Application and Research of Optically Cholesteric Liquid Crystals in Reflective Displays

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Abstract
We have developed a single-layer color reflective display using cholesteric liquid crystal, which changes the pitch of the liquid crystal through exposure, thereby altering the reflection wavelength and forming different colors. Single layer color cholesteric liquid crystal displays are not only lightweight and low-cost, but can also be applied in harsh outdoor environments, significantly enhancing competitiveness.

Author Keywords
Optically controlled cholesteric liquid crystal; Low-power reflective display; Outdoor display; Bistable state.

1. Introduction
In recent years, with the popularization of low-carbon environmental protection and the concept of paperless, electronic tags, e-books, electronics, tables and cards have become more and more popular. Electronic ink display is a representative technology. Compared with electronic ink display technology, cholesteric liquid crystal display technology not only has the characteristics of bistable and low power consumption, but also has better low temperature reliability than electronic ink screen, which is more suitable for outdoor applications in harsh environments.

The cholesteric liquid crystal molecules are arranged in a flat layer, and the long axis is parallel to the layer plane. There is a small torsion angle in the long axis direction of the adjacent layer molecules. The molecules of each layer rotate continuously and uniformly along the normal direction, so that the overall structure of the liquid crystal forms a spiral structure. The distance between the two layers of the spiral torsion 360 ° is called pitch [1].

Cholesteric liquid crystal has selective reflection characteristics. When a beam of white light is incident on the surface of the cholesteric liquid crystal, the cholesteric liquid crystal will only selectively reflect a certain wavelength of light, which satisfies the Bragg reflection law. Different colors of light can be reflected by adjusting the pitch [2]. In addition to selective reflection, cholesteric liquid crystal also has the characteristics of multi-stable state. When the input voltage is low, the liquid crystal is in the Bragg reflection state, also known as the planar texture state, known as the P state (steady state) ; by applying a certain pulse voltage to the liquid crystal in the P state, the alignment direction of the liquid crystal molecules is disordered, forming a similar isotropic state, which can make the incident light penetrate or scatter, and no specific light is reflected. This state is called the focal cone state, referred to as the FC state (steady state) ; when the high voltage pulse is input, the liquid crystal molecules are arranged vertically, and there is no birefringence in the horizontal direction. The incident light passes through. This state is called the field nematic state (H state), which is an unstable state [3]. The conversion from H state to P state can be realized by quickly disconnecting the H state voltage to the P state voltage ; the conversion from H-state voltage to FC-state voltage can be realized by slowly switching the power supply from H-state voltage to FC-state voltage. The transition from P state to FC state can be realized by energizing the voltage from P state to FC state, as shown in Fig. 1.

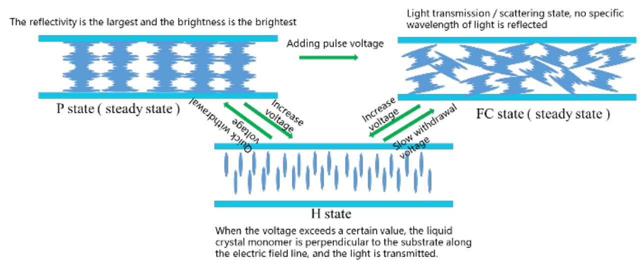

Figure 1. State transition diagram of cholesteric liquid crystal.

The technology of cholesteric liquid crystal display has been developed for over yeas. Hashimoto K et al [4] developed a tri-layer cholesteric liquid crystal reflective display, using blue cholesteric liquid crystal, green cholesteric liquid crystal, and red cholesteric liquid crystal as a display layer, respectively. As shown in Fig. 2, by controlling the mixing of the three layers of colors, this display can display 512 colors. Harada H et al [5] also developed cholesteric liquid crystal electronic paper, using blue and green cholesteric liquid crystal double layers, and red cholesteric liquid crystal as the absorption layer. As shown in Fig. 3, they made a display with a paper-like effect of A6 size. Chin C L et al [6] developed a single-layer color cholesteric liquid crystal reflective display. The veneer is divided into three straight pixel regions, and blue, green, and red cholesteric liquid crystals are injected into them by channel injection or inkjet, respectively. As shown in Fig. 4, the color cholesteric liquid crystal display device using a single-layer substrate is reduced by 50 % in both weight and thickness compared to the traditional color cholesteric liquid crystal display, which lays a good foundation for the further development of cholesteric liquid crystal reflective display devices. However, the previous work mainly focus on multi-layer cholesteric liquid crystal display, which can increase the procession steps, complexity and cost.

