Video-Rate Holographic Display Using Azo-Dye-Doped Liquid Crystal

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***Abstract*—A video-rate optical holographic display is achieved by using an azo-dye-doped liquid crystal as the passive, updatable recording material. The response time of this material is measured in the order of several to tens of milliseconds, depending on recording beam intensities, polarization directions, and polarization states. A holographic video at a refresh rate of 25 Hz, sourced from a spatial light modulator, is demonstrated in the experiments.**

***Index Terms*—3D display, dye-doped, holographic display, liquid crystal, real-time, video-rate.**

I. Introduction

HOLOGRAPHIC display [1] is considered as an ultimate three-dimensional (3D) technology as it is capable of creating lifelike 3D images as if the real objects are out there. However, holographic display has not yet entered into the commercial markets, let alone competes with the mainstream 3D displays, e.g., the glasses-type liquid crystal display (LCD) [2], [3]. Of several main reasons, one is that the current holographic display can only show still images rather than movable objects or a video. In this regard, many efforts have been made to achieve this goal. Computer generated holography (CGH) [4], which digitally generates holographic interference patterns, i.e., holograms, is one feasible approach as long as the computational power of the hardware is strong enough. Unfortunately, so far the computers that can meet such requirement are unavailable. The other approach is known as the optical holography, which relies on the recording materials to both record and reconstruct the holograms from real objects or spatial light modulator (SLM). Compared to CGH, this approach could eliminate the need for huge amount of computational processing [5], [6]. Furthermore, those organic photorefractive materials can be readily scalable, thus possible to make large-size panels [7]–[11]. Hence, the pursuit of recording mediums suitable for dynamic holographic display has become a hot issue in this field.

Recently, many research groups are working on such media. Peyghambarian *et al.* reported a photorefractive polymer, through which, a quasi-real-time dynamic display was realized at a refresh rate of 0.5 Hz [12], [13]. Despite its breakthrough at that time, an externally applied voltage of 7 kV and a high-power pulsed laser shall undercut its practical usage. Later in 2012, Tsutsumi *et al.* from Kyoto Institute of Technology disclosed a novel photorefractive polymer composite using poly-N-vinyl carbazole, which not only has a faster response time of tens of milliseconds, but also a higher and controllable diffraction efficiency (DE) [14]. Nonetheless, it still needs a very high driving voltage to function.

In this paper, we present a real-time holographic display featured by an azo-dye-doped liquid crystal (LC) without any external voltage. This material enables a video-rate display as each hologram can be refreshed in the order of several milliseconds. Its operational principle, dependence of response time on various factors, and experimental proofs have been given in what follows.

II. Operational Principle

Of various photorefractive materials, dye-doped LC lends itself to a recording medium for holographic display due to the extraordinarily large optical nonlinearity, usually in the range of 1–2000 cm^2/W [15]. This would translate into a reduced power requirement by several orders for the laser. The presence of dichroic dye plays an important role in this mixture. For dynamic modulation purpose, it is supposed to be chemically reversible, fast-response, and highly sensitive. According to this principle, azo dye, characterized by an azo group, $-N=N-$, is one of the preferred choices.

The mechanisms underlying the photorefactivity of the dye-doped nematic LC are primarily attributed to two reasons: (1) The molecular conformation change [15]. When the dye molecules are mixed with the LC molecules, they follow the movement of the LC molecules and vice versa. In other words, the orientations of the dye and LC molecules are coupled. If exposed to light radiation, the dye molecules undergo trans-cis-trans geometrical isomerization. Due to this isomerization effect and the coupling between the dye and the LC, the alignment or order of the LC molecules can be changed; (2) light-induced charges [16]. When an azo dye gets excited

