Edge-lit LCD backlight unit for 2D local dimming

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Abstract: Local dimming technology has been highly desired for integration with liquid crystal displays (LCDs) in order to improve their contrast ratios (CRs) as well as to overcome power efficiency bottlenecks. In this paper, we propose and demonstrate a slim (~1 mm) edge-lit LCD backlight unit (BLU) capable of 2D local dimming. We designed a semi-partitioned light guide plate (LGP) patterned with inverse-trapezoidal microstructures, which allows the ultra-slim BLU to function without prism sheets. Since light emitting diodes (LEDs) are placed in the middle of the LGP, the BLU can freely define illuminated areas and the whole BLU can be modularly expanded like a tile canvas. The fabricated BLU achieves uniformity in both local and global luminance distributions, as well as in high local dimming performance. Experimentally, the BLU increases the CR of the display up to two orders of magnitude compared to conventional BLUs.

1. Introduction

Liquid crystal display (LCD) technology has been widely used in the commercial display market because of its remarkably low cost and its ability to produce slim and large-size displays. Despite its great success in the display market, LCD technology has the fundamental drawbacks of low optical efficiency and low display contrast ratio (CR). Unfortunately, both weaknesses are growing more and more significant.

The origin of these two problems is the backlight unit (BLU), which conventionally illuminates the entire area of the display screen with maximum brightness at all times of operation. This consumes large amounts of power and deteriorates the display’s CR.

In order to improve the power efficiency and CR of LCDs, the concept of local dimming has been proposed, which locally adjust the BLU’s luminance according to a given scene’s brightness distribution. Through local dimming, the BLU illuminates only when and where the light is required, thus dramatically enhancing both the LCD’s CR and energy efficiency [1–5].

Since the first proposal of local dimming, the concept has evolved to 0D, 1D, and 2D local dimming, in accordance with the distribution of local illuminating blocks. It is well known that of the three types of local dimming, 2D local dimming, which divides a BLU into local illuminating blocks, is most effective at enhancing the LCD’s power efficiency and CR [5]. The 2D local dimming feature is conventionally implemented by using a direct-lit BLU, which can easily modulate local luminance [1–3,5]. However, the edge-lit BLU capable of 2D local dimming is an absolute necessity for integrating local dimming into thin and light displays.

Compared with the direct-lit BLU, it is more difficult to implement 2D local dimming functionality than with the edge-lit BLU since the light sources can only be placed at the edge of the display. The illumination area should contain at least one edge of the LGP, so its performance is insufficient when the bright spot is located away from the edge of the display.
Moreover, the lateral spread of the light inside LGP causes blur in defining the local blocks. These two inherent problems impede to focus light to the target area while decreasing image quality and power efficiency.

Therefore, advanced edge-lit BLUs with partitioned LGPs [7,8], or with light-confined micropatterned LGPs [9,10], were utilized to define local block more clearly. These previous studies improved the local luminance modulation performance of the BLUs, but it is still challenging to demonstrate true 2D local dimming in an edge-lit BLU with local illumination blocks non-adjacent to the edge of the display.

In this paper, we propose a true edge-lit 2D local dimming BLU. In order to define each 2D local illuminating block clearly, we use a novel semi-partitioned LGP. Different from previous studies, light sources are located in the middle of the LGP while maintaining edge-lit illumination, and hence, the BLU can freely illuminate specific local blocks - even blocks located away from the edge. To emphasize slim feature of the proposed edge-lit BLU, we eliminate prism sheets from the BLU by using our previously proposed specially-shaped light out-couplers on the LGP [11].

The proposed BLU is based on our previous study, which was presented in [12]. However, the prototype BLU and the analysis completed by that time were not sufficient to prove the usefulness of our concept completely. In this work, we substantiate our concept and the design of a previously proposed BLU [12] via optical simulation and optical measurement of the fabricated BLU which is made by the revised fabrication process.

2. Design of the 2D local dimming LGP

Figure 1 shows the scheme of the proposed 7-inch diagonal locally dimmable BLU. The BLU uses 0.6 mm-thick edge-lit LEDs and 1 mm-thick LGP. The LGP was designed to achieve both a uniform spatial luminance distribution and 2D local dimming by placing some LEDs in the middle of the LGP. Twenty-seven LEDs are used, in total, for nine local blocks in the proposed design.

