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Optical Simulation Study on the Effect of Reflecting Properties of Reflection Films on the Performances of Collimating Films for the LCD Backlight Applications

Jeong Ho Lee[a], **Young Hyun Ju**[a], **Ji-Hee Park**[**a], **Ji-Young Lee**[**a], **Kie-Bong Nahm**[a], **Jae-Hyeon Ko**[*a], **and Joong Hyun Kim**[*b]

Abstract

The dependence of optical performances of collimating films such as prism films and pyramid films on the reflecting properties of reflection films were investigated by using a ray tracing technique. The angular distribution of the luminance and the on-axis luminance gain were obtained by using a simple backlight model composed of a reflection film, a virtual flat light source, and a collimating film. Three kinds of reflecting properties were used, which were a perfect Lambertian reflector, a perfect mirror reflector, and a reflector having both diffuse and specular properties. It was found that the on-axis luminance gain was the highest in the simulation where a mirror reflector was used, while the viewing angle was the widest where the Lambertian reflector was used. This result indicates that it is necessary to optimize the simulation condition such as the reflecting properties in order to predict the optical performances of collimating films accurately. Quantitative correlation between the optical characteristics of collimating films and the reflecting properties of reflection films can be used to improve simulation technique for the development and the optimization of collimating films for LCD backlight applications.

Keywords : backlight unit (BLU), pyramid film, collimation film, prism film, luminance gain

1. Introduction

Display technology today is being dominated by flat panel displays such as liquid crystal displays (LCD) and plasma display panels (PDPs). In particular, the market size of LCD has increased substantially during the last few years due to the large growth of the LCD-TV market. LCD is a representative non-emissive display because it always needs white light that must be supplied by an independent unit called backlight unit (BLU). The function of BLU is to supply LCD with a bright, uniform, and white light having an appropriate correlated color temperature. The orientation of liquid crystals in LCD, which is controlled by thin film transistors (TFT) on the back plate, combined by two crossed polarizers determines the amount of transmitted light, while the color filter on the front glass of the panel reshapes the spectrum of the incident white light for the formation of at least three primary colors. The luminance, the color temperature and the optical uniformities of LCD are dominantly determined by the quality of the white light coming from BLU.

BLU consists of many parts such as light sources, a light guide panel (LGP) for edge-lit type BLU, a diffuser plate for direct-lit type BLU, several optical films, mold frames, driving circuits, etc[1,2]. Among them, optical films are used to homogenize the light and/or manipulate the angular distribution of the output light on BLU, causing the on-axis luminance to increase [3]. In case of direct-lit BLU, tubular fluorescent lamps such as cold cathode fluorescent lamps (CCFL) are arranged in parallel, below which a reflection film is placed to redirect the white light generated from CCFLs toward the LCD panel. Above CCFLs, a diffuser plate is used to homogenize the distribution of the output light resulting in the Lambertian distribution on it, which means equal luminance irrespective of the viewing angle. A diffuser film on the diffuser plate further homoge-

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[*] Member, KIDS; [**] Student Member, KIDS
Corresponding Author : Jae-Hyeon Ko
[a]Department of Physics, Hallym University, Hallymdaehakgil 39, Chuncheon-si, Gangwondo 200-702, Korea
[b]AMLCD Division, Samsung Electronics Co. Ltd., Asan, Chungnam, Korea
E-mail : hwangko@hallym.ac.kr
Tel : 81-33-248-2056 **Fax** : 81-33-256-3421

nizes the light and slightly modifies the angular distribution of the light coming from the diffuser plate, enhancing the on-axis luminance by approximately 20~28%. The collimating film further collimates the light toward the LCD panel and thus enhances the on-axis luminance by more than 30 %. The light-collimating power of collimating films such as prism films depends on many parameters such as the refractive index, apex angle or cross-sectional shapes, density of micro-lenses, etc.[4]. In addition, a reflective polarizer may be used to increase the on-axis luminance without disturbing the viewing-angle characteristics [5].

Recently, efforts have been put into developing new collimating films for better optical performances and/or hybrid films incorporating both the diffusing function and the collimating function [6-8]. However, it normally takes a long time of at least a few months to design, fabricate, measure, feedback the experimental results, redesign and finalize the development of new optical films for backlight applications. Optical simulation using the ray tracing technique has thus been widely used to test the optical performances of new-concept optical films and shorten the developmental time [9]. For carrying out correct simulation in order to predict accurate performances of optical films, it is necessary to consider detailed simulation conditions such as the reflecting properties of reflection films, refractive index of each part, absorption coefficient of the materials, etc. In many of the previous works [4, 10-11], a perfect mirror reflector has conventionally been used in the simulation in order to investigate the optical performances of collimating films. This simple assumption gives us a powerful and convenient method to predict relative luminance gain of collimating films under various conditions [12]. However, the reflecting property of reflection films is expected to have substantial effects on the viewing-angle characteristics of collimating films, since it will control the direction of reflected rays toward the collimating film and the optical properties of the collimating film is very sensitive to the distribution of the incident light from below.

Therefore, the purpose of the present study is to investigate the correlation of the reflecting properties and the viewing-angle characteristics as well as the on-axis luminance of two representative collimating films, a prism film and a micro-pyramid film. Quantitative correlation between the optical characteristics of collimating films and the reflecting properties of reflection films can be used to improve the optical simulation technique for the development and the optimization of collimating films for LCD backlight applications.

