Liquid Crystal Optics for AR/VR/MR Near Eye Displays

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Abstract

Liquid crystal optics are highly favorable for AR/VR/MR near-eye displays because of the capability of modulating polarization and phase in an ultra-compact profile. In this presentation, we discuss state-of-the-art LC polarization hologram solutions for AR/VR/MR display technical needs, followed by remaining challenges and opportunities in the way towards high-image-quality and all-day-wearable near-eye displays.

Author Keywords

Liquid crystal; polarization hologram; full-color optics; AR/VR/MR; waveguide; pancake optics; steered retinal projection.

1. Introduction

Augmented reality/Virtual reality/Mixed reality (AR/VR/MR - XR) near-eye displays (NEDs) are envisioned as the next generation information display platform. They are expected to offer excellent image quality, daily wearable comfort and safety within an affordable budget. LC diffractive optics reduces the package size and lowers the weight of XR devices by replacing geometrical lenses and mirrors and doubles the design space by the polarization multiplexing of different optical paths. Moreover, the low fabrication cost makes LC optics especially attractive.

2. LC Optics Working Principles

Liquid crystal (LC) elements modulate light by the spatial and temporal variation of refractive indices and birefringence. Figure 1 summarizes the light modulation of LC optics, where the blue rays and the red rays stand for opposite circular polarization (CP) states or opposite linear polarization (LP) states, except for representing the color of light in the Full-color LCPH block.

Polarization Switcher: An active LC layer can modulate polarization as a switchable half-wave plate (sHWP): it keeps the incident polarization or flips the polarization to the opposite in response to the external voltage.

Polarization Selective LC Polarization Hologram (LCPH): A LCPH element modulates light according to the incident polarization. Figure 1 and the following discussion are based on 1D gratings for illustration purposes, while the actual element can be made as a lens or with a freeform pattern.

Transmissive PBP/tPVH. A Pancharatnam-Berry phase (PBP) grating typically has a HWP thickness that flips the incident CP; the incident light in left-handed (LH) CP and right-handed (RH) CP are transmitted to the +1st order and the -1st order, respectively. On the contrary, a transmissive polarization volume hologram (tPVH) grating has an asymmetric LC volume patterning, which only deflects one CP to the 1st transmissive order and flips the CP.

Reflective CLC/rPVH. A cholesteric liquid crystal (CLC) reflective polarizer (RP) or a reflective polarization volume hologram (rPVH) grating reflects light in one CP in the Bragg reflection wavelength range and transmits the else. Ideally, the transmitted light and the reflected light remain in their respective incident CP.

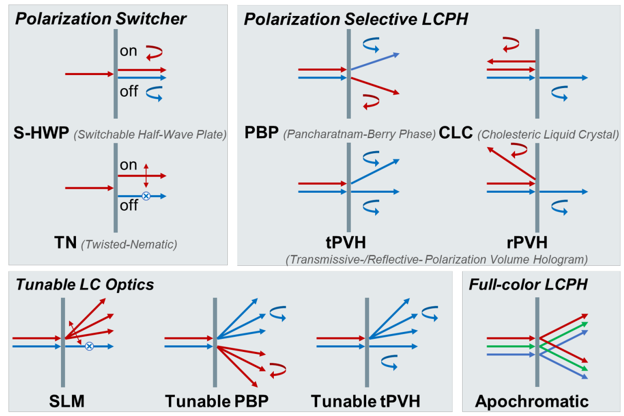

Figure 1. Polarization response of LC optics.

Full-color LCPH: For full-color XR displays, two LCPH design goals are high efficiency and the same diffraction angle for R/G/B.

Broadband CLC/rPVH by gradient pitch stacking. According to $\Delta\lambda_{Bragg} = \Delta n \cdot P_{Bragg}$, we can widen the Bragg reflection band ($\Delta\lambda_{Bragg}$) by increasing the LC material birefringence (Δn) and stacking layers with various Bragg pitch (P_{Bragg}). To be noticed, the structure in Fig. 2(a) with various P_{Bragg} only improves the diffraction efficiency over a broader spectral range. As long as the layers share the same surface pitch, R/G/B colors are diffracted to different angles.

