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ORIGINAL ARTICLE

Advantages of white LED lamps and new detector technology in photometry

Tomi Pulli[1], Timo Dönsberg[1,2], Tuomas Poikonen[2], Farshid Manoocheri[1], Petri Kärhä[1] and Erkki Ikonen[1,2]

Light emitting diode (LED) lighting is becoming more and more popular, as incandescent lamps are being phased out globally. LEDs have several advantages over incandescent lamps, including energy efficiency, robustness, long lifetime, and good temporal stability. The three latter features make LEDs attractive candidates as new photometric standards. Because the spectra of white LEDs are limited to the visible wavelength range, a novel method for the realization of photometric units based on the predictable quantum efficient detector (PQED) can be utilized. The method eliminates the need of photometric filters that are traditionally used in photometry, and instead relies on carrying out the photometric weighting numerically based on the measured relative spectrum of the source. The PQED-based realization simplifies the traceability chain of photometric measurements significantly as compared with the traditional filter-based method. The measured illuminance values of a white LED deviate by only 0.03% when determined by the new and the traditional methods. The new PQED method has significantly lower expanded uncertainty of 0.26% ($k=2$) as compared with that of the traditional filter-based method of 0.42% ($k=2$). Furthermore, when filtered photometers that measure LED lighting are calibrated using LED lamps as calibration sources instead of incandescent lamps, a significant decrease in the uncertainty related to the spectral mismatch correction can be obtained. The maximum spectral mismatch errors of LED measurements decreased on average by a factor of 3 when switching from an incandescent lamp to an LED calibration source.

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INTRODUCTION

Incandescent lamps are phased out globally in favor of more energy-efficient solutions such as light emitting diodes (LEDs)[1,2,3,4,5]. This trend raises some important questions, since tungsten filament incandescent lamps are widely used as source standards in photometry[6,7,8,9,10]. For example, will tungsten filament standard lamps still be available in the future, and if so, what will be their price? Besides availability, would there be any benefits in using single LEDs or LED lamps as photometric standards? Perhaps most importantly, when lighting solutions based on LEDs are becoming more and more popular in the future, then is it reasonable or justified to continue using tungsten filament incandescent lamps as photometric standard lamps? This paper focuses on the latter two questions.

An obvious benefit of using LEDs as photometric source standards is that their lifetimes are typically much longer than those of incandescent lamps[11,12,13,14]. Certain LED lamps have also been shown to be exceptionally stable in terms of their luminous flux output[14]. LED lamps are more robust than incandescent lamps, which would make transportation and handling of the new standard lamps less cumbersome. Moreover, tailoring various properties of LED lamps to meet the needs of applications is relatively straightforward[15]. These properties include dimensions of the illuminating area, angular distribution of radiation, and the shape of the emission spectrum. Furthermore, the spectra of most white LED lamps – unlike those of incandescent lamps – do not extend needlessly to the ultraviolet (UV) or the infrared (IR) regions which are, by definition, of no interest in photometry.

In this paper, we discuss a new method[16] for the realization of photometric units that can be utilized when white LED lamps are used as light sources because their spectra are limited to the visible wavelength range. The method relies on an unfiltered detector with a known absolute responsivity and on carrying out the photometric weighting numerically based on the measured relative spectrum of the light source, thus eliminating the need of using photometric filters in the unit realization. When the predictable quantum efficient detector (PQED)[17,18,19] – a new primary standard for optical power that is based on an induced junction photodiode trap and that has a near unity quantum efficiency – is used as the broadband detector, high accuracy can be achieved, because the absolute spectral responsivity of the PQED can be predicted with a relative uncertainty of less than 0.01%[20,21]. We will demonstrate that the PQED method is more accurate than the photometer method when white LED lamps are used as light sources. The method will also be shown to simplify the traceability chain of photometric unit realization to known standards considerably. In addition to enabling a new method for photometric unit realization, LED-based photometric standard lamps significantly decrease the uncertainty component in photometric calibrations related to the spectral mismatch between the calibration source and

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[1]Metrology Research Institute, Aalto University, Espoo, Finland and [2]MIKES Metrology, VTT Technical Research Centre of Finland Ltd, Espoo, Finland
Correspondence: T Pulli, Email: tomi.pulli@aalto.fi

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the LED-based source to be measured as compared to the case of incandescent standard lamps. We will also demonstrate that it is possible to come up with practical definitions for LED-based standard illuminants.

MATERIALS AND METHODS

PQED-based method for realizing photometric units

Photometric quantities X_v can be calculated from the corresponding radiometric quantities $X_{e,\lambda}(\lambda)$ by taking into account the relative spectral responsivity of the human visual system, as[22,23]

$$X_v = K_m \int X_{e,\lambda}(\lambda)V(\lambda)d\lambda, \tag{1}$$

where $K_m = 683.002 \text{ lm W}^{-1}$ is the maximum luminous efficacy of photopic vision and λ is the wavelength in standard air. The luminous efficiency function $V(\lambda)$, defined by the CIE, describes the relative spectral responsivity of the human visual system for photopic vision.

