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1 Executive Summary

Introduction

The 21st century is the century of optics and photonics. Optics will drive all important technologies and applications: information & communication, earth observation, manufacturing, healthcare & life science, lighting & displays, and photonics for safety & security. Accessing the advantages offered by optical technologies in every one of these fields requires that there must be an “eye” to see the light thus making photodetectors the indispensable enabling devices.

Europe is in a world-leading position in the market for optical technology in industrial production, with the world’s largest laser companies and manufacturers of key laser components located in this region. To ensure that this competitive edge is maintained, the principal research and engineering efforts have to focus on maintenance-free manufacturing equipment and more efficient light detection. Underpinning all the proposed activities is the objective of optical radiation metrology.

The Problem

Historically the standards for optical power have been based on the requirements of incandescent lighting and the advent of Solid State Lighting (SSL) brings new challenges and opportunities for optical traceability. These rapidly evolving technologies require the lowest levels of uncertainty in the realisations of the basic and derived radiometric units combined with rapid, low-cost dissemination and uptake via the calibration chains. The development of low-cost primary standards would also help meet the needs of those European countries that currently depend on another country for the reference for their calibration services.

The Solution

In response to this problem, NEWSTAR developed a new radiometric standard, a device, previously existing as a detector called the Predictable Quantum Efficiency Detector (PQED) based on the photoelectric effect in Silicon semiconductors. Its spectral responsivity is predicted by fundamental constants and material parameters. The developed primary standard has approximately the same cost and functionality as the current transfer standard detectors, but with uncertainties much lower than the current transfer standard detectors even at room temperature, enabling the primary standard to be integrated into different applications taking full advantage of the properties of Silicon technology

Impact

NEWSTAR addressed the requirement for SI traceable radiometry within the European metrology landscape and has therefore bolstered innovation and competitiveness in optical technology industries providing strategic impact for Europe.

Just at the cusp of the traceability chain needed by optical radiation technologies, NEWSTAR contributed to ensure that key manufacturing sectors in Europe, dependant on optical technology, remain competitive. New instruments and techniques were developed, new practical primary standards were implemented and new more accurate and cost-effective calibration methods for radiometry and photometry are now available.

All NMIs/DIs benefit from the results because of the direct contribution to the improvement of the current uncertainty in the realisation of primary standards and the development of new devices to ensure traceability. NEWSTAR specifically targeted small NMIs and DIs in Europe which are not yet equipped with cryogenic radiometer-based primary standards by incorporating capacity building activities embracing excellence in science.

NEWSTAR allowed Europe to take a global lead in the development of the SI in the field of radiometry, by improving the metrology infrastructure for radiometry in the visible range and for photometry. Reference to the standard developed in this project is contained in the document “*Mise en pratique for the candela and associated derived units for photometric and radiometric quantities in the International System of Units (SI)*” approved by the CIPM. The project will accelerate the development of new measurement capabilities among the NMIs in Europe and will improve significantly accurate and reliable dissemination of quantities.

In the longer term, the simplified realisations of the SI units based on the results of NEWSTAR are expected to improve the calibration Measurement Capabilities of European NMIs for most services related to spectral responsivity quantities.

2 Project context, rationale and objectives

2.1 The context and rationale

As clearly highlighted by the Technology Platform Photonics21, the European Commission has acknowledged the importance of optical technologies by identifying them as a Key Enabling Technology for Europe, and set the time to combine resources at all levels; European, national and regional, to significantly strengthen the sector.

The European market share for optical measurement and sensors currently exceeds 30 % of the total 23 € billion world market. Moreover, the significant market uptake of SSL will allow Europe's lighting industry to strengthen its number one global position. By its unique expertise in lighting design, European industry will be the leading player able to offer high quality light with a lower carbon footprint. In order to preserve and extend this competitive position, Europe's R&D efforts in the field need to focus on a number of key areas, in particular more efficient light detection.

For many applications, the goal has traditionally been to achieve ever-greater sensitivities. However, in some areas, the fundamental physical limits of these devices are fast being approached and other approaches must be explored. These new functionalities require radical new design concepts to be developed, together with the corresponding enhanced reference standards, and this involves a significant degree of fundamental research.

Radiometry is the measurement of optical radiation in the frequency range from 3×10^{11} Hz to 3×10^{16} Hz, including the frequency regions commonly referred to as ultraviolet, visible and infrared.

The candela has been one of the base units since the inception of the SI. Although it is historically related to human vision, it was always expressed in physical terms within the SI. The current definition of the candela provides NMIs with the opportunity to base their photometric measurements on optical detector technology. In many NMIs, the candela is based on the spectral responsivity of detectors calibrated by means of a high accuracy cryogenic radiometer, as the primary standard for the measurement of optical power.

A radiometric detector is considered a primary standard if its responsivity is calculable or predictable by fundamental physical laws. Primary detector standards, also referred to as "absolute detectors", in the field of radiometry are mainly electrical substitution radiometers (ESR). ESRs are based on the electrical substitution principle, whereby the heating effect of the optical radiation to be measured is compared with the heating effect produced by a measured quantity of electrical power (Joule effect). The operation of these detectors at temperatures below 20 K enables the measurement uncertainty to be around 50 ppm.

The absolute spectral responsivity scale is transferred to working standards by special photodetectors, the so-called trap detectors. The relative uncertainty for a single spectral responsivity value is approximately 10^{-4} whereas the "continuous" spectral responsivity function of the traps, derived by a fitted trap model, introduces strong correlations between measurement points, which are disregarded within current uncertainty evaluations. Finally, the integral luminous responsivity is measured with respect to those point-by-point calibrated trap detectors, where additional uncertainty components due to correlations, uncertainties of the effective apertures for the transition from power to irradiance mode and uncertainty components due to the properties of the filters used are subsumed. Taking all uncertainty components of this traceability chain into consideration, results in an uncertainty level of roughly 10^{-3} for the realisation of the quantity luminous responsivity – which still needs to be transformed into a luminous intensity.

Historically the standards for optical power have been based on the requirements of incandescent lighting and the advent of SSL brings new challenges and opportunities for optical traceability. Therefore, there is a need for the development of the SI system and the widespread uptake of the units as required for the rapidly evolving optical technologies.

In particular, the need is to provide the lowest levels of uncertainty in the realisations of the basic and derived radiometric units combined with rapid, low-cost dissemination and uptake via the calibration chains. The development of low-cost primary standards would also help meet the needs of those European countries that currently depend on another country for the reference for their calibration services.

The need to deliver and validate new absolute primary standards is promoted by the Consulting Committee for Photometry and Radiometry of the International Committee for Weights and Measures. Though the SI base unit candela has been reformulated over the years and is now derived from optical power, it has a high uncertainty when obtained experimentally. For example, time can be measured with a relative standard uncertainty of better than 10^{-15}. The lowest uncertainty when determining the spectral responsivity of photo detectors by absolute cryogenic radiometers was achieved in the iMERA-Plus T1.J2.3 project qu-Candela "*Candela: Towards quantum based photon standards*" with a relative standard uncertainty 3 x 10^{-5}. Thus, there is a need to improve radiometric accuracy to harmonise the SI.

Previous work on PQED and cryogenic radiometers has shown the potential for improvements in both areas beyond a 10^{-4} relative uncertainty. Comparing results obtained by these high accuracy standards will play an important role in improving the reliability of these underpinning radiometric scales.

NEWSTAR both complements and builds on some results of the iMERA-Plus T1.J2.3 project qu-Candela. The qu-Candela Project was aimed at developing standards for photon metrology from the signal level (10^{13} photons/s - 10^{14} photons/s) of existing radiometric standards (10 µW - 100 µW) down to single photons.

Excellent results were obtained by introducing the concept and demonstrating the feasibility of a new radiometric standard, based on the photoelectric effect in silicon semiconductor, working at liquid nitrogen temperature, called the Predictable Quantum Efficiency Detector (PQED).

After the qu-candela project, there was the need to optimise the PQEDs and to validate experimentally the PQED performance using improved cryogenic radiometers which will contribute to the CCPR efforts to promote the development of new devices (such as the PQED), and the improvement of the existing ones as the huge step towards improved cryogenic radiometry.

The characterisation activities necessary for the experimental validation of the PQED will also enable more accurate characterisation of all optical power scales and, thus, the extended operation and evaluation of systematic errors that are paramount for optimal characterisation and determination of associated uncertainty contributions for metrology and technology applications. With this improved accuracy the PQED comes close to an ideal travelling artefact for top-level intercomparisons.

2.1 The objectives

The main goal of NEWSTAR was to develop an improved silicon detector primary standard for radiometry having approximately the same cost and functionality as the current transfer standard detectors, but with lower uncertainties at cryogenic temperatures (~77 K), enabling the primary standard to be built into different applications taking full advantage of the properties of Predictable Quantum Efficient Detectors (PQEDs)

To this aim, NEWSTAR addressed two scientific and technical objectives:

1. To develop primary standards for absolute radiometry at 1 ppm uncertainty in the visible wavelength range by:
   - Optimising PQED operation at low temperatures and their predictability through 3D simulations.
   - Improving modelling and understanding of PQED charge-carrier losses.
   - Designing and manufacturing customised photodiodes with near unity internal quantum efficiency.
   - improving cryogenic radiometers based on the electrical substitution principle in view of validating the expected ultra-low uncertainty by the best possible measurements
   - Evaluating the stability of the PQED over time.
2. To establish traceability to spectral radiometry by implementing room temperature primary standards (PQED) in applications, including:
   - Traceability to filter radiometry and photometry at a 100 ppm uncertainty.
   - Modelling and understanding of polarisation related issues.
   - Demonstrating the wide dynamic range of PQED.
   - Evaluating the robustness of the standards and their stability with time.
   - Evaluating the ease of use of PQEDs as travelling artefact for comparisons
   - Disseminating the use of the room temperature PQEDs to NMIs that do not have access to cryogenic radiometers; and to industry in order to shorten the traceability chain regionally and internationally

3 Research results

3.1 Objective 1: To develop primary standards for absolute radiometry at 1 ppm uncertainty in the visible wavelength range

3.1.1 PQED for absolute radiometry

NEWSTAR has developed new primary standards for absolute radiometry based on Predicable Quantum Efficient Detectors (PQED) with uncertainties in the visible wavelength range of 1 ppm and 100 ppm respectively for low temperature (~77 K) and room temperature.

This was achieved by designing and manufacturing customised silicon photodiodes with a predictable internal quantum deficiency at the 1 ppm level at low temperature and 100 ppm at room temperature, and by optimising light traps to suppress the polarisation dependence and dark signal for measurements below the 100 ppm level.

The photodiodes have to be assembled into trap detectors (PQED) to be operated at cryogenic temperature (CT-PQED) and at room temperature (RT- PQED). Then, the responsivity of the PQEDs can be predicted by modelling the total losses from the detectors below 1 ppm for the CT-PQED and 100 ppm for the RT-PQED.

<u>The silicon photodiodes</u>

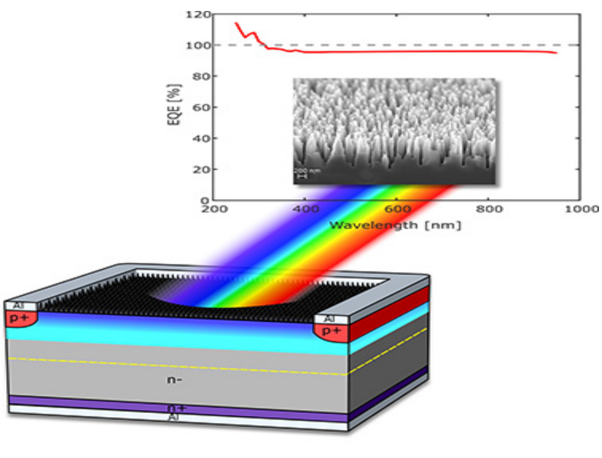
NEWSTAR's main objective was to develop a new absolute primary standard at 1 ppm uncertainty in the visible wavelength range with approximately the same cost and functionality as normal transfer standards. These transfer standards are usually silicon photodiodes in the visible wavelength range, which is a mature technology. In order to achieve this overall goal a redesign of photodiodes relative to standard photodiodes is needed. This makes it necessary to have custom made photodiodes with close to unity internal quantum efficiency (IQE). As the expected internal losses are expected to be small it is more convenient to use the internal quantum deficiency (IQD) to describe the losses of the photodiode.

