**DOI:** 10.21122/2220-9506-2023-14-2-96-105

# The Use of Fresnel Lenses in LED Sources of Local Illumination to Optimize the Distribution of Illumination of the Working Plane

**P.S. Bogdan, E.G. Zaytseva, I.A. Kovalenok, T.D. Tarasenko, E.V. Duboysky**

*Belarusian National Technical University,
Nezavisimosty Ave., 65, Minsk 220013, Belarus*

*Received 27.02.2023*
*Accepted for publication 25.05.2023*

**Abstract**

For widely used LED sources there is a sharp decrease in the illumination of the working plane from the center to the edge. The purpose of this study was to analyze the effectiveness of Fresnel lenses usage as a fairly simple and technological element to increase the uniformity of illumination created by LED lamps of local lighting.

A method has been developed for calculating of the distribution of illumination created by the combination of "LED matrix – Fresnel lens" when the distance between the lens and the matrix is less than the focal length of the lens. Comparison of the calculation results and experiments for the case when the lens is located at a distance of 50 cm from the working plane indicates the correctness of the developed calculation method. This made it possible to use this technique to solve the problem of improved uniformity of illumination distribution in the working plane of local lighting LED sources.

It was found that the change in the distance between the matrix and the lens in the range of 0.5–1.5 cm affects the maximum illumination and its uniformity to a lesser extent than the change in focal lengths in the range of 10–100 cm. Analytical dependences of the uniformity of the working surface illumination as a function of the Fresnel lens focal length and its distance to the LED matrix were obtained for three cases. In the first case one lens is used for the entire matrix while the axes of symmetry of the light intensity curves of LEDs are parallel to the axis of the lens. In the second case one lens is also used for the entire matrix, but the continuations of the axes of symmetry of the light intensity curves pass through the front focus of the lens. In the third one an individual Fresnel lens is used for each LED. It is established that for all three cases dependencies have almost the same character. Therefore, the choice of using one of these three options may be due to manufacturability, cost-effectiveness, thermal stability, and other considerations.

Calculations using the above-mentioned analytical dependences made it possible to determine values of the parameters of the "LED matrix – Fresnel lens" system at which the indicators of illumination and uniformity meet the standards' requirements.

**Keywords:** mathematical modeling, LED matrix, Fresnel lens, RGB LED, illumination distribution

***Адрес для переписки:***
*Зайцева Е.Г.*
*Белорусский национальный технический университет,*
*пр-т Независимости, 65, г. Минск 220013, Беларусь*
*e-mail: egzaytseva@bntu.by*

***Address for correspondence:***
*Zaytseva E.G.*
*Belarusian National Technical University,*
*Nezavisimosty Ave., 65, Minsk 220013, Belarus*
*e-mail: egzaytseva@bntu.by*

***Для цитирования:***
*P.S. Bogdan, E.G. Zaytseva, I.A. Kovalenok,*
*T.D. Tarasenko, E.V. Duboysky.*
The Use of Fresnel Lenses in LED Sources of Local Illumination to Optimize the Distribution of Illumination of the Working Plane.
Приборы и методы измерений.
2023. – Т. 14, № 2. – С. 96–105.
**DOI:** 10.21122/2220-9506-2023-14-2-96-105

***For citation:***
P.S. Bogdan, E.G. Zaytseva, I.A. Kovalenok, T.D. Tarasenko,
E.V. Duboysky.
The Use of Fresnel Lenses in LED Sources of Local Illumination to Optimize the Distribution of Illumination of the Working Plane.
*Devices and Methods of Measurements.*
2023, vol. 14, no. 2, pp. 96–105.
**DOI:** 10.21122/2220-9506-2023-14-2-96-105

*Devices and Methods of Measurements*
*2023, vol. 14, no. 2, pp. 96–105*
*P.S. Bogdan et al.*

**DOI:** 10.21122/2220-9506-2023-14-2-96-105

# Использование линзы Френеля в светодиодных источниках локального освещения для оптимизации распределения освещённости рабочей плоскости

**П.С. Богдан, Е.Г. Зайцева, И.А. Ковалёнок, Т.Д. Тарасенко, Е.В. Дубойский**

*Белорусский национальный технический университет,*
*пр-т Независимости, 65, г. Минск 220013, Беларусь*

*Поступила 27.02.2023*
*Принята к печати 25.05.2023*

Для широко используемых светодиодных источников света имеет место резкий спад освещённости рабочей плоскости от центра к краю. Целью настоящего исследования являлся анализ эффективности применения линз Френеля как достаточно простого и технологичного элемента для увеличения равномерности освещённости, создаваемой светодиодными светильниками локального освещения.

Разработана методика расчёта распределения освещённости, создаваемой комбинацией «светодиодная матрица – линза Френеля», когда расстояние между линзой и матрицей меньше фокусного расстояния линзы. Сравнение результатов расчёта и экспериментов для случая, когда линза располагается на расстоянии 50 см от рабочей плоскости, свидетельствует о корректности разработанной методики расчёта. Это позволило использовать данную методику для решения задачи повышения равномерности освещённости рабочей плоскости в светодиодных источниках локального освещения.

