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RESEARCH ARTICLE

Solution of topical spectroradiometric problems using synchrotron radiation

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Abstract
Objectives. In order to solve fundamental metrological problems concerning the reproduction and transmission of spectral radiometry units, as well as developing methods and tools for metrological support of modern technologies such as nanophotolithography in the electronics industry, synchrotron radiation can be used. When developing solid-state sources and receivers of radiation, new topical problems arise in connection with the metrological characteristics of light-emitting diodes (LEDs), multi-element array receivers, charge-coupled device (CCD) cameras and telescopes, whose successful solution depends on the properties of a reference source of synchrotron radiation. Therefore, the purpose of the present work is to develop spectral radiometry methods for obtaining metrological channels using an electron storage ring in order to control the characteristics of electronics components, as well as for studying and calibrating radiometers, photometers, and emitters operating in the visible, ultraviolet and infrared regions of the electromagnetic spectrum.
Methods. Methods for transmitting spectroradiometric units on an electron storage ring are based on the classical theory of Julian Schwinger, which describes the electromagnetic radiation of a relativistic electron to calculate the spectral and energetic synchrotron radiation characteristics taking polarization components into account.
Results. The possibility of developing methods for transmitting spectral radiometric units using synchrotron radiation was evaluated by means of a test setup, which included a monochromator-based comparator, a telescope with a CCD array, a spectroradiometer, a radiometer, a photometer, a goniometer, and an integrating sphere. This allowed the full set of spectroradiometric and photometric characteristics of radiation sources and receivers to be measured: from the most differential distribution of the spectral radiance density of the emitting region to the integral radiation flux. The results were compared with the reference synchrotron radiation source.
Conclusions. Among possible approaches for determining the metrological characteristics of LED emitters, multi-element array receivers, CCD cameras, and telescopes, synchrotron radiation seems to be the most promising. This approach allows the small size of the emitting region of synchrotron radiation, the Gaussian distribution of radiance over the emitting region of the synchrotron electron bunch, as well as the wide dynamic range of spectrum tuning due to changes in the energy and number of accelerated electrons, to be taken into account.

Keywords: spectral radiometry, synchrotron radiation, radiance, radiation intensity, LED, photometer, radiometer

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НАУЧНАЯ СТАТЬЯ

Решение актуальных задач спектрорадиометрии с использованием синхротронного излучения

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Резюме
Цели. Использование синхротронного излучения позволяет решать фундаментальные метрологические задачи воспроизведения и передачи единиц спектрорадиометрии, разрабатывать методы и средства метрологического обеспечения современных технологий, таких как нанофотолитография в электронной промышленности. Развитие твердотельных источников и приемников излучения формирует новые актуальные задачи исследования метрологических характеристик светодиодов, многоэлементных матричных приемников, ПЗС-камер и телескопов, успешное решение которых зависит от использования свойств эталонного источника синхротронного излучения. Целью работы является развитие методов спектрорадиометрии для метрологических каналов электронного накопительного кольца при контроле характеристик компонентов в электронной промышленности, при исследованиях и калибровках радиометров, фотометров, излучателей в видимой, ультрафиолетовой и инфракрасной областях спектра.
Методы. Методы передачи единиц спектрорадиометрии на электронном накопительном кольце основаны на использовании классической теории Ю. Швингера, описывающей электромагнитное излучение релятивистского электрона, для расчета спектральных энергетических характеристик синхротронного излучения с учетом поляризационных компонентов.
Результаты. Рассмотрены возможности развития методов передачи единиц спектрорадиометрии с использованием синхротронного излучения и создания испытательной установки. Эта установка включает в себя компаратор на основе монохроматора, телескопа с ПЗС-матрицей, спектрорадиометра, радиометра, фотометра, гониометра и интегрирующей сферы, позволяющих проводить измерения полного набора спектрорадиометрических и фотометрических характеристик источников и приемников излучения – от наиболее дифференциального распределения спектральной плотности энергетической яркости по излучающей области до интегрального потока излучения с прослеживаемостью к эталонному источнику синхротронного излучения.

Выводы. Определение метрологических характеристик светодиодных излучателей, многоэлементных матричных приемников, ПЗС-камер и телескопов с использованием синхротронного излучения представляется наиболее перспективным направлением с учетом малых размеров излучающей области синхротронного излучения, Гауссова распределения энергетической яркости по излучающей области электронного сгустка синхротрона, широкого динамического диапазона перестройки спектра за счет изменения энергии и числа ускоренных электронов.

Ключевые слова: спектрорадиометрия, синхротронное излучение, энергетическая яркость, сила излучения, светодиод, фотометр, радиометр

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INTRODUCTION

The unique synchrotron radiation properties of accelerated relativistic electrons in cyclic accelerators opened up significant opportunities for metrology, allowing electron storage rings (ESRs) to be used as primary reference sources of electromagnetic radiation. This results in a clean, plasma-free, continuous spectrum, which is free of spectral lines and easily tunable by changing the energy and number of electrons in orbit [1].

