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Optical diffusers based on silicone emulsions

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ABSTRACT

The present study provides an experimental approach for fabricating optical diffuser films based on silicone emulsions. The silicone emulsion consisting of silicone polymer (Sylgard 184) and NaCl aq. solution was used as the optical material of diffusers, wherein NaCl aq. solution was severed as surfactant to stabilize the emulsions. After stirring mechanically, microscaled water drop with various sizes distributed randomly in silicone polymer, wherein water drop was used as scattering diffusion particles. To modulate the volume of NaCl aq. solution, the diffusing performance of diffusers could be change by different amount drop particles. Thereafter, an optical examination was carried out to characterize optical properties, transmittance, and light diffusivity of volumetric diffuser films.

1. Introduction

Optical diffuser films play critical roles to spread the incident light from sources over a wide angle to prevent light sources from being seen directly by viewers in lighting systems. Two distinct types of diffusers are recognized, namely, surface-relief and volumetric type. Surface-relief diffusers depend mainly on microstructures on the surface to scatter light, such as microlenses [1–3], pyramids [4], rough surfaces [5–6] and other microstructures. Volumetric diffusers depend mainly on the transparent micro beads or fillers located uniformly inside the plates to scatter light [7]. Much research has been developed on optical materials to fabricate hologram diffusers [8], such as photopolymerizable material with an ionic liquid [8], silver-halide sensitized gelatine [9], dichromated gelatine [10], photopolymers [11–12], and azobenzene polymers [13], owing to these properties of controllable diffusion angle, directional property, volume refractive index variation and high transmittance. To compare with hologram materials, commercial microscaled fillers added directly into matrixes that are simpler ways to fabricate diffusers. However, these fillers aggregated easily to lead nonuniform dispersion due to van der Waals' forces. Hence, well-controlled methods for fabricating volumetric diffusers are still very much expectable.

Emulsions are heterogeneous systems consisting of one immiscible liquid dispersed in another, in the form of droplets which may have thermodynamic instability [14]. Silicone emulsions have wide applications in industry and are used for waterproofing surfaces, antistatic coatings, and defoaming agents [15]. However, little literature reported silicone emulsions had been used in the application of optics. Silicone polymer is typically insoluble in water and has a good optical transmittance in the wavelength range of 290–1100 nm, including ultraviolet rays, visible light, and a part of infrared rays. We considered silicone emulsions have a potential to fabricate optical elements, especially optical diffusers.

In this study, emulsions were prepared only by the use of silicone and NaCl aq. solution. NaCl aq. solution was added directly into silicone polymer and subsequently mechanically stirred it, resulting in the formation of emulsions. In stead of solid scattering fillers, microscaled water drop can be served as scattering particles after curing water-in-oil silicone emulsions. Thereafter, an optical examination was carried out to characterize optical properties, transmittance, and light diffusivity of diffusers.

2. Experiment

Silicone elastomer (Sylgard 184) and curing agent were obtained from Dow Corning and the liquid silicone mixtures composed of silicone elastomer and curing agent with the weight ratio of 10:1 could be solidified. The emulsions were prepared by following steps: The 1 molarity (1 M) NaCl aq. solution with suitable volume, such as 10, 15 and 20 vol %, and curing agent were added simultaneously into the silicone elastomer and subsequently mechanically stirred with 600–1000 rpm. After stirring continually

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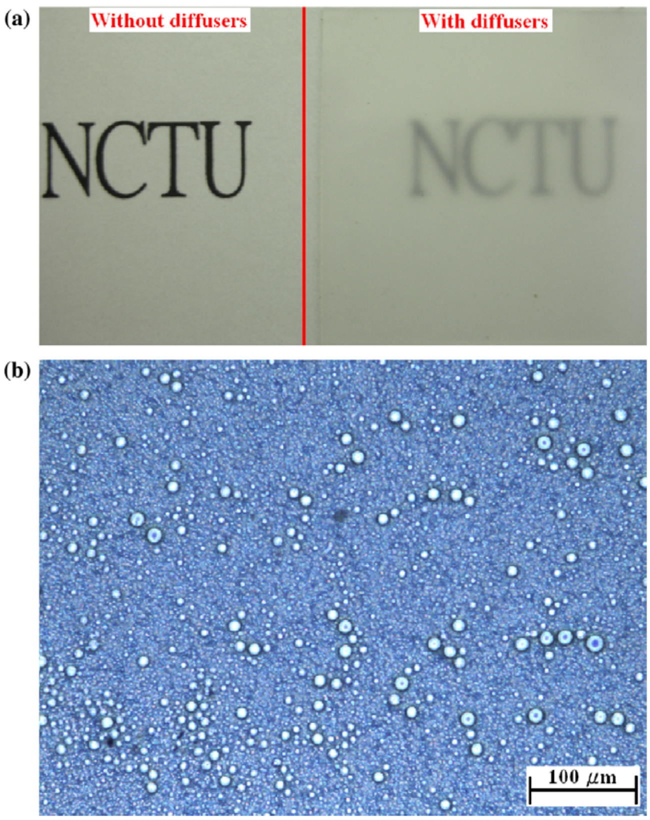

