Journal of Information Display
Vol. 12, No. 4, December 2011, 167–171

Indirect estimation of the reflection distribution function of the scattering dot patterns on a light guide plate for edge-lit LED backlight applications

Su Seong Jeong, Yong Woong Jeong, Min Woo Park, Su Jin Kim, Jae Hyun Kim and Jae-Hyeon Ko*

Department of Physics, Hallym University, Hallymdaehakgil 39, Chuncheon-si, Gangwondo 200-702, Republic of Korea

(*Received 9 April 2011; Revised 17 June 2011; Accepted 23 June 2011*)

The angular distribution of the luminance on each optical component of 40-inch light-emitting diode backlight was measured and studied, using the optical-simulation method. Several scattering functions were investigated as the reflection distribution function of the scattering dots printed on the bottom surface of the light guide plate (LGP). It was found that both the diffuse Lambertian and near-specular Gaussian scattering functions were necessary for the successful reproduction of the experimental angular distribution of the luminance. The optimization of the scattering parameters included in these scattering functions led to almost the same luminance distribution as that obtained from the experiment. This approach may be an effective way of indirectly estimating the reflection distribution function of the scattering dots of the LGP, which cannot be made accessible through any other experimental method.

Keywords: backlight unit; light guide plate; reflection distribution function; scattering dot; LED TV (categories: (1) display materials and components; (2) liquid crystal and other non-emissive displays)

1. Introduction

LEDs (light-emitting diodes) have become one of the dominant light sources for LCD (liquid crystal display) applications. LEDs are usually adopted in edge-lit backlight units (BLUs) for realizing super-slim, narrow-bezel, and low-power LCD TVs. The optical performances of edge-lit LED backlights were found to be superior to those of the conventional fluorescent-lamp-based backlights [1–3]. In the case of edge-lit LED backlights, a light guide plate (LGP) plays a key role in the formation of bright, uniform light on the BLU because LEDs are attached onto the side surfaces of the LGP, through which white light is spread on the two-dimensional area under the LCD, owing to the total internal reflection (TIR). Various scattering dots or microstructures, such as white dots, microlens, or micro-prism arrays, have been adopted at the bottom and/or on the top surface of the LGP to break the TIR and to emit the guided light towards the LCD [4–6].

To meet the required luminance uniformity of BLU, it is essential to design appropriately and optimize the distribution of scattering dots on the bottom surface of the LGP. As the available light power in the LGP decreases with the increasing length from the light source, the density or size of the scattering dots should be adjusted to compensate for this light loss. Optical simulation may be a very effective way of designing these scattering dots because the optical performances of the LGP can be evaluated without fabricating the real LGP. For this purpose, exact optical structures of LGP as well as their surface properties should be inputted in the process of optical simulation. In particular, the bi-directional scattering distribution functions (BSDF) of the reflecting/transmitting surfaces of the optical components constituting the BLU should be evaluated and used as important information for the optical simulation [7,8]. Usually, the BSDF of optical surfaces can be obtained by using a goniometric scatterometer [8]. The exact reflecting nature of the scattering dots positioned at the bottom surface of the LGP, however, cannot be easily investigated because the scattering events occur in the LGP, in which the direct measurement of BSDF is expected to be very complex. In this case, a certain plausible functional form for BSDF should be assumed for the optical simulation, and should be compared with the experimental works.

In the current study, the BSDF of the scattering dots was indirectly estimated based on the results of the comparison between the experimental viewing-angle property and the optical simulation results. An elliptic Gaussian functional form combined with a perfect Lambertian reflection was assumed for the BSDF of the dot patterns of the LGP incorporated in the edge-lit LED backlight for LCD TV applications. This study shows that the optimization of the parameters of the proposed BSDF results in the complete reproduction of the experimental viewing-angle properties of the LED backlights. This method can be used to estimate

*Corresponding author. Email: hwangko@hallym.ac.kr

ISSN 1598-0316 print/ISSN 2158-1606 online

http://dx.doi.org/10.1080/15980316.2011.621307
http://www.tandfonline.com

the BSDF of the scattering dots indirectly, which cannot be obtained, using any other experimental method.

