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Brightness Enhancement with a Fingerprint Chiral Nematic Liquid Crystal

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We demonstrate a brightness enhancement element that can be laminated to a linear polarizer for increasing the optical efficiency of a liquid crystal display device. The device structure is a chiral nematic liquid crystal (CNLC) with a fingerprint texture. For an unpolarized incident light, our experimental results show that the combination of a CNLC film and a conventional linear polarizer can achieve a transmittance of over 50%. The CNLC film increases the optical efficiency of a conventional polarizer by 21.7%. The detailed mechanism of such a CNLC-polarizer system is analyzed.

1. Introduction

Polarizers are widely used in high-contrast liquid crystal display (LCD) devices. The transmittance of a pair of crossed polarizers is usually below 40%. A low optical efficiency leads to high power consumption. To increase transmittance, several brightness enhancement films have been developed, such as dual brightness enhancement films (DBEF),[1–3] cholesteric reflective polarizers,[4–7] and polarization converters.[8,9] The underlying mechanism for these brightness enhancement films is to transmit a designated polarization, for example, a p-wave, but recycle the s-wave and convert it to the p-wave.

In this paper we demonstrate another type of brightness enhancement film based on the fingerprint texture of a chiral nematic liquid crystal (CNLC). The stripe direction of the fingerprint texture depends on the substrate rubbing condition and the d/p_0 ratio of the CNLC film, where d is the film thickness and p_0 is the natural pitch of the CNLC.[10] In our device configuration, the sample film is initially aligned parallel to the rubbing direction on the substrate surface. When an ac voltage is applied, the sample is converted to fingerprint texture with the stripes of the fingerprint structure parallel to the rubbing direction. This kind of film is easy to manufacture and low-cost, and can function as a polarization convertor for enhancing the brightness of LCDs.

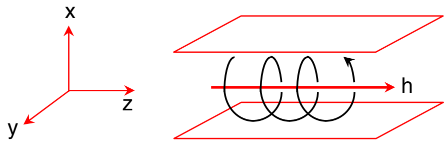

Fig. 1. (Color online) Director $\mathbf{n}(\theta)$ of the fingerprint texture varying in space. The helical axis h is parallel to the substrates.

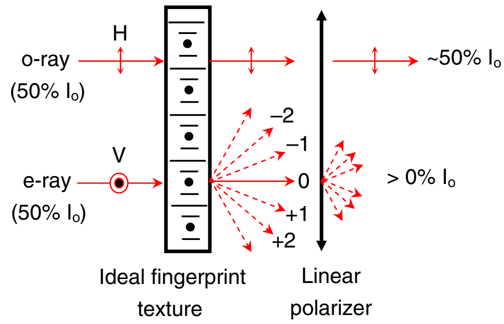

Fig. 2. (Color online) Polarization-dependent light transmittance of a CNLC-polarizer system. The CNLC film has ideal fingerprint texture. Both the incident light and transmitted light have the H and V components. Numbers (−2, −1, 0, +1, and +2) denote diffraction orders.

2. Theory

Figure 1 shows a fingerprint structure. In the ideal state, the director $\mathbf{n}(\theta)$ varies in free space as follows:

$$\begin{aligned} n_x &= \cos\theta, \\ n_y &= \sin\theta, \\ n_z &= 0, \\ \theta &= q_0 z + \text{constant}, \end{aligned} \tag{1}$$

where the z-axis is the helical axis, $q_0 = |2\pi/p_0|$ is the spatial angular frequency, and p_0 is the natural pitch of CNLC.[11]

Let us consider an unpolarized light beam (I_0) normally incident on an ideal fingerprint film, as shown in Fig. 2. The incident beam has two polarization components: the H-component, which is parallel to the helical axis, and the V-component, which is perpendicular to the helical axis. The H-component (also known as ordinary ray or o-ray) passes through the fingerprint texture without changing polarization direction because it experiences the ordinary refraction index (n_o) in the fingerprint texture. On the other hand, the V-component (also known as extraordinary ray or e-ray) is diffracted by the fingerprint texture because the encountered refraction index changes along the helical axis. For the V-component, apart from the 0th order, all the diffracted beams will become elliptically polarized as they traverse the chiral nematic film. That is to say, the V-component will also partially transmit through the linear polarizer. Therefore, the CNLC-embedded polarizer theoretically allows an unpolarized light to transmit through a linear polarizer with more than 50% efficiency, as Fig. 2 illustrates. This efficiency is higher than that of a conventional polarizer.

However, in reality, the fingerprint texture in a CNLC film may not be ideal. Taking into account the substrate surface anchoring energy and the minimum deformation energy of a CNLC film, the molecular alignment always exhibits a double-twist structure. This phenomenon has been proven both experimentally and theoretically.[12–15] Thus, both the

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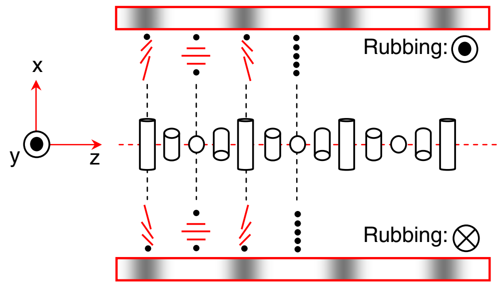

Fig. 3. (Color online) Symbolic representation of the double-twist alignment in *x*- and *z*-axes. The fingerprint stripes (gray shadow) are parallel to the rubbing direction of the substrates. Cylinders and segmented solid lines represent LC molecules and direction of the LC directors, respectively.

