Turning film for widening the viewing angle of a blue phase liquid crystal display

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We report a new turning film structure for widening the viewing angle of a vertical-field-switching blue-phase liquid crystal display, which employs a directional backlight. The turning film consists of periodic prismatic structures: each period has three prisms with different base angles so that the output light can be spread to a larger angle. Simulation results show that a full width at half-maximum of ±80° in the horizontal direction and ±45° in the vertical direction can be achieved.

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1. Introduction

Polymer-stabilized blue-phase liquid crystal (PS-BPLC) [1–5] is emerging as the next-generation display technology [6] because of the following attractive features: no alignment layer, microsecond response time [7,8], and an optically isotropic dark state provided Bragg reflection is in the UV region [9]. Especially, the microsecond response time enables color sequential display, which eliminates color filters and consequently, both optical efficiency and resolution density are tripled [10,11]. However, its widespread application is hindered by the relatively high operation voltage.

To overcome the high operation voltage problem of a blue-phase liquid crystal display (BP-LCD), two major device configurations have been developed: (1) protruded in-plane switching (IPS) mode [12–17] with strong horizontal field and (2) vertical-field-switching (VFS) mode [18–20]. The IPS mode works well for normally incident light, whereas the VFS mode requires an obliquely incident directional backlight. Compared with the IPS mode, the VFS mode has advantages of a low driving voltage, no hysteresis, and faster response time due to the uniform and weaker electric field for achieving 1π phase retardation. However, the major challenge is the viewing angle, which is particularly important for large-sized displays.

We have investigated phase compensation schemes to achieve wide view in terms of contrast ratio [21]. Contrast ratio is mainly determined by the dark state. On the other hand, wide view in terms of brightness is equally important because contrast ratio can be very high as long as the dark state is good, even if the bright state is poor. Therefore, it is also desirable to obtain a uniform and wide brightness distribution.

In this paper, we report the design of a turning film structure to direct the modulated backlight to several different directions and then use a low-haze diffuser to achieve a uniform and wide brightness distribution. The full width at half-maximum

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(FWHM) of the brightness distribution is widened to ±80° in the horizontal direction and ±45° in the vertical direction.

2. Device Configuration

The structure of a VFS BP-LCD has been reported in [18]. Since a larger incident angle in the BPLC layer results in a larger phase retardation, which helps to reduce the operating voltage, a well-collimated backlight [22,23] with a 70° incident angle and a ±5° divergence angle is commonly used. The bottom coupling film is designed to couple such a directional light into the BPLC cell at a large incident angle and the top coupling film couples the light out of the BPLC cell to avoid total internal reflection (TIR). The turning film steers the output light in the viewer's direction. This design requires precise alignment between the top coupling film and the turning film, which increases the manufacturing complexity. Moreover, the sharp tip of the turning film poses two problems: (1) they could be damaged easily and (2) they could scratch the coupling film. To solve the alignment problem, here we combine the coupling film and the turning film into one turning film sheet, as shown in Fig. 1. A low-haze front diffuser is laminated on top of the turning film to help widen the viewing angle.

Figure 2(a) shows the proposed turning film structure. This turning film should be laminated on top of the analyzer. Because the light sources are usually placed on top or the bottom of the panel and the viewer is in the z direction, we assume that the y–z plane is the horizontal plane and x–z is the vertical plane. The central light is propagating in the vertical plane with incident angle $\theta = 70°$. The divergence angle is ±5°, with uniform intensity distribution, designated as BLU_1. In the x direction, the prisms have a periodic distribution. Each period consists of three prisms with different base angles φ_v covered by one display subpixel, as shown in Fig. 2(b). However, there is no need to align the prisms with the pixels. The purpose of designing different base angles is to steer the incident light in different directions so that the viewing angle in the vertical direction can be improved.

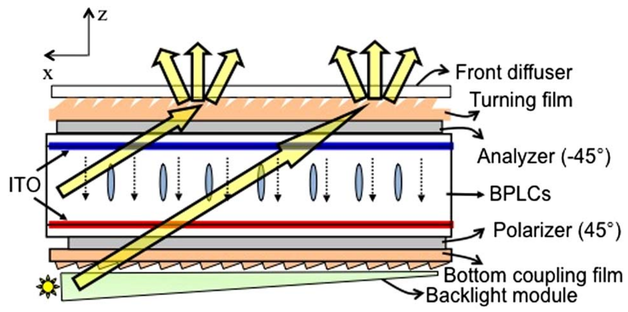

Fig. 1. Device configuration of the proposed VFS BP-LCD.