2. Simulations

A ray tracing technique using the ASAP (Advanced Systems Analysis Program, Breault Research Org., 2006 V2R1) was adopted for the simulation. It is necessary to design a simple simulation model which incorporates important core components of backlights. In the present study, a simple backlight model composed of a reflection film, a virtual flat light source, and a collimating film was constructed as given in Fig. 1. A virtual detector was put over the backlight in order to investigate the distribution of the output light. Although this kind of simple backlight does not include all components of the conventional BLU, relative optical performances of various collimating films can be estimated accurately [12]. The wavelength of the light from the light source was fixed to 555 nm and the output distribution of the light source was set to be Lambertian. The collimating film constructed for the simulation consisted of a substrate and micro-lenses attached on it. The thickness of the substrate was 125 μm with a refractive index of 1.575. The micro-lens was either a one-dimensional prism conventionally used in the present backlight technology or a pyramid having a shape of tetrahedron. The apex angle and the refractive index of both micro-lenses were fixed to 90° and 1.55, respectively. The pitch of the prism and the pyramid was 60 μm, and thus the height of each micro-lens was 30 μm. The total area of the substrate was

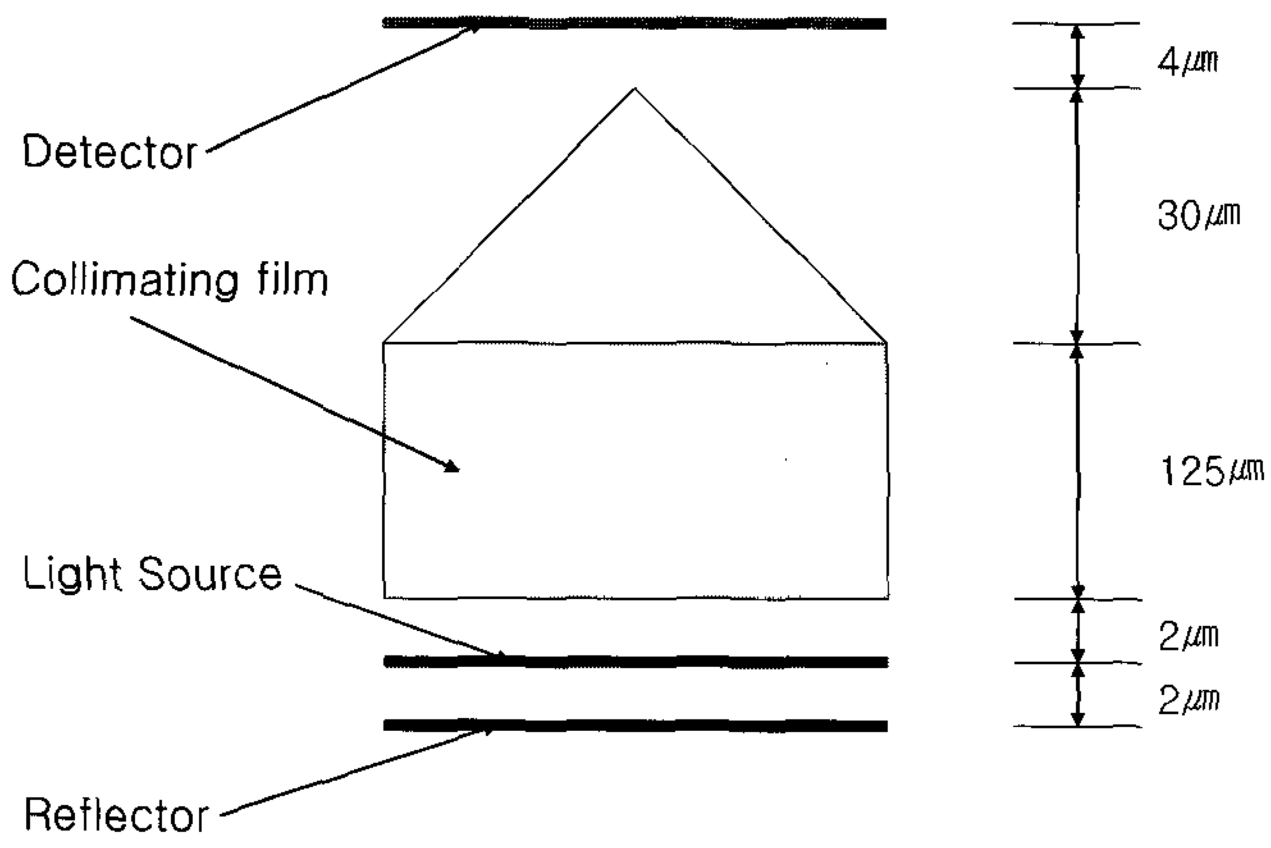
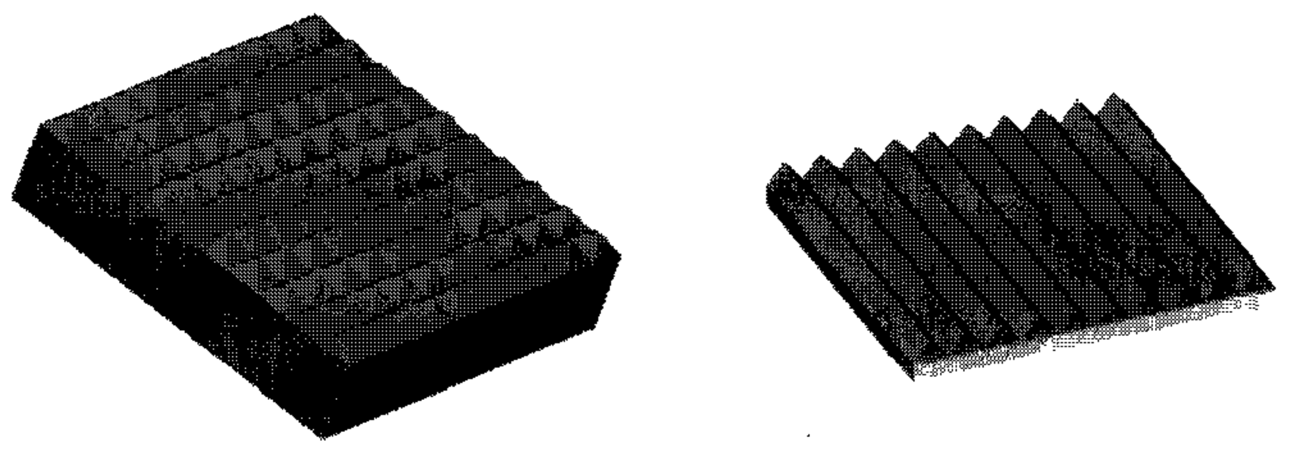


Fig. 1. A cross-section of the simple backlight model used in the present simulation study.



(a) (b)

Fig. 2. The schematic 3-dimensional views of (a) a pyramid film and (b) a one-dimensional prism film.

12×12 mm^2. Other material properties such as the absorption coefficients and the roughness of surfaces were not considered in the present simulation study. Figs. 2(a) and (b) show the schematic 3-dimensional views of the pyramid film and the prism film, respectively. The dispersion of the materials of optical films, i.e., the dependence of the refractive index on the wavelength was neglected in the present study.