As NEWSTAR is a follow on project from the iMERA-Plus T1.J2.3 project qu-Candela, further study of the photodiodes developed in the qu-candela project was made. One of the key issues that could not be tested in the previous project was the stability of the custom made photodiodes over time. This is a key point for the usability of the photodiodes as a quantum based stand-alone standard detector. Measurements have been performed by cryogenic radiometers on a number of different PQEDs equipped with photodiodes manufactured in 2010, and at different wavelengths. No drift was observed and the external quantum deficiency (EQD) was well below 200 ppm for all PQEDs at all wavelengths over six years. This is an exceptionally good result as the state-of-the-art commercial transfer standard photodiodes over the same period of time would have drifted typically with a large spectral component ranging from 400 ppm, at best over six years, to 1000 ppm, over two years.

The superb stability of the diodes relates to the simple structure of the photodiodes and that the key element in the working principle of the diodes are the fixed oxide charge located in the oxide close to the interface between silicon dioxide (SiO_2) and silicon. The simple structure of the photodiodes makes them suitable to model and hence to predict the responsivity of the photodiodes. In the qu-candela project, simulations were made with the one dimensional model whereas in this project more advanced simulations with 3D modelling tools was made. JV developed the 3D model with Genius software and performed the initial simulations. Cogenda, the software manufacturer was a collaborator in the project and implemented useful changes in their software on JVs request so that simulations could be more efficiently analysed. The most useful change was the separation of the bulk and surface losses of the internal quantum deficiency. This modification enabled JV to study and model various loss mechanisms and their influence on the IQD at various wavelengths. With the simulation model JV looked at the sensitivity on various design parameters of the photodiodes. One of the major results is that it is the surface recombination velocity (SRV) that limits the achievable internal quantum deficiency of the photodiodes. The SRV depends on a number of interface states, thermal velocity and charge carrier capture cross section. This means that the actual passivation of the surface is limiting the performance of the photodiodes over most of the spectral range. In other words, the achievable IQD of the photodiode is limited by the surface passivation technology. The improved models developed in this project quantified this effect and the one to one relation between SRV and IQD and hence contributed to increased knowledge of the photodiodes.

There are usually two fundamentally different ways to improve the passivation of the surface of semiconductors; namely chemical passivation and field effect passivation. Each strategy is inherently different. Good chemical passivation is achieved when the number of interface states are low, whereas field effect passivation has the strategy to reduce the recombination probability of e-h pairs by reducing their co-existence. This is achieved by storing charge in the passivation layer that attracts one charge carrier and repels the other type. Field effect passivation is therefore inherently achieved when improved induced photodiodes are manufactured. Therefore, the finding in this project is that a good and robust photodiode is achieved with a large concentration of charges in the passivation layer. There are many possible outcomes of increased fixed charge. One of the outcomes is that the increased charge is also increasing the number interface states and neutralises the positive effects of the charge. REG(UiO) and REG(TUT) with semiconductor manufacturing capabilities and analysis tools studied in more detail the passivation of the photodiodes and the actual parameters of the photodiodes. Alternative passivation processes and materials were developed by making test samples and characterising them through lifetime measurements. By measuring the minority carrier lifetime it is possible to extract the surface recombination velocity. The work revealed that very high lifetimes could be achieved with good passivation. In addition, varying the deposition process will result in various densities of fixed charge, but not in a one to one relationship between the lifetime measurement and the fixed oxide charge. The reason for this is that the number of interface states is also changing and making the relationship between fixed charge and lifetime inconclusive. Other examinations of charge increasing techniques showed that with a certain passivation, the increased charge resulted in an increased minority carrier lifetime and reduced SRV. This is consistent with lifetime measurements made by the photodiode manufacturer, with and without, corona charge.

Having a fixed charge is important in order to have a working photodiode with a good surface passivation. Al_2O_3 is known to generate a high fixed negative charge when deposited on silicon as compared to the moderate fixed positive charge generated by SiO_2 on Si. REG(Aalto) studied the possibility of using Al_2O_3 on top of black silicon as a reflection reduced and induced photodiode.



Excellent results were achieved by manufacturing black silicon induced junction photodiodes with near unity quantum efficiency. A device was demonstrated with an external quantum efficiency above 96 % over the wavelength range 250–950 nm. Instead of a conventional p–n junction, negatively charged alumina was used to form an inversion layer that generates a collecting junction that extends to a depth of 30 µm in n-type silicon with large bulk resistivity. Nanostructuring enhanced the collection efficiency by the photodiode surface, resulting in higher effective charge density and increased charge-carrier concentration in the inversion layer. Nanostructuring and efficient surface passivation allow for a reliable device response with incident angles up to 70°..

The outcome of this research lead to a publication in Nature Photonics and a patent application.

Simulations with the model at JV compared the performance of p-type photodiodes with SiO_2 passivation and n-type photodiodes with Al_2O_3 passivation. When keeping all the simulation parameters the same (except for polarity) n-type photodiodes with an Al_2O_3 passivation layer would give 2-3 times lower IQD than p-type diodes. The difference is attributed to the mobility of the charge carriers. This means that better photodiodes with lower IQD can be achieved with an inverted structure of the photodiodes, as compared to the photodiodes from the qu-candela project.

PQED traps assembled from single photodiodes

In order to measure optical power accurately all photons must be absorbed by the photodiode and converted into e-h pairs. To achieve this, two photodiodes are mounted into a trap configuration with an angle between them so that the aperture and number of reflections are sufficient to absorb the photons to the desired level of uncertainty (independent of polarisation state). These PQED trap detectors were used in various applications (see below). VTT and Metrosert evaluated theoretically alternative trap configurations for CT-PQED and RT-PQED with the aim of minimising reflectance losses

VTT chose chip carriers and assembled Individual photodiodes into trap detectors enabling the responsivity of the detectors to be predicted with an uncertainty below 1 ppm for the CT-PQED and 100 ppm for the RT-PQED, by reducing the reflectance losses from the devices. To meet this aim, alternative trap configurations were evaluated theoretically for CT-PQED and RT-PQED in order to minimise reflectance losses.

INRIM studied new trap configurations in the development of a specially designed fibre optic-PQED (FO-PQED), taking into account the diverging beam in fibre optic applications and the oxide thickness necessary (compatible with the 850 nm wavelength) to minimise the number of reflections in the FO-PQED. Metrosert assembled one FO-PQED using the chosen trap configuration.

Measurements of various PQEDs have shown the importance of keeping the photodiodes clean in order to maintain their responsivity. In an environment that is not clean, free ions can be stuck in the impurities on the surface of the photodiodes as they are attracted by the fixed charge in the passivation layer. This is an unwanted situation that causes a reduced effective fixed charge in the passivation layer which in turn reduces the field effect passivation and increases the IQD of the photodiodes. This effect is more pronounced for thin oxide layers as compared to thick oxide layers and it alters the predicted value from the manufactured photodiodes. This shows that thin oxide layers are more susceptible to impurities and surface charge and underlines the importance of keeping the photodiodes clean in order to maintain their predicted value.

Predicting the responsivity of PQEDs

In NEWSTAR n-type silicon photodiodes were manufactured with Al_2O_3 passivation on top. Based on simulation results, low-doped high lifetime n-type wafers were used to give a low Internal Quantum Deficiency (IQD) over a wide spectral range. Low-doped wafers aided by a reverse bias give a wide depletion region where the recombination probability of the charge carriers is approaching zero. To monitor the quality in the manufacturing process, wafers excess carrier lifetimes are measured as a function of injection level. This information was exploited in the modelling and was used to predict the SRV of the wafers. Studies in this project showed that the SRV is the limiting parameter in the IQD of the photodiodes. This is an important outcome of the project because with the new models, enabled by the collaboration with the simulation software manufacturer, the IQD of the photodiodes can be predicted based on manufacturers lifetime measurements and passivation layers fixed charge.

> This means that when the manufacturer supplies the necessary information with the diodes, the Internal Quantum Deficiency is known through simulations without additional characterisations.

Measurements made by VTT on NEWSTAR photodiodes showed very good agreement with predicted values and thereby confirmed the predictions. This is a big step towards simplified traceability and improved radiometric accuracy in various applications stemming out of the NEWSTAR project.

In order to have a larger up-take of PQEDs as a standard detector, confidence in their predicted response is needed. Simplified experimental techniques that could validate the performance of the PQEDs are required. In NEWSTAR, an early stage researcher mobility grant, CSIC, JV, and ESRMG(CSIC) worked on new experimental techniques to predict the internal quantum deficiency of the photodiodes. The results of this self-calibration procedure were promising.

> The potential was demonstrated for self-calibration to predict the Internal Quantum Deficiency to 0.1 % accuracy in unstabilised room temperature; this value meets most of the current needs in optical power measurements.

Using the same experimental technique at cryogenic temperatures is expected to give orders of magnitude improvement in this estimate due to the more favourable material parameters and experimental conditions at cryogenic temperatures.

When cooling down the photodiodes, reduced IQD is expected, in addition to a reduced absorption coefficient as compared to room temperature. The absorption coefficient is important for the accuracy of the prediction of the responsivity of the photodiodes. REG(UiO) studied the effect of the absorption coefficient change with temperature and they provided new reliable data for the absorption coefficient at both room temperature and liquid nitrogen temperature. The absorption coefficient is influenced by the photon and phonon interaction. This interaction also influences the quantum gain. The quantum gain is the probability that one photon generates more than one e-h pair. In order to meet the target uncertainty of 1 ppm in the internal quantum deficiency, the contribution from the quantum gain had to be examined. This study has not been conducted before to the level of uncertainty needed in this project. The conclusion from this work is that this effect does not need to be taken into account as long as the wavelength is kept above 405 nm.

Simulations predict an improved response from the photodiodes when they are cooled down. As cooled materials contract due to their thermal expansion coefficient, when a photodiode is attached to a chip carrier and cooled down this will cause some strain in the photodiode if the carrier has a different thermal expansion coefficient than the photodiode. By taking advantage of semiconductor process technology, to avoid strain in the photodiode when cooled to liquid nitrogen temperature (LN2) and to have a robust chip carrier, the carriers are made of thick silicon. In this way, the materials of the photodiode and chip carriers are exactly the same and strain free mounting of the carrier is achieved independent of temperature.

Towards the radiometric determination of fundamental constants

One of the major impacts of NEWSTAR was the acceptance of the PQED as a primary standard in the “Mise-en- Pratique” of the Candela. This means that both the PQED and the cryogenic radiometer are accepted as primary standards for measuring optical power by the CCPR.

This link between the PQED and the cryogenic radiometer (CR) can be established by the measurement of the e/h ratio. By measuring the photocurrent from the PQED and the optical power from the CR it is possible to solve the equation with respect to the e/h ratio, thus establishing a radiometric measurement of the e/h ratio. In this way, both of the fundamentally different radiometry primary standards are linked through the measurement of fundamental constants.

The proposed redefinition of the new SI system is based on fixing the numerical constants of a range of fundamental constants like Planck’s constant (h), elementary charge (e) and speed of light in vacuum (c).

> The radiometry community can take advantage of the redefinition of the new SI as the comparison of the two primary standards can be used to express the measurand as the ratio between fundamental constants and thereby test the equivalence between the two primary standards.

In other words, the outstanding performance of the PQED at 77 K offers the opportunity to search for consistency between thermodynamics and electromagnetisms by comparing the results obtained by high accuracy standards based on thermodynamics (i.e. absolute cryogenic radiometers) from one side and electromagnetisms (PQED at 77 K) on the other. The experimental foundations have been established for this ambitious goal, with cryogenic radiometers having been shown to support the radiometric determination of fundamental constants with an expected relative standard uncertainty as low as 10 ppm.

The radiometric measurement of the e/h ratio is important also in identifying systematic effects in the PQED. In particular, REG(TUT), with support from Metrosert and a simulation overview from JV, studied theoretically the physical limits for the generation of exactly one electron-hole pair by a photon in the low-doped silicon structure.

3.1.2 CT-PQED: cryogenic primary radiometric standards at 1 ppm

The expected ultra-low uncertainty of CT-PQEDs has to be validated by the best possible measurements (10 ppm nominally) using cryogenic radiometers based on the electrical substitution principle. In fact, many of the prediction parameters of the PQED such as, for example the reflectivity, can be measured, however only the comparison of the PQED with cryogenic radiometers provides an absolute value of the external quantum efficiency of the PQED and, thus, is the only method to determine the absolute value of the internal quantum deficiency of the PQED. In addition, primary standard cryogenic radiometers are the only reference detectors that have the temporal stability necessary to determine the possible influence of the aging of the photodiodes on the external quantum efficiency. Therefore, these measurements are fundamental as checks for the modelling work and for the validation of the prediction of the PQED.

