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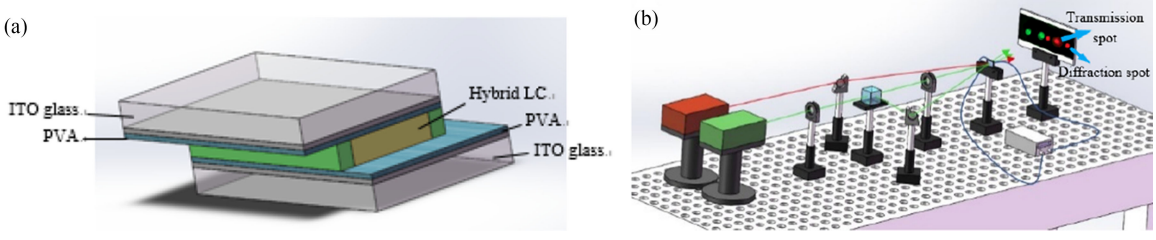

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Super-Fast Refresh Holographic Display Based on Liquid Crystal Films Doped With Silver Nanoparticles

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Abstract: Holography as a true three-dimensional (3-D) technique is thought to be the ultimate display technique. However, dynamic holographic materials still have problems such as slow refresh, high applied electrical field, etc., to be solved to realize video-rate 3-D display. We present silver nanoparticles (Ag NPs) doped liquid crystal films with very big birefringence and super-fast hologram refresh speed as real-time dynamic holographic medium, which can be applied in holographic video display. And the fastest response time of both build-up and self-erasure of hologram can be up to 0.1 ms, which means the material has the ability to realize a smooth holographic video-rate display. The holographic diffraction efficiency dependent on the intensity of recording light, applied electrical field, etc. is investigated. The maximum diffraction efficiency is measured up to 50% under a low applied electrical field of 0.12 V/μm. Real-time holographic videos at red, green, and blue colors are obtained and the process of hologram formation is analyzed, which shows that the *LC* films doped Ag NPs can be a good candidate for applications of large-size, real-time, color holographic true 3-D display in future.

Index Terms: Holographic true 3D display, holographic materials, silver nanoparticles.

1. Introduction

Recently, with the rapid development of digital information technology, three-dimensional (3D) display has attracted growing attention [1]–[3]. Some 3D techniques are demonstrated to be true 3D reconstruction, i.e. the reconstructed light wavefront just like that from objects. It is necessary for the display to replicate not only light intensity and color of 3D image, but also its depth cue. holography is supposed to be a true 3D technique to provide a vivid image of a real object or a scene because it has the ability to rebuild both the intensity and phase information of the true nature of an object or a scene, making it possible for the observer to perceive the light as it would be scattered by the real object itself without the need of a special eyewear [4]–[7]. However, it has not been widely applied in commercial display because there are some problems that have not been solved. One of the problems to be dealt with is to realize large size holographic 3D display. It may be solved by

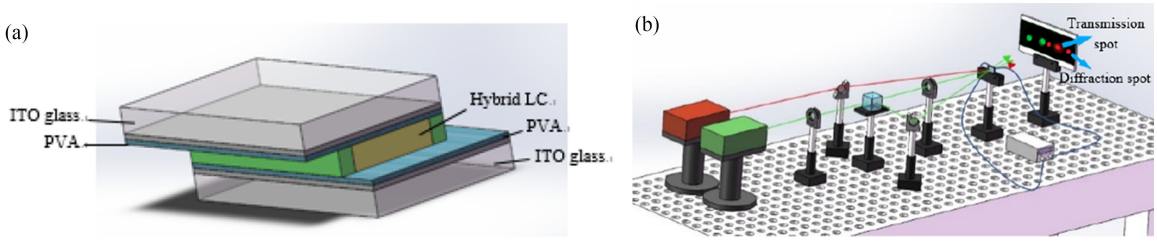

Fig. 1. (a) Structure of the LC cell, and (b) two beam coupling experiment setup.

developing large size holographic materials that can update hologram instantly [4], [8]. Over the past few years, many materials have been discovered such as photosensitive crystals, photochromic polymers, polymer dispersed liquid crystals, etc. [9], [10] to get dynamic holographic display.

