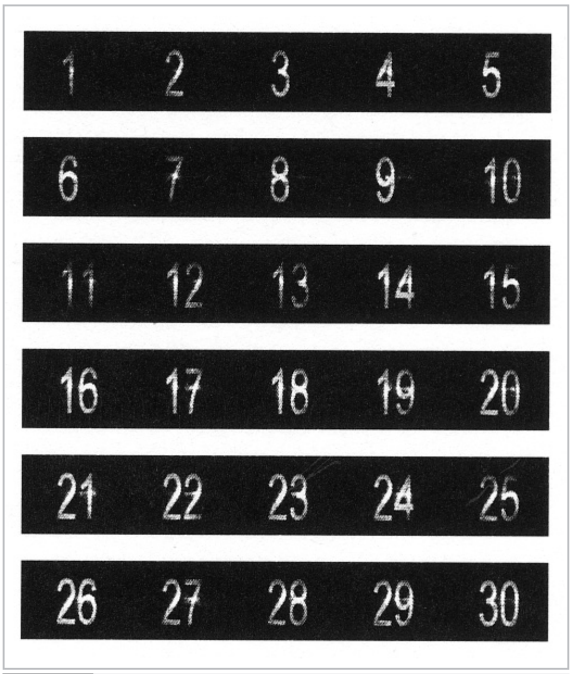

Fig.9 Reproduced images

image storage techniques using the photorefractive effect, where the random reference scheme has been introduced to increase the storage capacity of the system. The common feature of our techniques is the use of a bundle of multimode fibers to produce random reference patterns. We have proposed three methods. In the first method, the crystal exposed to the output light from the fiber bundle has been spatially shifted to record plural holograms. In the second approach, a wedge prism has been employed to control the light illuminating the input surface of the bundle. The latest method has directly rotated the fiber bundle and eliminated other moving parts in the optical setup. The experimental investigations of these methods have shown the validity to build a compact setup with keeping the capacity of hologram multiplexing.

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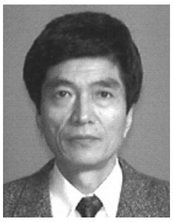

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