Non-imaging optical systems focus on transferring light efficiently and controlling its distribution.

Taming Light


ILLUSTRATION BY MICK WIGGINS

By William Cassarly, Optical Research Associates

Non-imaging optics is all about the controlled transfer of radiation for applications in which creating an image is not the primary concern. Image formation is not, however, excluded from a non-imaging design. The two primary radiation-transfer design problems that non-imaging optics attempt to solve are maximizing the efficiency of radiation transfer and creating a controlled illuminance distribution. These two design areas are often described simply as concentration and illumination. A diverse set of applications uses non-imaging optics, covering a range that includes solar collection, lithography, fiber-optic illumination, display systems, and LED lighting.

what to do about étendue

Non-imaging optical designers cannot break the second law of thermodynamics, although most have tried—for example, trying to concentrate more light through an aperture than physics allows. To avoid the temptation of designing the impossible, an optical invariant can be computed to guide non-imaging designs. Called the Lagrange invariant, or étendue, it tells us how much light can be transmitted through an aperture. Without it, a designer might try to do something impossible like focus an infinitely large source into an infinitely small hole.

The precise calculation of étendue can be numerically intensive; however, approximations can often be applied that enable “back of the envelope” calculations to determine feasibility of a design approach. Étendue helps to explain why the peak intensity from a 4-in.-diameter flashlight is 16 times higher than the peak intensity of a 1-in. flashlight. The value of understanding étendue cannot be overstated for non-imaging optical designs.

Étendue is a key parameter in the design of many illumination systems, especially projectors. It describes the integral of the area and the angular extents over which a radiation transfer problem is defined. One mathematical definition is

$$\text{étendue} = n^2 \iint \cos(\theta)\, dA\, d\Omega, \qquad [1]$$

where n is the index of refraction and θ is the angle between the normal to the differential area dA and the centroid of the differential solid angle $d\Omega$. In general, computing this integral is complicated, which is one reason why illumination software generally performs these computations using Monte Carlo ray tracing.

For a Lambertian source, multiplying the source luminance by the étendue yields the flux. For a Lambertian disk with a half cone angle of θ_{max},

$$\text{étendue} = n^2 \text{ area } \pi \sin^2\theta_{max} = n^2 \pi R^2\, \pi \sin^2\theta_{max}. \qquad [2]$$

Note that increasing either θ_{max} or R requires a corresponding reduction in the other quantity.

Engineers make a number of common mistakes when computing étendue. One mistake is to multiply the area of the disk by the solid angle of a hemisphere ($4\pi\sin^2(\theta_{max}/2)$) instead of $\pi\sin^2\theta_{max}$). Equation 1 already includes a $\cos(\theta)$ term to compensate for the solid angle, so adding a solid-angle term produces a result that is two times larger than the result in equation 2. (In other words, the solid angle of a hemisphere is 2π, whereas $\pi\sin^2(90) = \pi$.)

Another common problem is that imaging designers often learn to use a form of the Lagrange invariant that includes the small angle approximation $\sin(\theta) = \theta$, which reduces equation 2 to $n^2\pi R^2\ \pi(\theta_{max})^2$. This is appropriate for imaging systems, which are generally designed with the paraxial ray approximation. For non-imaging systems, however, the paraxial ray approach—and hence the small angle approximation—are often not valid.

design assumptions

Because non-imaging systems cover such a wide range of applications, there are a number of different design specifications for non-imaging systems. The specifications are commonly based on the 2-D illuminance, luminance, intensity, chromaticity, and polarization distributions. Using these distributions, typical specifications include total flux, beam diameter (average, minimum, maximum), contrast ratio, smoothness, and center-to-edge ratio. Human-factor issues also come into play, but they are typically harder to specify using simple parameters.

In the non-imaging optical-design community, the classic optical concentration problem is solar collection. The design goal is to maximize the flux density (irradiance) at the detector for a given collection area. A non-imaging device commonly applied to solar collection is the compound parabolic concentrator (CPC). In practice, concentrators often use the same design principle as the CPC; however, they often don't have parabolic profiles and are referred to as CPC-type (see figure 1).

