



UDC 621.327.43:535.6

The influence of added components on light and color characteristics of an LED luminaire

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Abstract

The paper studies the influence of additional structural elements on the light and color characteristics of an LED luminaire. The main attention is paid to the analysis of the role of specialized optical lenses, limiting plates and a protective polycarbonate diffuser in the formation of lighting parameters of radiation. The key facet of the paper is the evaluation of the influence of a polycarbonate diffuser on the quality of color rendering. For this purpose, a modern approach to colorimetric evaluation was applied in accordance with the CIE 224:2017 recommendations and the ANSI/IES TM-30 standard using the color rendering accuracy index R_f . It is shown that polycarbonate material partially absorbs the short-wave component of the LED radiation spectrum, which leads to a decrease in the luminous flux within 5–12%. In the absence of a complete restoration of the real spectral distribution of radiation, comparative analysis using reference LED templates is an effective and promising colorimetric approach. It allows one not only to objectively evaluate the quality of light, but also to predict the influence of design changes on the color characteristics of luminaires at the design stage of modern lighting systems. As a result of applying a polycarbonate diffuser, the increased R_f index value provides a better correspondence of color rendering indicators to subjective visual perception compared to an open LED module.

Keywords: Color Rendering Index; LED luminaires; Fidelity Index.

Received: 06.01.2026

Edited: 05.03.2026

Approved for publication: 10.03.2026

Introduction

LED luminaires are characterized by high energy efficiency, durability, and the ability to flexibly control light parameters. At the same time, their lighting and color characteristics are predominantly determined not only by the properties of the LED module, but also by structural components, such as optical lenses, limiting plates, and protective diffusers. The use of these elements allows one to form a given light distribution and increase the operational reliability and level of protection of the luminaire. However, it can lead to changes in the luminous flux, luminous efficiency, and spectral composition of radiation. Of particular relevance is the study of the influence of polycarbonate diffusers, which are widely used to protect LED modules and reduce glare, but at the same time can change the spectral distribution of radiation and color rendering indices.

Modern methods for evaluating the quality of color rendering, in particular the indices recommended by the CIE and ANSI/IES standards, allow for a more accurate determination of the influence of such components on the visual perception of lighting [1]. In this regard, there is a need for a comprehensive experimental analysis of the influence of the introduced structural components on the light and color characteristics of LED luminaires. The purpose of this paper is to thoroughly study the influence of structural and embedded components in LED luminaires on their photometric and color characteristics. Particular attention was paid to the transition from traditional color rendering indices (R_a) to modern metric systems (R_f , R_g , CVG) as defined in CIE 224:2017 and TM-30 [2]. The object of the study is industrial-type LED luminaires. The subject of the study is the light, spectral and color

characteristics of an LED luminaire depending on its design.

To achieve the set goal, the paper provides for the following tasks: to analyze the measured lighting parameters of the spotlights; to compare the results obtained for Ra and Rf and identify potential differences; to evaluate the global and local accuracy of color reproduction for different types of diffusers and materials; to determine the practical value of using Rf and CVG as tools that may detect hidden spectral distortions that are not captured by the classic CRI.

Spectrum and Rf analysis using a “calculator”

As part of experimental studies of the lighting characteristics of LED floodlights, a series of measurements and tests were performed to assess the spatial distribution of the light flux, the stability of optical parameters, and the performance of the equipment in an extended temperature range [3]. The objects of the study were general lighting floodlights made with different layouts of LED modules and secondary optics, the photos are shown in Figs. 1, 2.



