Holographic Near-Eye Display with Steerable Exit-Pupil Array Based on Bi-Stacked Quarter-Wave-Conditioned Geometric Phase Prism Module

Erkhembaatar Dashdavaa[1,2], Munkh-Uchral Erdenebat[1,2], Jin-Hyeok Seo[2], Min-Seok Kim[2], and Hak-Rin Kim[1,2,3]*

[1]Center for Semiconductor-Specialized University, Kyungpook National University, Daegu, Korea
[2]School of Electronic and Electrical Engineering, Kyungpook National University, Daegu, Korea
[3]School of Electronics Engineering, Kyungpook National University, Daegu, Korea

Abstract

This paper presents an innovative exit-pupil steering system for expanding the eyebox in holographic near-eye displays. By integrating bi-stacked quarter-waveplate geometric phase prism modules with active polarization switching, the proposed system enables nine selectable beam steering effects, expanding the eyebox without compromising the field of view or form factor.

Author Keywords

Holographic display; geometric phase element; pupil steering; polarization-dependent optics; beam steering.

1. Introduction

Holographic near-eye displays (NEDs) provide true three-dimensional (3D) imaging, delivering complete depth cues for an immersive visual experience [1]. Widely considered one of the most promising technologies for augmented reality (AR) and extended reality (XR), NEDs use a spatial light modulator (SLM) and computer-generated holograms (CGH) in combination with a holographic optical element (HOE) or BS combiner to create virtual scenes in front of the observer's eye [2-3]. The HOE is recorded through the interference of two coherent light beams. Key advantages of HOEs include their lightweight, compact form factor, low manufacturing cost, and optical see-through capabilities, making them ideal for AR applications.

In conventional holographic NEDs, two key factors influencing visual comfort are the field of view (FOV) and the eyebox. The FOV refers to the angular extent of the reconstructed object as perceived by the human eye, while the eyebox is the area where perceived information changes with the observer's pupil position. Conventional SLM-based holographic NEDs often face limitations in eyebox size due to the restricted pixel count of the SLM. This creates a trade-off between FOV and eyebox size, making it challenging to achieve both a wide FOV and a large eyebox simultaneously in holographic NEDs.

Two main approaches are currently used to address the limited eyebox size in holographic NEDs: passive pupil replication and active pupil steering. The first approach replicates the exit pupil in one or two dimensions, ensuring that at least one viewpoint remains within the pupil as the eye moves. This method is cost-effective since it doesn't require an additional eye-tracking system [4]. However, it can lead to issues like ghost images and reduced optical efficiency. In contrast, pupil steering is often seen as a superior solution, as it eliminates concerns about optical efficiency loss and ghost imaging. This method typically uses an eye-tracking module and 2D steering mirrors to dynamically adjust the exit pupil position within the pupil plane [5]. Typically, a 2D scanning mirror directs the laser beam, which is then reflected by a pupil-shifting HOE combiner to generate the corresponding point source. This method overcomes the limitations mentioned by ensuring that only one viewing point is presented at any given time [6-7].

The geometric phase (GP), also known as the Pancharatnam-Berry phase, arises from the spatial phase difference along the optic axis of a birefringent medium. GP optics enable polarization-dependent wavefront modulation and feature lightweight, thin device characteristics [8-11]. These properties make GP optics particularly advantageous for optical systems that require a compact form factor and multi-step optical functions. GP elements can produce varying wavefront control effects based on the handedness of the incident circular polarization, directing light in different directions within a plane defined by the grating and incident light vectors, creating a prism-like effect. Furthermore, these elements can steer incident light in multiple directions by leveraging polarization switching and selective features.

In this study, we present advancements in the exit-pupil steering system to tackle the small eyebox challenge in holographic NEDs. By employing polarization-dependent, bi-stacked quarter-waveplate (QWP)-conditioned GP prism (GPP) beam steering modules, the proposed system effectively steers the exit pupil in multiple directions within the pupil plane. This approach enables up to nine distinct exit-pupil steering effects using a 3×3 steered point source array, expanding the eyebox without compromising the field of view (FOV).

