Achromatic Liquid-Crystal Diffractive Optical Elements for High-Efficiency Near-Eye Displays

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Abstract

Liquid crystal Pancharatnam-Berry optical elements (PBOEs) enable compact, efficient augmented and virtual reality displays but face chromatic aberration challenges. We propose a multi-twist narrowband PBOE structure to mitigate color crosstalk as validated by both experiment and simulation. Our approach significantly suppresses the chromatic aberration, offering design flexibility for RGB laser and quantum dot light sources.

Author Keywords

Near-eye display; Achromatic diffractive optical elements; liquid crystal planar optics.

1. Introduction

Near-eye displays have gained significant attention for delivering immersive experiences and enabling interaction between the virtual and real worlds, as seen in virtual reality (VR), augmented reality (AR), and mixed reality (MR). With the rising demand for wearable AR and VR devices, achieving lightweight and compact designs has become increasingly important. Liquid crystal Pancharatnam-Berry phase optical elements (PBOEs) are particularly promising due to their exceptional optical performance, including high diffractive efficiency, ultrathin form factor, strong polarization selectivity, and dynamic switching capabilities [1-2]. Despite these advantages, the chromatic aberration inherent to PBOEs poses a big challenge to their applications using RGB light sources.

One straightforward solution to mitigate chromatic aberration involves laminating PBOE films onto a refractive lens, leveraging their opposite dispersion characteristics [3-4]. However, this approach results in a bulky and heavy system. To address this issue, planar optical elements have been explored. For instance, switchable PBOEs operating on RGB frames in a color-sequential display can reduce the chromatic aberration [5-6]. However, this method requires high frame rates for both the PBOEs and display panels to avoid color breakup. Another approach is to stack multiple PBOEs or combine PBOEs with half-wave plates (HWPs). For example, chromatic aberration can be mitigated when RGB lights sequentially pass through a broadband PBL, a blue HWP, and a blue-red PBL [7-9]. Nevertheless, these achromatic systems often suffer from a reduced optical efficiency, limited design freedom for different wavelengths, and ghost images due to limited spectral bandwidth, leading to color crosstalk. To overcome these limitations, a new approach combining homogeneous LC layers with ultrathin twisted LC layers has been developed [7]. This method allows the optical axis of each homogeneous layer to adopt a different azimuthal angle, enabling narrowband performance. However, it requires a relatively large $d\Delta n$ (≈2.8 μm) LC film for each color, where d is the LC layer thickness and Δn is the LC birefringence. This complexity increases the fabrication challenge, exacerbates color crosstalk, and results in significant optical losses and ghost images.

To address the abovementioned issues of chromatic aberration in PBOEs, here we propose a counterintuitive multi-twist structure to achieve narrowband achromatic PBOEs, as opposed to traditional broadband designs [10-13]. The multi-twist structure is optimized using Rigorous Coupled-Wave Analysis (RCWA) to minimize the crosstalk for RGB light sources. Based on this design, narrowband Pancharatnam-Berry lenses (PBLs) were fabricated, showing an excellent agreement between experimental results and RCWA simulations. The achromatic performance of these narrowband RGB PBLs was validated using a laser projector, demonstrating a significant reduction in chromatic aberration compared to a broadband PBL system. Furthermore, to confirm the design flexibility for achieving narrowband PBOEs at any RGB wavelengths with high contrast, polarization raytracing was conducted in OpticStudio using both laser projector and quantum dot light-emitting diodes (QD LEDs). This approach offers high optical efficiency, reduced fabrication complexity, and exceptional design freedom, paving the way for widespread applications of achromatic PBOEs.

2. Working principles

Unlike refractive optics, which rely on optical path differences to create desired phase patterns, LC-based PBOEs consist of spatially patterned HWPs with LC axes oriented in varying azimuthal directions, as illustrated in Fig. 1(a). Specifically, spatial phase patterns can be introduced into HWPs via holographic methods, forming PBOEs. Taking the PBL as an example, it exhibits a strong polarization selectivity. For instance, a PBL could converge with a right-handed circularly polarized (RCP) light while diverging the left-handed circularly polarized (LCP) light, or vice versa. This unique feature enables versatile applications through appropriate design. However, the relationship between the incident wavelength ($\lambda_{R,G,B}$) and the corresponding focal length ($f_{R,G,B}$) is governed by:

$$\lambda_R f_R = \lambda_G f_G = \lambda_B f_B. \tag{1}$$

Eq. (1) implies that chromatic aberration is inherent when the incident light is polychromatic.

