Semiconductor Physics, Quantum Electronics & Optoelectronics, 2022. V. 25, No 1. P. 076-082.

Optoelectronics

RGBW lighting systems: Influence of the white LED

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Abstract. People spend most of the time under artificial light sources, so it is important to create a comfortable lighting environment for work and rest. Four-component RGBW systems are the most effective for this. It is needed to create methods for obtaining white light with the specified parameters and choose the most optimal LED components. In this work, the influence of the white LEDs parameters on the resulting white light of the RGBW systems is studied. Two different methods proposed by us earlier for obtaining white light are applied for three RGBW systems with different warm white LEDs. It is shown that the use of white LEDs with a colour rendering index close to 80 is more optimal for most applications. In this case, they provide the resulting white light with the colour rendering index above 90 and luminous efficacy above 130 lm/W.

Keywords: LED, RGBW system, tuneable white light, colour rendering, smart lighting.

https://doi.org/10.15407/spqeo25.01.076
PACS 42.72.-g, 85.60.Jb

Manuscript received 20.07.21; revised version received 28.01.22; accepted for publication 22.03.22; published online 24.03.22.

1. Introduction

Technological progress has caused people to spend most of their time indoors often using artificial lighting. But natural light is the most comfortable for us in terms of visual and non-visual impact due to the human adaptation to the environment during the evolutionary process. Therefore, it is important to reproduce all aspects of the daylight in artificial lighting systems, including dynamics of spectral and intensity changes with a high colour rendering.

The RGBW (red/green/blue/white) lighting systems are the most promising in terms of creating a comfortable lighting environment, since they are able to provide a wide range of the required light parameters at relatively high luminous efficacy. However, the development of these systems is associated with an ambiguity problem in determining the LEDs brightness contributions in the resulting light to obtain given *x*-*y*-chromaticity coordinates at a fixed correlated colour temperature (CCT) [1]. There is an infinite number of variants of the spectral power distributions (SPDs) of the resulting light with different parameters, namely: colour rendering index (R_a), fidelity index R_f, gamut index R_g, luminous efficacy η (lm/W), *etc*. In addition, due to the wide range of various types of LEDs with different photometric characteristics, there are many combinations for using LEDs [2, 3].

Recently, we have proposed two methods for the white light synthesis in the RGBW lighting systems [4, 5]. These methods include certain supplementary conditions, which leads up to the unambiguous solution of the four-component problem for obtaining the white light. On the other hand, they provide visual and circadian features of the lighting close to the natural ones. The first method [4] is based on the condition of minimization of the RGB LEDs contribution in the resulting light. This allows the simultaneous use of only two colour LEDs and one white LED to provide the dynamic change of the white light hues, as well as to optimize the luminous efficacy of the system. The method implies the maximum distance of the chromaticity coordinates of the colour generated by the RGB LEDs ("RGB" point in Fig. 1) from the chromaticity coordinates needed to be obtained ("LS" point in Fig. 1), *i.e.*, their location on one of the sides of the Maxwell triangle. The side is determined by the intersection of the ray with vertex in the chromaticity coordinates of the white LED and that passes through the coordinates of the resulting light needed to be obtained ("W" and "LS" points in Fig. 1, respectively). Thus, the white LED and two colour ones lying on the corresponding side of the Maxwell triangle form the required white light. It was shown that in order to obtain high values of colour rendering parameters in the wide CCT range, it is optimal to use white LEDs with CCT in the lower part of the reproducible range (*i.e.*, about 3000 K).

