Fast-Switching Liquid Crystal Devices for Near-Eye and Head-Up Displays

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Abstract

Fast-switching liquid crystal Pancharatnam-Berry (PB) optical elements for near-eye and head-up displays are reviewed. A submillisecond-response PB deflector helps double the apparent resolution and enable foveated display with eye-tracking. A PB lens enables time- and polarization-multiplexed multi-focal-plane displays to overcome the vergence-accommodation conflict.

Keywords

Liquid crystal devices; near-eye displays; head-up displays.

1. Introduction

Displays beyond flat panels, such as near-eye displays (NEDs) and head-up displays (HUDs), can enhance the human-machine interface, making the information display process much simpler and more natural. However, some critical challenges remain to be overcome in these emerging displays, such as insufficient resolution and vergence-accommodation conflict. Here, we propose to address these issues and enhance the performance of near-eye and head-up displays with novel liquid crystal (LC) devices called Pancharatnam-Berry phase optical elements (PBOEs) [1], which are also referred to as diffractive waveplates [2] or geometric phase holograms [3]. Conventional optical elements function by the optical path difference, while PBOEs generate the desired phase profile by spatially varying the LC directors, as Fig. 1 depicts. Due to their high efficiency, polarization dependency and decent imaging quality, these promising functional PBOEs, especially the PB deflectors (PBDs) [4,5] and lenses (PBLs) [6-9], have been implemented in quite a few information display systems.

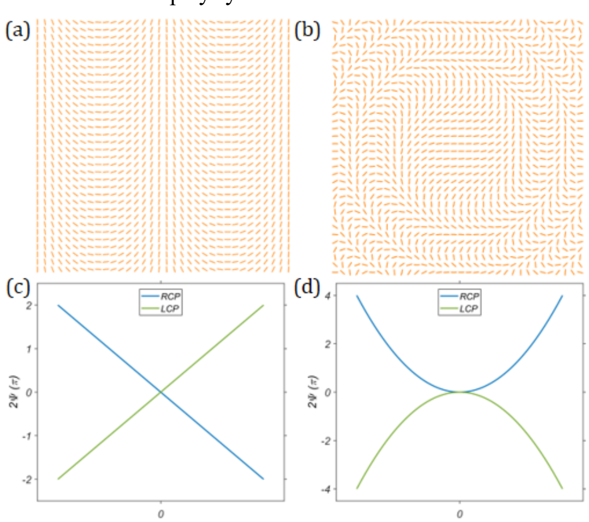

Fig. 1. Schematic distribution of LC anisotropy axis orientation in (a) a PB deflector and (b) a PB lens. The corresponding phase change of the (c) PBD and (d) PBL.

Since these transmissive PBOEs are half-wave plates, the handedness of incident circularly polarized light is converted after passing through. Also, the left- and right-handed circularly polarized (LCP and RCP) lights accumulate opposite PB phase for a single PBOE. If a PBL is converging with positive optical power for LCP, then it is a diverging lens with negative optical power for RCP. A PBD would also diffract light with orthogonal circular polarizations to opposite directions, as depicted in Fig. 2.

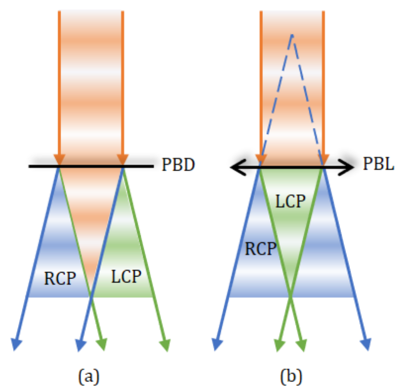

Fig. 2. Illustration of polarization dependency of PBOEs: (a) PBD diffracts RCP light to +1 order and LCP light to -1 order; (b) PBL serves as a diverging lens for input LCP light but a converging one for input RCP light.

Both active and passive switching of PBOE can be realized. For active switching, the PBOE is made of liquid crystal, while for passive switching it is LC polymer with a dynamic polarization rotator. The polarization switch can be a 90° twist-nematic LC cell with a $\lambda/4$ plate, such that the input linear polarization can be converted to LCP or RCP by demand. By controlling the polarization handedness of the incoming beam, the PBOE will function differently as Fig. 2 depicts. By designing the axial LC structure, the passive polymeric PBOEs can manifest broadband and high diffraction efficiency [6,7]. On the other hand, for active switching, the PBOEs are usually made with conductive transparent substrates, such as indium tin oxide (ITO) glass. By directly applying a voltage across the PBOE device, the LC directors will be reoriented from the patterned half-wave plate to homeotropic state, as illustrated in Fig. 3. The switching time is about 1 ms, depending on the LC material and cell gap.

