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Optimization of the Emitting Structure of Flat Fluorescent Lamps for LCD Backlight Applications

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The emitting structure of multi-channel-type flat fluorescent lamps (FFLs) combined by a lenticular-lens-patterned diffuser plate was optimized by the ray tracing technique. The optimal parameters such as the distance between the channels of the FFL and the distance between the FFL and the diffuser plate were suggested from the viewpoint of the luminance uniformity. The best luminance uniformity, which was higher than 90%, was obtained at the channel distance of 4 mm and the distance of 12.5 mm between the FFL and the patterned diffuser plate.

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I. INTRODUCTION

A Liquid crystal display (LCD) is basically a non-emissive display, and thus needs an additional light source which supplies the LCD with uniform, bright, white light. The transmission of each pixel is controlled by using birefringent liquid crystals combined by two polarizers, while the color filter is used to carry out color separation of the incident white light into three primary colors. Backlight unit (BLU) plays the role of a light source for an LCD and has become one of the core technologies of LCD since the picture quality and cost of LCD are considerably determined by the performances and the cost of the BLU. For example, the luminance and its uniformity, the color gamut, the lifetime, even the quality of moving-pictures and the contrast ratio of LCD can be easily controlled by modifying the performances and characteristics of BLU.

BLU is constructed by using many components, for example, light sources, optical films, driving circuits, mold frames, etc. Light sources generate visible light, and optical components transform the generated light into the condition of homogeneous, collimated, two-dimensional planar illumination. Several kinds of light sources have been adopted and developed for BLU, such as cold-cathode fluorescent lamps (CCFL), external-electrode fluorescent lamps (EEFL), flat fluorescent lamps (FFL), light emitting diodes (LED) [1]. Among these, FFL BLU has recently attracted great attention owing to its superior structural simplicity and brightness uniformity.

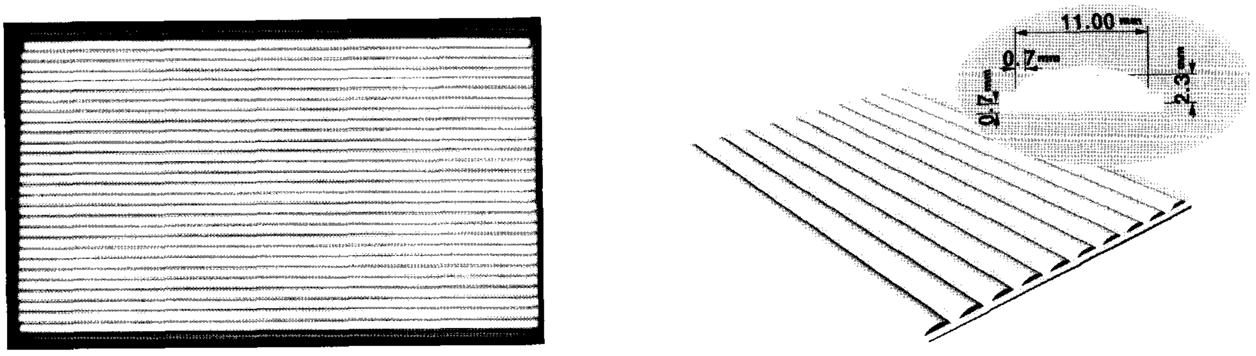
FFL can be categorized into mercury (Hg)-type and xenon (Xe)-type depending on the element generating ultraviolet light. Xe-type FFL is still under development for BLU applications owing to its much lower efficiency, and Hg-type FFL has recently been commercialized for 32- and 40-inch LCD [2]. Hg-type FFL has normally a multi-channel structure, which exhibits a multiple of parallel discharge channels from which visible light is generated [3]. The multi-channel structure is usually made by using the glass-forming technology, which simplifies the fabrication process of FFLs substantially. For better uniformity of FFL BLU, the multi-channel structure should be optimized including the cross-section and the distance between channels. In addition, unique optical films used for homogenization and collimation of white light from FFL should also be developed and optimized for better performances of FFL BLU. The present study is devoted to the optimization of the emission structure of Hg-type FFLs including the channel structure as well as a patterned diffuser plate for FFL BLU by using a ray-tracing technique [4]. Detailed numerical parameters for the optimized structure of FFL BLU have been suggested based on the simulation work.

