Final Publishable JRP Summary for SIB57 NEWSTAR
New Primary Standards and Traceability for Radiometry

Overview

Optical technologies are important for many applications: information & communication including fibre optic networks, 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 or optical power. Photodetectors, which are sensors and measurers of light, act as this eye.

Historically the standards for optical power (or radiometry) 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.

This project improved photodetector efficiency and provided simpler traceability routes and lower uncertainties for the radiometric units, used to measure light. It developed new primary standards for radiometry based on Predictable Quantum Efficiency Detectors (PQED) that for the first time can be easily used by calibration and testing laboratories, improving access to the candela, the SI unit of luminous intensity.

Need for the project

Europe is home to some of the world's largest laser and optics companies but, in order to remain competitive, new research needs to focus on developing more efficient photodetectors, able to detect more of the light present. The rapidly evolving optical technologies require the lowest levels of uncertainty in the photodetector standards combined with rapid, low-cost dissemination of the standards and uptake. The development of low-cost primary standards for optical power would also help meet the needs of those European countries that currently depend on another country for their calibration services.

It is difficult to reduce the uncertainty of measurement for optical power with existing technology because the fundamental physical limits of current silicon devices are fast being approached. This means that radical new design concepts must be developed, together with correspondingly enhanced reference standards such as new PQED primary standards.

Before this project, photometric transfer standards used in calibration and testing laboratories were calibrated via a long measurement chain starting with the few NMIs able to perform the measurement, using an instrument called a cryogenic radiometer at the very low temperature of 4 Kelvin (-269 °C). In order to make reliable optical measurements more easily, a new primary standard was needed which could be characterised and used by calibration laboratories under easily reproducible conditions including at room temperature.

This project addressed this need by developing a new primary standard for radiometry, i.e. the measurement of light. The new PQED primary standard has approximately the same cost and ease of use as current transfer standard detectors, but with uncertainties of 1 ppm that until now have only been possible under specialist conditions at an NMI.

Scientific and technical objectives

This project addressed the challenge of developing an improved primary standard for radiometry with the following two objectives:

1. *To develop primary standards for absolute radiometry at 1 ppm uncertainty in the visible wavelength range by:*

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- 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 (meaning that they detect nearly all the light present, with little loss).
- Validating the expected ultra-low uncertainty by comparison with the best possible measurements using improved cryogenic radiometers based on the electrical substitution principle (where optical power is compared with electrical power).
- Evaluating the stability of the PQED over time.

2. *To establish traceability to spectral radiometry by implementing room temperature PQED primary standards (RT-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 artefacts for laboratory intercomparisons.
    - Disseminating the use of the RT_PQEDs to NMIs that do not have access to cryogenic radiometers; and to industry in order to shorten the traceability chain.

Results

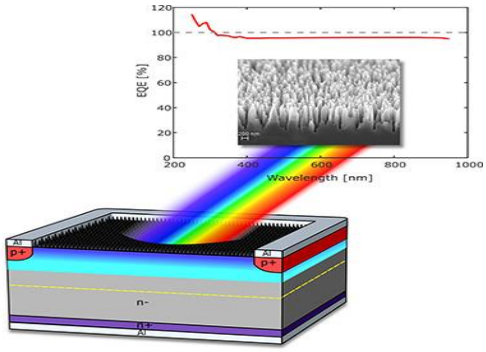
The PQED was made of silicon, a material that exhibits the photoelectric effect, where electrons are emitted (and therefore can be measured) when light is shone onto it. In addition, the PQED standard has the special ability to be self-calibrating (known as an ‘absolute’ calibration), and therefore does not need to be calibrated via a long and complicated traceability chain of transfer standards.

The PQED’s spectral responsivity, or response to radiation at specified wavelengths, was predicted by fundamental constants and material parameters. At 77 K (-196 °C, the temperature of liquid nitrogen), the uncertainty of the predicted responsivity was better than10 ppm, i.e. a factor of 5 less than previously obtained with other methods. At room temperature, the internal quantum efficiency (a measure of the effectiveness) of the PQED agreed with the predicted value within an uncertainty of 100 ppm over the visible wavelength range. This means that the project found that a PQED operating at room temperature is almost equally accurate as a cryogenic radiometer operating at cryogenic temperatures i.e. 4 K.

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

3D modelling was used to study the influence of the key design parameters of the PQED photodiodes on their spectral responsivity. The improved models can now accurately determine the responsivity of the diodes.

