International Commission on Illumination
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Internationale Beleuchtungskommission

OP58

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DOI 10.25039/x46.2019.OP58

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

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LONG-TERM SPECTRAL RESPONSIVITY STABILITY OF PREDICTABLE QUANTUM DETECTORS

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DOI 10.25039/x46.2019.OP58

Abstract

In recent years a Predictable Quantum Efficient Detector (PQED) has been developed by a joint European effort in the framework of the EUROMET iMERA+/EMRP programs. The PQED consists of two custom-made induced junction Silicon photodiodes in a wedge trap configuration. The most notable property of this type of detector is that its external quantum efficiency (EQE) value in the spectral range from 400nm to 850nm is dependent only on fundamental constants. The PQED is therefore potentially an ideal candidate for a new primary standard for optical radiometry in the visible range. A considerable effort has been spent to validate the absolute value of the PQED spectral responsivity against the current standard for optical radiometry, the cryogenic radiometer, with standard uncertainty below 100 ppm. The aim of this work is to investigate the PQED long term temporal stability when operated at room temperature.

Keywords: Radiometry, Photometry, Predictable Quantum Efficient Detector (PQED)

1 Methods

The spectral responsivity values of several PQEDs, used to estimate their EQE, have been measured by the Czech Metrology Institute (CMI) and the Physikalisch-Technische Bundesanstalt (PTB) against cryogenic radiometers over a period of more than eight years: starting from about one year after the photodiode manufacturing in 2011 to the current date. The measurements are being performed with the highest level of accuracy on a set of laser lines covering the visible spectral range: 476nm, 532 nm, 647 nm, 760nm, 800 nm and 850 nm. To reduce dust contamination on its photodiodes the PQEDs are kept in dust free environment when stored and with a dry Nitrogen gas flow when the PQEDs are illuminated. All the measurements reported have been carried out with the PQEDs at room temperature.

1.1 PTB Facility

The cryogenic-radiometer-based calibration facility of PTB has been designed and set up to achieve lowest possible uncertainties for the spectral responsivity calibration of semiconductor detectors by avoiding and reducing main uncertainty contributions such as, e.g., those caused by stray light and the determination of the transmittance of the Brewster window. The power-stabilised laser radiation enters the setup through the common Brewster window (BW). The cryogenic radiometer (CR) and the detector under calibration (DUC) are mounted on a swivelling table with a vertical swivel axis to move either the CR or a DUC behind the BW into the laser beam. CR and the DUCs are positioned on the swivelling table in that way that the distances of their apertures to the swivel axis are almost identical. Therefore, they are at a nearly identical position behind the fixed Brewster window when they are moved into the beam. Thus, a window-correction-free and distant-error-free setup is realised. To further reduce the effect of stray light, the DUCs are equipped with apertures having the same diameter as the aperture in front of the absorber cavity of the cryogenic radiometer. Hence, the remaining effect of stray light on the calibration result depends on the small difference between the aperture areas and the stray light level near the edges of the circular apertures and can be corrected. To measure the latter quantity a special stray light detector consisting of a large area Si photodiode behind an annular aperture is positioned concentrically to the laser beam and in the same distance to the Brewster window as CR and DUC. The measured stray light in the vicinity of the apertures is used to determine the correction and uncertainty contribution arising from the stray light. The following power-stabilised lasers were used in the calibrations reported here: Kr ion laser, frequency-doubled Nd:YAG laser, distributed feedback diode laser, Ti:sapphire lasers. The laser vacuum wavelength was measured with an uncertainty better than 1 pm. The calibrations were performed at a laser power of about 100 µW and by applying a reverse bias voltage of 5 V to the PQED. The PQEDs were aligned before each calibration in a way similar to that described for the CMI facility (see below). Mainly by reducing or avoiding the uncertainty contributions arising from stray light and Brewster window, the total relative standard uncertainty of the spectral responsivity measurement could be reduced to the range of 25 ppm to 40 ppm.