Broadband PBP/tPVH by twist and compensation. The simple PBP/tPVH design only works in a limited wavelength window and angular cone where the HWP condition is met. The work window can be enlarged by introducing polarization rotation effect through LC twist along the thickness and by adding a compensation layer. For example, the PBP structure in Fig. 2(b) having a positive A-plate sandwiched between two symmetric twisted nematic (TN) layers can offer >99% diffraction efficiency over the visible wavelength range provided proper anti-reflection coating. The "PBP white" in Fig. 3(b) represents such broadband PBP.

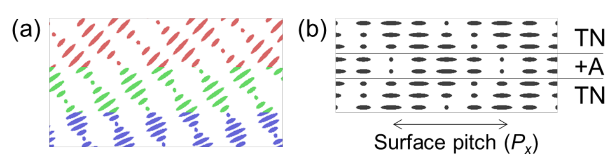

Figure 2. (a) Broadband rPVH. (b) Broadband PBP.

Address angular dispersion by color selective PBP/tPVH. Independent R/G/B control solves the angular dispersion issue of grating diffraction. Two methods can separate the R/G/B channels. The first is to make R/G/B color selective layers; each layer is a HWP for one color while a full-wave plate (FWP, with an integer-wave effect) for the other two colors. Such function can be achieved by LC materials with customized dispersion. Taking the "green" layer in Fig. 3(a) as an example, if the R/G/B birefringence (Δn_R, Δn_G and Δn_B) at wavelength (λ_R, λ_G and λ_B) meet the condition $\Delta n_R/\lambda_R : \Delta n_G/\lambda_G : \Delta n_B/\lambda_B = 2 : 1.5 : 1$, such a layer with thickness = $1.5\lambda_G/\Delta n_G$ functions as a HWP for green light as well as a FWP for red light and blue light. In other words, a PBP/tPVH grating made of such a material is color selective that deflects green light while maintaining the direction and polarization of red light and blue light. Similar method can make a color selective waveplate (WP). For instance, the "WP green" layer in Fig. 3(b) is a FWP for green light while a HWP for red light and blue light. The second approach to make a color selective WP/PBP is to adopt multilayer structures where each layer can be a +/- A-plate, a +/- C-plate or a twisted nematic layer; the multilayer interference gives a HWP effect for one or two colors while a FWP effect for the other color(s).

Figure 3 shows two designs for apochromatic PBP/tPVH that diffracts narrowband R/G/B wavelengths to the same angle. Figure 3(a) shows the first design that stacks R/G/B color selective PBP; each PBP has a distinct surface pitch ($P_x = \lambda_{R/G/B}$ / $\sin\theta_d$) calculated by the target diffraction angle (θ_d) and the wavelength (λ_R, λ_G and λ_B). Figure 3(b) shows the second design that combines color selective WPs with broadband PBPs; the WPs give R/G/B light distinct CP states to determine the steering direction on the following PBP; the PBPs have surface pitches calculated to make the same net steering angle for R/G/B light.

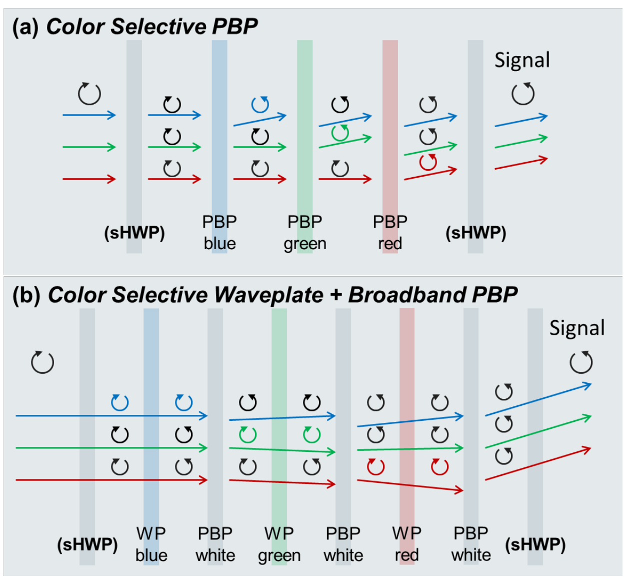

Figure 3. Two designs of full-color transmissive LCPH.

