Emerging Near-eye Displays with Pancharatnam-Berry Optical Elements

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ABSTRACT

Near-eye displays with enhanced images quality are developed with planar optics employing Pancharatnam-Berry (PB) phase. Advanced broadband PB deflectors and lenses are fabricated to enhance the apparent pixel density and reduce the chromatic aberrations in immersive near-eye displays. Both simulation and experimental results are presented.

1 INTRODUCTION

Thanks to the rapid development of powerful mobile processors, high-pixel-density display panels, and optics fabrication capabilities, virtual reality (VR) displays have manifested tremendous growth in recent years. VR offers eye-opening immersive experiences, where the artificial simulated environment can be as fascinating as the real one. To offer immersive VR experience, the field-of-view (FOV) is usually designed to be >100° in the viewing optical system, which results in limited angular pixel density and considerable color break-up around objects at the peripheral FOV.

Currently, mainstream commercial VR products manifest ~6 arcmin angular resolution with ~100° FOV, while human eyes with 20/20 vision can resolve 1 arcmin. That is to say, a six-fold enhancement in resolution density is required. For a low-resolution display, the screen-door effect caused by the black matrix degrades the desired immersive experience considerably. To mitigate the screen-door effect, display panels with a higher pixel-per-inch (PPI) are urgently needed. However, as the PPI increases, display luminance may decrease because of the reduced aperture ratio, and data flow rate in driving electronics would increase accordingly.

Also, the noticeable color break-up at the edge of FOV is known as chromatic aberration (CA), caused by the wavelength-dependent focal length of the viewing optics, which is originated from the dispersive nature of electric permittivity. Although the noticeability of this phenomenon is dependent on the user's gaze point and the displayed image content, it is still preferable to provide chromatic aberration correction (CAC) for better user experience. There are mainly two types of CAC method, digital and optical. At the cost of extra graphic computation power, the CA can be reduced by pre-processing images according to the chromatic dispersion of viewing optics, which is a digital compensation method similar to the lens correction in photography. The digital CAC helps decrease but cannot eliminate CA since each color channel has a spectral bandwidth.

On the other hand, optical CAC has been widely applied as a useful and necessary part in chromatic imaging systems since the 18th century. The conventional optical CAC approach utilizes two or more lens materials with different refractive index dispersions, or Abbe numbers, in the system to unite the focal length at two or more wavelengths. However, achromatic doublets are more expensive and heavier than singlets in head-mounted display systems, causing discomfort for the users.

In this paper, an optical approach based on polarization multiplexing is proposed to enhance the resolution density without compromising the frame rate. This approach consists of separating each physical pixel spatially into two virtual pixels with subpixel precision using a passive polymer-based Pancharatnam-Berry phase deflector (PBD) and thus creating a new apparent pixel grid with smaller effective pixel pitch. Meanwhile, we propose to apply low-cost yet high-quality diffractive Pancharatnam-Berry phase lenses (PBLs) to correct the chromatic aberrations. Compared to conventional diffractive optical elements, the fabrication of PBLs is simpler and more cost-effective. Moreover, PBLs usually have a flat physical geometry with a thickness of only several microns, which can flawlessly satisfy the need for lightweight and compactness in head-mounted displays.

2 EXPERIMENT

2.1 Pancharatnam-Berry Optical elements

The Pancharatnam-Berry phase optical elements function by a spatial-varying phase change generated through a closed path in the polarization parameter space, which is commonly realized using a patterned half-wave plate. Despite the spin-orbit interaction of light embedded in this effect, it can be conveniently represented by Jones calculus with a circularly polarized input:

$$\begin{bmatrix} \cos 2\varphi & \sin 2\varphi \\ \sin 2\varphi & -\cos 2\varphi \end{bmatrix} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} = \begin{bmatrix} 1 \\ \mp i \end{bmatrix} e^{\pm 2i\varphi} \qquad (1)$$

where φ denotes the fast axis orientation angle of the half-wave plate. A phase change of 2φ occurs while the handedness of circular polarization is inverted. PBDs

and PBLs can be fabricated by patterning φ in a linear and paraboloidal manner, respectively. Thanks to its continuous phase profile, PBDs and PBLs provide higher optical quality and less stray light compared with conventional phase gratings and Fresnel phase lenses. It should be noticed that PBDs deflect right and left circularly polarized light into ±1 order and PBLs manifest opposite optical power for right and left circularly polarized light, as indicated in Eq. (1).

