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Review Article

Bandlimited illumination with engineered diffusers

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Abstract

Engineered diffusers are refractive, achromatic optical elements with the capability to not only spread and homogenize an input beam but also shape the distribution of energy as well as intensity profiles. Bandlimited illumination is of particular interest for many applications that require certain intensity profiles over specific angular range with maximum efficiency. Here, we describe the concept and design of engineered diffusers as well as the method to fabricate them, from the initial resist master to volume production. Engineered diffusers are found to provide nearly ideal bandlimited illumination without image artifacts and with acceptable manufacturing tolerances.

Keywords: bandlimited illumination; engineered diffusers; manufacturing; OCIS codes: 230.1980; 230.3990.

1. Introduction

Diffusers constitute a particularly useful class of optical components [1, 2], often utilized to spread and/or homogenize a beam that shows undesirable non-uniformity. Before micro-optics manufacturing reached maturity, a handful of diffuser solutions available included ground glass, holographic diffusers [3], and opal glass [4]. The first two are surface diffusers that scatter an incident beam with far-field Gaussian intensity profile. Opal glass is a volume diffuser [5] that generates a Lambertian intensity profile. We refer to these components as random diffusers because the basic features responsible for the diffusion process are only known in a statistical sense [6]. Random diffusers have very desirable properties including robustness to input beam variations and loose fabrication tolerances but have very limited beam shaping capabilities.

Although random diffusers do provide the means to homogenize and spread an input beam, it has long been recognized that, for a variety of applications, diffusers with the ability to efficiently produce uniform illumination would be of great practical interest [7, 8]. It is interesting to note that for the past half-century several approaches have been proposed to solve this problem with limited success [9], to some extent due to the lack of an appropriate manufacturing technology.

Illumination confined to a well-defined angular region is termed bandlimited illumination and a diffuser capable of producing such illumination pattern is known as a bandlimited diffuser [10]. An ideal bandlimited diffuser spreads all available energy within its angular range and no energy outside of it, within the limits of diffraction (Figure 1). The region of uniform illumination is defined by a specific angular range, the target region. Immediately outside the target there is always a fall-off region where the intensity drops from its value at the edge of the target region towards zero. Unless spread by design, the amount of energy within the fall-off region is mostly dictated by diffraction and is therefore dependent on the structures that define the diffuser. An ideal bandlimited diffuser is one whose fall-off region is limited only by diffraction with close to zero energy outside of it. Note that bandlimited illumination does not have to be necessarily associated with uniform illumination. Batwing intensity profiles where the intensity is higher at the edges or the opposite case with higher intensity at the center and lower at the edges but with a sharp intensity cut-off also qualify as bandlimited illumination. The total fraction of light scattered within the target region represents the target efficiency. The ideal bandlimited diffuser maximizes target efficiency with the only losses coming from Fresnel reflections and diffraction-induced broadening in the fall-off region.

Engineered diffusers [11] constitute a new class of diffuser elements that distinguish from random diffusers in the sense that their surface structure at each location is deterministically designed with a beam-shaping goal. Consequently, engineered diffusers enable the control of both the energy distribution as well as intensity profiles in the far-field. In particular, engineered diffusers have made possible the production of diffusers that come very close to the bandlimited ideal while retaining the advantageous features of random diffusers of robustness to input beam variations, absence of image artifacts, achromatic behavior, high transmission efficiency, and manufacturability. Here, we describe in some detail the design aspects of engineered diffusers and illustrate several of its performance features. A brief description of the manufacturing method used to produce engineered diffusers and its current state-of-the-art is also presented.

2. Design of engineered diffusers

It is possible to associate with any diffuser a basic element or family of elements responsible for its particular scattering properties, the scatter centers. In the case of ground glass or

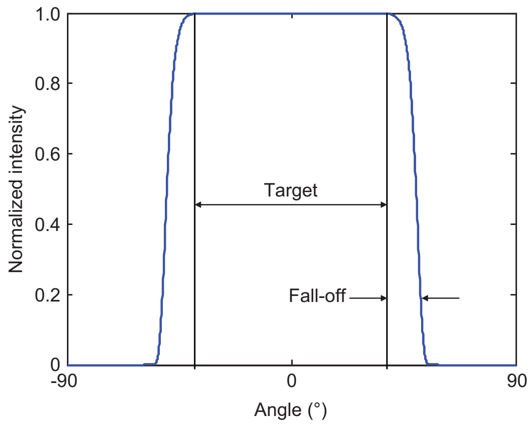

Figure 1 Far-field scatter from an ideal bandlimited diffuser with a uniform target region and a diffraction-limited fall-off.

