Color temperature tunable RGBW cluster with optimize color rendering and efficacy

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Abstract. Our work is devoted to the optimization of 4-component RGBW smart lighting systems that are able to obtain the resulting white light with a combination of high color rendering and luminous efficacy for a certain fixed correlated color temperature. Three approaches for the determination of the optimal brightness contributions of the light emitting diodes (LEDs) are studied. They are accordingly based on: (1) maximization of the color rendering, (2) prioritizing to reduce the color rendering maximum by 1 to 6 units to increase luminous efficacy, and (3) getting a constant value of RGB contribution and luminous efficacy while maintaining high color rendering. A comparison of the three systems with different base white LEDs is demonstrated. The obtained theoretical results are verified experimentally. [DOI: 10.1117/1.OE.62.4.045102]

Keywords: RGBW color mixing; effective lighting; light emitting diode; color rendering index; tunable white light; smart lighting.

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1 Introduction

Extensive research activity on the creation of an efficient, healthy, and comfortable lighting environment for work and leisure is in full swing.[1–20] With the arrival and development of solid-state light sources, the possibilities in this field have expanded significantly due to a great scope for improvement of energy efficiency, spectral tunability, and brightness controllability[4,5] that contribute to the creation of smart lighting systems (SLSs). Despite the fact that light emitting diodes (LEDs) have quickly replaced the other types of light sources, the potential of LED lighting systems in terms of optimization and generation of desired spectral distributions is far from being realized, to provide both visual and nonvisual effects for the improvement of lighting environment in buildings. Since humans nowadays spend more than 80% of their lives in buildings, it can be argued without exaggeration that the development of SLS with optimized parameters is an urgent problem. SLSs coupled with various integrating sensors (e.g., timer tuned to circadian rhythms, motion, and occupancy sensors) enable automatic optimized light control for the light quality improvement as well as the reduction of energy consumption.[21,22] In addition to reproducing the daylight characteristics and their corresponding changes during a day,[6,7] SLSs can also be helpful in obtaining various aspects of psychoemotional states, e.g., relaxing or vigorous.

Theoretical and experimental studies on the development of illuminating systems with tunable correlated color temperature (CCT) are based usually on two of the most common approaches: (1) utilizing a couple of white LEDs with different CCTs[8,9] and (2) the use of three or more different LEDs.[9–14] The advantages of the second approach include the ability to get a wider range of CCT and, what is more important, to obtain spectra and CCT tuning along the Planckian or daylight loci in a chromaticity color space, e.g., the Commission Internationale de l'Eclairage (CIE) x, y chromaticity diagram.[15] The tunable spectra and/or CCT are needed to follow daylight parameter changes for supporting human circadian cycles. There is no unique

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solution for getting a specific color with more than three types of LEDs, i.e., a desired point in the CIE x, y chromaticity diagram can be obtained using many combinations. In this case, additional conditions including optimal brightness and energy consumption of each LED must be involved. Luminous efficacy and color rendering are two important characteristics of artificial lighting[16,17] that must be as high as possible. But an improvement in one of them often leads to a deterioration in the other.[11,18] Therefore, it is necessary to get an optimal ratio between them. SLSs with three colored LEDs and a broadband white LED give not only opportunities for optimal lighting in terms of high color rendering and efficacy but also are able to get the needed circadian performance.[23] Existing works on lighting systems often provide an approach for white light generation that is based on a theoretical study of hypothetical LEDs.[11] This, in turn, may complicate the result reproduction in practice. The calculated luminous efficacy of radiation is usually different from a real value.

In this paper, we primarily focus on determining the optimal conditions for 4-component RGBW (red/green/blue/white) SLSs. The capabilities and potential of such systems are explored, to ensure both high color rendering and luminous efficacy (η, lm/W) are at a fixed CCT. In order to determine the color rendering, the standardized metric CIE color rendering index (CRI)[16] is used. At the same time, we also utilize the Illuminating Engineering Society (IES) color fidelity index Rf and gamut index Rg,[17,20] which are found expanding implementation in the lighting community due to their higher accuracy and informational contents of color rendering, such as colors saturation. The considered approaches and obtained results in the work can be helpful for the creation of efficient SLSs.

