SPECIAL TOPIC — Physical research in liquid crystal

Holographic storage of three-dimensional image and data using photopolymer and polymer dispersed liquid crystal films*

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We present holographic storage of three-dimensional (3D) images and data in a photopolymer film without any applied electric field. Its absorption and diffraction efficiency are measured, and reflective analog hologram of real object and image of digital information are recorded in the films. The photopolymer is compared with polymer dispersed liquid crystals as holographic materials. Besides holographic diffraction efficiency of the former is little lower than that of the latter, this work demonstrates that the photopolymer is more suitable for analog hologram and big data permanent storage because of its high definition and no need of high voltage electric field. Therefore, our study proposes a potential holographic storage material to apply in large size static 3D holographic displays, including analog hologram displays, digital hologram prints, and holographic disks.

Keywords: holographic displays, holographic information storage, photopolymer, collinear holography

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1. Introduction

Holographic storage is expected to become one of the main optical storage techniques because of its significant advantages, such as large capacity, high density, fast data transmission, and because it is spatially addressable parallel.[1–3] This technique relates to many significant areas, such as holographic three-dimensional (3D) displays, holographic disks, volume holographic correlators, and holographic prints,[4–7] making it an important research area. Recently, some achievements have been reported. One of the good results is the news that the GE Global Research announced 500 GB data could be recorded on media in an ordinary DVD size in their holographic data storage system.[8] Furthermore, Horimai *et al.* developed a collinear holographic system to write and read data for holographic disks, greatly simplifying the original optical systems.[4] Chen *et al.* proposed a dually modulated multiplexed holographic storage technique for holographic disks, providing a novel idea to improve storage capacity.[5] Cao *et al.* combined holographic storage and optical pattern recognition. They have made great progress in volume holographic correlators.[6] Blanche *et al.* used a holographic printing technique to time-sequentially write each "hogel" of computer-generated holograms into recording media, and obtained 3D reconstructed images.[7]

Recording media is one of the key factors in holographic storage. Holographic storage materials mainly include silver halide,[9] inorganic crystals,[10–13] and polymers.[14,15] Among these media,[16–34] photopolymer is considered to be a good candidate for big data storage and other commercial applications because it has some good properties such as high sensitivity, large optical nonlinearity, simple production process, and low cost.

The difference between the polymer and polymer dispersed liquid crystal (PDLC) for holographic storage has not been discussed before. In addition, in-line holographic storage using TMPTA-based polymer has also been reported yet in previous works. In this paper, we investigate holographic storage of 3D images and data in photopolymer films without an applied electric field. The diffraction efficiency in the film can exceed 80% and the definition of hologram is better than those in the PDLC film. This work would be useful to study holographic recording materials.

2. Schematic of hologram formation in photopolymer

Figure 1 shows a schematic diagram of hologram formation in a photopolymer sample. The object beam and reference beam are set as the collinear, and they are used to generate interference pattern inside the sample. In the bright areas, the excited initiators generate radicals, and the monomers are polymerized by the radical polymerization reaction. The monomer density in the bright areas decreases, therefore, density differ-

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ence is formed, and non-polymerized monomers diffuse from the dark areas into the bright areas. The polymerization reaction terminates until the monomer density regains balance. A difference in refractive index between the bright and dark areas is built in this process. Therefore, the recording beam profile can be stored as the difference in refractive index, and the hologram is formed.

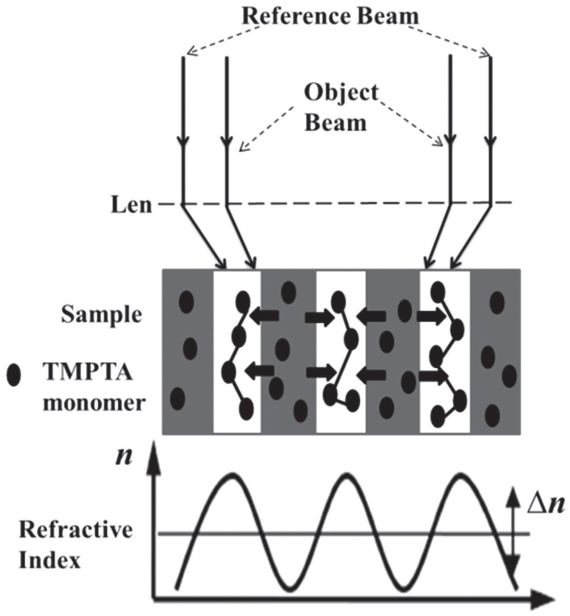


Fig. 1. Formation of hologram in photopolymer sample.

