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Method for determination of the spectral mismatch correction factors for the luminous responsivity of photometers when measuring the characteristics of LED lamps

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Abstract

This paper describes the challenges associated with the metrology of LED sources. The main problem is the difference between the spectra of LED lamps and the spectrums of reference lamps, which are mainly highly stable and well-reproducible incandescent lamps. The difference in spectra leads to the fact that the luminous responsivity of the calibrated photometer will be different for the reference incandescent lamp and for the LED lamp. The difference is caused by the fact that a relative spectral characteristic of the photometer responsivity is always different from the spectral responsivity of the human eye ($V(\lambda)$ curve), which determines all luminous quantities. The greater the difference between the relative spectral responsivity of the photometer and $V(\lambda)$ is, the more the luminous responsivity of the photometer will differ for the reference lamp and for the LED lamp. The paper describes a method developed at the NSC "Institute of Metrology" for experimental determination of mismatch correction factors of luminous responsivity that account for the difference in the LED spectra to solve the problems of metrological support of LED sources. Methods of experimental study of mismatch correction factors for measuring instruments of luminous quantities of LED radiation sources are presented.

Keywords: luminous flux; luminous responsivity; spectral mismatch correction factor; integrating sphere photometer; LED light source; standard lamp; standard photometer.

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Introduction

The significant growth in the production of lighting products based on light-emitting diode (LED) sources, which is associated with their higher energy efficiency compared to incandescent lamps, has caused problems with reliably determining the luminous characteristics of these products. This is because spectral characteristics of incandescent lamps significantly differ from the characteristics of LED sources, which leads to a difference in the responsivity of integrating sphere photometers when measuring the luminous flux from incandescent lamps and LED sources. Since national luminous flux measurement standards that are available today at national metrology institutes are established (designed) by measurement methods using integrating sphere photometers [1–4] and incandescent standard lamps, this difference may lead to significant (up to 5%) uncertainties in measurements / calibrations of LED sources.

When measuring / calibrating incandescent lamps, this difficulty does not exist, since the spectrum of reference incandescent lamps (for example, Type A) (used to calibrate integrating sphere photometers) and the spectrum of the measured incandescent lamps are approximately the same. Then, accordingly, correction factors for the luminous responsivity of the integrating sphere photometer are the same for them. But when measuring LED sources with integrating sphere photometers calibrated with incandescent lamps, a problem may arise due to the difference in the spectral responsivity of integrating sphere photometers from $V(\lambda)$. This issue may be solved by the methods described in [5]. This paper is dedicated to the development of methods [5], which would allow solving the problem of the difference between the spectra of incandescent lamps and LED light sources.

Calculation of the mismatch correction factor for the responsivity of the integrating sphere photometer to the LED luminous flux

The difference in sensitivities may be determined from the formulas for correction factors for the luminous responsivity of an integrating sphere for a standard incandescent lamp (1) and for a measured LED light source (2):

$$k(\mathrm{st}) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,st}}(\lambda) \cdot V(\lambda) d\lambda}; \quad (1)$$

$$k(\mathrm{LED}) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot V(\lambda) d\lambda}, \quad (2)$$

where:

$\Phi_{e,st}(\lambda)$ is a relative spectral flux from the standard incandescent lamp used to calibrate the integrating sphere photometer;

$\Phi_{e,LED}(\lambda)$ is a relative spectral flux from the LED source, which is measured using the integrating sphere photometer;

$S_{rel}(\lambda)$ is a relative spectral responsivity of the integrating sphere photometer;

$\lambda_{min}-\lambda_{max}$ is the spectral responsivity range of the integrating sphere photometer, nm.

The mismatch correction factor for adjusting the responsivity of the integrating sphere photometer to the LED luminous flux is determined as follows:

$$k = \frac{k(\mathrm{LED})}{k(\mathrm{st})}. \quad (3)$$

It can be seen from the formulas that the closer $\Phi_{e,st}(\lambda)$ to $\Phi_{e,LED}(\lambda)$ is, the closer k to one is, and the more accurate the LED calibration is.

If a standard incandescent lamp is used to calibrate a LED source (source of Type A), then $F^* = k^{-1}$ is a spectral mismatch correction factor [6].

