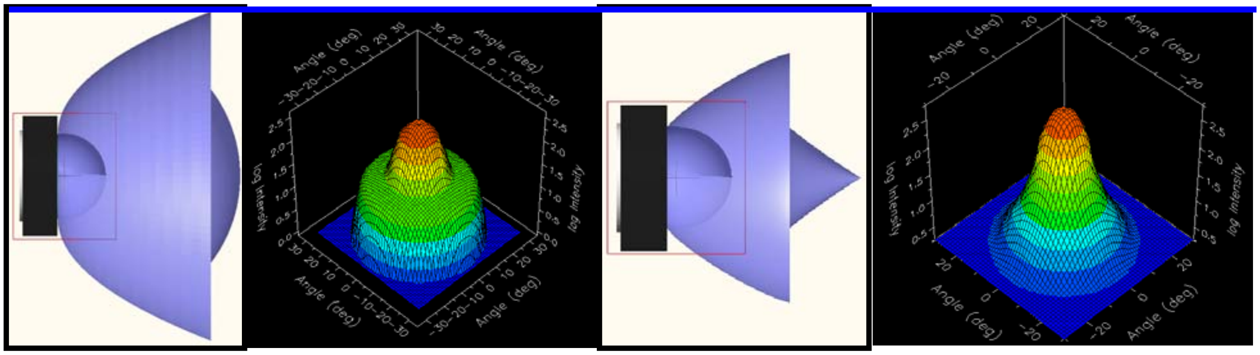
FRED® Optimum
Optimization Application Note



Optimization of optical systems allows the user to improve system performance based on user-defined requirements. Lens design optimization is a mature field with well established methods and algorithms that employ a figure of merit (FOM) to minimize spot size at the image plane while also addressing user-entered metrics such as reduction of distortion, chromatic aberration, and so forth. Nonsequential optical systems, especially those in the nonimaging, illumination, coherent, and stray light fields, cannot use the standard imaging FOMs, but employ user-tailored FOMs to enhance system performance. Such FOMs will include such metrics as maximizing the source flux transferred to a target, minimizing distribution non-uniformity at the target, minimizing stray light at the target, and so forth. **FRED Optimum** uses a simplex optimization scheme, which was introduced in J. A. Nelder and R. Mead, *Comput. J.* **7**, 308 (1965).

This application note illustrates the utility of optimization in **FRED Optimum** by improving the performance of a LED-collimating optic. These optics, which we call hybrid optics, use both, among other optical phenomena, refraction and total internal reflection (TIR) to provide the highest level of collimation by increasing flux transfer into a desired angular range around the optical axis (i.e., ±10°), while also reducing the non-uniformity in the resulting intensity distribution. This type of optic is becoming more prevalent in the solid-state lighting industry of the illumination field. This application note also shows the utility of swept NURBS curves to generate rotationally symmetric optics. This application note is based on the Optics and Photonics 2008 paper: R. J. Koshel, "Fractional optimization of illumination optics," SPIE Proc. **7061**, Novel Optical Systems Design and Optimization XI, 70610F (2008).

Base Design of the Hybrid Optic

Figure 1 shows the initial hybrid optic that is optimized in this application note. The LXHL-PL01 Luxeon I Lambertian LED available from Lumileds is placed in a shape-conforming recess within the optic. There is a 0.001-mm air gap between the LED and the optic. The base shape of the side walls is parabolic with the focus placed at the optically corrected die position. The side walls are characterized by a NURBS curve, which is then revolved around the optical axis of the system. The front lens base shape is a convex surface that collimates the direct on-axis radiation from the LED die. The front lens is also described by a NURBS curve that is revolved around the optical axis. Finally, the annulus curve connects the side walls and the front lens curves via a line segment. This curve is revolved around the system optical axis to create a surface.

The NURBS nature of the optic in Fig. 1 allows for the designation of variables for the control and end points that comprise the curves of the hybrid optic. The important parameters are the positions (*y*, *z*) and weight factors (*w*) for the points of the optic. The *y* coordinates are in the vertical (transverse) direction, while the *z* coordinates are in the horizontal (longitudinal) direction. The LED recess is static, but, as per Fig. 1, the following points are allowed to vary:

- Point #4 (side wall control point): y_4, z_4, and w_4;
- Point #5: (side wall – annular region end point): y_5 and z_5;
- Point #6 (annular region – front lens end point): y_6;
- Point #7 (front lens control point): y_7, z_7, and w_7; and
- Point #8 (front lens end point): z_8.

Each of the *z* coordinates have a range of [2.801 mm, 12.7 mm] and the *y* coordinates have a range of [2.801 mm, 12.7 mm]. The weight factors, *w*, have ranges of [0.001, 1000]. A value of 0.001 indicates that the control point has little effect on the shape of the line that joins the two end points, thus the curve approaches a straight line between the two end points. A value of 1000 indicates that the control point has a strong effect on the shape of the line that joins the two end points, thus the curve approaches two straight lines between each end point and the control.

