Fast-response Pancharatnam-Berry Lens for Head-up Displays

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ABSTRACT

In this paper we demonstrate fast-response Pancharatnam-Berry lenses (PBLs) based on polymer-stabilized liquid crystal. After photo-alignment technique and UV curing, the PBLs show submillisecond response time. Based on two identical PBLs, a head-up display system that can generate four different diopters is demonstrated.

1 INTRODUCTION

Augmented reality (AR) [1], which superimposes virtual scenes onto the real world, has been developed extensively in recent years with widespread applications. In modern automobile industry, head-up displays (HUDs), which are aimed at enhancing road safety and driving comfort, have been intensively developed [2]. HUDs can project important driving information such as driving speed, navigation information, road conditions and automobile working information to the driver's field of view directly. Thus, the driver can possess the important information rendered in front of the windshield without shifting attention from the traffic.

Although HUDs have already been commercialized in some smart cars, several critical technical problems still need to be addressed. So far, most commercialized HUDs render the virtual image at a fixed distance [3]. However, the attention of drivers may not always focus on a fixed distance during driving. So a HUD that can provide virtual images at different distances are highly desired. To accommodate to the fast-changing driving environment, fast depth switching of virtual images is also important [4].

In this paper, we have proposed a HUD system based on two identical Pancharatnam-Berry lenses (PBLs) [5], which are fabricated by polymer-stabilized liquid crystal (PSLC) [6] films. After non-interferometric single-exposure technique [7] and UV curing, the fabricated PBLs show high diffraction efficiency and submillisecond response time. The HUD system can generate four different diopters of -1.1, 0, +1.1 and +2.2 D with fast switching speed, so that different virtual image depths can be rendered for drivers with low latency.

2 EXPERIMENT

A PBL is a phase modulation device, whose phase distribution is not generated by optical path length difference, but by the spatial variation of optic axes of anisotropic materials such as liquid crystals [5]. Here, to achieve fast switching time, the PBLs are fabricated based on PSLC, which is known to exhibit fast response due to strong polymer network. The fabrication process of the PBLs based on PSLC is shown in Fig.1 (a) and (b). The LC sample consists of four ingredients: a nematic LC, a monomer, a photosensitive dye and a UV photo initiator. Frist, the optical setup in Fig. 1 (a) is used to generate a two-dimensional linear polarization field (green laser 532 nm), which is used to photo-pattern LC alignment [7]. Next, polymer networks are formed and LC alignment stabilized after the sample being exposed to UV light, as shown in Fig.1 (b).

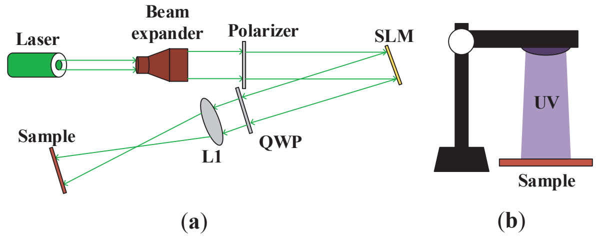

Fig.1. Fabrication of PBLs based on PSLC: (a) Optical setup of the single-exposure photo-alignment method [6] and (b) polymer stabilization process.

In our experiment, the ratio of the monomer (RM257, HCCH) and LC (E7, HCCH) was 6:94. Next, we added ~ 1 wt.% methyl red (MR, Sigma Aldrich) and a small amount of UV photo-initiator (Irgacure 651, Ciba Specialty Chemicals). The well stirred precursor was injected into premade empty LC cells. The samples then underwent the two-step exposure process. First, a polarization field (532nm) was generated by the spatial light modulator (SLM), and illuminated the samples, forming the lens phase profile by photo-patterning the LC. The first step requires about 10 minutes to achieve a stable state when the light intensity is ~100 mW/cm^2. Second, to form polymer network without disturbing the LC alignment, 365 nm UV LED illumination was used to induce cross-linking of the monomer. The second procedure took about 10 minutes giving light intensity is 5 mW/cm^2. The cell gap of all the LC cells used is approximately 3 μm, and there is no alignment layer on any of them. The SLM (PLUTO-VIS, Holoeye) has 1920 X 1080 pixels and the pixel size is 8 μm.

