Развитие светодиодного метода воспроизведения единицы силы света
Development of LED method of reproduction of luminous intensity unit

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Аннотация – Расширены функциональные возможности Государственного первичного эталона единицы силы света за счет внедрения методики воспроизведения, передачи и хранения импульсных световых величин. Предложен метод для воспроизведения единицы освечивания на основе воспроизведения единицы силы света при использовании узкополосного светодиода с симметричным распределением спектра.

Abstract – The functionality of the State primary standard of luminous intensity unit is expanded through introduction of reproduction, transmission and storage of pulsed light quantities. A method for reproduction of illumination unit characterizing pulsed light quantities is proposed based on reproduction of luminous intensity unit when using a narrow-band LED with symmetrical spectrum distribution.

Introduction

In recent years, the field of application of light-emitting diodes (LED) and LED-based lighting equipment is rapidly expanding. LEDs have become widely used in various fields of industry, modern life and science. This also applies to metrology, in which the field of using LEDs as reference sources of optical radiation during reproduction and transmission of light units is developing [1]. The reason for such dynamic development is a number of significant advantages of LEDs (long operating time, spectra variety, energy efficiency, location of spectrum in the eye sensitivity area) against other light sources. Together with introduction of light-emitting diodes the necessity to measure pulsed light values, which may be present in some LED equipment structures, has become more significant. This, in particular, stipulates the importance of development of appropriate metrological support for health care [2].

This research was carried out as part of work on expansion of functionality of the State primary standard of luminous intensity unit in the part of reproduction and transmission of flashing light quantities using LED source. Illumination unit (cd·s) is one of the main light units for characterization of pulsed light quantities. For reproduction of illumination unit, the luminous intensity unit (cd) shall be reproduced on the source that can give ability for modulation of light radiation with different frequency, amplitude and signal form. All this leads to the necessity to create appropriate standards and equipment for calibration of measuring equipment for both continuous and pulsed radiation (photometers, luxmeters, flicker meters).

The purpose of this research is expansion of functionality of the State primary standard of luminous intensity unit through introduction of the method of reproduction, transmission and storage of pulsed light values. For this purpose, it is necessary to develop a method for LED selection for reproduction of luminous intensity unit and use the obtained luminous intensity unit (cd) for reproduction and transmission of the illumination unit (cd·s).

In 2015, the method of reproduction of luminous intensity unit [1] based on white LED with a trap detector was proposed. Since the LED emission spectrum is located in the area of relative spectral luminous efficacy of radiation for human daylight vision $V(\lambda)$ (Fig. 1), the filter for bringing the sensitivity of the detector to $V(\lambda)$ may be not used [1]. In the research [3], a comparative analysis of methods of reproduction of luminous intensity unit was performed using various sources of optical radiation (LED, a source of monochromatic radiation and a type A source). The main line of research was aimed at uncertainty associated with spectral quantities. The results showed that in case of using LEDs one of the main sources of uncertainty components are the results of LED radiation spectrum measurement. It shall be noted that there is no standardized LED source at the current moment. It is obvious that upon availability of a standardized LED source of optical radiation, the spectrum measurement uncertainty will disappear, the total extended uncertainties for a Type A source and LED will be equated, and the existence of unsuppressed spectral areas of the Type A source will make the LED using method more advantageous.

One of the most accurate sources of radiation used at reproduction of the unit of luminous intensity is laser, which is a source of monochromatic radiation. In this case the accuracy of reproduction is affected by determination of the center frequency and the radiation power. To reduce the uncertainty components associated with the accuracy of radiation line definition, this type of sources is usually located in the vicinity of 555 nm (the maximum of *V*(*λ*) function), where the dependence on the wavelength is minimal. If the source spectrum is not monochromatic, but quasi-monochromatic (as in the case of LED), the spectrum measurement uncertainty increases.

