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Optimized pattern design of light-guide plate (LGP)

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We have investigated the light intensity distributions of a 7-inch LGP to increase output illuminance uniformity by reducing the bright and dark areas caused by a plurality of LED. We analyzed the effects of the LED–LED gap and LED–LGP space to the light intensity distribution in the LGP inside. We have found that the density function of LGP pattern has a simple exponential terms. We analyzed the output light intensity of the LGP through the comparison of the simulation results between adopting the hemisphere pattern density function and adopting the equidistance pattern density function. And also, to reduce the bright spot and dark areas, we have introduced a convex elliptical LED reflector. As a result, the output illuminance uniformity was improved effectively by the adoption of the pattern density function and the new LED reflector.

Keywords: TFT-LCD, backlight unit (BLU), light-guide plate (LGP), pattern density function, hot spot.

1. Introduction

A thin film transistor-liquid crystal display (TFT-LCD) is a standard for mobile devices such as note PC, navigation, PDA, cellular phone, *etc*. Since LCD panels are not emissive devices, backlight unit (BLU) which is usually located behind the LCD panel is used for an LCD system as a light source unit. A typical BLU consists of an light-guide plate (LGP), a diffusion sheet, two prism sheets, a reflector and a light source which is located at edges of the LGP to minimize the thickness of the BLU, as shown in Fig. 1. Radiated light from the light source enters the LGP and is guided inside the LGP along the horizontal *y*-axis based on the principle of total internal reflection. The light is reflected by an array of diffusive microscopic patterns which is fabricated on the bottom of LGP and emitted out of the front surface of the LGP along the direction of *z*-axis. The emitted light from LGP is scattered by the diffusion sheet and collimated by horizontal and vertical prism sheets before it reaches the LCD panel.

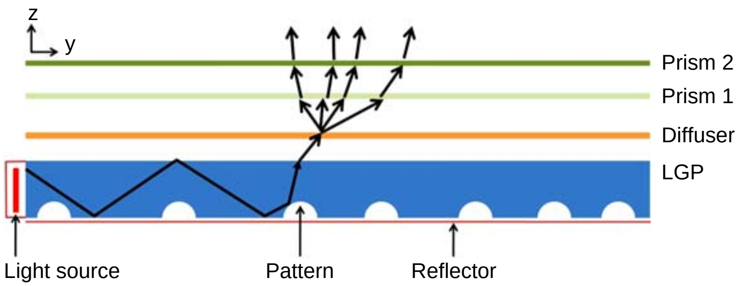

Fig. 1. Conceptual description of BLU.

Recently, super media devices (SMDs) such as tablet PC, Galaxy Tab and iPad are already attracting attention of users, despite the enthusiastic response of smart-phones in the world market. Therefore, the display devices applied in these SMDs are rapidly changing to large panels over 7 inches. Thus the pattern design technology [1–3] of former small size LGP should be improved to apply to large size LGP [4]. At this point of time, pattern design technology systematization of LGP for TFT-LCD which is applied in SMD is needed.

In this study, we investigated some essential conditions of LGP pattern design for large size 7-inch TFT-LCD. Especially, we analyzed the illuminance distribution in the LGP according to various LED–LED gap and LED–LGP space and tried to suggest optimized LGP pattern design conditions.

2. Simulation analysis of LGP output characteristics

The design of BLU, whose goal is to maximize the light intensity and optimize the light intensity distribution on the front surface of LGP, requires the assistance of illumination design simulators. We have used SPEOS (OPTIS, France) for simulation analysis of output light intensity characteristics for LGP. In this study, we adopted a plate of a size of 110 mm × 140 mm × 0.7 mm with "optical polished" surfaces as a basic structure of 7 inch LGP, as shown in Fig. 2. Each of the four light sources of 0.6 mm × 3.0 mm in size, (LED is typically used), emits 1 million rays of 550 nm monochromatic wavelength toward y-direction with Lambertian intensity distribution. Each of the side surfaces of LGP, except light incident and emergent ones, was surrounded by a 100% reflector to prevent escape of light rays from LGP. The reflective

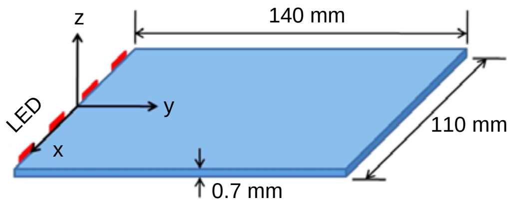

Fig. 2. Simulation model.

index and light absorption ratio of the LGP which assumes as PMMA quality material were 1.49 and 1.70×10^{-3} mm, respectively.