Manuscript received April 01, 2013; revised June 19, 2013; accepted September 10, 2013. Date of publication September 16, 2013; date of current version May 05, 2014. This work is supported by 973 Program (2013CB328804), National Natural Science Foundation of China (NSFC) underGrants 61275026 and 61307028, by the Science and Technology Commission of Shanghai Municipality under 11JC1405300 and 13ZR1420000, and by the Fundamental Research Funds for the Central Universities under Grant XDJK 2011C047. *(Corresponding authors: C. P. Chen; Y. Su)*

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Digital Object Identifier 10.1109/JDT.2013.2281918

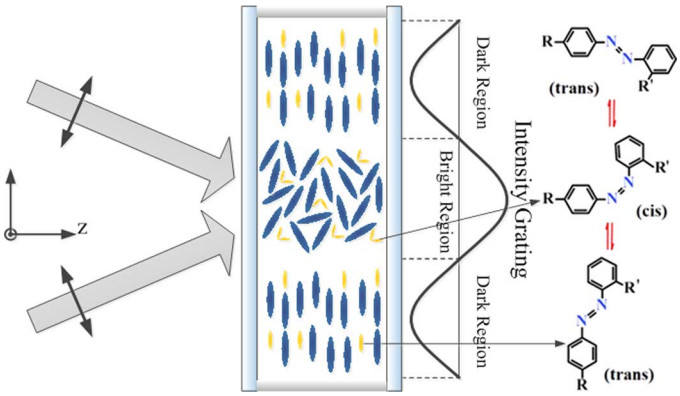


Fig. 1. Photorefractive mechanism of the azo-dye-doped LC.

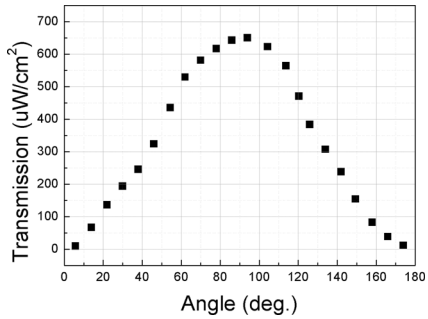


Fig. 2. Transmission intensity versus the angle between the polarized incident beam and the LC director.

by the field of light of the absorption band, the electron cloud of the molecule becomes distorted, which induces the space charges and local fields. Different dyes could exhibit the above effects to different degrees. Fig. 1 schematically depicts the formation of an intensity grating within a dye-doped LC cell, where the light-induced charges are ignored. The dark region below a certain level favors the conformation of trans-isomer of the dye, leaving the LCs in their initial direction, whereas the bright region above some level prefers cis-isomer, bending in its molecular axis and causing the LCs randomly aligned. This resultant change in the molecular alignment is therefore responsible for the spatial variation of refractive index.

III. Liquid Crystal Cell Fabrication

The material used in our experiments is a mixture of a nematic LC (5CB) doped with a 4 wt% of an azo dye (disperse red 1, DR1) [16]. Mylar slips with a thickness of about 50 μm are sandwiched by two glass substrates to maintain the cell gap. The surfaces of top and bottom substrates are rubbed in parallel to align the long axis of the LC molecule, i.e., the LC director. The LC-dye mixture is stirred for 12 hours and filtered with a 0.2-μm minipore, and then filled into the cell via capillary action at the room temperature.

The dichroic nature of an azo dye is to absorb light strongly along the principal molecule axis, known as, the absorption axis (AA), and to transmit light easily along the perpendicular direction. This is examined by rotating the polarization directions of an incident light of 488 nm to observe the varying transmission, as shown in Fig. 2. The absorption coefficients of the dye, including parallel component $\alpha_{//}$ and perpendicular component $\alpha\perp$, can be calculated according to Beer–Lambert law [17]. Hence, a dichroic ratio (DR) is found out as 2.7. In addition, typical material parameters are summarized in Table I.