Photometric measurements are typically carried out by using a photometer, i.e., a filtered detector whose normalized spectral responsivity $s_{rel}(\lambda)$ is close to the defined $V(\lambda)$ function. Before such an instrument can be used in absolute photometric measurements, it has to be calibrated. In a typical photometer calibration, the reading of the detector to be calibrated is compared with the reference value which is produced by a standard light source or by using a reference detector[6,7,8,10]. Tungsten filament incandescent lamps with a correlated color temperature $T_c = 2856$ K are commonly used as photometric standard light sources to approximate Standard Illuminant A which is defined by the CIE[24] to have a relative spectral power distribution of a Planckian radiator at 2856 K.

A typical reference photometer consists of a precision aperture, a photometric filter and a detector, usually a silicon photodiode or a photodiode-based trap detector. The illuminance E_v measured by such an instrument can be calculated as[10]

$$E_v = \frac{K_m}{As(\lambda_0)} F_r i, \tag{2}$$

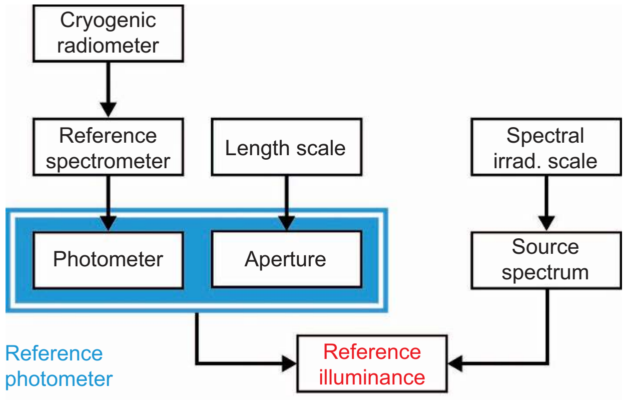
where i is the photocurrent given by the detector, A is the area of the precision aperture of the detector, and $s(\lambda_0)$ is the absolute spectral responsivity of the detector at the air wavelength of $\lambda_0 = 555$ nm. The spectral mismatch correction factor is defined as[10]

$$F_r = \frac{\int \Phi_{e,\lambda}(\lambda)V(\lambda)d\lambda}{\int \Phi_{e,\lambda}(\lambda)s_{rel}(\lambda)d\lambda}, \tag{3}$$

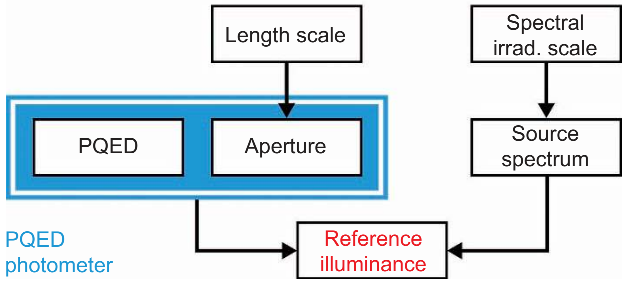
and can be derived with the aid of Equation (1) using the spectral radiant flux $\Phi_{e,\lambda}(\lambda)$ as the radiometric quantity $X_{e,\lambda}(\lambda)$. It should be noted that only the relative spectral radiant flux $\Phi_{e,\lambda}(\lambda)/\Phi_{e,\lambda}(\lambda_0)$ is important for Equation (3).

The main difference between the novel PQED-based method and the traditional photometer-based method for the realization of photometric units is that the former does not utilize filters of any kind. Instead, a room-temperature PQED[19] with a precision aperture and a nitrogen flow system to prevent dust and moisture contamination is used in combination with a spectroradiometer to carry out the measurement. The photometric weighting is performed numerically by applying the spectral mismatch correction of Equation (3). Though the relative spectral responsivity of the PQED – approximately $s_{rel}(\lambda) \approx \lambda/\lambda_0$ – is drastically dissimilar to the $V(\lambda)$ function, it can be modeled very accurately. This means that even though the spectral mismatch correction F_r may deviate significantly from unity, the uncertainty associated with this correction is still relatively small and determined mainly by the uncertainty in the relative spectrum of the light source $\Phi_{e,\lambda}(\lambda)/\Phi_{e,\lambda}(\lambda_0)$. The PQED-based method for the realization of photometric units can only be utilized when the spectrum of the light source is limited to the responsivity range of silicon photodiodes, as is the case with white LEDs. Because the PQED measures light propagating along the optical axis, the method is not suitable for general lighting measurements, typically carried out with photometers equipped with diffuser heads. Therefore, the use of the PQED method should be reserved for applications where the lowest possible uncertainties are required, such as the determination of the reference illuminance, needed for example during the calibration of laboratory-grade standard illuminance meters.

