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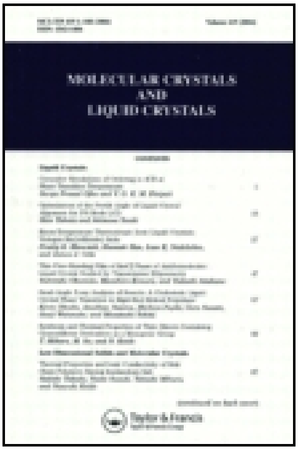

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
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Highly-Efficient Backlight for Liquid Crystal Display Having no Optical Films

Takamitsu Okumura [a b], Akihiro Tagaya [a b], Yasuhiro Koike [a b], Masahiro Horiguchi [a] & Hiromasa Suzuki [a]

[a] Department of Applied Physics and Physico-Infomatics, Keio University, Yokohama, Kanagawa, Japan

[b] Exploratory Research for Advanced Technology (ERATO) Koike Photonics Polymer Project, Japan Science and Technology Agency, Kawasaki, Kanagawa, Japan

Version of record first published: 18 Oct 2010

To cite this article: Takamitsu Okumura, Akihiro Tagaya, Yasuhiro Koike, Masahiro Horiguchi & Hiromasa Suzuki (2004): Highly-Efficient Backlight for Liquid Crystal Display Having no Optical Films, Molecular Crystals and Liquid Crystals, 418:1, 299-313

To link to this article: http://dx.doi.org/10.1080/15421400490483014

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Mol. Cryst. Liq. Cryst., Vol. 418, pp. 299/[1027]–313/[1041], 2004
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400490483014

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HIGHLY-EFFICIENT BACKLIGHT FOR LIQUID CRYSTAL DISPLAY HAVING NO OPTICAL FILMS

Takamitsu Okumura, Akihiro Tagaya, and Yasuhiro Koike
Department of Applied Physics and Physico-Infomatics, Faculty of Science and Technology, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan
and
Exploratory Research for Advanced Technology (ERATO) Koike Photonics Polymer Project, Japan Science and Technology Agency, E-building, K^2 Town-Campus, 144-8, Ogura, Saiwai-ku, Kawasaki, Kanagawa 212-0954, Japan

Masahiro Horiguchi and Hiromasa Suzuki
Department of Applied Physics and Physico-Infomatics, Faculty of Science and Technology, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan

We propose a highly-efficient backlight that requires no optical films with a polymer containing spherical particles of micron size. The backlight developed is provided with microprisms at the bottom surface, which can reflect the incident light directly into the front direction. A modeling simulation program, employing a Monte Carlo method based on Mie scattering theory, has optimized both the prismatic condition and the multiple scattering characteristics. We confirm that a uniformity of brightness can be achieved without using any optical films, resulting in a high optical efficiency of 62%.

Keywords: backlight; liquid crystal display; microprism; Monte Carlo method

INTRODUCTION

Liquid crystal displays (LCDs) can provide uniformity of brightness as well as thinness and low weight and, as such, are being used in portable information devices including notebook computers and mobile phones. Backlighting

*Corresponding author. Tel.: +81-45-566-1593, Fax: +81-45-562-7373, E-mail: takamitsu_o@nifty.com

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technology for LCDs has recently developed remarkably; specifically, many studies have been conducted for improving the optical efficiency that leads to longer battery lifetime. The main reason is that a typical backlight consumes more than 60% of the total energy consumption in LCD modules. Most current LCDs employ an edge-light backlight that converts a linear light source such as a cold cathode fluorescent lamp (CCFL) into an area of uniform light. Figure 1(a) shows the structure of a typical backlight. Since the typical backlight light guide is made of a highly transparent acrylic material, it is provided with diffusing white dot spots at the bottom surface to obtain the brightness uniformity on the top surface. Many optical films are required for backlighting LCDs, including a reflective film to reduce the optical loss from the bottom surface, a diffusing film to eliminate the images of dot spots, and prism films to condense the diffused light.