In order to investigate the effect of the reflecting property of the reflection film on the optical performances of these collimating films, three kinds of reflector were used in the simulation. First two were a perfect mirror reflector and a perfect diffuse Lambertian reflector. The last was an intermediate one having both diffuse and specular reflecting properties. This last one was modeled by the bi-directional reflection distribution function (BRDF) of white PET of E60L (Toray Co.), and will be called white-PET reflector hereafter. The BRDF describes the angular distribution of radiation scattered from a surface and is formally defined as the differential radiance divided by the differential irradiance, which can be measured by a scatterometer [13]. The BRDF of the white-PET reflector was measured and modeled by the Harvey scattering model[14], which was incorporated into the ASAP software. The Harvey scattering function is given by the following equation.

$$BRDF = b\left[\frac{\left|\sin\theta - \sin\theta_0\right|}{0.01}\right]^s \qquad (1)$$

In this equation, θ_0 and θ denote the incident angle of the probe beam and the angle of the scattered ray, b is the BRDF at 0.01 rad from the specular component, and s is the slope of the BRDF on a log-log plot. The measured BRDF of the white-PET reflector (E60L) was fitted by the superposition of two Harvey functions, and the fitted result is shown in Fig. 3 as a function of the incident angle.

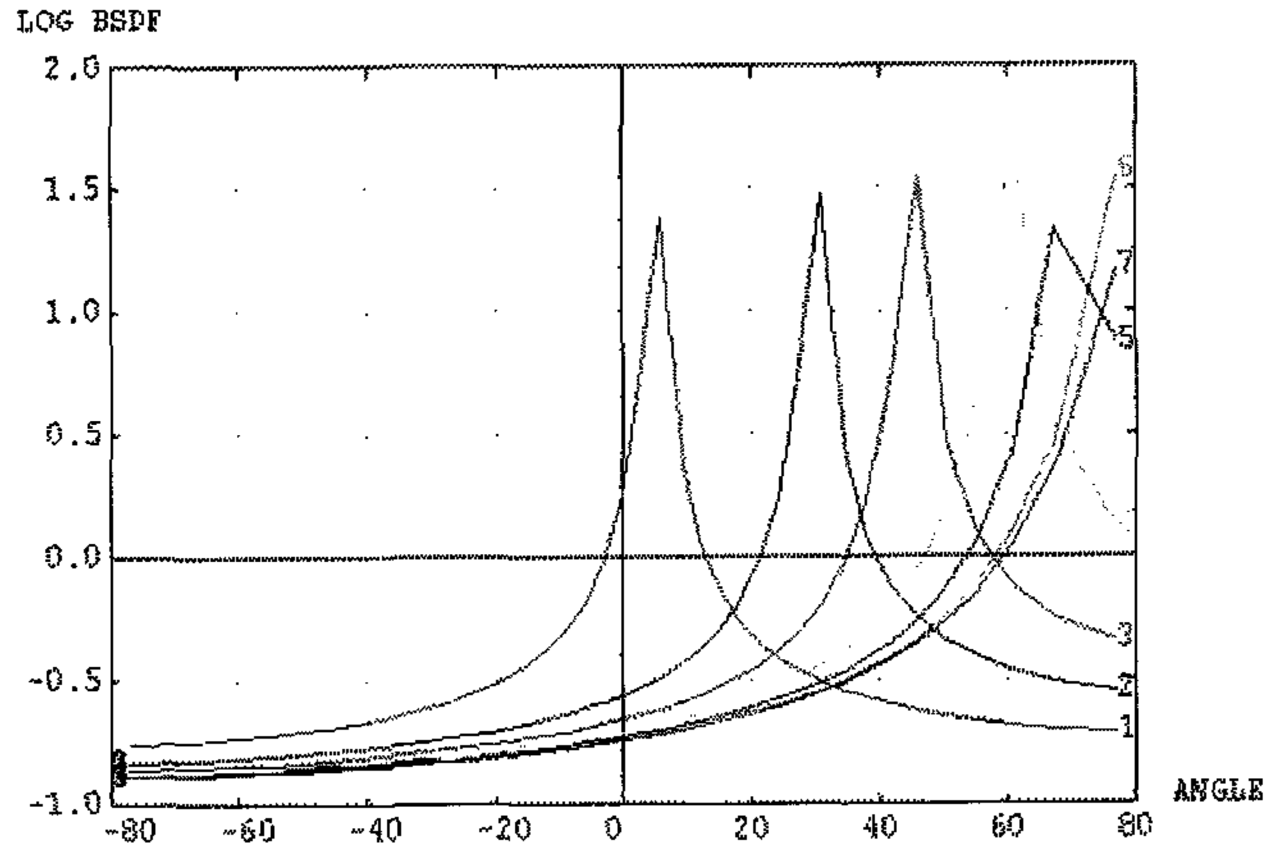


Fig. 3. (Color online) The BRDF of the white-PET (E60L) reflector as a function of the scattered angle plotted in a semi-log scale. Each colored line corresponds to the incident angle of the probe beam as 1-5.0°, 2-30.0°, 3-45.0°, 4-60.0°, 5-70.0°, 6-80.0°, 7-85.0°.

3. Results

Fig. 4 shows the dependence of the luminance on the viewing angle of the pyramid film. In contrast to the one-dimensional prism film, the pyramid film exhibits almost the same property along both vertical and horizontal directions due to the tetragonal shape of its micro-lenses. The viewing-angle, which is defined by the full-width at half-maximum (FWHM) of the luminance distribution, is the widest when using the diffuse reflector, while the on-axis luminance is the highest when using the mirror reflector. The white-PET reflector shows intermediate characteristics, but is similar to those of the diffuse reflector. Fig. 5