Fig. 1. Overview of the studied sample of the LED lamp in full modification



Fig. 2. Modularity of the luminaire due to increased power

The first sample is a fully modified floodlight with C14541 optics, equipped with six lenses and twenty-four JR5050 LEDs. For this configuration, a light intensity curve (LIC) measurement was performed, which allows one to determine the nature of the spatial light distribution, the degree of light flux concentration, and compliance with the declared optical parameters. The obtained LIC results indicate the formation of a directional light beam with a clearly defined central zone, which is typical for the use of secondary lens optics of this type and confirms the feasibility of its use in floodlight fixtures. The second sample is a powerful floodlight with two lines of LED modules, equipped with C14541 optics, sixteen lenses, and sixty-four XPG-3 LEDs. For this luminaire, in addition to measuring the light intensity curve, additional tests were performed in a climatic chamber under extreme temperature conditions. The studies were

performed in the range from $-40\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$ to assess the temperature stability of lighting and electrical parameters, as well as to verify the reliability of structural and optical elements. The results of the LIC measurements for the second configuration showed a more uniform spatial distribution of the light flux compared to the single-row scheme, which is due to the increased number of lenses and LEDs and their optimized location. Tests in a climatic chamber confirmed the stability of the projector operation in the entire studied temperature range, the absence of critical changes in the light flux, and the preservation of the LIC shape after thermal cycling [4]. This indicates the high thermal stability of the XPG-3 LED modules, the efficiency of the heat dissipation system, and the reliability of the secondary optics used. Considering the measurements and climatic tests, it was determined that the use of C14541 type optics in projectors provides predictable light distribution and stable optical characteristics, while the multi-line arrangement of LEDs allows one to improve the uniformity of lighting and increase the operational reliability of the luminaires in conditions of significant temperature fluctuations. For further studies, the spotlight shown in Fig. 1 was used, the power of which was 136 W.

In lighting systems, the choice of the type of polycarbonate or diffuser significantly affects the resulting optical parameters of the luminaire, including light transmission, stability of spectral characteristics, change in correlated color temperature (CCT), and color rendering index (CRI) [5]. Transparent polycarbonate provides the highest light transmission at 90–92%, with practically no change in CCT (up to -10 K) and almost no effect on CRI. However, its resistance to ultraviolet radiation is low, which causes the risk of yellowing and degradation of the material without additional UV coating. Opal or matte polycarbonate is characterized by a wider transmission range of approximately 80–92%, depending on the specific type and thickness of the material. Such diffusers typically exhibit a CCT reduction of 10–150 K and a possible slight increase in CRI (up to +2) due to more uniform spectral mixing. Many commercial brands include UV stabilization, which improves long-term optical stability. Specialized diffusers such as Lumen XT or DLCW (Makrolon, Lexan) have high light transmission in the range of 85–95%, but can significantly reduce CCT (by 20–200 K depending on brand and thickness). Such materials can improve CRI by 1–3 units due to better angular uniformity and smoothing of local spectral peaks. Tinted polycarbonate has a reduced light transmission of about 60–85%, which is often accompanied by a significant decrease in CCT (by 100–400 K) due to greater absorption of the blue component of the spectrum. This, in turn, can lead to a decrease in CRI by 1–5 points, since the emission spectrum becomes less balanced. Polycarbonates with fillers, in particular with TiO_2 , have a transmission in

the range of 70–90% and usually cause a decrease in CCT by 20–100 K, while providing high angular uniformity of light distribution. Due to more effective mixing of spectral components, such materials can even increase the visible CRI (by 1–5 points). Old or unstabilized polycarbonates exhibit significant optical degradation after prolonged UV exposure: light transmission can decrease by 5–30%, and CCT shifts to the warmer side due to yellowing of the material, sometimes by hundreds of Kelvin. This is accompanied by a deterioration in CRI and general degradation of the material structure, which emphasizes the need for UV-stabilized polymers in outdoor and industrial luminaires [6].

The color characteristics of a luminaire refer not only to the color of the light flux (correlated color temperature CCT, color rendering index CRI, spectral composition), but also to the color shade/filtration introduced by the diffuser material (for example, polycarbonate). Polycarbonate affects the color characteristics provided that it has the appropriate composition and the feasibility of using the luminaire in a particular area: it can be transparent polycarbonate, which almost does not change the CCT and CRI, losses are minimal (~1–3%), depends on the thickness; milky/opal, here the situation is different – it provides diffusion (soft light, lower brightness of the point) but has light absorption, which reduces the light flux (typically 5–15%) and a slight “warming” of the spectrum (shift of Δ CCT towards the yellow wavelength); tinted (smoked, tinted PC), acts as a color filter: changes the spectrum, can significantly reduce the luminous flux (10–30%) and shift the color coordinates (x, y); UV-stabilized polycarbonate, does not change the color, but preserves the original characteristics – in general, unstabilized polycarbonate turns yellow from UV, which leads to an uncontrolled shift of CCT. During the experimental studies, comprehensive spectrophotometric and electrical measurements of the LED luminaire in four different design configurations were performed:

