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Fabrication of light-shaping diffusion screens

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Abstract

This study presents the fabrication of a light-shaping diffuser, made by recording the far field laser speckles projected from a ground glass on photoresist plate. Elliptical speckles are created by illuminating the ground glass with a line shape He–Cd laser beam. The recorded elliptical speckles can diffuse incident light into different spread angles in vertical and horizontal directions. The speckles are inscribed with the appropriate density and depth on the surface, to diffuse incident light uniformly without a hot spot, by controlling the separation and duration of exposures. A nickel master is then electro-formed from the speckled plate for embossing the pattern on plastic plate for mass production. The diffuser is used in front and rear projection screens with high gain, the displays of ATMs, LED display illumination shapers, LCD backlight and laser beam shaping homogenizers as well as other applications.

Keywords: Diffusion screen; Light-shaping diffuser; Laser speckle

1. Introduction

Light can be scattered into special patterns from a rough surface, which can be classified into surfaces with periodic and those with random profiles. The pattern of light scattered from a periodic surface is periodic. The pattern of light diffused from a random granular surface spreads uniformly. Ground glass has a random granular surface, and thus functions as a Lambertian diffuser that can uniformly redistribute incident light. The most common daily application of ground glass is the lamp mask, which can soften the harsh light from a lamp bulb. Another popular application is the projection screen of front and rear projectors. In recent years, ground glass diffusers have been used as light-homogenizing devices in LED display panels, and LCD backlights, as well as beam-homogenizing devices. Light that passes through a surface with a random granular pattern spreads circularly and is suitable for applications in theaters where the required vertical-view-angle is as wide as the horizontal-view-angle. However, the circular spreading is not suitable for certain

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applications. For example, in a conference room, the illumination of a projection display must be concentrated in a specific area, where viewers are gathered, rather than scattered over a wide area. The shortcoming of a conventional diffuser in such applications is that it wastefully illuminates the useless area. If a diffuser forms an image in a more spatially selective manner, then that image will appear brighter and the diffuser is said to have gain. Conceptually, if a diffuser's granules can be made elliptical (like an American football) rather than circular (like a baseball), then the incident beam will be diffused into an appropriate pattern, schematically shown in Fig. 1. Light with circular cross-section is diffused into circular pattern by circular granules and into elliptical pattern by elliptical granules.

In the literature, many optical methods for fabricating a special diffuser that can diffuse light into a specific area have been reported. The first method uses a Fresnel lens combined with a lenticular structure [1] for rear projection. The Fresnel lens collimates incident light and the lenticular structure then expands the light in particular dimension. However, this method is limited by the Morie patterns (seen as wavy dark bands) that are formed by the beating of the lenticular structure pitch and the displaying pixel. The second method creates high-density dies to mark mechanically a metal surface [2]. Designing and controlling the aspect ratio of a scattering pattern are difficult. Mass production is also difficult and expensive. The third method implants shaped particles by recording speckles in a phase volume holographic medium [3]. Design and control are easy, but mass production is difficult since the duplication of volume diffusers is not trivial. Recently, a research team at the Physical Optical Corporation (POC) proposed surface-relief

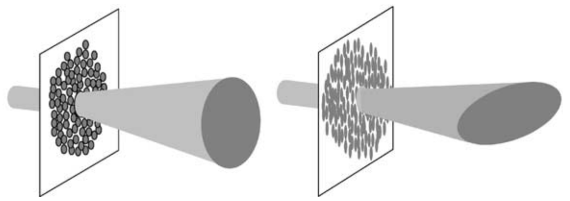

Fig. 1. Schematic diagram of the light patterns scattered from diffusers with random circle and elliptical speckles, respectively.

holographic optical elements, named light-shaping diffusers [4–6]. However, POC did not provide any details concerning the patterns molded on the surface, and the elucidating of the diffraction physics is difficult. Research in more advanced diffuser, called the "holographic diffuser" is reported in the literature [7]. The holographic diffuser is essentially based on the holographic recording of a speckle pattern generated by an optical system that contains conventional diffusers. Such a diffuser exhibits controllable scattering angles, aspect ratio, position of the scattering lobe, and multiple scattering lobes. Its design and manufacture are more complicated than the non-holographic method and are beyond the scope of this works since its function far exceeds that required for aforementioned applications.