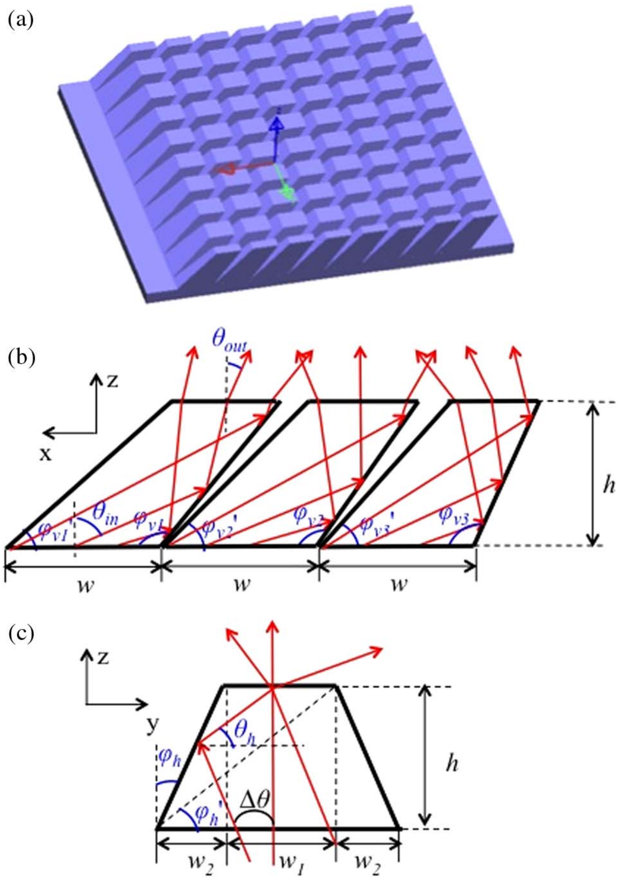

Fig. 2. Proposed turning film structure: (a) structure overview, (b) cross section of a single prism in the x–z plane, and (c) cross section of a single prism in the y–z plane.

To optimize the base angle φ_v, we need to consider following factors: (1) all incident light has to hit the right surface of the prisms and the incident angle on the right surface has to be larger than the critical angle so the light would experience TIR and (2) the reflected light is preferred to exit from the top surface instead of hitting the left surface. For example, to redirect the central light to the normal direction, φ_v should be 125° and φ_v' should be chosen according to the bottom width w and the divergence angle of the incident beam. Here we choose prism height $h = 30$ μm and bottom width $w = 36$ μm. Assuming the refractive index of the prisms is 1.5, the optimized angles φ_{v1}, φ_{v2}, and φ_{v3} for the three prisms are 133°, 125°, and 117°, respectively, and φ_{v1}', φ_{v2}', and φ_{v3}' are 36°, 42°, and 51°, respectively. The relationship between the input light with an incident angle θ_{in} and the output light with an output angle θ_{out} can be described by the following equation:

$$\sin\theta_{\text{out}} = n_p \sin(\theta_{\text{in}} - 2\varphi_v), \tag{1}$$

where n_p is the refractive index of the prism and φ_v is the base angle of the corresponding prism.

In the y direction, we design periodic isosceles trapezoid structures, as shown in Fig. 2(c). The central light can still exit the prism in the normal direction. For light with a small divergence angle $\Delta\theta$, after being reflected by the left or the right surface, the output angle becomes larger, and this helps to widen the viewing angle. The design principle for the prism is that light has to exit from the top surface after being reflected by the left or the right surface. In more detail, angle θ_h should be larger than φ'_h so the reflected light would not hit the right surface. Besides, the incident angle on the top surface, $90° - \theta_h$, should be smaller than the critical angle so the light can exit without TIR. After optimization, we choose $\varphi_h = 15°, w_1 = 14\ \mu\text{m}$, and $w_2 = 8\ \mu\text{m}$.

To obtain a uniform brightness distribution, a low-haze front diffuser [24] is laminated on top of the turning film in the design. A heavier diffuser helps improve the uniformity as well as the viewing angle, but it degrades the contrast ratio because it reflects the ambient light. Here, we assume that the diffused light has a Gaussian distribution $f(x) = \exp(-x^2/2\sigma^2)$ with standard deviation $\sigma = 20°$.

