High-Efficiency Video-Rate Holographic Display Using Quantum Dot Doped Liquid Crystal

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***Abstract*—We demonstrate a real-time holographic display using quantum-dot doped liquid crystal with a build-up time of several to tens of milliseconds, and the maximum diffraction efficiency is measured up to 30%. Holographic videos of red, green, and blue colors at a refresh rate of 60 Hz are realized. The dependences of response time on the recording intensity, applied voltage, and grating period are investigated.**

***Index Terms*—Dynamic, holographic display, liquid crystal, quantum dot, real-time.**

I. INTRODUCTION

HOLOGRAPHY is a true three-dimensional (3D) technique based on coherent light interference, providing complete information of natural 3D images [1]–[10]. To achieve real-time 3D display at video rate, fast response photorefractive materials with low cost, scalability, and easy fabrication are desired [4].

In a pioneering work on dynamic holographic display, a quasi-real-time holographic display with images refreshed every two seconds was realized in a photorefractive copolymer, by employing a pulsed laser holographic recording system and a high applied voltage ($\sim$7 kV) [5], [6]. A reversible holographic display without an applied electric field was developed by optical reinforcement mechanism with a rise time of nearly 50 s [7]. Another study demonstrated a 3D holographic display using a monolithic organic compound [8]. The time for recording and displaying new images was within a few seconds, and the images can sustain for a long time without an applied electric field. They also presented a quickly updatable hologram image using photorefractive (PR) polymer composite. The response time was 59 ms at a voltage of 45 V/μm [9]. These refreshable photorefractive polymers have the potentials to realize 3D holographic displays by combining integral holography technique. Yet, the response time of these photorefractive polymers is far from the requirement of video-rate response.

More recently, a holographic movie was reconstructed using photoconductive ferroelectric liquid crystals (FLCs) that contain photoconductive chiral compounds, with a response time of 8 ms [10]. To achieve shorter response time, we proposed a dynamic holographic display with a refresh rate of 25 Hz using azo-dye doped liquid crystal (LC) [11], [12]. The shortest response time was 1.6 ms, without applying any external voltage. However, the problem of the previous work was that the diffraction efficiency was low, around 0.3%. In addition, azo-dye doped LC usually suffers from serious thermal effect [13].

For practical applications, optical holographic displays with high diffraction efficiency and good stability are desired. Doping quantum dots (QDs) into LC may be an effective approach. QDs have high quantum efficiency, broad absorption band and narrow emission linewidth, and thus have been widely used to improve light efficiency and color performance in LCD displays [14], [15]. Doping QDs into LC can induce abundant photocharges and enhance photoconductivity under light exposure, which substantially improve diffraction efficiency in holographic displays [16]–[18].

In this work, we perform detailed investigation on a real-time holographic display based on QD-doped LC. The diffraction efficiency is improved to 30%, and the refresh rate is increased to 60 Hz, showing much improved performances than our previous results [19]. The dependences of the diffraction efficiency and response time on recording light power, polarization, grating period in the LC and externally applied voltage are studied by experimental means. In addition, the image quality is significantly improved by using an amplitude spatial light modulator (SLM). This work indicates that QD-doped LC could be a promising candidate towards future video-rate dynamic 3D holographic display.

II. PHOTOREFRACTIVE EFFECT IN QUANTUM-DOT DOPED NEMATIC LC

In a QD-doped LC cell, the grating formation is induced by orientational photorefractive (PR) effect related to photoexcitation and transportation of charge carriers [20]. The interference of two coherent beams leads to alternant dark and bright regions in the material. In the bright regions, the QDs are excited to generate charge carriers (electrons and holes) and then the electrons transfer to the bulk of the LC mixture and LC-alignment