Optical processes are less expensive than mechanical ones, and a surface-relief diffuser is more easily mass produced than a volume one. Therefore, a surface optical diffuser, manufactured by an optical process, is more effective in display applications. This work proposes an optical, non-holographic method to make surface-relief diffusers for diffusing light into special scattering patterns with high gain. In addition, the diffuser is highly promising for mass production.

2. Theoretical background

2.1. Shaped speckle pattern

The speckle pattern generated from coherent light can be treated by laser speckle theory. The phenomenon is related to the general interference theorem of light scattered from a rough surface. The Huygens–Fresnel principle states that the relationship between the electric field $\varepsilon(x, y)$ at the scattering surface and the electric field $E(u, v)$ in the observation plane, in the Fresnel approximation, is [8]

$$E(u,v) = \frac{1}{\lambda z}\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}(u^2+v^2)\right] \times \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \varepsilon(x,y)\exp\left[-\mathrm{i}\frac{\pi}{\lambda z}(x^2+y^2)\right] \times \exp\left[\mathrm{i}\frac{2\pi}{\lambda z}(ux+vy)\right]\mathrm{d}x\,\mathrm{d}y, \quad (1)$$

where λ is the wavelength of the incident beam, and z is the distance between the scattering surface and the observation plane. The relative coordinates of Eq. (1) are shown as Fig. 2(a). The figure also illustrates that light with cross-section defined by the aperture P, incidents on the rough surface will create speckles in a specific pattern on the observation plane. On the contrary, Fig. 2(b) shows that light incidents on the speckled plane defined in Fig. 2(a) creating light pattern similar to the incident light on the rough plane in Fig. 2(a). For a surface with specific roughness, the field $E(u,v)$ can be determined from $\varepsilon(x,y)$. However, for a randomly rough surface, a statistical analysis should be performed to determine the distribution of the average intensity. The autocorrelation relation between $E(u,v)$ and $\varepsilon(x,y)$ must be considered. In the case of a focal plane to focal plane system, the relationship between the relative intensities on the scattering surface (x,y) and those on the observation surface (u,v) neglecting the quadratic terms is [8]

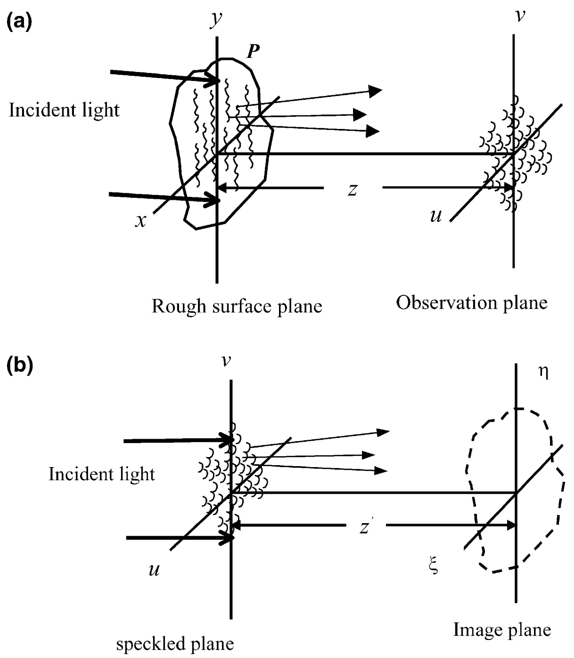

Fig. 2. The relative coordinates of (a) the rough surface plane (x,y) and the observation plane (u,v), z is the distance from (x,y) to (u,v), and (b) the speckled plane (u,v) and the image plane (ξ,η). Z is the distance from (u,v) to (ξ,η).