3. Samples and experiments

In our experiment, the photopolymer is a mixture consisting of TMPTA monomer, Rose Bengal, N-phenylglycine and N-vinylpyrrollidone, whose weight ratio is 66:2.0:1.8:25.2. Then, the mixture was made uniform by ultrasonic mixing for about 30 min. A cell was formed by sandwiching two glass substrates with the thickness controlled by Mylar spacers. The uniform mixture was poured into the cell by a capillary action, and then the thin polymer film was fabricated. The preparation process requires the reduction of interference from visible light in case of unnecessary polymerization, and air bladders in the cell should be eliminated as soon as possible. We made a sample of size, 40 mm×40 mm, and a thickness of 100 μm. The absorption spectrum of this sample is illustrated in Fig. 2. The spectral curve shows that this material is sensitive to light at wavelengths of 450 nm–600 nm in visible wavelengths.

The diffraction efficiency was investigated by using two-beam coupling setup, as shown in Fig. 3. An Nd:YAG laser ($\lambda = 532$ nm) was used as the recording light, and an He–Ne laser was used as the probe light. Recording angle θ, the angle between the two coupling beams, was set to be 26°, and the probe angle φ, the angle between the probe beam and the normal perpendicular to the sample plane, was 15°. There was no electric field applied to this film.

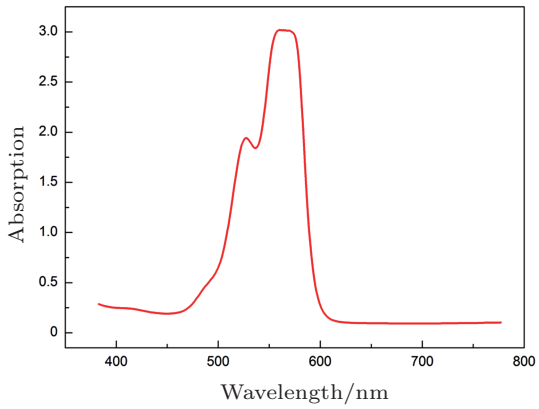


Fig. 2. (color online) Absorption spectrum of the polymer film.

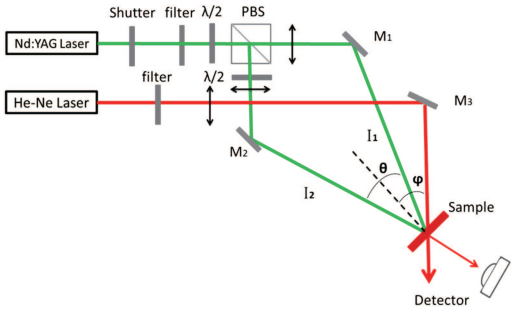


Fig. 3. (color online) Two-beam coupling setup for diffraction efficiency measurement. M1, M2, and M3 are mirrors, PBS is a polarizing beam splitter, $\lambda/2$ is a half-wave plate. Recording angle θ is the angle between the two coupling beams, and the probe angle φ is the angle between the probe beam and the normal perpendicular to the sample plane.

The diffraction efficiency as a function of recording intensities was measured, as illustrated in Fig. 4. In Fig. 4(a), it shows that the diffraction efficiency slowly increases under lower exposure intensity, and it takes about 20 s to reach the maximum, 35%, at the intensity of 1 mW/mm^2. The diffraction efficiency reaches the maximum value of 84% and does not change at the intensity of 5 mW/mm^2, when the recording light is turned off in less than 2 s. However, the diffraction of efficiency would immediately reduce and stay at a low value if the film is over exposed, as shown by the red curve in Fig. 4(a), and exposure time is more than 60 s. This is due to the absorption of this material. The sample absorbs more recording light at higher exposure intensity and too much absorbed energy erases the recorded holograms in the film, then, the diffraction efficiency decreases. Therefore, there is optimal recording time at different exposure intensities. If the recording laser is turned off when the diffraction efficiency reaches its highest level, the diffraction efficiency can maintain the maximum. Furthermore, there is also optimal intensity for the film, i.e., the diffraction efficiency would not increase with the increase of the recording intensity above the optimal intensity. Figure 4(b) shows that the diffraction efficiency of the recorded hologram in film is more than 80% at the recording intensity,

5 mW/mm^2–7 mW/mm^2. Therefore, the recording beam intensity and exposure time should be strictly controlled when the material is used as a holographic storage medium.

