Analysis of the Luminous Effect by the Patterns of Light Guide Plate Combined with Side-Emitting System

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A light guide plate (LGP) applied to an edge-type backlight unit is combined with a plastic optical fiber (POF) optical system, and a scattering pattern is applied at the bottom of the LGP. Then, the luminous effect of the LGP on the light emitted from the light source is analyzed. The proposed side-emitting system is bent to surround the edge of the LGP, and the light-emitting diodes (LED) are combined at the end of a POF. Computer simulations are performed to realize indirect light by controlling the light from the light-emitting holes in the cladding of the POF. In this paper, the illuminance produced inside the LGP due to the light-emitting grooves of the side-emitting system and the uniformity of the brightness of the upper portion are analyzed to confirm the efficiency of the side-emitting system coupled with the LGP. In addition, to establish the criteria for the LGP processing condition combined with the side-emitting system, we optimize the control conditions of the light-emitting holes in the cladding and the conditions of the scattering pattern at the LGP bottom to improve the optical characteristics of the LGP. Thus, the low-efficiency problem can be addressed from an optical perspective.

Keywords: Light guide plate (LGP), Plastic optical fiber (POF), Scattering pattern, Illuminance, Uniformity

I. Introduction

Liquid-crystal displays (LCDs) are widely used as flat-panel displays because they have the advantages of applying the electro-optic properties of liquid crystals to display devices, a low operating voltage, low power consumption, and portability. However, LCDs do not have any self-luminous capability, and therefore a backlight unit (BLU) is needed to illuminate the screen from the bottom. A light guide plate (LGP), which is a major component, acts as a light source when the light from the light source is directed toward the LCD panel [1–4]. The most common approach is to apply a small backlight, and this technique is being developed to reduce the number of parts to as much as that of a medium-size backlight. However, most small products use light-emitting diodes (LEDs) as the light source, and hence they must be matched with the surrounding optical components. Moreover, it is difficult to process fine patterns of the order of several microns in an optical pattern because of its small size. Recently, many new techniques using optical microscopes have been reported, such as a method for directly forming a micro-lens array on an LGP, a method for forming a diffraction grating, and a hologram-based method. Photolithography is a common processing method, and various other processing methods, such as those based on microelectromechanical systems technology, stamp technology, and mold working method, are also utilized. For small LCDs, the optical coupling between the LED light source and the parts is the most important issue [5–7]. The use of LEDs as the backlight source of LCDs makes it possible to manufacture thinner products, which is the primary advantage of flat-panel displays. It also has the advantages of rich color reproduction and color rendering, as well as a high...
contrast ratio. However, with regard to product design, it is important to overcome the barriers of control technology in optical design in order to achieve uniformity of brightness and color over the entire area. To reduce the cost, it is important to develop an LGP to reinforce the LED so that the luminance does not drop, even if the number of LEDs is reduced. If slimness can be achieved, the best product can be realized with regard to color reproducibility [8–11].

Various attempts have been made to maximize the optical efficiency of LGPs. However, when the side of an LGP is processed and the light source is inserted, the emitted light will be planar. Therefore, a large amount of light will be concentrated on the light-incident portion, and the efficiency will deteriorate in other optical areas [12–15]. To resolve this issue, I propose a method of combining the light source device, which processes a line pattern on the cladding of the POF and the two LEDs at both ends, to one side of the LGP and using the emitted light. As a result, the loss of light intensity in the LGP is minimized, and the illuminance distribution is improved compared with the case of directly inserting the LED into the LGP. However, because of the luminescent spot formed around the light source device that is applied to the BLU, the image quality is degraded or the incident light on one side of the LGP is effectively controlled, and the performance is improved [16–19]. In previous studies, I implemented a POF light guidance system in which light-emitting holes are processed by a cladding of POFs combined with LEDs. This system was combined with the four outer surfaces of an LGP to control the light extraction in an LCD display, and indirect light was realized so that the light-emission effect of the LGP could be analyzed. From the results, it is possible to examine the criteria for the measurement and evaluation of the characteristics of a side-emitting system that is not yet standardized.

