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 incandescent 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 incandescent 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 equipment are still calibrated using incandescent light spectrum that causes spectral errors in measurements of 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, incandescent standard lamps used in photometric calibrations are disappearing from the market, so there is an urgent 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 class 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, and in many cases cannot be easily corrected for. 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 uncertainty 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 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 blue LEDs and phosphors 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 RGB (red, green, blue) and ultraviolet LEDs combined with phosphors were chosen as potential LED illuminants for colorimetry. The project has submitted the analysed LED illuminants to CIE Division 1 for consideration to be included as possible LED illuminants in a revision of the CIE Technical Report no. 15: Colorimetry which is expected to be published in 2018.

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 analysed in the project were used as the starting point for determining how many LED reference spectra are needed for illuminance responsivity calibration of photometers and which of them would lead to the smallest spectral errors in measurements of light with different spectra. 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 4000 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 meausured 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 4000 K LED reference spectrum showed that it lead 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 4000 K LED reference spectrum performed best in all cases, except when measuring incandescent light and one type of discharge lamp. The influence of the LED reference spectrum on the CIE photometer spectral quality index f_1' was studied using the different LED illuminants. It was found out that the smallest change of the calculated f_1' values is obtained using the 4000 K LED reference spectrum instead of the CIE Standard illuminant A that is currently used in the definition of the quality index f_1', further supporting the selection of the 4000 K spectrum as an LED reference spectrum. A proposal for an alternative calculation of a corresponding quality index as f_1' including influence of LED spectra has been studied, and is currently under further investigation. Based on these results, the project has selected the 4000 K LED reference spectrum to be used in selection of suitable LEDs for the new LED standard lamps under development.

LED standard lamps for photometry

The project is developing new photometric standard lamps for luminous intensity and luminous flux. Using the new LED reference spectrum as the basis, suitable LEDs have been 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, the first prototypes being assembled and tested. The luminous intensity standard lamps will be operated using DC current. In the case of luminous flux standard lamps, two electrically different DC and AC versions will be built, and the driver for the AC-operated lamp and other boundary conditions has already been investigated. The new standard lamps will be fully characterised and evaluated in two different comparisons to demonstrate their applicability as direct replacements for obsolete incandescent standard lamps.

New photometers and photometric measurement methods

New reference photometers based on the predictable quantum-efficient detector (PQED) of SIB57 NEWSTAR are being developed to be operated without optical $V(\lambda)$ filters, accompanied with specially characterised spectroradiometers, to allow illuminance measurement of the new LED-based standard lamps with uncertainties as low as 0.2 % (k = 2). The design plan of the new photometers has been completed. The new photometers based on commercial photodiodes have been manufactured and are being characterised for spectral responsivity. New mechanical parts have been manufactured for the existing PQEDs, including precision apertures. Work is ongoing to calibrate the effective area of the new apertures using different optical methods, including a new method based on laser scanning and measurement with a PQED. The new reference photometer will allow calibration of illuminance responsivity of standard photometers using the new LED reference spectrum and the room-temperature PQED, 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 will allow the units of luminous intensity and luminous flux to be transferred from NMIs to test laboratories for the calibration of photometers and other systems, such as integrating spheres 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 in the testing will be reduced to 1/2 on average, compared to using incandescent standard lamps for the calibration of the system responsivity. Furthermore, the quick and convenient fish-eye camera method targeted specially for test laboratories will allow the angular intensity distribution of SSL products to be measured inside an integrating sphere, enabing the spatial non-uniformity correction to be used also in laboratories that do not have goniophotometers. Suitable camera modules for the fisheye camera method have been investigated. 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.* [1]. A wider measurement round for validation of the fisheye camera method has commenced with a group of LED lamps with different angular properties being measured with integrating sphere photometers and goniophotometers of different types. The results of the validation and comparison of angular intensity distributions will be published in a scientific paper by the partners during summer 2018.

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.

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 for developing the new LED illuminants. The project is participating in many other TCs of Division 2 to ensure that the introduction of new physical LED standard lamps and supporting measurement methods will be included in these technical documents. A proposal to establish a new CIE Division 2 TC was sent to CIE in January 2018 with aim of publishing the official LED reference spectrum for photometer calibrations.

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. 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).

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