НАУЧНО-ТЕХНИЧЕСКИЙ ВЕСТНИК ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ, МЕХАНИКИ И ОПТИКИ
март–апрель 2021 Том 21 № 2 http://ntv.ifmo.ru/
SCIENTIFIC AND TECHNICAL JOURNAL OF INFORMATION TECHNOLOGIES, MECHANICS AND OPTICS
March–April 2021 Vol. 21 No 2 http://ntv.ifmo.ru/en/
ISSN 2226-1494 (print) ISSN 2500-0373 (online)

ОПТИЧЕСКИЕ СИСТЕМЫ И ТЕХНОЛОГИИ

OPTICAL ENGINEERING

doi: 10.17586/2226-1494-2021-21-2-147-153

Designing a side-emitting lens using the composing method

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Abstract
The paper considers a design method for a side-emitting lens working with a single LED source and providing a narrow light beam in the horizontal direction within 360°. The authors deal with the composing method in the design, which is usually used to synthesize the initial scheme of the imaging systems. However, in this case, a similar approach is applied to the synthesis of a system, the task of which is to provide a certain shape and characteristics of the light beam. The stage of choosing an initial principal design and synthesis for non-imaging optics is especially important since this area is characterized by the use of so-called local optimization, the result of which strongly depends on the original system. Therefore, the stage of forming an initial approximation of the system becomes crucial. In this case, the composing method can provide the most effective choice of an initial scheme of a side-emitting lens. The application of the composing method and the theory of aberrations in the field of synthesis of the initial design of a side-emitting lens is shown. The paper describes a method for selecting the key parameters of the system, and presents the relationships that allow a preliminary evaluation of the characteristics of the designed system without the use of time-consuming calculation or optimization procedures. The presented approach makes it possible to ensure the choice of the initial point of the system for further optimization, as well as to achieve high efficiency of using the light flux by the optical system of the lens (up to 90 %), only due to the optimal size of the zones into which the beam is divided and to the optimal parameters of the generating curves. In this case, the lens profile is formed by two zones in each the profile is a conic curve, hence, the curve can be described by a small number of parameters, which is very convenient at the stage of searching the initial scheme. The proposed approach can be applied in the design of such systems, as well as applied at the stage of preliminary assessment of achievable characteristics, which can significantly speed up the development process.

Keywords
non-imaging optics, composing method, aberration theory, side-emitting lens, LED light sources

Acknowledgments
Xuanlin Qiao acknowledges support from the China Scholarship Council (ID 201908090046).

For citation: Romanova G.E., Qiao X., Strigalev V.E. Designing a side-emitting lens using the composing method. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2021, vol. 21, no. 2, pp. 147–153. doi: 10.17586/2226-1494-2021-21-2-147-153

УДК 535.317, 681.7.01

Разработка линзы бокового свечения с использованием метода композиции

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Аннотация
Предмет исследования. Рассмотрен метод проектирования линзы бокового свечения, работающей с одиночным светодиодным источником света и обеспечивающей формирование узкого светового пучка в горизонтальном направлении в пределах 360°. **Метод.** При проектировании использован метод композиции, который применяется

для синтеза исходной конструкции систем, формирующих изображение. В работе данный подход применен к синтезу системы, задача которой заключается в обеспечении определенной формы и характеристик светового пучка. Этап выбора принципиальной конструкции и синтеза для неизображающей оптики особенно важен, для которой характерно применение так называемой локальной оптимизации. Результат оптимизации в данном случае существенно зависит от исходной системы. В связи с этим особенно важным является этап формирования начального приближения системы. При этом метод композиции может обеспечить наиболее эффективный выбор начального приближения для проектирования линзы бокового свечения. **Основные результаты.** Показано применение метода композиции и теории аберраций в области синтеза принципиальной схемы линзы бокового свечения. Приведено описание метода выбора ключевых параметров системы. Представлены соотношения для предварительной оценки характеристики проектируемой системы без использования трудоемких процедур расчета или оптимизации. Предложенный подход позволяет обеспечить выбор начальной точки системы для дальнейшей оптимизации, а также добиться высокой эффективности использования светового потока оптической системой линзы до 90 %. Это достигается только за счет оптимального размера зон, на которые разделяется пучок, а также за счет оптимального выбора параметров образующей кривой. При этом профиль линзы формируется двумя зонами, в каждой из которых профиль представляет собой кривую второго порядка, которую можно описать малым числом параметров, что удобно на этапе компоновки. **Практическая значимость.** Рассмотренный метод может найти применение при проектировании подобных систем, а также применяться на этапе предварительной оценки достижимых характеристик, что может существенно ускорить процесс разработки.

