СЕКЦИЯ 3. СВЕТОИЗЛУЧАЮЩИЕ ПРИБОРЫ И СТРУКТУРЫ

http://dx.doi.org/10.35596/1729-7648-2019-125-7-39-45

Оригинальная статья
Original paper

UDC 628.981

COLOR AND SPECTRAL CHARACTERISTICS OF WHITE LIGHT EMITTING DIODES AND THEIR VARIATION DURING AGING

ALEXANDER L. GURSKII[1], MIKALAI V. MASHEDA[2]

[1]Belarusian State University of Informatics and Radioelectronics, Minsk, Republic of Belarus
[2]BELLIS Testing and Certification of Home Appliances and Industrial Products, Minsk, Republic of Belarus

Submitted 31 October 2019

Abstract. The relation between numerical values of photometric characteristics (total luminous flux TLF, correlated color temperature CCT, color rendering index CRI) of white light emitting diodes (LED) and the variation of the spectral shape of their radiation during aging has been investigated. All the measurements were made on internationally adopted test methods, taking into account environmental conditions, electrical parameters and evaluated measurement uncertainty. Every piece of test and measurement equipment has actual verification or calibration with traceability to national and international references. It was demonstrated that in the luminescence spectra consisting of the "blue" band around 450 nm originating from the semiconductor heterostructure, and the broad "yellow" band from luminophor, the last band is non-elementary and consists of at least two bands: the "green" one around 530 nm and the "orange" one around 580 nm. The most unstable "green" band has the highest impact on photometric characteristics. As a consequence, further investigation should be performed on how instability of elementary bands and its quantity will link not only with photometric characteristics, but with production conditions and material properties of LED heterostructure and luminophor itself. In particular, for improvement of the color stability of white LED, the parameters of luminophor forming the "green" band should be stabilized. A unified method for accelerated testing of LED products and method for long-time lifetime prediction shall be developed, taking into account not only depreciation of TLF, but also shift of other photometric and spectral characteristics of white LED.

Keywords: LED aging, color characteristics, spectral variation, spectra, color temperature, luminous flux, color rendering index.

Conflict of interests. The authors declare no conflict of interests.

For citation. Gurskii A.L., Masheda M.V. Color and spectral characteristics of white light emitting diodes and their variation during aging. Doklady BGUIR. 2019; 7(125): 39-45.

Introduction

White light emitting diodes (LEDs) are widely used for liquid crystal display (LCD) backlighting, including low cost color displays. It is essential for these LEDs to provide stable characteristics through life cycle, including luminous flux, chromaticity and color rendering. Therefore, care shall be taken for LED aging (including degradation of luminophor coating), because intense degradation will cause invalid color perception, especially when using common bichromatic white LEDs as backlight source.

Currently, there is not any unified approach for measurement of LEDs photometric and life characteristics. For example, there is international standard for performance requirements of LED modules IEC 62717, at the same time, Europe adopted standard EN 13032-4 and Illuminating Engineering Society developed for United States a separate standard LM-80-15. Therefore, without unified test method it is difficult to achieve the same results within different test houses and provide peer conformity assessment. Although a lot of work was devoted to the white led degradation problems (see for example reviews [1, 2] and the book [3]), the information about the relations between the photometric (especially colorimetric) parameters and spectral shape of luminescence bands forming white light is still insufficient.

In this work, the change of colorimetric and spectral parameters during aging of some white LEDs was investigated. Experimental results and analysis of the drift of some photometric and spectral characteristics of white LED lamps within time and under impact of additional thermal and electrical acceleration factors are described, with the aim to obtain more information about the relation between the colorimetric and spectral data.

Experimental details

For experiment, a set of Philips white LEDs was used and several accelerating factors were applied, namely aging in normal work regime for 6000 h; normal work at 50 °C for 1000 h; switching cycles of power supply (70000 cycles of 10 seconds).

Selection of number of samples is based on provisions of cl. 4.1.2 IES TM-28-14.

Within these tests, several parameters were measured, namely total luminous flux (TLF); chromaticity coordinates; correlated color temperature (CCT); color rendering index (CRI) and the luminescence spectra of LEDs under study. Measurements were carried out using Bentham Integrating sphere IS1800 with Bentham IDR300-PSL double monochromator-spectroradiometer. LEDs under study were supplied using stabilized power source Extech 6720 and controlled with power analyzer Yokogawa WT210. It should be mentioned that all used measurement and testing equipment have actual calibration with traceability to national and international references.

