Near-eye light field display with polarization multiplexing

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ABSTRACT

We report a polarization-multiplexed additive light field display for near-eye applications. A polarization-sensitive Pancharatnam-Berry phase lens is implemented to generate two focal depths simultaneously. Then, a spatial polarization modulator is utilized to control the polarization state of each pixel and direct the two images to designated focal planes. Based on this design, an additive light field display system is constructed. The vergence-accommodation conflict is suppressed successfully without increasing space and time complexities.

Keywords: Near-eye display, vergence-accommodation conflict, virtual reality, multiplane display

1. INTRODUCTION

Recently, head-mounted displays (HMDs), including augmented reality and virtual reality, are emerging and enabling many novel applications in gaming, entertainment, education, medical surgeries, etc. Stereoscopic display based on binocular disparity is usually adopted by most of current HMDs, to create 3D depth perception. Two different images are separately sent to left and right eyes to generate illusion of depth. While stereoscopic 3D perception would result in the well-known vergence-accommodation conflict (VAC) issue. The mismatch between vergence and accommodation distances is the main cause of visual discomfort and fatigue when wearing such a headset. VAC issue remains one of major challenges for HMDs [1].

Several approaches have been proposed to overcome the VAC issue. Basically, these solutions can be divided into two categories: static space-multiplexed and dynamic time-multiplexed approaches. Static category typically includes stacked panels [2-3], integral displays [4], and scanned fiber array. Major challenges of static approaches are the difficulties to stack multiple focal planes in a compact way, and the loss of display resolution and contrast. Time-multiplexed methods do not necessarily involve multiple display panels, which enables compact designs. These approaches usually change the image depth time-sequentially to provide the correct focus cues. However, some tunable optical elements, such as deformable mirror [5], tunable lens [6-7], or switchable diffuser, are needed in a dynamic design. The major technical challenges of time-multiplexing approach are high display frame rate and fast-response tunable optics, in order to avoid image flickering. Actually, the required refresh rate is proportional to the number of focal surfaces. Especially for current commercial VR headsets, a refresh rate over 90 Hz is commonly used to reduce motion picture response time. Thus, as to time-multiplexed approaches, 180 Hz refresh rate is required for two focal depths and 270 Hz for three focal depths. Such a high frame rate would undoubtedly lead to higher power consumption and complicated driving circuitry.

In this work, we demonstrate a polarization-multiplexed additive light field display with a polarization-sensitive Pancharatnam-Berry phase lens (PBL) to resolve the VAC for near-eye displays. In our design, a liquid crystal (LC) spatial polarization modulator (SPM) is applied to send correct images to PBL’s two focal planes simultaneously. Finally, we demonstrate an additive light field display without the need for time-multiplexing nor switchable lenses. Thus, the proposed design can effectively reduce the frame rate by one half.

2. PANCHARATNAM-BERRY PHASE LENS

In a Pancharatnam-Berry (PB) phase optical element, a half-wave (\(\lambda/2\)) plate is spatially patterned with varying crystal axis direction [8-9]. Its phase modulation is directly related to the crystal axis orientation, namely LC azimuthal angle \(\phi(x, y)\). The working principle can be explained by Jones matrices. A circularly polarized light can be expressed as:
\[
J_{\pm} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \pm i \end{bmatrix},
\]

(1)

where \(J_+\) and \(J_-\) stand for the left- and right-handed circularly polarized light (LCP and RCP), respectively. After the circularly polarized light passing through a \(\lambda/2\) plate, the output can be calculated by [9]:

\[
J'_{\pm} = R(-\varphi) \cdot W(\pi) \cdot R(\varphi) \cdot \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} = e^{\pm i \varphi} \cdot \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \mp i \end{bmatrix},
\]

(2)

where \(R\) presents the rotation operation matrix and \(W\) is the phase retardation matrix. From Eq. (2), the handedness of the outgoing circularly polarized light is reversed. In addition, the \(\lambda/2\) plate also introduces a phase delay of \(\pm 2\varphi(x, y)\) to LCP and RCP, respectively. In a PBL, the spatial distribution of LC director azimuthal angle \(\varphi(x, y)\) follows paraboloid function, as Fig. 1(a) illustrates. Thus, for a circularly polarized light, a paraboloid phase distribution can be constructed. Please note that the phase profiles of LCP and RCP lights have opposite signs [Fig. 1(b)]. Therefore, if the PBL is designed to work as a focusing lens for RCP, then it is a defocusing lens for LCP, as Fig. 2 depicts. Basically speaking, PBL is a polarization-sensitive bifocal lens with high polarization selectivity.

\[\text{Figure 1. (a) Top view of the LC director distribution and (b) phase change profile of a PBL with \(\pm 0.8\)D optical power for RCP and LCP, respectively.}\]

\[\text{Figure 2. (a) PBL serves as a diverging lens for LCP light and (b) it is a converging lens for RCP light.}\]

From Fig. 2, a PBL can offer two focal planes, depending on the incident light polarization state. Therefore, time-multiplexing operation is not necessary to generate multiple image planes. However, achieving multiple image planes is just the first step to realize light field display. Next, we need to assign correct and independent images to these focal planes. As discussed above, PBL exhibits excellent polarization selectivity. Based on that, we can adopt the polarization-multiplexing operation to send independent images to the focal planes. The LCP and RCP are a set of basis for optical
polarization state space. For a polarized light, it can be represented as a superposition of LCP and RCP waves, and its LCP and RCP components can be independently sent to PBL’s two focal planes, respectively. Thus, by modulating the incident light polarization, we can easily control the ratio of LCP and RCP, and generate independent images for two focal planes.