holographic diffusers, for example, the random surface variations created by the fabrication process (grinding or speckle recording) constitute the scatter centers. Differently from random diffusers, however, where only a statistical description of scatter centers is meaningful, the design of engineered diffusers requires the definition of three basic properties of scatter centers: functional form, boundary shape, and spatial arrangement.

The functional form refers to the surface prescription, or sag, of each scatter center and can be characterized by a number of parameters, depending on how the surface is defined. The boundary shape refers to the geometry of the edges that limits the spatial extent of each scatter center. For example, boundary shape can be circular, square, rectangular, a general shape, or combinations of shapes. Finally, the spatial arrangement dictates how scatter centers are placed throughout the available diffuser surface as well as how the overlap between lenses is treated. Each and all of these components that define the engineered diffuser has an effect on its scatter behavior and are characterized by probability distribution functions that govern their statistical properties. In what follows, we discuss each component individually and illustrate their significance to the performance of the diffuser.

The typical functional form of an engineered diffuser scatter center is that of a microlens element. There are several ways to define the function that specifies the surface sag of a microlens but, for simplicity, we consider here the case of a microlens characterized by a radius of curvature R and a conic constant κ, given by:

$$y=\frac{(x-x_c)^2}{R^2+\sqrt{R^2-(\kappa+1)(x-x_c)^2}}, \tag{1}$$

where x designates a coordinate point on a local coordinate system associated with a particular lens element. The lens diameter is D and x_c represents a decenter parameter from the origin. The sag function, Eq. (1), is mainly responsible for controlling the far-field intensity profile. It is particularly instructive to look into the point spread function (PSF) of an elementary scatter center as it provides important information relative to the diffuser as a whole and it also sets limits on the maximum attainable target efficiency. Figure 2 illustrates the dependence of the PSF with conic constant for a single lens that spreads a 633-nm input collimated beam into a 40° full-width output (index of refraction is assumed to be 1.5 and lens diameter 100 μm). The input beam is assumed to be coherent, thus the intensity oscillations, a clear signature for the presence of diffraction effects but without 100% modulation, indicate single-lens diffraction. In the present discussion, we assume the input beam is coherent and consider diffraction-based propagation in our calculations and thus we obtain an accurate description of target efficiency, which would not show on a purely ray-based picture. In the case of incoherent illumination, such as from light-emitting diode (LED) sources, the intensity oscillations would be absent but target efficiency would still be diffraction-limited.

Note how the conic constant controls the intensity profile from a uniform profile, on average, at κ=-1 to a Gaussian-like dependence at κ=+1 to batwing for κ=-2. For the functional form, Eq. (1), the conic is the main tool used to control intensity versus angle in the far-field. If a specific dependence of intensity against angle is required that cannot be properly generated by the sag function given by Eq. (1), one may need to generalize the sag function by introducing additional aspheric coefficients.

Another aspect of particular importance in the design of engineered diffusers is that of feature size. In the case where scatter centers take the form of microlenses the feature size is given by the microlens diameter. There are two factors to consider in this regard: sag and averaging. To ensure best uniformity, a large number of scatter centers should be illuminated implying that the lens diameter should be small relative to the input beam size. At the same time, for a certain set of parameters such as spread angle, index of refraction, and conic constant the lens depth decreases as the microlens diameter decreases. If the process continues one eventually reaches a diffractive regime where the lens depth only imparts a phase delay that is a small fraction of 2π. In this respect, it is useful to define the phase number:

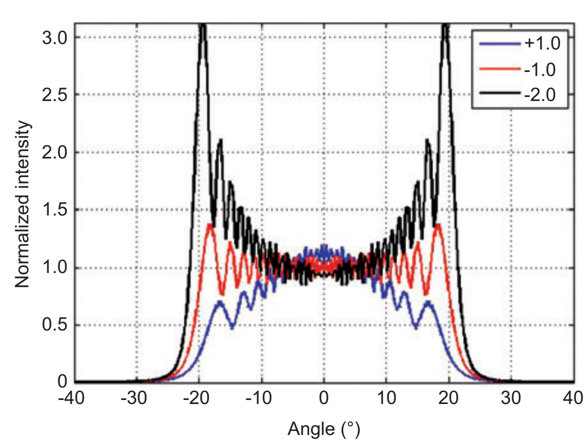

Figure 2 Point spread function (PSF) from a single conic microlens element for various values of conic constant.

$$M=\frac{y_{max}}{\left(\lambda/\Delta n\right)}, \tag{2}$$

where y_{max} represents the total lens sag in the nomenclature of Eq. (1), λ is the wavelength under consideration, and Δn equals $n(\lambda)$-1, with n the index of refraction at wavelength λ, for a diffuser in air. The phase number basically expresses the total sag in the language of phase cycles and defines the regime, diffractive or refractive, the microlens operates on: M=1 implies a diffractive element with exactly 2π phase shift. For a microlens to operate in the refractive regime, as is desirable for an achromatic component with high target efficiency, the phase number M should be as large as possible. Consider again the case of a microlens that scatters a collimated beam with a 40° spread. Figure 3 shows the far-field PSF for various values of diameter. The legend shows diameter and, in parentheses, the phase number. As the diameter gets smaller the far-field scatter shows coarser oscillations and more sloped fall-off, translating into lower target efficiency.

A simple rule of thumb to help decide the minimum feature size or lens diameter to utilize is given by the following equation:

$$D\geq 230M\frac{\lambda}{\theta_0}, \tag{3}$$

where θ_0 is the half-width diffuser angle in degrees where, to ensure one is safely in the refractive regime, M should be around 8 or more. Going back to the example of Figure 2 where θ_0=20° and λ=0.633 μm, we obtain, with M=8, $D\geq$58.2 μm, resulting in a PSF vs. angle very similar to that shown in Figure 2 for D=50 μm. It should be noted that Eq. (3) only applies to parabolic profiles and angles no larger than approximately 20–30°, strictly speaking. However, it is useful in providing a starting point for more accurate calculations. Under the assumption of parabolic lenses the calculated target efficiency is shown in Figure 4 for various values of full-width spread angles and assuming $M\geq$8. The target efficiency calculation based on parabolic lenses is particularly significant as it can be seen as a fundamental limit for microlens-based diffusers. The sag function of the form given by Eq. (1) can be expanded in a power series where the first element is that of a parabolic lens plus higher-order terms. The effect of the higher-order terms in the far-field is given by a convolution with the parabolic contribution, which can only lead to its further spread. As a result, for a microlens diffuser, the best possible target efficiency is given by a diffuser with parabolic microlens elements.

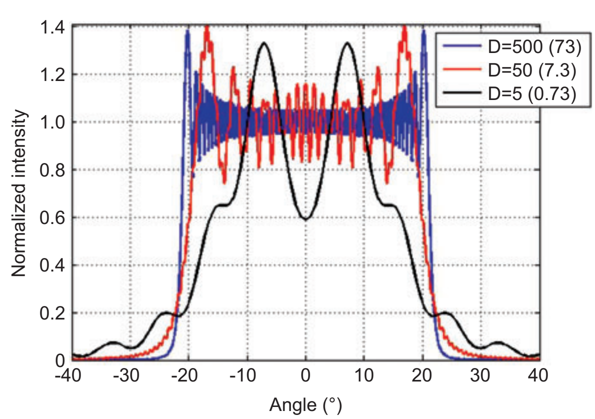

Figure 3 PSF for a single microlens for various values of diameter.

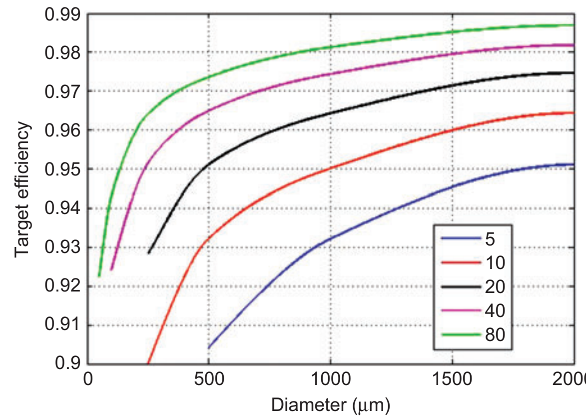

Figure 4 Engineered diffuser target efficiency as a function of lens diameter for various values of full-width angular spread.