Recently, the rapidly increasing demand on LCDs is to be thinner, lighter, and brighter all at once. For this purpose, several types of backlights were reported, which replaced the conventional dot spots and the diffusing film with a modification on the backlight light guide [1–3]. These backlights, however, exhibit moiré patterns that deteriorate the image quality of LCDs. This is due to the optical interference between the microstructures on the backlight light guide and the liquid crystal cells; thus, they require the technique of randomizing the arrangement of microstructures to be eliminated [4]. In previous studies, we reported another type of backlight using a highly scattering optical transmission (HSOT) polymer, and achieved twice the brightness as the conventional backlight [5–7]. We have proposed an advanced backlight for improving the optical efficiency in large size LCDs more recently, as shown in Figure 1(b) [8]. Although the advanced HSOT backlight is provided with microprisms in the direction perpendicular to that of the CCFL, it exhibits no moiré due to the multiple light scattering by spherical particles dispersed in the polymer matrix. Nonetheless, all backlights reported so far, including the advanced HSOT backlight, are not easily adapted to applications requiring LCDs with less than 1.0 mm thick. The following two factors mainly causes this problem. (1) The optical efficiency is lowered with decreasing thickness of the backlight light guide. (2) At least two optical films are required: the reflective films and the prism film of 0.1 to 0.2 mm thickness; thus, backlight light guide must be less than 0.6 to 0.8 mm thick.

In this paper, we report a new class of backlights having no optical films while being thin and highly efficient. The backlight developed, which we call the HSOT-II backlight, is provided with an array of microprisms at the bottom surface in the direction parallel to that of the CCFL, as shown in Figure 1(c). The microprisms can reflect the light directly into the front direction, as opposed to the conventional backlight that converts the light direction by prism films. The modeling simulation program developed in the present

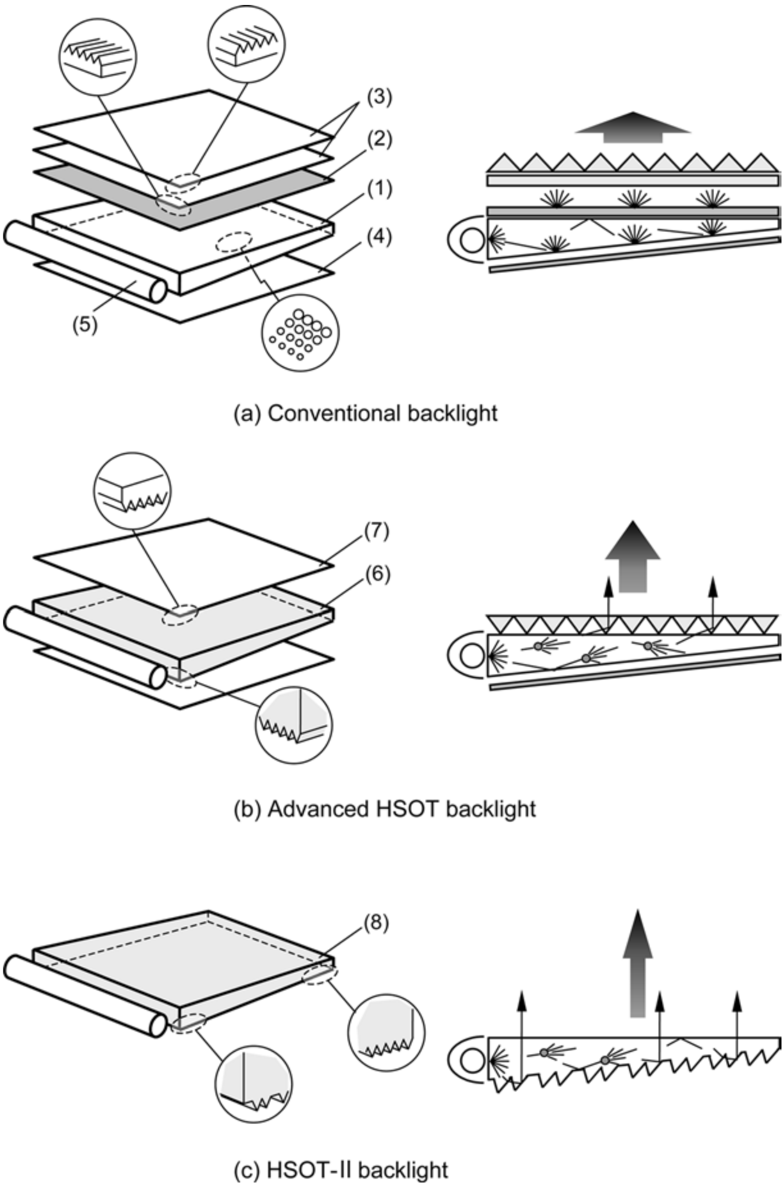

FIGURE 1 Schematic diagrams of LCD backlights; (a) a typical backlight, (b) the advanced HSOT backlight, and (c) the HSOT-II backlight. Optical components for each backlight are as follows: (1) a backlight light guide made from a transparent polymer of which the bottom surface is provided with dotted white spots, (2) a diffusing film, (3) prism films, (4) a reflective film, (5) a CCFL, (6) the advanced HSOT backlight light guide, (7) the prism film optimized for the HSOT polymer, and (8) the HSOT-II backlight light guide.

