Publishable Summary for 15SIB07 PhotoLED
Future Photometry Based on Solid-State Lighting Products

Overview

The aim of this project is to address the obsolescence of traditional tungsten filament standard lamp technology used in photometric calibrations and the need to support the introduction and uptake of new solid-state lighting (SSL) products. The project will develop and validate the basis for a new photometric system based on white light-emitting diodes (LEDs), by developing new LED standard lamps and measurement techniques supporting the specific properties of the new light sources and detector technology, including illuminance measurement of the new LED standard lamps without optical $V(\lambda)$-filters in calibrations of photometers and measurement facilities used for determining the energy efficiency of new SSL products coming to market.

Need

Classical photometry relies heavily on the use of incandescent standard lamps and $V(\lambda)$-filtered photometers as transfer standards in calibrations of luminous intensity, luminous flux and photometer illuminance responsivity. Photometric measurement methods and illuminants, i.e. spectral data of different types of light sources, used in colorimetric analysis of lighting were established long before SSL products became available. As the spectral responsivities of $V(\lambda)$-filtered photometers differ from the $V(\lambda)$ curve defined by the International Commission on Illumination (CIE), all photometers are typically calibrated using incandescent standard lamps with spectral power distributions (SPDs) close to the CIE Standard Illuminant A that describes typical incandescent lighting with correlated colour temperature of 2856 K.

During the last few years, the phasing out of consumer tungsten filament lamps has changed the lighting market and the work of test laboratories and other companies involved in measurement of light. Users of photometric instruments no longer measure incandescent lighting, but more often SSL products based on white LEDs. However, all typical photometric instruments are still calibrated using incandescent light spectrum. Spectral errors are perceived in measurements of other types of light, including SSL, due to the optical $V(\lambda)$ filters used in photometers, and the differences between the SPDs of two types of light sources. In addition, some typical incandescent standard lamp types used in photometric calibrations have disappeared from the market, so there is a need to develop new LED illuminants and LED reference spectra with agreed SPDs for colorimetry and photometry, including new LED standard lamps for calibrations that are based on a technology that is widely available and spectrally compatible with measurements of SSL products.

Luminous flux (lm) and active electrical power consumption (W) of new SSL products coming to market are measured by test laboratories to determine the luminous efficacy (lm/W) and energy classification of the products. The luminous flux is often measured using an integrating sphere photometer that allows quick and convenient testing of SSL products compared to mechanically more demanding and time consuming measurements with goniophotometers. Typically the highest sources of uncertainty in measurement of luminous flux of SSL products using an integrating sphere are due to the spectral and angular errors that originate from the measurement system and the differences between incandescent calibration lamps and SSL products under test. Correcting for these errors often requires NMI-level expertise and time-consuming measurements. New LED standard lamps with well-defined spectra and a new quicker method for determining angular corrections for SSL products in measurements with integrating spheres need to be developed for photometric calibrations to reduce uncertainties and enable more reliable testing and classification of new SSL products coming to market.

Objectives

The overall aim of the project is to develop and validate the performance of a new photometric system based on white LED sources, including new transfer standard lamps and supporting measurement techniques that will complement and eventually replace the classical photometric system based around tungsten filament lamps. The specific technical objectives of the project are:

1. **To develop LED illuminants and LED reference spectra that can complement or replace the CIE Standard Illuminant A** in photometric calibrations and in analysis of colorimetric parameters and to evaluate the consequences of the defined new spectra.
2. **To develop new LED standard lamps for dissemination and maintenance of the units of luminous intensity, illuminance and luminous flux triggered by the ban on incandescent lamps.** The new LED standard lamps will be optimised for compatibility with existing calibration facilities, spectral properties close to the defined LED reference spectra, well-defined angular uniformity, long lifetime and temporal stability of electrical (DC- or AC-operation), photometric and colorimetric characteristics to enable low uncertainties in measurements of their photometric and radiometric properties.
3. **To develop new photometers and photometric measurement methods that enable illuminance measurement of the new LED standard lamps with uncertainties as low as 0.2 % (k = 2)** in the primary realisation of photometric units, or in calibrations of photometer illuminance or luminous flux responsivities at NMIs, accompanied by high-end spectral irradiance measurement of the new standard lamps with uncertainties as low as 0.4 %.
4. **To reduce the uncertainties of luminous flux and luminous efficacy measurement of solid-state lighting (SSL) products** at national metrology institutes to 0.5 % (k = 2) and to demonstrate that uncertainties as low as 1 % (k = 2) can be achieved in a test laboratory.
5. **To facilitate the uptake of the measurement methods developed by the project** by the measurement supply chain, ensuring traceability of measurement results to the end users (test laboratories, lighting manufacturers) and contribute to the development of standards by the international standardisation committees (CIE) concerning solid state lighting.

Progress beyond the state of the art

For the new LED-based photometric system, new LED illuminants, i.e. defined SPDs of specific types of lighting that provide the basis for comparing images or colours recorded under different lighting conditions, will be defined that describe typical SSL products. From the LED illuminants, a well-chosen subset of SPDs will be selected as LED reference spectra that will form the basis for development of the new physical LED standard lamps to complement the existing incandescent standard lamps in photometric calibrations. Recent studies have shown that the spectral errors in measurements of SSL products can be reduced by a factor of three on average in testing of SSL products and in field measurements of SSL by utilising two LED standard lamps with warm and cold white spectra in calibrations of photometer illuminance responsivity. Due to the limited spectral bandwidth of white LEDs (approximately 380 – 850 nm), the illuminance of an LED standard lamp can be measured with novel detector technology without an optical $V(\lambda)$ filter. Instead, the photometric weighting can be made numerically with accurate measurement of the LED spectrum during calibration of photometric instruments for measurements of SSL.

Photometry based on modern LED technology will provide an alternative to the classical photometric methods used at NMIs and at test laboratories. The new standard lamps based on white LEDs will enable the units of luminous intensity, illuminance and luminous flux to be transferred from NMIs to industrial test laboratories and allow calibration of photometers and testing of SSL products with lower uncertainties due to spectral properties compatible with typical SSL products. In addition to providing new LED transfer standard lamps and measurement methods for general photometric calibrations, a new revolutionary fish-eye-camera method for measuring the angular intensity distribution of SSL products quickly and reliably without a large goniophotometer will be developed for the use in the integrating spheres of test laboratories. By utilising these new methods, it is expected that test laboratories will be able to drastically reduce the spectral and angular errors, and measure luminous efficacy of SSL products with uncertainties as low as 1 %.

Results

LED illuminants and reference spectra

During the first year of the project, a total of 1500 spectral power distributions of white LED products were measured and collected from the partners and stakeholders for the analysis of new LED illuminants and LED reference spectra. The white LED spectra that were based on phosphor-converted blue LEDs were categorised according to their correlated colour temperatures (CCTs) into 8 different bins between 2700 K and 6500 K. In addition, 4 special shapes including red, green, blue (RGB) and phosphor-converted ultraviolet LEDs were chosen as potential LED illuminants for colorimetry. The project submitted the analysed LED illuminants to TC1-85 of CIE Division 1 for consideration to be included as possible LED illuminants in a revision of the CIE Technical Report no. 15: Colorimetry, 4th Edition. This document, with the LED illuminants, was published in October 2018, and is available from CIE.