Fig. 1. (a) A real image of diffusers located on a paper with written words. (b) Optical magnification image of diffusers consisted of spherical water drop with various sizes in silicone polymer.

for 10 min, the transparent silicone polymer gradually became white emulsions, wherein NaCl aq. solution was used as surfactant to stabilize the emulsions [16–17]. After spreading out and curing thermally (40 °C and 6 h) the emulsions, three volumetric diffusers with 200 μm thickness were fabricated.

3. Results and discussions

To add the electrolyte, NaCl, into the oil/water system, it could avoid the coalescence of microscaled water drop and promote the generation of microscaled water drops. This is because like charges located the outside of water drop to form the barrier of charges and to generate the electrostatic repulsive-forces. As two drops closed gradually each other, the repulsive-forces increased gradually to decrease the possible of water drop of coalescence. Hence, aggregated drops were hardly observed. If the emulsions had no NaCl, the emulsions would easily separate to recovery oil/water two phases after a short time. On the other hand, the emulsions would keep a steady state for more than a month if the emulsions had NaCl. Once the emulsions were solidified to form diffusers, their character will be held.

Fig. 1a shows a real image of diffusers, made of emulsions with 20 vol % NaCl aq. solution, located on a paper with written words. It implied diffusers were translucent and the distance between words was shortened as diffusers located on the words. Fig. 1b shows the optical image of spherical droplet located randomly inside diffusers (20 vol % NaCl aq. solution). The spherical droplet of which the size ranged from 0.1 to 20 μm could serve as spherical scattering particles to scatter light as light illuminated on them.

Diffusers were first examined to understand the effect of diffusing ability for the concentration of diffusing fillers, the volume of NaCl aq. solution was modulated, including 10, 15 and 20 vol %. A He–Ne laser with 632.8 nm wavelength was used to illuminate

