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White Colour Hues in Displays and Lighting Systems Based on RGB and RGBW LEDs

Andrii Rybalochka
National Academy of Sciences of Ukraine / V.E. Lashkaryov Institute of Semiconductor Physics, Kyiv, Ukraine
Email: andriy.rybalochka@gmail.com

Vasyl Kornaga
National Academy of Sciences of Ukraine / V.E. Lashkaryov Institute of Semiconductor Physics, Kyiv, Ukraine
Email: vasyak1284@gmail.com

Daria Kalustova
National Academy of Sciences of Ukraine / V.E. Lashkaryov Institute of Semiconductor Physics, Kyiv, Ukraine
Email: dariakalustova@gmail.com

Vadym Mukhin
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute," Kyiv, Ukraine
Email: v_mukhin@i.ua

Yaroslav Kornaga
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute," Kyiv, Ukraine
Email: slovyan_k@ukr.net

Valerii Zavgorodnii
State University of Infrastructure and Technologies, Kyiv, Ukraine
E-mail: zavgorodniivalerii@gmail.com

Sergiy Valyukh
Linköping University, Department of Physics, Chemistry, and Biology, Linköping, Sweden
Email: sergiy.valyukh@liu.se

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Abstract: In this paper, aspects of obtaining white colour hues for displays/monitors and lighting by using three- and four-components LED systems are discussed. Photometric equipment developed by us for multichannel LEDs control is used in an experimental study to verify theoretical calculations. Three-component RGB and four-component RGBW LED systems, which utilise the same RGB light sources and two white LEDs with warm and cold hues, are investigated. Results of testing of luminous efficacy of such systems at different values of light intensity and comparison of the corresponding circadian action factor as the value of impact of summarized RGB and RGBW white light on human circadian rhythms are presented. It is demonstrated that the four-component RGBW LED systems are more preferable for lighting and displays than the three-components RGB LED systems, because of significant higher luminous efficacy and slightly lower circadian factor over the entire range of correlated colour temperature from 2500K to 7000K studied.

Index Terms: Lighting system, RGB, RGBW, LED display, hues of white, multichannel LEDs control facility.

1. Introduction

Although displays and monitors have much in common with artificial lighting systems in terms of obtaining and displaying hues of white colour, they also have a significant difference. It is primarily a way to get light into the human eye from display devices and lighting systems. A lot of efforts are directed to the improvement of artificial lighting systems. One of the main tasks is to create conditions as close to natural light sources as possible [1]. In contrast to lighting, which is used to form a light field reflected from observed objects, the majority of displays themselves are light sources. [2-4]. At the same time, it should be noted that there is a large class of reflective displays that work on different physical principles and that require external illumination [5]. Their advantage is energy efficiency. Moreover, some of them can store images without consuming energy at all and require power only to rewrite it [6,7]. But displays of this type have a limited scope, they are not suitable for displaying a large number of colours and dynamic scenes. Consideration of them is out of this work purposes.

Our focus is systems of external artificial lighting so that the intensity of light reflected from surrounding objects is sufficient for the human eye in daylight mode, when the receptors of human colour perception are involved. In this case, a display can be considered as a system that emits light in a multipixel and multicolor mode.

The following requirement can be formulated for displaying hues of white: the total light from RGB or from RGBW LEDs must correspond to the selected coordinates of white colour hues on the chromatic diagram. It should be noted that the use of RGB LEDs allows only unambiguous determination of the proportions between these components to obtain any colour coordinate in the RGB triangle on the chromatic diagram [1]. Therefore, all other spectral, photometric, energy characteristics of the corresponding total spectrum of radiation have certain constant and unambiguous parameters. Adding a white LED to such a system removes this ambiguity and significantly expands the possibilities of obtaining in RGBW displays a colour with any colour coordinates (including hues of white) [8]. It is possible to obtain an infinite number of spectral power distributions that will correspond to one coordinate on the chromatic diagram, but will have a difference in its saturation and purity (which is not very important when displaying hues of white along the Planck curve) and energy efficiency of its display. That is, the use of RGBW systems in displays makes it possible to find the optimal ratio between the components of RGBW to display white colour hues with maximum energy efficiency, which is especially important for mobile display devices.