Method for experimental determination of the mismatch correction factor for the responsivity of the integrating sphere photometer to the LED luminous flux

A mismatch correction factor (3) may be measured using a reference photometer with known coefficients

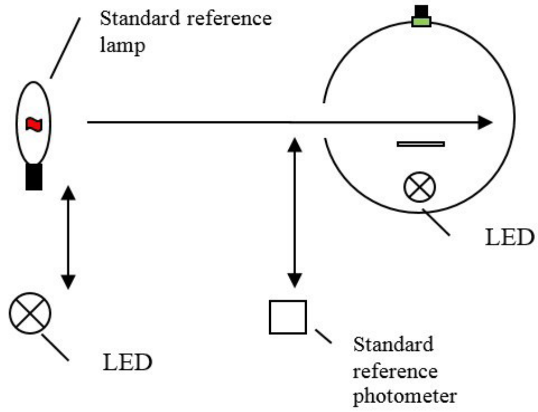

Fig. 1. Scheme of measuring the mismatch correction factor k for adjusting the responsivity of the integrating sphere photometer to the LED luminous flux

(5) and (6), as well as the mismatch index f_1' [6], which is close to 0.

A measurement diagram for k is shown in Fig. 1. Directional collimated luminous flux from a standard lamp and LED is alternately fed into the integrating sphere photometer and the reference photometer. In this case, the currents of the integrating sphere photometer and the reference photometer are measured.

The mismatch correction factor for the responsivity of the reference photometer to the LED luminous flux is determined similarly to (3) as follows:

$$k_{\mathrm{ph}} = \frac{k_{\mathrm{ph}}(\mathrm{LED})}{k_{\mathrm{ph}}(\mathrm{st})}; \quad (4)$$

$$k_{\mathrm{ph}}(\mathrm{st}) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda}{\int_{360\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,st}}(\lambda) \cdot V(\lambda) d\lambda}; \quad (5)$$

$$k_{\mathrm{ph}}(\mathrm{LED}) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot V(\lambda) d\lambda}, \quad (6)$$

where $S_{rel,ph}(\lambda)$ is a relative spectral responsivity of the standard photometer.

Using formulas (1–6) the following expression are obtained:

$$\frac{k}{k_{\mathrm{ph}}} = \frac{k(\mathrm{LED})}{k(\mathrm{st})} \cdot \frac{k_{\mathrm{ph}}(\mathrm{st})}{k_{\mathrm{ph}}(\mathrm{LED})} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot V(\lambda) d\lambda} \cdot \frac{\int_{360\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,st}}(\lambda) \cdot V(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda} \times$$
$$\times \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda}{\int_{360\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,st}}(\lambda) \cdot V(\lambda) d\lambda} \cdot \frac{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot V(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel}}(\lambda) d\lambda} \times \quad (7)$$
$$\times \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,st}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{\mathrm{e,LED}}(\lambda) \cdot S_{\mathrm{rel,ph}}(\lambda) d\lambda} = \frac{I_{\mathrm{sp}}(\mathrm{LED}) / I_{\mathrm{sp}}(\mathrm{st})}{I_{\mathrm{ph}}(\mathrm{LED}) / I_{\mathrm{ph}}(\mathrm{st})}; \quad k = \frac{I_{\mathrm{sp}}(\mathrm{LED}) / I_{\mathrm{sp}}(\mathrm{st})}{I_{\mathrm{ph}}(\mathrm{LED}) / I_{\mathrm{ph}}(\mathrm{st})} \cdot k_{\mathrm{ph}},$$

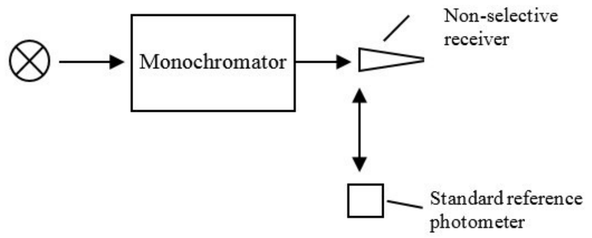

Fig. 2. Scheme of measuring the relative spectral responsivity $S_{rel,ph}(\lambda)$ to correct the responsivity of the integrating sphere photometer to the LED luminous flux

