Augmented Reality Waveguide providing Image Depth Modulation and Manification-Neutralized Full-Color Real Scenes with Geometric Phase-Based Ultra-Thin Form-Factor Optics

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ABSTRACT

We present a compact waveguide-based AR system incorporating switchable geometric phase lens (GPL) to project images at multiple depths. This mitigates the vergence-accommodation conflict and enables seamless integration of virtual and real-world content, enhancing immersion and visual comfort in AR displays.

1 Introduction

Extended reality (XR) optical technology has the potential to revolutionize how humans interact with digital content by seamlessly integrating virtual elements into the physical environment. This could drive progress in fields such as healthcare, education, and entertainment through spatially aligned virtual information. However, widespread XR adoption is limited by user discomfort and bulky devices. A major source of visual fatigue is the vergence-accommodation conflict (VAC), which arises when vergence and accommodation cues do not match, causing eye strain—especially during prolonged use of VR, AR, and XR headsets. This issue stems from current near-eye displays lacking focus-tunable optics, making it difficult to replicate natural depth cues. In XR scenarios requiring close interaction between virtual and real objects, VAC effects are more severe over long durations. Various solutions, including Maxwellian, light field, and multifocal displays, have been explored. Multifocal displays stand out for providing discrete focal planes without mechanical parts. Recently, lightweight waveguide-based multi-depth displays have shown promise in addressing VAC. Dual-focal waveguide AR systems using polarization-dependent or diffractive optics have demonstrated feasibility but often involve multiple waveguides and image sources, increasing complexity. To address this, researchers are developing flat optical modules with polarization-dependent, focus-tunable lenses, leveraging polarization multiplexing to encode multiple focal states in a single optical path.

Geometric phase (GP)-based wavefront control has emerged as a promising method for next-generation XR optics [1]. Among GP devices, the geometric phase lens (GPL) is particularly suited for XR systems. By spatially modulating the optic axis, a GPL creates a lens phase profile that enables lightweight, ultra-thin, polarization-dependent focus-tunable optics [2]. A single GPL layer can function as either a convex or concave lens, supporting dual imaging modes. In this work, we present a compact waveguide-based AR near-eye display with depth modulation using GPLs. The system includes a holographic optical element (HOE) as the waveguide out-coupler, which also provides lensing. Combined with GPLs, the system delivers dynamic accommodation cues with minimal optical volume. It enables accurate multi-depth virtual image rendering while maintaining full-color, distortion-free real-world transmission [3]. The design achieves experimentally validated depth-resolved AR imagery and shows strong potential for portable, fatigue-free, multi-depth AR displays—positioning GPLs as a key technology in XR optical innovation [4].

2 Proposed method

2.1 Depth-Switching AR Waveguide System with Varifocal Lens

Fig.1 illustrates the conceptual design of the proposed dual depth modulation AR waveguide system. The system is centered around a waveguide architecture that incorporates an out-coupler HOE lens with embedded focusing functionality. This structure guides AR imagery into the waveguide and projects it toward the user's eye, focusing it at two spatially distinct depth planes. A key contribution of this work lies in the integration of two GPLs, enabling the realization of two distinct optical functions within a single, compact waveguide system. The first GPL, designated for Depth-Switchable AR Imaging, is designed to generate two different focal lengths depending on the polarization state of the incident light.

This polarization dependent dual-focus capability enables the same AR content to be optically projected at either a near or far depth plane, depending on the selected polarization. As a result, the system provides multiple visual depth cues within a single optical path, supporting depth-switchable AR rendering and facilitating user accommodation responses for enhanced depth perception. The second GPL, referred to as the GPL for Real-Scene Magnification Self-Compensation, serves to automatically compensate for magnification distortion that can occur when viewing the real world through the optical stack. This GPL is designed such that, even during polarization-based modulation for AR image depth control, the full-color real scene is transmitted with its original scale preserved, free from magnification shifts or geometric distortions. This feature enables a distortion-free, see-through viewing mode, allowing natural integration between AR content and the surrounding physical environment. These two GPLs are strategically positioned before and after the waveguide, while the out-coupler HOE lens placed between them diffracts and focuses the virtual AR image at the designated depth. By merely switching the input polarization state, the system enables both depth-varying AR image projection and undistorted see through vision within a single optical path. Consequently, the system achieves these advanced functions within a highly compact optical form factor, avoiding the need for bulky mechanical components or dynamic optics.