Before moving on to the construction of the diffuser array from elementary scatter centers, we note that boundary shape is directly related to the distribution of energy in angle space in the sense that a circular microlens produces a circular scatter pattern, whereas a rectangular aperture produces a rectangular pattern. This relationship follows directly from diffraction theory and although it is possible to violate it and have, for example, a square aperture produce a round scatter pattern, we are presently interested in structures that lead to uniformly distributed scatter patterns and those typically originate from matching patterns between far-field energy distribution and boundary shape. In other words, circular, elliptical, square, rectangular, etc., microlenses are naturally suited to produce circular, elliptical, square, rectangular, etc., scatter patterns, even though this condition is only sufficient but not necessary.

The final component in the definition of the engineered diffuser is the spatial distribution of elementary scatter centers where the main issue is how to treat the inevitable overlap between scatter elements. In the present treatment, we will assume that the engineered diffuser is created by randomly placing scatter centers on available locations of a substrate, where 'available' means the center location is not already occupied by another lens. In carrying out this procedure, there will be instances where portions of a lens overlap portions of another lens. For simplicity, we assume here that the lens portion that remains is that associated with the lens introduced the latest. A scanning electron microscopy picture of an engineered diffuser produced with this algorithm is shown in Figure 5.

We now have all ingredients necessary to consider a random array of microlens elements. The family of scatter

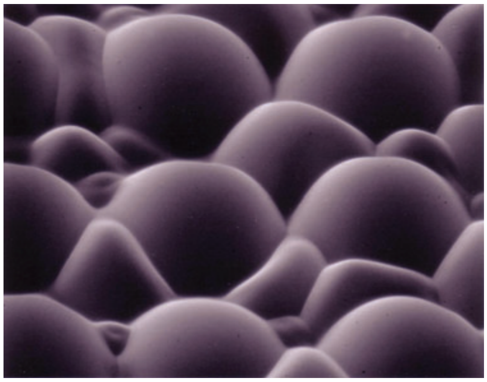

Figure 5 Micrograph of the surface topography of an engineered diffuser.

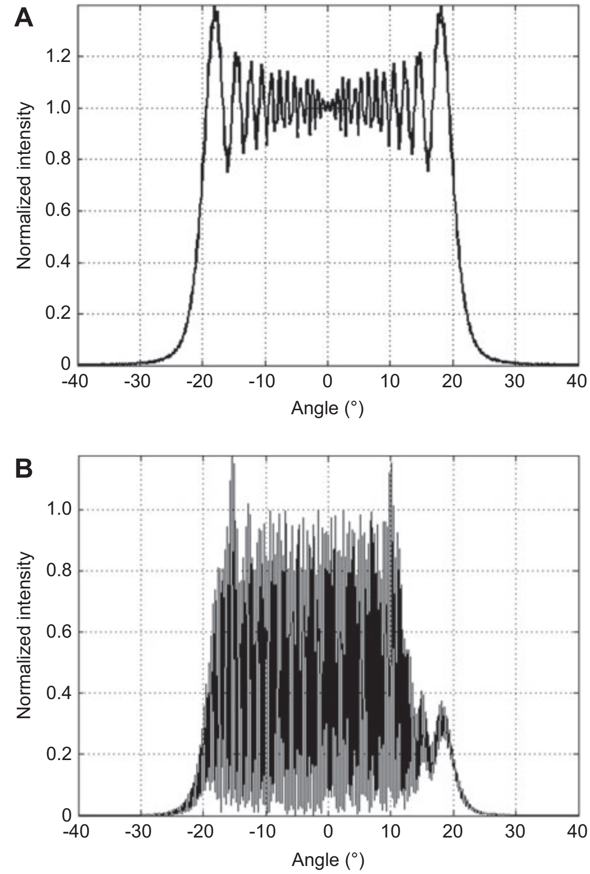

Figure 6 Far-field for (A) a single microlens and (B) two microlenses.

centers is defined as a conic microlens element with a certain boundary shape to match a specific distribution of energy in the far-field. To prevent the presence of diffraction artifacts microlenses are randomly distributed with varying design parameters, thus creating a robust design concept that is largely insensitive to the nature of input beam and robust to deviations from the nominal design prescription of individual microlens elements during manufacturing.

