High-ambient-contrast augmented reality with a tunable transmittance liquid crystal film and a functional reflective polarizer

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Abstract — We have proposed a compact, yet high ambient contrast ratio augmented reality (AR) system by incorporating a tunable transmittance liquid crystal (LC) cell and a thin functional reflective polarizer. The broadband polarization-independent guest–host LC cell can change the transmittance from ~73% to ~26% with merely 8 V. Its response time (~50 ms) is at least 10× faster than that of photochromic materials used in commercial transition glasses. Combining the LC cell with a light sensor, the tunable transmittance LC cell can efficiently improve the ambient contrast ratio of the AR system under different lighting conditions. Meanwhile, the functional reflective polarizer works similarly to a polarizing beam splitter, except that it is much more compact and lighter weight. With some modification, we also designed a functional reflective polarizer to help people with color vision deficiency.

Keywords — *variable transmittance, reflective polarizer, color vision deficiency.*

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1 Introduction

Augmented reality (AR) has become quite popular as it works as a bridge between the real world and the virtual world. An optical see-through AR system can successfully combine the ambient environment and the display light.[1–4] To achieve this goal, a polarizing beam splitter (PBS) is usually utilized by reflecting the display light and transmitting a portion of the ambient light.[5] However, the PBS encounters two shortcomings: (i) it makes the whole system bulky and heavy[6,7] and (ii) it is still challenging to obtain high contrast ratio when the ambient light is strong.

In this paper, we propose an AR system combining a tunable transmittance liquid crystal (LC) film[8] with a reflective polarizer to replace the PBS. The LC film exhibits high transmittance when the ambient light is weak but low transmittance when the ambient light is strong. As a result, it improves the ambient contrast ratio (ACR). The reflective polarizer works similarly to the PBS, except it is much lighter and more compact. Moreover, if we replace the reflective polarizer with our specially designed functional reflective polarizer,[6,7] the system can help those users with color vision deficiency (CVD).[9,10] Our approach works well as long as the light from the display panel is polarized. Its application can extend to vehicular head-up displays (HUDs).

2 The AR system

The structure of the AR system is shown in Fig. 1. The tunable transmittance LC film is laminated on the front surface of the eyeglass, and the reflective polarizer/functional reflective polarizer is laminated on the back surface of the eyeglass. For the polarized display, a possible choice is a liquid-crystal-on-silicon (LCoS)[11–13] pico-projector with an output angle range of ±15°.

The electrically tunable-transmittance LC film works together with a light sensor so that the LC film is clear at low ambient light conditions, and it turns to a dark state at high ambient light conditions, thus ensuring a high ACR under all conditions. The performance of the tunable transmittance LC film will be discussed later in Section 3. The reflective polarizer, also known as dual brightness enhancement film (DBEF),[6,7] works the same way as the PBS by reflecting one polarization while transmitting the other. The main advantages of the reflective polarizer are twofold: its size can be much larger, and its weight much lighter than those of PBS. Moreover, if we replace the reflective polarizer with our specially designed functional reflective polarizer, such system can help people with CVD, more precisely people with anomalous trichromacy.[14] The design and performance of the functional reflective polarizer will be shown in Section 4 and Section 5, respectively. Besides AR systems, our device can also be laminated to the windshield for high ACR vehicular displays. In this case, both films can be laminated on the inner surface of the windshield.

3 Tunable transmittance LC film

A tunable transmittance system is desirable for applications where the ambient light is strong, for example, outdoor

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displays, energy efficient windows and car windshields. Several approaches have been developed to achieve tunable transmittance. The most mature one is the photochromic materials[15] used in transition glasses. However, besides their exceptional performance, transition glasses often suffer from sluggish response time,[15] as shown in Fig. 2(a)–(b). In experiment, we irradiated UV light onto a commercial transition glass and measured its time-dependent transmittance, as Fig. 2(a) depicts. From Fig. 2(a), the transmittance drops from ~83% to ~10% in 30 s. As soon as the UV lamp was turned off, the transmittance changes back to ~83% gradually in 25 min [Fig. 2(b)]. Such a slow response time is not practical for AR systems, and thus we proposed a fast-response tunable transmittance LC film.