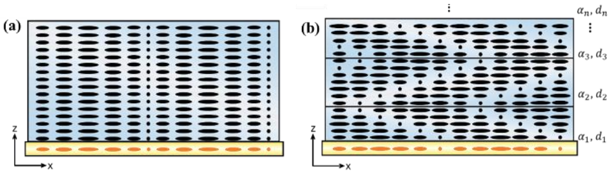

Figure 1. Working principles of PBOEs. (a) Planar LC structure of a general PBOE. (b) Chromatic aberration in a broadband PBL.

To suppress or eliminate chromatic aberration, three narrowband R/G/B PBLs are designed, each optimized to focus red, green, or blue light with the same focal length. However, when the RGB light simultaneously passes through the stacked PBLs, crosstalk occurs. To effectively reduce crosstalk, a multi-twist narrowband structure is proposed, where each layer is designed with specific twist angle α_i and thicknesses d_i, as shown in Fig. 1(b). For instance, the red PBL focuses only on red light while allowing green and blue light to pass through unaffected. This ensures that RGB incident light is focused onto the same focal plane by the narrowband PBL combination. During the design and optimization process, the twist angles and thicknesses of each layer are fine-tuned to achieve the

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desired phase retardation for each color. As a result, narrowband multi-twist structure PBLs without crosstalk could be achieved and extended to other spatial patterns for various applications.

3. Results and Discussion

For comparison, three narrowband R/G/B PBLs are designed for the wavelengths of 445 nm, 520 nm, and 639 nm, validated through both experiments and simulations. The LC material used has a birefringence of $\Delta n = 0.123 + \frac{10990}{\lambda^2}$. The lens pattern is recorded using a Mach-Zehnder interferometer. Following exposure, reactive mesogen RM257 is repeatedly spin-coated and cured with UV light to fabricate the layers. The fabricated R/G/B PBLs exhibit focal lengths of 87.3 mm, 87.8 mm, and 87.3 mm, respectively. Their spectral performance is measured by placing the samples between two circular polarizers, and the results are compared with optimized simulation data in Fig. 2. Overall, the experimental results show strong agreement with simulations, demonstrating high diffractive efficiency at the respective R/G/B wavelengths. Minor mismatches are attributed to discrepancies in the twist angle and layer thickness during fabrication.

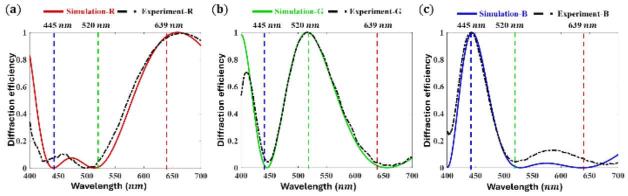

Figure 2. Simulation and experimental spectrum of (a) red PBL, (b) green PBL, and (c) blue PBL.

To investigate the achromatic performance of the three narrowband RGB PBLs, experiments were conducted using a laser projector for imaging, and the corresponding spectra were measured for comparison. The working principle of each narrowband R/G/B PBL is illustrated in Fig. 3(a-c). Each PBL functions for its respective color, with experimental images shown in Fig. 3(a-1), (b-1), and (c-1). For instance, the R PBL converges red light from the laser projector, resulting in the smaller "PBL" image in red, as seen in Fig. 3(a-1). Green and blue light pass through without divergence, as indicated by the larger "PBL." This behavior is similarly observed in the G PBL and B PBL. To reduce chromatic aberration in the full-color system, the narrowband R/G/B PBLs are combined, as shown in Fig. 3(d). The white "PBL" indicates that R/G/B colors from the laser projector are focused onto the same plane and merge effectively. However, weak chromatic aberration arises from the weak crosstalk between the R/G/B PBLs and the mismatch in focal length due to glass substrate thickness. For comparison, the schematic of a broadband PBL is shown in Fig. 3(e), where the focal length depends on the incident wavelength (Eq. 1). This results in the R/G/B color images being focused on different planes, as shown in the experimental image in Fig. 3(e-1). The chromatic aberration in the combined narrowband PBL system (Fig. 3(d-1)) is almost imperceptible compared to that in the broadband PBL system (Fig. 3(e-1)).