Ключевые слова
неизображающая оптика, метод композиции, теория аберраций, линза бокового свечения, светодиодные источники света

Благодарности
Сюаньлинь Цяо благодарит за поддержку Китайский стипендиальный совет (ID 201908090046).

Ссылка для цитирования: Романова Г.Э., Цяо С., Стригалев В.Е. Разработка линзы бокового свечения с использованием метода композиции // Научно-технический вестник информационных технологий, механики и оптики. 2021. Т. 21, № 2. С. 147–153 (на англ. яз.). doi: 10.17586/2226-1494-2021-21-2-147-153

Introduction

LED sources are used everywhere to illuminate architectural objects, posters, shop windows, advertisements, for road illumination, in lighthouses, signal lighting, and other lighting devices [1].

The expansion of the fields of LEDs application has led to the rapid development of design methods for such systems. Most methods are based on the direct solution of the problem of finding the surface profile with the known characteristics of the light source or on automated design methods using specialized software (ASAP, LightTools, Zemax).

In practice, optical engineers widely use the selection of the shape of surfaces and elements based on approximate requirements for the ray paths and methods of automated design (optimization) of optical systems. However, even when applying this approach, it is necessary to have an idea of what shape the lens should be (one or more surfaces, the presence of total internal reflection, the division of the beam into zones, etc.). Besides, when using the SMS (Simultaneous Multiple Surface) method [2–4] or ray-mapping method [5], there is no way to preliminarily evaluate the achievable characteristics (for example, beam divergence when designing a collimator). Therefore, even for a standard element in the form of a collimating system operating on the Total Internal Reflection (TIR) effect, there are many solutions and methods proposed by many scientists [6–8].

For lenses and systems operating with one or multiple sources and providing a narrow beam in an annular zone for the full azimuth angle of 360°, methods based on finding the surface profile using the ray-mapping technique have also been proposed in a number of works [9, 10].

An alternative method of designing optics, which allows finding an initial solution quickly enough, is the so-called composing method. The composing method is understood as combining elements (optical surfaces or lenses) with studied and / or well-known properties. For imaging optics, these properties are aberration properties, but it is necessary to take into account the achievable distribution of luminous intensity or illumination distribution for non-imaging systems [11, 12].

As a rule, aberration theory is not applicable for the case of a source emitting inside a wide angle. To apply it to the area of non-imaging systems, it is necessary to consider not the aberration properties, but their influence on the light beam characteristics. For a collimating lens or a side-emitting lens these properties are the possible residual divergence.

Collimating optics can act as the basic version of the system making it possible to confirm the effectiveness of the proposed approach [12]. The authors have previously considered the application of the composing method for the initial scheme synthesis and analysis of the properties of a collimating lens operating on the effect of TIR. In this work, it is proposed to apply this approach for designing a side-emitting lens that provides a horizontal narrow light beam within azimuth angle 360°.

The composing method for designing a side-emitting lens

Let us consider at the first stage a point light source emitting within a hemisphere and a schematic layout of a side-emitting lens. Below, when composing a side-emitting lens, we consider several basic solutions, the properties of which are well known from the theory of geometric aberrations [13–15]:

— a lens with a first convex hyperboloid surface facing a point source and a second flat surface. The conic constant of the profile (hyperbola) $k = -n^2$. In the case of a point source located in the focal plane of such a lens, it provides an ideal parallel beam;
— a lens with a first spherical surface, concentric to the source point, and a second ellipsoid surface. The conic constant for the profile (ellipse) $k = -1/n^2$;
— parabolic mirror surface. Provides a parallel beam when a point source is located at the focal point;
— a spherical surface. It does not change the divergence of the beam if the center of the beam is in its center of curvature;
— a flat surface. It does not change the divergence of a parallel beam of rays incident perpendicular to it.

It should be noted that the elements listed above provide a strict absence of spherical aberration, that is, a strict stigmatic beam.

