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Methods for decreasing uncertainties in LED photometry

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Abstract. Even though energy-efficient and sustainable solutions, such as light emitting diodes (LEDs), have become popular in general lighting, mainly incandescent lamps are used as measurement standards in photometry. Optical properties of the LED lamps together with the often unstable built-in power converters bring challenges to NMIs and testing laboratories. Due to the narrow and complicated spectra of the LED lamps, the uncertainties of traditional photometers calibrated by incandescent lamps tend to increase when LED lamps are measured. Switching from an incandescent lamp to an LED-based calibration source would decrease the uncertainty related to the spectral mismatch correction. LED-based photometric standard lamps would also have other benefits, such as long lifetime and good temporal stability. Moreover, as spectra of white LED lamps are limited to the visible wavelength range, a novel method for illuminance measurements based on the Predictable Quantum Efficient Detector (PQED) can be used to characterize these standard lamps with luminous flux uncertainties significantly below 1 % ($k = 2$) at NMIs. The method eliminates the need of photometric filters in realization of the illuminance unit. Instead, the photometric weighting is carried out numerically using a separately measured relative spectrum of the source. Well characterized LED-based calibration lamps, together with improved electrical power measurement, would reduce measurement uncertainties of illuminance, luminous intensity, luminous flux and luminous efficacy measurements of LED lamps at NMIs and testing laboratories. This would have a high impact on the development of energy-efficient LED lamps and on the assessment of the energy saving potential of solid state lighting. It is also shown, that recent advances in illuminance and electrical power measurement will enable luminous efficacy measurements of LED lamps with uncertainty well below the present state-of-the-art level of about 1 % ($k = 2$).

1 Introduction

Light emitting diodes (LEDs) have become popular in general lighting, while incandescent lamps are being phased out globally. Incandescent lamps, however, are still widely used as measurement standards in photometry. As the industry and the know-how needed for the manufacturing of traditional lamps might eventually be lost, the availability of incandescent standards in the future is unknown. Moreover, if the majority of the lamps to be measured are LED-based, the use of tungsten filament lamps as photometric standard might not be mandatory or even justified, as the spectra of the two differ drastically [1].

Luminous efficacy, given in lumens per watt, is one of the most important photometric quantities in the assessment of the energy saving potential of lighting products, and also the main interest of this work. The main sources of uncertainty in luminous efficacy measurements of LED lamps are the electrical power measurement and the reference illuminance measurement needed in the determination of the luminous flux responsivity of the system. The former is challenging due to the various types of built-in power converters for driving the LEDs which often have high total harmonic distortion (THD), low power factor and poor stability [2, 3]. The latter is caused by the uncertainty of the reference photometer illuminance responsivity. In addition, the narrow and complicated spectra of LEDs tend to increase the uncertainty associated with spectral mismatch when measured with traditional filtered photometers [1-2, 4].

Over hundred laboratories took part in a recent comparison measurement of solid state lighting products [5], in which measured luminous efficacy values were in agreement within ±5 % between most of the participants. More reliable measurements conducted by calibration and testing laboratories would be highly desirable, as it would promote development of more energy efficient lighting products. One important factor in reducing the uncertainties at secondary laboratories is the state-of-the-art level of uncertainty achieved at national metrology institutes (NMIs), which in the case of luminous efficacy of LED lamps is about 1 % ($k = 2$) [2].

The scope of this work is twofold: to investigate the advantages of replacing conventional incandescent standard lamps with white LED lamps, and to discuss

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methods to reduce the uncertainty of luminous efficacy measurements of LED lamps significantly below the present state-of-the-art level. The latter part is further divided into two sections, one considering the electrical power measurements [3] – especially the effect of source impedance on luminous efficacy measurement [6] – and the other considering a novel method for the realization of photometric units [4]. The new method utilizes the Predictable Quantum Efficient Detector (PQED) [7-9] operated at room temperature directly in the measurement of illuminance and luminous intensity. The PQED is a primary standard of optical power based on induced junction photodiodes, whose absolute spectral responsivity can be predicted with a relative uncertainty of less than 0.01 % [7-8, 10].

The PQED-based method does not utilize a $V(\lambda)$-filter. Instead, the photometric weighting is taken into account numerically by measuring the relative spectral irradiance separately. As there is no filter to limit the spectrum of the light source, the method is only applicable to light sources whose emission spectra do not extend outside the visible wavelength range. This is the wavelength range where the responsivity of the PQED is accurately known. In addition to improved uncertainty, the new method simplifies the traceability chain of photometric measurements considerably [1].

