Prototyping illumination systems with stock optical components

Edwin Diaz, Edmund Optics Inc., Barrington, New Jersey, USA
Matthias Knobl, Edmund Optics GmbH, Karlsruhe, Germany

In most imaging system designs, development efforts focus on the imaging optics. But illumination can be an equally important factor in the success of such systems. The primary concerns in illumination optics are not aberrations and image quality but optical throughput, good spatial or angular uniformity, and the ability to efficiently spread the light over a specified area at a given distance from the source. This article will explain how aspheric lenses, compound parabolic concentrators (CPCs), and microlens arrays can be used to tailor the source's light distribution to achieve a specific illuminated area. It will also discuss the use of light pipes and microlens arrays to improve illumination uniformity.

Figure 2: Some typical aspheres

1 LED collimation

Suppose we wish to collimate an LED with a radiant intensity distribution as given by **figure 1**. The cone angle θ of the light emitted by the LED (i.e. the full-width at half maximum) is roughly ±50° or 100°. The numerical aperture of the source's beam (NA_{beam}), defined as the sine of half the cone angle, is:

$$NA_{beam} = \sin\left(\frac{\theta}{2}\right) = \sin\left(\frac{100}{2}\right) = \sin(50) \approx 0.77 \quad \text{(Eq.1)}$$

The LED can be collimated by using an aspheric lens (**figure 2**) whose NA is greater than or equal to NA_{beam}. This choice maximizes light throughput by ensuring that the majority of the LED's emission strikes the collimating lens. Due to the finite size of the source, the beam will diverge somewhat after collimation. For a given source diameter (D_s) and lens focal length (f_{col}), the full beam divergence (θ') in radians after collimation will be:

$$\theta' = \frac{D_s}{f_{col}} \quad \text{(Eq.2)}$$

This identity shows that a small beam divergence may be achieved by either reducing the source size or by increasing the focal length of the collimating lens. As the beam divergence of the light source is reduced, the collimated beam diameter increases proportionately. The collimated beam diameter (D_c) right after the collimating lens can be estimated as follows:

$$D_c = 2\, NA_{beam}\, f_{col} \quad \text{(Eq.3)}$$

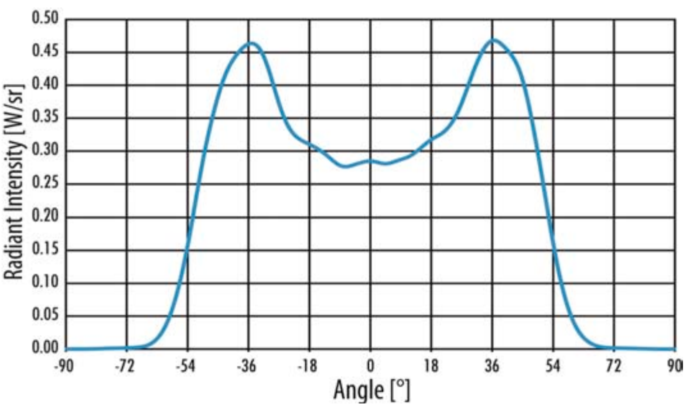

Figure 1: Representative spatial radiation pattern for Luxeon emitter red (LXHL-BD01)

As the focal length of the lens is increased while the lens diameter stays constant, there is a tradeoff between maximizing light throughput and minimizing beam divergence.

LED collimation can be more complicated than this example reveals. Any non-uniformity in the radiant intensity distribution of the source appears as non-uniformity in the irradiance profile of the collimated beam. Additionally, some LEDs radiate over angles as wide as 180°, making it difficult to efficiently collect all of the light. Optical components such as CPCs, light pipes and microlens arrays can address these issues, as will be shown in sections 3 – 5.

2 Aspheric lens pairs

A second aspheric lens can be added in front of the collimating lens to focus the light over a desired area. The illuminated spot diameter at the focal plane (FP) is given by:

$$\text{Spot Diameter} = D_s\left(\frac{f_{focus}}{f_{col}}\right) \quad \text{(Eq.4)}$$

Where D_s is the LED source diameter and f_{focus} and f_{col} are the effective focal lengths of the focusing and collimating lenses respectively.