Since it is necessary to provide a horizontal parallel beam for the case when the LED light source radiates into the upper hemisphere, several solutions are possible using the elements listed above. Relatively powerful LED light sources often emit within a hemisphere, and according to the law close to Lambert's law $I = I_0\cos\theta$ (I, I_0 — is the luminous intensity in a given direction θ and along the axis, respectively), therefore, taking into account the wide beam, it is necessary to split the light beam into several zones, i.e., at least two zones. As we will show below, for the minimum number of zones we can balance the zones' size very quickly. The decision on whether it is necessary to further increase the number of zones is based on the analysis of the achievable beam divergence and the required dimensions. However, increasing the number of zones may lead to greater difficulties in manufacturing. Thus, our goal in this work is to show how we can increase the efficiency of using the light flux just by choosing the optimal size of the zones and the shape of the profile.

Fig. 1 shows the cross-section profiles of possible variants of a lens built from the basic elements, the side-emitting lens is formed by rotating the profile about the *OY* axis. Fig. 1, *a* shows a system where the beam is divided into two zones. The region of zone *I* can be considered as a sphero-ellipsoid lens, a parabolic reflecting surface operates in zone *II*, and surfaces are added that do not affect the divergence of the beam from a point source (spherical surface, concentric to the point where the source is located, indicated by the green line in the figure, and a flat surface). Fig. 1, *b* shows a variant where a sphero-ellipsoid lens is also used in zone *I*, but zone *II* is a plane-hyperbolic lens, into which an additional flat surface is introduced, providing the corresponding direction of the beam axis. Rays that correspond zone *II* are depicted in a red color, the edge ray for zone *I* is shown in blue.

A plane-hyperboloid lens for zone *I* is not considered since it will not be possible to manufacture the configuration obtained in this way by molding, and the variant with a sphero-elliptical lens for zone *II* is not analyzed, since in this case the dimensions of the system significantly increase or it is impossible to ensure full capture of the light beam in zone *II*.

For a lens of the first type (Fig. 1, *a*), the residual beam divergence in the horizontal direction will be determined by the source size, as well as by the coma aberration. For the central zone, the divergence angle due to the source size (ω_I') and aberrational (due to coma) ($\omega_{I\,coma}'$) can be determined on the basis of geometric relations and formulas of the theory of the third-order aberrations [16]:

$$\omega_I' \approx y/f_I',$$

$$\omega_{I\,coma}' \approx \frac{3y}{2(n-1)f_I'}\sin^2\sigma_I,$$

where y — size of the luminous area of the source; f_I' — focal length of a sphero-ellipsoidal lens; n — refraction index of the material.

Full beam divergence is defined by the full divergence angle that is the sum of the values:

$$\omega_I' + \omega_{I\,coma}'.$$

Besides, it is convenient to introduce dimensional relationships for zone *I*. The diameter of the side-emitting

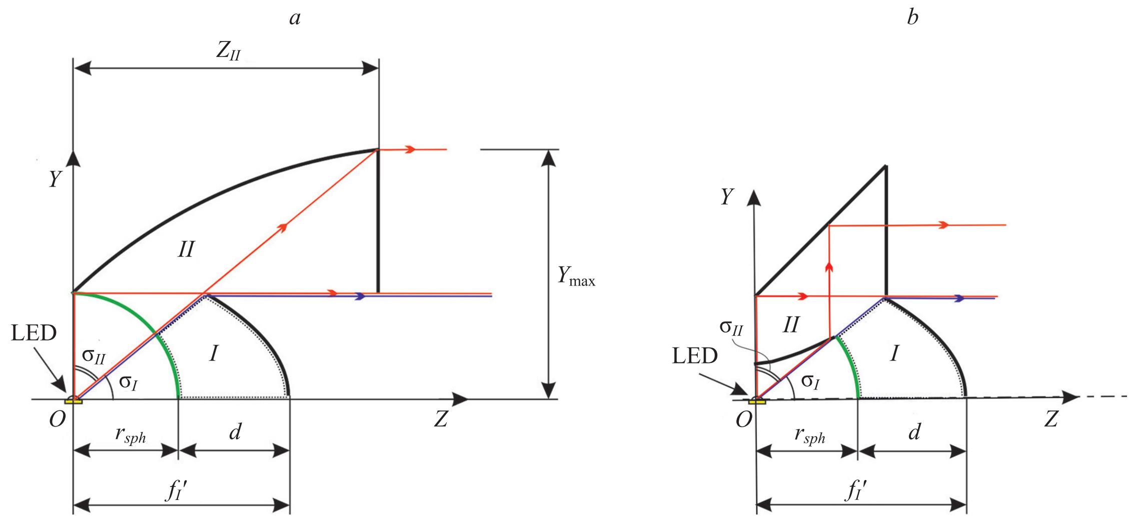

Fig. 1. Possible profiles for generating a side-emitting lens: a sphero-ellipsoidal lens and paraboloid surface (*a*); a sphero-ellipsoidal lens and plano-hyperboloidal lens with an additional flat surface (*b*)

lens (lower part — zone *I*) is determined by the parameters of the sphero-ellipsoidal lens. It can be shown that with this configuration, the focal length of a sphero-ellipsoidal lens is described by the expression:

$$f_I' = r_{sph} + d,$$

where r_{sph} — the radius of the spherical surface; d — lens thickness.