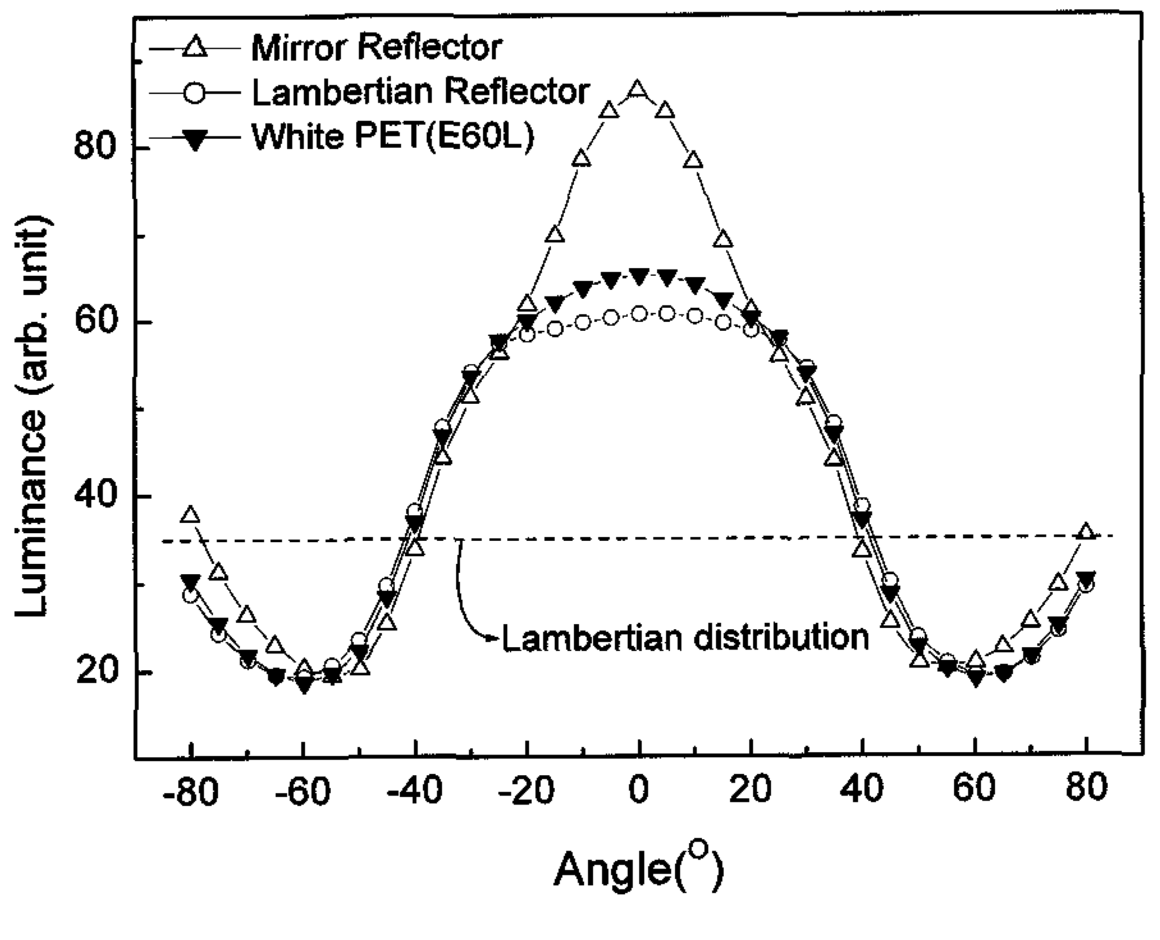


Fig. 4. The angular distribution of the luminance of the pyramid film for three kinds of reflector.

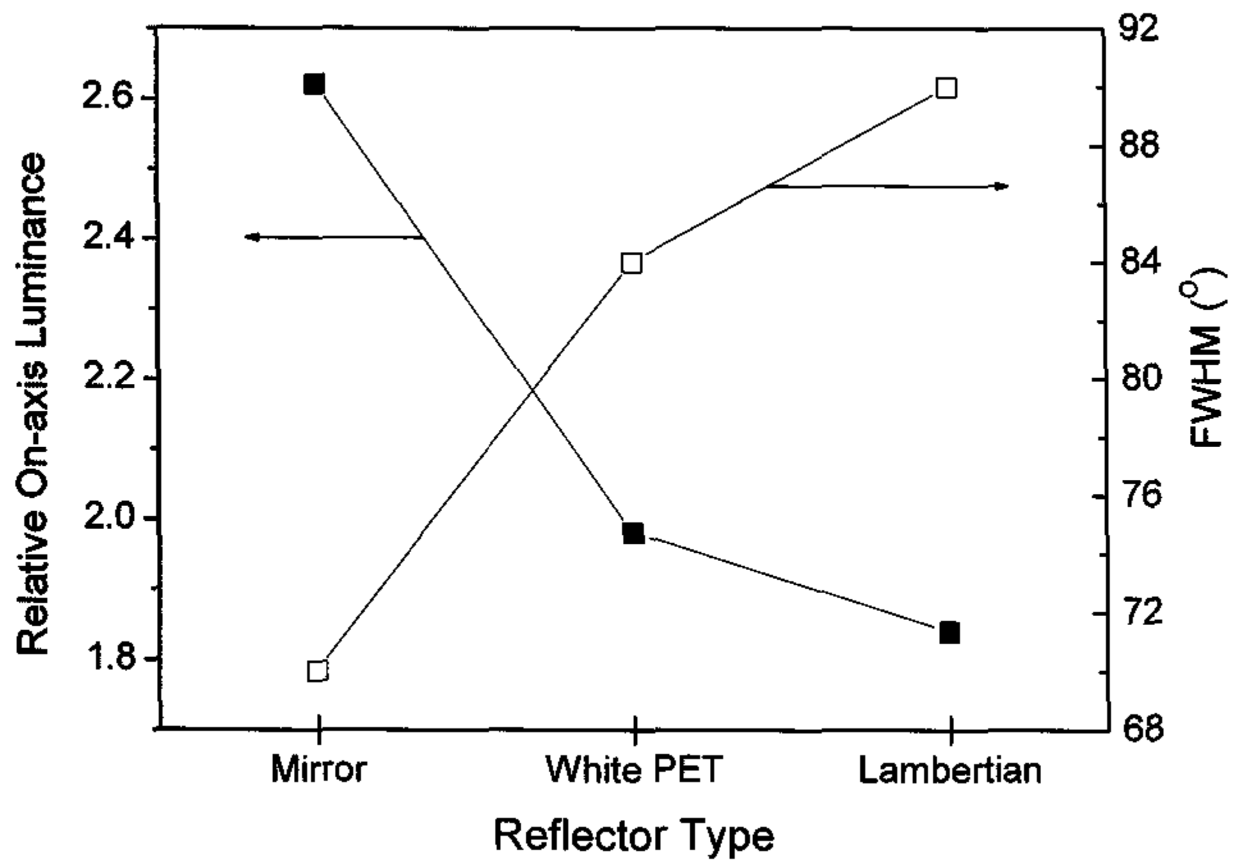


Fig. 5. The dependence of the on-axis luminance gain and the FWHM of the pyramid film on the reflecting property of three reflectors.

summarizes the dependence of the on-axis luminance and the viewing angle on the reflecting property of three kinds of reflectors. The luminance of the Lambertian light source was set to be 1. Fig. 5 shows that the two properties are inversely related to each other, which is a natural outcome from the energy conservation of lights and since we neglected any possible absorption of rays by materials.