II. Simulation

1. Optical design of LGP combined with side-emitting system

A POF consists of a core made of high-purity acrylic resin (polymethyl methacrylate, PMMA), which transmits light from a light source, and a cladding, which is surrounded by a thin layer of fluorine PMMA. The numerical aperture is relatively large, and it has excellent bendability. It is easy to bend, easy to process, and has a high ratio of core to cross-sectional area. The POF causes repetitive refraction because the core and cladding have different refractive indices; thus, it is possible to induce total reflection. Therefore, if the light is uniformly transmitted to the end of the designed POF, it would be sufficient as a light source device for the LGP. When the POF light guidance system proposed in this study is coupled to the LGP, light can be guided to enter the LGP from several divided light emitting grooves to control the amount of light, thereby improving uniformity by weakening the hot spot generated in the LED. However, the optical fiber propagates or leaks depending on the critical angle, with the degree of leakage being proportional to the curvature of the optical fiber. Even if the optical fiber is bent with a very large curvature, it will not break; however, light loss due to light leakage is unavoidable at the bent portion due to bend loss in the optical fiber. Therefore, in order to implement an effective light source device, a light leakage protection device with a thickness of 0.5 mm, which reflects optimized conditions, is coupled to the entire region of the coupled LGP and POF light guidance system. The LED coupled with the side-emitting system is very small compared to conventional light sources. In addition, compared with conventional light sources, it has low power consumption and very good characteristics, and its reaction speed is approximately 1,000 times higher. However, the energy in the active layer is released not only in the form of light but also in the form of heat. When a POF having a low heat resistance is attached to an LED light source, a curing phenomenon caused by the heat transmitted from the light source to the light-receiving surface of the POF arises over time. Therefore, to prevent the loss of light that is transmitted from the light source to the POF, and to prevent the generated heat from being directly transmitted to the POF, a light guide is attached to the end of the POF so that an LED can be inserted. As shown in Fig. 1, the light source device applied to the computer simulation was designed to have a rectangular bent shape in order to surround the sides of the LGP. Its dimensions were 40 mm (width) × 40 mm (length) × 3 mm (thickness). The light-emitting holes that were
used in the POF were designed to have a width of 0.5 mm in accordance with the laser beam that will be applied for actual processing in the future, and a total of 28 light-emitting holes were applied at 5-mm intervals. The diameter of the core was 2.95 mm, and the thickness of the cladding was 0.025 mm; thus, the total thickness of the POF was 3 mm.

2. **Computational simulation conditions for three pattern types processed in LGP**

Before proceeding with the computer simulation, as shown in Fig. 2, the sample of the POF was photographed using an electron microscope after being processed with a CO$_2$ laser. This was done to determine the suitability of processing PMMA resin with high light transmittance in order to select the optimum pattern to process on LGP. The CO$_2$ laser that was used for the pattern processing was a beam-scanning CW (continuous output) TEM00 mode laser beam with an average output of 14 W and a wavelength of 10.64 µm. It uses a pulse-width modulation (PWM) operation method, and has a computer-controlled beam scanning device for high-speed processing. The field-emission scanning electron microscope used for the pattern imaging was a model S-4800 (Hitachi, Japan), and an ion sputter (E-1030, Hitachi, Japan) was applied at an acceleration voltage of 5 kV to coat the sample with Pt for 60 s. Based on these results, the pattern to be processed in LGP was selected as v-groove pattern with a depth and width of 500 µm and a length of 38 mm.

The light source body of the side-emitting system and LGP were designed using the LightTools (Optical Research Associates) analysis program, which designs optics and lighting equipment using the Monte Carlo ray-tracing technique. Computer simulations were carried out using 1,000,000 tracking beams emitted from the POF light guidance system within an error range of 5%. The specifications of the LED used as the light source were as follows: Photometric Flux 3.5 W, HPWT-MH00-G4000 (Lumileds Co.) with a view angle of 70°, placed in the z-axis direction incident on the POF, and emitting in the form of Lambertian light distribution. As a modeling condition for the POF, the light can be received at the end with a numerical aperture of 31°; the refractive index of the core is set to 1.495, and that of the cladding is set to 1.402. The LGP applied to the computer simulation was PMMA with a refractive index of 1.49 and an absorption rate of $1.7 \times 10^{-13}$ / mm. To realize the LGP effectively, the transmittance of the light incident side and the upper side of emitted light is 100%. A 0.01-mm-thick reflective film (RF) with the intrinsic property of a reflectance of 100% was placed at the bottom of the LGP pattern so that the light emitted to the back surface of the LGP was reflected back to the front surface. Three
types of v-groove patterns were designed in the processing area $x$-$z$ plane (38 mm $\times$ 38 mm) on the backside of the LGP, in the horizontal direction (A), in the vertical direction (B), and in lattice form (C). A schematic diagram of the patterned LGP is shown in Fig. 3.