3. SYSTEM CONFIGURATION

3.1 Working principle

Figure 3 depicts the device configuration of the proposed polarization-multiplexed light field display. The display panel shown in Fig. 3 can be a liquid crystal display (LCD) or an organic light emitting diode (OLED) display panel with a circular polarizer. Without losing generality, we can assume the display panel emits a linearly polarized light along \( z \)-axis (0°). Then a spatial polarization modulator (SPM) is closely integrated and aligned to the display panel. The SPM in Fig. 3 is designed to achieve full modulation between two orthogonal polarization states, namely from 0° to 90° in our system. With a broadband quarter-wave plate oriented at 45°, these two orthogonal linear polarizations would be converted to RCP and LCP waves, respectively. In addition, SPM can continuously control the polarization state, so that the relative ratio of RCP and LCP components can be tuned. With the help of polarization-sensitive PBL, RCP and LCP components will be sent to two virtual planes simultaneously, as Fig. 3 shows. In brief, the PBL simultaneously provides two focal image planes and SPM directs the images to these two focal planes.

![Figure 3. Configuration of the proposed polarization-multiplexed light field display system.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)
two orthogonal polarizations. The polarization state of each pixel can be independently modulated to $0^\circ$, $45^\circ$, $90^\circ$ or any intermediate polarization states. Each pixel may have different polarizations after SPM. After passing through a $\lambda/4$ waveplate (optical axis $45^\circ$), the $0^\circ$ polarization would be converted to LCP, and $90^\circ$ polarization is converted to RCP. These intermediate polarization states will also be converted to elliptical polarizations. PB lens is highly sensitive to hardness of circular polarization state. With the help of PBL, for each pixel, its LCP component will be sent to virtual plane 1, and RCP component will be assigned to plane 2. Then, the gray level can be generated. Finally, we can get two focal image planes at the same time, and are able to send independent images to virtual plane 1 and 2 simultaneously. In summary, display panel provides total intensity of two virtual planes, and SPM separate it to two independent images.

3.2 Experimental setup

In experiments, we used a 4.7-inch 60-Hz LCD panel with resolution $1334 \times 750$ as the display panel. In order to prepare a SPM, we removed the polarizers of a commercial twisted-nematic (TN) LCD (5.0-inch, 60-Hz, $800 \times 480$) and successfully made it into a spatial polarization modulator. The reasons why we chose TN LCD are twofold: 1) it can easily offer a full-range modulation, and 2) it is a broadband device. Next, we fabricated a 2.5-inch PBL with optical power $\pm 0.8D$ by interference exposure [9-10]. In our fabrication, a glass substrate was first cleaned and spin-coated with a thin photoalignment layer. A Mach–Zehnder interferometer with $\lambda=442$ nm (He-Cd laser) was set up for exposure, whose two arms had opposite circular polarizations. A convex lens was positioned in one arm to obtain the desired interference pattern. After interference exposure, a UV-curable diluted LC monomer (RM257) was coated on the exposed substrate surface. Then the coated substrate was cured by a UV light, forming a thin cross-linked LC polymer layer. The LC birefringence and thickness were carefully tuned to match the half-wave requirement for $\lambda=550$ nm. More detailed fabrication procedures of PBL can be found in prior publications [9-10]. Please note that the depth difference can be easily tuned by changing the optical setup of interference exposure. Moreover, in our system [Fig. 3], a positive lens with optical power 10D was applied to provide a biased focusing power and to place two virtual planes at the suitable depths. Thus, the accommodation depths of two focal images are 0.1 D and 1.7 D, respectively. The horizontal field of view is close to $\pm 35^\circ$ in our proof-of-concept experimental demonstrations.