CPC-type designs are based on what is called the edge-ray principle or sometimes the string method. The main concept behind the edge-ray method is that extreme rays at the input aperture are also extreme rays at the output aperture. Rays in between the edge rays also strike the receiver, although the path they take may involve multiple reflections. In many cases, the result is that the edge of the source is imaged to the edge of the receiver, and the reflector profile that performs the mapping is an off-axis conic. This raises the interesting comparison that imaging designers often focus their efforts in the center of the field, whereas non-imaging designers focus their efforts at the edge of the field.

tailoring and diffusion

A fundamental non-imaging optics problem is generating a uniform irradiance distribution for a specific source with a single reflective surface. The technical design goal is to maximize the collection efficiency, given package-size constraints, although the

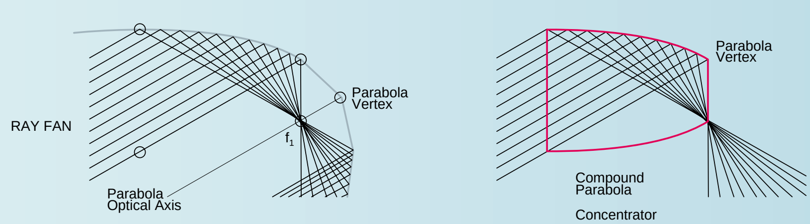
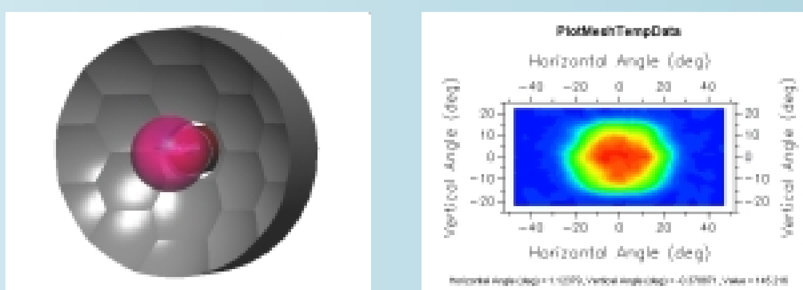


Figure 1 CPCs are the classic non-imaging concentrator device. The parabolic curve (left) focuses light to a maximum at the vertex.The concentrator (right) has a partial parabolic profile, focusing the light to a small area.

Figure 2 An automotive tail lamp with multiple tailored reflective facets (left) is one example of a non-imaging optics application. According to the model calculations, it produces the beam pattern on the right.



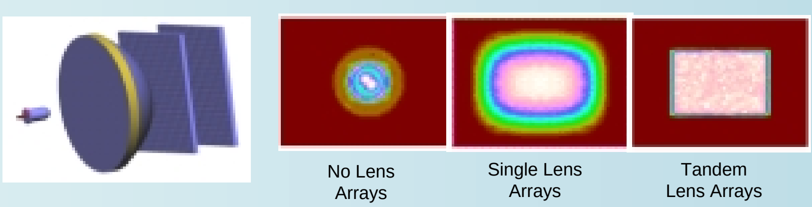


Figure 3 An LED with a tandem lens array (left) provides a smooth output distribution. A single lens array breaks the flux into subsections and recombines them. A second lens array ensures that the edges of the output distribution are well defined.

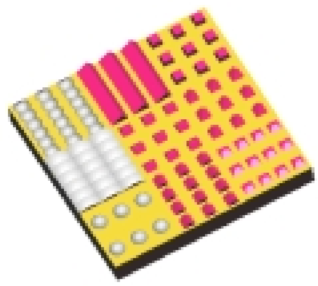


Figure 4 Texturing on lightguides is used with LCDs to diffuse the backlights. This lightguide shows some of the many patterns used on lightguides.

appearance of the reflector is sometimes just as important. The procedure to compute the reflector surface profile is often called tailoring or beam shaping. If the source is small, then tailoring simply maps angles from the source to specific target positions. Tailored reflector profiles are typically modeled using spline fits, although the profile is sometimes matched to the polynomials familiar to imaging designers (see figure 2 on page 17).

