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INCREASING THE LEVEL OF PHOTO BIOLOGICAL SAFETY OF THE EMISSION SPECTRUM OF AN LED LIGHT SOURCE

The **subject** of research is the emission spectra of light sources based on LED structures. The **purpose** of the work is to formulate proposals to improve the photo biological safety of LED lighting systems. The article solves the following tasks: analyzing the situation in the field of photo biological safety of light sources based on LED structures, proposing a concept for improving it in sources based on LED modules with a two-component phosphor. **Methods** such as comparative analysis, spectrometric method are used. The following **results** were obtained. A brief analysis of the factors affecting the photo biological safety of artificial light sources based on LED modules and a review of modern technological developments aimed at improving it is carried out. Since the implementation of these developments has a limited volume in the structure of the production of LED modules and a high cost, the concept of increasing the photo biological safety of light sources using cheap white light modules with a two-component phosphor and additional color modules to fill the gap in the spectral characteristic of white light has been proposed. A simple criterion is proposed for calculating the required ratio of white and color modules based on their spectral characteristics to activate the natural mechanism of eye protection due to pupil constriction. The work investigated color modules at wavelengths 480 nm, 492 nm and 503 nm. It has been shown that color modules with a shorter peak wavelength are needed less in relation to the number of whites to create a safe emission spectrum. The paper also estimated the fraction of the emission power with a wavelength of less than 450 nm in the emission spectra of the three investigated variants of combinations of white and color modules and four SunLike modules with different color temperatures. The share of the blue part of the spectrum in the emission power distribution of SunLike LED modules turned out to be higher than in traditional modules with a two-component phosphor at similar color temperatures. **Conclusions.** The proposed method increases the photo biological safety of the spectrum of LED light sources to the level of natural illumination due to adequate regulation of the pupil diameter and does not increase the total fraction of the emission power in the region $\lambda \leq 450$ nm, which is dangerous for vision. This fraction is even less than in SunLike modules at close values of color temperature, since their emission spectrum is expanded to the region of shorter wavelengths and starts from $\lambda \approx 370$ nm). Considering that the CVC characteristics of color and white LEDs are close, but not identical, their series connection leads to a redistribution of the emission power. In addition, LEDs from different manufacturers differ in energy efficiency and electrical parameters, therefore calculations in practice need to be adjusted in each specific case.

Keywords: Emission spectrum; photo biological safety; wavelength; LED; module; energy efficiency; colorful temperature; color rendering; illuminator; design; CVC.

Introduction

As you know, the protective functions of the retina are adapted to the conditions of sunlight and the main defense mechanism is the constriction of the pupil, which reacts to the intensity at the maximum of the sun's emission spectrum in the region of 480 nm [1].

The emission spectrum of white light LEDs, based on the luminescence of the LED crystal, has a characteristic blue peak (445 to 460 nm), the so-called "Blue peak" and a blue-green notch (480 nm). A dip at 480 nm, which is absent in the solar spectrum, leads to an inadequate response of the pupil to illumination: an increase in the area of the pupil, and hence the "photo biological" danger from excess power in the blue part of the spectrum [2, 3, 4].

Emission in the blue part of the spectrum with a wavelength shorter than 450 nm has a destructive effect on the cells of the elements of the optical system of the eye and especially the retina in the long term 25–30 years, and the effect is cumulative [2]. In addition, one of the factors on which the quality of vision depends is the proportion of blue in the spectrum, since blue is scattered in the optical environment more significantly than yellow or red light. In the optical system of the eye, blue light is scattered more strongly and this is perceived as a decrease in visual acuity [1, 2].

There is an international Eye Safety certification based on spectrum analysis. It is defined in the international standard CIE S 009: 2002 and takes into account the factors of exposure to the eyes and skin described in the IEC/EN 62471 standard. The highest No Risk level corresponds to sources that do not pose a "photo biological" hazard to humans. An RG1 (Low Risk) level means there is no risk in normal daily use. An RG2 (Intermediate Risk) level means there is no risk but may feel uncomfortable due to bright light or heat. The RG3 (High Risk) level indicates that the light source is dangerous even with short-term exposure [6].

