Color Holographic Display Based on Fast-Response Liquid Crystal Cell

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Abstract

A multiplexed holographic video has been achieved with a passive liquid crystal cell, whose response time is in the order of several milliseconds. Meanwhile, reconstructed RGB images are merged as a white color image, providing a possibility of real-time color holographic three-dimensional display. In addition, the dependence of the intensities of reconstructed images on the polarization direction of reading beam is investigated.

Keywords

holographic display; multiplexing; 3D display; liquid crystal; real-time; fast response.

Introduction

Ever since the runaway success of science fiction blockbuster Avatar, a three-dimensional (3D) revolution has been sweeping the whole world in recent years. Usually, 3D displays are classified into two types according to their operational principles. One is based on binocular parallax with eye-glasses/helmet stereoscopic displays or with parallax barriers or lens array. With the mature development of liquid crystal display (LCD), these techniques have been widely adopted as the mainstream. The other type is based on 3D scene reconstruction, also known as the true 3D techniques, e.g., integral imaging and volumetric display. Of various 3D displays, holographic display is considered as an ultimate technique for both recording and displaying 3D images of an object. Unlike the glasses-type 3D, it is inherently autostereoscopic since it could allow the viewer to perceive the light as it would be scattered by the real object itself without any special eye wear. Holographic display is considered to be the next generation flat panel display for 3D video images. Recently, many research groups are being dedicated to studying the holographic display and its applications, including updatable materials [1-2], holographic backlight used for flat panels [3], digital holography [4], and spatial light modulator (SLM) [5] etc. In the traditional holography, dichromated gelatin and silver halide are used as recording medium [6]; however, such materials are incapable of supporting video-rate updates, thereby limiting their application merely to still pictures. Due to the huge amount of processing information for the holograms as well as the computational power, digital holography (DH) is difficult to realize the video-rate image reconstruction [7].

To achieve quality 3D real-time holography—realistic and comfortable to view—the search for a nonlinear photonic material with fast response less than a second now becomes a hot issue [8-9]. In fact, real-time holographic display is an important and challenging problem to solve and a number of technologies have been proposed to address this problem. Among them, purely optical reconstruction based on dynamic recording materials is one of the most effective ways for the video-rate holographic display without post data processing. As a candidate, photorefractive inorganic crystals are the most common materials for the above use, but they are quite difficult to scale up to a large area. On the other hand, photorefractive polymers can be an alternative, but extremely high voltages will be applied to them during both recording and reading.

In this paper, we present a real-time color holographic display using a fast-response liquid crystal (LC) cell without any applied electric field. With this cell, holograms can be refreshed on the order of one millisecond, which is fast enough to enable video application. By angular multiplexing of holograms, a color image can be obtained by superposition of R/G/B sub-images. We also discuss the influence of polarization direction of reading beams on the image quality.

Experiments

The material used in our experiments is a mixture of a liquid crystal and a photosensitive dopant. A mylar slip with a thickness of about 50 μm is sandwiched by two glass substrates to form the liquid crystal cell. Figure 1 illustrates the experimental setup for an angular multiplexed holographic display. A reference beam and a signal beam, both derived from a Nd:YAG laser (λ=532.8 nm), are set to be p-polarization via a half-wave plate. Three sets of spatial light filters (SLFs), SLMs, and condenser lens are placed along the signal beam path, where the phase information of three videos is generated by SLMs. The SLMs are mounted with pure phase modulating microdisplay with a resolution of 1920×1080, equal to a pixel pitch of 8.0 μm. In our previous paper [8], a monochromic, video-rate holographic display had been realized with this cell. By angular multiplexing, three holograms are recorded in the LC cell at the same time. The reference beams have a power density of 13 mW/cm^2, and each signal beam has a power density of 8.0 mW/cm^2.

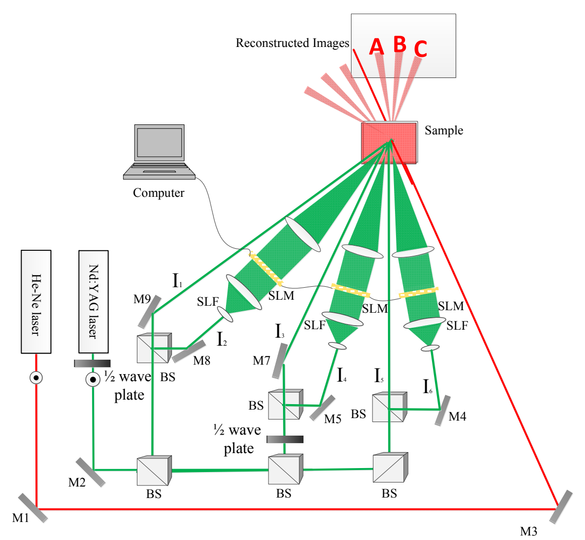

Figure 1. Experimental setup for tri-multiplexed holography.

