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Novel polarization-dependent combiner for wide field-of-view glass-like near-eye displays

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Abstract
We propose a glass-like wide field of view near-eye display with a polarization-dependent combiner (PDC). The novel PDC consists of two polarization volume lenses with strong polarization selectivity. By inserting a PDC to the proposed polarization-time multiplexing system, we demonstrate an overall horizontal FOV of 50° while maintaining a compact form factor.

KEYWORDS
augmented reality, liquid crystals, polarization multiplexing, polarization volume lens

1 | INTRODUCTION

Augmented reality (AR) displays enable novel applications in entertainment, education, medical surgeries, and engineering.[1,2] Through overlapping the real environment with computer-generated images, AR technology as an information platform is revolutionizing the relationship and interactions between viewers and displays.[3,4] Recently, the free space combiners with adequate field of view (FOV) and a high degree of design freedom have attracted increasing attention. Based on different working principles, the free space combiners can be further divided into reflective and diffractive combiners.[5] The diffractive type free space combiner with a thin form factor and lightweight is more favorable in the current stage to satisfy the needs for glass-like AR devices.

Usually, the diffractive type free space combiner is realized by holographic optical elements with imaging capability.[6] Based on different system designs, the computer-generated image is presented to the designed depth or infinity at an off-axis incident angle. The FOV of the system is dependent on the viewing angle of the combiner lens and system design. To extend the viewing angle, reducing the f-number of combiner lens is an effective and straightforward approach. However, when the f-number is reduced, the imaging aberrations become more serious.[7] Therefore, expanding the FOV becomes one of the most pressing challenges in glass-like AR system.[8,9]

Recently, cholesteric liquid crystal (CLC) based novel polarization volume lens (PVL) has been developed.[10,11] Due to self-organized structure, PVLs possess several unique features, such as strong polarization selectivity, large off-axis angle, and simple fabrication process. Aside from advances in the combiner lens, a new optical system design with polarization multiplexing concept has been proposed with metagratings[12] and then successfully proven in the waveguide-based AR system using polarization gratings.[13]

In this paper, we propose and demonstrate a glass-like see-through AR system with a novel polarization-dependent combiner (PDC) to expand the FOV. Similar concept to the polarization division multiplexing in optical fiber communications, where two orthogonal polarizations are used to double the information capability. Here, we extend the viewing angle by presenting the left and right FOVs into two orthogonal polarization states, left-handed and right-handed circularly polarized light (LCP and RCP), respectively. The PDC consists of two PVLs with opposite polarization response and different off-axis angles and is designed to selectively diffract LCP and RCP images. By using an optical engine and a liquid crystal polarization modulator (LCPM) to simultaneously create two images with orthogonal polarization states, the proposed configuration presents extended FOV while maintaining a compact form factor.

2 | OPERATION PRINCIPLES

2.1 | Polarization dependent combiner

The PDC is a critical optical component in the proposed system, which can distinguish orthogonal polarization states while offering different responses. To meet these requirements, we propose a novel PDC consisting of two PVLs with opposite polarization responses and different diffraction angles. Figure 1A shows the PVL with strong polarization selectivity (LCP or RCP) and imaging power.[10] Specifically, the PVL is a patterned CLC device with a specifically designed lens profile. By following the alignment pattern (Figure 1B) on the bottom surface, CLC molecules continuously and periodically rotate in the *xy*-plane and twist along a tilted helical axis (Figure 1C) in the *xz*-plane. The off-axis angle and focal length of PVL can be designed by tuning the phase change on surface patterning, which is determined by the interference exposure during fabrication process. Besides, the PVL is a polymerized ultrathin film (from hundreds of nanometers to several microns) with a controllable diffraction efficiency. Here, we stack two PVLs (PVL-L and PVL-R) with opposite polarization responses as the PDC. As Figure 1D shows, the PVL-R diffracts the RCP light while PVL-L diffracts the LCP light to a different angle. Due to the thin film form factor, the combined PDC can increase the polarization responses while keeping a flat and ultrathin profile.