For all artificial lighting systems, including LED, one of the most important tasks is to create lighting with spectral power distributions of white colour hues as close as possible to the parameters of the daylight of the same hue. One of the main required parameters of light is the colour rendering index (CRI), which is a quantitative characteristic of the ability to correctly reproduce the colours of illuminated objects or images by artificial lighting compared to natural one with the same hue of white [9]. The implementation of lighting systems based on RGB LEDs has shown its low efficiency. It is clear that the accuracy of colour in terms of chromaticity coordinates in the CIE (the International Commission on Illumination) x, y chromaticity diagram is similar to RGB display systems, but the CRI of 30-50 (with a maximum of 100) makes them unacceptable for use in artificial lighting systems. For ordinary household and office needs, the value of this parameter should be at least 80, and for many medical, some special technical, as well as for a wide range of artistic and aesthetic needs at least 90-95 [10,11]. In this case, you can get LED lighting systems with the ability to dynamically change the integral value of the white colour hue with the help of "Dynamic White" technology which uses the principle of mixing two white colours with different correlated colour temperatures (CCT) [2,12]. But adding a white LED to RGB LED lighting systems greatly expands its capabilities. In RGBW LED lighting systems it is possible to implement a number of algorithms for optimizing white parameters both in terms of luminous efficacy and in terms of significantly increasing the values of the CRI to values greater than 90 in a wide range of CCT [2,13-15].

It should be noted that the human eye is a detector of electromagnetic radiation in the visible wavelength range, which consists of receptors for both visual and non-visual perception of light. That is, there are certain receptors of the so-called circadian perception of light, which monitor the "dose" (component) of the shortwave component in the range of circadian sensitivity of the respective receptors relative to the total light effect on colour perception receptors [16-19]. In the vast majority of cases for artificial light sources such as incandescent lamps, gas-discharge fluorescent lamps, LED lamps of various types, the circadian influence on the intensity of photometric light perception is almost linearly increasing from the CCT of white light, as well as for the natural one [20]. Moreover, usually the intensity of the circadian effect of artificial lighting on human circadian rhythms is commensurate with the influence of daylight of the same hue of white. It follows that an important task in creating artificial light sources and displays is to meet the "lighting hygiene" requirements, which are in accordance with the white colour hue of an artificial source to the relevant natural indicators depending on the time of day. Generally it can be formulated as a preference for warm white colour hues (not more than 3000 - 3500K) in the evening, night and early morning times. During the daytime, on the contrary, for a healthy adult it is possible and necessary to increase the correlated color temperature of white colour to 5000K and above, given that light with its values of 7000 - 8000 K should be analyzed in terms of physical harm for the organs of vision for a long time with a long duration and intensity of its influence on them. To meet these requirements, in both lighting systems and display devices they create gadgets with the ability to dynamically change white colour hues in manual or automatic modes. For example, special function, which consists in changing the hue of white from cold to warm tones in the evening and at night, has been widely implemented in mobile displays for a number of manufacturers for several years.

This paper will present the results of using a number of algorithms for obtaining white colour for lighting systems and display devices based on three-component RGB and four-component RGBW systems, which use the same RGB components and two white LEDs with warm and cold hues for RGBW system. The experimentally obtained electrical and light characteristics of each LED component of RGB and RGBW systems will be presented, and based on them the parameters of luminous efficacy and components of circadian impact on humans in obtaining white light hues in the range from 3000 K to 7000 K for RGB and RGBW systems will be analyzed. The experimental part was realized with the help of our multichannel LEDs control facility [21].

2. Research Equipment and Methods

The paper [21] presents a system of group LEDs control, which we developed to study methods of colour mixing using different types of LEDs (Fig. 1). This system can be used to study LEDs based on which boards (displays) or lighting systems are developed.

Fig. 1. Multichannel LEDs control facility.

The system has 8 independent channels. The current on each of the eight channels can be set in DC mode and PM mode in the range from 0 mA to 1000 mA with 1 mA interval. Maximum voltage at the output of one channel is 18 V. Automation of measurement is performed by connecting the layout to a computer via RS232, which provides a node to change the levels of signals UART/RS-232. The system implements feedback through the control of the current value of the output current in each channel. Management of the developed system is possible both through specialized programs when connected to a personal computer, and in offline mode without the use of a PC through available physical control buttons. Management when using a computer involves setting current values for each channel through specialized programs and selecting channels to be enabled. In the offline mode, the system can be configured using the available buttons.