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work enabled us to calculate the multiple light scattering in the HSOT polymer, and to obtain the uniformity of brightness on the top face of the light guide, with the result that we have eliminated all optical films in the HSOT-II backlight. This makes the HSOT-II backlight most suitable for thin LCDs of application devices. We describe in this paper the technique developed for designing the HSOT-II backlight that offers the optimum conditions of microprisms and multiple light scattering, and its potential to be highly efficient in commercial applications requiring thinness.

MATERIAL AND METHODS

Material

The material used in the HSOT-II backlight is a HSOT polymer that contains spherical particles of micron size in a polymer matrix of poly(methylmethacrylate) (PMMA). The spherical particles used in this paper are commercially available silicone particles $[(CH_3SiO_{1.5})_n]$. As the full width at half maximum (FWHM) of the diameter distribution of the silicone particles is 0.75 μm, they can be treated as monodisperse particles. Additionally, the particles exhibits no absorption peak in the visible light range with the measurement of transmittance [9]; this suggests that the total energy abstracted from the incident light is not lost within the particles by absorption, but consumed by scattering in all directions.

The HSOT polymer is prepared by the following procedure. First, particles were dispersed in methylmethacrylate (MMA) by ultrasonic treatment for 20 min at room temperature. Then the blended sample containing 0.05 to 10.0% wt/wt particles is polymerized in the mold by free-radical polymerization for 5 h at 60°C and 24 h at 70°C, and was dried for 24 h at 90°C.

Modeling Simulation Program

For calculating the multiple light scattering and designing the HOST-II backlight, a modeling simulation program, employing the Monte Carlo method [10] based on Mie scattering theory [11,12], has been developed. The multiple scattering caused by dispersed particles can be described as a sequence of single scattering events. A light scattering intensity profile (I) and a scattering efficiency (Q_{sca}) of a spherical particle can be calculated based on Mie scattering theory. In the Monte Carlo method, an expected photon path length (L) and a scattering angle (θ) are determined as follows:

$$\sigma = \pi \int_0^\infty \int_0^\infty r^2 n_a(r) f(\lambda) Q_{sca}(\alpha, m)\, dr d\lambda, \tag{1}$$

$$L = -\ln(\text{random1})/\sigma, \tag{2}$$

$$F(\theta) = \frac{\int_0^\theta 2\pi I(\theta)\sin\theta\, d\theta}{\int_0^\pi 2\pi I(\theta)\sin\theta\, d\theta,} \tag{3}$$

$$\theta = F^{-1}(\text{random2}), \tag{4}$$

where σ is the extinction constant, $F(\theta)$ is the probability density distribution function of the scattering angle, r is the particle radius, λ is the wavelength of incident light, $n_a(r)$ is the particle density, and $f(\lambda)$ is the density distribution function of wavelength. In Eq. (1), the size parameter (α) is defined as $2\pi r/\lambda$, and the relative refractive index (m) is defined as n_s/n_m, where n_s and n_m are refractive indices of a particle and the matrix, respectively. random1 and 2 are uniform random numbers generated between 0 and 1. This method allows us to calculate the multiple light scattering by altering internal particle conditions in the HSOT-II backlight.

Equally important is that we have devised a technique for improving the brightness uniformity that optimizes the prism distribution density. This technique determines lengths of the flat surface between adjacent prisms, R_p shown in Figure 2, for improving the brightness uniformity. In this method, the prism density (D_n) is defined as follows:

$$D_n = D_0 + (1 - D_0)\left(\frac{n}{N}\right)^x, \quad (n = 0, 1, 2, \ldots), \tag{5}$$

where n is the prism number, x is the exponential parameter, and D_0 and D_n are the prism distribution densities at prism number 0 and n, respectively. N is the aggregate number of the prism array if all prisms are arranged sequentially, defined as l_t/l_p, where l_t and l_p are the lengths of the light guide and the prism pitch, respectively. The arrangement of prisms is determined by the following conditions:

$$P_n = \begin{cases} 1 & \text{if } \left(\sum_{i=0}^{n} P_i\right)/n < D_n \\ 0 & \text{if } \left(\sum_{i=0}^{n} P_i\right)/n \geq D_n \end{cases}, \quad (n = 0, 1, 2, \ldots). \tag{6}$$

Here, P_n is the parameter that specifies whether the prism is placed at the position of the prism number n, where a value of 1 represents a prism present and 0 represents a prism absent. Due to P_n determined by altering x and D_0 in this technique, we optimized the brightness distribution on the top face of the HSOT-II backlight.