Our voltage-driven tunable transmittance LC film is powered by AlphaMicron's e-Tint technology based on the guest–host approach.[8] In this approach, the LC host ($\Delta\varepsilon < 0$) is doped with ~3% black dichroic dyes and a small amount of chiral agent. The working principle of the guest–host LC cell is illustrated in Fig. 3(a)–(b). At V = 0, the LC directors and dichroic dyes are homeotropically aligned, and the absorption loss of the incident white light is minimal. Thus, the LC cell is highly transparent. Once the voltage exceeds a threshold, the LC directors and dichroic dyes are reoriented by the electric field to form a 180° super twisted nematic (STN) mode[8] because of the doped chiral agent. Such a 180° STN guest–host structure absorbs the incident light strongly, and the effect is insensitive to the polarization of the incident white light. The detailed mechanisms of such a chiral-homeotropic cell (without dyes) have been described in Ref. 16.

The voltage-dependent transmittance of our LC cell is shown in Fig. 4, and from the bright state (V = 0) to the dark state (8 V), the transmittance varies from ~73% to ~26%. With an embedded ambient light sensor, the LC film can control the transmittance adaptively according to its brightness. As a result, it helps to obtain high ACR. Besides the tunable transmittance, the measured turn-on time (bright to dark) is 3.8 ms, and turn-off time (dark to bright) is 50.5 ms. Such response time is at least 10× faster than that of transition glasses.

A see-through AR system projects the displayed images onto real world background. That means the "dark" state of the LC cell cannot be totally dark, and our LC film can successfully achieve this purpose, as demonstrated in Fig. 5 (a) and (b). The photos were taken under normal indoor lighting. From Fig. 5, we can tell that the LC cell is quite clear at the bright state (V = 0). At the darkest state ($8V_{rms}$), although the transmittance drops we can still distinguish the RGB colors clearly.

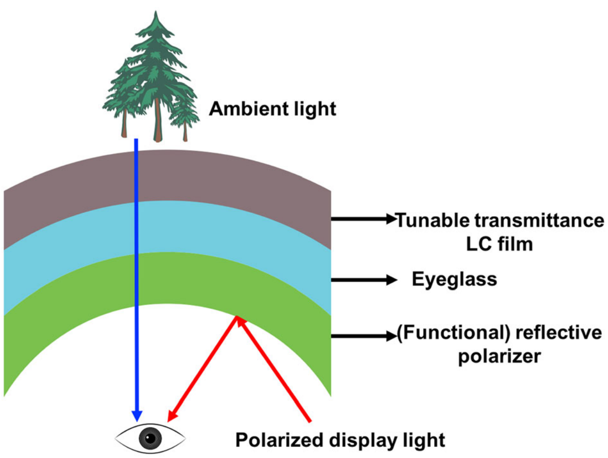

FIGURE 1 — Device structure of the proposed AR system.

4 Functional reflective polarizer

Reflective polarizer has been widely used in display backlights, and here we extend its application into AR systems. Figure 6(a) depicts the structure of a contemporary reflective polarizer consisting of hundreds of stacked isotropic and uniaxial layers. In the x direction, the light sees alternative refractive indices n_1 and n_2, and the film works as a dielectric reflector, while in the y direction the light sees uniform index (n_1) so that the light is transmitted. For our functional reflective polarizer, we modified the design by varying the refractive index in both x and y directions.

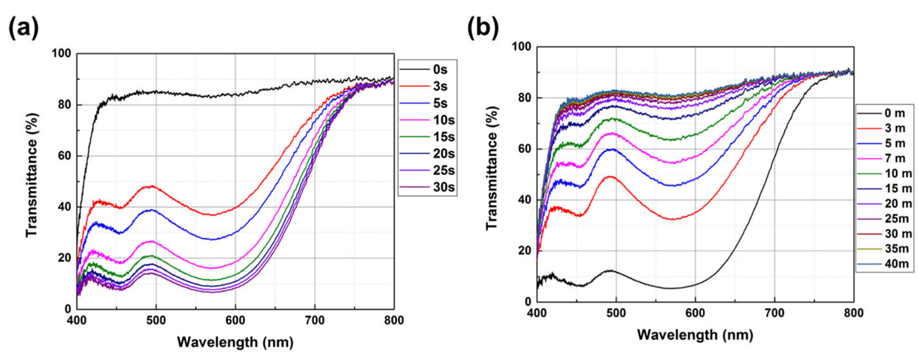

FIGURE 2 — Time-dependent transmittance of a commercial transition glass: (a) from bright state to dark state and (b) from dark state to bright state.