1.2 CMI Facility

The CMI cryogenic radiometer (CR) facility uses a spatially filtered Kr laser beam stabilized by a feedback controlled Pockels cell to irradiate alternatively the PQED under test and the CR absorbing cavity. A Brewster window is placed only in front of the CR cavity and therefore the relative optical losses have to be measured. Since the PQED and cavity are placed at different distances the laser beam stray light must be minimized to negligible level by good shaping beam and proper spatial filtering. The laser beam size used is about 3mm diameter. The stray light on the cavity plane is measured by a Si quadrant photodiode that is placed on the cavity entrance aperture. Thanks to the excellent laser beam power stability (better than 30 ppm/hour) its uncertainty contribution to the measurement is close to negligible. The laser power impinging the cavity and the PQED ranged between 150 µW to 300 µW. In order to extend the PQED linear operational range at these power levels a bias of 10 V was applied to it (Salffner, et al., 2018). The PQEDs under test are placed on a manual gimble for pitch and yaw angular adjustment and on vertical and horizontal motorized stages. First the PQED back reflected beam is manually aligned with respect of the impacting laser beam then a series of two automatized horizontal and vertical scans that include all the PQED sensitive area are performed with a typical step of 100µm. The PQED middle position is determined as the centre of the mass of the second horizontal and vertical scans signals. The same scans' data is used to quantify the uniformity of the PQED around the middle point that for most of the laser wavelengths values used during its calibration has been measured to be better than 50 ppm/mm. The laser vacuum wavelengths that were used in CMI to cover the visible spectrum are: 476.4 nm, 568.4 nm, 647.3nm, 752.8nm and 799.5 nm. Each laser vacuum wavelength was measured by a calibrated wave-meter with uncertainty better than 1 pm. The PQED external quantum losses (EQL) were measured in CMI on most of the wavelengths by slightly tilting (< 1 degree) the PQED and collecting the reflected radiation by a calibrated photodiode. The measured PQED external losses values agreed with the predicted value calculated in (Sildoja, et al., 2013).

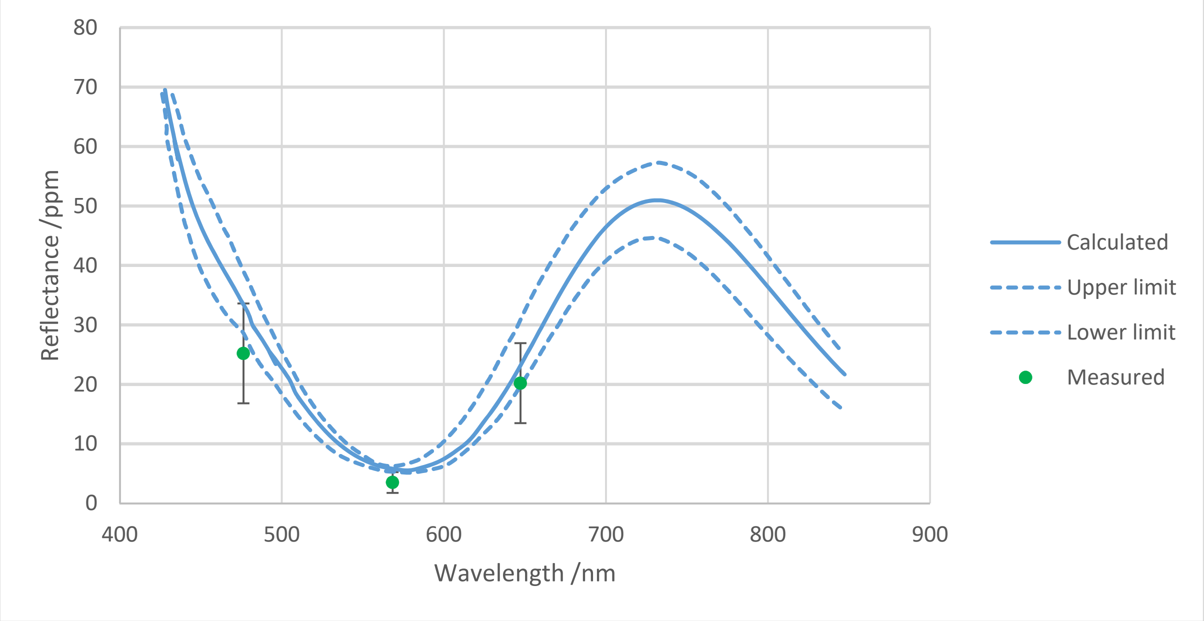

Figure 1 – PQED EQL value measured and calculated

2 Results

The measurements result of the PQEDs' EQE by each laboratory are reported in the tables below. They cover a time period of about eight years. The values are reported with their associated total expanded uncertainty (*k* = 2). It is important to notice that the measurements were performed on four distinct PQEDs. The latest measurements were performed in CMI at the beginning of 2019. The higher uncertainty value for the wavelength of 799 nm are mostly caused by the measurement of the optical losses due to the cryogenic radiometer's Brewster window

Table 1 – PQEDs' EQE value measured in PTB

Wavelength [nm]	2011	2014	2015	2016
476.4			0.99990 ±0.00007	
531.0				0.999899 ±0.00005
532.1		0.999891 ±0.000075		
532.3	0.99991 ±0.00006			
647.3			0.999899 ±0.00007	
757.4	0.999833 ±0.00006			
799.5				0.999967 ±0.000085
850.2		0.99984 ±0.00012		

