# LIGHTING

## New Technology, New Techniques

TIMOTHY FOHL, EDWARD R. FRENIERE, and JEFFREY T. REMILLARD

The emergence of diode lasers as sources of illumination has created opportunities for greatly improved quality and efficiency in lighting systems. It has also created a demand for new methods of designing and fabricating optics to exploit these advantages.

For most of the twentieth century lighting technology experienced healthy growth. In the first three quarters of the century the efficiency of electric light sources increased by more than a factor of ten. However, as is often the case in other fields, the technology has now become saturated: there has been little improvement in efficiency in the past 25 years.

But the diode laser is about to change all this. Diode lasers can have efficiencies more than twice that of the most efficient conventional lamps. Because they are more efficient, they can produce more light per unit volume and last far longer than conventional lamps. Ultimately they will also be cheaper to manufacture than light bulbs. Another advantage is that the light is emitted from a very small area and is highly directional. This allows very efficient optics to be used without going to excessive sizes.

The obvious difficulty with using lasers to carry out everyday lighting tasks is that their inherent radiance or brightness is so high that they present a hazard to the eye. However, work by Ford Motor Co., in partnership with the Technology Integration Group, Inc., has developed new classes of optics that are eye safe. These optical systems have been applied to brake light and turn signal functions on vehicles.[1–3] In these applications, they provide a number of distinct advantages. Because of the efficiency of the lasers and the optics, power requirements can be reduced by 90% or better. A number of styling advantages are also made possible by the unique optics: among these are radical shaping and the ability to make the optics completely transparent, allowing them to blend into the color of the car. As the cost of lasers decreases, the costs of the lighting systems will be less than that of conventional systems because of major reductions in size, heat loads and weather protection requirements.

More recently, diode laser illuminators have been applied to infrared (IR) night vision systems for road vehicles.[4,5] Laser-based night vision systems have been used in military applications for years but the problem of eye safety has prevented their widespread application in civilian markets. The concepts developed for laser-based signal lighting can be adapted to the problem of eye-safe IR lighting. Of course, these optics also present distinct advantages in terms of efficiency and styling.

The eye-safe optical systems that Ford and the Technology Integration Group have developed, called Sheet Optics because they are implemented in plastic sheets a few millimeters thick, have areas of tens of thousands of square millimeters. As compared to the raw beam area, the area of the beam as it exits the laser can often be increased by these systems by a factor of a million. Efficiencies can be well over 50%. These concepts make use of refraction, reflection and diffraction in various combinations. Because of their novelty, an important part of the development of these systems has been creation and use of new methods of designing, fabricating and testing the optics. We discuss some of these methods in this article.

### Methods of design and design validation

The starting point for any illumination optics design is the specification of the desired illumination distribution at the target area and the distribution of radiance of the light source. If the light

1047-6938/01/08/0050/4-$0015.00 © Optical Society of America

source dimensions are comparable to the dimensions of the optics, as is the case with many illumination systems using conventional light sources such as incandescent lamps, it is very desirable to have access to the details of the radiance distribution over the source surface. This is sometimes called the near-field distribution. Such distributions can be acquired by using an electronic imager mounted on a goniometer.[6] The source image is recorded from the directions of interest and the results are tabulated in a file. This file is then used to specify the source in an optical simulation program.

If the source dimensions are small compared to the size of the optic, which is often true of laser-based systems, the situation is somewhat simpler. In this case it is only necessary to specify the angular distribution from the source, which is treated as a point. This is termed the far-field distribution. The far-field distribution can be measured with a photocell mounted on a goniometer. A somewhat quicker method can be used to measure far-field distributions if the angular spread of the light from the source is relatively small. In this method the light from the source is allowed to fall on a diffuse screen, mounted at a distance from the source, that is much larger than the source dimensions. The radiance distribution of the light scattered by the screen is proportional to the light flux density at the screen surface.

The radiance distribution can then be recorded with an electronic camera viewing the screen in reflection or transmission. The digitized image can be analyzed using image-processing software to obtain a wide variety of parameters. These include detailed determination of flux distributions, various statistical parameters and total flux within a defined zone. The total flux of the entire distribution can be used to calibrate the measurement in absolute units by measuring the total flux in the beam with an integrating sphere or large detector and equating this value to the spatially integrated value of the image. When this method can be used it greatly expedites data acquisition, especially when complex beam patterns must be analyzed. For example, this method is widely used to characterize vehicle headlamp beams.

