A High-Ambient-Contrast Augmented Reality System

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Abstract:

We report a compact, yet high ambient contrast ratio augmented reality system by incorporating a tunable transmittance liquid crystal cell and a thin reflective polarizer. Moreover, if we replace the reflective polarizer with a functional reflective polarizer, the system would benefit those users with color vision deficiency.

Keywords: variable transmittance, reflective polarizer, color vision deficiency

1. Introduction

In an optical see-through augmented reality (AR) system, polarization management is of vital importance to improve the brightness and contrast ratio [1]. The key component of polarization management is the polarizing beam splitter (PBS), which makes the whole system bulky and heavy [2-4]. Meanwhile, even with PBS, it is still challenging to improve the contrast ratio of the system when the ambient light is strong.

In this paper, we propose an AR system [5] combining a tunable transmittance liquid crystal film [6] with a reflective polarizer to replace the PBS. Moreover, if we replace the reflective polarizer with our specially designed functional reflective polarizer [4], the system can even help those users with color vision deficiency (CVD) [6]. Our approach works well as long as the light from the display is polarized. Its application can extend to vehicular head-up displays (HUDs).

2. The AR system

The device structure of the AR system is shown in Fig. 1. The tunable transmittance LC film is laminated on the front surface, while the reflective polarizer/functional reflective polarizer is laminated on the back surface of the eyeglass.

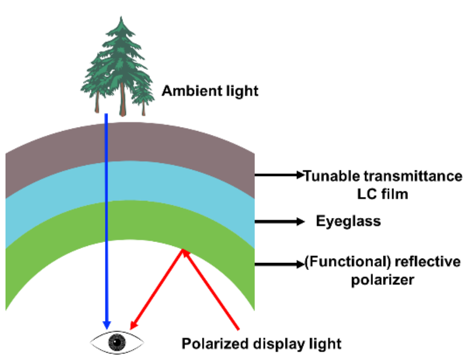

Figure 1. Structure of the proposed AR system

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 gets darker as the ambient light intensity increases, thus ensuring a high ambient contrast ratio (ACR) under all conditions. The performance of the tunable transmittance LC film will be discussed in Sec. 3. The reflective polarizer, also known as dual brightness enhancement film (DBEF) [2,3], 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 yet thinner, 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 [7, 8]. The design and performance of the functional reflective polarizer will be shown in Sec. 4. Besides AR systems, our proposed two films can also be laminated onto the car 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 displays, energy efficient windows and car windshields. Several approaches have been developed to achieve tunable transmittance. The most mature one is the photochromic materials [9] used in transition glasses. However, besides their exceptional performance, transition glasses often suffer from sluggish response time [9]. For our voltage-driven tunable transmittance LC films, it is powered by AlphaMicron's e-Tint technology [10] based on guest-host LC in a chiral-homeotropic cell [11]. 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. 2(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 [11] because of the doped chiral agent. Such an 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) has been described in Ref. [11].

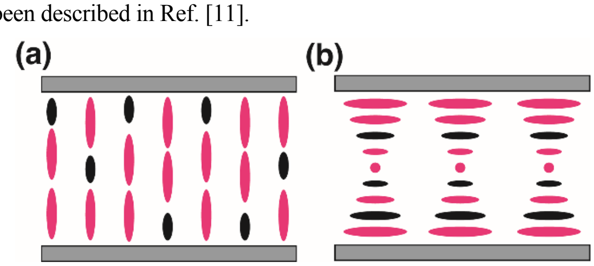

Figure 2. Working principle of the tunable transmittance LC film at (a) bright state and (b) dark state.

The voltage-dependent transmittance of our LC cell is shown in Fig. 3, and from the bright state (V=0) to the dark state (8V), the transmittance varies from ~73% to ~26%, which means with ambient light sensing, the LC film can efficiently control the transmittance to remain a high contrast ratio.

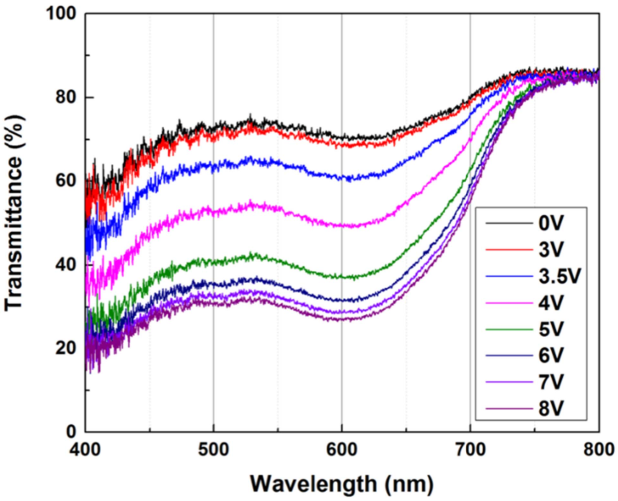

Figure 3. Voltage-dependent transmittance of the LC cell.