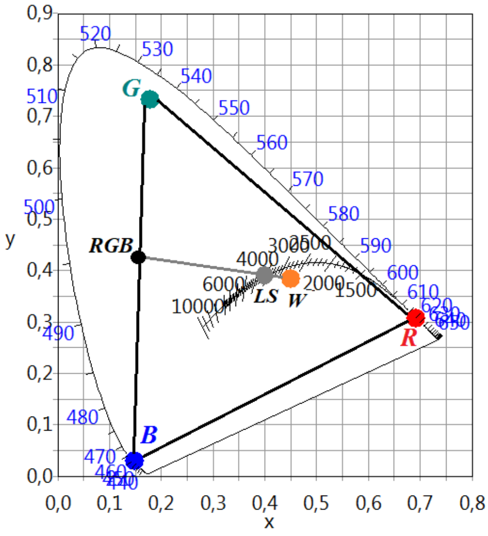

Fig. 1. CIE *x*, *y* chromaticity diagram with the chromaticity coordinates of the R, G, B, W LEDs, and example of the resulting RGBW light on the Planckian locus (LS).

The second method for obtaining the desired white light [5] is based on fixing the ratio between brightnesses of the white and red LEDs (W/R ratio). It allows one to uniquely determine the brightnesses of all the LEDs at a fixed CCT and, in addition, simplifies and optimizes the driving circuit owing to reducing the number of the control channels (from four to three) by using one channel for two LEDs (white and red).The study showed that it is needed to stabilize the W/R ratio at the level of 0.06 to get the optimal R_a values of the resulting white light, and at the level of 0.09 for optimal R_f values.

This work is aimed at determining the optimal parameters of white LEDs for the use in the RGBW lighting systems having high colour rendering and high luminous efficacy. For this purpose, we study the influence of colour rendering index of the white LED on the parameters of the resulting light of the RGBW systems. Due to the practical reasons, the study is advisable to carry out by using two methods mentioned above. This enables us also to make an additional comparison.

Fig. 2. Measuring system based on the Spectrometer and Integrating Sphere manufactured by Instrument Systems.

2. Components and methods

To explore the influence of the white LEDs' colour rendering index on the parameters of the resulting light of the RGBW-systems (R_a, fidelity index R_f, gamut index R_g, luminous efficacy η, *etc*.), three different white (W) LEDs were studied. The three RGB LEDs used in the system were XMLCTW series manufactured by Cree, Inc. The W LEDs had the similar CCT but different values of R_a. The first white LED (W1) is STW7C2PB-E2 (V53GY1) series manufactured by Seoul Semiconductor CO., LTD, its R_a is 73. Two other white LEDs (W2, W3) are 5630 (LEMWS59R) series manufactured by LG Innotek with R_a equal to 82 and 95, respectively.

The photometric and colorimetric parameters of the LED system were measured by using the Spectrometer CAS 140 CT-151M and Integrating Sphere ISP 2000 with internal diameters 1900 mm manufactured by Instrument Systems (Fig. 2). The measurements were made in the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine.

Table 1 shows the measured photometric and colorimetric parameters of all LEDs at the supply current of 100 mA. They include the chromaticity coordinates (*x*, *y*), luminous flux (*F*, lm), luminous efficacy (η, lm/W), peak wavelength (λ_p, nm), full width at half maximum (λ_{hp}, nm), CCT, R_a and R_f. The normalized SPDs of colour RGB and three white LEDs are presented in Fig. 3.

Table 1. Parameters of the LEDs used in the studied RGBW-systems at direct current 100 mA.

LED type	(*x*, *y*)	*F*, lm	η, lm/W	λ_p, nm	λ_{hp}, nm	CCT, K	R_a	R_f
Red LED (R)	0.693, 0.307	18.3	92	630	14.1	–	–	–
Green LED (G)	0.178, 0.733	45.4	155	521	31.9	–	–	–
Blue LED (B)	0.149, 0.030	6.45	22	453	16.8	–	–	–
1st White LED (W1)	0.435, 0.407	54.1	199	595	–	3059	73	73
2nd White LED(W2)	0.434, 0,404	44.5	163	603	–	3057	82	81
3rd White LED(W3)	0.428, 0.399	35.4	130	625	–	3126	95	92

