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Advanced modelling and luminance analysis of LED optical systems

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Abstract. Designing, optimizing and analyzing optical systems as part of the implementation process into production of modern luminaires require using advanced simulation and computational methods. The progressive miniaturization of LED (light emitting diode) chips and growth in maximum luminance values, achieving up to 10^8 cd/m^2, require constructing very accurate geometries of reflector and lens systems producing complex luminous intensity distributions while reducing discomfort glare levels. Currently, the design process cannot function without advanced simulation methods. Today's simulation methods in the lighting technology offer very good results as far as relatively large conventional light sources such as halogen lamps, metal halide lamps and high pressure sodium lamps are concerned. Unfortunately, they often fail in the case of chip-on-board LED light sources whose luminous surface dimensions are increasingly often contained inside a cube of the side length below 1mm. With the high sensitivity of such small chips and lenses with dimensions ranging from a just a few to between 10 and 20 mm, which is presented in this paper, modern luminance distribution measurement methods, luminance modelling and ray tracing methods should be used to minimize any errors arising from incorrectly projecting the design in the final physical model. Also, very importantly, focus should be directed towards reducing a chance of making a mistake while collimating the position of the light source inside the optical system. The paper presents a novel simulation calculation method enriched with an analysis of optical system sensitivity to a light source position. The results of simulation calculations are compared with the results of laboratory measurements for corresponding systems.

Key words: lighting technology, luminance distribution, luminance modelling, LED, optical systems design.

1. Introduction

The second decade of the 20th century was a period of very rapid development of light sources and luminaires that now achieve luminance levels of up to 10^8 cd/m^2 [1, 2]. "Rapid development" is in fact an understatement. At that time, in the field of lighting technology, floodlighting and measuring technology [3–5], we were facing an actual revolution. The methods of design and analysis of optical systems were also changing [6–9]. The construction and specificity of light distribution in the light sources themselves in general applications has also changed considerably [10]. In the 20th century, the optical system design was mainly based on the use of mathematical methods and prototyping techniques. The design of a single luminaire required constructing several prototypes in order to verify the results and to modify the adapted assumptions. With the iterative method, the optimum solutions often meeting the complex assumptions in fields such as automotive lighting, road lighting or asymmetrical surface lighting were reached. The dynamic development of computers, knowledge how the light is distributed and how it interacts with the materials reflecting and transmitting the luminous flux allowed us to effectively simulate optical systems [11–13]. To a great extent, it reduced the time required to design the luminaires and then minimized the prototype production needs. In most cases, the knowledge of luminous intensity distribution (LID) of the light source, its luminous flux and dimensions was sufficient for conducting simulations.

Some slightly more advanced simulation methods taking account of the simplified luminance model of light sources allowed us to achieve the simulation results very close to the laboratory measurement results of analogical luminaire models [14, 15]. In more advanced models, the starting point was the precise luminance distribution of the light source placed in a three-dimensional geometric model of the optical system [16–18]. The largest differences in calculated luminous intensities for the needs of determining the luminous intensity distributions, as compared to the laboratory measurement results, did not exceed but a few percent [2, 18, 19]. The methods related to broadly understood ray tracing [20], such as the Monte Carlo method [21] and modified methods in the form of, for example, backward ray tracing methods, were developed and met the expectations of simulation and analysis of the photometric parameters of virtual models of the luminaires. Today's world of lighting technology and light sources, however, is completely different than it was just 10 years ago. It is common to design optical systems for very small light sources whose luminous surface is close to 1 mm^2 (Fig. 1).

Even in the case of analysis of light sources of much larger dimensions, the luminance distributions observed on their surfaces are most frequently not homogeneous (Fig. 8d). For the purposes of this paper, the basic calculations and measurements were made as for the example of the OSRAM OSTAR Headlamp Pro LE UW U1A5 01 chip, consisting of 5 sections, with a surface area of 1.012 mm^2 each (Fig. 2). The total maximum luminous flux of the light source is 2240 lm. Therefore, the average luminance of each luminous chip with the maximum luminous flux exceeds $1.4 \cdot 10^8$ cd/m^2.

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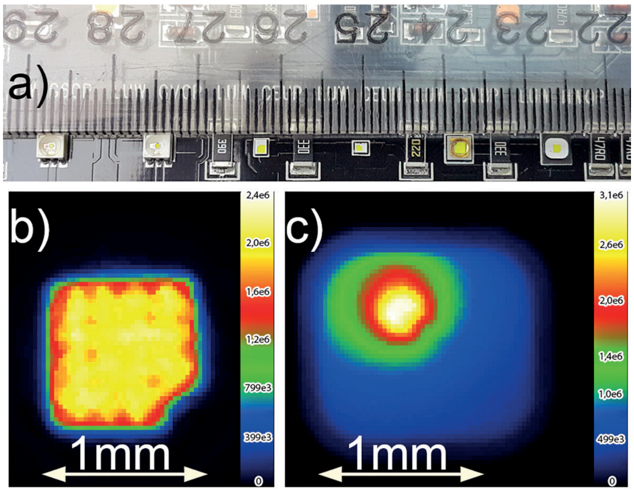


Fig. 1. Presentation of typical dimensions of high-luminance LEDs: a) the dimensions of light chips in millimeters, b) the luminance distribution of the OSRAM OSLON Signal LCB CRBP diode, c) the luminance distribution of the OSRAM Mini TOPLED LW MVSG diode (image enhancement: 800%, measuring distances: 200 mm, focal length: 50 mm)

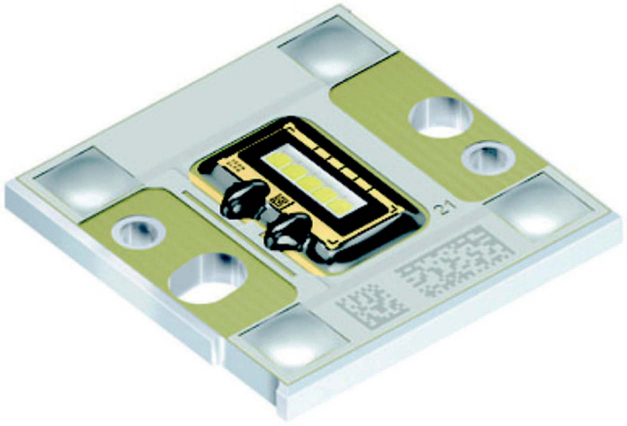


Fig. 2. Structure of the OSRAM OSTAR Headlamp Pro LE UW U1A5 diode

For such small LED chips of very high luminances, it is obvious that it is not only the precision of the designed lens system that is of key importance in the context of the obtained LID. The precision of placing the light source inside the optical system is even more important (Fig. 4). That is why it is crucial to reproduce the real position of the light source very accurately after implementing, with respect to the position of the light source inside the designed optical system in the virtual three-dimensional space.