Switchable LCPH: Switchable LCPH elements are made by active LC materials; an electrical field can erase the hologram pattern and turn off the polarization selectivity. Making active full-color LCPH is challenging because the additional substrates between active layers destroy the multilayer interference. Alternatively, we can use a sHWP to switch the incident polarization to indirectly control the steering, and add a sHWP after the stack to reset the output polarization for ghost clean-up purposes, as shown in Fig. 3. Stacking multiple switchable elements can also do multistate steering/focusing.

Tunable LCPH: Stacking switchable elements for multistate steering/focusing is expensive in volume, power consumption and cost, which calls for tunable LCPH where a single element supports (semi)continuous steering. Such a LCPH element can be a spatial light modulator (SLM) or a PBP/PVH grating.

SLM for LP incidence. The SLM pixel size limits the maximum beam steering angle or the display FOV. Taking 30°-diffraction at wavelength λ = 500 nm as an example, the phase period λ/sin(30°) = 1 μm demands a 500-nm pixel size assuming two pixels per period. It is extremely challenging to make phase LCoS with sub-μm pixel pitch because the interpixel crosstalk of the electric field gives rise to LC orientation crosstalk. Additionally, the optical diffraction effect becomes strong when the pixel size is approaching wavelength.

Heliconical CLC for CP incidence. The change of steering angle or optical power must require the change of surface pitch, making heliconical CLC a unique candidate. Heliconical CLC is made of LC materials whose ratio of bend elastic constant to twist elastic constant satisfies K33/K22 < 0.5 (such as CB7CB) and can show a rPVH-like structure with appropriate electric field. When the applied electric field is stronger than a critical value, the helical axis and the Bragg pitch can be respectively controlled by the direction of electric field and the strength of electric field. The main performance gaps of heliconical CLC are the slow response time (~second) and the limited polarization contrast caused by deformed helical structure.

3. LC Optics Applications in XR Displays

Waveguide Coupler: Waveguide (WG) AR displays use total internal reflection (TIR) within the substrate to guide the display light from the projector to the eyes. WG couplers – input grating, folding grating and output grating (IG/FG/OG) – have a net k-vector sum of zero that preserves the ray direction from entering to exiting the WG. Key challenges of WG AR are limited field of view (FOV), low optical efficiency, color uniformity and see-through defects.

Many technologies can be used to make WG couplers, such as the LCPH grating, the surface relief grating (SRG), the volume Bragg grating (VBG) and the geometrical reflector (GR). Among them, the LC rPVH grating offers high coupling efficiency by varying the slant angle, good color uniformity by varying the grating thickness, small form factor by stacking FG and OG on the same substrate, and low fabrication cost by the etch-free process.

FOV vs. refractive indices. The FOV window supported by a WG is determined by the lower value of the WG substrate refractive index (n_g) and the grating extraordinary refractive index (n_e). Figure 4(a) is a 1D pupil expanded WG for simple illustration. The single-color FOV is calculated by the propagation angle in the WG for the rightmost FOV (the blue ray) and the leftmost FOV (the green ray); the former is the air-substrate TIR critical angle $\theta_{c\_air\text{-}sub} = \text{asin}(1/n_g)$, and the latter is a reasonably large angle that balances the FOV range and the exit pupil density. When $n_e < n_g$, the coupling of the green ray can be suppressed when the propagation angle is larger than the grating-substrate TIR critical angle $\theta_{c\_grt\text{-}sub} = \text{asin}(n_e/n_g)$. As a result, the leftmost FOV is cut off by n_e instead of n_g. This calculation also applies to full-color WGs using color-selective VBGs and/or nondispersive GRs. On the contrary, on full-color WGs using broadband and dispersive couplers such as SRGs and LCPHs, R/G/B colors have distinct mapping between the FOV in air and the propagation angle in WG. Figure 5 shows that the full-color FOV (the overlap of R/G/B FOV) shrinks dramatically from the single-color FOV.