3 RESULTS

3.1 PBL test

At voltage-off state, the phase retardation (phase difference between o- and e- rays) of the PBL is approximately 2π. This is equivalent to no phase

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retardation, and as a result the lens function is turned off. At 18 V_{rms}, the liquid crystal directors are tilted towards the direction normal to the substrate, and a smaller phase retardation of π is induced. So the half wave condition is satisfied and the maximum diffraction efficiency is achieved for the PBL. Thus, the lens is turned on.

Fig.2 (a) is a microscopic picture of the PBL. Fig.2 (b) and (c) shows the images captured in the focal plane (~90 cm) of the PBL when it was illuminated with left-handed circular polarized (LCP) collimated red laser light (633 nm) at voltage-off and voltage-on (18 V_{rms}) states, respectively. One can see that most incident light was focused to a point at 18 V_{rms} because the PBL worked as a positive lens for LCP light. And we used an 18 V_{rms} alternative-current square-wave signal with a frequency of 60 Hz to measure the response time of the PBL. As shown in Fig.2 (d), the rise time is about 367 μs, and the decay time is about 464 μs.

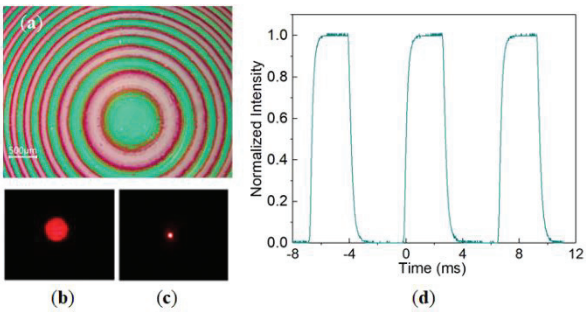

Fig. 2 (a) Microscopic image of the PBL. Diffraction patterns of the PBL in the focal plane at (b) voltage-off state and (c) voltage-on state, respectively. (d) Response time of the PBL.

3.2 HUD system design

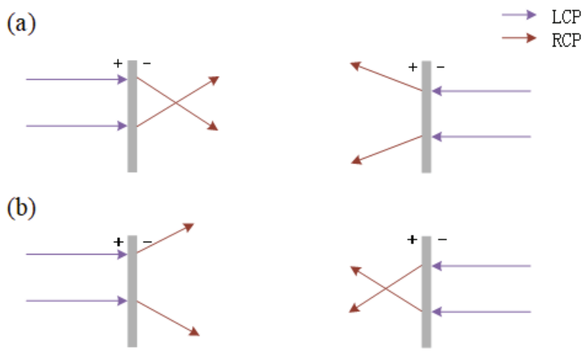

Fig 3. The lensing effects of a PBL for (a) LCP and (b) RCP light from different sides when it is turned on.

The same PBL would function as a positive lens for left-handed circularly polarized(LCP) light, but as a negative lens for right-handed circularly polarized (RCP) light as shown in Fig.3. Moreover, as circularly polarized light passes through a PBL, the handedness of the diffracted light is set to the opposite. That is, LCP becomes RCP, and RCP becomes LCP. More interestingly, the direction of the incident light determines the sign of the optical power of the lens. As one can see from Fig.3 (a), when LCP light comes from the left side, the PBL is a positive lens, but when the same LCP light comes from the right side, the PBL is negative. Similarly, RCP light coming from the left and right sides encounters a negative and a positive lens, respectively, as shown in Fig.3 (b).

To better illustrate this special property of a PBL, a symbol '+' is placed on the side of the lens that has a positive focal length for LCP incident light. On the other side of the lens, a symbol '-' is marked because it exhibits a negative focal length for LCP. Of course, if RCP light comes from the '+' side, the PBL is a negative lens, and when RCP light propagates from the '-' side, the PBL becomes a positive lens.

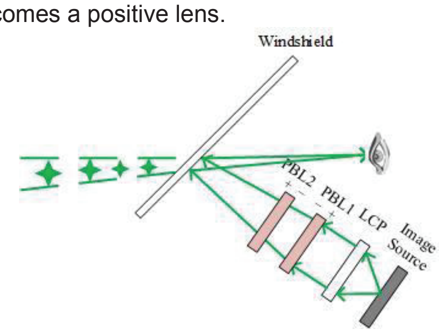

Fig. 4 Schematic design of the proposed HUD design.

