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Analysis of Illumination Generated by LED Matrices Distribution

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Abstract

Creation of indoor lighting systems with the possibility of changing its parameters in space and time is a promising direction within the framework of the intellectual environment system. The aim of this work was to create a methodology for calculating the illumination created by LED matrices which does not require the use of specialized software products and is adapted to the possibility of varying the parameters of LEDs and illuminated rooms.

The urgency of creating a room lighting system that simulates the conditions of natural lighting taking into account the need to change its spectral composition in time, in space taking into account the physical and psychological state of a person is substantiated. The possibility of using well-known computer programs to calculate the distribution of illumination in the room is analyzed.

A method has been developed for calculating the distribution of illumination on a plane using both a flat LED matrix and a matrix with an inclined arrangement of the planes of individual LEDs. It is shown that the distribution of illumination is a function of the indicatrix of the light intensity of the LED, its location in space, the number of LEDs in the matrix.

Illumination distribution has been calculated for various light sources consisting of RGB LEDs both for desktop and ceiling lighting was calculated. It is established that when using matrices containing the same LEDs distribution of illumination is very nonuniform. The inclined arrangement of LED planes slightly increases uniformity reducing the maximum illumination. For ceiling lighting the option of uniform distribution of LEDs within the ceiling plane provides more uniform illumination than when the same number of LEDs are arranged in groups of matrices.

Results of LED sources modeling indicate the need to modernize simple orthogonal matrices containing the same type of elements with the same power modes for all elements in order to increase the uniformity of illumination and efficiency. Such modernization can be carried out by changing the geometry of matrices differentiating the power modes of individual LEDs. The developed calculation program can be supplemented with options for introducing the above changes, as well as options for analyzing the spectral distribution of light in space.

Keywords: mathematical modeling, RGB LED, light intensity distribution indicatrix, led matrix, illumination distribution.

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Анализ распределения освещённости, генерируемой светодиодными матрицами

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Создание систем освещения помещений с возможностью изменения его параметров в пространстве и во времени является перспективным направлением в рамках системы «интеллектуальная окружающая среда». Целью данной работы было создание методики расчёта освещённости, создаваемой светодиодными матрицами, которая не требует применения специализированных программных продуктов и адаптирована к возможности варьирования параметров светодиодов и освещаемых помещений.

Обоснована актуальность создания системы освещения помещений, имитирующей условия естественного освещения с учётом необходимости его изменения по спектральному составу во времени, в пространстве с учётом физического и психологического состояния человека. Проанализирована возможность использования известных компьютерных программ для расчёта распределения освещённости в помещении.

Разработана методика расчёта распределения освещённости на плоскости при использовании как плоской светодиодной матрицы, так и матрицы с наклонным расположением плоскостей отдельных светодиодов. Показано, что распределение освещённости является функцией индикатрисы силы света светодиода, расположения его в пространстве, количества светодиодов в матрице.

Произведён расчёт распределения освещённости для различных источников света, состоящих из RGB светодиодов, как для настольного, так и для потолочного освещения. Установлено, что при использовании матриц, содержащих одинаковые светодиоды, велика неравномерность распределения освещённости. Наклонное расположение плоскостей светодиодов незначительно увеличивает равномерность, уменьшая максимальную освещённость. Для потолочного освещения вариант равномерного распределения светодиодов в пределах потолочной плоскости обеспечивает более равномерное освещение, чем при расположении такого же количества светодиодов в виде групп матриц.

Результаты моделирования светодиодных источников свидетельствуют о необходимости модернизации простых ортогональных матриц, содержащих однотипные элементы с одинаковым для всех элементов режимом питания, с целью повышения равномерности освещённости и экономичности. Такая модернизация может осуществляться за счёт изменения геометрии матриц, дифференциации режимов питания отдельных светодиодов. Разработанная программа расчёта может дополняться опциями для введения перечисленных выше изменений, а также опциями для анализа спектрального распределения излучения в пространстве.

Ключевые слова: математическое моделирование, RGB светодиод, индикатриса распределения силы света, светодиодная матрица, распределение освещённости.