Our work focused on LC thin films with broadband birefringence, large optical nonlinearity, low voltage tunability etc., and studied the fast refresh holography in them. In 2007 and 2012, we reported realtime dynamic holographic display based on Disperse Red 1 doped liquid crystal thin film with fast response [11], [12]. Optical holograms can be refreshed in the order of a millisecond and there is no cross talk between the recorded holograms because of the complete self-erasure of the hologram in this film. In 2013, Sasaki *et al.* proposed a ferroelectric LC doped with 10 wt.% of 3T-2MB (chiral dopant) and 0.1 wt.% of TNF to realize dynamic holography with the applied electric field of 1 V/μm and the rise time is 8ms [13]. In 2016, Li *et al.* proposed a mixture of a nematic LC (5CB) doped with 0.05 wt.% of quantum dots (Zns/InP) to obtain the fastest rise time to 6.4ms, while the memory time is 140 ms, using an applied voltage of 17V [14], [15]. Recent advancements [16]–[18] in transient holographic recording media may be helpful for dynamic holographic display.

In this work, we perform detailed investigation on a real-time holographic display based on LC doped with Silver Nanoparticles (Ag NPs) films without any additional semiconductor layer. The experiment reveals that the maximum diffraction efficiency of the LC films is up to 50%, using an applied electrical field of 0.12 V/μm. The fastest build-up and self-erasure time of hologram are both 0.1 milliseconds in the material. We investigate efficiency dependent on recording light power and polarization, externally applied voltage, etc. and response time dependent on recording light power. We obtain the real-time holographic videos of red, green and blue colors in LC films, which means that it may be a prospective material for advanced applications in real-time dynamic holography.

2. Samples and Experimental Setup

In experiments, we propose a LC film doped with Ag NPs as real-time dynamic holographic material. The material is prepared by mixing Ag NPs with the nematic LC (5CB), which has very broadband birefringence and transparency [19], [20], and large susceptibility to applied electrical field and optical field, and then the material is heated to 80 °C for 12 hours in a vacuum oven to make Ag NPs and LC better compatibility. The clearing point of 5CB is 35.3 °C and it can be raised up to about 43 °C after Ag NPs are doped. There is a optimal Ag NPs concentration to get the best transmission and diffraction efficiency, above or below this concentration will result in material properties [21]. After several experiments with a concentration of Ag NPs from 0.01 wt.% to 0.1 wt.%, we find that 0.03 wt.% is an optima concentration. The LC film doped with 0.03 wt.% of Ag NPs is sandwiched between two transparent indium tin oxide (ITO) substrates coated with Polyvinyl Alcohol (PVA), and the thickness of crystal layer is 25 μm. The structure of the LC cell is shown in Figure 1(a).Two-wave mixing experiments are performed in the LC films. As shown in Figure 1(b), two polarized beams (object light (I_1) and reference light (I_2)) from Nd:YAG laser at 532 nm wavelength and with a diameter of 2 mm are incident onto the LC cell, generating an interference intensity pattern and forming the hologram in the film under an applied electric field. The readout beam is from He-Ne

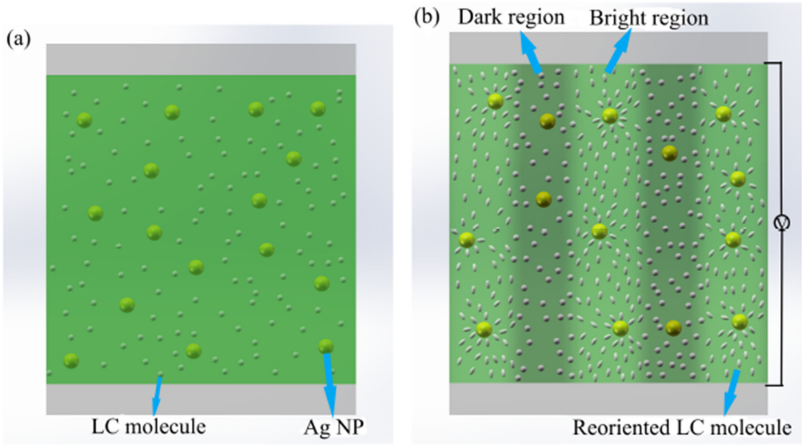

Fig. 2. (a) and (b) are different distributions of Ag NPs doped LC without and with holographic light exposure, respectively.

laser at 633nm wavelength. In our experiment, the first-order diffraction of readout light is measured which is an important parameter related to holographic display application.