TABLE I
Material Parameters

	Quantity	Values
Cell	d	50 μm
	concentration (dye)	4 wt%
LC (5CB)	n_o	1.542
	n_e	1.729
	Δn	0.187
	clearing point	35.3 °C
Dye (DR1)	$\alpha_{//}$	3590/mm
	$\alpha\perp$	1570/mm
	DR	2.7

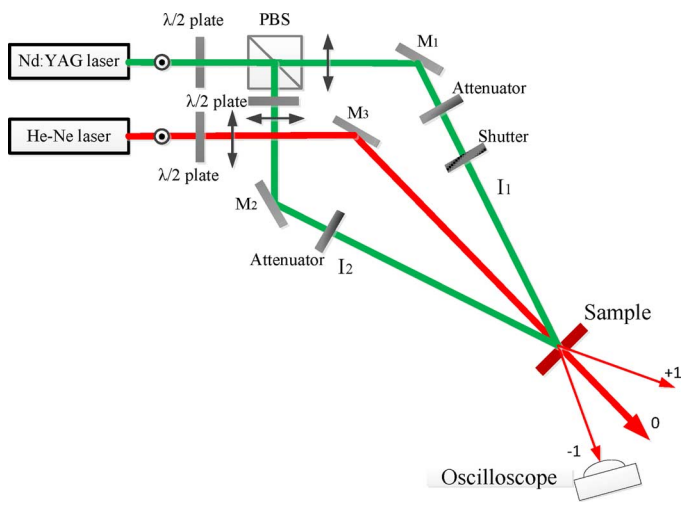


Fig. 3. Experimental setup for response time testing. M1–M3 are mirrors, BS is a beam splitter, $\lambda/2$ is a half-wave plate.

IV. Response Time

A. Response Time Versus Light Intensity

For real-time holographic display, the image refreshing rate is a key performance indicator, associated with the response time—the time it takes for both recording and erasing a single hologram. We shall first investigate the relation between response time and various intensities of the recording beams that consist of reference and object beams. The experimental setup for measuring the response time is illustrated in Fig. 3. It shall be mentioned that there is no external electric field applied to the cell during the experiment. Two recording beams with the same diameter of 3 mm are both derived from an Nd:YAG laser and set to be p-polarization by half-wave plates (HWPs). The incident plane defined by the wave vectors of two recording beams with an angle of 13° is perpendicular to the surface of the cell. A beam from a He–Ne laser with p-polarization is used to probe

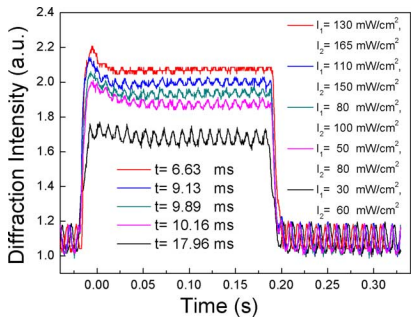
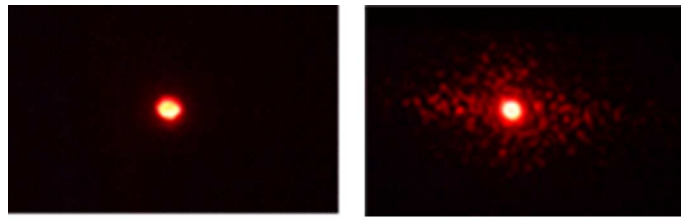


Fig. 4. Measured response time with respect to different combinations of recording intensities.

the interference region with a power of 20 mW and a diameter of 2 mm. A shutter is used to control the on and off states of the recording beams.