2.2 Resolution Enhancement by PB Deflector

Firstly, regarding resolution enhancement in VR, an optical approach based on the pixel superimposition method is designed, as shown in Fig. 1. Through shifting the pixel grid diagonally in opposite directions, a new pixel grid with half the pitch can be generated. Here, a PBD in the Raman-Nath regime [1] is chosen to function as the pixel separation component, considering its high diffraction efficiency in the ±1 orders and polarization selective nature. Polymer-based PBDs have shown great potential for display applications [2] because of its nearly 100% diffraction efficiency and fabrication simplicity [3]. Fig. 2(a) illustrates the liquid crystal orientation and characteristic polarization selectivity of a PBD. If an unpolarized light or linearly polarized light is incident on a PBD, then the left-hand and right-hand circularly polarized (LCP and RCP) components is deflected into +1 and -1 order, respectively. Making use of the polarization selective nature of PBD, the brightness separation ratio between two virtual pixels can be tuned by modulating the ratio between LCP and RCP fraction of input light using a pixelated polarization modulation layer (PML). Each pixel of the PML is a twisted-nematic liquid crystal cell with a quarter-wave plate (QWP), as shown in Fig.3, applied to change the polarization state of the output beam. With pixelized intensity and polarization modulation from the display panel and PML, the pixel value of the two separated pixels from an original pixel can be assigned independently and simultaneously. Thus, the desired image content can be displayed on the two virtual pixel grids at the same time, as Fig. 2(b) shows. Without a pixelated PML, the PBD may still help to fill the black matrix but does not enhance the resolution because the two orthogonal polarizations share the same image content. In experiment, a resolution target 'Siemens star' was used as an example to demonstrate the resolution enhancement effect. The display panel and the PML have a resolution of 800x480 and a size of 5 inches. The focal length of the viewing lens is 55 mm, and the period of the fabricated PBD is controlled to be ~0.6 mm for the desired shift.

2.3 Chromatic Aberration Correction by PB Lens

Secondly, to address the chromatic aberration at the peripheral FOV, a broadband diffractive LC lens is designed [4] and fabricated to compensate the chromatic dispersion of the refractive lens in VR, making use of their opposite chromatic dispersion, as shown in Fig. 4. The experiment setup is shown in Fig. 5(a), where a circular polarizer is added to eliminate the zero-order leakage from the PBL, making using of PBLs' polarization sensitivity, as illustrated in Fig. 5(b). To achieve a broadband high-efficiency of PBL, a complex twist-homo-twist liquid crystal polymer structure is implemented in the axial direction of PBL as depicted in Fig. 5(c). As a result, the fabricated PBL manifest >95% first-order diffraction efficiency in the LCD spectrum range. Fig. 5(d) shows the measured zero-order leakage of the PBL and white light spectrum from the LCD. It is clear that over 95% of the light from display panel can be utilized by the PBL in most of its spectral range. Based on the Zemax analysis of the proposed system, adding a diffractive PBL can improve not only the chromatic color shift but also the general imaging quality of a VR system, as compared in Fig. 6.

3 RESULTS and DISCUSSION

Regarding the resolution enhancement performance, in comparison with the apparent image captured at the original resolution [Fig. 7(a)], the resolution enhancement is clearly observed, especially at the sloped contours [Fig. 7(b)]. Moreover, the screen-door effect is significantly reduced, and the boundaries between pixels are not as apparent as the original image.

To experimentally verify the CAC performance of the proposed system, an image was directly displayed on the LCD screen without barrel distortion correction, which shows a set of evenly spaced bars with RGB segments [Fig. 8(a)]. When viewing through the plastic Fresnel singlet, as presented in Fig. 8(b), the test pattern bars are blurred and the RGB colors are apparently displaced due to transverse CA at the peripheral FOV. When the proposed hybrid optics module is implemented, the color breakup at the edge of FOV is significantly reduced [Fig. 8(c)]. With the proposed optical structure, the CA can be corrected effectively at the cost of adding planar optical elements without affecting the compactness of the system. It should be emphasized that not only the chromatic aberrations but also the monochromatic ones are also reduced with the help of a thin-film PBL.

Although the resolution and image quality of the virtual reality displays can be efficiently improved by Pancharatnam-Berry phase optical elements, there are some practical limitations and drawbacks of the proposed methods.

The diffraction efficiency of PBDs and PBLs are not ideal in real applications, which may lead to some ghost images that cannot be eliminated. At normal incidence, the first-order diffraction efficiency of PB optical elements can be achromatically high, ~100% over the whole visible spectrum, using multi-twist method [5] in the axial

direction. However, at oblique incidence, the multi-twisted LC structure may significantly reduce the first-order diffraction efficiency. Although it is possible to achieve ideal spectral and angular bandwidth theoretically, such as adding a C-plate, the fabrication processing would be too demanding to match the simulation perfectly.