2.2 | System configuration

Figure 2 shows a typical configuration of free space AR system with diffractive combiner.[6] The system usually has a pupil-forming design. The image is first projected to the space by a relay optics, and then the diffractive combiner delivers the intermediate image to the viewer's eye. The depth and size of the virtual image can be controlled through changing the distance between the intermediate image and the combiner lens.

To expand the FOV, here we propose a polarization-time multiplexing system based on two orthogonal polarization states to tile the left and right images together. Figure 3 depicts the system configuration. The optical engine in the system can be a conventional 2D display, a liquid-crystal-on-silicon (LCoS), or a digital light processing (DLP) projector. Without losing generality, we add a polarizer in front of the optical engine to make the emitted light with linear polarization in *xz*-plane (0°). Then a LCPM, aligned after the polarizer, is designed to obtain modulation between two orthogonal polarization states, namely 0° (in *xz*-plane) and 90° (along *y*-axis) in our system. With an integrated λ/4 plate oriented at 45°, these two orthogonal linear polarizations would be converted to LCP and RCP waves, respectively. When switching the computer-generated sub-frame images in time domain, the LCPM can offer corresponding polarization state for each sub-frame simultaneously. Due to time multiplexing design, the final refresh rate of the system is jointly determined by the number of sub-frames, LCPM, and the LCoS. Generally, the response time of LCPM can be controlled between 1 ms (1 kHz) and 2 ms (500 Hz), depending on the material and cell gap. Here, the number of sub-frames is two. Therefore, if the refresh rate of LCoS is 240 Hz,[14] the final system refresh rate would be 120 Hz. Moreover, the tiled image can only be observed when both beams come into the viewer's eye, which means the eyebox should be the overlapping area

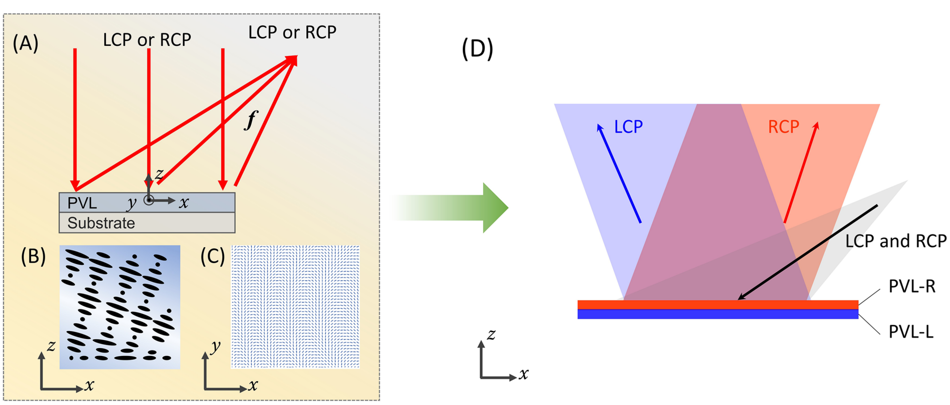


FIGURE 1 Schematic illustrations of (A) a PVL with (B) surface alignment and (C) CLCs structure. (D) Schematic diagram of the PDC with two cascaded PVLs