The results of the response time with respect to the different intensity combinations of the recording beams are given in Fig. 4, where the intensities of the object and reference beams are denoted as I_1 and I_2, respectively. With a boost in the recording intensity, DE increases, while the recording time becomes faster, as can be seen in Fig. 4. The former is mainly due to the stronger coupling effect between the dye and the LC at a higher intensity, thereby rotating more LC molecules to contribute to the refractive index modulation [18]. The latter can be explained by the fact that the more energy the dye absorbed, the faster the isomerization process could be fulfilled [19], [20]. However, as the intensity of the recording beam further increases, DE will reach its maximum as a result of the saturated birefringence. Meanwhile, the exposure to the higher intensity of light would also increase the temperature of the sample, which is able to enhance the diffusion of cis molecules from the bright area to dark area. The photo-induced birefringence thus lessens. Such trend is reflected as the bump occurring in the course of the recording under the high intensity conditions. The shortest response time measured on an oscilloscope (DSO-X 2012A, Agilent) is 6.63 ms, of which, the recording time is 1.82 ms and the erasing time is 4.81 ms. The recording time measures the time when DE ascends from 10% to 90%, while the erasing time measures the duration when DE descends from 90% to 10%.

Although the response time can be reduced by amplifying the intensity of the recording beams, it has also been found out that this will no longer hold once the intensity reaches a critical level. At this level, due to the thermal accumulation over time, the LC can be heated up to its clearing point, which is as low as 35.3 °C, resulting in transition from the anisotropic phase to isotropic phase. Correspondingly, the refractive index modulation will fail. In the circumstance of the intensity ratio of the object beam to the reference beam is 1:1, the minimal recording intensity of each beam that can be responsive is measured as 1.29 $\mathrm{mW/cm^2}$, while the critical level is 176 $\mathrm{mW/cm^2}$. Fig. 5 shows the diffraction spots when the recording intensity is below and above the critical level, respectively. For the latter case, the diffraction effect is somewhat diminished in less than a few seconds. Based on this observation, a LC with a higher



(a) (b)

Fig. 5. Diffraction spots when the intensity of recording beams is (a) below and (b) above the critical level, 176 $\mathrm{mW/cm^2}$.

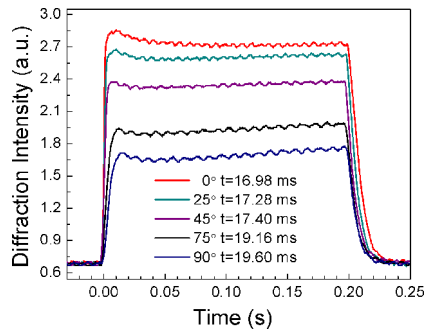


Fig. 6. First-order diffraction intensity and response time as a function of the angle between the recording light polarization direction and the director axis of liquid crystal $I_1 = I_2 = 159\ \mathrm{mW/cm^2}$, $\theta = 21°$.

clearing point is recommended for the sake of both faster response time and wider range of operation.

B. Response Time Versus Polarization Direction

Since both the LC and the dye are anisotropic materials, it can be expected that the polarization directions of the recording beams have an influence on their optical nonlinear response. As the polarization direction is rotated from 0° to 90° relative to the LC director, also the AA of the dye, absorption effect gradually weakens as the absorption coefficient encountered by the light becomes smaller. Consequently, the recording time gets longer, as shown in Fig. 6. This implies that the energy absorbed by dyes would positively contribute to the formation of a hologram. Erasing time, on the other hand, exhibits the opposite tendency toward the polarization direction, getting shorter in time. By totaling the recording and the erasing time, the response time has a slight increase, meaning that it is less dependent on the polarization direction than on the intensity. However, the DE drops dramatically as polarization direction approaches 90°. Overall, the best polarization direction for the case of linearly polarized recording beams should be parallel to the AA of dye.

C. Response Time vs. Polarization State

The response behaviors of the azo-dye-doped LC with respect to the polarization state of the recording light is investigated by comparing the case of the intensity grating with that of the polarization grating. For intensity grating, two interfering beams are of the same polarization, causing the intensity to vary in a sinusoidal fashion [see Fig. 7(a)]. Besides, the above polarization direction is the same as the rubbing direction as well as AA of the dye. Polarization grating, on the contrary, is formed by two beams of crossed polarizations, but with the intensity

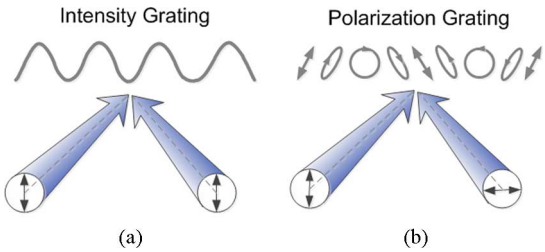


Fig. 7. Schematic illustrations of: (a) an intensity holographic exposure using parallel polarizations and (b) a polarization holographic exposure using crossed polarizations.