Since this system is integrated into a lighting parameters measuring complex, which consists of an integrating sphere, spectrophotometer and computer, it is important that the measuring system allows automatically determining the dependence of LED brightness and spectral characteristics of current and supply voltage. To do this, the system was improved (Fig. 2), which is based on the use of the synchronizing output of the spectroradiometer, the signal from which carries information about the completion of the spectral power distribution measurement. This allows the multichannel LEDs control facility to automatically change the current on the LED when the measurement is completed and start a new measurement. During this time, the data on supply voltage and current are transmitted to the computer via RS232.

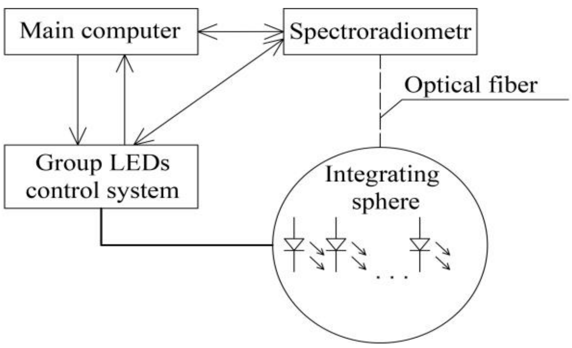

Fig. 2. Block diagram of the integration of the multichannel LEDs control facility into the measuring complex.

This improvement allows you to automatically measure the spectral characteristics in the range of specified currents with a given interval. That allows to reduce during LEDs characteristics research and to expand possibilities of a measuring complex.

Measurement of electrical, light and colour parameters is performed using a specialized measuring system (Fig. 3), which consists of a spectrometer "HAAS-2000" and an integrating photometric sphere (internal diameter 0.3 m) manufactured by EVERFINE Corporation, and power supply direct current.

Fig. 3. Photograph of the complex for measuring the parameters of LEDs.

Research methodology:

1. Measurement of electrical, light and colour parameters of individual LEDs in a forward current range of 1 – 350 mA and CCT range of 2500 – 7000 K using a measuring complex (Fig.3) with an integrated multichannel LEDs control facility (Fig.2). The complex measures spectral power distribution of each LED in the wavelength range of 380 – 780 nm with a 1 nm step and then calculates the light and colour parameters. The measurements were carried out for each given forward current with a 1 mA interval. The integrated multichannel LEDs control facility allows optimizing this process.

2. Investigation of the parameters of the resulting light of the three-component RGB system (red / green / blue). The resulting chromaticity coordinates (X, Y, Z) of such a system can be uniquely expressed as:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

where the matrix elements are the chromaticity coordinates of the LEDs [9], and R, G, and B are the brightness of the LEDs. This procedure allows you to find the area in the CIE x, y chromaticity diagram (through normalization, z = 1 - x - y), within which the colour changes due to changes in the brightness of the LEDs (R, G and B), i.e. their contributions to the resulting light. The contributions of LED components (their brightness) are uniquely determined for each selected CCT (from 2500 to 7000K). Then their forward current is determined, considering into account the corrections from the obtained for each LED ampere-luminance characteristics. This allows measuring the electrical, light and colouring parameters of the resulting light of the RGB system using the measuring complex and the integrated multichannel LEDs control facility.

3. Investigation of the parameters of the resulting light of two four-component systems with different basic white LEDs - RGB-WW (red / green / blue / warm white) and RGB-CW (red / green / blue / cold white). When using four LEDs, the definition of their contributions to the resulting light is ambiguous and light with certain specified chromaticity coordinates can be obtained in many ways. Therefore, the imposition of an additional condition is required. We have chosen the condition of minimization the contribution of colour RGB LEDs [13], assuming that reducing the contribution of less efficient LEDs should increase the luminous efficacy of the resulting light. Thus, the resulting chromaticity coordinates can be unambiguously determined as follows:

$$\begin{cases} X = RX_R + GX_G + BX_B + WX_W \\ Y = RY_R + GY_G + BY_B + WY_W \\ Z = RZ_R + GZ_G + BZ_B + WZ_W \\ \frac{R+G+B}{R+G+B+W} = min \end{cases} \quad (2)$$

where W is the white LED brightness. When using this method, the parameters of the resulting light of RGB-WW and RGB-CW systems are measured. This is carried out according to the algorithm described in the first two stages.