Synchrotron radiation is widely used in fundamental metrological research and developing metrological support for modern nanophotolithography technologies used in the electronics industry [2]. The Decree of the President of the Russian Federation[1] and the Decree of the Government of the Russian Federation[2] pay great attention to the development of optical radiation spectroradiometry using synchrotron radiation.

The first work on spectroradiometry carried out at the DESY[3] synchrotron in Hamburg was aimed at measuring the spectral density of energy brightness of ultraviolet (UV) radiation using the relative spectral distribution of synchrotron radiation with absolute referencing in the visible region to the standard black body model. By this means, the spectral range of the deuterium continuum could be calibrated up to the vacuum ultraviolet (VUV) limit—that is, up to photon energies of 6 eV, which is not possible using the black body model. Electron storage rings and synchrotrons are used in Russia, Germany, and the USA to expand the range of absolute spectral measurements to the VUV region, first to the Schumann region up to 10 eV, and then to the Lyman region to 30 eV. With the development of extreme VUV for nanoelectronics based on contemporary advances in nanophotolithography, synchrotron radiation metrology can be used to determine the dimensions of microcircuit elements down to several nanometers at photon energies of about 100 eV [3, 4]. With the creation of the Metrological Light Source (MLS) storage ring at the National Metrological Institute RTV (Berlin), spectroradiometric work began on the use of synchrotron radiation to access the terahertz range for photon energies ranging from 10^{-2} to 10^{-3} eV [5]. Meanwhile, the Siberia-1 and Siberia-2 ESRs hosted at the Kurchatov Institute in Russia are also engaged in developing spectroradiometric methods using synchrotron radiation. Thus, synchrotron radiation has been instrumental in providing absolute spectral measurements at the world's leading national metrological centers across a wide range of wavelengths from radio frequencies to X-rays.

In national metrological centers, fundamental and applied metrological research is not only carried out using synchrotron radiation in the extreme VUV and terahertz ranges, but also in the visible and near infrared (IR) regions of the spectrum, where the successful solution of certain challenging metrological problems involved in the study of the metrological characteristics of LEDs, multi-element array receivers, as well as

[1] Decree of the President of the Russian Federation of July 25, 2019 No. 356 "On measures to develop synchrotron and neutron research and research infrastructure in the Russian Federation" (in Russ.).

[2] Decree of the Government of the Russian Federation of March 16, 2020 No. 287 "On Approval of the Federal Scientific and Technical Program for the Development of Synchrotron and Neutron Research and Research Infrastructure for 2019–2027" (in Russ.).

[3] Deutsches Elektronen-Synchrotron—German electronic synchrotron (National Research Center DESY, Germany).

CCD[4] cameras and telescopes, depends directly on the properties of a reference source of synchrotron radiation.

METHODOLOGY AND APPARATUS FOR MEASUREMENTS

In accordance with the existing GOST 8.888-2015[5], GOST R 54814-2018[6], and GOST R.8.749-2011[7] standards, the main tasks in the study of the metrological characteristics of LEDs involve measurements of the spectral power density of the radiation and the total radiation flux. Measurements of the metrological characteristics of LEDs are especially important for carrying out technological control in the production of emitters of white cold, neutral, and warm colors for the development of illumination and indication equipment used in land, aviation, and marine transport, as well as lighting products used for office, street and domestic purposes. The study of the electro-optical, luminosity, and thermal characteristics of semiconductor nanoheterostructures of solid-state radiation sources also requires the development of spectroradiometric methods. To determine the radiation characteristics of sources used in units of the spectral power density of radiation (SPDR), spectral comparators are used to integrate the spectral density of energy brightness (SDEB) within the radiating region and at a fixed solid angle [6].

When using synchrotron radiation in spectral radiometry, the main problem involves the need to take into account the complex angular dependence of the intensity of the polarization components [1]. The comparator for calibrating the SPDR of LEDs comprises focusing optics, a spectral device, light filters, and a radiation receiver. The method of transmitting a unit of SPDR on an electron storage ring should take into account two polarization components of synchrotron radiation whose oscillations lie in the electron orbit and perpendicular planes, respectively. The equation describing the comparator signal $i_{SR}(\lambda)$, which is proportional to the SPDR [7, 8] in the polarization components of the synchrotron radiation, is written as follows:

$$i_{SR}(\lambda) = \int_{\psi_0} I_{SR}^{\parallel}(\psi,\lambda)\tau^{\parallel}(\psi,\lambda)S^{\parallel}(\lambda)\Delta\lambda\Delta\varphi d\psi + \int_{\psi_0} I_{SR}^{\perp}(\psi,\lambda)\tau^{\perp}(\psi,\lambda)S^{\perp}(\lambda)\Delta\lambda\Delta\varphi d\psi, \quad (1)$$

where Ψ is the angle of deviation from the plane of the electron orbit; Ψ_0 is the aperture angle of deviation from the plane of the electron orbit; λ is the wavelength; $I_{SR}^{\parallel}(\psi,\lambda)$, $I_{SR}^{\perp}(\psi,\lambda)$ are the spectral power densities of synchrotron radiation polarized in the orbit and perpendicular planes, respectively; $\tau^{\parallel}(\psi,\lambda)$ and $\tau^{\perp}(\psi,\lambda)$ are the transmission coefficients of the comparator spectral device for radiation polarized in the orbital plane and perpendicular planes, respectively; $S^{\parallel}(\lambda)$, $S^{\perp}(\lambda)$ are the spectral sensitivities of the comparator detector for radiation polarized in the orbit and perpendicular planes, respectively; $\Delta\lambda$ is the spectral resolution of the comparator; $\Delta\varphi$ is the aperture angle of the comparator in the plane of the electron orbit.

