Advancements in Polarization Volume Gratings for Waveguide Display Technology

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Abstract

Polarization volume gratings (PVGs) have emerged as a promising technology due to their exceptional diffraction properties, showing significant potential in various optical applications, particularly in augmented reality (AR). This presentation offers a comprehensive review of PVG technology, including its physical principles, diffraction characteristics, and fabrication methods, drawing on the latest research advancements. Additionally, the current progress of PVG in DOW-AR applications will be reviewed, focusing on color imaging, field-of-view extension, and pupil extension, demonstrating the feasibility and practicality of PVG technology for waveguide applications while providing insights for future research.

Author Keywords

Polarization volume gratings; diffractive optical waveguides; augmented reality; field-of-view extension; pupil extension; color imaging

1. Introduction

Augmented reality (AR) displays have emerged as a promising technology for enhancing human perception and interaction with the real world[1]. Diffractive Optical Waveguides (DOWs), as a solution for various AR display technologies, have received a lot of attention for providing high-quality display performance while maintaining a lightweight, compact and unobtrusive form factor.

Typical DOW devices use diffraction gratings or other diffractive optical elements to direct light through a thin, transparent waveguide substrate. Diffractive elements are typically tens of nanometres to tens of micrometres thick, while waveguide substrates can be controlled to a few millimetres thick. Compared to other AR optical solutions, such as Birdbath or Freeform Prism, DOW can significantly reduce the size and weight of the optics in front of the human eye while maintaining a high level of transparency to the real scene. Additionally, DOW can provide larger eye box sizes through coupled grating extensions, which enhances the user experience and allows for smaller imaging system designs, resulting in a lighter, more compact AR device. As a key component of DOW, the performance of the diffraction grating determines the display imaging quality, including optical efficiency, field of view, eye box size, color performance, and backward light leakage.

Surface relief gratings(SRG) and volume holographic gratings(VHG) have been widely studied and adopted as waveguide-coupled gratings for DOW-AR systems. However, both types of gratings face a number of challenges in achieving optimal performance. For example, SRGs require high diffraction efficiencies while maintaining acceptable levels of production complexity and cost. VHGs have limited angular and spectral bandwidths due to the small refractive index modulation values of the holographic material.

In recent years, polarization volume gratings (PVGs) have received much attention due to their unique diffraction properties, which make them ideal for waveguide coupling[2]. Compared to SRGs and VHGs, PVGs provide a wide response bandwidth while maintaining high diffraction efficiency. The unique polarisation selectivity adds dimension to the design and guarantees at least 50% transmittance. These features make PVG a promising candidate for advanced AR display applications. In addition, PVG has a simple and low-cost manufacturing process that enables mass-production. Over the past few years, extensive research has been conducted on PVGs to investigate various aspects of the technology, including physical modelling, simulation methods, diffraction properties, fabrication processes, waveguide device design and imaging optimisation. These studies have contributed significantly to the understanding and development of PVGs, paving the way for their potential application in DOW-AR systems.

This paper presents a comprehensive review of the current state of PVG technology and its potential to enhance the performance of DOW systems for AR applications. The physical models, optical properties, fabrication methods, and advances in PVG for AR display performance enhancement are presented. By presenting the research progress related to PVG, this paper aims to provide a comprehensive reference for the later research and further promote the PVG technology applied to AR.

2. Physical Structure and Principles of PVGs

Compared to conventional CLC devices, PVGs are composed of anisotropic materials and exhibit a periodic refractive index distribution resulting from the three-dimensional periodic rotation of birefringent material molecules, such as liquid crystal molecules. The rotation of liquid crystal molecules is controlled in two dimensions: the longitudinal dimension is controlled by the chiral doping concentration, while the horizontal dimension is controlled by a pattern on the alignment material. As depicted in Fig. 1, two PVG structures, namely planar and slanted, are illustrated. In the initial stages of PVG research, the liquid crystal molecule distribution was ideally considered to be a planar structure. The horizontal and longitudinal periods were controlled independently. The liquid crystal molecules within the planar PVG exhibit periodic rotation in the xy-plane. The angle of rotation about the y-axis, denoted as α, can be defined based on the period dx and dz as:

$$\alpha(x,z) = \frac{\pi}{d_x}x + \frac{\pi}{d_z}z \tag{1}$$

As the research into PVG developed, Lee et al. found that slanted PVG structures exhibited lower free energy at ~25° tilt angle[3]. The planar structure can only be stabilized at very thin thicknesses or very small Bragg tilt angles. The diffraction efficiencies of the two PVG structures have almost similar response properties for wavelength, angle and thickness variations. However there are some differences in the polarization characteristics. The diffracted light from the slanted

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structure tends to remain in a circularly polarized state, while the planar structure provides more retardatance towards the diffracted light.

