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Optical system design method for the concentration of radiation from a high-power LED

Galina E. Romanova[1], Xuanlin Qiao[2], Olga K. Kozlova[3]✉

[1,2,3] ITMO University, Saint Petersburg, 197101, Russian Federation

[1] romanova_g_e@mail.ru, https://orcid.org/0000-0001-9348-8540
[2] qiaoxuanlindhr@gmail.com, https://orcid.org/0000-0002-3957-9270
[3] okk812@mail.ru✉, https://orcid.org/0000-0002-7038-5618

Abstract
An optical system is considered that ensures the concentration of radiation from an LED emitting within a hemisphere onto a near-field illuminated area. The system is proposed to consider such a system as a composition of two zones — the central zone, which is a lens, and the zone responsible for capturing radiation from the LED within an angle of 40 to 90 degrees. Variants with a central zone in the form of bi-aspherical and sphero-elliptical lenses of finite thickness are analyzed. The alternative variant of the concentrating system composed from a collimating TIR lens and additional focusing lens is also analyzed. The expressions are given that allow analyzing possible concentration efficiency and the light spot size, and examples of systems are given designed with taking into account theoretical analysis results. Factors are discussed that define the choice of the required configuration. The results have shown the good agreement between the theoretical approach and practical design results. The optical elements designed as examples showed the high optical efficiency (near 90 %), thus such approach can be used for designing the LED optical systems for efficient light flux concentration, for example operating with fiber bundle as needed in some optical — electronic devices.

Keywords
LED, fiber bundle, concentration of radiation, optical systems design

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Метод проектирования оптической системы для концентрации излучения мощных светодиодов

Галина Эдуардовна Романова[1], Сюаньлинь Цяо[2], Ольга Кирилловна Козлова[3]✉

[1,2,3] Университет ИТМО, Санкт-Петербург, 197101, Российская Федерация

[1] romanova_g_e@mail.ru, https://orcid.org/0000-0001-9348-8540
[2] qiaoxuanlindhr@gmail.com, https://orcid.org/0000-0002-3957-9270
[3] okk812@mail.ru✉, https://orcid.org/0000-0002-7038-5618

Аннотация
Предмет исследования. Рассмотрена оптическая система, обеспечивающая концентрацию излучения светодиода, излучающего внутри полусферы, на освещаемую площадку, расположенную в ближней зоне. **Метод.** Систему предлагается рассматривать в виде композиции центральной зоны, которая представляет собой классическую собирающую линзу, и рабочей зоны, отвечающей за работу с излучением светодиода в пределах угла от 40 до 90° относительно оси. **Основные результаты.** Выполнен анализ вариантов с центральной зоной в виде биасферической и сфероэллиптической линзы конечной толщины. Проанализирован альтернативный вариант концентрирующей системы в составе коллимирующей линзы, которая работает на основе эффекта полного

внутреннего отражения и дополнительной фокусирующей линзы. Приведены математические выражения для оценки возможной эффективности концентрации и размеров светового пятна. Показаны примеры систем, разработанных с учетом результатов теоретического анализа. Обсуждаются факторы определения выбора требуемой конфигурации системы. Представлены примеры оптических элементов, которые показали близкую к 90 % оптическую эффективность. **Практическая значимость.** Предложенный подход может быть использован при проектировании светодиодных оптических систем для эффективной концентрации светового потока в некоторых оптико-электронных системах, в частности, при передаче сигнала по волоконно-оптическому жгуту.

Ключевые слова
светодиод, волоконный жгут, освещение в ближней зоне, концентрация излучения, проектирование оптических систем

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Introduction

Lighting systems are often an essential part of various optoelectronic devices, and in modern compact devices for various purposes high-power LEDs are used as a source of illumination. For example, systems of modern Liquid Crystal Display and Digital Light Processing projectors can be built using Light-Emitting Diode (LED) optics [1–4]. LEDs can also be used in systems that utilize light guides and fiber optics when it is necessary to transmit the light flux over a relatively long distance to ensure the operation of the device [5].

Among the systems used as components of optoelectronic devices, one can distinguish collimating systems that form a beam close to parallel, and systems whose role is to concentrate the light flux on the illuminated area.

Methods for LED optics design usually come down to calculating a generating curve for a cross-section of the system or several curves (for the case of non-axisymmetric systems), among these methods Simultaneous Multiple Surface (SMS) methods [6] and ray mapping methods [7] should be mentioned. These methods make it possible to accurately restore the generating curve from a known or desired illumination distribution; however, they, as a rule, are quite time-consuming and require extensive mathematical calculations.