2. Experiment and simulation

A 40-inch edge-lit LED backlight for LCD TV applications was used for this study, as shown in Figure 1. The detailed specifications of the backlight are shown in Table 1. As can be seen in Figure 1, the backlight consists of an LGP, a diffuser sheet (DS), a one-dimensional prism film (BEF II from 3M, abbreviated as 'BEF'), and a reflective polarizer (DBEF-D from 3M, abbreviated as 'DBEF' or 'RP'). The LGP was made from polymethyl methacrylate material. White LEDs were arranged on the two large side surfaces of the LGP, as shown in Figure 2. White ink was used to print dot patterns on the bottom surface of each LGP. The dependence of the luminance on the viewing angle was investigated on the LGP and each optical film, using a spectro-radiometer (PR670, Photo Research Inc.) combined with a home-made rotator on which the backlight was positioned.

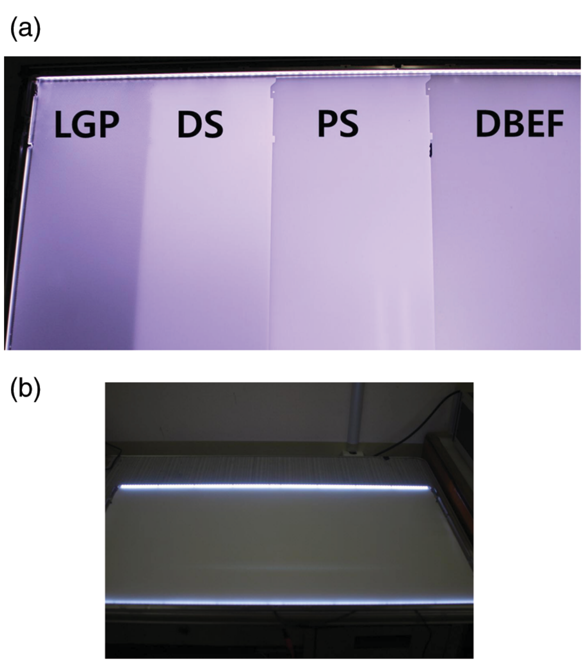

Figure 1. Photographs of (a) the 40-inch two-side LED backlight that was used in this study, and (b) the emitting LED modules.

Table 1. Specifications of the 40-inch edge-lit LED backlight.

Size	40 inch
LED configuration	2 sides (up–down)
Number of LEDs	224 (56 ea∗4 modules)
Size of the LEDs	$5.0 \times 3.0\,\text{mm}^2$
LGP thickness	3.5 mm
Power	80 W
Optical film configuration	LGP + DS + PS + RP

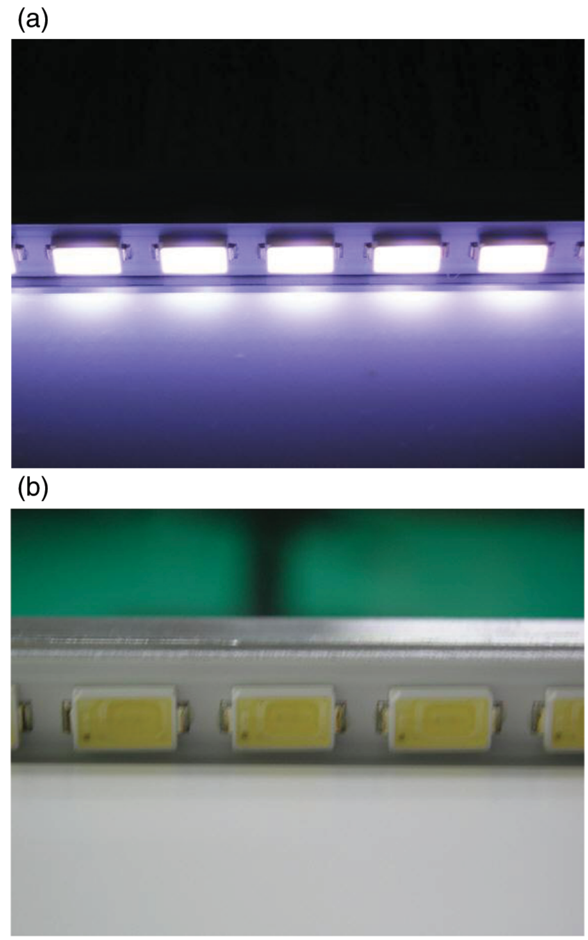

Figure 2. (a) Picture of the emitting LEDs that were used for the 40-inch backlight. (b) LEDs with off current. The yellow part is the phosphor layer covering the blue LED chip.