Based on the modeling simulation program, we have optimized the prismatic condition (internal angles, θ_1 and θ_2, shown in Figure 2, and prism

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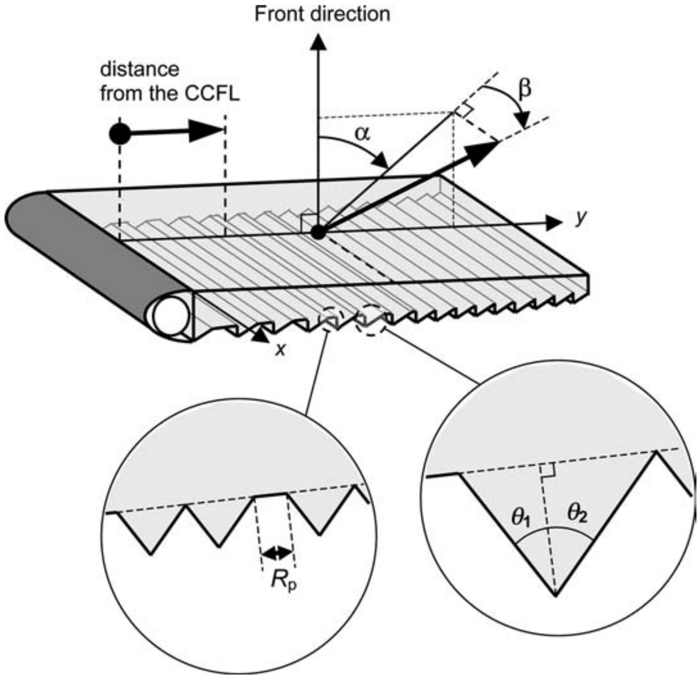

FIGURE 2 Geometry for the HSOT-II backlight.

distribution density) and the particle condition (diameter and concentration) at the same time. Optimized conditions of the prism and particle, therefore, can offer two key features of the HSOT-II backlight: the light condensed into the front direction and the brightness uniformity with no optical films.

RESULTS AND DISCUSSION

Optimal Design of Microprisms

Firstly, the internal angles of microprisms, θ_1 and θ_2 were optimized to obtain the condensed light distribution in the front direction, where the luminance distributions were simulated by altering θ_1 and θ_2 ranging from 0° to 90°, respectively. Figure 3(a) shows the calculated photon intensity i.e. luminance as a function of viewing angle α dependent on the internal angles of microprisms. Note that inadequate angles failed to convert the light into the front direction [curves (10°–30°) and (10°–70°) in Fig. 3(a)], while the incident light is converted and condensed with the

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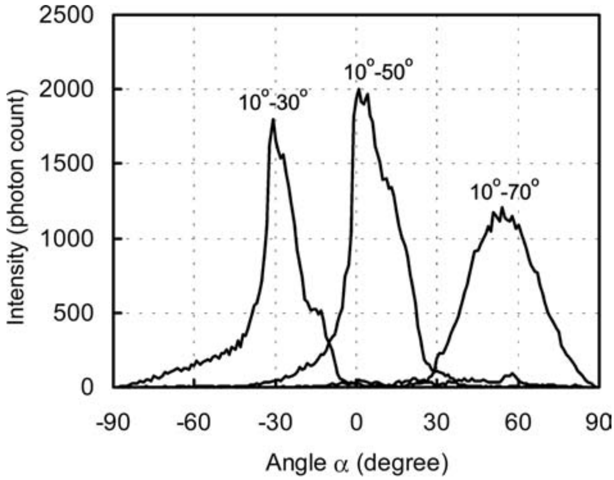
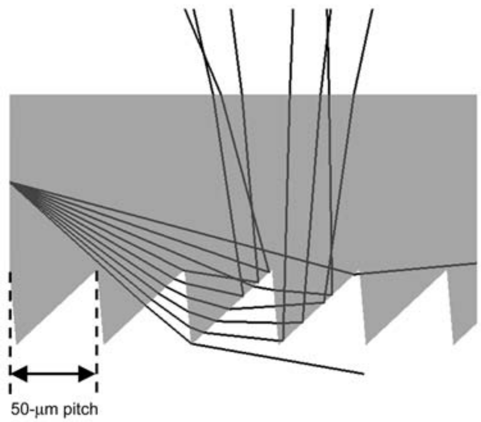


(a)



(b)

FIGURE 3 (a) The calculated luminance distribution as a function of viewing angle; $(\theta_1, \theta_2) = (10, 30)$, $(10, 50)$, and $(10, 70)$. (b) A schematic diagram of the ray trajectory with the optimum prism angles.

optimum angles [curve (10°–50°) in Fig. 3(a)]. Although we found several pairings of θ_1 and θ_2 that convert the light into the front direction, the most efficient pairing is with values of θ_1 that are from 0° to 10°. This is because almost all the light can refract at the primary surface without being reflected that causes the optical loss from the bottom surface [See Fig. 3(b)].