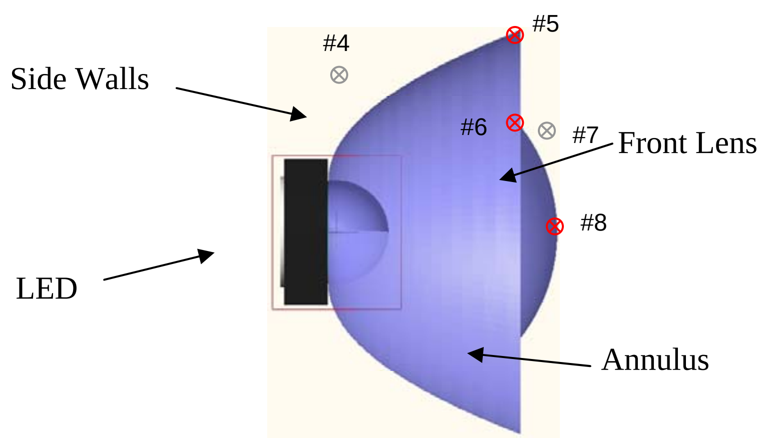


Figure 1. LED and the Hybrid optic to be optimized in this study and placement of the control (#4 and #7) and end (#5, #6, and #8) points of the hybrid optics curves.

Figure of Merit

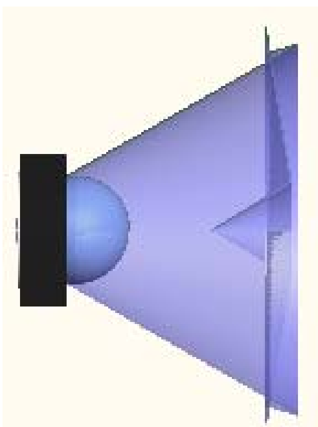
In **FRED Optimum** we use two components for our FOM: maximize power transfer into the desired angular range of ±10° around the optical axis and intensity distribution non-uniformity within this angular range. The specific FOM for this case is:

$$FOM = \frac{\sigma_{Int}}{I_{Peak}} \frac{1}{\eta_t^2}, \qquad (1)$$

where σ_{Int} is the standard deviation of the obtained intensity distribution and I_{peak} is the peak intensity in the distribution. The goal is to minimize the variation in the intensity distribution at the target, which is realized by reducing the intensity standard deviation, while also maximizing the transfer efficiency to the target. The peak intensity term in the denominator provides normalization of this standard deviation metric. Through preliminary studies of the optimizer in use, it was found that squaring the transfer efficiency term provided the desired weighting for the Eq. (1) merit function. With only an inverse relation to the transfer efficiency, it was found that the transfer efficiency would be undesirably low. In FRED **Optimum**, the transfer efficiency is a standard selection found in the optimizer interface while the uniformity metric is set through the use of a simple user-defined script. Convergence is realized when the simplex size does not change appreciably from one iteration of the optimization scheme to the next.

Initial Results: Loosely Constrained Optics

Optimizing the base system of Fig. 1 using the criteria established in the previous sections, we obtain the hybrid optic as shown in Fig. 2. A closer inspection of this optic indicates that the various curves that define the surfaces cross one another as shown in Fig. 3. Thus, while it successfully traces, in no way can it be manufactured successfully. We need a method to keep the various control and end points constrained such that inner points are held in check by outer ones, as per the discussion in the Introduction. The method of factional optimization can accomplish this through using dynamic constraints.



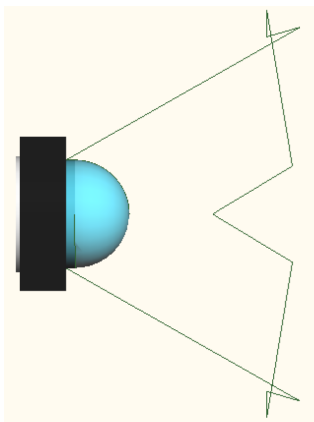


Figure 2. Rendering of the optimization.**Figure 3.** Curves that define the Fig. 3 optic.

Final Results: Fractional Optimization

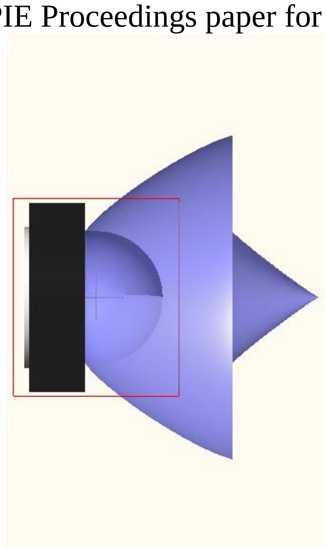
Using the material presented in the SPIE proceedings paper (see the Introduction), we use fractional optimization variables of FRED **Optimum** to constrain inner variables by outer ones. We rewrite our equations that define the constraints for the hybrid optic optimization such that fractional terms are used rather than deterministic coordinates. Note that the maximum y and z values for the baseline optic in Fig. 1 drive the ordering of the fractional variables. This result means that y_5 defines the maximum transverse coordinate, while z_8 defines the maximum axial component. Thus, inner variables mean those geometrically less than y_5 or z_8, for the y or z