2. Proposed method

In the following section, we introduce the proposed multi-step selective exit-pupil steering system for holographic NEDs, which leverages bi-stacked QWP-GPP beam steering modules with active polarization-switching and selection schemes. GP optics utilize birefringent materials, such as liquid crystals (LC) or reactive mesogens (RM), to modulate the optic axis, enabling precise control over the incident wavefront. By manipulating the optical axis, various wavefront modulation effects can be generated. This element selectively modulates the incident light based on its polarization state. Using a GP prism element, the incident light can be steered according to the handedness of the input polarization, enabling precise control over the light's direction. In the case of the conventional half-wave plate (HWP)-conditioned GPP, as shown in Fig. 1(a), beam steering is limited to two directions, depending on the incident polarization state. When the input polarization is left-handed circular polarization (LCP), as illustrated in Fig. 1(a), the output light polarization switches to right-handed circular polarization (RCP). Additionally, when the incident wave is LCP, it is modulated into a -1st order diffractive wavefront pattern. In contrast, when the incident light is RCP, the output light is modulated into a +1st order diffractive wavefront, with its polarization changing to LCP. Therefore, in a single HWP-based GPP module, up to two distinct wavefront modulations (±1st order diffraction patterns) can be achieved by switching the handedness of the input polarization states. The proposed QWP-conditioned GPP introduces an additional 0th - order diffracted term, enabling up to

ISSN 0097-996X/25/5603-1828-$1.00 © 2025

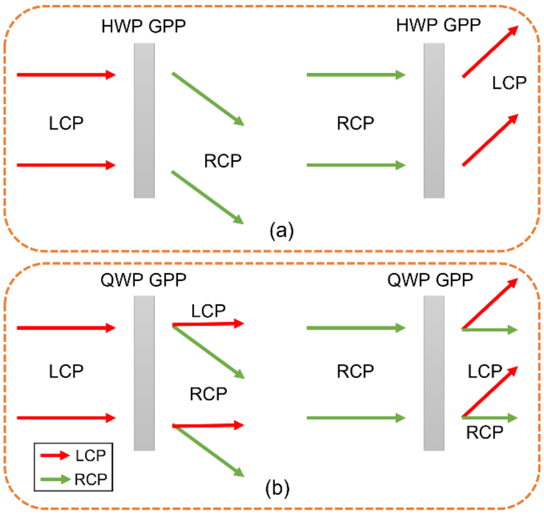

Figure 1. Operation principles of polarization-dependent GP prism beam steering according to the handedness of the incident beam polarization states with (a) conventional HWP condition; (b) proposed QWP condition.

three distinct beam-steering effects, as illustrated in Fig. 1(b). Therefore, the proposed polarization-dependent beam-steering system allows for more versatile and precise beam control, expanding the potential applications of the QWP-GPP compared to the conventional HWP-GPP. As shown in Fig. 2, under the bi-stacked QWP-GPP structure combined with an active polarization switching module, it can achieve nine (3^2) selective beam steering functions. Each QWP-GPP module consists of a liquid crystal (LC) layer designated as a switchable half-wave plate (S-HWP), a quarter-wave phase retarders, and a linear polarizer. In the polarization switching and selection unit depicted in Fig. 2, the first S-HWP adjusts the angle of linearly polarized light of incident collimated beam (0 or 90 degree) by applying the voltage on and off. The resulting linearly polarized light is then converted into circularly polarized light by the first quarter-wave plate (QWP) film which is oriented at +45 degrees. By selectively allowing either LCP or RCP light to pass, the first QWP-GPP

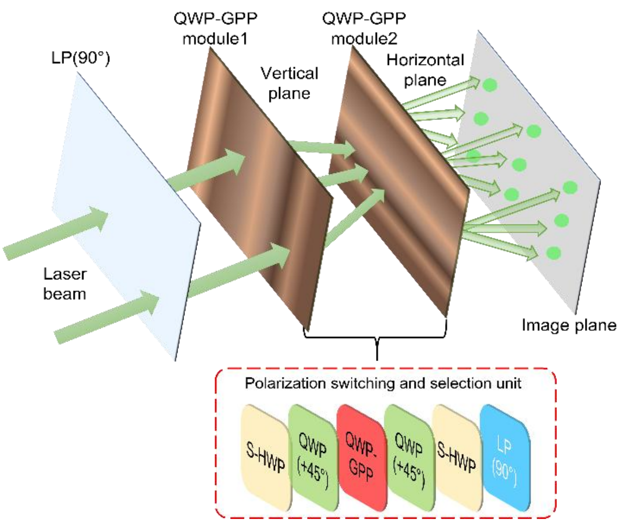

Figure 2. Schematic configuration of polarization-dependent wavefront modulations in the proposed bi-stacked QWP-GPP beam steering modules.