FIGURE 2 Schematic illustration of a free space AR system

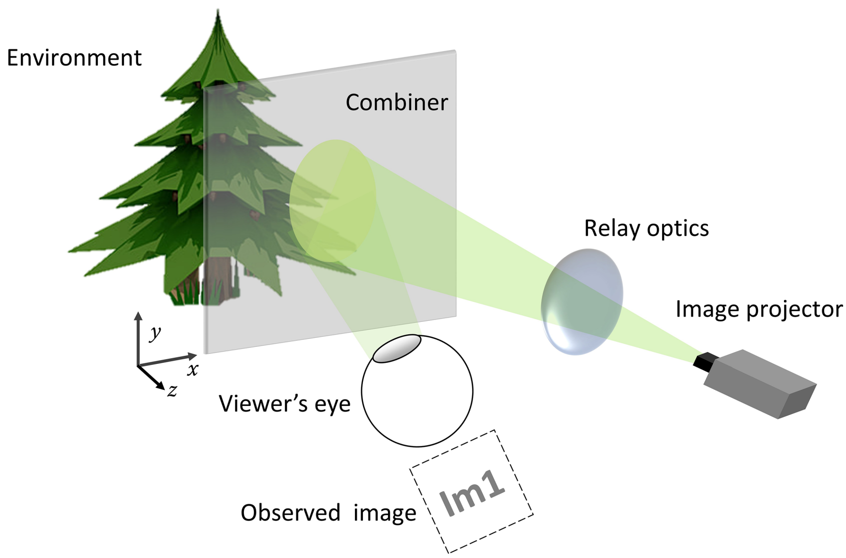
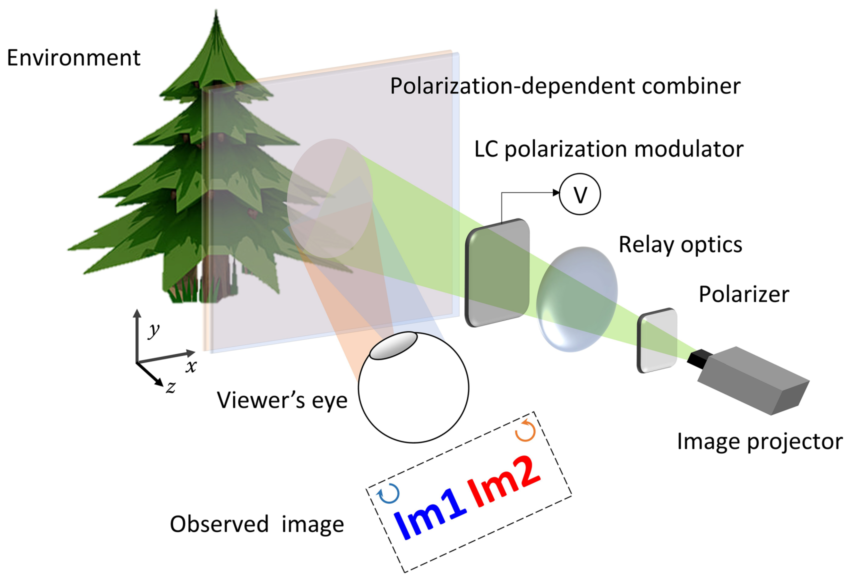


FIGURE 3 Schematic illustration of the polarization-time multiplexing free space AR system



of the two polarization paths. This area can be further enlarged when the eye relief is decreased, the size of the intermediate image is increased, or the divergence angle of the two paths is reduced.

As shown in Figure 3, when the displayed content is Image 2, the LCPM will be turned-on and it will synchronize the polarization to RCP. Then, the optical engine switches the content to Image 1, and the LCPM changes the corresponding polarization to LCP at the voltage-off state. In brief, the LCPM and the optical engine jointly control the polarization state and content of the intermediate image. How to input the intermediate image to the PDC needs to be carefully considered as well. Assume the focal length of PVL-L and PVL-R is f_L and f_R, respectively. The angle between the incident beam and the normal direction of PCD is θ. To diffract two images into left and right, the diffraction angle of PVL-L and PVL-R should be $\theta + \varphi_L$ and $\theta - \varphi_R$, respectively. When the intermediate image is placed at a distance $d_{1\text{-}L}$ from the PVL-L, the image distance $d_{2\text{-}L}$ can be estimated by the thin lens conjugate equation:

$$d_{2-L} = \frac{f_L d_{1-L}}{f_L + d_{1-L}} \tag{1}$$

Here, $d_{2\text{-}L}$ is the approximate depth of the observed virtual image from human eye. The size of the virtual image $A_{2\text{-}L}$ should be