The necessary condition of an ideal BLU is to be a plane-wave light source. Thus, the incident light from LEDs spreads throughout the inside of the LGP and then is uniformly emitted through the emergent surface. However, the greater the distance from LEDs, the more the light intensity decreases, which is typical of LGP. And also, there are a dark area between LEDs and a bright area around LEDs. Generally, in order to remove the dark area or bright area, special patterns, so-called serration, are fabricated on the entrance side surface of the LGP. The design parameters of the serration, *e.g.*, the pattern size, shape and fabrication area, are different in each case. In this study, we encountered many difficulties to describe consistently the effects of serration; we analyzed the LED effect itself by investigating the light intensity distribution inside the LGP without serration.

3. Pattern design for increasing the uniformity of LGP output

To analyze the characteristics of the LGP output light intensity distribution, we introduced a hemisphere pattern fabricated on the LGP bottom surface using intaglio printing. And there are four LEDs at x = +37.5, +12.5, –12.5, and –37.5 mm along a line of y = –0.2 mm. In this simulation analysis, we set up some illuminance detector inside the LGP on a x–z plane at an interval of 10 mm. Using the data measured with the detectors, we tried to find an optimum pattern density function.

In the process of finding the pattern density function, we considered two effects. One is the LED effect and the other is light reflector effect located at the end surface of LGP. Thus, there are two effective light sources in this analysis, the LED itself and the reflector as an imaginary light source. Light emitted from LED passes through the inside of LGP by total internal reflection in positive y-direction. However, the reflected light goes back to negative y-direction because of the reflector.

3.1. LED effect

Light intensity is diminished when passing through the LGP due to absorption. This intensity reduction phenomenon in a medium is different from that in the air. It is well-known that illuminance from a point light source is decreased as the inverse to the square of the distance in the air. However, the illuminance in a medium decreases in a somewhat complicated way. The complication comes from spreading, absorption, reflection and refraction. It is impossible to analyze each effect independently, since we should consider all these effects simultaneously.

To achieve this, we have set up illuminance detectors inside the LGP on a x–z plane at an interval of 10 mm. The detectors have counted for all the lights which passing through the detector's surface. Figure 3 shows the detected flux data (square solid points) and also fitting line with an exponential function (solid line). The fitting

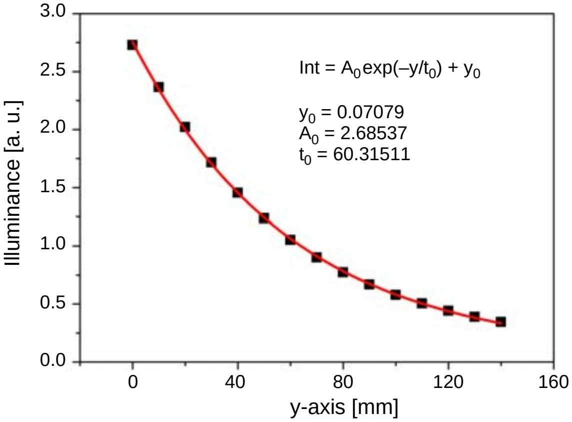

Fig. 3. LED effect: inside the LGP illuminance distribution versus y-axis by the four LED at $y = -0.2$ mm.

constants A_0, y_0, t_0 will be changed for a given model in each case. However, the constant y_0 is outside our interest because of the constant depends on the light source intensity but on the geometry of the LGP.

3.2. Reflector effect

Figure 4 shows the flux distribution of light reflected by the reflector located just on the LGP side surface at $y = 140$ mm. The reflector functions as a light source with the same size of the reflector itself. Light intensity of the imaginary light source assumes as the value of the light intensity of the LED at the same position. Square solid points in Fig. 4 shows the simulation data and solid line is the line fitting to exponentially decrease. In the same manner of the LED effect, the coefficients A_1, y_1 will be changed for a given simulation model. In this case, the fitting exponent