$$\langle EE^* \rangle = \frac{1}{\lambda^2 z^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \langle \varepsilon\varepsilon^* \rangle \times \exp\left[\mathrm{i}\frac{2\pi}{\lambda z}(u_1 x_1 - u_2 x_2 + v_1 y_1 - v_2 y_2 \right] \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}y_1\, \mathrm{d}y_2 \tag{2}$$

which is derived from Eq. (1) and valid for large z. The $\langle\ \rangle$ represents the ensemble average of the intensity distribution. The autocorrelation $\langle \varepsilon\varepsilon^* \rangle$ of the field ε on the scattering surface can be approximated as in [9]

$$\langle \varepsilon\varepsilon^* \rangle \cong \kappa |P(x_1,y_1)|^2 \mu_\varepsilon(\Delta x, \Delta y), \tag{3}$$

where $\Delta x = x_1 - x_2$, $\Delta y = y_1 - y_2$ and $\mu_s(\Delta x, \Delta y)$ is the normalized complex coherent factor of the surface (x,y), indicating the spatial coherence of transmitted beams from adjacent positions $P_1(x_1,y_1)$ and $P_2(x_2,y_2)$ on the surface. $P(x,y)$ is the amplitude of the incident beam and k is a constant of proportionality. Substituting Eq. (3) into Eq. (2) yields

$$\langle EE^* \rangle = \frac{k}{\lambda^2 z^2} \int_{-\infty}^{\infty} \int |P(x_1,y_1)|^2 \times \exp\left[\mathrm{i}\frac{2\pi}{\lambda z}(\Delta u x_1 + \Delta v y_1) \right] \mathrm{d}x_1\, \mathrm{d}y_1 \times \int_{-\infty}^{\infty} \int \mu_\varepsilon(\Delta x, \Delta y) \times \exp\left[\mathrm{i}\frac{2\pi}{\lambda z}(u_2 \Delta x + v_2 \Delta y) \right] \mathrm{d}\Delta x\, \mathrm{d}\Delta y, \tag{4}$$

where $\Delta u = u_1 - u_2$, $\Delta v = v_1 - v_2$, and (u_1, v_1), (u_2, v_2) are the position coordinates of two adjacent positions on the observation plane. For a random rough surface, the profile must be treated using random processes. Assume that the deviation of a surface from the reference smooth surface is represented by h. For a one-dimensional system, h is a function of x. The distribution of the surface height h is then given by the distribution function, $p(h)$, where $p(h)\,\mathrm{d}h$ is the probability that the surface height of a point on the surface is between h and $h + \mathrm{d}h$. Consequently, the distribution of h satisfies

$$\langle h \rangle_s - \int_{-\infty}^{\infty} hp(h)\, \mathrm{d}h = 0, \tag{5}$$

where $\langle\ \rangle_s$ indicates the spatial average across the surface. The root mean square (RMS) height of the surface then equals the standard deviation given by, $\sigma = \sqrt{\langle h^2 \rangle_s}$. Assume that the distribution function of the surface height of a random rough surface is a Gaussian distribution given by [10,11]

$$p(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right). \tag{6}$$

The autocorrelation coefficient of the rough surface is $C(\tau) = \exp(-\tau^2/T_0^2)$, where $\tau = \sqrt{(\Delta x)^2 + (\Delta y)^2}$ and T_0 is the correlation distance over which $C(\tau)$ drops to e^{-1}.

The complex coherence factor is obtained from [12,13]

$$\begin{aligned}\mu_\varepsilon(\Delta x, \Delta y) &= \langle \exp(i\Delta\phi) \rangle \\ &= \exp\left[-v_z^2\sigma^2(1 - C)\right],\end{aligned} \tag{7}$$

where $\Delta\phi$ is the phase induced by autocorrelation. For a reflective type rough surface shown as Fig. 3, the change of momentum in the Z direction is $v_z = (2\pi/\lambda)(\cos\theta_s + \cos\theta_i)$, where θ_i and θ_s are incident and scattering angles, respectively. According to Eq. (4), in the case of random roughness, the first Fourier transform factor yields a narrow function of $(\Delta u, \Delta v)$, which determine the mean size of speckles. The second yields a broader function of (u_2, v_2), which represents the large envelope of the intensity distribution in the (u, v) plane. The shape of the illumination aperture, given by $|P(x_1, y_1)|$ in Eq. (4), is included to define the shape of the speckles on the observation plane. Accordingly, if the illumination aperture has unequal widths in the x and y directions, then elliptical speckles will be generated on the observation plane. The aperture acts like a small cylindrical lens, which distributes the incident beam into a particular shape.