$$A_{2-L} = AM_L = A_1 \frac{d_{2-L}}{d_{1-L}} \tag{2}$$

where A_1 stands for the size of intermediate image and M_L is the magnification of PVL-L. The same goes for the PVL-R. It is worth mentioning that the perceived image depths from two PVLs must be matched to tile the retina image seamlessly, as Figure 3 illustrates. Thus, the image distance $d_{2\text{-}L}$ and $d_{2\text{-}R}$ should be equal, namely, d_2. In addition, there can be some space between the two virtual images, but they cannot be overlapped. Therefore, the overall horizontal FOV is generally expressed as

$$FOV = \arctan\left(\frac{A_2}{2d_2} + \tan\varphi_L\right) + \arctan\left(\frac{A_2}{2d_2} + \tan\varphi_R\right) \tag{3}$$

where A_2 stands for the size of the virtual image. If the two images are symmetrically and perfectly tiled without any space, then the horizontal FOV can be simplified as 2arctan (A_2/d_2).

3 | EXPERIMENT

3.1 | System setup

The system setup basically follows the layout plotted in Figure 3. In our experiment, an LCoS projector (LG-PH150B) connected to a computer is employed as the optical engine to provide the computer-generated images. The PDC consists of two PVLs with LCP and RCP responses, respectively. For PVL-L, the focal length is $f_L = 3$ cm and the off-axis angle is 52°, and for PVL-R, the focal length is $f_R = 3$ cm and the off-axis angle is 27°. Both PVLs are fabricated following the procedures reported in Xiong et al.[6] First, a thin film of photo-alignment (PA) material (BY, Brilliant Yellow from Tokyo Chemistry Industry) is spin-coated onto cleaned glass substrates. Then, the substrates with BY coating are mounted on the exposure setup to record the surface alignment pattern. After exposure, the liquid crystal mixtures (LCM) with opposite chiral dopants, R5011 and S5011, are spin-coated for the PVL-L and PVL-R, respectively. Finally, the samples are cured and polymerized by a UV light. More detailed principles and fabrication procedures of the PVL can be found in previous studies.[10,15]

Figure 4A shows a photo of the fabricated PVL. The PVL is circled in the red dashed lines and the lens surface is clear and uniform. The images observed are the ceiling fluorescent lamps in our labs. Then we fabricate the other PVL and laminate them together using a UV optical glue (NOA65), as Figure 4B shows. The PDC region is circled by the red dashed lines. The thickness of each PVL is ∼1 μm, and the total thickness of PDC, including the substrates, is ∼1 mm. The clear background seen through the PDC region indicates the combiner has a high transmittance and negligible scattering. The photo-alignment material (Brilliant Yellow) we used has color; thus, the sample appears a little yellowish, which can be eliminated easily by using a colorless photo-alignment material.

To prepare an LCPM, we fill liquid crystal Merck MLC-6686 into a commercial twist-nematic (TN) cell (4.9 μm) and apply a voltage to switch between the on- and off-states. Then we use a broadband quarter-wave film to convert the linearly polarized light into circular polarization. The whole experimental setup is constructed on an optical table. As captured in Figure 5, a positive lens with focal length f = 12 cm is utilized as the relay optics in our experiment. A camera is placed in front of the PDC to capture the displayed images. To eliminate the ghost images generated by dispersion from diffractive optics, we add a notch filter (NF533-17 from Thorlabs) after the polarizer.