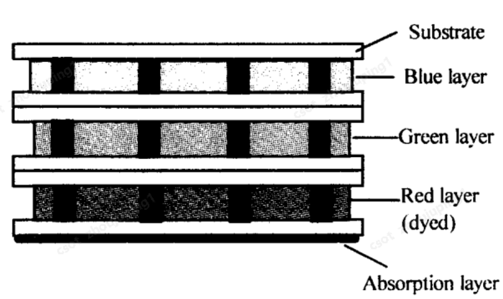

Figure 2. Three-layer schematic of cholesteric liquid crystal

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reflective display [4].

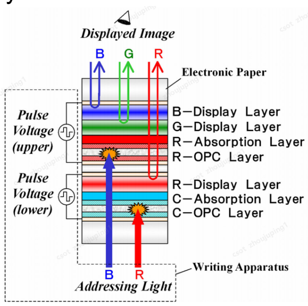

Figure 3. Cholesteric liquid crystal reflective display multi-layer schematic diagram [5].

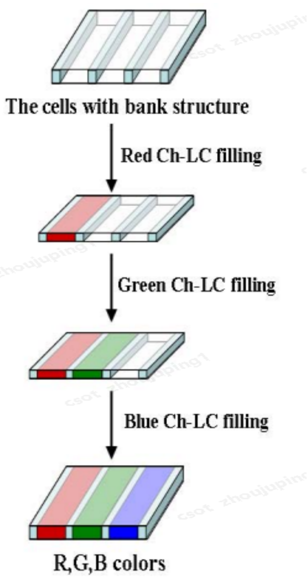

Figure 4. Single-layer cholesteric liquid crystal reflective display process flow chart [6].

Herein, we have developed a new display technology, which can realized reflective color display with only single-layer cholesteric liquid crystals. The precise control of cholesteric liquid crystals pitch was achieved through exposure, thereby altering the reflection wavelength and forming different colors. The detailed steps are described as followed. Firstly, forming a pixel sized polymer barrier structure on a TFT glass substrate, then the cholesteric liquid crystal is encapsulated in the polymer barrier to form a box. Secondly, the cholesteric liquid crystal encapsulated in the polymer barrier is sequentially exposed to light, resulting in the formation of blue, green, and red colors. Finally, altering the exposure dose to achieve different cholesteric liquid crystals pitch.

By optimizing the molecular structure of photo controlled chiral molecules in cholesteric liquid crystals and reducing their photoreactive properties, the exposure time required for blue, green, and red color changes can be maintained within a relatively wide range, thereby improving the operability and controllability of the illumination process. At the same time, the solubility of chiral molecules and liquid crystals has also been improved, which broadens the operating temperature of cholesteric liquid crystals.

2. Method description

The structure diagram of the cholesteric liquid crystal single-layer multi-color reflective display is shown in Fig.5. The complete process route is as follows :

(1) A pixel-sized polymer wall is formed on the TFT substrate by photolithography or nanoimprinting. (2) The liquid crystal is injected into the polymer wall. The injection methods include inkjet printing, screen printing, slit coating, etc., (3) The ITO substrate is aligned with the polymer wall substrate containing liquid crystal by vacuum bonding. (4) After the cell process is completed, blue, green and red are formed by exposure in turn. The process flow is shown in Fig.6.

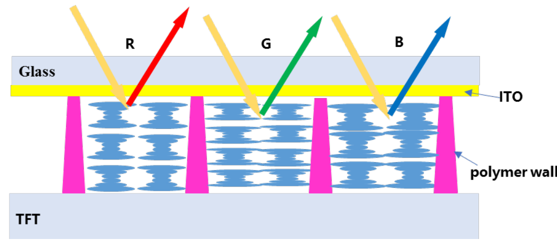

Figure 5. Structure diagram of cholesteric liquid crystal single-layer multicolor reflective display.