II. MODEL CONSTRUCTION

Figure 1 (a) shows the photograph of a commercialized 32-inch Hg-type FFL, which emits visible light through 28 discharge channels. Figure 1 (b) shows one example of FFLs simulated in the present study. The total area of the FFL is 152×106 mm^2, where the longer axis is along the channel direction. One FFL is composed of two glass plates whose refractive index is 1.52 and thickness is 0.7 mm. The lower glass plate of the FFL is flat while the upper glass is multi-channel-structured. The number of channels on the upper formed glass is determined by the distance between channels. If the distance between channels is 4 mm, the total number of channels becomes 10. Phosphor layers are normally coated on the inner surfaces of these two glass plates, which generate visible light via the photoluminescence process excited by ultraviolet (UV) photons. In this simulation, visible light is generated from elliptic volume emitters, of which the lengths of major and minor axes are 6 mm and 0.6 mm, respectively, positioned at the center of the discharge channel. This virtual light source emits rays according to the Lambertian distribution. On the lower glass plate, a diffusely reflecting layer is positioned, which redirects downward rays to the LCD panel.

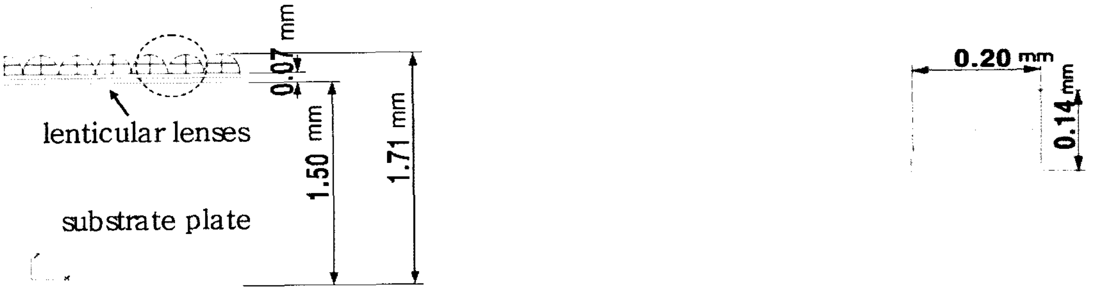
The encircled inset figure in Fig. 1 shows the cross-section of each channel. The width and the maximum height of the discharge cross-section are 9.6 mm and 2.3 mm, respectively. This ratio should be determined according to the optimization condition of the discharge efficiency and thus should be kept larger than 3 [5]. The curvature of the upper part of the channels was determined by analyzing the channel structure of the commercialized FFLs and was modeled by using a Bezier curve with a weighting factor of 0.707 [6]. The total transmission of the upper glass was set to be 0.8 based on a transmission experiment on the real upper glass plate of FFL on which the thin phosphor layer was coated.

Conventional diffuser plates in direct-lit BLUs are made by dispersing beads into the transparent polymeric plate having a refractive index different from that of the beads. In the present study, a lenticular-lens-patterned plate was used as a diffuser plate for FFL BLU [7]. Figure 2 (a) exhibits the cross-section of the patterned diffuser plate which is put over the FFL at a certain distance. The thickness of the substrate plate is set to 1.5 mm, on which lenticular lenses are formed whose directions are parallel to the channel direction of the FFL. These lenticular lenses may be made from UV resin by using the conventional roll-molding method. The refractive indices of the substrate and the lenticular lenses are 1.58 and 1.50, respectively. The pitch of the parallel lenticular lenses is 200 μm,



(a) (b)

FIG. 1. (a) A photograph of the commercialized 32-inch, Hg-type FFL. (b) A schematic diagram of one of the FFLs simulated in the present study. The encircled inset figure shows the fixed cross-section and related dimensions of the discharge channel.