Active WG. The optical efficiency of a 2D pupil expanded WG is very low (typically 1~10%) due to multiple paths of loss, as denoted by the black rays in Fig. 4(a). Additionally, the OG can diffract environment light to human eyes which forms the annoying "rainbow" artifact. An active WG selectively turns on the IG/FG/OG region according to the FOV being displayed and the pupil location. As an example, only the grating region for the right FOV and the right pupil location is turned on in Fig. 4(b). Such dynamic control allows significant improvement of optical efficiency and color uniformity as well as reducing artifacts.

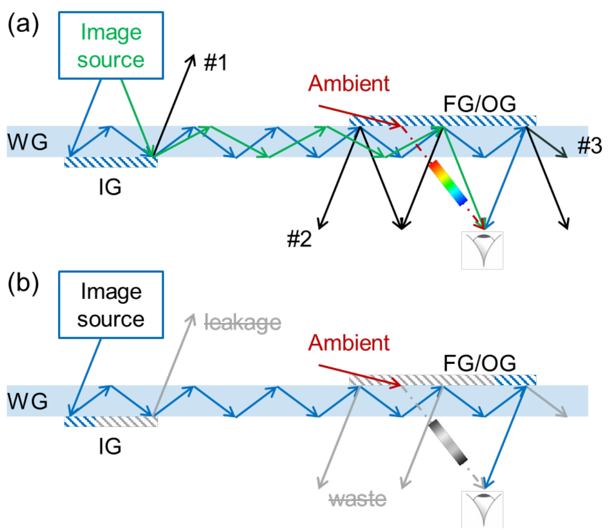

Figure 4. (a) WG AR with passive IG/FG/OG. (b) WG AR with active IG/FG/OG.

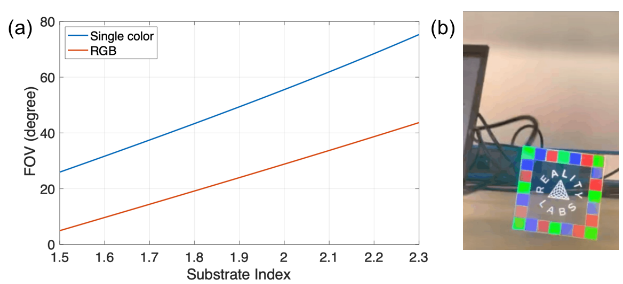

Figure 5. (a) WG FOV vs. substrate refractive index (n_g). (b) See-through and displayed image by a LCPH WG AR.

Pancake RP: Pancake VR/MR optics significantly reduces the optical system thickness, which uses a 50/50 mirror, a quarter-wave plate (QWP) and a linear RP to fold the optical path [1]. A CLC circular RP or a rPVH lens can replace the QWP and the linear RP [2]; the former features half the thickness of the linear RP, and the latter expands the design flexibility. Key challenges of Pancake VR are two folded. First, 75% optical efficiency is lost on the 50/50 mirror. Second, the off-axis polarization deviation causes ghost images and reduces signal efficiency.

Reflective Lens Combiner and Steering: Retinal projection AR uses an off-axis combiner to reflect the laser-formed microdisplay image to the eyes [3]. The off-axis combiner can be made by a rPVH lens or a holographic optical element. Due to etendue conservation, the small display size and the collimated beam make a small eye box. As shown in Fig. 6, active LC elements can solve the small eye box issue by steering the pupil from the projector side (#1) and/or on the combiner side (#2). Aberration is another issue of retinal projection AR. The off-axis combination leads to an optical path difference between the left FOV and the right FOV. Correcting the resulting astigmatism aberration for all pupil locations needs a volume-taking lens set, calling for LC flat optics for form factor reduction and/or a SLM microdisplay for active aberration correction.

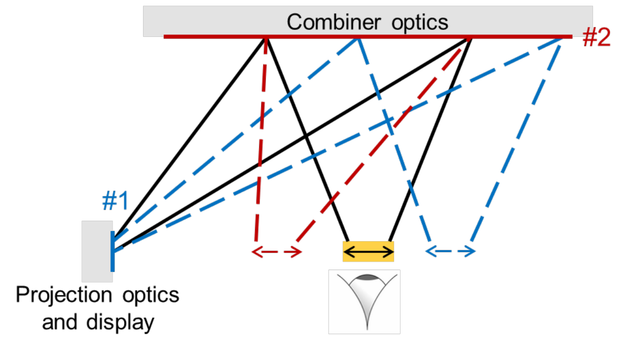

Figure 6. Retinal projection AR with pupil steering.