Установлено, что изменение расстояния между матрицей и линзой в диапазоне 0,5–1,5 см влияют на максимальную освещённость и её равномерность в меньшей степени, чем изменение фокусных расстояний в пределах 10–100 см. Получены аналитические зависимости равномерности освещённости рабочей поверхности как функции фокусного расстояния линзы Френеля и её расстояния до светодиодной матрицы для трёх случаев. В первом случае используется одна линза для всей матрицы, при этом оси симметрии кривых силы света светодиодов параллельны оси линзы. Во втором случае также используется одна линзы для всей матрицы, но продолжения осей симметрии кривых силы света проходят через передний фокус линзы. В третьем – для каждого светодиода используется индивидуальная линза Френеля. Установлено, что для всех трёх случаев зависимости имеют практически одинаковый характер. Поэтому выбор использования одного из трёх вариантов может быть обусловлен технологичностью, экономичностью и термической устойчивостью и др.

Расчёты с использованием выше упомянутых аналитических зависимостей позволили определить значения параметров системы «светодиодная матрица – линза Френеля», при которых показатели освещённости и равномерности соответствуют требованиям стандартов.

**Ключевые слова:** математическое моделирование, светодиодная матрица, линза Френеля, RGB светодиод, распределение освещённости

***Адрес для переписки:***
*Зайцева Е.Г.*
*Белорусский национальный технический университет,*
*пр-т Независимости, 65, г. Минск 220013, Беларусь*
*e-mail: egzaytseva@bntu.by*

***Address for correspondence:***
*Zaytseva E.G.*
*Belarusian National Technical University,*
*Nezavisimosty Ave., 65, Minsk 220013, Belarus*
*e-mail: egzaytseva@bntu.by*

***Для цитирования:***
*P.S. Bogdan, E.G. Zaytseva, I.A. Kovalenok,*
*T.D. Tarasenko, E.V. Duboysky.*
The Use of Fresnel Lenses in LED Sources of Local Illumination
to Optimize the Distribution of Illumination of the Working Plane.
Приборы и методы измерений.
2023. – Т. 14, № 2. – С. 96–105.
**DOI:** 10.21122/2220-9506-2023-14-2-96-105

***For citation:***
P.S. Bogdan, E.G. Zaytseva, I.A. Kovalenok, T.D. Tarasenko,
E.V. Duboysky.
The Use of Fresnel Lenses in LED Sources of Local Illumination
to Optimize the Distribution of Illumination of the Working Plane.
*Devices and Methods of Measurements.*
2023, vol. 14, no. 2, pp. 96–105.
**DOI:** 10.21122/2220-9506-2023-14-2-96-105

## Introduction

Currently LED sources are widely used for indoor lighting of premises. Their advantages include high energy efficiency and durability. In addition, ability to adjust the power parameters of LED arrays and to introduce LEDs with different spectral characteristics into their composition allows you to vary the brightness and spectral composition of light. Space inside the luminous intensity curve (the distribution of luminous intensity obtained by the cross section of the photometric body of the illuminating device by a characteristic plane or surface and represented in the form of a light beam graph[1]) is limited by a small solid angle [1, 2]. Therefore, there is a sharp decline in the illumination of the working plane from the center to the edge [3] which is not consistent with the requirements of the standard[2] for lighting parameters.

To expand this spatial angle and consequently the uniformity of illumination of the working surface additional optics are used (an optical system in the form of a lens and/or a reflector designed to create the necessary light intensity curve) [4–10] and diffusers [11, 12]. The latter have two versions: with the use of diffusants [11] or with an additional microprismatic surface [12].

These technical solutions have a different level of complexity and provide a different degree of uniformity of illumination of the working plane. The purpose of this study was to analyze the effectiveness of the use of Fresnel lenses in LED lamps of local lighting as a fairly simple and technological element to increase the uniformity of illumination of the working plane within the limits regulated by the standard[2].

## Mathematical modeling of the distribution of illumination created by the combination of "LED matrix – Fresnel lens"

The scheme for calculating the distribution of illumination contains 2 elements: an LED matrix 1 and a Fresnel lens 2 (Figure 1). Parallel to them are the rear focal plane 3 of the lens and the working plane 4. The planes of the LED matrix 1, lens 2 and working plane 4 are parallel, and the distance between the LED matrix 1 and lens 2 is less than the focal length of the lens.

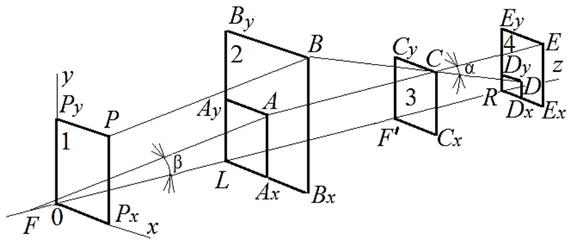


**Figure 1** – Scheme of the beam path from the LED through the lens to the working plane: 1 – the plane of the LED matrix; 2 – the plane of the Fresnel lens; 3 – the rear focal plane of the Fresnel lens; 4 – the working plane

