Tailoring the light distribution of liquid crystal display with freeform engineered diffuser

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Abstract: We propose a versatile design approach of engineered diffuser based on freeform optics that can tailor the light distribution of a liquid crystal display (LCD) to meet different applications. The proposed LCD system consists of a quasi-directional backlight, liquid crystal panel, and an engineered diffuser. It offers high efficiency, wide view, high contrast, as well as low ambient light reflection. For large size LCDs, we design a wide view diffuser to match the light distribution with state-of-the-art organic light emitting diode (OLED) TV. For mobile displays, we design a diffuser to replicate current LCD performance. Our design can also provide flattop light intensity distribution for privacy protection. These exemplary designs prove that our engineered diffuser is versatile for different applications.

OCIS codes: (230.1980) Diffusers; (220.0220) Optical design and fabrication; (080.4298) Nonimaging optics; (120.2040) Displays.

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1. Introduction

Optical diffusers have been widely used in liquid crystal displays (LCDs) [1, 2], general lighting [3], and spatial light modulators [4]. However, it is not very flexible to control the light intensity distribution through traditional holographic diffuser [5] or ground-glass-based diffuser. Several approaches have been proposed to control the light intensity distribution with diffuser, such as two-dimensional (2D) random Dirichlet surface [6, 7] and light shaping diffuser with individually designed 2D scattering centers [8]. Although these diffusers can achieve amazing performance, they are not designed specifically for display applications. Thus they may only work for coherent light [8], or they may introduce strong haze [9]. Moreover, the optical diffusers used in LCDs are not powerful enough to achieve a light intensity distribution as wide as an organic light emitting diode (OLED) TV.

In this paper, we propose an engineered diffuser to significantly widen the light distribution of a large-size LCD TV based on freeform optics, which has been widely used in display backlight [10, 11], general lighting [12–15], and solar concentrator [16]. However, freeform optics has not yet been applied to designing optical diffusers. Our engineered diffuser not only controls the light pattern but also improves the ambient contrast ratio by reducing the ambient light reflection [17]. Compared to the spherical-beads based diffuser commonly used in LCDs, our diffuser exhibits a greatly enhanced performance. Next, we modify our design to optimize the diffuser for small-to-medium size LCDs for mobile displays. Finally, we demonstrate that our diffuser can achieve a flattop light distribution like a privacy film.

2. Design principle of the engineered diffuser

Figure 1 illustrates the design principle of the engineered diffuser. For each diffusing unit, the incident rays hit the first freeform surface, refracted to the second surface, and then diverted by the second flat surface, as Fig. 1(a) shows. As the diffuser is designed specifically for display applications, for the whole diffuser film, black matrix (BM) is deposited on either the bottom or the top surface of the film, as depicted in Figs. 1(b) and 1(c), respectively. The most important reason to employ BM is to reduce ambient light, thus enhancing ambient contrast ratio of the system. In the meantime, BM can efficiently reduce unwanted multi-refractions

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between different diffusing units, which greatly simplifies our calibration and iteration process. The main difference between the top configuration and the bottom configuration is that as the BM is closer to the viewer, it is more efficient for reducing the ambient light. However, compared to the bottom configuration the top configuration blocks more input light, thus the efficiency of the diffuser is lower. The equation governing the design of the diffuser is as follows [12]:

$$\iint T(x,y,z)\bullet E(x,y,z)ds = \iint I(\theta,\varphi)d\Omega, \tag{1}$$

here $E(x,y,z)$ is the incident light illuminance at point (x,y,z) on the first freeform surface, $T = T_1T_2$ is the total transmittance after passing through two surfaces, $I(\theta,\varphi)$ is the required light intensity at polar angle θ and azimuthal angle φ, and s and Ω are the corresponding surface area and solid angle, respectively. The required light intensity distribution could be different for different applications. For a large size display, such as TV, we usually require high light intensity and luminance at large viewing angle to make sure viewers sitting at the edge of the sofa can still perceive a vivid image. Three typical requirements [18] are listed in Eq. (2):

$$I(\theta,\phi) = \begin{cases} I_0 \text{ (Isotropic distribution)} \\ I_0 \cos\theta \text{ (Lambertian distribution)}. \\ I_0 \cos^{1.5}\theta \text{ (LG OLED TV)} \end{cases} \tag{2}$$

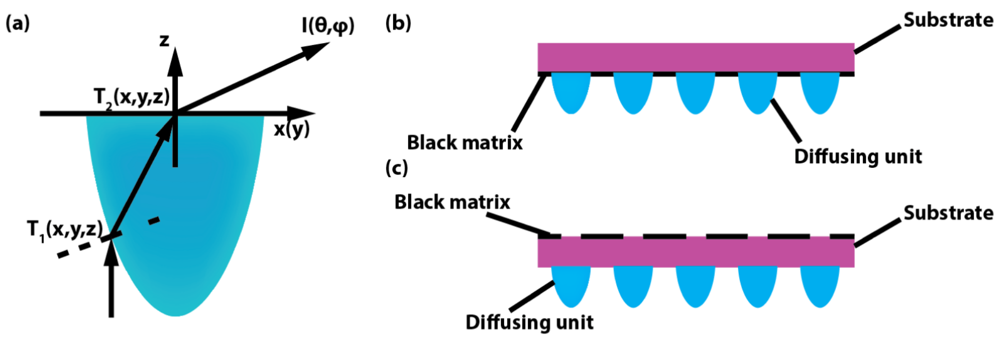

Fig. 1. (a) Configuration of a single diffusing unit, (b) bottom configuration of the engineered diffuser, and (c) top configuration of the engineered diffuser.

