Modeling and optimization of freeform lenses for LED street lighting

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Freeform lenses are widely used for LED street lighting applications. A proper non-symmetrical light distribution on a roadway can be obtained with it. This optical solution is efficient, simple and low-cost. Modeling of freeform lenses based on two Bezier surfaces are discussed in this article. A mathematical model of such lens was created as a DLL-object and imported into the special illumination design software Lighttools. Ray-tracing and optimization of this lens was provided with Lighttools using a standard merit-function approach. In this work, a practical example of an extreme wide beam lens for bicycle and foot paths is demonstrated and discussed. Simulation results are compared with the measured data.

1 Introduction

White LEDs are already used in general lighting for about the last 10-15 years due to its high efficiency, long lifetime, compact size and other advantages. Nevertheless, white LEDs have also some issues. One of these is a so called “color over angle effect”. The ray perpendicular to the chip surface and one at the large angle to the surface normal have different optical path lengths d_1 and d_2 through the phosphor layer (see 0) and thereby different spectra and different correlated color temperatures (CCT). In practice, the difference in CCT can exceed one thousand Kelvin. For this reason, color consistency has to be taken into account during optical design with white LEDs.

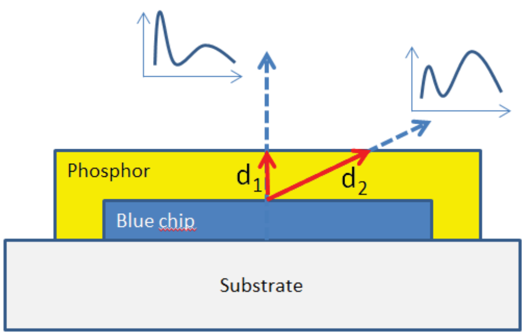

Fig. 1 *Schema of high-power white LED: spectrum and CCT variation over the angle of radiation.*

The most modern street lamps consist of high-power white LEDs in a combination with freeform lenses. This optical solution is very simple, efficient and low-cost. Freeform lenses achieve predefined light distributions and precise illumination of the roadway. Therefore, freeform lenses are so important for street lighting applications.

2 Modeling of freeform lenses for street lighting applications

The most commonly used mathematical methods to model freeform surfaces are: Bezier splines, B-Splines or NURBS (or Non Uniform Rational B-Splines). Each method has its own advantages and disadvantages. For street lighting applications, you do not need a very fine or complex shape. In most cases a Bezier-surface is enough to model freeform lenses for street lamps. The main advantage of Bezier polynomials is its simplicity and robustness during optimization.

Lighttools, a special illumination design software [1], was used to design and optimize these street lighting lenses. Freeform lenses were firstly created with Microsoft Visual Studio as DLL-objects and then imported into Lighttools.

A model of a freeform lens for street lighting applications is presented in 0. This lens consists of two freeform surfaces: an external and an internal one. The most street lighting illumination scenarios are symmetrical, thus the lens model is symmetrical, too. In order to accelerate the optimization process, only one half of the lens was modeled and optimized. The other half of the lens was simply mirrored.

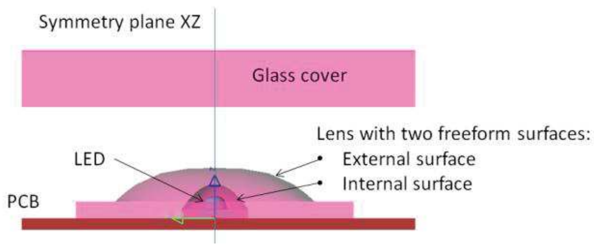

Fig. 2 *Model of a freeform lens for street lighting applications.*

3 Practical example: lens design for bicycle and foot paths

For one project, a special lens for bicycle and foot paths was developed. An extreme wide beam light distribution was created with the lens. The technical requirements in this project were:

- lamp mounting height H = 4 meters;
- pole distance L >= 40 meters;
- street width B = 3 meters;
- lighting class S5.