### III. Results and analysis

To analyze the illuminance inside the LGP for the LCD display combined with the side-emitting system, as shown in Fig. 4, seven detectors with dimensions of 3 mm $\times$ 38 mm were installed vertically on the $x$-$z$ plane and the $x$-$y$ plane at intervals of 5 mm inside the LGP. The detector VD1 in the vertical direction was set at $x = 6.5$ mm from the light source, and VD2 ($x = 11.5$ mm), VD3 ($x = 16.5$ mm), VD4 ($x = 21.5$ mm), VD5 ($x = 26.5$ mm), VD6 ($x = 31.5$ mm), and VD7 ($x = 36.5$ mm) were installed at intervals of 5 mm along the $x$-axis direction. The detector HD1 in the horizontal direction was set at $z = 6.5$ mm from the light source, and HD2 ($z = 11.5$ mm), HD3 ($z = 16.5$ mm), HD4 ($z = 21.5$ mm), HD5 ($z = 26.5$ mm), HD6 ($z = 31.5$ mm), and HD7 ($z = 36.5$ mm) were installed at intervals of 5 mm along the $z$-axis direction. In addition, to analyze the luminous effect at the upper portion of the LGP according to the processing conditions of the pattern, a 38 mm $\times$ 38 mm detector was installed 10.025 mm ($Y = 11.525$ mm from the surface of the LGP.

![Fig. 3. (Color online) Three types of patterns processed in the LGP combined with the side-emitting system.](image)

![Fig. 4. (Color online) Design of detectors installed to analyze the illuminance of the area illuminated by the light emitted from the side-emitting system to the inside of the LGP and the luminance uniformity of the light emitted to the top.](image)
Fig. 5. (Color online) Illuminance results for seven detectors installed inside four types of LGPs. The left side shows the results from the detectors installed in Part I and Part III regions (vertically), while the right side shows the results from the detectors installed in Part II and Part IV areas (horizontally). (a) Illuminance inside the unpatterned LGP. (b) Illuminance inside the LGP processed with a horizontal pattern. (c) Illuminance inside the LGP processed with a vertical pattern. (d) Illuminance inside the LGP processed with a lattice pattern.

from the side-emitting system into the LGP is scattered by the pattern processed at the bottom of the LGP, and the illuminance inside the LGP is reduced. In addition, Fig. 5(d) shows the case where a grid pattern composed of a combination of the pattern in the horizontal direction and the pattern in the vertical direction is processed. There is no significant difference in the amount of light inside the LGP compared with the result for the LGP pattern processed in the vertical direction.

Figure 6 shows the illuminance results obtained inside the LGP for each area measured at intervals of 5 mm in Part I and Part III (vertical direction) according to the pattern processed at the bottom of the LGP. The average illuminance was almost the same for the LGPs without a pattern (7,806.93 lux) and with a horizontal pattern (7,688.6 lux). The average illuminance of the LGP with a vertical pattern was 5,236.15 lux, which is >32.4% lower than that for the horizontal pattern. In addition, even if the pattern was the same as that formed in the horizontal direction, the amount of light emitted upward increased for the LGP that was processed in the vertical direction. These results show that the amount of light emitted to the top of the LGP varies depending on the pattern of the LGP combined with the side-emitting system. Thus, the direction of the combined LED light source of the side-emitting system is correlated with the direction of the pattern that is processed at the bottom of the LGP.

Fig. 6. (Color online) Illumination results obtained for seven detectors installed in the vertical direction (the same direction for Parts I and III).

Figure 7 shows the illuminance results inside the LGP for each area measured at intervals of 5 mm in Part II and Part IV regions (horizontal direction) according to the pattern processed at the bottom of the LGP. The average illuminance inside the LGP without a pattern was 2,841.6 lux, and the average illuminance inside the LGP with the pattern in the horizontal direction was 2,430.3 lux. There is little difference between these values. The average illuminance inside the LGP with the pattern in the vertical direction was 2,255 lux, and the average illuminance inside the LGP with the lattice pattern was 2,116.7 lux, which are similar to the results shown in the chart of Fig. 6. Based on these results, we confirmed the efficiency of the side-emitting system with the LGP and found that the optical pattern plays a significant role in the efficiency of the emission of the LGP. In addition, it was possible to examine the measures needed to guide the establishment of the criteria for measuring and evaluating the characteristics of side-emitting system, which have not yet been standardized.