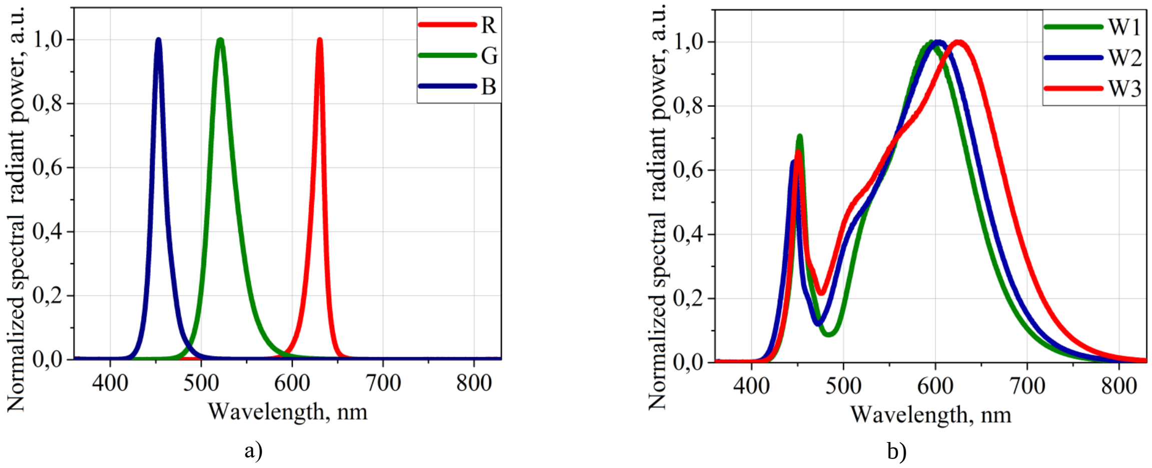

Fig. 3. Normalized SPDs of the three W LEDs (a) and RGB LEDs (b) used in the RGBW clusters.

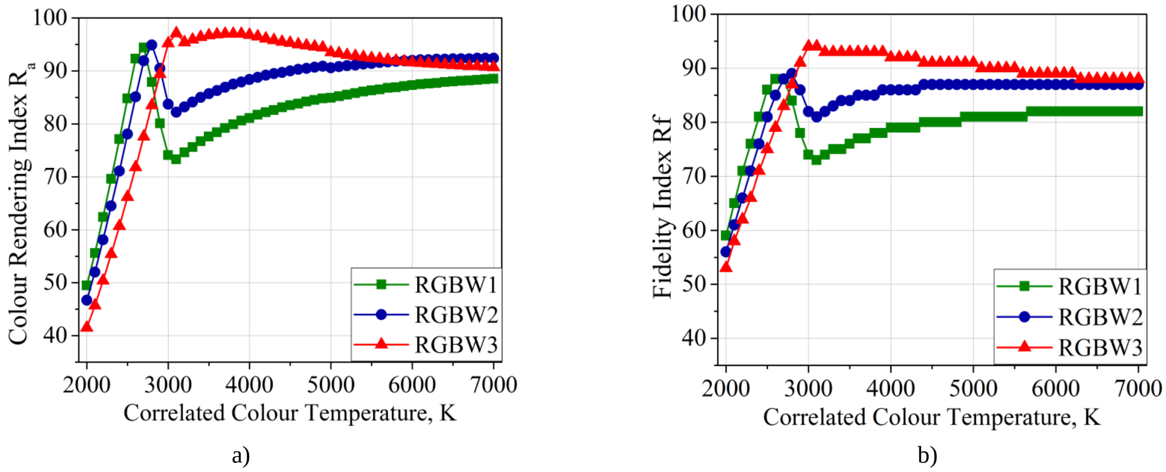

Fig. 4. R_a (a) and R_f (b) *versus* CCT for three RGBW clusters, when using the condition of minimization of the RGB LEDs contribution.

