Improved calibration strategy for luminous intensity

P Schneider1, K Salffner1, A Sperling1, S Nevas1, I Kröger1, T Reiners2

1Physikalisch-Technische Bundesanstalt Braunschweig und Berlin, Bundesallee 100, 38116 Braunschweig, Germany
2LMT Lichtmesstechnik GmbH Berlin, Helmholtzstrasse 9, 10587 Berlin, Germany

E-mail: philipp.schneider@ptb.de

Abstract. To improve the realization of luminous intensity a new photometric detector has been developed at Physikalisch-Technische Bundesanstalt (PTB). This detector will be used to realise a radiometric traceability chain for luminous intensity with a lowered measurement uncertainty. To allow a short and direct calibration hierarchy, a trap detector was chosen that will be used with several modular attachments for each calibration step. Achieving a reduced measurement uncertainty requires careful design and characterization of each module used. The new calibration strategy and the detector with its several setups are described here.

1. Introduction

The realisation and maintenance of the unit of luminous intensity at Physikalisch-Technische Bundesanstalt (PTB) is done in two complementary ways to provide confidence in the disseminated unit. These two ways are a detector-based radiometric approach and a lamp-based approach. The radiometric realisation of the candela at PTB [1] is based on the following equation for the luminous intensity $I_v(T)$ at the distribution temperature $T$ of an incandescent lamp:

$$I_v(T) = \frac{K_m}{s_0(\lambda_d)} \cdot \frac{r^2}{\Omega_0} \cdot y \cdot F(T)$$

with the spectral-mismatch factor

$$F(T) = \int_0^\infty S(\lambda, T) V(\lambda) d\lambda \cdot \left(\int_0^\infty S(\lambda, T) s_r(\lambda) d\lambda\right)^{-1}$$

Here $K_m = 683$ lm/W is the luminous efficacy of radiation at 540 THz, $s_0(\lambda_d)$ is the absolute irradiance responsivity of the photometer at wavelength $\lambda_d = 555$ nm, $r$ is the distance between the incandescent lamp and the photometer, $y$ is the measured photocurrent, $V(\lambda)$ is the luminous efficiency function as defined by CIE, $s_r(\lambda)$ is the relative spectral responsivity of the photometer normalized at $\lambda_d$ and $S(\lambda, T)$ is the spectral distribution of the incandescent lamp at distribution temperature $T$.

The two complementary ways to realize the unit of luminous intensity was already described by Erb and Sauter [2]. The radiometric realization of the unit is traceable to the cryogenic radiometer via several steps which will be presented in more detail in this paper as the base of the new improved realization strategy. This radiometric realization of the unit results in an expanded uncertainty for the luminous intensity of $U(I_v) = 2.5 \times 10^{-3}$ ($k = 2$). In addition, the unit is maintained by a network of lamps. This network still consists of those lamps which were involved during the comparison of realizations of the candela in the late 1970s which finally led to the defined constant in the current candela definition.
Mainly the superior reproducibility of these lamps determines the uncertainty of the maintained unit at PTB. With an additional network of photometers, the maintained luminous intensity is currently provided at an uncertainty level of $U(I_v) = 2 \times 10^{-3}$ ($k = 2$). When comparing both ways to establish the unit it becomes apparent that despite the comparable uncertainties the reproducibility of the radiometric realization is worse than the reproducibility of the maintained unit as described elsewhere in more detail [3]. This implies that using the lamp based route the uncertainty of the calibration of a luminous intensity standard can be even smaller while such a calibration using the detector based route would be even larger. This discrepancy poses the requirement of an improved radiometric calibration strategy with reduced measurement uncertainty, thus ensuring a more stable detector based realization of the unit of luminous intensity in future.

2. Steps of the radiometric realization

Multiple steps are necessary to determine the aforementioned radiometric properties of a photometer. With known absolute irradiance responsivities $s(\lambda)$ the photometric responsivity with respect to CIE Standard Illuminant A based on a distribution temperature of $T_A = 2856$ K can be determined following the formula:

$$s_v = \frac{1}{K_m} \int_0^\infty S(\lambda, T_A) s(\lambda) d\lambda \cdot \left( \int_0^\infty S(\lambda, T_A) V(\lambda) d\lambda \right)^{-1}$$  \hspace{1cm} (3)

The calibration hierarchy for the photometric responsivity of a photometer using the current realization is shown in comparison to the new calibration strategy in figure 1.

![Figure 1. Radiometric calibration hierarchy for photometric detectors.](image)

The first step in the traceability chain is the calibration of silicon trap detectors with a cryogenic radiometer regarding their spectral power responsivity as described by Werner et al. [4]. The spectral power responsivity is measured at several cw laser wavelengths across the visible spectral range and interpolated by the model mentioned in [4]. The spectral power responsivity is transferred to additional trap detectors using spectrally tunable measurement setups with lamp-monochromator based light sources. By adding mechanically manufactured precision apertures the spectral irradiance responsivity of the trap detectors and photodiodes can be determined. The calibrated trap detectors and photodiodes are used as reference detectors at two setups in PTB. The DSR setup [5] and the TULIP setup [6] can...
both be used to calibrate the spectral irradiance responsivity of photometric detectors. The DSR setup is also operated with a lamp-monochromator based light source and uses photodiodes as reference while the TULIP setup performs measurements with specially treated tunable quasi-cw laser radiation to illuminate the detectors while using the trap detectors as reference detectors.