We still cannot solve Eq. (1) with Eq. (2), thus we need to apply Snell's law to determine the transmitted light direction [19]:

$$\begin{aligned} & n'\mathbf{r} - n\mathbf{i} = \Gamma\mathbf{n^0} \\ & \Gamma = \sqrt{n'^2 - n^2 + n^2(\mathbf{i}\bullet\mathbf{n^0})^2} - n(\mathbf{i}\bullet\mathbf{n^0}), \end{aligned} \tag{3}$$

where $\mathbf{i}$ and $\mathbf{r}$ are the normalized incident and refracted ray vectors, respectively; n and n' are the refractive indices of the incident and refraction media; and $\mathbf{n^0}$ is the surface normal. The surface normal $\mathbf{n^0}$ at point (x,y,z(x,y)) can be expressed as [19]

$$\mathbf{n^0} = \frac{1}{\sqrt{z_x^2 + z_y^2 + 1}}(-z_x, -z_y, 1). \tag{4}$$

Here z_x and z_y are the first-order partial derivatives of the coordinate z with respect to x and y, respectively. With Eqs. (3) and (4), it is possible to deduce the angles of incidence (θ_i) and refraction (θ_t), and then the transmittance can be calculated by [20]:

#235279 - $15.00 USD Received 27 Feb 2015; revised 28 Apr 2015; accepted 12 May 2015; published 20 May 2015

$$
\begin{aligned}
r_s &= \frac{n\cos\theta_i - n'\cos\theta_t}{n\cos\theta_i - n'\cos\theta_t},\\
r_p &= \frac{n\cos\theta_t - n'\cos\theta_i}{n\cos\theta_t - n'\cos\theta_i},\\
T_s &= 1-\left|r_s\right|^2,\\
T_p &= 1-\left|r_p\right|^2.
\end{aligned}
\tag{5}
$$

In Eq. (5), the subscripts *s* and *p* stand for the *s* and *p* polarizations, respectively.

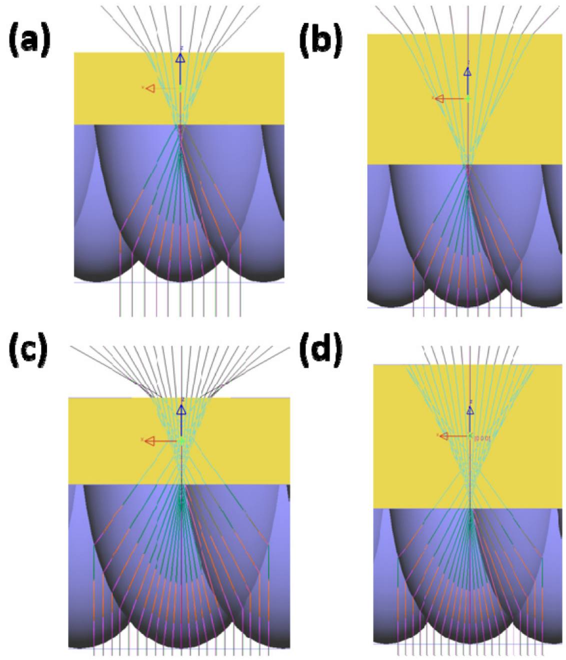

Fig. 2. Effect of substrate thickness on the light distribution of the diffuser. For the bottom configuration when the substrate thickness increases from (a) 30μm to (b) 60μm, the light distribution remains unchanged. For the top configuration, as the substrate thickness increases from (c) 30μm to (d) 60μm, not all the light transmitted by the diffusing element can transmit through the corresponding pupil. For demonstration purpose, the light reflected back by the elements is ignored.

From Fig. 1, we can see that the structure of the whole diffuser film is not identical to a single diffusing element because of the substrate and the black matrix. However if properly designed, the light distribution is still mainly determined by the single diffusing element. The reasons are twofold: 1) the black matrix can efficiently reduce the crosstalk between different diffusing elements, and 2) in our design, the substrate and the diffusing element use the same material so that we can avoid the refraction at the structure/substrate interface. In this sense, the refraction at the element/air interface shown in Fig. 1(a) is the same at the substrate/air interface shown in Fig. 1(b) and 1(c). In device fabrication, if we have to use different materials for the substrate and the diffusing elements, we just need to take an extra step by considering the refraction between the structure and substrate interface. This is not too difficult. However, the size of the light transmitting pupil and the substrate thickness will influence the light distribution for the top configuration as illustrated in Fig. 2. For the bottom configuration, when the substrate thickness increases from 30μm (Fig. 2(a)) to 60μm (Fig. 2(b)), the light distribution remains the same. However for the top configuration, as the

#235279 - $15.00 USD Received 27 Feb 2015; revised 28 Apr 2015; accepted 12 May 2015; published 20 May 2015

substrate thickness increases from 30μm (Fig. 2(c)) to 60μm (Fig. 2(d)), a portion of the light is blocked by the black matrix so that the light distribution will no longer be the same. Thus, we need to consider both substrate thickness and pupil size to assure that the light refracted by the diffusing element can transmit through the corresponding pupil. Fortunately, we can determine the substrate thickness and pupil size by a quick ray-tracing simulation.

3. Display system

To obtain the incident light distribution of the display system shown in Fig. 3, we need to solve Eq. (1). From Fig. 3, the LEDs and the light guide plate (LGP) form a directional backlight. The light then travels through the LCD panel (TFT and color filters are not drawn) and is spread out by the diffuser. Such a display system has been proposed in the 1990s [1], however, at that time this design didn't work too well because the employed strong diffusers introduced much haze, resulting in a poor ambient contrast ratio. Therefore, designing an appropriate diffuser is vital for this approach.

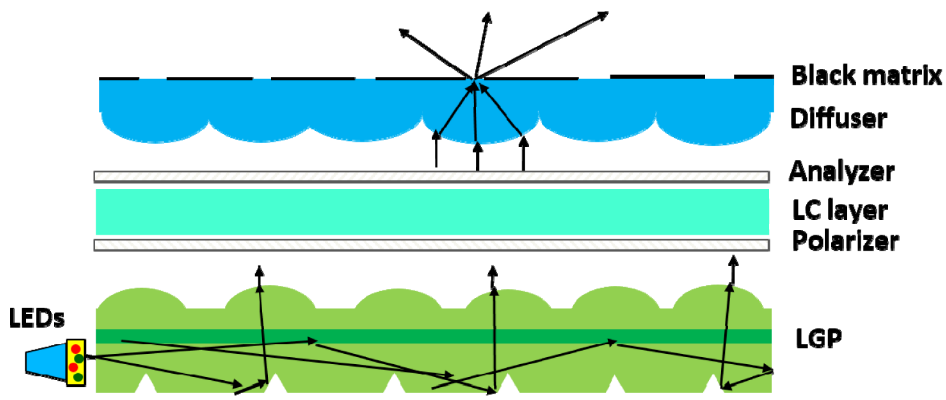

Fig. 3. Schematic setup of the display system.