(a) (b)

FIG. 2. (a) Cross-section of the lenticular-lens-patterned diffuser plate and (b) an expended view of the semi-elliptic lenticular lenses.

and the height of each lens is 140 μm. Between the base plate and the lenticular lenses, a thin film having a thickness of 70 μm and a refractive index of 1.50 was inserted in order to reflect the practical condition of optical films resulted from the fabrication process where a thin UV resin film remains beneath the patterned micro-lenses. The expanded view of the lenticular lenses is also shown in Fig. 2 (b). The cross-section of each lens is a semi-ellipse whose lengths of major and minor axes are 0.28 mm and 0.2 mm, respectively.

The FFL BLU is constructed by combining one FFL and one patterned diffuser plate. Figure 3 shows the basic construction of the FFL BLU as well as the expended view of the patterned diffuser plate in the encircled inset. The distance between FFL and the diffuser plate was changed between 4.5 mm and 12.5 mm. A typical distance between the lamp and the diffuser plate in commercialized FFL BLUs is 12.5 mm. A virtual detector was put over the diffuser plate in order to investigate the ray distribution incident on it.

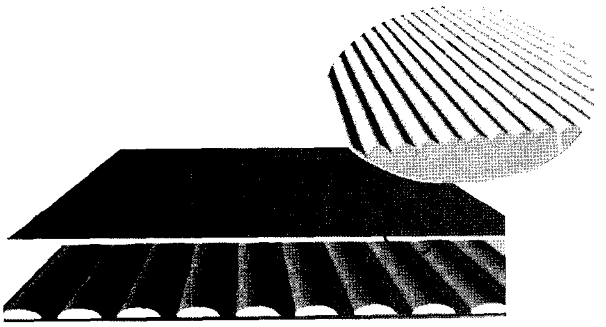


FIG. 3. A schematic diagram of the FFL BLU composed of one FFL over which one patterned diffuser plate is positioned. The encircled inset shows the expanded view of the patterned diffuser plate.

Ray tracing technique using the ASAP software (Breault Research Org.) was adopted for the simulation of the FFL BLU. Normally, more than 10 million rays were used to simulate the FFL BLU at one condition. The brightness distribution on the diffuser plate was investigated as functions of the distance between the FFL and the diffuser plate as well as the distance between channels. In order to examine the brightness uniformity of FFL BLU, the number of rays confined in a cone defined by an angle of 4 degrees with respect to the normal direction was investigated as a function of position on a detector which was put above the diffuser plate with a gap of 10 μm. The simulation condition of the FFL BLU is summarized in Table 1.

III. RESULTS AND DISCUSSION

Figure 4 (a) is one example of the traced rays in the FFL BLU where the distance between channels is 4 mm and the distance between the FFL and the diffuser plate is 12.5 mm. The total number of channels is 10

TABLE 1. Simulation conditions of FFL BLUs

FFL	Area	152×106 mm^2
	Number of channels	8~10
	Dimension of the cross-section of the discharge space	width = 9.6 mm, height = 2.3 mm
	Distance between channels	4~8 mm
	Light source	Lambertian-type elliptic volume emitter in channels
	Reflector	Diffuse Lambertian reflector
	Refractive index of the glass	1.52
	Transmission of the upper glass	0.8
diffuser	Cross-section of the micro-lens	Semi-elliptic (major axis = 0.28 mm minor axis = 0.2 mm)
	Pitch	200 μm
	Total height	1.71 mm
	Refractive index of the lenses	1.5
	Refractive index of the substrate	1.58
BLU	Combination	FFL + diffuser
	Distance between the FFL and the diffuser	4.5~12.5 mm
Simulation	Number of rays	10^7 rays

in this case. Lambertian volume emitters in the discharge channels emit rays that propagate in the BLU according to the Fresnel conditions or the pre-determined transmission and reflection conditions. Figure 4 (b) and (c) show the distribution of rays incident on the detector along the normal direction without and with the diffuser plate. Without the diffuser plate, clear images of emitting discharge channels can be seen, while the channel images are hardly seen on the detector with the diffuser plate inserted. Figure 5 shows the luminance distribution along the direction perpendicular to the channel axis. Rapid alternation of bright and dark images seen on Fig. 4 (b) is reflected on the substantial changes of the luminance in the curve denoted as "without the diffuser plate", while the luminance uniformity has been significantly improved when the diffuser plate is inserted. If the averaged maximum luminance occurring at the center of all channels is denoted by $L_{\max}$ and the averaged minimum luminance observed at the mid-points between channels by $L_{\min}$, the luminance uniformity U is defined by the following equation:

$$U(\%) = \frac{L_{\min}}{L_{\max}} \times 100\% \tag{1}$$

The luminance uniformities of the two curves in Fig. 5 are estimated to be approximately 3% and 91% for the cases without and with the diffuser plate, respectively. This result indicates that the lenticular-lens-patterned plate can be adopted over the FFL as a diffuser plate for hiding the bright images of the discharge channels and thus improving the luminance uniformity substantially, similar to the role played by the conventional beads-dispersed diffuser plate.

As a next step, the luminance uniformity was investigated by changing the distance between channels while fixing the distance between the FFL and the diffuser plate to 12.5 mm. Figure 6 (a) shows the distribution of the luminance on the diffuser plate, estimated along the direction perpendicular to the channel axis. As the distance between channels increases from 4 mm to 8 mm, the minimum luminance observed between channels decreases while the maximum luminance observed at the center of each channel increases, resulting in the degradation of the luminance uniformity. The estimated luminance uniformity is plotted in Fig. 6 (b) as a function of the distance between channels. The distance between channels can become shorter than 4 mm, where better luminance uniformity is expected. However, if the channel distance becomes shorter than 4 mm, the capacitive coupling between discharge paths becomes larger and the dimming capability of the FFL BLU becomes worse. Requirement on the dimming range of BLU is normally

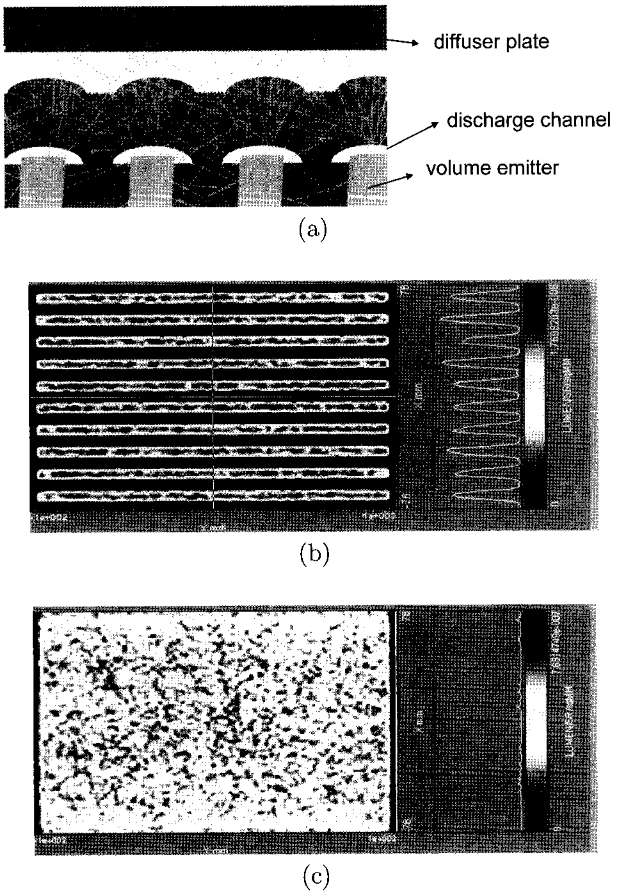


FIG. 4. (a) One example of traced rays in the FFL BLU where the distance between channels is 4 mm and the distance between the FFL and the diffuser plate is 12.5 mm. (b) The image showing the luminance distribution without the diffuser plate. (c) The image showing the luminance distribution with the diffuser plate.