As follows from Equation (1), metrological analysis is complicated when using a monochromator, photomultiplier, or spectral radiometer as part of a comparator, whose efficiency depends on the plane of polarization of the incident radiation. While a photodiode or CCD array can be used to eliminate the complex dependence of the signal on the degree of polarization, for spectral measurements, a normal incidence monochromator or set of interference filters is used [9, 10].

This allows Equation (1) for the comparator signal to be reduced to:

$$i_{SR}(\lambda) = S(\lambda)\Delta\lambda\Delta\varphi\Delta\tau\left[\int_{\psi_0} I_{SR}^{\parallel}(\psi,\lambda)d\psi + \int_{\psi_0} I_{SR}^{\perp}(\psi,\lambda)d\psi\right]. \quad (2)$$

For an LED, the equation describing the comparator signal $i_{LED}(\Omega, \lambda)$ in a fixed solid angle Ω, which is proportional to the spectral power density of the unpolarized radiation $I_{LED}(\Omega, \lambda)$ [11], has the form:

$$I_{LED}(\Omega, \lambda) = S(\lambda)\Delta\lambda\Delta\tau\Omega I_{LED}(\Omega, \lambda). \quad (3)$$

In order to take the polarization components into account in the system of equations (1) and (3) on the synchrotron radiation metrological channel of the ESR BESSY-II[8] in Berlin, the monochromator is rotated

[4] CCD is a charge-coupled device.

[5] GOST 8.888-2015. National Standard of the Russian Federation. State system for ensuring the uniformity of measurements. Reference Light-emitting diodes (LED) of noncoherent radiation. Technical requirements. Moscow: Standartinform; 2019 (in Russ.).

[6] GOST R 54814-2018. National Standard of the Russian Federation. Light emitting diodes (LED) and LED modules for general lighting and related equipment. Terms and definitions. Moscow: Standartinform; 2018 (in Russ.).

[7] GOST R 8.749-2011. National Standard of the Russian Federation. State system for ensuring the uniformity of measurements. Light-emitting diodes. Methods of photometric measurements. Moscow: Standartinform; 2019 (in Russ.).

[8] BESSY-II Electron storage ring is a third-generation synchrotron radiation source (Helmholtz-Zentrum Berlin, Germany). URL: https://www.helmholtz-berlin.de/forschung/quellen/bessy/index_en.html. Accessed December 10, 2021.

around the optical axis without violating the alignment. For a comparator with a small aperture angle relative to the plane of the electron orbit, only the polarization sigma-component of the synchrotron radiation is considered, which makes it possible to obtain a relatively simple solution for the spectral density of the radiation intensity of the LED in accordance with the Schwinger formula [12].

$$I_{\mathrm{LED}}(\Omega,\lambda) = 0.0273N(i_{\mathrm{LED}} / i_{\mathrm{SR}})\Delta\varphi(\mathrm{e}^2\mathrm{c} / \Omega R^3)\times \\ \times(\lambda_\mathrm{c} / \lambda)^4\gamma^8 \int\limits_{\psi_0} K_{2/3}^2(\lambda_\mathrm{c} / 2\lambda)d\psi, \quad (4)$$

where N is the number of electrons in the orbit; γ is the relativistic factor; e is the electron charge; R is the radius of the electron orbit; c is the speed of light; $K_{2/3}$ is MacDonald function; $\lambda_\mathrm{c} = (4/3)\pi R\gamma^{-3}$ is the critical wavelength.

For determining the electron energy and the relativistic factor on storage rings, electron bunch backscattered laser radiation allows the magnetic field induction to be measured in orbit alongside methods based on relative spectral measurements of the synchrotron radiation flux. The most accurate method for determining the number of electrons is based on the use of a telescope with a CCD array to isolate an individual electron in the orbit of the accelerator. The radius of the orbit is determined by the frequency of the accelerating field of the electron storage rings. To fulfill the condition $\Omega = \Delta\varphi\Psi_0$, the sizes of aperture diaphragms and the distance to the radiating point of the orbit are determined.

At wavelengths much greater than the critical λ_c (i.e., in the visible-, near UV-, and near IR regions of the spectrum), along with an increase in the aperture angle of the optical system of the comparator in the plane of the electron orbit Ψ_0 for the synchrotron radiation source, the integrated values of the SPDR in the total angle of deviation from the plane of the orbit (normalized to one electron) can only be determined by the radius of the orbit at the point of emission. This means that in the visible-, near UV-, and near IR regions of the spectrum, the accurate calculation of the spectral density integral of the synchrotron radiation intensity across all angles of deviation from the orbital plane is constant for each synchrotron radiation source and does not depend on the electron energy. This conclusion is especially important for metrological studies when creating primary spectroradiometric standards based on fundamental physical constants.