directions respectively, of the variables listed in the **Base Design of the Hybrid Optic** section. Using these maxima, the equations governing the 10 variables are:

$$
\begin{aligned}
y_5 &= 9.88(\hat{y}_5 - 0.1) + 2.801, \\
y_6 &= y_5(\hat{y}_6 - 0.1), \\
y_7 &= y_6(\hat{y}_7 - 0.1), \\
y_4 &= (y_5 - 2.801)(\hat{y}_4 - 0.1) + 2.801, \\
z_8 &= 9.439(\hat{z}_8 - 0.1) + 2.801, \\
z_8 &= 9.439(\hat{z}_8 - 0.1) + 2.801, \\
z_7 &= (z_8 - 2.801)(\hat{z}_7 - 0.1) + 2.801, \\
z_5 &= (z_7 - 2.801)(\hat{z}_5 - 0.1) + 2.801, \\
z_4 &= (z_5 + 0.46)(\hat{z}_4 - 0.1) - 0.46, \\
w_4 &= 10^{(\hat{w}_4 - 3.1)}, \text{ and} \\
w_7 &= 10^{(\hat{w}_7 - 3.1)},
\end{aligned}
\qquad (15)
$$

where the hats ("^") denote variables normalized by the respective maximum value, which is 12.7 mm for the *y* and *z* directions and the log of the weight factors. Each has an offset of +0.1 so that a value of 0.0 is not obtained for the variables.

The optimization of the hybrid optic using fractional variables provides the optic as shown in Fig. 4. The resulting luminous intensity distribution in log base 10 form is shown in Fig. 5. For comparison the original shape and luminous intensity distribution are shown in Figs. 6 and 7, respectively. There is about a factor of two improvement in transfer efficiency while maintaining a high level of uniformity in the intensity distribution. Note that the hybrid optic shape has been reduced in volume, while maintaining, loosely, the parabolic side-wall form. The front lens has been modified from a traditional convex lens to that of a traditional axicon. Please see the SPIE Proceedings paper for more details about this optimization.



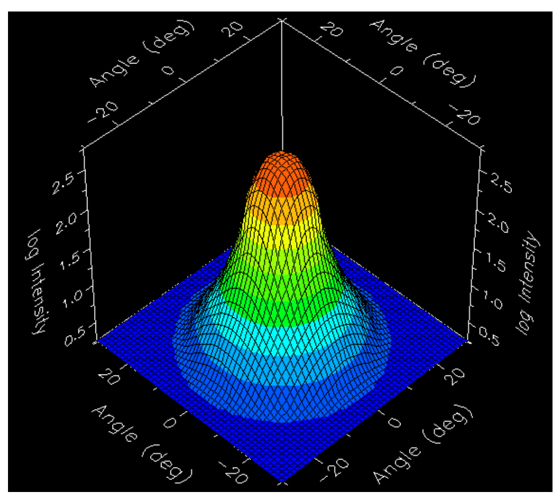


Figure 4. Optimized optic rendering.**Figure 5.** Log intensity distribution of the optic in Fig. 4.

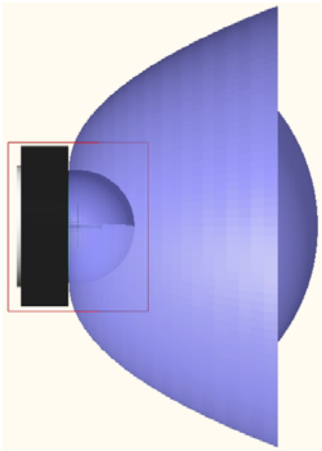


Figure 6. Initial optic rendering.

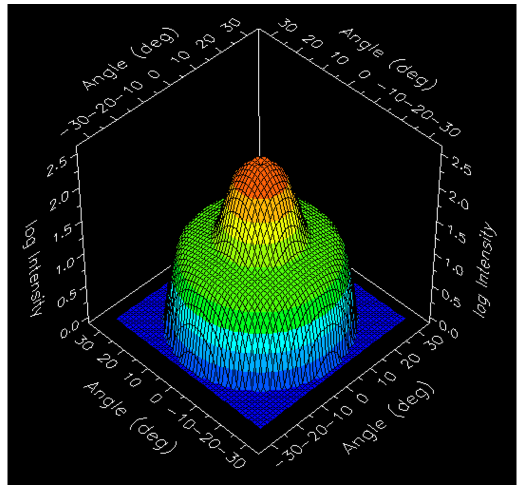


Figure 7. Log intensity distribution of the optic in Fig. 6.