Optimization of the methods for measuring color characteristics of light-emitting diodes in laboratory conditions

A A Pavlova, A N Ramazanov, V A Simon, D K Kostrin and A A Uhov
Department of electronic instruments and devices, Saint Petersburg Electrotechnical University “LETI”, 197376, Saint Petersburg, Russia
E-mail: ainapavlova-leti@yandex.ru

Abstract. In this work the features of measuring color characteristics of light-emitting diodes are described. Methods allowing increasing the accuracy of measurements in the laboratory conditions are shown. The results of determination of the color characteristics of white light-emitting diodes using the described technique are analyzed.

1. Introduction
Light-emitting diodes (LEDs) due to their reliability, low energy consumption and long service life are currently almost universally applied to replace previously used sources of optical radiation. Application areas of LEDs are not only devices providing light of one color, such as traffic lights, but also various lighting systems used in residential and industrial premises and also for illumination of sidewalks and roads [1, 2].

Extension of the application areas of LEDs increases the need for the accurate measurement of their parameters. Characteristics of LEDs from different manufacturers vary considerably; also spread of parameters even within the same batch is possible. That is why measurement of light and color characteristics, as well as the possibility of visual examination of emission spectra of the investigated LED is very important. During the evaluation of LEDs the photometric, radiometric, colorimetric, goniometric and operational characteristics should be analyzed [3–5].

The aim of this work is to develop and study simplified express methods for measuring some key color parameters of light-emitting diodes using compact optical spectrometer, which allow achieving results with an acceptable accuracy.

2. Characteristics of light-emitting diodes and methods of their measurement
Let us consider the colorimetric characteristics of LEDs, defining the perception of the color of light by a human eye. Human color perception is very complex, because it depends not only on the physical properties of light, but also from the surrounding objects, properties of the emitter and the psychological state of the observer [6, 7]. Colorimetric parameters of LEDs are usually expressed as chromaticity coordinates and dominant wavelength, for white LEDs the value of correlated color temperature is also used.

The measurement of LED parameters should be conducted in strictly regulated by the International Commission on Illumination (CIE) conditions [8]. However, in laboratory conditions and also for the tuned technological process, it is possible to use a simplified method of measurement. The most popular instruments for the study of LEDs are spectrometers constructed using CCD (charge-coupled
device) photodetectors. To analyze the parameters of LEDs an optical resolution of the device of 1.0...1.5 nm is sufficient [4].

It should be noted that prior to achieving the emission spectrum of the investigated sample it is necessary to perform an operation of obtaining the reference spectrum from the source of A type (incandescent lamp with tungsten spiral). For this task the program Aspect2010 developed in Saint Petersburg Electrotechnical University “LETI” to control optical spectrometers ISM3600 [9, 10] can be used. For the implementation of the spectral correction the reference spectrum of the A type source with the subtraction of a dark spectrum should be obtained using an adjustable device. Next, in the program a prepared ideal spectrum of a reference source (i.e. spectrum in a form in which it should be observed using the spectrometer if it did not have its non-linear spectral dependence) is used. Later, using these two spectra (real and ideal), the program calculates a correction function, by which all obtained spectra are automatically multiplied. Figure 1 shows fragments of the emission spectra of white LED with and without the correction of the spectrometer spectral dependence. It can be seen that this procedure leads to a significant change in the spectrum and, consequently, to a change in the results of calculation of the chromaticity coordinates and other parameters of a radiation source.

Figure 1. Emission spectra of a white LED with (1) and without (2) spectral dependence correction.

It is also necessary to take into account the dark signal of the CCD photodetector and to take care of the noise filtering in the region of wavelengths 380...780 nm, in which the integration when calculating the color of light takes place [11]. CCD photodetector has some noise level consisting of several components. The first component is a “geometric” noise, emerging due to the topology of a sensor; it can be programatically deleted using linear interpolation of odd and even pixels. The next component is an intrinsic noise. For its reduction it is possible to make averaging of the multiple spectra taken.