By integrating the SPDR of LEDs over different wavelengths, it is possible to determine the radiant and luminous intensity in a fixed solid angle taking into account the relative spectral luminous efficiency in accordance with GOST 8.332-2013[9]. In accordance with the recommendations of the International Commission on Illumination (CIE 127:2007[10]), the measurement of the radiation intensity in regime A is carried out at a distance of 316 mm in a solid angle of 0.001 sr; in regime B—at a distance of 100 mm in a solid angle of 0.01 sr. To determine the radiation intensity and luminous intensity of LEDs, integrated comparators including radiometers, photometers, or spectroradiometers are used [13]. Here the main difficulties are associated with the need of accurate measurements of the spectral correction coefficients of the comparator sensitivity in accordance with the recommendations of CIE 053-1982[11].

Spectral correction of the sensitivity of the luxmeter in accordance with regulatory documents is only carried out for five types of control emitters. This means that the spectral correction of the sensitivity of the luxmeter is mainly carried out at the maximum sensitivity in the "green" region, as well as on the falling wings in the "blue" and "red" regions of the spectrum. Since the relative spectral sensitivity of the luxmeter can differ from the relative spectral light efficiency by an order of magnitude, significant errors can occur, for example, when assessing the hazardous effects of radiation when using bright blue LEDs [14].

When using an integral radiometer, significant difficulties are encountered due to the practical impossibility of realizing the required top-hat profile in the relative spectral sensitivity of the radiometer. Therefore, the creation of universal integral radiometers and photometers for determining the radiation intensity and luminous intensity of a LED comprises a nontrivial metrological problem [14]. When using ESR, radiometers and photometers are calibrated in accordance with expression (4), while spectral correction coefficients are determined for specific types of emitters and comparators. The use of spectroradiometers calibrated with respect to synchrotron radiation allows the values of the radiation intensity and luminous intensity to be obtained by integrating signals proportional to the SPDR of LEDs. However, here it is necessary to consider the level of scattered radiation, higher diffraction orders, and the impact of the degree of polarization of synchrotron radiation [16].

[9] GOST 8.332-2013. Interstate Standard. State system for ensuring the uniformity of measurements. Light measurements. Values of relative spectral luminous efficiency function of monochromatic radiation for photopic vision. Moscow: Kodeks; 2015 (in Russ.).

[10] CIE 127:2007. Technical report "Measurement of LEDs". ISBN 978-3-901906-58-9.

[11] CIE 053-1982. Methods of characterizing the performance of radiometers and photometers. ISBN 978-92-9034-053-9.

When determining the total standard uncertainty of measurements of radiation intensity and luminous intensity, it is also necessary to consider the linearity range of sensitivity and noise, as well as the sensitivity threshold of the spectroradiometer's detectors.

The main difficulties encountered in measuring the characteristics of solid-state emitters are associated with the complex angular dependence of the SPDR and the high energy brightness of solid-state LED emitters [17]. When measuring the angular distribution of the radiation intensity of LEDs in metrological laboratories, goniometers are used to obtain the value of the radiation flux and luminous flux. Goniometer detectors include radiometers, photometers, spectroradiometers, and CCD arrays calibrated against a synchrotron radiation source.

When measuring the total flux, the detector is mounted on the movable arm of the goniometer and adjusted in horizontal and vertical planes to obtain the maximum signal. With step-by-step fixation of signals, the angular distribution of radiation intensity is determined. To improve the accuracy of measurements, the minimum step of the angle of rotation relative to the geometric axis of the LED is used. Depending on the angle of deviation from the geometric axis of the emitter and when the emitter is rotated around the geometric axis, the signals of the radiometer or photometer are normalized to the maximum signal of the angular distribution and measured in a solid angle fixed during calibration at the synchrotron radiation source.

By integrating the angular dependence of the normalized goniometer signals, it is possible to calculate the total radiation flux or luminous flux of the LED. However, this requires the processing of a large amount of information on measurements involving angle gradations of several thousand points, as well as involving significant measurement time due to the need to stabilize the LED power regime and maintain the thermal regime. Measurement of the total radiation flux using a goniometer is characterized by a significant systematic error due to the absolute calibration of the reference radiometer or photometer while taking into account the spectral sensitivity correction, setting the angle of rotation of the goniometer arm, measuring the distance from the detector to the center of rotation, angular resolution and angular step, noise of the radiometer or photometer, high scanning speed at the corners of the scattered radiation, and instability of the radiation source [18].

The use of highly sensitive multi-element detectors allows the measurement time to be reduced while maintaining the requirements of spectral sensitivity correction. A 3D computer diagram illustrating the results of measurements of the angular dependence of the LED radiation intensity is shown in Fig. 1.