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 Figs. 4(a) and 4(b). The photos were taken under normal indoor lighting. From Fig. 4, we can tell that the LC cell is quite clear at the bright state (V=0). At the darkest state ($V=8V_{rms}$), although the transmittance drops we can still distinguish the RGB colors clearly.

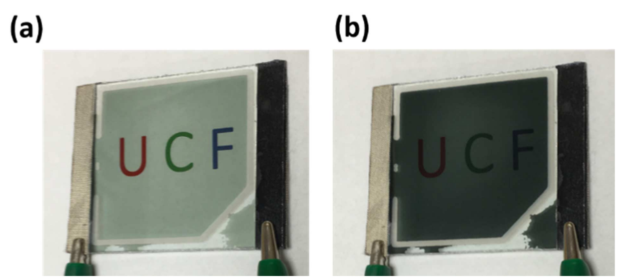

Figure 4. The performance of the guest-host LC cell at (a) bright state (V=0) and (b) dark state ($V=8V_{rms}$).

Besides transmittance, the response time of the guest-host LC cell is also much faster than that of transition glasses. The measured rise time (dark to bright) is 50.5ms and decay time (bright to dark) is 3.8ms.

4. Functional reflective polarizer

Reflective polarizer has been widely used in LCD backlight system and lately its application is expanding into AR systems. Figure 5(a) depicts the structure of a contemporary reflective polarizer consisting of hundreds of stacked isotropic and uniaxial layers. In the *x* direction, the incident light experiences alternative refractive indices n_1 and n_2, and the film works as a dielectric reflector. At the same time in the *y* direction, the light sees uniform index (n_1) so that the light is transmitted. However, as there is no refractive index change along the *y* direction, it is not possible to control the transmittance/reflectance of the y-polarized light. The most straightforward way to control the transmittance/reflectance of the y-polarized light is to introduce refractive index variation in the y direction. To help design the functional reflective polarizer, we need to take a look at the 4×4 method [3], which is used for analyzing optical waves in anisotropic media, especially in liquid crystal devices, and the transfer matrix approach [12], which is used in general for thin film coating design. We can tell that the main difference between the transfer matrix approach and the 4×4 method is that in the latter we introduce polar and azimuthal angles to describe the tilt and twist deformations of the LC directors. The incurred LC reorientation will introduce polarization rotation effect into the system. However, in the case of functional reflective polarizer, the problem can be greatly simplified if we assume that the uniaxial material is oriented along x-axis or y-axis. Then the polarization rotation effect would be negligible and the design process of the functional reflective polarizer can be simplified.

For our functional reflective polarizer, we modified the design by varying the refractive index in both *x* and *y* directions. 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) [13], and the uniaxial material is liquid crystal polymeric film (BL038, n_e=1.82, n_o=1.57) [3]. The design of the functional reflective polarizer is based on the transfer matrix method and the 4×4 method, the schematic view of the functional reflective polarizer is shown in Fig. 5(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. The detailed design process is explained in [4].

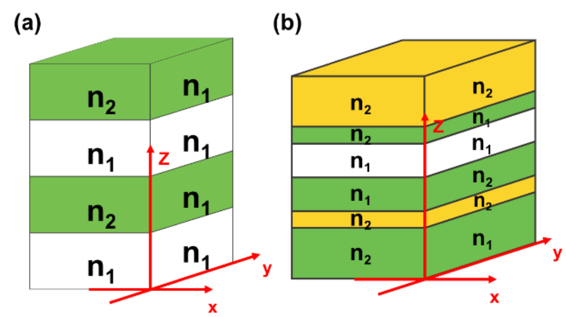

Figure 5. The device structure of (a) a reflective polarizer and (b) a functional reflective polarizer.

Based on the transfer matrix approach and the 4x4 matrix method, we designed the functional reflective polarizer for people with CVD. The performance of the functional reflective polarizer is shown in Fig. 6. 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. For the polarized display light, which has been tailored for people with CVD, it will be reflected into the viewer's eye, and for the environment light, the functional reflective polarizer works as a notch filter. How this notch filter helps people with CVD will be discussed later in Sec. 5.