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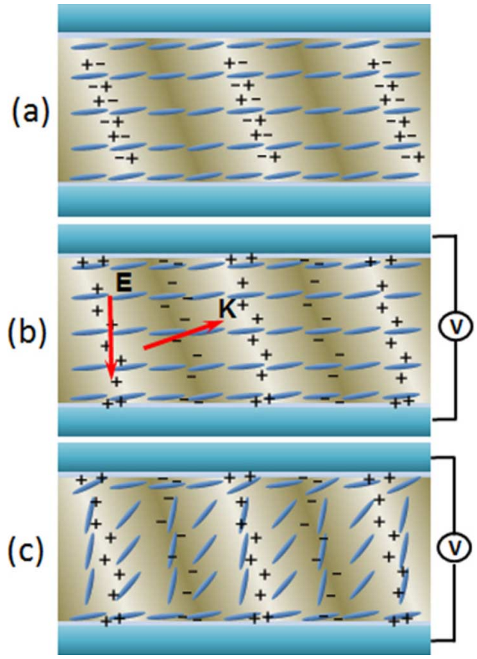

Fig. 1. Photorefractive mechanism of the QD-doped LC. (a) Generation of electron-hole pairs. (b) Separation of electron-hole pairs. (c) Reorientation of liquid crystals.

layer interfaces [21]–[23]. The distributions of the charge carriers are thus modulated by the light intensity [Fig. 1(a)] [24]. In our experimental configuration, the transmission grating vector is not orthogonal to the external electric field. Driven by an external electric field, the electrons drift across the fringes and are trapped in the dark regions [25]. Such charge separation gives rise to spatial modulation of the electrons and holes, forming a spatially varying electric field known as space charge field [Fig. 1(b)]. Then, due to the large optical anisotropy and high sensitivity to electric fields, the LC molecules are reoriented by the resultant effects of the external electric field and the internal space charge field [26], [27]. As a result, a phase grating corresponding to the light intensity pattern is formed [Fig. 1(c)].

III. CHARACTERIZATIONS

A. Optical Setup

Our optical setup for measuring the photorefractive properties of the QD-doped LC is shown in Fig. 2. Two polarized recording beams with a diameter of 2 mm, from an optically pumped semiconductor continuous-laser at 488 nm wavelength, are set to be s-polarized and intersected at an angle of 2θ. The incident plane (xz plane) defined by the wave vectors of the two recording beams is perpendicular to the cell substrate. The sample is titled at 45° with respect to the bisector of the two recording beams, so that there is a projection of the grating vector onto the electric field vector to separate the electron-hole pairs [25]. Thus, space charge field is formed to realign the LC director, resulting in periodic refractive index modulation and grating formation. The interference region is probed by a linearly polarized coherent beam with a wavelength of 633 nm and a diameter of 2 mm, which is from a He-Ne laser with

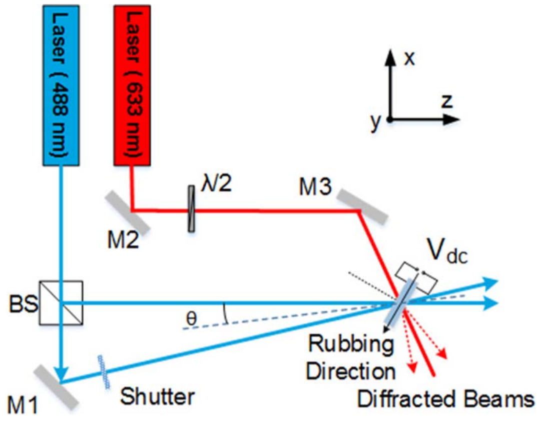

Fig. 2. Experimental setup for measuring photorefractive properties. M1-M3: mirrors, BS: a beam splitter, $\lambda/2$: a half wave plate.