Based on discussions with CIE Division 1 and Division 2, it was found important that the LED reference spectra used in photometry should be a subset of the LED illuminants used in colorimetry. On this basis, the LED illuminants were used as the starting point for analysing suitable LED reference spectra for illuminance responsivity calibration of photometers and which of them would lead to the smallest spectral errors in measurements of light with different SPDs. The analysis was carried out using Monte-Carlo simulation, including calculation of spectral mismatch errors for measurements of the 1500 LED products using the relative spectral responsivity data of over 100 real photometers and SPDs of 8 analysed LED illuminants as possible LED reference spectra. The results show that a single LED reference spectrum with CCT close to 4100 K would lead to the smallest spectral errors on average, when measuring SSL products of different types, reducing spectral errors by a factor of two on average compared to using an incandescent source with the CIE Standard Illuminant A spectrum for calibration of the photometers. Using two different LED reference spectra in the calibration would reduce the spectral errors by a factor of three on average. However, using two LED reference spectra would require laboratories to invest in two physical calibration sources and require the customer to estimate the CCT of light being measured in the field and using that information to select one of the calibration factors available. Taking into account the possibility of user error in selecting the correct CCT of light in the analysis, it was evident that the selection of a single LED reference spectrum for calibration of photometers was the optimal solution, drastically simplifying the method proposed for the end users. Further tests with the 4100 K LED reference spectrum showed that it led to the smallest spectral errors even in the case of measuring sources other than SSL, including daylight, fluorescent and high-pressure discharge lamps. A calibration source with 4100 K LED reference spectrum performed best in all cases, except when measuring incandescent light and one type of discharge lamp. The results of this spectral analysis have been published by A. Kokka *et. al.* [1].

The influence of the LED reference spectrum on the CIE general $V(\lambda)$ mismatch index f_1' was studied using the different LED illuminants. It was found out that the smallest changes in the calculated f_1' values for photometers can be obtained using the 4100 K LED reference spectrum, as compared to the CIE Standard Illuminant A that is currently used in the definition of the mismatch index f_1', further supporting the selection of the 4100 K spectrum as an LED reference spectrum. A proposal for an alternative calculation method for the mismatch index f_1', including influence of LED spectra in combination with broadband spectra, has been studied and published by A. Ferrero *et. al.* [2]. The results show that it is possible to define an alternative mismatch index which has better correlation between the spectral errors in measurements of light of different types and the calculated mismatch index for the photometer. The new mismatch index has been presented to CIE Division 2 for consideration to be taken into use in the future.

Based on this extensive analysis, the project has selected the 4100 K LED reference spectrum for selection of suitable LEDs for the new LED standard lamps of the project.

LED standard lamps for photometry

The project has developed new photometric standard lamps for luminous intensity and luminous flux. Using the new LED reference spectrum as the basis, suitable LEDs were selected for the new standard lamps using the expertise of the project's industrial partners. The mechanical, electrical and optical specifications of the new standard lamps have been investigated. For luminous intensity, a source consisting of multiple white LEDs with output aperture and luminous intensity similar to those of a Wi41/G standard lamp was developed. The source can be operated with a laboratory DC current source and an external thermoelectric controller (TEC). A total of 8 standard lamps for luminous intensity were constructed, including seasoning of 1000 h and full characterisation of their luminous intensity, stability and spectral properties.

The project has developed three types of luminous flux standard lamps with E27-base to ensure compatible with existing measurement facilities. All lamps produce approximately 800 lm of total luminous flux. Lamp A operates with DC-voltage and includes built-in precision current source and a TEC that control the LED PCB temperature by heating. Lamp B operates directly with DC-current supplied by external laboratory DC current source. Lamp C operates with 230 V AC voltage and is supplied by external laboratory AC voltage source. This lamp consists of a constant power AC/DC converter [3] and it is aimed at test laboratories who prefer to calibrate their measurement system without changing the voltage source or wiring. The first individual prototypes of all three luminous flux standard lamps were assembled and tested in November 2018. A total of 6 lamps of each type will be constructed by the end of the year, after which they will be aged for up to 1000 h, and characterised for electrical, photometric and radiometric properties.

During the ongoing work being carried out by the project partners on the comparison of luminous intensity, the new standard lamps for luminous intensity were taken into use in September 2018. Measurements of photometer directional quality index f_2 have started as well, with aim to compare the results of the photometer characterisation with two LED intensity sources having CCTs close to 2700 K and 4000 K, and finally comparing the results with those obtained using incandescent standard lamps. The luminous flux standard lamps will be fully calibrated and taken into use as transfer standards of luminous flux in luminous efficacy comparison that will run on the 1st half of 2019 with the project partners.