At both setups, the major contributions to the measurement uncertainty when calibrating a photometer are the uncertainty of the responsivity of the reference trap detector and photodiode, respectively, and the area of the mechanical aperture to enable measurements in irradiance mode. With the monochromator based DSR setup the uncertainty contributions of wavelength and of the spectral bandwidth dominate the combined uncertainty when not measuring close to the peak of the $V(\lambda)$-function. For the TULIP setup, the combined measurement uncertainty is mainly influenced by the aforementioned uncertainty of the responsivity of the reference and the aperture as well as by the uncertainty of the wavelength determination.

3. Modular photometric $V(\lambda)$-trap detector system
To enable the usage of a shorter traceability route with reduced measurement uncertainty a new modular detector system was developed. The detector can be setup in optimized configurations for each of the steps shown in the blue box in figure 1. However, avoiding the additional transfer steps of the current traceability chain already offers a reduced uncertainty for the photometric responsivity. The core of the $V(\lambda)$-trap detector is a six-diode transmission trap detector similar to the one described by Kübarsepp et al. [7]. For the photometric trap detector six photodiodes with $18 \times 18 \text{ mm}^2$ active area were used enabling a slightly larger acceptance angle compared to the $10 \times 10 \text{ mm}^2$ photodiode setup from Kübarsepp when used with the same aperture of 6 mm. The maximum usable active area perpendicular to the optical axis is approximately 150 mm$^2$. It is defined by the size and positioning of the six photodiodes in the trap detector. A light cone entering the detector aperture must not exceed this area due to divergence so that all light is only incident on the diodes. When using the 6 mm aperture the optical path length within the trap of 160 mm from the aperture to the last diode results in a half acceptance angle of only 1.2 degree.

![Figure 2. Assembly drawing of the six-element transmission trap detector with front caps A, B and C with different aperture and filter elements and the rear modules 1 and 2 that can be moved into the transmitted beam.](image-url)
The six-element transmission trap detector is in theory independent of polarization effects and, thus, suitable for polarized laser beam as well as for incandescent lamp measurements. To carry out each of the steps in the calibration strategy, different attachments can be mounted to the front side of the trap detector in the optical pathway of the incoming beam or to the rear side of the detector to measure the transmitted beam. The attachable modules and their use during calibration are described in the following sections and depicted in figure 3.

3.1. Front modules of the detector
A front cap with a mechanically manufactured aperture (see figure 2, module A) will be attached to the trap detector for the calibration in radiant power mode with the cryogenic radiometer. The aperture will have the same nominal area as the entrance aperture of the cryogenic cavity. It is not required to have the most precise knowledge of the area of the aperture when measuring the spectral power of incident laser beams. This aperture only affects the outer part of the beam, namely the straylight in forward direction. As the straylight makes only a minor part of the incident power, the usage of nominally equal sized apertures in front of the trap and the cavity is sufficient to match the straylight fractions entering both detectors.

For using the detector in irradiance mode, a precision chrome aperture deposited on a glass substrate (see figure 2, module B) is used. Deposited apertures pose the advantage of having sharper aperture edges and thus the aperture area can be determined with lower uncertainty compared to conventional mechanically manufactured apertures. To enable the transfer from power responsivity to irradiance responsivity with a low uncertainty contribution, the power responsivity of the trap with attached deposited aperture must be determined. The transmittance of the used substrate will be determined in power mode for this purpose via direct comparisons with measurements using module A. As the calibration with the cryogenic radiometer is carried out using cw-laser radiation, effects of the deposited aperture such as transmission and diffraction should also be measured with cw-lasers. For this purpose, the aperture was specially manufactured to have low interference effects. This is achieved by adding a glass wedge to the aperture substrate by means of optical contact bonding. The currently remaining interference effect on the transmission is in the range of a few parts in 10³ and will be corrected for when using cw-lasers.

To match the responsivity of the detector to the $V(\lambda)$-function, a suitable $V(\lambda)$-filter having a deposited aperture (see figure 2, module C) is used. The area of the aperture is nominally the same for the modules B and C. The transmittance of the filter of module C will be determined by relative measurement with respect to module B with tunable lasers in irradiance mode. The filter and also the deposited aperture were assembled on top of a glass wedge to reduce interference caused by interreflection between the outer interfaces. By using the same angle of 0.5° for the glass wedge in both modules, the diffraction caused by the tilted interface is the same in both cases. The transmittance of such a filter is expected to show a spectrally dependent temperature dependence [8]. To avoid effects of the temperature the filter and the trap are temperature controlled to about 30 °C with a stability of 0.05 K.