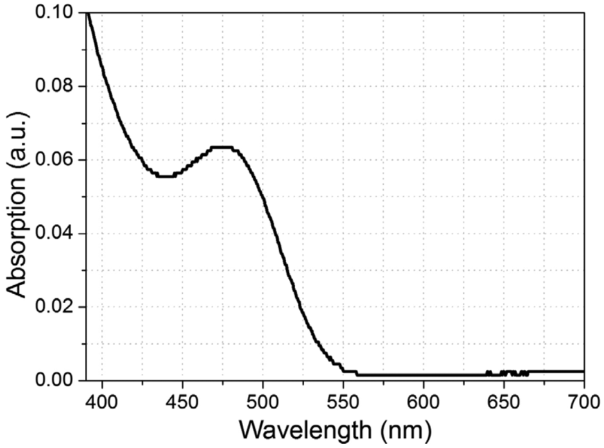

Fig. 3. Absorption spectrum of ZnS/InP QDs dispersed in the chloroform.

a power of 7 mW. It is worth noting that both s- and p-polarized recording beams can record holograms; nevertheless, self-diffraction, namely, diffraction of recording beams, is only accompanied with the p-polarized beams.

The material used in our experiments is a mixture of a nematic LC and quantum dots (ZnS/InP). The weight percent of the ZnS/InP is 0.05%. The obtained mixture was pretreated in a vacuum drying oven for 10 hours at 70 °C to evaporate the chloroform and was then filled into the cell via capillary action at room temperature. The maximum absorption of the ZnS/InP QDs occur around 475 nm as shown in Fig. 3. Mylar slips with a thickness of about 20 μm are sandwiched by two ITO glass substrates to maintain the cell gap. The cell alignment is homogeneous along the horizontal direction as shown in Fig. 2.

B. Diffraction Efficiency

For holographic displays, the diffraction efficiency plays a primary role in determining the image brightness. The formation of the photorefractive gratings is due to the inhomogeneous distribution of carriers, which is induced under nonuniform illumination. By using pump-probe technique [28] as shown in Fig. 2, the diffraction grating is characterized.

The diffraction efficiency η is defined as the ratio of the first-order diffracted beam intensity I_{d} to the incident reading

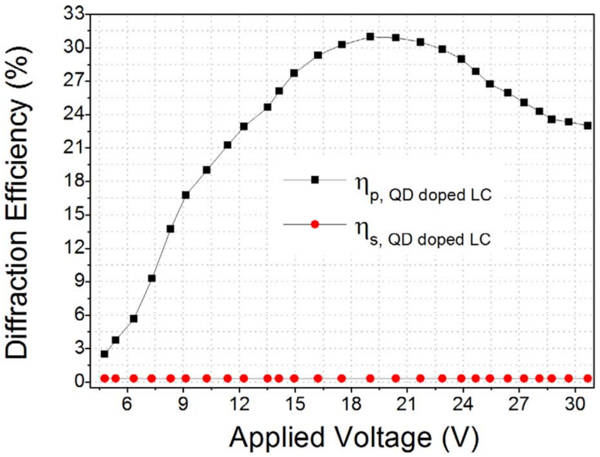

Fig. 4. Dependence of first-order diffraction efficiency on applied voltage for QD-doped LC with s- and p-polarized reading beams. $\theta = 0.6°$.

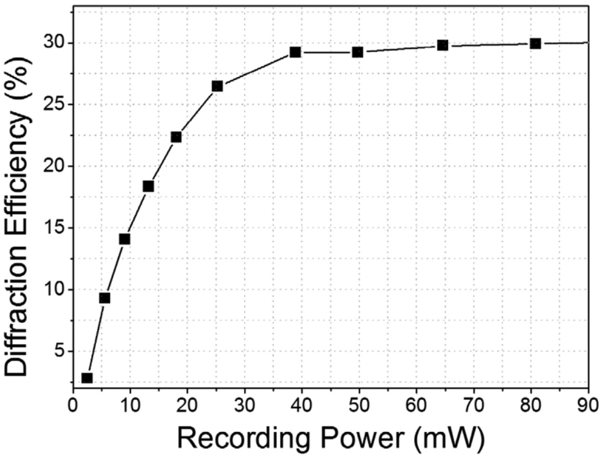

Fig. 5. Dependence of first-order diffraction efficiency on recording laser power. $\mathrm{V_{dc}} = 20$ V, $\theta = 0.6°$.