Figs. 6 (a) and (b) show the luminance distribution of the prism film depending on the viewing angle along the vertical and horizontal directions, respectively. In this case, the vertical and horizontal directions indicate the directions perpendicular and parallel to the direction of the one-dimensional grooves of the prism film, respectively. Due to the strong directionality of the micro-prisms, the luminance distribution shows strong anisotropy as can be seen in this figure. The viewing angle along the vertical direction is much narrower than that along the horizontal direction due to the refraction of rays at the inclined surfaces of micro-prisms. Similar to the case of the pyramid film, the viewing angle becomes wider and the on-axis luminance becomes lower as the reflecting property gets more diffusive. The comparison of these properties among the three reflectors is summarized in Fig. 7. In our previous simulation on the prism film[11], it was found that the on-axis luminance became higher when the apex region of micro-prisms were cut to become flat at a certain height combined by a mirror reflector. In order to check whether the same effect is expected from simulations using different types of reflectors, cut-prism films were designed and simulated on three kinds of reflectors, and the on-axis luminance gain was obtained

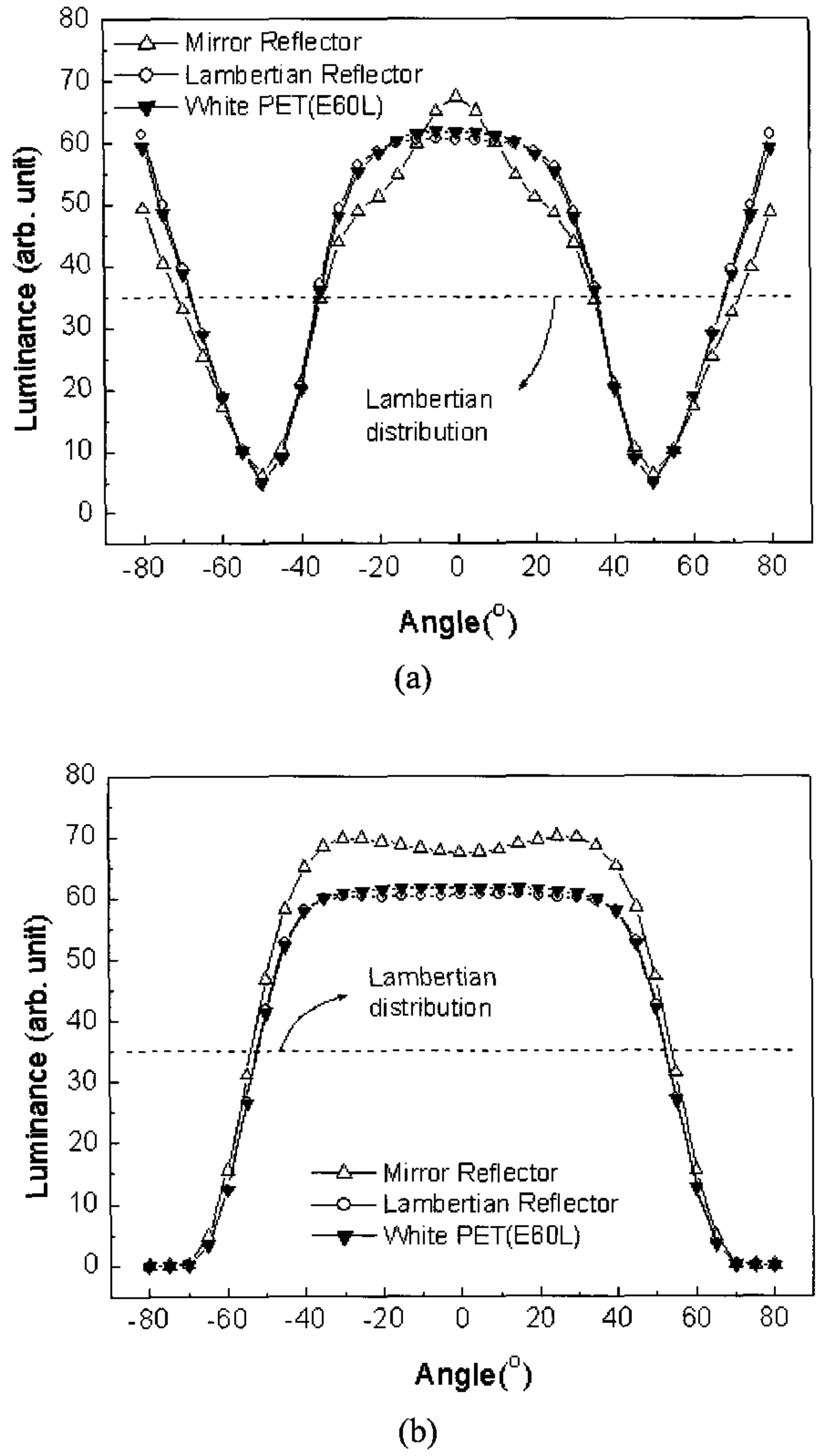


Fig. 6. The angular distribution of the luminance of the prism film for three kinds of reflector along the (a) vertical and (b) horizontal directions. .