2 Theory

The luminous efficiency function $V(\lambda)$, defined by the CIE, describes the relative spectral responsivity of the photopic (daylight adopted) vision. By definition, any photometric quantity X_v can be calculated from the corresponding radiometric quantity $X_{\mathrm{e},\lambda}(\lambda)$ with the $V(\lambda)$ function using the equation [11]

$$X_\mathrm{v} = K_\mathrm{m}\int X_{\mathrm{e},\lambda}(\lambda)V(\lambda)d\lambda\,, \tag{1}$$

where K_m = 683.002 lm/W is the maximum luminous efficacy of photopic vision and λ is the wavelength in standard air. The luminous efficacy of a light source is defined as

$$\eta_\mathrm{v} = \Phi_\mathrm{v}/P\,, \tag{2}$$

where Φ_v is the total luminous flux and P is the electrical power consumption of the lamp. The total luminous flux can be determined with either goniometric [12] or absolute integrating sphere method [2, 13] which both require an absolute illuminance measurement (i.e. luminous power incident on a surface) as a calibration procedure.

Photometric measurements usually utilize a photometer, a filtered detector that has the normalized spectral responsivity $s_\mathrm{rel}(\lambda)$ close to the $V(\lambda)$ function. For absolute photometric measurements, such a device has to be calibrated. Usually the reading of the photometer to be calibrated is compared with the reference value which is produced by a standard light source, or by using a reference detector. A typical reference photometer [14] consists of a precision aperture, a photometric filter and a photodetector. The illuminance E_v measured by such an instrument can be calculated as [14]

$$E_\mathrm{v} = \frac{K_m F i}{A s(\lambda_0)}, \tag{3}$$

where i is the photocurrent produced 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 photometer at the air wavelength of λ_0 = 555 nm. The spectral mismatch correction factor F_d corrects for the deviation between the $V(\lambda)$ and the relative spectral responsivity of the photometer, $s_\mathrm{rel}(\lambda) = s(\lambda)/s(\lambda_0)$. It can be derived as

$$F_\mathrm{d} = \frac{\int \Phi_{\mathrm{e},\lambda}(\lambda)V(\lambda)d\lambda}{\int \Phi_{\mathrm{e},\lambda}(\lambda)s_\mathrm{rel}(\lambda)d\lambda}, \tag{4}$$

where $\Phi_{\mathrm{e},\lambda}(\lambda)$ is the spectral radiant flux of the light source.

When a photometer is calibrated using a standard lamp, or by substitution with a reference detector, both the relative spectra of the calibration source $\Phi_\mathrm{cal}(\lambda)$ and the lamp to be measured $\Phi_\mathrm{source}(\lambda)$ have to be taken into account. The spectral mismatch correction factor is then calculated as

$$F_s = \frac{\int \Phi_\mathrm{source}(\lambda)V(\lambda)d\lambda}{\int \Phi_\mathrm{source}(\lambda)s_\mathrm{rel}(\lambda)d\lambda}\cdot\frac{\int \Phi_\mathrm{cal}(\lambda)s_\mathrm{rel}(\lambda)d\lambda}{\int \Phi_\mathrm{cal}(\lambda)V(\lambda)d\lambda}. \tag{5}$$

The most commonly used photometric standard light source is a tungsten filament incandescent lamps with a correlated colour temperature T_c = 2856 K, which approximates the Standard Illuminant A defined by the International Commission on Illumination, CIE.

3 Decreasing uncertainty of luminous efficacy measurements of LEDs

3.1 PQED-based method for realization of photometric units

The PQED consists of two induced-junction photodiodes with almost unity internal quantum efficiency (IQE), meaning that nearly all absorbed photons produce a collectable charge carrier. The IQE of such diodes operated at room temperature can be modelled with an estimated standard uncertainty of 70 ppm in the visible wavelength range [10]. Due to the wedged trap configuration of the PQED, shown in figure 1, the uncertainty of the PQED reflectance is less than 30 ppm for most of the visible wavelength range [7, 15]. As both the reflectance and the IQE are small, the relative responsivity of the PQED can be approximated as $s_\mathrm{rel}(\lambda) \approx \lambda/\lambda_0$.