beam intensity I_{o}, i.e., $\eta = I_{\mathrm{d}}/I_{\mathrm{o}}$. In the doped LC material, the orientational photorefractive effect occurs simultaneously with the application of direct-current (DC) voltage. Fig. 4 shows the comparison of the first-order diffraction efficiencies of the QD-doped LC at different applied voltages, for s- and p-polarized reading beams, respectively. The diffraction efficiency with s-polarized reading beam, η_{s}, keeps nearly zero; whereas, diffraction efficiency with p-polarized reading beam, η_{p}, changes significantly. The highest η_{p} is 30%, at about 20 V and with a grating period of 20 μm. η_{p} turns to decrease after its maximum, indicating that a higher voltage induces LC directors to reorientate towards homeotropic alignment and thus weakens the refractive index modulation.

The incident plane of the two recording beams I_1 and I_2, as shown in Fig. 2, is in the xz plane. The induced periodic reorientation of nematic director is thus restricted within the xz plane. For the reading beam with s polarization, the refractive index of the formed grating is uniform and thus the grating is invisible. On the contrary, the light with p-polarization can read out the hologram [28]. Such characteristics reveal that the optical modulation in the QD-doped LC exhibits high anisotropy properties and the formation of the hologram mainly originates from the orientational photorefractive effect [27].

Fig. 5 shows how the diffraction efficiency changes with the intensity of the recording laser power at room temperature (about 20 °C) with an applied voltage of 20 V. Stronger laser power leads to more photo-induced charges and thus higher photoconductivity [29]. As the power of the recording laser increases, the diffraction efficiency increases and gradually reaches a plateau.

C. *Response Time*

For a real-time holographic display, the image refresh rate is a key performance indicator. The response time is dependent on many factors, including the total energy of the recording beams, the applied voltage, and the grating period. A shutter is used to control the on and off states of the recording beams for the measurement of the response time. The influence of the incident recording power on build-up time is shown in Fig. 6. Higher powers of the recording beams lead to faster photocharge generation and transportation, which reduce the build-up time of the grating.

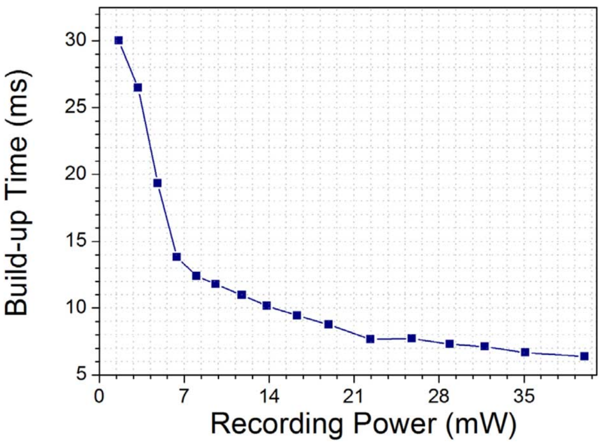

Fig. 6. Dependence of build-up time on the recording power, $\mathrm{V_{dc}} = 27$ V, $\theta = 4°$.

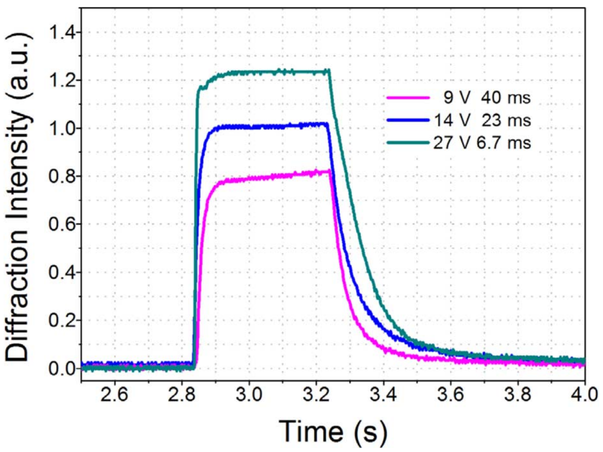

Fig. 7. First-order diffraction intensity and build-up time with respect to different applied voltages. $\mathrm{P_1} = \mathrm{P_2} = 40$ mW, $\theta = 4°$.