2 Definition of the Problem

There are three important parameters of a lighting system: color, luminous efficacy, and ability to correctly reproduce the colors of illuminated objects. In the case of white lighting, there are often requirements that the color of illumination should be similar to natural lighting, i.e., the chromaticity coordinates should be on the Planckian or daylight loci of the CIE x, y chromaticity diagram. To explore the potential of an RGBW SLS and to achieve optimal illumination at high CRI, Rf, and luminous efficacy, the spectral power distributions (SPDs) of the resulting light corresponding to a fixed CCT should be investigated in terms of the contributions of each LED.

Figure 1 of the CIE x, y chromaticity diagram shows schematically the chromaticity coordinates of three colored LEDs forming the RGB triangle and a white LED (the point W), as well as a point on the Planckian locus of the desired CCT (the point P) and the resulting light of RGB components (the point RGB). For a chosen SLS, the position of W and the distance w between W and P are fixed and determined by the color parameters of the white LED and the point RGB. W, P, and RGB lie on one straight line. By varying the RGB LEDs contributions, i.e., by manipulating the distance d between P and RGB, we change the SPD and the other parameters of the resulting white light (CRI, Rf, Rg, η). These parameters can be changed significantly while the chromaticity coordinates (P) remain constant. As the distance d increases, the RGB LED contribution to the resulting light decreases. The direction in which the point RGW can be moved along the WP line defines by the positions of P and W. The dashed lines in Fig. 1 show examples of directions along which RGB moves for generating the corresponding color from the Planckian locus.

Recently, it has been reported about the study on RGBW SLSs when the contribution of the RGB LED to the white light generation is minimal.[14] In this case, the RGB point lies on a side of the RGB triangle. The corresponding approach enables one to use a three-channel control circuit because only three of the four LEDs work. However, it is unclear if it is an optimal solution in terms of maximum color rendering and luminous efficacy.

In order to argue on the effect of the RGB components contribution to the parameters of the resulting white light, it is necessary to study how the distance d, or a position of the point RGB with respect to P and W, affects these parameters in a wide range of CCT. Also it is good to know how the obtained results depend on position of W, i.e., CCT of the white LED. Clarification of these issues pushed us to develop Software for simulation of an RGBW SLS and calculation of the parameters of the resulting white light. One can use the web version[24] for examination of the

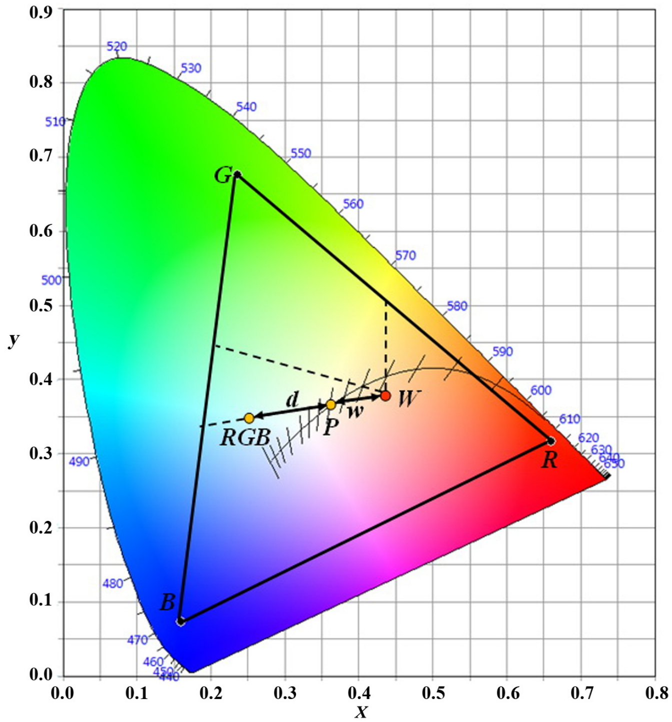

Fig. 1 CIE x, y chromaticity diagram with schematic chromaticity coordinates of white, blue, green, and red LEDs (W, B, G, and R), the point on the Planckian locus (P), and resulting light of the colored LEDs (RGB).

results obtained in this work or for own computations. This software is based on the open-source Python package Color.[25]