New photometers and photometric measurement methods

New reference photometers based on the predictable quantum-efficient detector (PQED) of SIB57 NEWSTAR have been developed to be operated without optical $V(\lambda)$ filters, accompanied with specially characterised spectroradiometers, to allow illuminance measurement of the new luminous intensity LED standard lamps with uncertainties as low as 0.2 % ($k = 2$). New photometers based on commercial photodiodes have been manufactured and characterised for spectral responsivity. A new optical method for calibration of the area of the precision entrance aperture of the new detectors was tested for the first time. The method is based on scanning the aperture with a laser beam, while the aperture and the detector are moved in front of the laser beam as a single package using a a precision linear xy-translator. The new method was compared with existing mechanical and machine vision area measurement methods. The results of the methods are in agreement, with the new optical method showing a potential to provide lower uncertainty than the existing methods used, for most aperture area calibrations. The new reference photometers allow calibration of illuminance responsivity of $V(\lambda)$-filtered standard photometers using LED standard lamps built using the new LED reference spectrum. In the case of the room-temperature PQED, the calibration is carried out directly against the new primary standard of optical power used at NMIs.

Reducing uncertainties of luminous flux and luminous efficacy of SSL products

The new LED standard lamps for luminous flux will allow the unit of luminous flux to be transferred from NMIs to test laboratories for calibration of integrating sphere photometers that are used for measuring luminous flux and efficacy of new SSL products. Due to the new LED technology used in the transfer standard lamps, spectral errors when testing SSL products will be reduced to 1/2 on average, compared to using incandescent standard lamps for the calibration of the system responsivity.

Furthermore a fisheye camera method has been developed as a quick and reliable way to measure the angular intensity distribution of light sources during measurements with integrating spheres. The system consists of a camera module, fisheye lens, port adapter and automated measurement software. The principle of the method, results of the first test measurements and the practical use of the measurement system have been published by A. Kokka *et. al.* [4]. A large measurement campaign with the fisheye camera method was carried out during 2018, measuring different types of LED lamps with several different integrating spheres and goniophotometers. The results show that the spatial nonuniformity corrections measured with the fisheye camera method differ from those obtained using goniophotometers by 0.05 % on average, with maximum observed deviation of 0.22 %. The results of the validation measurements will be published as a scientific paper early 2019.

Impact

The first Stakeholder Workshop to gather input from CIE and industry for the development of LED calibration spectra and standard lamps was held on 11 May 2017 at METAS, Switzerland. The workshop was arranged during the CIE Tutorial and Practical Workshop on LED Lamp and Luminaire Testing to CIE S025 with a total of 36 participants from test laboratories, instruments manufacturers and people working in CIE TCs. The project participated actively in the CIE 2017 Midterm Meeting on Jeju, Korea in October 2017 with a total of 5 talks and 1 poster on topics related to the new LED illuminants, LED reference spectrum and the new measurement methods under development. In addition, a workshop and a dedicated meeting of two hours was arranged with a total of 30 participants, including 7 PhotoLED partners, to agree the start of a new technical committee on defining the LED reference spectrum within the CIE.

The project partners submitted 8 abstracts for the CIE 29th Quadrennial Session, to be held in Washington DC, USA, in June 2019. A training session will be organised in january 2019 for the members of Euramet TC-PR in their annual meeting at IPQ, Portugal. Furthermore, two training sessions are planned for the stakeholders in 2019. The first stakeholder training will focus on illuminance measurement of LED standard lamps with unfiltered detectors. The second stakeholder training will be arranged to coincide with the final meeting of the project. All light sources developed in the project will be presented. The training session will also focus on calibration of integrating sphere photometers using LED standard lamps, and measuring angular intensity distribution of SSL products with the fisheye camera method.