Optical simulation was carried out using LightTools (ver.7.1, Optical Research Associate), a ray-tracing tool. The LGP area was reduced to one-fifth of its original size to reduce the simulation time. All other conditions (thickness, LED pitch, etc.) were the same as those of the real BLU, except for the LGP area. The scattering dot patterns

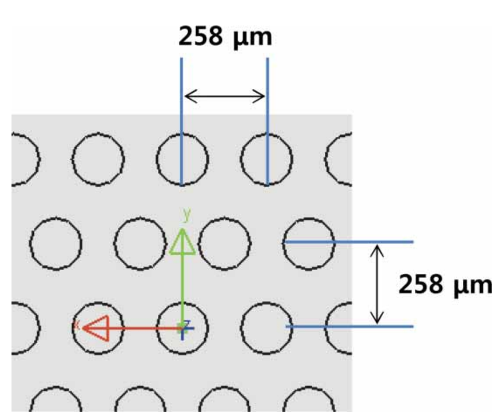

Figure 3. A part of the scattering dot patterns with a 258 μm pitch. The radius of these dots was set within the 75–79 μm range.

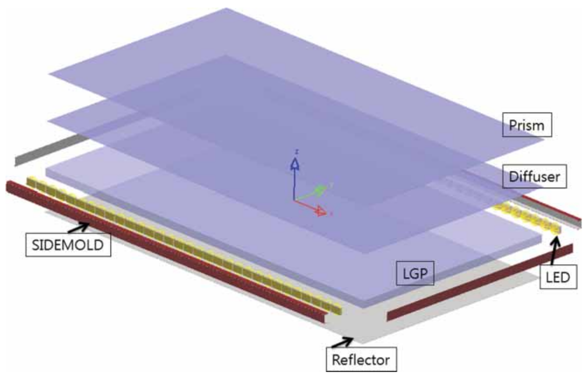

Figure 4. Three-dimensional schematic diagram of the simulated LED backlight.

with a radius within the 75–79 μm range were arranged according to the hexagonal array, with a pitch of 258 μm, as shown in Figure 3. The dot radius was increased linearly with the increasing distance from the LED modules, which assured the illuminance uniformity on the LGP. A reflection sheet was inserted below the LGP, and its reflecting property was set to be Lambertian. The diffuser and prism sheets (PSs) were modeled according to the procedure described in these authors' previous study [6]. Figure 4 shows the three-dimensional schematic diagram of the simulated LED backlight.

3. Results and discussion

Figure 5 shows the experimental angular dependence of the luminance on each optical component. The angular-luminance data were shown along the two representative directions: the horizontal direction (parallel to the prism grooves) and the vertical direction. The escaped rays from the top surface of the LGP tend to be directed along high viewing angles due to specular components of the diffuse reflection distribution function of the scattering dots printed on the bottom surface of the LGP (see Figure 5(b)). On the other hand, the angular luminance is almost Lambertian along the horizontal direction (see Figure 5(a)) because the LED modules are attached onto the upper and lower side surfaces of the LGP. The DS on the LGP has several optical functions: It turns the direction of the rays on the LGP, towards the normal direction, makes the light distribution on it more homogeneous, and hides the distribution of the scattering dots. The PS on the DS further collimates the rays towards the normal direction via refraction, enhancing the on-axis luminance at the expanse of the viewing-angle characteristics. If the RP is on the backlight, the polarization component whose direction is perpendicular to the transmission axis of the bottom polarizer of the LCD is recycled via the polarization-recycling process, resulting in the enhancement of the on-axis luminance of LCD [9].

To reproduce the viewing-angle characteristics of LED backlights on each optical component, a simulation

