LED - Lighting Design with LucidShape

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At present, the lighting industry is undergoing a fundamental technological change due to the proceeding deployment of a new powerful light source: the light-emitting diode (LED). Rapidly improving LED technology triggers new trends in lighting design and provides unprecedented product differentiation, small installation size, enhanced safety, energy-efficiency, and cost-effectiveness. But it also simultaneously poses new challenges to lighting designers due to the LED's unique characteristics. Proper treatment of LED emitters and their optics in the virtual world allows a thorough design process and optimized lighting solutions.

1. Introduction

Visualization and simulation of LED systems, such as the new solid-state automotive headlamps, in illumination design software like LucidShape allows users to familiarize themselves with the performance, the drawbacks and potential of the new light source in a virtual environment. In simulations, the light designer can perform the development of faceted and freeform reflectors (or lenses) to be utilized in LED applications. Not only is it time-efficient this way to select the best configuration from readily available optical components for the specific purpose, but it is further possible to design optical components that optimally fulfill the requirements of the task.
The development of high-quality LED lighting solutions requires more than just the availability of high-quality components. Usually, more than one approach will lead to satisfying results. The power of a virtual development however, is not the capacity of multiple series of plain trial and error. It offers the chance to test more than one appropriate design with focus on the application and assist already at early stages of development. Even then, to make sure that the obtained results are representative, the developer should have not only a variety of techniques, data and design concepts at his or her hands, but also reliable knowledge on their usability. A good lighting development, even for a design sketch should always be "quick and clean".
We present in this article a discussion of typical types of source models for LEDs and an overview of the basic design options for an optical setup for the solid-state luminaries, focusing on selected components in more detail. Further, we present some examples of simulations and applications designed in LucidShape.

2. Modeling the LED light source

In virtual experiments, the adequate representation of the light source is essential. The better a real light source is implemented in simulations, the better it will be represented, and the closer the results will be to reality. Naturally, if the resolution of an angular distribution curve is higher, or if more details are incorporated in a geometric model, the resulting light pattern from a simulation can become hard to differ from experimental measurements at real light samples. An LED source model can be of one of three types:

- Point light source, using an intensity distribution;
- Geometrical model of the emitter, with varying level of detail;
- Extended ray file source model, using externally acquired (measured) ray files.

These approaches differ in complexity and resulting precision, especially in terms of the angular distribution and symmetry. The intensity distribution of an LED can be obtained from the manufacturer or distributor. In most cases, the curves are plotted in the component's datasheet. The geometric dimensions of the housing, lens etc. of an LED are also found there. Geometric models for computer-aided design software may also be provided, and allow a precise build up of an geometric model of the light source. Finally, the LED ray files are directly available from the major manufacturers and can be imported as ray file source models into state-of-the-art lighting developing software.

2.1 Point source model

The simplest model of an LED is the point source model. Here, the known angular intensity distribution is attributed to a mathematical point source. This approach is consistent, if the distribution is measured in far-field (typical). Of course, it neglects all near-field peculiarities. But these properties are of importance! LED lighting is in almost any case influenced by the near field properties of the emitters, since diodes are very small light sources and are often mounted at very short distances to also small optical components. One exception is the use of primary optics only. Further, the angular emission curves will often contain only 2D data, assuming a flawless rotational symmetry of the emission characteristic. The level of detail in this approach is low. For possible far-field applications and for a quick proof of principle for a new optical design, it is a valuable aid – as long as its limitations are kept in mind.

2.2 Geometrical model

The simplest example of a geometrical LED model of an extended, finite size (not a point) can be considered to be the emitting surface model. First, a surface that resembles the LED aperture is chosen, for example the die area or the primary optics (lens) on the LED chip. Then, an emitter property, for example of Lambertian kind is assigned to this surface.