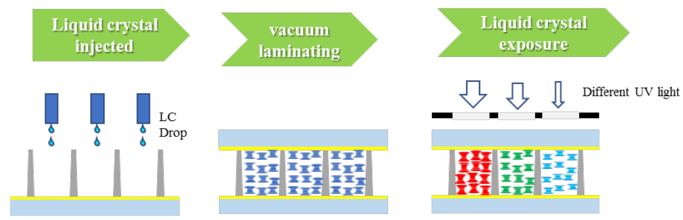

Figure 6. Cholesteric liquid crystal single-layer multi-color reflective display process flow chart.

3. Experiment

The optically controlled cholesteric liquid crystals were provided by Shijiazhuang Chengzhi Yonghua Display Material Co., Ltd. The model numbers are SLC061 and SLC056. The basic physical property parameters of the liquid crystals are shown in Table 1. The two cholesteric liquid crystal have different chiral agents.

Table 1. Basic physical property parameters of optically controlled cholesteric liquid crystal materials.

Mixture	SLC056	SLC061
S→N(℃)	≪ −40	≪ −40
Viscosity(mPa·s,25℃)	68	37
Clearing Point(℃)	85	79
Δn(598nm,25℃)	0.241	0.223
ne(598nm,25℃)	1.754	1.735
$\Delta\varepsilon$(1KHz, 25℃)	35.1	36.4
$\varepsilon_{\perp}$(1KHz, 25℃)	7.1	7.16
K11(pN, 25℃)	9.6	9.5
K22(pN, 25℃)	4.8	4.75
K33(pN, 25℃)	13.9	13.2
$\gamma 1$(mPa·s,25℃)	239.9	180.8

Following the process flow described in Fig. 6, we prepare 10x10 cm test cells and 23.8-inch panels, using SLC056 and SLC061. The panel fabrication was performed at the G4.5 generation production line of China Star Optoelectronics Technology Co., Ltd..

4. Results and Discussion

4.1. Exposure time

Cholesteric liquid crystals satisfy the Bragg reflection law: $\lambda = \Delta n \cdot P$, where P is the pitch of the cholesteric liquid crystals. By adjusting the value of P, the reflection wavelength of the cholesteric liquid crystals can be adjusted, thus regulating the color of the cholesteric liquid crystals. A chiral agent is introduced into the liquid crystals. Exposure makes the liquid crystal chiral agent generate a helical torque force. By adjusting the exposure time, the magnitude of the helical torque force can be regulated, thereby adjusting the magnitude of the pitch.

The correlation of exposure time and color of SLC056 are shown in Fig. 7, while the exposure time and color of SLC061 are shown in Figure 8. The light source is an LED UV lamp with an illuminance of 50 mW/cm². By lengthening the exposure time, the cholesteric liquid crystals continuously changed from blue to green and to red color. We determined the time parameters by using visual method to judge the time range when RGB appears.

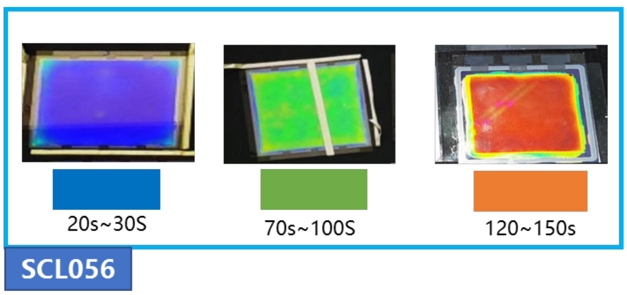

Figure 7. The exposure time and color of SLC056.

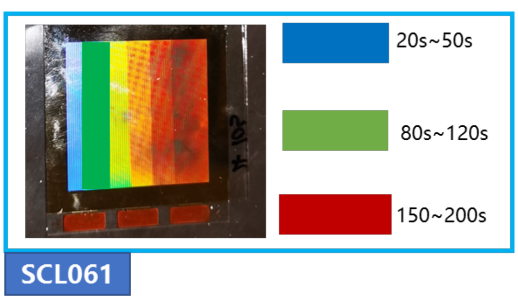

Figure 8. The exposure time and color of SLC061.