From the LED belonging to the matrix 1 and located at point *P* with coordinates $P_x$, $P_y$, the beam hits the Fresnel lens 2 at point *B* with coordinates $B_x$, $B_y$. There its refraction occurs. Then, crossing the rear focal plane 3 of the lens at point *C* with coordinates $C_x$, $C_y$, the beam comes to the working plane 4 at point *D* with coordinates $D_x$, $D_y$. To determine the direction of the beam *PB* after refraction by lens 2 allows the trajectory of the additional beam passing through points *F*, *A*, *C*, *E*. This ray is parallel to the *PB* ray up to the intersection with the lens plane 2 and comes from the front focus of the lens *F*. After refraction in the plane of the lens 2 at point *A* with coordinates $A_x$ and $A_y$, this ray becomes parallel to the optical axis of the lens *FF'*, crossing the rear focal plane 2 at point *C* with coordinates $C_x$, $C_y$, and the working plane 3 at point *E* with coordinates $E_x$, $E_y$. Since the rays *PB* and *FA* are parallel before refraction by lens 2, after refraction they intersect at one point *C* belonging to the rear focal plane.

In accordance with the Methodological Manual[3] on the design of artificial lighting of public and residential buildings, the illumination $E_D$ at the point *D*

[1] GOST 34819-2021. Lighting devices. Lighting requirements and test methods. Access mode: http://nt-led74.ru/media/uploads/2022/07/06/gost-34819-2021.pdf?ysclid=lgdc0fqlh4478346242. – Access date: 25.04.2023 (in Russian)

[2] GOST R 55710-2013. Lighting of workplaces inside buildings. Norms and measurement methods. Access mode: https://ecolight.ru/sadm_files/Documents/2940421_GOST_R_55710-2013.pdf. – Access date 26.01.2022 (in Russian)

[3] Design of artificial lighting of public and residential buildings. Methodical manual // Ministry of Construction and Housing and Communal Services of the Russian Federation. Federal Center for Standardization, Standardization and Conformity Assessment in Construction. – M., 2016, 141 p. Access mode: https://www.faufcc.ru/upload/methodical_materials/mp15.pdf. – Date of access: 28.01.2022 (in Russian)

on the working plane 4 is proportional to two values. Firstly, it is the light intensity $I$ in the direction of the angle β between the beam direction $PB$ and the axis of symmetry of the light intensity curve parallel to the optical axis of the lens 2. Secondly, it is the cosine of the angle α between the beam $CD$ incident on the working plane 4 and the perpendicular $CE$ to the working plane 4. In addition, the illumination of $ED$ is inversely proportional to the square of the sums of the distances $l_{PB}$ and $l_{BD}$ between the radiation source $P$ and the illuminated point $D$, which are the sum of the segments $PB$ and $BD$:

$$E_D = \frac{I(\beta)\cos\alpha}{(l_{PB}+l_{BD})^2}. \quad (1)$$

Taking into account the geometric relations in Figure 1, the formula for calculating the illumination $E_{i,j}(x,y)$ created by an LED with the number $i$ horizontally and $j$ vertically at point $D$ with $x$, $y$ coordinates on the working plane 4 has the form:

$$E_{i,j}(x,y) = \frac{I(\beta)\cos\alpha}{(l_1+l_2)^2}, \quad (2)$$

where β is the angle of inclination of the light beam to the axis of symmetry of the light intensity curve parallel to the axis $FF'$ of the Fresnel lens 2, and simultaneously to the axis of symmetry of the Fresnel lens; $I(\beta)$ is the dependence of the light intensity on the angle β; α is the angle of inclination of the beam after refraction by the Fresnel lens 2 perpendicular to the illuminated plane 4; $l_1$ is the travel length of the light beam from the LED with the number $(i, j)$ on the matrix 1 to the Fresnel lens 2; $l_2$ is the travel length of the refracted beam from the Fresnel lens 2 to the working plane 4.

Since the orientation of the segments $PB$ and $BD$ of the light beam is considered in the three-dimensional space $xyz$, when calculating the illumination, the values of the quantities in the right part of formula (1) are determined through their projections on the $x0z$ and $y0z$ planes.

The angle β is related to its projections $\beta_x$ and $\beta_y$ on the $x0z$ and $y0z$ planes by the ratio (Figure 2):

$$\beta = \arctan\sqrt{\tan^2\beta_x + \tan^2\beta_y}. \quad (3)$$

Similarly, the angle α is determined by its projections $\alpha_x$ and $\alpha_y$ on the $x0z$ and $y0z$ planes:

$$\alpha = \arctan\sqrt{\tan^2\alpha_x + \tan^2\alpha_y}.$$

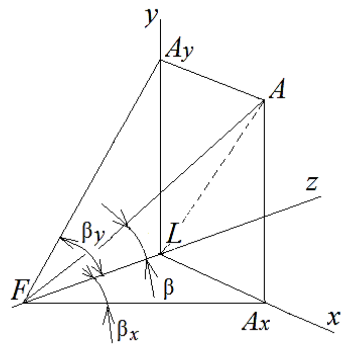


**Figure 2** – Scheme for establishing relations between angle β and its projections $\beta_x$ and $\beta_y$ on the $x0z$ and $y0z$ planes

The tangents of the projections $\beta_x$ and $\beta_y$, $\alpha_x$ and $\alpha_y$, angles β and α, in turn, are functions of the coordinates $x_P$, $y_P$, $x_D$, $y_D$ of the points $P$ and $D$ in Figure1 and the parameters $d$, $f$, $g$:

$$\tan\beta_x = \frac{(d-f)x_P + x_D f}{f(g+d) - dg};$$

$$\tan\beta_y = \frac{(d-f)y_P + y_D f}{f(g+d) - dg};$$

$$\tan\alpha_x = \frac{(f-g)\tan\beta_x + x_P}{f};$$

$$\tan\alpha_y = \frac{(f-g)\tan\beta_y + y_P}{f},$$

where $d$ is the distance $LR$ between the Fresnel lens 2 and the working plane 4 in Figure 1; $f$ is the focal length of the Fresnel lens 2, equal to $FL$ and $LF'$ in Figure 1; $g$ is the distance $0L$ between the LED matrix 1 and the Fresnel lens 2 in Figure 1.

