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Luminance enhancement without sacrificing the viewing angle in a direct-lit backlight by addressing the angle-dependent characteristic of the prism film[☆]

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ABSTRACT

In a conventional backlight, suppression of light loss caused by the prism film(s) is desired to enhance the luminance without sacrificing the viewing angle. In this paper, in a direct-lit light-emitting diode (LED) backlight, where an LED array is placed under the display panel, the transmission efficiency against the prism film(s) is investigated for incident light with different zenith and azimuth incident angles. A strong angle-dependent characteristic is found, even when the reflective recycling effect is available. To address this angle-dependent characteristic in a direct-lit LED backlight, a freeform lens is designed to deflect the light emitted from an LED into the incident angle range with high transmission efficiency. Two design examples are implemented by adopting dual- and single-layer prism film(s). The simulation results show that the freeform lens can enhance the on-axis luminance by 26% and 35%, respectively, while the viewing angle remains nearly unchanged. Furthermore, using a single layer of prism film, a 19-in. direct-lit LED backlight module is constructed for experimental verification. By fabricating the freeform lenses and adding them to the backlight module, the on-axis luminance is enhanced by 24%, and the viewing angle is decreased by no more than 2°. Finally, the influence of the diffusers, which causes the experimental results to degrade slightly compared with the simulation results, is analyzed.

1. Introduction

Currently, although several emerging display technologies, such as organic light-emitting diode (OLED) displays, quantum dot (QD) displays, and micro light-emitting diode (LED) displays, are gaining increasing attention, liquid crystal displays (LCDs) using LED backlights still dominate the commercial display market [1–6]. Moreover, as has been widely predicted, LCDs will remain the dominating display technology for a long time because of their balanced performances and mature production technology [5,6]. In particular, for large-sized displays (e.g., TVs), it is too expensive for the emerging display technologies to be commercialized in a short time [2–4]; thus, it is necessary to further improve the performances of the LCDs currently on this market.

A backlight unit (BLU), comprising backlight sources and optical films, is an essential component of an LCD that provides light transmission through the LC panel, as shown in Fig. 1(a). BLUs can be categorized into edge-lit and direct-lit types, where the backlight sources are placed at the side of and under the LC panel, respectively [7]. Above the backlight sources, a bottom diffuser (diffuser #1) and one or two layers of prism films are placed; occasionally, a top diffuser (diffuser #2) is also used, as shown in Fig. 1(a). These optical films manipulate light from the sources to produce high uniformity, high luminance, and an appropriate viewing angle [7–15]. Of the optical films, the prism film(s), also known as brightness enhancement film (BEF) [7,10,12], plays an important role in enhancing the on-axis luminance by utilizing prism refraction to converge light into a narrower profile; the prism film(s) also ensures a high energy efficiency via the reflective recycling effect, as shown and explained in Fig. 1(b). Because of light convergence, the side effect of using prism film(s) is a narrower viewing angle, which is considered acceptable in some scenarios, e.g., the vertical direction of a TV. As a result, it is common practice to use prism film(s) in an LCD to achieve a higher on-axis luminance; however, the essential mechanism has been given little attention.

Essentially, using prism film(s) is a trade-off between luminance and viewing angle; in addition, a certain amount of light loss occurs [7,10,12]. The amount of light loss determines how much light energy

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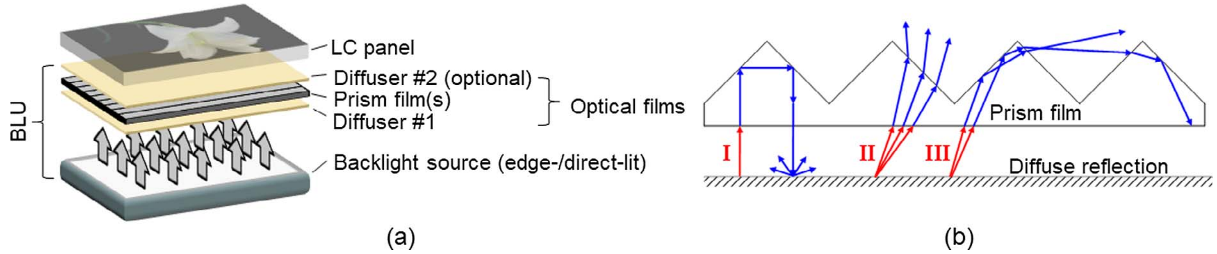

Fig. 1. (a) Typical configuration of an LCD; (b) working mechanism of a prism film: ray I is totally reflected and recycled by the diffuse reflection in the backlight, ray II is converged by the prism refraction and contributes to the effective luminance, and ray III contributes to the non-effective side lobe or is recycled by other prisms.

can be utilized for this trade-off; i.e., the luminance can be further enhanced without sacrificing the viewing angle by suppressing the light loss. Therefore, the goal of this paper is to investigate the light loss caused by the prism film(s), and address this loss mechanism to further enhance the luminance without sacrificing the viewing angle. By reviewing the working mechanism of the prism film(s) in Fig. 1(b), the behavior of incident light, which includes contributing to the effective luminance, the non-effective side lobe, or the recycled light, is related to the incident angle. Inspired by this observation, in this paper, we utilize simulations to investigate the behaviors of prism film(s) of different incident angles in the zenith and azimuth directions. The prism film(s) is found to exhibit a strong angle-dependent characteristic. In particular, a range of incident angles has quite low transmission efficiencies against the prism film(s), even when the reflective recycling effect is available, and thus contributes much less to the effective luminance than do those incident angles with high transmission efficiencies. To address the angle-dependent characteristic of the prism film(s), a direct-lit LED backlight, in which the light from the LED sources can be controlled by applying secondary optics on LEDs, is adopted [16–18]. Next, two cases, i.e., dual- and single-layer prism film (s), are studied. For either case, a freeform lens is designed to deflect the light emitted from an LED to the incident angular range with high transmission efficiency. The simulations results show that the freeform lens can significantly enhance the on-axis luminance while keeping the viewing angle nearly unchanged. In addition, the case of using a single-layer prism film is experimentally verified.