To study the influence of the white LEDs colour rendering index on the parameters of the resulting light, computer simulation of the SPDs for the resulting light of three RGBW systems with further calculation of the photometric and colorimetric parameters were carried out. The parameters were calculated using the two above-described methods to obtain white light: the 1st method was minimization of the RGB LEDs contribution and the 2nd method was based on the fixed W/R ratio.

Computer simulation was based on our web program [6] by using the open-source Python package Color [7] (for the 1st method) and the Software LED ColorCalculator from Osram [8] for both methods. Colour rendering parameters R_a, R_f, R_g, and luminous efficacy of the resulting white light were calculated within the CCT range 2000 to 7000 K with 100 K step for the 1st method, as well as in the CCT range 3000...7000 K with 500 K step for the 2nd method.

We carried out experimental verifications of the obtained theoretical results for the studied RGBW-systems. Accomplish this, the eight-channel system of group control of LEDs [9] and above-described measurement system (Fig. 2) were used.

3. Results and discussions

3.1. Method of minimization of the RGB LEDs contribution

Three RGBW-systems were studied with the 1st method for minimization of the RGB LEDs contribution. The photometric and colorimetric parameters of the resulting white light under the mentioned condition were calculated in the CCT range 2000...7000 K.

The obtained dependences of colour rendering parameters on CCT are similar for all the RGBW-systems (Fig. 4). From these results, it is seen that when the CCT of the resulting white light is higher than CCT of the white LED (CCT_W), R_a of the resulting light is close to R_a of the white LED. As CCT and accordingly RGB LEDs contribution to the resulting light increase, R_a and R_f values of the resulting light gradually increase, too. It takes place due to the selected condition whereby at the point CCT = CCT_W the contribution of RGB LEDs is close to zero. For the same reason, the maximum luminous efficacy of the resulting light is observed at this point, where the contribution of low efficacy colour LEDs is non-essential (Fig. 5).

Table 2. Ranges of R_a, fidelity index R_f, gamut index R_g, and luminous efficacy η (lm/W) in the CCT range 3000...7000 K for three RGBW systems, when using the 1st method.

	$R_{a\,min}$ ($R_{a\,max}$)	$R_{f\,min}$ ($R_{f\,max}$)	$R_{g\,min}$ ($R_{g\,max}$)	η_{min} (η_{max}), lm/W
RGBW1	73 (88)	73 (82)	95 (100)	148 (197)
RGBW2	82 (92)	81 (87)	99 (103)	133 (162)
RGBW3	91 (97)	88 (94)	101 (106)	117 (130)

The use of the white LEDs with R_a of about 70 (W1) provides the highest luminous efficacy (148...197 lm/W) among the considered systems but R_a of the resulting light is less than 90. This is not enough for places with high colour discrimination requirements. Although in general R_a values of the resulting white light are up to 15 unities higher then R_a of W1 LED within the CCT range 3000...7000 K. At the same time, luminous efficacy of the resulting light is 26% lower than η of the W1 LED (199 lm/W).

The most appropriate among the considered systems is to use white LEDs with R_a of about 80, *i.e.*, W2 LED. This allows obtaining the resulting white light with R_a of 82...92 and R_f of 81...87 at the luminous efficacy higher than 133 lm/W within the CCT range 3000...7000 K (Table 2). The colour rendering index is up to 10 unities higher than R_a of W2 LED, while luminous efficacy is up to 18% lower.

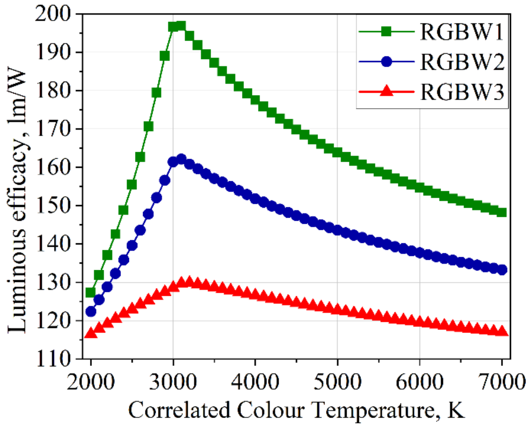

Fig. 5. Luminous efficacy *versus* CCT for three RGBW clusters, when using the condition of minimization of the RGB LEDs contribution.