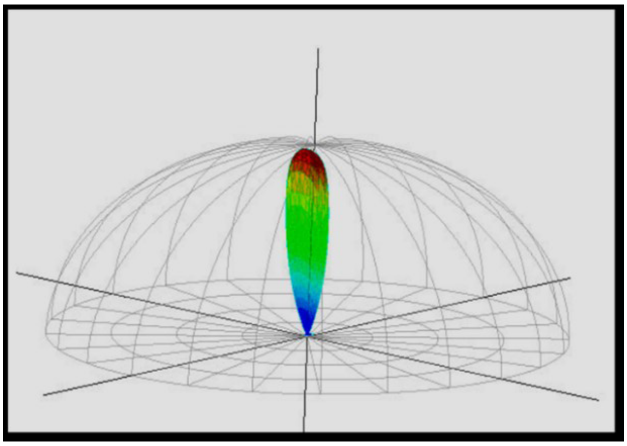

Fig. 1. 3D computer diagram depicting the results of measuring the angular dependence of the LED radiation intensity

The above example shows that the maximum of the radiation intensity angular distribution can be shifted relative to the axis of the LED, while the radiation flux is concentrated in a small solid angle. The resulting angular distribution allows the radiation intensity and flux to be determined in an arbitrary solid angle.

The corresponding 2D diagram is presented in Fig. 2. Here, the red line represents the half-width of the angular distribution of the LED radiation with a shift relative to the geometric axis.

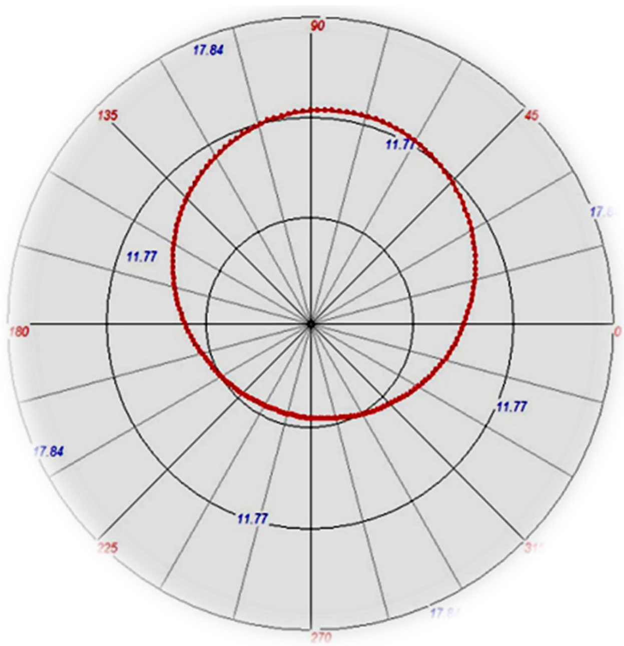

Fig. 2. 2D diagram of the half-width of the angular distribution of the LED radiation

In order to measure the luminous flux of high-power LEDs used for illumination, it is necessary to investigate the angular distribution of the radiation intensity according to the regime in which LEDs are used in working modules. A controllable heat sink is used to ensure the desired temperature when measuring the characteristics of high-power LEDs.

In spectroradiometry, it is particularly important to accurately measure the most differential characteristics of radiation, involving the spatial distribution of brightness and radiance of LEDs over the emitting region. The radiance comparator includes an optical system, a set of corrective filters and a cooled CCD matrix.

The calibration of the relative sensitivity of the pixels of the CCD array and measurement of the distribution of the radiance of various emitters is possible due to the Gaussian distribution of the radiance over the emitting region of the ESR electron bunch, which comprises a fundamental property of synchrotron radiation.

Figure 3 shows the results of registration of the Gaussian distribution of energy brightness over the radiating region of the ESR. Fig. 4 depicts the energy brightness across the emitting region of the LED [19].

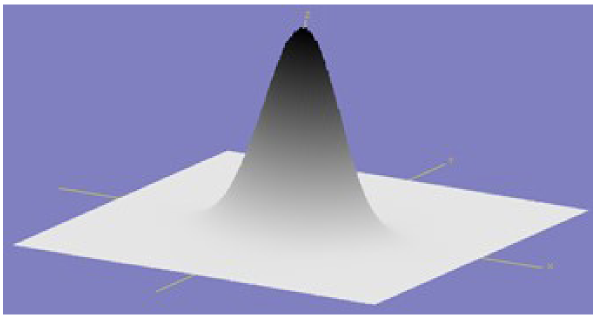

Fig. 3. Registered Gaussian distribution of brightness for emitting region of ESR

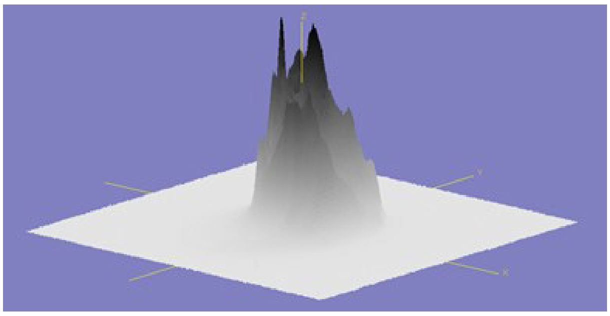

Fig. 4. Registered distribution of brightness for emitting region of the LED

The significant inhomogeneity of the LED's spatial brightness distribution is associated with the distortion of the distribution due to the focusing lens [20]. To eliminate this distortion over the radiating region, secondary reference LEDs featuring a specially shaped surface and temperature control using a Peltier element were developed (Fig. 5).