By selecting the focal length of the focusing lens to be longer than that of the collimating lens, it is possible to reduce the numerical aperture to below that of the source (NA_{beam}). For distances greater than f_{focus}, the full beam divergence (θ') in radians becomes:

$$\theta' = 2\, NA_{beam}\left(\frac{f_{col}}{f_{focus}}\right) \quad \text{(Eq.5)}$$

One drawback to the aspheric lens pair is that it images any source surface structure directly to the focal plane. To remove any source structure from the focused beam,

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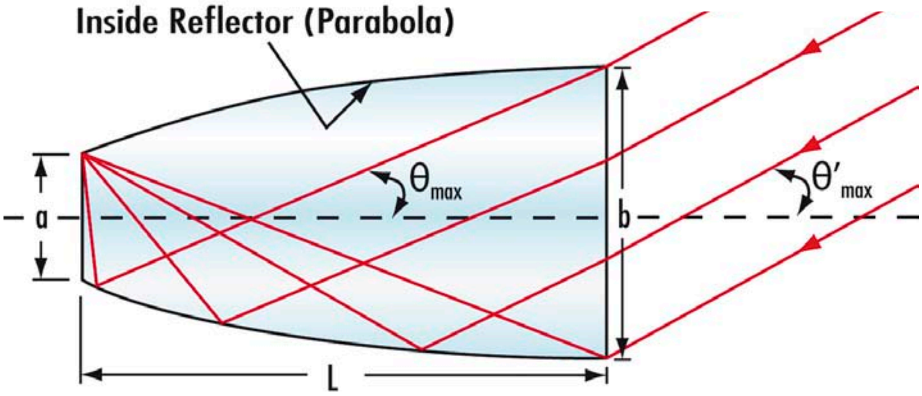

Figure 3: A compound parabolic concentrator (CPC) is composed of two curves

Figure 4: Hexagonal light pipe, made from N-BK7 glass

either the source or the lens pair position relative to the focal plane can be adjusted. Other approaches include inserting a light pipe near the focal plane or placing a low-angle holographic diffuser or a pair of microlens arrays between the two aspheric lenses.

3 Compound parabolic concentrators

In the previous sections, an aspheric lens is used to collimate the LED. However, some LEDs emit light over a full hemisphere (i.e. ±90° beam divergence), making it impossible to collect the entire emission cone with a stock aspheric lens. For such sources, a compound parabolic concentrator (CPC, **figure 3**) can be used to collect the light and reduce the beam divergence of the LED.
A CPC is often used to concentrate sunlight onto a solar cell placed in contact with aperture *a*. It can be made as a hollow reflector or as a solid dielectric (e.g., glass or polymer). As a collimator, the CPC's small aperture (*a*) is placed in contact with or as close as possible to the LED.
The key advantage of a CPC when used as a collimator is that the output beam divergence is restricted to angle θ_{max} for a hollow reflector CPC (and θ'_{max} for a dielectric CPC) over the minimum possible aperture *b* while having a collection angle of 180° at aperture *a* [1]. By choosing a smaller value for θ_{max}, a higher degree of collimation is achieved. But, this also quickly increases the required length L of the CPC. It can be shown that, for a hollow reflector, L, *a*, and θ_{max} are related as follows [2]:

$$L = \frac{a(1+\sin(\theta_{max}))}{2\sin(\theta_{max})\tan(\theta_{max})} = \left(\frac{a+b}{2}\right)\cot(\theta_{max}) \quad \text{(Eq.6)}$$

A similar expression can be obtained for dielectric CPCs recognizing that $\sin(\theta'_{max}) = n \sin(\theta_{max})$.
If a smaller beam divergence is desired, an aspheric collimating lens with NA greater than or equal to $\sin(\theta_{max})$ or $\sin(\theta'_{max})$ may be placed in front of the CPC.

4 Light homogenizing rods

As was mentioned previously, one drawback to the aspheric lens pair is that it images any source surface structure directly to the focal plane. If the light source being imaged was, e.g., a series of LEDs or the filament of an incandescent lamp, the resulting irradiance at the focal plane may not be as uniform as required for a given application. In such cases, one may use light pipes to improve the projected light spot homogeneity.
As an example, an ellipsoidal reflector can be used to image an incandescent filament placed at focal point f_1 into a hexagonal light pipe placed at or near focal point f_2 (**figure 4**). The uniformity of the irradiance profile can be compared before the light enters and after it exits the light pipe.
Along a line profile of length X across the desired spot size, the mean ($\bar{U}(x)$) or peak-to-peak uniformity ($U_{pp}(x)$), can be calculated as follows:

$$\bar{U}(x) = \frac{E_{avg}}{E_{max}} \quad \text{or} \quad U_{pp}(x) = \frac{E_{min}}{E_{max}} \quad \text{(Eq.7)}$$

where E_{max}, E_{min}, and E_{avg} are the maximum, minimum and average irradiance values. It's also helpful to calculate the rms variation $\phi(x)$ of the light using the average and standard deviation *s* of the irradiance over the same line profile length:

$$\phi(x) = \frac{s}{E_{avg}} \quad \text{(Eq.8)}$$

The advantage of using $\phi(x)$ as defined above is that it allows data sets with different units to be compared.
From **table 1**, it's clear that adding the light pipe improves uniformity. The numbers also suggest that increasing the light pipe length results in a diminishing gain in uniformity. The key parameter for homogenization is the amount of mixing, or number of bounces that the light undergoes in the component. A light pipe with a hexagonal or square cross section will provide better mixing than one with a round cross-section. Generally, the number of bounces N is proportional to the length L of the light pipe and to NA_{beam}, while it's inversely proportional to the refractive index (*n*) and aperture (A) of the light pipe:

$$N \propto \frac{NA_{beam}\, L}{n\, A} \quad \text{(Eq.9)}$$

A beam with a higher divergence will require a shorter light pipe length to achieve the same uniformity as that of a beam with smaller divergence. Also, a light pipe with a higher index glass will need to be longer than one made of a

	Uniformity prior to entering light pipe	Uniformity after passing through light pipe		
Light pipe length		50 mm	100 mm	150 mm
U_{pp}(6)	44.34%	82.70%	94.47%	96.49%
$\bar{U}$(6)	78.70%	87.80%	97.29%	98.01%
ϕ(6)	15.75%	6.17%	1.46%	0.90%

Table 1: Uniformity calculations for 8 mm aperture cross-section light pipes based on normalized irradiance values taken over the central 6 mm light pipe aperture cross-section

lower index material to achieve the same uniformity[1].

Hexagonal light pipes discussed thus far have equal input and output aperture cross sections. They improve homogeneity while preserving the angular divergence (the numerical aperture) of the input beam.

Tapered light pipes, on the other hand, have unequal input and output aperture cross sections (**figure 5**). Typically, the entrance and exit faces are square and differ in size by the magnification factor M. Light entering the small aperture face as in **figure 6** emerges homogenized and with a reduced beam divergence:

$$M = \frac{D_{out}}{D_{in}} = \frac{NA_{small\ aperture}}{NA_{large\ aperture}} \approx \frac{u}{u'} \quad \text{(Eq.10)}$$

A digital micromirror projection device is a typical illumination system where light homogenizing rods are used, such as the one shown in the diagram on the cover of this magazine.

5 Microlens arrays

Due to space constraints, sometimes it is not possible to use a light pipe to homogenize a light source. In such applications, a good alternative is a single or a pair of microlens arrays (**figure 7**). They improve uniformity by breaking the incident light distribution into a number of sub-regions and superimposing them [4].

[1] This falls out of $n_{air}\sin(\theta_1) = n_{glass}\sin(\theta_2)$ applied at the entrance aperture to the light pipe.

Consider a collimated beam of light incident on a microlens array as shown in **figure 8**: As the beam passes through the microlens array it divides the incident beam into beamlets, which are reimaged by a convex spherical lens at the focal plane (FP), providing an averaging effect. For a microlens with pitch P_{LA} and focal length f_{LA} reimaged by a convex spherical lens with focal length f_{FL}, according to [3], the homogenized spot size (D_{FT}) becomes:

$$D_{FT} = P_{LA}\left(\frac{f_{FL}}{f_{LA}}\right) \quad \text{(Eq.11)}$$

D_{FT} is a scaled version of the microlens aperture size and shape. If the microlens aperture is square, the homogenized spot will also be square, even if the input beam is round.

