Optimizing LED illumination systems

Sergey Kudaev and Peter Schreiber

Getting the best application-specific illumination systems involves direct optimization of non-imaging optical elements.

From imager illumination and special inspection systems to general internal and even external lighting, LEDs are promising light sources for a variety of applications because of their compactness, good color control, dimming capability, short switching response, and long lifetime. Already, modern high-power LEDs are comparable to incandescent lamps in their electro-optical conversion efficiency. However, to be competitive with incandescent lamps, illumination systems need to operate with maximal performance in such areas as transmittance, homogeneity, and size. This is because of the current but temporarily high lumen cost of LED light.

Modular approaches are most common in the design of optical systems, so we separate our design into primary optics (for collimation of Lambertian-like light sources with small residual divergence, typically ±3…± 20°) and secondary optics (for further beam shaping and transformations). Classical design of non-imaging collimators includes externally generating a mathematical description of the element and then converting it to CAD formats. Then, the CAD model is imported into ray-tracing software for performance evaluation. This approach has several drawbacks as typically the designer needs different design tools for different collimator types. This approach also provides insufficient freedom to explore the parameter space, with possible loss of precision due to multiple data-format conversions. Thus, we use direct optimization of the collimator shape according to different criteria.

The general trade-off in non-imaging optics is between conservation of etendue (in optical systems the product of emitting area times the solid angle of emitted light cannot decrease without losses) and both mechanical and technological constraints. Optimization makes it possible to find the best compromise solution to fulfill the requirements and to limit the constraints. For instance, it is almost impossible to analytically design a system with limited sizes producing maximal light flux, or a system that is insensitive to misalignments of LEDs relative to optical elements. Design with optimization makes these possible if the designer has the required tools: parametrical description of the object, a definition of the merit function, and the appropriate optimization algorithms. All these tools differ from classical optical design because only non-sequential ray-tracing can adequately simulate non-imaging optics. Our design methods consist of add-ons for commercially available optical design software, ensuring the necessary flexibility and robustness.

For parametrical modeling of optical elements we use rational Bezier splines to ensure sufficient flexibility in representing standard conic curves and even piecewise Cartesian ovals. High-order Bezier splines are numerically stable (we are using curves to the 20th order) even with highly non-uniform sampling. A very important feature of rational Bezier splines is that the curve order (i.e. the number of degrees of freedom for optimization) can be increased without changing the already optimized shape. After searching for a global optimum with a small

Continued on next page
The choice of optimization algorithm and merit function depends strongly on the problem definition. If it is possible to find a simple abstraction, that is, to describe the properties of the system in a geometrical manner, then we can use optimization algorithms with derivatives (for example, dumped least squares or DLS). An example of such an abstraction is the edge-ray principle: rays from the edge point of the extended light source should propagate under the angle of residual divergence of the output beam after leaving the collimator. Thus, we are optimizing the system in such a way that each ray in two ray fans from edges of the source propagates collinear and under the maximum target angle. Rotationally symmetrical collimators (see Figure 1), designed according to this principle operate almost at the etendue-conservation limit.

A couple of applications require additional, special (typically, homogeneous) light distributions. For these applications it is impossible to find the geometrical abstraction for the merit function. Instead, we optimize them by estimating overall flux and its distribution within residual divergence (see Figure 2). The flux is determined by tracing a limited number of rays (Monte-Carlo ray-tracing). In essence, we apply methods of non-linear optimization without derivatives for such a design, which is stable even in the tasks of statistical estimation of merit functions. Note that DLS algorithms fail to optimize such a system.

In summary, we use direct optimization of non-imaging collimators for design of application-specific illumination systems. Compared with ‘off the shelf’ optical components, our approach ensures size reduction, the increase of useful transmission, and irradiance homogenization without the use of secondary optics.

Figure 2. Rectangular cross-section and optimized profile ensure homogeneous near-field light distribution (optimization with Monte-Carlo ray-tracing) in this collimator with residual divergence ±10°.

Figure 3. On the left, the collimator has residual divergence ±5° (transmission more than 80%, 34mm, length 12mm). On the right, the collimator has residual divergence ±15° (transmission ∼90%, 14mm, length 15mm). Both are made of polymethyl methacrylate for OSRAM OSTAR® LED modules.

Author Information

Sergey Kudaev and Peter Schreiber
Micro-optical Systems Department
Fraunhofer IOF
Jena, Germany
http://www.microoptics.org

Sergey Kudaev received his first-class diploma in electronic engineering in 1996 and PhD in 2000 from Vladimir State University in Russia. Currently, he works at the Fraunhofer Institute of Applied Optics and Precision Engineering in Jena, Germany. His research interests include developing new methods of non-imaging optical design.

References