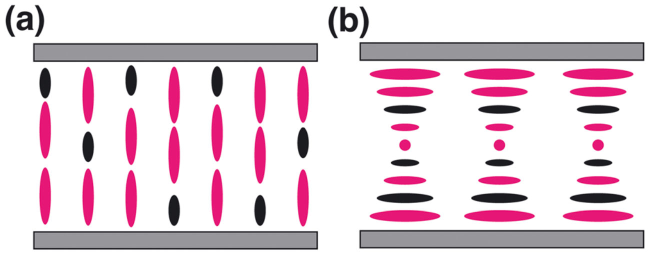

FIGURE 3 — Working principle of the tunable transmittance LC film at (a) bright state and (b) dark state.

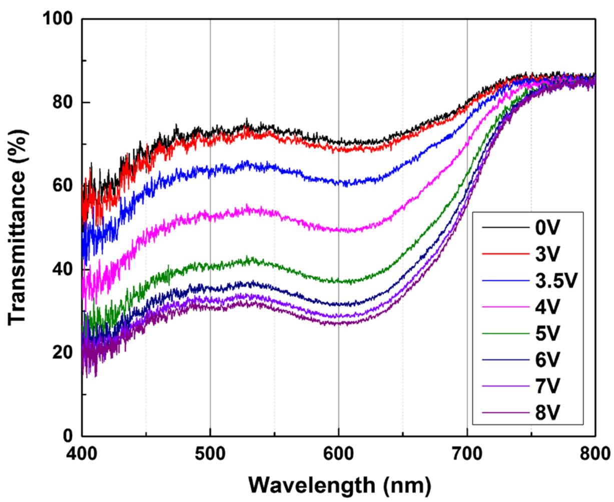

FIGURE 4 — Voltage-dependent transmittance of the LC film.

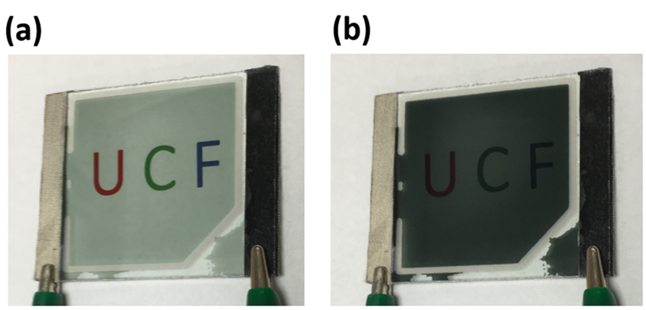

FIGURE 5 — The performance of the LC cell at (a) bright state and (b) dark state.

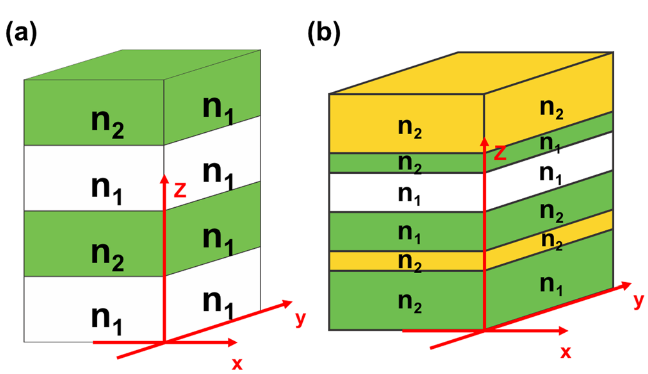

FIGURE 6 — Structure of (a) a conventional reflective polarizer and (b) our proposed functional reflective polarizer.