In this method, the use of white LED with R_a above 90 generally provides the highest colour rendering parameters for the resulting white light, but the lowest values of its luminous efficacy (lower than 130 lm/W). It is up to 25% less than in the system with W2 LED. In the RGBW3 system in some parts of the CCT range, the R_a value of the resulting light is even lower (down to 4 unities) than that of the W3 LED. Thus, the addition of coloured LEDs to the W3 has a minimal effect on the parameters of the resulting light. Thus, it is advisable to use RGBW3 system in the place with high requirements for colour discrimination, for example, museums, art galleries *etc.*

It is worth noting that in all the studied RGBW systems only three LEDs are used (namely, white, blue and green) to generate white light within the CCT range 3200...7000 K. This is due to the location of chromaticity coordinates of white LEDs relatively to the Planckian locus.

3.2. Method of fixed W/R ratio

The RGBW systems were also studied using the 2nd method when fixing W/R ratio at the level of 0.06 and 0.09. Parameters of the resulting white light were calculated within the CCT range 2900...7000 K (Figs 6 and 7).

Table 3. Ranges of R_a, fidelity index R_f, gamut index R_g, luminous efficacy η (lm/W) in the CCT range of 3000 to 7000 K for the three RGBW systems, when using the stabilized W/R ratio.

	$R_{a\,min}$ ($R_{a\,max}$)	$R_{f\,min}$ ($R_{f\,max}$)	$R_{g\,min}$ ($R_{g\,max}$)	η_{min} (η_{max}), lm/W
RGBW1 (W1/R = 0.06)	85 (93)	82 (86)	100 (105)	142 (182)
RGBW1 (W1/R = 0.09)	90 (94)	85 (88)	102 (106)	139 (176)
RGBW2 (W2/R = 0.06)	90 (94)	87 (90)	103 (107)	130 (155)
RGBW2 (W2/R = 0.09)	88 (95)	87 (91)	105 (109)	128 (152)
RGBW3 (W3/R = 0.06)	85 (95)	85 (94)	104 (109)	116 (128)
RGBW3 (W3/R = 0.09)	83 (90)	84 (92)	105 (110)	115 (128)