The PQED method for photometric unit realization has several advantages over the traditional photometer method. By eliminating the need to use a $V(\lambda)$ filter, we also get rid of associated problems such as the temporal and temperature drifts of the transmittance of the filter, and the drop in the signal level caused by the filter. The most significant advantage of the PQED method, however, is that it greatly simplifies the traceability chain of the photometric unit realization, which generally translates into lower uncertainty in the realization. This effect becomes evident when comparing the traceability chains of the traditional reference photometer method with the traceability chain of the PQED method illustrated in Figure 1. As the PQED is a primary standard for optical power, there is no need to transfer the traceability from the cryogenic radiometer. Moreover, as the spectral responsivity of the PQED is well known and as the $V(\lambda)$ filter is not used in the realization, a reference spectrometer is not needed for spectral responsivity determination.



(a) Photometer method



(b) PQED method

Figure 1 Traceability chains of (**a**) the traditional photometer method, and (**b**) the new PQED method for reference illuminance determination. irrad., irradiance.

It is possible to utilize a conventional photodiode-based trap detector[25] in place of the PQED to set the absolute level of the spectral irradiance measurement. However, the trap detector needs to be calibrated against the cryogenic radiometer and its spectral responsivity needs to be measured or modeled. It should also be possible, in theory, to determine the illuminance directly from the absolute spectral irradiance measurement carried out with a spectroradiometer using Equation (1). In practice, however, it may be difficult to reach sufficient accuracy with an absolute spectroradiometric measurement for this method to be competitive with the PQED-based method.

Comparison measurement

We compared the PQED- and the reference photometer-based methods for realizing photometric units by measuring the illuminance of a white LED lamp using both methods. The schematic of the measurement setup used in the comparison is shown in Figure 2. The setup consists of a light source, a set of baffles to block the stray light, as well as a linear translator with three detectors: the PQED, the reference photometer, and the diffuser head of a double-monochromator scanning spectroradiometer. The PQED and the reference photometer were equipped with precision apertures of 3 mm in diameter. The distance between the outermost part of the light source and the reference planes of the detectors was 3 m. The measurement setup was located in a light-tight enclosure. The photocurrents of the PQED and the reference photometer were measured using a combination of a current-to-voltage converter and a digital voltmeter. The current-to-voltage converters and digital voltmeters were calibrated on-site with a DC calibrator that is traceable to MIKES Metrology, the National Metrology Institute of Finland.

A commercial E27-base AC LED lamp was used as a light source in the comparison measurement. The relative spectrum of the light source, along with the $V(\lambda)$ function, is presented in Figure 3. The correlated color temperature of the lamp was 3018 K. The lamp was driven with a DC power supply in order to improve the stability of the lamp. Despite the relatively large diameter of the opaque dome of the LED lamp (58 mm), the fields of view of both the PQED and the reference photometer covered the illuminating area of the lamp at the distance of 3 m.

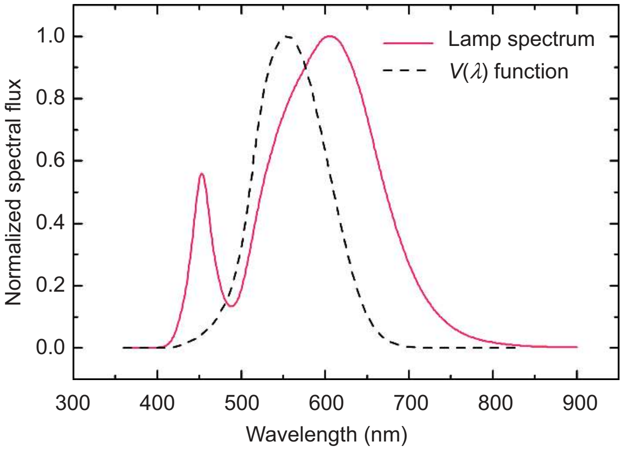


Figure 3 Normalized spectrum of the LED lamp and the $V(\lambda)$ function (dashed line).

Before the measurements, a two-beam alignment laser was used to visualize the optical axis, and the detectors were aligned so that the back-reflection of the beam from the detector was parallel with the optical axis with both detectors. The angles between the normals of the detector apertures and the optical axis were then measured. These angles were taken into account in the illuminance measurement by calculating the projected areas of the apertures on the plane perpendicular to the optical axis.

The comparison measurement was carried out by determining the illuminance of the lamp with the PQED and the reference photometer in sequence. The relative spectral irradiance of the lamp was then measured using the spectroradiometer in order to determine the spectral mismatch correction factors F_r of Equation (3) for both measurement methods.