Alternatively, for collimating optics, it is possible to use the method of analysis and synthesis of lens profile by combination of the curves in the zones that correspond to different beam angles of the source, and in each zone the theory of third-order aberrations is applied to find the optimal shape [8–11]. This approach makes it possible both to preliminary estimate the dimensions of the system and to quickly and efficiently synthesize the shape of a lens that works with an LED.

In optical devices, a case often occurs when a beam that is close to parallel does not provide optimal operation of the device. For example, it is necessary to fill the aperture of a micro-objective with light, to collect the light flux on a certain area, to concentrate the light beam on the input end of a bundle of fibers or a light guide, etc. In these cases, the direct application of the method based on the theory of the third-order aberrations, developed for the case of collimating optics, is impossible. Existing methods, such as SMS and ray-mapping technique, as in other cases, have the same disadvantages as was mentioned above.

Therefore, it is important to supplement the method for calculating systems working with LEDs by considering the case when the illuminated area is located at a finite distance, and it is required to ensure the maximum use of the luminous flux.

Theory

The classical method for calculating an optical system at the first stage includes an assessment of its capabilities — as a rule, using the Lagrange-Helmholtz invariant [12]. However, a preliminary assessment of the potential properties of the system does not make it possible to evaluate its design. Known solutions condenser lenses and lens systems, for which recommendations on the number of elements are approximately known, depending on the magnification of the system and the angle of coverage of the condenser, which, in the case of an LED, will determine the efficiency of using the light flux. Table 1 shows the calculated values of the efficiency of using the luminous flux when working with condensers with different coverage angles of 2Ω. In this case, the efficiency is calculated as the fraction of the flux that falls within the considered angle using the model of an ideal flat Lambertian source [12].

High-aperture condenser systems can be used when working with high-power LED assemblies and matrices that require additional heat removal. Thus, such systems have large dimensions. On the other hand, in such systems

Table 1. The efficiency of using the luminous flux depending on the condenser coverage angle for a Lambertian source emitting into a hemisphere

Angle Ω, deg	Efficiency, %
15	6.7
30	25
45	50
60	75
75	93.3
90	100

it is not so crucial to achieve high efficiency of using the luminous flux.

However, when working with light sources embedded into modern optoelectronic devices, an important factor in their choice can be the dimensions, and, accordingly, the dimensions of the lighting device. At the same time, the efficiency of work (the efficiency of capturing and transmitting the light flux from the source to the illuminated object) can have a great effect on the illumination quality as well as affect the energy consumption of the device. Therefore, the task is important that consists in the development of a design method that allows, at the stage of selecting the source and the principal layout design of the device, to evaluate the efficiency as well as dimensions.

As was shown before for the case of a collimator [8, 9], for initial synthesis of a system operating with an LED it is sufficient to consider two zones of the light beam. In the case of severe dimensional constraints, more zones may be considered.

The first option — systems for concentration is a combination of a lens in the central zone and a reflective surface in zone *II* (Fig. 1). In this case, the concentration of the light flux is carried out due to the projection of the luminous area of the source onto the illuminated area. In Fig. 1 the angle σ defines the size of the central zone.

Let us consider the central zone *I*. If the central zone is a thick lens, it has several parameters for providing necessary aberration correction and scale of the light spot: for a thick lens both surfaces could have aspherical shape and the shape of the lens could be chosen to find optimal balance of the aberration and required optical power. Even though the systems under consideration are not designed for imaging, the correction of aberrations will affect the efficiency of energy transfer and the distribution of energy on the spot.

If we assume that the first surface of the lens is spherical with the center of curvature coinciding the source position, and the second surface is convex aspherical (Fig. 1, *b*), we can obtain simple expressions describing the aberration properties of the lens: the coefficients of spherical aberration B_0 and coma K_0 [13] of such a lens can be expressed in the form:

$$B_0 = \frac{1+\tilde{d}}{2}\left[\frac{n(n-V)(V-1)^2}{V^3(n-1)} + \frac{(1-nV)^3}{V^3(n-1)^2}k_2\right], \quad (1)$$