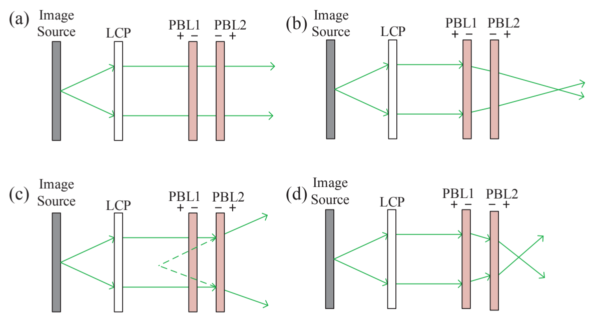

Fig 5. Schematic diagrams of four diopters generating.

Fig.4 depicts the design of the AR system we proposed. The two identical PBLs are closely stacked with the "-" sides facing each other. The incident polarization is switched into LCP by a broadband left-handed circular polarizer. And a half mirror is used to combine real scene with virtual images. The key of this system to show four different depths with two PBLs is that they have different functions for LCP and RCP light as shown in Fig.3.

There are four different cases shown in Fig.5: First, in Fig. 5(a), when both of the two PBLs are turned off, the focal length is ∞ (diopter is 0). Second, as Fig. 5(b) shows, when PBL1 is turned on but PBL2 is off, the focal length is +90 cm (diopter is +1.1). Third, Fig. 5(c) shows that when PBL1 is off and PBL2 is on, the focal length is

-90 cm, and the diopter is -1.1. Last, when both two PBLs are turned on, PBL1 converges the LCP light as a positive lens, and converts it into RCP light. So PBL2 also works as a positive lens for the converged RCP light as shown in Fig. 5(d), and the total effective focal length of the two PBLs is approximately a half of each, +45 cm (diopter is +2.2).

In a word, this simple system can generate four different focal lengths and diopters (~ -1.1, 0, 1.1, and 2.2). Therefore, with reasonable optical elements arrangement, four different depths of the virtual image can be observed.

3.3 HUD system results

We used a laptop screen to display virtual images in the demonstration experiment. And we put a camera in the eye place shown in Fig.4 to capture the virtual images superimposed onto the real world.

In our experiment, we used the laptop showing the letters “SJTU” serve as the image source of our HUD system. Fig. 6 (a-d) shows pictures captured when the virtual letters “SJTU” were displayed at 30 cm, 40 cm, 70 cm, and 230 cm by the two PBLs when the effective diopter was -1.1, 0, 1.1 and 2.2, as in the abovementioned four cases, respectively.

Fig. 6. Photographs captured when “SJTU” were rendered at (a) 30 cm, (b) 40 cm, (c) 70 cm and (d) 230 cm, respectively.

As Fig. 6(a) shows, when the camera was focused at 30 cm, the virtual image “SJTU” and the first polarizer that was placed at 30 cm away from camera were clear, while the second polarizer and letters on the white and black boxes were blurred. When the digital camera was focused at 40 cm, as Fig. 6(b) shows, the virtual letters “SJTU” and the second polarizer placed at 40 cm away from the camera were clear, letters on the white and black boxes remained blurred while the first polarizers changed blurred. As Fig. 6(c) shows, when the camera was focused at 70 cm, the virtual letters “SJTU” and the “SLIEDS” on the white box were clear, while the first, second polarizers and the words on the black box were blurred. As Fig. 6(d) shows, when the camera was focused at 230 cm, the virtual image “SJTU” and the words (“Maya”) on the black box placed at 200 cm away from the camera were clear, while the two polarizers and the words on the black box were blurred. These results proved our display can render virtual images at different depths with correct depth cues. The virtual image can be switched fast among different depths.

4 DISCUSSION

Compared to conventional HUDs proposed before, our system is more simple and can switch the information with different depths in submillisecond level. And we do not need to use the same number of PSLC films [8] as that of depth planes. We use only two PBLs with the same diopter and low driving voltage to generate four different planes. Furthermore, when placing N switchable PBLs appropriately, 2^N finite focal planes can be generated theoretically, leading to higher depth resolution.

5 CONCLUSIONS

In this paper, a new kind of HUD based on fast-response PBLs has been demonstrated. In our design, we employ only two pieces of PBL to produce four different focal lengths, so that multiple or switchable virtual image depths can be observed by drivers. And the switching time of the PBL is submillisecond, which can render different virtual image depths for drivers with low latency.

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