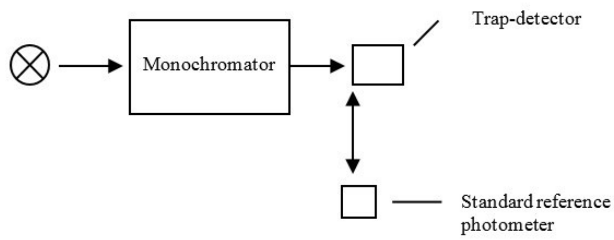

Fig. 3. Scheme of measuring the relative spectral responsivity $S_{rel,ph}(\lambda)$ based on the trap detector

where:

I_{sp}(LED) is a current of the integrating sphere photometer when illuminated by the LED;

I_{sp}(st) is a current of the integrating sphere photometer when illuminated by the standard lamp;

I_{ph}(LED) is the current of the standard photometer when illuminated by the LED;

I_{ph}(st) is a current of the standard photometer when illuminated by the standard lamp.

To determine k, it is sufficient to perform relative measurements under the same irradiance conditions for photometers from a LED source and standard lamp.

Experimental determination of the mismatch correction factor for the responsivity of the standard photometer to the LED luminous flux k_{ph}

To determine k_{ph} of a standard photometer, it is necessary to measure its relative spectral responsivity $S_{rel,ph}(\lambda)$.

These measurements are usually performed on a spectroradiometric installation shown in Fig. 2.

Using a radiation source and a monochromator, a uniform monochromatic illumination is generated at a small distance from the output slit of the monochromator. A non-selective receiver and standard photometer are illuminated alternately at each responsivity wavelength of the standard photometer. The relative spectral responsivity of the standard photometer is determined from as follows:

$$S_{rel,ph}(\lambda) = S_{ph}(\lambda) / S_{ph}(\lambda_{max}), \quad (8)$$

where:

$S_{ph}(\lambda) = I_{ph}(\lambda) \cdot S_{ns}(\lambda) / I_{sn}(\lambda)$,

$I_{ph}(\lambda)$ is the reference photometer signal,

$I_{sn}(\lambda)$ is the non-selective receiver signal,

$S_{ns}(\lambda)$ is a relative spectral responsivity of a non-selective receiver (close to 1 over the entire spectral range),

$S_{ph}(\lambda_{max})$ is a maximum value of $S_{ph}(\lambda)$.

Instead of a non-selective receiver, a receiver with a known characteristic of relative spectral responsivity, for example, a trap detector (Fig. 3, 4) [7–11], may be used.

A trap detector with a filter that corrects a visibility curve $V(\lambda)$ (Fig. 3) can also be used as a standard photometer [7]. Its spectral responsivity is approximately linear and well known in the visible range, so it is sufficient to perform high-precision measurements of the spectral transmittance of the correction filter to determine the spectral responsivity of a reference photometer.

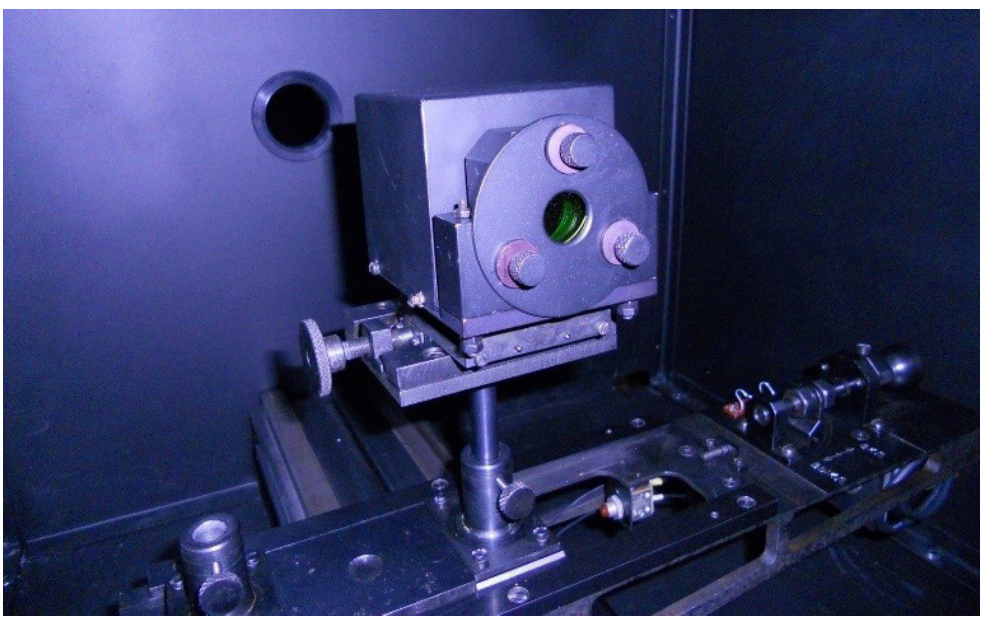

Fig. 4. Standard photometer based on trap detector with $V(\lambda)$ corrective filter