If the source is large then there are design procedures that compute the exact reflector profile for some specialized cases; however, more often there are multiple solutions and the design procedure is iterative. This suggests the use of optimization routines. The imaging community has used optimization methods for decades. Optimization of non-imaging optics is, however, only now becoming available in commercial software.

Tailoring can be sensitive to fabrication and tolerance issues. For example, if one region of the reflector is distorted, then the corresponding region of the output pattern is also distorted. Another example is that subtle details in the source, such as the coiling in a tungsten halogen lamp, may create structure in the target distribution.

A tailored diffuser that spreads the flux over a small range of angles can remove fine structure. Diffusers can be analyzed and designed using the concept of convolution. For first-order estimates, the range of scatter angles added by the tailored diffuser is the angular distance between peaks in the fine structure relative to the location of the diffuser. The required diffuser distribution may be asymmetric.

Tailored diffusion can be produced using holographic sheets, embedded microspheres, lens arrays, or pseudo-random surface texturing or faceting techniques. In some cases, the scatter distribution of the diffuser may vary spatially.

degrees of freedom

As the specifications for an imaging system become more complicated, the designer needs to increase the degrees of freedom. Typically, the designer adds more lens elements or applies small perturbations to spherical shapes using aspheric surfaces. In comparison, designers of non-imaging systems add degrees of freedom to the system by breaking the surface into multiple regions. In effect, imaging systems add degrees of freedom using surfaces in series, whereas non-imaging systems add degrees of freedom using surfaces in parallel.

One technique designers use to improve the reliability of their systems is to provide redundancy through superposition, in which the optical system is spatially subdivided into numerous channels that are combined to create the optical distribution at the receiver. If a single channel is distorted, the impact can be small because the contribution from the channel itself is small, and the flux from each channel is spread over a large portion of the receiver. Many non-imaging systems look good on paper but fail when system tolerances are included. Using superposition in the underlying design often means the difference between success and failure.

Lens arrays demonstrate the use of superposition and represent key non-imaging optical design concepts used in many portable projectors (see figure 3 on page 17). The arrays are widely used for two reasons: They can eliminate the smearing near the edges of the receiver distribution that arises with the use of a single tailored diffuser, and they can preserve the étendue but still provide uniformity by using superposition.

The order in which rays hit the surfaces in an imaging system is known a priori in sequential ray tracing. In the case of non-imaging systems such as lightguides, nonsequential ray tracing provides a better representation. In a nonsequential system, rays may hit the same surface multiple times, and the order in which rays hit the surfaces varies from ray to ray.

Numerous non-imaging applications rely on the use of lightguides to transport flux to a remote location and/or create a display with a uniform spatial luminance. With the ubiquitous use of LCDs, backlights based on lightguides have undergone a quiet revolution (see figure 4). In the past, backlights were typically fabricated using paint patterns in which changes in the density of the pattern on the surface of a lightguide yielded spatial variations in the reflectance. As design expertise and computer speed have increased, many designs have moved toward patterns of indentations that require fewer process steps and typically offer higher output.

Non-imaging optical designs surround us—automotive headlights, solar concentrators, conventional light fixtures, and LED flashlights, to name a few. The software and analytic tools for non-imaging system designers have changed dramatically in recent years. These new tools make it possible for general engineers, as well as dedicated non-imaging optical designers, to develop effective products. **oe**

Bill Cassarly is principal engineer at Optical Research Associates, Mason, OH. Phone: 513-336-0416; fax: 513-336-0496; e-mail: billc@opticalres.com. All figures made using LightTools.

For Further Reading

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