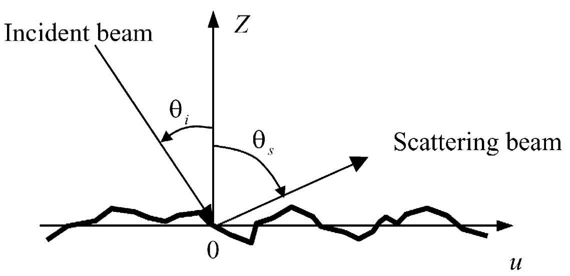

Fig. 3. The reflective scattering diagram of incident and scattered beams from any rough surface u.

2.2. Speckles to diffuse light without a hot spot

Fig. 2(b) is the inverse of Fig. 2(a), which shows that a plate filled with speckles from Fig. 2(a) can diffuse light into a pattern similar to the cross-section of the incident light on the rough surface in Fig. 2(a). However, the diffuser is required to diffuse light without a hot spot. For hot spot free scattering, the speckled surface should be rough enough to diffuse the incident beam completely away from its specular direction. Thus, the recorded speckle patterns must be etched to a certain depth. The appropriate etching depth is determined by the far field distribution of light scattered from the rough surface on the observation plane in Fig. 2(a), defined in Eq. (1).

Fig. 2(b) also defines the relative coordinates of speckled plane and the image plane. From [12], the scattering coefficient for a plane wave incident on a one-dimensional diffusion speckled plane is

$$\begin{aligned}\rho &= \frac{E}{E_0} = \frac{F}{2L}\int_{-L}^{L} \exp[i(\vec{v}_u \cdot \vec{r}_u + v_z\zeta)]\, du \\ &= \frac{F}{2L}\int_{-L}^{L} \exp[i(\vec{v}_u \cdot \vec{r}_u + \phi)]\, du,\end{aligned} \tag{8}$$

where $\vec{r}_u = u\hat{u}$; L represents the half width of illumination aperture; ζ represents the surface height on the speckle surface; $v_u = (2\pi/\lambda)(\sin\theta_s - \sin\theta_i)$; and ρ, F are functions of incident angle θ_i and scattering angle θ_s; E is the scattered field, and E_0 is the field reflected in the specular direction from a smooth surface. ϕ is the phase term induced by a rough, speckled surface. Thus, after passing through the speckle plane, the normalized far field power distribution of scattering is then as described in [14]

$$\langle \rho\rho^* \rangle = D\{\rho\} + \langle\rho\rangle\langle\rho\rangle^*, \tag{9}$$

where $D\{\rho\}$ is the variance of ρ. In the one-dimensional case, this equation can be rewritten as

$$\langle \rho\rho^* \rangle = e^{-g}\rho_0^2 + D\{\rho\}, \tag{10}$$

where $g = v_z^2\sigma^2 = 4\pi^2(\cos\theta_i + \cos\theta_s)^2(\sigma^2/\lambda^2)$, representing the ratio of the surface height to the wavelength; $\rho_0 = \sin c(v_u L)$ is the scattering coefficient of a smooth surface. Elementary manipulation yields [14]:

$$\langle \rho\rho^* \rangle = D\{\rho\} + \langle \rho \rangle \langle \rho \rangle^* \approx \begin{cases} \mathrm{e}^{-g}\left(\rho_0^2 + \frac{\sqrt{\pi}F^2 T_0 g}{2L}\,\mathrm{e}^{-v_u^2 T_0/4}\right) & \text{for } g \ll 1, \\ \mathrm{e}^{-g}\left(\rho_0^2 + 0.43\frac{F^2 T_0}{L}\right) & \text{for } g \approx 1, \end{cases} \tag{11}$$

$$\langle \rho\rho^* \rangle \approx D\{\rho\} \approx \frac{T_0 F^2 \sqrt{\pi}}{L v_z \sigma} \exp\left(-\frac{v_u^2 T_0^2}{4 v_z^2 \sigma^2}\right) \quad \text{for } g \gg 1, \tag{12}$$

where L is the half width of the illumination aperture. According to Eq. (11), when $g \approx 1$ or $g \ll 1$, the $\mathrm{e}^{-g}\rho_0^2$ term is in the specular direction, and is therefore the hot spot term. These two cases correspond to slightly and moderately rough surfaces, respectively, in which light cannot be diffused sufficiently to form a uniform pattern. From Eq. (12), when $g \gg 1$, the specular term is negligible and the scattering power depends only on T_0/σ. The smaller T_0/σ yields the larger scattering power to diffuse beam away from its specular direction. The speckles must be corrugated with a high aspect ratio to diffuse light effectively.