Imaging photometry using diffuse screens is not limited to far-field measurements. Any plane in a light flux field can be defined by a screen and the flux density can be determined at its surface. By placing the screen at a series of locations in a flux field, a three-dimensional (3D) mapping can be readily obtained. Through the use of data visualization software with interpolation capability, the flux density at any point in the 3D flux field can be easily determined. This process would be extremely tedious to carry out using any other method.

The flux or irradiance distribution on a defined plane is an output of several optical simulation programs. By making a detailed comparison of the predicted values and those measured with an actual optical system, a valuable check on the validity of the simulation can be made. Such a detailed comparison can also yield useful information on the integrity of the fabrication of the optics and on parameters such as scattering that are difficult to measure directly. We illustrate this process with an analysis of a Sheet Optic used with diode lasers.

## A Sheet Optic example

A typical example of a Sheet Optic is shown in Fig. 1. It is a monolithic acrylic piece 100 millimeters in length. The entering beam is collimated by a small lens in the lower corner. The collimated beam is spread in one dimension by a row of reflecting surfaces on the lower edge. It is spread in the other dimension by a series of reflecting elements on the back surface. The ray paths are illustrated in Fig. 2.

This example is used because it conveniently illustrates the ideas upon which Sheet Optics are based, but such a design is not particularly efficient for a variety of reasons, including machining irregularities.

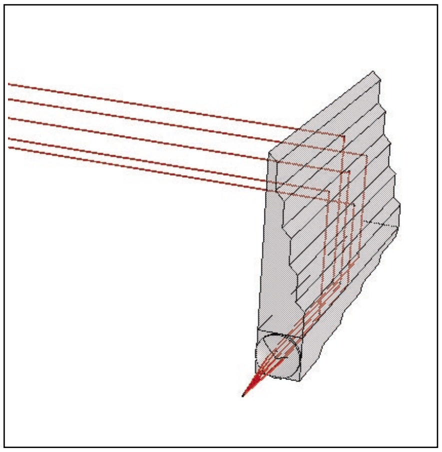

**Figure 2.** Ray paths in the Sheet Optic shown in the example in Fig. 1.

The process for designing and fabricating such prototype optics is as follows. First, the light output distribution from

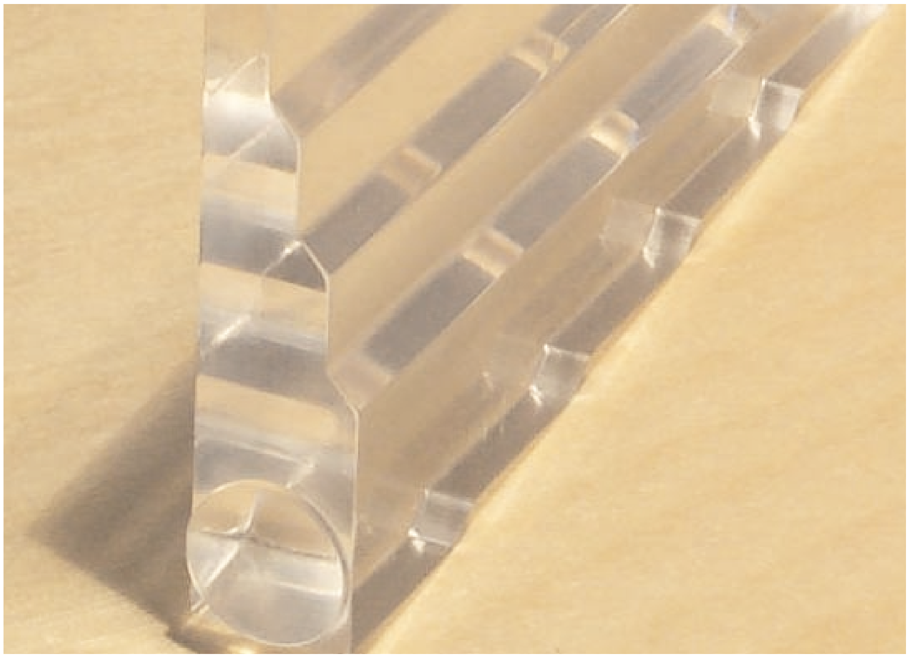

**Figure 1**. Example of a Sheet Optic about 100 mm in length.

the source is determined. In this example the source is a fiber with a 400-μm diameter core and is located about 25 millimeters from the optic. This justifies the approximation that the far-field distribution is sufficient to characterize the source. The distribution was measured by the imaging method described above. The distribution is shown in arbitrary units in Fig. 3.