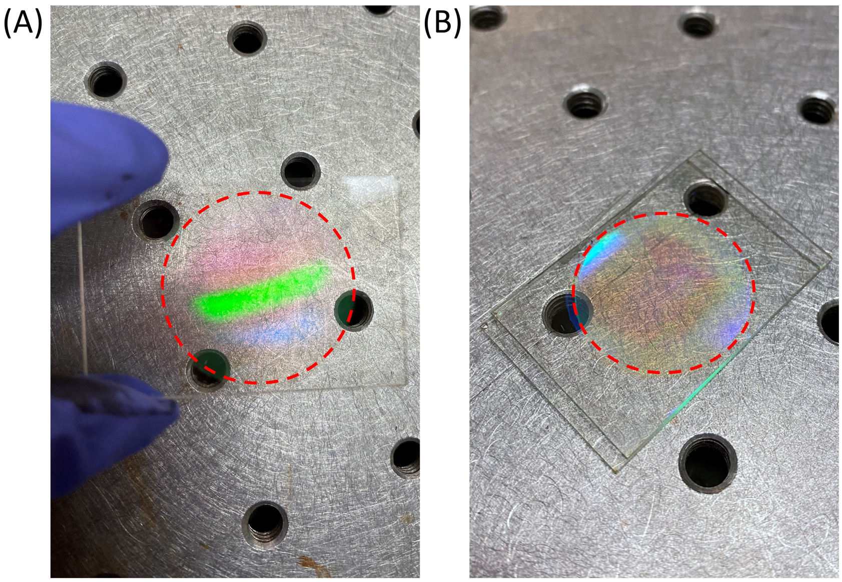


FIGURE 4 Photo of (A) the PVL-L and (B) the PDC consisting of PVL-L and PVL-R

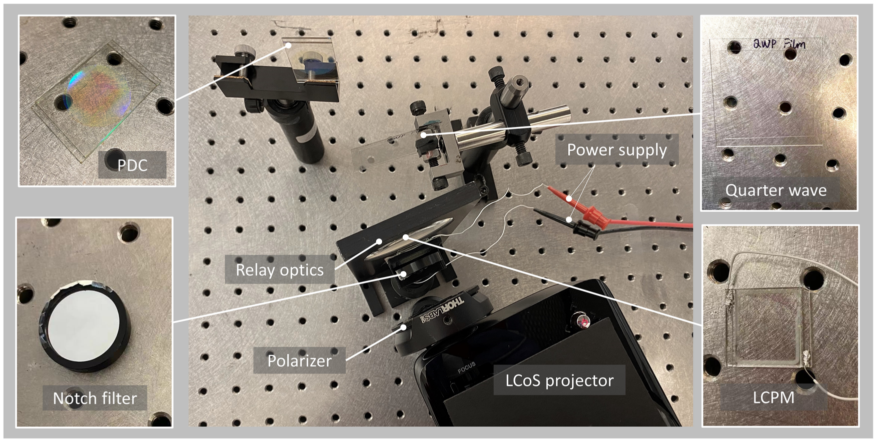


FIGURE 5 Experiment setup

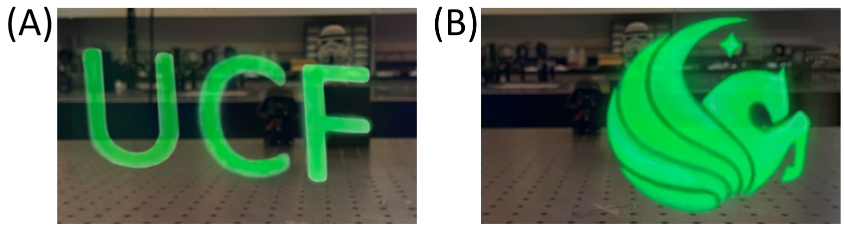


FIGURE 6 (A) Captured images of LCP light, UCF. (B) Captured images of RCP, school logo

FIGURE 7 Image of combined image

3.2 | Results

Figures 6 and 7 show the experimental results. The intermediate image is 2.9 cm away from the PDC. The angle between the input beam and the normal of the PDC is approximately 40°. When we turn the LCPM on, there will be only LCP light. The viewing angle of LCP alone is approximately 26° with UCF letters displayed as Figure 6A shows. Due to the large off-axis imaging, we can see an obvious distortion, especially for the letter U. This optical aberration can be mitigated through pre-processing the input contents, which results in more burdens to both computation and information transform. By