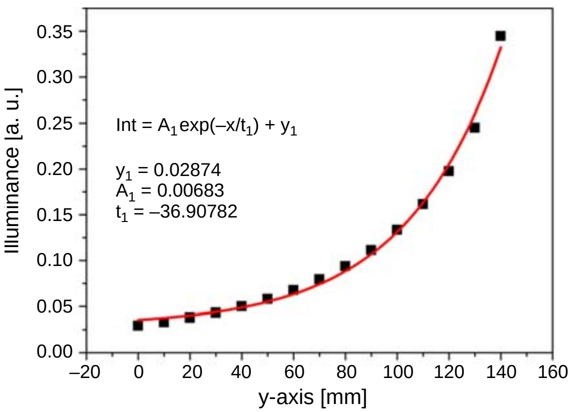

Fig. 4. Reflector effect: inside the LGP illuminance distribution versus y-axis.

coefficient was 36, as shown in Fig. 8. The reflector contributes inversely as compared with LED on the intensity distribution as expected.

3.3. Effects of both the LED and the reflector

Let us introduce a pattern density function [5, 6], including both LED and reflector effects,

$$\text{Pattern density} = \left[P\exp\left(\frac{-y}{60}\right) + Q\exp\left(\frac{y}{35}\right)\right]R \tag{1}$$

Here, P and Q are pattern density control coefficients of the front and the rear part of the LGP, respectively. For a large P, the distance between patterns in the front part of the LGP is large and then the pattern density is low. The constant Q works the same way as the constant P in the rear part of the LGP. And, by using the coefficient R, we can fill the LGP up with patterns. When one applies Eq. (1) to a given model, one can also adjust the exponents a little bit to make an optimum pattern design.

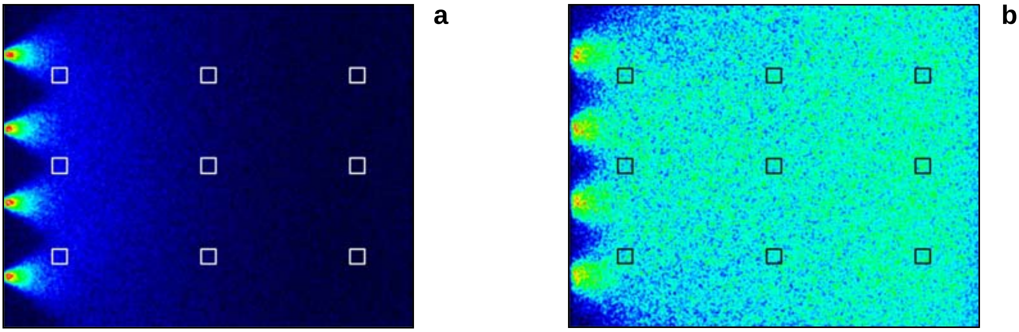

Fig. 5. LGP output illuminance distribution of (**a**) equidistance pattern (**b**) adjusted pattern by pattern density function.

Figures 5**a** and 5**b** show the LGP output illuminance distribution for equidistance pattern and adjusted pattern by pattern density function, respectively. We can easily see that the illuminance uniformity of Fig. 5**b** is certainly improved. To improve it quantitatively, we calculated the ratio of illuminance defined as

$$\text{Illuminance uniformity} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \times 100\% \tag{2}$$

Here, I_{max} and I_{min} are maximum and minimum values, respectively. In the definition of the ratio, we divided intensity difference by minimum intensity because a perceptible difference between bright point and dark point in human eyes depends on the overall level of brightness. The smaller the ratio the better the intensity uniformity.

We obtained the ratio of illuminance following Eq. (2) for nine points as marked in Figs. 5**a** and 5**b**. We obtained the ratio of 299.9% and 10.1% for equidistance pattern and adjusted pattern, respectively. The results show an evidence that the uniformity of light intensity is improved by using the density function.

4. LED back mirror effect on the reduction of bright area

In the previous section, we introduced a pattern density function to improve the output light intensity uniformity of the LGP. And we showed that the function performs well as we expected. However, we had have one more problem of how to reduce the bright area around the LEDs to enhance the light intensity uniformity. For this purpose, it is necessary to analyze the characteristics of light intensity distribution.

4.1. LED–LGP space effect on the light intensity distribution of the LGP inside

In the case of an edge light-type BLU, radiated light from light source LED enters the LGP through a side surface and then is spread out all over the LGP inside. Since every material has light absorptive property, light intensity decreases as the distance from the light source increases, even though the LGP is made of a good transparent material. And also, there are some dark areas between LEDs. The dark areas are easily recognized in the human eyes even though the gap between LED and LED is narrow. In this section, we want to find out the correlation between LED–LGP gap and light intensity uniformity around the LED spot point to correct the imbalance of light intensity.