For the microlens element under consideration here, we have previously seen that the far-field intensity profile can be controlled by the conic constant (Figure 2). The parameters available for randomization are then microlens diameter and lens decenter. Going from a single scatter center to an ensemble the first thing to note, particularly, under coherent illumination is the presence of speckle, which shows up as soon as more than one scatter center is illuminated. This is illustrated in Figure 6, where we show the far-field pattern from a single lens and that of just two lenses. The strong speckle modulation is readily noticeable, which is unavoidable when illuminating any structures whose feature sizes are smaller than the coherence area of the source. In some applications where detection occurs over an area that includes several modulation cycles, the presence of speckle does not pose problems. For other applications, such as laser projection, speckle is objectionable and measures need to be taken to reduce it to a level where it cannot be perceived by the observer. This is usually accomplished using multiple diffusers in relative motion to average out speckles. Another feature readily observed is the non-uniformity of the light distribution due to just two scatter centers. In practice, a large number of microlenses should be illuminated creating an averaging effect that produces better uniformity. It is important to realize that the concept of uniformity here depends on the size of the detection area or, similarly, how many speckles are averaged at each detection point. Obviously, if the detection area is on the order of the speckle size then uniformity will be limited by the coherence area of the source. If, by contrast, the detection area is sufficiently large to allow averaging of a large enough number of speckles then uniformity will be limited by the diffuser design. In the present discussion, we consider the second case and look at uniformity that is driven by the design features of the diffuser.

Best uniformity and lack of periodic artifacts is thus ensured by enough randomization of the two available parameters of the engineered diffusers under consideration: lens diameter and decenter. In the case of space-invariant diffusers, where the scatter properties are independent of the point of incidence, both parameters should be randomized within a certain range and with uniform probability distribution. Diameter, for instance, would be chosen from a range $[D_{min}\ D_{max}]$. We define decenter using a normalized measure given by $\delta[-D/2\ D/2]$, where D is the diameter of a certain lens and δ is the normalized decenter parameter. Selection of diameter range is based on input beam size to provide the best compromise between efficiency and uniformity (Figure 4). Larger diameter leads to higher target efficiency but reduces the number of elements illuminated by the incident beam. Thus, depending on the application, there is a best compromise between input beam size, microlens diameter, efficiency, and uniformity. A typical example of the relation between uniformity and beam size is shown in Figure 7 for various values of δ and diameter in the range of 100–140 µm. This diffuser design assumed in the calculation has an angular spread of 40° with speckle averaged over 1° intervals. Uniformity is defined as $(I_{max}-I_{min})/(I_{max}+I_{min})$ over the region of uniform intensity. Best uniformity is achieved with larger input beam sizes and, to achieve better than 5% uniformity, beam size should be around 2–3

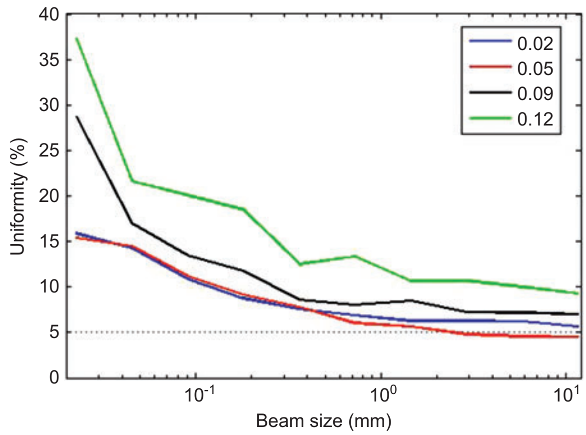

Figure 7 Uniformity within the target region vs. input beam size for several values of the decenter parameter.

mm for this particular case of diffuser angles and speckle averaging. Associated with optimum uniformity there is also associated an optimum value of decenter parameter, in this case 0.05. For general situations, the specific design parameters as well as achievable performance will be different but the results are qualitatively similar.