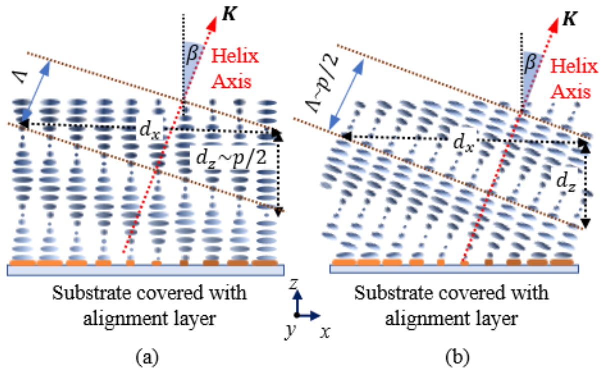

Figure 1. The structure of PVG. (a)Planar PVG, and (b) slanted PVG.

In the case of slanted PVG, liquid crystal molecules rotate around both the y-axis in the xz-plane by an angle φ and the z-axis in the xy-plane by α. Consequently, the permittivity tensor in equation (2) can be modified to the following form :

$$\varepsilon(x,z) = (R_\alpha * R_\varphi)^{-1} \varepsilon_r (R_\alpha * R_\varphi) \qquad (2)$$

Such a volume structure gives rise to distinctive diffraction behaviors, including polarization selectivity and Bragg diffraction. When the grating thickness approaches a specific value, the two-dimensional periodic grating structure will generate a volume effect. By configuring the horizontal and longitudinal periods, reflective PVG and transmissive PVG can be realized. Fig. 2 illustrates the diffraction behavior of those two gratings. In contrast to conventional VHG, PVG exhibits sensitivity to polarization, whereby PVG diffracts circularly polarized beams with the same spin direction as the chiral helix in the birefringent material[4].

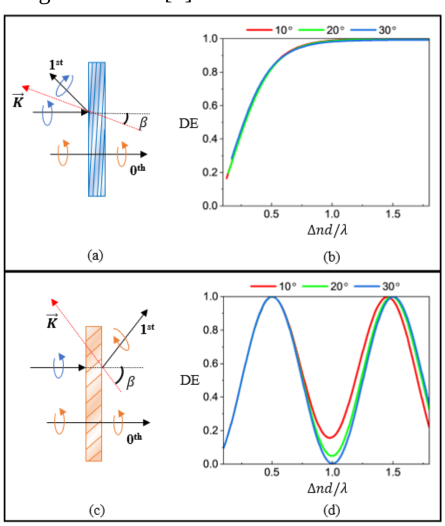

Figure 2. Diffraction behaviors of (a) reflective PVG and (c) transmissive PVG for different polarized light incidents. And the relationship between diffraction efficiency (DE) and thickness for (b) reflective and (d) transmissive PVG with different grating slanted angles

For waveguide-coupled elements, the response wavelength and angular bandwidth determine the imaging performance. The diffraction efficiency of reflective PVGs is easier to control than that of transmissive PVGs, which can be coated with a specific thickness. The diffraction characteristics of reflective PVGs were investigated by a self-programmed procedure based on rigorous coupled wave analysis (RCWA). As shown in Fig. 3, the wavelength and angular bandwidth expand as the refractive index modulation (RIC) increases. This means that a larger field of view(FoV) and better color performance can be achieved. In PVG, the RIC is determined due to the birefringence of the liquid crystal material, and the birefringence of the current common liquid crystal material can easily reach 0.2. It has a very big advantage over the traditional VHG material in terms of bandwidth.

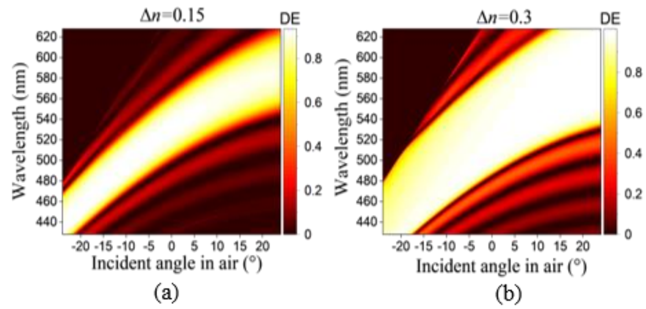

Figure 3. The diffraction curve of PVG.(a)The RIC is 0.15,(b) The RIC is 0.3

The preparation process of PVG is shown in Fig. 4. This is achieved by first applying a photo-alignment (PA) layer to the substrate, subsequently exposing it to patterned polarized light, and then applying a cholesteric liquid crystal reactive mesogens material (CLC-RM) on top of it. The film is then completely cured through the exposure to ultraviolet (UV) radiation. The resulting PVG serves as a stable film, the stability of which is largely dependent on the crosslink density of the selected CLC-RM material system after curing[4,5].

