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Invited

Application of Polarization Volume Holographic Grating in New Display Technologies

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ABSTRACT

Near-eye holographic diffractive waveguide display using novel polarized volume holographic gratings (PVG) have lately gotten a lot of interest. Here, we briefly introduced the fundamental concepts of PVG before sharing our work progress on PVG, which included procedure, imaging simulation, and experimental results. Simultaneously, these prospective PVG-based application directions were also discussed.

1 Introduction

As a new type of display technology, augmented reality (AR) display technology has aroused broad interest across a wide range of industries [1,2]. To the best of our knowledge, because of its advantages of being thin and lightweight with an expanding exit pupil, diffractive waveguide technologies are often considered as a viable optical solution for AR near-eye displays.

However, conventional diffractive optical elements (DOE), which are the core of AR devices, tend to have a number of issues, including low diffraction efficiency, a non-adjustable refractive index, a narrow diffraction angle, and a difficult manufacturing process, which results in a low efficiency and a huge volume of the overall device, severely limiting their applications in high efficiency and comfort desired devices such as Head Mounted Display (HMD), AR glasses, Vehicle head-up display (HUD), and so on. In comparison to classic DOE [3-6], polarized volume gratings (PVG) offer a higher diffraction efficiency, a larger diffraction angle, and polarization selectivity for waveguide coupling elements. Many studies have proven that PVGs are ideal for today's AR near-eye display systems [7-11].

PVG has a two-dimensional anisotropic periodicity via periodically rotating the liquid crystal molecules in a two-dimensional direction [12-15], retaining the same high single-order diffraction efficiency as the traditional volume holographic grating (VHG) which is nearly four times higher than the surface relief grating (SRG) theoretically, and the PVG-based waveguide has an 80% lower backward light leakage than the SRG-based waveguide due to this high efficiency, and also possessing a huge angular bandwidth that is more than three times larger in angular bandwidth and four times wider in wavelength bandwidth than VHG, and simultaneously having the polarization selectivity to the incident light, which brings many new design possibilities to relevant applications. Furthermore, the preparation of PVG just involves holographic exposure and coating operations, eliminating expensive and difficult etching or nanoimprinting processes, ensuring efficient mass production with minimal manufacturing costs.

In this article, we will first explore the concept of PVG creation and the mass-production process methodology. The designable dimensions of such gratings will next be described using theoretical and simulation. Finally, we will discuss the current PVG-based prototype devices and other application directions.

2 The mass-production process of PVG

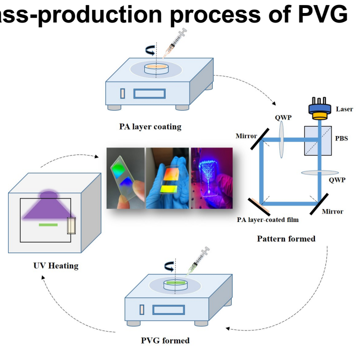

Fig. 1 The preparation process schematic of PVG.

The preparation procedure is described in Figure 1. Specifically, the photo-alignment (PA) material which is obtained by dissolving Brilliant Yellow (BY) in dimethylformamide (DMF), and then is coated on the available glass substrate. Following that, the polarized interference exposure method is utilized to expose the substrate with the PA film, in which two opposite-handed circularly polarized beams are overlapped on the photo-alignment film sample at a certain angle to form the polarized interference patterns. After that, the liquid crystal mixture solution is spin-coated on the PA film to form the PVG. Finally, UV irradiation process results in a stable PVG film.

Herein, PVG may be incorporated on many types of flexible materials substrates, such as PET, PS, etc. and has fulfilled the display requirements of diverse demands in terms of preparation process and formation mechanism. This outstanding property is unrivaled by any typical diffractive components.

3 The unique structure of PVG

Such a unique PVG can produce single-order diffraction with high diffraction efficiency when the Bragg condition is satisfied, and possesses polarization sensitivity characteristics with the chiral dopant injected. Furthermore, we discovered that the diffraction feature of PVG under such a tilted arrangement in the Figure 2 did not differ considerably from the ideal structure that the helix axis is perpendicular to the substrate through rigorous simulation and reliable tests. In addition, the uniformity of the lateral period can be maintained by the intermolecular force. In other words, PVG films that respond to various central wavelengths can be layered one on top of the other to widen the bandwidth.

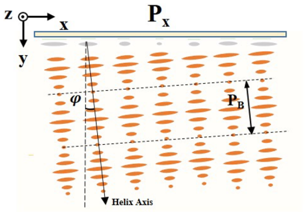

Fig. 2 Schematic diagram of a PVG.

The black dashed line in the Figure 2 is similar to the Bragg period plane which realizes the Bragg diffraction. The angle between this Bragg plane and the x-axis is defined as φ. The Bragg period is expressed as the P_B. When the incident angle is θ_i, the Bragg condition of PVG can be expressed as:

$$2nP_B\cos(\varphi-\theta_i)=\lambda_B \tag{3.1}$$

Where λ_B is the Bragg wavelength in vacuum, n is the effective refractive index of the anisotropic medium, the ordinary refractive index of the anisotropic material is n_o, and the refractive index of extraordinary light is n_e, then the n can be expressed by the following formula:

$$n=\sqrt{(n_0^2+2n_e^2)/3} \tag{3.2}$$

and the geometric relationships between the P_x and the P_B are determined by:

$$P_x\sin\varphi=P_B \tag{3.3}$$

So, controlling the exposure angle and material ratio allows for the production of PVG with a tunable diffraction angle.