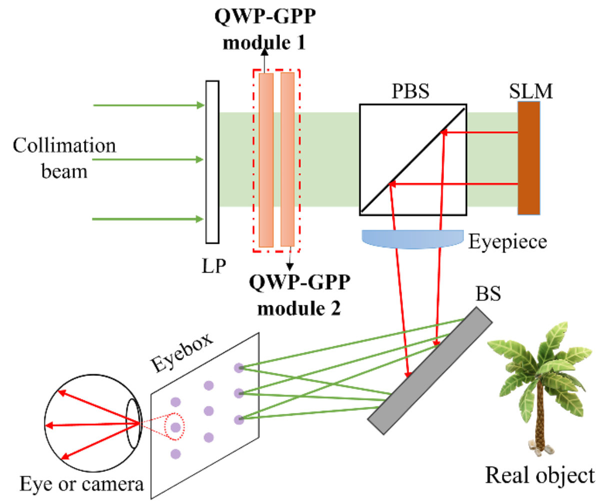

Figure 3. Concept of exit-pupil steering in holographic near-eye display with nine selective steered beams based on the proposed bi-stacked QWP-GPP modules.

modulates the beam separation in the vertical plane. Consequently, the 0^{th} and $\pm1^{st}$ diffracted beams are separated vertically, depending on the handedness of the incident polarization states. When the second S-HWP is activated, the split light becomes 45-degree linearly polarized after passing through the second QWP film. This process allows the incident light to be steered based on the input polarization. The second QWP-GPP module can deflect each beam horizontally in three directions and the proposed bi-stacked beam steering modules can steer incident light into a 3-by-3 points array as shown in Fig. 2. For the same image with the same eyebox, QWP-GPP can create diffraction gratings with wider periods because they utilize the 0^{th} order wavefront state even with smaller diffraction angles. As shown in Fig. 3, the proposed bi-stacked QWP-GPP beam-steering modules can be integrated into a holographic NED, enabling nine steerable exit-pupil positions and expanding the eyebox for an enhanced viewing experience. This can be achieved by using compact bi-stacked GP prism modules to deliver angularly steered illumination beams to the spatial light modulator, aligned with the viewer's eye movement, in combination with the optical beam splitter combiner. The polarization-dependent GP prism grating has a period of 4.2 µm, with a measured diffraction angle of 7.27 degrees. By adjusting the grating period, the steering angle can be optimized to achieve a larger viewing angle for holographic NEDs. To expand the eyebox in the holographic NED system, phase-only holograms of the virtual object are pre-calibrated and calculated using an optimized algorithm, ensuring distortion-free optical reconstruction for various steered viewpoints in combination with the HOE combiner.

3. Results and Discussion

To validate the feasibility of the proposed bi-stacked QWP-GPP beam steering module for achieving a nine exit-pupil steerable holographic AR imaging system, a simple optical system was designed to integrate the polarization-dependent bi-stacked QWP-GPP modules, SLM and BS combiner as shown in Fig. 3. Additionally, we numerically and experimentally demonstrated 3 (H) x 3 (V) distinct steered beam arrays using bi-stacked QWP-GPP modules. We first simulated our bi-stacked QWP-GPP grating for polarization-selective beam steering, demonstrating

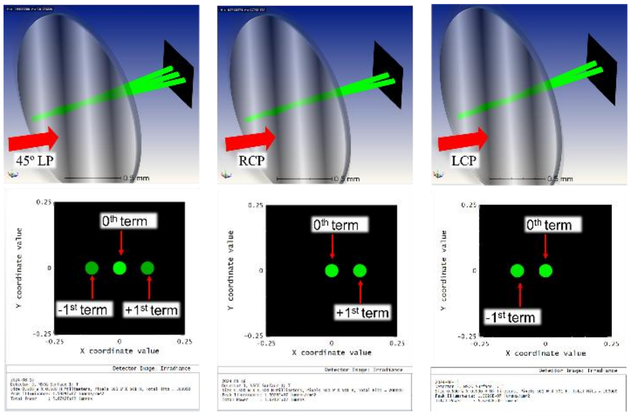

Figure 4. GP prism grating simulation model (top row: Zemax) and beam steering results depending on the polarization states of incident light (bottom row).