The second step is to develop a concept for the optic. This is most conveniently done using software that outputs a solid model. In this example the model was constructed with the model-building module of the optical simulation program. The output model is based on the ACIS kernel. In other instances the model is developed in a CAD program, also based on the ACIS kernel, and seamlessly transferred to the optical simulation program. This approach allows the powerful capabilities of a full-featured CAD program to be used to design the model.

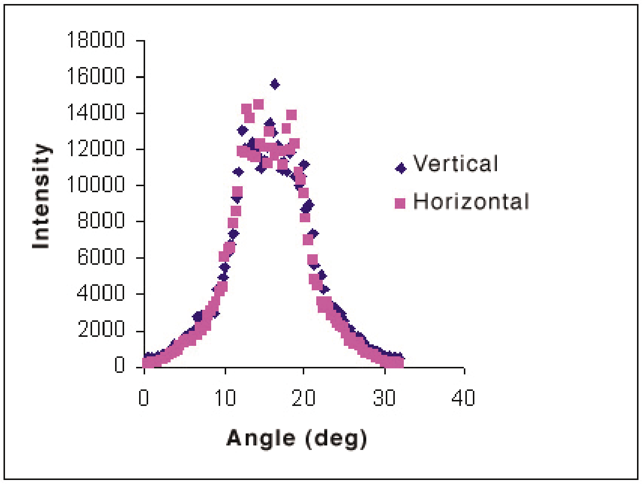

**Figure 3.** The angular distribution of intensity from the fiber.

The next step is to use the model in the optical simulation program and see if the output is as desired. If not, the model is modified until the desired result is obtained. The simulation in this example used one million rays, with over eight million rays reaching the screen due to ray splitting between specular and scattered components. In normal use far fewer rays are required to obtain the results needed but we ran more rays to reduce statistical irregularities in the output distribution. The predicted irradiance distribution at the output surface (the smooth surface on the front of the optic) is shown in Fig. 4. The intensity increases from aqua through blue, red and is maximized in yellow.

When the predicted irradiance distribution seems satisfactory, the model is sent to a shop. At the shop it is directly converted into tool path instructions. If the optic is to be molded, these can be used to create a mold. In our example, since only one piece was needed the optic was machined directly. Compared to molding, direct machining of prototypes results in rougher surfaces and other difficult-to-predict features. On the other hand there are huge savings in costs and turnaround time. For many prototyping applications, deviations from the ideal are not as important as rapid response.

After the optic has been fabricated, it can be tested in various ways. The most informative is to measure the actual distribution of irradiance over some plane using imaging photometry. Imaging methods are not as precise as some more traditional methods such as an integrating sphere, for example, for determinations of parameters like optical efficiency. However, when carefully calibrated, imaging methods can be accurate to better than 10%. They also give far more detailed information on the performance of the optic. The geometric distribution of irradiance can be used to diagnose the performance of the optic and suggest specific parts that could be modified. Imaging methods are particularly advantageous when used in conjunction with an optical simulation program that can give predictions of detailed spatial distributions of irradiance for comparison. Imaging methods can also give quantitative information on scattering and other small-scale effects that are difficult to address directly.

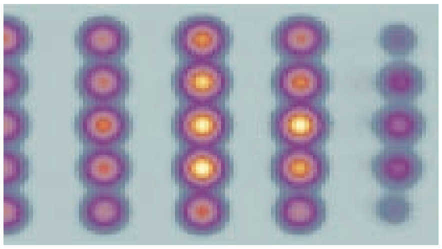

**Figure 4.** Predicted irradiance distribution at the exit plane of the Sheet Optic.

The irradiance distribution at the exit plane of the example Sheet Optic was measured by placing a translucent screen over the exit plane. The radiance distribution on the screen, which is proportional to the irradiance, was recorded with a cooled CCD camera with 16-bit resolution. The measured distribution is shown in Fig. 5. Both Figs. 4 and 5 show data that have the same degree of smoothing applied.