4. Prospectives and Opportunities

High Refractive Index LC: As discussed in Section 3, n_e of the coupler limits the FOV when it is notably lower than the substrate index. High n_e RM materials are highly desirable for WG AR. For example, n_e = 2.0 and 2.2 support ~50° and ~60° single-color FOV, respectively.

Polarization Maintenance: While Section 2 describes the ideal polarization modulation, the polarization deviation on practical elements causes signal efficiency loss and ghost/leakage, which is crucial for the low-efficiency Pancake VR and WG AR as well as the off-axis combined Retinal projection AR.

Waveplate effect of CLC. Out of the Bragg reflection band and the responsive CP, a CLC RP composed of traditional rod-like molecules ("-C CLC") functions as a negative C plate. Because the effective refractive index along the helical axis ($n_{axis} = n_o$) is lower than that in the helical plane ($n_{in\text{-}plane} = \frac{1}{2\pi}\int_0^{2\pi}\sqrt{(n_e^2\cos^2\phi + n_o^2\sin^2\phi)}\,d\phi$). Figure 7 clearly shows the polarization modulation agreement of a -C CLC and a -C plate for the red light passing through a blue narrowband CLC. A broadband and wide view CLC must be thick, making it vulnerable to the polarization deviation on such a thick "-C plate". Taking the broadband CLC in Fig. 8 as an example, only the high reflection band overlap of the yellow solid line region and the yellow dashed lines region work for R/G/B wavelength and 0~30° angle of incidence (AOI). If we consider the broadband CLC as a stack of R/G/B narrowband CLC layers, the B/G layers partially change the CP of the 30° incidence red light and disable the full reflection on the red CLC layer, which can be observed as the reflection efficiency drop on the yellow dashed lines at 550~650 nm.

"Isotropic" CLC/rPVH. An "iso CLC" with isotropic effective refractive index ($n_{axis} = n_{in\text{-}plane}$) can maintain the polarization out of Bragg band (as shown by the red solid line in Fig. 7) for broadband and wide-view high reflectance (as shown by the red dashed lines in Fig. 8). Such "iso CLC" can be made by using novel LC materials exhibiting isotropic index profile after self-assembling, by adding a tilt angle towards the helical axis to increase the n_{axis} from n_o and to reduce $n_{in\text{-}plane}$, or by stacking self-compensating A/B/A/B layers where "A" can be "-C CLC" layers made of rod LC molecules and B can be "+C CLC" layers made of disc LC molecules.

"Isotropic" rPVH. Such isotropic effective refractive index has a more significant improvement on rPVH performance. Because rPVH has an inherent large angle between the incident/transmitted/reflected light and the helical axis, causing severer polarization deviation. For example, a 70° off-axis rPVH reflector loses >20% efficiency on polarization deviation, which can be mostly restored by an "iso rPVH".

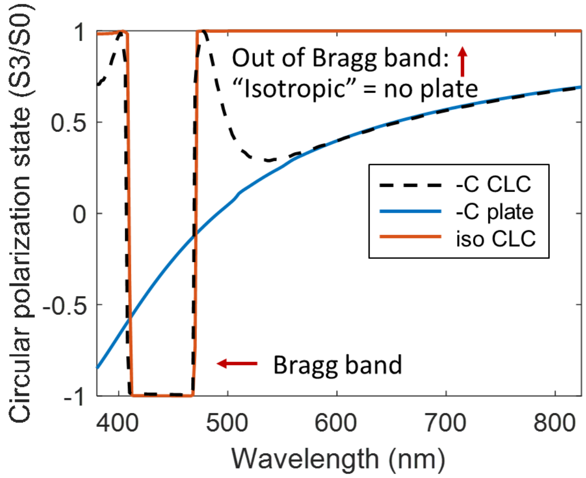

Figure 7. CP state of the transmitted light through a blue narrowband RH CLC layer. The incident light is in RH CP state with S3/S0 = 1.