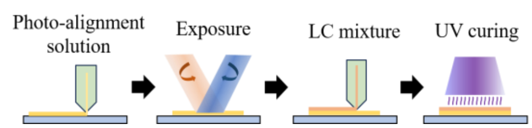

Figure 4. The PVG preparation processes

3. Application of PVG on AR

In the preceding section, the fundamental structure, diffraction characteristics, and fabrication methodology of PVG were elucidated, which illustrate the distinctive appeal of PVG on AR. This section presents a review of recent research progress concerning the application of PVG on AR.

（a）Color imaging

Typically, holographic waveguide systems achieve color displays by simultaneously propagating light fields of red (R), green (G), and blue (B) wavelengths. The most straightforward implementation is to propagate images in the red, green, and blue wavelengths separately through three separate waveguides, which theoretically ensures complete isolation of the three RGB channels. This approach permits the optimization of each channel individually, thereby enhancing the FoV and color performance. However, this configuration presents certain limitations in terms of waveguide thickness and manufacturing cost, due to the necessity of preparing and integrating the three waveguide layers separately. In 2018, Weng tl al. proposed a two-layer PVG waveguide design as a means of enabling full-color AR displays[6]. As illustrated in Fig. 5, the wavelength-multiplexing configuration of the PVG coupler enabled the concurrent propagation of two channels, green and blue, within a single waveguide, while the red band was transmitted separately through an alternative waveguide. Based on this design, a PVG waveguide full-color AR display with a diagonal FoV of 35° was successfully realized. Nevertheless, employing a single waveguide layer to simultaneously accommodate the two wavelength ranges results in a constrained total internal reflection (TIR) angular range for the waveguide substrate, thereby limiting the attainable FoV. This phenomenon can be attributed to the influence of grating dispersion.

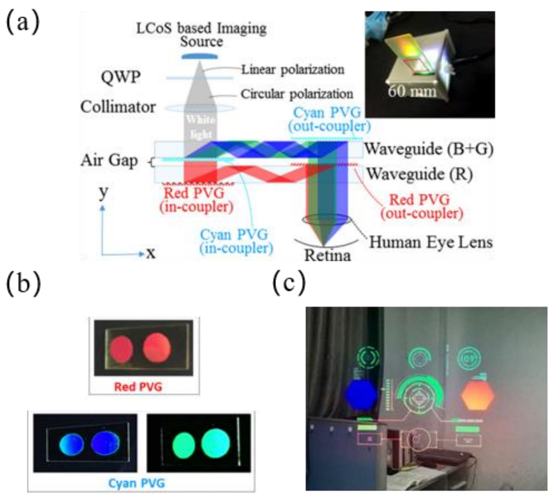

Figure 5. Double-layer PVG waveguide design to realize full-color AR display.(a)The double-layer PVG waveguide structure,(b) The appearance of the gratings,(c) imaging result, reproduced with permission from The Optical Society.

（b）FoV optimization

The response bandwidth of PVG is the main factor limiting the FoV. For this reason, Gu et al. designed a multiplexed PVG structure to increase the response bandwidth from 60 nm to 100 nm, realizing a single green display with a diagonal FOV of 55°[7], as shown in Fig.6(a). Yan and colleagues proposed a novel method for the fabrication of three-dimensional gradient periodic PVGs. The method involved the design of mask plates with two-dimensional UV transmittance region variations and the optimization of the liquid crystal material through the addition of UV absorbers. They successfully fabricated the corresponding waveguides and verified the validity of their proposed principle[8], as illustrated in Fig.6(b). The resulting gradient PVGs exhibit an angular bandwidth of 61° while maintaining a diffraction efficiency of 80% and a peak efficiency of nearly 100%. The enhanced angular bandwidth facilitates the expansion of the FOV of the PVG waveguide.

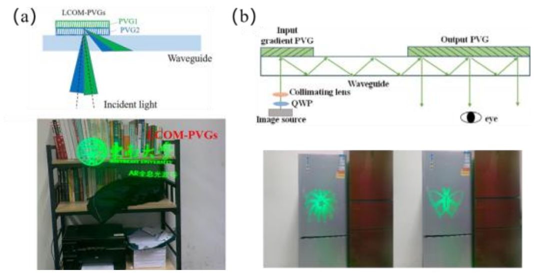

Figure 6.(a)The multiplexed PVG-based waveguide,(b) The gradient periodic PVGs-based waveguide, reproduced with permission from The Optical Society.