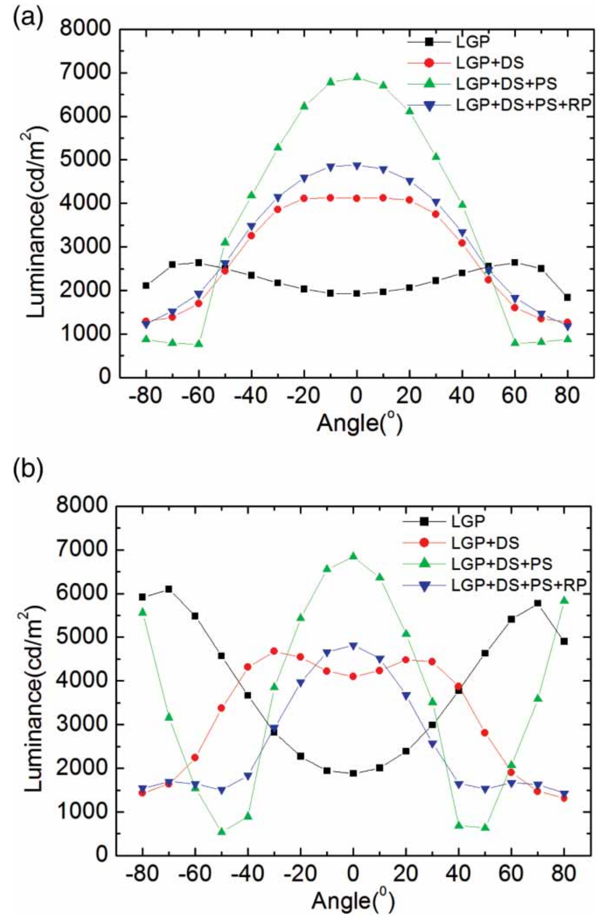

Figure 5. Experimental angular dependence of the luminance of the 40-inch two-side LED backlight along the (a) horizontal and (b) vertical directions.

model was constructed according to the description in the previous section. A Gaussian scattering function given by Equation (1) was first tried as the reflection distribution function of the scattering dots.

$$P(\theta) = P_0 \exp\left[\left(-\frac{1}{2}\right)\left(\frac{\theta}{\sigma}\right)^2\right]. \quad (1)$$

In this equation, θ denotes the shift-invariant scattering angle defined as $\sin^{-1}(|\sin\theta_i - \sin\theta_s|)$, where θ_i and θ_s are the incident and scattered angles, respectively [10], and $P(\theta)$ and P_0 are the radiant intensity in the θ and specular directions, respectively. σ is the standard deviation of the Gaussian distribution in degrees, which reflects the width of the distribution. Rotational symmetry is conserved in this distribution, and Figure 6 depicts this Gaussian distribution. The change in σ results in the modification of the emitting distribution on the LGP. This Gaussian function was incorporated in the optical simulation as a BSDF for the scattering dots under various values of σ. Figure 7 shows the simulation result for the angular distribution of the luminance along the vertical direction, along with

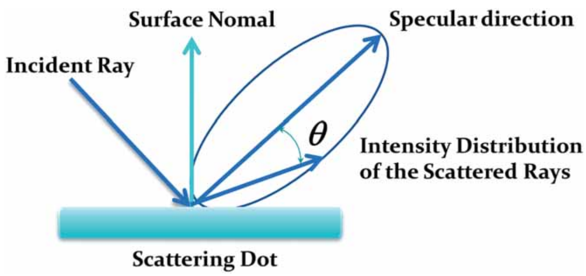

Figure 6. Schematic diagram showing the intensity distribution of the scattered rays from the scattering dot on the bottom surface of the LGP.

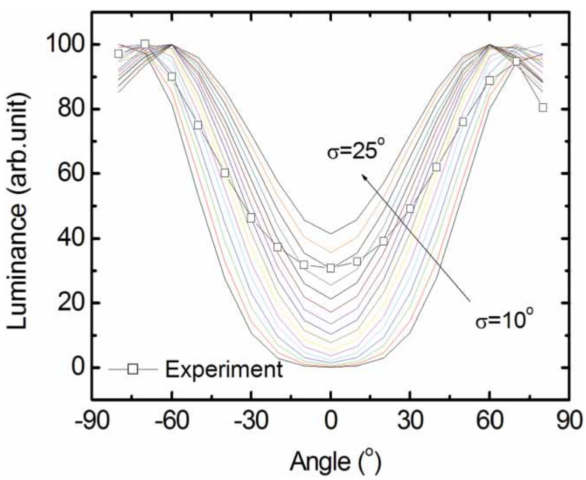

Figure 7. Angular distribution of the luminance obtained from the experiment (open square) and simulation (solid lines) based on a Gaussian distribution function whose standard deviation σ was within the 10–25° range at a 1° step.

