Highly Scattering Optical Transmission Polymers for Bright Display

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SUMMARY: We proposed a highly scattering optical transmission (HSOT) polymer and applied it to a light pipe of a backlighting system for liquid crystal displays. Although the HSOT polymer backlighting system was composed of fewer parts than those of the conventional transparent one, the HSOT polymer backlighting system showed not only twice the brightness but also twice the efficiency of the conventional one. In addition, the HSOT polymer backlighting system had no degradation of color uniformity due to scattering in the HSOT polymer.

Introduction

In the market of portable information terminals, lower electric power consumption liquid crystal displays (LCDs) are strongly required for longer battery lifetime. However, the electric power consumption and image quality of recent LCDs are still insufficient for use as portable display devices. The power consumption of backlighting system is about 60 % in a typical LCD units. Illumination property of the backlight has an effect directly on the visual quality of LCDs. In many trials for developing the LCD backlighting systems, it was thought that light pipe should be transparent, because scattering phenomenon due to heterogeneous structures inside optical materials seems to cause transmission loss and degrade color uniformity. However, the specified microstructures inside the light pipe homogenize incident light effectively without color dispersion.

We proposed a highly scattering optical transmission (HSOT) polymer for use as a high efficiency illumination medium and applied it to a light pipe of a backlighting system for LCDs[1-3]. The incident light is scattered inside the HSOT polymer repeatedly because of the internal microscopic heterogeneous structures, and then radiated uniformly from the entire surface of the HSOT polymer. High luminance and uniform

 CCC 1022-1360/00/$ 17.50+.50/0

white color illumination of the LCD backlighting system can be achieved by controlling the microscopic heterogeneous structures, details of which are discussed in this paper.

Structure of HSOT Backlighting System

Schematic diagram of the HSOT and conventional backlighting systems are shown in Fig. 1. All conventional edge-light type backlighting systems have consisted of a transparent PMMA light pipe with printed dot patterns and other surrounding light-controlling devices (shown in Fig. 1 (a)). The printed dot patterns are necessary at the bottom of the light pipe in order to obtain uniform luminance. Also, a diffusing film is indispensable to hide the printed dot pattern. Furthermore, two brightness enhancement films (BEF, trade name of 3M) are employed to achieve higher luminance in the normal direction. On the other hand, in the HSOT backlighting system (shown in Fig. 1 (b)), only the prism sheet optimized for the HSOT light pipe is necessary on the output surface. The luminance from all over the surface of the light pipe is almost uniform without any light controlling devices for making luminance uniform, such as the printed dot patterns or the diffusing film because high-order multiple scattering inside the HSOT polymer makes the luminance from the surface uniform.

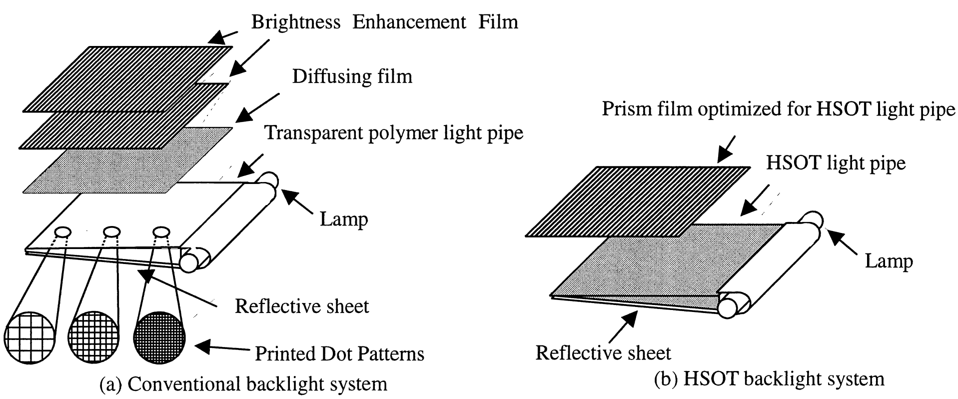


Fig. 1: Schematic diagram of LCD backlighting systems.

HSOT Modeling Simulation

The light homogenization effect caused by the multiple light scattering phenomenon in the HSOT polymer was analyzed by the HSOT modeling simulation using the Monte Carlo method[4)] based on the Mie scattering theory[5)]. A light scattering intensity profile of each particle (the internal microscopic heterogeneous structure) with various diameters was exactly calculated from the Mie theory. The Monte Carlo method was used to analyze random and repeating processes in the multiple light scattering phenomenon, because the Monte Carlo method is a powerful method to solve problems that have no immediate probabilistic interpretation.