The interference of two coherent beams leads to alternant dark and bright regions. As shown in Figure 2(a), without light exposure, the Ag NPs and liquid crystal molecules in a stable state are uniformly distributed. When they are placed in the region of interference and the frequency of the incident light is close to the vibration frequency of the free electrons of Ag NPs, the vibration of electrons will be significantly enhanced because of the Localized Surface Plasmon Resonance phenomenon. The Localized Surface Plasmon Resonance can generate two effects: (1) both absorption and scattering will be greatly enhanced; (2) the electromagnetic field around the particles will be greatly improved. The electric field strength of dark and bright regions is locally different as the change of light intensity due to interference. As show in Figure 2(b), the orientation of liquid crystal molecules are different under the influence of internal electric field and external electric field in bright regions from those in dark regions. And the reorientation of liquid crystal molecules generates spatial modulation and causes a change in refractive index. This is the hologram generation process in the liquid crystal thin film doped with Ag NPs. The permittivity of the Ag NPs can be calculated according to the Drude model and the effective refractive index of nano-dispersed liquid crystal (NDLC) may be calculated by using the Maxwel Garnett mixing rules [22], [23].

3. Results and Discussion

3.1 Diffraction Intensity Dependent on Recording Light Power and Polarization Direction

The diffraction efficiency is one of important parameters which determines the brightness of a holographic image. The diffraction efficiency is dependent on many factors, two of which are the energy and polarization direction of the recording light. We measure the diffraction efficiency with the change of energy and polarization direction of the recording light and keep the intensity of readout light at 8 mW/mm^2. Figure 3(a) and (b) show that the diffraction efficiency changes with increase of intensity of recording light I_1 under $I_1 = I_2$ and under $I_2 = 32$ mW/mm^2, respectively. In Figure 3(a), it can be observed that when the intensity of the recording light is less than 32 mW/mm^2, the diffraction efficiency is positively correlated with the recording light intensity. When it is above 32 mW/mm^2, the diffraction efficiency reaches the maximum and almost does not change. In Figure 3(b), the diffraction efficiency increases with the increase of the recording intensity when it is less than 15 mW/mm^2, reaches the maximum value at the intensity, 15 mW/mm^2, and decreases with its increase when it is above 15 mW/mm^2 with the reference intensity, 32 mW/mm^2. It is found that when the intensity ratio of recording and reference light is about 1:2, the diffraction

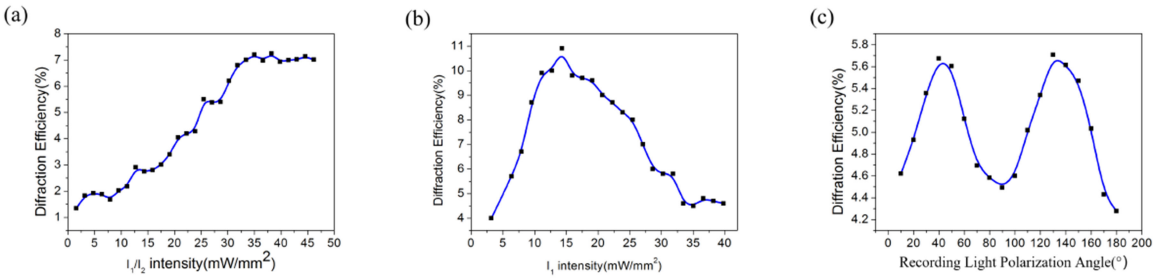

Fig. 3. Diffraction efficiency dependent on (a) the intensity of recording light, I_1 or I_2, under $I_1 = I_2$, (b) the intensity of recording light, I_1, under I2 = 32 mW/mm^2, and (c) recording light polarization angle, under $2I_1 = I_2 = 32$ mW/mm^2.