For the proposed diffuser, the incident light distribution is jointly determined by the directional backlight and the LC cell. For different single-domain LC modes (TN, VA, IPS etc.), the contrast ratio and color shift of the display can be quite different [21]. However, the output light irradiance and illuminance vary little for different LC modes, because these LC cells can all be treated as π phase retarders at the bright state [22]. Thus, the incident light distribution can be referred from the directional backlight. There are quite a few approaches for designing a directional backlight [23]. The detailed design of our directional backlight has been published in [24] recently. Here we just show the spatial and angular light distributions in Fig. 4. All the results presented in this paper are simulated by LightTools V8.1.0.

From Fig. 4(a), the uniformity of the directional backlight is as high as 92.9%. The angular emission pattern of the directional backlight illustrated in Fig. 4(b) indicates that the light is quasi-collimated. To demonstrate the backlight is indeed "directional", we average the light intensity along the azimuthal direction, and the resultant average light intensity distribution along the polar angle shows an emitting cone (FWHM) as small as ± 7.5° [Fig. 4(c)]. Such a quasi-collimated directional backlight plays a key role for achieving high contrast ratio and small color shift for the display [24]. What's more, with this quasi-collimated backlight, the design approach can be simplified to two steps: (1) Designing a preliminary structure by assuming the incident light is uniform and collimated, and (2) Calibrating the structure by employing the real light distribution. In addition, because of the rotational symmetry, Eq. (1) can be reduced to:

$$\iint T(x,y,z) \bullet E(x,y,z) ds = 2\pi \int I(\theta) \sin\theta d\theta. \quad (6)$$

#235279 - $15.00 USD Received 27 Feb 2015; revised 28 Apr 2015; accepted 12 May 2015; published 20 May 2015

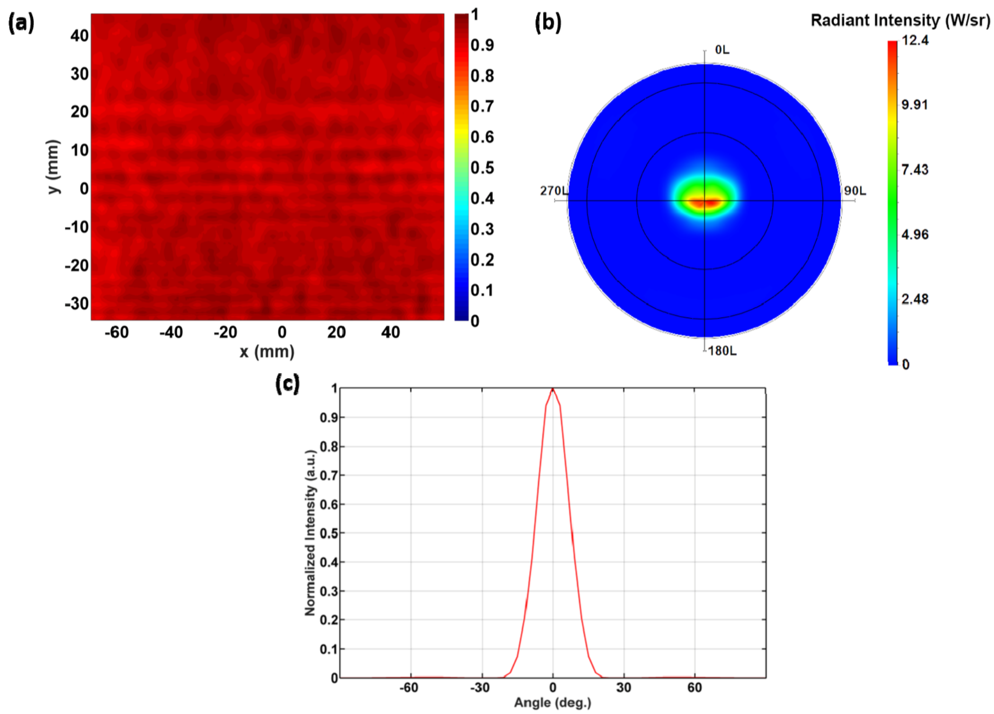

Fig. 4. (a) Normalized light illuminance distribution of the directional backlight, (b) light intensity distribution of the directional backlight at different polar and azimuthal directions, and (c) normalized average light intensity at different polar angle.

4. Evaluation Metrics of the engineered diffuser

The engineered diffuser can effectively tailor the intensity distribution of the display system, and the black matrix that comes with the diffuser efficiently absorbs the ambient light, thus the ambient light reflectivity can be greatly reduced. However, part of the emitted light will also be absorbed by the black matrix; this means the engineered diffuser introduces a paradox between ambient light reflectivity and optical efficiency. Thus, we need to introduce different evaluation metrics to analyze the performance of the engineered diffuser systematically. The three evaluation metrics are:

1. Light distribution error (*LDE*): this metric describes how the achieved light intensity distribution $I_a(\theta)$ differs from the target value $I_t(\theta)$, the *LDE* can be quantified as:

$$LDE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{I_a(\theta_i)}{I_t(\theta_i)}-1\right)^2}. \tag{7}$$

Here N describes how many angles are sampled and θ_i is the corresponding viewing angle. A smaller *LDE* indicates the achieved light intensity is closer to the target value.

2. Ambient light reflectivity (*AR*): this metric describe how much of the ambient light is reflected by the engineered diffuser, and is denoted as:

$$AR = P_r / P_t. \tag{8}$$

Here P_r and P_t are the reflected ambient light power and the total ambient light power, respectively. A smaller *AR* means the display can render higher contrast under ambient light. This is beneficial for transmissive display. For a commercial display, the *AR* is mainly

#235279 - $15.00 USD Received 27 Feb 2015; revised 28 Apr 2015; accepted 12 May 2015; published 20 May 2015

determined by the surface reflection, and is about 4%; this can be regarded as the benchmark for evaluating the ambient light reflectivity.