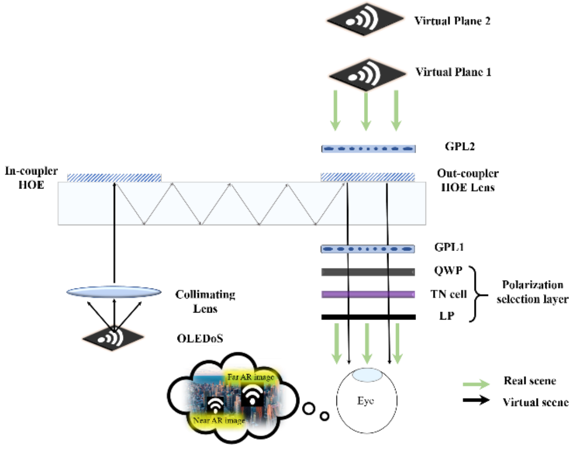

Fig. 1 Schematic diagram of proposed GPL-based depth-switching waveguide AR system : linear polarizer (LP), twisted nematic liquid crystal (TN cell), quarter waveplate (QWP), geometric phase lens (GPL).

2.2 Geometric Phase Lens Modulation

The geometric phase effect is phenomenon in which a spatial relative phase difference occurs at the exit plane of geometric optics compared to the incident wavefront, resulting in modulation of the output wavefront due to the spatially distributed optic axis of the anisotropic material like liquid crystals or reactive mesogens. The GP component enables the implementation of optical elements with various functionalities of wavefront modulations according to the optic axis distribution of the anisotropic material. When the thickness of the anisotropic material satisfies the half-waveplate (HWP) condition, it achieves a wavefront modulation efficiency of 100% ideally at the designed wavelength. This allows for the creation of thin, lightweight, and flat optical elements. Additionally, by switching the handedness of the incident circular polarization state, an opposite phase difference can be induced at the output of the GP device, ultimately enabling its operation as switchable wavefront modulation optics. Among these, the GPL, designed with an optic axis distribution that follows a lens phase profile, can function as either a concave (-f) or convex (+f) lens depending on the handedness of the incident circular polarization, as illustrated in Fig.2.

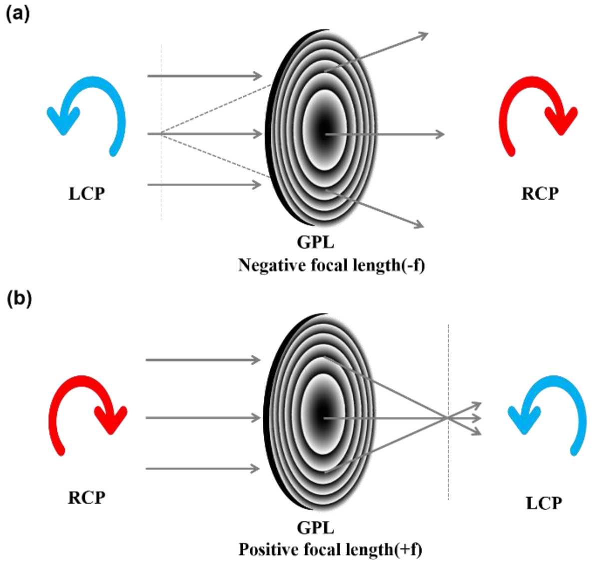

Fig. 2 Schematic illustration of the operational principle of a geometric phase lens under left- and right-circularly polarized incident light.