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Introduction

Lighting has a significant effect on the human body. According to [1] light radiation determines many physiological and behavioral reactions ranging from hormonal rhythms and pupil reactions, ending with sleep, alertness, cognitive abilities and mood. In particular, it was found [2] that patients who experienced a stay of at least 48 hours in an intensive care unit without windows had a disturbed idea of the duration of their stay in the department and their orientation in time worsened, as well as the frequency of hallucinations and delusions increased more than 2 times compared to patients in similar departments with translucent windows. To eliminate these phenomena, the authors [2] proposed using a system to simulate the daily cycle of natural light in a medical hospital. Since natural lighting is not always optimal for human life (seasonal changes in the duration of daylight, individual characteristics and preferences of a person), the urgency of creating a combined (natural and artificial lighting) system is obvious, which should quickly adapt to both changes in the natural component and individual characteristics and preferences of a person.

The parameters of the lighting system elements must comply with regulatory documents and comfort conditions. The requirements for lighting and radiation sources are set out in regulatory documents[1–3]. The main normalized parameters are illumination and its uniformity in space. In addition, in the standard[3] of the Association of Manufacturers of LEDs and systems based on them, the criterion for choosing parameters is the comfort of the light environment for different age groups, taking into account the need to change these parameters over time. Hence, the need to develop adaptive lighting systems is obvious, and the change in illumination in space should be determined by the age of a person, as well as his physical and psychological state. Therefore, the lighting system must contain not only the source itself, the power supply circuit, the unit for measuring the parameters of the natural component of lighting, but also devices for monitoring the human condition, appropriate software.

To the greatest extent, the adaptability requirement is satisfied by LED light sources, whose brightness and spectral composition are quite easy to control. Their important advantage is also the low power consumption. At the same time, the use of LEDs as light sources revealed two significant drawbacks: the small angular size of the light beam and the excessive brightness when the source enters the field of view. To get rid of these shortcomings, optical elements (lenses, reflectors [3–8]) and scattering filters [9] are used in the lighting device. A large number of proposed architecture options for LED lighting systems complicates the process of optimal selection of lighting systems, taking into account compliance with the requirements of current standards and the need for dynamic lighting. Therefore, for such optimization, it is necessary to be able to computer simulate the distribution of illumination in the room in the function of the LED radiation indicatrix and the coordinates of its placement in the room.

Currently, several packages of computer calculation of optical system parameters are used: Zemax, Code V, Oslo, DEMOS, SARO, OPAL, etc., the advantages and problems of their application are given in [10]. Some of them are focused on foreign element base, norms and standards, the main purpose of these programs is modeling and analysis of various optical systems. In [11], optimization of secondary lenses for LED lamps is performed using ray tracing using the Monte Carlo method without image processing. A program has been developed using the particle swarm algorithm (PSO) in order to optimize the layout of lamps for the general lighting scheme of premises [12]. The last two methods are closer to solving the problem of optimal illumination, but the algorithms used in them are quite complex and require significant technical resources. The aim of the work was to create a methodology for calculating the illumination created by LED matrices, which does not require the use of specialized software products and is adapted to the possibility of varying the parameters of LEDs and illuminated rooms.

Mathematical modeling of the illumination distribution generated by the LED matrix

As the initial data for calculating the illumination on the plane, the light intensity distribution of the source, the coordinates of the source relative to

[1] GOST ISO 8995-2002. Principles of visual ergonomics. Lighting of working systems indoors (in Russian).
[2] GOST R 55710-2013. Lighting of workplaces inside buildings. Norms and measurement methods (in Russian).
[3] STO. 69159079-05-2020. LED lighting devices. Requirements for a comfortable light environment (in Russian).

the plane are used. The result of the calculation is the dependence of the illumination on the plane as a function of its orthogonal x and y coordinates.

Let us first consider the location of the source A relative to the illuminated plane P, when the axis of symmetry of the indicatrix $A0$ is perpendicular to the plane P (Figure 1).

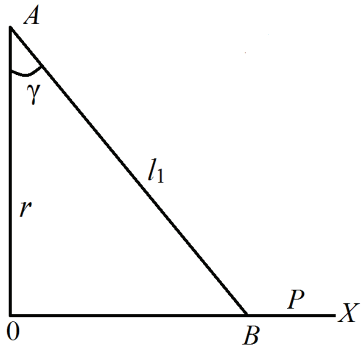

Figure 1 – Scheme for the transition to the dependence of illumination on the spatial coordinate x in the plane P