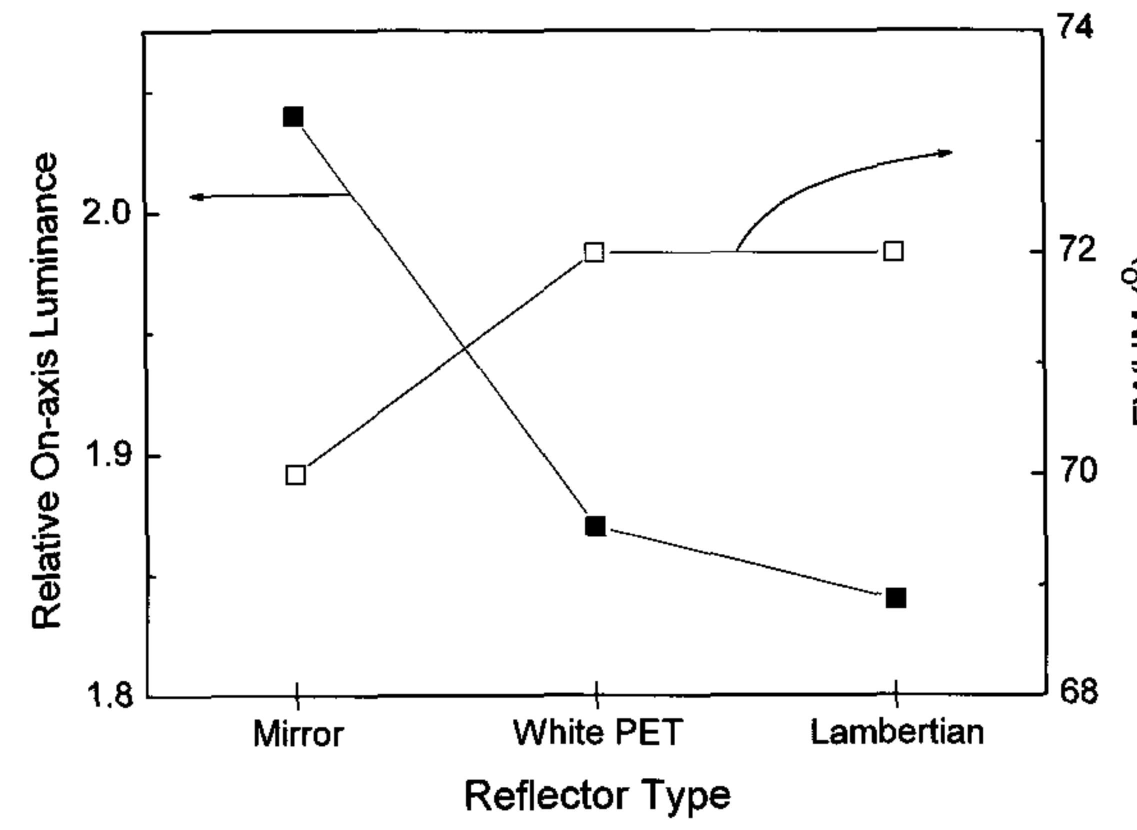


Fig. 7. The dependence of the on-axis luminance gain and the FWHM of the prism film on the reflecting property of three reflectors. The FWHM was estimated from the angular distribution of the luminance along the vertical direction.

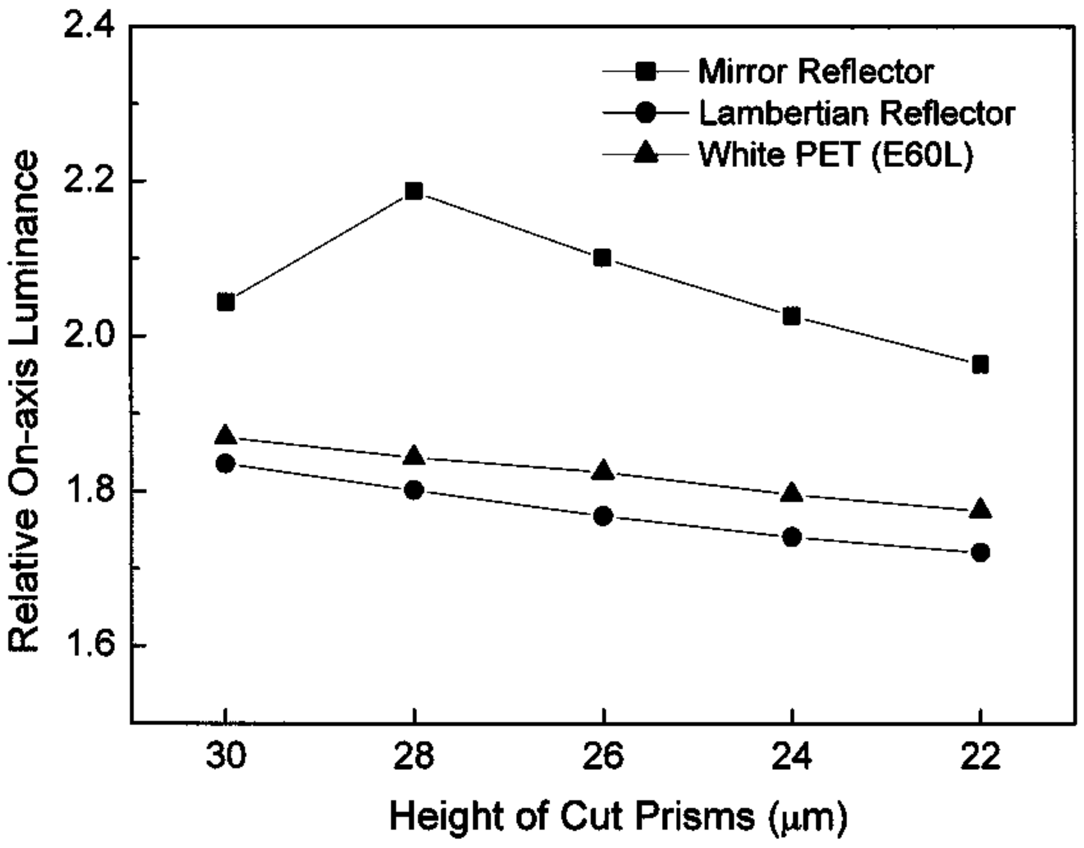


Fig. 8. The relative on-axis luminance of cut prism films as a function of the height of the cut prisms for the three reflectors.