3. Optical efficiency (T_d) or the optical loss (L_d): for a commercial diffuser, its transmittance is around 50%~70% and the optical absorption is negligible. However, as the diffuser is part of the backlight system, the reflected light is recycled by the Enhanced Specular Reflector (ESR), which has a reflectance of 98%. In this sense, it is hard to determine the actual optical efficiency of the diffuser alone. For our engineered diffuser, that is different story. Our engineered diffuser is on the viewer's side. When the light reaches the engineered diffuser, it has already been modulated by the LC panel. Thus if the light is reflected instead of transmitted by the engineered diffuser, it will be re-modulated by the LC panel and degrade the image quality. In this sense, the optical efficiency of the engineered diffuser is equivalent to the optical transmittance of the engineered diffuser:

$$T_d = P_t / P_0. \tag{9}$$

Here P_t is the transmitted power, and P_0 is the total emitted power. Correspondingly, the optical loss L of the engineered diffuser is

$$L_d = 1 - T_d. \tag{10}$$

Special attention should be paid to the difference between the optical efficiency of the engineered diffuser and the optical efficiency of the whole display system. As mentioned above, the optical efficiency of the engineered diffuser is the same as the optical transmittance of the diffuser. While the total efficiency (η) of the system can be estimated as the product of the optical efficiency of the backlight T_b, the transmittance of the LC layer $T_{LC,}$ the transmittance of the crossed polarizers $T_{P,}$ the transmittance of the color filters (CF) T_{CF} and the optical efficiency of the engineered diffuser T_d:

$$\eta = T_b T_{LC} T_P T_{CF} T_d. \tag{11}$$

We can see that the system efficiency is quite different from the efficiency of the engineered diffuser. In this paper, we will mainly talk about manipulating the light distribution with the engineered diffuser and we will talk more about the efficiency of the engineered diffuser in Section 5.2 and the efficiency of the display system in Section 8.2.

After defining the three metrics, we can evaluate the performance of the engineered diffuser as a whole. A most strict way is to define a merit function (MF) for the diffuser:

$$MF^2 = \sum_{i=1}^{3} W_i (V_i - T_i)^2 / \sum_{i=1}^{3} W_i. \tag{12}$$

Here i = 1, 2 and 3 correspond to the *LDE*, *AR* and L_d, respectively, W_i is the weight ratio and usually $\Sigma W_i = 1$, V stands for the actual value, whereas T is the target value. A smaller MF indicates the quality of the engineered diffuser is better.

The merit function evaluation is quite strict and accurate. However, this evaluation process is a little bit too complex for freeform optics as numerous rays need to be traced for a single structure. The other problem for the MF evaluation is that it is quite tricky to determine the weight ratio. For our display application, considering our target the evaluation standard can be simplified by the following rules: 1) The actual light distribution should be as close as possible to the target value, namely, *LDE* should be as close to zero as possible. 2) The ambient light reflectivity should be lower than contemporary products, namely, AR<4%. 3) The optical efficiency of the engineered diffuser should be comparable to contemporary strong diffuser, namely, T_d >50%. If the engineered diffuser meets these rules, we can safely say that the engineered diffuser is qualified for the application. The above-simplified rules only work for displays. If the engineered diffuser is intended for other applications, such as

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spatial light modulators, then we should define another set of rules to evaluate its performance or use the merit function directly.

5. Design example: Wide view diffuser for large TV application

5.1 Designing process

After analyzing the display system, we first design a diffuser to achieve OLED-like light distribution for a LCD TV through Eqs. (1)-(6). At first, the light source is assumed to be perfectly collimated and the engineered diffuser utilizes the top configuration shown in Fig. 1(c). The required intensity distribution shown in Eq. (2) is rotational symmetric, and thus we can consider the *rOz* plane only, as is shown in Fig. 5. As the incident light is assumed to be collimated, $E(x,y,z) = E_0$ is a constant, for this situation, Eqs. (1)-(6) can be greatly simplified.

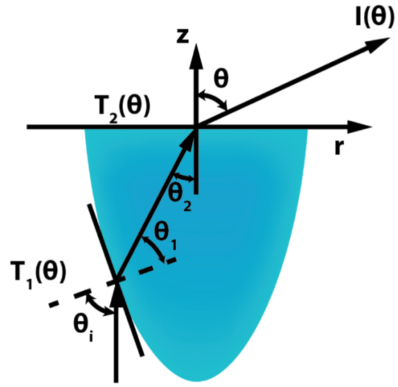

Fig. 5. Diffusing element structure in the *rOz* plane

Assuming that the viewing angle is θ and the incident angle is θ_i, from Fig. 5 we can see that:

$$\begin{aligned} &\sin(\theta_i) = n\sin(\theta_1) \\ &n\sin(\theta_2) = \sin(\theta). \\ &\theta_i = \theta_1 + \theta_2 \end{aligned} \tag{13}$$

Where n is the refractive index of the diffusing element, for our design, we use PMMA as the material because of its low dispersion, the refractive index of PMMA is ~1.5. With Eq. (13) we can determine that the incident angle θ_i satisfies:

$$\theta_i - \arcsin(\frac{\sin\theta_i}{n}) = \arcsin(\frac{\sin\theta}{n}). \tag{14}$$

Equation (14) can be easily solved numerically, and then we have the relation between the viewing angle θ and the corresponding incident angle θ_i. Meanwhile, with Eqs. (5), (13) and (14), for a given viewing angle, we can determine its corresponding transmittance $T(\theta) = T_1(\theta)\, T_2(\theta)$. Thus, Eq. (6) can be re-written as:

$$\iint E_0 ds = 2\pi \int \frac{I(\theta)}{T(\theta)} \sin\theta d\theta. \tag{15}$$

Here $I(\theta)/T(\theta)$ can be regarded as the equivalent light intensity, and because of the rotation symmetry, Eq. (15) can be simplified further:

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$$
\begin{aligned}
&ds = 2\pi r' dr' \\
&2\pi E_0 \int_0^r r' dr' = 2\pi \int_0^\theta \frac{I(\theta)}{T(\theta)} \sin\theta d\theta.
\end{aligned} \tag{16}
$$

From Eq. (16) we can define the function $r(\theta)$, however, with $r(\theta)$ alone we still cannot determine the profile of the single element as we do not know the relation between the height z and the viewing angle θ. Luckily, from Fig. 5 it is straightforward that the surface tangent satisfy that:

$$
\frac{dz}{dr} = -\tan\theta_i. \tag{17}
$$

With Eqs. (5), (14), (16) and (17), we can determine the profile of the single element. Meanwhile, as Eq. (16) shows, $r(\theta)$ is scalable with different E_0; this means our diffusing element can be scaled up or down based on the pixel size. Thus, describing the elements in normalized profile is more practical.

