Real-Time Holographic Display Using Quantum Dot Doped Liquid Crystal†

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Abstract

A dynamic optical holographic display featuring a quantum-dot-doped liquid crystal is presented. Its response time of holographic recording is measured in the order of several to tens of milliseconds, depending on recording beam intensities, applied voltage and grating periods. The transient first-order diffraction efficiency is up to 20%. A reconstructed holographic video at a refresh rate of 25 Hz is demonstrated by the experiments.

Author Keywords

Holographic display; 3D display; quantum dot; liquid crystal; real-time; dynamic.

1. Introduction

Three-dimensional (3D) display technology has attracted worldwide attention and been developed vigorously since the blockbuster movie "Avatar" was released. Usually, 3D displays can be classified into two types according to principles of stereopsis. One type is based on binocular parallax [1-2] and the other type is based on light field reconstruction. Among these 3D display techniques, holographic display is considered as an ultimate goal to provide realistic image of a real object or a scene, because it has the ability to reconstruct both the intensity and phase information of a true nature of an object or a scene, allowing the observer to perceive the light as it would be scattered by the real object itself without the need for a special eyewear [3]. Therefore, many research groups have studied the holographic displays of real 3D images, including photorefractive materials, holographic backlight [4], computer-generated holography (CGH) [5] and microelectro mechanical systems (MEMS) [6] etc.

Optical holography based on the dynamic recording materials might be an effective way for the video-rate holographic display. Peyghambarian *et al.* reported a quasi-real-time dynamic display at a refresh rate of 0.5 Hz. However, an externally applied voltage of 7 kV and a high-power pulsed laser shall undercut its practical usage [7-8]. In 2012, Tsutsumi *et al.* from Kyoto Institute of Technology reported a novel photorefractive polymer composite using poly-N-vinyl carbazole, and obtained the reconstructed 3D images with a faster response time of tens of milliseconds [9]. In our previous work, we proposed a real-time holographic display using a dye-doped liquid crystal [10]. Due to the low solubility and high mobility of dye molecules in liquid crystal, the diffraction efficiency and thermal stability of the system are insufficient [11]. Semiconductor nanoparticles doped liquid crystal materials are a kind of photorefractive (PR) materials based on the effect of space charge field and liquid crystal's birefringence. By doping the semiconductor nanoparticles into the liquid crystal, the photoconductivity is found to be greatly enhanced [12-13]. With an external voltage applied to the material, our device exhibits fast response, high diffraction efficiency and rewritability.

In this paper, we present a real-time holographic display based on semiconductor quantum-dot (QD)-doped liquid crystal with an applied voltage around 30 V. Real-time holographic video is realized in this device and the diffraction efficiency is improved by two orders of magnitude compared to the previous work [10]. The real-time videos of red (R), green (G), blue (B) colors are obtained. The influence of recording light intensity and external voltage on the device performance are studied hereafter.

2. Mechanism and Materials

In our photorefractive material, when the inhomogeneous intensity pattern is formed by the interference of writing beams, electron-hole pairs denoted as positive and negative charges are generated in the bright region, as shown in Fig 1. With the assist of externally applied electric field, the electro-hole pairs are separated and undergo the processes of both transportation and trapping. Then, mobile holes are transported to the dark regions whereas electrons remain in the bright regions. This charge separation could give rise to the formation of internal space charge field. As a result, the refractive index modulation in response to the space-charge field occurs due to electro-optic effect originated from the reorientation of the liquid crystal molecules, and the holograms are recorded in the photorefractive material [14-15]. Since all the above processes can be reversible, this material is a candidate for the real-time holographic display.

The material used in our experiments is a mixture of a nematic LC (E7) and QD. Silica spacers with a thickness of about 20 μm are sandwiched between two ITO glass substrates to maintain the cell gap. The ITO glassed are coated with polyimide layers to obtain the planar alignment. The quantum dot used in our experiment is ZnS/InP with a core/shell structure. The absorption spectrum of synthesized ZnS/InP is shown in Fig. 2. A droplet of QD dispersed in chloroform is mixed with E7. The obtained mixture is pretreated in the vacuum drying oven for 10 hours at 70 °C to expel the chloroform from the mixture and then filled into the cell via capillary action at the room temperature.