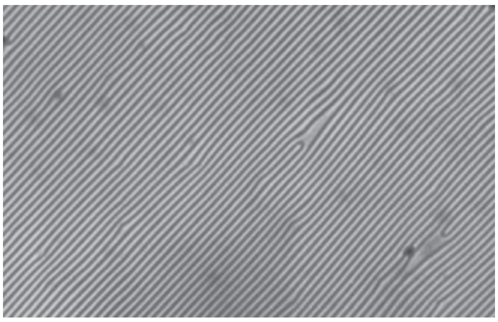

Fig. 4. Fingerprint texture of a CNLC film with film thickness of $d = 5.6\,\mu m$ and thickness-to-natural pitch ratio of $d/p_0 = 1.5$.

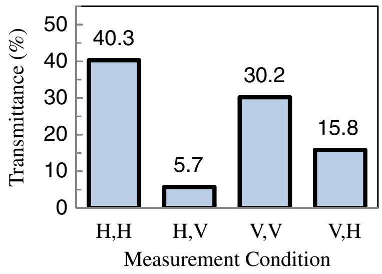

Fig. 5. (Color online) Total transmittance under the four measured conditions: (H, H), (H, V), (V, V), and (V, H).

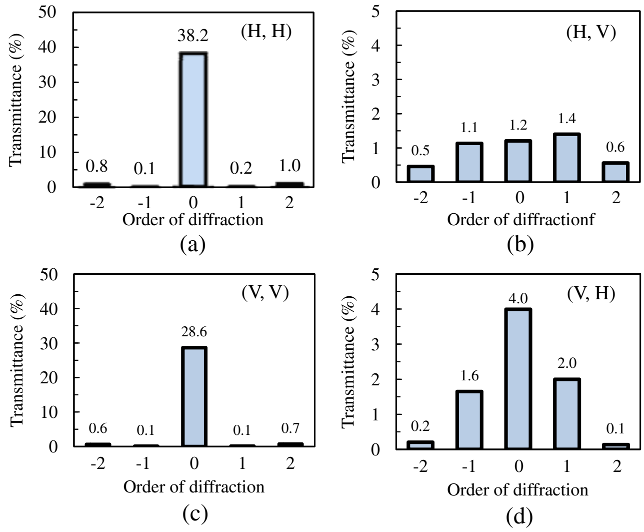

Fig. 6. (Color online) Measured transmittance of five diffraction orders: −2, −1, 0, +1, and +2. The four measured conditions are (a) (H, H), (b) (H, V), (c) (V, V), and (d) (V, H).

H and V components of the incident light shown in Fig. 2 will be diffracted by the fingerprint texture, although the diffraction phenomenon is similar to that of an ideal fingerprint. A simple example of the double-twist structure is shown in Fig. 3. The optical property is difficult to calculate using current simulation software, but the brightness enhancement capability of the CNLC film can be validated experimentally.

3. Experimental Procedure

In the experiment, the CNLC material was obtained by doping nematic E7 (dielectric constant $\varepsilon_0 = 19.0$, $\Delta\varepsilon = 13.8$ at 1 kHz, refractive index $n_e = 1.746$, $\Delta n = 0.225$ at 20 °C) with the chiral agent S811 (both from Merck). S811 had a helical twisting power of $1/p_0C = -11.3\,\mu m^{-1}$ at room temperature, where C is the dopant concentration in weight percentage. The chiral mixture was sandwiched between two glass substrates with indium–tin-oxide (ITO) electrodes. The CNLC film thickness is $d = 5.6\,\mu m$. The electrodes were coated with a commercial planar-parallel alignment layer, JSR-2021, and rubbed to provide a pretilt direction for molecular orientation. The rubbing alignment was antiparallel (180°). The applied voltage was an ac sinusoidal wave of $2.5\,V_{rms}$ at 1 kHz. Figure 4 shows the fingerprint texture observed under a polarizing microscope.

The measurement setup was arranged as shown in Fig. 2. The light source was a linearly polarized He–Ne laser. The polarizer was laminated to the CNLC film. At normal incidence, the linear polarizer together with an ITO glass substrate has maximum transmittance of ~92%. The 8% loss mainly results from surface reflections. Rotating the CNLC and polarizer independently, the transmittance of four combinations, (H, H), (H, V), (V, V), and (V, H), was measured. The two symbols of each condition represent the incident and transmitted polarization of light, respectively. For example, (V, H) means the CNLC cell was rotated to the condition where the incident light had only the V-component, and the polarizer was rotated such that the transmitted light through the CNLC-polarizer system had only the H-component.