With the perfectly collimated light assumption, the normalized profile of each diffusing element is shown in Fig. 6(a), where r is the radius of the element and z is the height of the element. Here r_{max} is 36μm. Next, as mentioned in Sec. 1 we can determine the substrate thickness and pupil size by a quick ray-tracing simulation. After this, we can determine the total thickness of the diffusing film, which is defined as the thickness of the substrate and the height of the diffusing element, and the resultant total thickness is 98μm. The black matrix on the top surface needs to be designed so that the circular light transmitting pupil is registered with the diffusing elements, and covers 20% of the top surface. The light transmitting pupil has a radius of 19μm and the diffusing elements are hexagonal packed, which covers 90% of the whole film.

The normalized light intensity distribution I is depicted in Fig. 6(b) and it fits the following cosine-like equation well:

$$
I = \cos^{1.522}\theta, \tag{18}
$$

where θ is the viewing angle. Such light intensity distribution is quite close to the desired OLED-like light intensity distribution in Eq. (2), this confirms the reliability of our approach.

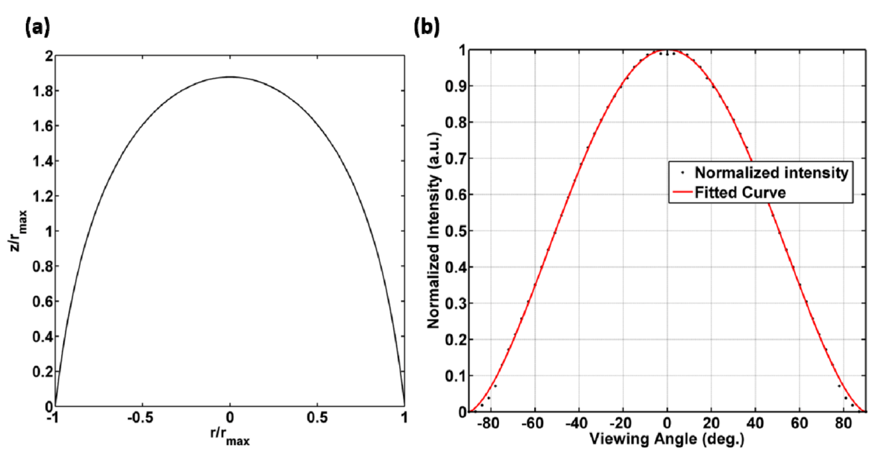

Fig. 6. (a) Normalized profile of a single diffusing element and (b) Normalized light intensity of the display system.

Next, we employ the real light distribution of the directional backlight [Figs. 4(a) and 4(b)], as the real light distribution of the directional backlight is no longer collimated, it requires us to solve Eqs. (1)-(6) strictly. However, if we use the engineered diffuser shown in

Fig. 6 and employ the real light distribution of the quasi-collimated backlight, the output light intensity distribution of the LCD is shown in Fig. 7. From Fig. 7, we can deduce that even though the intensity distribution of the directional backlight is not perfectly rotational symmetric, because of the hexagonal packed diffusing elements, the light intensity is still symmetric around the azimuthal angle. In the meantime, even though the preliminary engineered diffuser is too strong and diffuse too much light to the large off-axis angle, the light intensity distribution still follows a cosine-like equation:

$$I = \cos^{1.207}\theta, \tag{19}$$

Such property makes our calibrating process less tedious; we just need to modify the target light intensity distribution $I(\theta)$ to a different provisional value and see what happens to the real intensity distribution. After a few iterations, we can obtain the final engineered diffuser. The main reason we can do this is that our directional backlight is still quasi-collimated. This iterative compensation process has been widely used in freeform illumination design with extended source [25].

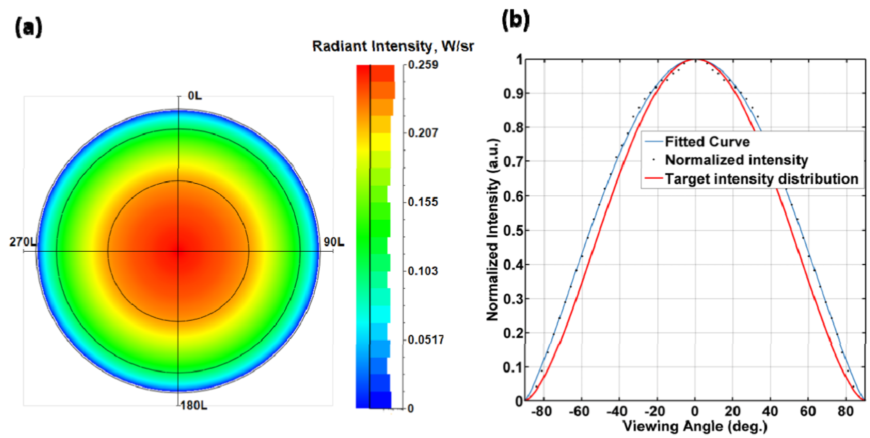

Fig. 7. (a) 2D light intensity distribution with the real directional backlight and the engineered diffuser designed based on collimated light assumption and (b) the corresponding 1D light intensity distribution.

5.2 Performance evaluation of the engineered diffuser

After a few iterations, we find that if we set the preliminary "fake" target intensity distribution to $I(\theta) = \cos^{1.8}\theta$, the resultant final intensity distribution will be $I(\theta) = \cos^{1.501}\theta$ and satisfies our requirements. The performance of the final diffuser is shown in Fig. 8. For comparison, a spherical-beads based diffuser designed for displays with directional backlight is also utilized. For both diffusers the diffusing elements are hexagonal packed and cover 90% of the whole film. The spherical-beads based diffuser, which also comes with black matrix, is shown in Fig. 8(a). It consists of two spherical lens arrays: lens array A focuses the incident light to the center of the lens array B and then lens array B further diffuses the light. The thickness of the diffusive film is slightly less than the focal length of the lens in array A to prevent emitted light from being absorbed by the black matrix, and to ensure the total focal power of two lens arrays is larger than that of individual array. Here we use this double layer spherical-beads based diffuser as a comparison because it is also specially designed for single domain LCD and we use double layer to enhance the light distribution at large off-axis angle. In our design, the film is 60μm thick, and the radii of the lenses in lens array A and array B are 52μm and 100μm, respectively. The heights of the lenses in lens array A and B are 37.8μm and 2.8μm, respectively. The profile of the lenses in lens array A and B can be determined accordingly. For the engineered diffuser, the profile of a single diffusive element is illustrated in Fig. 8(b), in comparison with the preliminary engineered diffuser. Here r_{max} is still 36μm and the total thickness of the diffusing film has been tweaked to 82μm. Both spherical-beads based diffuser and engineered diffuser have a black matrix coverage area of 80%. The resultant normalized luminance distribution is shown in Fig. 8(c).