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Results and Discussion

The size of liquid crystal cell is 2.5 cm × 2.0 cm, while the area exposed to the laser is about 2.5 mm in diameter. During recording, beams I_1 and I_2 interfere with each other to form Hologram A, I_3 and I_4 for Hologram B, I_5 and I_6 for Hologram C, respectively. At the same time, these three holograms are read out together by a red laser. The adjacent reference and recording beams are set to different polarization directions to avoid the crosstalk among three holograms. As shown in Fig. 2, the response time of recording is measured as about 1 ms, which is read from an oscilloscope. So the holograms formed in the sample are transient, and the videos loaded on SLM can be reconstructed in real time, free from the crosstalk between two neighboring frames. Besides, the conditions used in the experiments are summarized in Table 1.

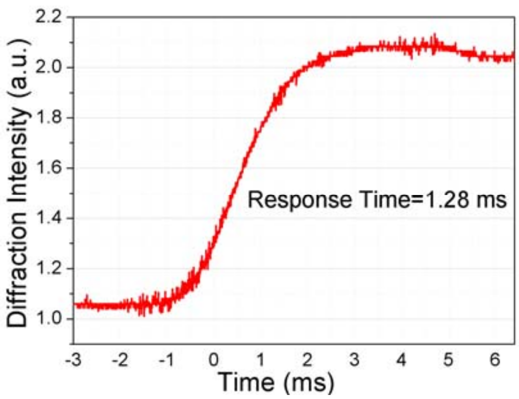

Figure 2. Measured response time for recording.

Table 1. Parameters used in the experiments.

Cell size	2.5 cm × 2.0 cm
Cellgap	50 µm
Spot size	2.5 mm
Reference beam intensity	141 mW/cm^2
Signal beam intensity	198 mW/cm^2
Probe beam intensity	230 mW/cm^2
Angle between reference and signal beams	21°

Figure 3 shows a series of snapshots taken from a holographic video demonstrating the revolving letters A, B, and C. Those results directly validate the capability of angular multiplexed dynamic display of being refreshed at a video rate. Then, according to the color holography theory, to achieve a color holographic dynamic display video, one of the approaches is to record three holograms at the same location by angular multiplexing and read out by red, green and blue lasers, respectively. With the same optical arrangement shown in Fig. 1, we attempt to combine a color image by using R, G, B lasers to read the three holograms A, B and C. Dynamic holographic videos at red, green, and blue laser wavelengths are obtained, and R/G/B holograms can be displayed at the same time and the same location of this cell through angular multiplexing.

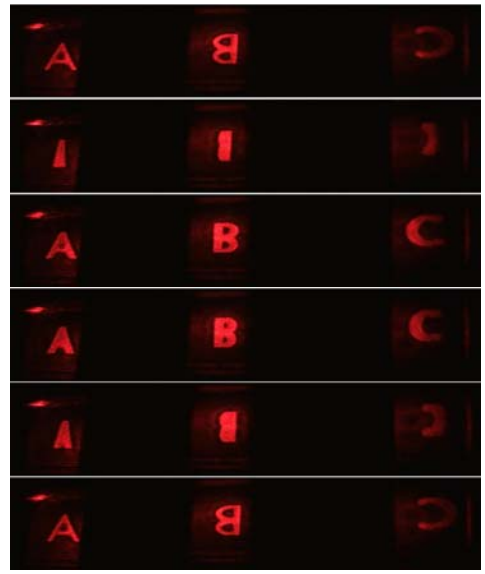

Figure 3. A series of snapshots taken from the real-time holographic video.

