H-PDLC-Based Volume Holographic Gratings with High Diffraction Efficiency for Augmented Reality

Hua Huang, Gang Chen, Changhan Xie, Miaomiao Jia, Yongqi Sun, Chengtan Zhao, Kang Guo, Xin Gu

***BOE Technology Group CO. LTD., Beijing, China**
E-mail: huanghuahq@boe.com.cn

Abstract

An optical platform has been set up, which can achieve the hologram recording and the measurement of the diffraction efficiency of grating. By adjusting the recording beam configuration and optimizing the ingredient, transmissive and reflective H-PDLC-based volume holographic gratings have been fabricated, of which the maximal diffraction efficiency are 69.3% and 36.7%, respectively.

Author Keywords

volume holographic grating; H-PDLC

1. Introduction

Augmented reality (AR) [1, 2] is an emerging display technology that can seamlessly blend real surrounding environments with virtual digital content. As one kind of the see-through near-eye display, AR has gained increasing attention in academia, industry, gaming and military for its unprecedented visual experience. And it has great potential to become the next-generation display. The diffracted optical waveguide, a typical AR display system, is regarded as a promising approach for commercial products, for the advantages of glasses-type form factor and large design freedom to achieve high image performance [1].

In the diffracted optical waveguide system, one of the core elements is the incoupler grating and the outcoupler grating. The former directs the image source from display panel into the waveguide, and the latter directs the image source from the waveguide into the viewer's eye. For reducing power dissipation and improving the brightness of the AR, the diffraction efficiency of the incoupler grating and outcoupler grating becomes a key factor, for which decides the light utilization ratio from the display panel. So in all kinds of grating, the volume holographic grating (VHG) has become the focus of research for its high first-order diffraction efficiency and simple preparation method compared to relief grating [3]. Based on the diffraction characteristics of VHG, the refractive index contrast of the grating stripes affects the bandwidth characteristic of the grating [4]. A larger bandwidth facilitates the design of colorized optical waveguides and improves the field of view (FOV). Among these, holographic polymer-dispersed liquid crystal (H-PDLC), as a VHG material, possesses a higher refractive index contrast and has become one of the primary directions in the field of VHG [5,6].

So, in this paper, we first set up an optical platform, which can achieve the fabrication of H-PDLC and the measurement of the diffraction efficiency of the grating simultaneously. Then we fabricated the transmissive H-PDLC and reflective H-PDLC, and further studied the relationship between the diffraction efficiency and ingredient of H-PDLC.

2. The set up of the optical platform

For achieving the fabrication of the H-PDLC, we first set up a hologram recording setup. Considering the requirement of the measurement of the diffraction efficiency, we have coupled a measurement light path into the hologram recording setup. In another word, an optical platform has been set up, which can achieve the hologram recording and the measurement of the diffraction efficiency of the grating simultaneously.

As shown in Figure 1 and Figure 2, a 532 nm laser is split into two light beams by a polarization beam splitter (PBS). One light beam, which is transmitted by the PBS, is further directed into turn table 4 (TT4). A test sample, such as a grating, is put on the TT4. Through measuring the intensity of incident light and diffraction light, the diffraction efficiency of the test sample could be measured. The TT5 is coaxial with TT4 and used to character the incident angle and diffraction angle. Another light beam, which is reflected by the PBS and further directed into the beam expander (BE), can be split into another two beams by a beam splitter (BS). These two beams interfere above TT1. When holographic recording material is put on the TT1, the holographic record occurs and the holographic grating could been fabricated. The intensity of the transmitted light and the reflective light of the PBS could be adjusted by the changing the included angle between the optical axis of the 1/2 wave plate (WP) and the polarization direction of the laser. The interference beam angle φ_{set} could be adjusted by changing the reflection angle α of the TT2 and TT3, which gives by Equation 1:

$$\varphi_{\text{set}} + 2\alpha + 90° = 360° \quad (1)$$

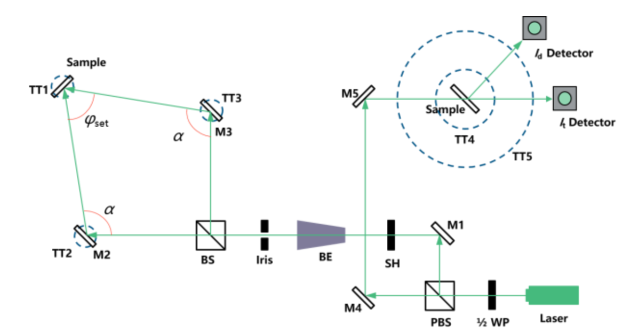

Figure 1. The diagram of optical platform. 1/2 WP: 1/2 wave plate; PBS: polarization beam splitter; M1-M5: mirror; SH: shutter; BE: beam expander; BS: beam splitter TT1-TT5: turn table.

