Lux junior 2011
23. bis 25.9.11 Dörnfeld

Inverse Problems in LED secondary optics design

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Abstract

The LEDs stepped in the lighting technique and started shifting the conventional light sources – incandescent and discharge lamps from their traditional applications. The specifics of the LEDs make the conventional optical systems inefficient, because these solid state light sources do not emit luminous flux in the upper hemisphere and with reflective optical system the needed light distribution of the luminaires cannot be achieved. For modeling of the light distribution of the LED luminaires, secondary lenses are used.

The task for design of the lenses' geometry, in a way that the needed light distribution can be reached can be classified as an inverse problem.

The current paper represents an attempt for solving of such a problem through bringing the inverse problem to an optimization task.

Intoduction

The LEDs (Light Emitting Diodes) are the most dynamically developing contemporary light sources, with continuously increasing field of applications. The LEDs can be characterized as point sources, so for achieving different light distribution for the different applications an individual approach is required. Currently the LEDs are mainly used for architectural lighting, light advertisements and signs, displays and for street lighting. For further development and wider use of these new light sources, different optical systems have to be designed aiming redirection of the light distribution of the LEDs in a way corresponding to the application. This is possible to achieve by means of different methods – optimal space distribution of the individual LEDs in a module, using different reflective systems or usind secondary lenses and optics – standard or freeform, according to the application and the specific requirements [1]. The efficacy of an optical system may be estimated through estiomation of the light losses. There are two basic components, in which such losses are possible and namely: losses in the secondary optics and losses in the luminaires. The secondary optics is an optical system that is not part of the LED, like lenses and reflectors, put over the LEDs. The efficacy of a luminaire depends on the light source used, the material of the optical system and the shape of the luminaire.The nature of LEDs as light sources leads to higher efficacy of the luminaires and the losses occur mainly in the secondary optics.The losses in the secondary optics depend on the specific element that is used. The losses in the luminaires are due to absorbtion, transmission and reflection of light beams from the optical system, before they reach the illuminated field. The basic goal of the secondary optical devices used for LED luminaires is the opportunity for redirecting the luminous flux of the sources thus achieving a desired light distribution. In case that the needed light distribution is close to the light distribution of the LEDs, the luminaire can be designed without using secondary optics. In these cases the cost of the luminaire is lower, there are less light losses and fewer components are needed. On the other hand the drawbacks of the LED luminaires without secondary optics are that the multiple - source shadow effect appears and it is impossible to achieve needed light distribution when it differs significantly from that of the LEDs as light sources. This problem can be eliminated through use of multiple LEDs, appropriately placed and pointed, but in this case the problem with the cooling of the LEDs emerges. Another decision for redirecting of the luminous flux is to use single reflector or refractor for all of the LEDs in the luminaire. In this case the efficacy of the luminaires is bigger, the multiple-source shadow effect is eliminated, but again the needed light distribution cannot be achieved. So the general conclusion is that the best method for achieving needed light distribution curve with LED luminaires is by using secondary optics. The main types of secondary optics are optical elements, used in addition to the primary optics of the LEDs and aiming the formation of needed distribution of the luminous flux of the light sources. Basically the secondary optics can be classified as optical elements, reflecting the light and optical elements, refracting the light. Through use of separate lenses for each LED in a luminaire it is possible to model different light distribution curve, according to the application.This approach has its drawbacks – more components are used and the manufacturing of the luminaires is harder and more exspensive [2].

Most of the LEDs emit their luminous flux symmetrically to their optical axis. This allows their light distribution to be shown in two dimensional graphs, showing the dependence of the light intensity and the angle to the optical axis of the LED. The basic parameter of the light distribution is the Full-Width Half-Max (FWHM) angle (fig.1). It gives the angular width of the light distribution in a point, where the intensity decreases to half of the maximum intensity.