Light scattering intensity profile and scattering efficiency of a single particle was calculated by using equations (1)-(6) which had been derived from the Mie scattering theory.

$$I(\alpha,m,\theta) = \lambda^2(i_1 + i_2)/8\pi^2 \tag{1}$$

$$K(\alpha,m) = \left(\frac{\lambda^2}{2\pi^2 r^2}\right)\sum_{\nu=1}^{\alpha}(2\nu+1)\left\{|a_\nu|^2 + |b_\nu|^2\right\} \tag{2}$$

$$i_1 = \left|\sum_{\nu=1}^{\infty}\frac{2\nu+1}{\nu(\nu+1)}\left\{a_\nu\frac{P_\nu^1(\cos\theta)}{\sin\theta} + b_\nu\frac{dP_\nu^1(\cos\theta)}{d\theta}\right\}\right|^2$$
$$i_2 = \left|\sum_{\nu=1}^{\infty}\frac{2\nu+1}{\nu(\nu+1)}\left\{b_\nu\frac{P_\nu^1(\cos\theta)}{\sin\theta} + a_\nu\frac{dP_\nu^1(\cos\theta)}{d\theta}\right\}\right|^2 \tag{3}$$

$$a_\nu = \frac{\psi_\nu'(m\alpha)\psi_\nu(\alpha) - m\psi_\nu(m\alpha)\psi_\nu'(\alpha)}{\psi_\nu'(m\alpha)\zeta_\nu(\alpha) - m\psi_\nu(m\alpha)\zeta_\nu'(\alpha)}$$
$$b_\nu = \frac{m\psi_\nu'(m\alpha)\psi_\nu(\alpha) - \psi_\nu(m\alpha)\psi_\nu'(\alpha)}{m\psi_\nu'(m\alpha)\zeta_\nu(\alpha) - \psi_\nu(m\alpha)\zeta_\nu'(\alpha)} \tag{4}$$

$$\alpha = 2\pi r n_m / \lambda_0 \tag{5}$$

$$m = n_s / n_m \tag{6}$$

where I and K mean scattering intensity and scattering efficiency, α is a size parameter, m is a relative refractive index between particle (n_s) and matrix (n_m). r means particle radius, and λ means wavelength of incident light in the matrix. $P^1_\nu(\cos\theta)$ is a Legendre polynomial, Ψ_ν, ζ_ν are the first two orders of the Ricatti-Bessel functions.

By the Monte Carlo method, scattering angle θ and expected photon path length L were defined as equations (7)-(9). The random and repeating processes in the multiple scattering phenomenon were analyzed by equations (7)-(9).

$$L = -\ln(random2)/\pi r^2 KC \tag{7}$$

$$\theta = F^{-1}(random1) \tag{8}$$

$$F(\theta) = \frac{\int_0^{\theta} I(\theta)W(\theta)d\theta}{\int_0^{\pi} I(\theta)W(\theta)d\theta} \tag{9}$$

Here, *random* 1 and 2 are uniform random numbers generated between 0 and 1. C means particle concentration. Probability density distribution function $F(\theta)$ of scattering angle is defined by the scattering intensity profile $I(\theta)$ and the solid angle $W(\theta)$. Scattering angle θ at the each scattering point is determined by using both the function $F(\theta)$ and random number. Photon path lengths L are determined by the scattering efficiency K, particle radius r, and particle concentration C. This Monte Carlo simulation method is applied to examine the multiple light scattering phenomenon in the HSOT polymer with using more than ten thousands photons.

Figure 2 shows calculated and experimental luminance profiles radiated from the output surface of the HSOT light pipe whose size was 2.5-inch diagonal. Angle of the luminance profile was defined as Fig.3. Validity of the simulation for multiple light scattering phenomenon was confirmed based on the good agreement between the calculated and experimental profiles.

Table 1 shows the power efficiencies measured at the center of the backlights by illumination intensity meter (TOPCON IM-3M), in which the symmetric prism optimized for the HSOT light pipe was used in order to convert the luminance profile peak around 63 degree into zero. The HSOT backlighting system has not only twice the brightness but also twice the efficiency of the conventional one.

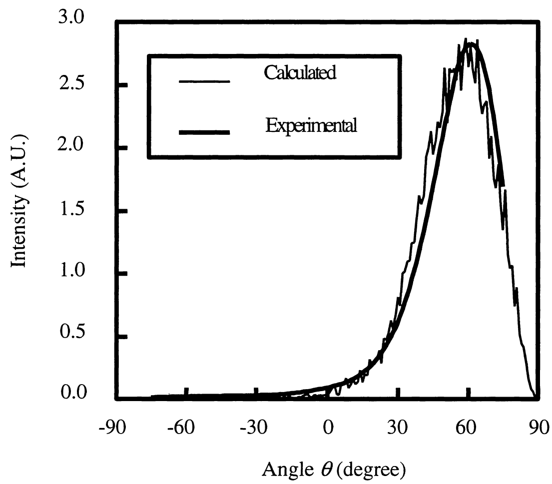


Fig. 2: Calculated and experimental luminace profiles radiated from the HSOT light pipe whose size was 2.5-inch diagonal.