All the acquired data was analyzed and relative extended measurement uncertainty was calculated with provisions of applicable documents: EN 13032-4 and IEC Guide 115.

Results

Photometric characteristics

All types of tests yield clear tendency of decreasing TLF and increasing CCT and CRI during aging. In our experiments, chromaticity coordinates have drift, but still within 6 step Mac-Adam ellipse. The time dependencies of these parameters have some peculiarities depending on accelerating factor used. TLF decreasing is correlated with common practice [1, 4–6] and are usually described with monoexponential or bi-exponential decay curve according to Arrhenius law [2]. At the same time, several experimental results [2, 7] point out initial segment of TLF growth that lead to deviation from both monoexponential and bi-exponential decay laws commonly used, and can be caused by luminophor stabilization, but omitted from long-time prediction of LED life. Experimental data of TLF aging curve can be more accurate approximated with equation taking into account an initial rise of the TLF. For example for TLF time dependence $I(t)$, we propose the following function:

$$I(t)=\left(I_1+\left(1-A\exp\left(-\frac{t}{\tau_1}\right)\right)\right)\left(B\exp\left(-\frac{t}{\tau_2}\right)+C\exp\left(-\frac{t}{\tau_3}\right)\right), \qquad (1)$$

where I_1 is the initial value of TLF, τ_1 is the rise time constant; τ_2 is the fast decay time constant; τ_3 is the slow decay time constant; *A, B,* and *C* are parameters defining contribution of each process in resulting dependence.

An another solution may be to exclude the initial rise area of data from the bi-exponential approximation procedure, as suggested in [7], but this approach neglects some physical processes in LEDs.

In our experiments, TLF was decreased for 15,7 % over 6000 h aging in normal regime, CCT increased for 1,5 % and CRI increased for 1,2 % (see Fig. 1, *a*–*c*). The highest impact on LED chip TLF was shown under normal work at 50 °C for 1000 h: TLF decreased for 4,1 %, while CCT increased for 0,8 % and CRI increased for 0,2 % (see Fig. 2, *a*–*c*).

Additionally, it was investigated how additional stress factors (ambient temperature and switching of power supply) will change color and spectral characteristics of white LEDs.

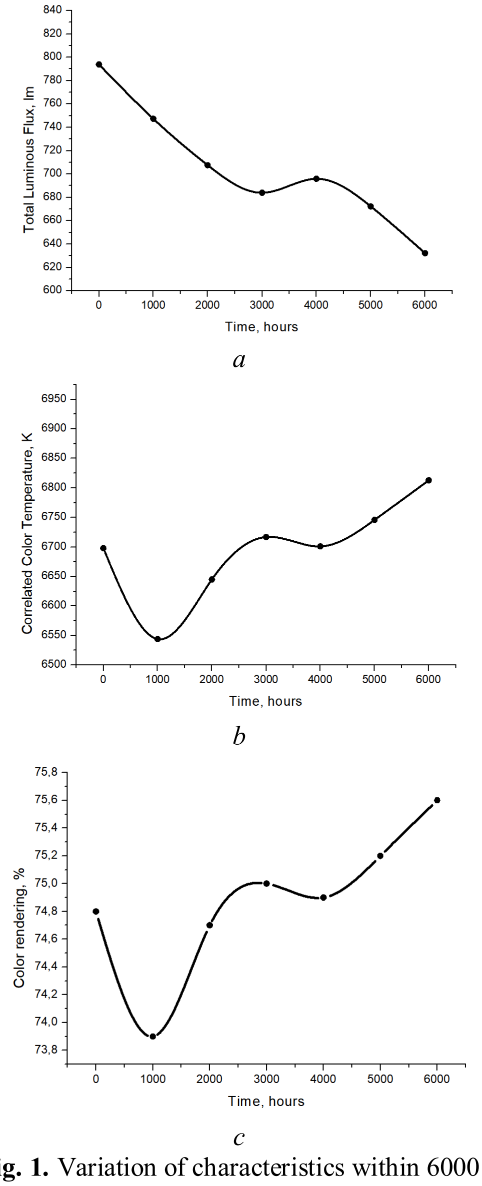


Fig. 1. Variation of characteristics within 6000 h ageing under normal conditions: *a* – total luminous flux; *b* – correlated colour temperature; *c* – colour rendering index

