# Cost-Efficient Polymer Flat Lens for Chromatic Aberration Correction in Virtual Reality Displays

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## Abstract
***An optical chromatic aberration correction method for virtual reality displays is demonstrated. With a cost-efficient ultra-broadband liquid crystal flat lens based on the Pancharatnam-Berry phase, the proposed method can reduce the lateral color breakup by more than 10 times. Both simulation and experimental results are presented and discussed.***

## Author Keywords
liquid crystal device; chromatic aberration; virtual reality; near-eye display; Pancharatnam-Berry phase.

## 1. Introduction
Recent advances in virtual reality (VR) technology, enabled by high-pixel-density displays and powerful mobile processors, have provided unprecedented ability to immerse the user in a virtual world. VR has already demonstrated its ability to transform how people and businesses interact with each other and their environment. Despite how widely VR has been used for gaming, this technology is expanding to a plethora of applications, including but not limited to education, retail, and healthcare.

Although more than 10 million VR devices have been shipped since 2016, the imaging quality of current VR products is still not satisfactory when compared with that of the real world. Since compact and light-weight are always desired for head-mounted displays, currently only one singlet lens is employed in most of commercialized VR devices, making it quite challenging to keep a decent imaging performance within the whole field of view (FOV), which is usually >100° for an immersive impression [1]. As a consequence, fringes of color at the edges of objects can be clearly observed due to chromatic aberrations (CAs) at the margins of the displayed image. Even though the significance of this effect is dependent on the image content and users' gaze point, it is still preferable to prove chromatic aberration correction (CAC) for better user experience.

Digital CAC is usually utilized in current VR devices. With extra graphics computation, the perceived CA can be substantially reduced by means of image pre-processing [2]. The digital image compensations are applied to each color channel independently, employing different coefficients to each color channel. With correct subpixel implementation, the CA can be reduced appreciably. However, from the system perspective, the digital CAC still has several challenges and may compromise the display performance:

1. Sub-channel aberrations. There are a range of wavelengths within each color channel, and each part of it suffers from different lateral shift. Thus, digital CAC is for the peak wavelength, thus cannot correct the CA in each color channel. This impotency would put extra burden on display color accuracy.
2. Interpupillary distance (IPD) variation. Since the digital CAC is usually set for a fixed point in the eyebox, this method cannot offer the ideal correction for users with different IPDs.
3. Image rendering. Digital CAC would exaggerate the pressure for image rendering, which is already quite challenging for high-resolution and high-quality graphics in VR. To share the burden on the graphic processing unit (GPU), a new display processing unit (DPU) has been developed, dedicated to supporting CAC in VR [3].
4. Processing time. High framerate is usually required in VR devices for a small latency. The digital correction would occupy extra time in each frame, and it will be longer with a higher display resolution.

Therefore, the software-based digital pre-distortion is not an ideal solution to CA in VR displays at present. In this work, we demonstrate a hardware-based CAC approach using novel flat optics, a Pancharatnam-Berry phase lens (PBL) made of liquid crystal (LC) polymer that shows negative chromatic dispersion. After the hybridization of a plastic Fresnel lens and a PBL, the CA can be evidently reduced, as illustrated in Fig. 1. Firstly, the system configuration is determined by the sequential raytracing simulation. Then, the desired broadband LC lens is fabricated, characterized and then assembled with a plastic Fresnel lens as the achromatic viewing optics in our VR prototype. Finally, the CAC performance of the proposed system is experimentally evaluated, and its potential application in folded VR optics is also discussed.

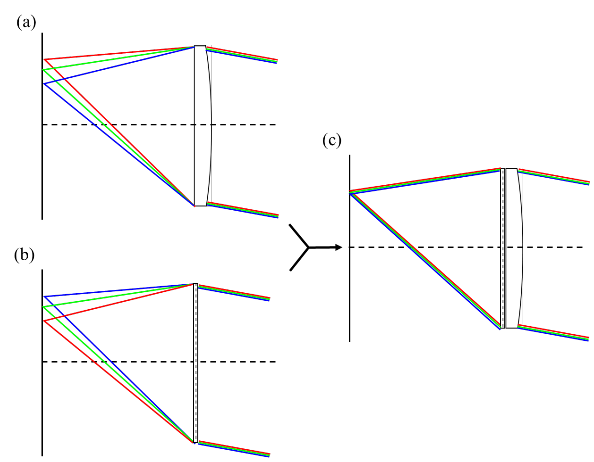


**Figure 1.** Illustration of transverse chromatic aberrations in a) a compact refractive Fresnel lens, b) a diffractive LC lens, and c) the proposed hybrid doublet exhibiting achromatic performance.