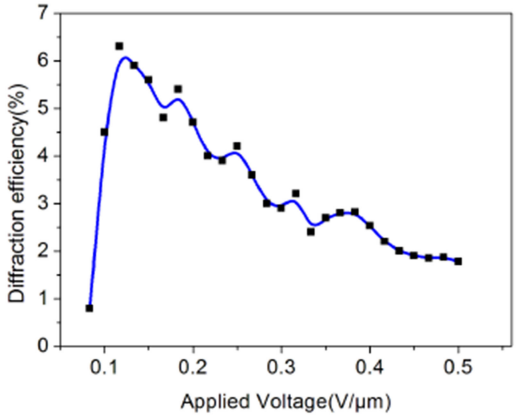

Fig. 4. Diffraction efficiency in dependence of the voltage applied on the film.

efficiency reaches the maximum value. Recording light linear polarization direction also influences the diffraction efficiency. Figure 3(c) shows that the diffraction efficiency changes with the variation of polarization direction of recording light I_1 under $2I_1 = I_2 = 32$ mW/mm^2. 0° indicates the horizontal polarization direction of the recording light. The maximal diffraction efficiency appears at at polarization angle, 40°. The diffraction efficiency increases with the increase of the polarization angle, less than 40° and decreases with its increase, more than 40°. When the polarization angle of recording light is 90°, the diffraction efficiency reaches the minimum value.

3.2 Diffraction Efficiency Dependent on External Electrical Field

In our work, as shown in Figure 4, Ag NPs doped LC film reaches the maximum value of the diffraction efficiency under applied electrical field of 0.12 V/μm, under I2 = 32 mW/mm^2 and the intensity of readout light, 8 mW/mm^2. When the electrical field is less than 0.12 V/μm, the diffraction efficiency increases rapidly with the increase of the electrical field. When the electrical field is above 0.12 V/μm, it gets to decrease. Compared with photorefractive polymer with external electrical field of up to 50 V/μm [24], [25], and some other liquid crystal cells with the electrical field of 1-2 V/μm [10], our LC film has a fast-nonlinear photosensitive response with much lower electrical field. This may be because Ag NPs are easy to be excited by optical and electrical fields and then orientations of LCs induced by them can be performed fast. Therefore, index refractive hologram can formed in the film under low electrical field.

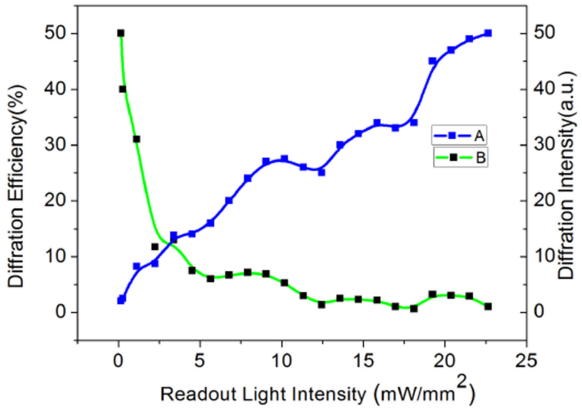

Fig. 5. A and B are curves of the diffraction intensity and diffraction efficiency dependent on the readout light power, respectively.

3.3 Diffraction Efficiency Dependent on Readout Light Power

The diffraction efficiency in this film can be affected by the readout light intensity. Curve A in Figure 5 shows the diffraction intensity versus the intensity of readout light under $2I_1 = I_2 = 32$ mW/mm^2 with the polarization angle of recording light, 40° and the electrical field, 0.12 V/μm. The diffraction intensity is proportional to the readout intensity from 0.1 mW/mm^2 to 23 mW/mm^2. Curve B in Figure 5 shows the diffraction efficiency versus the power of readout light under the same condition. According to the formula $\eta = I_d/I_t$, the diffraction efficiency of the material, η, is calculated, where I_d is the intensity of diffraction light, and I_t is the intensity of readout light. The maximum of diffraction efficiency is about 50%. The measured diffraction efficiency is inversely related to the intensity of readout light. As the intensity of readout beam increases from 0.1 mW/mm^2 to 4.5 mW/mm^2, the diffraction efficiency declines rapidly from 50% to 7% and then slowly decreases. We think the reasons are that the light loss, such as reflected and absorbed light by films is increasing with the increase of readout intensity, and if the readout light is too strong, the recorded hologram in the material may be affected by it. Therefore, we can choose suitable readout intensity according to the need in practical application.