![Schematic view of the proposed LGP for edge-lit 2D local dimming BLU. (a) Top and side view of the BLU with nine local blocks. (b) The inverse-trapezoidal shaped light out-couplers patterned on the plate and (c) details of the block isolator.](image-url)
Fig. 2. Simulation results of the light flux and luminance distribution with respect to channel thickness. (a) The relative flux of the light entering to the channel without the light out-coupler, (b) the relative luminance with respect to thickness of the patterned LGP, (c) the relative luminance with respect to thickness of the channel with the light out-coupler, and (d) the surviving normalized light flux after passing through the patterned LGP with respect to thickness of the patterned LGP.

On the top surface of the LGP, the inverse-trapezoidal microstructures were patterned as light out-couplers. This structure has a negatively-sloped sidewall so that light can be reflected out by total internal reflection (TIR) at the sidewall as shown in Fig. 1(b). Therefore, the LGP can produce an on-axis angular luminance profile solely by adjusting the side angle of the microstructures (the detailed analysis of the optical effect of the side angle is in [13]), which reduces the entire thickness of the BLU by eliminating prism sheets [14,15].

The proposed LGP can control local luminance by means of the isolators that optically separate each local block. The isolators also provide space for LEDs, prevent bright hot spot generation by concealing the LEDs, and make a thin channel for seamless lighting among local blocks all at the same time.

Figure 1(c) depicts a detailed side view of the isolator with LEDs. The isolator is composed of a backside trench, a thin optical channel above the trench, and a reflective barrier. The trench acts as a huddle for the light traveling between local blocks and its sidewalls are coated with reflective material except for the LED-facing sidewall. Therefore, most of the traveling light is reflected back to the body plate and only a small amount of the light can enter the channel above the trench. The entered light escapes up from the LGP through the light out-couplers on the channel. Therefore, the intermediate area between local blocks can be illuminated while the light crossing over to the next block is limited. A metallic reflective barrier in the trench conceals the LEDs. Considering fabrication margin, the barriers above the LEDs are slightly wider than the trenches in our design to completely cover the LED cavity for ensuring there is no bright line by the LEDs.
The following section will explain how the proposed BLU can make a uniform spatial luminance distribution when all of LEDs are lit, and how the isolators can prevent leakage of the light to the neighboring local block, even though there is a channel through which the light pass.

3. Design of the 2D local dimming LGP

We describe the design procedure in the following sequence: the isolator itself (Fig. 2), a single local block (Fig. 3), and all the local blocks (Fig. 4) of the BLU. LightTools, which is an optical ray-tracing simulator, was used for the simulation.

3.1 Analysis of the isolators

Figure 2 shows the results of optical simulations which are designed to explain how the isolators work. The isolator should act as a barrier to light even though there is an optical channel. At the same time, the channel area should not be darker than the illuminating block area for seamless illumination. The key is that as the channel thickness decreases the light flux entering the channel decreases while the light extracting efficiency of the channel increases. This results in a continuous and uniform illumination from the prior illuminating block as well as exhaustion of all light in the channel region escaping only a small amount of light to the next illuminating block. This is how we can get the uniform luminance distribution in the channel region (Fig. 2(a)-2(c)). The details are explained below.

The forward-traveling light flux is proportional to the local thickness of the LGP when the thickness decreases abruptly. Figure 2(a) shows the relative flux of light entering the channel. The graph tells us that the light flux entering the channel is exactly proportional to the channel thickness. In other words, if the channel is thin enough, the isolator acts as a light barrier for local dimming.

Meanwhile, the light traveling in the channel region meets the surface of the LGP more frequently in a thinner channel as shown in Fig. 2(b). In the simulation, the pattern density and the input light flux were constant. Figure 2(b) shows that the light extracting efficiency is inversely proportional to the channel thickness. Figures 2(a) and 2(b) show that the thinner channel reduces the light that enters the channel and extracts most of that light.

Because the total amount of the illuminating light flux in the channel can be expressed as a product of input light flux and the light extraction efficiency, the spatial luminance is independent of the channel thickness as shown in Fig. 2(c). Therefore, the spatial luminance level can be maintained in the channel area even though there is much lower input light flux.

The entered light flux to the thin channel is rapidly reduced while passing through the channel. As shown in Fig. 2(d), the survived light rapidly decreases in the thinner channel because the thinner LGP results in a higher light extracting efficiency as mentioned above.

In other words, even though the channel area is bright, the light passing to the next local block can be dramatically reduced because i) only a small amount of light can enter the channel, ii) all the light entering to the channel is dissipated out (upward) that a small amount of light is escaped to the next local block, and iii) the recovered (increased) LGP thickness in the next local block reduces light extracting efficiency.