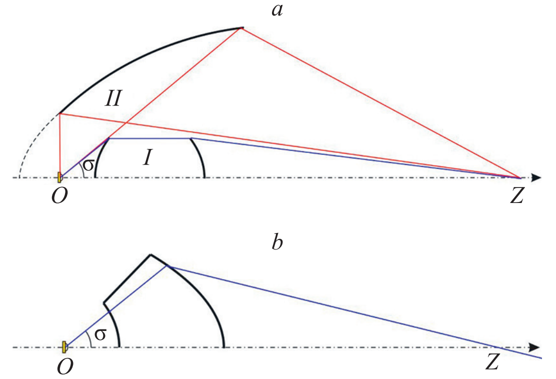

Fig. 1. Configuration of the system for concentrating the source radiation: beam splitting into zones, biconvex lens in the central zone (*a*); configuration with a sphero-elliptical lens in the central zone (*b*)

$$K_0 = -\frac{1}{2}\frac{(n-V)(1-V)}{V^2(n-1)}, \quad (2)$$

where $\tilde{d}$ is the thickness of the lens, expressed on the scale of source distance (the distance from the first surface to the source); V is the linear magnification; n is the index of refraction of the material; and k_2 is the coefficient of aspherical deformation of the second surface of the lens (conic constant). Obviously, one can correct spherical aberration by varying conic constant k_2, however coma will be uncorrected. The plot showing the dependence of K_0 on magnification value is presented in Fig. 2.

An analysis of formulas (1), (2) shows that at a negative magnification ($V < 0$) the shape of the second lens surface is an ellipsoid, as in the case of a system that forms a parallel beam. In addition, from formula (2) and the graph in Fig. 2, it can be seen that the coma coefficient K_0 decreases in absolute value with increasing the absolute value of magnification V, and in the case of small magnification it can reach significant values, thus decreasing the system efficiency. Therefore, for configurations where illumination of a small area is formed due to the projection of the luminous body of the source, it would be more rational to choose a configuration that is closer to symmetrical.

For preliminary analysis in the system, it can be assumed that the marginal ray inside the lens is parallel to the optical axis (paraxial angle $\alpha = 0$). Then the coefficients of spherical aberration and coma for that case can be expressed in the form:

$$B_0 = \frac{n^2(1-V^3) + k_2 - V^3k_1}{2V^3(n-1)^2}, \quad (3)$$

$$K_0 = -\frac{n^2V(V^2-1)(n-1) - \tilde{d}(n^2+k_2)}{2nV^3(n-1)^2}. \quad (4)$$

In this case, as can be seen from the obtained formulas (3) and (4), due to two aspherical coefficients k_1, k_2, even when an additional condition is imposed (parallel marginal ray inside the lens), two aberrations can be corrected.

When designing the second zone of the system — a reflecting surface — for concentrating LED radiation in

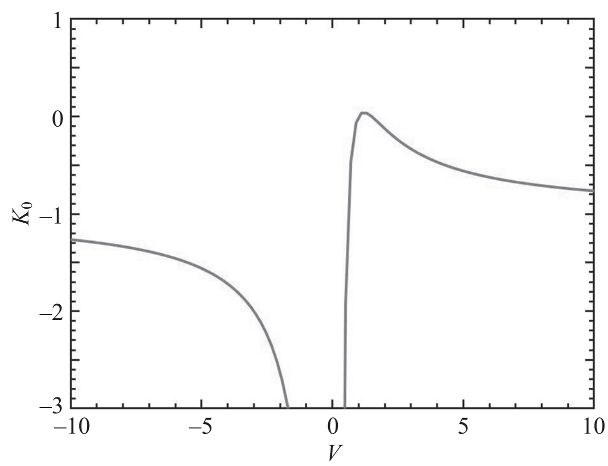

Fig. 2. The plot of third-order coma coefficient K_0 versus linear magnification V for $n = 1.5$ and $\tilde{d} = 1$

zone II (Fig. 1, *a*), several factors need to be considered: geometry constraints — the rays in zone II must be completely captured by the reflecting surface; the projection distance must match the projection distance for the lens (central part) system; the projection magnification must match that of the central part.

In this case, the simultaneous exact fulfillment of these conditions seems difficult, since the mirror part in the case under consideration will be a mirror ellipsoid the aperture of which is limited. Thus, such an element could be effectively used only in certain cases. In practice, some balance of efficiency and fulfillment of constraints above could be found as we will show below.

The alternative variant of designing the concentration system is following two steps of beam transformation: on the first stage we use the same theoretical expressions to evaluate the possible dimensions and parameters of the optimal collimation lens [8]; on the second stage we can choose parameters of the more standard element — focusing lens that collects the light onto the desired region.

The two possible collimation lens types are: lens with central zone of plano-hyperboloidal lens (type I); and lens with central zone of sphero-elliptical configuration (type II).

For both cases outer zone is formed by the paraboloidal surface.