In order to avoid cumbersome mathematical calculations, the method used can be explained as follows. Since we know the chromaticity coordinates (and tristimulus values) of colored RGB LEDs, it is possible to calculate the contributions of their brightness to obtain the resulting RGB light with the given tristimulus values ($X_{\mathrm{RGB}}, Y_{\mathrm{RGB}}, Z_{\mathrm{RGB}}$), i.e., for a given RGB point:

$$\begin{cases} X_{\mathrm{RGB}} = g_R X_R + g_G X_G + g_B X_B \\ Y_{\mathrm{RGB}} = g_R Y_R + g_G Y_G + g_B Y_B \\ Z_{\mathrm{RGB}} = g_R Z_R + g_G Z_G + g_B Z_B \end{cases}, \tag{1}$$

where $X_{R(\mathrm{GB})}, Y_{R(\mathrm{GB})}, Z_{R(\mathrm{GB})}$ are tristimulus values of the R, G, B LEDs and g_R, g_G, and g_B are the corresponding brightness of these LEDs. From two points on the CIE x, y chromaticity diagram (the point RGB and W), it is possible to unambiguously determine their brightness for the generation of white light with any chromaticity coordinates on the Planckian or daylight loci (P).

By changing the distance d, it can be obtained an infinite number of the LEDs' brightness combinations for the generation of white light with defined chromaticity coordinates and various photometric parameters. Since we calculated the brightness of the LEDs and measured their SPDs [$\Phi_{eR}(\lambda), \Phi_{eG}(\lambda), \Phi_{eB}(\lambda), \Phi_{eW}(\lambda)$], it is possible to calculate the SPD of the resulting light [$\Phi_e(\lambda)$]:

$$\Phi_e(\lambda) = \frac{g_R \Phi_{eR}(\lambda)}{X_R + Y_R + Z_R} + \frac{g_G \Phi_{eG}(\lambda)}{X_G + Y_G + Z_G} + \frac{g_B \Phi_{eB}(\lambda)}{X_B + Y_B + Z_B} + \frac{g_W \Phi_{eW}(\lambda)}{X_W + Y_W + Z_W}. \tag{2}$$

As a result, it is possible to unambiguously calculate the main luminous parameters using general formulas for CRI, Rf, luminous efficacy, etc.[16,17] and the open-source Python package Color.[25] The proposed method is suitable for any set of RGBW LEDs and can be applied using the web version of our developed software.[24]

Table 1 Values of the parameters of the W LEDs.

	CCT (K)	CRI (—)	Rf (—)	Rg (—)
Warm W LED (WW)	3057	82	81	98
Neutral W LED (NW)	3999	83	77	88
Cold W LED (CW)	5020	83	82	95

3 Results and Discussion

3.1 *Three Studied SLS*

Three RGBW SLSs consisting of widespread LEDs have been studied. The colored LEDs (Cree Inc., XMLCTW series) are the same for all three systems and possess the following characteristics: the *R* LED has the peak of the wavelength 630 nm and luminous efficacy 92 lm/W, the G LED has 521 nm and 155 lm/W, respectively, and the *B* LED has 453 nm and 22 lm/W, respectively. The use of three WLEDs in combination with the color LEDs has been tested. There are a warm *W* LED (LG Innotek), a neutral *W* LED (Cree Inc.), and a cold W LED (Seoul Semiconductor Co. Ltd.). The white LEDs will be denoted as WW, NW, and CW, respectively. Their parameters at 100 mA are presented in Table 1. The luminous efficiencies of all the W LEDs are very close and amount to 180 lm/W. The parameters of the resulting white light of the RGBW SLS were obtained from its SPD. In order to get a picture on the optimal conditions for obtaining high color rendering and efficacy, these parameters have been analyzed as functions of the distance *d* (Fig. 1).

The CIE CRI and luminous efficacy were calculated and analyzed for the different ratios between the luminous flux of the colored LEDs and the total luminous flux of the SLS. The corresponding dependencies for SLS with WW LED are demonstrated in Fig. 2. As seen, almost all the CRI curves have a similar behavior. Some of them, in particular 3000, 3500, and 4000 K, consist of two linear parts. In the beginning, the CRI values increase with increasing the RGB contribution by about 10 units, then reach a peak, and after that decrease. The curves corresponding to CCT equal to 2500 and 3000 K are obtained by moving the point RGB toward the side RG of the triangle (Figure 1), whereas the other curves (3500 to 7000 K) are associated with directions to the side BG. The maxima of CRIs (CRI_{max}) in the RGBW system with the WW LED are observed for the RGB contribution at the level of 20% to 34% in the CCT range 3000 to 7000 K and 41% for 2500 K. In these cases, the resulting spectra are close to spectra of daylight. A further increase in the colored LEDs contribution leads to their dominance over the white LED. The resulting light spectrum becomes less flat with sharp peaks from the color LEDs and, as a result, the CRI decreases. The luminous efficacies for all CCTs monotonically decrease versus the RGB contribution and look like linear dependencies [Fig. 2(b)]. This behavior of the curves is explained by the fact that the luminous efficacies of the RGB LEDs are much lower than that of the W LED. It is worth to notice that the relative difference in the values