Segments $l_1$ and $l_2$ are connected with their projections $l_{1x}$, $l_{1y}$ and $l_{2x}$, $l_{2y}$ expressions:

$$l_1 = \sqrt{l_{1x}^2 + l_{1y}^2}; \; l_2 = \sqrt{l_{2x}^2 + l_{2y}^2},$$

where $l_{1x}$ is the projection of the segment $PB$ of the light beam from the LED $P$ to the Fresnel lens 2 on the $x0z$ plane; $l_{1y}$ is the projection of the segment $PB$ of the light beam from the LED $P$ to the Fresnel lens 2 on the $y0z$ plane; $l_{2x}$ is the projection of the segment $BD$ of the refracted beam from the Fresnel lens 2 to the working plane 4 on the $x0z$ plane; $l_{2y}$ is the projection of the segment $BD$ of the refracted beam from the Fresnel lens 2 to the working plane 4 on the $y0z$ plane; and

$$l_{1x} = \frac{d}{\cos\beta_x}; \; l_{1y} = \frac{d}{\cos\beta_y};$$

$$l_{2x} = \frac{d}{\cos\alpha_x};\ l_{2y} = \frac{d}{\cos\alpha_y}.$$

At each point of the working plane 4 (Figure 1) with $x, y$ coordinates, there is a summation of the energy flows that have come to this point along the directions of the light rays from all LEDs at different angles of incidence and with different angles of deviation from the axis of symmetry of the light intensity curve. The values of these angles depend on the location and, consequently, on the number of the LED in the matrix. The total distribution of illumination $E(x, y)$ generated by all LEDs of the matrix 1 at the point of the working plane 4 with $x, y$ coordinates can be calculated by the formula:

$$E(x,y) = \sum_{i=-n}^{i=n}\sum_{j=-m}^{j=m} E_{i,j}(x,y), \quad (4)$$

where $i$ is the number of the LED in the matrix on the $x$ axis; $j$ is the number of the LED in the matrix on the $y$ axis; $n$ is the number of the first and last LED in the matrix at the beginning of the reference from the middle LED on the x axis; $m$ is the number of the first and last LED in the matrix at the beginning of the reference from the middle LED on the $y$ axis; $E_{i,j}(x, y)$ is the illumination distribution created by an LED having the number $i$ horizontally and the number $j$ vertically, calculated by the formula (2).

Expression (4) is used for the case when one common Fresnel lens is used for all LEDs. Another option is also possible, when an individual Fresnel lens is used for each LED. In this case, the optical axis of this individual lens coincides with the central axis of the LED. In this case, it is necessary to first calculate the illumination distribution created by the “LED – individual Fresnel lens” system. Then all these illumination distributions are summed up taking into account the displacement of each LED – lens pair relative to the zero coordinate on the working surface. Then the sum of the illumination distribution is described by formula (5):

$$E(x,y) = \sum_{i=-n}^{i=n}\sum_{j=-m}^{j=m} E_0(x - i\Delta_x, y - i\Delta_y), \quad (5)$$

where $E_0(x, y)$ is the distribution of illumination created on the working surface by one pair of “LED – lens” having a zero coordinate on the working surface; $\Delta x$ is the pitch of the LEDs in the matrix horizontally; $\Delta y$ is the pitch of the LEDs in the matrix vertically.

In the considered second variant, the plane of LEDs $P$ in the matrix is perpendicular to the axis of the matrix, and, accordingly, to the optical axis $FR$ of the Fresnel lens (Figure 3$a$). In this case, the beam $PK$, which is the axis of symmetry of the luminous intensity curve (in its direction, the luminous intensity is maximum), is parallel to the axis of the lens. After being refracted by the lens, it passes through the back focus of the lens and hits the working plane $DR$ at some angle. And the ray of the luminous intensity curve $PK'$, the continuation of which passes through the front focus of the lens $F$ and in the direction of which the intensity of the luminous intensity curve is less than for the ray $PK$, after refraction is perpendicular to the working plane $DR$.

Another variant of the layout of the LED matrix is possible, using an individual Fresnel lens for each LED (Figure 3$b$). Here, the plane of each LED $P$ of the matrix is rotated so that the continuation of the beam $PK$ on the axis of symmetry of the luminous intensity curve passes through the front focus $F$ of the lens at such an angle $\gamma$ that, after refraction by the lens, this beam is perpendicular to the working plane $DR$. The angle $\gamma$ depends on the coordinates of the LED $P$, so its values are different for each LED. Since the luminous intensity in the direction of the symmetry axis of the luminous intensity curve is maximum with respect to the rays of other directions, in this case the radiation intensity in the direction perpendicular to the working surface is greater than in the previous case, illustrated in Figure 3$a$.