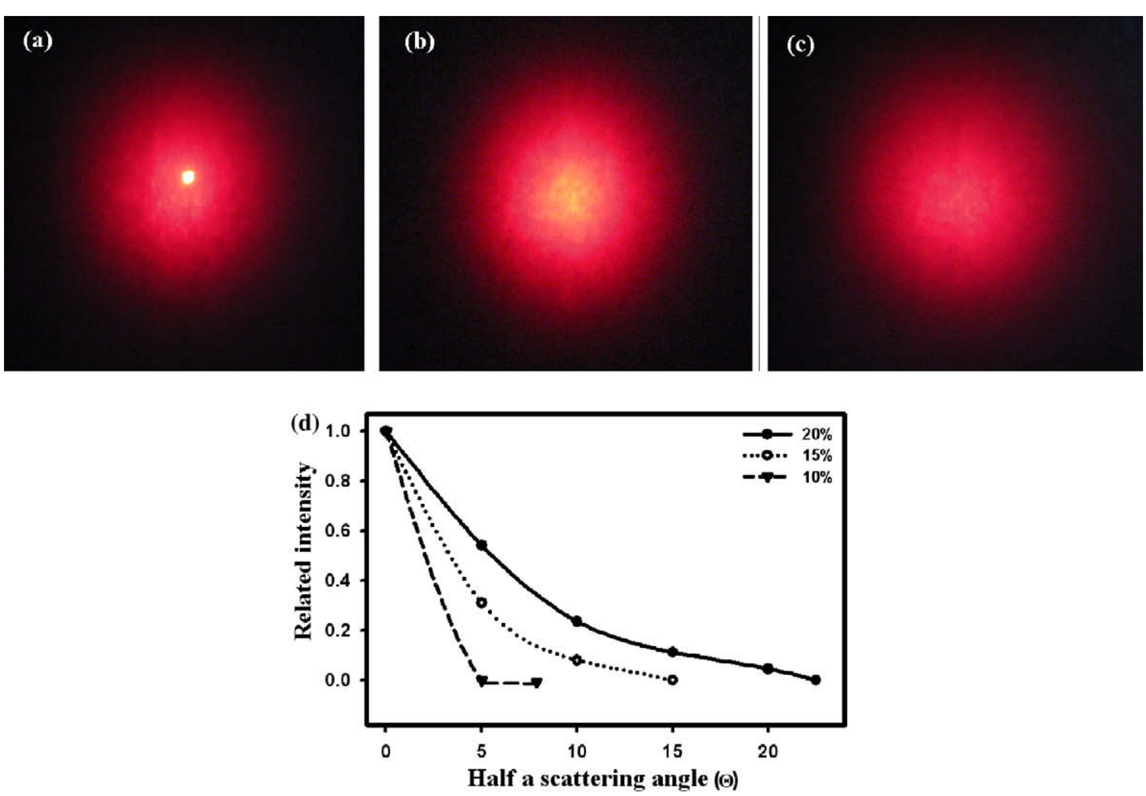

Fig. 2. Optical images of diffusion pattern for emulsions with (a) 10, (b) 15, and (c) 20 vol % NaCl aq. solution. (d) The related brightness for (a–c) as a function of half a scattering angle.

directly on diffusers and the optical pattern was recorded by digital camera. Fig. 2 a–c shows the optical images of diffusion pattern, including emulsions with 10, 15, and 20 vol % NaCl aq. solution and Fig. 2d shows the related brightness for Fig. 2a–c as a function of half a scattering angle, wherein the related brightness is defined as the measured flux divided by the maximum flux. Therefore, the percentage of the 0th order beam, defined as the flux in the center of diffusing beam divided by the overall flux of a laser beam, was also evaluated. Based on the results, the scattering angle for three diffusers (10,15 and 20 vol %) was given by 10°, 30° and 46° and the percentage of the 0th order beam was 84.3%, 10.83% and 1.21%, respectively. It revealed that the scattering angle and the percentage of the 0th order beam could be modulated by the change of the volume of NaCl aq. solution. In other words, the diffusing performance of volumetric diffusers depended on the amount of microfillers. Besides, the microscaled dispersed on the inside of emulsions was not of uniform size, causing the generation of different focal length. It was also helpful to promote the laser beam to spread uniform and to obtain a large scattering angle. Hence, diffusers with a low percentage of 0th order beam and a wide scattering angle could be obtained by using water-in-oil emulsions.

In addition, the transmittance of emulsions with different volume NaCl aq. solution was measured by UV–vis spectrometer. Fig. 3a shows the transmittance of silicone emulsions as a function of incident wavelength ranged between 350 and 700 nm. The