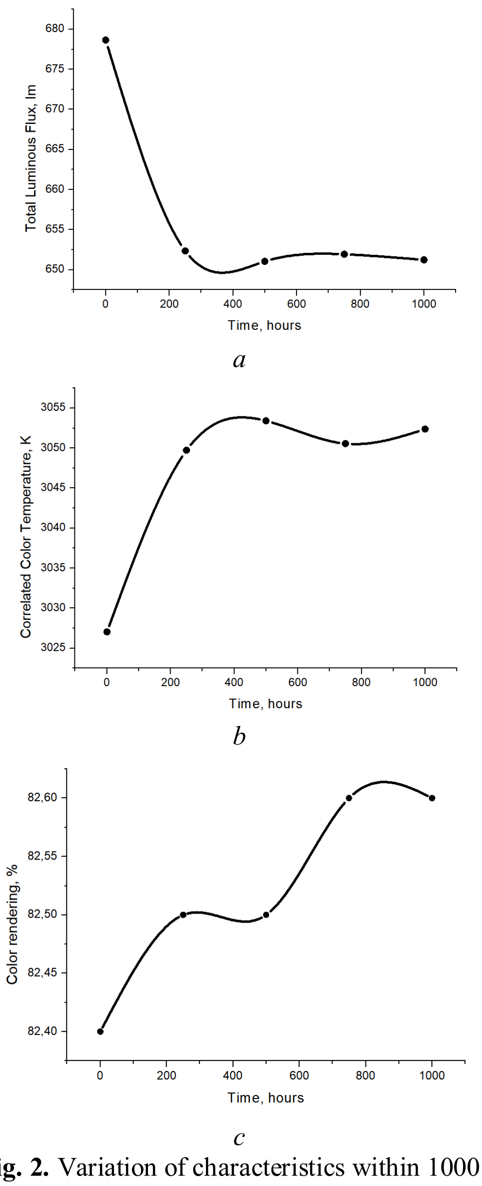


Fig. 2. Variation of characteristics within 1000 h aging at 50 °C temperature: *a* – total luminous flux; *b* – correlated colour temperature; *c* – colour rendering index

Spectral characteristics

At first, it is essential to determine how many bands are forming the summary spectra. It was done using Alentsev-Fok method [8], which allows dividing summary spectrum into separate bands without any a priori information about their shape and number of peaks. Fig. 3, resulting from deconvolution of spectrum using [8], shows that white LED spectra are consisting of at least three bands. Two of them ("blue" and "orange") are almost Gaussian curves, and the third, "green" one has an asymmetrical shape. It can be approximated by two Gaussian curves, and sometimes even one Gaussian curve gives a good approximation (Fig. 4). In common practice, however, only two bands ("blue" and "yellow") are considered [9], in spite of the non-elementary nature of the "yellow" band.

In Figures for spectra, the X scale is wavelength in nm, it will be more accurate to use scale of energy in eV, because of the reciprocal relation between energy and wavelength. However, since the shape of the spectral bands does not change significantly, the presented figures also clearly show expected characteristics, and the integration of spectra does not lead to the significant errors if we compare the relative (not absolute) intensities of the separate bands.

Since measured spectra are not absolute, to compare them, and to define intensity, integration of the initial spectra was performed to make correction and link them to the photometric characteristics (TLF). At the next step it was investigated how separate bands intensity behaves during aging and how it affects photometric characteristics. Fig. 5, *a*, *b* indicates accordingly quasi-absolute and normalized intensity of three bands within white LED spectra during 6000 h aging. Fig. 6, *a*, *b* shows the absolute and normalized intensity of three bands within white LED spectra during 1000 h aging at 50 °C temperature, respectively.

It is seen from Fig. 5, *b* and 6, *b* that while the "orange" band repeats the behaviour of the "blue" one with small deviation, the "green" band around 530 nm demonstrates the most unstable behavior, and, thus, has the most significant impact on the photometric parameters of LEDs.

Fig. 7, *a*, *b* shows variation of relation of "blue" to "yellow" band intensity during 6000 h aging, and during 1000 h aging at 50 °C temperature, accordingly. The comparison of these data with Fig. 1, *b* and Fig. 2, *b*, respectively, demonstrates a good agreement between them, as expected.

