Temperature Dependence of Dynamic Holographic Displays using Doped Liquid Crystals

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Abstract

The temperature dependence of diffraction efficiency and response time in two holographic systems using doped liquid crystals (LC) is investigated. For dye-doped LCs, the response time is generally robust to temperature variation but the diffraction efficiency is temperature-sensitive; whereas, the QD-doped LC remains robust for both characteristics around room temperature.

Keywords:

Holographic display; 3D display; quantum dot; dye; liquid crystal; temperature dependence.

1. Objective and Background

A holographic display produces three-dimensional (3D) imagery, which can be seen with naked eyes and are similar to how humans see objects in the real world [1-3]. In recent years, the technology has attracted considerable interests. Significant developments in holographic displays have been achieved such as electro-holographic display based on liquid crystals (LCs) [4], liquid crystal on silicon (LCoS) [5], microelectro mechanical systems (MEMS) [6], acoustic light modulator [1], and photorefractive materials [7-11], etc. Among them, holographic display based on photorefractive materials may be an effective method to achieve practical applications due to low cost, large size, and easy fabrication. Refreshable holographic displays have been demonstrated based on photorefractive materials. Peyghambarian et al. reported a quasi-real-time dynamic display at a refresh rate of 0.5 Hz [7, 8]. However, an externally applied voltage of 7 kV and a high-power pulsed laser shall undercut its practical usage. In 2012, Tsutsumi et al. from Kyoto Institute of Technology reported a novel photorefractive polymer composite using poly-N-vinyl carbazole, and obtained reconstructed 3D images with a faster response time of tens of milliseconds [9]. Our group has proposed dynamic holographic displays using dye-doped and quantum dot doped (QD) liquid crystals (LC) [10, 11], whose response times are only several to tens of milliseconds without applying a high external voltage.

In practical applications, the performances of the systems such as diffraction efficiency and response time should be stable. And those properties are related to the optical nonlinearity of the doped LCs. It is reported that the optical nonlinearity could be affected by thermal effect due to order parameter variation [12]. Therefore, in this paper, we study the dependence of dynamic holographic displays on ambient temperature in dye (Dispersed Red 1, DR1) doped liquid crystal and QD-doped liquid crystal. Based on the results, he temperature ranges of holographic displays based on doped LCs in practical applications are investigated.

2. Experiments

For the sake of easy comparison and observation, we use 5CB LC which has a low clearing temperature to investigate the dependence of dye-doped and QD-doped LCs on temperature. When employed in a practical system, a LC of a higher clearing temperature such as E7 is needed.

Table 1. Parameters of the two holographic systems

Dopant	LC	Concentration	Cell gap	Applied voltage
DR1	5CB	2%	20 μm	0 V
ZnS/InP	5CB	0.05%	20 μm	27 V

As shown in Table 1, two kinds of materials were used in our experiments: mixtures of nematic LCs (5CB) doped with DR1 and QD respectively. Mylar slips with a thickness of about 20 μm were sandwiched by two ITO glass substrates to maintain the cell gap. The cell alignment was homogeneous along the horizontal direction indicated by arrows as shown in Fig. 1.

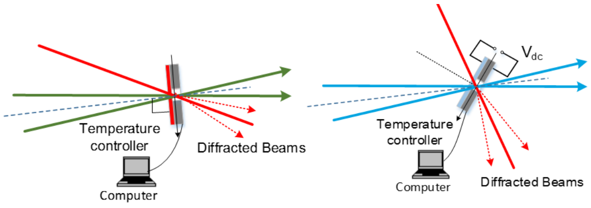

Figure 1. Experimental setups for (a) DR1-doped LCs and (b) QD-doped LCs

Figure 1 illustrates the experimental setups for measurement. A temperature controller was used to change the ambient temperature of the samples. Two polarized recording beams with a diameter of 2 mm were set to be p-polarized, and then interfered in the sample. For the DR1-doped LC, the strongest absorption is around 532 nm while QDs' absorption spectra is in the range of ultraviolet and around 488 nm in the experiment [13]. We used a Nd: YAG (532 nm) laser and an optically pumped semiconductor (OPS) (488 nm) laser for DR1- and QD-doped LCs, respectively. The incident plane defined by the wave vectors of the two recording beams with an inter-beam angle of 2° was perpendicular to the cell substrate. For the DR1-doped LCs, the bisector of two recording beams was perpendicular to the surface of the sample without an applied voltage as shown in Fig. 1(a). As for the QD-doped LC, we used the setup as shown in Fig. 1 (b). Photo-induced charges were excited by the laser in the mixture. The sample was titled at 45° with respect to the bisector of two recording beams with an applied voltage of 27 V, so that there was a horizontal electric field component to separate the photoinduced charges (electrons and holes), resulting in refractive