In Figure 4, the data obtained from the modeling simulation program is compared with that obtained experimentally, which is plotted as a function of viewing angle α. In the measurement, a commercially available luminance colorimeter (TOPCON Co., BM-7 Fast) was employed with a measuring field of 0.1°. Note that the calculated results are in good agreement with the measured results, and the light distribution is condensed into the front direction. We see from these results that the microprisms with optimized angle reflect the light in the front direction, and there exists little optical loss due to the light passing through prisms at the bottom surface. This indicates that the condensed light distribution has been obtained by multiple scattering, refracting, and reflection among several prism arrays, without reflection with any optical films.

Secondly, the prism distribution density i.e. the length of flat surface between adjacent prisms was optimized for improving the brightness uniformity on the top surface. Using Eqs. (5) and (6), the luminance distributions were simulated by altering the prism distribution density, i.e. D_0 and x. Figure 5 shows the calculated luminance distribution as a function of distance from the CCFL. In Figure 5(a), an ever-increasing curve has been observed along the distance from the CCFL with a lower value of D_0, which generates too large flat surfaces between adjacent prisms to obtain the sufficient light in the front direction near to the CCFL. In contrast, the

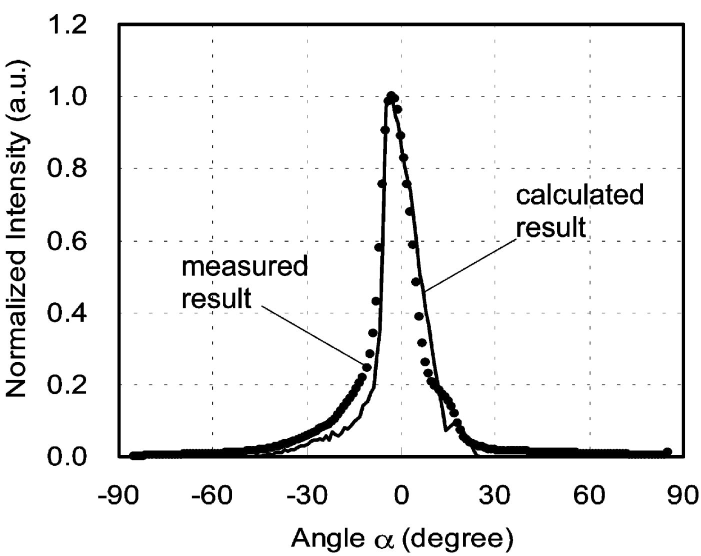


FIGURE 4 The relative luminance distribution as a function of viewing angle. Vertical axis is normalized at 0°.

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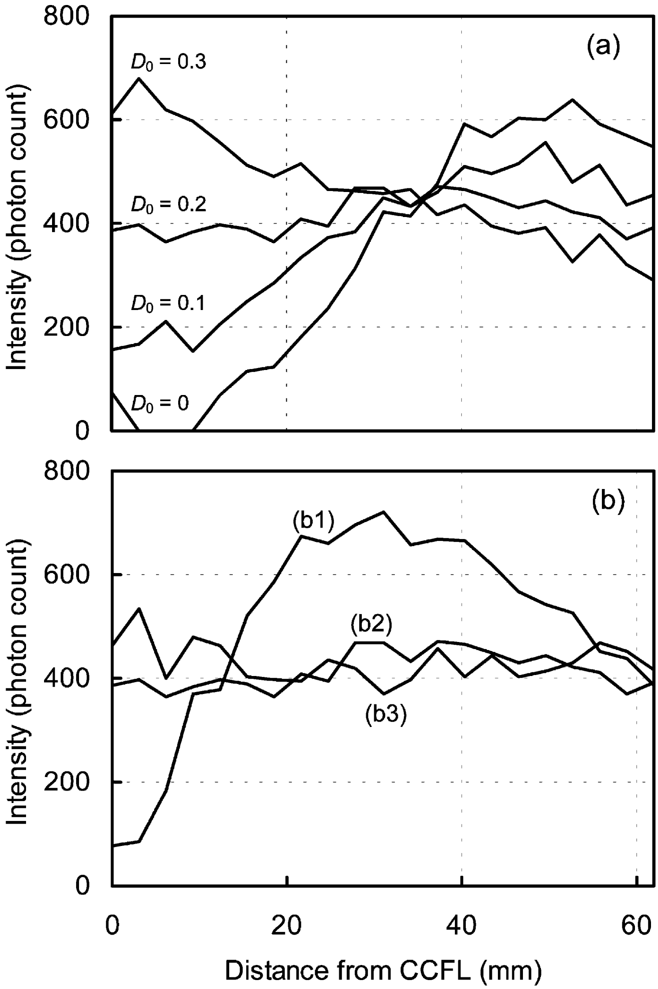