And instead of one uniaxial material and one isotropic material, we stacked two isotropic materials and one uniaxial material alternatively. The isotropic materials we used in our design are NOA81 (n = 1.57) and polyferrocenes (n = 1.82),[17] and the uniaxial material is LC (BL038, $n_e = 1.82$, $n_o = 1.57$) polymeric film.[7] The design of the functional reflective polarizer is based on the transfer matrix method and the 4 × 4 method,[7] the schematic view of the functional reflective polarizer is shown in Fig. 6(b) and we can see that to design a functional reflective polarizer, three materials are used and the uniaxial material can be aligned along either the x direction or the y direction.

Based on the 4 × 4 matrix method, we designed the functional reflective polarizer for people with CVD. This functional reflective polarizer consists of 800 layers with a total thickness of 30 µm. The transmittance of the functional reflective polarizer is shown in Fig. 7. For the polarized display light, which has been tailored for people with CVD, it will be efficiently reflected into the viewer's eye. As for the environment light, half of it is reflected back, while for the other half the functional reflective polarizer works as a notch filter. How this functional reflective polarizer can help people with CVD will be discussed later in Section 5. Here we assume the display light is polarized along the x direction, in which the functional reflective polarizer works at the reflective state. For the y polarized light, the functional reflective polarizer is highly transmissive. The angular performance of the functional reflective polarizer is simulated, and results are depicted in Fig. 7. We can see that the transmittance curve for the reflected state is really broadband and does not change much at the incident angle of 15°. For the transmissive state, the blue shift of the transmittance curve is only ~5 nm. These results indicate that our functional reflective polarizer can work for a relatively large incident angle. For practical applications, we can optimize the transmittance curve of the functional reflective polarizer to make it work for even larger incident angles. One possible optimization is to fine-tune the notched band to compensate for the blue shift at large incident angles.[7]

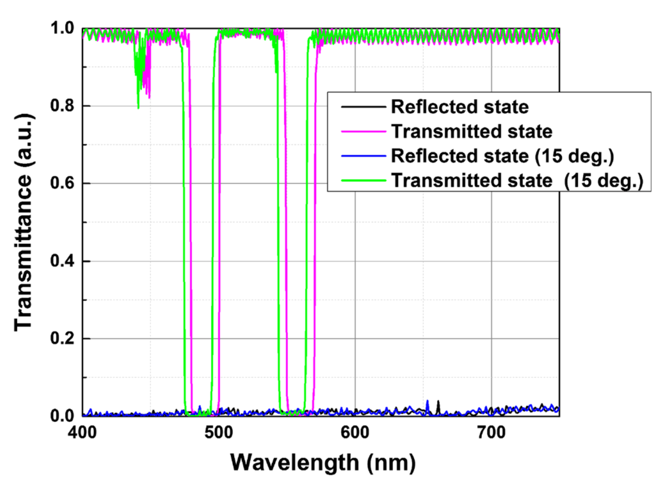

FIGURE 7 — Angular-dependent transmittance of the functional reflective polarizer.

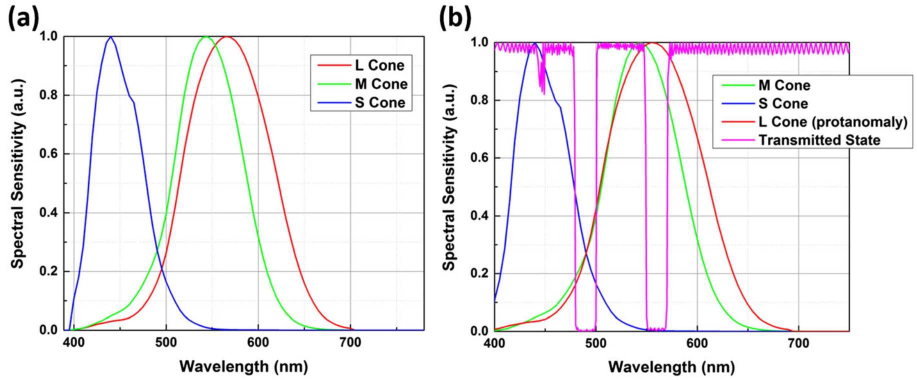

FIGURE 8 — Spectral sensitivity of people with (a) normal vision and (b) protanomaly. The magenta line is the transmittance of the functional reflective polarizer for the transmitted state.