Also the processing of the received data of the radiation spectral distribution using a spline digital filter is quite effective. During the measurement of LED parameters the influence of the background signal close to the zero level leading to “whitening” of the perceived color can be further reduced. In this case, when performing color measurements signal with a value less than selected will be zeroed. To provide that the ambient light has no effect on the results of the LED color characteristics determination, LED and the optical input of the spectrometer should be placed under an opaque cover [12].

LED parameters are largely affected by the temperature – both ambient and achieved during the self-heating of a semiconductor crystal. The shift of the LED emission spectrum with increasing temperature occurs in the direction of longer wavelengths. The color coordinates of the LED radiation when the temperature changes from –60 to +55 °C can change considerably, by almost 10 % [13]. Therefore, before starting any measurement of characteristics LED should be warmed for some time, achieving an established thermal equilibrium. All of the approaches for improving the accuracy of measurements described above have been applied in this study.

In 1931 the CIE recommended the data of colors summing for the standard colorimetric observer, embodied in two different, but equivalent color coordinate systems RGB and XYZ [14, 15]. To describe the color characteristics of an optical radiation source the XYZ system is commonly used. There are several characteristics of LEDs that present a practical interest, such as chromaticity
coordinates, dominant wavelength, correlated color temperature, color rendering indexes (general and partial) and efficacy of a light source. At this step of the study we will focus on the first three of them.

3. Results and discussion

As objects for study white LEDs SvL-03 manufactured by JSC “Svetlana-Optoelectronics” [16] that are used to create ceiling lamps were selected. Figure 2 shows the emission spectrum of such a LED.

There are several methods of obtaining white LEDs. In this case, an application on a LED with a blue emission spectrum of a yellow phosphor coating is used. This method is simple in implementation and inexpensive, but has some disadvantages. One of them is the uneven application of the phosphor layer on the blue LED crystal, which may lead to a different perception of the shades of color not only for LEDs of one batch, but even for a single LED at different angles of examination [12, 17].

Figure 3 shows the results of determining the chromaticity coordinates $x$ and $y$ (chromaticity coordinate $z$ is redundant, since it can be determined from the other two) for a sample of 42 LEDs forming a ceiling lamp TIS-15M1. The study was conducted using a described above technique. Line in figure 3 shows the boundary of the chromaticity group B2 [18] stated by the manufacturer as the characteristic of the lamp. The measurements show that all LEDs belong to this chromaticity group. Sorting of the LEDs used in this lamp is made with sufficiently high quality – points corresponding to the chromaticity coordinates of LEDs do not fill all the shown area, but a little more than a half, which leads to the rise of device consumer properties, in particular the homogeneity of the radiation perception.

Another important factor characterizing the color of light [19] is a dominant wavelength, which means the wavelength of monochromatic light, located on the edge of the color chart on the shortest distance from the point with the chromaticity coordinates of the source. To determine the dominant wavelength a straight line to the edge of the chart passing through the point of equal energy of a white light source ($x = 0.3333, y = 0.3333$) and the point with chromaticity coordinates $(x, y)$ of the test LED is drawn. The point of intersection of this line with the outer border of the color chart will determine the dominant wavelength of the source.

For white LEDs the most important colorimetric parameter is a correlated color temperature equal to the temperature of a black body at which it emits radiation with the same chromaticity as
considered. This measure is an objective impression of the color of a light source expressed in kelvins. LEDs produced today have a fairly wide range of shades of white color with a correlated color temperature of 2600...10000 K. The most comfortable radiation for a human is sunlight, with a correlated color temperature of about 2800...3500 K. Noonday sunlight has a correlated color temperature of about 5500 K. It follows that the source of illumination shall have approximately the same correlated color temperature value. Knowing the chromaticity coordinates of the LED radiation, its correlated color temperature $T_c$ can be found using the following formula [20]:

$$T_c = 5520,33 - 6823,3 P + 3525 P^2 - 449 P^3,$$

where $P = (x-0,332)/(y-0,1858)$. Figure 4 shows the values of dominant wavelength and correlated color temperature for 42 LEDs of a ceiling lamp.