2. Analysis of luminescent effect according to pattern processing condition of LGP combined with side-emitting system

Based on the above results of analyzing the illuminance inside the LGP, as the light emitted from the side-emitting system proceeded into the LGP, the luminescent effect emitted to the top of the LGP was analyzed through three types of patterns. To predict the commercialization feasibility, we focused our analysis on
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Fig. 7. (Color online) Illumination results for seven detectors installed in the horizontal direction (the same direction for Parts II and IV).

Fig. 8. (Color online) Modeling of the LGP, in which the side surface is processed and the light source is inserted, and the proposed side-emitting system.

The average luminance and uniformity compared to the case in which the LED is inserted on the side of LGP, as shown in Fig. 8. For the 38 mm × 38 mm pattern region, the light emitting area of the LGP was divided into four regions of 19 mm × 19 mm and further divided into 16 regions of 9.5 mm × 9.5 mm. The luminance of each of these sections measured at the top of the LGP was then calculated. The resultant values were used to calculate the average brightness, and the minimum value was divided by the maximum value to quantify the uniformity for the detector regions.

When the light source is inserted after processing the side surface of the LGP, the light emitted to the inside forms a flat shape. As shown in Fig. 9, this causes a problem by which a large amount of light is concentrated on the light-incident portion and the efficiency of the optical surface is lowered.

To address these problems, the side-emitting system, which is proposed to efficiently control the light incident into the LGP and improve performance, was coupled, and the same conditions were used. Figure 10 shows the results of the raster chart, and compares and analyzes the total amount of light and the luminance distribution transmitted to the upper portion of the LGP with respect to the amount of light incident from the side-emitting system.

As shown in Fig. 11, compared to the case of the LGP coupled with the side-emitting system in which the LEDs are directly inserted into the several divided light emitting grooves, while luminance is lowered, the light incident from the light emitting grooves are uniformly emitted to the upper surface through the v-groove pattern, thereby improving uniformity.

The analysis of the illuminance inside the LGP indicates that the amount of light emitted to the upper portion of the LGP varies depending on the pattern. As shown in Table 1, when the LED is applied under the same conditions which the pattern in the vertical direction is processed, the brightness uniformity was considerably low (4.667%). Conversely, the average luminance of the LGP coupled with the side-emitting system was relatively unsatisfactory (37.989 Nit); however, the bright-
Fig. 10. (Color online) Simulation results according to the pattern processed at the bottom of the LGP coupled with the side-emitting system (a) the horizontal-direction-engraved LGP, (b) the vertical-direction-engraved LGP, and (c) the lattice-engraved LGP.

Fig. 11. (Color online) Graph comparing the average luminance and uniformity of the two types of LGP constructions (LGP with LED inserted and LGP coupled with the proposed side-emitting system) according to three pattern types.

Fig. 10. (Color online) Simulation results according to the pattern processed at the bottom of the LGP coupled with the side-emitting system (a) the horizontal-direction-engraved LGP, (b) the vertical-direction-engraved LGP, and (c) the lattice-engraved LGP.

Fig. 11. (Color online) Graph comparing the average luminance and uniformity of the two types of LGP constructions (LGP with LED inserted and LGP coupled with the proposed side-emitting system) according to three pattern types.

ness uniformity was 86.18%, resulting in 18 times higher enhancement than that of the conventional LED units.

The luminous effect at the upper surface of the LGP is influenced by the intensity of the light source as well as the scattering pattern formed inside. To confirm this, we applied a photometric flux of 10.5 W for the LED coupled to the side-emitting system. The computer simulation confirmed that satisfactory uniformity was achieved while the average luminance of the LGP inserted into the LED was increased. For the LGP pattern with LED inserted, the uniformity in the horizontal direction with an average luminance of 131.959 Nit was the highest at 30.39%. Comparing this in Table 2, the average luminance of the LGP processed with the lattice pattern was 131.175 Nit, which is almost the same value, while the uniformity was 91.74%, which is almost three times as large.