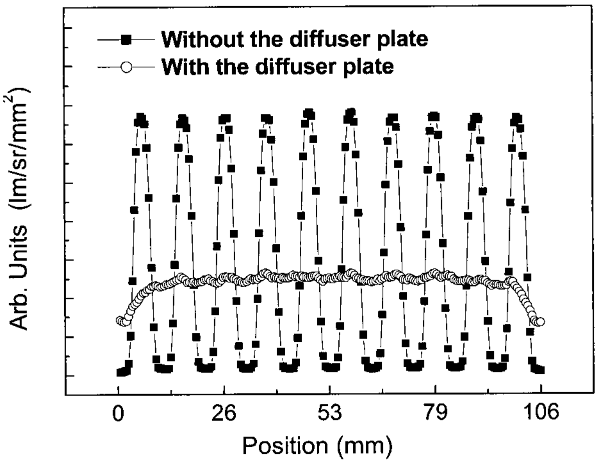


FIG. 5. The luminance distribution along the direction perpendicular to the channel axis for two cases without and with the diffuser plate in the BLU. The simulated condition is described in the text.

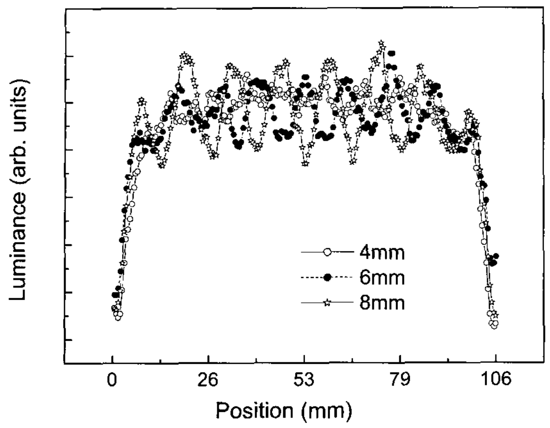


FIG. 6. (a) Luminance distribution on the diffuser plate along the direction perpendicular to the channel axis as a function of the distance between channels.

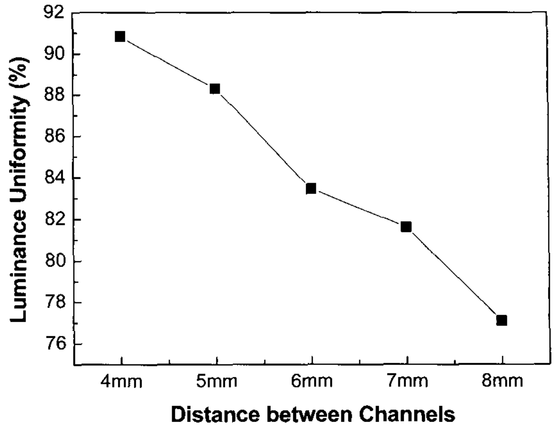


FIG. 6. (b) Luminance uniformity as a function of the distance between channels.

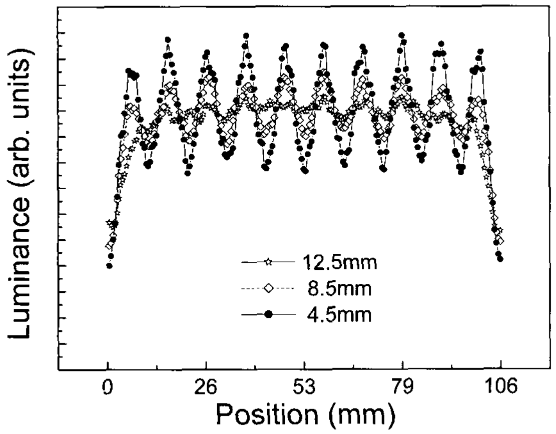


FIG. 7. (a) Luminance distribution on the diffuser plate along the direction perpendicular to the channel axis as a function of the distance between the FFL and the diffuser plate.