Table 2 – PQEDs' EQE values measured in CMI

Wavelength [nm]	2012	2016	2019
476.4	0.99995 ±0.00018	0.999998 ±0.00015	0.99993 ±0.00016
568.4			0.99987 ±0.00016
647.3		0.999980 ±0.00015	0.99985 ±0.00017
752.8			0.99997 ±0.00011
799.5			1.00011 ±0.00025

In the figure below the graphical rapresentation of the all the PQEDs EQE values measured by both PTB and CMI in conjunction with the typical temporal EQE behavior of the typical transfer standard trap detector based on the Hamamatsu S1337 photodiodes (TD)

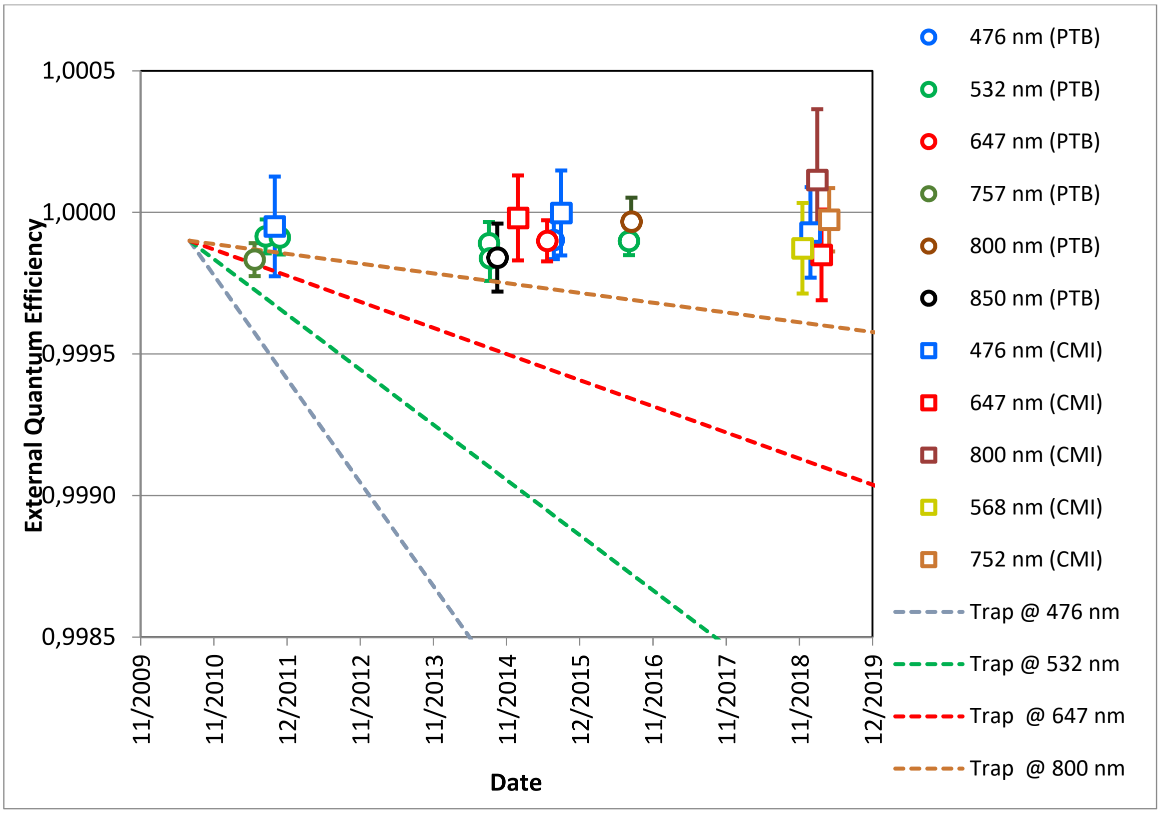

Figure 2 – PQED vs TD EQE temporal stability
(The marker “532 nm (PTB)” includes the PTB measurement at 531 nm.)

3 Conclusions

The EQE values of a set of PQEDs have been measured using two independent state of the art cryogenic radiometer facilities in PTB and CMI with the highest accuracy currently available. The data collected by for a period of time of over 8 years either don’t show any noticeable temporal degradation within the stated measurement uncertainties. As shown in figure 2 the PQED outperform the traditional trap detectors in terms of EQE temporal stability over all visible spectral range, most remarkably at shorter wavelengths where the TD exhibit the largest temporal drift: about 370 ppm/year.

4 Acknowledgments

The research leading to these results has received funding from the European Community’s Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No 217257 and from the European Metrology Research Programme (EMRP) project SIB57 ‘New Primary Standards and Traceability for Radiometry’. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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