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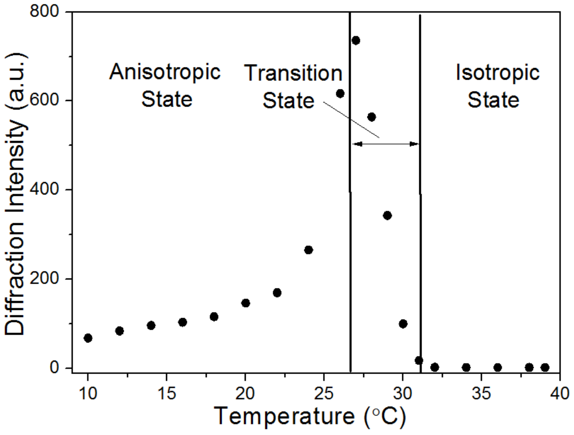
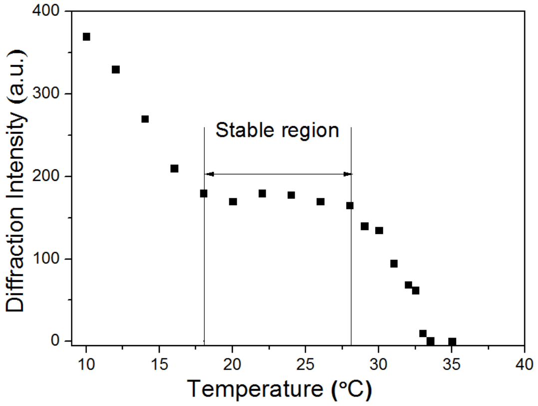
index modulation and the formation of grating. A beam from a He-Ne laser with p-polarization was used to probe the interference region with an angle of about 30° with respect to the normal. A shutter was used to control the on and off states of the recording beams to measure the response time of the formed grating.



(a) DR1-doped LC



(b) QD-doped LC

Figure 2. Dependence of diffraction efficiency on emperature for: (a) DR1-doped LC and (b) QD-doped LC.

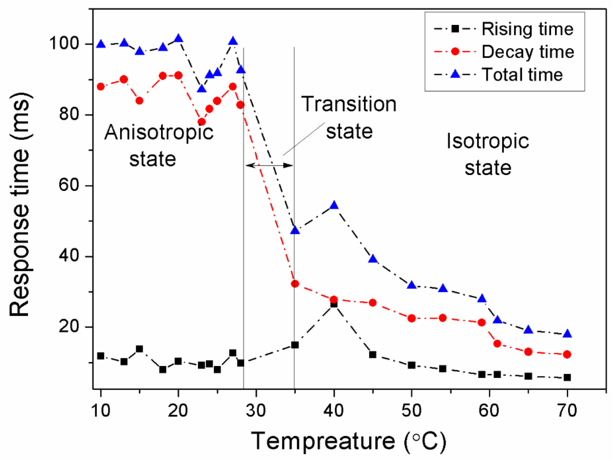
3. Results and discussions

(a) Diffraction efficiency vs. Temperature

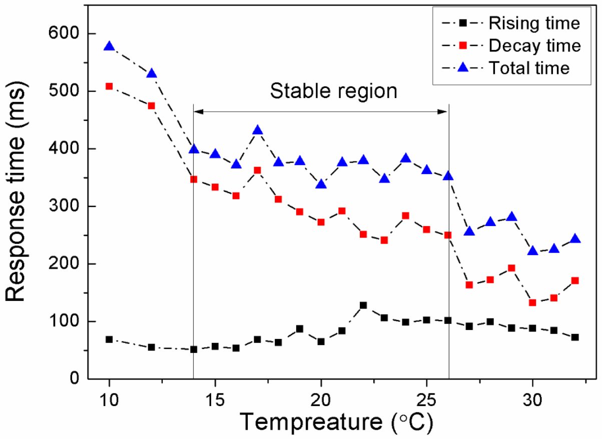
The dependence of diffraction efficiency on temperature for the DR1-doped LC is shown in Fig. 2(a). The changes of diffraction efficiency are different in three regions: 10℃~26℃ , 26℃~32℃ and above 32℃. In the first region where the DR1-doped LC is in an anisotropic state, the diffraction efficiency rises dramatically as the temperature increases and reaches its maximum at a temperature slightly below the clearing point temperature. Upon continuous laser illumination, DR1 molecules absorb a large amount of light, and heat the sample up. Therefore, the doped LC mixture reached T_c even when the apparent temperature (indicated by the temperature controller) is at a lower temperature (26℃). The second region is a transition state where the diffraction intensity dramatically decreases and reduces to nearly zero. During this process, the diffracted spot becomes fuzzy and unstable, which might result from the phase transition of the LC in the brighter illuminated region. In the third region where the DR1-doped LCs is in an isotropic state, the grating is formed again and the diffracted spot becomes weaker. In this region, the diffraction efficiency keeps a constant while the temperature continues to rise. We use half wavelength plate to change the polarization of reading light and study the properties of the gratings formed in the third region, the gratings in this region are independent on the polarizations of reading light. The diffracted spot might be due to thermal expansion and contraction in the sample.