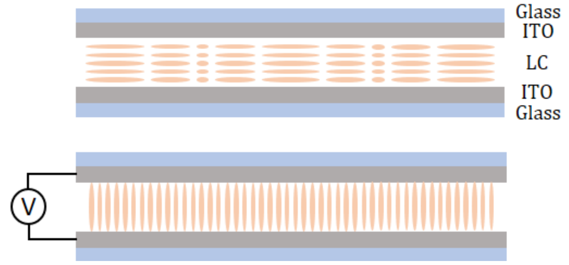

Fig. 3. Schematic illustration of PBOEs made of LCs sandwiched between transparent electrodes (upper) before and (lower) after dynamic switching.

2. PB Deflector

2.1 Pixel Density Enhancement

Although several near-eye displays have been developed rapidly in recent years, the visual experience is still not satisfactory in most commercialized virtual reality (VR) headsets. The main issue is the limited resolution. To satisfy the angular resolution of 20/20 vision, an angular pixel density of ~60 pixels per degree (PPD) is required, while the current VR headset can only offer ~15 PPD. The image quality degradation caused by this limited pixel density and the resulting apparent screen-door effect is annoying for VR users. To satisfy the human acuity and provide a 100° field of view (FOV), a display panel with 6K resolution is required for each eye. However, such high-pixel-density panels are challenging and costly in fabrication, driving and power consumption. Thus, simply adding more pixels to display panels is important but not an easy task for achieving high angular resolution in near-eye displays. Instead, we developed two optical technologies to enhance the resolution without changing the display panels.

The first attempt to enhance PPD is to use a switchable PBD to boost the pixel density without changing the physical pixel density of the display panel [10]. The PBD in the proposed near-eye display system works as a non-mechanical pixel shifter to double the apparent pixel density, as illustrated in Fig. 4(a). In such a VR system, each pixel on the display panel is collimated by the viewing optical lens. So, the spatial location of each pixel is actually mapped to an angular direction before the human eye, which is nothing but a Fourier transform. Each angular direction containing the information of each pixel can be deflected by the actively switching PBD, which accordingly creates another pixel matrix in addition to the original one. The PBD is constructed to optically shift the original pixel grid by half pixel pitch in the diagonal direction, such that a new virtual pixel grid with doubled pixel density can be realized, as depicted in Fig. 4(b).

Then, the original high-resolution image is computationally factorized into a pair of low-resolution images with half-pixel number in each dimension. The two low resolution images are supposed to be displayed on the shifted and unshifted pixel grids, overlapping with each other to re-construct the original high resolution image. After synchronizing the PBD and computationally generated sub-frames for the original and shifted pixel grids, an image with doubled resolution could be displayed, as shown in Fig. 5. Due to the improved pixel density, the edges in the resolution-enhanced image looks smoother than that in the original display. Furthermore, the screen-door effect is also diminished since the black matrix between the original pixels is now occupied with the shifted pixels.

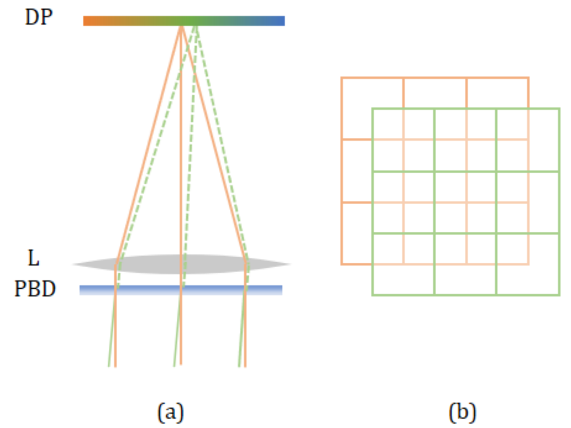

Fig. 4. (a) Schematic illustration of the optical system for pixel density enhancement with a PBD. (b) The generation of a half-pitch pixel grid by overlapping the original (orange) and shifted (green) pixel grid. (DP: display panel; L: magnifying lens.)

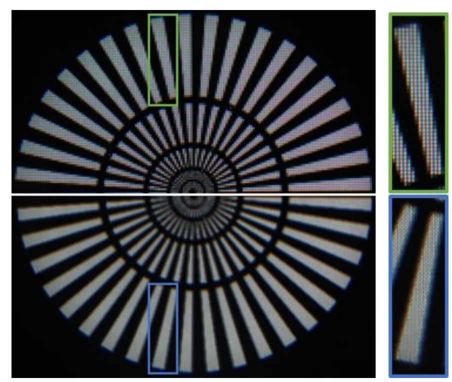

Fig. 5. Observed images from the near-eye display system without (upper) and with (lower) pixel density enhancement enabled by a PBD.