Figure 6 shows the light intensity distribution along the x-axis for y = 2, 10, 20 mm line inside the LGP. The difference in brightness is evident in the front of the LGP near light source LED. That is, the difference between maximum and minimum is very large. We can see that the difference becomes smaller as y-coordinate increases, as shown in Fig. 6.

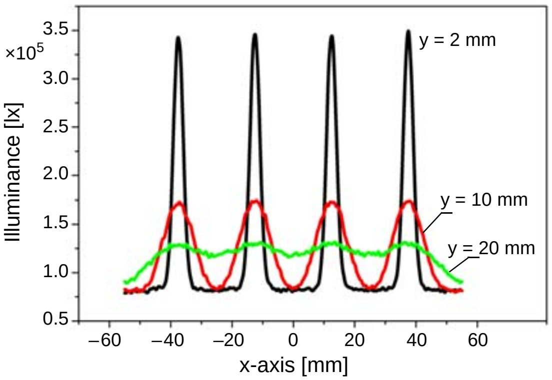

Fig. 6. Illuminance distribution along x-axis for y = 2, 10, 20 mm.

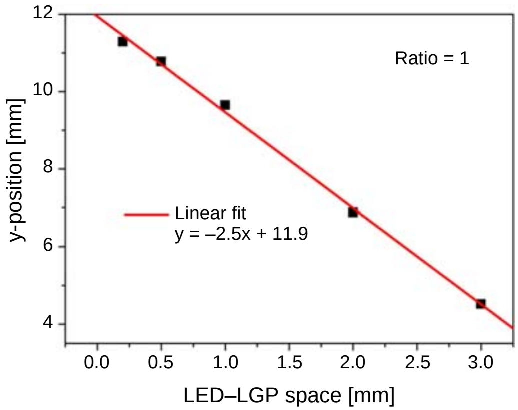

Fig. 7. *Y*-position of *illuminance uniformity* = 1 versus LED–LGP space.

Figure 7 represents *y*-coordinate for the illuminance uniformity defined in Eq. (2) is 1 for the variance of LED–LGP space. The *y*-position of *illuminance uniformity* = 1 is in reverse proportion to the space with the proportional constant –2.5. Thus a large LED–LGP space is of help for the dark area to be reduced effectively. However, there is a limit as to what we secure enough space because of a thin and small size of BLU.

4.2. LED–LED gap effect on the light intensity distribution of LGP inside

In the same manner as in the former case, LED–LGP space effect, we can easily expect a smaller gap between LED and LED to reduce dark area inside the LGP. We have

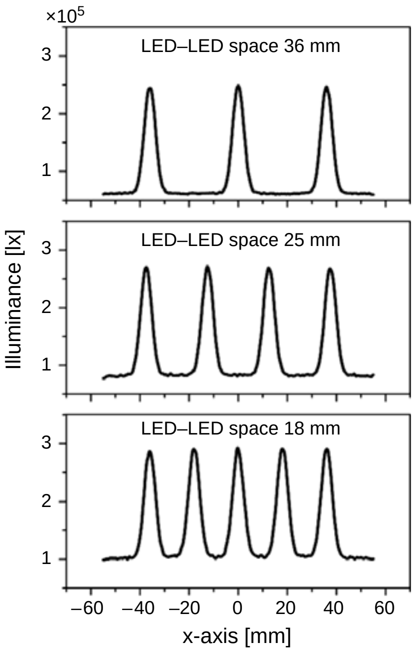

Fig. 8. Illuminance distribution along *x*-axis of *y* = 4 mm for different LED–LED space.

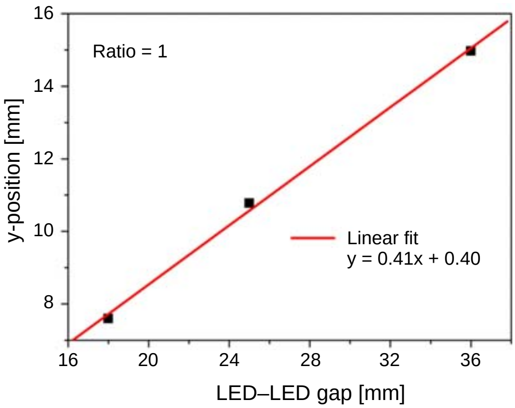

Fig. 9. *Y*-position of *illuminance uniformity* = 1 versus LED–LED gap.

analyzed the effect of LED–LED gap quantitatively. Figure 8 shows illuminance distribution along the *x*-axis of $y = 4$ mm. In all three cases of 36, 25, 18 mm LED–LED gap, there are deep valleys between peaks. The valleys are the dark region of the inside of LGP nearby LED. Thus, it is necessary to narrow the gap between peak point and bottom level by an appropriate pattern design and adding some new ideas.