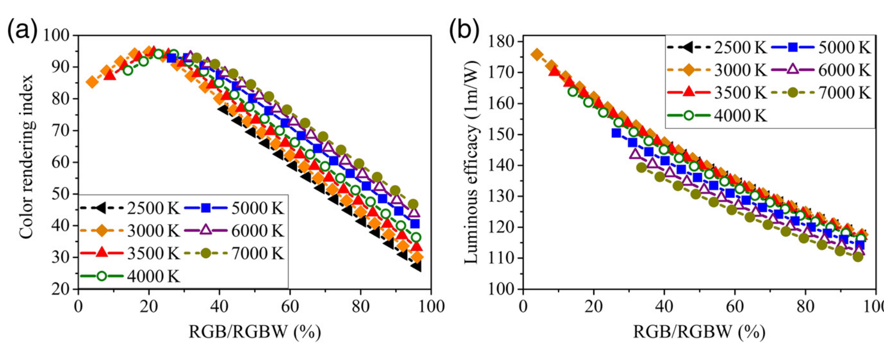

Fig. 2 (a) CRI and (b) luminous efficacy versus RGB contribution for the CCT range of 2500 to 7000 K for the RGBW system with basic WW LED.

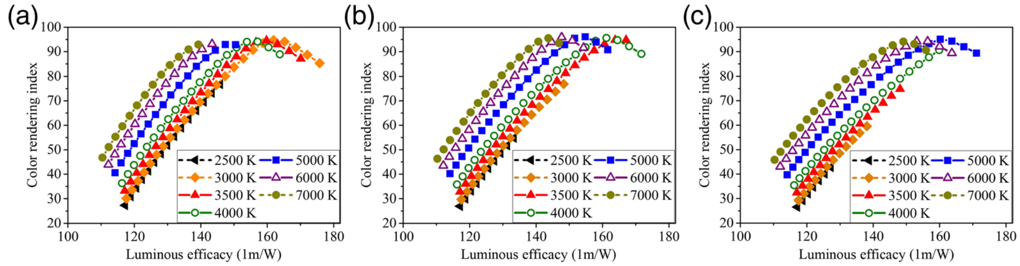

Fig. 3 CIE CRI versus luminous efficacy for the CCT range of 2500 to 7000 K for the RGBW systems with (a) basic warm, (b) neutral, and (c) cold white LED.

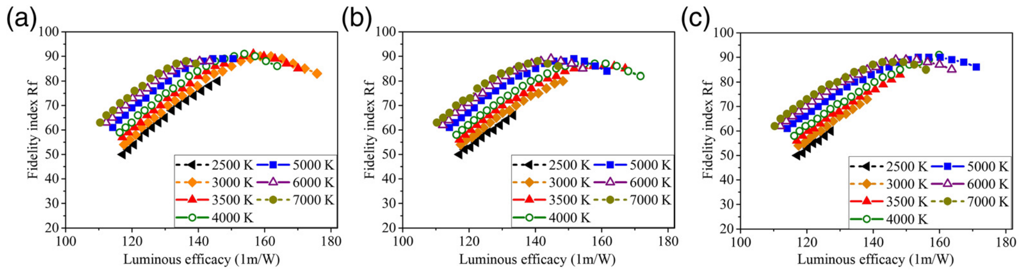

Fig. 4 IES fidelity index Rf versus luminous efficacy for the CCT range of 2500 to 7000 K for RGBW systems with (a) basic warm, (b) neutral, and (c) cold white LED.

at a constant ratio RGB/RGBW for different CCTs does not exceed 8%. Since all the considered W LEDs have the same luminous efficacy, for the other two SLSs, the luminous efficacy will also decrease linearly with an increase in the RGB contribution. Therefore, for further analysis of all the three SLSs, we can consider the dependence of color rendering on luminous efficacy, which will allow us to find an optimal combination of high color rendering and efficacy.