4. Comparison of light and circadian parameters of the resulting light of the three studied systems (RGB, RGB-WW and RGB-CW) obtained at the second and third stages. Comparison include following dependences: luminous efficacy vs CCT, colour rendering index vs CCT, circadian action factor vs CCT. For the analysis, several fixed values of the luminous flux are selected for all CCT due to the change of LED parameters when the forward current changes. The chosen values of the luminous flux are 50 lm and 100 lm. Analysis and comparison of the considered systems allows choosing the most optimal system depending on the scope and tasks.

3. Results and discussion

Three LED systems were studied: RGB, RGB-WW and RGB-CW. All systems used the same colour RGB LEDs manufactured by Cree Inc. The WW and CW white LEDs were manufactured by LG Innotek and Seoul Semiconductor Co Ltd, respectively. Table 1 shows the parameters of LEDs (chromaticity coordinates, peak wavelength Lp, correlated color temperature (CCT, K) and luminous efficacy (η, lm/W)) when powered by a direct current of 100mA. Spectral power distributions were measured in the wavelength range 380 - 780 nm. The corresponding normalized spectral power distributions are presented in Fig.4.

Table 1. Parameters of R, G, B, WW, CW LEDs at forward current of 100mA

	X	y	Lp, nm	CCT, K	η, lm/W
R	0,693	0,307	630	-	92
G	0,178	0,733	521	-	155
B	0,149	0,030	453	-	22
WW	0,434	0,404	-	3057	163
CW	0,346	0,362	-	5020	170

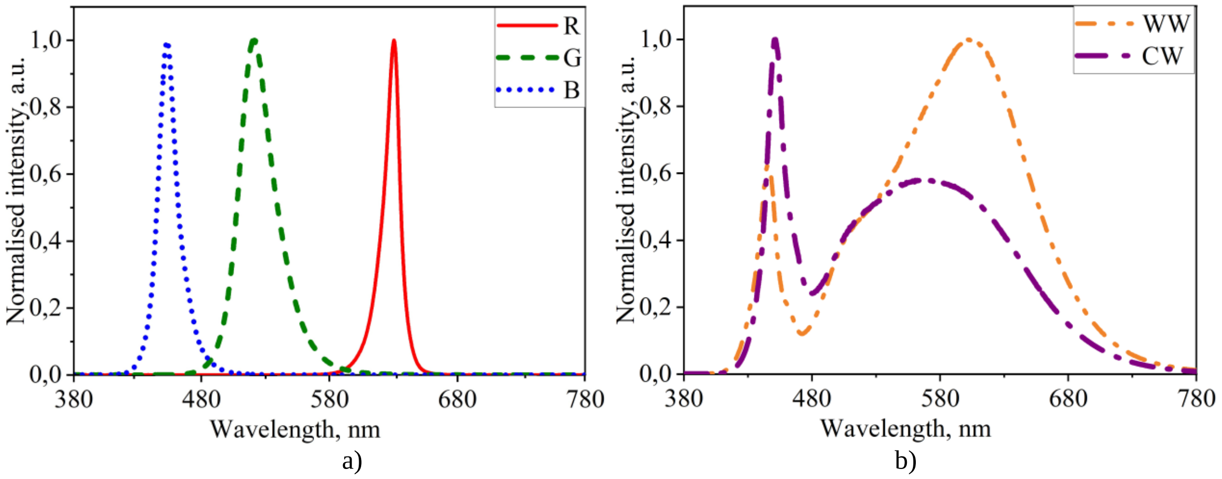

Fig.4. Normalized spectral power distributions of colour R, G, B LEDs (a) and WW, CW LEDs (b).

The selected colour LEDs form a Maxwell triangle in the CIE x, y chromaticity diagram, which fully covers the colour gamut of the current international standard sRGB [22], as well as Adobe RGB from Adobe Systems [23] and NTSC from the National Television Standards Committee (Table 2).