The spectral responsivity of the standard photometer can be represented as the following formula:

$$S_{ph}(\lambda) = S_{trap}(\lambda) \cdot \tau(\lambda), \qquad (9)$$

where $\tau(\lambda)$ is the spectral transmittance of the correction filter and $S_{trap}(\lambda)$ is the spectral responsivity of the trap detector.

The responsivity of the trap detector can be represented as follows:

$$S_{trap}(\lambda) = (e \cdot \lambda / h \cdot c) \cdot (1-\rho(\lambda)) \cdot (1-\delta(\lambda)), \qquad (10)$$

where:

e = 1.60217733E-19 C is the elementary charge,

h = 6.6260755E-34 J·s is the Planck's constant,

c = 299792458 m/s is the speed of light,

$1-\rho(\lambda)$ is the absorbance of the trap detector,

$\delta(\lambda)$ is the charge-carrier losses (IQD) of photodiodes.

The determination of k_{ph} of a trap detector with a filter can be calculated by formulas (4–6) using the Mathcad program, in which the functions $\Phi_{e,st}(\lambda)$, $\Phi_{e,LED}(\lambda)$, $S_{rel,ph}(\lambda)$, $V(\lambda)$ can be presented in a tabular form.

The algorithm of the procedure described above for transferring the size of the responsivity correction factor from the standard photometer to the integrating sphere photometer is shown in Fig. 5.

