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Dependence of the Gain Factor of the Reflective Polarizer on the Configuration of Optical Sheets

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Abstract

The correlation between the optical performance of the reflective polarizer, which is a key optical component for the brightness enhancement of the liquid crystal display (LCD), and the configuration of optical sheets was investigated in a direct-lit CCFL (cold-cathode fluorescent lamp) backlight. The optical gain of the reflective polarizer, the polarization state of the light emitted from each film, and the loss factor for the polarization conversion process occurring in the lower part of the backlight were determined using a phenomenological approach for the polarization recycling process. The present study suggests that the correlation between the optical performance of the brightness enhancement films and the backlight configuration should be carefully considered in the optimization of the backlight structure.

Keywords : LCD backlight, reflective polarizer, gain factor, loss factor

1. Introduction

The reflective polarizer is one of the key components for the brightness enhancement of liquid crystal displays (LCDs). This optical sheet recycles the orthogonal polarization component, which is perpendicular to the transmission axis of the LCD panel's bottom polarizer, of the incident light from the backlight unit (BLU) by reflecting it downwards. Some of these downward rays are diffusely reflected on or transmitted through the optical components of BLU, such as a diffuser plate (DP), a diffuser sheet (DS), light sources, and a diffuse reflector, where their polarization state may be changed and recycled.

There are three types of reflective polarizers: the multilayer type [1], the wire grid type [2], and the cholesteric-liquid-crystal (CLC) type [3]. Among these, the multilayer-type reflective polarizer is the most widely used in the LCD technology. It may be included in the BLU or directly attached to the bottom surface of the LCD panel. The optical performance of the reflective polarizer is substantially affected by the polarization conversion process, which takes place in the lower part of the BLU (i.e., the optical sheets and light sources). Therefore, the overall optical gain obtained by the reflective polarizer can be increased only if the detailed correlation between the reflective polarizer and the optical configuration of the BLU is revealed.

There are few reports so far on the aforementioned subject, however, which include these authors' previous studies [4-7]. Part et al. showed that the optimization between the prism sheet and the reflective polarizer is very important for the improvement of the overall performance of BLU [4]. You et al. showed that the optical gain by the reflective polarizer is greatly affected by the structure of the light source and by the configuration of the optical sheets [5-7]. The present study reports a more detailed correlation between the optical performance of the reflective polarizer and the configuration of the optical sheets. The study's results may be used to optimize the backlight structure and to thus attain the best combination of optical sheets for a given light source.

2. Experiments

Fig. 1 shows a schematic diagram of the experimental setup that was used in the present study. A 32-inch direct-lit CCFL (cold-cathode fluorescent lamp) BLU was used for

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the measurement. Included in this BLU were 16 CCFLs with an outer diameter of 3 mm. Various combinations of conventional optical sheets were placed over the CCFLs for luminance measurements, such as a diffuser plate (DP), a diffuser sheet (DS), a one-dimensional prism film (BEF II from 3M, abbreviated as "BEF"), and a reflective polarizer (DBEF-D from 3M, abbreviated as "DBEF"). The sheets were attached to one another with minuscule air gaps between them. Such air gap conditions between the films are the same as the one in which they are combined in the commercial backlight unit. To these optical-sheet combinations was attached an absorptive polarizer whose transmission axis was set to be parallel to that of DBEF, and the normal luminance was measured using a colorimeter (PR670, Photo Research), first without and then with DBEF. In this measurement, the gain factor in the normal luminance by DBEF can be calculated. In addition, the normal luminance on each sheet was measured as a function of the angle of the transmission axis of the absorptive polarizer with respect to the reference direction (horizontal direction). This experiment was conducted to investigate the polarization state of the light that was transmitted to or reflected on each optical sheet. All the experiments were carried out at the temperature of 25 ± 1^{o}C and without any noticeable wind and ambient light.