Thus, as was shown before [8], the divergence $\Delta\omega_I$, rad, for the central zone:

$$\Delta\omega_I = (1 - 3\sin^2\sigma K_0)\frac{y}{f_I'}, \qquad (5)$$

where y is the source size; f_I' is the focal length of the central zone lens; σ is the angular size of zone I; and K_0 is coma coefficient. Here for the case of a plano-hyperboloidal lens (type I) coma coefficient is described by:

$$K_0 = -\frac{n}{2(n-1)}. \qquad (6)$$

For type II collimator lens with sphero-elliptical central part coma coefficient is described by:

$$K_0 = -\frac{1}{2(n-1)}. \qquad (7)$$

Thus, formulas (6), (7) together with the expression (5) provide the possibility to evaluate the divergence for both options of the central zone, taking into account both factors (the aberrations and the size of the source area).

For the outer zone of the collimating lens, the divergence is:

$$\Delta\omega_{II} = -3\frac{y}{4f_p'}\cos^2\sigma + \frac{y}{f_p'}, \qquad (8)$$

where f_p' is the focal length of the outer surface; σ is the angular size of the zone; and $\Delta\omega_{II}$ is the divergence of the beam for the outer zone.

The configurations of possible types of the system based on collimation lens are presented in Fig. 3 schematically: in Fig. 3, *a* the system could be manufactured as a single element, thus decreasing the Fresnel losses, and for the second case (Fig. 3, *b*), as was shown before, the collimation may be better despite the two pieces — collimating lens and focusing lens — are needed.

Thus, the light spot size for the case of combination these lenses together with focusing lens is defined by the divergence of the beam $\Delta\omega_{max}$ before the lens — the maximum from the two values $\Delta\omega_I$ or $\Delta\omega_{II}$ (formulas (5) and (8)).

$$D_{spot} = 2f'\tan\Delta\omega_{max}, \qquad (9)$$

where D_{spot} is the spot size on the illuminated area, f' is the focal length of the focusing lens.

The second factor that also defines the spot is coma, mm, for the plano-hyperboloidal lens with corrected spherical aberration coma:

$$coma = -3f'\tan\Delta\omega_{max}K_0\sin^2\sigma_A. \qquad (10)$$

Here coma coefficient for plano-hyperboloidal lens is described by equation (6).

In equation (10), σ_A is the aperture angle of the lens. For the lens with the given diameter, it could be expressed by the approximate expression:

$$\sin\sigma_A = \mathrm{NA} = \sin\sigma_A \approx \frac{D_{lens}}{2f'}. \qquad (11)$$

Obviously, by choosing focal length of the lens together with the parameters of the collimating part one can analyze possible properties and find the balance of aberration taking into account the dimensions of the system. Hence, these

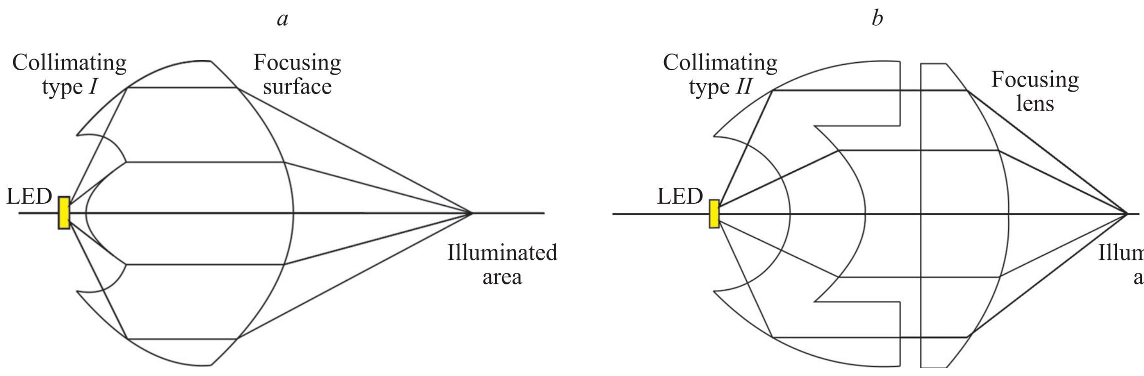

Fig. 3. Scheme of optics for fiber bundle: type I collimating lens with focusing surface (*a*) and collimating type II with additional focusing lens (*b*)

simple ideas could help in choosing and designing the optimum from the point of view of system dimension and efficiency configuration for the illumination part in optical-electronic devices.

Optical simulation

As was mentioned above, the configuration for the central zone with sphero-elliptical lens and bi-convex lens provides different aberration correction, hence different efficiency. To show the difference visually, two types of lenses were designed. Fig. 4 shows the graphs of the illumination distribution in the system that provides a projection of a 1 × 1 mm LED area with magnifications $V = -4$ and $V = -10$ in two different system configurations — a system with a sphero-elliptical lens and a bi-aspherical one (biconvex with two aspherical surfaces), and in the latter case, the coma of the third-order is corrected.