2. Design and simulation problems in lens systems

The key design requirement is to achieve simulation results and laboratory photometry results for analogical systems at the same level, burdened by only the slightest error. In this case, the optical system designer's knowledge and experience as well as the lens injection mold constructor's knowledge and experience are essential.

The complicated knowledge of how the material behaves during the injection and cooling phase is required to minimize the differences between the design and the final production models. However, we should be aware of the fact that even the best design and the best made model will change their parameters drastically when the luminous center of the light source changes its position or is placed in the optical system inaccurately (Fig. 4). In support of this thesis, some laboratory tests were carried out using the existing lens made according to the design of the author of this paper, with a diode whose surface area of the chip is 1.4 mm × 1.4 mm.

Figure 4 explicitly shows that the displacement of the light source, whose luminous surface dimensions are 1.4 mm × 1.4 mm, by 0.5 mm towards the lens interior, causes some crucial changes in the LID. The maximum luminous intensity value is achieved for a different angle (C0, γ59 degrees against C0, γ63 degrees) with the simultaneous fall in the maximum luminous intensity value by up to 25%. There are two reasons for this situation. The first one is the above-mentioned displacement of very small diode in the small optical system. The second reason, of equal importance, is the accuracy or inaccuracy of the models of light sources used to design the optical systems. Today, a "rayfile" type model, whose structure is based on a model of a package of rays (Fig. 3b) sent into specific directions of space is dominant [14, 15, 22]. These rays, most often from 500 000 to 20 000 000, constitute the starting point in the process of photometric calculations of the luminaire optical systems. The precision of this model and the accuracy of placing it in the virtual optical system analyzed is responsible for the extent to which the results of simulation will be close to the photometric results of the physical model. The IES TM25 [23] model with its versions [14, 22] and simplifications (Fig. 3a and Fig. 3b) [24] is one of the most frequently used models. Figure 3 shows the idea of the rayfile package model in relation to the data pre-

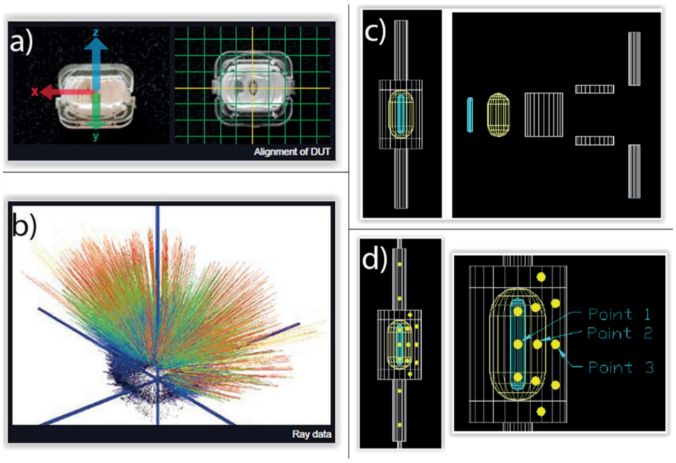


Fig. 3. Example model of the "rayfile" (a and b) and structure of the light source model implemented in the LTI Photopia software (c and d)

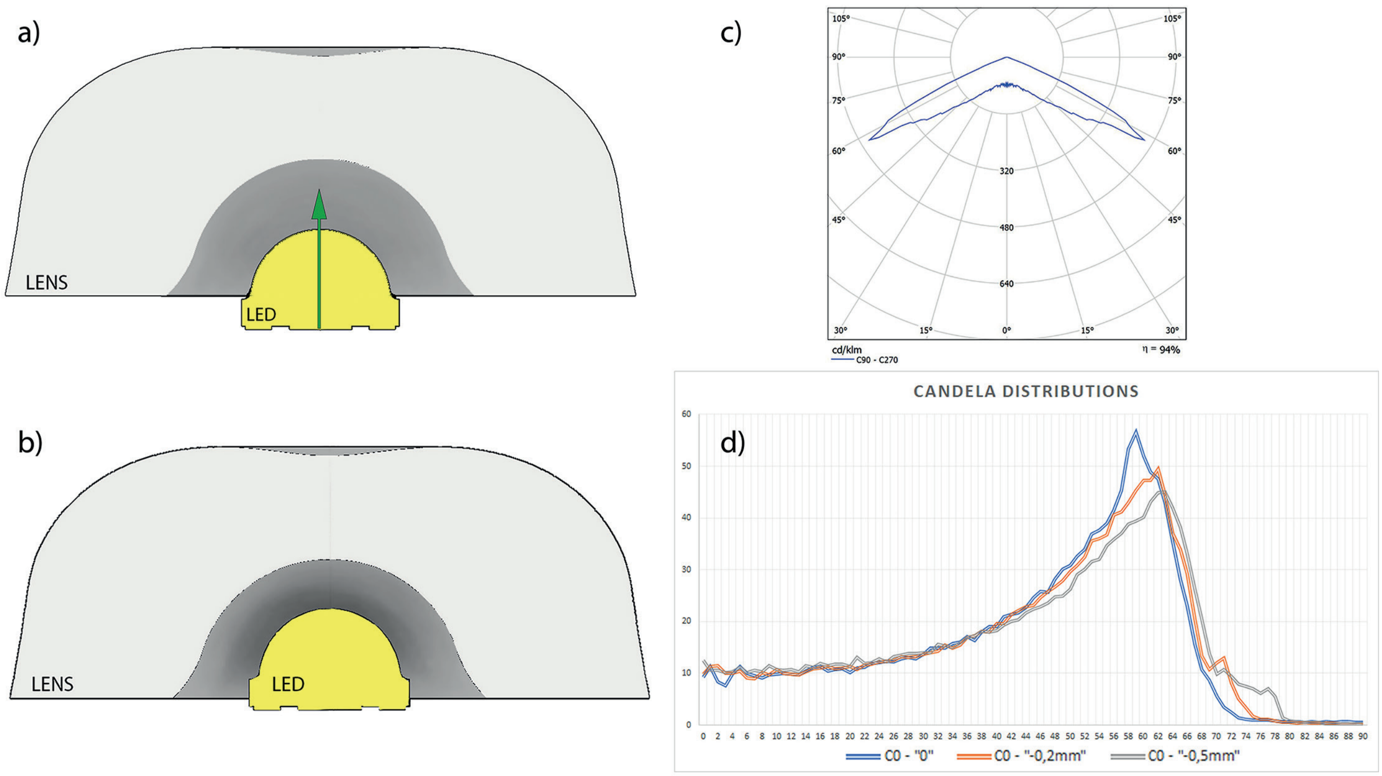


Fig. 4. Visualization of the position of light source against the optical system: a) zero position of the light source with the marked direction of changes, b) extreme position of light source, shifted by 0.5 mm against the zero position, c) output LID in the polar system for the zero position, d) changes in the luminous intensity distribution curve in the C0 plane for 3 positions of the light source (zero, shifted by 0.2 mm and shifted by 0.5 mm)

sented by the equipment manufacturers who offer the luminance photometry systems commercially [14, 22, 25].

