Enhancement of on-axis luminance of flat fluorescent lamps (FFLs) by using micro-lens arrays

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Abstract

The effect of the modification of the front surfaces of flat fluorescent lamps (FFLs) on the light-output distribution has been investigated by using a ray tracing method and several kinds of microlenses. It was found that microlenses have substantial effects on the light-output distribution, which might be used to reduce the number of optical films in the FFL-backlight unit for LCD applications.

1. Introduction

The backlight unit (BLU) technology has become the core component for large-size liquid crystal displays (LCDs). Various light sources have been developed and adopted in the BLU such as light-emitting diodes, flat fluorescent lamps (FFLs), field-emission lamps, etc[1]. FFL has attracted great attention owing to the possibility of a simple manufacturing process, superior uniformity as well as cost-down, and has recently been commercialized [2]. The shape of the upper plate of FFLs can be planar, multi-channel-structured, or embossed depending on the operating principles such as discharge characteristics and electrode structures. However, there has been no detailed study on the distribution of the output light emitted from FFLs and its modification in order to optimize the performance of FFL backlight. In contrast, intensive efforts have been carried out on the increase of the output coupling of the generated visible light from the inside of the solid state lighting such as LED (light emitting diode) or OLED (organic LED) [3].

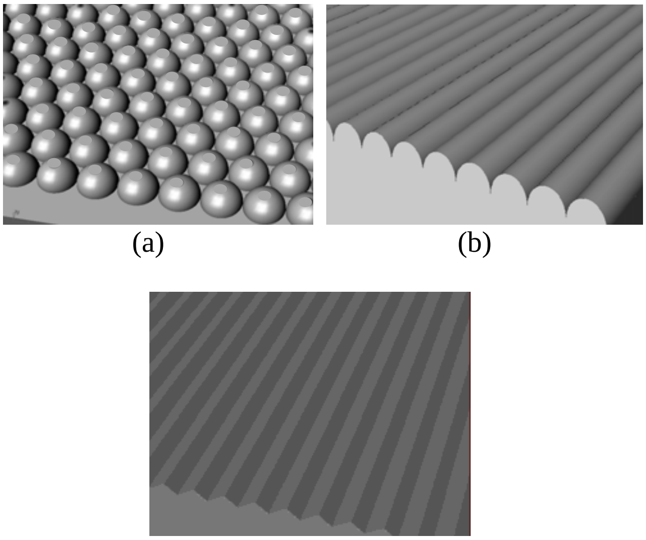
Various techniques applied to LED and OLED for increasing output coupling and external quantum efficiency were mainly focused on breaking the waveguide mode of the trapped light via total internal reflection (TIR) [4]. In case of FFL, visible light is generated from phosphor powder attached on the inner surfaces of both upper and lower glasses. The role of the upper flat glass is just displacing the transmitting ray slightly via double refraction at both surfaces without modifying the direction of the ray and thus the distribution of the output light on FFL. Therefore, the distribution of the output light from FFL is basically Lambertian. The amount of the trapped light in the glass plate might be small in contrast to the case of LED and OLED. Additional structure on FFL other than a flat surface may supply us with the possibility of reshaping the distribution of light-output from FFL.

Recently, two important technological issues in the backlight field are lowering both cost and power consumption. In this respect, it is very important to improve the light-generating efficiency as well as to reduce the number of optical components required in the BLU. Although mercury-type FFLs have recently been commercialized and demonstrated by several companies, there has been no effort to modify the light-output distribution without using optical films. The purpose of the present contribution is to reveal the quantitative correlation between various microlenses formed on the upper surface of FFLs and the distribution of the output light by using optical simulation and thus to find out optimal shapes of FFLs for increasing the total system efficiency of FFL BLU.

2. Simulation

A ray tracing technique using the ASAP software (Breault Research Org.) was used for the simulation. In order to model the FFL, two glass plates were set to be parallel to each other. The area of the model FFL was 12*12 mm^2, and the refractive index was 1.523. Transmission of two glass plates was set to be determined by the Fresnel condition ignoring any possible absorption in the glass material. The thickness of the discharge space was 1 mm. Three kinds of microlenses were formed on the outer surface of the upper glass plate. First one is hemi-spheres with a diameter of 60 μm, arrayed in a closed-packed hexagonal lattice. Second one is one-dimensional lenticular lenses whose crosssections are a semi-circle with a diameter of 60 μm. The last one is one-dimensional prismatic lenses whose crosssections are an isosceles triangle with a pitch of 60 μm and an apex angle of 90°. Figure 1 shows schematic diagrams of the shapes of three microlenses formed on FFL.