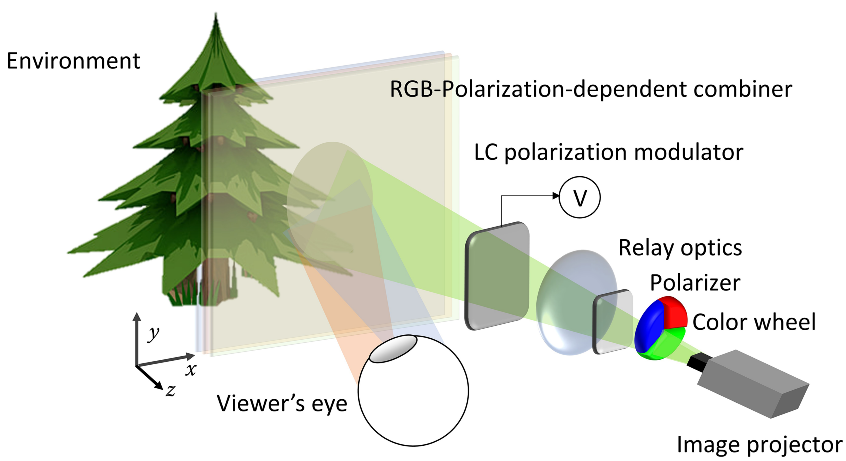


FIGURE 8 Schematic illustration of the RGB system

switching the LCPM from on to off state, we can observe the RCP image. As depicted in Figure 6B, the viewing angle is 23° with school Pegasus logo. Then we simultaneously switch the LCPM and the computer-generated images to obtain the combined image.

As expected, in Figure 7, the extended FOV is dramatically extended to 50°. Although the PDC's diffraction efficiency for RCP mode is slightly lower than that for LCP, the intensity for each polarization channel can be improved by precisely control the film thickness or be compensated by pre-image processing.

Moreover, the proposed method can be applied to display a full-color image with multilayered PVLs. To achieve this function, the narrowband image source is needed to avoid dispersion and crosstalk. Here, we propose a polarization-time multiplexing system with a color wheel. The color wheel serves as a switchable notch filter to provide narrowband light for corresponding PVLs. The color wheel can be placed in front of the projector, as illustrated in Figure 8, or integrated to the light engine.

4 | CONCLUSION

In conclusion, we propose and demonstrate a polarization-time multiplexing system with an enlarged FOV for glasses-like AR. The multiplexing is achieved by PDC, which is physically realized by combining two PVLs with orthogonal polarization responses. In experiment, a PDC is fabricated using patterned CLC polymers which achieved high uniformity and negligible scattering. By constructing the proposed system with electronically controlled LCPM, the enlarged overall horizontal FOV 50° is achieved. Our work shows a very promising approach of FOV extension in a glasses-like AR system while maintaining simple system configuration, compactness, and lightweight.

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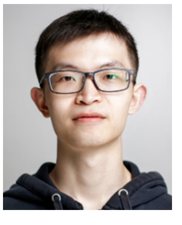
Kun Yin received her BS degree in Opto-Electronics from Tianjin University of China in 2016 and is currently working toward her PhD degree from the College of Optics and Photonics, University of Central Florida, Orlando. Her current research interests include optical gratings and augmented reality and virtual reality displays.



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Shin-Tson Wu is Pegasus Professor at the College of Optics and Photonics, University of Central Florida. He is among the first six inductees of the Florida Inventors Hall of Fame (2014) and a Charter Fellow of the National Academy of Inventors (2012). He is a Fellow of the IEEE, OSA, SID, and SPIE, and an honorary professor at Nanjing University (2013) and at National Chiao Tung University (2018). He is the recipient of 2014 OSA Esther Hoffman Beller Medal, 2011 SID Slottow-Owaki Prize, 2010 OSA Joseph Fraunhofer Award, 2008 SPIE G. G. Stokes Award, and 2008 SID Jan Rajchman Prize.

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