The "rayfiles" contain a set of the start rays that can be used for simulation calculations. For 20 million start rays, the file takes up over 500 MB of data. In the "rayfile", such as, for example, TTR (TechnoTeam rayfiles), there may be information about luminous intensity distribution, luminance images, DUT (device under test) alignment, the burn-in protocol and acquired measuring values of external measuring devices (e.g. Power Analyzer). Additionally, integration of spectral information is possible (spectrum and wavelength per ray).

This type of data is used by the majority of commercial formats and applications available in the market, such as ASAP, Optis, LucidShape, LightTools, Zemax, TracePro, SimuLux, Photopia, etc. Being aware of the shortcomings, some commercial software producers, apart from a chance to use the above-mentioned file formats, try to develop their own models of light sources. There is the example of LTI, the company that developed its Photopia software. It designed its own model of light source (Fig. 3c and Fig. 3d). The basic geometrical data and information about luminous intensity distribution are supplemented with some simplified information about the light source luminance in a few defined points (Fig. 3d). Very small file sizes (even below 1MB) and inclusion of the light source's precise geometry that is taken into account in the "rayfiles" are important advantages of such model. Unfortunately, the inclusion of very limited luminance information is simultaneously a disadvantage.

Differences between the luminous intensity distributions obtained from the simulation with the use of the "rayfile" model and the results of laboratory measurements for the analyzed examples do not exceed 3% (Table 2). However, such systems are very sensitive to the quality of equipment used for measurements and analyses [26]. So far, the author of this paper has not met any scientific publication which presents detailed research for the complex collimator systems (Fig. 5) with SMD LEDs and lens systems in a universal manner. It should be expected that in such cases differences may be slightly higher, which will be directly related, for example, to the difficulty in ideally reproducing the position of the light source in the optical system, without the opportunity to verify luminance distributions for the 3d model and physical model.

Figure 4 clearly shows how quickly the LID is deformed as a result of changing the light source position. Therefore, what should be done to make the simulation results in the design phase as similar to the results of photometry for physical models of optical systems as possible? This "similarity" is very important because it significantly reduces the costs associated with the implementation of a specific design. The costs of injection molds represent an enormous part of the costs of the design and implementation process of new optical systems. One of the potential solutions to this problem of excessive sensitivity of the LID as a function of the light source position is to maximize the lens dimensions as compared to the light source dimensions. Unfortunately, most often it is impossible to increase the

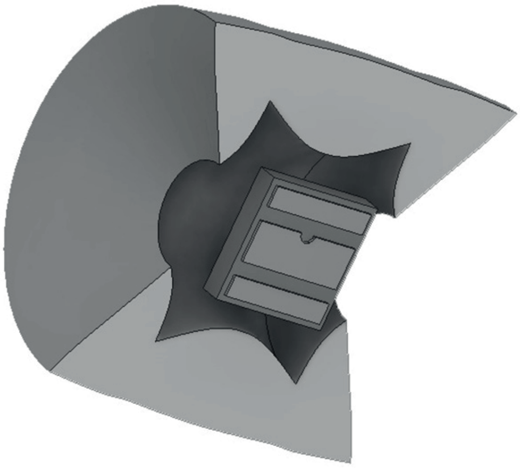


Fig. 5. Example design of modern optical system for LED Cree XP-G3

dimensions of the lens, since in most cases, the design process is subject to optimization in the opposite direction, i.e. it leads to the maximum possible minimization of the optics dimensions. An example of a collimator design whose solid is inside a cuboid with the dimensions of 8.7 mm in width×9.0 mm in depth×4.5 mm in height, is shown in Fig. 5.

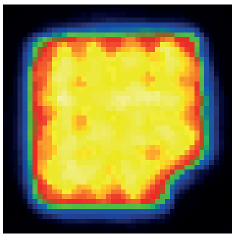
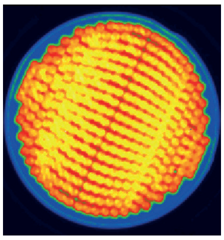
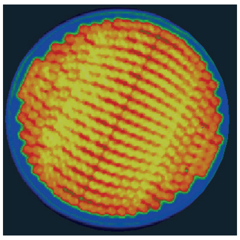
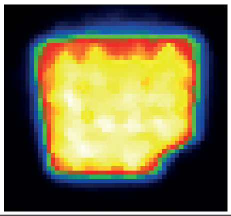
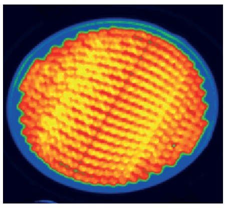
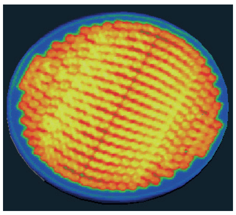
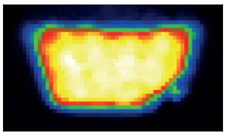
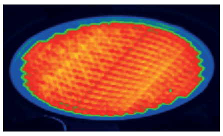
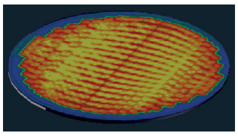
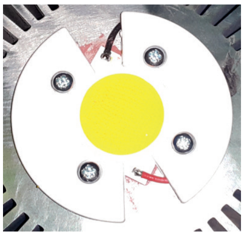
In the case of this solution, the contracting entity insisted that these dimensions be even more minimized although currently the largest dimension of the lens diagonal is 12.2 mm.

Increasing the proportion between the light source dimensions and the largest lens dimension is not an option. The focus should be on the other elements influencing the accuracy of the simulation calculations as compared to the results of photometry of the physically existing optical systems.

3. Simulation method for traditional light sources

The central point of the rest of this paper will be shifted towards the most accurate reproduction of the physical properties of the light source in the computer memory space. Research proves [18, 26] that it will be a slight mistake to adapt the assumption of the Lambertian surface of the light source model (Table 1).