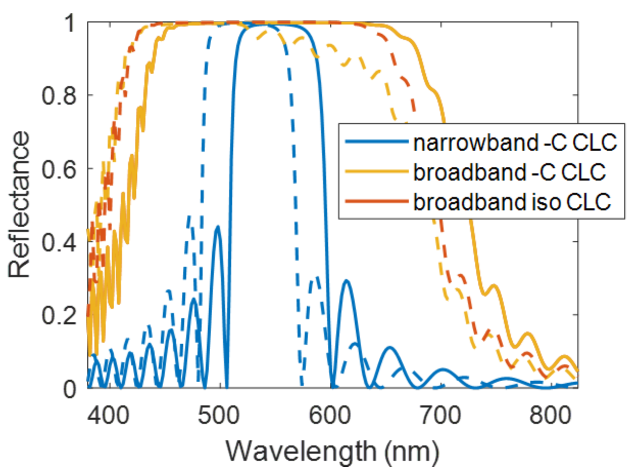

Figure 8. Spectral reflectance of RH CP incident light on a RH CLC RP. Solid lines stand for normal incidence and dashed lines represent 30° incidence.

Active LC: Switchable and tunable LC components are highly useful if the following technical blocks are developed well.

Highly transparent electrodes. Indium tin oxide (ITO) electrodes have good transparency for light to pass twice. However, light needs to pass the electrode layer for 100s times on an active WG, making the active grating electrode absorption very critical. For example, 0.1% absorbance on the electrode means 20% efficiency loss after 100 passes. On the other hand, pupil steering and varifocal lens using switchable elements stack a bunch of electrodes. Taking 6 active layers with 12 electrodes as an example, 4% efficiency cut per layer means ~40% efficiency loss in total.

Fast response LC materials and novel modes. A few ms response time is critical to fit in the display frame time (e.g., 10 ms for 100 fps). And active WGs need faster-responsive gratings to follow the FOV scanning within each frame. Also, identifying LC modes such as heliconical CLC with tunable surface pitch is highly impactful, which can significantly reduce the number of active layers for multistate manipulation to benefit pupil steering, accommodation and dimming.

Non-XR Applications: LCPH optics open up the application space beyond XR displays. For miniaturized optical systems, LCPH flat optics enables high *f*/# lens designs without suffering from field curvature aberration. Additionally, the negative dispersion of LC diffractive optics can compensate for the positive dispersion of refractive optics materials, which dramatically reduces the size and weight of imaging systems keeping the same chromatic aberration criteria.

LCPH optics can be applied as a high-performance solution for 3D imaging and sensing such as medical imaging, Lidar and machine vision. The strong diffractive dispersion enables single-shot depth imaging by wavelength multiplexing; each wavelength extracts the image at one of the depths or spatial samplings. The polarization selective response of LCPH makes it a high efficiency thin-film interference generators for structured light illumination in depth sensing. It also works for polarization imaging and phase imaging.

Polarization Patterning for Mass Production: LCPH elements are fabricated by coating a RM film on a photoalignment layer with spatially varying polarization patterning. Various polarization patterning techniques have been proved [4]. While direct photo-patterning methods (direct writing freeform patterns and two-beam interference) generate high quality patterns in a small area for lab use, duplication methods via a LC phase mask seem favorable for mass production for the advantages of large aperture size, fast patterning speed and flexible in-plane orientation profile. Especially, projection duplication projects the phase pattern from the mask plane to the sample plane through a lens set, which protects the mask from scratching and enables the clean-up of undesired diffraction orders.

Waveguide couplers have a surface pitch of 250~400 nm; each pitch (180° polarization rotation) needs 8~10 steps for high quality PVH forming. Such high resolution requires coherent light source and projection optics working at a UVA wavelength that can transmit the LC mask and induce photopolymerization on the recording sample. Developing such patterning tools will make a huge impact on the mass production of LCPH optics for XR and non-XR applications.

5. Acknowledgements

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