4. Results and Discussion

First, we measured the total transmittance with a photodiode detector attached to the polarizer. Results are plotted in Fig. 5. Next, we measured the transmittance of each diffracted beam at a distance of 15 cm from the polarizer to avoid the other diffraction beams spreading to the same detector. The transmittance of five diffraction orders (−2, −1, 0, 1, and 2) was measured and results are shown in Fig. 6. For each of the four conditions: (H, H), (H, V), (V, V), and (V, H), the sum of the diffraction beam transmittances shown in Fig. 6 is always smaller than the corresponding total transmittance plotted in Fig. 5. One reason is that the total transmittance shown in Fig. 5

includes all the higher diffraction orders. Another reason is that our photodiode detector could not precisely measure the intensity of a diffraction beam at 15 cm from the polarizer because the diffracted beam might be larger than the sensitive area of the detector.

Figure 5 shows that, under the (H, H) condition, the result is very similar to the ideal o-ray condition shown in Fig. 2, in which most of incident H-component passes through the CNLC-polarizer system. Our experimental results demonstrate that, under the (H, H) condition, 40.3% of the H-component is transmitted through the CNLC-polarizer system and only 5.7% of the V-component is absorbed by the polarizer. On the other hand, under the (V, V) condition (e-ray), the diffraction phenomenon is obvious: only 30.2% of the incident He–Ne laser beam was transmitted, the other 15.8% is transformed to the H-component and absorbed by the polarizer.

The power distributions related to the diffraction orders are shown in Fig. 6. It can be seen that both the H and V components of the incident light are diffracted by the CNLC film. For the H-component incident light [Figs. 6(a) and 6(b)], most of the diffracted light intensity (38.2%) is concentrated at the H-component of the 0th-order. The polarization states of other diffraction orders change so that the light intensities of their V-components increase. This means that, under the (H, H) condition, a large part of the higher-order diffraction light is absorbed by the polarizer. On the other hand, for the V-component incident light, the diffraction phenomenon is obvious, as shown in Figs. 6(c) and 6(d). The power at higher diffraction orders became large, and the diffracted light changed the polarization state such that the total diffracted light had a larger H-component than the V-component. From the experimental results shown in Fig. 5, the transmittance could reach 15.8% under the (V, H) condition. Therefore, when a randomly polarized light is normally incident to the CNLC-polarizer system, the maximum transmittance is the sum of the transmittances of the (H, H) and (V, H) components and is 56.1%.

Because the transmittance through the polarizer and glass substrate was 46% for an unpolarized incident light, the optical efficiency increased by the CNLC film can be calculated as follows:

$$(56.1 - 46)/46 = 21.7\%. \qquad (2)$$

In this study, the angular dependence and bandwidth of the diffracted light are also very interesting. Figure 7 shows photographs of the CNLC film and polarizer on a LCD backlight module. In the area without a polarizer, with or without the CNLC film, the backlight brightness is almost the same. This implies that the CNLC hardly absorbs visible light. In addition, the light through the CNLC film seems to have no color dispersion at any viewing angle. It might be due to the fact that the LCD backlight is a random scattering light source and the diffracted light is mixed up so well that the angular dependence of the whiteness and bandwidth of the diffracted light does not seem to change.

5. Conclusions

We propose a CNLC-polarizer system that is applicable to LCD backlight modules. For an unpolarized incident light, the transmittance of the CNLC-polarizer system (56%) is better than that of an ideal polarizer (50%). The CNLC film increases the optical efficiency of a conventional polarizer by 21.7%. Some improvements, e.g., eliminating the glass substrates, substituting the CNLC film with a polymer film, antireflection coating, or other materials are still needed before the element is ready for practical application.

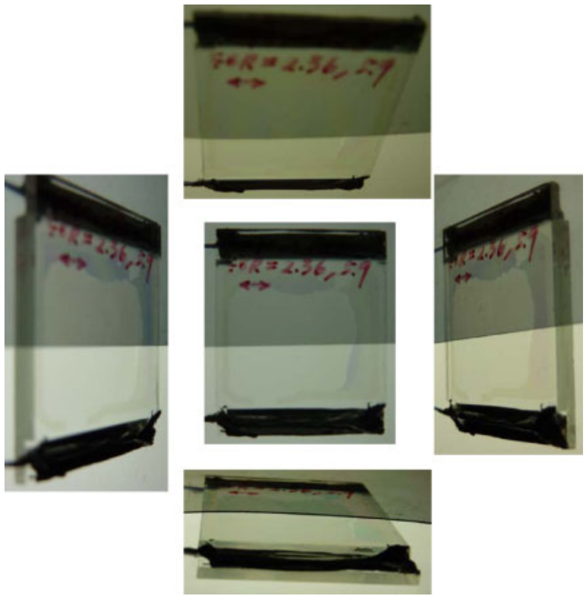

Fig. 7. (Color online) Photographs of the CNLC film between a linear polarizer and a LCD backlight module.

Acknowledgments

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