Table 1
Dependence of LED luminance distribution as a function of the observation direction for the selected SMD diode and COB type (image enhancement: SMD 300%, COB 150%)

	C0 plane				
	Laboratory measurements			Simulation	
	a	b	c	d	e
γ	LED SMD	cd/m^2	COB	COB	cd/m^2
0^0					
30^0					
60^0					
0^0					

Nevertheless, the impact of such an important simplification on the accuracy of simulation calculations will also be subject to verification.

The author's earlier research on discharge lamps, developed for the simulation calculation purpose, yielded very good results. The results of simulation calculations showed very high similarity to the results of laboratory photometry of luminaire models [17]. Therefore, it should be tested whether the developed and verified methods based on the analysis and mapping of luminance distributions on the models of geometric light sources will also yield good results as far as LED is concerned. In addition, one more issue is interesting. Will the luminance image on the surface of optical systems, used as a starting point in the luminous intensity calculations, yield results similar to the luminance image obtained on the surface of specular reflectors in the traditional systems [2, 27]?

$$I(C,\gamma) = \int_S L(C,\gamma)\cos\varepsilon\, ds \qquad [28]\ (1)$$

where:

$I(C,\gamma)$ – the luminaire luminous intensity in the C, γ direction;

$L(C,\gamma)$ – the luminance of a given point of the output luminaire surface in the C, γ direction;

ds – the elementary surroundings of a given point of the output S surface;

ε – the angle that creates a normal vector to the output surface in a given point with the C, γ direction.

The basic dependence for calculating luminous intensity [(1)] clearly shows that the value of luminous intensity in the (C, γ) direction is directly related to the luminance distribution of luminaire and the size of apparent surface area of this distribution in the analyzed direction. Thus, shaping the LID comes down to maximizing or minimizing the luminance image of the light source on the surface reflected from the reflector or on the outer surface of the lens (Fig. 6).

Assuming the constant luminance of the light source, the luminous intensity value will be directly proportional to the size of apparent surface area of the light source on the outer part of the optical system. In the algorithms developed for the needs of the described design, the real luminance distribution registered on the LED surface is used (Table 1). For the purposes of the current research, the luminance distributions of 10 light emitting diodes made in different technologies were registered. This paper presents the individual luminance distributions for the selected observation directions, for the example of the COB diode, SMD LED (Table 1).

The results of measurements (Table 1 – column a and c) and of simulations (Table – column d) clearly show that in the analyzed cases, adaptation of the preliminary assumption of the Lambertian luminance distribution on the surface of a precise model of the luminous LED chip surface will not be burdened with a large error. Some small differences in luminance distribution appear only as for the COB diodes above the γ angles = 60 degrees. These differences do not exceed 5% of the luminance value as compared to the γ direction = 0°. The comparison of column d with column c in Table 1 shows that the use of only one luminance distribution characteristic of the (C0, γ0) direction in the analyzed case for the whole simulation calculation cycle will be eligible.

However, attention should be paid to the fact that the diode luminance distributions used for calculations should be verified against laboratory methods each time. This is required to ensure that the assumption of the Lambertian luminance distribution on the chip surface will not generate a significant computational error. When some significant differences in the luminance distributions for axial directions and for those almost perpendicular to them have been found, the method will have to be modified in such a way that the luminance map used for calculations will have to be changed depending on the direction (Table 1 – column c).

The method developed by the author, assuming the mapping of luminance distribution on the surface of the geometric model of a metal halide lamp arc tube, yielded very good calculation results [16–18]. Currently, the author is attempting to change and verify the algorithms for the needs of lens systems for LEDs.

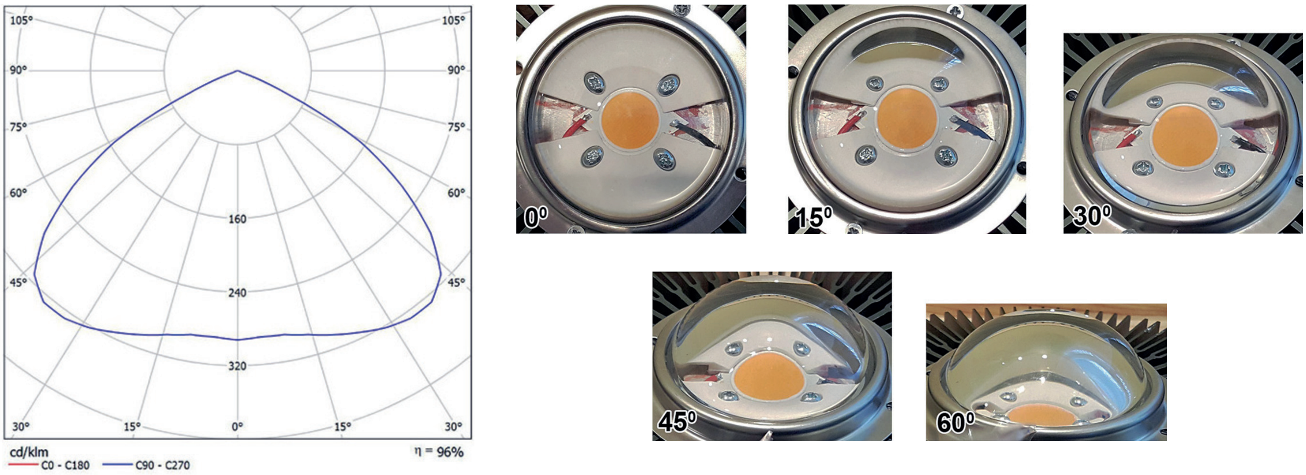


Fig. 6. Shaping the LID by optimizing the size of luminance image of the light source

4. Simulation method for LED sources

The method consists in developing a geometric model of the luminous surface of the light source and mapping the registered luminance distributions on it. If a simplifying assumption, covering the Lambertian luminance distribution independent of the observation direction is accepted, then the luminance distribution registered from one direction will be sufficient in the extreme case (Table 1). If this assumption is omitted, it will be necessary to use a large number of the registered luminance distributions characteristic of many directions in space. With very variable luminance distributions for spatial light sources, it may be required to use luminance distributions even for more than 145 directions in space. This number results from the necessity of registering the luminance distributions of the light source in the C system, γ for the C planes every 30 degrees (0°, 30°, 60°, 90°), with a variability of the γ angles of 5 degrees ranging from $\gamma = -90°$ to $\gamma = 90°$. Of course, in the extreme case, with small dependence of luminance distributions of the light source on the observation direction (Table 1, column d), assuming the Lambertian feature of changes to luminance, it becomes possible to use only the luminance distribution registered for direction (C0, γ0). In further calculations, the light source models presented in Table 1 were used.