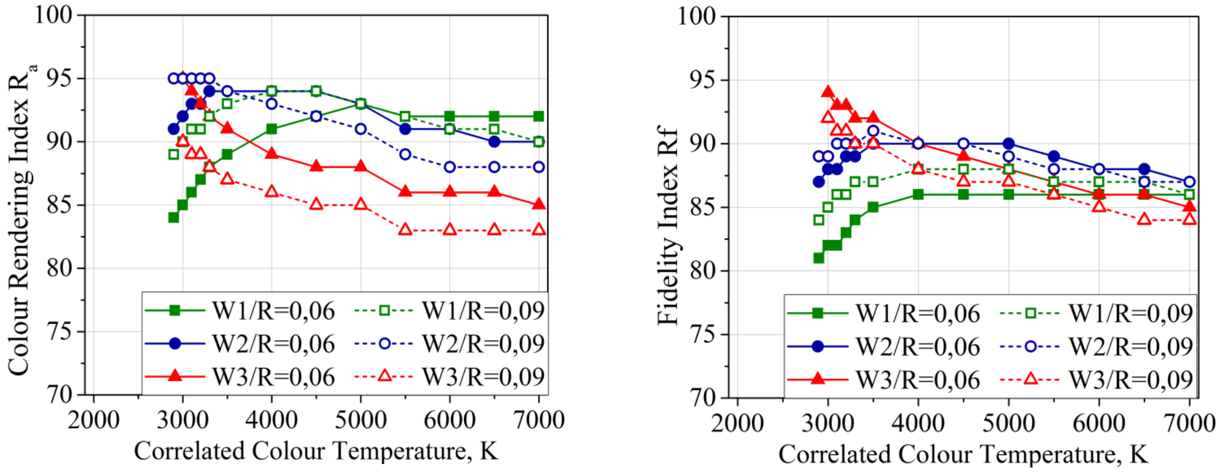

Fig. 6. R_a (a) and R_f (b) *versus* CCT for three studied RGBW clusters, when using the stabilized W/R ratio at the level of 0.06 and 0.09.

As seen in Fig. 6, in general the dependences of the R_a and R_f parameters on CCT are similar, but their dependence on the white LED parameters differs. For example, RGBW1 system has higher R_a values than RGBW3 system and, at the same time, lower R_f values in most of the CCT range. It can be explained by the fact that less test colour samples are used to calculate the R_a parameter than during calculations of R_f (namely, 8 *vs.* 99). The dependence of luminous efficacy on CCT (Fig. 7) differs from that presented in the section 3.1 (Fig. 5) due to the use of four LEDs simultaneously. In this method, the value of luminous efficacy gradually decreases with increasing R_a of the white LED and the red LED contribution. Also, the use of fixed W/R ratio has improved colour rendering parameters at the point $CCT = CCT_W$.

Considering all the measured parameters, it is most expedient to use the RGBW2 system, in particular when fixing the W/R ratio at the level of 0.06. It provides the

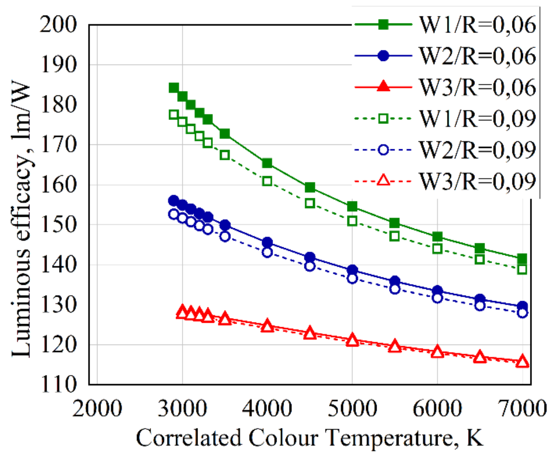

Fig. 7. Luminous efficacy *versus* CCT for the three studied RGBW clusters, when using the stabilized W/R ratio at the level of 0.06 and 0.09.

highest values of colour rendering parameters and high values of η in the wide CCT range. Namely, it provides the colour rendering index from 90 to 94 and R_f from 87 to 90 at luminous efficacy within the range 130...155 lm/W at the CCT range 3000...7000 K (Table 3). The resulting light of W2 and red LEDs with the W/R ratio at the level of 0.06 has the following parameters: CCT = 2696 K (0.453, 0.397); $R_a = 89$; $R_f = 83$. Thus, it is possible to use one LED with these parameters instead of two (red and white) to create a three-component lighting system with similar parameters of the resulting light.

In places with higher requirements for luminous efficacy, it is also advisable to use RGBW1 system, when fixing the W/R ratio at the level of 0.09. It allows to obtain the same values of R_a as those in the RGBW2 system (at the W/R ratio 0.06) and only 2 unities lower R_f values, while luminous efficacy of the resulting light is up to 14% higher (139 to 176 lm/W). The resulting light of W1 and R LEDs with the W/R ratio at the level of 0.09 has 2554 K (0.462, 0.396), $R_a = 84$ and $R_f = 78$.