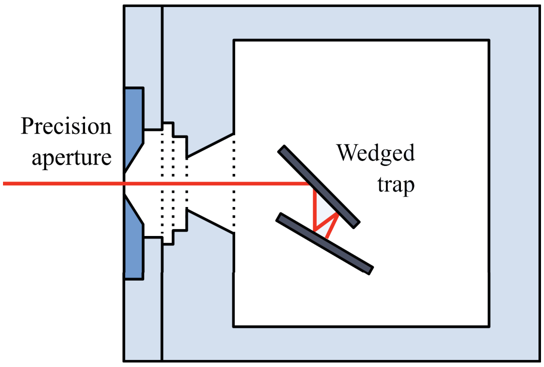

Figure 1. Schematic structure of the PQED and the precision aperture. The angle between the photodiodes is 15°.

The most significant difference between the PQED-based method and the traditional photometer-based method is that the former does not utilize filters of any kind; only a precision aperture is placed in front of the photodiodes. The photometric weighting is performed numerically by applying the spectral mismatch correction F_d. Thus, the new method requires an accurate determination of the relative spectral flux $\Phi_{e,\lambda}(\lambda)$ using, for instance, a double monochromator scanning spectroradiometer.

As the relative responsivity of the PQED is very accurately known, the uncertainty of the illuminance value is dominated by the measurement of the relative spectrum of the light source. In traditional filter-based reference photometers the largest uncertainty components are associated with the transmittance of the $V(\lambda)$-filter or the responsivity of the $V(\lambda)$-weighted detector-filter combination, typically measured using a monochromator. In both methods, the accuracy of the wavelength scale produces a large contribution to the uncertainty. However, the wavelength scale of the spectroradiometer can be conveniently calibrated using well-known laser lines, and the method is more accurate than the wavelength scale calibration of monochromators using wavelength transmission standards.

In a test measurement, the illuminance produced by a white LED was determined using the new method and a conventional reference photometer [1]. The values obtained by the two methods deviated only by 0.03 % from each other. Moreover, the PQED-based method has significantly lower standard uncertainty of 0.13 % as compared with that of the traditional filter-based method of 0.21 %. In addition to improved uncertainty and simplified traceability chain, the PQED-method overcomes other problems associated with $V(\lambda)$-filters, such as temporal and temperature drifts.

3.2 Electrical power measurement

The above discussed state-of-the-art level of uncertainty in luminous efficacy requires that the measured lamp has stable built-in electronics. Unfortunately, many lamps have THD above 200 % and power factors below 0.4, which together with high crest factors may cause temporal variation up to 1 % in the electrical power measurement [2]. Some lamps require long stabilization times, up to several hours, but the electrical parameters of some lamps fluctuate randomly regardless of the stabilization time. Therefore, achieving low uncertainty in the luminous efficacy measurement for all the lamps available in the market is challenging.

The most interesting frequency range in the electrical power measurements of LED lamps is from 50 Hz to 200 kHz [3]. Due to the significant high frequency content of some lamps, the frequency responses of the power meter and the current measurement shunt have to be linear for a large enough frequency range. Also the resistance value of the shunt should be optimized: a larger shunt resistor will provide better signal-to-noise ratio, but also adds to the effective source impedance seen by the lamp electronics during the measurement. In addition to the specifications of the measurement instruments, special attention should be paid to the appropriate wiring configuration to avoid measurement errors due to systematic errors, such as leakage currents through voltage measurement circuits [3]. Yet another problem causing increased measurement uncertainties is the lack of commonly accepted methods for calibration of power meters with non-sinusoidal waveforms.

The low-voltage distribution networks typically suffer from instability, voltage peaks, and distortion, as compared to regulated AC voltage sources used in measurement laboratories for supplying the lamps in the measurements. With right instrument selection, the effects of AC voltage source stability, noise and distortion cause negligible uncertainties. However, the output impedances of AC voltage sources may differ from each other, and the operation of the LED lamp electronics may depend on the effective source impedance [6]. Also, the impedance of a real power system may differ significantly from the output impedance of an AC voltage source. Consequently, differences of several percent in the measured power values can occur depending on the lamp type and the measurement equipment used [3].

The effect of the source impedance can be reduced by using an impedance stabilization network between the lamp and the AC voltage source. Typically such networks are used in measurements of conducted electro-magnetic interference (EMI), and might not be directly suitable for the frequency range of LED lamps. A recently developed adjustable power line impedance emulator (APLIE) [16], on the other hand, can emulate various impedance curves found in typical low-voltage distribution networks. The APLIE can be used as a stabilization network, and for testing the sensitivity of LED lamps to various source impedances.