（c）2D exit pupil extension(EPE)

One of the advantages of holographic waveguide displays for AR applications is the EPE capability. Commonly, there are 1D and 2D EPE structures for exit pupil expansion. 1D EPE structures are capable of realizing eye box expansion in a single direction. Therefore, in order to obtain sufficient output eye box dimensions in both directions, the incidence pupil size in the non-expanded direction (y-direction) must be significantly larger than that along the expanded direction. Consequently, it is challenging to further minimize the dimensions and mass of the image projector for the 1D-EPE waveguide configuration. The 2D EPE structure is capable of realizing an expansion of the eyebox in both dimensions, which significantly reduces the size of the image projector while ensuring a sufficient eyebox size. Based on the above fundamentals, Cui et al. in 2021 applied the “L-shape” scheme, which is commonly used in current diffractive optical waveguide systems, to PVG waveguide devices[9]. In 2022, Weng et al. proposed another 2D-EPE scheme for PVG waveguide technology[10], and the related results are shown in Fig. 7. This solution utilizes the principle of polarization multiplexing by designing the out-coupled PVG as a composite grating that simultaneously deflects the propagating light in multiple directions and unidirectionally couples the outputs. Compared to the "L-shaped" structure, this theme only requires two grating areas, allowing for a more compact grating layout and shorter light propagation distances. Consequently, this design helps reduce the loss and scattering of light energy during waveguide propagation, ultimately enhancing image quality.

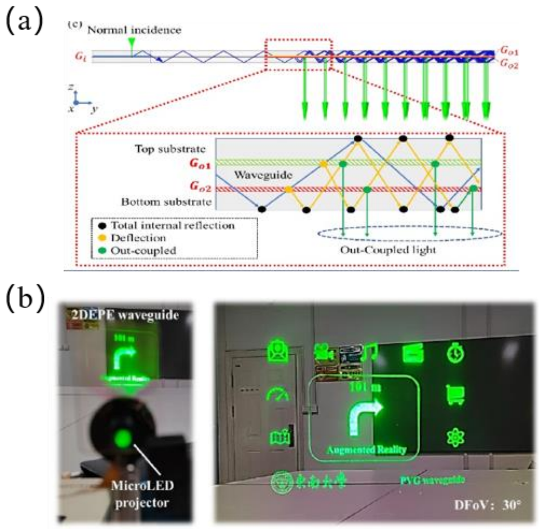

Figure 7. Y-shaped 2D EPE structure. (a) Schematic of light propagation in the out-coupling region,(b) the photographs of the AR imaging results, were taken at distances of 100 mm and 18 mm from the waveguide, reproduced with permission from The Optical Society.

4. Ultra-broadband PVG

It is well known that diffractive elements determine the quality of AR imaging. The response bandwidth and efficiency are important indicators to characterize the diffraction properties of gratings. Many researchers have done a lot of work on improving the grating performance, such as extending the bandwidth while maintaining high diffraction efficiency through stacked structures or gradient-periodic structures. However, the diffraction response bandwidth is still an important influencing factor limiting the further development of PVGs. In order to further enhance the display performance of PVG-based waveguide devices, we propose an ultra-broadband polarization volume grating (UPVG) that responds to the visible wavelength band and maintains a diffraction efficiency of more than 80%, as shown in Fig. 8. Such a grating offers the possibility of realizing a single-layer full-color optical waveguide and is important for improving color performance, optical efficiency and FoV.

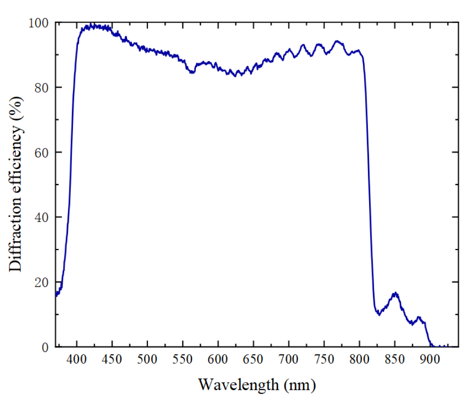

Figure 8. The diffraction efficiency curve of UPVG

5. Conclusion

In summary, this paper presents an overview of the physical properties, fabrication methods and applications of the technology known as polarization volume gratings (PVGs). Firstly, the physical structure and preparation process of PVGs are introduced, and their diffraction properties are analyzed. Subsequently, we present the advancement of PVGs in AR, encompassing three key areas: color imaging method, FoV improvement and exit pupil extension structure. Finally, we present our latest progress, ultra-broadband polarization volume gratings with high diffraction efficiency and response properties in visible band coverage. This paper aims to provide researchers with an overview of PVGs and to inspire new ideas to promote PVGs.

6. Acknowledgements

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