The use of white LEDs with R_a above 90 in this method is impractical, as it provides the lowest values of colour rendering index and luminous efficacy among all the considered systems. Moreover, R_a of the RGBW3 system is up to 10 unities less than R_a of the used W3 LED.

Comparing the two considered methods may be noted that the 2nd method of fixed W/R ratio provides higher CCT and R_f values of the resulting white light than the 1st method of minimization of the RGB LEDs contribution. Namely, for the RGBW2 system, it is expressed by R_f (87...90 *vs.* 81...87) and R_a (90...94 *vs.* 82...92). At the same time, the 2nd method provides lower luminous efficacy of the RGBW2 system (130...155 lm/W *vs.* 133...162 lm/W). It is associated with the continuous operation of the red LED with low luminous efficacy in this method, and its shutdown in the 1st method in the most of CCT range.

It is also worth to notice that the use of the red LED allowed us to obtain higher values of the important parameter $R9$ (strong red). Thus, in the RGBW2 system under the 1st method of minimization of the RGB LEDs contribution, its value comprises the range from 8 to 75, and under the 2nd method $R9$ is 53…98.

Additional experimental verification of several theoretically calculated parameters of the considered systems was performed. Measurements were performed using the eight-channel system of group control of LEDs [9] and measurement system from Instrument Systems (Fig. 2). The difference in R_a values is 0...2 unities and increases with increasing the CCT values. At the same time, the difference in CCT is up to 80 K within the range 3000...7000 K.

These deviations are related with the fact that the theoretical calculations do not consider the change in LEDs SPDs with a change in direct current value and when heated. In addition, there is an error in setting the current on the power supply (less than 1%).

4. Conclusions

In this work, we have demonstrated the influence of the colour rendering index of white LED on the RGBW system parameters by using two methods of obtaining white light. The presented methods provide values of luminous efficacy at the level of existing white LEDs with R_a of about 95 and WW systems with R_a close to 90, while the functionality of the presented systems is higher.

The study of RGBW systems with white LEDs having different colour rendering index values showed that it is most appropriate to use warm white LEDs with a colour rendering index close to 80, to provide the resulting white light with high values of colour rendering and luminous efficacy. Fixing the W/R ratio at the level of 0.06 in the RGBW system with this white LED (W2), it is possible to obtain the resulting white light with R_a above 90 and fidelity index R_f above 87 at luminous efficacy 130…155 lm/W within the CCT range 3000...7000 K. It has been also shown the practicality of using RGBW systems with a white LED having R_a of about 70 (W1) at a fixed W/R ratio of 0.09 to obtain up to 14% higher luminous efficacy at 2 unities less R_f.

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Author contribution

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Kornaga V.: Software, Investigation, Formal analysis, Writing - Original Draft.
Rybalochka A.: Methodology, Investigation, Formal analysis.
Valyukh S.: Software, Formal analysis, Validation, Writing - Review & Editing.

RGBW системи освітлення: вплив білого світлодіода

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Анотація. Люди проводять багато часу під штучними джерелами світла, тому важливо створити комфортне світлове середовище для роботи та відпочинку. Найбільш ефективними, з цієї точки зору, є чотири-компонентні RGBW системи. Потрібно створити методи отримання білого світла із заданими параметрами, а також вибрати найбільш оптимальні світлодіодні компоненти. У цій роботі досліджено вплив параметрів білих світлодіодів на результуюче біле світло RGBW систем. У трьох RGBW системах з різними теплими білими світлодіодами використано два методи отримання білого світла, запропоновані раніше. Показано, що використання теплих білих світлодіодів з індексом кольоропередачі близьким до 80 є найбільш оптимальним для більшості застосувань. У цьому випадку вони забезпечують генерацію білого світла з індексом кольоропередачі вищим за 90 і світловою віддачею вищою ніж 130 лм/Вт.

Ключові слова: світлодіод, RGBW система освітлення, регульоване біле світло, індекс кольоропередачі, розумне освітлення.