3. Simulation Results and Discussion

We use LightTools (version 8.0.0; Synopsys Optical Solutions) to simulate the brightness distribution with our designed turning film structure. A surface light source is employed in the calculation. In the simulation, the phase retardation of the BPLC is simply treated as 1π, without dispersion for different incident angles. There are two reasons for this treatment: (1) LightTools does not support the polarization simulation with angular dispersion and (2) the divergence angle is only ±5° and is even smaller inside the BPLC medium due to Snell's law. The phase retardation dispersion is negligible for such a small divergence angle. All simulations were conducted at $\lambda = 550$ nm.

Figure 3(a) depicts the calculated luminance distribution in the x–y plane as a reference with $\varphi_v = 125°$ and $\varphi_h = 0°$. The reference turning film just rotates the incident light to the normal direction without spreading the light. The horizontal direction is y axis and the vertical direction is x axis. Figure 3(b) shows the simulated results with the proposed turning film structure with $\varphi_v = 133°$, 125°, and 117° and $\varphi_h = 15°$. The viewing angle is greatly widened, while the peak luminance is lower than the reference because the total energy is conserved.

To achieve an even wider viewing angle, we employ a different backlight, designated as BLU_2 in the simulation. Since the phase retardation of the BPLC in the VFS mode depends only on the incident angle but not the azimuthal angle, we can use a backlight with a narrow polar angle distribution but wide azimuthal angle distribution. Such a backlight is easier to realize because it only requires one-dimensional convergence. To achieve such a backlight, we incorporated a prism sheet in our backlight design. The prism sheet has microstructures in the x direction to collimate light only in the x–z plane but diverges in the y direction. With such a backlight, the horizontal viewing angle is intrinsically wider with the reference turning film, as depicted in Fig. 4(a). With

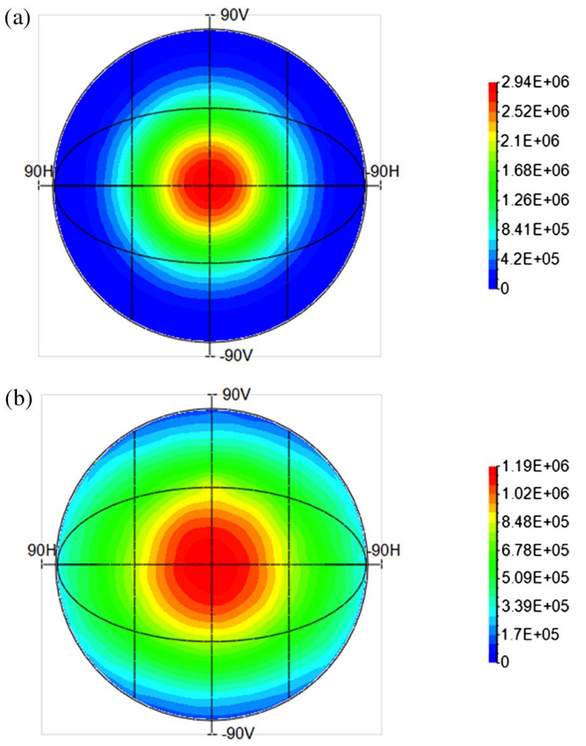

Fig. 3. Calculated brightness distribution using BLU_1. (a) Reference turning film with $\varphi_v = 125°$ and $\varphi_h = 0°$. (b) Proposed turning film with $\varphi_v = 133°$, 125°, and 117° and $\varphi_h = 15°$.