It can be seen that for SLC056, color B is displayed between 20 and 30 seconds, color G is displayed between 70 and 100 seconds, and color R is displayed between 120 and 150 seconds. For SLC061, blue is displayed between 20 and 50 seconds, green is displayed between 80 and 120 seconds, and red is displayed between 150 and 200 seconds. SLC061 requires a longer exposure time. The difference between SLC061 and SLC056 lies in the difference in the activity of the liquid crystal chiral agents.

Moreover, the exposure time range required for SLC061 to display RGB is wider, which is extremely beneficial for the exposure process. This is because the realization of single-layer multicolor requires exposure on the laminated panels, and the glass substrate has a refractive effect on light. For example, when exposing for color G, the light will crosstalk into the area of B, causing the color in the B area to change. However, SLC061 has a relatively wide range of exposure times for RGB, so even if there is light refraction, it has no impact on the colors.

4.2. Solubility

Cholesteric liquid crystals are prone to the precipitation of foreign matter lumps at low temperatures, which leads to the failure of the liquid crystals and makes them unusable. We have investigated the characteristics of bulk cholesteric liquid crystals and test cells at different low temperatures, as shown in Table 2.

Table 2. Low-temperature characteristics of cholesteric liquid crystals.

Type	Bulk					Cell	
Item (℃)	0	-10	Rocker -10	-20	-30	-20	-30
SLC056	>T240	NG	NG	NG	NG	>T240	>T240
SLC061	>T240	>T240	>T240	>T240	>T240	>T240	>T240

It can be seen that SLC061 can work normally over 240 hours (T240) under the temperature of <-30℃, and its clearing point is 79℃. Therefore, the applicable temperature range of the light-controlled cholesteric liquid crystals can reach from -30℃ to 79℃, which is suitable for various extreme environments. Thus, in outdoor scenarios, it has a very strong competitiveness compared with the currently mainstream electronic ink screens.

4.3. Reflectivity and driving voltage.

The reflectivity parameters after RGB exposure are shown in Fig. 9.

The reflectivity values are as follows: at 450 nm (Blue): 31% for SLC056 and 30% for SLC061; at 550 nm (Green): 30% for SLC056 and 29% for SLC061; at 650 nm (Red): 27% for SLC056 and 25% for SLC061. The reflectivity performance of SLC056 and SLC061 is quite comparable.

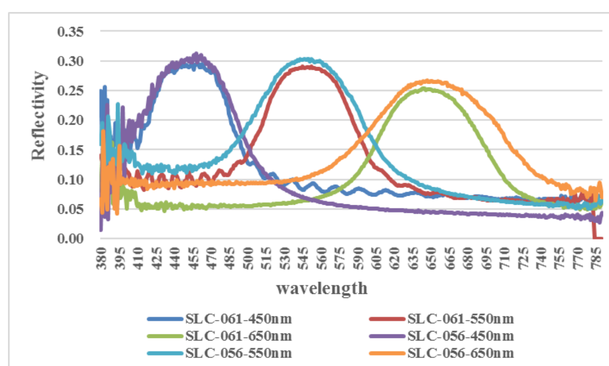

Figure 9. Reflectivity parameters after RGB color display.

Theoretically, the reflectivity of cholesteric liquid crystals can reach 50%. According to Bragg's law of reflection, cholesteric liquid crystals will specifically reflect light of a certain wavelength, while light of other wavelengths will pass through. Moreover, for light of a specific wavelength, 50% of the light with the same optical rotation property as the cholesteric liquid crystals will be reflected, and 50% of the light with the opposite optical rotation property will pass through. This is because cholesteric liquid crystals have optical rotation characteristics. For example, if the cholesteric liquid crystals have a left-handed structure with a specific pitch, then 50% of the left circularly polarized light of a specific wavelength in natural light will be reflected, and 50% of the right circularly polarized light will pass through. It can be seen from Fig. 9 that the reflectivity of RGB is all below 50%, indicating that not all the states in the cholesteric liquid crystals are in the P state, but a mixture of the P state and the FC state. Since the FC state has a scattering effect on light, the surface presents a matte state and the reflectivity is reduced. If it is necessary to improve the reflectivity and contrast, an alignment layer needs to be used, and either photo-alignment or rubbing alignment is acceptable.