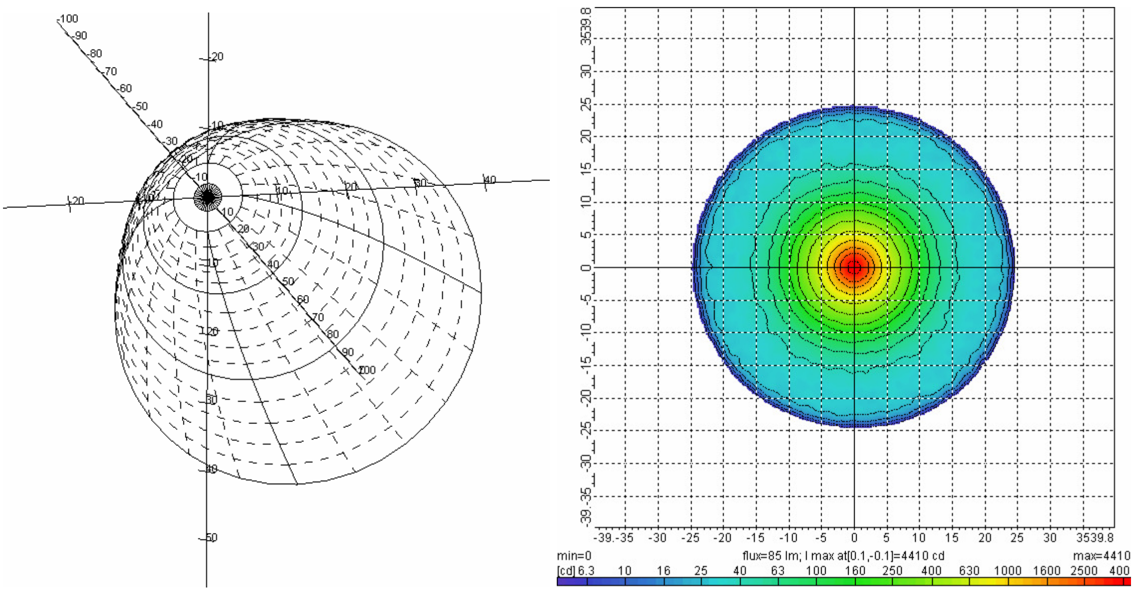

Fig.1: simple parabolic reflector setup, using a plane disk emitter geometry (left); the simulated candela distribution (right) creates at the hot spot a maximum of 4410 cd.

This approach has the advantage of using an extended size (in contrast to a point source), but suffers from the use of a theoretical intensity distribution. Fig.1 shows the example of a (deep) parabolic reflector and a very simple lambertian disk emitter model.
Of course, instead of a purely Lambertian distribution, we can also assign a Gaussian profile or any other curve that is closer to the known properties. It is also possible to use the distribution curves for point sources, which have to be applied with care. The basic parameters from the LED's datasheet are the following: the size of the LED (diameter of die or lens), the FWHM (angle) and a sketch of the angular emission profile. Incorporating only these into a simple geometry model will for sure yield a limited representation of the LED's properties.

More sophisticated geometric models include not only the main components like the die and lens, but cover all relevant aspects of the LED: for example a possible reflector cup, the encapsulation, mounting assemblies, and perhaps even shading contact wires. The additional details provide an improved precision in the representation of the LED's near field. Such models have proven to be reliable source representations when a higher level of detail is required.

