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Polarized Light Out-coupling in Backlight by Collimating the Beam into Lightguide Plate

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Abstract

We developed a new configuration of polarized light out-coupling lightguide plate (LGP) in the LCD backlight. By collimating the light into the LGP, one linear polarization component experienced total internal reflection at the planar interface of LGP and anisotropic layer, whereas the orthogonal polarization was out-coupled along the normal direction through a birefringent layer and subsequent isotropic microstructures.

Keywords : lightguide plate, backlight, total internal reflection, collimator, polarization separation, anisotropic layer

1. Introduction

The overall light efficiency of conventional LCDs is limited to approximately 5%. One of the main reasons for such poor efficiency is the light absorption in the linear polarizers.

To improve the LCD performance by using non-absorptive polarizers, two main approaches were studied. One is using reflective polarizers that transmits one linear or circular polarization and reflects the orthogonal polarization [1, 2]. But these reflective polarizers are not cost-effective and have poor recycling mechanisms, resulting in the limited light efficiency improvement.

An alternative approach is integrating the polarizing and recycling functions in the LGPs, which directly emit linearly polarized light and recycling the orthogonal polarization [3-6]. In most of the earlier works, the polarization separation was achieved in the microstructures between an isotropic LGP and an anisotropic film laminated onto it. However, these approaches have some drawbacks such as complicated manufacturing processes including diamond-cutting the anisotropic film and possible scattering losses at the microstructured interface.

In this paper, we propose a new type of polarized light out-coupling LGP, where one linear polarization experiences total internal reflection at the planar interface between the isotropic LGP and the anisotropic layer.

2. Simulation and Experimental Results

We first estimated the polarization out-coupling efficiency of our proposed idea by comparing it with a polarized LGP using a microstructured interface [4], which is composed of a microstructured isotropic LGP and the anisotropic layer laminated onto it. In that LGP, the polarization separation and out-coupling occur mainly due to the total internal reflection (T.I.R) at the isotropic/anisotropic interface, as shown in Fig. 1(a). The integrated intensity of out-coupled s-polarized light has some limitations because not all the s-polarization rays can meet the critical angle condition of the T.I.R. According to our new configuration as depicted in Fig. 1(b), the incident light from the light source is collimated upon entering the collimator-integrated LGP. Thus, the p-polarized light can be reflected back into LGP at the planar isotropic/anisotropic interface by T.I.R, and the perpendicular s-polarization refracted through the index-matched interface can be out-coupled more efficiently by optimally designed subsequent isotropic microstructure. Fig. 1(c) shows ray tracing simulation results for the out-coupled luminance distribution as a function of the inclination angle.

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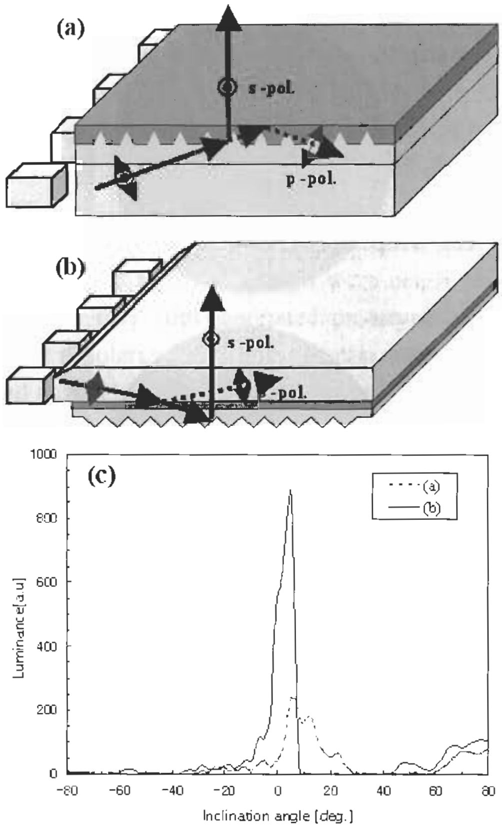

Fig. 1. Schematic of (a) a polarized LGP using a microstructured interface, (b) proposed new configuration, and (c) simulation results.

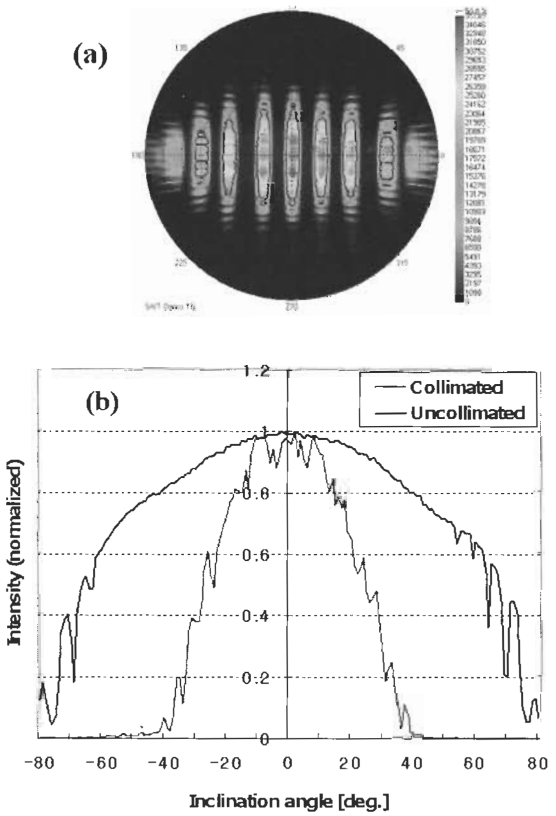

Fig. 2. (a) Measured angular luminance distribution of a collimator-unified LGP and (b) cross-section of the luminance at an azimuth angle of φ=90°