According to the features of the emission spectrum noted above, the LED lighting modules belong to the RG3 level. The smaller the dip in the spectrum at 480 nm in relation to the peak in the blue region, the longer you can stay in the light environment formed by artificial sources with such a spectrum.

In [5], based on the analysis of the IEC/EN 62471 standard, recommendations are given for choosing a less hazardous LED illuminator, where it is indicated that it is advisable to use LED lamps with a spectrum in which the emission intensity in the dip is at least 40% of the intensity of the short-wave peak (a situation when spectral characteristic corresponds to a color temperature from 2700K to 3000K). However, it should be noted that as the color temperature decreases, the energy efficiency of the light source decreases.

Undoubtedly, in the general trend of increasing the energy efficiency of light sources for the formation of luminous fluxes in a wide power range, there is no alternative to universal LED-based illuminators, therefore, leading manufacturers are engaged in the technological

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implementation of modern concepts of organizing the structure of LED modules to eliminate the shortcomings of the spectral characteristics.

Analysis of the latest achievements and publications

Analyzing the situation in the LED market, Seoul Semiconductor concluded that the race for cheap and efficient lumen makes no further sense, since the small benefit from LEDs on the scale of the entire luminaire is small. At the same time, the quality of light and safety suffer noticeably [7].

Seoul Semiconductor, together with Toshiba Materials, has developed fundamentally new products using TRI-R technology - SunLike LED modules with an emission spectrum close to the sun to create a safe light environment. Their mass production was launched in early 2017.

This technology allows you to use light that is comfortable for the eyes with correct color reproduction, which is characterized by clarity and absence of glare. Since the blue part of the spectrum negatively affects the perception of light and human health, the new technology makes it possible to eliminate the intense peak in the blue part of the spectrum. This technology uses LED structures with an emission peak in the violet zone, which is converted into full-spectrum emission with red, green and blue components of the spectrum by a three-component phosphor [8, 9, 10] (fig. 1).

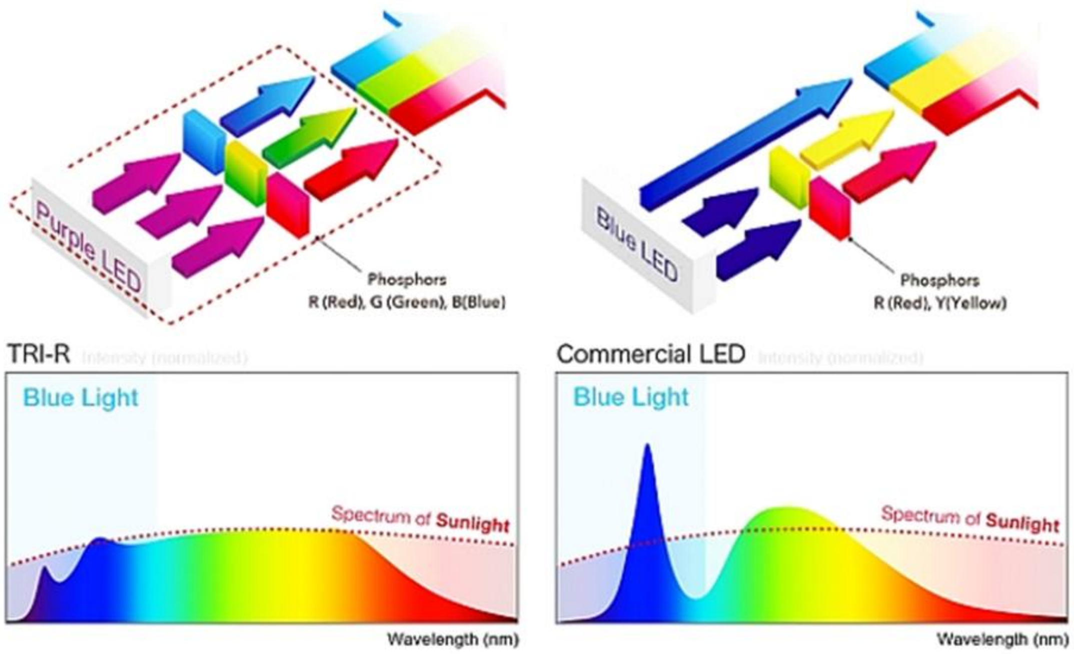

Fig. 1. The structure of SunLike LEDs and traditional lighting LEDs, as well as their corresponding emission spectra [10]