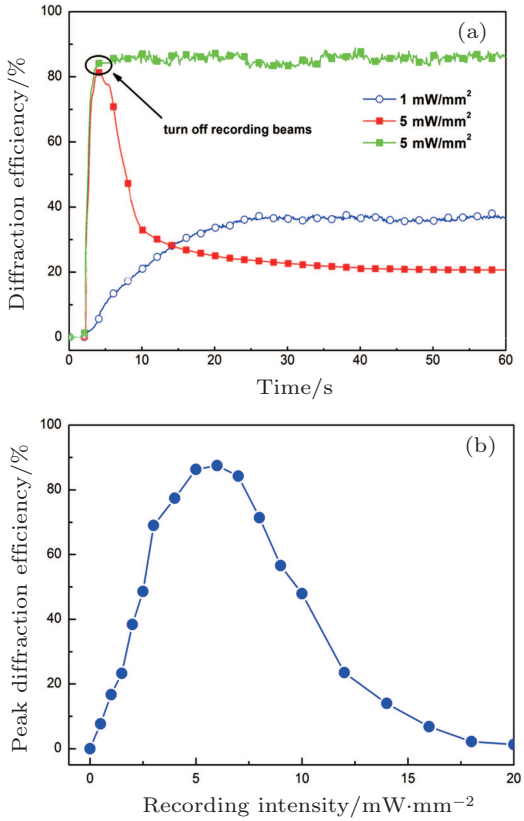


Fig. 4. (color online) (a) Hologram formation process and (b) diffraction efficiency as a function of the recording beam intensity.

4. Holographic storage

4.1. Holographic storage of 3D objects

A holographic recording optical setup was built for holographic storage of 3D objects, as shown in Fig. 5(a). An Nd:YAG laser ($\lambda = 473$ nm) was used as the recording beam. The beam from the laser was expanded and well-collimated, and was transmitted through the sample. Then, the beam illuminated on an object and reflected back from its surface. The reflected beam carrying both phase information and amplitude information of the object, coupled with the original laser beam in the sample, and finally, holograms formed in the film. In our experiment, a coin with size $D = 19.5$ mm was used as the original object, the bottom and upside of the coin are shown in Figs. 5(b) and 5(c). The recording beam intensity is about 2.4 mW/mm^2, and exposure time is about 20 s.

We used both the polymer and PDLC as the recording media. The PDLC is a mixture of TMPTA monomer, Rose Bengal, N-phenylglycine, N-vinylpyrrollidone, and liquid crystals by weight. The two samples thet we fabricated are in the size of 40 mm×40 mm, and the thickness of 100 μm. The 3D images were reconstructed from the recorded holograms in polymer and PDLC film by white light, as shown in Figs. 5(d)–5(g), photos were taken by camera. Depth cue of both sides of the coin can be observed from the holographic images in polymer, as shown in Figs. 5(d) and 5(e). However, the reconstruction in PDLC is not as good as those in polymer, as shown in Figs. 5(f) and 3(g). The liquid crystal in PDLC contributes to higher holographic diffraction efficiency (near 100%, with high voltage electric field applied to the film) because of its large change of the refractive index.[21,22] This makes PDLCs a good candidate for applications such as optical switches for telecommunication, specific lenses, and other electro–optical devices. However, they may not be suitable for static high quality holographic 3D image displays because the liquid crystal droplets in PDLCs (in the order of sub-micron) are too big for high resolution and definition refractive index hologram in materials. The polymer with little lower diffraction efficiency has no such disadvantages for static holographic 3D displays, and its applications need no electric field for holographic recording and reconstruction. Therefore, it is a potential material for hologram storage.

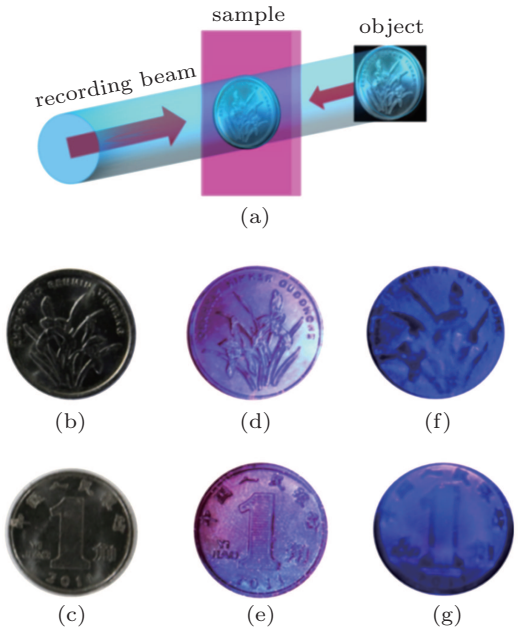


Fig. 5. (color online) (a) Holographic 3D image recording setup, (b) and (c) bottom and upside of a coin, respectively, (d) and (e) holographic images reconstructed in polymer, and (f) and (g) holographic images reconstructed in PDLC.

4.2. In-line holographic storage of information

We have built a collinear holographic storage setup, as shown in Fig. 6. An Nd:YAG laser ($\lambda = 532.8$ nm) was used as the recording beam, and the probe beam. The signal light is modulated by the SLM to carry information of images, and was reflected into a two-lens system. Then, the signal beam was focused in the sample.