3.4 Response Time

For dynamic holographic display, the refresh rate is an important performance parameter and the refresh rate of video-rate display is required at least 24 Hz, which means the response time should be less than 40 ms. An electronic shutter is used to control the opening and closing of the recording beam, and once the hologram is formed, we shut down the recording light, and and the recorded hologram can be self-erased. As shown in Figure 6, we get the minimum response time is 0.1 ms, which means that the refresh rate can reach 5000 Hz. Therefore, the LC films doped with Ag NPs have the ability to realize smooth holographic video display.

4. Holographic Display

The results of the response time and diffraction efficiency show that real-time holographic display can be realized in the LC film doped with Ag NPs. Figure 7 shows the experimental setup for the holographic display. Nd:YAG laser at wavelength of 532 nm is used to provide the reference and recording beams, and the image of F is loaded onto object beam by spatial light modulator with the intensities of object beam and reference beam, 20 mW/mm^2 and 35 mW/mm^2, respectively. In this experiment, holographic images are clearly reconstructed with low electrical field applied to the films. Figure 8 shows a series of snapshots captured from a real-time holographic video. Three

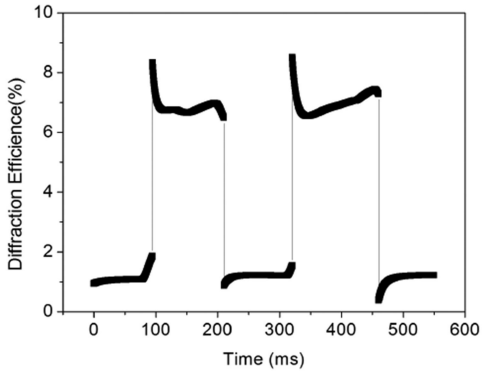

Fig. 6. Dynamic response curve of hologram formation and self-erasure in the film.

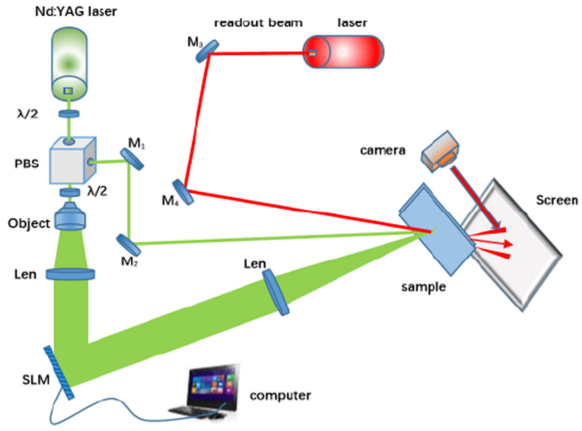

Fig. 7. Experimental setup for holographic display.

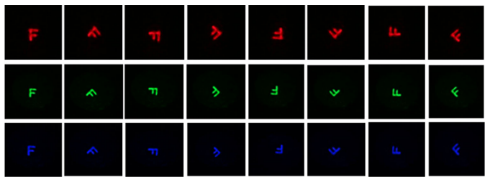

Fig. 8. Snapshots of the holographic videos reconstructed by three different wavelengths of 632.8nm, 532nm, and and 473nm at an applied electrical field of 0.12 V/μm.

lasers at different wavelengths of 632.8 nm, 532 nm, and 473 nm as readout light to probe the recording region of the sample, respectively. Diffracted videos of rotating image of F are observed. The response time of the LC film doped with Ag NPs is fast enough to realize a smooth holographic movie without cross talk.

5. Conclusion

In conclusion, we present holographic characteristic of LC thin films doped with Ag NPs, which have excellent photosensitivity and fast response speed and are easy to realize large size display. The hologram formed in this material has the property of self-erasure. Its build-up and self-erasure time of holograms are both 0.1 millisecond, which are sufficient for practical real-time display applications.

The holographic diffraction efficiency dependent on recording intensity and polarization direction, readout intensity, applied electrical field, is investigated. The maximum diffraction efficiency of the LCs thin films can reach 50% under electric voltage of 0.12 V/μm. Real-time dynamic holographic videos in red, green and blue colors are obtained without cross talk in our sample, which indicates that non-pixellation Ag NPs doped LCs films as holographic screen can be a good candidate for applications in large size, dynamic, color holographic 3D display.

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