Unlike traditional LEDs that form a white light stream, with a CRI (70-85) units, SunLike LEDs have a high CRI (98). Lighting with a high color rendering index is used in the work of personnel and industries associated with the correct color rendering, where until recently halogen lamps were used [8].

In addition, SunLike LEDs allow you to create illuminators with a changing color temperature in the range of 2700–6500K (fig. 2) [8, 9, 11, 12, 13].

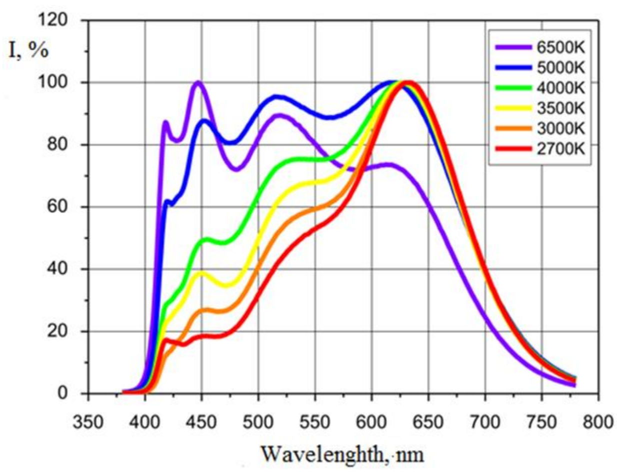

Fig. 2. Emission spectra of SunLike LEDs with different color temperatures [8]

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It should be noted that the SunLike lighting LED, whose spectrum is closest to the spectrum of sunlight, has received the RG1 Eye Safety certification. This is the highest level of safety among 25 W COB LED modules [9].

Currently, the production volume of SunLike products accounts for a small share of the total LED production volume. While this is an expensive product, its share is constantly growing; in 2020, Seoul Semiconductor planned to increase the market share of SunLike products to 10–15%. This technology is just developing, so lamps based on it are still an order of magnitude more expensive than traditional lamps with a two-component phosphor [7, 9].

Seoul Semiconductor is not the only company to launch the next generation of LEDs. Chinese Yuji LED also began to produce modules with violet LEDs and RGB phosphor, giving light with CRI 97, but the violet peak in the spectrum is much larger and the efficiency of the modules is less - 65-85 lm/W versus 85-105 lm/W for SunLike [6].

Based on the foregoing, it is clear that in the coming years, a significant change in the balance of produced lighting LEDs in favor of modules with an RGB phosphor with a safe emission spectrum is not expected due to the complexity and high cost of the technology.

Proposed solution to the problem. Objective of the work

There are two ways to increase the photo biological safety of the light environment created by artificial light sources. One involves the use of filtering the emission of the lighting system to reduce the proportion of the blue part of the spectrum and is implemented as a means of personal protection in the form of glasses with glasses such as BlueBlocker [15]. Another way is related to the alignment of the spectral characteristics for the natural functioning of the pupil, as in SunLike modules.

The article proposes a low-budget way to increase the photo biological safety of light sources based on traditional LED modules, in which additional modules with an emission spectrum that partially fill the gap are used to reduce the gap in their spectral characteristic. Although such a solution seems obvious, the criteria for calculating the required ratio of the number of white and additional color modules are unclear. In addition, the proposed method is justified, according to the authors, for the following reasons.