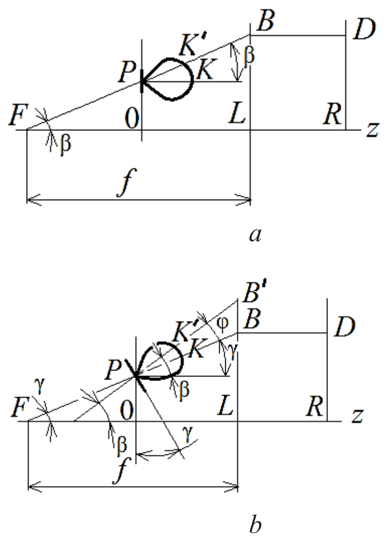


**Figure 3** – Scheme of the course of rays with continuation through the front focus of the lens when the axis of symmetry of the light intensity curve is parallel to the axis of the lens ($a$) and when the axis of symmetry of the light intensity curve passes through the front focus of the lens ($b$)

For the variant shown in Figure 3*a*, the illumination distribution is calculated using formulas (2) and (4). For the case illustrated in Figure 3*b*, instead of formula (2), the expression is used:

$$E_{i,j}(x,y) = \frac{I(\varphi)\cos\alpha}{(l_1 + l_2)^2}, \quad (6)$$

where φ is the angle of inclination of the light beam *PK′* to the axis of symmetry *PK* of the light intensity curve (Figure 3*b*), φ = β–γ; β is the angle of inclination of the light beam *PK′* to the axis of the Fresnel lens *FL*, calculated by the formula (3); γ is the angle of inclination of the axis of symmetry *PK* of the light intensity curve to the axis of the Fresnel lens *FL*.

The angle γ is determined by its projections $\gamma_x$ and $\gamma_y$ on the plane *x*0*z* and *y*0*z* similarly to the angle β calculated using the expression (3):

$$\gamma = \arctan\sqrt{\tan^2\gamma_x + \tan^2\gamma_y},$$

where $\tan\gamma_x = \frac{x_P}{f-g}$; $\tan\gamma_y = \frac{y_P}{f-g}$ other designations are given earlier.

In order to evaluate the possibility of practical use of the proposed mathematical model, the results of calculating the illumination distribution on the working surface according to formula (4) were compared with experimental data.

For an experimental study of the dependence of illumination on the distance between the LED matrix and the lens, the distribution of illumination on the plane was measured. The RGB LED matrix had a height of 55 mm and a width of 94 mm, 5 WS2812b LEDs were located vertically, 10 horizontally in 9 mm increments. A rectangular Fresnel lens with a height of 26 cm and a width of 18 cm with a focal length of 20 cm was installed parallel to the matrix plane. The distance between the matrix and the lens was 1 cm. The matrix and the illuminated plane were located at a distance of 50 cm from each other.

Measurements were made at 6 points of the illuminated matrix, starting from the optical axis of the matrix with a step of 10 cm in two directions: horizontally and vertically. 2 devices were used for measurements: the Opple Light Master III device with a photosensitive diameter of 17 mm (relative measurement error of 5 %, measurement limit of 0–5000 lx) and an original measuring device containing a photodiode with a photosensitive diameter of 6.5 mm, an amplifier and a power supply. The use of the original measuring device made it possible to reduce the diameter of the measuring platform in relation to conventional luxmeters and thereby increase sensitivity to changes in illumination on the plane. The readings of the measuring device were translated into illumination units using a calibration curve. This curve was obtained by measuring different levels of illumination on a plane with a uniform distribution of illumination both by the original device used and by the Yu 116 luxmeter.

For calculations according to formula (3), data on the light intensity curve *I*(β) of a three-crystal RGB-SMD LED LM1-TPP1-01 TTQ from COTCO with a delta-like arrangement of crystals inside the case [1] having the same arrangement of crystals and the same angle of the light intensity curve (120°) were used, as with the WS2812b LED. The calculated values of the matrix pitch, the distances between the matrix, the Fresnel lens and the illuminated plane corresponded to those used in the experiment.

Comparison of the calculation results and experiments showed their correspondence, sufficient to solve the problem of optimizing the distribution of illumination of the working plane in LED sources of local illumination. The standard deviations of the calculated values from the measured values are shown in Table 1.

*Table 1*

**Standard deviations of calculated values from those measured in relative units**

| Distance between lens and matrix, cm | By the *x* coordinate | | By the *y* coordinate | |
|---|---|---|---|---|
| | Original device | Opple Light Master III | Original device | Opple Light Master III |
| 1 | 0.083 | 0.034 | 0.085 | 0.023 |

It is obvious from the mathematical model that the distribution of illumination on the working plane is a function of the focal length of the Fresnel lens, the distance between the lens and the LED matrix, the distance from the lens to the working plane. To investigate the effect of the focal length of the lens and the distance between the lens and the LED matrix on the illumination distribution on the working plane, calculations of this distribution were made for the distances between the lens and the matrix of 0.5 cm, 1 cm, 1.5 cm and the focal lengths of the lens of 10 cm, 50 cm, 100 cm. The distance from the Fresnel lens to the working plane was chosen to be 50 cm. This distance provides an optimal combination of the height of the lamp for local lighting and

Devices and Methods of Measurements
2023, vol. 14, no. 2, pp. 96–105
P.S. Bogdan et al.

the distance between the light source and the working plane.