without additional components, with lenses installed, with lenses and side plates, as well as with lenses, side plates, and a polycarbonate protective element. The measurements were performed using the SPL200 test system under stable ambient conditions. During the studies, lighting parameters (luminous flux, luminous efficacy, stability), color characteristics (CCT, color coordinates, CRI), spectral parameters, and electrical indicators (voltage, current, power, power factor) were determined. The purpose of the measurements was to assess the influence of optical and structural elements on the energy efficiency, lighting characteristics, and light quality of the LED luminaire, as well as to determine the optimal configuration in terms of light output and operational properties.

The initial stage was the measurement of the characteristics without all components, only the housing and LED chips [7]. The measurement results are shown in Fig. 3 and Table 1. The measured color parameters of the luminaire indicate the formation of neutral white light, which is typical for industrial and outdoor lighting. The color coordinates indicate the permissible color uniformity within the limits of serial production [8]. The spectral characteristics, in particular the peak wavelength of 445 nm and the half-width of the spectrum of 21.4 nm, confirm the use of an LED source with a blue chip and phosphor conversion. At the level of 17.1%, the share of red radiation provides an acceptable balance of the spectrum without a significant shift in color rendering. At a luminous efficiency of 126.3 lm/W, the luminous flux of 16908.7 lm characterizes this configuration of the luminaire as an energy-efficient light source with an average level of color rendering.

All components were added to the luminaire design in turn: a special lens for each LED, then side plates for the lenses, and the last polycarbonate package. The emission spectrum does not graphically convey changes, so it was decided to analyze the spectra and Rf indicators using a computer tool called a “calculator”.