Mapping the geometric model of the LED with the measured luminance distribution has an additional massive implementation advantage. It makes it easier for the designer to precisely place a diode in the physical model of an optical system consisting of a lens, electronics and other components that make up the final luminaire model. Additionally, it enables unambiguous verification of the precision of placing the light sources inside the optical system by comparing the simulation luminance distributions and luminance distributions measured on the physical surface of the model, with the use of the imaging luminance measuring device (ILMD).

Like in publications [2, 16, 17], a specific variant of the ray tracing method was used for the calculations. It consists in applying the backward ray tracing method. In the backward ray tracing method, for each of the analyzed directions, from the observer towards the luminaire, as many parallel rays are sent as is the number of the discrete elements that the outer surface of the optical system model is divided into. In other words, the last surface of the lens or reflector, on which the light point figure (LPF) lands is subject to evaluation. The LPF is treated as a light source image on the reflector or lens surface (Fig. 7).

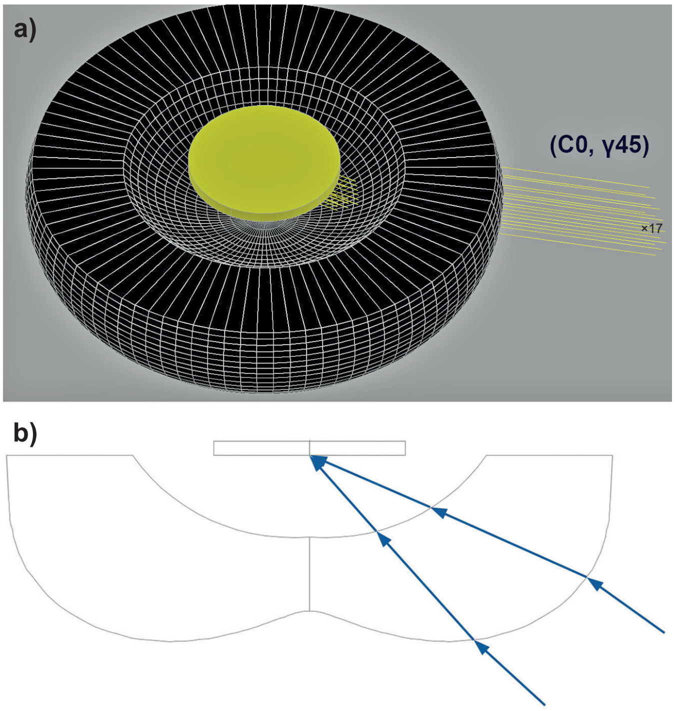


Fig. 7. Visualization of implementation of the backward ray tracing method: a) 17 example rays from one direction in 3D space, b) the course of example rays in lens cross-section

Each of the inverse rays, hitting one discrete element, undergoes reflection or refraction. In the case of specular reflection, this is a single reflection for a typical reflector. As far as the lens is concerned, it is a series of successive refractions and total internal reflections of each ray. Next, the relation of each ray with the geometric luminance model of the light source is checked (Table 1 and Fig. 7a). If the analyzed ray does not hit the luminous part of light source, the analyzed optical component is black in the analyzed direction (Fig. 8c). In other words, the analyzed component does not participate in generating the luminous intensity in the analyzed direction. If the tracked ray hits the luminous part of the light source, it means the output component of the optical system takes the value of luminance characteristic of the light source point which the ray has hit (Fig. 8c).

After performing full analysis, for all discrete elements that the optical system model is divided into (Fig. 8a or Fig. 8b), the luminance distribution that is responsible for the value of luminous intensity in the analyzed direction is obtained on the optics surface. The procedure should be repeated as many times

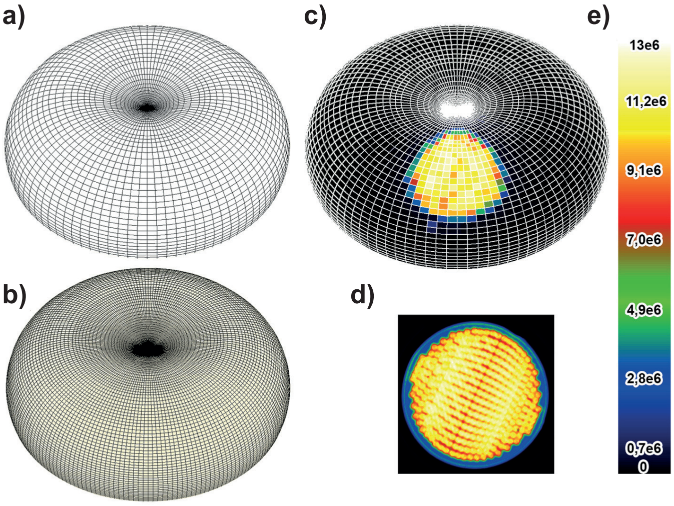


Fig. 8. Elements directly influencing the accuracy of calculations: a) and b) density of division of the optical system model, c) simulation result for the C0, γ45 direction, d) light source model used for calculations, e) false color scale of luminance for Fig. c and d

as there are directions subject to analysis for the subsequent directions (C, γ).

The computational complexity of the presented method is much lower than in the case of the typical ray tracing [20]/Monte Carlo method, because only the directions that were predefined are analyzed – the ones interesting to the designer, with a certain accuracy of calculations. To increase the accuracy of simulation calculations, only the computational mesh should be made more complicated. This means and increase in the number of discrete elements that the luminaire optical system is divided into (Fig. 8a and Fig. 8b). The increase in accuracy comes directly from the fact that a particular analyzed discrete element for a given direction is characterized by one luminance value for its entire surface. The surface area of this element from the analyzed direction is its projection on a plane perpendicular to the observation direction. Increasing the density of the measurement mesh is nothing else but reduction of each individual element to which the specified luminance value coming from the intersection point of the inverse ray and the output surface of light source with the characteristic LPF corresponds (Fig. 8).

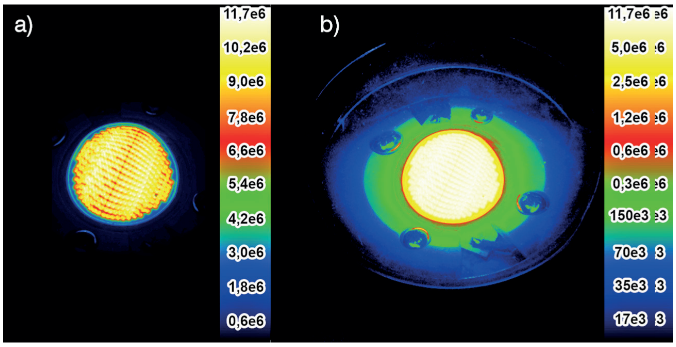


Fig. 9. Result of measurement of luminance distribution of the analyzed system for direction (C0, γ30) on the false-color scale – a). To show the geometry of the lens, the logarithmic scale was used – b)

5. Measurement and calculation results

In order to verify the method, a precise three-dimensional model of the glass lens for COB was made (Fig. 6 and Fig. 8). The measurements of luminance distributions and luminous intensity values for the existing luminaire were carried out on a laboratory stand with an H-V goniophotometer and ILMD.