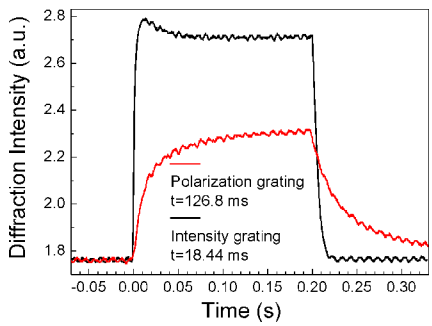


Fig. 8. Comparison of diffraction intensity and response time for intensity and polarization holographies with 488 nm laser, $I_1 = 115$ mW/cm^2, $I_2 = 106$ mW/cm^2, $\theta = 21.7°$.

unchanged while the polarization states continuously changing [see Fig. 7(b)] [20]. Referring to Fig. 8, intensity grating exhibits a faster response during both recording and erasing and a higher DE as well. The difference in the response of two cases can be understood as the order difference. Since in the polarization grating, the dye molecules are excited in different ways, which could greatly reduce the order of LCs, thereby slowing down the LC's hydrodynamic velocity. This is more pronounced during the erasing as the light is turned off. As for the difference in DE, the polarizations within the intensity grating are all parallel to the AA of dye, indicating that the absorption effect is maximized in this case. In agreement with the above discussion, the stronger the absorption is, the higher the DE will be.

V. Video-Rate Holographic Display

To verify whether our dye-doped LC is capable of recording and reconstructing holograms in real time, a set of optical elements are arranged as in Fig. 9. A Nd:YAG laser ($\lambda = 532$ nm) is used to yield the coherent reference and object beams, both of which are set to be p-polarization. On the other hand, a He-Ne laser ($\lambda = 632.8$ nm) is also set to be p-polarization to probe the writing region of the sample, or the active area. The diameter of the reference beam is about 3.5 mm and the active area is about 4 mm^2. The intensity ratio of the reference and object beams has to be finely tuned via an HWP so as to obtain the reconstructed images with good quality. As a result, the intensity of the object beam is chosen as 100 mW/cm^2, while that of the reference beam is 160 mW/cm^2. 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. Reference and object

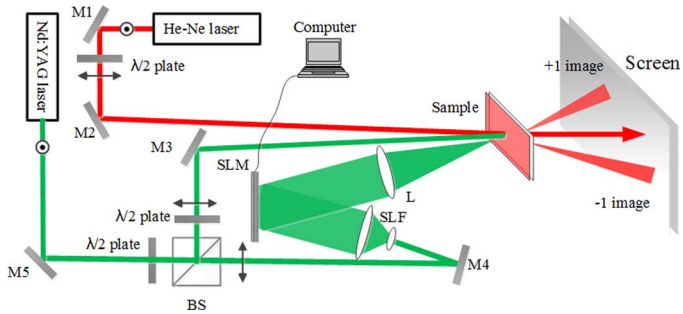


Fig. 9. Experimental setup for holographic video display.