4 Discussion

4.1 Optical properties

As we known, as a waveguide coupling element, the response bandwidth of angle and wavelength is the factor that directly impacts the display performance. The diffraction properties via self-built RCWA for the unique structure of PVG are presented in the Figure 3.

Figure 3(a) illustrates that when the diffraction angle increases, the angular bandwidth of PVG decreases, suggesting that the diffraction angle of PVG must be regulated to assure complete reflection by structural control. Figure 3(b) shows that the wavelength response bandwidth of PVG with varied diffraction angles is nearly independent of the diffraction angle. This distinguishing characteristic is highly advantageous to the diffractive waveguide display system based on the PVG coupling grating because the color display performance does not vary with the fixed diffraction angle. It is worth noting that the PVG has more than three times the angular bandwidth and three times the wavelength bandwidth of typical VHG.

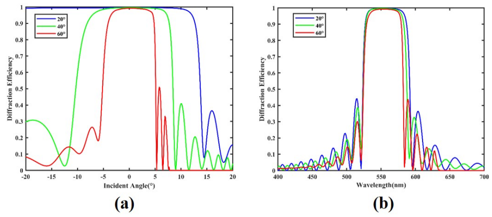

Fig. 3 (a) Angular and (b) wavelength response of the PVG. The diffraction angles are 20°, 40° and 60° in the RCWA model.

Because of its strong polarization selectivity to the polarization state of the incident light beam, PVG has a high transmittance while maintaining effective single-order diffraction. we utilized the self-built RCWA model to simulate the polarization characteristic of grating under various polarized incident light sources. The polarization state of the entering light is represented in local coordinates by the Jones matrix:

$$J=\begin{pmatrix}-E_Z\\ E_X\end{pmatrix}=\begin{pmatrix}\sin\psi\\ \cos\psi\times e^{j\Delta\varphi}\end{pmatrix} \tag{4.1}$$

Where ψ and $\Delta\varphi$ are the polarization state phase angles, the value range of ψ is [-90°, 0°], the value range of $\Delta\varphi$ is [-180°, 180°]. For example, the right-handed circularly polarized (RCP) light can be expressed as (ψ, $\Delta\varphi$) = (-45°, -90°). the left-handed circularly polarized (LCP) light can be expressed as (ψ, $\Delta\varphi$) = (-45°, 90°).

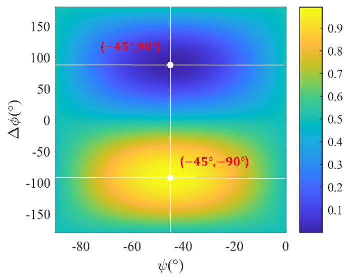

Fig. 4 The diffraction efficiency of PVG with different incident polarization states.

Figure 4 illustrates that when the helical form of the liquid crystal molecules is right-handed, the highest diffraction efficiency of PVG corresponds to the entering light's polarization state, which is RCP. The lowest point of diffraction efficiency corresponds to LCP, which indicates that the diffraction efficiency is about zero and there is no diffracted light, while the diffraction efficiency of lined polarization (LP) is approximately 50%.

In conclusion, the wide response bandwidth and unique polarization selectivity enable the PVG-based diffractive waveguide's large FOV and high optimization potential. PVG's optical properties as a waveguide coupling element can meet the performance standards of a present or prospective waveguide AR display.

4.2 Imaging simulated of PVG

Following the investigation of the optical behavior of the PVG, the imaging simulation of the PVG can be analyzed using the self-built dynamic link library (DLL), giving commercial software ZEMAX the ability to simulate the imaging of the PVG-based waveguide display [14-15].

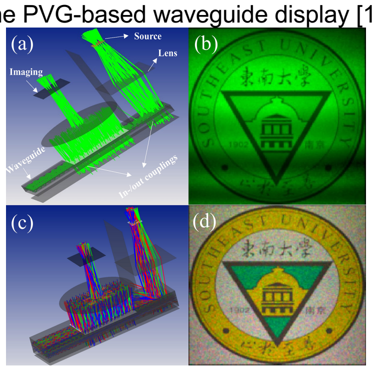

Fig. 5 One-dimensional expansion waveguide configuration model in ZEMAX. (a) Single-layer waveguide with green source at 532nm, (b) Simulation results of the retina, (c) Three-layers waveguide with full color, (d) Full-color image output.

In Figure 5(a), the single-layer waveguide structure is first simulated under the green source. Figure 5(b) depicts the actual simulation process diagram. As we know, using a multilayer waveguide is an effective way to increase the angular response bandwidth, which means that the red (630nm), green (532nm), and blue (457nm) PVG each use a waveguide to achieve separate propagation of each single waveguide under the same diffracted angle in Figure 5(c), reducing cross talk of each grating and obtaining the true full color image in Figure 5(d).