For applications involving the illumination of a large area (i.e. large D_{FT}), one microlens array is often sufficient. For applications requiring uniform illumination with well-defined edges, it's better to use a combination of two microlens arrays. The second one then acts as an array of field lenses. These improve the overlap between on-axis and off-axis ray bundles at the focal plane (FP), resulting in better uniformity [4]. For the tandem microlens array, the homogenized spot size becomes:

$$D_{FT} = P_{LA1}\left(\frac{f_{FL}}{f_{eff}}\right) \quad \text{(Eq.12)}$$

Where $$f_{eff} = \frac{f_{LA1}f_{LA2}}{f_{LA1}+f_{LA2}-a_{12}} \quad \text{(Eq.13)}$$

With $f_{LA1} < a_{12} < f_{LA1} + f_{LA2}$ and a_{12} being the separation of the microlens arrays. In this case, the size of the uniform spot (D_{FT}) depends on the separation a_{12} of the two microlens arrays. The microlens pitch is often chosen to be the same for both arrays.

Figure 9 shows the irradiance profile of an incoherent source before and after travelling through a tandem microlens array configuration with $P_{LA1} = P_{LA2} = 300$ µm, $f_{LA1} = f_{LA2} = 4.8$ mm and $f_{FL} = 100$ mm. **Figure 10** shows the irradiance profile of a Gaussian laser beam before and after traveling through the same microlens array configuration. For a coherent beam, the microlens arrays behave like a diffraction grating, creating an array of spots rather than uniform illumination, as multiple beamlets interfere at the focal plane. Techniques to reduce these interference effects include using a larger microlens pitch, defocusing the microlens components, or, for continuous wave lasers, a rotating diffuser [3].

6 Summary

Aspheric lenses, microlens arrays, CPCs, and light pipes all have unique properties which make them useful in various lighting applications. Aspheric lenses, due to their large numerical apertures, can collect light from highly divergent sources. CPCs can collect light from sources which emit over a full hemisphere, restricting the output to a more manageable divergence. Light pipes and microlens arrays use the principle of superposition to homogenize the light distribution from single or multiple sources.

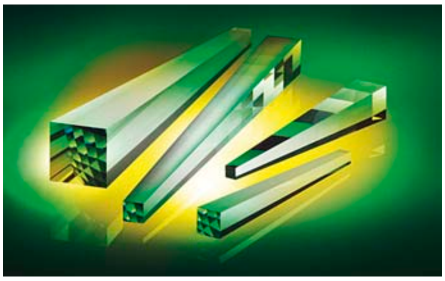

Figure 5: Tapered light pipes

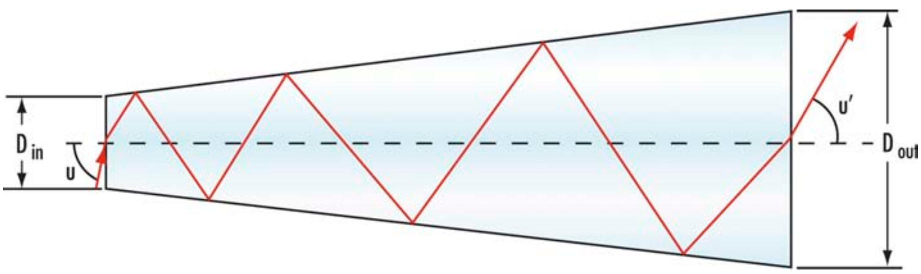

Figure 6: Raytrace through a tapered light pipe

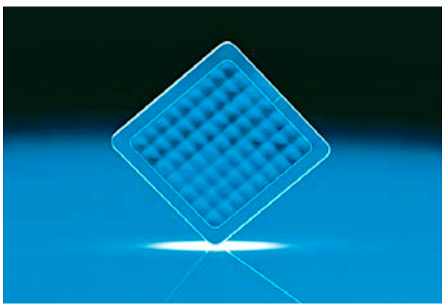

Figure 7: A microlens array, featuring a square pattern of microlenses

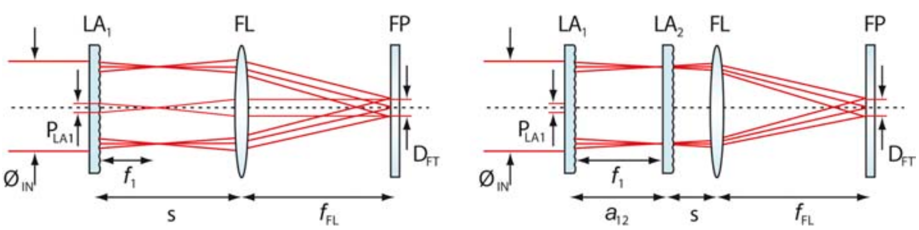

Figure 8: Microlens array LA1 divides incident beam into beamlets which are then imaged by a condenser lens FL to the image plane. Introducing a second microlens array LA2 at or near the focal plane of LA1, as shown on the right, produces illumination with better uniformity and well defined edges