Since CIE CRI are widely used nowadays in metrological measurements and at the same time it has been demonstrated in the scientific community that IES fidelity index Rf is more accurate for describing a light source's color rendering properties,[26] further calculations will be performed for both indices. Meanwhile, the example of the considered SLSs can be used for tracing the similarities and differences between CIE CRI and IES Rf. Figures 3 and 4 show the obtained CIE CRIs and IES Rf, respectively, for the resulting light versus luminous efficacy for the three RGBW systems. The calculations have been carried at different ratios RGB/RGBW (or the distance d). Since the luminous efficacy decreases with increasing the RGB contribution, the leftmost points correspond to the maximum RGB contribution, whereas the rightmost ones correspond to the minimum RGB contribution, i.e., when the point RGB lays on the triangle side or, in other words, when only two color LEDs are used.[14]

Both CIE CRI and IES Rf curves have in general similar behavior. The maxima of CRI and Rf (Rf_{max}) coincide with the maxima of the corresponding luminous efficacies only for a few CCT. In fact, the luminous efficacy values at CRI_{max} and Rf_{max} are ~0% to 8% less than the corresponding maximum luminous efficacies. A comparison of the characteristics of the three SLSs enables us to clarify how namely the white LED affects the parameters of the resulting light. In particular, the CRI and Rf values in the considered SLSs decrease with an increase in the CCT of the white LED. The CRI_{max} and Rf_{max} for this set of LEDs are presented in Fig. 5(a). As seen, the CRI values in the RGBW system with WW LED are higher than 90 in the widest CCT range in comparison to the other SLSs. In general, the difference between the CRI_{max} and Rf_{max} averages 1 to 7 units but sometimes it can reach up to 17 units. When Rf values are at their maximum, the values of the gamut index Rg decrease with increasing CCT of the base white LED and reaches 104 to 111 for WW LED, 95 to 107 for NW LED, and 102 to 114 for CW LED.

As shown in Fig. 5(a), the CRI value of WW LED (82) increase with adding colored LEDs by 11 to 13 units in the CCT range of 3000 to 7000 K and slightly decrease at 2500 K, the CRI value of NW LED increase by 12 to 13 units in the range 3500 to 7000 K, whereas the CRI value of

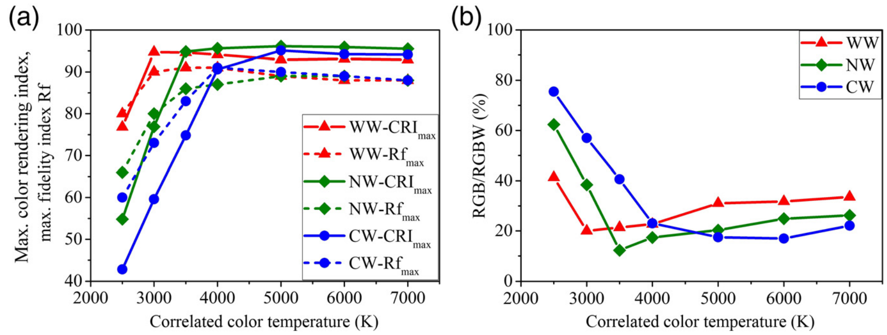

Fig. 5 Maximal CRI (solid curves) and maximal fidelity index Rf (dashed curves) for the CCT range of 2500 to 7000 K for three RGBW systems with (a) different basic white LEDs and (b) the contribution of the RGB component to the resulting white light at these CRI_{max}.

CW LED increase by 8 to 12 units only in the range 4000 to 7000 K. At the same time, the luminous efficacies decrease in the full CCT range by 10% to 23% for WW LED, by 7% to 26% for NW LED, and by 11% to 29% for CW LED. Thus in terms of increasing the CRI values and reducing losses in luminous efficacy, the RGBW system with WW LED is the most promising among the considered systems.

Figure 5(b) shows the dependences of the RGB contribution in the resulting light on the CCT at the CRI_{max} and Rf_{max}. In the RGBW system with WW LED, the maximum rendering values are achieved with the RGB/RGBW at the level of 20% to 41% [Fig. 2(a)], in the system with NW LED—at the level of 12% to 62% and in the system with CW LED—at the level of 17% to 75%. Moreover, the behavior of the resulting curves allows for approximating most of them by linear functions and easily evaluating the RGB contribution for any CCT step.