The calculation results showed that a change in the distance between the lens and the matrix in the range from 0.5 cm to 1.5 cm slightly affects the distribution of illumination when changing the focal length of the lens in the range from 10 cm to 100 cm. At the same time, at different values of the focal length, the nature of the distribution of illumination and its maximum value changes, which is illustrated in Figure 4.

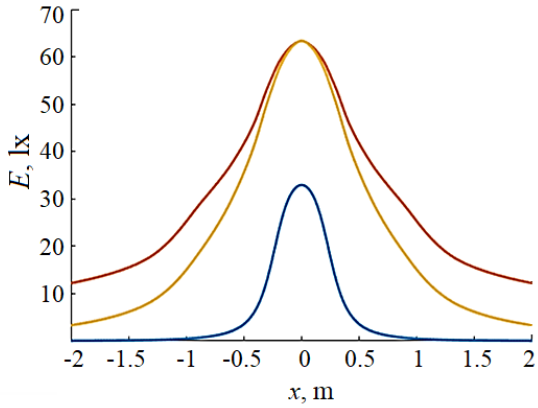


**Figure 4** – Graphs of the dependence of illumination *E* as a function of the spatial coordinate *x* for the distance between the Fresnel lens and the matrix of 0.1 cm with a focal length of the lens of 10 cm (lower graph), 50 cm (upper graph), 100 cm (middle graph)

The calculation results indicate that in a given range of numerical values, a change in the focal length affects the nature of the illumination distribution in the working plane to a greater extent than a change in the distance between the lens and the matrix. In addition, with a focal length of 50 cm equal to the selected distance from the lens to the working plane, there is a more uniform distribution of illumination than for focal lengths of 10 cm and 100 cm. At the same time, starting from the focal length value of 50 cm and above, the maximum illumination value does not increase.

## Using the developed mathematical model to optimize the illumination distribution of the working plane in LED sources of local illumination containing a Fresnel lens

Based on the previously developed methodology for calculating the illumination distribution of the working plane [3], variants of LED sources of general and local illumination without secondary optics were studied, providing illumination regulated by standards and its uniformity. If it was possible to develop an acceptable option for general lighting that meets the requirements of regulatory documents[2,4], then an acceptable solution was not found for local lighting.

According to the requirements for local lighting according to GOST R 55710[2] for work with video terminals, writing, typing, reading, data processing, the operational illumination should be 500 lx, and the uniformity of illumination *k* (the ratio of the minimum illumination value to the average value on a given surface[2]) should be at least 0.6. In accordance with the Methods of hygienic assessment of indicators of artificial light environment in the premises of buildings and constructions[5] for the distance to the illuminated plane of 0.5 m, the radius of the working area is 0.6 m.

Previous studies [3] have shown that the main problem in the development of an LED source of local illumination without secondary optics was the achievement of the required uniformity of illumination. To calculate the uniformity of illumination in accordance with GOST[2], it is necessary to find the quotient of the division of the minimum illumination (as a rule, it takes place at the edge of the working area) to the average over the entire working area. Therefore, the uniformity of illumination *k*, as well as the values of the illumination itself, is a function of the focal length of the Fresnel lens and the distance between the lens and the LED matrix.

To determine which values of these distances correspond to the required uniformity of illumination, an analytical dependence of the uniformity of illumination *k* of the working surface as a function of the focal length f of the Fresnel lens and its distance g from the matrix was obtained for three cases. In the

[4] Hygienic standard "Indicators of safety and harmlessness for humans of natural, artificial and combined lighting of residential buildings". Approved by the Decree of the Ministry of Health of the Republic of Belarus on June 28, 2012 No 82. Access mode: https://minzdrav.gov.by/upload/lcfiles/text_tnpa/000348_136669_PoatMZ_N82_2012_GN.pdf. – Access date: 05/03/2023

[5] Methods of hygienic assessment of indicators of artificial light environment in the premises of buildings and structures. Instructions for use // Republican unitary Enterprise "Scientific and practical center of hygiene". Reg. No. 007-1217. – Minsk, 2018. – 14 p. Access mode: http://med.by/methods/pdf/007-1217.pdf. – Access date: 28.01.2022 (in Russian)

first one, one lens is used for the entire matrix and the axes of symmetry of the light intensity curves of the LEDs are parallel to the axis of the lens. The second one also uses one lens for the entire matrix, but the continuations of the axes of symmetry of the light intensity curves pass through the front focus of the lens. In the third case, an individual Fresnel lens is used for each LED. In the first case, formulas (2, 4) were used for calculation, in the second – (6, 4), in the third – (2, 5).

Analysis of the calculation results allows us to conclude that for all three cases the dependencies are similar, and the minimum allowable value of the uniformity of illumination *k*, equal to 0.6, corresponds to a large number of possible combinations of focal lengths of the lens and the distances between the lens and the matrix. In addition, changing the distance between the lens and the matrix in the selected range slightly affects the uniformity of illumination. As an example in Figure 5 graphically shows the dependence of the uniformity of illumination on the focal length of the lens and the distance between the lens and the matrix for the first case.