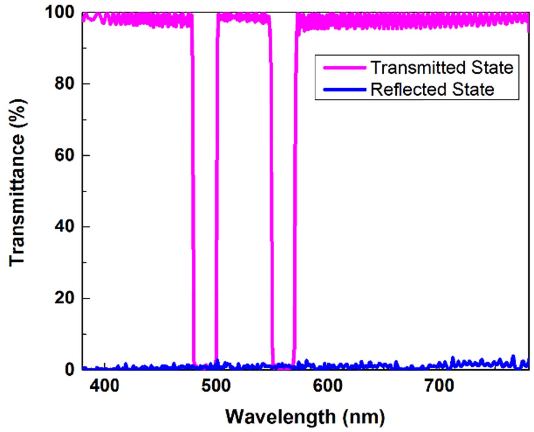

Figure 6. Transmittance of the functional reflective polarizer.

5. Functional reflective polarizer for people with color vision deficiency

Color vision deficiencies can be classified as anomalous trichromacy, dichromacy, and monochromacy [7, 8]. 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. 7(a) and (b), in the case of protanomaly, the spectral sensitivity of the anomalous L cones has larger overlap with that of the M cones, as compared to a person with normal vision. Here we assume that the severity of protanomaly is 0.4 (8nm 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.

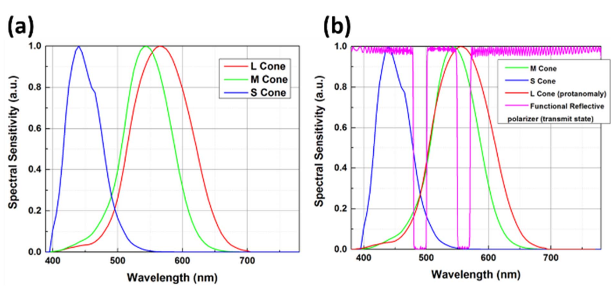

Figure 7. Spectral sensitivity of people with (a) normal vision and (b) protanomaly, the magenta line is the transmittance of the functional reflective polarizer for the transmission state.

For people with anomalous trichromacy, the perceived images with and without the functional reflective polarizer is simulated with the open source isetbio Toolbox [14], and the simulation method is based on [8]. 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 close-up view of a ladybeetle. We assume that the ladybeetle is displayed by the OLED panel specified in [14]. In our simulation we consider two cases: (1) the severity of anomalous trichromacy is 0.4 (8nm spectral shift), which means the anomalous trichromacy is not very severe and (2) the severity of anomalous trichromacy is 0.8 (16nm spectral shift) where the CVD is quite severe. The test photo is from Wikimedia Commons and results are shown in Fig. 8. We can clearly see that with our functional reflective polarizer, it can help people with anomalous trichromacy to see more colors, especially when the anomalous trichromacy is not severe. Even when the anomalous trichromacy is severe, our functional reflective polarizer helps to enhance the contrast of the environment.

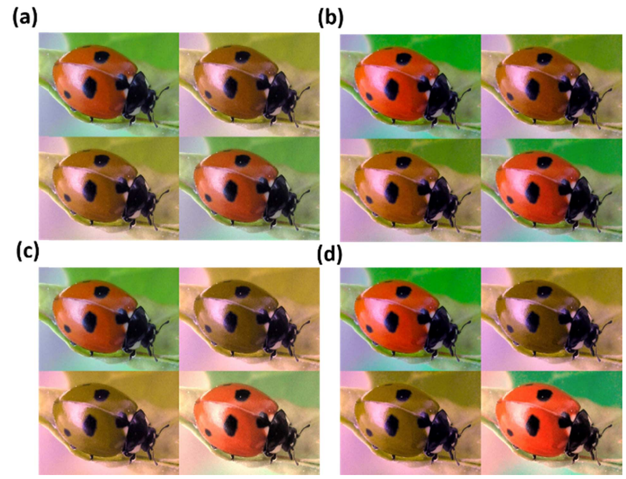

Figure 8. (a) The perceived image without functional reflective polarizer. From upper left to bottom right, the images correspond to people with normal vision (upper left), protanomaly (upper right), deuteranomaly (bottom left) and tritanomaly (bottom right); (b) the perceived image with functional reflective polarizer. For (a)-(b), the spectral shift is 8nm. (c) The perceived image without functional reflective polarizer when the spectral shift is 16nm and (d) the perceived image with functional reflective polarizer when the spectral shift is 16nm.

6. Conclusion

With our proposed tunable transmittance LC cell, the ambient contrast of AR systems can be greatly improved. In the meantime, 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 color vision deficiency.

7. Acknowledgments

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