Overall, the narrowband PBLs were successfully fabricated, and their achromatic performance was experimentally validated using a laser projector. However, due to the limited thickness and birefringence of RM257, the contrast ratio remains relatively low.

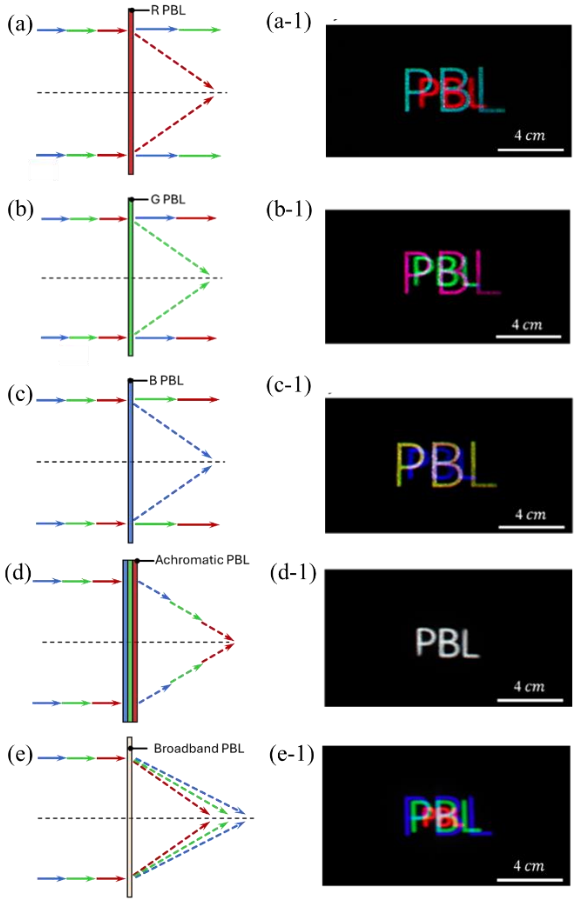

Figure 3. Optical response of the incident RGB lights to a (a) red PBL, (b) green PBL, (c) blue PBL, (d) a stacked narrowband RGB achromatic PBL and (e) a broadband PBL. Corresponding experimental results of (a-1) red PBL, (b-1) green PBL, (c-1) blue PBL, (d-1) a stacked narrowband RGB achromatic PBL and (e-1) a broadband PBL.

To maximize the potential of the multi-twist structure for designing narrowband PBOEs and achieving full achromatic performance, we optimized thicker narrowband PBOEs with RM257, achieving a contrast ratio exceeding 500:1 for RGB wavelengths at 464.5 nm, 527 nm, and 633 nm. Notably, there are no restrictions on the choice of RGB wavelengths or the birefringence dispersion of LC materials. The spectra of the high-contrast narrowband PBOEs were simulated using the RCWA model, as shown in Fig. 4(a-c).

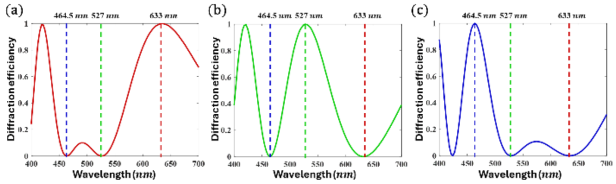

Figure 4. Spectral response of the designed narrowband PBLs with high contrast ratio. Spectra of (a) the red PBL, (b) the green PBL, and (c) the blue PBL with RCWA simulations.