2.3 Principle of In/Out Coupler HOE

A HOE is an optical component, such as a lens, mirror, or diffraction grating, fabricated through a holographic recording process. In this study, a compact waveguide-based augmented reality (AR) optical system incorporating switchable GPL is proposed. The system is based on a waveguide architecture utilizing HOEs as both the in-coupler and out-coupler. Notably, the out-coupler HOE is designed to function as a lens, which, in conjunction with the GPL, enables depth modulation within an ultra-thin optical module. The in-coupler and reflective out-coupler HOEs were designed and fabricated to achieve efficient light coupling into and out of a glass waveguide under total internal reflection (TIR) conditions. When a 532 nm laser beam is normally incident on the grating, it is diffracted at an angle of 60 degrees, corresponding to the direction of the reference beam used during the holographic recording. This configuration ensures stable light propagation within the waveguide. To maximize diffraction efficiency, it is essential to satisfy the Bragg condition, which requires that the recording and reconstruction parameters, including wavelength and incident angles, be matched. Diffraction efficiency is evaluated by measuring the relative intensities of the diffracted and transmitted beams using an optical power meter. As shown in Fig. 3, the principle of the reflective out-coupler HOE involves a recording process in which two coherent beams interfere within a photopolymer film. The reference beam is typically collimated or planar, while the object beam is transformed into a spherical wavefront through an objective lens. The resulting interference pattern encodes the lens wavefront into the holographic medium. During reconstruction, when the recorded HOE is illuminated by a beam similar to the original reference beam, it reproduces the optical function of the lens, focusing or diverging the incident light accordingly. This approach allows the embedding of a lens-like phase profile within the HOE structure, enabling compact and lightweight optical components suitable for waveguide-based near-eye display systems.

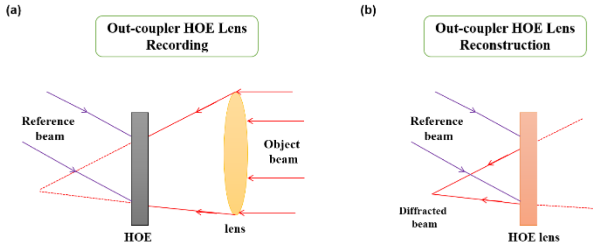

Fig. 3 Principle of HOE for out-coupling with lens-function : (a) recording geometry and (b) reconstruction process.

2.4 Depth-Switching Augmented Reality Display Mode

The polarization-based depth selection optics module comprises a stacked configuration of a quarter-wave plate (QWP), a twisted nematic liquid crystal (TNLC) cell, and a linear polarizer (LP), as illustrated in Fig 4. The TNLC dynamically generates two orthogonal linear polarization states depending on the applied electric field, which are subsequently converted into orthogonal circular polarization states by the QWP. Owing to its low chromatic aberration across the visible spectrum, the TNLC minimizes crosstalk between depth planes, enabling precise achromatic polarization control—ideal for GPL-based focus-tunable AR near-eye displays. In the optical path, the out-coupler HOE and the first GPL (GPL1) are spaced according to the waveguide thickness. Unpolarized light from the display is reflected by the HOE and passes through GPL1, producing two circularly polarized wavefronts with distinct focal lengths. The QWP (45° optic axis) converts them into 0° and 90° linear polarizations. When the TNLC is ON (Fig.4a), the LP transmits the 90° polarization component, resulting in the longer focal length. When the TNLC is OFF (Fig.4b), the polarization is rotated and the LP transmits the orthogonal component, corresponding to the shorter focal length. This compact architecture allows for the integration of GPLs with polarization-based depth selection optics, offering an electrically switchable mechanism to alternate between two focal planes without mechanical movement. This capability supports precise depth control critical for immersive, multi-depth AR experiences in near-eye display systems.

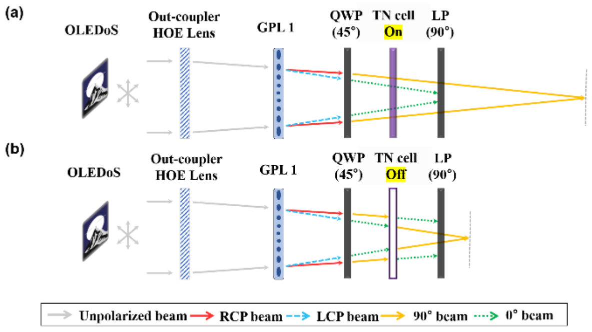

Fig. 4 Structural diagram of the GPL-based depth-switching waveguide AR system display mode according to the polarization switching combinations of the TN cell by field on/off operations.