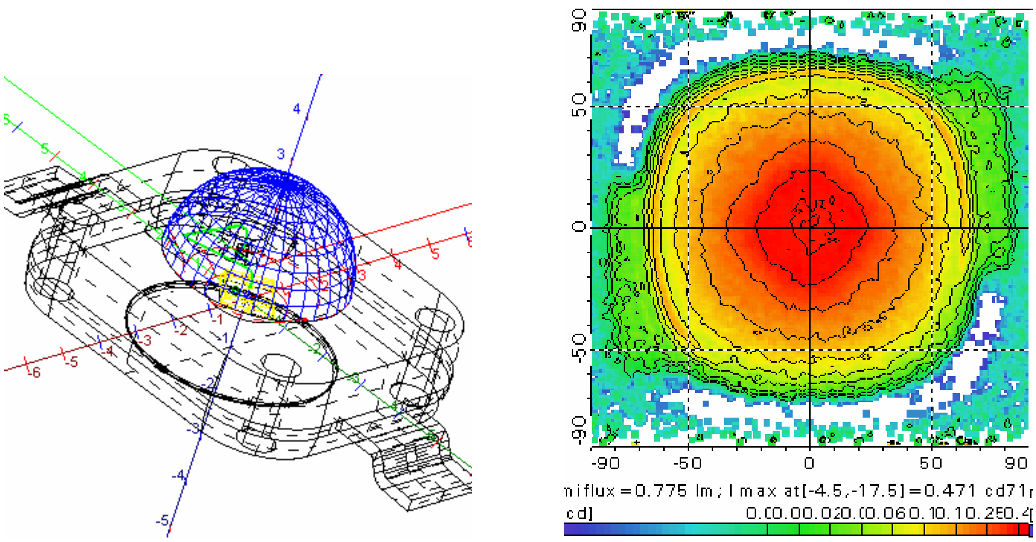

Fig.2: Complex geometry model, example is the OSRAM Golden Dragon (left): includes complete housing, lens, die, and also the bonding wire. The candela distribution (right) shows very well the asymmetrical features of this LED.

2.3 Ray file model

The use of measured optical data from a rayfile is the most precise model of an LED. The resolution of the emitter's virtual representation, however, depends on the number of rays in the rayfile. If faster simulations are performed by using only a certain amount of the rays from a larger file, it is important that the single rays are randomly selected. The Fig.3 shows a distribution from the simple parabolic reflector example in Fig.1. It uses exactly the same setup. Here, the hotspot marks 18300 cd of luminous intensity, while the geometry emitter model reaches only 4410 cd. The simple geometrical model certainly lack in precision.

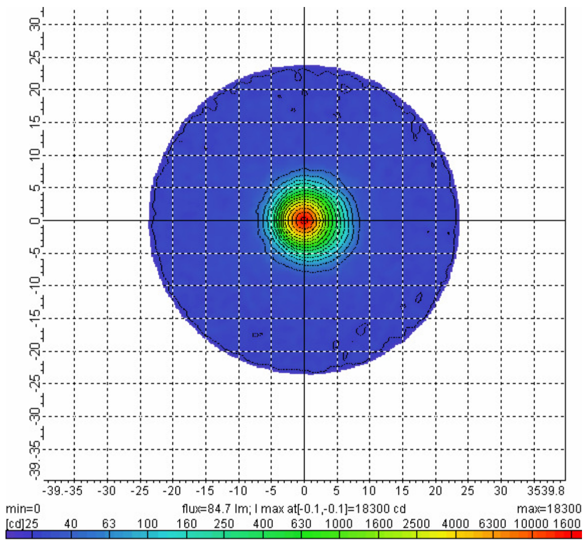

Fig.3: candela distribution after using the rayfile (Luxeon K2, $5*10^6$, 85 lm)

3. Design Options

Currently, LEDs can be considered as half-space emitters. In contrast to most other luminaries, they emit almost all the light into one half-space, which is a consequence of the nature of surface emitters in combination with the opaque substrates. This brings plenty of advantages and additional design options, but leads sometimes also to the need for new and different approaches to otherwise well known classical lighting solutions.

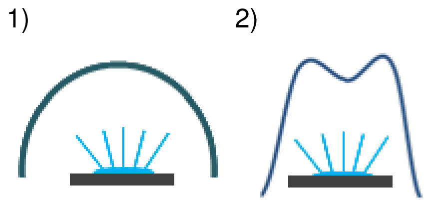

Fig. 4: Primary optics type: (1) Lambertian, (2) Batwing

Already the **primary optics** ("the lens") directly on top of the emitter molds the flow of light and has strong impact on the angular characteristic of an LED. As a matter of fact, the angular distribution is more or less defined by the primary optics. So is also the size of the effective aperture. Side emitters, for example, can be specially designed for the illumination of on-axis reflectors or background lighting applications. In Fig.4, the Lambertian (1) and Batwing (2) type are sketched. The Batwing characteristic has been developed to produce a uniformly illuminated area within a certain angular range in front of the LED.

Like with other luminaries, control of the emitted light from LED is achieved with lenses and reflectors. In detail, the archetypical design options are briefly described in the following, starting with the application of reflectors.