The calculations were carried out by tracing 10 million rays in the scheme with a Lambertian source with 1 ×1 mm in size, with a flux of 1 W (the chosen value of the flux is due to the convenience of the calculation) using Zemax Optic Studio [14]. Lens configurations were preliminary designed using the third-order aberration theory and then optimized to correct for spherical aberration more accurately. As can be seen from the graphs, the sphero-elliptical lens configuration provides more uniform illumination; however, the bi-aspherical lens provides higher illumination due to more efficient energy concentration in the case of coma correction.

An example of a system consisting of a central lens part and a mirror ellipsoid is shown in Fig. 5. At the same time, such a system can be implemented in practice as a mirror reflector and a central lens fixed with special mechanical spiders or mounts. Of course, the elements of the lens attachment will affect the efficiency of the transmission of the light flux. The system given below corresponds to the case of the magnification $V = -4$, where the central lens works with the numerical aperture $A = \sin\sigma = 0.4$.

The parameters of the designed examples are given in Table 2.

Parameters of the central part presented in Table 2 are calculated based on the theoretical expressions given above, whereas parameters of the mirror were optimized to find optimal balance between the efficiency of the whole system and its dimensions; because, as was mentioned above, all the geometry constraints and efficiency requirements could

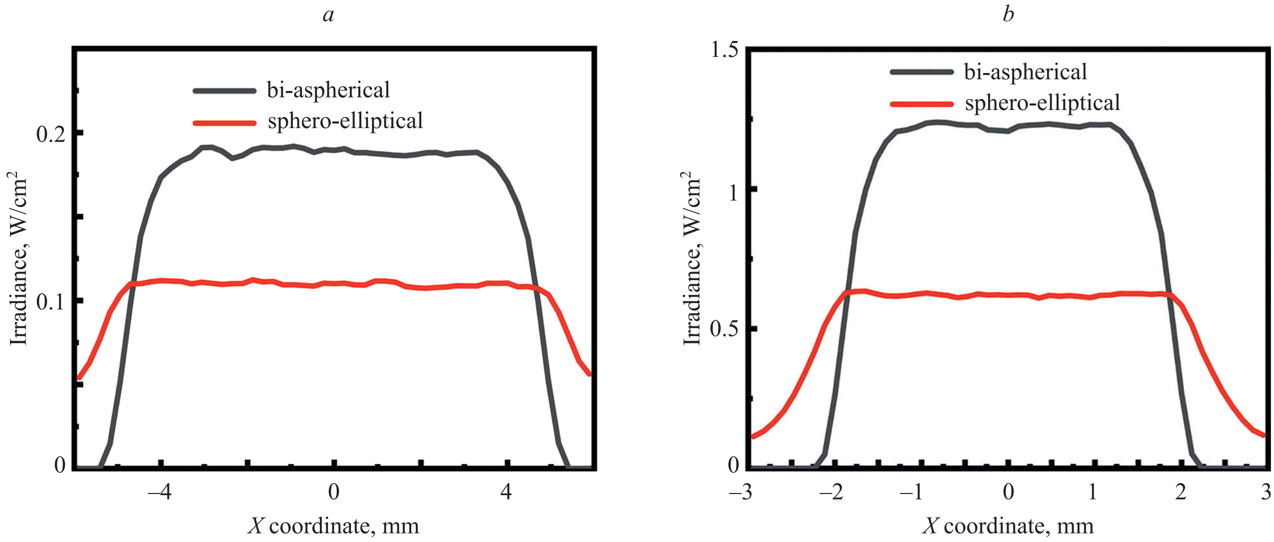

Fig. 4. Graphs of the illumination distribution in a system with a sphero-elliptical lens and a bi-aspherical one at $V = -10$ (*a*) and $V = -4$ (*b*)

Table 2. Parameters of the optical system

		Mirror with sphero-elliptical lens	Mirror with bi-asphere lens
Vertex radius of mirror r_M, mm		13	10
Conic of the mirror k_M		–0.82	–0.76
Thickness of the central lens d, mm		12	12
Radius of the first surface of the central lens r_1, mm		–12	7.926
Radius of the second surface of the central lens r_2, mm		–6.794	–13.776
Conic of the first surface k_1		0	–1.469
Conic of the second surface k_2		–0.61	–6.186
% of the energy:	in the 10 × 10 mm area	83	92
	in the 6 × 6 mm area	80	**87**