2.5 Optical See-Through Mode for Real Scene View Mode

To prevent magnification distortion of the real-world scene, a self-magnification compensation GPL, referred to as GPL2 is placed on the exit side of the waveguide, closer to the eye. As shown in Fig 5, GPL2 is designed to optically cancel the focal power introduced by the depth-switchable AR imaging GPL (GPL1), thereby preserving the perceived scale and depth of the external environment. The out-coupler HOE, located between GPL1 and GPL2, is polarization-independent and does not affect the optical interaction between the two GPLs. When GPL1 acts as a convex lens, GPL2 functions as a concave lens, and vice versa. This symmetric configuration ensures that the total optical power of the system is effectively neutralized, regardless of the polarization state of the incident light. Consequently, the system can modulate virtual content depth while maintaining an undistorted optical path for real-world light. The external scene is perceived at a true 1:1 scale, without refractive distortion. This power-compensated architecture is essential for AR systems that overlay virtual images on the real world within a shared field of view. It enables accurate perception of real-world geometry while delivering focus-tunable virtual content, ensuring visual consistency and enhancing the immersive quality of the near-eye display.

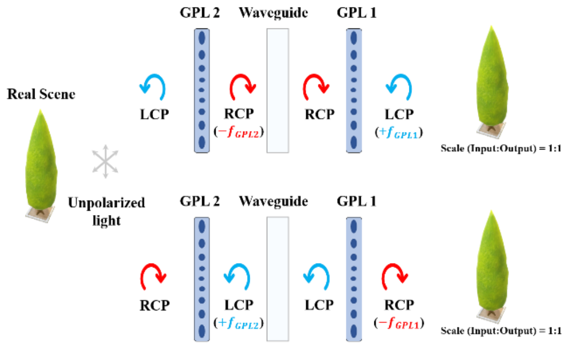

Fig. 5 Structural diagram of the GPL-based depth-switching waveguide AR system optical see-through mode for self-compensation of magnification at GPL1 according to the polarization conversion principles of GPL1 and GPL2.

3 Experimental Results

As illustrated in Fig 6, the system was designed to simulate the typical eye-to-glasses distance with adjustable positioning to explore multiple focal planes. The fabricated HOE-based waveguide, shown in Fig 6(b), uses a semi-transparent glass slide (76 mm × 26 mm × 1 mm, n = 1.515 at 530 nm, ~91% transmittance). Input/output couplers are 15 mm × 15 mm volume holograms created using a Mach–Zehnder interferometer. The input coupler diffracts light at 60°, inducing total internal reflection, while the output coupler acts as a lens (focal length ≈ 3.99 cm), selectively diffracting specific rays.

To validate depth cues, physical objects (a snowman and a dice) were placed at 13.1 cm and 27.4 cm, respectively. With the TN cell OFF, near-field AR content aligned with the snowman appears sharp; with it ON, far-field content aligned with the dice is clearly resolved. These results confirm that the electrically tunable GPL module enables depth-selective image generation. The waveguide's high transparency also allows undistorted, full-color viewing of real-world scenes.

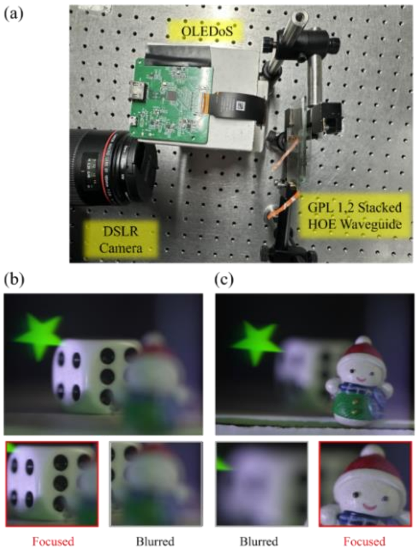

Fig. 6. Captured images of the GPL-based depth-switching waveguide AR system with the camera focused at (a) 13.1 cm and (b) 27.4 cm, respectively.

4 Conclusions

In this study, we proposed a near-eye AR display system that implements dual focal planes using a GPL capable of polarization-dependent focal tuning. The developed prototype projects virtual images at two distinct depths, while allowing real-world scenes to be transmitted in full color without distortion. By employing ultra-thin, planar optical components such as the GPL and waveguide, the system supports scalability to multiple depth planes while maintaining a compact and lightweight form factor. The chromatic dispersion inherent to the GPL is effectively compensated by a color-corrected HOE used as the output coupler, enabling depth modulation across the full visible spectrum. Consequently, the proposed system enhances depth rendering and mitigates VAC, a common issue in AR displays, thereby providing a more comfortable and immersive visual experience.

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