The direct **reflector** (*A*) is a common arrangement, especially for spots or other narrow beam applications. A good example for applications are flashlights (torches). The off-axis indirect reflector setup (*B*) provides an enhanced control of light. The major share of light is thrown at the reflector in this asymmetrical design. Especially free-form reflector LED lights use this simple, yet effective arrangement. Besides a protective front lens, it may consist of only two parts: one emitter and one reflector. It can also be a component in projector setups (see below: H,I). The reverse indirect reflector approach (*C*) completely eliminates the LED's direct contribution to the final light pattern. The luminous flux is completely controlled by the reflector. However, mounting the emitter within the path of light as well as the wiring and the thermal management at such an exposed position make this design type more complicated than most other approaches. If a desired light pattern is created using sophisticated reflectors, typically either a procedural surface (PS), poly curve system (PCS), or the macrofocal concept (MF) is applied.

Lens optics are always arranged in front of the emitter. Besides simple lenses (*D*), aspherical lenses or total internal reflection optics (TIR) and Fresnell-lenses, also free-form lenses (*E*) are used.

Compound Parabolic Concentrators (**CPC**) are non-imaging optical components with offset parabolic base curves. They can be constructed as IR optics but also as reflector cups.

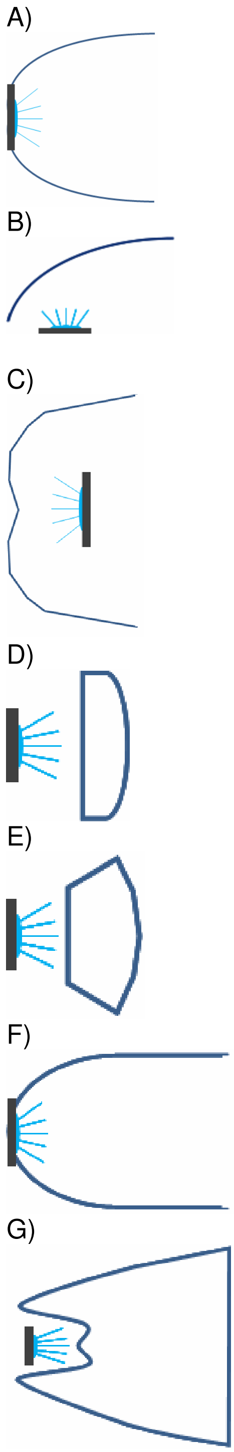

Fig. 5a: Design type examples of LED secondary optics

Also very promising and thus quite common is the use of **collimator optics** situated directly above the emitter (*G*). These secondary optics can be used to collimate or focus light, to diverge it, to couple light into light pipes or to create a shaped virtual source, e.g. for projector applications. TIR optics are usually made of acrylic (polymethylmetacrylat: PMMA) or polycarbonate (PC). Thus, they can be injection-molded, which allows for a cost-efficient mass production.

A combination (*H*) using both types of optics, reflector and lens, is the basic setup for more complex projector systems. This is schematically shown in Fig.6. **Projectors** and similar complex optical imaging systems can simultaneously make use of, for example, secondary optics (such as collimators), elliptical main reflectors, reflective light shields (instead of absorbers which would waste light) and aspherical lenses (I). This way, the produced image can be engineered and sharp cutoffs can be precisely created in the final light pattern. Consequently, such projector approaches have aroused special interest from automotive lighting.

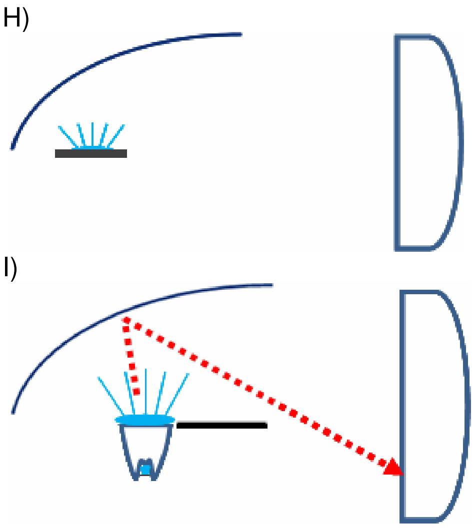

Fig. 6: LED designs with multiple optics, projector setup make use of an imaging front lens

4. Collimator Optics

This TIR secondary optic is mostly referred to as collimator, independently of its actual function. Due to the dependence of the internal reflection from the angle of incidence at the interface between a high index component (e.g. PMMA) and the surrounding air, they can cover only a limited angular range. Collimators are not suited for strongly diverging the LED's light. An example for collimation to a light exit angle of 0° is shown in Fig.7.