FIGURE 5 The calculated luminance distribution as a function of distance from a CCFL; (a) the dependence on the prism density at the incident edge D_0, $x = 2.0$, (b) the dependence on the exponential parameter x. (b1) $x = 1.0$, $D_0 = 0$, $D_{avg} = 0.50$, (b2) $x = 2.0$, $D_0 = 0.30$, $D_{\mathrm{avg}} = 0.47$, and (b3) $x = 3.0$, $D_0 = 0.25$, $D_{\mathrm{avg}} = 0.43$.

luminance transition is completely different with a higher value of D_0, resulting in a downward-sloping curve. The data with $D_0 = 0.2, x = 2.0$, therefore, indicates that the optimized arrangement of prisms exhibits a brightness uniformity independent of the distance from the CCFL. However, a few conditions of the prism density distribution, which offer the uniform luminance distribution, have been observed with different prism distribution densities [curves (b2) and (b3) in Fig. 5(b)]. An other consideration is that no light is present in the front direction at flat surfaces between adjacent prisms except for multiply scattered light. This leads to the other essential requirement that the aggregate number of the prisms should be larger, which is specified by the average prism density (D_{avg}), defined as

$$D_{avg} = \left(\sum_{i=0}^{N} P_i \right) \Big/ N. \tag{7}$$

The resultant D_{avg} calculated from the prism distribution density in Figure 5(b) were (b1) 0.50, (b2) 0.47, and (b3) 0.43, respectively. Since the brightness uniformity can no longer be obtained with a larger value of D_{avg} [curve (b1) in Fig. 5(b)], the optimum prism density has been finally determined to be $D_0 = 0.2$, $x = 2.0$ for a 4.0-in. diagonal with a 2.0 mm thickness.

The experimental luminance distribution versus the distance from the CCFL is shown in Figure 6, which is also compared with the data obtained from the modeling simulation program. Note that constancy in the prism array lowered the luminance along the distance from the CCFL [curve (6a) in Fig. 6]. This problem is because almost all the incident light is

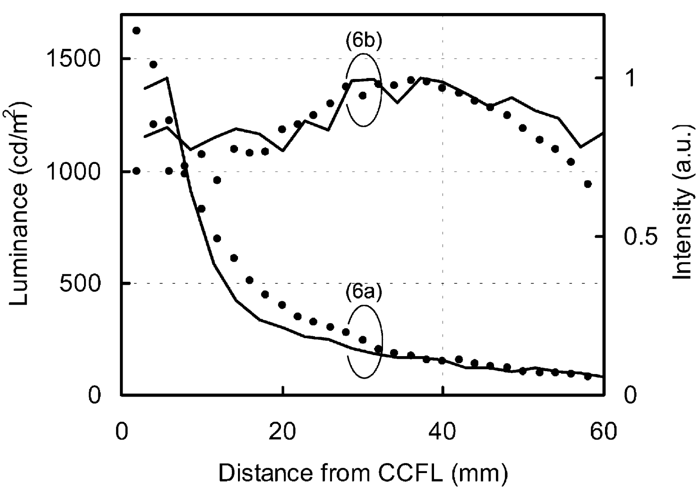

FIGURE 6 The brightness distribution of measured (dotted lines) and calculated (full lines) results dependent on distance from a CCFL for the HSOT-II backlight of 4.0-in. diagonal with 2.0-mm thickness. (6a) Prisms are provided uniformly, $D_0 = 1.0$, $x = 0$, and (6b) prisms are provided with the optimized distance between adjacent prisms, $D_0 = 0.2$, $x = 2.0$.

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reflected by the optimized prism angle near to the CCFL. In contrast, the optimized arrangement of prisms exhibits a brightness uniformity independent of the distance from the CCFL [curve (6b) in Fig. 6]. It should be also noted that calculated results are consistent with the experimental results in Figures 4 and 6; thus we confirm that the modeling simulation program has precisely reproduced the light distribution in the HSOT-II backlight.