For the analyzed direction (C, γ), the simulation results (the luminous intensity value and LPF luminance distribution), the results of luminance distribution measurements under laboratory conditions and the result of luminous intensity measurement (not calculations) were compared. On the basis of the data, the LIDs were drawn and the LPF was compared for the corresponding directions (Fig. 10b and Fig. 10c). At the high density of the computational mesh (Fig. 8b), the similarity between the results of simulation analyses, using the author's methods, and the results of laboratory measurements, based on the luminance distribution measurements and direct luminous intensity measurements, was very high (Fig. 10a). The largest difference in the luminous intensity distribution curve did not exceed a few percent (Table 2). This means the luminaires can be analyzed with this method for the purpose of designing advanced optical systems for LEDs and a chance of very accurate verification of the physical model by comparing the luminance distributions obtained by means of the virtual model simulation and laboratory measurements made for the physical model (Fig. 8 and Fig. 10). This is particularly important for very small LEDs and very small optical systems accompanying them (Table 1, column A).

Apart from the collimators dedicated to very small LED chips, special attention should also be paid to the optical systems cooperating with the light sources with inhomogeneous luminance distribution (Fig. 9a). The ratio of average luminance

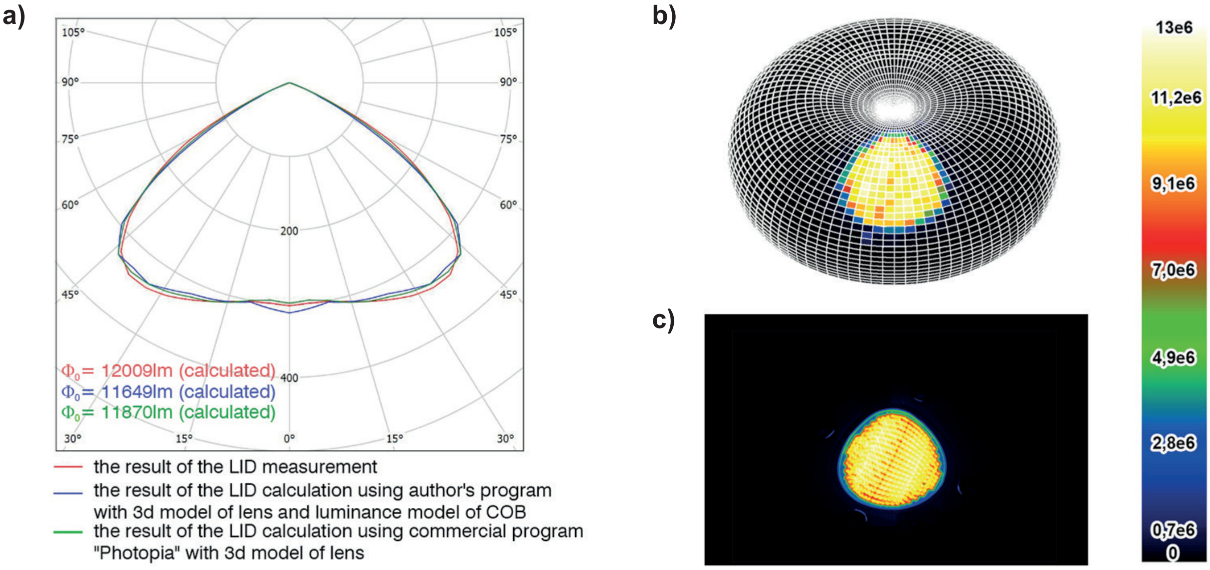


Fig. 10. Comparison of the lab results of luminous intensity distribution measurements with the results of simulation calculations – a), and comparison of the measured and calculated luminance distribution for the same (C, γ) direction – b) and c)

to the maximum luminance of such chips often exceeds 1:2 [1, 2, 27]. A short analysis of dependencies [(1)] shows that the luminance value used for calculations is of key importance and directly translates into the result of partial luminous intensity values in the analyzed direction that come from the individual discrete elements (Fig. 8c). For this reason, particular attention should be paid to the accurate registration of the light source luminance distribution, which should cover the ILMD sensor as much (more than 50% of the photosensitive surface) as possible during the measurement.

The performed analyses based on the simulation model with respect to the results of lab measurements [2, 18] and Fig. 10 clearly show that the proposed simulation method yields very good results. For the needs of presented simulations, the model of the lens was divided into 250 000 computational points. The used luminance distribution of the light source was registered by 500 000 photosensitive cells of the ILMD applied. In Fig. 10a, the results of laboratory measurements of luminous intensity distributions for the set shown in Fig. 6 are in red. The results of simulation calculations with the use of the three-dimensional lens model and the author's luminance model of the light source are highlighted in blue. The calculations were carried out on the computer software which was developed by the author of this paper, in AutoLISP language, working in the AutoCAD environment. The LID diagram in green (Fig. 10), presents the simulation results for the same three-dimensional lens solid carried out on the commercial software, Photopia [24], for 2 variants of the commercial models of light sources used (Fig. 3b and Fig. 3d). The Photopia software is unable to generate luminance distributions analogous to Fig. 10b and Fig. 10c, and for this reason they were not compared with the presented results of measurements and calculations made with the use of the author's software or with the laboratory measurements (Fig. 10b and Fig. 10c).

Its direct implementation, for both reflector systems and lens systems, gives very high similarity of measurement results and simulations. The type of light source used does not matter. Both discharge lamps such as metal halide lamps, multi-source LEDs of COB type (Table 1c and Table 1d) and single LED chips with extremely small luminous structures were analyzed (Table 1a). Typically, the largest difference in calculated and measured luminous intensity (Fig. 10a) does not exceed 3 percent. The largest differences may appear for small luminous intensity values and large viewing angles (Fig. 10a) obtained with the use of a very simplified light source model prepared on the basis of only one luminance distribution registered for the (C0, γ0) direction (Table 1d).