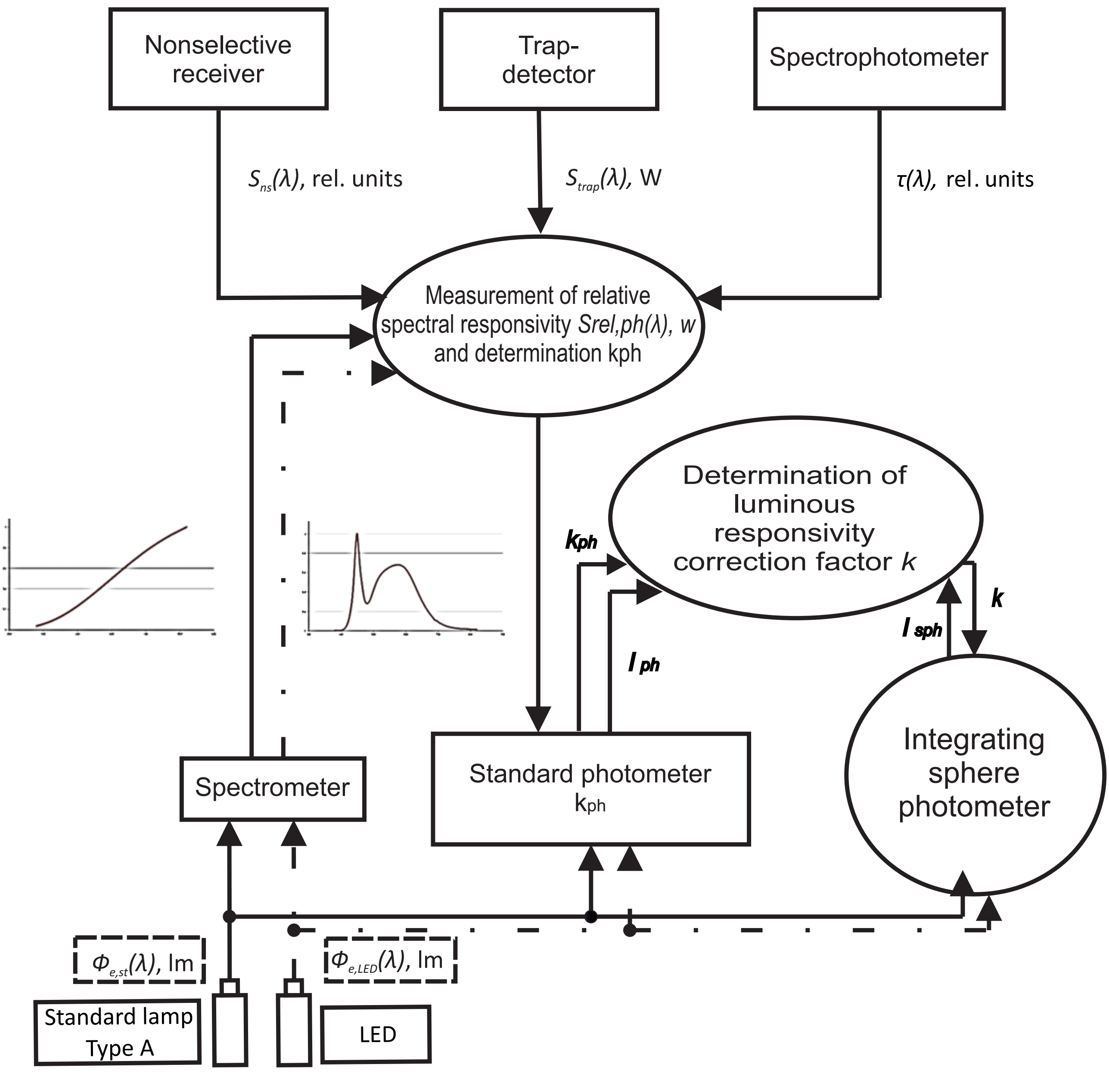

Fig. 5. Scheme of transferring the size of the mismatch correction factor for luminous responsivity from the standard photometer to the integrating sphere photometer

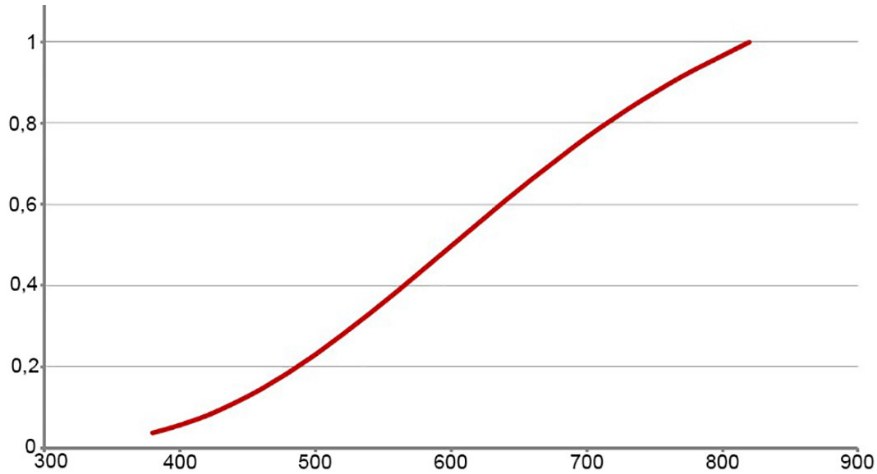

Fig. 6. Spectrum of CIE Standard Illuminant A

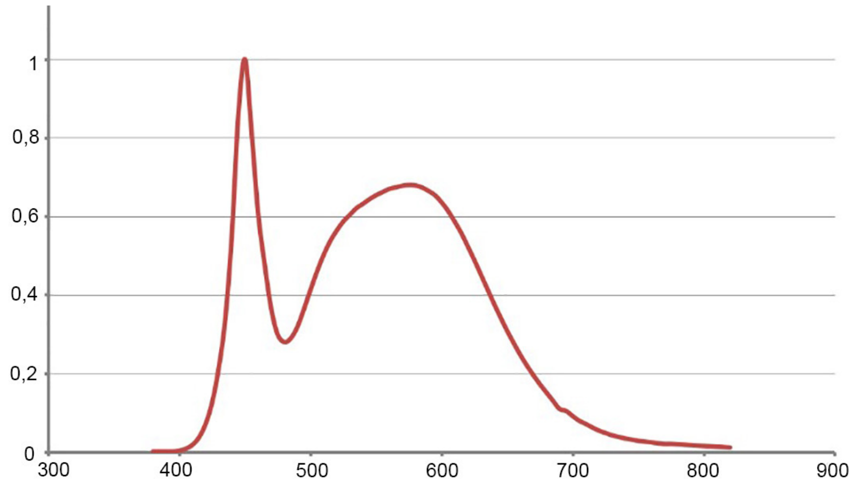

Fig. 7. Spectrum of standard white LED

Evaluation of the uncertainty of the result of measurements of the mismatch correction factor *k*

As an example, let us consider the budget of measurement uncertainty *k* for the national measurement standard of the unit of luminous flux, which is maintained at the NSC "Institute of Metrology".