As described previously, the optical pattern processed on the bottom plays an important role in the efficiency of light emitted from the LGP. According to these results, it can be predicted that side light emission is likely to be more efficient in terms of the LGP if the light-emitting holes are controlled to optimize the conditions of the side-emitting system. Because the emission effect of the LGP combined with the proposed the side-emitting system was analyzed using computer simulations, it was not possible to perform comparisons with an LGP for LCD displays that can be mass-produced. However, it is expected that because of the competition in this field, reasonable cost can be realized by performing further research on parts and materials that can lower the production cost. Developing a light guide plate to increase the brightness without reducing the number of optical sheets and LEDs is the key to lowering the cost, while balancing the amount of light across the entire surface and increasing the uniformity of light is an important challenge in product design. Therefore, rather than directly inserting the LEDs, applying optimal patterns to the LGP coupled with the proposed side-emitting system and applying high-efficiency LEDs can improve the fabrication efficiency and the optical characteristics of the LGP.

IV. Summary and discussion

I proposed an effective structure for an LGP with an optical pattern. The proposed structure was developed by applying the side-emitting system to an LGP, which was used as an edge-type LED BLU, functioning as a surface light source. The side-emitting system was designed in such a way that the light emitting holes processed in
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Table 1. Average luminance and uniformity of the LGP with the LED inserted and the side-emitting system according to the pattern.

<table>
<thead>
<tr>
<th>Pattern shape</th>
<th>Average luminance [Nit]</th>
<th>Uniformity of brightness [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>AH</td>
<td>131.959</td>
</tr>
<tr>
<td>Vertical</td>
<td>AV</td>
<td>103.748</td>
</tr>
<tr>
<td>Lattice</td>
<td>AL</td>
<td>201.086</td>
</tr>
<tr>
<td>B-type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>BH</td>
<td>6.105</td>
</tr>
<tr>
<td>Vertical</td>
<td>BV</td>
<td>37.959</td>
</tr>
<tr>
<td>Lattice</td>
<td>BL</td>
<td>43.725</td>
</tr>
</tbody>
</table>

Table 2. Average luminance and uniformity according to the pattern for an LED with a photometric flux of 10.5 W in the side-emitting system coupled with the LGP.

<table>
<thead>
<tr>
<th>Pattern shape</th>
<th>Average luminance [Nit]</th>
<th>Uniformity of brightness [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>CH</td>
<td>18.316</td>
</tr>
<tr>
<td>Vertical</td>
<td>CV</td>
<td>113.879</td>
</tr>
<tr>
<td>Lattice</td>
<td>CL</td>
<td>131.175</td>
</tr>
</tbody>
</table>

the cladding of the POF disperse the light emitted from the light source evenly in all directions. Three types of v-groove patterns were applied to the bottom of the LGP, and a computer simulation was performed. The results showed that for the pattern processed in a horizontal direction at the bottom of the LGP, most of the incident light was transmitted through the pattern without changing and it acted only as a waveguide. In addition, there was almost no difference between the unpatterned cases, because the incident light could not be sent to the upper portion of the LGP. However, when the LGP had a pattern in the vertical direction at the bottom, an increased amount of light was emitted to the top because the scattering by the pattern increased, and the average illuminance within the LGP was 5236.15 lux. I confirmed that the decrease in illuminance was > 32.4% compared with the case without a pattern, and it was also found that the pattern in the vertical direction was not greatly different from the lattice pattern. Therefore, in order to manufacture the side-emitting system by bonding it to the LGP, the conditions of the scattering pattern processed at the bottom of the LGP should be selected as one of the main variables in addition to the control of the light-emitting holes processed in the cladding. In addition, by analyzing the luminous effect under the same processing conditions, I confirmed that it is possible to balance the amount of light emitted to the upper part of the LGP coupled with the side-emitting system, compared to the case of directly inserting the LED. Moreover, I believe that applying an LED with high light efficiency can sufficiently improve the optical characteristics of the LGP. Research is in progress to develop a more precise and accurate design criteria to apply the LGP coupled with a more optimized side-emitting system to real laser processing experiments. By verifying the performance through actual processing experiments and deriving its correlation with computer simulations, I expect the system to be applicable in a variety of displays, which can improve the manufacturing efficiency and optical characteristics of the LGP through simple processing techniques and light source minimization.

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