3. Examples

In this section, we illustrate some of the diffuser patterns produced with the techniques discussed above. Figure 8 shows the case of a bandlimited diffuser with full-width at half-maximum of 84°, measured with an input collimated laser at 633 nm. Full-width at the 90% intensity level is 80°. The feature size for this diffuser is 100 µm and index of refraction is 1.56. The measured target efficiency for this diffuser is 95%, very close to the ideal bandlimited performance. For comparison, the plot also shows a Gaussian profile with the same full-width at the half-maximum point which makes it strikingly clear the significance of the bandlimited diffuser.

Figure 9 illustrates the case of another bandlimited diffuser but in this case with a batwing intensity profile and full-width

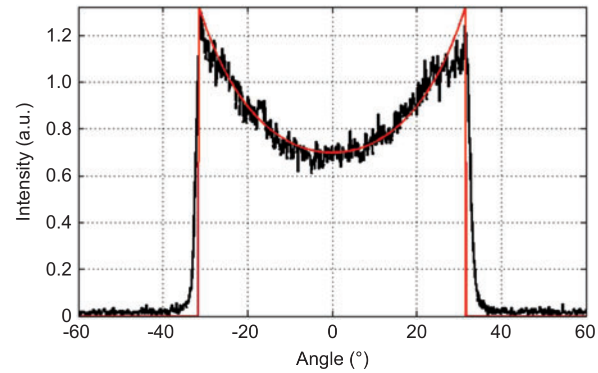

Figure 9 Batwing bandlimited diffuser (black curve). The red curve is a $\cos^{-4}$ fit.

of 63° measured to the intensity peaks (again measured with an input collimated laser at 633 nm). The intensity profile fits a $\cos^{-4}$ dependence with angle. The feature size for this diffuser is 80 µm and measured target efficiency for this diffuser is 94%, again nearly ideal bandlimited performance.

Figure 10 presents the case of another bandlimited diffuser where intensity falls from the center with a $\cos^2$ vs. angle. Full-width to the cut-off point is 70°. The feature size for this diffuser is 90 µm and measured target efficiency is 96%. A Gaussian profile with a close match over the target region and full-width 92° is also shown.

As a final example, we point out that bandlimited engineered diffusers are only a particular type of component, although important, that can be produced. In fact, technology has the potential to generate fairly general patterns, be it intensity profiles and energy distribution. On the other side of the spectrum, Lambertian diffusers are particularly important for general illumination and calibration purposes. Figure 11 shows the measured profile of a Lambertian diffuser created with two identical engineered diffusers in series. Conventional transmission Lambertian diffusers are usually very inefficient. Opal glass, for example, transmits approximately 20% of the incident illumination. The engineered diffuser solution is, by contrast, 80% efficient even with the use of two diffuser surfaces.

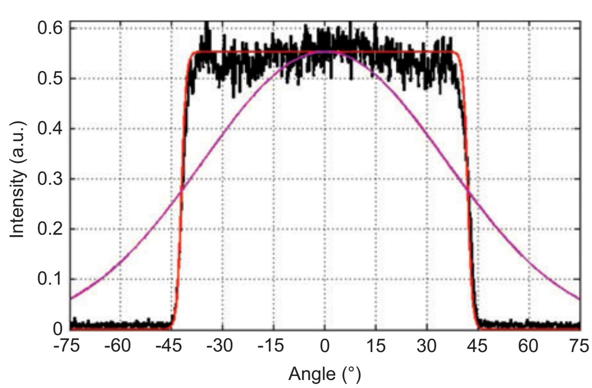

Figure 8 Uniform bandlimited diffuser (black curve). Red curve is a super-Lorentzian fit. The curve in magenta is a Gaussian profile with same width at half-maximum.

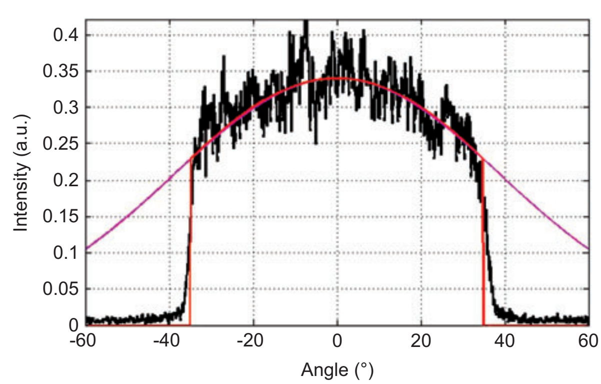

Figure 10 Bandlimited diffuser (black curve). The red curve is a $\cos^2$ fit. The curve in magenta is a Gaussian profile matching the target region of the scatter pattern.