Table 2. Gamut area coverage for RGB LEDs

Gamut	Coverage, %
sRGB	100.0
Adobe RGB 98	99.9
NTSC (1953)	98.4
NTSC (1987) SMPTE C	100.0

On Fig.5. corresponding areas in the CIE x, y chromaticity diagram for the selected RGB colour LEDs compared to sRGB and Adobe RGB are presented. For all five LEDs used, light and colour parameters were measured in the range of forward currents from 0 mA to 350 mA with 1mA interval. The corresponding volt-ampere characteristics are shown in Fig.6 and ampere-luminance characteristics are shown in Fig.7. The lighting characteristics of green and white LEDs are the most sensitive to changes in forward current, and they have the greatest impact on the parameters of the resulting light. These relationships are important to consider when calculating the contributions of LED components to the resulting light and their forward currents. It is needed to avoid large deviations between theoretical and actual parameters of the resulting light.

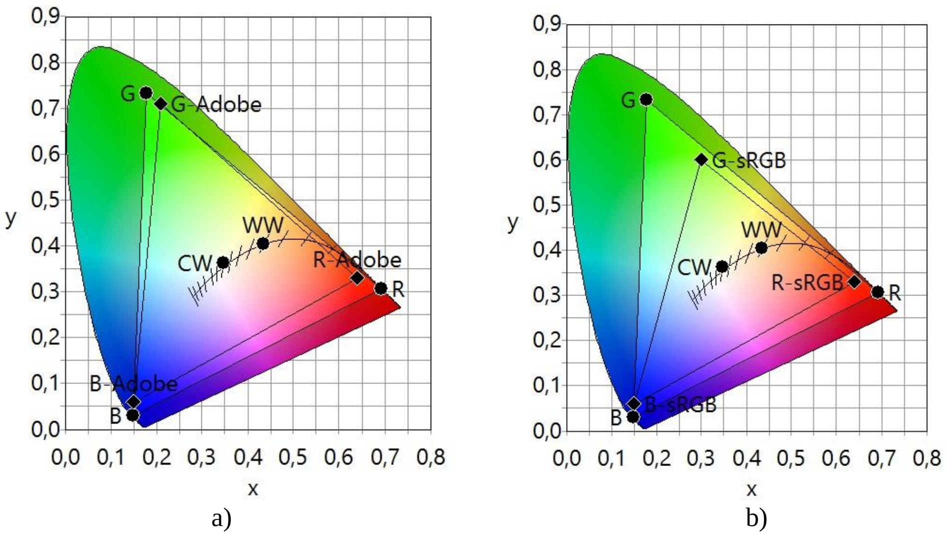

Fig. 5. Colour triangles for the set of RGB LEDs compared to Adobe RGB (a) and sRGB (b).

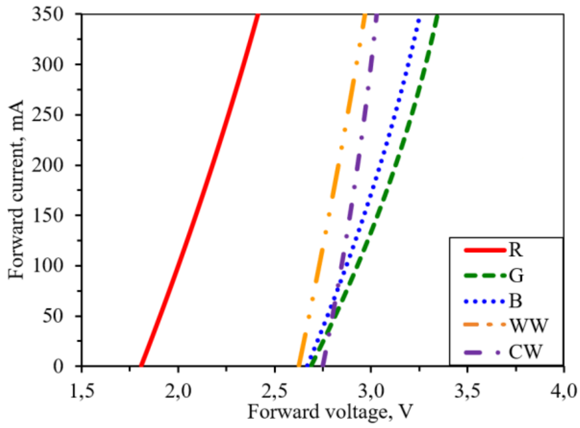

Fig.6. Volt-ampere characteristics of R, G, B, WW and CW LEDs.

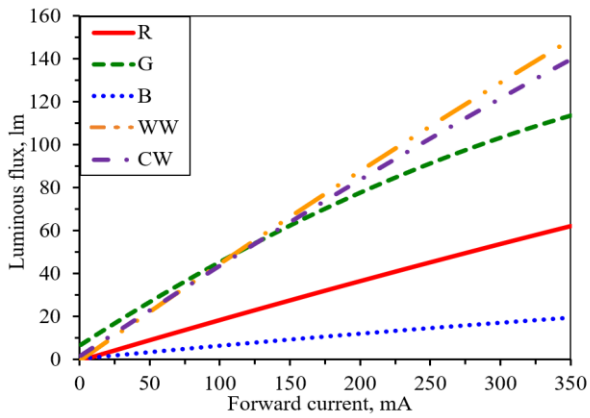

Fig.7. Dependence of luminous flux on forward current for R, G, B, WW, CW LEDs.