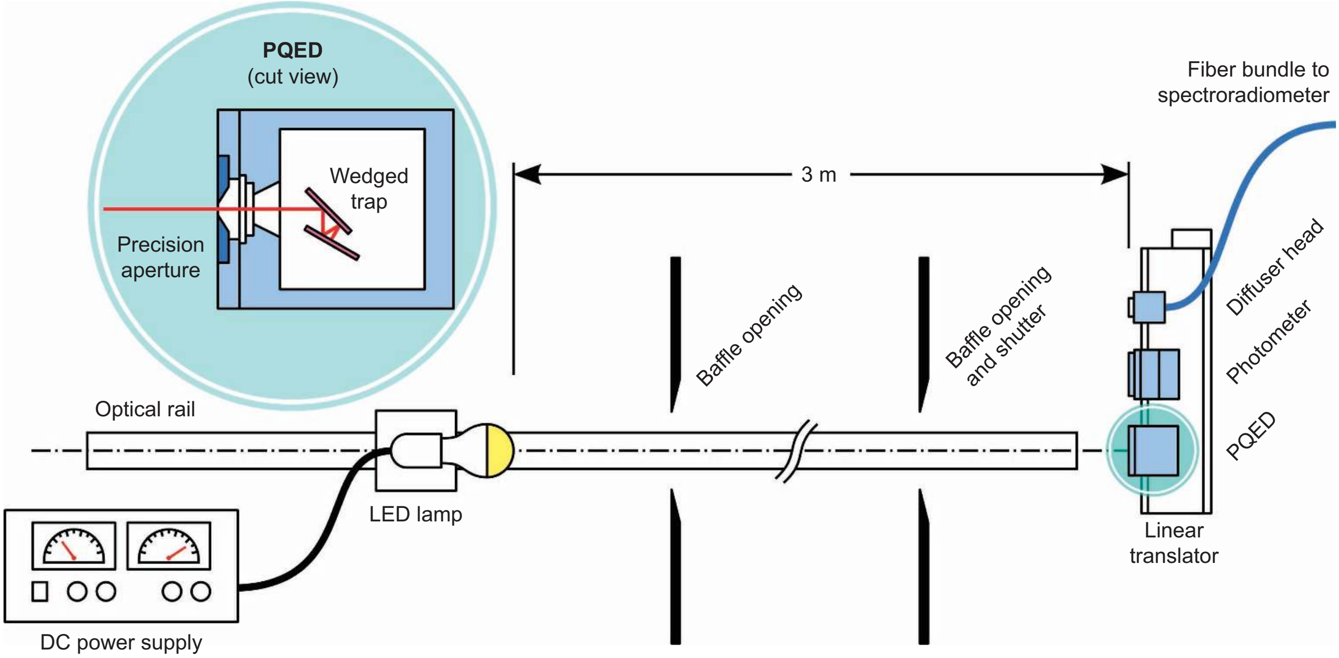


Figure 2 Schematic view of the measurement setup and of the PQED with a precision aperture (inset).

RESULTS AND DISCUSSION

Comparison measurement

The measured illuminance values with the PQED and the photometer were (12.178 ± 0.031) lx and (12.181 ± 0.050) lx, respectively, with a relative difference of 0.03%. The photocurrent of the PQED (136.0 nA) was significantly larger than the photocurrent of the reference photometer (30.19 nA). The spectral mismatch correction factors were 0.4254 and 0.9994 for the PQED and the photometer methods, respectively.

The uncertainty budgets of the illuminance realization for both measurement methods are given in Table 1. Most of the uncertainty components are the same or similar for both measurement methods. However, the absolute responsivity of the PQED[17] is known more accurately than that of the reference photometer. In case of the reference photometer, the accuracy of this parameter is severely limited by the repeatability of the spectral responsivity measurement.

The uncertainty related to the spectral mismatch correction factor F_r of the PQED method is dominated by the uncertainty of the measurement of the relative spectrum of the light source. The wavelength scale of the spectroradiometer was checked and corrected on-site using well-known laser wavelengths. The residual uncertainty of the wavelength scale was estimated to be less than 0.04 nm which translates into 0.03% standard uncertainty in the illuminance value of the PQED method. The effect of the uncertainty of the spectral irradiance scale on the measurement results was investigated by introducing a tilt of 1% across the visible wavelength range of the scale. In addition, the spectral irradiance scale was modified with a sinusoidal wave so that the peak-to-peak variation in the visible wavelength range was at most 1%. The period and the phase of the wave were varied in the analysis. The effect of these modifications of the spectral irradiance scale on the uncertainty of the illuminance measurement was less than 0.06%. The uncertainty due to the extrapolation of the spectrum below the noise floor of the measurement was estimated to be 0.08% for the PQED method. The uncertainty listed under F_r in Table 1 is the quadratic sum of the components discussed above. The effect of the spectral responsivity measurement on the uncertainty of the PQED method was negligible (<0.002%) when compared with other sources of uncertainty.