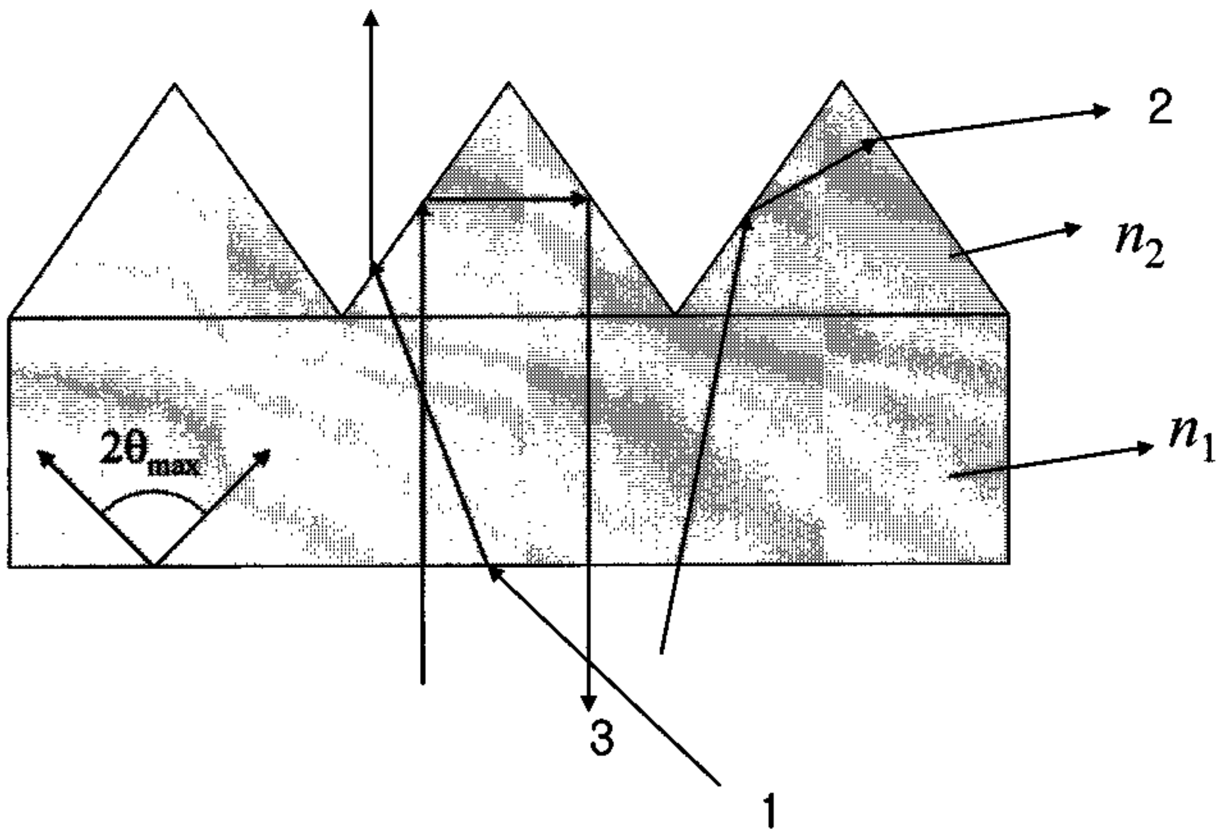


Fig. 9. The cross-section of prism films along with some representative rays at several incident angles.

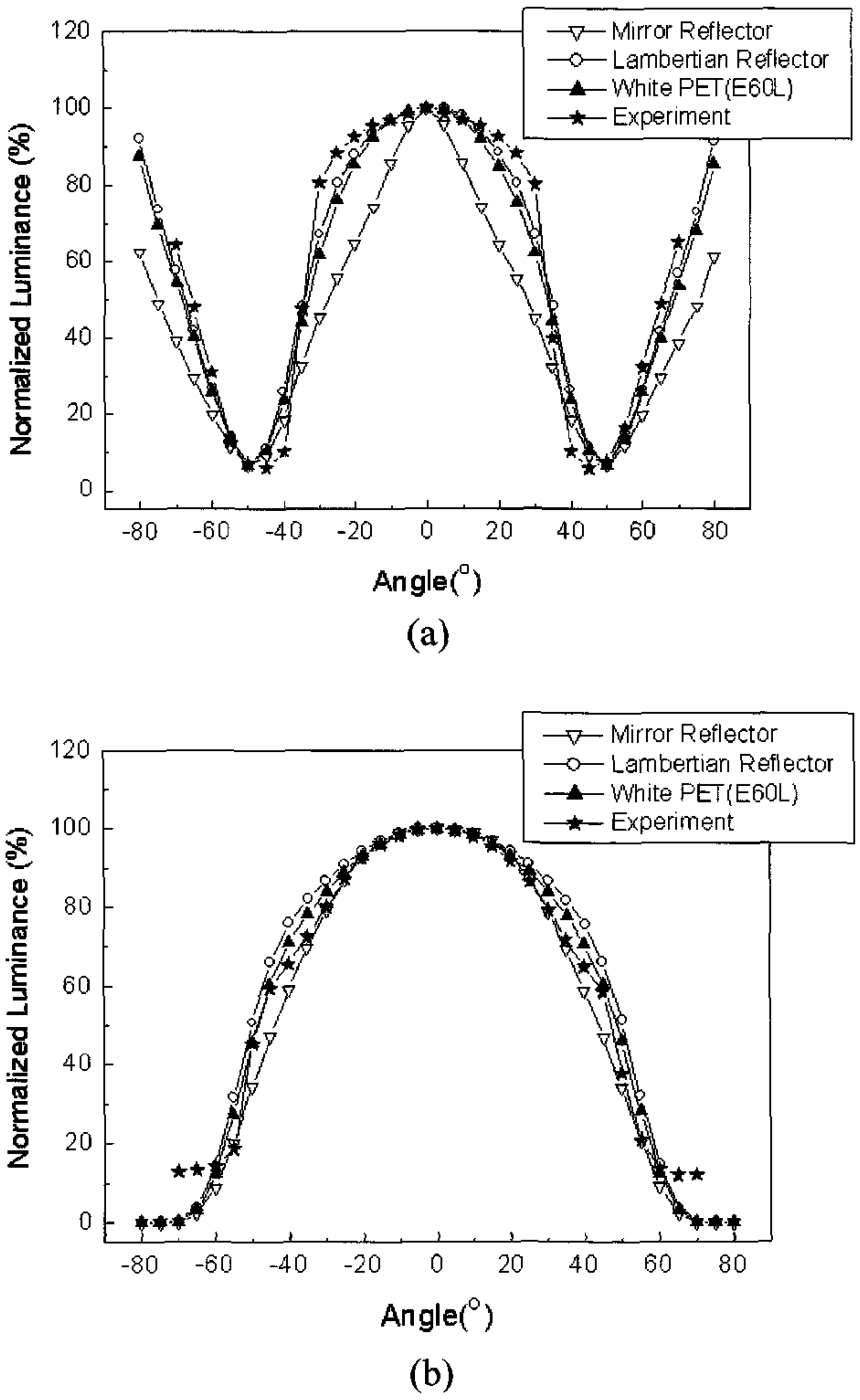
as a function of the height of the cut prisms. These results are shown in Fig. 8. In contrast to the case of backlight model with the mirror reflector, cut-prism films combined by diffusive reflectors do not give higher on-axis luminance. All cut-prism films show lower luminance gain and correspondingly wider viewing-angle characteristics than the case of uncut prism film. The reason for these results will be discussed in the next section.