3.2 *Three Optimization Approaches*

A study of the possibilities of RGBW SLSs has shown a large number of combinations of light and color parameters of the resulting light that can be obtained. Therefore, several optimization approaches should be offered to optimize LEDs contributions to get the resulting white light with the desired combination of high color rendering and efficacy. The choice of approach depends on the requirements and place of the application of the SLS. These approaches will also allow to simplify the SLSs.

The first approach is based on the maximization of the color rendering (CRI or Rf). This is especially suitable for places where an active visual work and high demands on color recognition are required. The solution in this case is unique that unambiguously determines the LEDs contributions.

The second approach implies an increase in the luminous efficacy by 3% to 7% (compared to the first one) due to a decrease in color rendering by 1 to 6 units. As it was shown, the difference between maximal luminous efficacy and its values at CRI_{max} and Rf_{max} for different CCTs does not exceed 8%. Both these approaches can be used for any RGBW SLS.

In the RGBW system with WW LED, another (third) approach for the optimization of the LED contributions can be applied due to the relatively narrow range of RGB/RGBW values (20% to 41%) in which CRI_{max} are achieved [Fig. 2(a)]. It is possible to find a constant value of the RGB LEDs contribution to get an almost constant value of luminous efficacy and a high CRI in a wide CCT range. Fixing the ratio RGB/RGBW allows one to simplify the SLS driving[13] because three control channels are needed. The CCT, in this case, is defined only by the ratio between R, G, and B LEDs. For example, when the RGB contribution is taken at the level of 30%, the luminous efficacy of the resulting light is 143 to 154 lm/W and the CRI is >91 (which is only 1 to 4 units lower than the CRI_{max}) in the CCT range of 3500 to 6000 K. In the SLS with NW and CW LED, the maximum rendering values are achieved in a much wider range of luminous efficacy and RGB/RGBW (Figs. 3 and 4). As a result, an application based on this optimization approach will provide high CRI and Rf only in a narrow CCT range and, therefore, it cannot be considered as optimal.

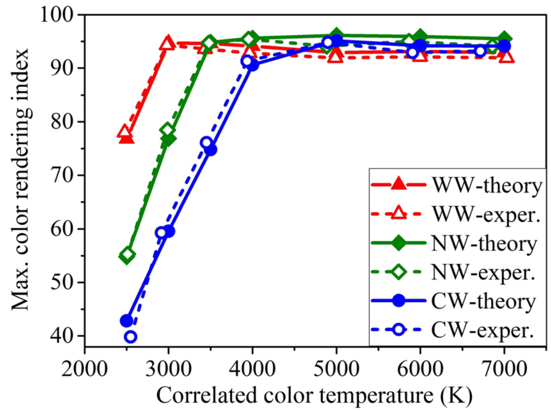

Fig. 6 Experimental (dashed curves) and theoretical (solid curves) dependence of the maximal CRI from CCT for the three studied SLS.

3.3 *Experimental Verification*

For additional verification of the obtained theoretical results, experimental measurements were carried out where the white light at the CRI_{max} in the full considered CCT range was obtained. To do this, after determining the LEDs contributions to the resulting light, we defined the forward current to supply each LED and obtained the desired parameters of the resulting light. It is important to consider the nonlinearity of ampere-luminance characteristics of the LEDs and to use corresponding correction factors for finding the forward current correctly. In order to calculate the correction factor, the light parameters were measured for each LED in the range of 0 to 350 mA. The experimental setup consisted of a Spectrometer CAS 140 CT-151M, Integrating Sphere ISP 2000 (Instrument Systems, Germany), and Power Supply HAMEG HMP4040. The measured results of the dependence of the CRI_{max} from CCT together with the corresponding theoretical calculations are plotted in Fig. 6. As seen from the graphs, the experimental data are in a good agreement with the theory. The difference in CRI values is <2 units (<1.5 in most of the range) and in CCT values is up to 3%. The discrepancy between theoretical and experimental CCT values increases with increasing CCT of the base W LED, e.g., 0.1% to 1.9% for the SLS with WW LED and 1.6% to 3.0% for the SLS with CW LED. At the same time, the difference in luminous efficacy is up to 6%.

The discrepancy between the results can be explained by the influence of the experimental factors: (1) theoretical calculations do not take into account the change in the LED's SPDs when changing current and heating and (2) the power supply has an error in setting current (up to 1%).