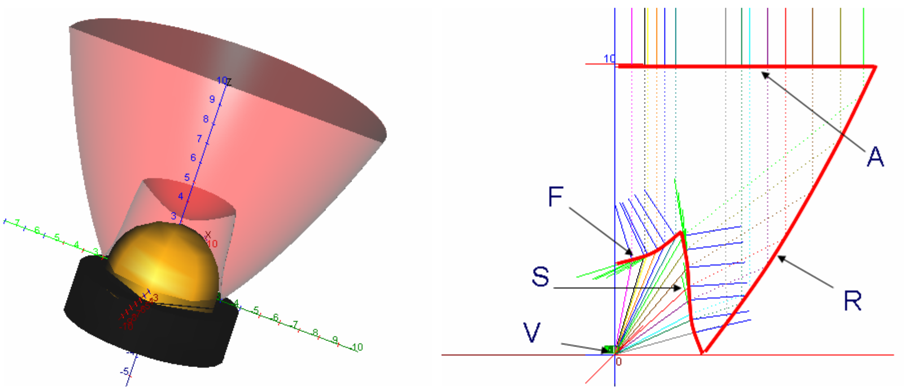

Fig.7:
LED collimator optics; (left) geometry cross-section and (right) a 2D raytrace sketch.

V: virtual focal point
S: side entry
F: front entry
R: TIR reflector
A: Front aperture

The front entry is a hyperboloid shape which images the emitter and already produces the 0° angle of light: collimators control also the direct illumination from the emitter via this front entry. At the side entry, light from the emitter is refracted in a way so that it illuminates the complete TIR reflector surface, which reflects the light into the desired 0° exit angle. The virtual focal point (of this side entry) must be matched to the virtual source point of the bare emitter (alignment). The front aperture in this example is planar.

To create asymmetrical light distributions from symmetrical collimator pieces, structured front apertures can be used. The finish of the front can incorporate riffle or Fresnel lenses to shape the distribution that was created by the TIR reflector and front entry before, e.g. to create elliptical patterns. TIR collimators do not allow light from the emitter to exit the component directly, instead it is forced to pass the entries and the front aperture.

5. Reflectors – LED in forward or reverse orientation

There are numerous design options for reflectors. Two archetypes, however, can be distinguished by the general orientation of the emitter. Either it is pointing forward, towards the main direction of light propagation (≤90°), or it is oriented in the reverse direction (>90°). The case of an exact 90° orientation angle is allocated to the forward type for simplicity. These design options equal the types A (0°), B (90°), and C (180°) in Fig. 5a.

The orientation of the emitter influences the amount of light that is controlled by the reflector. In forward orientation, the boundaries of the reflector opening define an angle from which the LED emits directly into the surroundings. In a reverse orientation, this direct light is reduced, even completely eliminated. Thus, the decision on the importance of direct light from the emitter should be made already at an early stage of design. The simplicity and the availability of off-the-shelf parts for the forward orientation make this approach the most common reflector arrangement type. Forward and reverse LED+reflector combinations are schematically shown in Fig.8.

For an efficient illumination of the reflector in forward orientation, a Lambertian emitter is not really well chosen. A major share of the emitted luminous flux is always “spilled” directly through the reflector’s aperture. Many lighting solutions make use of exactly this spill, but if this is not an option, side emitters or batwing emitters with adequate angular distributions are far better suited light sources for forward orientation reflector designs.

A good balance between the emission characteristic (type of primary optics) and the optical component from the possible design options (type of secondary optics) must be found.

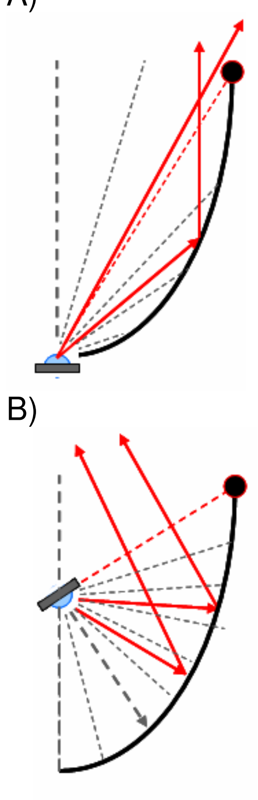

*Fig.8: LED reflector orientation examples: forward and, reverse.
(A) The reflector opening lets light directly from the LED escape.
(B) Reverse arrangements capture more light in the reflector.*