In multiplexing, due to the different recording conditions for the R/G/B holograms, three reconstructed images cannot have the identical size on the reconstructed image plane, which can be explained by Eq. (1) [10],

$$\sin\theta_m = \mathrm{m}\frac{2n_r\lambda_p}{n_p\lambda_r}\sin\theta_r - \sin\theta_p, \quad \mathrm{m} = 0, 1, 2\ldots \tag{1}$$

Where θ_m is the diffraction angle of the m$^{\text{th}}$-order light, n_p and n_r are the refractive indices encountered by probe and recording beams, respectively, λ_p and λ_r are the wavelengths of probe and recording beams, respectively, and θ_p and θ_r are the angles intersected by the probe and recording beams with the grating normal, respectively. It can be seen that the imaging regions of three holograms are determined by the above parameters. By properly adjusting the recording and reading angles of each hologram and the original image size, three reconstructed images of primary R/G/B colors are merged in the same location, as shown in Fig. 4. In practice, limited to some reading and recording conditions, three monochromatic reconstructed images are not perfectly uniform and superimposed. Incidentally, R/G/B colors are output by He-Ne (λ=632.8 nm), Nd:YAG (λ=532 nm), and sapphire (λ=488 nm) lasers, respectively.

Diffraction efficiency (DE) of a hologram is a key parameter in holography, which determines the brightness of the holographic image under some given conditions, such as recording intensity, readout intensity, and laser polarization. To improve the holographic display quality, we investigate the dependence of the diffraction efficiency on the reading light polarization parameters. The experimental setup is depicted in Fig. 5, where we find out that DE varies with respect to the polarization axis (PA) of the reading beam. In this experiment, we aligned the absorption axis (AA) of the sample in parallel with PA of the recording beam, for which, the absorption reaches its maximum. For the same reason, the display quality of the reconstructed images will be the best as well. In addition, the intensity variations of ±1 diffraction orders are the same and no asymmetric two-beam coupling is observed.

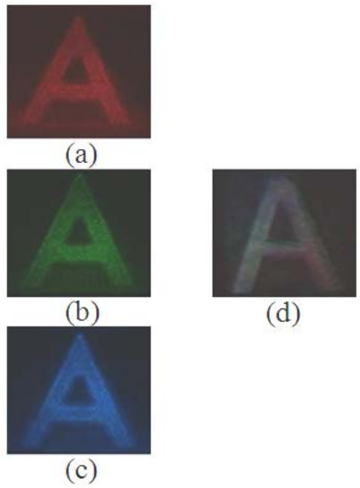

Figure 4. R/G/B images reconstructed by (a) He-Ne laser, (b) Nd:YAG laser, and (c) sapphire laser, and (d) the merged color image.

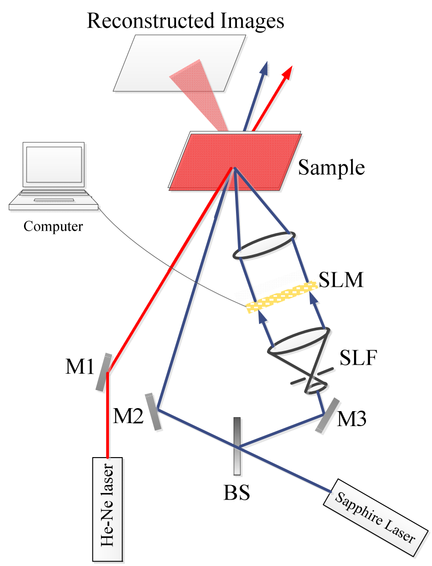

Figure 5. Experimental setup for investigating polarization dependence.

Conclusion

We have experimentally demonstrated a real-time multiplexed holographic display using a passive, fast-response LC cell. By merging three RGB reconstructed images, a real-time color holographic display is achieved. Compared to other work, our results may move one step further towards the goal of large-area, dynamic, and color holographic 3D display. More significantly, this organic photorefractive material can be readily scalable, thus lending itself to the large-size display applications.

Acknowledgements

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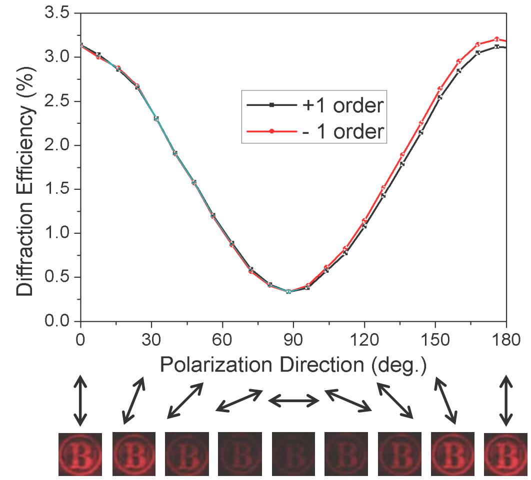

Figure. 6. The variation of diffraction efficiency of ±1 order with respect to the polarization axis of the reading beam.

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