that incident light can be steered according to input polarization states using commercial ray-tracing software Zemax. Figure 4 presents the nine-beam steering results of the bi-stacked QWP-GPP modules depending on the incident polarization states. By utilizing the thin and lightweight properties of GP elements, the proposed active switchable beam-steering modules can expand the eyebox size in holographic NEDs, enabling precise angular ray control from a single optical source or display panel. The designed parameters for the birefringence vary with position, with a grating period of 3 μm. Under a 532 nm wavelength, the grating thickness is designed to be 0.8 μm resulting in a phase retardation matched to π/2, which is the quarter-wave plate retardation condition. To fabricate this QWP-GPP, two-beam interference between two orthogonal circular polarized beams was configured to generate the desired alignment on the photo-alignment layer (PAL) by interfering with two obliquely incident beams of light. Figure 5 presents the experimental setup and fabricated QWP-GP prism which modulate the incident collimated beam into a two-dimensional point source array on the image plane. The laser source is expanded using a spatial filter (SF) and then collimated by a collimation lens (CL). The collimated laser beam, with a wavelength of 532 nm, is split into two separate beams by a polarizing beam splitter (PBS). After reflecting off mirrors (M), the two linearly polarized beams (s-pol and p-pol) are each converted to left-circular polarization and right-circular polarization states by the quarter-wave plates in each arm, respectively.

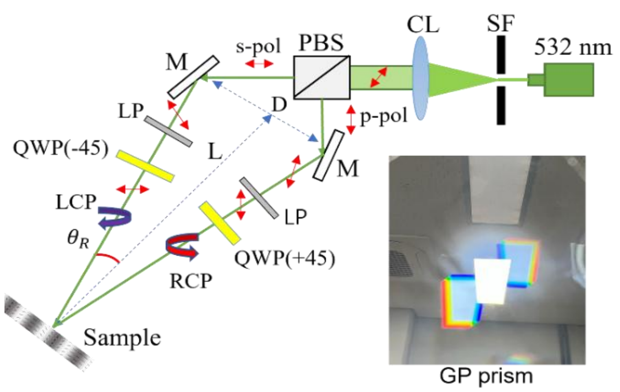

Figure 5. Experimental setup for fabricating the QWP-GP prism and fabricated GP prism under room environment showing the first- and zero-order diffraction images.

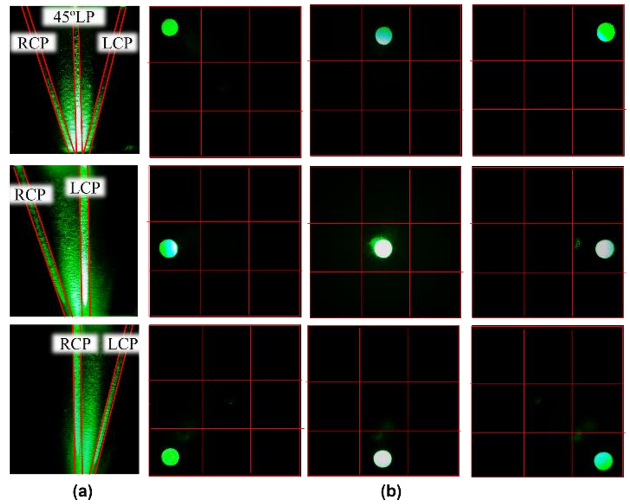

Figure 6. Experimental results: (a) beam propagation patterns of the QWP-GPP, depending on incident beam polarization states; (b) nine-step beam steering results achieved by an active polarization switching and selection unit.

The red arrow indicates the polarization states in each arm. The two linear polarizers (LP) are used to create orthogonally polarized linear beams in front of each QWP, before they are converted into orthogonally polarized circular beams. The grating period depends on the recording angle and can be defined by appropriately choosing the distance between the mirrors (D) and the length of the recording beams (L). Next, polarization interference between the two orthogonally circularly polarized beams is projected onto the photoalignment layer. After exposing the phase profile pattern of the GP prism grating, a reactive mesogen mixture (RMM) solution is spin-coated onto the substrate. RM141C is utilized to match the retardation of the grating to be QWP-condition which is half of π. Figure 6(a) presents the switchable beam propagation of the GP prism (GPP) with different polarization states of incident light, while Figure 6(b) illustrates the steered beam formation results from the bi-stacked QWP-GPP modules. Compared to the HWP-GPP, the proposed QWP-GPP approach increases the number of beams splitting cases by utilizing the 0th-order wavefront state, which allows for the splitting of additional light beams. By stacking QWP-GPP modules, both dynamic image superposition and beam steering can be simultaneously achieved on the image plane.