In a typical plate-type FFL, a reflection layer is attached on the inner surface of the lower glass plate, onto which a thick phosphor layer is formed. On the other hand, an upper phosphor layer is formed on the inner surface of the upper glass plate. In order to model the phosphor layers and the reflection layer, two virtual layer-type emitters were put on the inner surfaces of both glass plates, and a reflector was formed between the lower glass plate and the lower virtual emitter. A diffusive Lambertian-type reflector was used. Considering the diffuse nature of the phosphor and reflection layer, it is expected to be more appropriate to use the diffuse reflector instead of a perfect mirror as a reflection layer. The emitting distribution from these virtual emitters was set to be Lambertian. The light distribution from FFLs was monitored by using a detector, which was put on the FFL with a distance of 0.1 mm. The total number of rays used in one simulation was typically one million. The detected distribution of output light was examined as a function of the viewing angle.



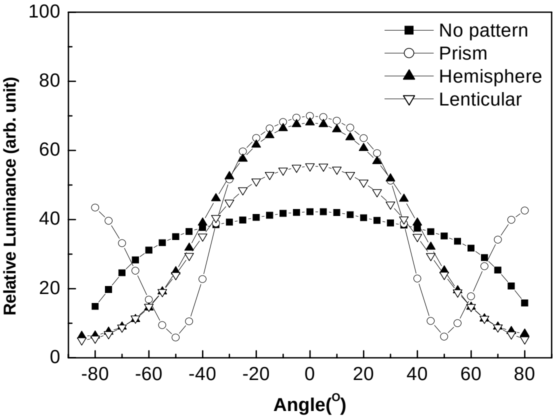
(a) (b)

(c)

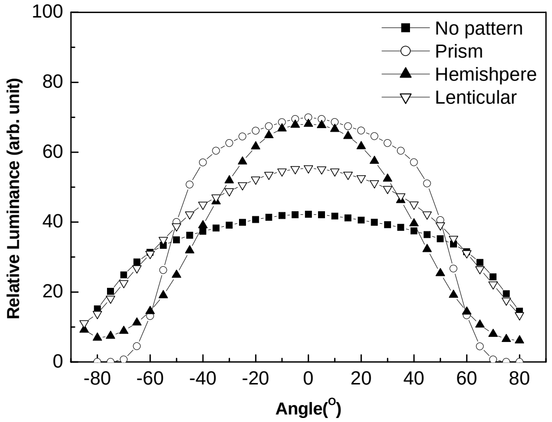
Fig. 1. Three kinds of microlenses formed on FFL: (a) hemispheres, (b) lenticular lenses, (c) prisms.

3. Results and discussion

Figure 2 summarizes the viewing angle characteristics of FFLs whose upper glass plate was shaped to have three kinds of microlenses. Fig. 2(a) and (b) correspond to the viewing angle property along the direction perpendicular and parallel to the one-dimensional lens patterns in the case of prism and lenticular lenses, respectively. “No pattern” in the figures indicates the case where no microlenses were formed on the flat upper glass of FFLs. The light-output distribution on the flat FFL with no pattern is almost Lambertian.



(a) perpendicular direction



(b) parallel direction

Fig.2. Relative luminance of four kinds of FFLs as a function of viewing angle along the (a) perpendicular and (b) parallel directions with respect to the directions of the one-dimensional microlenses.

The prism pattern formed on FFL is exactly the same as that of the conventional prism sheets incorporated into the backlight as additional optical films. The prism sheet is normally used to collimate the output light and thus restrict the viewing angle along the direction perpendicular to the prism direction. If we put prism lenses described above on the FFL, the output light is more collimated along one direction perpendicular to the prism direction than along the other direction. This effect is almost the same as the anisotropic collimating function of the prism sheet conventionally used in the backlight.

Lenticular microlenses also show the anisotropic collimating function similar to the one-dimensional prism lenses. However, lenticular-patterned FFL exhibits a wider viewing angle characteristics and a lower on-axis luminance gain compared to the prism-patterned FFL. In case of prism lenses with an apex angle of 90^o, approximately 50 % of the incident rays are reflected back towards the discharge space and reflection layer via two TIRs at the prism surfaces. Downward rays will be diffusely reflected on the reflection layer or phosphor layers and partly be transformed into useful light which can be collimated through refraction at the prism surfaces resulting in a narrow viewing angle. However, the surfaces of the lenticular lenses are rounded, and much portion of the incident light will just be refracted at these surfaces instead of being reflected back for recycling.