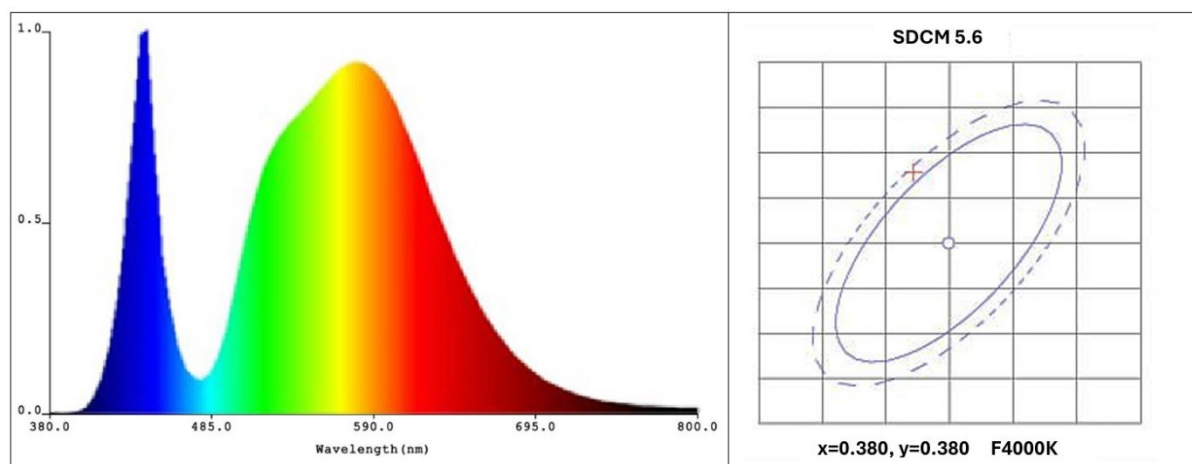


Fig. 3. Spectral power distribution of a lamp without components

Generalized measurement results of the LED lamp

Name	Parameter group	Without components	Lenses added	Lenses and side plates added	Added lenses, side plates, and polycarbonate
Color options	<i>x</i>	0.3767	0.3777	0.3781	0.3778
	<i>y</i>	0.3878	0.3887	0.3893	0.3894
	<i>u</i>	0.2183	0.2187	0.2187	0.2185
	<i>v</i>	0.3372	0.3376	0.3378	0.3378
	CCT, K	4175	4149	4146	4151
	Purity, %	29.4	30.0	30.3	30.3
	SDCM	5.6	5.5	5.6	5.8
	Main wavelength, nm	575.3	575.4	575.3	575.2
	Peak wavelength, nm	445.0	440.0	440.0	440.0
	Half-width of the spectrum, nm	21.4	20.6	21.1	21.0
Red ratio, %	17.1	17.1	17.1	17.0	
Color rendering indices (CRI)	Ra	69.7	69.1	69.3	69.2
	R1–R15	67, 74, 82, 71, 67, 66, 79, 52, –38, 41, 69, 42, 67, 90, 59	66, 74, 82, 71, 66, 65, 78, 50, –42, 40, 68, 41, 66, 90, 58	66, 74, 83, 71, 66, 65, 79, 51, –40, 41, 68, 41, 66, 90, 58	66, 74, 82, 71, 66, 65, 79, 50, –41, 40, 68, 41, 66, 90, 58
Lighting parameters	Luminous flux, lm	16908.7	22041.8	20952.1	19840.0
	Efficiency lm/W	126.3	164.6	156.5	148.2
Electrical parameters	Voltage, V	220.0	220.0	220.0	220.0
	Current, A	0.625	0.625	0.625	0.625
	Power, W	133.9	133.9	133.9	133.9

Additional study of modern color metrics

In traditional practice, the key indicator for evaluating lighting quality was the overall color rendering index (CRI, Ra) [9]. However, numerous studies have shown that this index has significant limitations: it is based on only eight test samples and the outdated CIE 1960 (*u,v*) color space, and therefore does not always correlate with real visual perception. This is especially true for LED and combined light sources, where the spectral distribution is uneven, “spiked”.

In this regard, a new evaluation system was introduced in CIE 224:2017 – the color accuracy index (Rf) – which is calculated based on 99 test samples in the modern uniform CAM02-UCS space. Additionally, the saturation index (Rg) and the TM-30 (Colour Vector Graphic, CVG) graphical representation are used, which allows assessing not only global compliance, but also local deviations in different sectors of the spectrum. For a broader understanding of the influence of the changes, a specialized spectral analysis “calculator” was used – a tool that allows one to see light through colorimetry numbers [10]. This tool builds the source emission spectrum based on the relative spectral power distribution (Relative SPD) and calculates modern color indices, in particular the color fidelity index Rf and the saturation index Rg. Its principle of operation is to compare the studied source with reference spectra of the same correlated color temperature and assess how accurately the studied light reproduces the colors of objects. In other words, it uses 99 test color samples in the

updated color space (for example, CIE CAM02-UCS) to measure the “accuracy” of color reproduction – in contrast to the traditional CRI Ra, which operated with only eight samples [11]. This approach gives a more accurate and objective vision of the quality of light. The Rf index actually measures how accurately the light reveals the true color palette of the world to our eye, without distortion. This is especially true for modern LED sources because the classic CRI did not account for the features of their spectrum. Relative SPD (spectral power distributions) of standard reference standards CIE LED-B1...B5 [12] for typical white LEDs on a blue crystal with different correlated color temperatures (from ~2700 K in LED-B1 to ~6600 K in LED-B5) are presented in Fig. 4. It is noticeable how the emission spectrum changes with increasing CCT: warmer diodes (LED-B1 – 2733 K, LED-B2 – 2998 K) have a relatively weaker peak in the blue part (~440–450 nm) and increased intensity in the long-wave red-orange region. The SPD graph (Fig. 4) of such “warm” diodes smoothly rises towards longer waves – the light “gets warmer”.