In NEWSTAR, the characterisations necessary for the experimental validation of the PQED have enabled more accurate characterisation of optical power scales and, thus, the extended operation and evaluation of systematic errors that are paramount for optimal characterisation and determination of associated uncertainty contributions for metrology and technology applications.

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Moreover, the in-house stability of the CT-PQED was checked over time. This is very important as photodiodes often suffer from a significant drift in the spectral responsivity for optical wavelengths around 400 nm.

The predictability of the PQED was also checked by comparing several PQEDs among themselves. By the direct comparison of two almost identical detectors, the comparison uncertainty can be reduced which makes this measurement the most sensitive way to test the sensitivity of the PQED to the input parameters.

Tools for the validation of CT-PQED and cryogenic radiometers

PTB developed and realised all the tools necessary for the validation of CT-PQED and cryogenic radiometers at the ppm-level thus advancing beyond the state-of-the-art of cryogenic radiometry.

In particular the major contributions to the cryogenic radiometer uncertainty budgets were minimised to advance beyond the state-of-the-art of cryogenic radiometry. These tools enabled radiometric measurements with cryogenic radiometers at uncertainty levels that are close to the expected uncertainty of prediction of the PQED.

The trap configuration for the CT-PQED was integrated into the limited space in the cryogenic radiometer facilities and the vacuum system of the common window cryogenic radiometer (CW-CR). This is of particular importance as two independent approaches to cryogenic radiometry place different crucial demands on the CT-PQED cryostats in order to achieve the lowest uncertainties. The cryostat was intended to be compatible with improved stray-light measurements for both Brewster window (BW) and common window (CW) configurations.

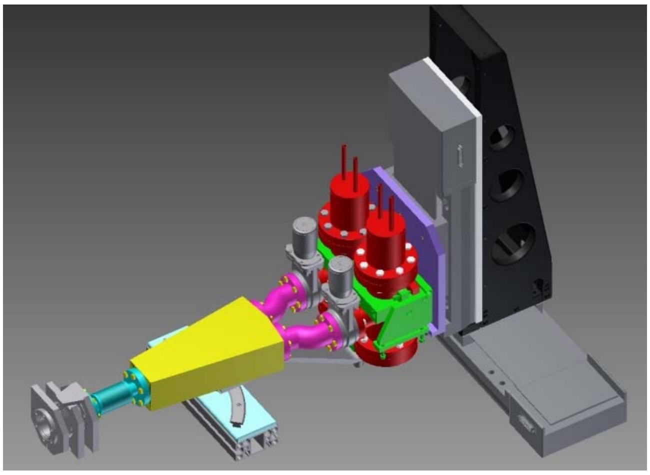
For this purpose, UHV-cryostats have been developed to assure the best experimental conditions for the experimental validation of the software models developed for the PQED. These UHV-cryostats use standard CF components wherever possible aiming to reduce costs but also to enhance the compatibility with the radiometric facilities that are operated under vacuum.

Additional effort was put into reducing the outer dimensions of the cryostats and to be compatible with different metrological tasks related to the CT-PQED such as an adjustable angle between the two PQED photodiodes, structures with fixed angles between the two photodiodes and holders for single photodiodes for, e.g., uniformity of the relative spectral responsivity measurements.

Improved methods and techniques were identified and defined that enhanced the traceability of radiometric measurements to the SI, and this led to improved heater power measurements in cryogenic radiometers (CRs). Two different methods based on metrology-grade resistance bridges and optimising the measurement sequence timing at CMI and an improved technique for the heater power measurement at PTB have been developed.

Furthermore, PTB developed a radiometric comparison facility that validated the predicted spectral responsivity of PQEDs at the 6 ppm level by direct intercomparisons of PQEDs. A Y-pipe design was chosen for the setup to be used to radiometrically compare two PQEDs by means of a shared Brewster-window (CW). The heater power measurement for the cavity of the PTB CW cryogenic radiometer (CW-CR) configuration has been improved. The existing temperature controller for the CW-CR has been adopted in order to improve the heater power measurement. The new heater power measurement procedure is based on the measurement of the heater current and voltage; and thus the heater power is measured with an external metrology grade digital voltmeter.

This setup has improved the traceability of the heater power measurement to the SI.



The figure (left) shows the design of the setup of the radiometric comparison facility for the UHV comparison of PQEDs. The PQED-cryostats are red coloured and the detectors are mounted on an x-y-stage and connected to the Brewster-window via flexible bellows.

The external quantum deficiency of a PQED equipped with photodiodes from the iMERA-Plus T1.J2.3 project qu-Candela was measured using the CW-CR at room and liquid nitrogen temperature and at three wavelengths (407 nm, 532 nm and 850 nm) with a relative standard uncertainty ranging from 21 ppm to 55 ppm.

Several improvements of the Brewster Window cryogenic radiometer (BW-CR) configuration have also been achieved. Through the optimisation of an external laser power stabilisation optical set up, a total stray light level of 1.5×10^{-9} W for a beam power of 3.3×10^{-4} W was reached. The stray radiation was measured with a relative uncertainty of 10 % at 10 K. Moreover, a temperature controller was realised for the cavity of CMI's BW-CR configuration. The latest generation of the temperature AC bridge measurements system was implemented in the CMI BW-CR. The system delivered higher stability of temperature data read from the cavity sensor, thus removing the previous barrier to reaching the required uncertainty on the nominal value of 0.5 mW of heating power. In other words, the uncertainty contribution of the heater power measurements of cryogenic radiometers was by a factor larger than 2 down to 5 parts per million.

Comparing PQED and primary standard cryogenic radiometers

The efforts invested to identify and define improved methods and techniques enhancing the traceability of radiometric measurements to the SI, led to improved heater power measurements in cryogenic radiometers (CRs). Thanks to a new temperature controller for the cavity of a CW cryogenic radiometer (CW-CR) configuration, PTB reduced the relative standard uncertainty of the measurement of the radiant power of laser sources down to 11 ppm at 100 µW radiant power and 10 ppm at 400 µW radiant power. This result was achieved by improving the measurement of the absorbance of the cryogenic radiometer cavity. This is the most fundamental correction for a cryogenic radiometer and the relative standard uncertainty of this component of the uncertainty budget was reduced from 13 ppm to 4 ppm.

Stray radiation can become a dominant uncertainty contribution if the amount and spatial distribution is unknown. In order to reduce the uncertainty contribution of the stray radiation below 10 ppm, PTB developed a stray radiation detector. This detector measures the stray radiation in the proximity of the apertures of the CT-PQED and the CW-CR cavity. This is only possible at the CW-CR because all the radiometric measurements are done at the same position relative to the laser beam and behind the same Brewster window. However, it is still necessary to reduce the stray radiation in order to minimise the influence of the stray radiation. PTB adopted the experimental techniques used at CMI to reduce the stray radiation down to the lowest possible level. PTB showed that:

> cryogenic radiometers can support the radiometric determination fundamental constants with expected relative standard uncertainties as low as 10 ppm.

PTB measured the spectral responsivity of a CT-PQED with ultra-low relative standard uncertainties of 20 ppm and 23 ppm at 531 nm and 407 nm, respectively. These are the lowest uncertainties that have been reported for the measurement of the spectral responsivity of an optical detector by means of a cryogenic radiometer thus far. This result was achieved by employing the techniques to reduce the uncertainties of the radiant power measurements with the cryogenic radiometer down to 11 ppm and the high quality of the CT-PQED. Hence:

> the objective to perform the best possible measurements using improved cryogenic radiometers based on the electrical substitution principle has been achieved, being 'first in the world' in terms of accuracy when determining the spectral responsivity of silicon photodiode based trap detectors by means of laser radiation and cryogenic radiometers.

Validation by comparison measurements between CT-PQEDs themselves

The assessment of the predictability of the PQED at the ppm level can only be achieved by comparing the radiometric measurements performed with several CT-PQEDs among themselves. By directly comparing two inherently identical detectors at a dedicated facility a number of uncertainty contributions occurring in the comparison of a PQED against a cryogenic radiometer can be avoided, e.g., those associated with the power measurement by the cryogenic radiometer, the photocurrent measurement, the beam profile and stray light. Thus, this is the most sensitive and the only measurement available to test whether the radiometric measurements with different PQEDs give identical results within 1 ppm as predicted by the modelling.

In addition, this measurement also provides an estimate of the variance of the responsivity of PQEDs assumed to be identical (because, for instance, they are made of photodiodes originating from one wafer). This variance is a fundamental estimation of the uncertainty of the responsivity caused by the uncertainty in the manufacturing conditions of the photodiodes and the setting up and handling of the PQED.

PTB was able to show that the expected uncertainties of 6 ppm could be achieved when the CT-PQEDs are directly intercompared. This extremely low uncertainty could be achieved, because the measured quantities, as photo and dark current, and the level and the influence of the stray radiation have been almost identical for all the systems tested. In addition, using identical equipment, like the same digital multimeters and the same current-to-voltage converter, for all measurements rendered it possible to measure relative values whilst avoiding or drastically reducing uncertainty contributions which have to be considered in absolute measurements. The achieved uncertainties are, by a factor larger than three, smaller than those achieved in absolute measurements with the CW-CR. Measurements at the radiometric comparison facility can be performed at different temperatures ranging from about 300 K down to about 77 K, in vacuum, in air or using a protective gas atmosphere. This facility was used to compare three identical PQEDs against each other and, in addition, to compare PQEDs equipped with different photodiodes.

> Three "identical" CT-PQEDs were compared showing, that cleanliness of the PQED photodiodes is a big issue. The deviation of the measured ratios can be explained by a non-perfect cleaning of the photodiodes before assembly into the cryostats.

The PQEDs with different parameters (two detectors had photodiodes with different oxide thicknesses and one PQED was equipped with photodiodes made from n-type wafers) could be compared with ultra-low uncertainties providing input for the modelling of PQEDs done by JV. These low uncertainties could not have been achieved in absolute measurements with cryogenic radiometers. The collaboration of PTB and JV provided high accuracy experimental data for JV, while JV supported PTB in the responsivity modelling of photodetectors by means of advanced three-dimensional simulation tools.

CT-PQED in-house stability over time

PTB assessed the in-house stability of the CT-PQED over time. The measurements of the external quantum deficiency of PQEDs equipped with photodiodes from the iMERA-Plus T1.J2.3 project qu-Candela at several wavelengths gave proof that:

PQEDs equipped with clean photodiodes show no temporal drift of the external quantum efficiency at the investigated wavelengths within the uncertainties of the measurements.

This evaluation gave input for the modelling of the PQED and eliminated several aging mechanisms that might need to be included into the prediction of the spectral responsivity of the PQED and set an upper value for the annual drift rates of PQED photodiodes.

To determine the in-house stability over time, the spectral responsivity of a CT-PQED at cryogenic and room temperature was to be measured in three campaigns over a time spread of about two years. After the last but one measurement of the ones scheduled during the first campaign from September to October 2014 the second photodiode of the PQED stopped working. Because this measurement was performed at cryogenic temperature it is assumed that the photodiode was damaged because of the different thermal expansion of silicon and the material on which the photodiode was glued on.

A second PQED was set up to perform the second and the third measurement campaigns. It was later decided to operate PQED only at room temperature to prevent damage to the photodiodes. Unfortunately, it turned out at the end of the measurements that the results obtained with this second PQED could not be used to evaluate the spectral responsivity stability of PQEDs because of cleanness issues.

However, the stability of PQEDs nevertheless could be evaluated taking into account all results obtained by PTB since 2011 on the spectral responsivity of PQEDs equipped with photodiodes manufactured together in mid 2010. The results obtained are based on PQEDs which are all equipped with photodiodes produced at approximately the same time by VTT within the iMERA-Plus T1.J2.3 project qu-Candela. Some of these photodiodes have been used and, thus, have been irradiated several times and some have been irradiated only during the measurements considered here to estimate the stability.

Within a period of six years, the performance of Si-based PQEDs was studied at several laser wavelengths from 407 nm to 850 nm by means of a cryogenic radiometer. The expanded (k = 2) measurement uncertainty lies between 50 ppm and 120 ppm. It was observed that:

the responsivity of PQEDs remains stable within the uncertainty of the measurements during the time period of the study.

This marks a major breakthrough to establish a primary detector standard based on induced junction photodiodes. With this improved accuracy the PQED comes close to an ideal travelling artefact for top-level intercomparisons.