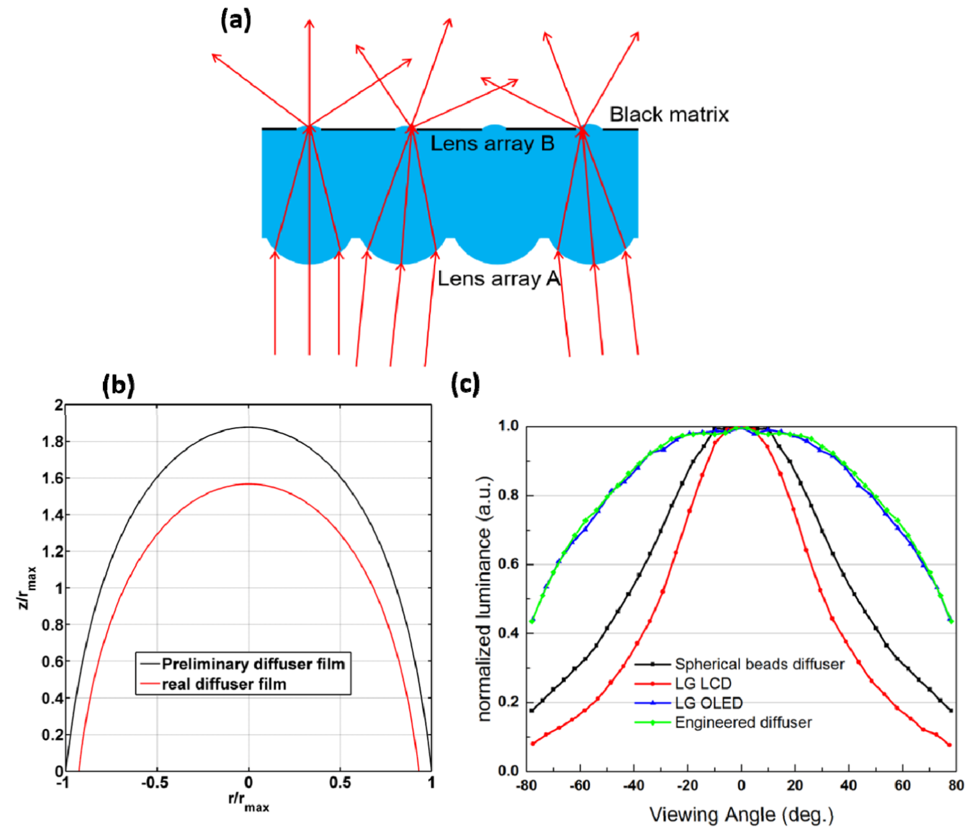

Fig. 8. (a) Structure of the spherical-beads based diffuser, (b) normalized profile of the preliminary and real diffusive elements, and (c) normalized light luminance of LG's LCD and OLED, LCD with spherical-beads based diffuser and LCD with our engineered diffuser.

From Fig. 8(c), in terms of luminance a spherical-beads based diffuser combined with directional backlight helps widen the viewing angle (FWHM) of an LCD from ± 30° to ± 42°, but is still inferior to an OLED display as it still has 50% luminance at ± 70° viewing angle. With our newly designed diffuser, the normalized luminance distribution almost overlaps with that of the OLED display, which enables high luminance at large viewing angle. In the meantime, our diffuser has black matrix on top of it, thus it can reduce the ambient light reflection and enhance the sunlight readability. The ambient light reflectivity of spherical-beads based diffuser is 2.04% and our diffuser is 3.30%. Such reflectivity is lower than that of commercial LCD and OLED products, which is usually 4% [26]. Because the light transmitting pupils are aligned with the diffusing elements, the efficiencies of these films will not drop much. For example, the efficiency of the spherical-beads based diffuser and the engineered diffuser is 70% and 65.1%, respectively, which is of the same magnitude compared to commercial high power diffusers [3].

The *LDE*, *AR* and T_d of this diffuser are 6.3%, 3.30% and 65.1%, respectively. These statistics meet the requirements discussed in Section 4. Here we use this structure as the starting point and see what will happen if we change the substrate thickness and pupil size. The results are shown in Fig. 9, from Fig. 9, when the substrate thickness is fixed, and the radius of the light transmitting pupil is changed from 15μm to 20μm, the corresponding *LDE* for the six radii are 8.0%, 7.1%, 6.8%, 6.8%, 6.3% and 6.9%, respectively. From Fig. 9, we can see the followings: 1) The *LDE* has no exact correlation with the pupil size; the best value can only be achieved by ray tracing. 2) As the size of the light transmitting pupil increases, the optical efficiency does not increase much as most of the unwanted rays have already been absorbed by the black matrix. However, the *AR* is quickly approaching the 4% benchmark, thus controlling the *AR* is vitally important. Combining these two factors, we can see that in our design, where the radius of the pupil is 19μm, both *AR* and T_d are quite good and it has the lowest *LDE* of 6.3%. This proves the validity of our engineered diffuser.

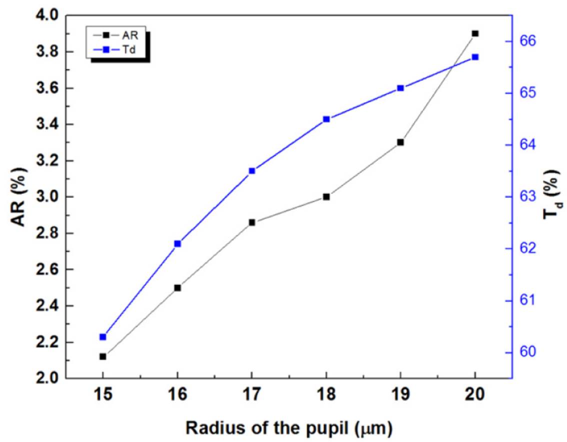

Fig. 9. Effects of the radius of pupil on the ambient light reflectivity (*AR*) and optical efficiency of the engineered diffuser.