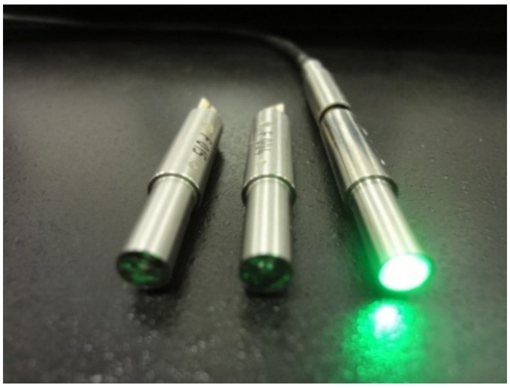

Fig. 5. Specially designed secondary reference LEDs

Figure 6 shows the results of measurements of the brightness distribution over the emitting area of the reference LED.

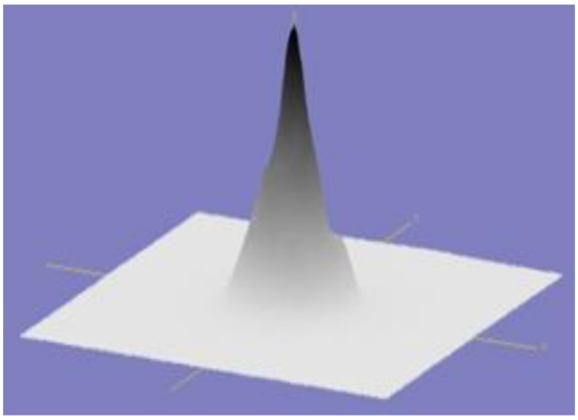

Fig. 6. Brightness distribution over the emitting area of the reference LED

To obtain the sensitivity of the comparator based on a telescope with a CCD array in accordance with the relative light efficiency, a set of corrective filters is used. This allows the spatial brightness distribution and average overall brightness to be measured to determine indicators of glare and visual discomfort of a light environment formed by super bright LED emitters.

The standard method for measuring the total radiation flux of an LED is based on an integrating sphere. This involves a correction of the spatial inhomogeneity of the diffuse reflection coefficient of the sphere surface, as well as the angular and spectral correction of the detector sensitivity [21]. To increase measurement accuracy, large diameter integrating spheres with a high ratio of sphere area to emitter size are used. In this case, the LED should be installed in the center of the integrating sphere in accordance with the CIE recommendations.

The LED calibration scheme and general view of the integrating sphere used are shown in Figs. 7 and 8. The radiation of an external reference source *6* or *7* enters the integrating sphere *1* through the aperture diaphragm and is detected by the radiation detector *2*. A photodiode or a CCD array with corrective filters, a photometer, a radiometer, or a spectroradiometer are used as the radiation detector *2*. The radiation of the calibrated LED *4* installed in the center of the integrating sphere is prevented from directly hitting the radiation receiver by screens *3*. The receiver *5* is used to detect radiation at the aperture diaphragm of the integrating sphere. External reference sources of radiation *6*, *7* and the receiver *5* are placed at an angle of 90°.

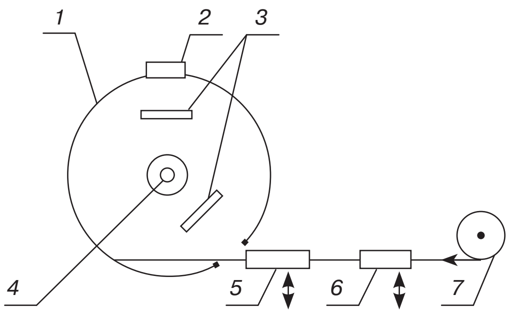

Fig. 7. Scheme for calibrating a LED on an integrating sphere using synchrotron radiation

Fig. 8. General view of the integrating sphere

The radiation flux from an external reference source is determined by integrating the radiation intensity within a solid angle fixed during the calibration against the synchrotron radiation source. The radiation flux from an internal LED source is determined by the ratio of the signals of the radiation receiver from external and internal sources along with correction factors that account for the imperfection of the integrating sphere [22].

In accordance with the CIE recommendations, correction factors are used during calibration to account for the spectral correction error relative to type A source, the inhomogeneity of the integrating sphere for internal and external radiation sources, and the difference in diffuse reflection coefficients of the sphere coating at different angles of incidence. The zonal inhomogeneity coefficient of the sensitivity of the sphere is determined by the angular dependence of the receiver signals, which allows the effects of screens, uneven coating thickness, and the state of the inner surface to be taken into account [23]. The sensitivity of the integrating sphere, which is calibrated according to the reproducibility of the metrological characteristics of ESR synchrotron radiation, is determined by the ratio of the signal received by the detector to the radiation flux at the input diaphragm.