## 2. Design

***Liquid Crystal Flat Optics:*** The Pancharatnam-Berry phase optical elements (PBOEs) [4,5] proposed here can be understood as dielectric metasurfaces or patterned half-wave plates with in-plane spatial-rotating crystal axis, denoted as ψ(x,y). With circularly polarized input light, the according Jones calculus can be established as:

$$J_{out} = R(-\psi) W(\pi) R(\psi) J_{\pm} = -je^{\pm 2j\psi} J_{\mp}, \quad (1)$$

$$J_{\pm} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \pm j \end{bmatrix}, \quad (2)$$

where R(Ψ) is the rotation operation matrix, W(π) is the phase retardation matrix of the half-wave plate. $J_{\pm}$ stands for the Jones vector of left- and right-handed circular polarized (LCP and RCP) light. It is indicated that the half-wave plate provides not only a CP handedness conversion but also a ±2ψ(x, y) phase delay. If the in-plane LC azimuthal angle is aligned in a paraboloidal manner, then a lensing wave-front can be constructed to function as a PBL. Meanwhile, for a broadband application covering most display spectrum, a tailored axial molecule orientation should also be adopted, including a twist-homo-twist structure [6], as shown in Fig. 2. The first and third LC polymer layer should manifest a twist with opposite direction by doping chiral dopants with opposite handedness, while the second LC polymer layer is not twisted. This waveplate broadband operation principle was firstly proposed by Pancharatnam with stacked discrete waveplates with designed orientation angles between their optical axis [7], then extended to waveplate with continuously rotating optical axis using twist nematic LC cells [8] and multilayer LC polymer films [9,10]. The proposed three-layer sandwich-like structure should be able to cover most of the light spectrum of the LCD panel, which is around 430nm-680nm. Moreover, from the material perspective, polymerizable LC material with small or even negative birefringence dispersion is ideal for a reduced variation of retardation over the visible spectrums. However, these materials are relatively expensive for applications in large-volume consumer devices at this stage. Thus, in this work, our design is based on one of the most cost-effective LC material, RM257, although it has a relatively large birefringence dispersion.

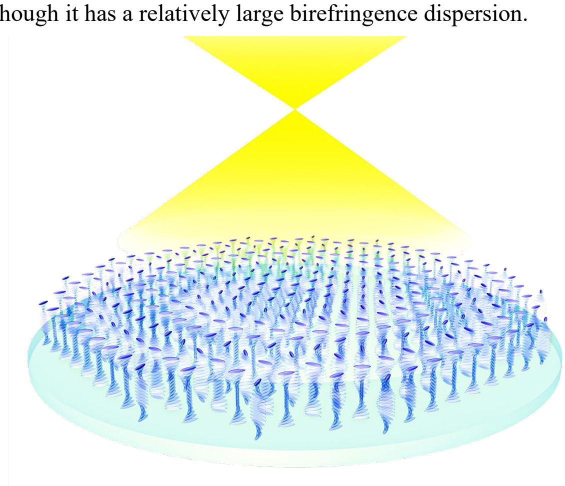

**Figure 2.** Schematic illustration of LC anisotropy axis orientation in the PBL with flat geometry and a twist-homo-twist structure for broadband operation.

***Optical Layout:*** The system configuration of the proposed VR viewing optics is presented in Fig. 3. Compared with conventional VR optics, our design only attaches three laminated flat optics parts, including a quarter-wave plate, a PBL, and a circular polarizer, adding negligible weight and volume to the existing system. The flat optical parts are attached to the Fresnel surface of the plastic lens for the convenience of alignment. Also, the PBL is placed between the display and Fresnel lens, where the angle of incidence is smaller than after the Fresnel lens, leading to a higher diffraction efficiency at PBL surface.