The ray of the indicatrix in the plane $A0X$, directed to the axis of the indicatrix at an angle γ, intersects the illuminated plane at point B. In accordance with the Methodological Guide[4] for the design of artificial lighting of public and residential buildings, the illumination E_B of point B on the illuminated plane P depends on the angle γ between the perpendicular to the plane P, the direction of the light beam from the source at point A and the distance l_1 between points A and B:

$$E_B = \frac{I(\gamma)}{l_1^2}\cos\gamma. \quad (1)$$

Expression (1) can be used for calculations in the case of a perpendicular arrangement of the axis of the light intensity of the LED relative to the illuminated plane. But when choosing the optimal arrangement of the LEDs in the lighting device, an inclined position of the axis of the indicatrix relative to the illuminated plane is also possible. In Figure 2 the axis of the LED's indicatrix forms angles φ_x and φ_y with a perpendicular to the illuminated plane $x0y$ in the planes $z0x$ and $z0y$, respectively.

[4] 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. Moscow, 2016, 141 p. Access mode: https://www.faufcc.ru/upload/methodical_materials/mp15.pdf. Date of access: 28.01.2022 (in Russian).

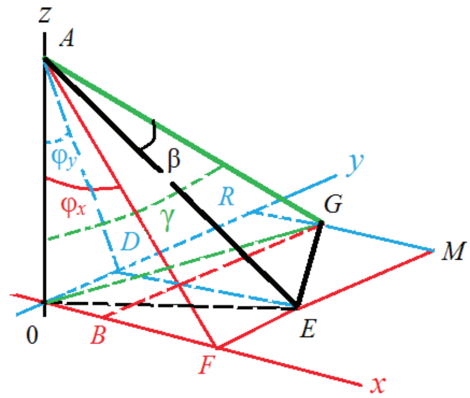

Figure 2 – The direction of light rays at an inclined position of the AE axis of the light intensity indicatrix relative to the illuminated plane $x0y$

In this case, the distribution of illumination on the illuminated plane $x0y$ is a function of the angle β of the inclination of the beam AG to the axis AE of the symmetry of the light intensity indicatrix for the LED, the angle of inclination γ of the beam AG to the perpendicular $A0$ to the illuminated plane $x0y$. The specified dependency has the form:

$$E(\beta,\gamma) = \frac{I(\beta)\cos\gamma}{l_1^2}, \quad (2)$$

where $I(\beta)$ is dependence of the intensity of the angle β of inclination of the beam AG to the axis AE of symmetry of the indicatrix; l_1 is the length of the path of the light beam from the LED to the illuminated surface.

Let's move from the distribution of illumination in the function of the angles β and γ to the distribution in the function of the coordinates x_G and y_G of the points of the illuminated surface and the distance r between the LED at point A and the illuminated plane $x0y$.

From the triangles $A0G$ and EAG it is obvious that:

$$\gamma = \operatorname{arc\,tan}\frac{\sqrt{x_G^2 + y_G^2}}{r}; \quad (3)$$

$$\beta = \arccos\frac{r + x_G\tan\phi_x + y_G\tan\phi_y}{\sqrt{r^2 + (x_G)^2 + (y_G)^2}\sqrt{1 + (\tan\phi_x)^2 + (\tan\phi_y)^2}}; \quad (4)$$

$$l_1 = AG = \sqrt{r^2 + (x_G)^2 + (y_G)^2}. \quad (5)$$

Taking into account the expressions (3, 4, 5), the formula (2) for calculating illumination will take the form:

$$E(x, y, \phi_x, \phi_y) = \frac{I\left(\arccos\frac{r + x_G\tan\phi_x + y_G\tan\phi_y}{\sqrt{r^2 + (x_G)^2 + (y_G)^2}\sqrt{1 + (\tan\phi_x)^2 + (\tan\phi_y)^2}}\right)\cos\left(\arctan\frac{\sqrt{(x_G{}^2 + y_G{}^2}}{r}\right)}{r^2 + (x_G)^2 + (y_G)^2}. \quad (6)$$

As a rule, not one source is used for lighting, but a matrix of LEDs. In this case, it is necessary to sum up the illumination values calculated for each LED, taking into account their displacement relative to each other.

Examples of using the developed mathematical model to calculate the distribution of illumination generated by LED matrices

Illumination in the premises is regulated by regulatory documents. For example, in accordance with GOST R 55710[2], workplaces with video terminals on a given surface, as well as those intended for writing, typing, reading, and data processing, should have an illumination of 500 lux with an illumination uniformity of 0.6, and canteens – 200 lux with a uniformity of 0.4.