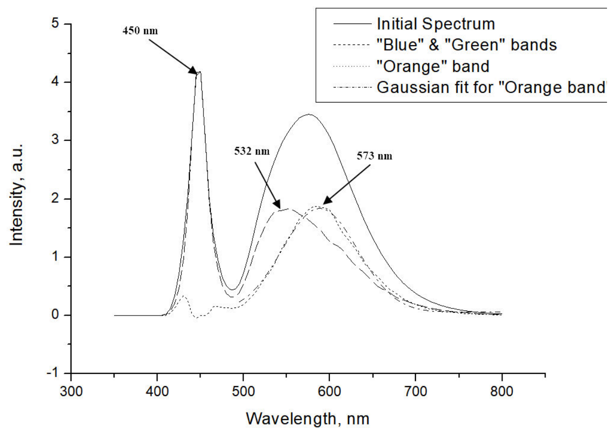


Fig. 3. Result of the Alentsev-Fok method application for deconvolution of the white LED spectra

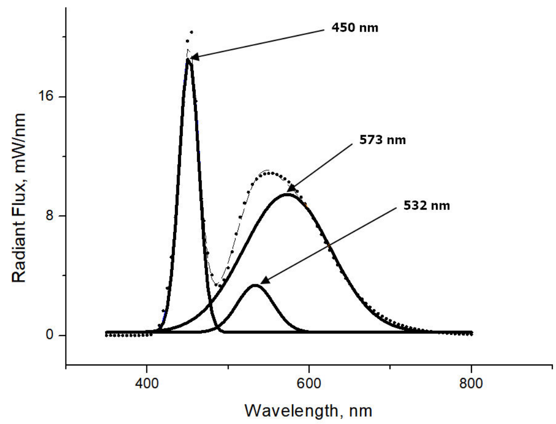
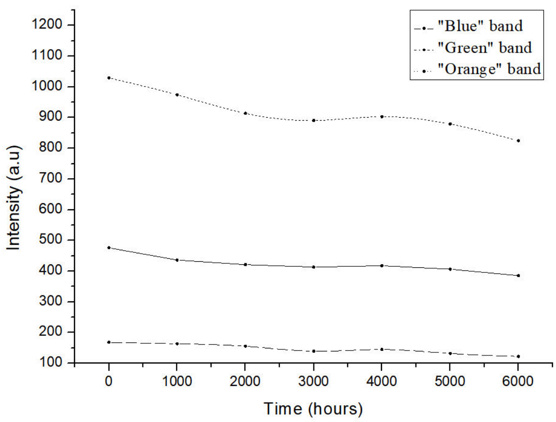
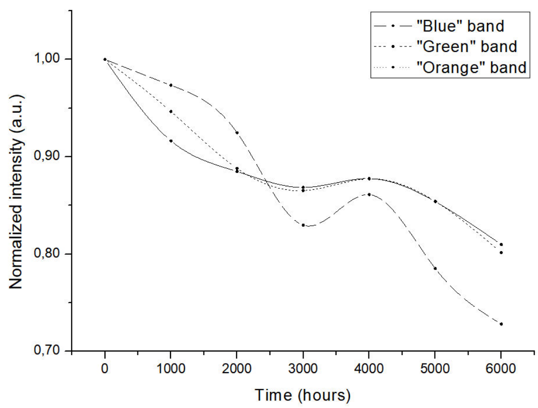


Fig. 4. Result of approximation of the white LED spectra by three Gaussian curves