In contrast to the above two cases, emitted light is expected to be homogeneously collimated on the hemispherical microlenses. The luminance gain on the on-axis direction becomes higher on the FFL when the lenticular lenses are replaced by the hemispherical lenses. This is a natural result considering the homogeneous and inhomogeneous collimation occurring in two cases, respectively. Recently, various technologies are used to fabricate refractive microlenses on glasses or plastics [5]. For example, the aspect ratio and the fill factor of hemispherical lenses can be adjusted by using three-dimensional diffuser lithography [6]. In this case, the viewing angle characteristics and the on-axis luminance gain can be controlled by optimizing the density and the aspect ratio of the microlenses.

Figure 3 summarizes the on-axis luminance and the full-width at half-maximum (FWHM) of the luminance curve as a function of viewing angle on each FFL along the direction perpendicular to the direction of the one-dimensional pattern. These values have been obtained from two kinds of reflectors, the diffuse reflector used to obtain all the previous results and a perfect mirror reflector. When the diffuse reflector is used, the on-axis luminance gain increases from 1.59 to 2.05 compared to the Lambertian-case when the microlense is changed from lenticular- to the prism-type. In inversely proportional to this trend, the FWHM becomes lower as the on-axis luminance becomes higher.

The on-axis luminance gain is slightly higher when the mirror reflector is used than the case when the diffuse reflector is adopted in the FFL. When a part of the rays are reflected from the upper surfaces toward the reflector, they will be reflected nearly normal to the reflector in case of the mirror reflector which will contribute to the on-axis luminance, while they will be diffusely reflected on the diffuse reflector resulting in a wider viewing-angle characteristic. Since the conventional reflection layer adopted in FFLs is made from powders such as Al_2O_3 or TiO_2, the results obtained from the FFL combined by the diffuse reflector are regarded to be more correct.

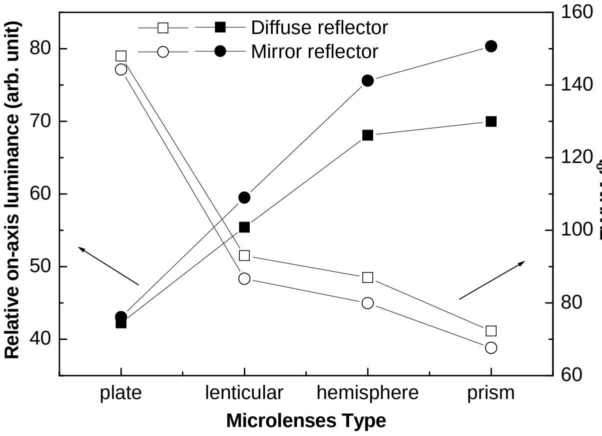


Fig.3 The relative on-axis luminance and the FWHM depending on the microlenses formed on FFL and the type of the reflector. The FWHM was estimated along the direction perpendicular to the one-dimensional microlenses.

For practical application of this concept to FFLs, two issues should be resolved.

First, spacers are usually incorporated into the FFLs in order to support the discharge space between the upper and lower glasses. These spaces normally form dark regions on FFLs. Although microlens-patterned upper glass might improve the luminance uniformity on FFLs slightly hiding the dark regions, it will not remove them completely. Therefore, additional designs should be applied to FFLs in order to achieve sufficient luminance uniformity. Cutting the upper phosphor layer around the spacer or using a patterned diffuser sheet, correlated with the location of spacers, on FFLs might be some examples of the additional necessary designs.

Second, cost-effective technologies for forming microlenses on FFLs should be developed. Lithography-based technologies are costly for this purpose. Conventional beads-dispersed diffuse layers might be applied to the upper plate of FFLs in order to increase the on-axis luminance as well as to homogenize the output light from FFLs.

4. Summary

Recent two key directions of BLU technologies are related to lowering the cost and decreasing the power consumption. It is hence very important to develop hybrid films to modify the light distribution other than using multiple optical films for achieving lower power consumption. In this respect, FFLs have additional degree of freedom compared to conventional tubular fluorescent lamps because optical components can be directly formed on the upper flat surfaces without any air gap. Formation of microlenses on the flat FFL would be one simple way to modify the distribution and thus to reduce the number of optical films without degradation of the performances of FFL BLU. From the present study, it has been clarified that one-dimensional microlenses such as prism or lenticular lenses can be used to achieve anisotropic collimation while hemispherical lenses can be used to collimate the output light homogeneously on FFL. Quantitative correlation between the shapes of microlenses and viewing-angle characteristics has been obtained.

5. References

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