Using the developed mathematical model, lighting modeling was carried out for the two above options, and the distance between the LED matrix and the illuminated surface in the first case was assumed to be 0.5 m (table lamp), in the second case 2.5 m (ceiling lamp). For the calculation, the indicatrices of the components of the COTCO three-crystal RGB-SMD LED L1-P1-01 TQ with a delta-shaped arrangement of crystals inside the case were used, shown in Figure 3 [13].

The introduction of information about the graphs in Figure 3 in numerical form into the calculations involves the use of two options. First, it is possible to apply approximations of the form:

$$I = d(\cos\beta)^n, \quad (7)$$

where I is the value of the luminous intensity, cd; β is the angle between the perpendicular to the illuminated surface and the direction of the light beam on the indicatrix, deg; d is the value of the luminous intensity at β equal to 0, n is the exponent.

Selecting the parameter n for the different parts of the indicatrix, it is possible to obtain a sufficiently high accuracy of the approximation, for example, for the blue led when maximum n is equal to 1 for all β, the relative error was 0.07 % (Figure 4).

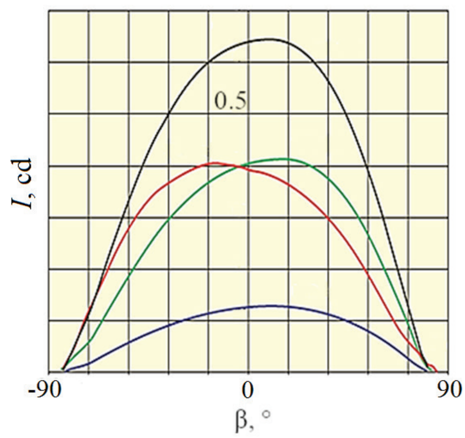

Figure 3 – The indicatrix of the light intensity I as a function of the angle β between the perpendicular to the illuminated surface and the beam direction for the three-crystal RGB-SMD LED LM1-TPP1-01 TTQ for total inclusion in white balance mode (black upper graph), for red, green, blue components (respectively red, green, blue graphs) [13]

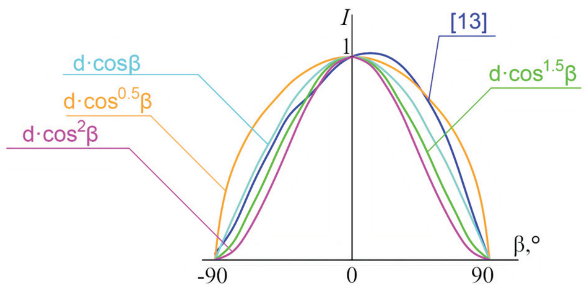

Figure 4 – The indicatrix of the luminous intensity I in relative units as a function of the angle β between the perpendicular to the illuminated surface and the beam direction for the blue component of the RGB-SMD LED LM1-TPP1-01 TTQ [13] and its approximation by formula (7) for different exponents

The second option for introducing the indicatrix in numerical form is to use the method of spline approximation by the pspline and interp functions in Mathcad packages, where the entered numerical values are connected by straight segments. In this case, the deviation of the actual and calculated values is practically reduced to zero, the error between the entered values depends on their number, the approximation formula is not presented in an analytical form. Figure 5 shows a graph of such an approximation and the actual values for the light intensity curve of the blue component of the LED LM1-TPP1-01 TTQ. The second option is more preferable due to less labor intensity.

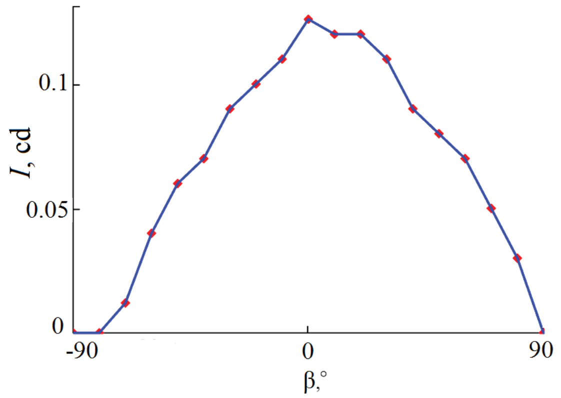

Figure 5 – The light intensity indicatrix I as a function of the angle β between the perpendicular to the illuminated surface and the beam direction for the blue component of the RGB-SMD LED LM1-TPP1-01 TTQ [13] (red icons) and its approximation using the Mathcad package (blue line)

The maximum illumination of the plane is a function of the number of LEDs in the matrix. In order to determine the required number of LEDs in the matrix to provide the required illumination for a table lamp and a ceiling lamp, the corresponding dependencies were obtained for both cases. The LEDs were arranged orthogonally in 9 mm steps. Calculations have shown that these dependencies are linear in nature and differ in the angle of inclination of the straight line to the horizontal axis.