On the one hand, the imaging effect of the three-layer waveguide has been significantly improved over the single-layer waveguide. On the other hand, Single-green imaging will be more sensitive and intuitive, particularly in low-light conditions, while color display will improve the visual experience outside.

5 Design and optimization of PVG-based waveguides

Now, the performance requirements of the PVG-based waveguide display device trend to be large FOV, lightweight and compact. In this case, the stacking PVG structure is used to increase the response bandwidth shown in the Figure 6. The widening of the display imaging field of view (FOV) is facilitated by increasing the bandwidth. It is important to note that the bandwidth expansion produced by this stacking approach does not result in ghosting due to the high-precision self-assembly properties of PVG.

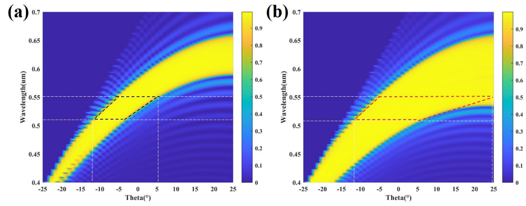

Fig. 6 Diffraction efficiency distribution of (a) single-layer PVG and (b) stacking-layer PVG at different incident angle and wavelength.

Polarization multiplexing based on this stacked PVG also allows more light to be diffracted into the waveguide from non-polarized light sources. The PVG-based polarization multiplexing example scheme for OLED image source is illustrated in Figure 7(a) and the actual output image is shown in Figure 7(d). The efficiency of the polarization multiplexing structure has approximately doubled when compared to a single left-handed PVG (L-PVG) or right-handed PVG (R-PVG) shown in the Figure 7(b) and (c), demonstrating that the adoption of this polarization multiplexing may actually improve the diffractive efficiency of the waveguide structure.

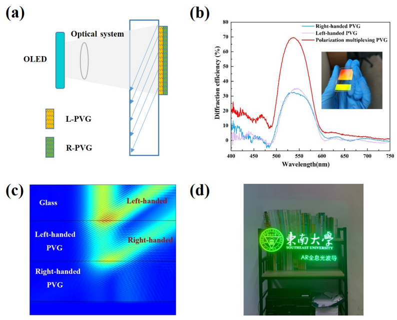

Fig. 7 (a) PVG-based polarization multiplexing waveguide in-coupling scheme for OLED image sources, (b) Diffraction efficiency spectra and the insert is PVG-based waveguide sample, (c) Simulated results for the PVG-based polarization multiplexing used as an in-coupled grating, (d) Photograph of output images from the OLED image source.

AR waveguide devices have always been lightweight and small in design. Smaller source system size, as we know, also means smaller waveguide entrance pupil size. PVG waveguides are promising to realize the reduced entrance pupil size and achieve outstanding AR waveguide display performance due to their superior characteristics and simple production procedure. In Figure 8(a), we suggested and designed this prototype using unique 2-Dimension (2D) exit pupil expansion (EPE) techniques based on PVG. In order to apply PVG's superior performance to AR-HUD, we also conducted preliminary simulation work, which suggested that polarization volume lens (PVL) film may be applied to any substrate shown in the Figure 8(b), and can be regulated by PVG's unique structure. To accomplish a function comparable to lens focusing imaging, PVG's potential application market in the field of AR display will be substantially expanded.

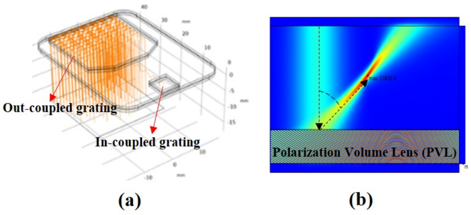

Fig. 8 The principle scheme of (a) 2D EPE and (b) PVL.

Figure 9 displays these two types of prototypes in the context of the full color 1D EDE display module, and 2D EDE-based single color waveguide display modules. PVG-based diffractive waveguide will be competitive in the field of new display technology in the future due to its excellent display performance and designability.

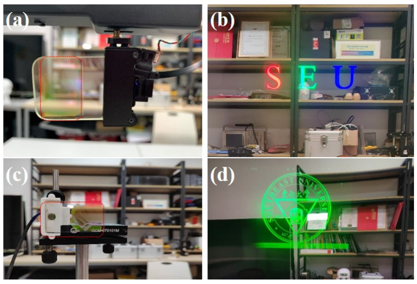

Fig. 9 (a) Full-color 1D EPE demo with Lcos projector, (b) Full-color output image, (c) 2D EPE with DLP projector, (d) Monochrome output image.

6 Conclusions

We discuss the advantages of PVG in terms of low cost and mass manufacturing based on its formation mechanism and preparation procedure. The display capabilities of PVG waveguides and various design strategies may be more thoroughly investigated by separately constructing a PVG-based simulation system. Finally, we suggested a range of display designs and solutions to fulfill the demands of AR display minimization and customization. According to our latest research advances, PVG offers distinct benefits as a diffractive waveguide element, and the application market includes not only AR glasses, but also AR-HUD and other applications.

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