The uncertainty related to the spectral mismatch correction factor F_r of the reference photometer method is dominated by the uncertainty of the spectral responsivity measurement of the detector. The uncertainty of the wavelength scale of the spectral responsivity measurement (0.1 nm) was significantly higher than that of the spectral irradiance measurement of the light source due to the fact that the former relies on wavelength transmission standards instead of more accurate laser-based standards. This uncertainty in the wavelength scale translates into 0.10% standard uncertainty in the illuminance value of the reference photometer method. The other included source of uncertainty in the determination of F_r of the reference photometer method is the repeatability of the relative spectral responsivity measurement which caused 0.06% uncertainty in the results. The effect of the spectral irradiance measurement of the light source on the uncertainty of the photometer method was negligible (<0.002%) when compared with other sources of uncertainty. This is due to the fact that the spectral responsivity $s_{\mathrm{rel}}(\lambda)$ of the reference photometer is relatively close to the $V(\lambda)$ function, which means that small changes in the spectrum affect both the numerator and the denominator of Equation (3) in a similar way.

Table 1 Uncertainty budgets of the illuminance measurement for the reference photometer and the PQED methods

	Relative standard uncertainty (%)	
Source of uncertainty	Photometer	PQED
Absolute responsivity of the detector, $s(\lambda_0)$	0.15	0.007
Spectral mismatch correction factor, F_r		
Due to LED lamp spectrum	0.002	0.10
Due to relative spectral responsivity of the photometer/detector	0.12	0.002
Aperture area, A	0.07	0.07
Aperture alignment	0.02	0.02
Stray light	0.01	0.01
Photocurrent measurement, i	0.02	0.02
Combined standard uncertainty	0.21	0.13
Expanded uncertainty ($k = 2$)	0.42	0.26

The uncertainty component related to the aperture alignment consists of terms associated with the angular alignment of the aperture normals with respect to the optical axis as well as the spatial alignment of the apertures. The uncertainty in the former affects the reading through changes in the projected area of the aperture, while the uncertainty in the latter affects the results due to non-uniformity in illumination at the measurement plane[16]. The uncertainty component of stray light includes the light of the measurement source entering the detectors through reflections from the elements of the measurement setup, such as the baffles and the walls of the light-tight enclosure, as well as the light from any other source that might be seen by the detectors[16]. The uncertainty in the photocurrent measurement is dominated by the repeatability of the measurement, which in turn is affected by the drift and short-term fluctuations of the light source as well as the noise and drift of the current-to-voltage converters and digital voltmeters.

The PQED method has previously been compared with the traditional photometer method in the case of illuminance measurements of blue and red LEDs[16]. It was found out that the expanded uncertainty of the PQED method (0.34% to 0.36%) was much lower than that of the photometer method (0.92% to 1.01%), in large part due to the better control over the wavelength scale during the measurement. As the spectral bandwidth of the white LED lamp (see Figure 3) is much wider than that of the single color LEDs, the wavelength uncertainties of the measurements contribute less to the combined uncertainty of the measurement than in the case of red and blue LEDs[16]. For the same reason, extrapolation of the tail of the high energy side of the blue LEDs of the lamp becomes less critical. However, as the tail of the phosphor peak of the lamp falls relatively gently in the red and near-IR regions and as the responsivity of the PQED is at its highest in that region, the extrapolation of the low energy side of the spectrum is still a considerable source of uncertainty in the PQED-based measurements. The responsivity of the photomultiplier tube (PMT) of the spectroradiometer that was used in the comparison measurements decreased rapidly after the wavelength of about 800 nm. The uncertainty due to the extrapolation of the spectrum beyond the noise floor of the measurement can be lowered significantly in the future by using in the spectral measurement a detector that is more sensitive in the near-IR region. For the PQED method, it is also critical that the source does not have unaccounted spectral features in the UV and IR regions. This was tested by measuring the LED lamp at close range with an array spectrometer that is sensitive at these regions. No such features were detected.

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Toward LED-based illuminant

While the PQED-based method of photometric measurements can be utilized directly in, e.g., the illuminance measurement of point-like LEDs and LED lamps, it is not suitable for some measurements, such as those requiring a large field of view. Nevertheless, the PQED can still be utilized as an alternative to a reference photometer in the calibration of photometric measurement instruments, such as illuminance meters with diffuser entrance and integrating sphere photometers that are used to measure LED light sources. The PQED can also be used for calibrating luminance meters, provided that the spectrum of the luminance source is limited to the responsivity range of silicon photodiodes. While the measurement geometries of these calibrations differ somewhat from each other, the basic principle is always the same, i.e. the measurement of the LED-based standard source with both the PQED and the device under test.