3. Methods

The experimental setup for holographic display is shown in Fig. 3. A reference beam and a signal beam, which are derived from a Nd:YAG laser (λ=532.8 nm), are set to be *p*-polarization by a half-wave plate. A spatial light filter, a spatial light modulator stable reconstructed images with good quality. The power of the object beam is 11 mW, while the intensity of the reference beam is 160 mW/cm^2. The two beams intersect at an angle of θ=7° in the sample, which is near the Fourier plane of Lens L (F=400 mm, d=24.5 mm). The reconstructed images are projected on a white screen. The SLM (Holoeye) used in our experiments is a pure phase modulating microdisplay with a resolution of 1920×1080, a pixel pitch of 8.0 μm, and a frame rate of 25 Hz. A He-Ne laser

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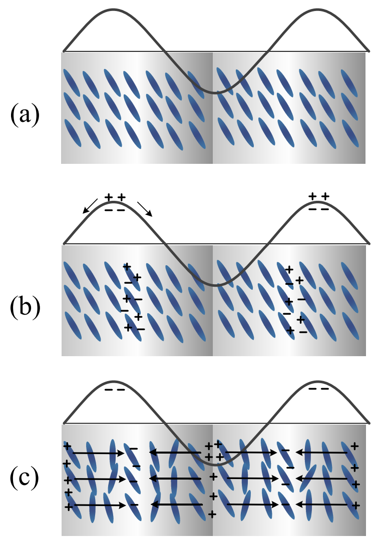

Figure 1. Process of the photorefractive grating formation. (a) light intensity modulation, (b) free charge transportation and (c) electro-optic index modulation

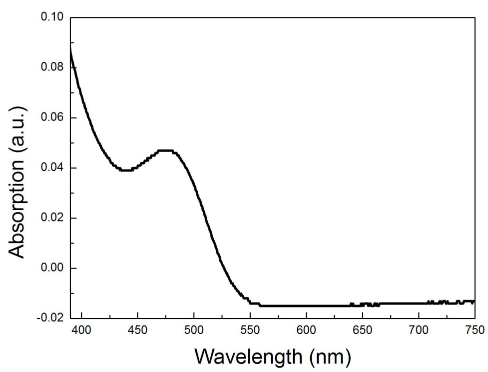

Figure 2. Absorption spectrum of ZnS/InP QDs in chloroform.

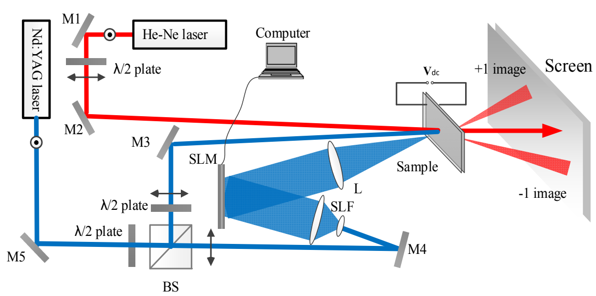

Figure 3. Experimental setup for real time display. M's are mirrors, BS is a beam splitter, λ /2 is a half-wave plate.

(SLM), and a lens are placed in the signal beam path, where the spatial information of an image is displayed on the SLM. In the experiment, we tune a half wavelength wave plate to change the intensity ratio between object and reference beams to obtain the beam (λ=632.8 nm) with a power of 9 mW is also set to be *p*-polarization to probe the writing region of the sample. The cell is perpendicular to the incident plane. The raw object beam, i.e., plane wave before reflection, is incident on the SLM at an angle of 15° for loading the image information. External voltage is applied to the cell before illuminating. The video with a refresh rate 25Hz is loaded to the materials to realize the real-time display.

4. Results and discussion

(a) Response time

In this experiment, a standard two-beam coupling arrangement is used to investigate the response time in the device. An external voltage is applied to the cell in the experiment. Two polarized recording beams of equal intensities derived from the Nd: YAG laser are set to be *s* polarized by half-wave plates and the same diameter of 3 mm. The incident plane defined by the wave vectors of two recording beams with the angle 13^o is perpendicular to the cell substrate. The sample is titled at an angle 40° with respect to the bisector of two writing beams. A beam from the He-Ne laser with *p*-polarization is used to probe the interference region with a power of 9 mW and a diameter of 2 mm. We use the mechanical shutter to control the on and off of one of the two recording beams. The response time is measured on an oscilloscope (DSO-X 2012A, Agilent).