3.2 Objective 2: To establish traceability to spectral radiometry by implementing room temperature primary standards (RT-PQED) in applications

3.2.1 RT-PQED as a room temperature primary radiometric standard at 100 ppm

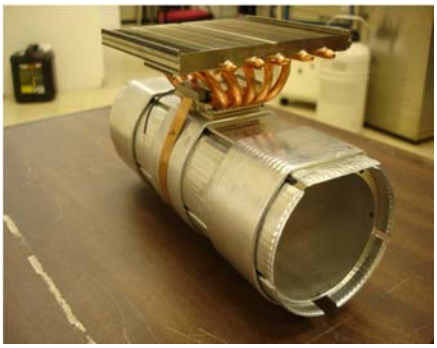
Room temperature primary standards based on PQEDs were implemented as spectral responsivity standards for applications at the 100 ppm uncertainty level. This led to the realisation of a primary standard for radiometry operating at room temperature and having approximately the same cost and functionality as transfer standard detectors. This enables NMIs to deploy primary standards into a wider spectrum of applications and to disseminate the reduced uncertainty into other measurement realisations.

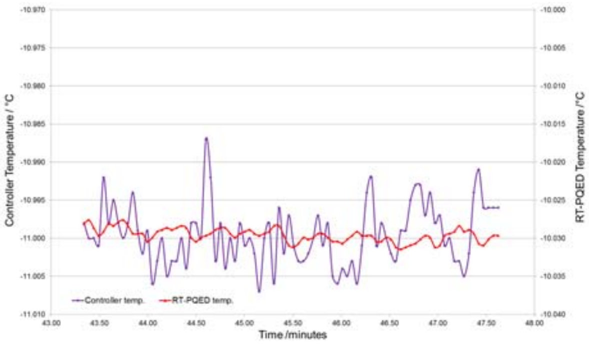
This was achieved by optimising the performance of RT-PQEDs in terms of their optical parameters and signal to noise ratio performance. For this purpose the linearity of response, dynamic range and their temperature dependence were characterised. The model of RT-PQEDs was then validated at room temperature for two distinct configurations of the cryogenic radiometer, with the Brewster window (BW) and without the window (WL), at three specific wavelengths.

RT-PQED optimisation

The RT-PQED was optimised by designing and realising the temperature controller/monitoring system with a stability better than ±0.05 °C and a temperature range from - 20 °C to +30 °C. The low temperature regime and high temperature stability are crucial for RT-PQED applications requiring low noise operation such as those in photometry and radiation thermometry. Moreover, a dust-free and temperature stabilised dry nitrogen purging system was realised with temperature stability ±0.1 °C, to avoid icing and condensation inside the PQED.

Temperature controller
A temperature control system has been designed for the predictable quantum efficient detector (PQED). The PQED requires temperature stabilisation at a set point to within ±0.05 °C and operability over the temperature range -20.0 °C to 30 °C. In addition, a gas simple purging system has been designed to prevent condensation and ice formation in the device when stabilised below the ambient dew point temperature when operated at lower temperatures. Two devices were developed and built in close collaboration between LNE and CI, one air cooled and the second one water cooled. The tests performed confirmed that the lowest temperature achieved was – 12 °C and the stability at this temperature was better than 0.005 °C for measurement times in excess of 2 hours.





Purging system
In order to reach the lowest possible level of uncertainty the PQED has to operated without its Brewster window. For this purpose a gas flow purging system has been developed and tested to avoid contamination of the surface of the photodiodes that will adversely affect their performance. The purging system has been implemented using both dry nitrogen and argon gases. A user manual has been written that explains the recommended purging system to be implemented when using the PQED without Brewster window with detailed description of the necessary components such as micro filters, flowmeters and the recommended gas flow value and all the precautions that the operator must take to minimise the risk of the detrimental contamination of the photodiode. The purging system has been used in different implementations by all of the consortium's laboratories that have been performing measurements with the RT-PQED. To prove the effectiveness of the purging system the uniformity of RT-PQED has been measured at different times during the project and no detectable contamination has been found.

RT-PQED characterisation

A set of room temperature PQEDs were thoroughly characterised with the aim of verifying and possibly validating their use as an optical primary standard with comparable uncertainty and with the current world wide accepted primary standard i.e. the cryogenic radiometer ($u = 2.10^{-4}$). The advantages of room temperature PQED are: much lower cost of the device, negligible running cost, much easier to operate and to transport if needed.

The performance of the RT-PQEDs are characterised in terms of their optical parameters and signal to noise ratio.

For this purpose the linearity of response, dynamic range and the RT-PQED temperature dependence was characterised. The polarisation and angular dependence were also evaluated. All necessary facilities for these studies were developed such as an active temperature stabilisation/monitoring system to measure the RT-PQED temperature sensitivity. Furthermore the boundary conditions (diameter of a collimated beam, polarisation state, angle of incidence) were studied using well defined laser beams.

Temperature dependence, linearity & dynamic range

To lead the metrological characterisation of RT-PQED in terms of its linearity, temperature dependence and the dynamic range, the measurements were carried out in CMI's laboratories in collaboration with MSL New Zealand.

The low temperature range of operation opened up interesting opportunities for low flux measurements thanks to the lower thermal noise generated by the PQED photodiodes. The noise equivalent power of an unbiased RT PQED measured in conjunction with a switched integrator amplifier at temperatures lower than 10 °C is as low as 80 fW/Hz½. The dynamic range of the PQED at the upper power levels depends on the bias voltage applied to the photodiodes. For a power level higher than 50 uW it is necessary to operate the PQED with a bias voltage of 5 V. In this configuration the PQED exhibited linear behaviour up to 0.5 mA of the photocurrent value generated, that is well inside the typical measurement conditions for the cryogenic radiometer.

The possibility emerged during the project to use the PQED in two regimes, biased for the high optical power level and cooled at 10 °C, and unbiased for the low optical power levels. The PQED dynamic range can cover in this way up to 8 decades from 10^{-3}W to 10^{-12} W.

Accordingly the measurements performed with the RT-PQED in biased mode and in the linear operation part of the dynamic range did not exhibit any temperature related variation at around room temperature.

By using the PQED in two regimes, biased for the high optical power level and cooled at 10 °C, and unbiased for the low optical power levels, the PQED dynamic range can cover up to 8 decades from 10^{-3}W to 10^{-12} W. When using the RT-PQED in biased mode and in the linear operation part of the dynamic range, it did not exhibit any temperature related variation around room temperature. RT 3.1.3

Angular dependence

PTB measured the angular dependence of the responsivity of the RT-PQED with a diverging beam and a collimated beam over the spectral range of interest (dependent on the type of beam). The results of the angular dependence measurements on the studied RT-PQED showed minor variations that are well within the measurement uncertainties and significantly less than 100 ppm in the mid-visible spectral range (measured at 515 nm and 680 nm). The measurements at 400 nm and 800 nm wavelengths revealed angular dependencies slightly exceeding the 100 ppm level. These angular dependencies are very likely caused by inhomogeneity in the photodiode oxide layers. As these layers differ from PQED to PQED it is not possible to derive a general working correction based on the measurement results of a single PQED. To prove this assumption another RT-PQED could be investigated.

At 400 nm and 800 nm, angular dependencies slightly exceed the 100 ppm level. RT 3.1.4

Polarisation dependence

Knowledge of the polarisation dependence enables PQED to be used in applications where non-polarised or partially polarised incoherent radiation is used. PTB investigated the polarisation dependence of the spectral responsivity of a windowless room temperature PQED over the spectral range from 360 nm to 900 nm. Therefore the signals measured with p-polarised and s-polarised laser beams were compared. The difference in signal intensity measured at the two different polarisation states were in turn compared to expected values of this signal difference. These expected values are taken from "Use of the predictable quantum efficient detector with light sources of uncontrolled state of polarisation," Sildoja et al, Meas. Sci. Technol. 25, 2014. The experimental results of the polarisation dependence measurements match the expected values based on the simulations of reflectance presented in the literature within the striven 100 ppm uncertainty level.

This experimental validation of the simulated PQED behaviour strongly supports the aim of using the PQED in applications where non-polarised or partially polarised radiation is used. RT 3.1.5

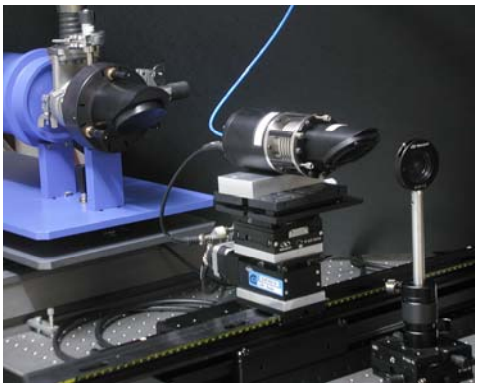
During the first approaches to develop a suitable optical setup for the polarisation dependence measurements, an unexpected negative effect of the nitrogen flow in the signal stability appeared. Measurements of the signal stability in the irradiance mode proved that the nitrogen flow at standard parameters (p = 0.5 mbar, flow rate = 2 l min-1) decreases the stability significantly. Detailed investigation showed that a pressure of 0.2 mbar and a flow rate of 1 l min-1 are preferable for an optimum trade-off between low disturbances and the cleanness of the PQED photodiodes.

Detailed investigation showed that a pressure of 0.2 mbar and a flow rate of 1 l min-1 are preferable for an optimum trade-off between low disturbances and the cleanness of the PQED photodiodes.

Validation of the RT-PQED model at 100 ppm uncertainty

CMI validated the RT PQED at two wavelengths 476 nm and 647.1 nm against the CMI cryogenic radiometer. To reach the lowest possible uncertainty a series of improvements were applied to this facility. In particular a significant reduction of the electrical power measurement uncertainty was reached by the implementation of a metrological grade voltmeter calibrated directly against fundamental voltage standard. The uncertainty of the electrical power measurement has reached the 5 ppm level. As the measurement plane of the cavity of the CMI Cryogenic Radiometer (CR) and of the detector under test are not coincident and because of the presence of the Brewster window only in front of the CR cavity, considerable efforts were necessary to minimise the stray light around the cavity. This stray light was measured by the silicon quadrant detector surrounding the input aperture of the cavity. After a calibration run, for particular wavelength, this system was able to detect the stray light around the absorbance cavity input aperture at the level of appx 0.1 nW with uncertainty around 2 % relative. With optimal placement of spatial filtering the stray light was minimised to a level lower than 10 ppm relative to the applied optical power of measuring beam. Thanks to all these improvements the total uncertainty for the measurement optical power with the CMI CR has been reduced from 150 ppm to 50 ppm. Significantly better temporal stability of the optical power of the measuring laser radiation was achieved. A typical level for a time span of 1 hour was 20 ppm, or in the best cases 10 ppm. The residual most significant contribution to the uncertainty budget has been demonstrated to be the statistical variance (40 ppm) of the cryogenic radiometer, which is probably due to the fluctuations in the background broadband radiation seen by the cavity.

To validate the spectral responsivity of the RT-PQED, at the requested uncertainty level, the wavelength of the optical radiation was measured with an uncertainty better than 10 ppm for the investigated spectral range of the optical radiation.



The validation of the RT PQED without a Brewster window has shown excellent agreement with the predicted values at the two wavelengths 476.2 nm and 647.1 nm, better than 10 ppm. This value takes into account both an accurate wave meter measurement of the laser radiation wavelength and the measured power of the residual reflected beam from the RT-PQED.

Comparison of two RT-PQEDs between themselves

Besides the absolute validation of the RT-PQED, a series of measurements were performed comparing two PQEDs during a time interval of six months. To optimise the PQED alignment, a motorised XY system has been implemented for each PQED to find the plateau position and to quantify, at the same time, the alignment sensitivity in horizontal and vertical axes. Thanks to the excellent uniformity of the PQED, and to a laser stability better than 20 ppm/hour, the agreement between the two PQED has been measured to be in the order of the 25 ppm level at two wavelengths 476 nm and 647 nm. While these measurements are not sufficient to demonstrate the RT PQED predictability it is a necessary requirement and it has been fulfilled.

Ratio photocurrents

An important achievement, reached in the framework of this project, was the demonstrated use of the ratio of the two photodiodes photocurrent to predict the PQED reflectivity. This method simplifies the reflectivity parameter quantification considerably and within the 5 ppm accuracy.