6. Medium-view diffuser for mobile displays

As described in Sec. 5, we employed freeform optics to design an engineered diffuser for LCDs exhibiting a wide luminance distribution, i.e., high luminance at large viewing angle as illustrated in Fig. 8(c) and low ambient light reflectivity. This kind of display is preferred for large-size, multi-viewer applications such as TV, as the viewers may sit at a large oblique angle. Nevertheless, for a small-to-medium size mobile display, it is mainly for single user so that the requirements are different. Here, we demonstrate the power of the engineered diffuser with two more examples.

The first example is related to mobile displays. Figure 10(a) shows our measured intensity distribution of two LCD tablets (6-inch and 10-inch Amazon Kindle Fire). For these small size displays, their FWHM (in terms of intensity) is about ± 30° to guarantee that the front viewer has sufficient on-axis brightness, while they have long tails at large viewing angle to make sure the display is still visible. For commercial LCDs, such light intensity distribution is usually enabled by stacking two crossed brightness enhancement films (BEFs) [27]. For our system shown in Fig. 4, we can achieve such light intensity distribution with only one engineered diffuser by setting a new target for the intensity distribution in Eq.(5) and modifying the structures based on Eqs. (5), (14),(16) and (17).

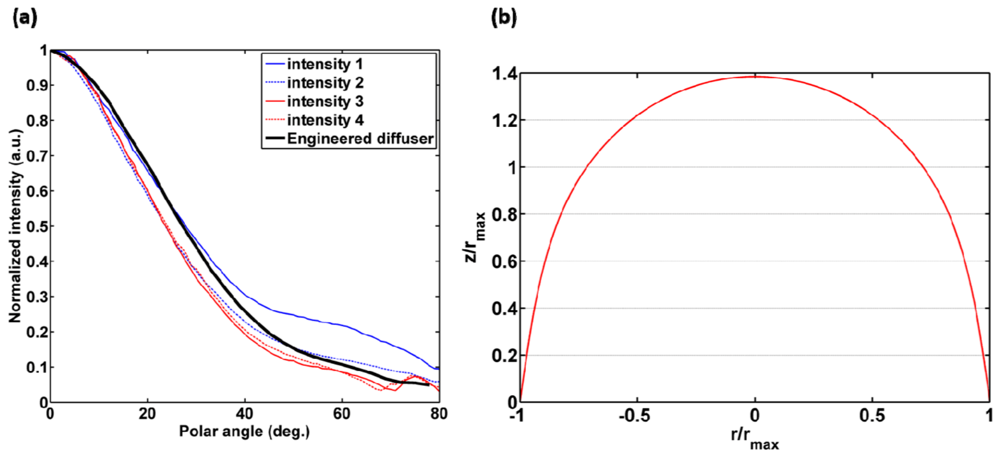

Fig. 10. (a) Measured intensity distribution of a 10-inch LCD tablet in the (1) horizontal direction (blue solid curve) and (2) vertical direction (blue dashed lines), a 6-inch LCD tablet in the (3) horizontal direction (red solid line) and (4) vertical direction (red dashed lines). The normalized intensity distribution of the engineered diffuser-based LCD is also plotted (black solid line). (b) Normalized profile of the diffusive element.

The top configuration shown in Fig. 1(c) is also used for the engineered diffuser, and the normalized profile of a diffusing element is shown in Fig. 10(b). Here r_{max} is 22µm and the total thickness of the engineered diffuser is 44µm. The radius of the light transmitting pupil is 12µm. All the other configuration of this diffuser remains the same as the engineered diffuser described in Sec. 5. With the same directional backlight, the performance of the engineered diffuser is also depicted in Fig. 10(a) as black line. It is obvious that the engineered diffuser has successfully met the requirements of mobile displays as it has similar light intensity distribution to that of commercial products, i.e. high intensity on axis and long tail at large viewing angle. If we further tweak the profile of the diffuser, we can even match the intensity distribution of the engineered diffuser based LCDs to that of the 6-inch or 10-inch tablet, as Fig. 10(a) depicts. Meanwhile, as mentioned in Sec. 5, this engineered diffuser also has a low ambient light reflectivity (~3.0%) and the efficiency of the diffuser is 62%.

7. Flattop diffuser for privacy sensitive applications

The second example is to use the engineered diffuser as a privacy film, which has been widely used in Automated Teller Machine (ATM) and in-flight personal displays. These privacy films usually come with an Gaussian-like intensity distribution, and it is not flexible for them to control the diffusing angle [28]. With the engineered diffuser, we can achieve a flattop light intensity distribution that cutoff at a specific angle. To do so, we utilize the bottom configuration shown in Fig. 1(b) to ensure high efficiency as in these cases, the ambient light reflectivity is no longer critical. We can tune the cutoff angle by adjusting the diffuser's profile [Figs. 11(a) and 11(b)] and achieve the flattop light intensity distribution. Moreover, when we adjust the profile of the diffusing elements we are able to shift the cutoff angle from ~30° to ~45°, and finally to ~60°. Here r_{max} is 39µm and the thickness of the substrate is 40µm. Such flexibility makes our engineered diffuser versatile for different applications.