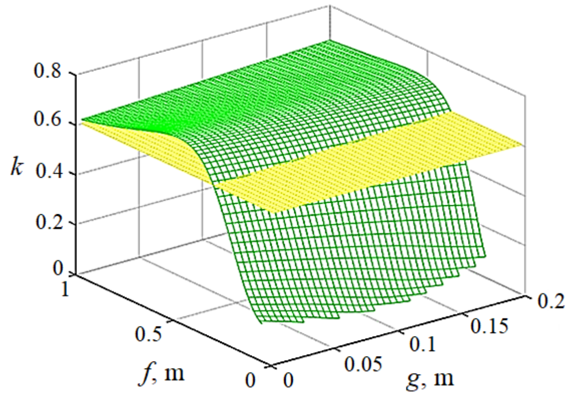


**Figure 5** – The dependence of the uniformity of illumination *k*, on the focal length *f* of the Fresnel lens and the distance *g* between the lens and the LED matrix (the common lens and the axes of the light intensity curves are parallel to the axis of the lens, the yellow plane is the minimum allowable value of the uniformity of illumination *k*, equal to 0.6)

From the many combinations of the focal length of the lenses and the distance between the lens and the matrix, for each of the three cases, the combinations given in Table 2 were calculated to ensure maximum uniformity of illumination.

*Table 2*

**The values of the maximum uniformity of illumination, and the corresponding values of the maximum illumination, the focal length of the lenses and the distance between the lens and the matrix**

| Type of "lens-matrix" combination | Maximum uniformity of illumination $k_{max}$ | Maximum illumination $E_{max}$, lx | Focal length of the lens *f*, cm | Distance between lens and matrix *g*, cm |
|---|---|---|---|---|
| A system with a common lens and axes of the light intensity curve parallel to the optical axis of the lens | 0.72364 | 63.973 | 50.29 | 0.5 |
| A system with a common lens and inclined axes of the light intensity curve | 0.72434 | 63.812 | 50.29 | 0.5 |
| System with individual lenses for each LED | 0.72364 | 63.973 | 50.29 | 0.5 |

It follows from the analysis of the table that all the values given in it are almost equal. Therefore, the choice of using one of the three options may be due to manufacturability, cost-effectiveness and thermal stability, and other considerations. At the same time, the number of LEDs selected for the calculation does not provide the illumination required by the regulatory documents 2.4, equal to 500 lx. An increase in illumination is possible due to an increase in the number of LEDs or by increasing their light output.

The number of LEDs in the matrix providing illumination of 500 lx, found by formula (4) for the values of *f* and *g* given in Table 2, was 400. The size of such a matrix with a 9 mm LED pitch is 18×18 cm.

Using formula (4), the illumination distribution on the working plane was calculated for a lamp with 400 LEDs with a Fresnel lens for the parameters *f* and *g* given in Table 2, as well as the illumination distribution was calculated in the absence of a lens and the same distance between the matrix and the working plane. The calculation results are illustrated in Figure 6.

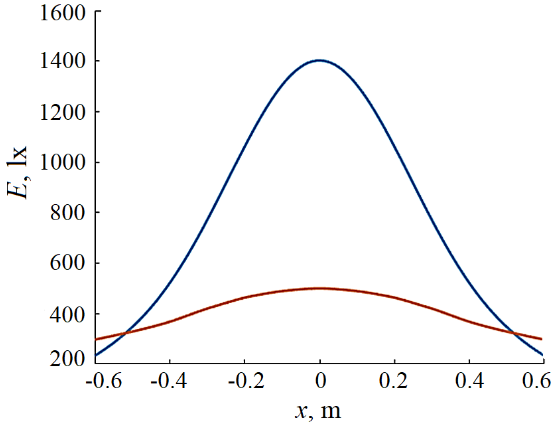


**Figure 6** – Dependence of the illumination distribution *E* of the working plane as a function of the spatial coordinate when using a Fresnel lens (red line) and without using a lens (blue line) when illuminated by a matrix (20×20)

It follows from the graph in Figure 6 that the use of a Fresnel lens in conjunction with an RGB matrix made it possible to fulfill the regulatory requirements for illumination and its uniformity, as well as to increase illumination outside the regulatory lighting zone. A matrix without a lens creates excessive illumination in the center of the field and unacceptable unevenness.

A significant number of LEDs (400) in the considered case is due to the low luminous efficiency of RGB LEDs (33.9 lm/W [1]). If it is necessary to reduce their number, it is possible to use more efficient white LEDs or a combined matrix of RGB and white LEDs. In the first case, the ability to adjust the spectral composition will completely disappear, in the second, the possible range of regulation will decrease due to the "dilution" of the radiation from RGB LEDs with white light. To simulate natural radiation, the second option is acceptable, since it allows for the possibility of varying spectral characteristics in a relatively small range inherent in natural radiation.

The required number of LEDs is inversely proportional to the light output. For example, if you replace RGB LEDs with "warm" ones (color temperature 3000 K) white SMD 1210 (3528) models with a luminous output of 66.7 lm/W, then the illumination distribution shown in Figure 6 will be provided by a matrix of 225 LEDs (15×15).