Based on the comparison of the illumination values regulated by GOST R 55710[2] for some types of activities of 500 lux (table lamp) and 200 lux (ceiling lamp) with the obtained dependencies, square matrices of 12×12 and 40×40 LEDs were selected for further calculations. For these matrices, the dependences of illumination on the plane on spatial coordinates are calculated by formula (6). The corresponding graphs of the dependence of the illumination E on the x coordinate are shown in Figures 6 (red curve) and 7 (red curve).

Analysis of the graphs in Figures 6 (red curve) and 7 (red curve) shows that the illumination varies significantly from the center to the periphery. In the first case (table lamp), in accordance with GOST R 55710[2] on a given surface uniformity of lighting should be 0.6, and the second (ceiling lamp) – 0.4. As a given surface in the first case, we consider the area of visual work, the radius R which is in accordance with the Methods of hygienic assessment of indicators artificial light environment in the premises of buildings and structures[5] is calculated as:

$$R = 1.2a, \tag{8}$$

where a is the distance from the eyes of the observer (employee) to the work surface, m.

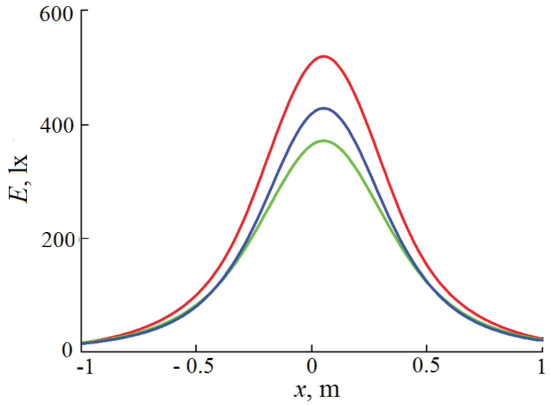

Figure 6 – Graphs of the dependence of the illumination of the E plane on the x coordinate for the distance between the matrix 12×12 and the plane equal to 0.5 m (table lamp): red curve for a flat matrix; blue – for a matrix with a gradual rotation of the LED planes from +45° to -45°; green – for a matrix with a gradual rotation of the LED planes from -45° to +45°

When working with the monitor, the distance to the conditional working surface is about 0.5 m, when writing, reading – about 0.4 m, then the radius of the working area is up to 0.6 m. According to the graph in Figure 6, at the boundaries of the working area, the uniformity is about 0.14, which is significantly less than the regulated value of 0.6. Therefore, it is necessary to modernize this lamp in order to increase the uniformity of illumination. This can be achieved by using more powerful LEDs on the periphery of the lamp, changing the location of the LEDs in the matrix.

To investigate the possibility of increasing the uniformity of illumination due to the rotation of the

[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).

LEDs in the matrix, each LED was rotated relative to the plane of the matrix from one edge to the other by an increasing value with a constant step in the range from -45º to +45º in the directions along the *x* and *y* axes, as well as in the range from +45º to -45º.The calculation was performed using the expression (6) for the 12×12 matrix and the distance to the illuminated plane of 0.5 m (table lamp).

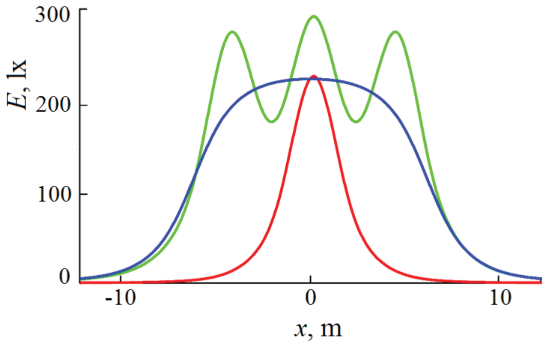

Figure 7 – Graphs of the dependence of the illumination of the *E* plane on the *x* coordinate for the distance between the matrices and the 2.5 m plane (ceiling lamp): red curve for the 40×40 matrix; green – for nine 40×40 matrices evenly spaced on the ceiling; blue – for the 120×120 matrix with a uniform step along the ceiling plane