That means that the ratio H to L should be better than 1:10. According to DIN EN 13201, lighting class S5 means:

- average illuminance (3.0 lx < E_m < 4.5 lx);
- minimal illuminance E_{min} > 0.6 lx.
- uniformity (E_{min} / E_m) > 0.133.

The lens based on the Bezier-model described above was optimized with Lighttools according to all these targets (see 0).

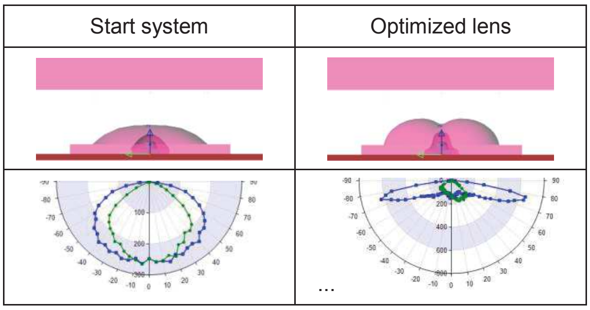

Fig. 3 *Lens shape and its light distribution for start and optimized lens.*

In the table below, the simulated illuminance and uniformity for the start system and for optimized lens are presented. All technical requirements for the project were fulfilled with the optimized lens as displayed in Tab.1.

	Requirements	Start system	Optimized lens
E_m (lx)	(3.0<E_m<4.5)	3.65	4.23
E_{min} (lx)	>0.6	0.09	0.93
(E_{min} / E_m)	>0.133	0.025	0.22

Tab. 1 *Comparison of simulation results for the start and optimized lens.*

4 Prototyping and measurement result

After the lens design was completed, the tolerance analysis was performed. Afterwards, the feasibility of the lens design was checked. Street lighting lenses are usually made of PMMA material in an injection molding process. Collisions and undercuts are not allowed. The minimal wall thickness of the lens is defined by the injection molding process. For the designed lens it was about 1 mm thick. After the feasibility analysis for the designed lens was completed successfully, some prototype lenses were molded from PMMA material.

A prototype luminaire including the modeled lenses was measured with a mirror goniometer. The measurement results are presented in Fig. 4. An extreme wide beam light distribution can be seen in Fig 4. The measured light distribution (LDT-file) was verified with the lighting planning software DIALux [2].

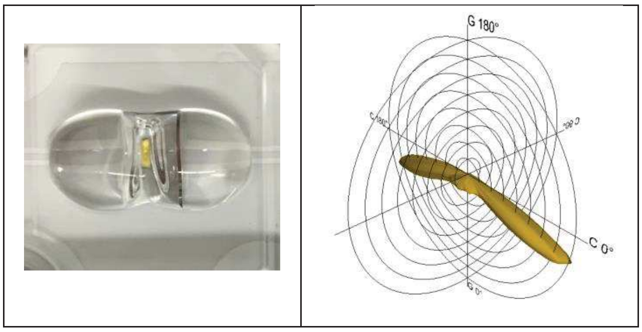

Fig. 4 *Lens prototype and measured light distribution.*

The simulated and the measured light distributions were compared to each other (see Tab. 2). Tab 2 shows a good agreement between the simulated and measured values.

	Requirements	Modeled LDT-file (18W)	Measured LDT-file (18W)
E_m (lx)	(3.0<E_m<4.5)	4.23	4.38
E_{min} (lx)	>0.6	0.93	0.92
(E_{min} / E_m)	>0.133	0.22	0.21

Tab. 2 *Comparison of simulated and measured light distributions*

5 Summary

Freeform lenses are very important for street lighting applications. Predefined light distributions and an exact roadway illumination can be obtained with these lenses. Freeform lenses were modeled with two Bezier surfaces. The freeform lens model was created with Microsoft Visual Studio as a DLL-object and optimized with the special illumination design software Lighttools.

A practical example of a special lens for cycle and foot paths with the ratio of lamp mounting height H to pole distance L better than (1:11) was demonstrated. A good agreement between the modeled and measured light distributions was achieved.

References

[1] *https://optics.synopsys.com/lighttools*

[2] *https://www.dial.de/dialux/*