## Conclusion

A method has been developed for calculating the distribution of illumination created by the combination of "LED matrix – Fresnel lens" when the distance between the lens and the matrix is less than the focal length of the lens. Calculations have shown that a change in the distance between the matrix and the lens from 0.5 cm to 1.5 cm at focal lengths from 10 cm to 100 cm affects the maximum illumination and its uniformity to a lesser extent than a change in focal lengths from 10 cm to 100 cm at distances between the matrix and the lens from 0.5 cm to 1.5 cm.

It is established that the use of a common Fresnel lens for the entire LED matrix as a whole and individual lenses for each LED individually provides almost the same illumination distribution. The rotation of the axes of symmetry of the light intensity curve of the LEDs from a position parallel to the axis of the common lens to a position where the continuations of the axes of symmetry of this curve pass through the front focus of the lens also almost does not change the distribution of illumination. Therefore, it is advisable to choose the optimal one from the above options according to other criteria, for example, manufacturability, economy and thermal stability.

## References

1. Nikiforov S. *«S-klass» poluprovodnikovoj svetotekhniki* ["S-class" of semiconductor lighting engineering]. *Komponenty i tekhnologii* [Components and technologies], 2009, no. 6, pp. 88–91 (in Russian).

2. Popova I.G., Grebenyuk T.I., Podoltsev V.V. *Postroenie i approksimaciya diagramm napravlennosti svetodiodov* [Construction and approximation of LED directional diagrams]. *Molodoj issledovatel' Dona* [Young researcher of the Don], 2019, no. 5(20), pp. 71–75 (in Russian).

3. Bogdan P.S., Zaytseva E.G., Baranov P.O., Stepanenko A.I. Analysis of illumination generated by LED matrices distribution. *Devices and Methods of Measurements*, 2022, vol. 13, no. 1, pp. 60–67.
**DOI:** 10.21122/2220-9506-2022-13-1-60-67

4. Shen D. *Kollimatornye linzy Edison Opto* [Collimator lenses Edison Opto]. *Poluprovodnikovaya*

*svetotekhnika* [Semiconductor lighting engineering], 2013, no. 1(21), pp. 20–21. [Electronic Resource]. Available at: https://led-e.ru/assets/listalka/2013_1/2013_1/assets/common/downloads/publication.pdf (accessed: 27.01.2022) (in Russian).

5. Vertli Y. *Linzy s nastraivaemym fokusom dlya svetodiodov* [Lenses with adjustable focus for LEDs]. *Semiconductor lighting*, 2013, no. 1(21), pp. 22–23. [Electronic Resource]. Available at: https://led-e.ru/assets/listalka/2013_1/2013_1/assets/common/downloads/publication.pdf (accessed: 27.01.2022) (in Russian).

6. Da Silva H. *Sovershenstvovanie konstrukcij svetodiodnyh lamp s pomoshch'yu plastichnyh opticheskih silikonov* [Improvement of LED lamp designs using plastic optical silicones]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 2013, no. 1(21), pp. 26–27. [Electronic Resource]. Available at: https://led-e.ru/assets/listalka/2013_1/2013_1/assets/common/downloads/publication.pdf (accessed: 27.01.2022) (in Russian).

7. Barbosa J., Calixto W., da Cunha Brito L. Secondary Lens Optimization for LED Lamps. *Journal of mechanics engineering and automation*, 2014, no. 4, pp. 46–51.

8. Moiseev M. *Nizkoprofil'nye linzy ot Khatod: novyj «kosmicheskij» vzglyad* [Low-profile lenses from Khatod: a new "cosmic" look]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 2017, no. 5(49), pp. 44–46 (in Russian).

9. Trofimov O., Golikov O. *Reflektory i gibridnye linzy ot Ledlink Optics* [Reflectors and hybrid lenses from Ledlink Optics]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 2013, no. 1(21), pp. 24–25. [Electronic Resource]. Available at: https://led-e.ru/assets/listalka/2013_1/2013_1/assets/common/downloads/publication.pdf (accessed: 27.01.2022) (in Russian).

10. Jian V., Schneider K. *Uluchshenie osveshchennosti ob"ekta pri ispol'zovanii optiki s polnym vnutrennim otrazheniem* [Improving the illumination of an object when using optics with full internal reflection]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 2013, no. 1(21), pp. 28–30. [Electronic Resource]. Available at: https://led-e.ru/assets/listalka/2013_1/2013_1/assets/common/downloads/publication.pdf (accessed: 27.01.2022) (in Russian).

11. Sharakshane A. *Ob effektivnosti matovyh svetorasseivatelej* [On the effectiveness of matte light diffusers]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 2014, no. 1(27). [Electronic Resource]. Available at: https:// led-e.ru/vtorichnaya-optika/ob-effektivnosti-matovyh-svetorasseivatelej-2 (accessed: 28.01.2022) (in Russian).

12. Ferrini R., Fernandez O., Barruetabena L., Ivanovich S. *Ul'tratonkij svetodiodnyj modul' pryamoj podsvetki s tonkoplenochnoj opticheskoj sistemoj* [Ultrathin LED direct illumination module with a thin-film optical system]. *Poluprovodnikovaya svetotekhnika* [Semiconductor lighting engineering], 201, no. 5(49), pp. 32–38 (in Russian).