An unexpected project outcome was black silicon induced junction photodiodes which were manufactured with near unity (or near 100 %) quantum efficiency, meaning that they detect almost all the radiation present. A was black silicon induced junction photodiodes device was demonstrated with an external quantum efficiency above 96 % over the wavelength range 250–950 nm (see figure).

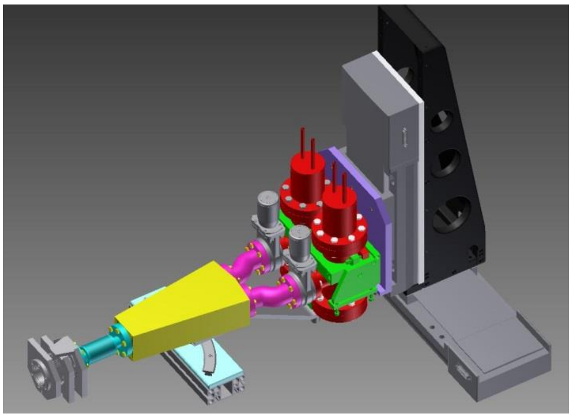


The outstanding quantum efficiency of the PQED at 77 K makes this device ideal for comparing the results using other high accuracy standards. The comparison showed for the first time that the absolute calibration of the PQED was accurate to an uncertainty as low as 10 ppm.

The work to improve techniques enhancing the traceability of radiometric measurements to the SI led to improved heater power measurements in cryogenic radiometers. Thanks to a new temperature controller for the cavity of a Common Brewster Window (which enables maximum transmission) cryogenic radiometer configuration, the relative standard uncertainty of the measurement of the radiant power of laser sources was reduced 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 a 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.

The spectral responsivity of a cryogenic temperature PQED was measured with ultra-low relative standard uncertainties as low as 20 ppm at 407 nm. This is the lowest uncertainty ever reported with cryogenic radiometers thus far. This result was achieved using 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 cryogenic temperature PQED.

The external quantum deficiency of a PQED was measured using a radiometer at room and liquid nitrogen temperatures and at three wavelengths (407 nm, 532 nm and 850 nm) with a relative standard uncertainty ranging from 21 ppm to 55 ppm. A 6 ppm uncertainty was achieved by directly comparing cryogenic temperature PQEDs. These results are key to demonstrating the equivalence between exisiting photometric standards (cryogenic radiometer) and the new PQED standards.



The figure (left) shows the design of the setup for the ultra high vacuum comparison of PQEDs. The PQED-cryostats (used to maintain a low temperature) are red coloured, and the detectors are mounted on an x-y-stage and connected via flexible bellows to the Common Brewster Window. This extremely low uncertainty was achieved because the uncertainty contributions, such as the photo and dark current levels and stray light, were almost identical for all the systems tested. In addition, the use of the same equipment, such as digital multimeters and current-to-voltage converters, allowed the measurement of relative values, avoiding the higher uncertainties of absolute measurements.

As the Common Brewster Window cryogenic radiometer currently has an uncertainty of 20 ppm, the comparison of a PQED with this instrument cannot validate the claimed uncertainty below 10 ppm. Instead the comparison amongst PQEDs gave an indication of their uncertainty.

Implementing room temperature PQED primary standards (RT-PQED) in applications

Results indicate that the RT-PQED can replace the current cryogenic radiometers as a primary standards of optical power in the visible wavelength range. A laminar airflow system over the cryogenic radiometer was implemented to improve windowless measurements of the RT-PQEDs; the Common Brewster Window transmittance measurement system was adapted with measurements demonstrating a relative uncertainty as low as 20 ppm. The windowless RT-PQED at two wavelengths (647 nm and 476 nm) was validated with respect to a cryogenic radiometer and showed an agreement of less than 30 ppm, with an achieved measurement uncertainty of 80 ppm.

The nitrogen flow system for the RT-PQED was demonstrated to be an effective method for protecting the open detector from dust contamination. 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 in the establishment of a primary detector standard based on induced junction photodiodes, and should benefit NMIs, testing laboratories and industry.

The primary photometric unit was based on a calibrated reference photometer which in turn was calibrated against an RT-PQED. The uncertainty achieved was similar to state of the art techniques. However, the advantage of using RT-PQEDs for applications in photometry is a shortening of the traceability chain, thus providing the potential to reduce uncertainties further.

The applicability of RT-PQEDs for radiation thermometry was investigated by performing direct calibrations of filter radiometers operating in the visible range. Although the RT-PQEDs have the advantage of the predictability of the spectral responsivity nonetheless, some drawbacks were found due to the sensitivity of the polarisation state of the optical radiation and the low shunt resistance, which requires further work.