3. Results and Discussion

Based on the operating principle of the reflective polarizer [1-3], a simple phenomenological approach for the polarization recycling process in BLU was suggested by Watson et al. [8]. In this approach, the incident light power on the bottom surface of DBEF is divided into the desired one (P_H), whose polarization is parallel to the transmission axis of DBEF, and the undesired one (P_V), whose polarization direction is orthogonal to that of P_H. It is assumed that P_H passes through while P_V is reflected 100% from DBEF without any absorption loss. The components of BLU, except for DBEF, will be called "conversion element" because they contribute to the polarization change of the downward rays from DBEF for polarization recycling. These downward rays (P_V) will experience one of three possible processes: Some of them will change their polarization state into P_H, some will remain in the same state (P_V), and the rest will disappear via some absorption loss processes. Each power portion of these three groups of rays with respect to that of the total downward rays will be denoted as c, s, and L_c, respectively, where $c+s+L_c$ should be 1 according to the amount of energy conserved [8]. When the conversion element includes diffuse reflecting/transmitting components such as DP, DS, or the diffuse reflector located below the CCFL, it may be assumed that $c=s$, i.e., half of the total power of the reflected rays from the conversion element will change their polarization state via diffuse reflection/transmission. The total transmitted power via DBEF can be calculated by considering a series of transmission, reflection, and loss processes occurring between the DBEF and the conversion element. The loss factor of the conversion element can be calculated from the measured optical gain factor G of the DBEF and the power of the two polarization states (P_V/P_H), as follows:

$$L_c = 1 - 2c == \frac{P_V / P_H - G + 1}{P_V / P_H + G - 1} \qquad (1)$$

The optical gain factor G of the reflective polarizer is defined by the ratio of the total transmitted power of DBEF to the power of the light of the same polarization without DBEF (P_H). Ref. [7] and [8] present more details about the derivation of this equation.

Fig. 2 shows the dependence of the luminance on the angle of the transmission axis of the absorptive polarizer on one investigated configuration of optical sheets in CCFL BLU. The light emitted from DP and DS is completely unpolarized due to the interaction between the rays and the randomly dispersed beads in these sheets. The light is polarized on the prism sheet (BEF) by about 8%, as has been reported [7]. The luminance with vertical polarization is larger than that with horizontal polarization on the one-dimensional prism sheet. Since the prism grooves are aligned along the horizontal direction in the direct-lit BLU, the rays with the horizontal polarization state (s-polarization) will be reflected more than those with vertical polarization (p-polarization), according to Fresnel's equations [9]. To confirm this suggestion, one more BEF with prism grooves of the same direction was put on the first BEF, and the same measurement was carried out, although two BEFs with the same groove direction is never used in the real BLU. As expected, the light emitted from the two BEFs was more polarized by about 4% than that emitted from the single BEF. Therefore, it can be concluded that the prism film plays the role of a very weak polarizer, which should be considered in the optimization of BLU and of the

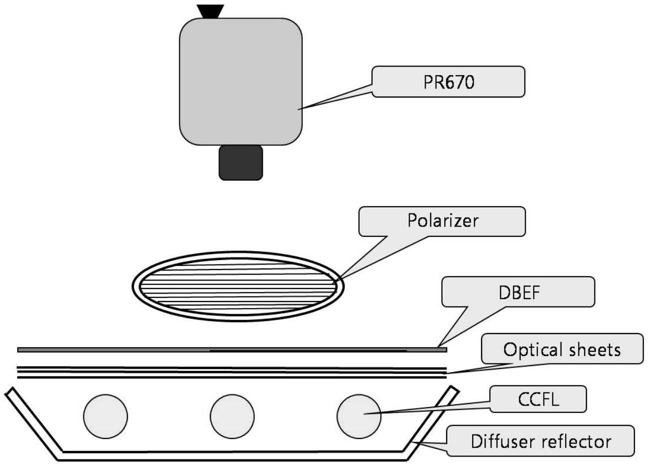

Fig. 1. A schematic diagram of the experiment setup that was used in the present study to estimate the optical gain factor of the reflective polarizer.