5 Performance of the functional reflective polarizer for people with CVD

Color vision deficiencies can be classified as anomalous trichromacy, dichromacy and monochromacy.[9,10] Our functional reflective polarizer works with anomalous trichromacy, where one of the L, M and S cones becomes anomalous and its sensitivity shifts to different spectral bands. As demonstrated in Fig. 8 (a)–(b), in the case of protanomaly, the spectral sensitivity of the anomalous L cones has larger overlap with that of the M cones, compared to a person with normal vision. Here we assume that the severity of protanomaly is 0.5 (10-nm spectral shift). And our functional reflective polarizer works by reducing the spectral overlap between different cones. For the cases of deuteranomaly and tritanomaly, the working principle is the same.

For people with anomalous trichromacy, the perceived images with and without the functional reflective polarizer is simulated with the open source isetbio Toolbox,[18] and the simulation method is based on the stage theory of human color vision.[14] Basically with the abovementioned toolbox, we can get the spectra of the colors by specifying the spectra of the light source. In our simulation we assume the environment is a view of lotuses. We assume that the lotuses are displayed by the OLED panel specified in the toolbox.[18] Here we assume the severity of anomalous trichromacy is 0.9 (18 nm spectral shift), which means the anomalous trichromacy is quite severe. The simulation results are shown in Fig. 9. We can clearly see that with our functional reflective polarizer, it can help people with anomalous trichromacy to see more saturated colors, and at the same time the overall image contrast is enhanced. These two properties of our functional reflective polarizer can help people with CVD distinguish between different objects.

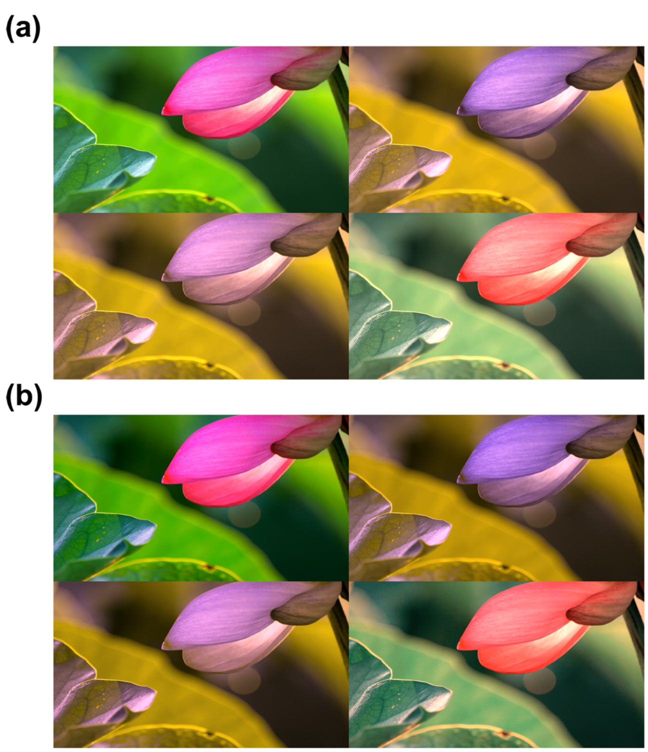

FIGURE 9 — (a) The perceived image without functional reflective polarizer. From upper left to bottom right, the images correspond to people with normal vision (upper left), protanomaly (upper right), deuteranomaly (bottom left) and tritanomaly (bottom right); (b) the perceived image with functional reflective polarizer. Here we assume the spectra shift is 18 nm.

6 Conclusion

With our demonstrated tunable transmittance LC cell, the ambient contrast of AR systems can be greatly improved. In the meantime, the system size can be greatly reduced by our functional reflective polarizer. What is more, with our proposed functional reflective polarizer, augment reality is no longer a privilege to people with normal vision; it can also be extended to those with CVD. The system can also be extended for usage in vehicular HUDs.

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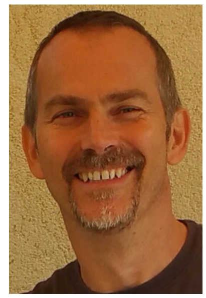

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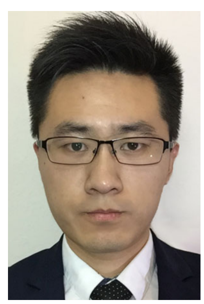

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