First, in terms of design and operating conditions. The use in mass production of designs of LED lighting lamps with standard bases E27, E14, GU10 and others is a transitional option for combining new light sources with traditional lighting equipment. The desire to reduce the cost of production forces developers to place a substrate with modules, a modest-sized cooling radiator and a power driver within the size and shape of incandescent lamps from the appropriate form factor. At the same time, the modules overheat due to the insufficient area of the radiator, which reduces their light output during the operation period, moreover, the driver functions in a difficult temperature regime. In general, such a general standard design does not provide a long service life of a lamp with stable light characteristics, although the service life of the modules themselves under recommended conditions is guaranteed by their manufacturers for at least 50 thousand hours.

At the same time, the market of components for LED lighting products allows, using a wide range of heat-conducting substrates, LED modules of various powers and sizes, drivers, to calculate and design LED custom lighting devices of any power and with an arbitrary emission spectrum. This is a modern practice of creating a light environment in rooms for various purposes, and it is used to solve the problem posed in the article.

Second, although the color rendering index of an LED illuminator with complementary LED modules varies, it can be used in situations where safety for vision is preferable to accurate color rendering. An example is long-term work with printed documents or the creation of a background light environment in a room where people are constantly staying.

The modern energy-saving approach to the organization of artificial lighting in premises assumes the presence of local lighting in the workplace, which forms an adequate color picture, and general background lighting for confident movement. Energy-efficient LED lamps and strips on white LED modules with a high color temperature (from 4500K to 6000K) or RGB LED lamps and strips are used as background lighting to regulate the overall emission spectrum. In any of these background illumination options, there is a gap in the spectral response between the blue peak and the right side of the spectrum, which leads to visual impairment.

The immediate goal of the work is to determine the required ratio of the number of additional color LED modules and white modules with a color temperature of 3200K to increase the photo biological safety of the emission spectrum of LED lighting modules.

Concept and solution methods

As a criterion for the required ratio of the number of color and white modules, it is proposed to use the intensity ratio at λ = 445 nm (the wavelength of the maximum emission of the white module in the blue part of the spectrum) and at λ = 480 nm in the resulting spectrum of the illuminator, which is characteristic of the solar emission spectrum, and namely, approximately 0.7 to 1.0, i.e.:

$$\frac{I_{col}(445)+N\cdot I_{WH}(445)}{I_{col}(480)+N\cdot I_{WH}(480)}=0{,}7\,, \qquad (1)$$

where $I_{col}(445)$ – emission intensity of the additional color module at a wavelength of 445 nm; $I_{col}(480)$ – emission intensity of the additional color module at a wavelength of 480 nm; $I_{WH}(445)$ – emission intensity of the additional module at a wavelength of 445 nm ("Blue peak"); $I_{WH}(480)$ – emission intensity of the additional

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module at a wavelength of 480 nm (dip); N – the number of white modules per color.

Then:

$$N = \frac{0,7 \cdot I_{col}(480) - I_{col}(445)}{I_{WH}(445) - 0,7 \cdot I_{WH}(480)}. \qquad (2)$$

By measuring the emission intensity $I_{col}(480)$ of the additional color module at λ = 480 nm and the spectrum of the white module under the same conditions, we can calculate the required ratio.

Various manufacturers in the range of produced modules offer LEDs with emission wavelengths in the dip region from 460 nm to 505 nm, which can be selected as additional ones. To fill the gap in the spectrum of a white LED, it is reasonable to use an LED with λ_{MAX}, located to the right of the λ_{MIN} dip, so as not to increase the fraction of emission at wavelengths less than 450 nm due to the left tail of the emission spectrum of the additional LED.

Modern commercial LED lighting lamps contain from 3 to 18 on the board, and LED strips contain several dozen white emitting modules, depending on the power. Some of them can be replaced by modules that complement the spectrum. We used additional modules of the same power and standard size as the white glow modules. This makes it possible to include them in the serial switching circuit of a standard board for mounting modules and to evenly distribute the input power between the modules. The forward voltage drops across additional LEDs with a spread of the nominal value, according to the technical specifications, approximately corresponds to the forward voltage drop across the white light module at the same forward currents. Some of the measured optical and electrical characteristics of the white and optional modules are presented in table 1.