CONCLUSIONS

In conclusion, the development of spectroradiometry methods developed for ESR metrological channels in Russia and abroad demonstrates synchrotron radiation source to comprise a high-precision primary standard used by national metrological centers to provide metrological support for the production of components in the electronics industry, as well as research and calibrations of radiometers, photometers and emitters (including LEDs), in the visible, UV, and IR regions of the electromagnetic spectrum.

Spectroradiometry methods based on the use of the fundamental properties of synchrotron radiation with a small emitting region and high radiation intensity and brightness controlled over a wide dynamic range can be used to provide absolute calibration of CCD-based telescopes and cameras, integrating spheres, goniophotometers, and spectroradiometers.

The spectroradiometric setup, which comprises a comparator based on a set of emitters, monochromator, telescope with a CCD array, spectroradiometer, radiometer, and photometer, allows the measurement of the full set of spectroradiometric and photometric characteristics of emitters used in the electronics industry—from the most differential SDEB distribution over the emitting region to integral total radiation flux.

When using a source of synchrotron radiation at wavelengths much longer than the critical one—that is, in the visible, near UV, and near IR regions of the spectrum—the integral values of SPDR in the full angle of deviation from the orbital plane normalized to the number of accelerated electrons are determined only by the radius of the orbit at the radiation point. These values, which do not depend on the energy of electrons and are calculated with high accuracy from fundamental physical constants, thus comprise invariable metrological characteristics for each source of synchrotron radiation.

Synchrotron radiation appears to be the most promising metrological approach for determining the metrological characteristics of LEDs, allowing the small size of the emitting region of synchrotron radiation compared to the emitting region of LEDs to be taken into account, as well as the Gaussian distribution of the brightness over the emitting region of the electron bunch of the synchrotron, the wide dynamic range of SPDR tuning due to changes in the energy and the number of accelerated electrons at wavelengths near critical.

Authors' contributions

A.S. Sigov—choice of the prospect area of research based on the use of methods and means of metrological support of modern technologies, such as nanophotolithography in the electronic industry; analysis and assessment of the results obtained.

N.B. Golovanova—assessment of the chosen research method effectiveness, participation in the choice of the experimental setup optimal composition in the study of characteristics of the electronics industry components, as well as in the calibration of radiometers and photometers of optical radiation.

O.A. Minaeva—conducting theoretical and experimental studies, participating in the development of a spectroradiometric installation for measuring the characteristics of radiation sources and receivers with traceability to a reference source of synchrotron radiation, estimating measurement errors.

S.I. Anevsky—conducting experimental spectroradiometric studies to solve fundamental metrological problems of reproduction and transmission of spectroradiometry units using the theoretical foundations of synchrotron radiation.

R.V. Shamin—theoretical justification for the use of a synchrotron radiation reference source to assess the characteristics of radiation sources and receivers.

O.I. Ostanina—participation in the measuring installation design, conducting measurements, and evaluation of metrological and technical characteristics of the developed measuring installation.

REFERENCES

1. Richter M., Ulm G. Metrology with Synchrotron Radiation. In: Jaeschke E., Khan S., Schneider J.R., Hastings J.B. (Eds.). *Synchrotron Light Sources and Free-Electron Lasers*. Springer; 2020. P. 1–35. https://doi.org/10.1007/978-3-319-04507-8_63-1
2. Li H., Li B., Wang S., Li Z., Qi J., Yu M., Huang Y., Li Y., Barboutis A., Lubeck J., Klein R., Kroth S., Paustian W., Ressin M., Thornagel R. Research on the irradiance calibration of a VUV dual-grating spectrometer based on synchrotron radiation. *Opt. Commun*. 2020;475:126254. https://doi.org/10.1016/j.optcom.2020.126254
3. Hurdax P., Hollerer M., Egger L., Koller G., Yang X., Haags A., Soubatch S., Tautz F.S., Richter M., Gottwald A., Puschnig P., Sterrer M., Ramsey M.G. Controlling the electronic and physical coupling on dielectric thin films. *Beilstein J. Nanotechnol*. 2020;11:1492–1503. https://doi.org/10.3762/bjnano.11.132
4. Chkhalo N.I., Gusev S.A., Nechay A.N., Pariev D.E., Polkovnikov V.N., Salashchenko N.N., et al. High-reflection Mo/Be/Si multilayers for EUV lithography. *Optic. Lett*. 2017;42(24):5070–5073. https://doi.org/10.1364/ol.42.005070
5. Steiger A., Kehrt M., Deninger A. A reference material for accurate THz measurements. In: *2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves* (*IRMMW-THz*). 2018:8510011. https://doi.org/10.1109/IRMMW-THz.2018.8510011
6. Sperling A., Meyer M., Pendsa S., Jordan W., Revtova E., Poikonen T., Renaux D., Blattner P. Multiple Transfer Standard for calibration and characterization of the setups for LED lamps and luminaires in industry. *Metrologia*. 2018;55(2):S37–S42. https://doi.org/10.1088/1681-7575/aaa173
7. Sigov A.S., Minaeva O.A., Anevsky S.I., Lebedev A.M., Minaev R.V. Metrological studies of the characteristics of multilayer surface coatings using synchrotron radiation. *Rossiiskii tekhnologicheskii zhurnal = Russian Technological Journal*. 2021;9(1):38–47 (in Russ.). https://doi.org/10.32362/2500-316X-2021-9-1-38-47
8. Schneider P., Salffner K., Sperling A., Nevas S., Kröger I., Reiners T. Improved calibration strategy for luminous intensity. *J. Phys.: Conf. Series*. 2018;972(1):012016. https://doi.org/10.1088/1742-6596/972/1/012016
9. Klein R., Kroth S., Paustian W., Richter M., Thornagel R. PTB's radiometric scales for UV and VUV source calibration based on synchrotron radiation. *Metrologia*. 2018;55(3):386. https://doi.org/10.1088/1681-7575/aab803
10. Reichel T., Gottwald A., Kroth U., Laubis C., Scholze F. Developments in calibration of EUV and VUV detectors for solar orbiter instrumentation using synchrotron radiation. In: *Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray*, 990547990547-6. https://doi.org/10.1117/12.2231405
11. Sildoja M., Nevas S., Pape S., Pendsa S., Sperfeld P., Kemus F. LED-based UV monitoring source. In: *13th International Conference on New Developments and Applications in Optical Radiometry* (*NEWRAD 2017*), Proceedings. 2017: 92–93.
12. Schwihys J. On the classical radiarion of accelerated electrons. *Phys. Rev*. 1949;75(12):1912–1925. https://doi.org/10.1103/PhysRev.75.1912
13. Sildoja M., Nevas S., Kouremeti N., Gröbner J., Pape S., Pendsa S., Sperfeld P., Kemus F. LED-based UV source for monitoring spectroradiometer properties. *Metrologia*. 2018;55(3):97–103. https://doi.org/10.1088/1681-7575/aab639