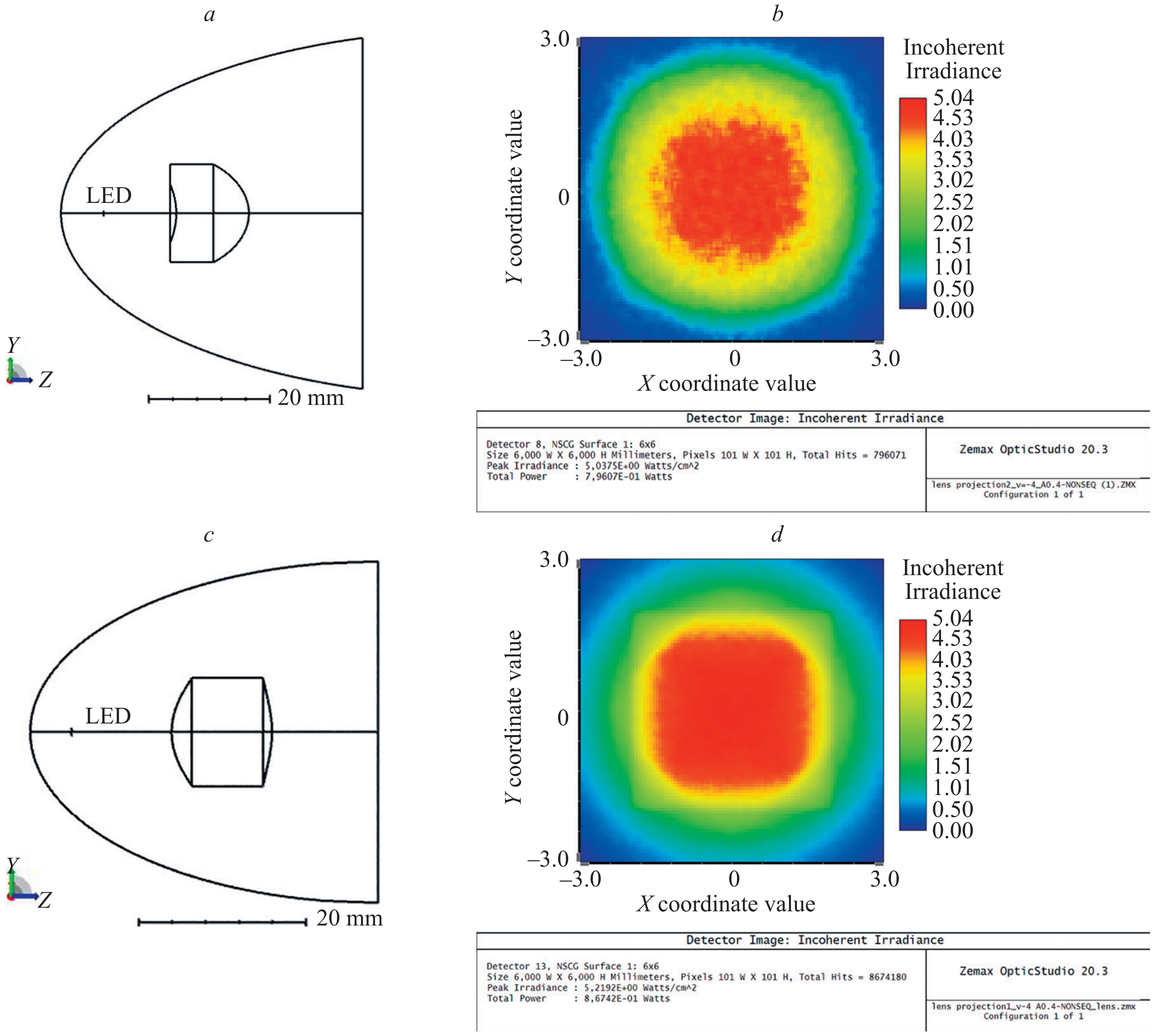

Fig. 5. Concentration system consisted of the mirror and the lens part: 2D layout of the system with sphero-elliptical lens (*a*); irradiance distribution for the system with sphero-elliptical central lens (*b*); 2D layout of the system with bi-aspherical lens (*c*); irradiance distribution for the system with bi-aspherical lens (*d*)

be rarely met for the mirror part of the system working together with the lens part.

Fig. 5 shows the 2D system shape and their optical performance. It should be mentioned that all simulations were done without considering Fresnel losses in the system.

The additional analysis has shown that the difference in efficiency and illuminance distribution is obviously due to the central lens part that was described above in details. Thus, choosing the central part configuration according to the requirements of the certain task can help in achieving higher illuminance.