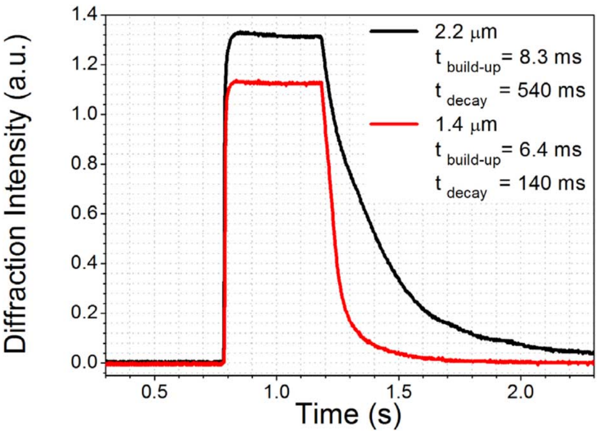

Fig. 8. First-order diffraction intensity and response time under different grating periods. $P_1 = P_2 = 40$ mW, $V_{dc} = 17$ V.

The response time of the grating in the doped LC is related to photocharges generation rate and charge mobility, which are dependent on the applied voltage. Fig. 7 shows how the response time changes with respect to the applied voltage. Higher voltage leads to higher charge mobility, and thus shorter build-up time. Unlike slow responses in other LCs doped with nanoparticle impurities like C_{60} and carbon nanotube (CNT) [27], the lifetime of the grating formed in the QD-doped LC is transient. It is observed that the build-up time decreases as the DC field increases, and at 27 V the build-up time is 6.7 ms as measured by an oscilloscope (Agilent, DSO-X 2012A). These results imply that the increase in the applied voltage increases the charge drift rate between the bright and dark regions, thereby speeding up the formation of the space charge field [22], [30]–[32]. A higher voltage leads to shorter build-up time, but it compromises the diffraction efficiency. Additionally, it should be noted that the decay time is prolonged at higher applied voltage (Fig. 7).

Fig. 8 shows the dynamic process for grating formation at two different recording angles. The grating periods are 1.4 μm and 2.2 μm, respectively. As the recording angle increases, the diffraction efficiency decreases, and the time to establish the grating becomes shorter. This is mainly determined by the trapping and recombination of the electrons and holes in the dark and bright regions of the interference fringes [32]. The process is accompanied with the formation and decay of space charge field, which changes the reorientation of LC directors. For a smaller grating period, the electrons and holes easily recombine and correspondingly the space charge modulation is weakened [33]. This leads to a small bias reorientation of the molecules, resulting in a shorter response time for the grating build-up and decay process. Similarly, if the grating period is larger, the build-up time and decay time are both longer.

IV. VIDEO-RATE HOLOGRAPHY DEMONSTRATION

The results in the previous section have shown that the photorefractive response in the QD-doped LC is fast enough to realize real-time holographic displays. Fig. 9 shows the experimental setup for a holographic display demonstration. An optically pumped semiconductor laser at 488 nm wavelength is used to provide the coherent reference and object beams, which are both set to be p-polarization. The power of the object beam is 20 mW and that of the reference beam is 30 mW. The two beams intersect at an angle of $\theta = 7°$ in the sample, which is near the Fourier plane of Lens L (Focal length = 400 mm, diameter = 24.5 mm). The reconstructed images are projected on a white board. The dynamic images at a refresh rate of 60 Hz loaded from a computer are rendered by an amplitude type SLM as the object source.

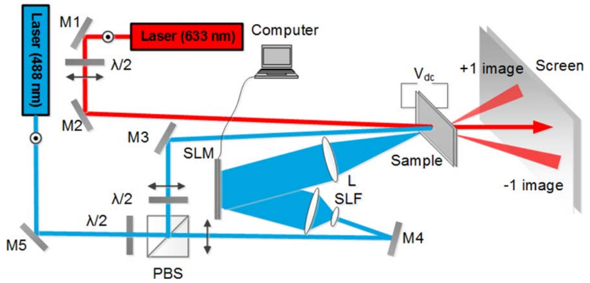

Fig. 9. Experimental setup for the holographic display. M1-M5: mirrors, SLF: spatial light filter, SLM: spatial light modulator.