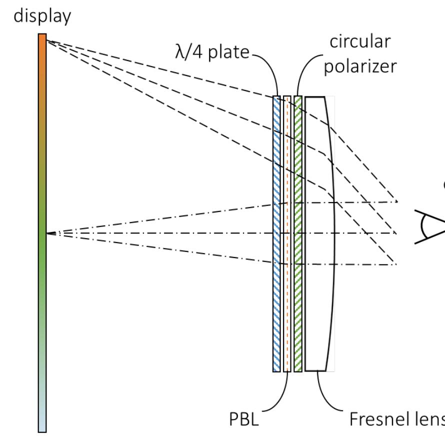


**Figure 3.** Optical layout of the proposed VR viewing optics.

Figure 4 illustrates the polarization changes through flat optical parts. The polarization state of the light from display panel is firstly converted from linear to circular polarization by the quarter-wave plate. After passing through the PBL, the polarization handedness of the first-order diffracted light would be switched while that of the zero-order leakage remains unchanged, as indicated in Eq. (1). To block the stray light from the PBL's zero-order leakage, especially from oblique incidence, a circular polarizer is inserted between the PBL and Fresnel lens. In this manner, only the desired diffracted light can pass through the imaging system and enter the eye. If light emitting from the display is unpolarized, such as micro-LED, then a polarization converter or a polarizer should be attached to the panel to keep the output linearly polarized. There is no denying that this may cut half of the light efficiency, but fortunately high brightness is not a necessity in VR displays.

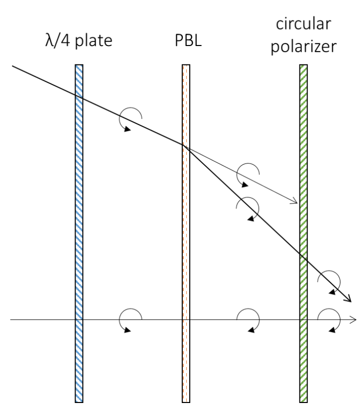


**Figure 4.** Illustration of polarization state changes through the planar optical parts in the proposed system.

***Ray-tracing Design:*** The optical power of the PBL needs to be designed for an optimized imaging performance with the Fresnel lens. Generally, similar to the design of an achromatic double [11], the following constraint should be satisfied:

$$\frac{K_{Fresnel}}{V_{Frensel}} + \frac{K_{PBL}}{V_{PBL}} = 0 \quad (3)$$

where K and V are the optical power and Abbe number of the optics. As a diffractive lens, the Abbe number of PBL is unique since it is equal to -3.45, no matter what kind of LC material it is made of. The Fresnel lens is made of polymethyl methacrylate (PMMA), whose Abbe number is 58. Thus, the optical power of PBL should be ~16 times smaller than that of the Fresnel lens. Then, sequential ray-tracing simulation and optimization are applied using OpticStudio™ from Zemax. The PBL is modeled as a holographic diffractive optical element with 100% first-order diffraction efficiency. Stray light generated by the PBL is not considered in this evaluation.