If such a solution is structurally impossible for some reason, then in practice the mirror part can be abandoned, and in the absence of restrictions on the number of elements used, a solution in the form of a multi-lens condenser can be applied, with an appropriate coverage angle, as mentioned earlier [10].

The second option for organizing the concentration of illumination on an object is a combination of a collimating system and a focusing lens. The analysis of the collimating system can be performed as described above, and the focusing system in this case can be a classical lens. Moreover, such a system can also be implemented as a single element[1], and the above considerations allow choosing the optimal option for the central part. This option can be effectively used to transfer radiation into a fiber, an optical homogenizer, etc.

Examples of systems built based on the lens with the central sphero-elliptical lens and the plano-hyperbolic one are shown in Fig. 6. The parameters and the divergence of the collimation for both lens types are presented in Table 3.

The maximum diameter of these lenses is 26 mm, so, by varying the focal length of the additional focusing lens, we can influence the optimal balance between the two factors that define the spot size, or, from the other hand, the efficiency of concentration for the given area size.

Thus, for the $\Delta\omega_{max} = 0.087$ and rad = 5°, we can find for the focal length of the lens $f' = 35$ mm the geometrical spot size $D_1 = 6.12$ mm due to the divergence and additional contribution due to coma is 1.67 mm.

Similarly, for the larger focal length $f' = 45$ mm, the geometrical spot size $D_1 = 7.87$ mm, and the coma is 1.365 mm. As can be seen from this example and from

[1] Carclo Optics. Available at: http://www.carclo-optics.com/optic-10356?optictype=fibre%20coupling (accessed: 29.03.2022).

Table 3. Parameters of the collimation parts of the optical systems

	Collimator type *I* (plano-hyperboloidal central part)	Collimator type *II* (sphero-elliptical central part)
Paraboloid part: Focal length f_p', mm	2.2	2.2
Focal length of the central lens part f_l', mm	2.5	11.35
Radius of the first surface of the central lens r_1, mm	1.234	– 4.35
Radius of the second surface of the central lens r_2, mm	∞	– 3.78
Conic of the first surface k_1	– 2.26	0
Conic of the second surface k_2	–	– 0.44
Theoretical full divergence	±20°	±5°6′0″
Share of energy inside the corner zone ±5°, %	70	80

analysis of the formulas (9)–(11), starting from some values of the focal length the main factor defining the spot size will be the divergence of the beam and the focal length of the focusing lens: the shorter focal length could give better concentration. However, another one factor that should be taken into consideration is the geometrical relations between the lens diameter and its focal length: even for plano-hyperboloidal lens the correction of the spherical aberration is exact for any reasonable aperture, the shorter focal length for given diameters leads to the larger lens thickness that is not optimal for manufacturing.

The focal length of the convergence lens used in the system examples here was chosen as 43 mm. The lens material here is set as PMMA whose index of refraction is about 1.491. In Fig. 6, *b*, *d* the irradiance distribution is shown for the area 6 × 6 mm, which is close to theoretical