In contrast, colder sources (LED-B4 – 5109 K, LED-B5 – 6598 K) have a clearly pronounced sharp peak in the blue (~440–450 nm) and a relatively smaller contribution in the red segment of the spectrum. Their SPD curves demonstrate a high narrow “spike” in the 450 nm region and a decline in energy at long wavelengths, which corresponds to a cold, white-blue hue of light. LED-B3 (4103 K) occupies an interme-

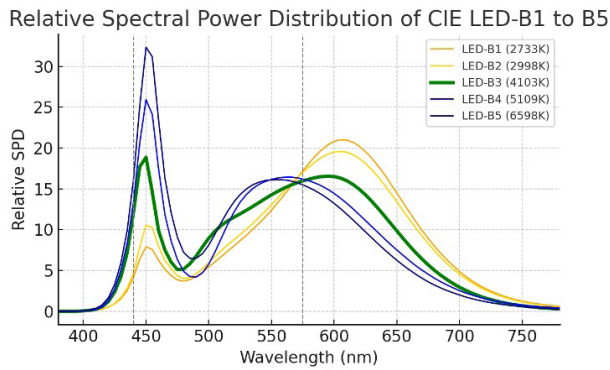


Fig. 4. Relative spectral power distribution (from LED-B1 to LED-B5)

diate position – its spectrum is balanced: the graph shows a moderate peak of radiation at ~440 nm (blue crystal) and a wide elevated “hump” in the yellow-green zone (maximum ~575–580 nm) from the phosphor. Such a two-component nature of the spectrum – a blue burst + broadband yellow-orange radiation – is inherent in typical white LEDs of medium color temperature. It is essential that the spectrum of this particular reference LED-B3 is very similar to the spectral characteristics of our experimental light source in various configurations: it has a CCT ≈ 4150 K, a fundamental wavelength of ~575 nm, a peak emission of ~440 nm, and a red fraction of ~17% – in fact, it almost coincides with the characteristics of LED-B3 (neutral white diode). The toolkit allowed one to overlay these spectra and verify their close correspondence, as can be seen in Fig. 5.

The most interesting thing is when comparing the numerical values of Rf for these spectra. The Rf index is very sensitive to changes in the SPD shape and shows how accurately the source reproduces all colors (from 99 test samples). Warm LED-B1 and B2, with their richer red component, reach Rf at the level of the mid-80s (about 83–84).

Despite the “yellowish” shade, their light reproduces colors quite accurately – the phosphor fills most of the spectrum, and the colors of objects are not too distorted. LED-B3 has Rf ≈ 85, the highest among the entire B1-B5 series. Due to the balanced spectrum (both deep blue and enough yellow-red waves are present), this neutral-white diode provides a very high level of color fidelity. That is why LED-B3 can be considered a kind of standard – neutral white light, which accurately reflects most of the shades of surrounding objects. In contrast, in the colder LED-B4, Rf is noticeably reduced (to ~77), and in LED-B5 – to ~79. These sources, due to the dominance of a narrow blue peak and the lack of a red component, lose accuracy: some colors (especially shades of red and some saturated tones) look darker or shifted under such light [12]. The Rf number clearly signals this loss – it is lower if the spectrum has “dips”. For example, LED-B5 (the coldest) gives the highest GAI (color gamut index, ~89), that is, it expands the gamut somewhat – under it, certain colors look more saturated than under reference lighting. However, a high GAI does not mean high-quality color reproduction: Rf ~79 indicates that fidelity suffers. In other words, under LED-B5 (Fig. 6), although more contrasting, the color palette, is not true – individual tones are distorted or muted. Rf accounts for these deviations and shows a spectrum with insufficient filling (say, almost no deep red) and a decrease in the integral fidelity estimate.

These tools were integrated into our own software and hardware complex. This allowed us to assess the influence of various design and material solutions (diffuser type, optical coatings, polycarbonate lenses) on the color fidelity of LED luminaires. The results confirmed that:

- for transparent polycarbonate materials, global Rf values remained at > 80, which corresponds to an acceptable level for most domestic and office premises;