Multiple Scattering

Another significant aspect for designing the HSOT-II backlight concerns the light distribution that is caused by being multiply scattered between dispersed spherical particles in the polymer matrix. So far we have found the following major characteristics of a multiple scattering required for large size LCDS of more than 10 in. diagonal. (1) To obtain a color uniformity, it should be independent of the wavelengths mixed into white light of a CCFL. (2) To obtain a high luminance, total scattering energy in all directions should be larger. On the other hand, the HSOT-II backlight is different from the advanced HSOT backlight in the sizes of less than 6-in. diagonal and configuration being provided with microprisms; thus almost all the multiply scattered light should be scattered in the forward direction to reduce the optical loss with the backward scattered light. At the same time, on the premise that flat surfaces between adjacent prisms can only make the light progress more deeply into the light guide, the multiple scattering should be hazy enough to smooth out the luminance distribution.

Shown in Figure 7 are the calculated results of the total luminous transmittance and haze dependent on the particle diameter, which is plotted as a function of a particle concentration. The haze (H), which demonstrates the degree of cloudiness in the transmitted light, is defined as follows:

$$H = (T_d/T_t) \times 100, \tag{8}$$

where T_t is the total luminous transmittance, and T_d is the diffuse luminous transmittance. In this calculation, each transmittance, described as the ratio of output photon intensity to input one, was simulated by altering the diameter and concentration of the particle. Note that the total luminous transmittance has decreased with increasing the particle concentration, while the haze has increased. Of particular note is that the sample containing particles with 13.0 μm-diameter exhibits much higher total luminous transmittance than those with 2.0 μm and 7.0 μm-diameter, where as the haze is more than 90% at almost all particle concentrations. This indicates that the forward scattered light, which involves little optical loss with

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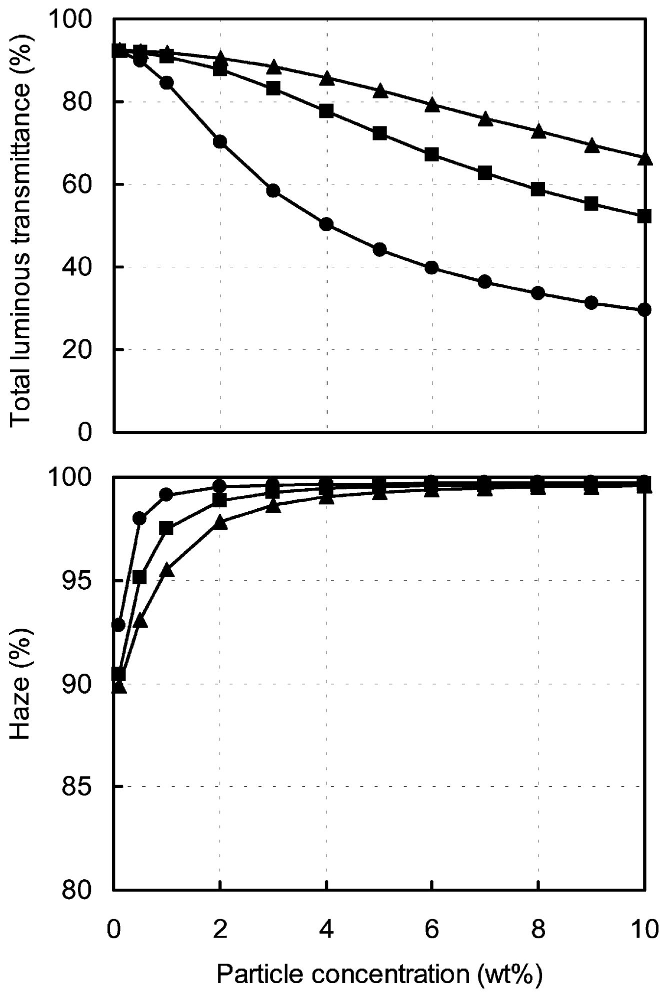

FIGURE 7 Calculated total luminous transmittance and haze versus particle concentration for test plates of a 2.0 mm thickness containing Tospearl; the particle diameters are ● 2.0 μm, ■ 7.0 μm, and ▲ 13.0 μm.

absorption and backscattering, can be obtained with a high cloudiness due to the large particle diameter of micron order. The brightness uniformity on the top surface of the HSOT-II backlight, therefore, has been achieved based on the following factors: (1) the optimum arrangement of microprisms, (2) the fine prism pitch of 50 μm, and (3) efficient forward scattering with a high cloudiness.