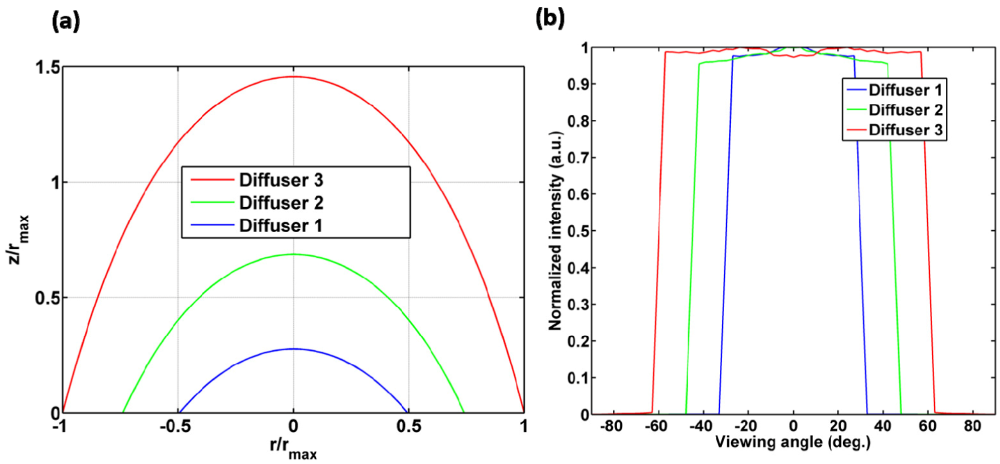

Fig. 11. (a) Normalized diffusing element's profiles for three different engineered diffusers, and (b) normalized intensity distribution with these three engineered diffusers.

8. Discussion

8.1 Tolerance of the engineered diffuser

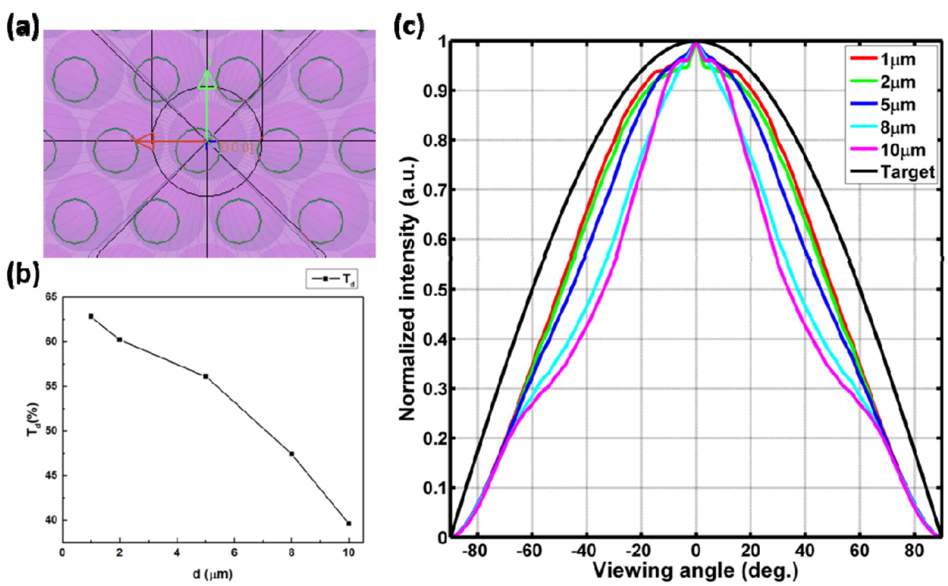

Fig. 12. (a) System error: the center of the light transmitting pupil (green circle) does not coincide with the center of the diffusing element (pink circle). (b) Misalignment effects of decentering on the efficiency of the diffuser, and (c) on the light intensity distribution.

As demonstrated by Koshel in [29], freeform optics is sensitive to the system error, gross error, process error, and roughness error. In this paper, we focus on system error. We will use the wide-view diffuser as an example. The system error mainly comes from the misalignment of the light transmitting pupil and the diffusing element, namely, the center of the light transmitting pupil does not coincide with that of the corresponding diffusing element, as shown in Fig. 12(a). When the light transmitting pupil is decentered, the *AR* remain intact and is still 3.30% because the ambient light is random, however, the intensity distribution and T_d of the engineered diffuser will be affected. As illustrated in Fig. 12(b) and 12(c), when the decentering (d) of the pupil center increases, the efficiency gets worse. For example, at d = 5μm the efficiency is still above 50%, but at d = 8μm the efficiency quickly drops to 47%, which is no longer usable for an LCD because of its low efficiency. For the light intensity distribution, the same is also true. When the misalignment is small (1μm~5μm), the light intensity distribution deviates from the target value, however, the light distribution is still cosine-like, and the deviation is not too severe. However, when the decentering reaches 8μm, the light intensity distribution is no longer cosine-like and it deviates much from the target value. This suggests that for the misalignment between the diffusing elements and their corresponding light transmitting pupil, there is a critical value, which is about 5μm. That is to say, if the misalignment is within ± 5μm, the performance of the engineered diffuser is still acceptable. Considering the size of the diffusing elements (r_{max} = 36μm) and the size of the light transmitting pupil (r = 19μm), the tolerance of our engineered diffuser is quite good. For the medium view diffuser and the privacy film, we can use the same approach to analyze their tolerance.

8.2 Efficiency of the display system

As mentioned in Eq. (11), the system efficiency is quite different from the efficiency of the engineered diffuser. Our quasi-directional backlight [24] has an optical efficiency of ~70%, which is about 10% lower than that of a commercial edge-lit backlight. As discussed in [24], the main advantage of our display system is that it enables single-domain LCD, instead of multi-domains, to achieve wide view. A multi-domain LCD has lower transmittance because the domain boundaries cause dead zones. For example, the multi-domain VA commonly used in TVs has a transmittance of ~70%. In contrast, our single-domain VA can reach 100% transmittance. Other advantages of our approach include indistinguishable image distortion, negligible color shift, and high contrast ratio over a very wide viewing zone. To improve the efficiency of our engineered diffuser, we can apply anti-reflection coating on the diffusing elements to avoid Fresnel loss.

Another factor we would like to mention is that the optical efficiency is not equivalent to the power consumption of the system. For example, in the outdoor, we need to boost the display brightness to compensate for the strong ambient light. As the ambient light reflection is smaller for our display system, we do not need to boost the brightness as high as a conventional LCD. In this sense, it saves the power consumption.

9. Conclusion

With the abovementioned three examples, we have proven that our engineered diffuser designed by freeform optics can successfully control the light intensity distribution, thus making it suitable for different applications. These engineered diffusers are quite promising for display applications as they are coupled with black matrix. At this stage the engineered diffuser is still rotational symmetric, but in principle we can optimize the design to generate asymmetric light intensity distribution as well.

Acknowledgments

The authors are indebted to AU Optronics (Taiwan) and AFOSR for the financial supports under contract No. FA9550-14-1-0279.