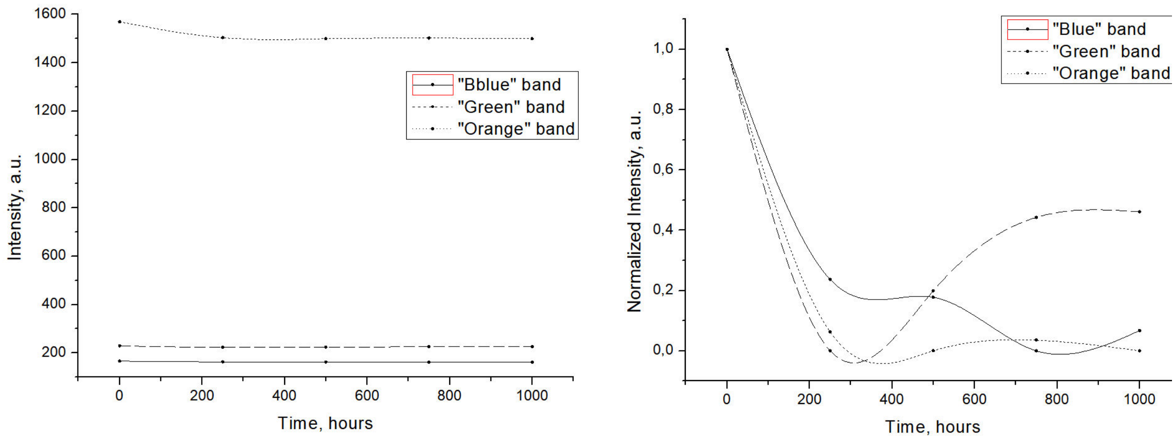


a



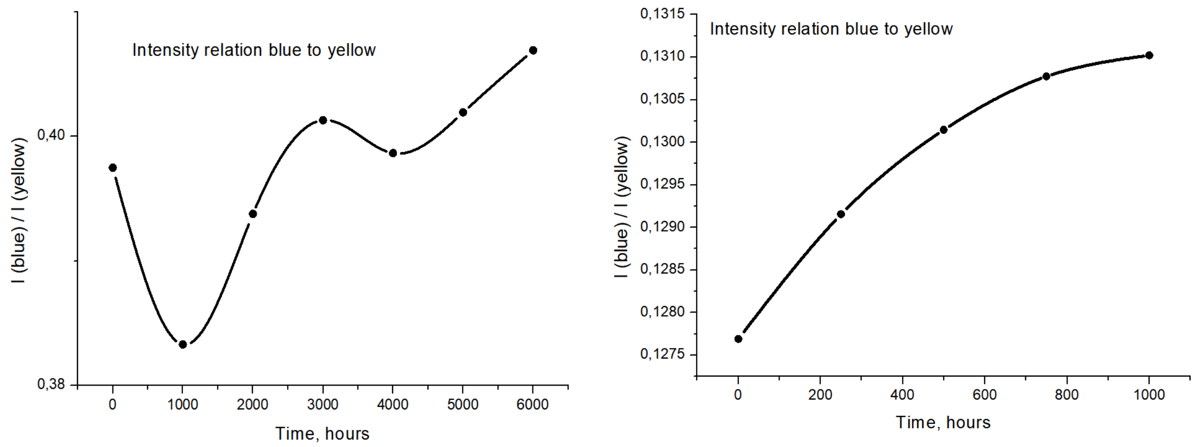
b

Fig. 5. Intensity variation of separate bands during 6000 h aging: *a* – quasi-absolute; *b* – normalized



a *b*

Fig. 6. Intensity variation of separate bands during 1000 h aging at 50 °C temperature: *a* – quasi-absolute; *b* – normalized



a *b*

Fig.7 Intensity variation of "blue" to "yellow" bands relation: *a* – during 6000 h aging; *b* – during 1000 h aging at 50 °C temperature

Thus, the analysis of luminescence spectra of investigated LEDs shows the change of intensity relation between blue and yellow bands of LED spectrum during aging. Since the blue band originates from diode heterostructure, and the yellow band from the luminophor coating, one may conclude that investigated white LEDs are degraded with lumen output due to faster luminophor degradation that LED chip itself. Blue light component become prevail in overall emission, resulting in invalid color perception if these LEDs are used as backlight sources of color displays. It is shown, however, that in our case the broad "yellow" band of luminophor is non-elementary and consists of at least two separate bands. One may find some discussions concerning the origin of this structure of the luminophor band in [10]. The described behavior is general for lamps of different manufacturers, although the degree of manifestation of the effect is different. It is believed that "green" and "orange" bands correspond to the radiative recombination transitions between spin-orbit splitted levels of excited state $(5s^2 5p^6)\ 5d^1$ and ground state $(5s^2 5p^6)\ 4f^1$ of YAG:Ce^{3+} based luminophor. In this case, the bands correspond to the transitions $^2T_{2g} – 2F_{5/2}$ and $^2T_{2g} – 2F_{7/2}$ respectively [11]. Thus, there is an increased instability of the radiative recombination channel $^2T_{2g} – 2F_{5/2}$, The causes of this instability are probably related to the population of the ground state and require further investigation. Figure of intensity of relation "blue" band to "yellow" band clearly show correlation with CCT behavior within time. Provided figures clearly show that "blue" and "orange" bands intensities have approximately similar behavior, but "green" band intensity is principally different and the most unstable and, consequently it have the most significant impact on the “blue” to “yellow” band relation, and, thus, on the photometric characteristics of white LEDs under study (TLF, CCT, CRI).

Conclusion

Based on provided results, it is obvious that unified method for accelerated testing of LED products and method for long-time lifetime prediction shall be developed and adopted internationally, taking into account not only depreciation of TLF, but also shift of photometric and spectral characteristics of white LED. Therefore, it is essential to take into account or exclude from consideration an initial segment of TLF growth and agree which method and which exponential relation shall be used for long-time prediction.