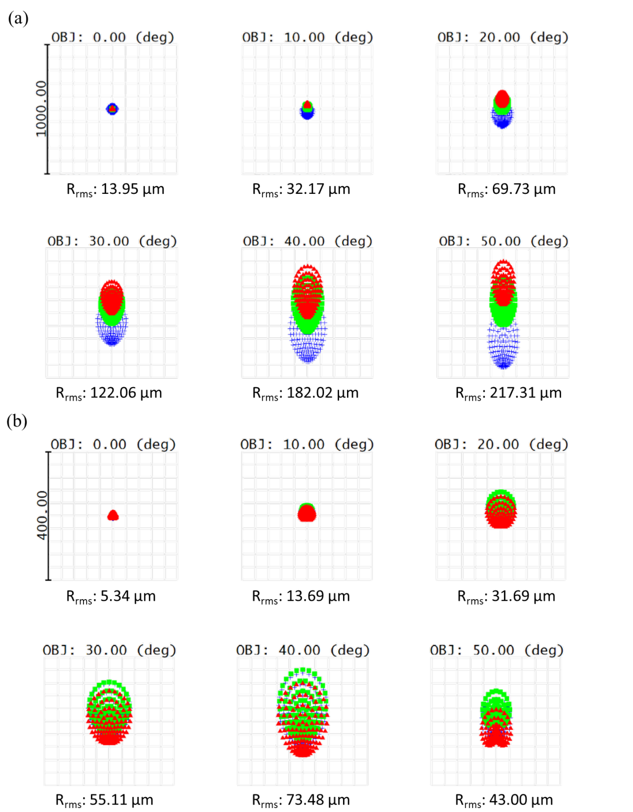


**Figure 5.** Standard spot diagram with RMS spot radius for (a) Fresnel singlet and (b) proposed hybrid optics. Color by wavelength, Red: 610nm, Green: 540nm, Blue: 450nm.

The polychromatic root-mean-square (RMS) spot radius of the Fresnel singlet and proposed hybrid optics are compared in Fig. 5. The three color channels are significantly separated when the field is larger than 30° in the Fresnel singlet VR devices. According to the simulated design, the proposed hybrid viewing optics can enhance the resolution by ~ 2.5 times, making the image much sharper from 0° to 50° field. At the 0° field, adding a PBL could make the RMS spot smaller than the according Airy disk, which is 5.6 microns in radius, making the whole system diffraction-limited at the center field of view. To quantitatively evaluate the CAC potential of PBL, lateral color shift is also calculated for the viewing optics with and without PBL compensation, as presented in Fig. 6. As expected, the PBL is able to shrink the color shift of the Fresnel singlet by > 10 times within the ±50° FOV.

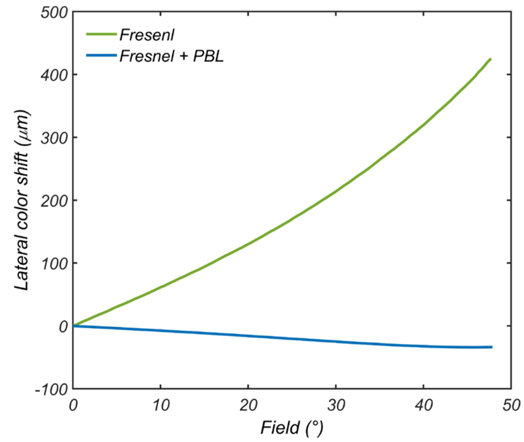


**Figure 6.** The lateral color shift of the VR viewing optics with and without PBL.

## 3. Implementation

The designed PBL is fabricated based on the photo-alignment method with multiple coating and curing processes. Firstly, a photo-alignment layer was created on a glass substrate by spin-coating a 0.2% solution of Brilliant Yellow (BY) in dimethylformamide (DMF) solvent. The designed lens profile with 2-inch diameter was encoded on the BY layer using polarization holography method to achieve the LC axis orientation pattern. Then, four LC mesogen layers were spin-coated on the aligned surface one by one, while each coated layer is crosslinked by UV light to form a solid surface and provide alignment for the next layer. The fabricated PBL shows clear image quality and wide spectral bandwidth, manifesting <3% zero-order leakage over the display spectrum of the LCD panel, as plotted in Fig. 7.

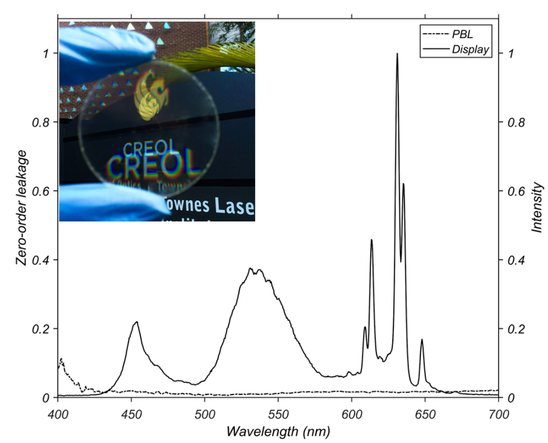


**Figure 7.** Measured zero-order leakage of the ultra-broadband PBL and the emission spectrum of the LCD displaying white light. Inside is a photo of the fabricated 2-inch PBL.