Vertex radius of the second surface (ellipsoidal):

$$r_2 = \frac{f'(n-1)}{n} = \frac{(d + r_{sph})(n-1)}{n}.$$

If the radius of the spherical surface is set as the initial parameter (the minimum value is determined by the required dimensions), as well as the focal length of the lens f_I' selected based on the required beam divergence, then the lens thickness is determined almost unambiguously. On the other hand, on the contrary, it is possible to set the thickness of the lens and the radius of the spherical surface and analyze whether the desired lens characteristics are achievable in this case.

These expressions are valid for both types of lenses since zone *I* in all cases has the same shape. It should be noted that in this case, the energy distribution of the source is not taken into account, as well as the fact that the source area is tilted relative to the profile axis.

For zone *II* in a system of the first type, the divergence due to the size of the source (ω'_{II}) and the aberration divergence (ω'_{IIcoma}) are defined similarly:

$$\omega'_{II} = \frac{y}{f'_{IIp}},$$

$$\omega'_{IIcoma} = -3\frac{y}{4f'_{IIp}}[\sin^2(\pi/2) - \sin^2\sigma_I] = -3\frac{y}{4f'_{IIp}}\cos^2\sigma_I,$$

where f'_{IIp} — focal length of the paraboloid.

Lens dimensions (Fig. 1, *a*) could be described by the formulas:

$$Y_{\max} = \frac{2f'_{IIp}}{\tan\sigma_{II}}[1 + \sqrt{1 + \tan\sigma_{II}}],$$

$$Z_{II} = Y_{\max}^2/f'_{IIp} - f'_{IIp}.$$

Full divergence angle for the lens of the first type is the maximum of the two values — divergence for zone *I* and zone *II*.

For a lens of the **second type** (Fig. 1, *b*) for zone *II*, the relations for a plano-hyperboloid lens are valid:

$$\omega'_{II} \approx y/f'_{IIph},$$

$$\omega'_{IIcoma} \approx \frac{3yn}{2(n-1)f'_{IIph}}\sin^2\sigma_{II},$$

where f'_{IIph} — focal length of the plano-hyperboloidal lens.

As for the previous case, the full divergence angle for the lens of the second type is the maximum of the two values — divergence for zone *I* and zone *II*.

As can be seen from the analysis of the formulas, the lens of the first type provides a lower divergence, since the focal length of the paraboloid can be greater than the focal length of a plane hyperboloid lens, which can be physically realizable in the structure of the side-emitting lens. Moreover, coma of a paraboloid is smaller (with the same characteristics). However, the second type could be more compact.

Design example of the side-emitting lens

Fig. 2 and 3 show the examples of lenses of the first and second types, built using the proposed approach, as well as the results of simulations performed in Zemax Optic Studio.

For the first type lens if we choose the focal length of paraboloidal part f'_{IIp} = 2.2 mm, $Y_{\max}$ = 13 mm, the focal length of a sphero-ellipsoidal lens f_I' = 11.35 mm, the conic constant of ellipsoidal surface (for zone *I*) k = –0.444, the radius of a spherical surface r_{sph} = 4.35 mm we obtain the divergence angles ω'_I = 2.5°, ω'_{Icoma} = 3.8°, the full divergence angle for zone *I* ω' = 6.4°, for zone *II* ω'_{II} = 13°, ω'_{IIcoma} = –4.9°, the full divergence angle for zone *II* ω' = 8.1°. It is worth noting that y = 0.5 mm was used in calculations, and the refraction index n = 1.5. The larger value of the divergence at the same sign determines the total divergence value. Thus we can see that residual divergence is more because of zone *II*. The second variant in Table presents the parameters of the lens of the second type — with the plano-hyperboloidal lens in zone *II*. The parameters of the profile for zone I are the same, and the parameters of the hyperboloid profile (for zone *II*) are as following: the focal length of the plano-hyperboloid lens f'_{IIph} = 1.5 mm, the conic constant for the hyperboloid k_1 = –2.2253. The values of the divergence angles for the two variants are given in Table below.