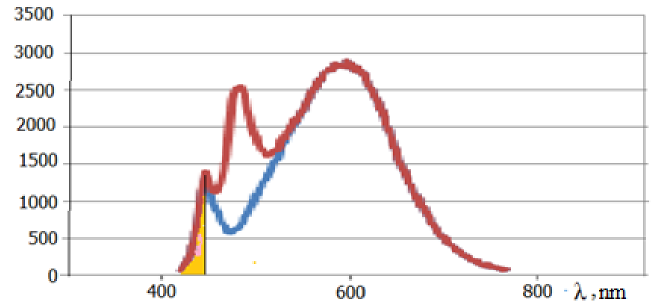
Table 1. *Emission intensity at the extrema of the spectral characteristics of LEDs*

No.	λMAX, nm	Peak intensity, rel. units	Dip intensity, rel. units	Intensity in green-red reg., rel. units	ΔU at I=300 mA, V
1	White	1355 at 446 nm	623 at 480,23 nm	2900 at 594 nm	2,98
2	480,76	14563	–	–	3,05
3	492,24	14410	–	–	3,01
4	503,6	14164	–	–	2,95

The emission spectra of the modules were measured using an LR1 USB spectrophotometer designed for measurements in the wavelength range from 300 nm to 1050 nm. An optical attenuator was used to match its sensitivity with the emission intensity of 1W LED module samples [16].

Research results and their discussion

Fig. 3 shows the spectral characteristics of emitters containing additional modules with different λMAX (tab. 1), constructed from the results of measurements and calculations.



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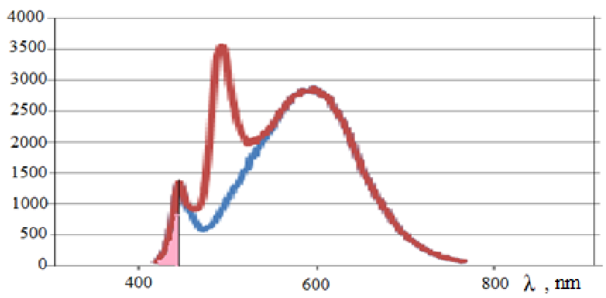

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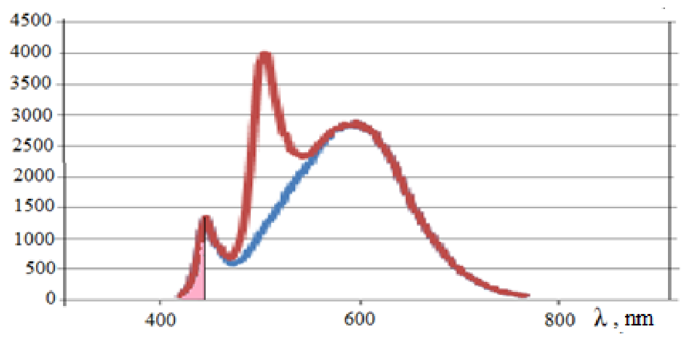

c

Fig. 3. Spectral characteristics of light sources with additional modules with different λ_{MAX} against the background of the emission spectrum of white modules in relative units: a) λ_{MAX} = 480.76 nm; b) λ_{MAX} = 492.24 nm; c) λ_{MAX} = 503.6 nm

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Table 2 shows the results of the measurements and the calculated ratios of the required number of additional color modules to the number of white ones based on them.

Obviously, the closer the wavelength of the maximum emission of the color module is to the wavelength of the minimum dip in the spectrum of the white module, the less additional color modules are required to fulfill relation (1).

The paper also estimated the fraction of emission power with a wavelength of less than 450 nm in the emission spectra for the three investigated variants of combinations of white and color modules. Similar calculations were carried out for the spectral characteristics of four SunLike modules with color temperatures of 3000K, 3500K, 4000K and 6500K. The calculation results are summarized in table 3.