Usually, a real time holographic display works in the first region around room temperature , where the diffraction efficiency is severely affected by temperature. Therefore, the temperature effect limits the operation temperature range and thus has substantial negative influences on the display stability.

Compared to DR1-doped LC, QD-doped LC exhibits higher temperature stability. The dependence of diffraction efficiency on temperature is shown in Fig. 2(b). In general, the diffraction efficiency decreases as the temperature increases. However, near room temperature, there is a stable region 18~28℃ where the diffraction efficiency is robust to environmental temperature variation. Moreover, when close to the clearing temperature, the diffraction efficiency decreases towards zero rapidly. Note that the setup for the QD-doped LC can be optimized to achieve much better performance in diffraction efficiency and response time



. (a) DR1-doped LC



(b) QD-doped LC

Figure 3. Dependence of response time on temperature for: (a) DR1-doped LC and (b) QD-doped LC.

(b) Response time vs. Temperature

Figure 3 shows the response time of the DR1 and QD-doped LCs versus the temperature. For the DR1-doped LC in an anisotropic state, both the rising time and decay time fluctuate in small ranges. The total response time defined as the sum of the rising time and decay time, ranges from 87.2 ms to 101.5 ms , which indicates that the response time of DR1-doped LC in an anisotropic state is relatively insensitive to environmental temperature. For the QD-doped LC, the rising time is relatively stable under the clearing temperature while the decay time decreases as temperature rises. However, the total time keeps generally unchanged in a stable region from 14℃ to 26℃, which is near the room temperature. In summary, the response time of both DR1 and QD-doped LC is robust to the temperature when operated around room temperature.

(c) Discussion

For the DR1-doped LC, the refractive index modulation might attribute to order parameter gradient in the material between bright and dark regions. Both thermal and photoisomerization effects in a dye doped LC can affect the order parameter and lead to refractive index modulation. Usually refractive index gradient is related to the temperature change [12]. When temperature rises, a bigger difference between bright and dark regions is obtained and such as a higher diffraction efficiency. Around the clearing temperature, the refractive index gradient with respect to temperature is the greatest. One can also see from Fig. 2(a) that the diffraction efficiency increases by two orders of magnitude very rapidly around the clearing temperature, which is consistent with the theory.

Different from the mechanism in the DR1-doped LC, the main reason of an optical nonlinearity in the QD-doped LC is from the nonuniform irradiation charge-density. Due to the electro-optic properties of the LC, the LC molecules reorientate corresponding to the light intensity patterns. Therefore, the grating formation in the QD-doped LC is mainly from the spatial modulation of LC reorientation determined by the external electric field and internal space charge field rather than the change of order parameter originated from the thermal effect and photo-isomerization effect. For QD doped LCs, the change of temperature influences not only the photoluminescence (PL) quantum yield of QDs but also viscosity coefficient, elastic constant and dielectric constant of the mixtures, leading to a strong nonlinearity of the QD doped LCs.

4. Conclusions

In conclusion, we have experimentally investigated the dependence of the electro-optical properties of holographic gratings on ambient temperature in DR1-doped and QD-doped LCs. The results indicate that the diffraction efficiency of the DR1-doped LC is seriously affected by temperature while the response time is relatively stable. Compared to the DR1-doped LC, the QD-doped LC is more robust to temperature variation near the room temperature, in terms of both diffraction efficiency and response time. Therefore, the QD-doped LC is more suitable for real-time holographic display applications. The temperature dependence of holographic system employing LCs with higher clearing temperatures will be investigated in our future work.

5. Acknowledgements

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