Bandwidth

PTB and CMI, using two independent experimental realisations, demonstrated the RT PQED responsivity independence to the vertically polarised input radiation bandwidth starting from 0.1 nm up to 10 nm and in different spectral regions. The bandwidth dependence of a Brewster windowed and windowless room temperature PQED has been investigated by comparing the illuminance determined with the PQED to the illuminance measured with a recently calibrated trap detector. This comparison was done with light of different spectral bandwidths. The measurements show no effect of the bandwidth on the measurement results and therefore they prove the independence of the PQED performance from the bandwidth.

In summary,

> The RT-PQED external quantum efficiency was validated at two laser wavelengths with 10 ppm agreement with a predicted value at the 65 ppm uncertainty level.
>
> The agreement of two RT-PQED compared between each other, within a period of 6 months, demonstrated better than 25 ppm with an uncertainty of 30 ppm.

The nitrogen flow system for the room temperature PQED resulted in an effective method to protect the open detector from dust contamination. Some measurements of the external quantum deficiency of the RT-PQED at three wavelengths (407 nm, 532 nm and 850 nm) gave proof that clean PQED-photodiodes show no temporal drift of the external quantum efficiency at the investigated wavelengths within the uncertainties of the measurements. This marks a major breakthrough towards the establishment of a primary detector standard based on induced junction photodiodes.

In conclusion, the results indicate that the RT-PQED may replace the cryogenic radiometer as a primary standard of optical power in the visible wavelength range. Considering all these positive results:

> RT PQED is a good candidate for an easier to use and cheaper primary standard detector system with the price of the transfer standard.

3.2.2 RT-PQED: applications to photometry, radiation thermometry and fibre optics

Room temperature (RT-)PQEDs were implemented in photometry and filter radiometry, including thermometry, applications at the 100 ppm uncertainty level.

In photometry, the basic unit, the candela, has been realised by a direct calibration of a reference photometer using a RT-PQED equipped with a precision aperture for operation in the irradiance mode. In so doing, the traceability chain for the realisation of photometric units was significantly shortened. Moreover the potential was provided for advancing beyond the state of the art uncertainties (currently about 1000 ppm).

In filter radiometry, the spectral irradiance responsivity was determined, together with the achievable associated uncertainty, for filter radiometers (FRs) in a direct one-step procedure in the visible spectral range. FRs operated in the irradiance mode are widely used in the determination of thermodynamic temperatures of blackbodies and are the most promising candidates for the future mise-en-pratique of the Kelvin (MeP-K).

In addition the application of the primary standard (PQED) as a fibre optic power meter FO-PQED at 850 nm (with a larger uncertainty of 1000 ppm) was investigated in order to increase the potential impact toward technological applications, which are, for example, driven by the interest of the fibre optics industry in better and easier traceability for fibre optics radiometer calibrations. Applying PQEDs with fibre optics also combined the advantages of the PQED with those given by the fibre optics geometry, concerning the control of key parameters such as the beam profile quality and the illumination geometry of the PQEDs.

RT-PQED for photometry

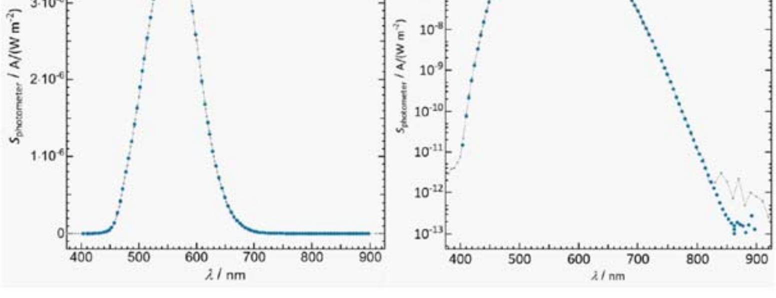
The RT-PQED was implemented for the realisation of the candela, the primary unit for photometry, using a reference photometer calibrated by a direct comparison with the RT-PQED equipped with a precision aperture for use as an absolute radiometric standard in the irradiance mode.

Current realisations of the photometric unit are traceable to the cryogenic radiometer via transfer standard detectors involving several steps in the chain of calibrations. The state-of-the-art uncertainty for the realisation of the photometric unit luminous responsivity is at the 1000 ppm level.

In order to implement reference photometer calibrations at the 100 ppm uncertainty level based on the RT-PQED the transition was established between a windowless RT-PQED measuring optical power and the RT-PQED fitted with an aperture operating in the irradiance mode. This transition required a dedicated investigation of the optical interaction between the RT-PQED and the aperture, i.e. the influence of scattering and diffraction from the aperture edge, the effect of back reflections and the optimal geometry for fixing the aperture in front of the RT-PQED.

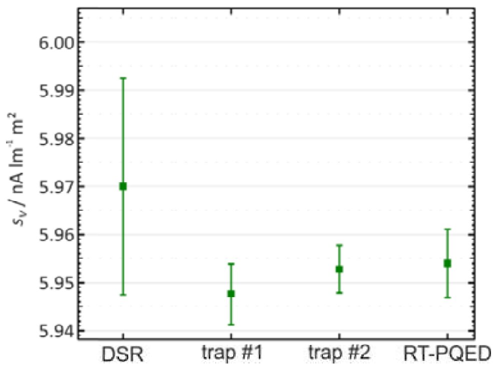
CNAM performed a preliminary numerical investigation on the expected diffraction and scattering effects of a precision aperture placed in front of an RT-PQED. The diffraction correction for a precision aperture of 7 mm in diameter has been estimated to be about $1.4 \cdot 10^{-4}$, while the diffuse light effect is expected to be negligible. A RT-PQED was equipped with a precision aperture in a clean room facility to avoid dust contamination, and the aperture area was calibrated with a non-contact method to avoid damage to the edge. Then scattering and inter-reflections were measured. The uncertainty of this calibration ($4 \cdot 10^{-4}$) is the most significant contribution to the estimation of the RT-PQED irradiance responsivity.

To validate the RT-PQED, equipped with the precision aperture, as an irradiance standard, PTB calibrated a reference photometer against the RT-PQED and the result was compared with the measurement obtained by classical calibration against a calibrated transfer trap detector. The following figures show the spectral responsivity of the reference photometer calibrated against the RT-PQED (blue dots) and against a calibrated transfer trap detector (grey curve); left: linear scale, right: logarithmic scale. The values are in very good agreement.



Finally, for validating the RT-PQED as an irradiance standard for photometric application, PTB realised the primary photometric unit, the candela, by measuring the luminous intensity emitted by an incandescent lamp with the photometer calibrated against the RT-PQED. The results have been compared with other different ways to measure the luminous responsivity of the reference photometer.

The next picture shows the luminous responsivity s_v of the reference photometer determined against photodiodes calibrated at the differential spectral responsivity (DSR) facility, against calibrated trap detectors at the TULIP facility and against the RT-PQED. The calibration was performed at the tuneable laser facility which has a high dynamic range, narrow spectral bandwidth, accurately known wavelength as well as high temporal stability of the laser radiation over the whole spectral range defined by $V(\lambda)$.



The values of luminous responsivity determined by different calibration methods agree well within the measurement uncertainties and within the 100 ppm goal.

The potential to shorten the traceability chain for the realisation of photometric units has been achieved by the results obtained in the direct calibration of a reference photometer against an RT-PQED, opening the way for advancing beyond the state-of-the-art uncertainties, as the final uncertainty is already competitive with the state of the art techniques.

RT-PQED for radiation thermometry

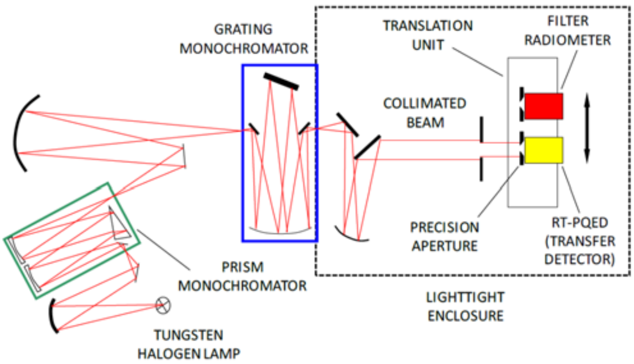
PTB, CSIC and BFKH investigated the applicability of RT-PQEDs for the direct, one step determination of the spectral irradiance responsivity of filter radiometers (FRs) in the visible wavelength range (~650 nm) and the achievable associated uncertainties.

FRs operated in the irradiance mode are widely applied for the determination of the thermodynamic temperatures of blackbodies and are the most promising candidates for the future mise-en-pratique of the Kelvin (MeP-K). At present, their spectral irradiance responsivity is determined in a two-step procedure traceable to the cryogenic radiometer as a primary standard via a trap detector as a transfer standard. The common calibration is based on a collimated beam setup using a monochromator and a tungsten halogen lamp. To obtain similar radiation source properties during the calibration and the application of FRs, a Lambertian source (e.g., integrating sphere) setup is highly desirable. These promising new setups are currently realised and investigated in a few NMIs. Due to the signal loss in the integrating sphere a high radiance source (e.g., tuneable laser or supercontinuum white laser) is required. The latter has the advantage of a tuneable spectral bandwidth avoiding the fringe issues observed with small bandwidth tuneable lasers in conjunction with interference filters. All three approaches are important for the future mise-en-pratique of the Kelvin and were investigated for the PQED based calibration of FRs.

The spectral irradiance responsivity of a narrow band, interference filter-based filter radiometer was determined in the visible wavelength range (~650 nm) with a RT-PQED as a transfer standard and the results were compared with the determination performed via a trap detector. In order to accurately determine the behaviour of the filter radiometer over a narrow bandwidth its spectral behaviour was measured over its bandwidth and checked for unwanted, out-of-bandwidth, leakage.

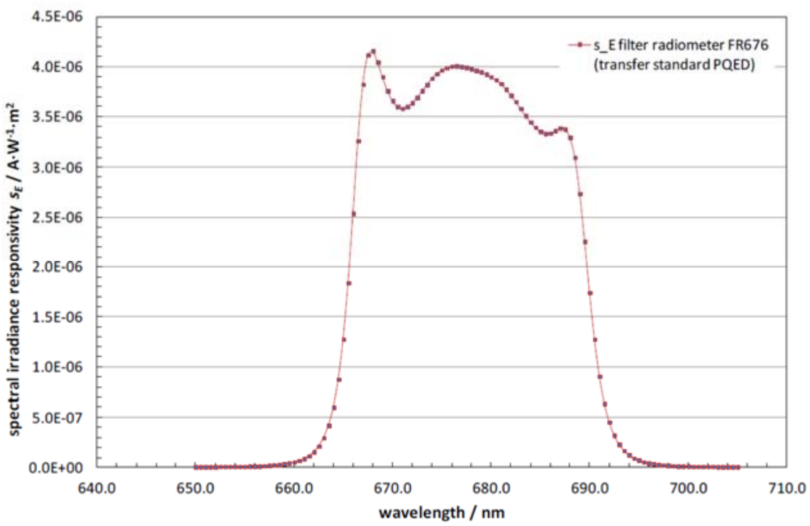
All three different approaches that are important for the future mise-en-pratique of the Kelvin were then pursued with respect to the instrumentation used:

The following picture is the schematic set-up, monochromator based, for the spectral irradiance responsivity calibration of a narrow band filter radiometer against the RT-PQED.



The monochromator-based setups employ a collimated beam with an arbitrary polarisation state. The RT-PQED used in this measurement with these setups was without a Brewster-window, thus requiring a continuous flushing with dry, dust-free nitrogen gas in order to prevent contamination of the photodiodes. In order to reduce noise, the RT-PQED was actively cooled with Peltier cells.

The spectral irradiance responsivity measured with respect to the RT-PQED is shown in the next picture.



Although the RT-PQEDs have the advantage of the predictability of the spectral responsivity nonetheless, in the actual measurement set-up, they show some drawbacks due to the sensitivity to the polarisation state of the optical radiation and the low shunt resistance. The measurement uncertainties for direct calibration against RT-PQED are worse than traditional methods and larger with respect to the 100 ppm goal.

The measurement uncertainties for direct calibration against RT-PQED are worse than traditional methods and larger with respect to the 100 ppm goal.

Further work is required to significantly improve the uncertainty when applying the RT-PQED as a reference detector for the calibration of the spectral irradiance responsivity of filter radiometers.

RT-PQED for fibre optics

INRIM, KRISS, and Metrosert investigated the applicability of Fibre Optics (FO-)PQEDs using a reference standard fibre optic power meter at a wavelength of 850 nm.