Microstructure dimension and the refractive index data are from [4] for a polarized LGP using a microstructured interface. For our new configuration, a collimator was integrated with a glass LGP, which has high refractive index (n_{LGP}=1.64). The incident light was collimated within ±20° inclination angle through the collimator. A uniaxial-like anisotropic layer (n_e=1.66, n_o=1.56) for the polarization separation was laminated beneath the LGP using the isotropic adhesive (n_{adh}=1.67). The extraordinary index of refraction, n_e, of the laminated anisotropic layer was aligned with the s-polarization direction. To obtain the maximum s-polarized light intensity along the normal direction, the prismatic microstructure made of isotropic resin (n_{out}=1.67) was designed and its apex angle was 110°. The LGP with our new configuration had about four times higher luminance along the normal direction and two times more luminous intensity than the conventional polarized LGP with a microstructured interface, as can be clearly seen in Fig. 1(c).

In the light of the above idea, we have fabricated the new configuration of highly efficient LGP for the edge-lit backlight unit (BLU). For the p-polarized light component which travels from an optically more dense LGP(n_{LGP}=1.64) to a medium with a lower refractive index (n_o=1.56), the critical angle for T.I.R is θ_c = 72°. As a result, to completely separate the p-polarized component, it is required that the incident light from the light source of LEDs be collimated within ±18° from the beam propagation direction. But the collimating capability of the collimator should not be compromised with the compactness and high coupling efficiency of LGP.

Various kinds of collimators were designed to fulfill the above-mentioned functions. As an example, one side of end facet of the LGP was tapered to the angle of about 4° within the very short range, as shown in Fig. 1(b). The angle of the incident rays decreases upon impinging on the inclined surface of the taper, resulting in the collimated beam distribution. To confirm the extent of collimation, we measured the emanating light distribution from the other flat end facet of the LGP using an EZcontrast 160R conoscope (Eldim, France). Fig. 2 manifests the collimating ability of our LGP-unified collimator, which shows the incident light into the LGP to be collimated within ±20°(FWHM).

As an anisotropic layer for polarization separation, we first adopted a polyethylene terephthalate (PET) film, which was uniaxially stretched using a tensile tester equipped with a thermostatically controlled oven. To maximize the refractive index difference between the machine- (MD) and transverse-direction (TD), we controlled such parameters as temperature and draw ratio, etc. The refractive indices of the PET film stretched at 85°C to a draw ratio of 4.5 were $n_{MD}=1.66$, $n_{TD}=1.56$ and $n_z=1.54$. The stretched film was subsequently laminated onto an LGP using index-matched resin, which was then cured with UV light. The liquid crystal polymer (LCP) was also applied as a birefringent material. For example, the reactive mesogen solution, RMS03-001 (Merck), was spin-coated on the rubbed LGP, which was subsequently polymerized using UV light. The refractive indices were $n_o=1.53$ and $n_e=1.68$. As a result of this refractive index distribution, the p-polarized light experienced T.I.R at the isotropic/anisotropic interface and could be recycled, while the s-polarized light passed through the interface since the refractive index was virtually matched between those layers (see Fig. 1(b)).

To out-couple the s-polarized light, another isotropic layer with microstructures was coated using the conventional UV replication method. The resin was carefully chosen such that the refractive index of the layer after photo-polymerization was the same as the extraordinary refractive index of the anisotropic layer. We optimized the apex angle of the prismatic microstructure to be 110° (full angle) for the out-coupling of the s-polarized light mainly along the normal direction.

We have investigated the optical behavior of the polarized LGP experimentally by illuminating it in a side-lit configuration using four LEDs as the light source. The luminance of the angular light distribution from the LGP was measured using the EZcontrast 160R conoscope. To determine the selectivity of the backlight to the polarization direction of the light, we have placed a polarizer in between the backlight and the detector. The polarizer could be rotated to have its transmission axis parallel or perpendicular to the extraordinary direction of the birefringent layer. (s-pol. direction in Fig. 1)

The measured angular luminance distributions for the s- and p-polarization direction in the case of a PET film laminated polarized LGP are shown in Fig. 3(a) and 3(b), respectively, where the angular distributions are plotted as a function of azimuth angle,φ, ranging from 0° to 360°, and the inclination angle,θ, ranging from 0° to 80°. From these figures, it is clear that the backlight produces significantly more s-polarized light than p-polarized light. The s-polarized light is out-coupled from the LGP approximately along the normal direction. The p-polarized light is lower in intensity and its peaks at the $\theta = 40°$ inclination angle along the direction of azimuth angle $\varphi = 0 - 180°$ are supposedly attributed to non-polarization selective scattering or leakage from the light of adjacent LEDs. The contrast, defined as the luminance ratio of the s-polarized light to the p-polarized light [4], is plotted again as a function of the azimuth angle and the inclination angle. Fig. 3(c) shows the exceptionally high s/p polarization ratio of our polarized LGP prototype, where the contrast along the normal is 154