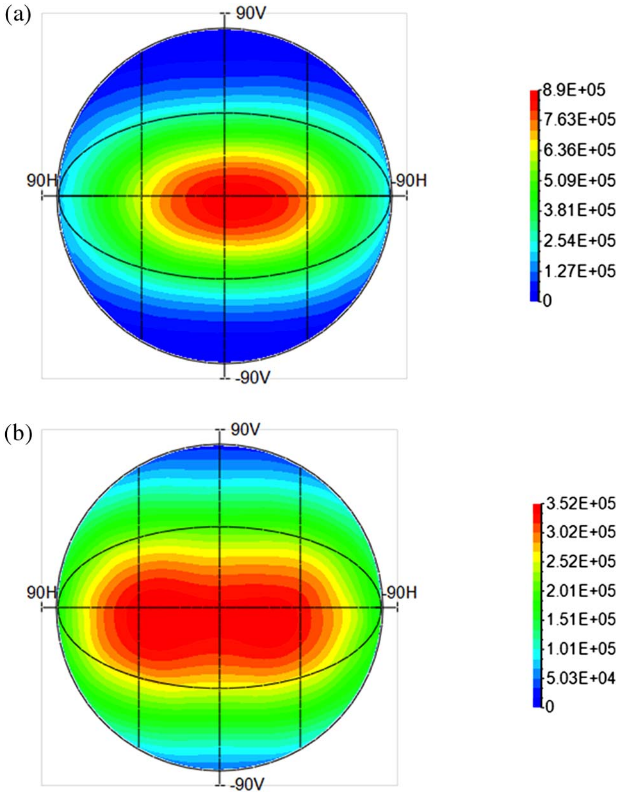

Fig. 4. Calculated brightness distribution using BLU_2 with wide azimuthal angle distribution. (a) Reference turning film with $\varphi_v = 125°$ and $\varphi_h = 0°$. (b) Proposed turning film with $\varphi_v = 133°$, 125°, and 117° and $\varphi_h = 15°$.

the proposed turning film structure, the brightness distribution is shown in Fig. 4(b). The viewing angle is even wider in the horizontal direction with BLU_2. The vertical viewing angle is narrower than the horizontal viewing angle, but it is more tolerable for a large-sized display such as a TV and a desktop monitor.

Figure 5 summarizes the calculated performances of the described configurations. Figures 5(a) and 5(b) depict the horizontal and vertical distributions, respectively. The proposed turning film structure helps to widen the viewing angle in both horizontal and vertical directions. With BLU_2, the vertical viewing angle is similar to that with BLU_1, but the horizontal viewing angle becomes even wider. The FWHM is widened to ±80° in the horizontal direction and ±45° in the vertical direction.

The challenge remaining for the proposed turning film is fabrication. However, its fabrication process is similar to that of brightness enhancement films, which have been used widely in backlight systems. As the manufacturing technology continues to advance, especially through optimization of the molding process, the fabrication of the proposed turning film should be possible in the near future.

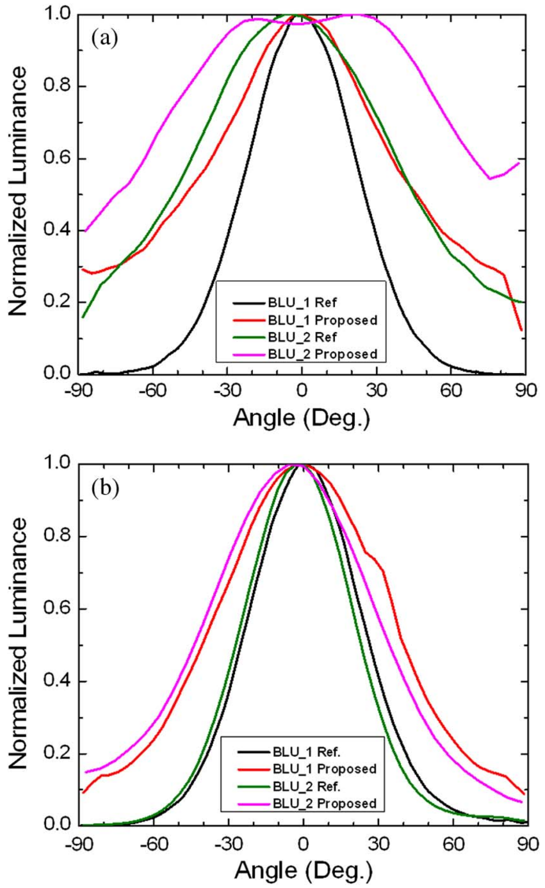

Fig. 5. Simulated brightness distribution in (a) the horizontal direction and (b) the vertical direction for the four described configurations.

4. Conclusion

We have designed a turning film structure to achieve a wide-view VFS BP-LCD. The proposed turning film helps to reduce the fabrication complexity of VFS BP-LCDs, has advantages of scratch resistance and does not need to register with LCD pixels, and enables using a lighter diffuser. Moreover, with the proposed turning film structure, the FWHM of the brightness distribution is widened to ±80° in the horizontal direction and ±45° in the vertical direction with a *light* diffuser.

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