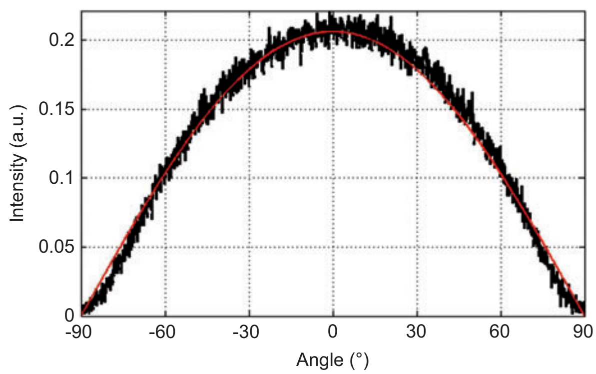

Figure 11 Cosine intensity profile from an assembly of two identical engineered diffusers to create Lambertian scatter.

4. Fabrication

There are a few alternative approaches that can be used to produce micro-optical components with an analog sag structure. The most well-established include grayscale masks [12] and direct laser writing [13]. Multi-mask exposure [14] has also been employed to create step-wise approximations of a continuous profile, particularly for diffractive elements. However, this method requires careful alignment of multiple binary masks to approximate a certain target profile. The further need to achieve much deeper sags than traditionally required for diffractive optical elements makes the multi-mask approach usable in principle but not very convenient in practice. Grayscale masks go a step further by eliminating the need for multiple mask exposure and alignment. In this case, a single mask with variable amplitude transmission is used in contact exposure to impart an analog pattern to a resist-coated substrate. This method has been successfully used to produce diffractive elements as well as microlens arrays [15]. Another approach, also useful for many applications, is based on thermal reflow of photoresist [16]. Our preferred approach, however, is based on direct laser writing [17].

Developments in micro-optics fabrication over the past decade or so have enabled the production of structures with control of sag on a point-by-point basis, both in terms of total area as well as maximum sag. To produce engineered diffusers we utilize a laser writing process where a focused beam exposes a photosensitive resist material. The laser beam exposure intensity is computer-controlled and scanned over an area of interest of the resist-coated substrate. After exposure, the resist is developed with an alkaline solution leaving a relief structure in direct relation to the laser exposure, as pictorially illustrated in Figure 12. The developed resist is the master from which durable copies can be used for volume production, such as reactive-ion etching, polymer replication, compression molding, injection molding, or roll-to-roll web processing. All of these processes are currently available and utilized to produce engineered diffusers.

Laser writing is particularly suited to produce engineered diffusers because it enables control of local sag and slopes while being a highly stable and repeatable process. With a focused beam

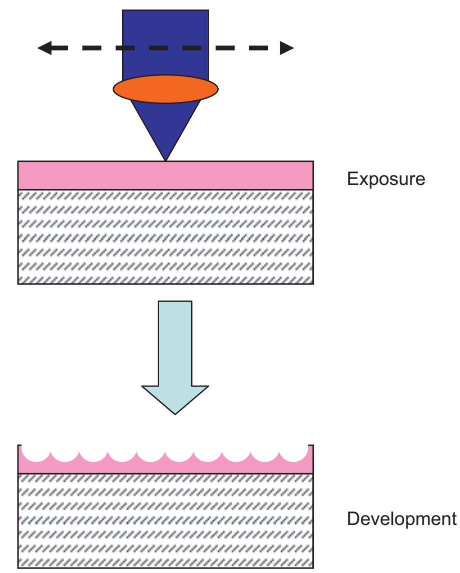

Figure 12 Two basic steps of the laser writing process. Exposure of a scanning focused beam and subsequent development to reveal the relief pattern.

size ranging somewhere from 10 μm to hundreds of microns, feature sizes on the order of 10 μm and up can be produced. Even though there has been recent academic interest in producing deep structures [18] to approximately 60 μm, deeper structures have been routinely achieved in industry for a while, as is not uncommon in the field of micro-optics fabrication. As early as 2001 [19], we have been able to produce microlenses with sags up to 100 μm with high surface quality. An example of an aspheric lens with total sag equal to 70 μm is shown in Figure 13.