Fig. 2, *a* presents the lens of the first type with the parameters from the first line in Table (variant 1). The distribution of the luminous intensity on the polar detector [17] in the system when working with a Lambertian light source having the dimensions of a luminous area 1 × 1 mm^2 is depicted in Fig. 2, *b*. The source flux in calculation equals 100 lm. The lens material is polymethylmethacrylate (PMMA). As can be seen from the figure, the lens provides the formation of an annular beam of rays, and about 91 % of the light flux is concentrated within an angle of ± 8°. Table also provides the value of the Full Width on the Half Maximum of the beam (FWHM).

In this case, reflection losses were not taken into account. The results of simulations have shown good agreement with theoretical values. If in theoretical evaluations we use the diagonal size of the area source (y_d = 0.7) the theoretical values will be even closer to the results. Hence, here we demonstrated how the parameters of the profile curves influence the resulting properties of the beam.

Fig. 3, *a* demonstrates the 3D model of the lens for the second variant from Table. Fig. 3, *b* shows the distribution of the luminous intensity in the system working with a lambertian light source with the same parameters as in the previous example. As shown in Fig. 3, *b*, the lens provides the annular beam of rays; about 68 % of the light flux is concentrated within an angle of ±8° from the horizon (for an angle ±5°, the corresponding value is 60 % of the energy). In this case, when the divergence angles are

Table. Parameters for the curves of the lenses and their characteristics

Variant	Parameters	Zone I	Zone II	Full divergence angle (theoretical)	Divergence angles in simulations
1	$f_I' = 11.35$ mm $r_{sph} = 4.35$ mm $r_2 = 3.783$ mm $k = -0.444$ $f'_{IIp} = 2.2$ mm $Y_{max} = 13$ mm	$\omega'_I = 2.5°$, $\omega'_{Icoma} = 3.8°$	$\omega'_{II} = 13°$, $\omega'_{IIcoma} = -4.9°$	$\omega' = 8.1°$	± 5° (corresponding solid angle contains 83.5 % of energy) ± 8° (91 % of energy) ± 15° (95 % of energy) Divergence FWHM = ±2.2°
2	$f_I' = 11.35$ mm $r_{sph} = 4.35$ mm $r_2 = 3.783$ mm $k = -0.444$ $f'_{IIph} = 1.5$ mm $k_1 = -2.2253$	$\omega'_I = 2.5°$, $\omega'_{Icoma} = 3.8°$	$\omega'_{II} = 19°$, $\omega'_{IIcoma} = 42°$	$\omega' = 61°$	± 5° (corresponding solid angle contains 60 % of energy) ± 8° (68 % of energy) ± 15° (76 % of energy) Divergence FWHM=±2°