To demonstrate the CAC performance of the proposed hybrid lens, an image was displayed on the LCD screen without barrel distortion correction, which includes a set of evenly spaced bars with RGB segments, as plotted in Fig. 8. When viewing through the plastic Fresnel singlet, the test pattern bars are blurred, and the RGB colors are apparently displaced due to the transverse CA at peripheral FOV. When the proposed planar optics module, including a PBL sandwiched by a λ/4 plate and a circular polarizer, is attached to the Fresnel surface of the plastic lens, the color breakup at the periphery of FOV is significantly reduced. Fig. 9 shows another testing result with a black-and-white image. Utilizing the proposed optical building, the CA can be rectified at the expense of three planar optical elements without changing the compact form factor of the system.

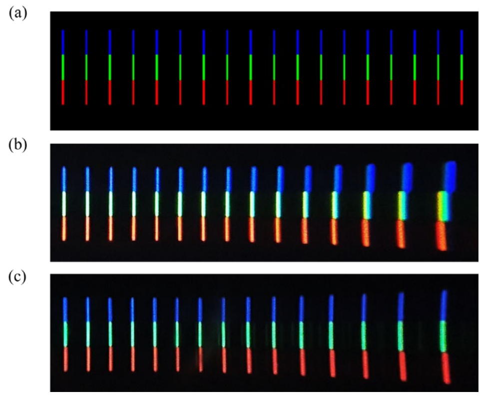


**Figure 8.** (a)Half-field CA testing pattern displayed on the LCD and the resulting images captured through the (b) conventional and (c) proposed viewing optics.

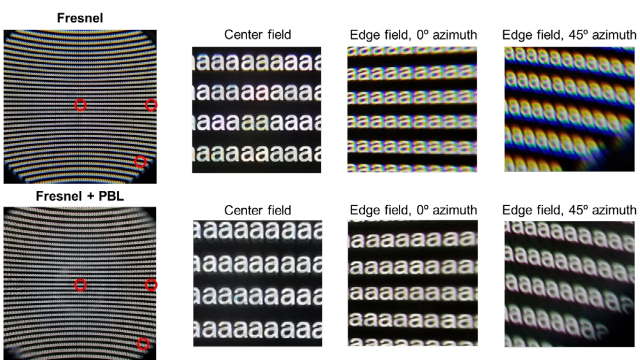


**Figure 9.** Full-field black-and-white image displayed on the LCD and the resulting images captured through the conventional and proposed hybrid viewing optics. The three enlarged parts are center field and edge fields at 0° and 45° azimuth from left to right.

## 4. Discussion

Although the PBL is applied to offer optical CAC for a Fresnel singlet in this work, other VR viewing optics can also benefit from PBL, such as the folded pancake VR lens, as Fig. 10 depicts.

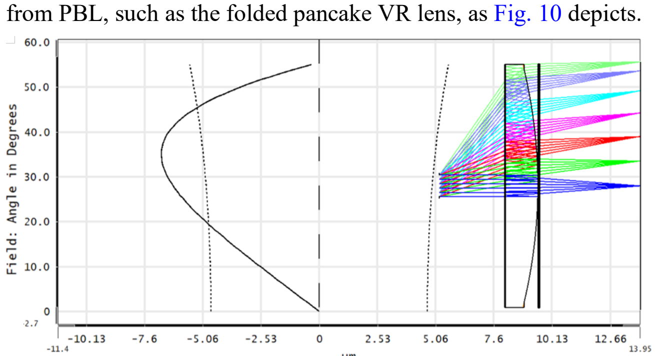


**Figure 10.** The lateral color shift of a pancake VR viewing optics with a PBL.

## 5. Impact

The proposed optical chromatic aberration correction approach provides a cost-effective hardware alternative to the conventional digital correction based on software rendering. The optical approach using flat optics is able to provide better imaging performance since it can correct the chromatic aberrations in each color channel, which is not achievable using digital correction. From the system perspective, the digital correction would put an extra burden on computation load, memory usage, and power drainage, while the optical approach just needs a flat polymer lens in the optical parts. Thus, the proposed system may benefit the future development of VR devices, offering better imaging quality while reducing the computation load and power consumption. Moreover, the proposed principle could also be applied to general imaging systems where chromatic aberration correction is desired.

## 6. Acknowledgments

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## 7. References

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