For non-imaging applications where engineered diffusers surface accuracy is not as critical and the ability to create surface structures with varying sag and slopes at arbitrary points of a substrate with reasonable accuracy is more relevant. A cross-section from a cylindrical microlens array used as a one-dimensional line diffuser is shown in Figure 14.

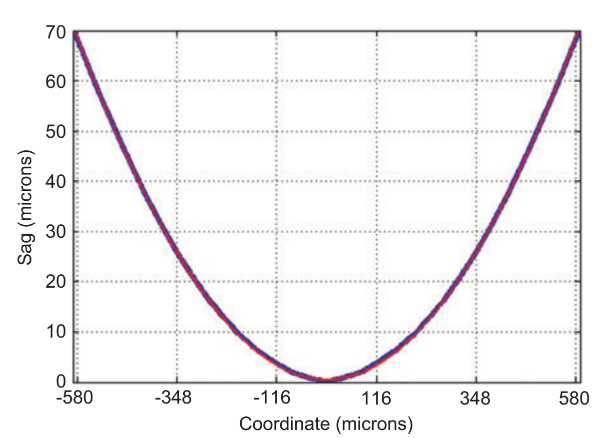

Figure 13 Sag profile from an aspheric lens with total sag of 70 μm and conic constant κ=-4.5. The blue curve is measurement and the red curve is theoretical design.

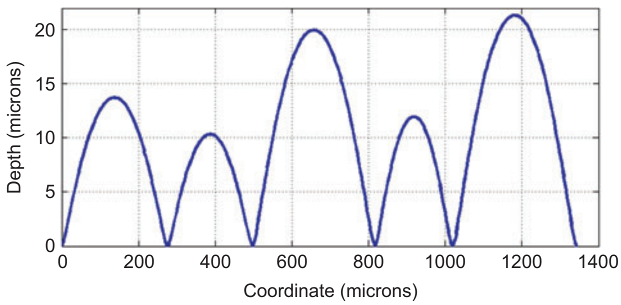

Figure 14 Measured section of the surface topography from a one-dimensional engineered diffuser.

The most significant challenges arise when trying to fabricate wide angle diffusers. Presently, the widest angle produced with our laser writing approach is 128° full-width on a material with an index of 1.56, corresponding to a maximum slope angle of 73°. To put this in perspective, a diffuser with a 180° spread that illuminates the whole hemisphere in this material would require a slope equal to just under 79°. Although improvements to technology are continually achieved, it is fair to say that for a significant number of practical problems laser writing does provide an appropriate approach to mastering.

5. Summary

In summary, engineered diffusers are actually more than mere diffusers, if one is limited to the usual sense of the word, where an input beam is spread and homogenized. They are true beam shapers with the capability to convert an input beam in fairly general light distributions and/or intensity profiles. We described the basic concepts that define engineered diffusers in terms of its basic micro-elements and their assembly to create a fully randomized diffuser surface. The basic element considered here was a conic microlens characterized by four design parameters, namely, diameter, radius of curvature, conic constant, and decenter. Diameter and radius of curvature are mainly responsive for the spread of light into a specified cone angle. The conic constant is the main parameter controlling the intensity profile in the far-field, whereas decenter is utilized to provide uniformity.

We have shown that engineered diffusers are well suited to produce bandlimited illumination where essentially all of the transmitted energy is confined to a certain angular range. Common random diffusers spread light with a Gaussian intensity profile which, by definition, is not bandlimited. Engineered diffusers, by contrast, are able to produce bandlimited illumination with controlled intensity profile to fit different requirements. Interestingly, however, nearly ideal bandlimited performance is only part of the general capabilities of these diffusers and more general distributions are feasible, from the usual Gaussian through uniform and even Lambertian scatter.

The capability to accurately produce micro-structures with deep sag and steep slopes is what enables engineered diffusers to become reality. We have briefly described the fabrication approach based on direct laser writing to produce a photoresist master that can be used to produce diffusers and microlens arrays in various materials such as polymers, fused silica, and silicon. As technology continues to evolve, we expect more sophisticated design techniques to emerge and new applications where engineered diffusers can provide a significant contribution.

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