The proposed method consists in using the property of the function of the visibility of the human eye *V*(*λ*). Instead of a broadband LED with several peaks, symmetrical narrow-band LEDs can be used. Based on the definition of candela, luminous intensity is considered to be a unit of luminous flux in a single solid angle.

$$\Phi = K\int_0^\infty \Phi_{LED}(\lambda)V(\lambda)d\lambda \, , \tag{1}$$

where Φ is luminous flux, lm;

K is 683 lm/W, a factor providing correlation of photometric and energy units;

Φ_{LED} is spectral density power of the LED radiation;

V(*λ*) is photopic luminosity function.

The expression written in formula 1 implies precise knowledge of the LED emission spectrum. The proposed method consists in expanding the function *V*(*λ*) in a Taylor series. The result of this expansion is the expression:

$$\Phi = K\sum_i(\Phi_{LEDi}\cdot\Delta\lambda)\left(V_0 + V'\sum_i\frac{(\lambda_i-\lambda_0)\cdot\Phi_i}{\sum_i(\Phi_{LEDi}\cdot\Delta\lambda)} + \frac{V''}{2}\sum_i\frac{(\lambda_i-\lambda_0)^2\cdot\Phi_i}{\sum_i(\Phi_{LEDi}\cdot\Delta\lambda)}\right). \tag{2}$$

where Φ_{LED} is the values of LEDs power spectral density measured at equidistant wavelengths λ_i;

$\Delta\lambda$ is the distance between λ_i;

V_0 is the V(λ) value at the point λ_0;

V' is the first V(λ) derivative at the point λ_0;

V'' is the second V(λ) derivative at the point λ_0;

That measurements of Φ_i shall be performed at all λ_i wavelengths, where the value of Φ_i is different from zero.

Let's consider each term of the given expression separately. The first term is the integral power $\Sigma(\Phi_{LEDi}\Delta\lambda)$ of radiation with the maximum of the LED spectrum at the point V_0. The power can be measured with a non-selective detector and does not require accurate knowledge of the LED emission spectrum.

The second term includes the first derivative of the function *V*(*λ*). Using of LEDs with a symmetrical spectrum brings the value of the second term $V'\sum(\lambda_i-\lambda_0)\cdot\Phi_i$ to small numbers, so this value shall be considered as equal to zero.

The main idea of the proposed method is that the zero point V_0 of the LED emission wavelength shall be selected so that the second derivative of the function *V*(*λ*) is minimal (Fig. 1); ideally, it shall be equal to zero. Such areas are supposed to be the regions of inflections of the function *V*(*λ*). Thus, in accordance with the results of calculations, for the regions of inflections of the function *V*(*λ*), the third term of the expression $\frac{V''}{2}\sum(\lambda_i-\lambda_0)^2\cdot\Phi_i$ will be non-significant.

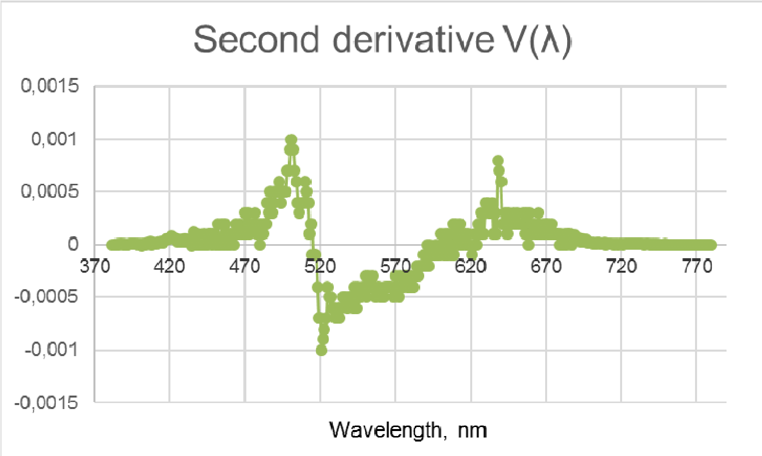

Fig. 1 – Distribution of the second derivative of the function $V(\lambda)$

As a result, we can see that the first term does not require spectrum measurement – it is the measurement of integrated power. The second one disappears due to contour symmetry, and the influence of the third term with the spectral component becomes significantly less. Analysis method applicability can be expressed in terms of the ratio of results for calculation of Φ by formula 1 and Φ by formula 2 presented in Table 1 for points V_0. Calculations were performed with step of 1 nm for various half-widths of the spectra of light-emitting diodes in both regions of inflection of the function $V(\lambda)$ and in maximum of the function $V(\lambda)$.