Impact on industrial and other user communities
This project is envisaged to change the way how the lighting industry will utilise photometry in the future. The project will demonstrate that the classical tungsten filament standard lamps can be replaced by standard lamps based on SSL technology that will offer much smaller spectral errors in measurements of SSL products, reduced signal noise, better stability, robustness and lifetime, for maintaining photometric scales in laboratories and shipping of the lamps between NMIs and test laboratories.

Achieving lower uncertainties in photometric measurements of SSL products will benefit the lighting industry and consumers. Manufacturers of SSL products will be better able to rely on the measurement results from test laboratories, thus speeding up product development and enabling better judgement of the performance of new products coming to market. With the development of a coherent and efficient European metrological infrastructure based on LED-based photometric standards, new measuring instruments and supporting measurement methods, as well as written standards, the benefits of SSL products such as energy efficiency, will be assured and market penetration will be increased.

Impact on the metrology and scientific communities
This project will not only contribute to solving the metrological problems caused by phasing out of incandescent standard lamps, but will also lead to an improved scientific and technical system of photometry for the measurement of LEDs and other SSL products for the benefit of the society which better reflects the characteristics and requirements of these type of lighting products.

Impact on relevant standards
This project is speeding up the work of CIE TCs to update the existing standards and technical reports which describe the recommended methods used in photometry and colorimetry. The development of the new LED illuminants and LED reference spectrum have been carried out with close connections to CIE since the start of the project, with both Division 1 and 2 included in the discussions. The project has been actively communicating with CIE TC1-85 related to the development of the new LED illuminants. These illuminants are now included in the revision of the CIE15: Colorimetry, 4th Edition, enabling colorimetric calculations with LED spectra of different types. The project partners participate in many TCs of CIE Division 2 to ensure that the introduction of new physical LED standard lamps and supporting measurement methods will be included in these technical documents. In June 2018, a new CIE Division 2 Technical Committee TC2-90 'LED reference spectrum for photometer calibration' was established to further analyse and publish the LED reference spectrum as a CIE Technical Report. Once the document has been published, commercial LED standard lamps with CIE recommended spectral properties will become available.

Longer-term economic, social and environmental impacts
The results of the project will enable more reliable classification of energy efficiency of lighting products based on SSL technology. When new technologies reach the market, the consumer will have better confidence in the stated performance of the products, i.e. the values printed on the box, thus enabling them to make more informed choices. A sound metrological framework is the backbone of all accurate measurements. Low uncertainties obtained by high quality measurements increase the confidence in the products and enable better differentiation between the characteristics of various products. Achieving lower uncertainties in the testing of SSL products will also result in less waste and reduced costs for manufacturers due to fewer SSL products being erroneously rejected from entering the market because of the use of large guard bands in determining the energy classes of products

List of publications

[1] A. Kokka, T. Poikonen, P. Blattner, S. Jost, A. Ferrero, T. Pulli, M. Ngo, A. Thorseth, T. Gerloff, P. Dekker, F. Stuker, A. Klej, K. Ludwig, M. Schneider, T. Reiners and E. Ikonen, "Development of LED illuminants and reference spectrum for colorimetry and photometry," *Metrologia* **55**, 526-534 (2018). https://iopscience.iop.org/article/10.1088/1681-7575/aacae7/meta

[2] A. Ferrero, J.L. Velázquez, A. Pons, and J. Campos, "Index for the evaluation of the photometric performance of photometers," *Opt. Express* **26**, 18633-18643 (2018). https://doi.org/10.1364/OE.26.018633

[3] Z. Yiting, *Development of Transfer Standards for SSL Measurement*, Master's thesis (Delft University of Technology, Netherlands, 2017). http://resolver.tudelft.nl/uuid:dd6df3c3-fb96-4fbe-8cfe-56d664d2d9b4

[4] A. Kokka, T. Pulli, T. Poikonen, J. Askola, and E. Ikonen, "Fisheye camera method for spatial non-uniformity corrections in luminous flux measurements with integrating spheres," *Metrologia* **54**, 577–583 (2017). https://iopscience.iop.org/article/10.1088/1681-7575/aa7cb7/meta

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