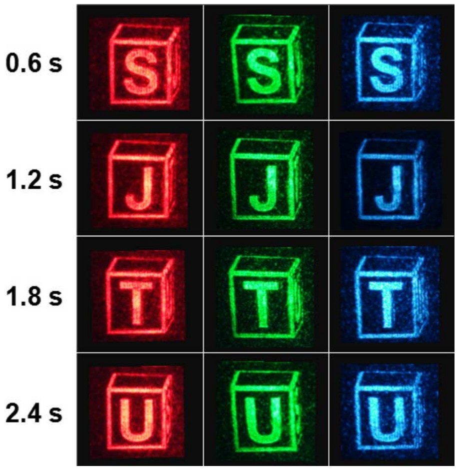

Fig. 10. Snapshots of the holographic videos reconstructed by three different wavelengths of (a) 632.8 nm, (b) 532 nm, and (c) 488 nm at a applied voltage of 27 V.

In our previous work [19], the images can be reconstructed by using a phase type SLM based on polarization rotation effect. However, the fidelity of reconstructed images was not satisfied and the gray levels of the original video were not well reproduced. By using an amplitude type SLM (Holoeye, LC-R-1080) with a contrast ratio of 1000:1, the reconstructed images exhibit higher fidelity and contrast ratio. Fig. 10 shows a series of snapshots captured from the holographic video at different times. One can see that the holographic images are clearly reconstructed. Three lasers of red, green, and blue colors are all set to be p-polarization to probe the recording region of the sample, respectively. The videos are reconstructed and captured by a digital camera. The letters on this cube are S, J, T and U, respectively. No residual images are observed. The holograms formed in the QD doped LC are dynamically reversible and the response time of the cell is fast enough to realize a smooth holographic movie. By using multiplexing technique and through adjusting recording- and reading- angles of the holograms and the original image sizes, three color reconstructed images can be merged and a dynamic color holographic video could be reconstructed simultaneously.

V. CONCLUSION

In summary, we have achieved a real-time holographic video display at a refresh rate of 60 Hz with high contrast ratio in the ZnS/InP QD-doped LC. Compared with pure LC, the doping of quantum dots endows the LC with much better photorefractivity. The maximum diffraction efficiency is measured up to 30%. The build-up time of the grating is of the order of several to tens of milliseconds, fast enough for the video-rate display applications. The performances of the device are investigated with respect to the recording power, polarization of the reading beam, the grating period, and the applied voltage. The QD-doped LC is a suitable candidate for holographic applications, for its high photorefractive nonlinearity, high efficiency, and easy fabrication, providing possibility towards large-size, dynamic, colorful holographic displays.

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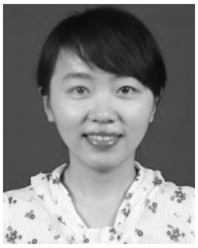

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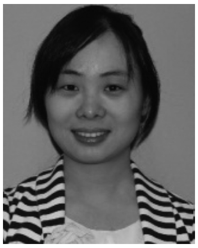

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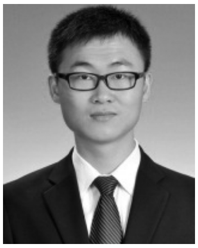

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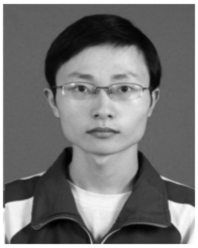

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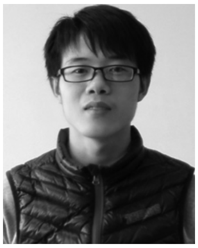

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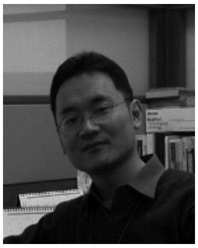

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