For the holographic video display, the image refreshing speed is a key parameter, which is determined by the response time of grating build-up. It has been found that the response time can be affected by several factors, such as the total energy of the recording beams, grating period, and the sample temperature. Here, we have investigated the influences of incident recording power on response time as shown in Fig 4. The higher recording beams power lead to the higher photocharges generation rate, which render the build-up of the grating faster. At an applied voltage of 17 V, the LC molecules can reorient in a few milliseconds. Moreover, compared to the previous work, the accumulation of heat in the cell is low due to the QD's weak absorption of visible light, therefore, higher beams power can be used without degrading the image quality.

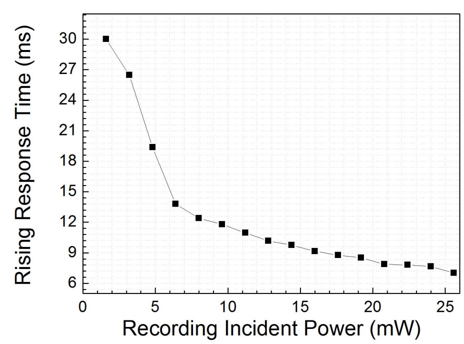

Figure 4. Dependence of response time on recording power.

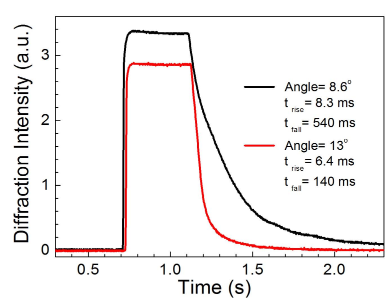

Figure 5. Comparison of rise and fall response times for different recording angles at a voltage of 16.7 V.

Figure 5 shows the results of the dynamic process for grating formation under different recording angles. The grating periods are 1.4 μm and 2.2 μm, respectively. As can be seen in Fig. 5, with the increase of the recording angle, the diffraction efficiency decreases, and the time to establish the gratings becomes shorter.

(b) Video-rate holographic display

For a hologram, the diffraction efficiency is a key parameter that determines the brightness of a holographic image. In the experiment, the diffraction efficiency of the QD doped liquid crystal is up to 20% and a real-time holographic display is observed.

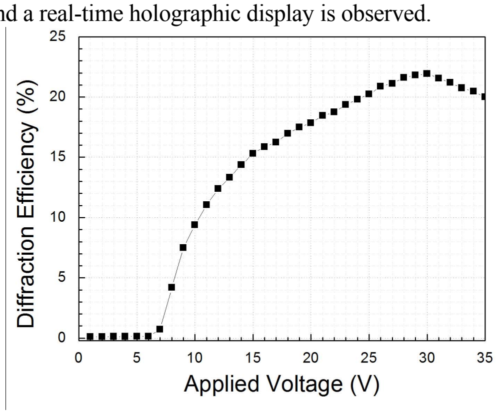

Figure 6. Experimental voltage dependence of diffraction efficiency for QD doped LC.

Figure 6 shows the diffraction efficiency with different applied voltages. One can see that the highest diffraction efficiency appears at the voltage of about 30 V. The value increases according to the increase of the voltage before 30 V, however, the diffraction efficiency will decrease with increasing applied voltage after 30 V. To obtain clear reconstructed images, we maintain the applied voltage at 30 V. The holograms formed in the sample are transient, and the diffractive images disappear immediately when the object beam is turned off. Because of the dependence of the diffraction on the applied voltage in PR materials, once the applied voltage is turned off, the reconstructed images disappear. Fig. 7 shows the pictures snapped from three diffracted holographic videos of a rotating letter "B", which is illuminated by three different wavelengths of 632.8 nm, 532 nm, and 488 nm.

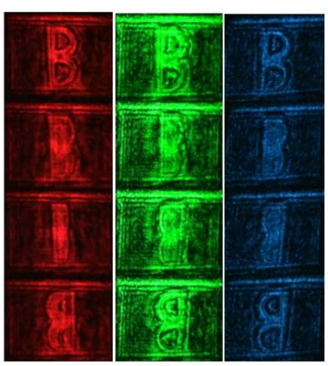

Figure 7. Four snap shots from R, G, B diffracted videos, illustrating real-time holographic video display.

5. Conclusions

In conclusion, we have realized real-time holographic display at a refresh rate of 25 Hz using a QD doped liquid crystal. The rising time of the real-time holograms is in the order of several to tens of milliseconds. The diffraction efficiency is up to 20%. The diffraction efficiency can be controlled by applying the external DC voltage. We also have demonstrated the R/G/B real-time videos and verified the feasibility as a color holographic display.

6. Acknowledgements

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7. References

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