Because energy efficiency parameters of the systems are important, the dependence of luminous efficacy on CCT was measured for all three considered systems in the range from 2500 to 7000K. For the example, the points of the resulting light (chromaticity coordinates) were chosen along the Planck curve. The parameters of the LEDs change when the forward current changes, so the luminous efficacy of the resulting light will change at different total intensity / luminous flux. In view of this, the comparison of luminous efficacy was carried out at fixed values of the luminous flux of the resulting light for all CCT, namely 50 lm (Fig.8a) and 100lm (Fig. 8b). The obtained dependences for four-component systems have a similar nature and similar values of luminous efficacy. In both cases, the RGB system showed significantly lower efficiency, namely up to 24% and 27% less than the RGB-WW and RGB-CW systems at 50lm, respectively, and up to 30% and 32% at 100lm. This is due to the chosen condition of minimization the contribution of the colour component, in which the largest contribution is made by a white LED with higher luminous efficacy than R, G, B LEDs.

The luminous efficacy of the RGB system depends more on the contributions of individual LEDs to the resulting light than the RGB-WW and RGB-CW systems. This is due to the fact that the change in forward current has the strongest effect on the light parameters of the green LED system in our operating range. Thus, when changing the total luminous flux from 50 to 100 lm, the luminous efficacy of RGB, RGB-WW and RGB-CW systems decreased by an average of 13%, 4.3% and 6.5%, respectively. The luminous efficacy of the resulting light of the RGB-CW system showed the highest values of luminous efficacy in most of the considered CCT range and this trend will continue at higher CCT. The value of its luminous efficacy is 134 - 164 lm/W at a total luminous flux of 50 lm and 123 - 153 lm/W at 100 lm. Thus, the RGB-CW system is the most effective among the considered systems for use in displays.

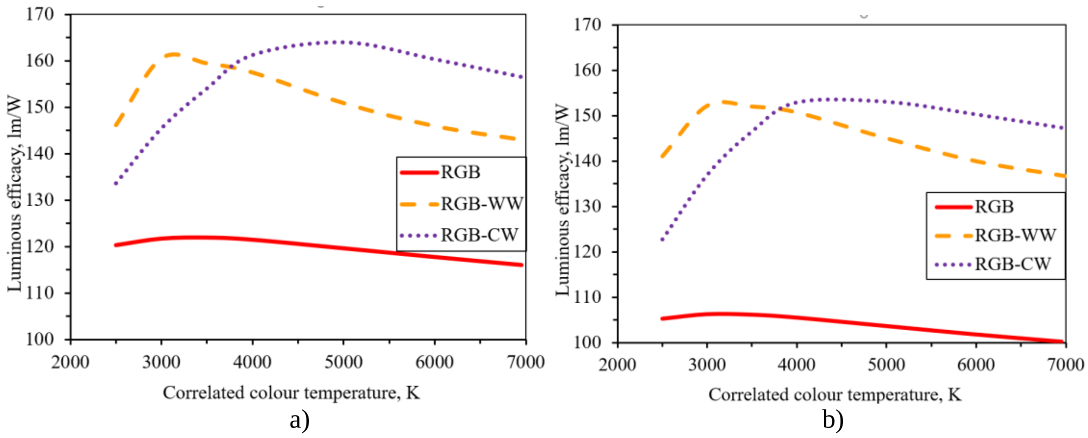

Fig.8. Dependence of luminous efficacy on correlated colour temperature for RGB, RGB-WW, RGB-CW systems at luminous flux of 50 lm (a) and 100 lm (b).

Additionally, the dependence of the CRI on the CCT for the three considered systems is shown (Fig. 9). Although this setting is not a priority for displays, it is important for lighting systems. It is less than 43 for the RGB system, 77–93 for the RGB-WW system and 43–91 for the RGB-CW system. In the case of a system with a warm white LED, the colour rendering index changes less in the considered CCT range than in a system with a cold white LED, because in the last one you need to significantly increase the contribution of red and green LEDs to obtain the resulting light 2500 – 3500K.

Thus, when creating lighting systems, systems with warm white LEDs are more optimal in terms of the quality of the resulting light, while for displays it is better to use systems with cold white LEDs given their high energy efficiency.