The uncertainty of correction factors was calculated for the reference photometer based on a trap detector with a filter correcting for visibility curve $V(\lambda)$ (Fig. 4) and the integrating sphere photometer with spectral characteristics described in [7].

The uncertainty was evaluated for a standard Type A source (CIE Standard Illuminant A, Fig. 6) and a standard white LED with spectral power distribution showing Fig. 7.

The components of the measurement uncertainty of the correction factor of the luminous responsivity of the integrating sphere photometer *k* are shown in Table 1.

Table 1

Uncertainty budget of measurements of *k* at the NSC "IM"

Component of uncertainty	The source of uncertainty	Value of relative standard uncertainty (%)
$u_{\mathrm{k\ ph}}$	Determination of k_{ph}	0.116
$u_{\mathrm{j\ trap}}$	Measurement of photocurrent ratio of standard photometer	0.005
$u_{\mathrm{j\ sphere}}$	Measurement of photocurrent ratio of integrating sphere photometer	0.005
$\boldsymbol{u_B}$	**Combined Uncertainty of Type B**	**0.116**
$\boldsymbol{u_A}$	**Standard Uncertainty of Type A (repeatability in independent measurements)**	**0.01**
$\boldsymbol{u_c}$	**Combined standard uncertainty**	**0.116**

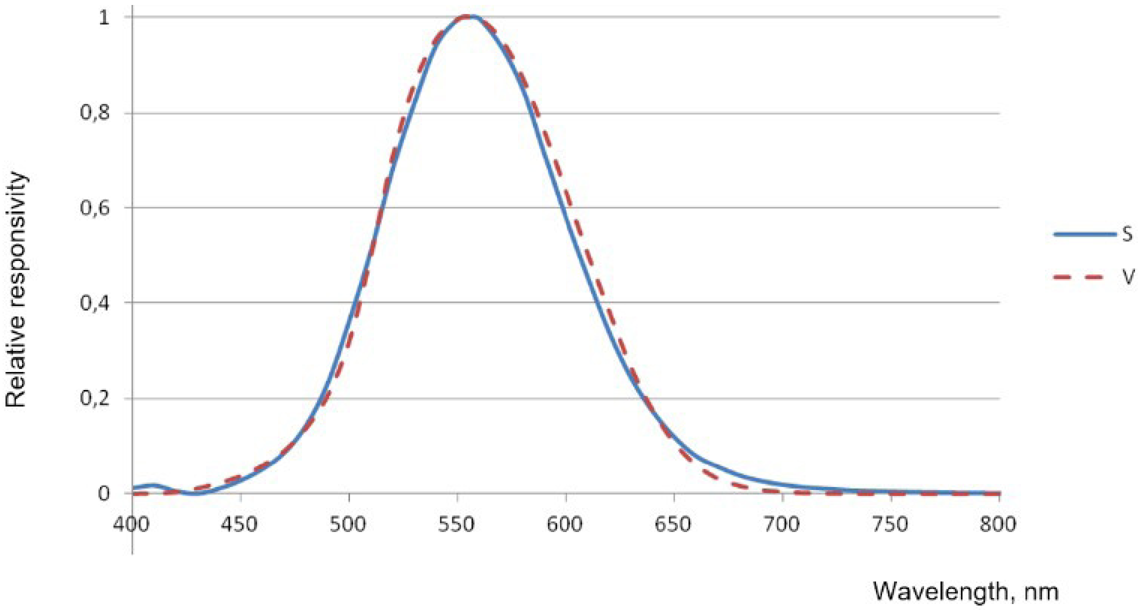

Fig. 8. Relative spectral responsivity of integrating sphere photometer – $S_{rel}(\lambda)$ and luminosity curve – $V(\lambda)$

Such a low value of the component of uncertainty u_{kph} is associated with the absence of reflections between the trap detector and the correction filter. The absence is caused by the fact that more than 99.9% of the light flux passing through the filter is absorbed by the trap detector. Therefore, in accordance with formula (9), u_{kph} is determined only by the uncertainty of $S_{trap}(\lambda)$ and measurements of the spectral transmittance $\tau(\lambda)$ of the correction filter. The linearity of the spectral function $S_{trap}(\lambda)$ in the visible range is affected only by the relative spectral function of the absorbance of the trap detector. The selectivity of this function does not exceed 0.05%. The contribution of measurement uncertainty $\tau(\lambda)$ to the determination of $S_{trap}(\lambda)$ does not exceed 0.104%.