The highest accuracy optical power meter detectors, such as trap detectors, are well suited only for nearly collimated or slowly diverging light input conditions. However, their design is not suitable for measuring the optical power emerging from the end of an optical fibre because the beam gradually expands to an area that is too large for the most distant diode of the trap detector. The ability of the FO-PQED developed in this project was evaluated to consistently measure optical power from a variety of sources including widely diverging as well as collimated sources. The ultimate goal was to test the absolute predictability of this standard with an uncertainty below 1000 ppm. The first prototype of a FO-PQED was realised and tested to work with a fibre optic connection as a fibre optic power meter at 850 nm. To meet this aim, a predictable quantum efficiency detector was designed especially to be “dressed” for fibre optic power measurements.

The FO-PQED is equipped with an input standard fibre connector (FC) mating sleeve and two output isolated BNC connectors (one for each photodiode) for the photocurrent measurements. The FO-PQED was assembled in a cleanroom.

The FO-PQED is a special version of the RT-PQED designed to collect radiation from a divergent beam at the output of an optical fibre. In order to fully benefit from the PQED predictability and to avoid accessory measurements, no lenses or mirrors have been used to re-collimate the beam. The FO-PQED is designed to operate in the first telecomm window (850 nm), because it is based on silicon photodiodes, with a single-mode fibre (NA ≤ 0.14).

In this operating condition the losses were tested to be below 1000 ppm.

Because of the large active area of the photodiodes, even with a diverging beam, a large part of the radiation is collected; on the contrary, the large surface (and reverse bias mode operation) increases the FO-PQED dark current thus increasing the calibration uncertainty in low-power measurements.

A weakness of this design, without Brewster window and without dry nitrogen flow, is the possible contamination of the photodiodes. This prototype must be operated in a clean environment. Preliminary measurement shows a very low return loss and a good agreement with the predicted spectral responsivity.

The results obtained show the possibility to shorten the traceability chain for the fibre optic power meter calibration and to improve the measurement uncertainty as required by the telecomm industry.

On the other side, the knowledge developed in the realisation of the FO-PQED and in the characterisation would suggest further investigation on the sensitivity to the polarisation or the predictability of the responsivity for a beam with higher divergence.

3.2.3 RT-PQED as a travelling artefact for spectral responsivity

The robustness of the RT-PQEDs was assessed and their stability over time was determined to be suitable for their use as travelling artefacts for comparisons. After having produced the RT-PQEDs for use as travelling artefacts, the ease of use and the robustness of the RT-PQEDs was tested by a star-like comparison among NEWSTAR partners in Europe and outside Europe. Meanwhile, the in-house stability was checked over time by using PQEDs that are similar to the travelling artefacts.

Travelling artefacts and tests

Fitecom produced three RT-PQEDs to be used as the travelling artefacts in comparisons. For normal operation of an RT-PQED, linearly polarised light enters the detector through a window inclined at the Brewster's angle. Measurements using a RT-PQED without a window require a flow of dry nitrogen through the detector housing in order to prevent dust contamination of the photodiodes. This was achieved by constructing and testing a test body which the participants of the comparisons used to check their dry nitrogen flow systems for the PQED measurements without a window. User instructions were written as well.

In order to determine whether room temperature PQED is a suitable device to be used as a travelling artefact, INRIM , CNAM, CSIC, INRIM and BFKH assessed the robustness and ease of use of the room temperature operated PQED. The nitrogen flow system by VTT allowed the room temperature PQED to be operated without the Brewster window without the risk of dust or moisture contamination. Each partner built their own nitrogen flow system. These systems were tested by circulating a PQED that was operated with each of the systems. The spatial uniformity of the circulating PQED was measured after each partner had operated it with their nitrogen flow system. Conclusion were as follows.

The nitrogen flow system is an effective way to prevent dust contamination, and the room temperature PQED is as convenient to use as a typical trap detector.

As the stability of RT-PQEDs over time was crucial, INRIM measured the spectral responsivity of the RT-PQEDs that remained in the lab during the time period from January 2014 to November 2014, and in August 2015 and June 2016.

INRIM assessed the in-house temporal stability of the room temperature PQEDs by measuring the relative difference in the spectral responsivity of these detectors at two different wavelengths, 488 nm and 633 nm. The uncertainty levels achieved for the two wavelengths were 100 ppm and 120 ppm, respectively. Figure 5.1 shows the relative responsivity changes of the detectors over the whole measurement period.

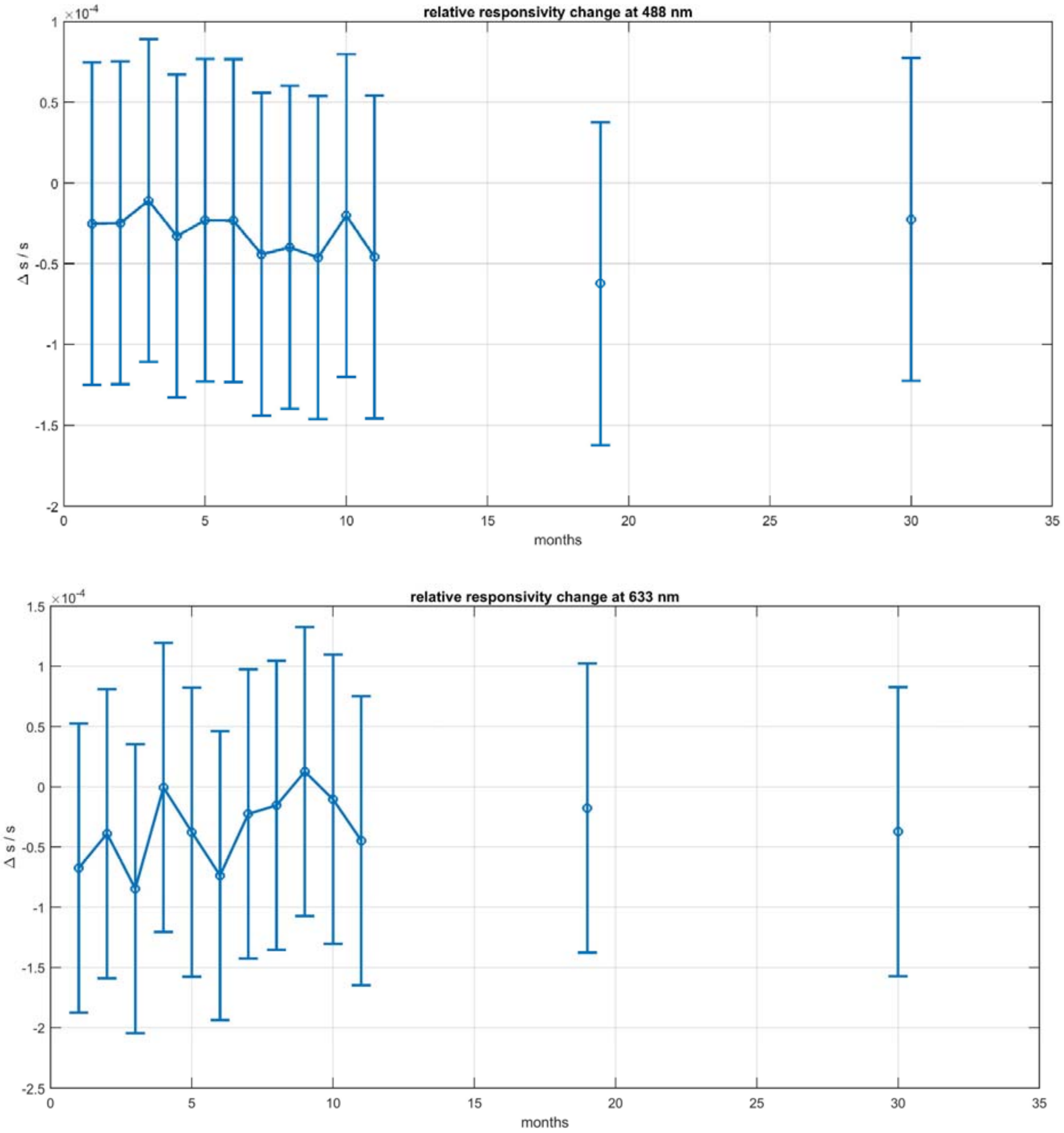


Figure 5.1. Temporal stability of the responsivity of RT-PQED at the wavelengths of 488 nm and 633 nm.

The detectors show no evidence of responsivity changes between each other within the measurement period of 30 months.

Star-like comparison - RT-PQED round robin among partners in Europe and outside Europe

INRIM piloted a star-like comparison where INRIM, CMI, PTB, CNAM, CI, Inmetro and KRISS participated to assess the robustness and ease of use of the room temperature operated PQED as travelling artefacts for comparisons at the 100 ppm uncertainty level. The spectral responsivity of the RT-PQED was measured with a window, not at the highest accuracy, but sufficient for testing the usability of the travelling artefacts. The wavelengths used were 488 nm (Argon ion laser) and 633 nm (HeNe laser). Other wavelengths could be used, i.e., 481 nm instead of 488 nm and 647.1 nm instead of 633 nm. Each participant had the travelling artefact for one month and another month was reserved for transportation and return measurements. To reduce the risk of an early failure of the artefact, hand-carriage of RT-PQED between the participants in Europe was required. For the air freight packages to New Zealand, Korea and Brazil, a massive amount of soft material within a strong outer casing was used and the package was marked as extremely fragile.

In general the comparison shows reasonably good agreement and the majority of the results are compatible with each other and are within the declared uncertainties.

Only minor problems arise from the use of a novel detector scheme, which requires some experience for different alignment, reverse biasing and the use of a nitrogen dry flow system. It is also apparent that if one would like to perform comparisons with RT-PQEDs at the lowest expected uncertainty (100 ppm), the vacuum wavelength of the laser source needs to be measured with adequate uncertainty. In fact, in this case it is no more sufficient to declare common values for laser lines; as laser sources operated at the same nominal laser line may have relevant changes in the operating vacuum wavelength of the emitted beam because of different gas pressure, operating current, magnetic field and resonator tuning.

All in all, the room temperature PQED is considered to be suitable for use as a travelling artefact for comparisons.

In summary,

Primary standards for absolute radiometry at 1 ppm uncertainty in the visible wavelength range

PQED for absolute radiometry

NEWSTAR has developed new primary standards for absolute radiometry based on Predicable Quantum Efficient Detectors (PQED). This was achieved by

- Designing and manufacturing customised silicon photodiodes with a predictable internal quantum deficiency close to zero.
- Optimising PQED light traps assembled from single photodiodes to suppress the polarisation dependence and dark signal for measurements below the 100 ppm level.

The silicon photodiodes: Excellent results were achieved by manufacturing black silicon induced junction photodiodes with near unity quantum efficiency. A device was demonstrated with an external quantum efficiency above 96 % over the wavelength range 250 nm – 950 nm. Nanostructuring and efficient surface passivation allow for a reliable device response with incident angles up to 70°. The outcome of this research lead to a publication in Nature Photonics and a patent application.

Predicting the responsivity of PQEDs. It was shown that,

- When the manufacturer supplies the necessary information with the diodes, the Internal Quantum Deficiency is known through simulations without additional characterisations.
- The potential was demonstrated for self-calibration to predict the Internal Quantum Deficiency to 0.1 % accuracy in unstabilised room temperature; this value meets most of the current needs in optical power measurements in industry.

Towards the radiometric determination of fundamental constants

One of the major impacts of NEWSTAR was the acceptance of the PQED as a primary standard in the “Mise-en- Pratique” of the Candela. This means that both PQED and cryogenic radiometers are accepted as primary standards for measuring optical power by the CCPR.

The radiometry community can take advantage of the redefinition of the SI as the comparison of the two primary standards can be used to express the measurand as the ratio between fundamental constants and thereby test the equivalence between the two primary standards.

Comparing CT-PQED and primary standard cryogenic radiometers. It has been shown that

- Cryogenic radiometers can support the radiometric determination of fundamental constants with expected relative standard uncertainties that are as low as 10 ppm.
- The objective to perform the best possible measurements using improved cryogenic radiometers based on the electrical substitution principle has been achieved, being the first in the world in terms of accuracy when determining the spectral responsivity of silicon photodiode based trap detectors by means of laser radiation and cryogenic radiometers.

Validation by comparison measurements between CT-PQEDs themselves. It has been shown that

An uncertainty of 6 ppm can be achieved when directly intercomparing CT-PQEDs. This marks a major breakthrough to the establishment of a primary detector standard based on induced junction photodiodes. With this improved accuracy the PQED comes close to an ideal travelling artefact for top-level intercomparisons of primary standards of spectral responsivity.