3. Experiment

Diffusion of a beam into a desired pattern by diffusion plane with shaped speckles can be viewed as the inverse of recording the speckles, as schematically shown in Fig. 4. Fig. 4(a) indicates that the speckles are formed with both axes inversely proportional to the dimension of the illuminating laser beam pattern. When a beam is incident on the speckled plate, a diffusion pattern similar to the pattern of the illumination is reproduced, as schematically depicted in Fig. 4(b).

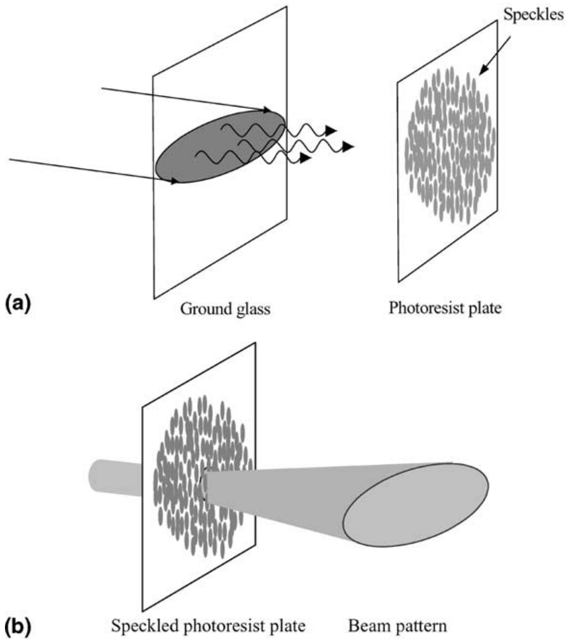

Fig. 4. (a) Elliptical speckles are generated on the photoresist plate when the ground glass is illuminated by a shaped beam spot. (b) The beam pattern diffused from the elliptical speckles is similar to the incident beam in (a).

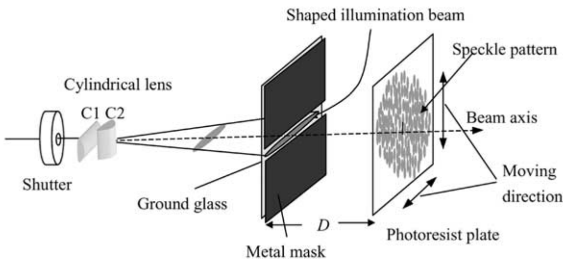

Fig. 5. Schematic diagram of the experimental setup.

Fig. 5 illustrates our experimental setup. A He–Cd laser with 442 nm wavelength was used as the light source, because the photoresist is more sensitive to this light. A shutter was positioned behind the laser head to control the period of exposure duration. The first cylindrical lens, C_1, expands the incident beam spot in the vertical direction. The second cylindrical lens, C_2, with its axis perpendicular to C_1, expands the beam in the horizontal direction. The magnification of C_2 is much larger than that of C_1. Consequently, the beam spot is expanded into a strip of light, as shown in the figure. The dimension of the light strip determines the shape of the speckles on the photoresist plate. Adjusting the relative position of the two cylindrical lenses tunes the shape of the

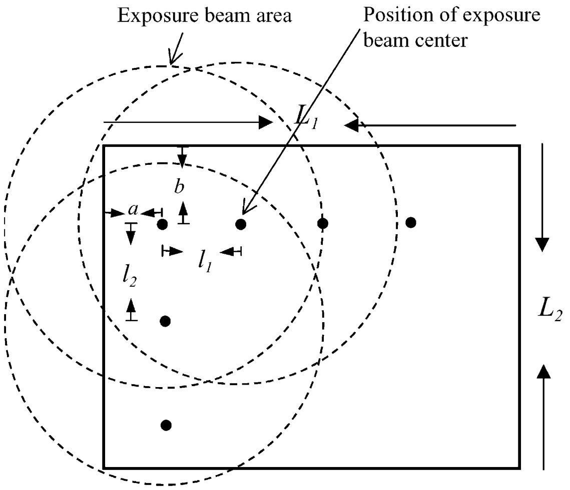

Fig. 6. The exposure steps for a hot spot free rectangular diffuser. The solid line defines the photoresist area, the dark spots represent the position of exposure beam centers, and the dash circle is the expanded beam area, centered at beam center.