The solution to this situation is the use of variable luminance distributions of the light source to read out the luminance value of the light source part which has been hit by the inverse ray, depending on the angle of incidence of this ray on the surface of the mapped LED model. As far as the traditional light sources are concerned, it is proven that in most cases, sufficient accuracy is provided by using the luminance distributions characteristic of measurements with a change of angle of $\Delta\gamma = 5°$ [16, 18].

At the last phase of this paper preparation, some precise calculations were made to compare the similarity of luminous intensity distributions obtained as a result of laboratory measurements and simulation calculations for the analyzed case (Table 1 and Fig. 6). All simulation calculations for the purpose of obtaining the LID were carried out with the use of the presented method on the application written by the author, and on commercial LTI Photopia [24, 29] software. Photopia has an option of using typical files with "rayfile" data (Fig. 3b), and allows for the use of additional description of the light source developed by LTI (Fig 3c and Fig. 3d).

Measurements and simulations results of LIDs were compared using a known method [19, 30]. Papers [19, 30] present the methods related to the calculation of differences between two luminous intensity distributions [(2) and (3)]. In an ideal case, all the results of analyses should be identical. In the case of no difference, the $f_{\mathrm{luminaire\_fit}}$ value should equal 100.

For the research conducted, the differences between LIDs, calculated with the Bergen method [19], were $F_{\mathrm{luminaire\_fit}} = 98.72$ and $F_{\mathrm{luminaire\_flux}} = 0.988$ for Photopia and $F_{\mathrm{luminaire\_fit}} = 97.61$ and $F_{\mathrm{luminaire\_flux}} = 0.970$ for the method and author's software presented in Table 2.

$$f_{luminaire\_fit} = = 100\times\left(1-\sqrt{\frac{\sum_{C=0}^{360}\sum_{C=0}^{180}\left(I_1(C,\gamma)-I_2(C,\gamma)\right)^2}{\sum_{C=0}^{360}\sum_{C=0}^{180}\left(I_1(C,\gamma)+I_2(C,\gamma)\right)^2}}\right) \qquad [19]\ (2)$$

where: $I_1(C, \gamma)$ and $I_2(C, \gamma)$ – the luminous intensities distributions 1 and 2, respectively, at the angle (C, γ)

$$f_{luminaire\_flux} = \frac{F_1}{F_2} \qquad [19]\ (3)$$

where: F_1 and F_2 – the luminous fluxes calculated from distributions 1 and 2.

Table 2
Results of comparison of LIDs obtained from simulations in relation with LIDs obtained from laboratory measurements

	$F_{\mathrm{luminaire,\ fit}}$	$F_{\mathrm{luminaire,\ flux}}$
$\mathrm{LID}_{\mathrm{\_measurement}}$	–	–
$\mathrm{LID}_{\mathrm{\_author's\ simulation}}$	97.61	0.970
$\mathrm{LID}_{\mathrm{\_Photopia\ simulation}}$	98.72	0.988

However, the purpose of this paper is not to perform a broad comparison of the results for many cases. The main goal is to present a new universal light source modelling method that allows to calculate parameters of optical systems with any light sources, regardless of whether any manufacturer provides "rayfile" models to them or not. Taking into account the results of comparison of LIDs, for the author's method and application with the commercial simulations based on the "rayfiles" and LTI's model that in relation to the reality for the analyzed case are below 2.5% (Table 2), it can be found that the precision of simulation with the use of the presented method offers results at a very good level of accuracy. The presented calculation results are based on the lens model, which was divided into 250 000 elements. Increasing the density of the computing mesh, over 250 000 elements, will provide an additional approximation of the results to the ideal value.

The universality of the presented method and the chance for cheap and quick implementation of the model of light sources can make it very attractive. It should be remembered that the calculation based on the "rayfile" documentation, in accordance with the ISO TM25 standard, forces the use of very expensive equipment [14] to obtain the initial model of the light source. Without such a model, the designer is unable to make the design and calculations using the possessed light source that was not measured by the manufacturer. This reduces the opportunity to use any light sources in the design process. As a result, it is required to use the light sources with the appropriate files offered only by the world's largest manufacturers, such as OSRAM, CREE, etc., that supply such models. The presented method eliminates this limitation completely. Any designer only needs to physically have a light source that they want to use as well as an ILMD very commonly encountered today and used in lighting technology.

6. Summary and conclusions

Modern LED light sources used to construct luminaires, characterized by very large luminous intensity magnification in the selected directions, require an innovative approach in the process of design and verification of optical systems. LEDs achieve very high luminance values, exceeding 10^8 cd/m^2, which is shown in the introduction section of this paper. With the size of a single chip often not exceeding 1 mm x 1 mm, it is necessary to approach the optical system design process with great care because a direct view of the light source or its reflection with such a high luminance value is associated with discomfort glare occurrence [1, 31, 32]. A conscious design using such high luminance values to optimize the luminous intensity is very important while cutting off luminous intensity in the directions that cause glare. It is possible thanks to analyzing the course of each light ray and its relation to a specific point on the light source surface. In the presented method, the luminance distributions, i.e. luminance images of light sources on the outer surface of optical systems, constitute the starting point for the process of calculating the luminous intensity value. Therefore, they are an inseparable element of the design process and can represent an excellent source of knowledge about the specifics of a particular optical system.

It should also be added that high-resolution 3D printing methods can be used to improve accuracy [33]. These methods are beginning to be widely used to verify three-dimensional models in lighting systems with reflectors. 3D printouts of optical systems so-far are offered in the market only as a service [34]. This fact results in a low speed of implementation of these technologies among companies involved in the design and implementation of optical lenses for LEDs.

The paper presents a novel method of photometric calculations of optical systems for LEDs and other high-luminance light sources, based on the analysis of high-resolution luminance distributions (most often more than a million pixels per diode structure). The verification research performed shows that skillful development and use of the model offer calculation results of very high similarity to the laboratory measurement results (the largest differences do not exceed 3–5%). Additionally, the luminance analyses are a perfect tool to evaluate the optical system workmanship quality and the light source mounting precision in the optical system with respect to the designed position.

This article uses a simulation program which was created by the author of this publication and is not commercially available yet. The program was written in AutoLISP language, using the above-described method of light sources luminance modeling along with the backward ray tracing method.

We should be aware of the fact that preparation of a luminance-geometric model of the light source for the needs of the presented method may prove more labor-intensive as far as typical "rayfile" packages are concerned. Preparation of a typical rayfile model with the use of an automated measuring stand equipped with a computer-controlled goniometer, with the imaging luminance measuring device, is fast because it typically does not require any human intervention [22]. Nevertheless, the presented gains resulting from the use of the method discussed herein compensate for a difference in labor intensity of this method.