2. Angle-dependent characteristic of the prism film(s)

2.1. Construction of a direct-lit LED backlight module

To investigate the characteristic of the prism film(s), we constructed a 19-in. direct-lit LED backlight module. In this module, a backlight cavity, whose dimension is 401 mm (horizontal) by 255 mm (vertical) by 12 mm (thickness), contains a 40 by 25 white-light LED array with a pitch of 10 mm. The emitting area of each LED is 3 mm by 2 mm, and the interior surfaces of the backlight cavity are all diffusely reflective, with a reflectance of 90%. Next, as shown in Fig. 2(a), diffuser #1 from Nexteck Corp. (model: 100-BDN) is attached to a 1-mm-thick polycarbonate (PC) plate, which is also a diffuser, denoted as diffuser #0. If enhanced luminance is desired in both the horizontal and vertical directions, two prism films, denoted as prism #1 and prism #2, from 3M Corp. (model: BEF3-T-205n) are placed on diffuser #1, as shown in Fig. 2(a). The apex of prism #1 is perpendicular to the horizontal direction of the display panel for luminance enhancement in the horizontal direction, and prism #2 is orthogonal to prism #1 for luminance enhancement in the vertical direction. If luminance enhancement is only desired in the horizontal direction, only prism #1 is used. The detailed structure of the prism film is shown in Fig. 2(b). Fig. 2(c) shows the power-on status of the backlight module. Moreover, we set up this exact backlight module in the LightTools software but do not apply the diffusers such that the incident angle of the light propagating onto the prism film(s) is equal to the emitting angle of the light emitted from the LEDs, defined by the zenith angle θ and azimuth angle φ, as shown in Fig. 2(d). In such a simulation model, the behaviors of the light propagating onto the prism film(s) with different incident angles can be investigated by controlling the light emitted from the LEDs.

2.2. Two layers of crossed prism films

First, two layers of crossed prism films (prisms #1 and #2) are adopted for luminance enhancement in the horizontal and vertical directions. Using the LightTools software, the zenith emitting angle θ of the light emitted from the LEDs is restricted in the ranges of θ = 0–5°, 5–10°, …, 85–90°, sequentially. Such a restriction of the emitting angle generates a series of segmental sources corresponding to different zenith emitting angles. For example, Fig. 3(a) shows two segmental sources. Next, the transmission efficiency of each segmental source, given by the ratio of the luminous flux escaping from the cavity to that the LEDs emit, is simulated and plotted in Fig. 4(a). In Fig. 4(a), the maximum efficiency is only approximately 60%, which is caused by the reflective recycling effect. For the light of an arbitrary incident angle, part of it directly transmits through the prism films, while the rest is reflected back to the backlight cavity, which is then reflected by the diffusely reflective surfaces of the backlight cavity. A small amount of light energy is lost during the reflections; moreover, the diffuse reflection produces new light of all the other incident angles, which further limits the overall transmission efficiency. Because a number of reflections and refractions occur as the light rays of a certain incident angle propagate in the cavity, the overall transmission efficiency is very difficult to theoretically calculate; as a result, simulations are utilized to investigate the transmission efficiency. In addition, the zenith angular range of θ = 20–75° has a transmission efficiency higher than 50%, which means that incident light in such a range contributes to the effective luminance more than other light rays do; i.e., the effective luminance will benefit from sources only emitting light at this “high-efficiency angular range”. Next, based on LEDs emitting light only in this zenith angular range of θ = 20–75°, we continue to restrict the azimuth angle φ in the ranges of φ = 0–10°, 10–20°, …, 350–360°, sequentially, to generate a series of azimuth segmental sources, as shown in Fig. 3(b). Similarly, the transmission efficiency of each azimuth segmental source is simulated and plotted in Fig. 4(b). In each quadrant, an azimuth angular range with a transmission efficiency higher than 50% can be found: φ = 20–70°, 100–160°, 200–260°, and 290–340°. Theoretically, two crossed prism films should give the transmission efficiency axial symmetries along both φ = 0–180° and φ = 90–270°. However, in a direct-lit backlight with a finite dimension, both reflections on the interior surfaces of the backlight cavity and positions of the LEDs relative to the prism films affect the transmission efficiency slightly. As a result, from Fig. 4(b), although two axes of symmetry can be generally found, the axial symmetries are not perfect. Such an asymmetry depends on the specific configuration of a backlight; thus, the transmission efficiency should be investigated based on specific cases. In summary, for two layers of crossed prism films, the transmission efficiency is found to have a significant angle-dependent characteristic, and the angular ranges with high efficiency are found to be θ = 20–75° and