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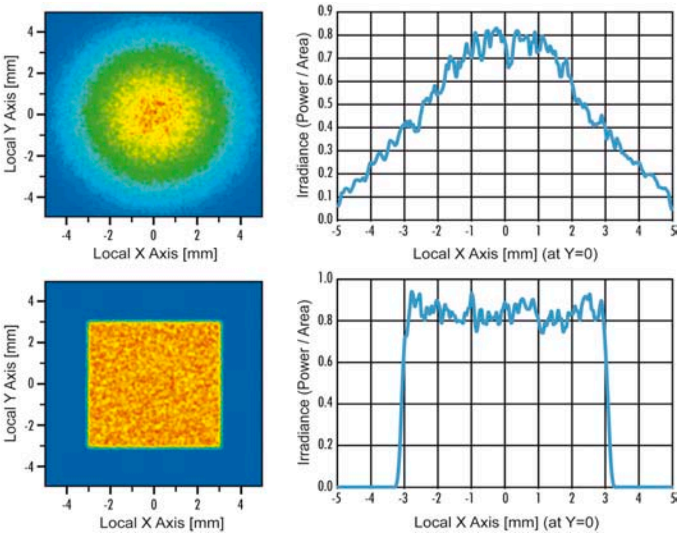

Figure 9: Top row: Incoherent source irradiance profile. Bottom row: Irradiance profile at the focal plane

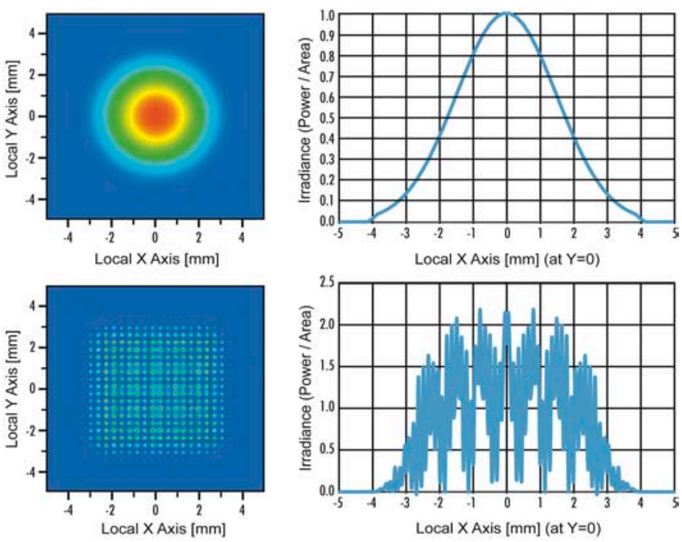

Figure 10: Top row: Coherent source (Gaussian laser beam) irradiance profile. Bottom row: Irradiance profile at the focal plane

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[1] W.T. Welford, R. Winston, *High Collection Nonimaging Optics*, San Diego, Academic Press, Inc, 1989, p. 206

[2] W.T. Welford, R. Winston, *High Collection Nonimaging Optics*, San Diego, Academic Press, Inc, 1989, p. 57

[3] *SMO Techinfo Sheet 10: Beam Homogenizing*, Version 2008-1.0, Suss MicroOptics SA, Jan. 2008, Web. 8 Jan. 2012, *www.suss-microoptics.com/downloads/SMO_TechInfo_Sheet_10.pdf*

[4] W. Cassarly, *Nonimaging Optics: Concentration and Illumination*, Handbook of Optics, Vol. 2, McGraw Hill, 2010

Author contact:

Edwin Diaz
Product Support Engineer
Edmund Optics Inc.
101 East Gloucester Pike
Barrington,
New Jersey 08007, USA
Tel. +1/856/573-6250
Fax +1/856/573-6295
eMail: ediaz@edmundoptics.com
www.edmundoptics.com

Matthias Knobl
Sales & Application Engineer
Edmund Optics GmbH
Zur Gießerei 19-27
76227 Karlsruhe
Germany
Tel. +49/721/62737-30
Fax +49/721/62737-33
eMail: mknobl@edmundoptics.de
www.edmundoptics.de

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