It should be remembered that if the manufacturer of the light source to be used in the project by the designer does not have an expensive measuring device to perform the "rayfile" model [14, 15], the designer will not have any chance to carry out any precise simulation calculations. The main advantage of the presented method is its versatility. Having an imaging luminance measuring device and a light source is sufficient to prepare the luminance model and perform calculations. Otherwise, the designer will be limited to the light sources from the largest global corporations that actually provide their "rayfile" models.

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References

[1] S. Słomiński, "Typical Causes of Errors during Measuring Luminance Distributions in Relation to Glare Calculations", 7th Light. Conf. Visegr. Countries, LUMEN V4 2018 – Proc. (2018).

[2] S. Słomiński, "Advanced Luminance Modeling of Light Sources for Simulation and Computational Purposes of Lighting Parameters", 7th Light. Conf. Visegr. Countries, LUMEN V4 2018 – Proc. 2–6 (2018).

[3] H. Cai, "Luminance gradient for evaluating lighting", *Light. Res. Technol.* 48, 155–175 (2016).

[4] M. Kayakuş and I. Üncü, "Research Note: The measurement of road lighting with developed artificial intelligence software", *Light. Res. Technol.* (2019).

[5] T. Porsch and F. Schmidt, "Assessment of Daylit Glare Parameters With Imaging Luminance Measuring Devices (Ilmd) and Image Processing", *Gmbh, Technoteam Bild*. 1, 5–6 (2010).

[6] A. Rozowicz, M. Lesko, and H. Wachta, "The technical possibilities of losses reduction in the LED optical systems", Proc. 2016 IEEE Light. Conf. Visegr. Countries, Lumen V4 2016 (2016).

[7] J. Rami, G. Lorge, and P. Tarroux, "LEDs optical modelling and simulation for lighting application", in 10th International Symposium on the Science and Technology of Light (2004).

[8] S. Zalewski, "Design of optical systems for LED road luminaires", *Appl. Opt.* 54, 163 (2015).

[9] L. Zhu, A. Ge, Z. Ge, R. Hao, J. Chen, and X. Tao, "A Fresnel freeform surface collimating lens for LED"*, Light. Res. Technol*. 6, 952–960 (2018).

[10] P. Tabaka and P. Rozga, "Assessment of methods of marking LED sources with the power of equivalent light bulb", *Bull. Pol. Ac.: Tech.* 65(6), 883–890 (2017).

[11] R. Krupinski, "Dynamically variable luminance distribution as the method of designing and architectural floodlighting", Proc. 2016 IEEE Light. Conf. Visegr. Countries, Lumen V4 2016 (2016).

[12] K. Guzek and P. Napieralski, "Measurement of noise in the Monte Carlo point sampling method", *Bull. Pol. Ac.: Tech*. 59(1), 15–19 (2011).

[13] K. Guzek and P. Napieralski, "Efficient rendering of caustics with streamed photon mapping", *Bull. Pol. Ac.: Tech*. 65(3), 361–368 (2017)

[14] K. Bredemeier, "Photometric data for the development of lighting components", *Engineering for a Changing World* 59, 1–16 (2017).

[15] K. Bredemeier and F. Schmidt, "Ray data of LEDs and arc lamps", Technoteam BV GmbH, Germany, W. Jordanov, ILEXA GbR, Germany (2005).

[16] S. Słomiński, "Dynamic mapping of luminance in analytical model of source of the light", *Przegląd Elektrotechniczny* 86 (2010).

[17] S. Słomiński, "Luminance mapping to the light source model – possibilities to use a MML in the lighting technology field", *Przegląd Elektrotechniczny* 87, (2011).

[18] S. Słomiński, "Mapowanie rozkładu luminancji źródła światła w obliczeniach fotometrycznych odbłyśników zwierciadlanych (Mapping the luminance distribution of a light source in photometric calculations of specular reflectors)", PhD Thesis, Warsaw University of Technology, (2010).

[19] ASJ. Bergen, "Practical method of comparing luminous intensity distributions", *Light. Res. Technol.* 44, 27–36 (2012).

[20] C. Filosa, J.H.M. ten Thije Boonkkamp, and W.L. Ijzerman, "Ray tracing method in phase space for two-dimensional optical systems", *Appl. Opt*. 55, 3599 (2016).

[12] K. Kinameri, K. Akazawa and M. Awata, "The Monte Carlo method in the predetermination of a luminous intensity distribution", *Journals Free Access* 10(2), 2_25–2_34 (1986).

[22] Opsira GmbH, "Ray data measurement," https://www.opsira.de/en/products/lightlab/ray-data-measurement.html.

[23] IES TM-25–13, "Ray File Format for the Description of the Emission Property of Light Sources", Illuminating Engineering Society, (2013).

[24] LTI Optics, LLC, http://www.ltioptics.com/en/photopia-general-2017.html (2017)

[25] M. Lopez, K. Bredemeier, N. Rohrbeck, C. Veron, F. Schmidt, and A. Sperling, "LED near-field goniophotometer at PTB", Metrologia, 49: 141–145 (2012)

[26] F. Schmähling, G. Wübbeler, M. Lopez, F. Gassmann, U. Krüger, F. Schmidt, A. Sperling, and C. Elster, "Virtual experiment for near-field goniophotometric measurements," *Appl. Opt*. 53, 1481–1487 (2014)

[27] S. Słomiński, "Selected problems in modern methods of luminance measurement of multisource led luminaires", *Light Eng*. 24, (2016).

[28] J. Bąk and W. Pabiańczyk, "Podstawy Techniki Świetlnej (Basics of Light Technology)", (1994).

[29] M. Tidd, "Freeform Optic Design Method with Multiple 2D Profiles: Type III Roadway Lens Example", *Optical Society of America*, paper JW1B.6. (2017).

[30] F. Gassmann, U. Krueger, T. Bergen, and F. Schmidt, "Comparison of luminous intensity distributions", *Light. Res. Technol*. 49(1), 62–83 (2017)

[31] S. Słomiński and R. Krupiński, "Luminance distribution projection method for reducing glare and solving object-floodlighting certification problems", *Build. Environ*. 134, 87–101 (2018).

[32] Y. Tyukhova and C. Waters, "Subjective and pupil responses to discomfort glare from small, high-luminance light sources", *Light. Res. Technol*. (2018).

[33] R. Walczak, "Inkjet 3D printing – towards new micromachining tool for MEMS fabrication", *Bull. Pol. Ac.: Tech*. 66(2), 179–186 (2018).

[34] S. Michaud, "Enabled by 3-D printing", *Optics & Photonics News 2* (2017).