Besides enabling a more accurate method for the realization of photometric units as compared with the traditional photometer method, LED-based photometric standard lamps can also reduce the uncertainty of photometric measurements in a more direct way. In addition to the uncertainty related to the calibration of the photometer, the combined uncertainty of a photometric measurement includes a component related to the spectral error which arises when the calibrated photometer is used to measure light sources whose spectral power distributions deviate from that of the calibration source. This occurs, for example, when a photometer is calibrated using an incandescent lamp but is then used to measure LED lighting[26].

The spectral error can be taken into account through a spectral mismatch correction factor[26]

$$F = \frac{\int \Phi_{\mathrm{source}}(\lambda)V(\lambda)d\lambda}{\int \Phi_{\mathrm{source}}(\lambda)s_{\mathrm{rel}}(\lambda)d\lambda} \cdot \frac{\int \Phi_{\mathrm{cal}}(\lambda)s_{\mathrm{rel}}(\lambda)d\lambda}{\int \Phi_{\mathrm{cal}}(\lambda)V(\lambda)d\lambda}, \tag{4}$$

where $\Phi_{\mathrm{cal}}(\lambda)$ and $\Phi_{\mathrm{source}}(\lambda)$ are the relative spectra of the calibration source and the lamp to be measured, respectively. Spectral mismatch correction factor has a value of unity when the photometer has ideal spectral responsivity, that is $s_{\mathrm{rel}}(\lambda) = V(\lambda)$, or when the spectra of the measurement and calibration sources have the same shape. If the spectral responsivity of the detector or the spectrum of the measured light source is not known, the correction cannot be applied. In this case, Equation (4) can be used to estimate the measurement uncertainty associated with the difference in the relative spectra of the calibration source and the source to be measured.

In order to study how the choice of the calibration light source and the photometer affects the spectral mismatch correction, we calculated F for different photometer and light source combinations. The spectral mismatch correction factors were calculated for three photometers, the reference photometer of Aalto University and two commercial photometers, with relatively good spectral responsivities to see how the differences in the responsivities affect the results. The normalized spectral responsivities of the three photometers, along with their absolute deviations from the $V(\lambda)$ function are shown in Figure 4. The quality factors f_1' of the photometers[27,28], which describe how well the spectral responsivities of the detectors approximate the ideal $V(\lambda)$ function, were 2.27%, 2.31%, and 1.80% for the reference photometer and the commercial photometers 1 and 2, respectively.

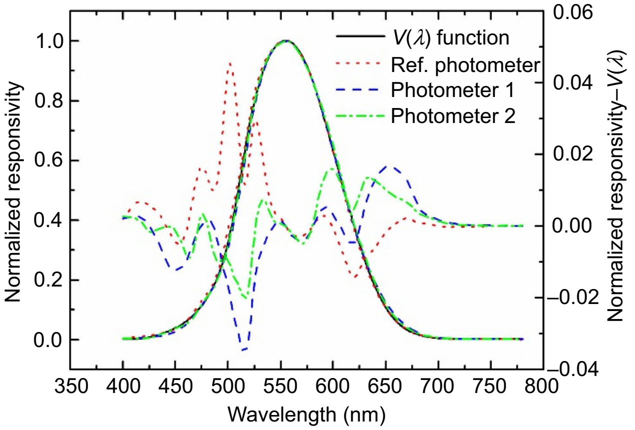

Figure 4 Normalized spectral responsivities of three photometers and their absolute deviations from the *V*(λ) function. Ref., Reference.

The spectra of 26 commercial E27-base LED lamps with relatively low correlated color temperatures (T_c = 2611–3332 K) and nine LED lamps with relatively high correlated color temperatures (T_c = 4178–8334 K) – denoted here as warm white and cool white LED lamps – were measured to be used as test sources in the analysis. The measured spectra of the LED lamps are shown in Figure 5. As there are no standardized LED-based illuminants at the time of writing, we generated two auxiliary LED illuminants by taking an average of the normalized spectra of the warm white and the cool white LED lamps. The spectra of two warm white LED lamps that contained red LEDs were excluded from the average. The warm white and the cool white LED-based illuminants, hereafter referred to as “Illuminant” $\mathrm{L_W}$ and “Illuminant” $\mathrm{L_C}$, along with Illuminant A were used as the spectra of the calibration sources in the spectral mismatch correction analysis. The correlated color temperatures of “Illuminants” $\mathrm{L_W}$ and $\mathrm{L_C}$ were 2935 K and 5716 K, respectively. The spectra of the generated illuminants are also shown in Figure 5.