Table 2. *Measurement results and calculated ratios of the number of white LEDs to the number of colored LED modules*

No.	λMAX, nm	I λ (480) measured, rel.units	I λ (445) measured, rel.units	I λ (480) calculated, rel.units	Color LED/White LED Ratio
1	White	623	1355	-	-
2	480,76	14560	408	1895	1/7,7 or≈ 2/15
3	492,24	7520	52	1387	1/5,4 or ≈ 2/11
4	503,60	1795	22	1344	1/1,3 or ≈ 3/4

Table 3. *Results of calculating the power fraction of the short-wavelength part with λ <450 nm in the full spectrum of the studied light sources*

Emitter type	White with one-component luminophor 3200 K	2:15 (480nm)	2:11 (492nm)	3:4 (503nm)	SunLike 3000 K	SunLike 3500 K	SunLike 4000 K	SunLike 6500 K
Emission power fraction with λ <450 nm, %	4,21	3,92	3,55	2,15	~ 4,3	~ 6,0	~ 7,1	~ 15,7

The share of the blue part of the spectrum in the emission power distribution of the SunLike LED modules turned out to be higher than in traditional modules with a single-component phosphor at similar color temperatures. Their photo biological safety is ensured by the form of the spectral characteristic that triggers the natural mechanism of eye protection due to constriction of the pupil, at least up to a color temperature of 4000K (fig. 2).

Conclusions

Based on the results of the measurements and calculations, the following conclusions can be drawn.

The proposed method increases the photo biological safety of the spectrum of LED illuminators to the level of natural illumination due to adequate regulation of the pupil diameter and does not increase the total fraction of the emission power in the region λ ≤ 450 nm, which is dangerous for vision (shaded area in fig. 3). This fraction is even less than in SunLike modules (table 3) at close values of color temperature, since their emission spectrum is expanded to the region of shorter wavelengths and starts from λ ≈ 370 nm).

The article deliberately does not indicate the specific types of the studied modules. The method is implemented with additional modules of different λMAX to the right of λ = 480nm within the dip; the closer λMAX is to 480nm, the fewer modules complementary to the spectrum are needed.

Considering that CVCs of color and white LEDs are close, but not identical, their series connection leads to a redistribution of the emission power. In addition, LEDs from different manufacturers differ in energy efficiency and electrical parameters, therefore, the calculated ratios from table 2 in practice need to be adjusted in each specific case.

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ПІДВИЩЕННЯ РІВНЯ ФОТОБІОЛОГІЧНОЇ БЕЗПЕКИ СПЕКТРА ВИПРОМІНЮВАННЯ СВІТЛОДІОДНОГО ДЖЕРЕЛА ОСВІТЛЕННЯ

Предметом дослідження є спектри випромінювання джерел світла на основі LED структур. **Мета** роботи – формування пропозицій з підвищення фотобіологічної безпеки світлодіодних освітлювальних систем. У статті вирішуються наступні **завдання**: аналіз ситуацій у сфері фотобіологічної безпеки джерел світла на основі світлодіодних структур, пропозиція

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концепції щодо її підвищення в джерелах на основі LED модулів з двокомпонентним люмінофором. Використовуються такі методи, як порівняльний аналіз, спектрометричний метод. Отримані наступні **результати**. Проведений короткий аналіз факторів, що впливають на фотобіологічну безпеку штучних джерел світла на основі LED модулів та огляд сучасних технологічних розробок, спрямованих на її підвищення. Оскільки реалізація цих розробок має обмежений обсяг у структурі виробництва LED модулів та високу вартість, запропонована концепція підвищення фотобіологічної безпеки джерел світла, що використовує дешеві модулі білого світла з двокомпонентним люмінофором та додаткові кольорові модулі для заповнення провалу спектральної характеристики білого. Запропонований простий критерій розрахунку необхідного співвідношення білих та кольорових модулів за їх спеціальними характеристиками для активації природнього механізму захисту очей за рахунок звуження зіниць. В роботі досліджувались кольорові модулі на довжину хвиль 480 нм, 492 нм і 503 нм. Показано, що кольорові модулі з меншою піковою довжиною хвилі потребують меншої кількості по відношення до кількості білих для створення безпечного спектра випромінювання. Доля синьої частини спектра у розподілі потужності випромінювання LED модулів SunLike виявилася вище, ніж у традиційних модулів з двокомпонентним люмінофором при близьких температурах колірності. **Виводи.** Представлений спосіб підвищує фотобіологічну безпеку спектра LED джерел світла до рівня природнього освітлення за рахунок адекватного регулювання діаметра зіниці та не збільшує сумарну долю потужності випромінювання в області $\lambda \leq 450$ нм, що є небезпечною для зору. Ця доля навіть менше, ніж у модулях SunLike при близьких значеннях температури колірності, оскільки їх спектр випромінювання розширюється в область більш коротких хвиль і починається з $\lambda \approx 370$ нм. Враховуючи, що ВАХ кольорових та білих світлодіодів близькі, але не ідентичні, їх послідовне з'єднання призводить до перерозподілу потужностей випромінювання. Крім цього, LED різних виробників відрізняються енергоефективністю і електричними параметрами, тому на практиці розрахунки потребують корегування в кожному конкретному випадку.