Our results show that the main cause of the “blue” to “yellow” band relation variation is the instability of the “green” component of the non-elementary “yellow” band. The change of this relation leads, consequently, to change of photometric characteristics. As a consequence, further investigation should be performed on how instability of elementary bands will link not only with photometric characteristics, but with production conditions and material properties of LED luminophor itself. In particular, for improvement of the color stability of white LED, the parameters of luminophor forming the “green” band should be stabilized.

References

1. Meneghini M., Dal Lago M., Trivellin N., Meneghesso G., Zanoni E. *Degradation Mechanisms of high-power LEDs for lighting applications: An overview. IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*. 2014; 50: 78-85. DOI: 10.1109/TIA.2013.2268049.
2. Moon-Hwan Chang, Diganta Das, P.V. Varde, Michael Pecht. *Light emitting diodes reliability review. Microelectronics Reliability.* 2012; 52: 762-782. DOI: 10.1016/j.microrel.2011.07.063.
3. W.D. van Driel, X.J. Fan. *Solid State Lighting Reliability. Components to Systems. Springer Science+Business Media, LLC*; 2013. DOI: 10.1007/978-1-4614-3067-4.
4. Meneghesso G., Meneghini M., Zanoni E. *Recent results on the degradation of white LEDs for lighting. J. Phys. D: Appl. Phys.* 2010; 43: 354007-354018. DOI: 10.1088/0022-3727/43/35/354007.
5. Meneghini M., Dal Lago M., Trivellin N., Mura G., Vanzi M., Meneghesso G., Zanoni E. *Chip and package-related degradation of high power white LEDs. Microelectronics Reliability.* 2012; 52: 804-812. DOI: 10.1016/j.microrel.2011.07.091.
6. Ming-Yi Tsai, Chung-Yi Tang, C. H. Wang, Y. Y. Tsai, Chun-Hung Chen. *Investigation on Some Parameters affecting optical degradation of LED package during high-temperature aging. IEEE transactions on device and materials reliability*. 2015; 15: 335-341. DOI: 10.1109/TDMR.2015.2441751.
7. M. Cai, D. Yang, K. Tian, W. Chen, X. Chen, P. Zhang, X. Fan, and G. Zhang. *A hybrid prediction method on luminous flux maintenance of high- power LED lamps. Applied Thermal Engineering*. 2016; 95: 482-490. DOI: 10.1016/j.applthermaleng.2015.11.034.
8. Fok M.V. Division of comlex spectra into individual bands using generalized Alentsev method. *Trudy FIAN=Proceedings of FIAN*. 1972; 59: 3-24 (In Russ.).
9. J. Xiao, Z. Guo, Y. Xiao, Y. Gao, L. Zhu, Y. Lin, Y. Lu, and Z. Chen. *Multichannel Online Lifetime Accelerating and Testing System for Power Light-Emitting Diodes. IEEE Photonics Journal*. 2017; 9: 8200911. DOI: 10.1109/JPHOT.2017.2692299.
10. Guogang Li, Ying Tian, Yun Zhao, Jun Lin. *Recent progress in luminescence tuning of* Ce^{3+} *and* Eu^{2+}*-activated phosphors for pc-WLEDs. Chem. Soc. Rev.* 2015; 44: 8688-8713. DOI: 10.1039/C4CS00446A.
11. T.-H. Yang, H.-Y. Huang, C.-C. Sun, B. Glorieux, X.-H.Lee, Y.-W.Yu, T.Chung. *Noncontact and instant detection of phosphor temperature in phosphor-converted white LEDs. Scientific Reports.* 2018; 8: 296. DOI:10.1038/s41598-017-18686-z

Authors contribution

Gurskii A.L. performed processing and analysis of the results.

Masheda M.V. conducted experimental studies; performed processing and analysis of the results.

Information about the authors

Gurskii A.L., D.Sci, professor, professor of the Department of Information Security of the Belarusian State University of Informatics and Radioelectronics.

Masheda M.V., deputy manager of accredites test laboratory of JSC BELLIS Testing and Certification of Home Appliances and Industrial Products.

Address for correspondence

220029, Republic of Belarus,
Minsk, Krasnaya st., 8,
BELLIS Testing and Certification of Home Appliances and Industrial Products, JSC
tel. +375-17-288-16-68;
e-mail: n.mashedo@gmail.com
Masheda Mikalai Vasilievich