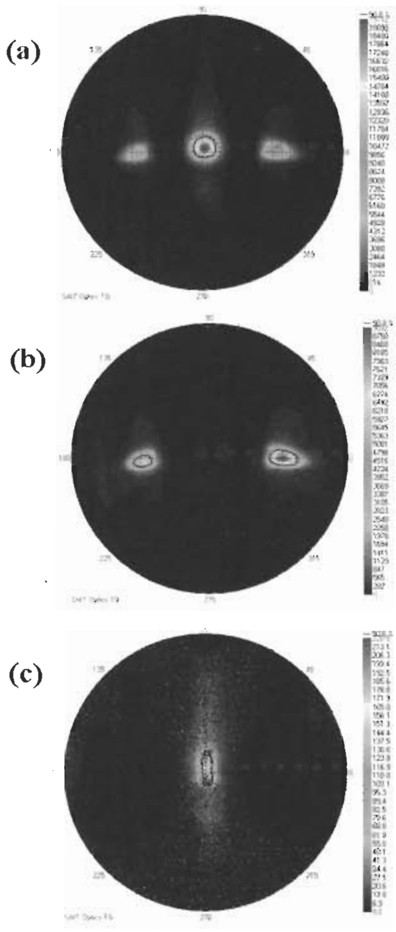

Fig. 3. Measured angular luminance distribution of (a) s-polarized light, (b) p-polarized light and (c) the s/p contrast from the PET film laminated polarized LGP prototype.

and the local maximum exceeds 200. The integrated intensity of the s-polarized light over all measured angular range (80°) is I_s=1974lm/m^2, which is approximately 3 times higher than that of the p-polarized light, I_p=674lm/m^2.

For the polarized LGP coated with a liquid crystal polymer, the similar angular luminance distributions were measured. The values of peak luminance and integrated intensity for the s-polarized light were nearly the same as those of the PET film laminated prototype. On the other hand, the p-polarized light had similar integrated intensity over all angles but higher peak luminance along the normal, resulting in the lower contrast ratio of 43. We attribute this p-polarized light leakage mainly to the disordering of LCP, thus expecting the enhanced contrast ratio if the alignment of the LC material and the surface roughness of the LGP had been improved.

Ideally, the collimated p-polarized light will be totally reflected into the LGP at the interface of anisotropic layer and consequently will not be extracted. Fig. 4 shows the numerical modeling results using a commercially available Monte-Carlo ray tracing software in the case of an LCP coated polarized LGP. The intensity of p-polarized light is clearly suppressed as shown in Fig. 4(b) and the calculated integrated intensity ratio of s-polarized light to p-polarized light can reach a factor of 180. This result implies that the performance of our polarized BLU prototype may be improved further. For instance, if the incident light is collimated in the azimuth direction as well it will greatly enhance the s/p integrated intensity ratio.

3. Conclusion

We have proposed and fabricated a new configuration of polarized LGP, where the s-polarized light is selectively separated and out-coupled along the normal direction. Using a collimator unified LGP, the p-polarized light is totally internally reflected at the interface of the isotropic and anisotropic layers. Our polarized LGP prototype shows the s/p luminance ratio of 154 along the normal direction. This extremely high luminance contrast and the increased integrated intensity of the out-coupled light should greatly improve the light efficiency of LCDs. Furthermore, because the polarization separation occurs at the planar interface between an isotropic LGP and a birefringent layer, the structure and manufacturing process of a polarized LGP can be simplified. Thus, this approach is expected to improve performance and reduce cost in the LCDs.

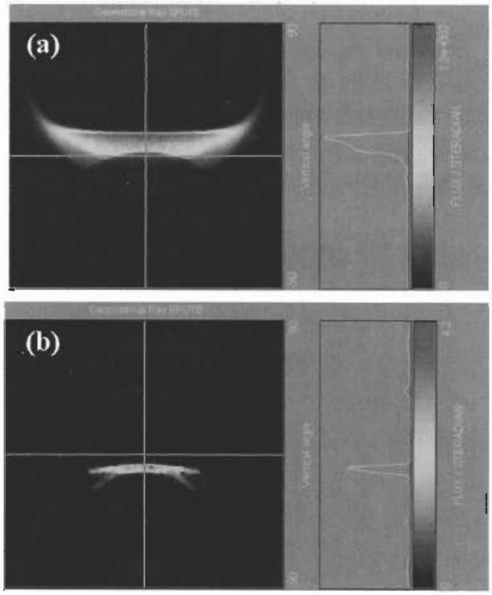

Fig. 4. Calculated angular distribution of (a) s-polarized light and (b) p-polarized light in the case of an LCP coated polarized LGP.

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