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Tutorial

Solving the optics equation for effective LED applications

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Abstract

This article provides an overview of optical design for high-power LEDs and collimating light, and it will detail all the key issues related to physics, design and manufacturing.

Keywords: collimator; design; illumination; intensity; LED; manufacturing.

The topics covered in this article are as follows:

- Why a secondary optic is required when using a high-power LED.
- Physical laws that should be taken into account.
- Main guidelines for the optical design of a collimator.
- Typical performances and side effects of a collimator.
- Manufacturing and tolerancing issues on plastic injection molded collimators.

A high-power LED is not a ‘plug and play’ light source. It requires electrical, thermal and optical management. However, unlike electrical and thermal management, optical management is still mysterious. A regular high-power LED emits light with a Lambertian intensity distribution. The intensity level vs. emitting angle is a cosine function meaning light is emitted in half-space, from -90° to +90° (Figure 1). With such a light distribution, it is impossible to build an efficient directional lighting device because only a small fraction of the light is sent on the area of interest [1, 2].

A LED collimator solves this issue by redirecting all the light on the area of interest. A collimator is an optical component usually made with plastic that generates a parallel – collimated – beam out of a compact light source. It is made of a first central area that works in transmission, and a second peripheral area that works in total internal reflection (Figure 2).

A collimator is limited by physics. The most important limitation is called the ‘etendue’ law. This is a fundamental physical law. For any light beam, the beam cross-section multiplied by the intensity distribution is a constant value, which depends only on the light source. In simple language, this means that any optical system that reduces the beam angle of a light source also increases the beam diameter proportionally. This should be seen as a lower limit for real optical systems, as real optical systems with geometrical aberrations or diffusion tend to increase the beam spread. As a consequence, one can determine the beam angle of the output beam with the following rule $\theta_{output\,beam}=\theta_{LED\,beam\,angle}\times\frac{\phi_{LED\,apparent\,size}}{\phi_{optic\,diameter}}$. As a consequence, we can see that a narrow beam can be only achieved with a LED that has a small apparent size and/or a collimator that has a big diameter. This is the reason why most narrow beam optics are large. It should be noted that this rule is just an approximate rule.

Another limitation is the existence of light losses. Two types of light losses occur in a collimator. A small fraction of the light is absorbed by the bulk material. Relative bulk absorption is given by the formula, $A=1-e^{-a\times d}$, where d is the material thickness and a is the volumic absorption of the material. For acrylic, which is the most commonly used optical grade plastic, a is in the order of magnitude of 2×10^{-3} mm^{-1}, which means absorption losses are usually lower than 2%. Then some light is also lost on the optical surfaces. Each time light travels through a transparent surface, a small fraction of the light is reflected instead of being transmitted – this is called Fresnel losses – and these losses represent around 4% per surface for most common optical materials. As a result, the light transmission of a collimator is usually between 80% and 90%.

A regular collimator has five rotationally symmetric optical surfaces: input and output surfaces for the central area, input, reflective and output surface for the peripheral area. Therefore, five ‘optical parameters’ – one per surface – have to be defined by the optical design. The optical design is usually done as follows.

First, create a parallel ray fan (image at the infinite) out of a single point light source (focus). The central and the peripheral area need to be treated separately but they both can be designed with the same principle. Therefore, we will see only how the peripheral area shall be treated, knowing that the central area follows more or less the same rule. Obtaining a parallel ray fan out of a single point light source implies that the optical path, computed from the focus to any plane located outside the collimator, is a constant. This leads to the following formula:

$$e_1+n\times e_2-n\times e_3-e_4=const$$

where n is the refractive index of the material, e_i is the distance travelled by light in the material (air or plastic), e_3 and e_4 are preceded by a minus sign because of the reflection on the reflecting surface, and ‘*const*’ is a constant value that can be determined by applying the formula to a marginal ray (border limit conditions).

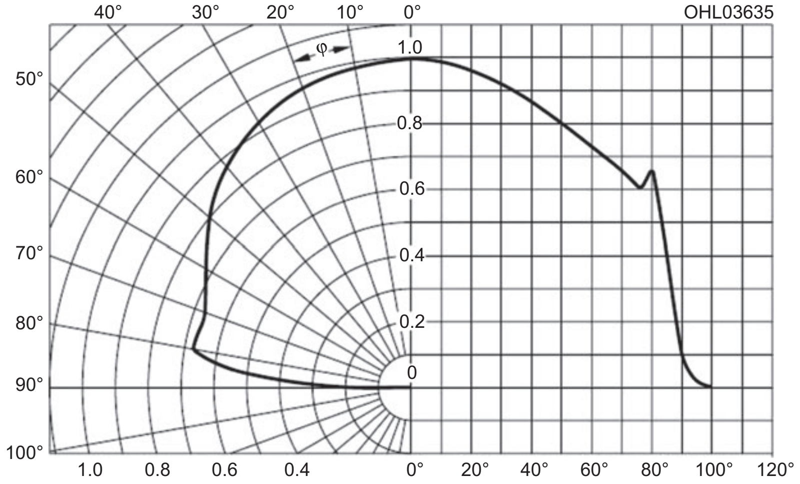

Figure 1 Typical intensity distribution (Osram Golden Dragon Plus).

Knowing that e_2 and e_3 depend on the coordinates (x,y) of the reflecting surface, one can deduce the exact coordinates (x,y) of the reflecting surface (Figure 3).