light strip to the desired dimensions to generate speckles with various shapes that satisfy different diffusion requirements. Common ground glass generates irregular phases is used as the irregular phase generator. A mask with a rectangular window blocks the ambient light during exposure. A photoresist plate from Towne Lab, including a 3 μm thick photoresist layer, is used to record the speckle pattern. Controlling the exposure and developing time enables the full thickness to be used to record the intensity profile of the speckles with sufficiently high contrast to meet the hot spot free conditions, specified as Eqs. (11) and (12).

Elliptical speckles were observed on the recording plate after exposure and development. However, a single exposure step did not create speckles sufficiently close to each other, yielded a high T_0/σ value and thus a hot spot. Therefore, multiple exposures were used to increase the den-

Table 1
Parameters for making a light-shaping diffuser with shaping ratio 2.5:1

Distance from ground glass to recording plate	Slit length	Slit width	Number of exposures (for a diffuser area of $L = 4$ cm square)	Exposure power intensity	Photoresist/ developer	Roughness RMS of ground glass
10 cm	10 cm	2 cm	12	63.8 mJ/cm^2 at 442 nm	Shipley 1400/ Shipley 351	1.73 μm

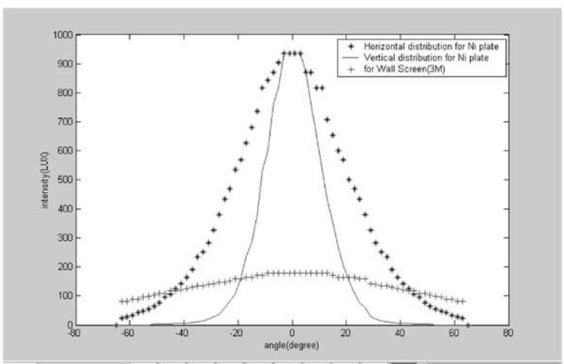

Fig. 7. Measured light distributions in the vertical and horizontal directions from the 2.5:1 light-shaping diffuser and a 3M's wall screen.

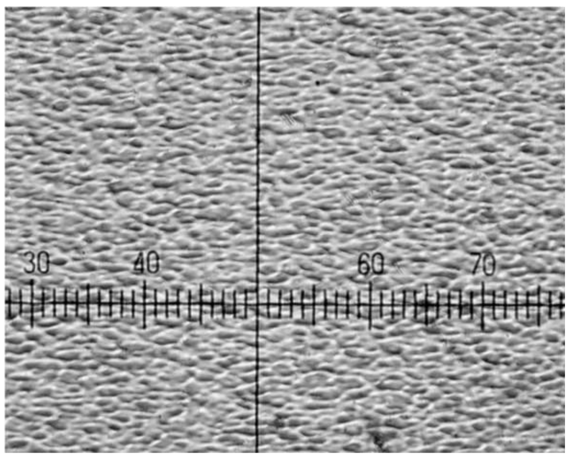

Fig. 8. Photograph of ellipitical speckles formed on the surface of the recording plate.

sity of the speckles. However, too many exposures within a specific area will reduce the contrast of the speckles. Therefore, exposure separation must be adjusted to yield optimum conditions of speckle density and speckle contrast. An exposure was taken and the photoresist plate shifted by a certain distance, both vertically and horizontally, before the subsequent exposure was taken. Fig. 6 shows the relative positions of the centers of the exposure beam and the photoresist plate, where l_1 and l_2 indicate the horizontal and vertical distances by which the plate was shifted, respectively, between