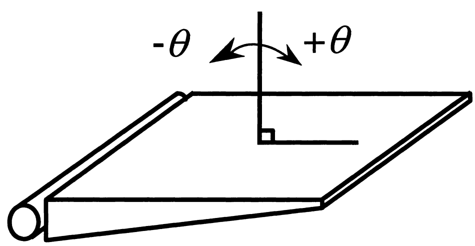


Fig. 3: Definition of angle θ for luminance profile.

Table 1. Illumination intensity of the HSOT and the conventional backlighting systems of 2.5-inch diagonal including the symmetirc prism sheet.

	Conventional Backlight	HSOT Backlight
Illumination intensity (lx)	4530	8870

Color uniformity

It was thought that scattering phenomenon inside the light pipe causes the degradation of the color uniformity, which means that the output light becomes yellowish in proportion to the distance from the lamp. This phenomenon is easily expected by the red sky of the sunset. However, if the size of the scatterer is specified, the general concept is not always true. The method of improving color uniformity is explained by considering the scattering efficiency based on the Mie scattering theory[6)]. The scattering efficiency K (Eq.(2)) of the single particle exhibits the characteristic patterns as shown in Fig. 4. Each curve undergoes a damped oscillation and approaches the limiting value $K = 2$. The numbers of 435, 545, and 615 nm mean main wavelengths of a typical fluorescent lamp spectrum. As shown in Fig. 4, in the case of smaller particles (A), blue light is scattered stronger than red, but in the case of the particle (B), blue light is not scattered stronger than red. Therefore, the color of illumination can be controlled, even if all of the materials are transparent.

Figure 5 shows the experimental result of the color temperature for the HSOT backlighting system. The HSOT backlighting system including scatterers following the general concept (curve (1)) showed a poor uniformity of color temperature, however, the HSOT backlighting system including the specified scatterers (curve (2)) showed much higher uniformity without dependence of the distance from the lamp.

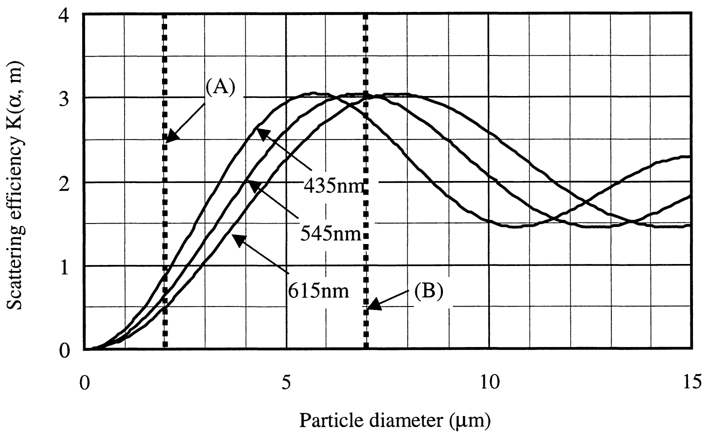


Fig. 4: Scattering efficiency of a single particle with each diameter. The numbers of 435, 545, and 615 nm mean main wavelengths of a typical fluorescence lamp spectrum. Δn: 0.05.

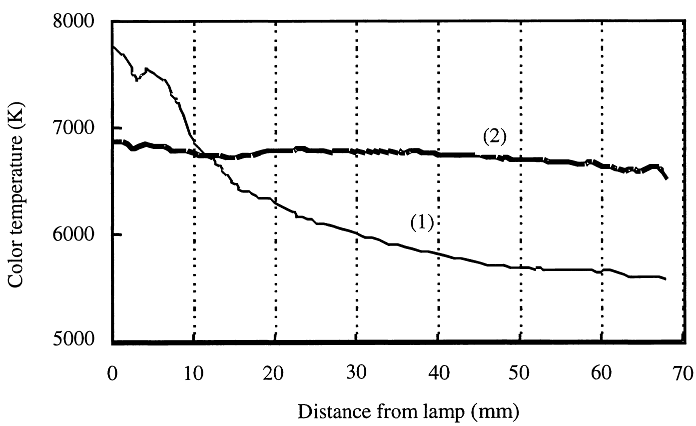
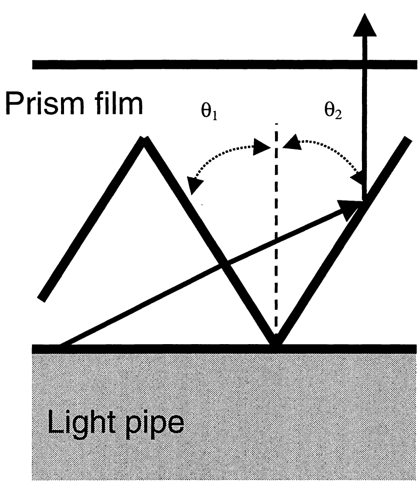