## Comparison and discussion

Qualitatively, the observed distribution of irradiance agrees well with the predicted distribution. The apparent differences in the left corners are probably due to minor misalignments of the fiber. Quantitatively, the comparison depends on the amount and character of scattering and small-scale irregularities of the fabricated part. The measured value of the efficiency, or total throughput, is 37% with an uncertainty of less than 5%. The calculated efficiency in the approximation of perfect surfaces and alignment is 77%. We experimented with varying degrees of scattering both Lambertian and directed. The result shown in Fig. 4 was obtained with 20% Lambertian scatter. The calculated efficiency for this case is 43%, sufficiently accurate for the applications for which these optics are intended.

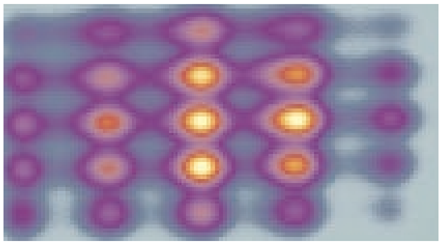

**Figure 5.** Measured distribution of irradiance at the exit plane of the Sheet Optic.

As would be expected, the effects of small-scale irregularities are more pronounced in the smaller scale features of the distribution. This can be seen in the elongation and widening of the spots generated by the actual optic compared to the predicted spots. This effect is due to microscopic tool marks and random rough-

*Continued on page 54*

ness on the reflecting surfaces. There is also some unavoidable rounding of corners which contributes to spreading of the beams. It is possible to characterize surface irregularities with atomic force microscopy and use the results to quantitatively predict scattering effects.[7] These surface characteristics can be incorporated into an optical simulation if such detail is needed.

## Conclusions

The objective of this article has been to describe several new technologies with the potential to create major changes in the state of the art of illumination. While none is a very recent breakthrough, their aggregate effect is still not widely known. To sum up:

- Diode lasers are the most efficient light sources known and the trends of cost and performance indicate that they will be competitive with conventional sources in the not-too-distant future.
- It is possible to design and build optics that allow lasers to be used with complete eye safety and comfort in virtually any illumination application. These optics are generally more compact and efficient, as well as less expensive, than conventional lighting optics.
- New optical simulation programs, closely connected with CAD software, can expedite the design and production of these intricate, unconventional optics.
- Imaging photometry facilitates the design process by providing accurate models of source output distributions and diagnostic information about the performance of actual optics units.

It will be interesting to observe the effects of these technologies as they spread into the world of illumination.

## References

1. J.T.Remillard, M.A. Marinelli and T. Fohl, Opt. and Phot. News **10** (8) 39-43 (1999).
2. J.T.Remillard, M.A. Marinelli and T. Fohl, Proc. of the Diffractive Optics and Micro-Optics Conference (Kailua-Kona, Hawaii, 1998), OSA Technical Digest Series **10**, 192-4.
3. M.A. Marinelli and J.T. Remillard, Proc. SPIE 3285, (SPIE Press, Bellingham, Washington, 1998) 170-7.
4. J.T. Remillard, W.H. Weber and T. Fohl, Proc. SPIE **4285**, (SPIE Press, Bellingham, Washington, 2001) 14-22.
5. M. Holz and E. Weidel, "Night vision enhancement system using diode laser headlights," SAE Technical Paper Series #982778, 1997.
6. R. F. Rykowski and C. B. Wooley, SPIE Proc. **3130**, (SPIE Press, Bellingham, Washington, 1997), 204-8.
7. J.T. Remillard, M. P. Everson and W. H. Weber, App. Opt, **31**, 7232-41 (1991).

**Jeffrey T. Remillard is a senior technical specialist at the Ford Motor Co. Research Laboratories, Dearborn, Michigan. Timothy Fohl is president of the Technology Integration Group, Carlisle, Massachusetts. Edward R. Freniere is president of Lambda Research Corporation, Littleton, Massachusetts.**