CT-PQED in-house stability over time

CT-PQEDs equipped with clean photodiodes show no temporal drift of the external quantum efficiency at the investigated wavelengths within the uncertainties of the measurements. The responsivity of PQEDs remains stable and within the uncertainty of the measurements during the time period of the study.

This marks a major breakthrough in establishing a primary detector standard based on induced junction photodiodes. With this improved accuracy the PQED comes close to an ideal travelling artefact for top-level inter-comparisons.

Traceability to spectral radiometry by implementing RT-PQED in applications

RT-PQED as a room temperature primary radiometric standard at 100 ppm

A primary standard for radiometry was realised operating at room temperature and having approximately the same cost and functionality as transfer standard detectors. The advantages of room temperature PQED are the much lower cost of the device, negligible running costs, and that they are much easier to operate and to transport if needed.

This enables NMIs to deploy primary standards into a wider spectrum of applications and to disseminate the reduced uncertainty into other measurement realisations.

RT-PQED characterisation

By using the PQED in two regimes, biased for the high optical power level and cooled at 10 °C, and unbiased for the low optical power levels, the PQED dynamic range can cover up to 8 decades from 10^{-3} W to 10^{-12} W. By using the RT-PQED in biased mode and in the linear operation part of the dynamic range, it did not exhibit any temperature related variation around the room temperature.

Validation of the RT-PQED model at 100 ppm uncertainty

The RT-PQED external quantum efficiency was validated at two laser wavelengths with 10 ppm agreement with a predicted value at the 65 ppm uncertainty level.

The agreement of two RT PQED compared between each other within the period of 6 months demonstrated better than 25 ppm with an uncertainty of 30 ppm.

In conclusion, the RT-PQED may replace the cryogenic radiometer as a primary standard of optical power in the visible wavelength range. Considering all these positive results, RT PQED is a good candidate for an easier to use and cheaper primary standard detector system with the price of a transfer standard.

RT-PQED for photometry

The basic unit, the candela, has been realised by a direct calibration of a reference photometer using a RT-PQED equipped with a precision aperture for operation in the irradiance mode.

In so doing, the traceability chain for the realisation of photometric units was significantly shortened.

Moreover, the potential was provided for advancing beyond the state of the art uncertainties (currently about 1000 ppm), as the final uncertainty is already competitive with the state of the art techniques.

The values of luminous responsivity determined by different calibration methods agree well within the measurement uncertainties and within the 100 ppm goal.

RT-PQED for fibre optic

The first prototype of a FO-PQED was realised and tested to work with fibre optic connection as a fibre optic power meter in the first telecomm window (850 nm).

The results obtained shows the possibility

- To shorten the traceability chain for the fibre optic power meter calibration.
- To improve the measurement uncertainty as required by the telecomm industry.

RT-PQED as a travelling artefact for spectral responsivity

The robustness of the RT-PQEDs was assessed by a star-like comparison - RT-PQED round robin among partners in Europe and outside Europe, showing that

- Their stability over time is suitable for use as travelling artefacts for comparisons at the 100 ppm uncertainty level.
- The nitrogen flow system is an effective way to prevent dust contamination, and the room temperature PQED is as convenient to use as a typical trap detector.
- The detectors show no evidence of responsivity changes between each other within the measurement period of 30 months.

4 Actual and potential impact

4.1 Metrology achievements

The main achievements by NEWSTAR are

a. the Cryogenic Temperature Predicable Quantum Efficient Detector (CT-PQED) working at 77 K whose
   - Internal Quantum Deficiency has been shown to be predictable through simulations without additional characterisations when the manufacturer supplies the necessary information with the diodes
   - External quantum efficiency has been shown to be stable within the uncertainty of the measurements during the time period of the study.
   - Spectral responsivity can be inter-compared with an uncertainty of 6 ppm with other CT-PQEDs. This marks a major breakthrough to establish a primary detector standard based on induced junction photodiodes. With this improved accuracy the PQED comes close to an ideal travelling artefact for top-level intercomparisons of primary standards of spectral responsivity.

b. the improved cryogenic radiometer based on the electrical substitution principle working at 4,2 K, which has been shown to be able to perform measurements with expected relative standard uncertainties as low as 10 ppm,

c. the Room Temperature primary standards (RT-PQED) whose predicted responsivity
   - o showed a 10 ppm agreement with the measured one at 65 ppm uncertainty level,
   - o compared with another RT- PQED between each other better than 25 ppm with uncertainty 30 ppm, within the period of 6 months

which therefore

- led to the realisation of a primary standard for radiometry operating at room temperature and having approximately the same cost and functionality as transfer standard detectors. In other words, it is an easier to use, easier to transport, and cheaper primary standard detector with the price of a transfer standard and negligible running costs
- enables NMIs to deploy primary standards into a wider spectrum of applications and have the reduced uncertainty benefit other measurement realisations, like
  - photometry: the basic unit, the candela, has been realised by a direct calibration of a reference photometer using a RT-PQED equipped with a precision aperture for operation in the irradiance mode. In so doing, the traceability chain for the realisation of photometric units was shortened significantly. Moreover the potential was provided for advancing beyond the state of the art uncertainties (currently about 1000 ppm), as the final uncertainty is already competitive with the state of the art.
  - fibre optics: The first prototype of a FO-PQED was realised and tested to work with fibre optic connection as a fibre optic power meter in the first telecomm window (850 nm), showing the possibility to shorten the traceability chain for the fibre optic power meter calibration and to improve the measurement uncertainty as required by telecomm industry
  - spectral responsivity comparisons: Seven project partners in Europe and outside Europe participated in a star-like comparison and the robustness and ease of use of the room temperature operated PQED was assessed as travelling artefacts for comparisons at the 100 ppm uncertainty level.

One of the major impact of NEWSTAR is the acceptance of the PQED as a primary standard in the “Mise-en-Pratique” of the Candela. Now that both PQED and cryogenic radiometer are accepted as primary standards for measuring optical power by the CCPR, the radiometry community can take advantage of the redefinition of the SI as the comparison of the two primary standards can be used to express the measurand as the ratio between fundamental constants and thereby test the equivalence between the two primary standards.

Excellent results were achieved by manufacturing black silicon induced junction photodiodes with near unity quantum efficiency. A device was demonstrated with an external quantum efficiency above 96% over the wavelength range 250–950 nm. Nanostructuring and efficient surface passivation allow for a reliable device response with incident angles up to 70°. The outcome of this research lead to a publication in Nature Photonics and a patent application. The prototypes are currently being tested in imaging applications related to medicine and safety.

The potential was demonstrated for self-calibration to predict the Internal Quantum Deficiency of a PQED to 0.1 % accuracy in unstabilised room temperature; this value meets most of the current needs in optical power measurements for industry.

4.2 Dissemination activities

4.2.1 Scientific publications

The project has generated twelve high impact publications in key journals, including Nature Photonics, Optical Review, Metrologia, and the International Journal of Thermophysics.

These incorporate the significant scientific outputs of the project. A list is provided in section 6.

4.2.2 Conferences and relevant fora

The work carried out in the project has already reached both the wider scientific audience in general conferences such as the CPEM, and the International Congress of Metrology as well as targeted audiences in specialised conferences such as NEWRAD 2014 (Espoo, FI, June 2014), and the IEEE Photonics (Reston, USA, October 2015). Most of the conference presentations resulted in published conference papers.

In total, thirty-four oral presentations as well as sixteen poster presentations have been given by the partners during the life time of the project. Positive reactions were received to all these contributions, attracting discussions and comments.

Presentations of the outcomes of the project have also been given at a number of key fora, in particular at EURAMET and BIPM-CCPR working groups' meetings, where it has resulted in the influence of future strategy ensuring on-going impact of the project into the future.

Furthermore, the activities on the Room Temperature PQED also have significant synergy with the EMPIR project 15SIB07 PhotoLED where methods of the measurement of luminous quantities of LED sources are being investigated. The generic methods developed under this project will feed through to the work of ENV05 in this area, providing significant added value for the EMRP endeavour. A one-day training course was organised and held on the 14th of September 2016 in conjunction with the Kick-Off meeting of JRP EMPIR 15SIB07 PhotoLED to maximise the impact of the training. The training course was targeted on stakeholders (industrial, national authorities etc.) and focussed on the new methods and techniques developed for use in traceability chains.

4.2.3 Stakeholder Engagement and Standards

The main objective of the project was the development of new standards and traceability for radiometry in the visible wavelength range. .

A Stakeholder Committee (SC) was created of 30 members from 29 organisations including photodetector manufacturers and metrology bodies, representing 17 countries in Europe and outside Europe. The aim of the stakeholder committee was to clarify the needs of the various interested parties and to feed these into the Project, and to maximise publicity for the impact of the work. The terms of reference of the SC were discussed during the establishment of the committee and agreed shortly afterwards including;

- o Dissemination of information regarding the progress of the Project to those working on the field and ensuring that the standards, apparatus and procedures being developed are in line with the requirements of these experiments.
- o Dissemination of information to the user community regarding the potential impact of the PQEDs and ensuring that end user requirements are accounted for in the outputs of the Project

Due to the disparate nature of the steering committee membership, interaction were achieved via a central website (see below) and ad-hoc meetings held at suitable events where a quorum of the committee were likely to be in attendance. Key stakeholders in the areas of manufacturing, standardisation and research, including those who submitted letters of support were contacted regarding membership of the SC.

Information on progress and results of the JRP were disseminated to a range of standardisation bodies and committees and feedback sought.

The representatives on the corresponding committee or WG from the NMI/DI JRP-Partners jointly asked the chairperson to include a point in the agenda to briefly present the outputs of the JRP related to the WG activities and to ask for comments from the other committee/WG members.

In order to engage with stakeholders, NEWSTAR results were presented at the Annual Meeting of EURAMET TCPR on the 2nd April 2014 in Trappes, France; at the Annual Meeting of Division 2 *Physical detectors of radiation* of the International Commission on Illumination (CIE), in April 2014, in Kuala Lumpur, Malaysia; at the 22nd CCPR meeting in Sévres, France, on the 17th of September 2014; at the EURAMET TC-PR in Warsaw in February 2016, and at the 23rd CCPR Meeting in Sévres in September 2016.

In September 2014, at the meeting of the Task Group on mise en pratique (TG5) of the CCPR Working Group on Strategic Planning (CCPR WG-SP), the decision was taken to include PQED in the document "Mise en pratique for the candela and associated derived units for photometric and radiometric quantities in the International System of Units (SI)". In particular, the PQED was explicitly mentioned in sub-section 2.1 Detector-based radiometric traceability.

In July 2015, the Task Group on mise en pratique (TG5) of the CCPR Working Group on Strategic Planning (CCPR WG-SP) submitted the document to the CCPR and subsequently to the CIPM for approval.

In October 2015, the CIPM approved the document "*Mise en pratique for the candela and associated derived units for photometric and radiometric quantities in the International System of Units (SI)*" as submitted by Task Group on mise en pratique (TG5) of the CCPR Working Group on Strategic Planning (CCPR WG-SP). See the Decision CIPM/104-45. The document includes the PQED, which is explicitly mentioned in sub-section 2.1. Such recognizion emphasizes the important role of the new method for optical power measurements, with EURAMET taking then lead in the field and coordinating the work outside Europe.

At the international level the International Commission on Illumination (CIE) and the CCPR are jointly developing revision of the basic Principles Governing Photometry. More specifically, within CCPR, WG-SP will develop the mise-en-pratique for the candela (for Appendix 2 of the SI brochure), whereas CIE JTC-2 will develop a draft for revision of Principles Governing Photometry (for CCPR) and revision of CIE 18.2 (for CIE). Once the document is completed in JTC-2, it will be balloted in both CIE and CCPR, and the corresponding publications will be prepared by each organisation.

PQED promotion is very active to other NMIs through presentations in Europe, North America and Asia for a wider appreciation of the benefits. Findings are being disseminated at conferences, through publications, via the NEWSTAR website, stakeholder workshops, training courses, standardisation activities, and within the metrology community via Metrology Regions. In particular, findings havee been disseminated at the annual meeting of SIM TC-PR and APMP TC-PR.

4.2.4 Workshops

Two stakeholders workshop have been organised during the life time of the project.

The 1st Stakeholder Meeting and Workshop on "New trends in absolute radiometry", was held on 01 April 2014 in Trappes, France. This was a half day meeting scheduled just before the EURAMET TCPR meeting (at the same place on 02 April 2014) to enable this stakeholder group to participate. 26 participants signed the attendance list. 11 attendees from 10 NMIs/DIs acting as stakeholders from other European NMIs/Dis, which are not member of the JRP-Consortium, took part in the meeting. In addition, 15 attendees from 8 JRP-Participants were present for discussions.