The range of values of correlated color temperature is 2985...3200 K, which corresponds to a “warm” white light with a yellowish tint. The variation in dominant wavelength is 1,6 nm (range – 578,8...580,4 nm). Given that the human eye can distinguish colors that differ by 1 nm, there is a need to use in this lamp of a diffuser with a frosted glass to ensure a greater uniformity of color perception.

As the last part of the research let us show the experimental data demonstrating the angle variation of the dominant wavelength (figure 5), where $\alpha$ – angle between the observation point and the vertical axis of symmetry of the LED, $\varphi$ – angle of observation in the horizontal plane.

![Figure 4](image1.jpg) Dominant wavelength and correlated color temperature of 42 LEDs of a TIS-15M1 lamp.

![Figure 5](image2.jpg) Spatial distribution of the dominant wavelength for a white LED.
The emission color of LED when observed from different angles is almost the same, except for large angles relative to the axis of symmetry. The differences in dominant wavelength at angles $\alpha = 10...50^\circ$ is not more than 2.5 nm.

4. Conclusion
In this paper the general approaches to the measurement of certain color parameters of LEDs with the use of the simplified techniques are presented. The obtained results confirm that the use of the developed spectrometric equipment and such methods allow obtaining sufficiently accurate results of measurements for a rapid assessment of LEDs parameters.

Acknowledgments
This work was performed within the framework of agreement on scientific-technical partnership between Saint Petersbarg Electrotechnical University “LETI” and JSC “Svetlana-Optoelectronics”.

References
[1] Judd D B and Wyszecki G 1975 Color in Business, Science, and Industry (New York: Wiley)
[2] Žukauskas A, Shur M S and Gaska R 2002 Introduction to Solid-State Lighting (New York: Wiley)
[3] Ohno Y 2006 Proceedings of SPIE 6046 25
[4] Kostrin D K and Uhof A A 2013 Biotechnosphere 3 21–5
[5] Kostrin D K and Uhof A A 2013 Testing. Diagnostics 7 47–50
[6] MacAdam D L 1942 Journal of the Optical Society of America 32 247–75
[7] Vogels I, Seuntiens P and Sekulovski D 2008 LED professional Review 5 12–6
[8] Ohno Y, Miller C and Zong Y 2008 LED Professional Review 5 17–20
[9] Uhof A A and Kostrin D K 2013 Proceedings of Saint Petersburg Electrotechnical University “LETI” 4 8–12
[10] Kostrin D K and Uhof A A 2013 Sensors and systems 5 13–5
[11] Yudin R V, Kostrin D K, Shishov D I and Uhof A A 2013 Proceedings of Saint Petersburg Electrotechnical University “LETI” 3 8–13
[12] Kostrin D K and Uhof A A 2014 Testing. Diagnostics 2 65–8
[13] Nikiforov S 2006 Components and technologies 1 18–23
[14] Smith T and Guild J 1931 Transactions of the Optical Society 3 73–134
[15] Fairman H S, Brill M H and Hemmendinger H 1998 Color Research and Application 4 259
[16] Molodtsov V 2010 Solid State Lighting 6 16–8
[17] Fairman H S, Brill M H and Hemmendinger H 1997 Color Research and Application 1 11–23
[18] Mazzochette J 2008 LED professional Review 5 30–1
[19] Kostrin D K and Uhof A A 2013 Proceedings of Saint Petersburg Electrotechnical University “LETI” 1 9–12
[20] Baklanov S A 2012 Proceeding of the Conference “Innovations – design and technology – TUSUR 2012” (Tomsk)