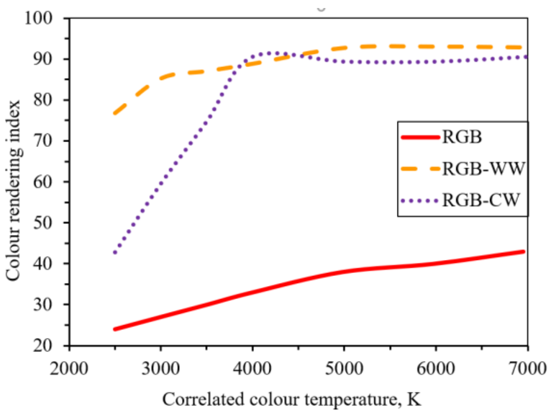

Fig.9. Dependence of colour rendering index on correlated colour temperature for RGB, RGB-WW, RGB-CW systems.

The circadian action factor a_{CV} was calculated for the three considered systems. It is the ratio of the integrals of circadian and photometric functions (visual and non-visual influence):

$$a_{CV} = \frac{\int_{380}^{780} V(\lambda)P(\lambda)d\lambda}{\int_{380}^{780} c(\lambda)P(\lambda)d\lambda} \tag{3}$$

where *V(λ)* is the photopic luminous efficiency function, *c*(λ) is the circadian spectral sensitivity according to the model of Rea et al. [24], *P(λ)* is the spectral power distributions of the resulting light. The corresponding a_{CV} parameters for different CCT are shown in Fig.10. There is an almost linear dependence of the circadian action factor on the CCT. At the same time for the RGB system its values are higher than for the RGB-WW and RGB-CW systems by 1.1 - 1.3 times in the whole considered range. Thus, systems with white LEDs have less effect on human circadian rhythms.

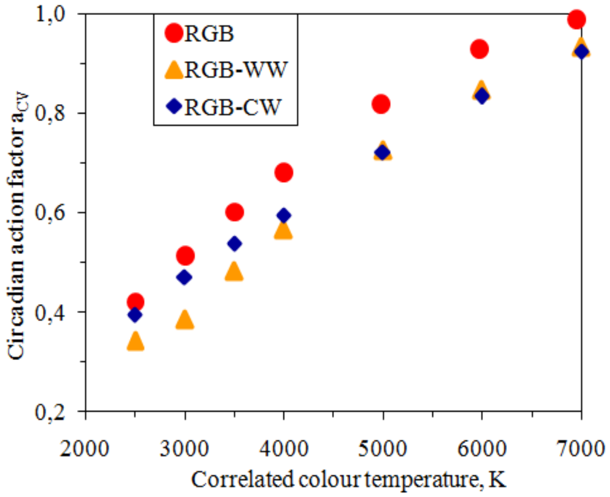

Fig.10. Dependence of circadian action factor (aCV) on correlated colour temperature for three systems: RGB, RGB-WW, RGB-CW.

4. Conclusions

The paper is devoted to comparison of three LED systems (RGB, RGB-WW, RGB-CW) for both lighting and displays. The comparison is carried out by a using a multichannel LEDs control facility developed by us with minimization the contribution of the colour RGB LEDs in four-component systems based on warm white LED (RGB-WW) and on cold white LED (RGB-CW LED). Analysis of luminous efficacy and circadian factor for resulting light for these three LED systems is realized in the range of CCT from 2500K to 7000K for two values of total luminous flux: 50 lm and 100 lm.

The three-component RGB system shows the lowest luminous efficacy (the maximal value is slightly above 120 lm/W) and lowest colour rendering index (less than 43) among the considered three LED systems. In addition, the RGB system has a 10-30% greater impact on human circadian rhythms in comparison with the RGB-WW and RGB-CW systems.

The four-component RGB-WW system allows obtaining the luminous efficacy of the resulting white light around 143 – 160 lm/W at the total luminous flux of 50 lm and 137 – 152 lm/W at 100 lm. It is very similar to the analogous parameters of the four-component RGB-CW system: 134 – 164 lm/W at 50 lm and 123 – 153 lm/W at 100 lm, respectively. However, investigation of dependences of the CRI on the CCT (that is not a priority for displays, but it is important for lighting) for the four-component systems gives the following result: 77 –93 for the RGB-WW system and 43 – 91 for the RGB-CW system. Also, the RGB-WW system has the same or lower impact on human circadian rhythms in corresponding to the RGB-CW system. Thus the four-component RGB-WW system gives the best possibility for realization of white colour hues for both displays and lighting applications.