Figure 2 shows the current waveforms of an LED lamp with direct connection to the AC-voltage source, and with the APLIE connected between the two. In addition to the reduced high frequency harmonics of the current, test measurements with APLIE have also shown improvement of the stability of the measurements. When APLIE is used together with the other methods above, an uncertainly of 0.1 % to 0.2 % can be achieved for electrical power measurement of LED lamps [16].

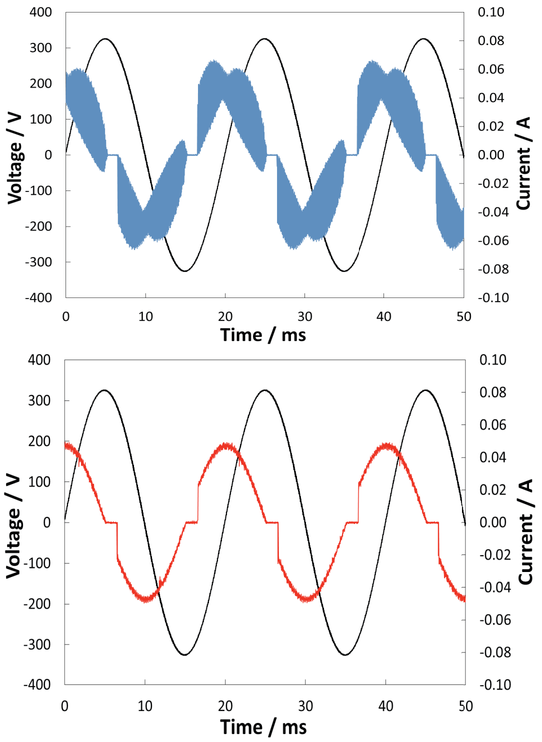

Figure 2. Voltage and current waveforms of an LED-lamp with direct connection of the lamp to the AC-voltage source (above) and with an impedance stabilization network emulating the maximum impedance of a power system (below) [16].

3.3 Anticipated uncertainty of luminous efficacy of LED lamps

A typical uncertainty budget of luminous efficacy measurements using the absolute integrated sphere method is given in Table 1. The first column shows uncertainty components in a conventional luminous efficacy measurement utilizing an ordinary photometer in the absolute illuminance measurement. The second column lists the anticipated uncertainties after the improvements discussed above are taken into use, and a well-behaving lamp is measured.

Table 1. Simplified uncertainty budget of luminous efficacy measurements of LED lamps. The achieved relative uncertainty for stable lamp is obtained from [2].

Source of uncertainty of efficacy	Relative standard uncertainty [%]	
	Stable lamp (achieved)	Anticipated with improvements
Measurement setup		
Luminous flux responsivity	0.3	0.1
Drift of the sphere photometer	0.1	0.1
Stability of the AC-power supply	0.1	0.1
Luminous efficacy measurement		
Stability of the luminous flux	0.1	0.1
Stability of the built-in electronics	0.2	0.1
Electrical power measurement	0.3	0.1
Photocurrent measurement	0.1	0.1
Spectral mismatch correction	0.2	0.2
Self-absorption correction	0.2	0.1
Spatial nonuniformity correction	0.1	0.1
Combined standard uncertainty	0.6	0.4
Expanded uncertainty (k = 2)	1.2	0.7

The APLIE improves the stability of the AC-voltage source and the lamp electronics and reduces the uncertainty in the electrical power measurement. Using a LED-lamp as the external source in the calibration procedure of the integrating sphere allows the PQED-based method to be exploited. The uncertainty due to illuminance measurement of the external source, and consequently the uncertainty due to luminous flux responsivity is thus reduced by a factor of 3. In addition, using an LED lamp as the auxiliary source to determine the self-absorption correction of the measured lamp reduces the uncertainty of the correction, as the spectra of the two are similar.

4 LED lamps as photometric standards

LEDs have many properties desirable for a photometric standard lamp. They are robust and generally have a much longer lifetime than incandescent lamps. For certain commercial LED lamps, the luminous flux is exceptionally stable [17]. Furthermore, various properties of LED lamps can be customized to fit different applications. These include the dimensions of the illuminating area, angular distribution, and the shape of the emission spectrum [1].