a *b*

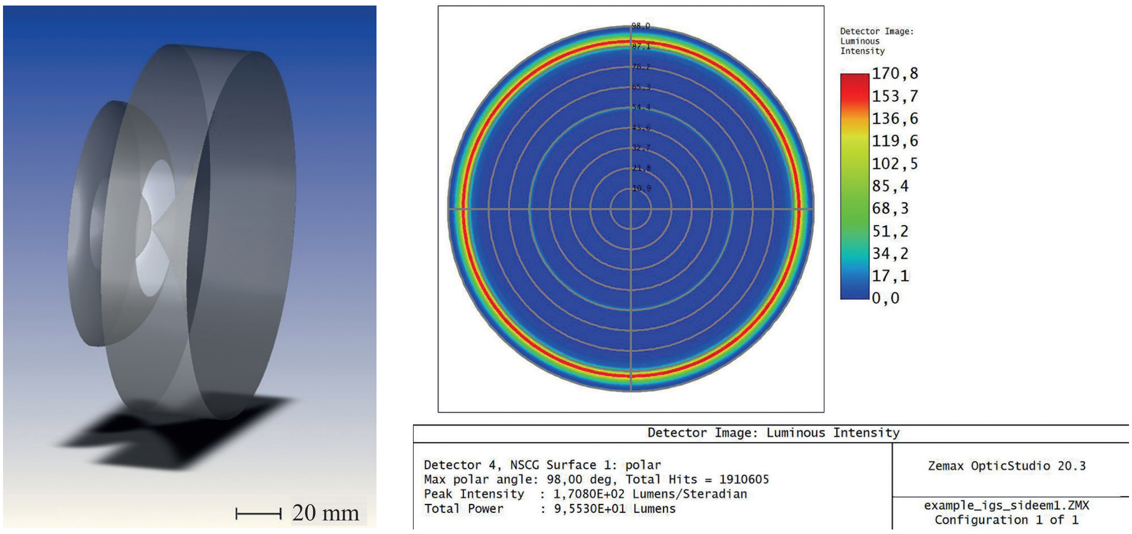

Fig. 2. The design example of a side-emitting lens of the first type: 3D lens model (*a*); light intensity distribution on a polar detector (*b*)

a *b*

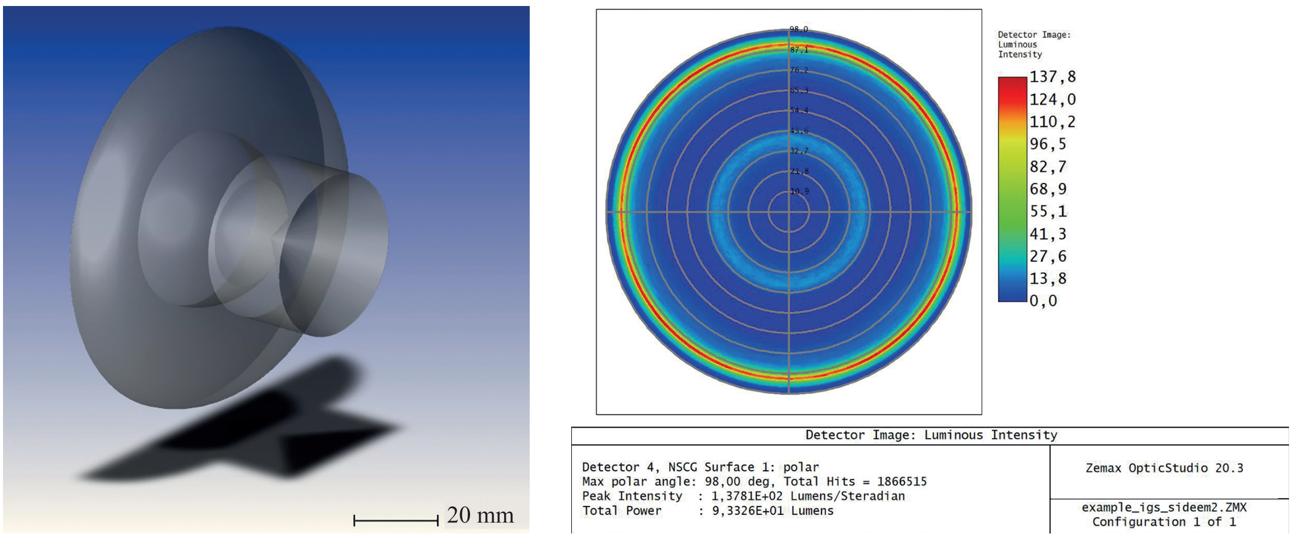

Рис. 3. The design example of a side-emitting lens of the second type: 3D lens model (*a*); light intensity distribution on a polar detector (*b*)

relatively large the correspondence between the theoretical values and simulation results is larger since trigonometric functions are omitted in the formulas. However, the agreement is still good enough. As can be seen, the theoretical expressions provide a clear understanding of what zone and what parameters are responsible for the divergence, thus they provide ideas about the ways of improving the lens characteristics.

In accordance with theoretical calculations, the second type of lens has lower efficiency, but it has smaller dimensions: the maximum lens diameter is determined in this case by the dimensions of the lower zone (a sphero-elliptical lens) and is equal to 22.7 mm.

Conclusion

In the work, it is proposed to compose the starting point of the side-emitting system for LED sources based on the ideas of the composing theory. Two possible configurations of the lens are considered, the relations that determine the collimation properties of a side-emitting lens (the size of the angular sector) are obtained. The work provides the formulas that allow generating a lens cross-sectional profile quickly without using complex mathematical relationships, taking into account overall constraints, as well as evaluating the properties of the system at the early design stage. An example is given to illustrate the proposed approach.

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Received 16.01.2021
Approved after reviewing 25.02.2021
Accepted 02.04.2021

Статья поступила в редакцию 16.01.2021
Одобрена после рецензирования 25.02.2021
Принята к печати 02.04.2021