4. Conclusion

We propose a multi-step selective beam steering optical system with a steerable exit-pupil array to expand the eyebox in holographic NEDs. This method leverages the unique properties of a QWP-conditioned GP prism with active polarization control and selection schemes. Unlike conventional HWP-conditioned GP prisms, which enable selective steering with up to two steps and require additional stack modules, the QWP-GPP beam steering modules incorporate an additional 0^{th}-order diffracted term. This allows for up to three distinct beam steering effects, increasing the selective deflection steps. By integrating bi-stacked QWP-GPP modules with an active polarization switching system, nine selectively steerable exit-pupil arrays can be formed, effectively expanding the eyebox size without compromising the field of view. This approach successfully resolves the trade-off problem between FOV and eyebox size in holographic NEDs.

5. Impact of Your Research

The proposed beam steering system creates a steerable exit-pupil array in the pupil plane, effectively addressing the limited eyebox size in holographic near-eye displays. This is achieved by using polarization-dependent, actively switchable, bi-stacked QWP-conditioned GP prism beam steering modules. Unlike conventional HWP-conditioned GPPs, which generate up to a 2×2 array of viewpoints, our method leverages the advanced light manipulation capabilities of QWP-GPPs and an active polarization selection scheme. This approach allows the steering of the exit pupil into a 3×3 array of viewpoints. By efficiently expanding the eyebox without compromising the field of view (FOV), the proposed method eliminates double-image and ghost-image artifacts, ensuring a seamless and immersive viewing experience.

6. Acknowledgements

This research was supported by the National Research Foundation (NRF) funded by the Korean government (MSIT) (No. RS-2024-00416272), the Technology Innovation Program (RS-2024-00433614) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea) Technology Innovation Program (RS-2024-00453508, Development of technology to commercialize core optical components and modules for AR/MR devices to lead the XR optical components supply market) funded By the Ministry of Trade Industry & Energy (MOTIE, Korea).

7. References

1. J.-H. Park, S.B. Kim. Optical see-through holographic near-eye display with eyebox steering and depth of field control, Optics Express. 2018; 26: 27076-27088
2. M.H. Choi, Y.G. Ju, J.H. Park. Holographic near-eye display with continuously expanded eyebox using two-dimensional replication and angular spectrum wrapping, Opt. Express. 2020; 28: 533-547
3. J. Jeong, J. Lee, C. Yoo, S. Moon, B. Lee, B. Lee. Holographically customized optical combiner for eye-box extended near-eye display. Optics Express. 2019; 27: 38006-38018
4. E. Dashdavaa, M. -U. Erdenebat, A. Khuderchuluun, N. Darkhanbaatar, K.-C. Kwon, S. -H. Jeon, N. Kim. Eyebox expansion of a lensless near-eye display using diverging spherical wave illumination and a multiplexed holographic optical element, Optics, and Lasers in Engineering. 2024: 181: 108380
5. X. Xia, W. Wang, F. Guan, F. Yang, X. Shui, H. Zheng, Y. Yu, Y. Peng. Exploring angular-steering illumination-based eyebox expansion for holographic displays, Optics Express. 2023; 31: 31563-31573
6. J. Zou, L. Li, S.-T. Wu. Gaze-Matched Pupil Steering Maxwellian-View Augmented Reality Display with Large Angle Diffractive Liquid Crystal Lenses, Adv. Photonics Res. 2022; 3: 2100362-2100369
7. J. Xiong, Y. Li, K. Li, S.-T. Wu. Aberration-free pupil steerable Maxwellian display for augmented reality with cholesteric liquid crystal holographic lenses, Optics Letters. 2021; 46: 1760-1763
8. H. Lee, J.-W. Lee, J. Shin, S. Hong, H. -R. Kim, H. -J. Choi. Flicker-free dual0volume augmented reality display using a pixelated interwoven integral floating technique with a geometric phase lens, Optics Express. 2022; 30: 42186-42198
9. H. -J. Choi, Y. Park, H. Lee, K. -I. Joo, T. -H. Lee, S. Hong, H. -R. Kim. Compensation of color breaking in bi-focal depth-switchable integral floating augmented reality display with a geometric phase lens. Optics Express. 2020; 28: 35548-35560
10. M. -K. Park, H. Park, K. -I. Joo, T. -H. Lee, K. -C. Kwon, M. -U. Erdenebat, Y. -T. Lim, N. Kim, H. -R. Kim. Fast-switching laterally virtual-moving microlens array for enhancing spatial resolution in light-field imaging system without degradation of angular sampling resolution. Scientific Reports. 2019; 9: 11297
11. T. -H. Lee, K. -I. Joo, H. -K. Rim. Switchable lens design for multi-view 2D/3D switching display with wide-viewing window. Crystals. 2020: 10: 418-436.