To reduce the ghost images from the PBL, a circular polarizer is implemented after the PBL to block the zero-order leakages. A similar issue is the distinction ratio of the circular polarizer may decrease as the incident angle increases. In mobile virtual reality displays, the circular polarizers employed are expected to have not only large spectral and angular bandwidth for reduced ghost image but also high transmittance for a sufficiently high light efficiency.

4 CONCLUSIONS

We have designed and demonstrated a prototype VR display system with significantly enhanced resolution and reduced chromatic aberrations using planar LC diffractive optics. We fabricated the key component in the prototype, ultra-broadband planar polymer deflector and lens employing Pancharatnam-Berry phase, manifesting high diffraction efficiency (>95%) over the display spectrum. Thanks to the low-cost manufacturing of the planar polymer deflectors and lenses and convenient additive adaptation from current VR devices, the proposed method and system should find potential utility throughout the near-eye display industry.

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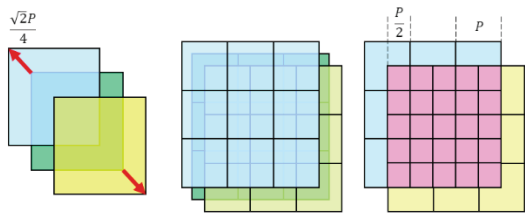

Fig. 1 Schematic diagram describing the principle of resolution enhancement by the shifted superimposition method.

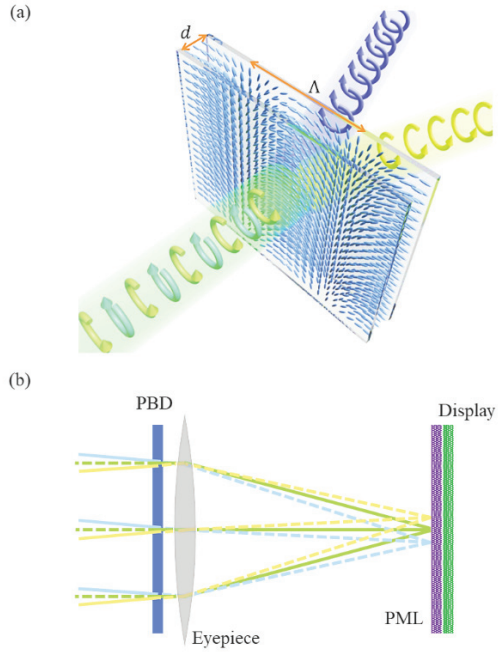

Fig. 2 (a) Illustration of orientation distribution of local liquid crystal anisotropy director in a polymer PBD. (b)Schematics of the resolution enhanced near-eye display prototype based on polarization multiplexing.

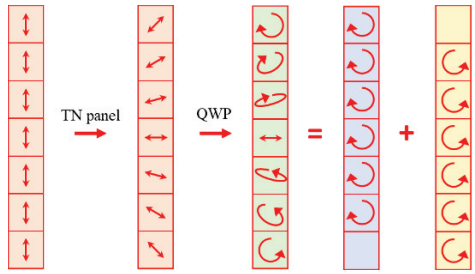

Fig. 3 Schematic illustration of the polarization modulation layer (PML).

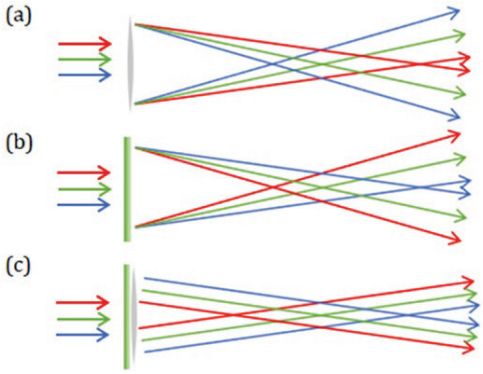

Fig. 4 Schematic illustrations of different dispersion scenarios: (a) positive chromatic dispersion in a refractive lens, (b) negative dispersion in a PBL, and (c) minimized dispersion in a compensated hybrid optical system.