Ключові слова: спектр випромінювання; фотобіологічна безпека; длина хвилі; LED; модуль; енергоефективність; температура колірності; передача кольору; освітлювач; конструкція; ВАХ.

ПОВЫШЕНИЕ УРОВНЯ ФОТОБИОЛОГИЧЕСКОЙ БЕЗОПАСНОСТИ СПЕКТРА ИЗЛУЧЕНИЯ СВЕТОДИОДНОГО ИСТОЧНИКА ОСВЕЩЕНИЯ

Предметом исследования являются спектры излучения источников света на основе LED структур. **Цель** работы – формирование предложений по повышению фотобиологической безопасности светодиодных осветительных систем. В статье решаются следующие **задачи**: анализ ситуации в сфере фотобиологической безопасности источников света на основе светодиодных структур, предложение концепции по ее повышению в источниках на основе LED модулей с двухкомпонентным люминофором. Используются такие методы, как сравнительный анализ, спектрометрический метод. Получены следующие **результаты**. Проведен краткий анализ факторов, влияющих на фотобиологическую безопасность искусственных источников света на основе LED модулей и обзор современных технологических разработок, направленных на ее повышение. Поскольку реализация этих разработок имеет ограниченный объем в структуре производства LED модулей и высокую стоимость, предложена концепция повышения фотобиологической безопасности источников света, использующих дешевые модули белого света с двухкомпонентным люминофором и дополнительные цветные модули для заполнения провала спектральной характеристики белого. Предложен простой критерий расчета необходимого соотношения белых и цветных модулей по их спектральным характеристикам для активации естественного механизма защиты глаз за счет сужения зрачков. В работе исследовались цветные модули на длины волн 480 нм, 492 нм и 503 нм. Показано, что цветных модулей с меньшей пиковой длиной волны необходимо меньше по отношению к количеству белых для создания безопасного спектра излучения. В работе также была проведена оценка доли мощности излучения с длиной волны короче 450 нм в спектрах излучения трех исследованных вариантов комбинаций белых и цветных модулей и четырех модулей типа SunLike с различными цветовыми температурами. Доля синей части спектра в распределении мощности излучения светодиодных модулей SunLike оказалась выше, чем в традиционных модулях с двухкомпонентным люминофором при близких цветовых температурах. **Выводы**. Предложенный способ повышает фотобиологическую безопасность спектра LED источников света до уровня естественного освещения за счет адекватного регулирования диаметра зрачка и не увеличивает суммарную долю мощности излучения в области $\lambda \leq 450$ нм, опасную для зрения. Эта доля даже меньше, чем в модулях SunLike при близких значениях цветовой температуры, поскольку их спектр излучения расширен в область более коротких длин волн и начинается с $\lambda \approx 370$ нм). Учитывая, что ВАХ цветных и белых светодиодов близки, но не идентичны, их последовательное соединение приводит к перераспределению мощности излучения. Кроме этого, LED разных производителей отличаются по энергоэффективности и электрическим параметрам, поэтому расчеты на практике нуждаются в корректировке в каждом конкретном случае.

Ключевые слова: спектр излучения; фотобиологическая безопасность; длина волны; LED; модуль; энергоэффективность; цветовая температура; цветопередача; осветитель; конструкция; ВАХ.

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