Less low illuminance uniformity defined by Eq. (2) means better light intensity uniformity. Figure 9 shows that *y*-position of the illuminance uniformity is unity for some LED–LED gaps of 36, 25, and 18 mm. As the LED–LED gap becomes large, the *y*-position increases linearly with the proportional constant +0.41. Because the proportional constant has a small value, reduction of LED–LED gap by increasing LED number is not an effective way of decreasing the dark region. Therefore, some creative ideas are required.

4.3. Introduction of a conceptual light diffusing LED reflector

We have analyzed the LED–LGP gap and LED–LED space effects as mentioned above. Moreover, we have introduced a convex elliptical LED reflector at the back of LED to reduce the bright area around the LED. The reflector diffuses light from LED into large angle and then the diffused light enters the LGP. Figure 10 shows a schematic diagram of diffused light by the action of the convex elliptical LED reflector. As a result of the diffusing effect, the dark area can be reduced. It could also facilitate reduction of LED number without demanding intensity uniformity.

Figure 11 shows the output light intensity distribution with the convex elliptical LED reflector. The illuminance averages for the rectangular area of Fig. 5**b** and Fig. 11 are 7.510×10^2 lx and 7.816×10^2 lx, respectively. There are no significant differences between the averages of the light intensities. However, there is a great difference between the two cases in the standard deviation. The values are 3.435×10^2 lx and

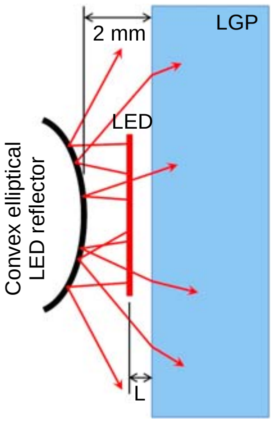

Fig. 10. Schematic diagram of the LED reflector.

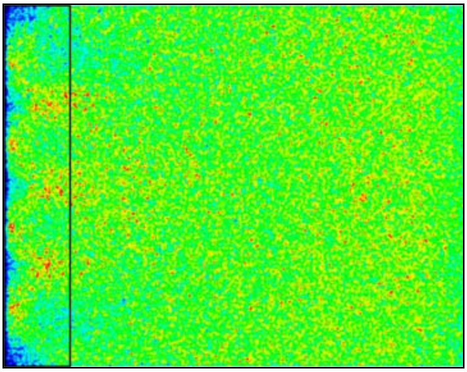

Fig. 11. LGP output illuminance distribution with the convex elliptical LED reflector.

2.315×10^2 lx for Fig. 5**b** and Fig. 11, respectively. Therefore, we can say that the convex elliptical LED reflector is highly effective in the reduction of dark area caused by a plurality of LED.

5. Summary and discussion

We investigated the LED–LED gap and LED–LGP space effects on the light intensity distribution inside the LGP. The y-position of *illuminance uniformity* = 1 is in reverse proportion to the space with the proportional constant –2.5. However, as the LED–LED gap becomes large, the y-position increases linearly with the proportional constant +0.41.

To analyze the characteristics of the LGP output light intensity distribution, we have introduced hemisphere pattern fabricated on the LGP bottom surface with intaglio printing. We have found the LGP pattern density function with a simple exponential function. The corresponding pattern density function was $[P\exp(-y/60) + Q\exp(y/35)]R$

for a 7-inch LGP. We have analyzed the output light intensity of the LGP by adopting the pattern density function, comparing with the result of the same interval pattern. We have confirmed that the illuminance uniformity is certainly improved.

To improve output illuminance uniformity of the LGP, we have introduced convex elliptical LED reflector. As the simulation result, the convex elliptical LED reflector is highly effective on the reduction of dark area caused by a plurality of LED. The standard deviation is decreased by 32.6%. Consequently, we could improve the output illuminance uniformity considerably through the adoption of the pattern density function and the new LED reflector.

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