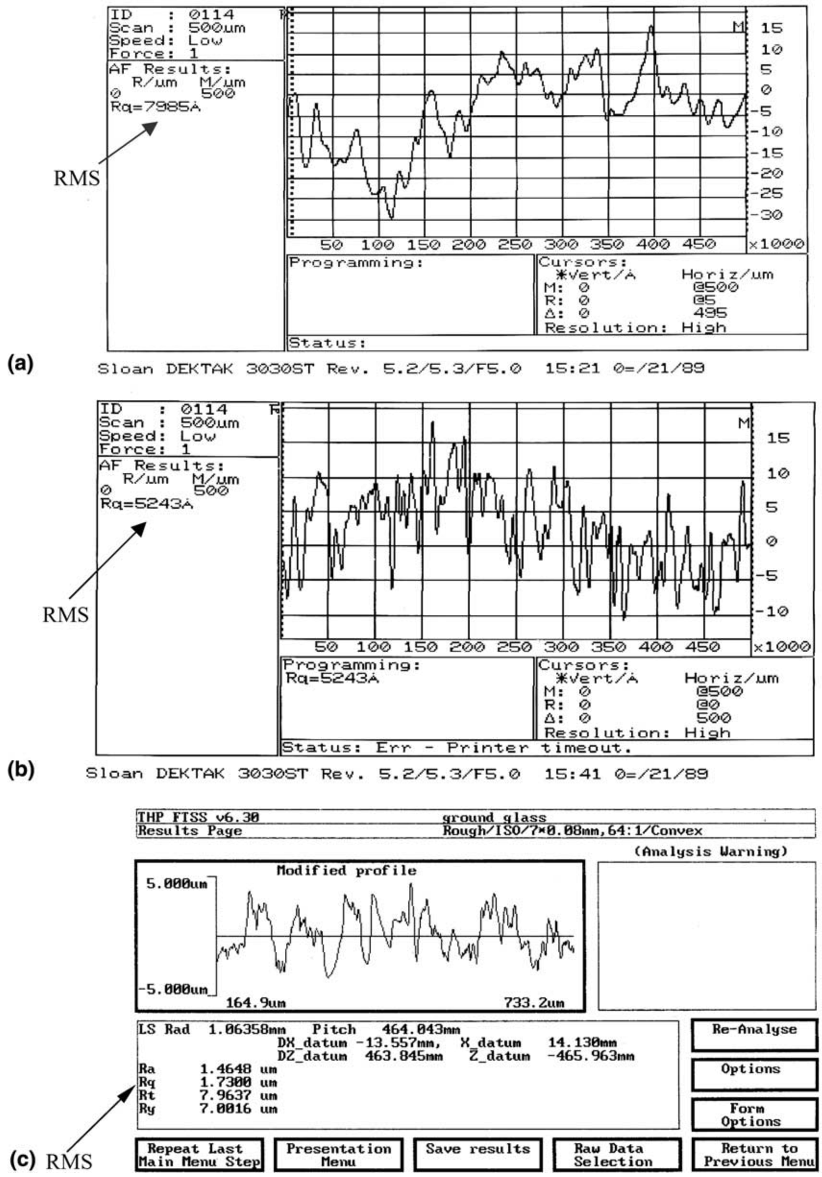

Fig. 9. (a) The profile of diffuser's surface in direction of speckles' short axis, (b) in the direction of speckles' long axis. The parameter Rq is the RMS roughness value in Angstrom (Å). (c) The profile of the ground glass with RMS value of 1.73 μm for making the diffuser.

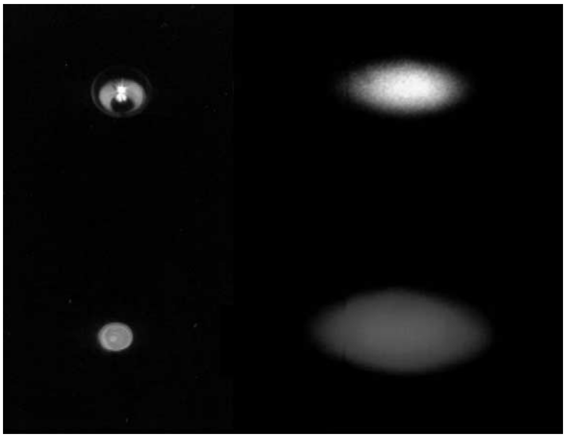

Fig. 10. The light source and its homogenized light-shaping patterns of a light bulb (up) and an LED (bottom), respectively.