These simulations considered only the light with an incident angle of 25-35 ° because the inverse-trapezoidal microstructure used here can extract only this light in the normal direction (Lambertian light sources are used in all simulations except the simulation results in Fig. 2). In the simulation model, the inverse-trapezoidal microstructures are patterned in a hexagonal array with a 60 µm-pitch on the channel region, and the pattern is 5 cm away from the LEDs (far enough away to spread the light in the BLU). The dimensions of the structure are the same as in Fig. 1(b).
3.2 Pattern density design for a uniform spatial luminance distribution

To simplify the pattern density analysis, we designed a single block of the LGP first and conducted optical simulations to confirm that the block with the isolator can produce a uniform spatial luminance distribution considering the previous simulation results. Figure 3 shows the designed single block of the LGP and its optical properties.
Using a pattern generation and optimization function in LightTools, we obtained the optimal pattern distribution for a uniform spatial luminance distribution in a 2-inch diagonal single local block as shown in Fig. 3(a). There is a thin region at the edge of the LGP to describe thin channels within the isolators. The width of the channel is 5 mm, which is the same as the channel in the multi-blocked LGP design shown in Fig. 1.

Different from the previous simulations in Fig. 2, in this case, most of the traveling light is reflected at the end of the LGP. This increases the light flux in the body of the local block while the amount of light incident to the channel is constant. Therefore, to maintain the luminance level, the pattern density in the channel area is denser than that in the body area as shown in Fig. 3(c).

Figure 3(d) is the 2D areal pattern density distribution map. In the maximum density area on the channel region, the pitch of the microstructures is 40 μm, which corresponds to 10 μm space between adjacent inverse-trapezoidal microstructures, considering fabrication margin.

Likewise, we designed a multi-blocked LGP as shown in Fig. 4. The dimensions of the LGP are the same as those in Fig. 1. Considering the light cross-talk of each local block, the average pattern density is different from block to block. The 1st row has a denser pattern.

![Fig. 5. The spatial luminance distribution chart when a single local block operation. In case of (a) various situations that only one of the nine local blocks are turned on in sequence, and (b) a single LGP when only the center block is lighting.](image)

![Fig. 6. The optical simulation results of angular luminance distribution in three different positions. (a) At the center of the body area, and (b, c) at the channel of with and without LEDs when all local blocks are turned on. The simulation results of angular distribution at the (d) center of a block, (e) channel with LEDs, and (f, g) channels without LEDs in case of only a center block is illustrated.](image)
because there is no leakage from the previous blocks. Using the generated pattern distribution, we could get about 85.5% in spatial luminance uniformity, which is measured by the 9-point measuring method, and this value is comparable to a commercial level [15]. The optimization result is strongly tied to simulation set-up such as mesh size, LED distribution, the shape of the local block, and so on, so there is a chance to increase optical efficiency further with more fine tuning.

3.3 Optical characteristics of the designed LGP

Figure 5 shows the spatial luminance distribution of the proposed LGP. Each block can operate individually as shown in Fig. 5(a), where only one of the nine local blocks is turned on in sequence. The blocks in the first row are slightly brighter than the other rows. This is because the pattern must be denser in the first row in order to achieve uniform luminance when all LEDs are turned on, as mentioned in the previous section.

Figure 5(b) shows a single LGP when only the center block is lit. Although some light enters into the neighboring blocks through the channels in the isolators, about 65% of all light was extracted in the target block. The confinement performance can further be engineered by controlling the channel thickness, width, and maximum pattern density more precisely. For example, an LGP with the same thickness and thinner channels (100 µm) shows that the isolation performance increased to 78.5% in other simulations.

According to the simulation, the isolator region in the center block is about 30% darker than the main block area (Fig. 5(b)). This is because the pattern distribution is optimized in the simulation for the case that all LEDs are turned on. When the next block is also turned on, the luminance in the isolator region reached to 93% of that of the main block area.

The angular luminance distribution of the LGP was also investigated via simulations. Figure 6 shows the angular luminance of the LGP at several points without any additional films. When all LEDs are turned on, vertical directionality was observed at every point on the LGP (Fig. 6(a)-(c)). In the case of the single block operation, vertical luminance directionality was also maintained in the body area as shown in Fig. 6(d). However, at the isolators, the angular luminance distribution was asymmetric (Figs. 6(e)-6(g)). This is because of the relative position between the light sources and the measured points. This simulation confirmed that the LGP results in vertical illumination in the entire area including the channel region, and the local illumination is not affected by the angular luminance distribution.