The reflectivity-voltage curve of cholesteric liquid crystals is shown in Fig. 10. Testing Principle: Use the DMS equipment in the reflection mode with a frequency of 25 Hz, apply electricity for 200 ms and then cut off the power. Subsequently, test the reflectivity under the voltage at that point.

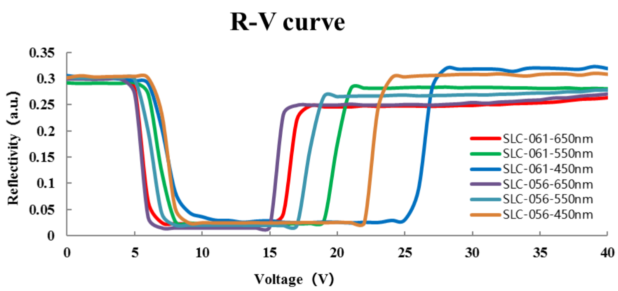

Figure 10. Reflectivity parameters after RGB color display.

In the design of cholesteric liquid crystal reflective displays, the reflectivity-voltage (R-V) curve is a key parameter. The driving voltage, gray scale and waveform can be designed according to the R-V curve. As can be seen from Fig. 10, the driving voltage of the light-controlled cholesteric liquid crystals is less than 30 volts, and the corresponding time can be less than 300 ms, enabling video display.

Generally speaking, cholesteric liquid crystal displays have relatively strong advantages over the currently mainstream electrophoretic display technology in terms of temperature operating range, colorization and response speed. The single-layer multi-color display technology realized by light-controlled cholesteric liquid crystals proposed in this paper has improved the competitiveness of cholesteric liquid crystal display technology. A simple demo of a 23.8-inch single-layer multi-color display is shown in Fig. 11.

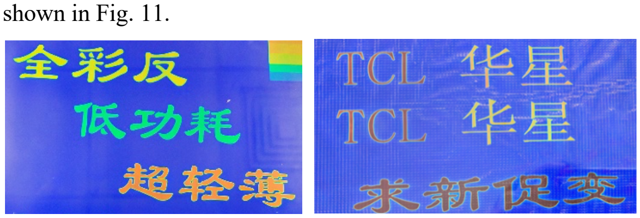

Figure 11. A simple demo of a 23.8-inch single-layer multi-color display.

5. Conclusion

In this work, a single-layer color reflective display technology for cholesteric liquid crystals has been developed. A kind of cholesteric liquid crystal is used to change the pitch of the cholesteric liquid crystal through exposure, thus altering the reflection wavelength of the cholesteric liquid crystal and forming different colors. By creating a polymer barrier structure with a pixel-sized dimension on the TFT glass substrate, the cholesteric liquid crystal is encapsulated within the polymer barrier to form a cell. Then, the cholesteric liquid crystal encapsulated in the polymer barrier is exposed in sequence, so that the cholesteric liquid crystal forms blue, green, and red colors one after another.

By optimizing the molecular structure of the optically controlled chiral molecules in the cholesteric liquid crystal, the photoreaction activity of the optically controlled chiral molecules in the cholesteric liquid crystal is weakened. As a result, the exposure time required for the color change to blue, green, and red can each be maintained within a relatively wide range, which improves the operability and controllability of the light exposure process. Meanwhile, it also enhances the solubility of the chiral molecules and liquid crystals and broadens the temperature range applicable for the cholesteric liquid crystal. The display working temperature range can reach from -30 °C to 79 °C. This kind of cholesteric liquid crystal display can be applied in harsh environments such as outdoors, significantly strengthening the competitiveness of cholesteric liquid crystal reflective displays in low-power displays.

6. References

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