CCT (K)	Duv	LER (lm/W)							
4103	-0,0007	316,9							
Rf	Rf1	Rf2	Rf3	Rf4	Rf5	Rf6	Rf7	Rf8	Rf9
85,3	92,3	84,4	83,5	86,7	71,9	84,7	77,1	72,6	97,6
Rf10	Rf11	Rf12	Rf13	Rf14	Rf15	Rf16	Rf17	Rf18	Rf19
81,8	79,2	78,8	85,3	94,6	90,7	77,1	80,3	88,1	81,0
Rf20	Rf21	Rf22	Rf23	Rf24	Rf25	Rf26	Rf27	Rf28	Rf29
66,5	76,6	77,4	91,9	82,0	75,8	80,0	94,0	90,6	82,4
Rf30	Rf31	Rf32	Rf33	Rf34	Rf35	Rf36	Rf37	Rf38	Rf39
92,7	84,5	78,2	88,2	84,3	91,1	87,9	89,1	99,2	97,8
Rf40	Rf41	Rf42	Rf43	Rf44	Rf45	Rf46	Rf47	Rf48	Rf49
94,7	97,1	89,6	87,0	99,3	92,3	90,7	93,0	88,3	89,7
Rf50	Rf51	Rf52	Rf53	Rf54	Rf55	Rf56	Rf57	Rf58	Rf59
95,1	95,2	94,7	89,6	92,4	91,2	87,2	86,8	87,4	92,5
Rf60	Rf61	Rf62	Rf63	Rf64	Rf65	Rf66	Rf67	Rf68	Rf69
92,6	88,9	90,8	87,2	82,4	79,9	79,2	77,5	79,7	83,6
Rf70	Rf71	Rf72	Rf73	Rf74	Rf75	Rf76	Rf77	Rf78	Rf79
75,3	71,7	89,9	68,0	94,8	73,0	72,9	82,2	71,9	91,1
Rf80	Rf81	Rf82	Rf83	Rf84	Rf85	Rf86	Rf87	Rf88	Rf89
88,0	84,9	94,7	94,5	90,8	82,0	80,5	85,6	89,8	80,6
Rf90	Rf91	Rf92	Rf93	Rf94	Rf95	Rf96	Rf97	Rf98	Rf99
90,2	75,8	71,3	83,2	69,3	76,6	85,7	91,1	86,8	80,5

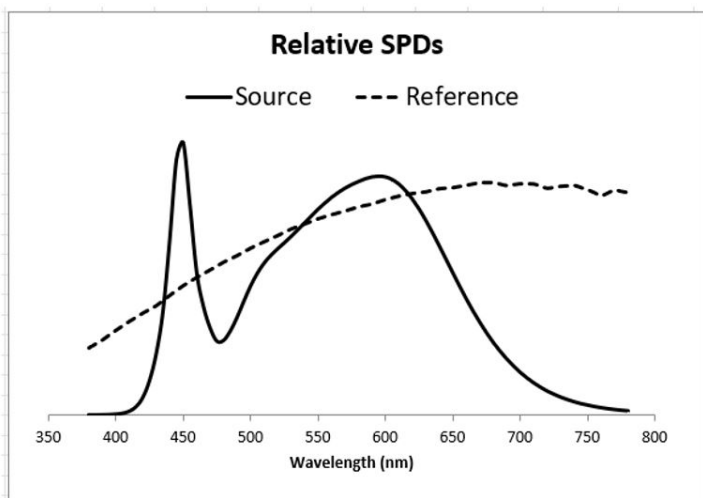


Fig. 5. Rf value for type LED-B3

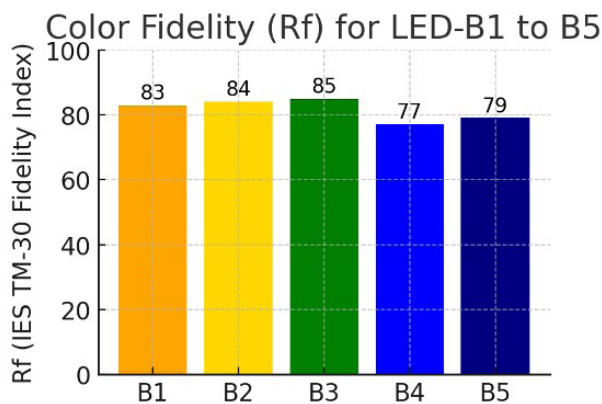


Fig. 6. Comparison of the fidelity index Rf for standard LEDs of the B1-B5 series

- when using opal and tinted diffusers, a decrease in global Rf by 4–7 points was observed, with the largest losses recorded in the short-wavelength zone (blue and violet shades);
- local analysis of $Rf_1 \dots Rf_9$ revealed that even with a high average Ra, significant distortions may occur in specific areas of the spectrum (for example, $Rf_{13} \approx 62$ in the blue-violet region).