2.2 Foveated Image Shifter

The second optical approach to enhance the resolution is called foveation, which is based on the spatial resolution distribution of the human vision system. The imaging cone cell density is high at a small area called fovea but drops rapidly away from this area on the retina. Thus, the high resolution display is only meaningful when it is imaged on the fovea area. In this case, the information displayed outside the fovea region do not need to keep the same high resolution. We may only need to provide high resolution image for the fovea area, which is a very small area on the retina. The total pixel number in this way is much smaller than the globally high resolution displays. This foveation concept has been utilized in some optical designs to provide high resolution in a small image part but not the entire FOV [11], which could help deal with the pixel density issue and reduce the heavy burden on display driving circuits and data transport rate. On the other hand, viewer's eye may saccade on different parts within the FOV, so the high resolution foveated imaging area should synchronize with the eye-tracking system rapidly. Thus, we propose to employ a PBD as an image shifter to steer the high-resolution foveated image following the eye movement.

Figure 6(a) illustrates the optical layout of a foveated VR display system with an active-driving PBD as the image shifter. Here two display panels are utilized, one for fovea area and one for peripheral area. The displayed image on display panel 1 (DP1) is directly transmitted to the viewer through the beam splitter and eyepiece (L), while the image displayed on the second panel (DP2) is firstly minified by a concave lens (CL) before being reflected to the viewer. With a switchable PBD, the high-resolution foveated image content from DP2 could be shifted, as shown in Fig. 6(b). By applying a voltage to the PBD, the LC directors are reoriented by the electric field so that no deflecting effect occurs. When the voltage is switched off, the foveated image area will be deflected by the PBD to off-axis positions following the location of human eye. The response time of PBD is less than 1 ms, which is sufficient for fast eye movement.

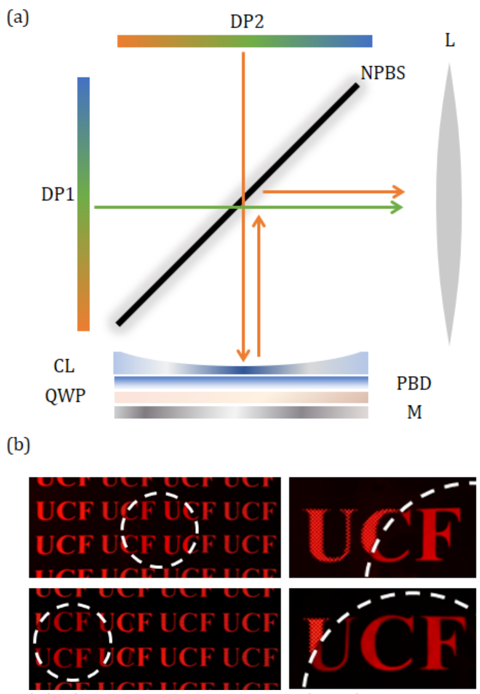

Fig. 6. (a) Schematic diagram of a foveated near-eye display system. (DP: display panel; NPBS: non-polarizing beam splitter; CL: concave lens; QWP: quarter-wave plate; M: Mirror; L: lens.) (b) Photography of foveated images from the near-eye display system before (upper) and after (lower) image shifting using a PBD.

3. PB Lens

3.1 Time-multiplexed multifocal NED with active PBL

The vergence-accommodation conflict (VAC) is another critical issue for near-eye and head-up displays. The current VR devices usually display a 2D image for each eye and stereoscopically generate the 3D effect for the viewers. But the loss of correct accommodation cue would cause severe 3D sickness, stopping a wide range of potential customers from using VR headsets. There are actually several solutions to the VAC, including but not limited to multifocal displays [12], integral imaging and focal surface displays. Here, we propose to generate a multifocal display using the LC diffractive lens, the PBL [13]. As an example, we demonstrated four focal planes with two actively switchable PBLs in Fig. 7(a). The proposed optical layout shares almost the same form factor with conventional VR headsets. The PBLs are sandwiched with refractive viewing optics to form an adaptive optical part. With the active driving mechanism illustrated in Fig. 7(b), the adaptive optical parts can generate four focal planes within each frame time. In addition to active driving, the PBLs can also be switched externally with a polarization rotator, as depicted in Fig. 7(c). If N PBLs are cascaded together, then 2^N focal planes can be generated in a time-sequential manner. The PBLs could also help generate multiple depths in the head-up displays based on the similar working principle [14].