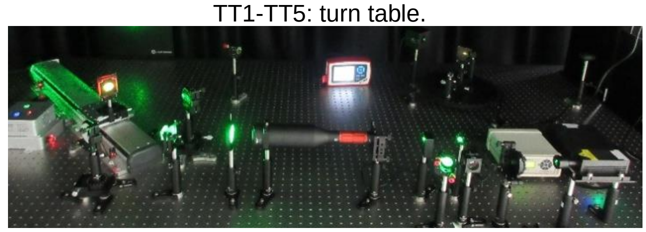

Figure 2. The photograph of the optical platform.

ISSN 0097-996X/25/5601-0628-$1.00 © 2025

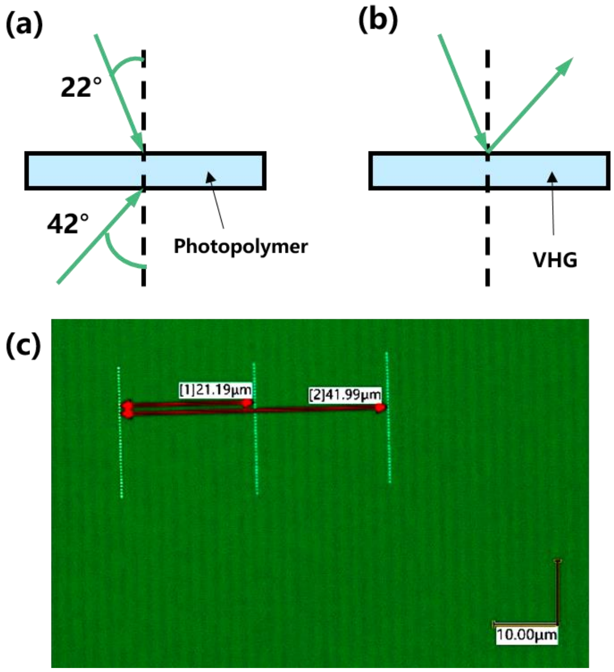

Figure 3. (a) The recording beam configuration of the photopolymer film. (b) The diffraction beam configuration of the photopolymer film. (c) The micrograph of the photopolymer film after interference exposure.

Then we tested the effect of interference exposure of the optical platform by a photopolymer film, Color Photopolymer Bayfol® HX 200, produced by Covestro AG. The thickness of the film is 16±2 μm, which is enough to prepare VGH. The recording beam configuration is shown in Figure 3(a). The two light beams are on the opposite side of the film, and the incidence angles are 22 °and 42 °, respectively. So, the final VGH is a reflective HVG, as shown in Figure 3(b). It's noted that in the field of VHG, we are only concerned with first-order diffraction that satisfies Bragg diffraction. The refraction index of the unrecorded photopolymer is 1.500. So the theoretical grating period Λ and grating tilted angle δ are 189.3 nm and 6.015 °, respectively. After interference exposure, the film renders high diffraction efficiency. The maximal diffraction efficiency is 88.3% when the incidence angle is 19 °and the diffraction angle is 36 °. The diffraction efficiency η used in this paper is defined by the Equation 2:

$$\eta = \frac{I_d}{I_i} \tag{2}$$

where the I_d and I_i are diffraction intensity and incident intensity of VHG. So the actual grating tilted angle δ is 5.248 °, which is evey close to the theoretical grating tilted angle δ, 6.015 °. As shown in Figure 3(c), the period structure of the grating is very apparent under optical microscope. The actual grating period is 192.8 nm according to the micrograph, which is close to the theoretical grating period Λ, 189.3 nm. This fully demonstrates that our optical platform has sufficient accuracy to achieve the fabrication of the VHG.