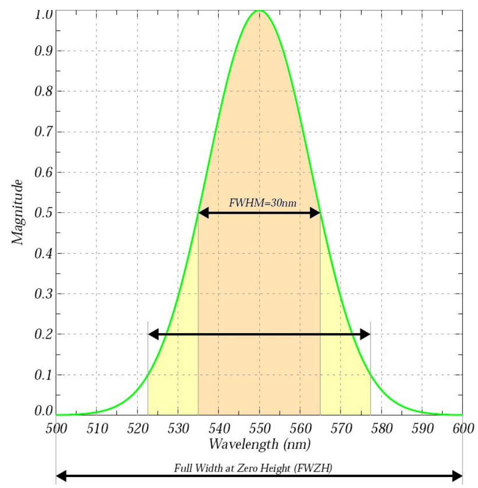
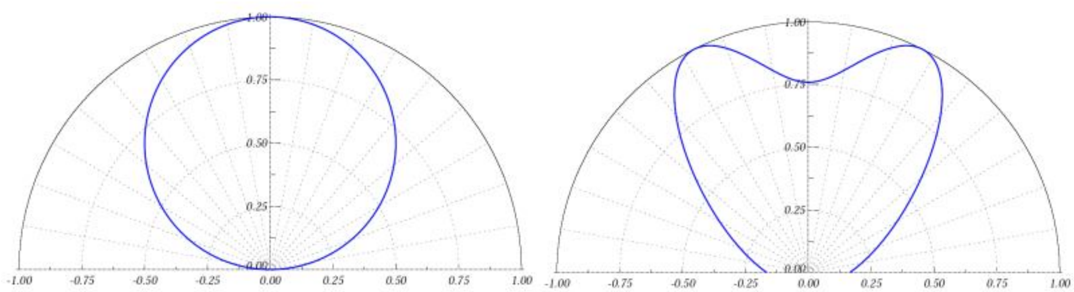


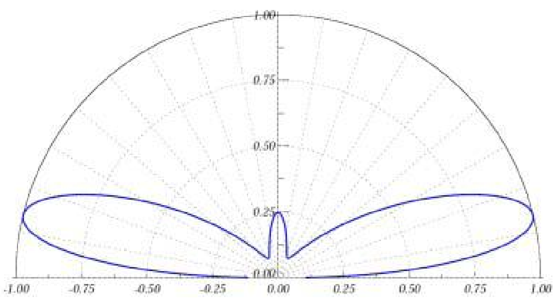
Fig. 1 LED Spectrum

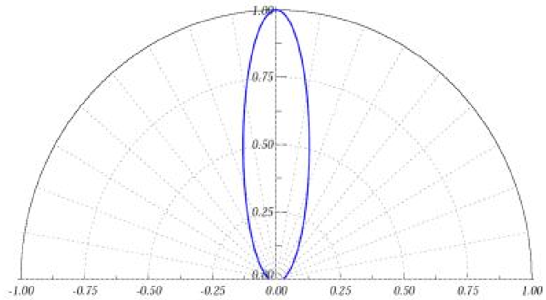
There are four basic types primary optics for LEDs - Lambertian, batwing, side-emitter and narrow angle (fig. 2 a), b), c), d)).



a) Lambertian light distribution

b) Batwing light distribution





c) Side-emitter light distribution d) Narrow angle light distribution

The Lambertian light distribution is most common for the LED light sources. The lambertian lens (primary optics) gives evenly distributed light output with cosine light distribution curve. For further redistribution of the light secondary optics is needed. Basically the secondary optical devices can be two main types – collimating and diverging. The cheapest types of secondary optics, which is also easier to manufacture are the simple lenses, which can be either conventional convex type, or Fresnel lenses. Such devices however have low efficacy, because they do not utilize the light that is emitted sideways from the LED chip, which leads to light losses up to 50%. Another decision is the use of TIR (Total Internal Reflection) lenses. They have high collection efficiency of around 85% Their disadvantageis that the optics are thick sections of plastic which makes them more difficult to injection mould and expensive compared to thin section injection moulded parts.Thick plastic sections also increase the optical absorption losses inside the optic which obey a cube law with optical path length. Another alternative is the use of simple reflector Simple parabolic reflectors, or more complex reflector forms, can be used to collimate LED outputs. However, the central cone of light projected forwards on axis from the LED is not controlled and therefore is lost outside the collimated beam. Unfortunately, this central cone of light is the highest intensity part of the beam and the reflection efficiency of the optic will decrease with increasing incidence angle. Typical overall collection efficiency is around 60-70%. The POL Hybrid Reflector design uses a central lens to collect and collimate the on-axis light from the LED. In this way, the light collection efficiency can be driven up to >90% [3].

In all the types of secondary optics, mentioned above the opportunity for redistribution of the luminous flux in a desired way is limited. That is why for specific applications, the design of more complex lenses and secondary optics is necessary.

Methods for secondary lenses design

For determinimg the shape of secondary lenses for individual LEDs, different approaches and methods can be applied. Freeform optical components are considered as the best technique to get the desired illumination. There are two methods to design the freeform lens: one is the trial and error method, which requires long time. The other is to construct the lens using the non-imaging tailoring method. These methods have lots of limitations and are time consuming.

A classical design approach of non-imaging optics includes generation of a mathematical description of the element and then converting it to CAD formats. Then, the CAD model is imported into raytracing 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. The general trade-off in non-imaging optics is between conservation of etendue and both mechanical and technological constraints. The optimization approachmakes it possible to find best solution, that simultaneously fulfills the requirements and meets 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. A design method that consists of add-ons for commercially available optical design software, ensuring the necessary flexibility and robustness is proposed in [5]. For parametrical modelling of optical elements rational Bezier splines are used to ensure sufficient flexibility in representing standard conic curves and even piecewise Cartesian ovals. High-order Bezier splines are numerically stable 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.