Fig. 5: Variation of color temperature for HSOT backlighting systems with 4-inch diagonal. (1) including scatterers following the general concept. (2) including new specified scatterers.

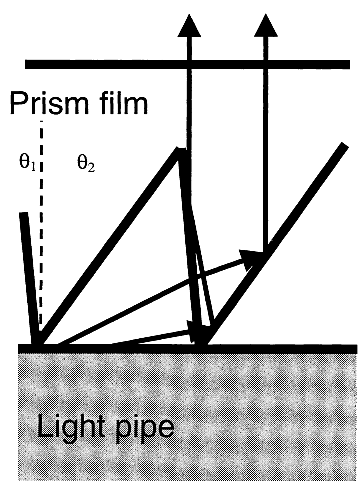
Novel Asymmetric Prism Sheet for the HSOT

As shown in Fig. 2, the HSOT light pipe of 2.5-inch diagonal had a narrow luminance profile peak around 63 degree. Therefore, a prism sheet to convert angle of the luminance peak into 0 degree is necessary for the HSOT backlighting system. We proposed a novel asymmetric prism sheet to achieve high luminance compared to the symmetric prism sheet which had been optimized for the HSOT light pipe. Figure 6 shows typical loci in the symmetric and asymmetric type prism sheets. Here, angle of the prism was divided into two parts θ_1 and θ_2. In the case of the asymmetric one, θ_1 is not equal to θ_2. Although only one locus with an angle from the light pipe can be converted into 0 degree in the symmetric type prism sheet, two loci with different angles can be converted into 0 degree in the asymmetric one. Furthermore, the luminance profile with the asymmetric one is narrow compared to symmetric one.

We optimized the asymmetric prism sheet for the 2.5-inch HSOT light pipe by using our prism sheet simulation program based on a ray tracing technique. Calculated and experimental output profiles from the prism sheets are shown in Fig. 4 in which optimized angles of the prism θ_1-θ_2 were 5.6-35.0 for the asymmetric type and 31.5-31.5 for the symmetric type, respectively. Luminance with the asymmetric prism sheet was about 30% higher than that with the symmetric one.



(a) Symmetric prism sheet



(b) Asymmetric prism sheet

Fig. 6: Typical loci in the symmetric and asymmetric type prism sheets.

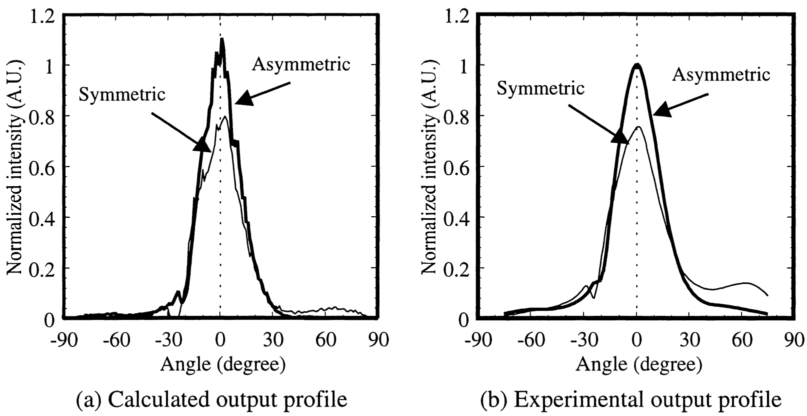


Fig. 7: Calculated and experimental output profiles from the prism sheets.

Conclusion

Analysis of the multiple light scattering inside the HSOT polymer and optimization of the HSOT polymer for a LCD backlight were carried out by using the HSOT modeling simulation. As a result, the HSOT backlighting system including the symmetric prism sheet optimized for the HSOT light pipe showed twice the brightness and efficiency of the conventional transparent PMMA plate backlighting system, and the uniform color temperature without dependence of the distance from the lamp. Furthermore, the asymmetric prism sheet was proposed and prepared for the HSOT light pipe by using the prism sheet simulation program based on the ray trace technique. The optimized asymmetric prism sheet system showed about 30% higher luminance than that of the symmetric prism system.

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