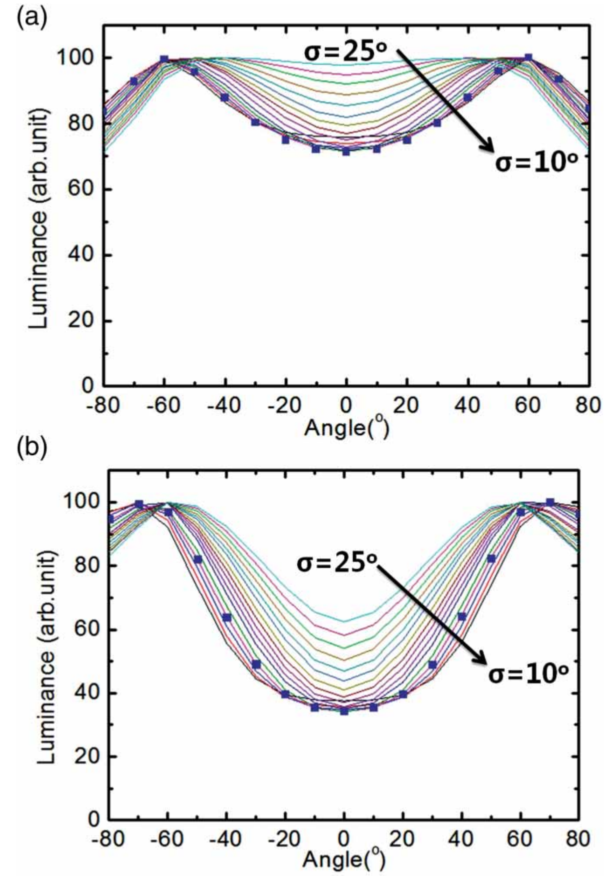

Figure 8. Angular distribution of the luminance obtained from the experiment (full square) and simulation (solid lines) based on an elliptic Gaussian distribution and Lambertian functions whose standard deviation σ was within the 10–25° range at a 1° step.

the corresponding experimental data. All the results were normalized to the maximum luminance value. The angular distribution obtained from the simulation is not consistent with the experimental data. When σ increases to make the on-axis luminance equal to the experimental value, the high-angle distributions become inconsistent with one another. This inconsistency was also found in the comparison of the angular distribution of the luminance along the horizontal direction.

The above result indicates that the Gaussian scattering distribution function is not a suitable BSDF of the scattering dots on LGP. This seems to be due to the fact that the Gaussian distribution is a narrow scattering function, lacking a wide scattering component. Therefore, the BSDF of the scattering dots was assumed to be a combination of the Gaussian scattering function and a diffuse Lambertian distribution. Lambertian distribution represents the diffuse scattering component of BSDF, according to which the radiant intensity changes into cos θ. Moreover, the Gaussian scattering function was assumed to be elliptical, as given by Equation (2), to reflect the possible rotational anisotropy of the BSDF of the scattering dots.

$$P(\theta) = P_0 \exp\left[\left(-\frac{\theta^2}{2}\right)\left(\frac{\cos^2\phi}{\sigma_x^2} + \frac{\sin^2\phi}{\sigma_y^2}\right)\right]. \quad (2)$$

In this equation, σ_x and σ_y denote the standard deviation of the Gaussian distribution parallel to the surface x and y axes, respectively, and ϕ the azimuthal scattering angle with respect to the x axis (see Figure 4 as to the coordinates). The ratio between the elliptic Gaussian component and the diffuse Lambertian component, in addition to σ_x and σ_y, was optimized to reproduce the measured angular distribution of the luminance shown in Figure 5. Figure 8 shows how the adjustment of σ_x and σ_y included in the elliptic Gaussian function could lead to the successful reproduction of the experimental luminance distribution. The ratio between the elliptic Gaussian component and the diffuse Lambertian component was 60:40 in this case. As σ decreases, the on-axis luminance value becomes lower in both cases.

The optimized energy ratio between the elliptic Gaussian and Lambertian components was found to be 60:40, and the corresponding optimized σ_x and σ_y were 13° and