Table 2 lists the spectral mismatch correction factors for different types of photometers, sources to be measured, and calibration illuminants. The numbers listed in Table 2 are an average of $(F-1)\cdot 100\%$ over all the sources to be measured within a given lamp type. The maximum deviations from the ideal case ($F = 1$) are marked in parenthesis for each measurement source and calibration illuminant combination.

As is expected, the spectral mismatch correction is unity when the spectra of the measurement and calibration sources match perfectly and close to unity when the two spectra are very similar to each other (red diagonals in Table 2). Conversely, a large spectral mismatch error is produced if the two spectra are drastically dissimilar. To alleviate this problem, CIE recommends using in LED measurements photometers with relatively good spectral responsivities ($f_1' < 3\%$), or the method of “strict substitution” where the test LED is compared to a standard LED “having the same color”[26]. The results of the analysis show that the average errors are considerable for Standard Illuminant A calibrated photometers – up to 0.53% for warm white and up to 1.36% for cool white LED lamps – even though the quality factors f_1' of the tested photometers are well below 3%. By using “Illuminants” $\mathrm{L_W}$ and $\mathrm{L_C}$ for the calibration of photometers measuring warm white and cool white LEDs, respectively, the average error related to the spectral mismatch correction can be reduced to below 0.05%. The worst case error is also reduced significantly when switching from Illuminant A calibration source to an appropriate LED illuminant, even though the spectra of the LEDs to be measured and the LED illuminant can deviate considerably (see Figure 5) and the substitution cannot be considered “strict”. Therefore, switching to LED-based standard lamps can lead to a significant improvement in the accuracy of photometric measurements in applications where F is not routinely

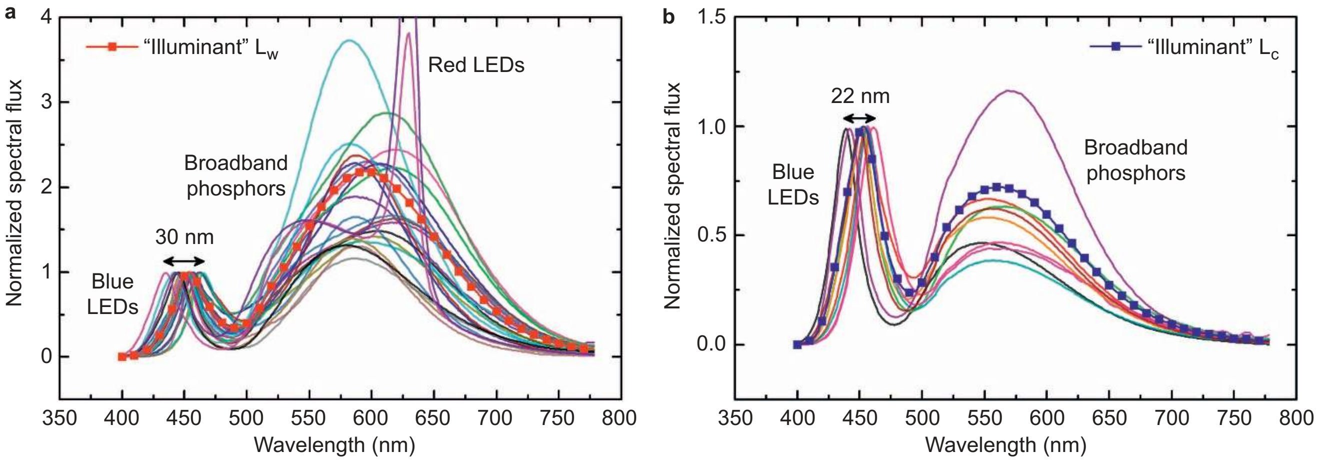

Figure 5 The spectra of (**a**) 26 warm white LED lamps and "Illuminant" L_W (red line with markers) and (**b**) nine cool white LED lamps and "Illuminant" L_C (blue line with markers) normalized to the blue peak. The correlated color temperatures were between 2611 K and 3332 K for the warm white LED lamps, and between 4178 K and 8334 K for the cold white LED lamps. The peaks of the blue LEDs span wavelength ranges of approximately 30 nm and 22 nm for the warm white and the cold white LED lamps, respectively. Due to the variation in the wavelengths of the blue LEDs, the blue peaks of the averaged spectra were below unity. For the figures, the spectra of "Illuminants" L_W and L_C are again normalized to the blue peaks, which raises the phosphorus parts of the spectra above the original average.

applied to correct for the spectral error. However, it should be noted that if the correlated color temperatures of the LED lamp to be measured and the LED standard lamp deviate dramatically, the error associated with *F* can be similar to or higher than the one in the case of Illuminant A calibration source. Therefore, two different illuminants – i.e. "Standard Illuminant" L_W and "Standard Illuminant" L_C – are required for LEDs with relatively low and relatively high correlated color temperatures, and in order to minimize the error related to *F*, the type of calibration source should always be selected according to the type of LED source to be measured.