The optical performance of the achromatic PBOE system was further analyzed through polarization ray tracing in OpticStudio (Ansys Zemax). Using a Pancharatnam-Berry phase deflector (PBD) as an example, the optical characteristics of the PBD were generated by the RCWA model and compiled into a dynamic-link library (DLL) file, which was then linked to OpticStudio operating in non-sequential mode. After a ray hits the PBD in OpticStudio, RCWA is invoked through the DLL to calculate and provide the return data [14]. The relationship between horizontal period of R/G/B PBD (Λ_{xR}, Λ_{xG}, and Λ_{xB}) and incident wavelength is shown as following equation:

$$\frac{\lambda_R}{\Lambda_{xR}} = \frac{\lambda_G}{\Lambda_{xG}} = \frac{\lambda_B}{\Lambda_{xB}} \tag{2}$$

which should be satisfied to eliminate chromatic aberration.

For comparison, the white light D65 spectrum from the laser projector is shown in Fig. 5(a), composed of R (464.5 nm), G (527 nm), and B (633 nm) with a power ratio of 1:1.22:1.70. The images from stacking narrowband RGB PBDs and broadband PBDs are compared in Fig. 5(c) and Fig. 5(e). Chromatic aberration is effectively eliminated by stacking narrowband RGB PBDs when the laser projector serves as the light source. Additionally, RGB QD-LEDs with specific bandwidths were also used to verify the performance of stacking narrowband RGB PBDs. The spectrum of RGB quantum dot LEDs is shown in Fig. 5(b). The image in Fig. 5(d), from stacking RGB PBDs, shows effective chromatic aberration reduction compared to the broadband PBD in Fig. 5(f). However, weak chromatic aberration remains, stemming from the correction method for chromatic aberration. Since the R/G/B narrowband PBOEs are designed for specific R/G/B wavelengths, chromatic aberration persists due to the bandwidth of the LED. Overall, using a narrower bandwidth light source helps to further suppress chromatic aberration.

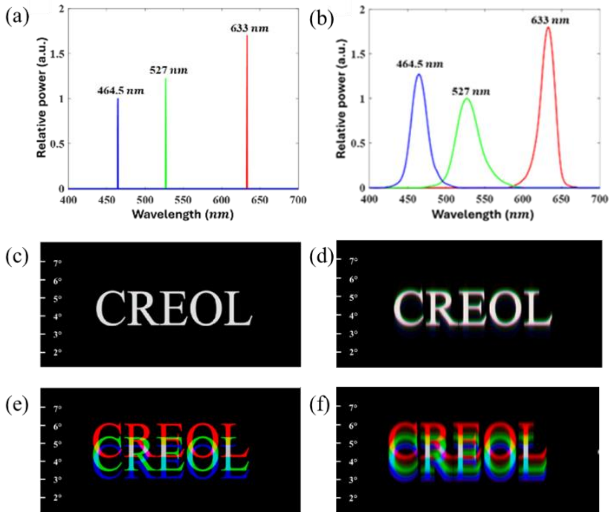

Figure 5. Polarization raytracing of an achromatic PBD using three narrowband PBDs with high contrast ratios. (a) Spectrum of an RGB laser projector. (b) Spectrum of the RGB QD LEDs. (c) Image in an achromatic PBD system with the laser projector. (d) Image with a nearly achromatic PBD system using the RGB QD LEDs. (e) Image with a broadband PBD system using a laser projector. (f) Image with a broadband PBD system using the RGB QD LEDs.

In addition, the design and optimization of the proposed PBOEs can be seamlessly extended to other achromatic optical systems. The narrowband stacking system achieves nearly 100% optical efficiency, significantly reducing stray light and ghost images. Moreover, the multi-twist narrowband PBLs and PBDs can be adapted to other spatial patterns, expanding their versatility. Notably, for short-pitch general PBDs, the angular response often shifts away from normal incidence due to stringent phase-matching requirements [15]. By optimizing the multi-twist structure, the angular response of short-pitch PBDs can be effectively aligned back to the normal incidence angle, enhancing their performance and applicability.

4. Conclusion

A novel multi-twist structure for narrowband PBOEs with high efficiency, compact formfactor and without crosstalk is proposed and analyzed in both experiment and simulation. This narrowband RGB structure dramatically suppresses the chromatic aberration for a laser projector and quantum dot light-emitting diodes.

5. References

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