Figure 7 shows examples of the resulting spectra of the RGBW cluster with WW, NW, and CW basic LED at 4000 K (neutral white) as it is often preferred for European and US offices. Since the base WW LED is the most promising for using in RGBW systems in comparison to NW and CW LED, there are the resulting spectra of the RGBW cluster with WW LED at 2500, 3000, 4000, 5000, and 6000 K in Fig. 7(b).

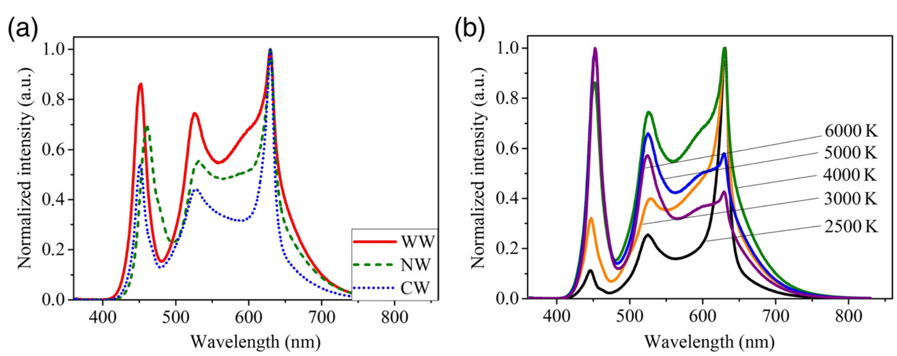

Fig. 7 Examples of the spectra of the RGBW cluster with (a) WW, NW, and CW basic LED at 4000 K and (b) WW LED at different color temperatures.

The conducted analysis is suitable for any set of RGBW LEDs. The considered samples were used as an example; therefore, the most informative are not the values obtained but the comparison of the considered SLSs and the change in the obtained characteristics versus the CCT of the basic white LEDs. Due to the author's software for any arbitrary set of spectral characteristics of RGBW LEDs, calculating the possible contributions of each component to obtain a specific shade of white light with coordinates on the Planckian loci of the CIE x, y chromaticity diagram according to the algorithm proposed by the authors (Fig. 1) is not an intricate problem. In this case, the dependences of the luminous efficacy and CCT on the ratio of the contributions of the white and color components (Fig. 2), as well as the dependences of CRI and Rf on the luminous efficacy (Figs. 3 and 4) can be obtained with any needed quantity of points for these curves. This, in turn, makes it easy to analyze the CCT ranges in which, for different sets of RGBW components, it is possible to implement illumination not lower than a certain efficacy, or vice versa, to analyze the SLS's luminous efficacy range while ensuring the quality of light is not lower than certain CRI and Rf values. In other words, it is possible to full analyze the potential of the RGBW system, depending on the priority of certain requirements criteria to luminous efficacy and color quality. To get higher values of color rendering and luminous efficacy, it is possible to use the base white LED with higher CRI, Rf, and luminous efficacy values, choose a near-white LED (e.g., lime), or add more colored LEDs.

4 Conclusions

Three 4-component RGBW systems with different white LEDs are considered and compared. Conditions to get the resulting white light with the desired combination of high color rendering and luminous efficacy are considered. This paper offers two approaches for choosing the LED contributions for any RGBW system: (1) the approach based on the maximum color rendering values and (2) prioritizing to reduce color rendering by 1 to 6 units of the maximum to increase luminous efficacy by 3% to 7%. For systems with WW LED, the third way is possible, when the choice of a constant value of RGB contribution and luminous efficacy while maintaining high CRI (above 91) in the CCT range of 3500 to 6000 K. In this case, the control scheme is simplified. In the absent of an unambiguous regularity in the dependence of color rendering on luminous efficacy and CCT, it is necessary to study each selected LED set to determine the conditions to get the high CRI, Rf, and luminous efficacy values simultaneously.

The base warm white LED is the most promising for use in RGBW systems in comparison to neutral and cold white LED. Thus the considered RGBW system with WW LED shows an increase in CRI of WW LED from 82 by 11 to 13 units and lower increase in Rf from 83 by 7 to 10 units in the CCT range 3000 to 7000 K. The results will help luminaire manufacturers and designers to choose the optimal LED and criterion for obtaining white light to create an efficient SLS.

Comparison of the CIE CRI and IES Rf methods showed that despite the difference in numerical values, their dependences on the CCT, LED contribution, and efficacy are similar. For each set of LEDs, it is possible to determine their optimal brightness ratio using any of these metrics.

Acknowledgments

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