The project also produced and tested the first prototype of a PQED version capable of being used with a fibre optic connection (FO-PQED). Preliminary measurements showed a very low return loss and a good agreement with the predicted spectral responsivity. Because of the large active area of the photodiodes, even with diverging beam a large part of the radiation is collected. However, the large surface (and reverse bias mode operation) increase the FO-PQED dark current thus increasing the calibration uncertainty in low-power measurements.

Actual and potential impact

This project addressed limitations of current primary standards for radiometry and developed new instruments and techniques, implemented new practical primary standards implemented and made available new more accurate and cost-effective calibration methods for radiometry.

Dissemination activities and stakeholder engagement

50 presentations about the work of the project were made at major international and national conferences such as CIE Division 2 Physical Measurement of Light and Radiation, the International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2014) and the IEEE Photonics conference.

12 peer-review papers were published in journals including Metrologia, Optical Review and Light: Science & Applications. Two papers were published in relevant trade journals.

9 training courses were held, including one on Measuring Light, which attended by stakeholders in the scientific community in higher education and public research organisations.

A stakeholder committee was set up to inform the consortium of industrial end user needs, and included representatives of large multinational enterprises, SMEs, accreditation, certification and standardisation bodies, and academic institutes.

Contribution to standards

The project has contributed to the following documentary standards:

- "*Mise en pratique for the candela and associated derived units for photometric and radiometric quantities in the International System of Units (SI)*". The document includes the project's PQED in the document's section on *Detector-based radiometric traceability*. This recognises the important role of the new method for optical power measurements, with EURAMET taking the lead in the field.

- CIE Technical Report *Absolute radiometers: concepts, characterisation and applications.* This draft report is currently in preparation, with the outcomes of this project contributing to its ongoing reviews and updates.
- CIE published documentary standard TC2-81 (an update of CIE 065-1985 (Absolute Radiometers) on the operating principle of absolute detectors of optical radiation based on the results of this project.

The project outcomes relating to the development of the FO-PQED have also providing input to the new The Consultative Committee for Photometry and Radiometry (CCPR) Task Group on Fibre Optics spectral responsivity (TG 13), with the goal to investigate measurement techniques required to reduce calibration uncertainties below 1 % as required by the telecommunication industry.

In addition, guidelines on PQED, RT-PQED luxmeter, standard filter RT-PQED, and FO-PQED were written, together with a review of the advantages of using the PQEDs for applications in photometry, thermometry, and fibre optics.

Early impact

- A patent application was filed for the new black silicon photodetector reaching near-unity response and ranging from the ultraviolet to the infrared part of the electromagnetic spectrum. The prototypes are currently being tested in imaging applications related to medicine and safety.
- A new company ElFys Oy was set up in Finland to commercialise the black silicon photodiode technology developed in the project, and for which a patent has been filed. The first proposals for customers are in preparation.
- The new instruments, techniques and practical PQED primary standards developed in this project provide new, more accurate and cost-effective calibration methods for radiometry, allowing EURAMET to take a global lead in the development of the SI, particularly by improving the metrology infrastructure for radiometry in the visible range and for photometry.
- End-users will benefit from the new robust high performing detectors, new techniques making dissemination of accuracy easier, and new simpler, better, faster and cheaper transfer standard detectors for applications like radiation thermometry and photometry. An RT-PQED primary detector standard will make absolute (calibrated) filter radiometers available for institutes and stakeholders (NMIs/DIs or e.g. companies that offer CCD-camera based thermometers) that do not have access to cryogenic radiometers. The PQEDs are already in use at NMIs, including NIM in China.
- The PQEDs are available for end-users such as accredited calibration and testing labs, giving wider access to the SI unit 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.

Potential impact

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

In the longer term, the simplified realisations based on the results of this project are expected to improve the Calibration Measurement Capabilities (CMCs) of European NMIs for responsivity, laser power, illuminance and fibre optic power.

The project will provide outputs to the photo-sensor industry, whose use and applications are rapidly expanding. For example, photo-sensors are being incorporated into advanced diagnostic devices and healthcare treatments for 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, e.g. in surveillance cameras; and they can facilitate the development of standards for atmospheric and climate monitoring.

The new PQED photometric standards will also be used in industry to improve quality control, and improve the performance of photodetectors. These are often integrated into advanced products such as diagnostic devices and the smart imaging technologies used by driverless vehicles. To support the uptake of energy efficiency lighting, the new standards are designed to work with energy efficient solid state lighting (SSL) technologies such as LEDs.

Finally, as silicon detectors such PQEDs are the most frequently used detectors in science and industry, this project will widely impact both.

List of publications

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[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"

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[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

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