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Optical Efficiency

In this paper, we evaluated the optical efficiency of the HSOT-II backlight of 4.0 in. diagonal, which was determined by the following method. First, the three-dimensional luminance distribution of the CCFL [$L_c(\alpha, \beta)$] and the backlight [$L_b(\alpha, \beta)$] at the center of each surface were measured. Then the optical efficiency (OE) was determined as

$$\mathrm{OE} = \frac{S_{\mathrm{out}} \int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} L_b(\alpha, \beta)\, d\alpha d\beta}{S_{\mathrm{in}} \int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} L_c(\alpha, \beta)\, d\alpha d\beta} \times 100, \tag{9}$$

where S_{in} and S_{out} are the area of the input and output surfaces of the backlight, respectively. This method assumes that the luminance distributions of the CCFL and the backlight are completely uniform on the output surface; thus each backlights whose incident edge ranges from 0.5 to 2.0 mm thick have been optimized for the brightness uniformity. Consequently, the experimental optical efficiency of the HSOT-II and the advanced HSOT backlight, of which the incident edge measures 2.0 mm thick, has been determined to be 50.8% and 62.6%, while the calculated optical efficiency are 51.5% and 64.0%, respectively. It follows that the experimental optical efficiency is almost as much a value as the calculated one. A small differences, however, may be an error due to the fact that the measured luminance distribution cannot be completely uniform on the output surface. Nonetheless, this result suggests that we can evaluate the optical efficiency by the modeling simulation along with designing the optimized conditions.

Figure 8 shows the calculated optical efficiency dependence on the wedge angle of the HSOT-II backlight and the advanced HSOT backlight, respectively. The thickness of the incident edge is also shown in Figure 8. In this calculation, the thickness of the edge remains constant of 0.5 mm, so that the wedge angle is lowered with decreasing the thickness of the incident edge. Note that the optical efficiency of the advanced HSOT backlight drops down to a lower value of 46% with decreasing wedge angle; this is a problem, as has been noted. On the other hand, as the data indicate, the optical efficiency of the HSOT-II backlight has risen up to 62% with a 0.5-mm thickness, which is considerably greater than that of the advanced HSOT backlight. These results confirm advantage of the HSOT-II backlight to be highly efficient in backlighting thin LCDs

CONCLUSION

In this paper, the HSOT-II backlight has been developed and evaluated as a backlight for thin LCD applications. The two key features of the HSOT-II backlight – the condensed light distribution at the front and the brightness

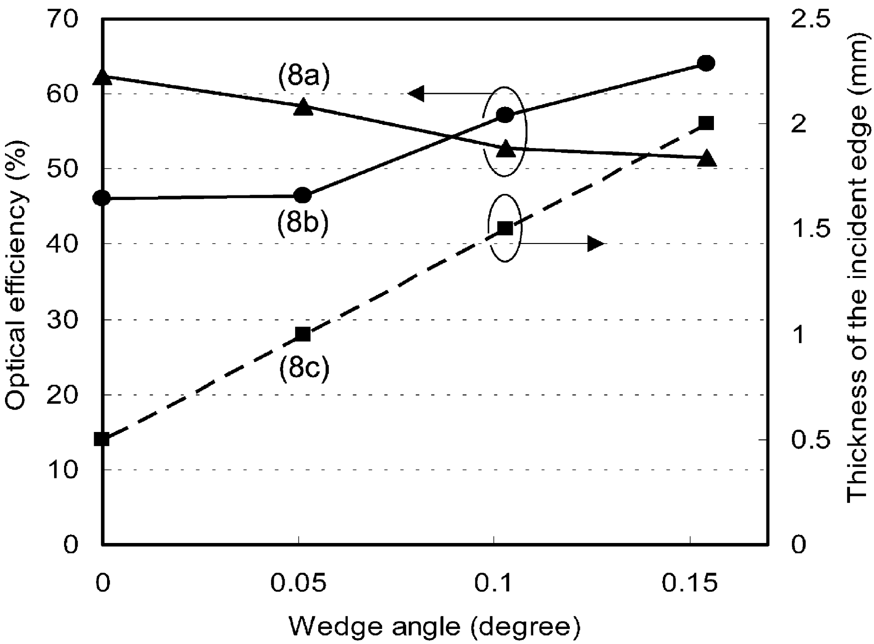

FIGURE 8 Calculated results of optical efficiency dependence on wedge angle for a 4.0 in. diagonal. (8a) The HSOT-II backlight, (8b) the advanced HSOT backlight, and (8c) thickness of the incident edge.

uniformity on the top face – have been achieved due to the optimization based on the modeling simulation program. The former is obtained with the optimum pairing of internal prism angles. The latter is obtained with the optimum arrangement of microprisms and the efficient multiple scattering in the forward direction. Furthermore, we confirm that all optical films used in the conventional backlight can be eliminated, while the optical efficiency can be enhanced up to 62% with a 0.5-mm thickness for a 4.0 in. diagonal.

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