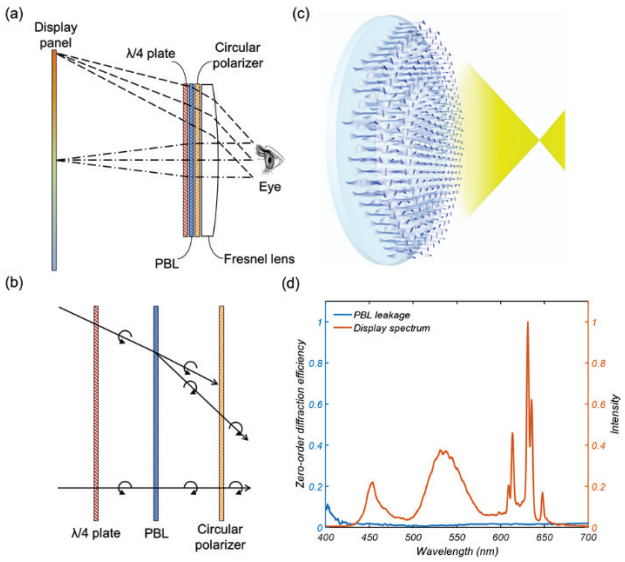

Fig. 5 (a) Experimental setup of virtual reality display system. (b) Schematic illustration of polarization handedness changes through the planar optical parts. (c) Complex liquid crystal orientation in the PBL for broadband high efficiency. (d) Measured spectrum of the PBL leakage and LCD white light spectrum.

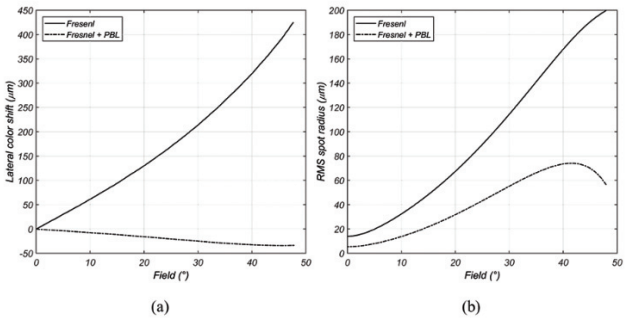

Fig. 6 Zemax analysis: (a) Lateral color shift and (b) RMS spot radius with and without PBL.

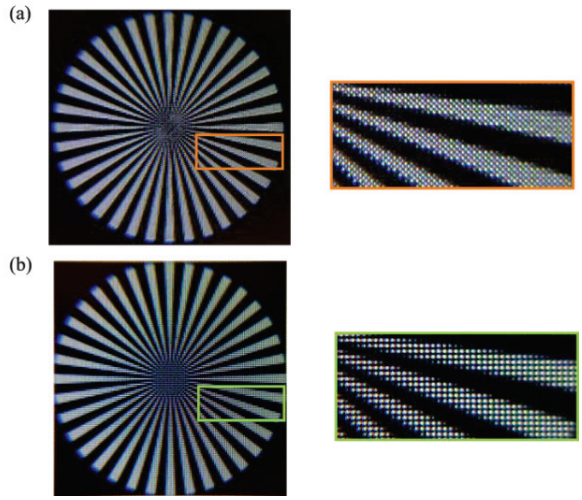

Fig. 7 Images captured through a camera with (a) original and (b) enhanced resolution of a "Siemens star" resolution target. The screen door effect is reduced, and the pixel density is doubled simultaneously.

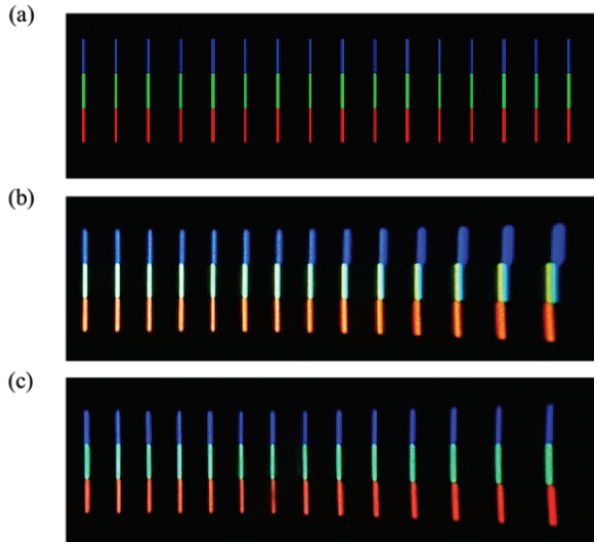

Fig. 8 (a) CA testing patterns displayed on the LCD and the resulting images captured through the (b) conventional and (c) proposed hybrid viewing optics with a PBL.