4. Fabrication and demonstration of the proposed BLU

We fabricated a prototype of an LGP for demonstration. The fabrication process of the LGP is depicted in Fig. 7. We first made three components individually: patterned top sheet, reflective barrier sheet, and body sheets (Figs. 7(a)-7(c), respectively). The patterned top sheet was fabricated by using 3D diffuser lithography and PDMS replication process [11,16]. The PDMS was chosen as an LGP material for this particular process considering its high elastic characteristic which helps in replicating the overhang-shaped microstructure from a mold. If other properties are required as an LGP material, other fabrication processes can be used which were proposed previously [17–19]. The reflective barrier was made with a 50 µm-thick PET film by using thermal evaporation and conventional photolithography process. Ag is suitable to use as a reflective layer because of its high reflectivity (96% in measurement), and the thickness of the layer was 200 nm; it is enough to screen the light from LEDs [20]. Flat and thick PDMS sheets were used as the bottom sheets. Finally, these three layers are bonded by liquid PDMS (as a glue) and cured.
Figure 7 shows the fabrication process of the proposed local dimming BLU. Each unit of (a) PDMS thin LGP sheet, (b) Ag patterned PET film, and (c) nine pieces PDMS sheets are bonded with liquid PDMS to make (d) the prototype BLU.

Figure 8 shows the fabricated 7-inch LGP, which has nine local blocks. Figure 8(a) is the fabricated LGP with a diffuser sheet and Fig. 8(b) shows the local dimming performance of the LGP. As shown in Fig. 8(b), the LGP can define the lighting area clearly because of its special design. The thickness of the entire LGP and the channels are only 1 mm and 0.2 mm, respectively (Fig. 8(c)). Figure 8(d) shows a SEM image of the inverse-trapezoidal microstructure. The diameter of the inverse-trapezoidal microstructure is 30 µm, the height is 12 µm, and the side-angle of the negative slope was well-designed to eliminate prism sheets from the LGP using vertical light extraction.

The optical measurement results are shown in Fig. 9. We measured the spatial luminance distribution of the LGP with an additional diffuser sheet for enhancing light uniformity. From the 9-point measurement, the luminance uniformity of the center block was 73% and 76% for the case where all LEDs are turned on (Fig. 9(a)) and the case only three LEDs in the center block are turned on (Fig. 9(b)), respectively, and the average luminance was 16% darker in the latter case (918.5 nit) than the former case (1092.7 nit). Figure 9(b) also shows the isolation performance of the fabricated BLU. The neighboring blocks are much darker than the illumination block (the luminance level of the blocks is only 1 to 10% to that of the blocks in the first row), and the results correspond very well with the simulations.
The angular luminance distribution of the LGP without any optical sheets such as prism and diffuser sheets was also measured at the center of a local block as well as at the channel area in a single block illumination in vertical and horizontal directions, as shown in Figs. 9(c) and 9(d), respectively. As we expected, the proposed LGP shows on-axis directional lighting performance without any additional sheets. This characteristic originates from reducing the entire thickness of the BLU by eliminating other optical sheets from the BLU. Similar to the simulation results in Fig. 6, the channel region shows asymmetric horizontal angular distribution characteristic because the light sources are placed only at the left side from the measured channel region as shown in Fig. 9(d).

Figure 10 and Table 1 show the experimental results of the proposed BLU. We prepared a test image of a white box in the center of the screen surrounded by a black background (Fig. 10(a)). The size of the white box is a quarter of the local block of the proposed BLU. Figure 10(b) and 10(c) are the photographs taken from the LCD screen, which display the test image with the conventional and proposed BLUs, respectively. All settings of the LCD panel to display the image are the same.

Because the conventional BLU has no local dimming function, expression of black color relies entirely on the light-concealing performance of the LCD panel. Moreover, all twenty-one LEDs in the conventional BLU were turned on during the display operation. As shown in Fig. 10(b), the image with conventional BLU cannot display real black. On the other hand,
owing to the conventional BLU, the luminance distribution of the proposed LGP shown in Fig. 9(b).

5. Conclusion

In this paper, we proposed and demonstrated a slim edge-lit BLU capable of 2D local dimming. To overcome the fundamental limitation of edge-lit local dimming BLUs, we designed an LGP with multiple local illumination blocks inside of the LGP. Due to the unique semi-partitioned design of the proposed LGP, the BLU can control the illumination area freely—even the illumination target blocks away from the display’s edge. Experimentally, the proposed BLU increases the CR up to two orders of magnitude higher than that of the conventional BLU without local dimming. The proposed BLU is remarkably slim (~1 mm), owing to the reduced number of optical sheets that the proposed LGP affords, which can make on-axis (vertical) light profile solely. Therefore, the proposed BLU is thought to be very promising for ultra-slim, energy-efficient, and high-CR LCDs.

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