two consecutive exposures. This work used ground glass with a RMS value of 1.73 μm. The distance between the ground glass and the photoresist plate, D, was 10 cm. A hot spot free diffuser was made by taking exposures separated by steps of $l_1 = 1$ cm and $l_2 = 1.5$ cm, with distances,

$$a = \left[L_1 - l_1 \cdot \mathrm{INT}\left(\frac{L_1}{l_1}\right)\right] \Big/ 2$$

and

$$b = \left[L_2 - l_2 \cdot \mathrm{INT}\left(\frac{L_2}{l_2}\right)\right] \Big/ 2$$

from the horizontal and vertical edges of the photoresist plate, respectively. INT( ) denotes the integer of the argument; L_1 and L_2 are the dimensions of the photoresist plate. After exposure and development, a diffuser was formed on the photoresist plate. Table 1 lists the parameters for making a diffuser that diffuses light with a shaping ratio of 2.5:1. An electro-forming process was then implemented to generate a metal master for plastic embossing duplication.

The electro-formed nickel plate was used to simulate a reflection display screen. The scattering characteristics of the nickel plate were measured and those of a conventional white screen (3M's Wall Screen) are also given for comparison. The measurement was made with a slide projector as the light source, a white screen or nickel plate as the reflecting surface, and an illuminometer (DIGILITE Model L-318B, SEKONIC) as the detector. Note that the light intensities on the white screen and the diffuser were equal. Measurements were made with the illuminometer at various positions over a vertical and horizontal half circles, centered on the surface of the white display screen or the nickel plate, to evaluate the power of the scattered light at various angles.

Fig. 7 presents the measurements for 3M's wall screen and light-shaping diffuser. The power curve for both the vertical and the horizontal scattering from the white display screen reveal a rather broad and flat pattern. This phenomenon is consistent with the fact that the white display screen is a Lambertian diffuser that diffuses light isotropically. The other curves are from the nickel plate light-shaping screen, and separately depict the vertical and horizontal scattered light power. The horizontal view angle (full angular width of 1/10 maximum) is approximately 100° and may satisfy certain wide-viewing-angle requirements. The vertical view angle of the same sample is approximately 40° and thus is moderately confined, enhancing the light intensity within the desired

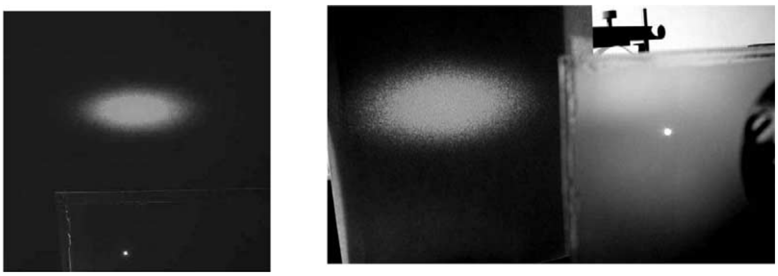

Fig. 11. The elliptical diffusion pattern with a laser beam transmitting through a light-shaping diffuser.

region. The maximum intensity of the diffuser is approximately 5.24 times that of the conventional white display screen, and thus the gain of the diffuser is 5.24. Moreover, no hot spots are observed. Fig. 8 shows a photograph of diffuser's surface. Elliptical speckles are observed on the surface of the diffuser. Figs. 9(a) and (b) show the roughness of diffuser's surface, measured along speckles' short axis and long axis using a Dektak 3030ST profile meter. The averaged standard deviation σ (= RMS) is approximately 0.6 μm. Therefore, for normal incidence $\theta_i = 0$, θ_s ranges from 0° to 90°, $g = 4\pi^2(\cos\theta_i + \cos\theta_s)^2(\sigma^2/\lambda^2) \geqslant 40$ at $\lambda =$ 0.55 μm, which far exceeds unity, meeting the requirement for the absence of hot spots. Fig. 9(c) also shows the roughness profile of the ground glass required to make the diffuser. Figs. 10 and 11 present examples of diffusion patterns from a light bulb, an LED, and a laser spot.

4. Conclusions

A method was elucidated for fabricating a diffuser with high gain, wide-viewing-angle and no hot spot. The diffuser is highly promising for mass production and applications that require efficient diffusion screens. The optical setup proposed in this work is flexible for making various diffusion screens to meet different light-shaping requirements. Furthermore, the diffuser is a potential light-shaping homogenizer with applications in advanced backlight and illumination systems.

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