The results of the spectral mismatch correction analysis suggest that a task of defining new LED-based illuminants would not only be useful, but that it would be feasible as well, despite the relatively complicated spectra of white LEDs. Even if the spectrum of the LED-based standard lamp deviates somewhat from the LED illuminant, the error associated with this discrepancy would be relatively small. This is evidenced by Table 2 and Figure 5 and can also be seen by manipulating the spectrum of the illuminants: Variations up to 30% within selected wavelength intervals changed the spectral mismatch corrections by less than 0.1%.

CONCLUSIONS

The potential advantages of white LED-based photometric standard lamps were investigated. White LED-based standard lamps would enable us to abandon the $V(\lambda)$ filters in the realization of photometric units by measuring the absolute irradiance using a combination of a PQED and a spectroradiometer and by performing the photometric weighting numerically. In this study, we compared the novel PQED-based method with the traditional photometer-based method of photometric unit realization by measuring the illuminance of a white LED lamp using both methods. The PQED method was shown to reduce the uncertainty related to the realization of photometric units by a factor of 1.6 when compared with the traditional photometer method. At the same time, the PQED method radically simplifies the traceability chain of the photometric unit realization. The increased accuracy of the realization of photometric units would directly translate into a reduced uncertainty in, e.g., luminous flux[29,30,31] and consequently luminous efficacy[32] measurements, which could potentially have significant economic impact.

We also investigated the effect of the calibration source on the spectral mismatch correction factors *F* of photometric measurements

Table 2 Average and maximum (in parenthesis) spectral mismatch correction factors, in the form (*F* − 1)·100%, for different types of calibration illuminants and sources to be measured. The values are listed for three different photometers

			Calibration light source		
			Illuminant A	"Illuminant" L_W	"Illuminant" L_C
			Spectral mismatch error (*F* − 1)·100%, average (maximum)		
Source to be measured	Reference photometer	Illuminant A	0.00% (0.00%)	−0.32% (−0.32%)	0.26% (0.26%)
		LED warm	0.32% (0.48%)	0.00% (−0.21%)	0.58% (0.75%)
		LED cool	−0.29% (−0.45%)	−0.61% (−0.77%)	−0.03% (0.22%)
	Photometer 1	Illuminant A	0.00% (0.00%)	−0.49% (−0.49%)	−1.30% (−1.30%)
		LED warm	0.53% (0.80%)	0.04% (0.31%)	−0.78% (−1.10%)
		LED cool	1.36% (1.57%)	0.87% (1.07%)	0.04% (−0.28%)
	Photometer 2	Illuminant A	0.00% (0.00%)	−0.29% (−0.29%)	−0.88% (−0.88%)
		LED warm	0.30% (0.47%)	0.01% (−0.25%)	−0.59% (−0.84%)
		LED cool	0.92% (1.05%)	0.63% (0.76%)	0.03% (−0.18%)

by calculating *F* for various detector and light source combinations. For this purpose, we defined two LED-based calibration illuminants – "Illuminant" L_W with relatively low and "Illuminant" L_C with relatively high correlated color temperatures – by taking an average of the normalized spectra of several commercial white LED lamps. The results of the analysis show that by using LED standard lamps as calibration sources instead of incandescent lamps for photometers that measure LED lighting, the uncertainty related to the spectral mismatch correction factor can be reduced significantly, provided that the two LED sources are of similar type – that is, either cool or warm white. For one of the studied photometers, the average error associated with the spectral mismatch was 0.53% and 1.36% for warm white and cool white LED sources, respectively, when an incandescent standard lamp was used as a calibration source. The average error was reduced to 0.04% when using appropriate LED-based illuminants. At the same time, the worst case errors associated with the spectral mismatch were reduced by factors of 2.6 and 5.6 for large groups of warm white and cool white LEDs, respectively. This is a considerable improvement particularly in applications where the spectral mismatch correction is not routinely applied, as might be the case – for example – in some test laboratories or in field measurements.

The results of the spectral mismatch correction analysis indicate that it would be possible to define practical LED-based standard illuminants for photometry, despite the more complicated spectra of the LED lamps as compared with those of incandescent lamps. Even if the spectra of the future LED-based standard lamps deviated slightly from that of the as-of-yet undefined illuminants, the uncertainty caused by this discrepancy would be relatively small. Even by an approximate matching of the spectrum of the standard lamp with the illuminant, this uncertainty can be reduced to less than 0.1% relatively easily. Moreover, the analysis of the spectral mismatch correction factors of various photometers suggests that different illuminants are required for LEDs with relatively low- and high correlated color temperatures.

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