In the recording process,[23–25] the patterns loaded onto the SLM were well designed. As shown in Fig. 7(a), the outer ring and the inner pattern were used for encoding the reference beam and object beam, respectively. The intensities of the two

beams could be changed by changing the shapes and sizes of the outer and inner patterns. In the read-out process, the shape of reference beam onto the SLM, as shown in Fig. 7(b), was used to reconstruct information of the signal beam from the hologram formed in the polymer films. In our experiment, the recording and probe beam intensity were 5.7 mW/mm^2 and 0.5 mW/mm^2, respectively. Some of the holographic reconstructed images are shown in Fig. 8. The results show that the data storage capacity of in-line holographic disk using the polymer film would be much higher than that of the current commercial optical disk. Holographic data storage has potential than that of applications in big data permanent storage.

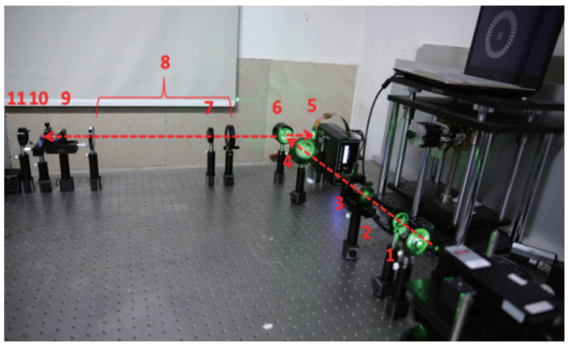


Fig. 6. (color online) The setup for coaxial holographic image storage, 1: filter, 2: $\lambda/2$ plate, 3: beam expander, 4: lens, 5: SLM, 6: PBS, 7: aperture stop, 8: two-lens beam narrowing element, 9: objective, 10: sample, and 11: aperture stop.

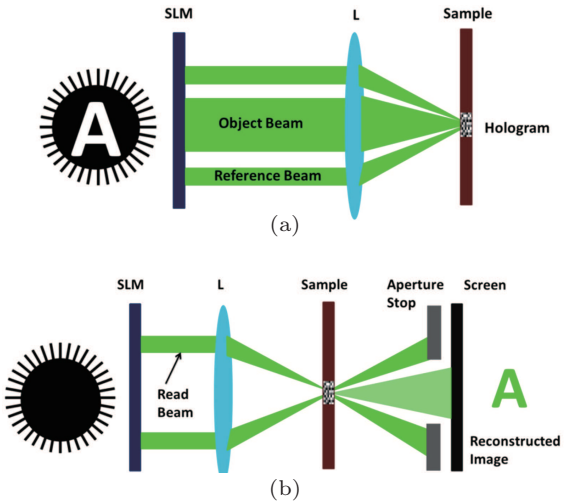


Fig. 7. (color online) Recording and read-out process, (a) a writing pattern was used in recording process, the outer ring and the inner pattern were used to encode the reference beam and object beam, respectively, (b) a read pattern was used in read-out process to reconstruct images.

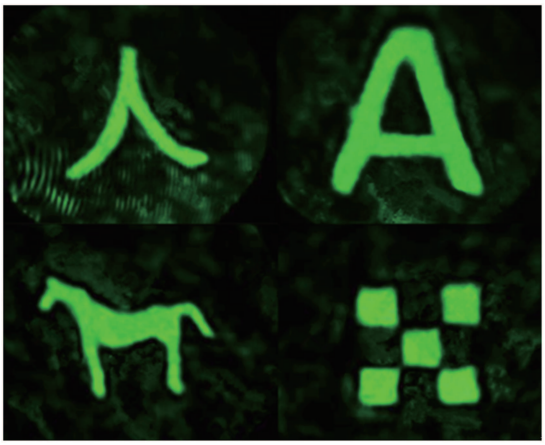


Fig. 8. (color online) Holographic reconstructed images.

5. Conclusion

For applications of static holographic 3D displays, holographic disks, we investigated holographic property of photopolymer and PDLC films. Absorption measurement of the polymer showed that it is sensitive to the visible wavelengths, range of 470 nm–600 nm. Therefore, blue and green lasers can be used as a recording light. The diffraction efficiency which is a key parameter of the refractive index hologram recorded in materials was studied, and hologram formation process was illustrated in polymer films. Furthermore, the static analog hologram carrying 3D image, i.e., the wavefront of the surface of real object was recorded in the films, and the 3D reconstruction with good quality was achieved. Compared to PDLC films, the polymer in holographic applications has more advantages, such as higher holographic definition and no need of any electric field in hologram recording and reconstruction. For big data storage in this polymer, we chose an in-line holographic writing system as a holographic disk system, which is simpler than an off-axis holographic system. The whole page of information was recorded at a small film point by one exposure, which needed no postprocessing, and the information was permanently stored. This paper focuses on 3D image and data storage by holography in photopolymer films. The work demonstrates that the applications of these films in analog and digital hologram storage may be helpful for static 3D display and big data permanent storage research.

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