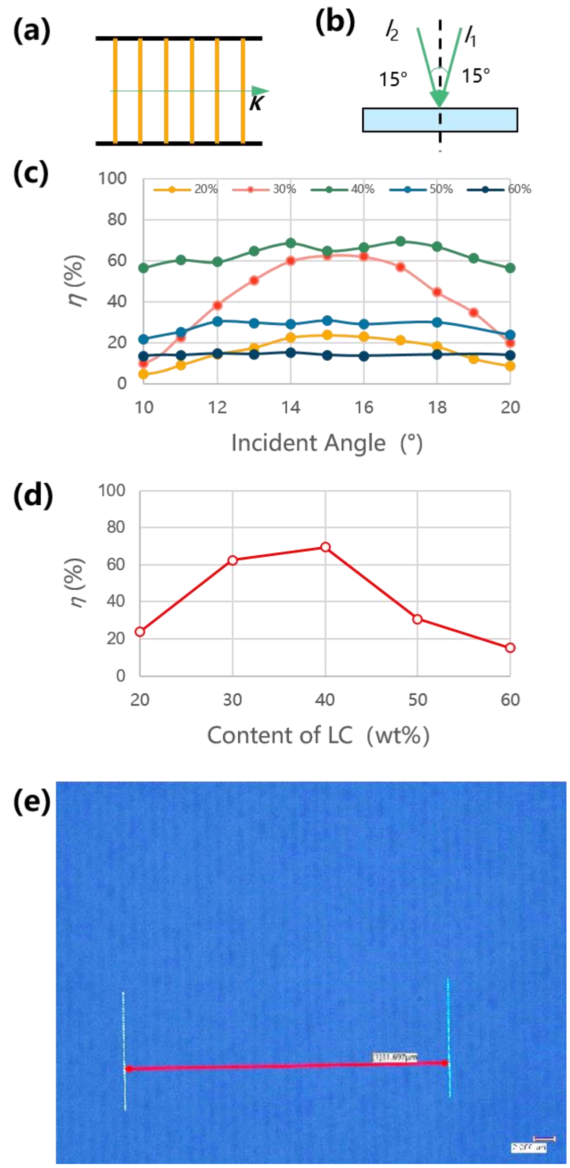

Figure 4. (a) The grating structure of the transmissive H-PDLC. (b) The recording beam configuration of the transmissive H-PDLC. (c) The diffraction efficiency of Sample A1-A5 in different incidence angles. (d) The relationship between the diffraction efficiency and the concentration of LC of Sample A1-A5. (e) The optical micrograph of the transmissive H-PDLC.

3. The fabrication of transmissive H-PDLC

To fabricate the transmissive H-PDLC, we designed a series of formulations, as shown in Table 1. The M1 is a kind of acrylate. The R1 is a kind of organic solvent, which can promote the various components to dissolve each other. The I1 and I2 are the photo-initiators. And the LC1 is a kind of nematic liquid crystal. To study the influence rule of the concentration of LC and obtain the higher diffraction efficiency, we designed five formulations with different concentration of liquid crystal. The formulations have been stirred well, and filled into liquid crystal cell. Then these samples were exposed on the optical platform to prepare H-PDLC.

Table 1. The composition of Group A (wt%)

Sample	M1	R1	I1	I2	LC1
A1	25	13	1.7	0.3	60
A2	35	13	1.7	0.3	50
A3	45	13	1.7	0.3	40
A4	55	13	1.7	0.3	30
A5	65	13	1.7	0.3	20

The grating structure of the transmissive H-PDLC was designed as shown in Figure 4(a). The grating vector is parallel to the surface of the H-PDLC. In another word, grating tilted angle δ of the H-PDLC is 90 °. The recording beam configuration of the H-PDLC is shown in Figure 4(b). The two light beams are on the same sides of the H-PDLC, and the incidence angles are +15 °and -15 °, respectively. The samples were exposed on the optical platform for 10 min, and then illuminated under an ordinary white light source for 30 min for bleaching. So, the sample preparation was complete. As shown in Figure 4(c), all the samples render typical diffraction feature of transmissive VGH, and have maximal diffraction efficiency when the incidence angle are about 15 °, which fit with the theoretical design. With the increase of the concentration of LC1, the diffraction efficiency increases first and then decreases, as shown in Figure 4(d). The maximum diffraction efficiency is 69.3% when the concentration of liquid crystal LC1 is 40 wt%.

We further measured the grating period of Sample A3. As shown in Figure 4(e), the grating period is clearly visible under optical microscope and the length of 30 periods is 31.697 um. In another word, the grating period is 1056.6 nm. For the refraction index of unexposed Sample A3 is about 1.50, we can calculate the theoretical grating period according to the Equation (3):

$$\Lambda = \frac{\lambda_{writing}}{2\left|\sin\frac{\varphi_{set}}{2}\right|} \quad (3)$$

where the laser wavelength $\lambda_{writing}$ is 532 nm. And the interference beam angle φ_{set} is 30 °. So the theoretical grating period is 1028 nm, which is very close to our measuring result.

4. The fabrication of reflective H-PDLC

To fabricate the reflective H-PDLC, we designed a series of formulations, as shown in Table 2. The M2 is another kind of acrylate, which has different functionality with M1. Like Sample A1-A5, we also designed five formulations with different concentration of liquid crystal. The formulations have been stirred well, and filled into liquid crystal cell. Then, these samples were exposed on the optical platform.