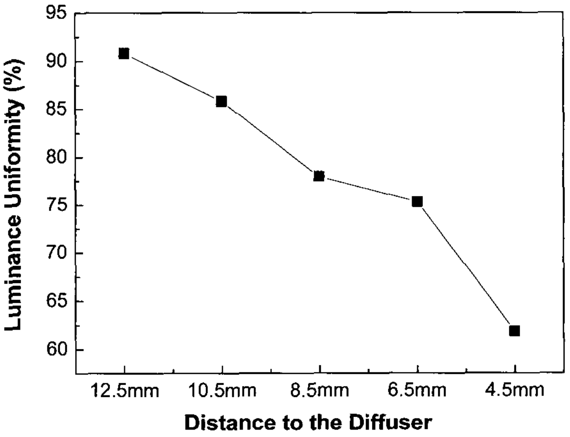


FIG. 7. (b) Luminance uniformity as a function of the distance between the FFL and the diffuser plate.

20~100%. It was found that the dimming range can only become as small as 20% at the channel distance of 4 mm and above from independent experiments carried out on 32-inch, multi-channel., Hg-type FFLs. Therefore, 4 mm should be considered as the minimum distance between channels of the FFL.

Finally, the distance between the FFL and the diffuser plate has been changed between 4.5 mm and 12.5 mm and the luminance uniformity has been investigated on the diffuser plate. Figure 7 (a) shows the luminance uniformity along the direction perpendicular to the channel axis at three distances. As the distance between the FFL and the diffuser plate becomes shorter, the difference between the maximum and the minimum luminance values becomes larger, which means that the mixing of rays from nearby channels becomes poorer at shorter distances. Figure 7 (b) shows the estimated luminance uniformity as a function of the distance between the lamp and the diffuser plate. This result indicates that the distance should be kept more than 10.5 mm in order to maintain the luminance uniformity above 85%.

The lenticular-lens-patterned diffuser plate has also been tried in a conventional tubular-lamp-based BLU [7]. Although semi-circular or semi-elliptic lens array diffuses the rays emitted from tubular lamps to some degree, it cannot screen the spatial modulation of the luminance completely due to the large distance between the independent CCFLs, which is normally 25 mm or larger. In contrast, the semi-elliptic lenticular lens array can be used to achieve enough luminance uniformity on the BLU thanks to the much shorter distance between discharge channels. In addition, the transmission of the present diffuser plate is expected to be much higher than that of the conventional beads-dispersed diffuser plate because there are no scattering beads in the substrate, which will contribute to the improvement of the efficiency and decrease in the power consumption in FFL BLUs.

However, a weak *periodic* modulation in the luminance of which the difference is about 5% might be perceived by human eyes at the practical luminance level of BLUs. Therefore, there is a possibility that the luminance uniformity of 90% might not be enough, and weak emitting patterns from discharge channels may be seen on the patterned diffuser plate. This potential problem can be improved by modifying the cross-section of the lenticular lenses, by imposing some diffuseness on the backside of the diffuser plate via, for example, etching process or by using one more optical film such as a diffuser film or collimation film on this patterned diffuser plate. In addition, interference between the lenticular-lens array and other periodic patterns such as the prismatic pattern on the collimation film or the periodic pixel structure of LCD might be prevented via some randomization of the lenticular microstructure [8].

The present study has been limited to the investigation of the on-axis characteristics of the FFL BLU, which are important from the viewpoint of the luminance uniformity. However, viewing-angle characteristics are also very important for better picture-quality of LCD. In addition, lenticular-lens-patterned diffuser plate is expected to collect the rays toward the LCD panel to some degree, in particular, along the direction perpendicular to the axis of the one-dimensional lens array. Detailed simulation results on the performances of FFL BLUs as a function of viewing angle will be reported in the near future.

IV. CONCLUSION

A ray tracing technique has been used to optimize the emitting structure of the FFL as well as the FFL BLU in which a lenticular-lens-patterned diffuser plate was adopted. Optimum distance between channels is found to be 4 mm while, at this channel distance, the distance between the FFL and the patterned diffuser plate should be kept to a value larger than 10.5 mm in order to achieve a luminance uniformity better than 85%. The present study showed that ray tracing simulation on FFL BLUs can be a powerful tool in the optimization of the emitting structure of FFLs as well as the structure of FFL BLUs including optical films whose patterns are correlated with the emitting structure of the FFL.

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