4. Discussion

Fig. 9 shows the cross-section of prism films along with some representative rays at several incident angles. If the rays of Lambertian distribution are incident on the back surface of the substrate of the prism film whose refractive index is n_1, their direction will be confined to a cone whose maximum angle with respect to the normal direction is $\theta_{max}=\sin^{-1}(1/n_1)$ according to the Snell's law. The ray "1" is the most desirable one since it will be refracted at the upper surfaces and collimated toward the on-axis direction, contributing to the on-axis luminance gain. On the other hand, the ray "3" will experience total internal reflections (TIR) twice at the prism surfaces and then be redirected downwards. The rays redirected downwards will partly be absorbed by other optical sheets or fluorescent lamps and partly be reflected and reenter the prism film again. These recycled rays are an important part for achieving the high luminance gain of prism films, and it is important to keep the apex angle to be 90° for better recycling effect and thus higher luminance gain. In addition, the luminance gain of the prism film will depend on the reflecting property of the reflection film due to the fact that it will determine the directional distribution of the reflected rays and that the luminance gain of collimating films is sensitive to the distribution of rays incident on them. Only few of the rays such as the ray "2" in Fig. 9 either strike neighboring prisms or are directed to directions of high viewing angles, contributing to the build-up of the so-called side lobes in the angular distribution of the luminance.

The most important finding of the present study is that the reflecting property of the reflection film has significant effects on the viewing-angle characteristics as well as the on-axis luminance gain. The viewing angle becomes the narrowest while the on-axis luminance the highest under the condition of the perfect mirror reflection in both prism and pyramid films. Specular reflection means that the law of reflection is strictly satisfied on the surface of the reflection film. If there are some rays which strike the upper surface of micro-lenses and then are redirected to the reflection film along the line close to the normal direction of the reflection film, they will be reflected according to the law of reflection and thus be incident on the collimating film along the line close to the normal direction. Since these rays will remain close to the normal direction in spite of multiple reflections between the mirror reflector and the prism/pyramid surfaces, they will contribute to the on-axis luminous flux when they begin to satisfy the condition of the ray "1" as shown in Fig. 9. This effect will be enhanced when there is some flat area on top of the micro-lenses since the rays which hit these flat regions under the condition of quasi-normal incidence will transmit and contribute the on-axis luminance except a few percent of rays due to the Fresnel reflection. These expectations have indeed been confirmed by our previous simulation works[10-11]. However, the condition of this strict specular reflection is not considered to be justified in the backlight unit because downward rays from the collimating film will meet several optical components such as the diffuser film, the diffuser plate, or the light sources in the real backlight unit, and the direction of rays will be scattered randomly on their surfaces. In this context, it is expected that the simulation model incorporating Lambertian reflector or white-PET reflector is more appropriate for estimating optical performances of collimating film. As a result, the luminance improvement of the cut-pyramid and cut-prism films confirmed from the simulation study on the simple backlight model with a perfect mirror reflector [10-11] is not expected in the real backlight units.

In order to confirm the above, we compared our simulation results with that obtained from the experiment on the backlight. The experiment was carried out on the 23-inch direct-lit backlight which consists of multiple CCFLs, a diffuser plate and a prism film(BEF, 3M). The angular distribution of the luminance was measured by the luminance colorimeter (BM-7, Topcon). The distribution on the diffuser plate was confirmed to be almost Lambertian. Figs. 10 (a) and (b) compare the simulated and experimental angular distribution of the normalized luminance along the vertical and horizontal directions, respectively. The luminance was normalized to the value of the on-axis luminance, since our purpose was to compare only the viewing-angle characteristics. As can be seen from Fig. 10 and as is expected from the above discussion, the luminance distribution becomes the narrowest under the condition of the mirror reflection. The experimental results show wider viewing-angle characteristics along both directions and more resemble to the distributions obtained from the simulation based on Lambertian and/or white-PET reflectors. This indicates that to apply the exact reflecting nature and BRDF to the reflection film used in the simulation model is very important for predicting correct optical performances, in particular, the viewing-angle characteristics of collimating films. However, the simple model based on a perfect specular reflector may still be used to estimate the relative change in the luminance gain as a function of various parameters of collimating films such as the refractive index, the apex angle, etc [12]. In addition, slight differences can also be seen between the simulations on diffusive reflectors and the experimental results in Fig. 10, which indicates more sophisticated and refined simulation approaches are necessary by including bi-directional scattering distribution functions of the diffuser plate, the absorption coefficients of each material, etc.



(a)

(b)

Fig. 10. The dependence of the normalized luminance on the viewing angle of simulation results for three reflectors and experimental work along the (a) vertical and (b) horizontal directions.

5. Summary

In summary, the optical performances of two collimating films, prism and pyramid films, were investigated by using a ray tracing tool in order to find out the effect of the reflecting property of reflection films on the on-axis luminance as well as the viewing-angle characteristics. The viewing angle became the narrowest and the on-axis luminance gain was the highest under the condition of the perfect mirror reflector in both collimating films. This result has been interpreted by analyzing the direction of rays in the collimating film and their interaction with the reflection film. By comparing the simulation results with that obtained from experimental works, we found that diffusive reflector is a more appropriate reflecting property for estimating accurate viewing-angle characteristics of the luminance of backlights. Further improvement of the simulation model is needed to accurately predict not only viewing-angle characteristics but also the on-axis luminance gain, which is our next research work and which is already in progress.

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