To estimate the unaccounted systematic component of the error of measurements of the luminous flux of a standard white LED, the relative spectral responsivity of the integrating sphere photometer was used. The latter is in turn used at the NSC “IM” (Fig. 8) [7] with a mismatch index [6] $f_1^{'} \times 100\% = 6.17\%$.

For an integrating sphere photometer, the difference in light responsivities for a standard Type A lamp (Fig. 6) and a standard white LED (Fig. 7) results in a systematic component of the measurement error: $(k-1)\times 100\% = -2.2\%$.

From the results of the calculations, it is concluded that this technique allows significantly reduce the systematic component of the measurement error. This is especially true in industrial laboratories, where spectral characteristics of spherical photometers can differ from $V(\lambda)$ much more significantly than those given above.

Conclusions

A method for measuring the mismatch correction factor for the responsivity of luminous values of working photometers k is proposed. The proposed method makes it possible to reduce the measurement/calibration uncertainty of LED sources associated with the difference between the spectra of standard incandescent lamps and the spectra of LED sources. Thanks to the proposed method, it is possible to use highly stable and well-reproducible incandescent lamps as standard lamps for reproducing and transferring units of luminous values, including LED sources, in the future.

To implement the method, it is sufficient to use a standard photometer with a well-known mismatch correction factor k_{ph} for a LED source. The implementation of the method provides only relative measurements, which greatly simplifies the measurement procedure and eliminates the need for absolute measurements.

Методика визначення поправкових коефіцієнтів спектральної розбіжності для світлової чутливості фотометрів при вимірюванні характеристик світлодіодних ламп

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Анотація

У статті описано проблеми, пов'язані з метрологією світлодіодних джерел. Основною проблемою є різниця між спектрами світлодіодних ламп і спектрами еталонних ламп, які в основному є високостабільними й добре відтворюваними лампами розжарювання. Різниця в спектрах призводить до того, що світлова чутливість відкаліброваного фотометра буде різною для еталонної лампи розжарювання й для світлодіодної лампи, тому що відносна спектральна характеристика чутливості фотометра завжди відрізняється від спектральної чутливості людського ока ($V(\lambda)$ кривої), яка визначає всі світлові величини. Чим більша різниця між відносною спектральною чутливістю фотометра і $V(\lambda)$, тим більше буде відрізнятися світлова чутливість фотометра для еталонної лампи й для світлодіодного випромінювача. Ця проблема особливо актуальна для великих сферичних фотометрів, які вимірюють весь світловий потік, що виходить від лампи, а проведення дослідження відносної спектральної характеристики є дуже складним, практично нездійсненним завданням, через великі розміри сфери фотометра, що вимагає великих рівнів потоку для забезпечення прийнятного рівня сигналу на приймачі сфери. Тому найбільш актуальним завданням є розробка методу визначення поправкового коефіцієнта спектральної розбіжності джерел випромінювання на основі не установок для визначення спектральної чутливості на основі монохроматорів із потужним джерелом випромінювання, а на основі установок з інтегральними джерелами випромінювання. Світлові потоки від інтегральних джерел випромінювання забезпечують достатній сигнал для приймача інтегруючої сфери.

У статті описано розроблений в ННЦ "Інститут метрології" метод експериментального визначення поправкового коефіцієнта спектральних розбіжностей світлової чутливості фотометра для вирішення завдань метрологічного забезпечення світлодіодних джерел. Наведено методи експериментального дослідження поправкових коефіцієнтів спектральної розбіжності для світлової чутливості засобів вимірювання світлових величин світлодіодних джерел випромінювання.

Ключові слова: світловий потік; світлова чутливість; поправковий коефіцієнт спектральної розбіжності; інтегруючий сферичний фотометр; світлодіодне джерело світла; стандартна лампа; стандартний фотометр.

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