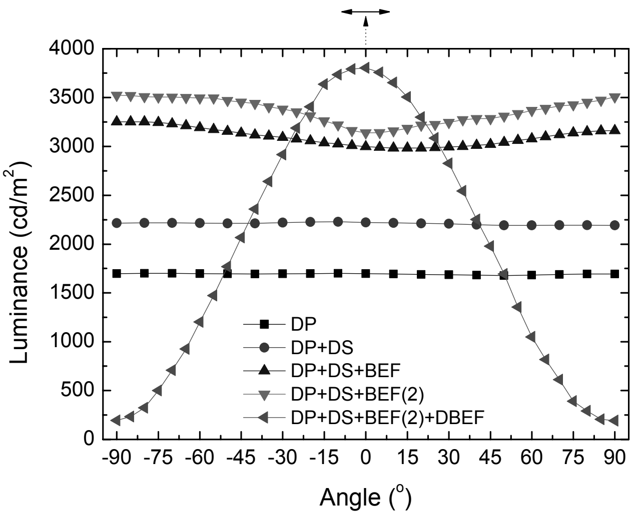

Fig. 2. The dependence of the luminance on the angle of the transmission axis of the absorptive polarizer on each configuration of optical sheets in the CCFL BLU. The 0-degree angle refers to the condition in which the transmission axis of the polarizer is horizontal (i.e., parallel to the direction of the prism grooves as well as to the transmission axis of DBEF). BEF(2) indicates that two BEFs are included. The transmission axis of the polarizer is denoted by the two-head arrow.

LCD panel for better performance.

Before the application of Eq. (1) to the measured data, an additional experiment was carried out to determine whether the assumption “*c*=*s*” is plausible in the backlight. For this purpose, a vertically polarized light from a diode-pumped solid-state laser (DPSS, MONOPOWER-532-100-SM, Alphalas) at the wavelength of 532 nm was applied to a diffuse reflector, from which the reflected light was made to pass through DP and DS. This configuration is one of the many possible routes that the light experiences before it meets the DBEF again. The final beam was found to be unpolarized, which was checked by using an analyzer and a laser power meter (PM120, Thorlabs). This result justifies the adoption of the assumption “*c*=*s*” to the analysis. Table 1 summarizes the normal luminance on several configurations of optical sheets, both with and without DBEF. The absorptive polarizer whose transmission axis was parallel to that of DBEF was inserted between the BLU and the colorimeter, as shown in Fig. 1. It should be pointed out that two DPs or two BEFs with the same groove direction, which were used in the present study to determine if there is a correlation between the performance of DBEF and the sheet configuration, are not used at all in the real backlights. Eq. (1) was applied to the measured data, and the conversion and loss factors were obtained, as shown in Table 1. Several interesting characteristics can be gleaned from these results.

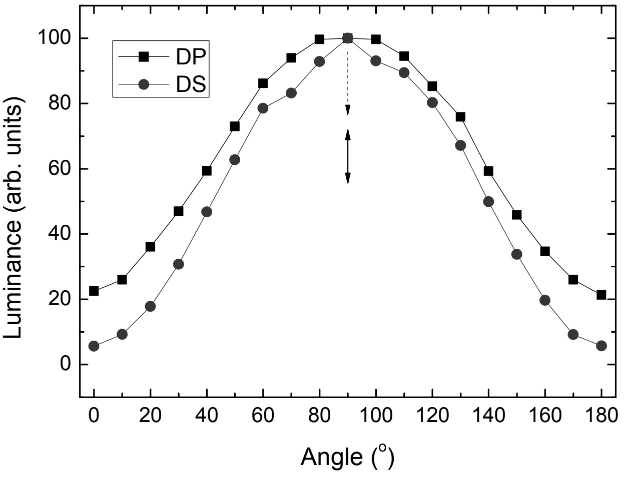

Fig. 3. The dependence of the normalized luminance of the transmitted beam on the angle of the transmission axis of the polarizer measured on DP and DS, where 90° indicates the condition in which the transmission axis of the polarizer is set to be vertical (i.e., parallel to the polarization of the incident laser beam). The transmission axis of the polarizer is denoted by the two-head arrow.