Before constructing an additive light field display, we need to examine the display reproduction capability for these two focal planes. Based on Eq. (3) and Eq. (4), we calculated $I_{DP}$, $I_{0^\circ}$ and $I_{90^\circ}$ for two target images with letter “A” and “B”. RGB channels in the full-color images were separately processed. Moreover, the gamma 2.2 correction in practical display panel was taken into consideration as well. Then we loaded the intensity information $I_{DP}$ to display panel and polarization modulation $I_{0^\circ}$ and $I_{90^\circ}$ to SPM. To examine the crosstalk between two focal plane images, we inserted right-handed and left-handed circular polarizers successively just after the quarter-wave plate. The experimental photographs are shown in Fig. 5. Our system can successfully reproduce two images with correct polarizations: letter “A” in RCP [Fig. 5(e)] and “B” in LCP [Fig. 5(f)]. While one may notice that there still exist very little crosstalk in Figs. 5(e) and (f). Detailed measurements indicate that the crosstalk between these two orthogonal polarizations is: 0.27%, 0.42% and 4.83% for $\lambda = 457$ nm, 514 nm and 633 nm, respectively. Actually, this crosstalk comes from the commercial TN panel, since it is optimized for display at $\lambda \approx 550$ nm, instead of polarization modulation.
With the help of PBL, these two images with orthogonal polarizations should be sent to different focal depths. Letters “A” and “B” exist simultaneously while they are located at different depths [Fig. 6]. With the camera focusing at front virtual plane 1 [Fig. 6(a)], letter “A” was on focus with clear and sharp edges, while letter “B” was blurred. When focusing at rear plane, “A” became blurry.

Figure 5. Target images: a) without CP, b) with right-handed CP and c) with left-handed CP. Experimental results: d) without CP, e) with right-handed CP, and f) with left-handed CP.

Figure 6. The photographs captured with camera focusing at a) virtual plane 1 and b) virtual plane 2.

4. ADDITIVE LIGHT FIELD DISPLAY

To create correct 3D perception, the display images on two focal planes should be designed and optimized. Several different image rendering methods can be applied on our system to generate 3D perception. Here we adopted an additive factorization method to generate all the 2D images for corresponding image depths [7, 11-12]. Since virtual planes 1 and 2 exist simultaneously as Fig. 7 depicts, total light intensity $I_{total}$ along a specific direction can be directly calculated by:

$$I_{total} = I_{1i} + I_{2j},$$

where $I_{1i}$ and $I_{2j}$ represent the intensity of specific pixels along specific direction from first and second virtual planes. After optimization, these two images can be generated. In our system with two virtual planes, we rendered two images for the 16×16 mm eye-box size with 5×5 viewing points. The rendered images are shown in Fig. 8.
With the rendered images obtained [Fig. 8], we calculated the intensity information $I_{DP}$ and polarization modulation $t_{\theta^0}$ and $t_{90^0}$ by Eq. (3) and Eq. (4). With the images correctly displayed at virtual planes, an additive light field display system was constructed. The experimental results are presented in Fig. 9 and Fig. 10. Two cubes located at two different depths: the red-yellow cube at near distance and the blue-green one at far distance. The blue-green cube was blurry when focusing at front plane [Fig. 9(a)], while the red-yellow cube became blurry when focusing at rear plane [Fig. 9(b)].
Figure 10 shows the photographs at different viewing positions. Obvious 3D parallax effect is clearly illustrated in Fig. 10. From different viewing points, we can see slightly different images. For instance, from left [Figs. 10(d)] to right [Figs. 10(f)], two cubes get closer and closer. Especially, at right viewing points [Figs. 10(c), (f) and (i)], the front pink-yellow cube blocks a portion of the rear blue-green cube. Figures 9 and 10 demonstrate that our proposed system can successfully realize a multi-plane display with correct 3D reproduction capability. Since there are only two image planes in this proof-of-concept experiment, the occlusion issue is not well addressed [Figs. 10(c) and 10(f)], in which more image planes are eventually needed.

5. DISCUSSION

From Fig. 9 and Fig. 10, there remains noticeable ghost images, which could originate from the TN panel’s polarization crosstalk [Fig. 5] and the wavelength-dependent efficiency of PBL. Normally, such a commercial TN panel is optimized for display applications at $\lambda \approx 550$ nm. Thus for the blue and red wavelengths, such a TN LCD deviates slightly from an ideal polarization rotator, which leads to the observed crosstalk between two focal image planes. One way to mitigate this issue is to increase the $\Delta n$ value of the TN LCD. To address the wavelength-dependency of PBL, a dual-twist structure [13] can be adopted to effectively improve the efficiency to $>95\%$ within the whole visible range.

As for virtual reality displays, a $6K \times 6K$ resolution is desirable to minimize the screen-door effect [14]. In our design, the SPM is utilized mainly to provide depth information. Thus, it is not required for SPM to match the resolution of display panel. A relatively lower resolution of SPM helps to reduce possible Moiré effect when two panels are aligned together, and to improve the optical efficiency.

In our demonstration, we use one PBL to achieve two focal planes. To further improve the quality and functionality, the number of image planes, spacing between adjacent planes and image rendering algorithm all need to be taken into consideration. The spacing between two adjacent planes should be $\sim 0.6D$ and 5~6 image planes are eventually needed [15]. The proposed polarization-multiplexed approach can also be integrated with space- or time-multiplexed configuration to provide more focal planes.
6. CONCLUSION

In conclusion, we propose a polarization-multiplexed additive light field display design to overcome the VAC issue in HMD. The proposed design utilizes a polarization-sensitive bifocal PB lens and a spatial polarization modulator to generate two independent focal image planes simultaneously. Then, an additive light field display is experimentally demonstrated. The proposed light field display requires no additional time-multiplexing operation, which can effectively reduce the display refresh rate by one half.

REFERENCES