Table 1 – Analysis of method applicability

Half-widths, nm	3	8	10	12	14	16	20	30	50
Green area, nm	515	515	515	515	515	515	515	515	516
Correlation	1,000052	1,001224	1,001791	1,002175	1,002298	1,002124	1,000905	1,006018	1,004872
Red area, nm	593	593	593	593	593	593	594	595	595
Correlation	1,000049	1,000241	1,000252	1,000179	15E-8	1,000301	1,000298	1,000772	1,006957
Max point V(λ), nm	555	555	555	555	555	555	555	555	555
Correlation	1,000001	1,000151	1,000319	1,000565	1,000909	1,001356	1,002532	1,004968	1,034221

Comparing the results obtained for points in the vicinity of 515 nm and 593 nm with the results at 555 nm, we can state that the proposed locations provide higher accuracy, even considering the non-monochromatic spectrum of LEDs.

Determination of inflection points of the function $V(\lambda)$ (Fig. 1) shows that the most preferable area, at a half-width of 10 nm, is the wavelength interval of 590...625 nm, where the value of the second derivative is minimal. The green spectrum region at Fig. 1 has no linear section; therefore, upon LED spectrum selection there will be a large contribution of uncertainty associated with inaccurate measurement of V_0.

The accuracy of measurement based on the proposed method is determined by the third term of expression 2. Accuracy increase can be measured quantitatively through the ratio of the third term and the result of Φ calculated by formula 1.

The complexity of method implementation remains is significantly dependent from the accuracy of determination of V_0. For inflection points, a deviation of 1 nm gives an deviation of about 1.5 %. To meet the accuracy requirement of 0.1 %, it is necessary to measure the LED spectrum maximum with an accuracy of 0.05 nm. Significant reduction in the requirements for LED power spectral density measurement accuracy, which is usually one of the main components of uncertainty at reproduction, makes the proposed approach promising.

By means of mathematical transformation, the results that differ from the generally accepted approach were obtained. This method can be applied to any narrow-band symmetrical source. However, considering that the currently used methods of luminous intensity unit reproduction based on incandescent lamps, mercury lamp and laser radiation cannot be used to provide measurements of pulsed light values, the proposed method of using a light-emitting diode was introduced during modernization of the State primary standard of luminous intensity unit (Fig. 2) providing pulsed light measurements.

Fig. 2 – State primary standard of the luminous intensity unit

The use of LEDs in pulse mode allows measurements of pulsed light values.

Conclusion

The method of reproduction of luminous intensity unit using a trap-detector and a colored narrow-band LED with symmetrical radiation spectrum was proposed. Due to absence of a correcting filter and selection of optimum LED wavelength in the part of the spectrum $V(\lambda)$, where the second derivative of $V(\lambda)$ has a minimum value, the requirements for accuracy of LED spectrum measurement are decreased and the expanded uncertainty of luminous intensity unit and illumination unit reproduction is decreased as well.

The method allows reproducing luminous intensity unit and illumination unit using the fundamental properties of human eye visibility curve. Location of the LED spectrum in the region of inflections of the function $V(\lambda)$ slightly increases the requirements for accuracy of the source spectrum maximum measurement; however, a significant reduction of requirements to this spectrum measurement accuracy makes it possible to reduce the reproduction uncertainty.

Based on the results of luminous intensity unit reproduction on the basis of LED, it was proposed to reproduce the illumination unit, which characterizes the pulsed sources of optical radiation.

Due to introduction of measurement of flashing light quantities, reproduction and transmission of illumination unit, the functional capabilities of the State primary standard of the unit of luminous intensity were expanded. It allows measuring the parameters of light pulsation and periodic (signal) light sources and analyzing the sources and detectors of continuous and pulsed optical radiation as well.

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