Further research will be aimed at exploring the possibility of using the three-component RGB systems for lighting with phosphor LEDs having a blue crystal base. Colour spectra with emission spectra by one and a half - two times wider band as in usual colour LEDs may will gives possibility to increase the colour rendering index up to values for the four-component systems with a decrease in the number of control channels. On the other hand, a study for the four-component LED systems is planned with involving different colour mixing algorithms, as well as replacing the RGB components on LEDs with other dominant wavelengths.

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Authors’ Profiles

Andrii Rybalochka received his PhD from V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine (ISP NASU) in 2009. Defense of thesis “Two-levels Drive Schemes for Bistable Cholesteric Liquid Crystal Displays”, specialty – optoelectronic systems. Since 2012, he has been the head of Semiconductor Lighting Test Centre (SLTC) in ISP NASU. Since 2015, the SLTC has been an accredited conformity assessment body according to DSTU ISO/IEC 17025. In 2016, Laureate of the Ukraine State Prize in the field of science and technology for work “Energy efficient LED Lighting Systems”.

His research interests include metrology, display and lighting technologies, and physics of liquid crystals. ORCID: https://orcid.org/0000-0002-4214-3654. E-mail: andriy.rybalochka@gmail.com.

Vasyl Kornaga received his PhD from V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine (ISP NASU) in 2017. He held a position as a research fellow from 2014 to 2019 and has been a senior research fellow since 2019 at the ISP NASU. In 2016, Laureate of the Ukraine State Prize in the field of science and technology for work "Energy efficient LED Lighting Systems".

His research interests include intelligent lighting systems, lighting plants, metrology, microelectronics, and optoelectronics. ORCID: https://orcid.org/0000-0002-4256-9647. E-mail: vasyak1284@gmail.com.

Daria Kalustova received her PhD (field of study 17 - Electronics and telecommunications) in 2021 from V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine (ISP NASU). She is researcher at the Department of Optoelectronics of ISP NASU.

Her current research interests include tunable lighting, smart lighting, and metrology ORCID: https://orcid.org/0000-0002-9503-3934. E-mail: dariakalustova@gmail.com.

Vadym Mukhin: Chair of system design department of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Doct. of Sc. Born on November 1, 1971. M. Sc. (1994), PhD (1997), Doct. of Sc. (2015) from the National Technical University of Ukraine ― Kiev Polytechnic Institute‖; Assoc. Prof. (2000), Professor (2015). Major Interest: the security of distributed computer systems and risk analysis; design of the information security systems; mechanisms for the adaptive security control in distributed computing systems; the security policy development for the computer systems and networks.

ORCID: https://orcid.org/0000-0002-1206-9131. E-mail: v_mukhin@i.ua.

Yaroslav Kornaga: Professor of Information Systems and Technologies department of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Doct. of Sc. Born on January 1, 1982. M. Sc. (2005), PhD (2015), Doct. of Sc. (2020) from State University of Telecommunications; Prof. (2020) of Information Systems and Technologies Department. Major interest: the security of distributed database and risk analysis; design of the distributed database; mechanisms for the adaptive decurity control in distributed data.

ORCID: https://orcid.org/0000-0001-9768-2615. E-mail: slovyan_k@ukr.net.

Valerii Zavgorodnii: Head of Department of the Information Technologies and Design of the State University of Infrastructure and Technologies, Ukraine, Kyiv, Doct. of Sc.

Born on May 25, 1982. PhD (2013), Assoc. Prof. (2015) of Department of Systems Software, Doct. of Sc. (2021) from the State University of Telecommunications.

Major interests: information technologies, databases, decision support systems, introduction of Information and communication technology in the educational process.

ORCID: https://orcid.org/0000-0001-9768-2615. E-mail: zavgorodniivalerii@gmail.com.

Sergiy Valyukh received his PhD from Taras Shevchenko National University of Kyiv in 2003 and was a postdoctoral at Dalarna University and Swedish LCD Center AB, Borlänge, Sweden. Several times between 2005 and 2014, he was a visiting researcher at Hong Kong University of Science and Technology. Since 2010, he has conducted research at Linköping University, Sweden. Since 2019, he is a visiting professor at Shanghai University.

His research interests include optical simulations and measurements.

ORCID: https://orcid.org/0000-0002-5966-590X. E-mail: sergiy.valyukh@liu.se.

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