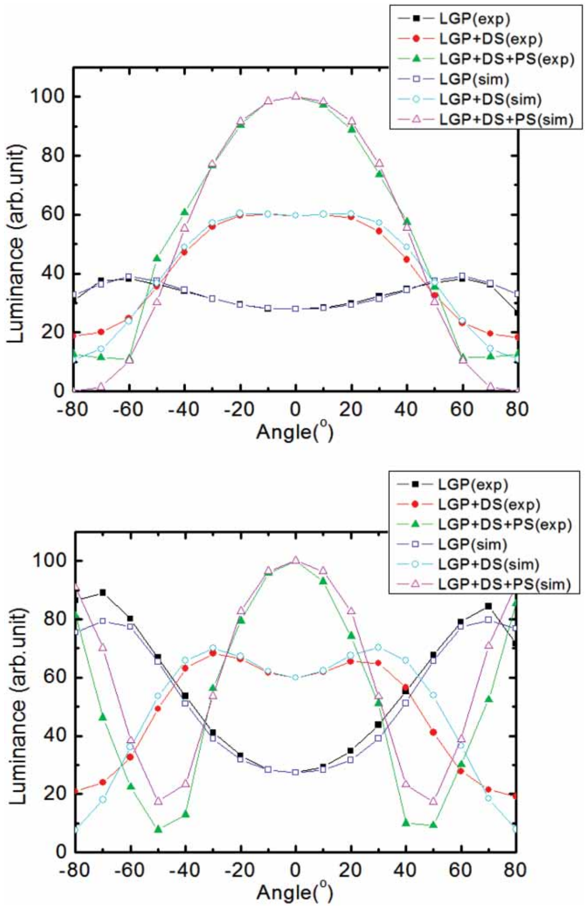

Figure 9. Angular dependence of the luminance on each optical component obtained from the experiment (full symbols) and simulation (open symbols).

12°, respectively. The angular distribution of the luminance obtained via simulation carried out under these optimized parameters was compared with the experimental data shown in Figure 9. The luminance values from the simulation were normalized to the on-axis luminance values from the experiment. It can be clearly seen that the experimental angular distributions of the luminance on the LGP were successfully reproduced by the simulation results along both directions. Moreover, when this luminance distribution was used as the input information of DS and PS, the detailed luminance distributions on these optical films were also correctly reproduced. Therefore, it can be concluded that it is essential to include both the diffuse Lambertian and near-specular Gaussian components in the reflection distribution function of scattering dots to explain the experimental results. The superposition of these two scattering functions, and the optimization of their parameters, may be an effective way of obtaining the phenomenological BSDF of the minute scattering structures formed on the LGP.

Finally, it should be pointed out that the emission distribution of the light from the LGP might be position-dependent on the LGP because the diameter of the scattering dots changes with the distance from the LED, and the boundary conditions of each position (e.g. the effect of the four sides of the LGP) also vary.

4. Summary

The angular dependence of the luminance of two edge-lit LED backlights for large LCD TV applications on each optical component was investigated. Simulation models were constructed to reproduce the measured angular distribution of the luminance. A simple Gaussian scattering function was not appropriate as a reflection distribution function of the scattering dots printed on the bottom surface of the LGP. Instead, an elliptic Gaussian distribution function combined with the Lambertian distribution function was assumed as the BSDF and was adopted in the simulation. The appropriate superposition of the elliptic Gaussian and Lambertian functions was found to be the optimum reflection distribution function by which the measured viewing-angle properties could be successfully reproduced. The current study showed that the reflection distribution function of the scattering dots of the LGP, which could not be measured directly through any other experimental method, could be indirectly estimated through the optical ray-tracing technique.

References

[1] J.-H. Ko, J.S. Ryu, M.-Y. Yu, S.-M. Park, and S.J. Kim, J. KIIEE **24**, 8 (2010).

[2] J.S. Ryu, M.-Y. Yu, S.-M. Park, S.J. Kim, and J.-H. Ko, New Phys. Sae Mulli, **60**, 56 (2010).

[3] J.S. Ryu, S.J. Kim, S.-M. Park, and J.-H. Ko, J. Inform. Display **11**, 39 (2010).

[4] W.Y. Lee, T.K. Lim, Y.W. Lee, and I.W. Lee, Opt. Eng. **44**, 014004 (2005).

[5] A. Funamoto and S. Aoyama, J. SID **14**, 1045 (2006).

[6] Y.H. Ju, J.-H. Park, J.H. Lee, J.-Y. Lee, K.-B. Nahm, J.-H. Ko, and J.H. Kim, J. Opt. Soc. Korea **12**, 25 (2008).

[7] J.C. Stover, *Optical Scattering, Measurement and Analysis* (McGraw-Hill, New York, 1990).

[8] G. Park, T.S. Aum, J.H. Kwon, J.H. Park, B.K. Kim, and J.K. Shin, J. Korean Phys. Soc. **54**, 44 (2009).

[9] P. Watson and G.T. Boyd, *Mobile Displays*, edited by A.K. Bhowmik *et al.* (John Wiley & Sons, Atrium, 2008), p. 219.

[10] LightTools, *Core Module User's Guide* (Optical Research Associate, Pasadena, 2010).