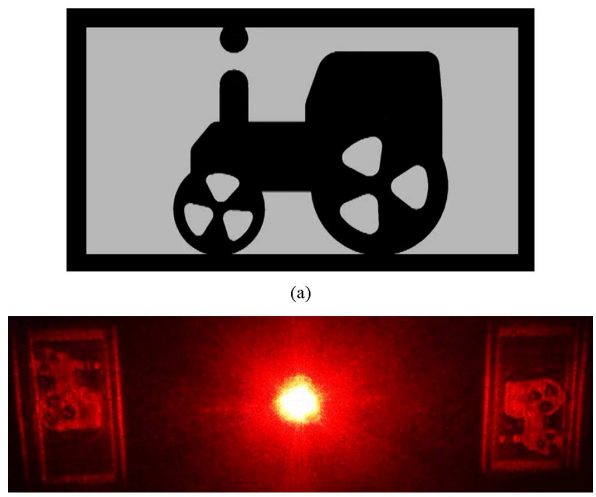


Fig. 10. Exemplary snapshots from (a) the original video rendered on the SLM, and (b) the reconstructed real-time holographic video (left: +1 order, right: −1 order).

beams intersect at an angle θ of 13° in the sample, which is located nearby the Fourier plane of the lens L (focus = 400 mm). By following the formula of grating spacing,

$$\Lambda = \frac{\lambda}{(2n \sin \theta_\circ)} \tag{1}$$

where λ is the wavelength of the recording light, n is the refractive index of the sample, and θ_0 is the incident angle, which is half of the above angle θ, the grating's spatial resolution is calculated as 714 lines/mm, which is much higher than that of most of the active SLMs [21], [22]. The reconstructed video is projected onto a screen 76 cm away from the sample. A reflective-type phase modulating SLM (PLUTO-VIS, Holoeye) is employed as the video source, which carries the spatial information of video images, and it has a resolution of 1920×1080 and a pixel pitch of 8.0 μm.

In our experiments, several holographic videos at a refresh rate of 25 Hz have been successfully achieved. As shown in Fig. 10(a), the original videos displayed on the SLM come in the moving picture experts group (MPEG) format. Then, these videos will be reconstructed by the dye-doped LC cell and captured by a digital camera. As shown in Fig. 10(b), where the light source is the He–Ne laser, one can clearly see the image of +1 order on the left with its conjugate image on the right.

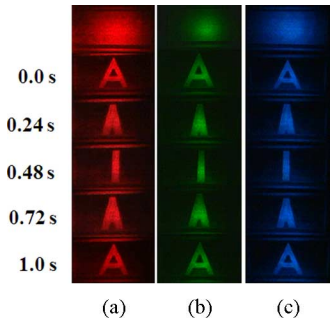


Fig. 11. A series of snapshots from holographic videos illuminated by three different wavelengths of: (a) 632.8 nm; (b) 532 nm; and (c) 488 nm.

Furthermore, a series of snapshots from holographic videos illuminated by three different wavelengths of 632.8 nm, 532 nm, and 488 nm are shown in Fig. 11, respectively. In fact, this is the direct evidence of the possibility of using this material for realizing color display with multiplexing method. Moreover, the DEs are 0.6%, 0.37%, and 0.16% measured at 632.8, 532, and 488 nm, respectively. We shall also mention that the time intervals of five snapshots are selected without preference and the original videos can be played smoothly.

VI. Conclusion

We have successfully demonstrated a real-time holographic video at a refresh rate of 25 Hz, sourced from an SLM and reconstructed by an azo-dye (DR1) doped nematic LC cell without any applied electric field. The performance of the proposed device is underlined by the response time, including both recording and erasing time. Its dependence on the recording intensity, polarization direction, and polarization state has been experimentally revealed. By adjusting the above parameters, response time can be measured in the order of several milliseconds, sufficiently fast for the video-rate display applications. In addition to its decent performance, the material availability as well as the scalability of this LC-based material grants itself a promising future for the large size, dynamic, colorful holographic display.

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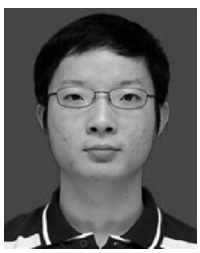

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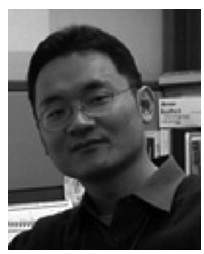

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