Conclusions

1. The analysis revealed that the classic color rendering index CRI (Ra) does not always allow one to detect local spectral distortions and can mask color rendering problems, especially when using diffusers or

tinted materials. The use of Rf and Rg indicators and CVG vector graphs provided a more in-depth and objective evaluation of light quality, allowing to detect the effects of desaturation and shifts in shades of individual color groups.

2. The combination of traditional parameters (CCT, Ra, LER) with modern color quality indices (Rf, Rg, CVG) forms a comprehensive approach to evaluating LED luminaires, which better corresponds to real visual perception and modern lighting requirements. The results obtained confirm the feasibility of switching from the exclusive use of Ra to multi-parameter color rendering assessment systems.

3. The use of spectral analysis tools and a conditional SPD “calculator” clearly demonstrated the influence of structural components on the spectral distribution of radiation and related color quality indicators, in particular the Rf index. It is shown that the basic luminaire without optical filters has spectral characteristics close to the LED-B3 reference template, while the addition of “colder” components can cause a shift in SPD towards LED-B4/B5 types and a potential decrease in Rf.

4. It was established that the studied LED luminaires correspond to the class of neutral white light for general purposes in terms of their main color parameters (CCT \approx 4150 K, the presence of a blue peak and broadband phosphor emission). Such a spectral profile is typical for architectural, office, educational, and industrial lighting, providing an acceptable compromise between energy efficiency and color rendering quality.

Вплив внесених компонентів на світлові та колірні характеристики світлодіодного світильника

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Анотація

Досліджується вплив додаткових конструктивних елементів на світлові та колірні характеристики світлодіодного світильника. Основна увага приділяється аналізу ролі спеціалізованих оптичних лінз, обмежувальних пластин та захисного полікарбонатного розсіювача у формуванні світлових параметрів випромінювання. Експериментальні дослідження проводилися на зразку світлодіодного світильника з поетапним додаванням зазначених компонентів, що дозволило провести коректний порівняльний аналіз отриманих результатів. Ключовим аспектом роботи є оцінка впливу полікарбонатного розсіювача на якість передачі кольору. Для цього було застосовано сучасний підхід до колориметричної оцінки відповідно до рекомендацій CIE 224:2017 та стандарту ANSI/IES TM-30 із використанням індексу колірної точності Rf. Показано, що полікарбонатний матеріал частково поглинає короткохвильову складову спектра випромінювання світлодіода, що призводить до зменшення світлового потоку в межах 5–12%.

Водночас, такий спектральний перерозподіл сприяє згладженню спектра та зменшенню локальних спектральних піків. За відсутності повного відновлення реального спектрального розподілу випромінювання, порівняльний аналіз із використанням еталонних світлодіодних шаблонів є ефективним та перспективним колориметричним підходом для об'єктивної оцінки якості світла і передбачення впливу конструктивних змін на колірні характеристики світильників на етапі проектування, що має велике практичне значення для сучасних систем освітлення. Отримані результати свідчать про збільшення значення індексу Rf при використанні полікарбонатного розсіювача, який забезпечує кращу відповідність показників колірного передавання суб'єктивному візуальному сприйняттю порівняно з відкритим світлодіодним модулем. У роботі обґрунтовано, що незначне зниження світлової ефективності є прийнятним компромісом за умови значного покращення якості освітлювального середовища. Зроблено висновок про доцільність використання полікарбонатних розсіювачів у сучасних світлодіодних лампах для практичних систем освітлення, де висока якість колірного передавання є пріоритетом.

Ключові слова: індекс передачі кольору; світлодіодні світильники; індекс колірної точності.

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