Table 2. The composition of Group B (wt%)

Sample	M2	R1	I1	I2	LC1
B1	35	13	1.7	0.3	50
B2	40	13	1.7	0.3	45
B3	45	13	1.7	0.3	40
B4	50	13	1.7	0.3	35
B5	55	13	1.7	0.3	30

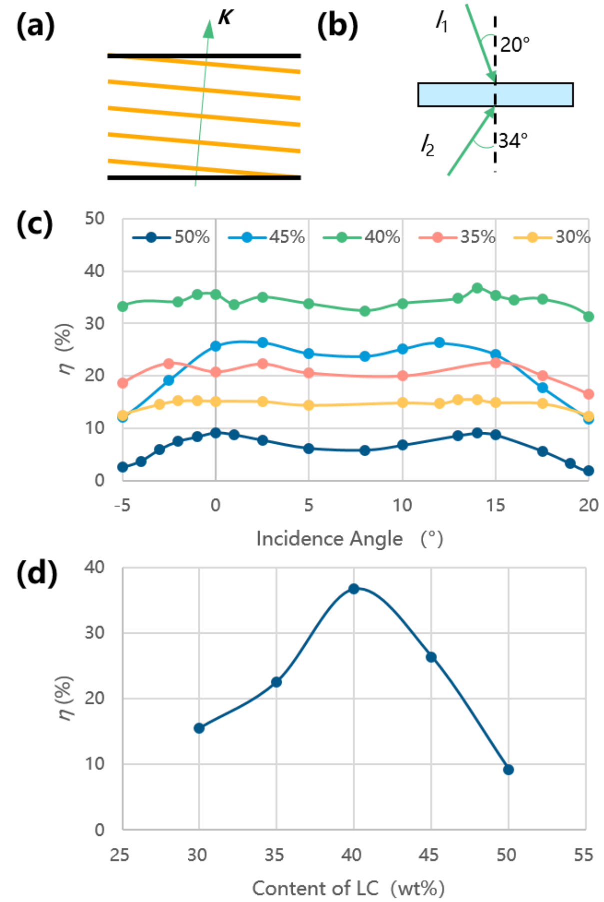

Figure 5. (a) The grating structure of the reflective H-PDLC. (b) The recording beam configuration of the reflective H-PDLC. (c) The diffraction efficiency of Sample B1-B5 in different incidence angles. (d) The relationship between the diffraction efficiency and the concentration of LC of Sample B1-B5.

The grating structure of the reflective H-PDLC was designed as shown in Figure 5(a). The grating vector is 83 ° from the grating surface. In another word, grating tilted angle δ of the H-PDLC is 7 °. The recording beam configuration of the H-PDLC is shown in Figure 5(b). The two light beams are on the opposite sides of the film, and the incidence angles are 20 °and -34 °, respectively. The samples were exposed on the optical platform for 10 min, and then illuminated under an ordinary white light source for 30 min for bleaching. So, the sample preparation was complete. As shown in Figure 5(c), all the samples render typical diffraction feature of reflective VGH. And with the increase of the concentration of LC1, the diffraction efficiency increases first and then decreases, as shown in Figure 5(d). The maximum diffraction efficiency is 36.7% when the concentration of liquid crystal LC1 is 40 wt%.

5. Conclusion

In conclusion, we have established an optical platform capable of recording holograms and measuring the diffraction efficiency of gratings simultaneously. By adjusting the recording beam configuration, transmissive and reflective H-PDLC-based volume holographic gratings have been fabricated. And by optimizing the ingredient, the maximal diffraction efficiency of transmissive and reflective H-PDLC are 69.3% and 36.7%, respectively. In the future, we will continue to optimize the structure design, material and process condition of the VHG to prepare VHG with higher diffraction efficiency and wider FOV for AR application.

6. References

1. Xiong J H, Yin K, Li K, Wu S-T. Holographic Optical Elements for Augmented Reality: Principles, Present Status, and Future Perspectives [J]. Advanced Photonics Research, 2021, 2, 2000049.
2. Jonathan D W, Alastair J G, Milan M P. DigiLens switchable Bragg grating waveguide optics for augmented reality applications [J]. Proceedings of SPIE, 2018, 10676.
3. Kogelnik H. Coupled Wave Theory for Thick Hologram Gratings [J]. The Bell System Technical Journal, 1969, 48(9), 2909–2947.
4. Li Y, Yang Q, Xiong J, Yin K, Wu S-T. 3D displays in augmented and virtual realities with holographic optical elements [J]. Optics Express, 2021, 29(26), 42696–42712.
5. Bunning T J, Natarajan L V, Tondiglia V P, Sutherland R. L. Holographic Polymer-Dispersed Liquid Crystals (H-PDLCS) [J]. Annual Review of Materials Science, 2000. 30:83–115.
6. Chen G, Ni M, Peng H, Huang F, Liao Y, Wang M, Zhu J, Roy V A L, Xie X. Photoinitiation and Inhibition under Monochromatic Green Light for Storage of Colored 3D Images in Holographic Polymer-Dispersed Liquid Crystals. ACS Applied Materials & Interfaces, 2017, 9, 1810−1819.