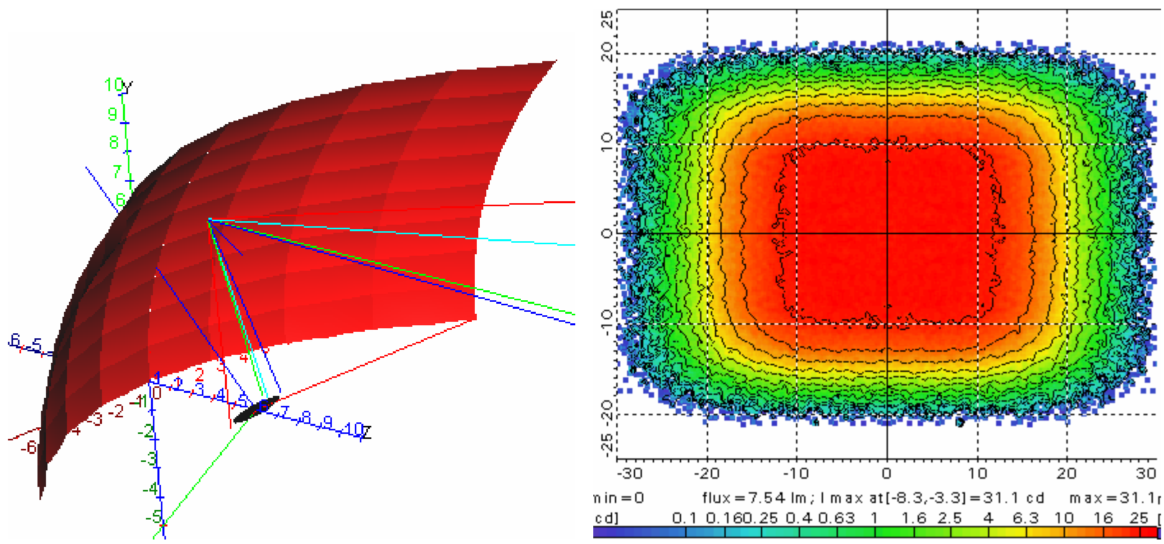

Fig.9: Reverse LED orientation with PS reflector, the Lambertian LED points towards the center of the reflector. This captures most of the emitter’s flux and allows for a good light control. The resulting pattern in this example is an almost square rectangular distribution. The falloff is set to a range of about ±30° by ±20° in angular width and height. Possible spill from the emitter is not directly pointing towards the main optical axis (into the desired angular range) and thus can easily be captured by the housing or a simple absorbing shield.

6. LED low beam automotive headlight

As an example of the off-axis reflector setup, we will briefly discuss an automotive low beam headlight. The regulations for automotive lighting demand a certain amount of light to be delivered by headlights. A single-die emitter alone can not produce enough light to comply with these demands. Therefore, either multi-source designs are created, which are recognized by their typical multi optics appearance – or a multi-die emitter is used. Examples for such LED for automotive applications are the OSRAM "*Ostar*", "*Joule"* or the Philips "*LAFLS*".

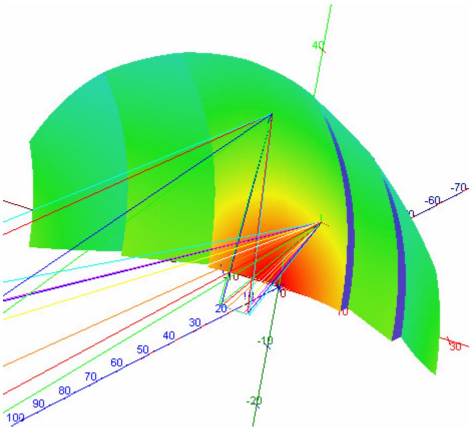

Fig.10: LED automotive low beam headlight: A multi-die emitter in reverse off-axis orientation illuminates the segments of the reflector.

In the design shown in Fig.10, a special collimator (see Fig.11) is used as secondary optics to illuminate the reflector. The orientation of the emitter is reverse (tilted), so the high luminance of the source is not directly visible. This systematically eliminates one of the possible sources of glare.