The graphs for both rotation options are shown in Figure 6 (green and blue curves, respectively). The analysis of the graphs in Figure 6 allows us to conclude that when the planes of the LEDs are rotated, the maximum illumination decreases, and when turning from -45º to +45º more than when turning from +45º to -45º. There is no significant increase in the uniformity of illumination within the specified rotation angles. A similar result was obtained for a 40×40 ceiling lamp.

The developed methodology made it possible to analyze the possibility of increasing the uniformity of illumination due to the use of several LED matrices. For a table lamp, the illumination distribution was calculated using three 12×12 matrices located at the vertices of an equilateral triangle with a side of 0.5 m. The graph of the dependence of the illumination *E* on the *x* coordinate passing through the vertex of the triangle and the middle of its opposite side is shown in Figure 8 (red curve). The analysis of this graph shows that such a three-matrix option increases the uniformity of illumination, but the required uniformity value is still not achieved. At the same time, the maximum illumination increases and the power consumption increases three times.

The use of a square matrix with a total of 288 LEDs and an "empty square" 6×6 inside (Figure 8, green curve) has the same disadvantages as the previous version.

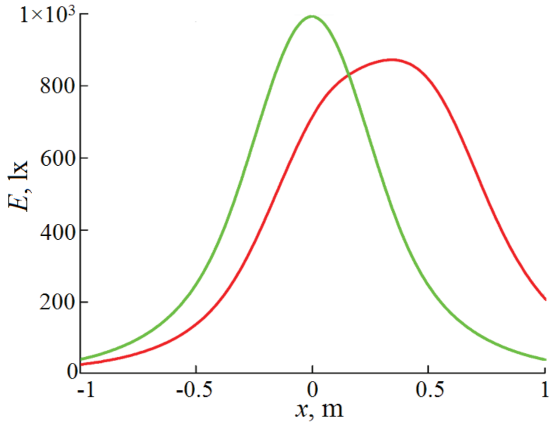

Figure 8 – Graphs of the dependence of the illumination of the *E* plane on the *x* coordinate for the distance between the matrices and the plane of 0.5 m (table lamp): red curve for three 12×12 matrices located at the vertices of an equilateral triangle with a side of 0.5 m; green curve for a square matrix of 288 LEDs with an "empty square" 6×6 inside

For a ceiling lamp, the permissible uniformity level of 0.4 according to GOST 55710[2] in accordance with Figure 7 (red curve) is achieved for a room measuring 3.6×3.6 m. To increase the size of the illuminated room with acceptable uniformity, a variant with nine lamps arranged in the form of an orthogonal 3×3 matrix with a step of 4.4 m was used, and each matrix was square, containing 40×40 elements. The corresponding light distribution graph is shown in Figure 7 (green curve).

According to the graph in Figure 7 (green curve), the permissible level of uniformity is achieved for a square room measuring 12.18×12.18 m. At the same time, the distribution of illumination on the plane has a wave-like character. As an alternative, a variant of orthogonal arrangement of all LEDs in a room of 12.18×12.18 m, i. e. for a 120×120 matrix with a uniform pitch, was analyzed (Figure 7, blue curve). A comparison of the green and blue graphs in Figure 7 allows us to conclude about the advantage of the uniform arrangement of all LEDs in relation to the arrangement in the form of separate matrices.

The use of a large number of RGB LEDs requires significant power consumption for their power supply. Therefore, it is promising to use combined matrices consisting of RGB and more powerful white LEDs.

Conclusion

A methodology has been developed for calculating the illumination distribution on the plane when using LED matrices as a lighting source. Illumination is a function of the indicatrix of the light intensity of the LED, the number and location of LEDs in space. The results of modeling LED sources indicate the need to modernize simple orthogonal matrices containing the same type of elements with the same power mode for all elements, in order to increase the uniformity of illumination and efficiency. Such modernization can be carried out by changing the geometry of the matrices, differentiating the power modes of individual LEDs. The developed calculation program can be supplemented with options for introducing the changes listed above, as well as for analyzing the spectral distribution of radiation in space.

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