First, the gain factor G (the loss factor L_c) becomes the highest (lowest) on DP. DP is made from a transparent plastic plate in which small beads of a refractive index different from that of the plate are randomly dispersed. Since the rays passing through DP experience multiple reflection and refraction at the boundaries between the microbeads and the

Table 1. Luminance values on an absorptive polarizer that was placed in the CCFL BLU at various combinations of optical films measured without and with DBEF. The transmission axis of the absorptive polarizer was set to be parallel to that of DBEF. The gain factor *G*, P_V/P_H, the conversion ratio *c*, and the loss factor *Lc* of each combination are also shown in the table.

Configuration	**Luminance without DBEF** (cd/m^2)	**Luminance with DBEF** (cd/m^2)	**Gain Factor** (***G***)	P_V/P_H	**Conversion Ratio** (***c***)	**Loss Factor** (L_c)
DP	1696	3005	1.77	1	0.44	0.13
DP+DP	1584	2662	1.68	1	0.41	0.19
DP+DS	2225	3419	1.54	1	0.35	0.30
DP+DS+DS	2464	3435	1.39	1	0.28	0.44
DP+BEF	2654	3788	1.43	1.05	0.29	0.42
DP+DS+BEF	3054	4041	1.32	1.08	0.23	0.54
DP+DS+DS+BEF	2807	3558	1.27	1.07	0.20	0.60
DP+DS+BEF+BEF	3138	3804	1.21	1.12	0.16	0.68

bulk material of DP, there is a high probability of polarization conversion of the incident light. DS shows a smaller *G* (thus, a higher loss factor L_c) than DP does, indicating that the conversion efficiency of DS may be worse than that of DP. This may be noticed in the simple experiment result shown in Fig. 3. In this experiment, a vertically polarized light from the DPSS laser at the same wavelength of 532 nm was applied to DP or DS, and the polarization state of the normally transmitted light was analyzed using an absorptive polarizer and a luminance meter. The dependence of the normalized luminance on the angle of the transmission axis of the polarizer is shown in Fig. 3, where 90^o indicates that the transmission axis of the polarizer is set to be vertical (i.e., parallel to the polarization of the incident laser beam). As can be seen in the same figure, the distribution of the polarization state of DP is wider than that of DS, which indicates that DP scatters the polarization state more effectively than DS does. The full width at half-maximum (FWHM) is 114^o on DP and 98^o on DS. In this context, the prism sheet is even worse than DS because the surfaces of BEF are specular rather than diffuse and are thus expected to be poor at the polarization conversion for the downward rays from DBEF.

Second, the loss factor L_c becomes higher as the number of optical sheets included in BLU increases. For example, the configuration of one DS on DP shows a loss factor of 0.33 while that of two DSs on DP exhibits an L_c of 0.44. Similar trends can be seen in other configurations, such as DP and DP+DP, or DP+DS+BEF and DP+DS+BEF+BEF. As more optical sheets are included in BLU, the probability that the rays reflected from DBEF that experience multiple reflections between the sheets will become bigger and will thus have a greater chance of being absorbed by the components of BLU, resulting in a lower optical gain and a higher loss factor. Similar results were obtained from the experiments carried out on CCFL and flat-lamp backlights at the same configuration of the optical sheets, where the loss factor of the flat-lamp backlights was much higher than that of CCFL BLU due to the much more complex internal structure and thus much higher possibility of absorption of the flat fluorescent lamps [5-7]. These results suggest that the reduction of the loss factor of the conversion element is very important for the optimization of the backlight structure and for enhancing the optical performance of the reflective polarizer.

4. Conclusions

To conclude, the correlation between the optical performance of the reflective polarizer and the configuration of the optical sheets was investigated by using a 32-inch CCFL backlight and the conventional optical sheets used in the commercially available LCD TVs. The optical gain factor of the reflective polarizer increases as the diffuse nature of the optical sheet is enhanced since the possibility of the polarization conversion becomes higher when the light is transmitted or reflected from more diffuse layers. In addition, the loss factor of the conversion element becomes higher as the number of optical sheets included in BLU increases. This is ascribed to the more frequent multiple reflections between the sheets, during which the rays reflected from the reflective polarizer may disappear due to the increased probability of absorption. The present study revealed that the low loss factor of the conversion element is of paramount importance to the improvement of the reflective polarizer in backlights for LCD applications.

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