The 2nd stakeholder meeting took place in Braunschweig, at PTB, on the 24th of November 2015, to coincide with the Annual Symposium of CIE. In total there were 18 participants. The audience was highly qualified, including representatives of large multinational Enterprises, SMEs, accreditation, certification, and standardisation bodies, and academies. CMI gave an overview on the project and its goal. PTB gave an overview on the current status of characterisation of RT-PQEDs. it was pointed out that the final price of a reference Detector containing PQEDs is the crucial argument when it finally comes to the question whether such detectors can (or better will) be used by testing and calibration laboratories.

4.3 Effective cooperation between JRP-Partners

NEWSTAR was very important in proving that the optical radiometry community in Europe is capable of working effectively together in metrology research.

NEWSTAR is a good example of the implementation of the European Metrology Research Programme (EMRP), facilitating closer integration of national research programmes and ensuring collaboration between National Measurement Institutes.

The Consortium brought together 7 European NMIs/DIs which have broad experience and expertise in radiometry. These laboratories include some of the leading experts in the field and were able to define a vision and to guide the necessary technological solutions such that this JRP will deliver maximum impact.

In addition, the Consortium included 3 NMIs from outside Europe, INMETRO (Brazilian NMI) KRISS (Korean NMI) and CI MSL (New Zealand NMI), as unfunded JRP-Partners who made highly focused, well-defined contributions to specific tasks.

In total, 10 NMIs/DIs and 3 Universities were included as Partners or via Researcher Excellence Grants. These institutes brought specific expertise to NEWSTAR enabling a coordinated response that did and will deliver an impact much greater than the sum of its parts. The participation of a large number of research groups from several countries shows the general interest of the topic and represents the first valuable impact created by the project. NEWSTAR was designed to limit the unnecessary duplication of skills and facilities. Activities were divided among the Partners such that the specific experience of each Partner was maximally exploited. Finally, in some cases overlap in activities was intentionally built into the project in order to ensure an improved output via interaction of the scientists at the different Partners. For example, several Partners worked on the comparison measurements in order to rule out drawing general conclusions based on specific configurations.

Some NMIs from countries which are smaller contributors to EMRP are also involved in the project. Furthermore, INMETRO (Brazilian NMI) KRISS (Korean NMI) and CI MSL (New Zealand NMI) have also collaborated on specific tasks of the project. CI-MLS, Inmetro, and KRISS were key partners in the round-robin exercise outside Europe. In addition to this, INMETRO provides the link to the SIM TC-PR.

Many exchanges between the partners have taken place. In the frame of a “Research Mobility Grant” one researcher from CSIC has spent two months at JV on the activities for the self-calibration of the PQED. The potential was demonstrated for self-calibration to predict the Internal Quantum Deficiency of a PQED to 0.1 % accuracy in unstabilised room temperature; this value meets most of the current needs in optical power measurements for industry.

Several tasks have taken benefit from the collaboration between the partners, as demonstrated by several joint publications and presentations and different methods have been validated thanks to the joint collaboration of partners.

NEWSTAR specifically targeted small NMIs and DIs in Europe which are not yet equipped with CR-based primary standards, and was chosen as a strategic priority by the NMIs of Estonia, Norway and Hungary, all of which had specialised roles in the JRP where their excellence was efficiently combined with larger NMIs.

4.4 Examples of early impact

Standards and regulation:

Several funded and unfunded JRP-partners are members of the International Commission on Illumination (CIE). A proposal was presented for establishing a Technical Committee on “Advances in absolute radiometry” in Division 2 *Physical detectors of radiation* of CIE on the 24th of April 2014.

After submission of the Terms of Reference at the Annual Meeting of CIE Division 2 in November 2014, the Director of CIE Division 2 informed the JRP-Consortium that work could start for preparing the draft of the Technical Report entitled *Absolute radiometers: concepts, characterization and applications* by the CIE Technical Committee *TC2-81: Update of CIE 065:1985*. This draft is currently under preparation, with the output of this project directly influencing its ongoing reviews and updates.

User uptake:

Partner JV developed the 3D model with Genius software for simulating the behaviour of the silicon photodiodes. The software manufacturer COGENDA, which was a collaborator to NEWSTAR, implemented useful changes in their software on JV request so that simulations could be more efficiently analysed.

The software is still not finalised, but the interaction between the partners involved in this topic and COGENDA is still active.

Scientific uptake and impact

The output of this JRP provided vital information for the development and publication of a written mise-en-pratique for the candela. Additionally, 4 guidelines on PQED, RT-PQED luxmeter, standard filter RT PQED, and FO-PQED, respectively were written and published on the NEWSTAR website, together with the review on the advantages of using the PQED for applications in photometry, thermometry, and fibre optics.

The target audience for the guidelines are NMIs/DIs which maintain primary standards. The guide outlining the impact is aimed at a wider audience to include end users in the optics community. All guides are produced in electronic form. Close liaison with the BIPM Consulting Committee of Photometry and Radiometry on the content and distribution of this document will be key to targeting the key audience.

The application of the Room Temperature PQED as a fibre optic primary standard at 850 nm has attracted large interest by both the EC and the scientific community.

In 2016, the CCPR Working Group on Strategic Planning (CCPR WG-SP) established a new Task Group on Fibre Optics spectral responsivity (TG13) with the goal to investigate measurement techniques required to reduce calibration uncertainties below 1% as required by telecomm industry; members of TG13 are NIST (radiometer with nanotubes absorber), and METAS. CMI and INRIM joined the task group thanks to the results in prototyping the FO-PQED.

The application of the Room Temperature PQED as a travelling artefact for key comparisons is also of interest to the CCPR- WG-KC Key Comparisons.

Participation in these Groups will allow the scientific knowledge developed in the framework of the project to be shared outside Europe.

NEWSTAR results will be presented also at the next meeting of the CCT Working Group for Non-Contact Thermometry (CCT-WG-NCTh) which is scheduled May 29-31, 2017.

To enable other interested parties beyond the high specialised metrology community to know about the development and results of NEWSTAR, in addition to general presentations made in international metrology congresses, 3 articles have been submitted to trade journals and popular journals. The results of this Project were also disseminated to a wide audience through presentation to high school and universities and participation in special popular science events such as the European “Researchers’ Night” held every year at the end of September.

4.5 Potential impact

This project is a challenge in the field of fundamental radiometry and photometry. As silicon detectors are the most frequently used detectors in science and industry, the impact of NEWSTAR will be transmitted to both.

The impact on the end-users results from new robust high performing detectors, new techniques making dissemination and uptake and thus the wider achievement of accuracy easier, and new simpler, better, faster and cheaper transfer standard detectors for applications like radiation thermometry and photometry.

The new instruments and techniques to be developed in this project and the new practical primary standards to be implemented will provide new, more accurate and cost-effective calibration methods for radiometry and radiation thermometry, allowing EURAMET to take a global lead in the development of the SI, particularly in the development of novel techniques for high-level standards, improving the metrology infrastructure for radiometry in the visible range and for photometry.

A RT-PQED primary detector standard will make absolute (calibrated) filter radiometers available for institutes/stakeholders (NMIs/DIs or e.g. companies that offer CCD-camera based thermometers) that do not have access to cryogenic radiometers.

With more research and development the self-calibrating technique of silicon photodiodes at room temperature is expected to achieve an uncertainty well below 0.1 % at room temperature, an uncertainty that currently meets most of the radiometric applications in health, environment and industry today. In this way, the radiometric community is ready to develop new instrumentation that are self-calibrated and that potentially reduce the need to take instruments out of their application for calibration.

In the longer term, the more simple and user-friendly measurement methods of the SI units based on the results of this project are expected to improve the Calibration Measurement Capabilities of European NMIs for the following services:

Responsivity, laser, power, A/W

Responsivity, spectral, power, Broadband detector. A/W in the wavelength range 500 nm to 900

Responsivity, illuminance, A/lx

Responsivity, fibre optics power meter, Reading/W at 852 nm.

The improved PQED will enable better accessibility for end-users, i.e. accredited calibration and testing labs, to one of the base SI units, the candela, thus improving quality control of production and strengthening competitiveness in global markets. Improved detectors and new methods will trigger future science and research within photometry and radiometry to further simplify and improve traceability.

The project will provide outputs to the photo-sensor industry, whose use and applications are rapidly expanding. Photo-sensors are being incorporated into advanced diagnostic devices and enable treatments meeting the healthcare needs of an aging society; they can be used to provide highly efficient manufacturing techniques tailored to the specific needs of the product; they can be used to improve safety and security through smart imaging, for example in surveillance cameras; they can also facilitate the development of standards for atmospheric and climate monitoring.

In the longer term smart photodetectors will rapidly impact numerous aspects of our everyday lives, e.g. the car of the future will be full of smart photonic sensors, which will recognise the driver as he enters the car, instruct the vehicle electronics to adjust to the driver's preferred settings and even monitor the driver's condition during the journey, allowing early detection and warning of the onset of 'micro sleep'. Additional photo-sensors will monitor the progress of the car during the journey, allowing intelligent driver-assistance control or night vision systems to ensure the safety of driver and other road users. In the longer term, photonic sensors will play a vital role in the development of fully autonomous vehicles, a development seen as being essential for maintaining the mobility of individuals in an aging society.

5 Website address and contact details

A public website has been live, where the main public deliverables have been made available for end-users and to keep them informed about project meetings and events: http://www.inrim.it/Newstar/

A partners' restricted area was also created, in order to enable all the partners to share work documents and deliverables (the password is available on request).

The contact person for general questions about the project is
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The contact person for the Room Temperature PQED is
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The contact person for the application of RT_PQED to photometry, radiation thermometry and Fibre Optics is
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6 List of publications

1. J. M. Mantilla, M. L. Hernanz, J. Campos, M. J. Martín, A. Pons and D. del Campo, *Monochromator Based Absolute Calibration of a Standard Radiation Thermometer*, Int. J. Thermophys, DOI 10.1007/s10765-014-1589-1

2. T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, E. Ikonen, *Primary standard of optical power operating at room temperature*, European Physical Journal Web of Conferences, , DOI: 10.1051/epjconf 20147700012"

3. T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, E. Ikonen, *A primary standard of optical power based on induced-junction silicon photodiodes operated at room temperature*, Metrologia, DOI: 10.1088/0026-1394/51/3/197

4. F. Manoocheri, M. Sildoja, T. Dönsberg, M. Merimaa, E. Ikonen, *Low-Loss Photon-to-Electron Conversion*, Optical Review , DOI: 10.1007/s10043-014-0048-3"

5. T. Dönsberg, T. Pulli, T. Poikonen, H. Baumgartner, A. Vaskuri, M. Sildoja, F. Manoocheri, P. Kärhä and E. Ikonen, *New source and detector technology for the realization of photometric units,* Metrologia, DOI: 10.1088/0026-1394/51/6/S276

6. Elisa Borreguero Martin, *Estudio de la relación entre la curva característica de linealidad de respuesta y la estructura interna de fotodiodos,* Proyecto Fin de Máster en Tecnologías Ópticas y de la Imagen, Facultad de Óptica y Optometría. Universidad Complutense de Madrid. Curso 2013-2014

7. T. Pulli, T. Dönsberg, T. Poikonen, F. Manoocheri, P. Kärhä, E. Ikonen, *Advantages of white LED lamps and new detector technology in photometry,* Light: Science & Applications, DOI:10.1038/lsa.2015.105"

8. T. Dönsberg, H. Mäntynen, E. Ikonen, *Optical aperture area determination for accurate illuminance and luminous efficacy measurements of LED lamps,* Opt Rev (2016) 23: 510. https://doi.org/10.1007/s10043-016-0181-2

9. Jeanne-Marie Coutin, Bernard Rougié, *Caractérisation et validation d'un nouveau radiomètre cryogénique au LNE-LCM,* Revue Française de Métrologie, Volume 2016-1 n°41, Vol. 2016-1,11-20, DOI: 10.1051/rfm/2016002 n° 41ISSN 1772-1792"

10. Bernard Rougié, Jeanne-Marie Coutin, *Références radiométriques pour les mesures de rayonnement optique,* Techniques de l'ingénieur, Article R6412

11. M. Juntunen, J. Heinonen, V. Vähänissi, P.Repo, D. Valluru, H. Savin, *Near-unity quantum efficiency of broadband black silicon photodiodes with an induced junction,* Nature Photonics, DOI: 10.1038/NPHOTON.2016.226