14. Schmähling F., Wuebbeler G., Krueger U., Ruggaber B., Schmidt F., Taubert R.D., Sperling A., Elster C. Uncertainty evaluation and propagation for spectral measurements. *Color Reseach & Application*. 2018;43(1):6–16. https://doi.org/10.1002/col.22185
15. McEvoy H.C., Martin M-J., Steiner A., Schreiber E., Girard F., Battuello M., Sadli M., Ridoux P., Gutschwager B., Hollandt J., Diril A., Pehlivan Ö. Report on the measurement results for the EURAMET 658 extension: project to examine underlying parameters in radiance scale realization. *Metrologia*. 2018;55(1A):03001. https://doi.org/10.1088/0026-1394/55/1A/03001
16. Zuber R., Sperfeld P., Nevas S., Sildoja M. A stray light corrected array spectroradiometer for complex high dynamic range measurements in the UV spectral range. In: *13th International Conference on New Developments and Applications in Optical Radiometry* (*NEWRAD 2017*), Proceedings. 2017:65–66.
17. Kokka F., Poikonen T., Blattner P., Jost S., Ferrero S., Pulli T., Ngo M., Thorseth A., Gerloff T., Dekker P., Stuker F., Klej A., Ludwig K., Schneider M., Reiners T., Ikonen E. Development of LED illuminants for colorimetry and recommendation of white LED reference spectrum for photometry. *Metrologia*. 2018;55(4):526–534. https://doi.org/10.1088/1681-7575/aacae7
18. Ferrero A., Velázquez J.L., Pons A., Campos J. Index for the evaluation of the general photometric performance of photometers. *Opt. Express*. 2018;26(14):18633–18643. https://doi.org/10.1364/OE.26.018633
19. Gutschwager B., Hollandt J. Nonuniformity correction of infrared cameras by reading radiance temperatures with a spatially nonhomogeneous radiation source. *Meas. Sci. Technol*. 2017;28(1):015401. https://doi.org/10.1088/1361-6501/28/1/015401
20. Strothkämper C., Ferrero A., Koo A., Jaanson P., Ged G., Obein G., Källberg S., Audenaert J., Leloup F.B., Martínez-Verdú F.M., Perales E., Schirmacher A., Campos J. Multilateral spectral radiance factor scale comparison. *Appl. Opt*. 2017;56(7):1996–2006. https://doi.org/10.1364/ao.56.001996
21. Kokka A., Pulli T., Poikonen T., Askola J., Ikonen E. Fisheye camera method for spatial non-uniformity corrections in luminous flux measurements with integrating spheres. *Metrologia*. 2017;54(4):577–583. https://doi.org/10.1088/1681-7575/aa7cb7
22. Kokka A., Pulli T., Ferrero A., Dekker P., Thorseth A., Kliment P., Klej A., Gerloff T., Ludwig K., Poikonen T., Ikonen E. Validation of the fisheye camera method for spatial non-uniformity corrections in luminous flux measurements with integrating spheres. *Metrologia*. 2019;56(4):045002. https://doi.org/10.1088/1681-7575/ab17fe

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