The SMS (Simultaneous Multiple Surfaces) method is another approach for optical design and gives good results, especially when the goal is to obtain a complex optical device that can efficiently distribute light from the light source to a surface that must be illuminated. In this method all the surfaces of the lens or reflector are calculated simultaneously from a predefined initial point [4]. SMS surfaces (in 2-D geometry) are piecewise curves made of several portions of Cartesian ovals, so that some of their characteristics are first detailed. Then the light rays are redirected after entering the medium of refractive index n.

An approach for optics optimization was considered in [6]. Based on refractive equation and energy conservation, a set of firstorder partial differential equations which represent the characters of LED source and desired illumination are presented. The freeform lens is constructed by solving these equations numerically. The numerical results show that throught this method, a freeform lens can be modeled, that gives light of uniformity near to 90%, with considerable high computation speed. The method shortens the designing time of the freeform lens with high accepted tolerance. It is based on the Snell’s law and the energy conservation.

Another approach for lenses optimization employs Genetic Algorithms. Such an approach is used for optical design where analytical methods are difficult to apply and other optimization techniques are extremely inefficient or fail to yield good solutions altogether. For the applications presented in [7], a GA method is developed that can be used to design beam-shaping optical systems. In order to judge the effectiveness of this optimization-based method, four increasingly difficult beam shaping problems are solved. A computational method, which builds upon proven ray-tracing techniques, is developed for determining irradiance profiles. This method is the key to quantifying the efficacy of a beam shaper in terms of a merit function. When this merit function is coupled with a GA, an optimization technique is employed. The GA is able to find a satisfactory solutions for such problems in a significant but reasonable amount of time. This is particularly interesting since the GA requires little (often no) user input once the problem is started.

In recent years, with the advancement of high-speed computing and optical analysis software packages, the computer-aided optical analyses of LED and optical lens can be accelerated, so as to save time, manpower and costs. However, for all analytical software used, a lens shape model must be set up before LED design analysis. A two-stage LED lens design optimization system is proposed in [8], that uses the viewing angle and the luminance uniformity as the optical quality objective. Optical design software (TracePro) and the orthogonal table of Taguchi method were used for simulation experiment. In the first stage, the viewing angle was used as the optical quality objective to find out the preliminary optimization of lens shape. The optimal LED lens size parameter combination of the first stage was used in the second stage to create L25(56) orthogonal table, and then the Back-Propagation Neural Network (BPNN) was used to establish the LED lens quality predictor to predict the FWHM angle and luminance uniformity in different overall sizes. The Genetic Algorithm (GA) with the quality predictor was used to find out the optimum design parameter combination of overall size according to the required quality objective. A LED with wide viewing angle and high luminance uniformity was taken as an example in this study to design a LED optical lens with 135° FWHM angle and 93.35% uniformity.

To apply the economic and popular conventional Fresnel lens to a lighting system with multiple-LED light sources, it is helpful to appropriately arrange the locations of LEDs and adjust their orientations. However, it is rather difficult and complicated to simultaneously design both locations and orientations of LEDs. Hence, in [9] are developed an efficient Genetic Algorithm to arrange LEDs' locations on x, y and z axes, and a Tabu Search Algorithm to adjust their orientations. The object is to optimize the illuminanc and uniformity of LED-based lighting system with a conventional Fresnel lens by appropriately arranging LEDs' locations and adjusting their orientations. During the evolution of arranging LEDs' locations, minimum distance between any two LEDs is maintained. Layout design of LEDs in an LED-based lighting system with a conventional Fresnel lens to optimize the illuminance and uniformity by using Genetic Algorithm and Tabu Search.

Problem definition and conclusions

There are a lot of complicated and time consuming algorithms for optical design. In all the above mentioned publications the goal function of the optimization task for lenses optimization is defined with respect to the size of the lenses and the uniformity of the illumination. The current paper presents the idea to optimize the lens' form using as input information the light distribution of the LED and the optimal light distribution curve for a given application that has to be achieved. This problem can be classified as an inverse problem. It is an optimization task that is chosen to be decided through a Genetic algorithm. The goal function is defined such as the optimal light distribution curve will be achieved with the simplest possible shape of the lens. The basic laws of reflection, transmission and absorbtion of light are taken in consideration. Feasible constraints are definated.

The results, obtained from the optimization task and the forms of the lenses obtained will be published and described in further works of the team.

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