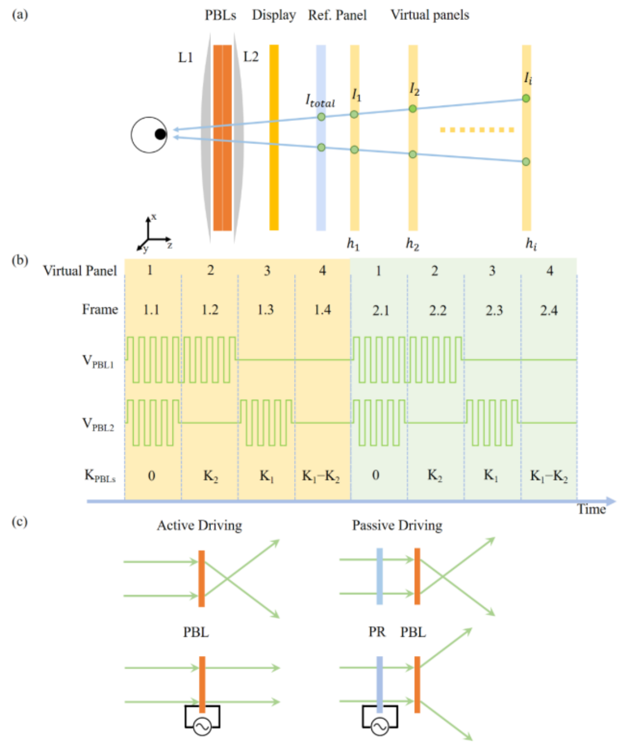

Fig. 7. (a) The principle of the additive light field display is illustrated with a stack of PBLs. Each virtual image panel, formed by a specific state of PBLs stack, generates independent additive light fields, which are merged into a single light field. (b) Time-multiplexing driving scheme of 4 additive virtual panels. (c) Illustration of active and passive driving modes of PBLs.

3.2 Polarization-multiplexed multifocal NED with passive PBL

Although the time-multiplexing approach could provide multi-focal displays effectively, a display panel with an ultra-high native frame rate is required for such a field-sequential operation. Thanks to PBL's polarization dependency, dual focal depths can be generated simultaneously using polarization multiplexing [15]. For the transition from 2D to 3D display, more amount of information is needed. The conventional time-multiplexing approach squeezes the new information in the time domain with fast-response adaptive optics. Here, we can also compress the information through the polarization channel with polarization sensitive optics, the PBLs. Although only two independent depths can be offered, since there are only two orthogonal polarization states, the polarization multiplexing can help reduce the requirement of frame rate to one half in the time-multiplexed system. Fig. 8(a) depicts the optical system for polarization-multiplexed dual-focal near-eye display. The dual-panel configuration, including a display panel (DP) and a polarization modulation layer (PML), controls both the intensity and polarization state of each pixel. For each pair of pixels on the dual focal depths, the sum of their intensity is displayed on the DP while the separation ratio is determined by the PML. The PML can be a modified twisted-nematic LC panel, which encodes the depth information by changing the outgoing polarization states, as shown in Fig. 8(b). Since the PBL manifests opposite focal length for RCP and LCP light, two virtual depths can be generated based on the polarization states.

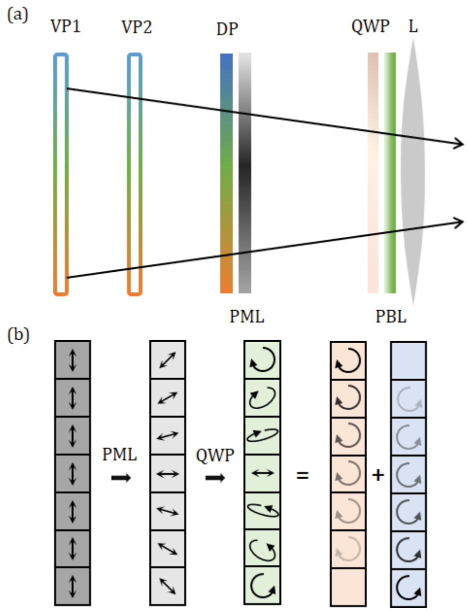

Fig. 8. (a) Schematic diagram of a polarization-multiplexed two-plane near-eye display system. (DP: display panel; VP: virtual plane; PML: polarization management layer; QWP: quarter-wave plate; L: lens.) (b) Schematic illustration of polarization state changes in the polarization multiplexed system.

4. Conclusion

We have reviewed some recent progress of liquid crystal diffractive optics for near-eye displays. This novel LC optics based on PB phase can be made into a wide range of diffractive optics but with high efficiency and good tunability. The PBDs can enhance the resolution of VR displays by generating sub-pixel shifting in the angular domain. In the foveated display system, the PBD can also function as a beam steering device to place the high-resolution area at the desired field of view. The PBLs are employed to generate multi-focal near-eye displays as a solution to the VAC. Both time- and polarization-multiplexing approaches have been demonstrated. As an emerging type of novel optics, the LC based PBOEs would find more promising applications in display industry.

5. Acknowledgments

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