At calibration and testing laboratories, the spectral responsivity of the photometer or the spectrum of the measured light source are often unknown, and, therefore, the spectral mismatch correction F_s cannot be applied. In such cases, it is highly desirable that the relative spectra of the calibration source and the lamp to be measured are similar. However, as shown in figure 3, the differences between the spectra of Standard Illuminant A and typical LED lamps are immense.

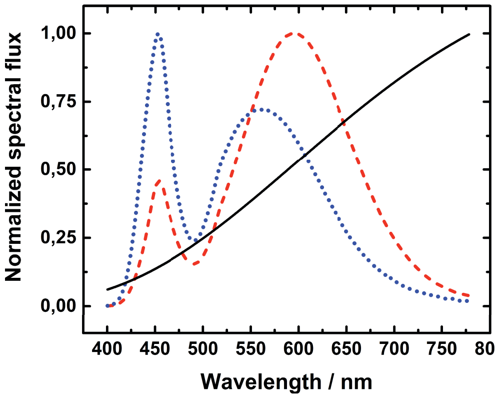

Figure 3. The spectra of Standard Illuminant A (solid line) and the standard illuminants proposed in [1] for warm (dashed line) and cool (dotted line) LED lamps.

An obvious benefit in using an LED lamp as a photometric standard lamp is that the spectra of the lamp to be measured and the calibration source are more alike. The effect of the calibration source on the spectral mismatch correction factors F_s can be investigated by calculating the F_s for various detector and light source combinations. Pulli *et al* [1] conducted such an analysis for 26 commercial E27-base LED lamps with relatively low correlated colour temperatures (T_c = 2611–3332 K) and 9 LED lamps with relatively high correlated colour temperatures (T_c = 4178–8334 K) used in combination with a reference photometer [14] and two commercial photometers. The simulations indicated that two new LED-based standard illuminants would be beneficial, one for warm and another for cool white LEDs. The spectra of these, shown in figure 3, were defined by taking an average of the normalized spectra of several commercial white LED lamps.

An important result of the analysis is that by using LED standard lamps as calibration sources instead of incandescent lamps when measuring LED lighting, the uncertainty related to the spectral mismatch correction factor can be reduced significantly. This requires that the calibration source and the LED lamp to be measured are of similar type – that is, either cool or warm white. Even if the spectra of the standard lamp deviate slightly from the LED-based illuminants, the uncertainty caused by this deviation is relatively small. The average error associated with the spectral mismatch was between 0.30 % and 1.36 % for the commercial photometers, when an incandescent standard lamp was used as a calibration source and an LED lamp was measured. The average error was reduced to 0.04 % when using the appropriate LED-based illuminant.

5 Conclusions

As the spectra of white LED lamps are limited to the visible wavelength range, a novel method for realization of photometric units based on the PQED can be used. The method reduces the uncertainty in illuminance measurements of LED lamps by a factor of 1.6. In addition, the method has other benefits such as operation without $V(\lambda)$-filter and significantly simplified traceability chain of the photometric unit realization.

Many LED lamps have built-in electronics, whose power consumption depend on the characteristics of the AC-voltage source used in the measurements. This effect of source impedance can be studied by using the recently developed power line impedance emulator, APLIE. The APLIE introduces impedance conditions close to the real power system, and improves the stability of the electrical power measurements in luminous efficacy measurements of LED lamps. When the source impedance and various other factors, such as distortion and stability of the AC-voltage source, frequency response of the power meter, and wiring of the equipment, are taken into account, the uncertainty due to the electrical power measurement can be reduced down to 0.1 %. This together with the PQED-based illuminance measurement method will enable luminous efficacy measurements below the present state-of-the-art of about 1 % ($k = 2$).

Switching from an incandescent lamp to an LED-based calibration source would have many benefits, such as long lifetime and good temporal stability of the standard lamp. The most important improvement would be the decrease in the uncertainty related to the spectral mismatch, especially at laboratories where the spectral mismatch correction is not applied. Analyses indicate that it would be possible to define practical LED-based standard illuminants for photometry. Even by an approximate matching of the spectrum of the standard lamp with the illuminant, the uncertainty due to spectral mismatch can be reduced to less than 0.1 % relatively easily.

New standard illuminants and calibration lamps based on white LEDs would allow measurements of LED lighting with much lower uncertainties than standard illuminant A and incandescent lamps. Moreover, NMIs would be able to characterize these lamps with luminous flux uncertainties significantly below 1 %. Both advances, together with the improved electrical power measurement, would have a high impact on the development of energy-efficient LED lamps, and on the assessment of the energy saving potential of solid state lighting.

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