This technique defines the exact reflecting surface for a given input and output surface. In the particular case of a spherical input surface and a plane output surface, then light is deviated only by the reflecting surface and the calculation leads to a parabola. However, a parabola may not be an interesting system because it is not optimized in terms of size and beam shape. In the general case of aspherical input and output surfaces, then the calculation usually does not lead to an analytical formula. The coordinates (x,y) of the reflecting surface shall be numerically defined with a computer.

In most collimators the input surface is usually a cylinder with a small draft angle. This reduces the height of the system by 10–30% compared to a parabola. The output surface can be flat or concave. A flat surface gives the possibility to add textures to the collimator, to obtain an elliptical output beam or a tilted output beam. A concave surface gives the possibility to reduce the collimator thickness and therefore the injection process is simplified.

Figure 4 shows a geometry defined with this technique. The raytrace from the focus to the infinite shows that the light beam collimation suffers no defect.

Now let us analyze a typical light distribution from a collimator. Approximately 85% of the output light comes from the peripheral area that works in total internal reflection, meaning that the peripheral area is always the most critical. The beam angle is always characterized by the FWHM (full width half maximum). Only 45% of the output light is contained within the FWHM, meaning that the complete light distribution is always much larger than the FWHM. For this reason, the full width at 10% from the maximum also gives relevant information on the intensity distribution. As an example, if the full width at 10% and the FWHM are close, then the intensity distribution will look like a ‘top hat’ function and the visual effect will be nice and homogeneous. If the full width at 10% and the FWHM are significantly different, then the intensity distribution will look like a ‘triangle’, and the visual effect will be a bright spot superimposed with a diffuse backlight. Therefore, when selecting a collimator, the end user shall not look only to the FWHM.

A regular collimator also has some drawbacks. Unlike a regular reflector, it displays the image of the LED chip. This side effect is solely due to the central area that behaves like an imaging lens. It will always occur on narrow beams; however, it can be corrected by adding some blur and/or diffusing structure. We can also see a satellite ring around the main beam. This ring is three orders of magnitude weaker

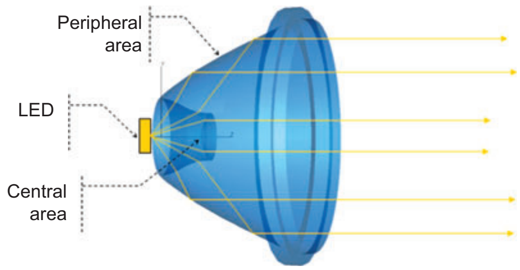

Figure 2 LED collimator.

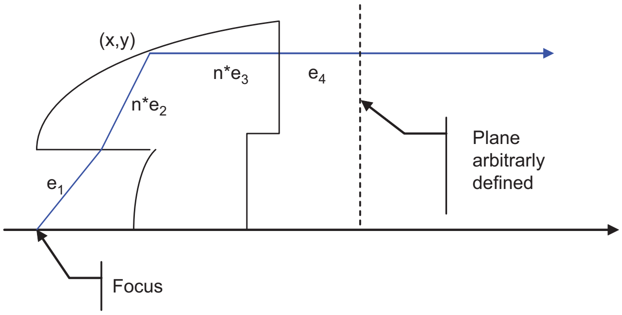

Figure 3 How to compute the reflecting surface.

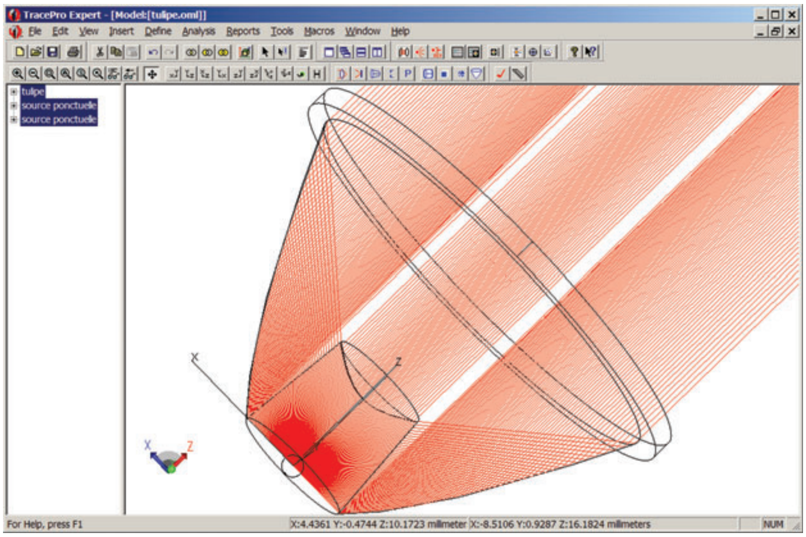

Figure 4 Single point source raytrace.

than the peak intensity, but due to the logarithmic response of the eye, it is visible in the dark. This is due to a reflection loss on the input surface that is sent back into the main beam. It can be reduced or smoothened; however, it cannot be removed.

The manufacturing is also a key issue on a LED collimator. The optical surfaces roughness has to be lower than 10 nm, otherwise light losses may occur. The optical surfaces shape accuracy has to be between 10 µm and 50 µm peak-to-valley depending on the surface, otherwise the beam spread may increase and homogeneity defects may occur. The centering and focusing is also critical, as a positioning tolerance >0.2 mm is likely to lower on-axis intensity and generate a non-rotationally symmetric beam.

A collimator is not a 'regular' plastic component. It is a complex combination of optical surfaces and it requires a high level of quality. Although it represents a small percentage of the total cost of ownership in any lighting device, it is the key component that shapes the light.

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