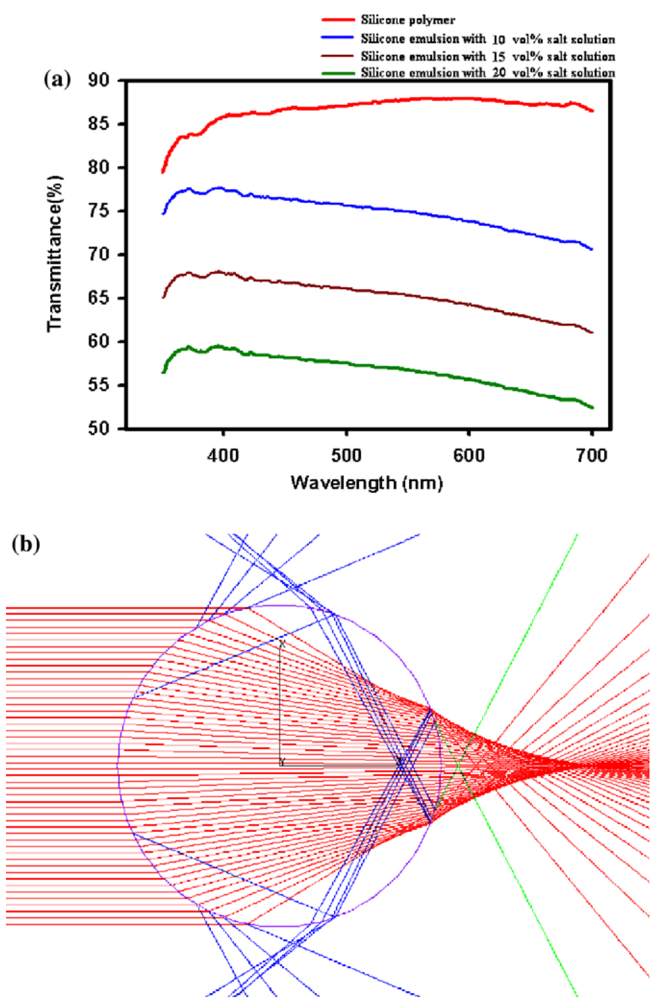

Fig. 3. (a) The transmittance of silicone emulsions as a function of incident wavelength ranged between 350 and 700 nm. (b) Simulated scattering profile of uniformly parallel incident light passing through water drop.

experimental result revealed that the emulsions have no peak caused by absorption in the visible range, and the transmittance of visible light decreased with the increase of NaCl aq. solution while diffusivity increased. Additionally, it was also found that the spectral transmittance slightly decreased with the increase of incident wavelength.

When light beams propagated the diffusers, the transparency (T) was attenuated due to scattering. Therefore, the optical thickness (τ) of a scattering medium can be written as follows: $\tau(\lambda) = \int_0^\infty \rho(r)\sigma_{ext}(\lambda, r)dr$ wherein $\sigma_{ext}(\lambda, r)$ is so-called extinction cross section, λ is the wavelength of an incident radiation, r is the radius of a scattering domain and $\rho(r)$ is the number size distribution function for scattering domains (e.g. water drops) [18]. Therefore, based on the Lambert–Beers Law, the transparency (T) of a medium could be expressed as follows: $T = \frac{I(\lambda)}{I_0(\lambda)} \approx e^{(-\tau)}$ wherein, $I(\lambda)$ is the intensity after passing through a layer of optical thickness, $I_0(\lambda)$ is the initial intensity emitted by the light source [18]. In general, σ_{ext} depends on wavelength of an incident radiation, characteristic size of the particles, and the dielectric function of material. For ideally spherical particles, the σ_{ext} depends on the ratio of radius to wavelength (r/λ) rather than on r and λ separately. If size of the scattering domains is much smaller than λ, the τ is approximately proportional to $(1/\lambda^{-4})$ which is called Rayleigh scattering. The T should rapidly grow with increasing the wavelength if the diffusers contained of Rayleigh particles. But this is not consistent with results in Fig. 3a. It meant the larger particles must be present in the diffusers. Next, when the particles' sizes are comparable or a bit larger than λ, optical thickness of particle ensemble is usually inversely proportional to wavelength. Hence, the T will still grow with the wavelength. However, experimental results showed that T was a decreasing function of the wavelength. This indicated that the diffusers must really contain particles with sizes above intermediate limit, For example, the particles are at least ten times larger than the incident wavelength. For such particles the concept of geometrical optics is an appropriate approach. By using a commercial software package TracePro, the trace of light through water drop could be clearly understand. Fig. 3b shows simulated scattering profile of uniformly parallel incident light passing through spherical scattering particles. As the parallel input rays illuminated on spherical particles, most of light would be focused and then diffused after passing through spherical particles but a small part of light would be depart from other directions after refracting, resulting in the decrease of transmittance. Although microscaled water drop in silicone emulsions would cause the decrease of the transmittance, the emulsions had still a great potential to be developed the material of diffusers, especially volumetric diffusers.

4. Conclusions

In summary, we demonstrated a simple, cost-effective technique for fabricating volumetric diffusers by using silicone emulsions. Silicone emulsions consisted of microscaled water drop with various sizes distributed randomly inside emulsions were prepared only by mixing silicone polymer and NaCl aq. solution. Therefore, these microscaled water drops could be acted as good diffusing fillers. Thereafter, the silicone emulsions were characterized in terms of transmittance and diffusing performance. We believe that silicone emulsions have a great potential for mass production of volumetric diffusers.

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