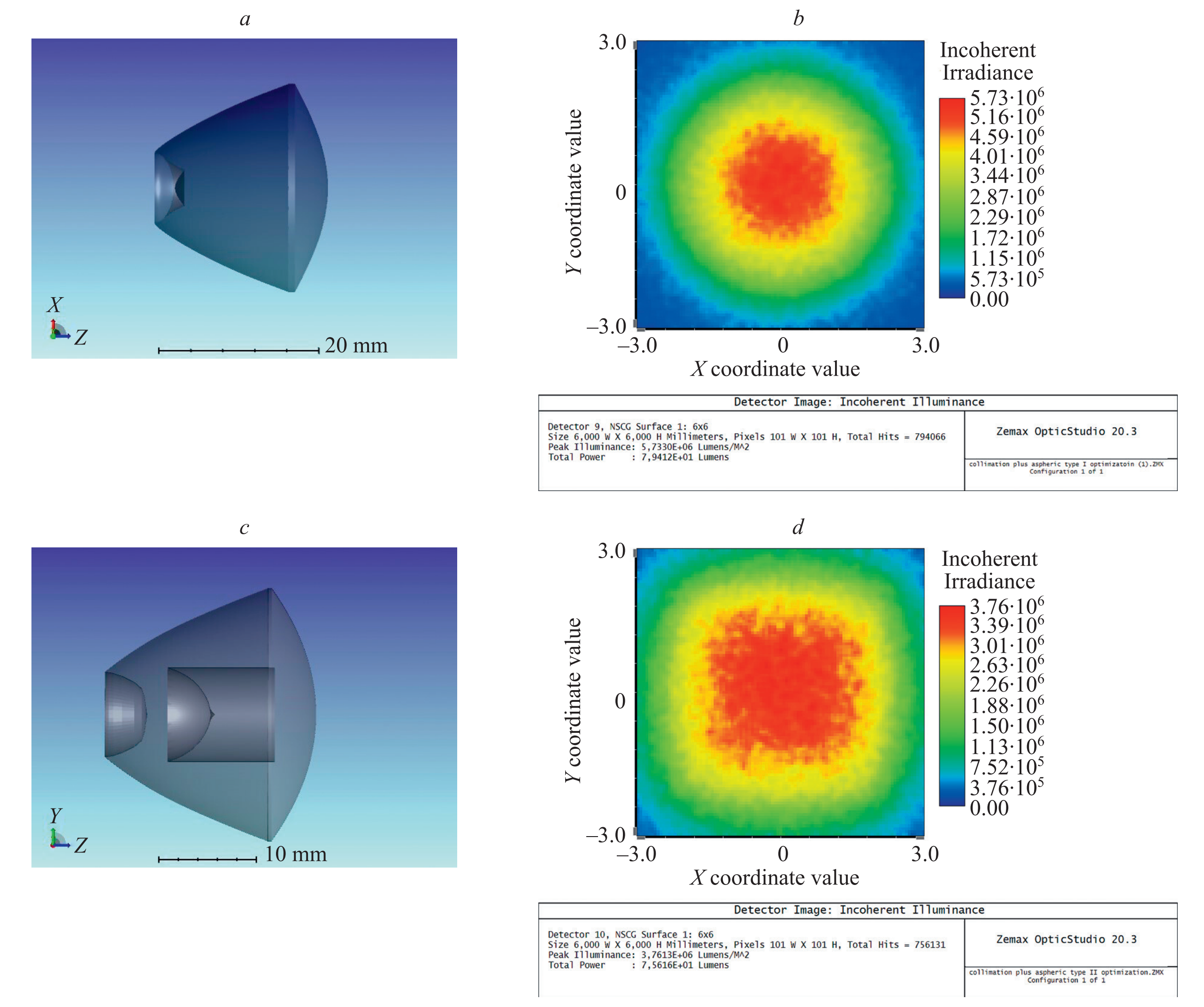

Fig. 6. Lens model for fiber bundle of the first type (*a*) and its detector view (*b*), and of the second type (*c*) and its detecor view (*d*)

size of the spot for this case, and the total flux for this area is close to 75–80 % of the total source flux that was predicted by theoretical approximate calculations.

Notably, the lens in Fig. 6, *c* may not be able to be manufactured as a whole lens because the air hole is lying between the focusing lens and the elliptical surface in the central zone. Hence, manufacturing of this lens could be implemented from two parts: collimation and convergence. Then one can join the two optical parts using a fixture or glue to attach one of it to the other.

Conclusion

The designing process of the concentration systems is described in the work. Theoretical expressions are presented providing necessary theoretical basics to choose optimally the parameters of the system in the conditions of dimensions restrictions and high required efficiency. Four possible configurations of a concentration system are considered. Concentration lenses that provide near field lighting with high optical efficiency near 90 % are designed both based on analysis of the third-order aberration theory and the composing of elements are given as a result demonstrating the proposed approach. The examples presented can be used for real-world application.

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Authors

Galina E. Romanova — PhD, Associate Professor, Associate Professor, ITMO University, Saint Petersburg, 197101, Russian Federation, SC 8215289000, https://orcid.org/0000-0001-9348-8540, romanova_g_e@mail.ru

Xuanlin Qiao — PhD Student, ITMO University, Saint Petersburg, 197101, Russian Federation, https://orcid.org/0000-0002-3957-9270, qiaoxuanlindhr@gmail.com

Olga K. Kozlova — Student, ITMO University, Saint Petersburg, 197101, Russian Federation, https://orcid.org/0000-0002-7038-5618, okk812@mail.ru

Авторы

Романова Галина Эдуардовна — кандидат технических наук, доцент, доцент, Университет ИТМО, Санкт-Петербург, 197101, Российская Федерация, SC 8215289000, https://orcid.org/0000-0001-9348-8540, romanova_g_e@mail.ru

Цяо Сюаньлинь — аспирант, Университет ИТМО, Санкт-Петербург, 197101, Российская Федерация, https://orcid.org/0000-0002-3957-9270, qiaoxuanlindhr@gmail.com

Козлова Ольга Кирилловна — студент, Университет ИТМО, Санкт-Петербург, 197101, Российская Федерация, https://orcid.org/0000-0002-7038-5618, okk812@mail.ru

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