3.2. Rear modules of the detector
For the detection (and investigation of the properties) of the light that is transmitted through the trap detector, two different modules can be placed at the rear of the detector.

A position sensitive diode (PSD) (see figure 2, module 1) is used for tracking the position of the beam across the active area during the measurements in optical power mode. This sort of photodiode utilises a PIN diode with a special electrode configuration. The position of the centroid of an incident light beam can be tracked by the change of the ratios of the photocurrents at the electrodes. The PSD will be used during the calibration of the trap detector with the cryogenic radiometer and the transmittance measurement of the aperture substrate. This way, the position of the beam can be tracked, which allows to account for the nonuniformity of the detector when switching from power to irradiance mode yielding the irradiance responsivity with a lower uncertainty. The nonuniformity of the $V(\lambda)$-trap detector was determined in a separate measurement [3].
In addition, a camera (see figure 2, module 2) with a large CCD of 27.65 mm × 18.48 mm can be used. When using the detector in irradiance mode the transmitted light is detected by the camera. The camera is used for a qualitative observation of the light field and to evaluate the illumination conditions inside the transmission trap, to recognize light hitting edges of the photodiodes. This way it can be assured that the detector is used only in the well-defined irradiance mode where all the light transmitted through the aperture area is seen by all six diodes. Since the geometry of the trap and the aperture allows only small acceptance angles, the camera offers a way to check for appropriate illumination.

4. Characterization of the $V(\lambda)$-trap detector

In order to show the suitability of the new detector system to reach the aimed uncertainty, several measurements were done to characterize the whole detector system and the trap detector individually before the new calibration strategy will be implemented. To use the detector both, in power and irradiance mode, the uniformity of the spatial responsivity of the detector is of highest importance and it was shown to be in the range of $10^{-4}$ [3].

As mentioned before, the design of the trap detector yields a theoretically polarization independent responsivity. To check for remaining polarization dependencies, the detector was rotated around its optical axis with a strictly linearly polarized incident laser beam. The relative maximum deviation of the measured photocurrent when rotating the detector by more than 180 degree was in the range of $\pm 4 \times 10^{-5}$. Within the standard deviation of $2 \times 10^{-6}$, it could not be distinguished between remaining effects of the mechanical fixation of the trap detector and the polarization dependency.

As a preliminary investigation of the spectral properties of the new detector its spectral irradiance responsivity with the $V(\lambda)$-filter was calibrated at two calibration setups using the current traceability route. The lamp-monochromator based DSR setup was used for calibration in the spectral range of 250 nm to 1200 nm while the measurements at the laser-based TULIP setup were recorded in the spectral range of 360 nm to 1000 nm. To compare the two calibrations, the results of the spectral irradiance responsivity are shown in figure 3. The uncertainty evaluation of the measurement with TULIP is preliminary and requires further investigation of the differences in the UV and NIR spectral range.

Figure 3. Relative spectral responsivity of the new detector normalized to the values at 555 nm. Calibration results of the irradiance responsivity from the DSR setup are shown in black circles, first results from the TULIP setup in orange squares and the $V(\lambda)$-function as a dashed green line, respectively. Error bars are shown for the DSR results representing the measurement uncertainties. For TULIP no error bars are visible as they are completely overlapped by the symbols representing the values.

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range. It is apparent that although the $V(\lambda)$-function is limited to the wavelength range 360 nm to 830 nm there is a residual responsivity in the infrared and UV spectral range. When using the detector in combination with an incandescent lamp at 2856 K distribution temperature, especially the infrared responsivity of the detector results in a contribution to the total photocurrent at the level of $10^{-4}$. As the target uncertainty of the new calibration strategy is within the same order of magnitude, an appropriate correction must be carefully determined and applied. To express the quality of the detector’s match to the $V(\lambda)$-function the $f'_1$ quality factor can be calculated. The calculation according to CIE S023 [9] results to be $f'_1 = (1.78 \pm 0.21) \%$.

5. Conclusion
A new detector system was set up at PTB allowing for a more direct calibration hierarchy to trace luminous intensity to optical power. The detector system is a modular one. The modules have been chosen carefully to fulfil the requirements of each step of the new calibration strategy. Modules of the $V(\lambda)$-trap detector were characterized to evaluate their suitability for the improved traceability chain allowing a reduced overall measurement uncertainty for the realization of the luminous intensity unit. Aperture and filter modules were designed and built in order to reduce interference modulation of the transmitted radiation, which is important for the detector calibration at the laser-based TULIP setup. Spectral irradiance responsivity calibrations following the current calibration strategy have shown a good match to the $V(\lambda)$-function with $f'_1 \approx 1.8 \%$. The calibration against the cryogenic radiometer following the presented calibration strategy is planned as a next step. The results including the final measurement uncertainty will be reported on in another publication.

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