The LEDs for automotive headlights currently consist of five emitters, aligned in a row. Thus, they form a segmented rectangle. The images of such a rectangular source are well-suited to produce the sharp cutoff or the European 15° angle which are required for low-beams.
The collimator optic not only ensures an appropriate and more uniform illumination of the reflector, it also reduces the spill from the otherwise almost Lambertian emission from the emitters. This share of the light is also directed onto the reflector, increasing the efficiency of the headlight.

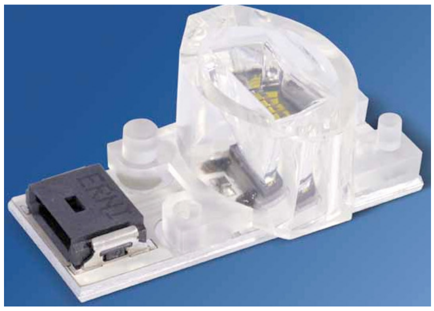

Fig.11: OSRAM Ostar (5 dies) with mounted collimator optics

The combination of a single light source (one multi-emitter LED) with only two optical components (one collimator and one reflector) makes a beautifully simple design approach. The small number of parts is a significant advantage. Also, the possible use of a clear outer lens offers a variety of design options and guarantees a distinct appearance of such headlights.

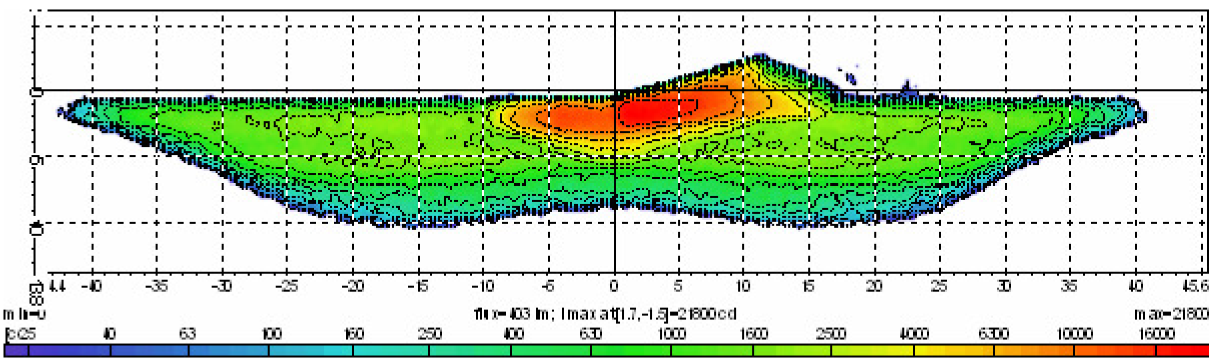

Fig. 12: Simulated LED low beam pattern [cd], showing sharp cut-offs and the 15° angle (ECE)

7. Conclusion

The special properties and characteristics of LEDs allow a variety of design options and degrees of freedom but imply certain peculiarities in comparison to classical light sources. Modern light development software supports the complex design process and allows detailed manipulation and optimization of an LED-based optical system and its individual components on the computer screen. The available LED source models, allow a precise treatment of the emitter characteristics and the near-field pattern of the LED, if sufficiently detailed rayfiles with an appropriate number of rays are used.

It is mainly the half-space emission of LEDs that dominates the design options. Satisfying solutions to a lighting problem can be approached in a virtual developing environment with different levels of precision and effort. If the requirements for a design are not so rigid to eliminate all but one basic design option, it can be of great value to investigate different approaches. The direct illumination from the emitter can be addressed in direct or more indirect setups (e.g. reverse reflector setup). Among the available optics are TIR components like collimators, different reflector types and more sophisticated tools of optic design and light control (PS, PCS, MF).

However, the important influence of the primary optic on the angular distribution of the LED and thus, on selection or design of all other optical components, requires a good balance between the primary and secondary optics. Only well-matched optics will lead to satisfying results.

Especially for lighting projects where precision is of utmost importance, such as automotive headlight design, projector systems for imaging applications and alike, only a thorough digital design process can provide outstanding solutions in a decent amount of time.