# Publishable Summary for 18SIB10 *chip*S·CAL*e*
# Self-calibrating photodiodes for the radiometric linkage to fundamental constants

## Overview

An improved and simplified traceability chain is vitally important for spectrally resolved measurements in photonics across industry and science. Using today's methods, the uncertainty on measurements of optical quantities is limited by the properties and insufficient stability of current silicon transfer standard detectors, as well as costs of operation and required expertise for use. *chip*S·CAL*e* aims to improve and simplify the traceability chain by developing new and improved technology, accompanied by new metrology, generating for the first time an "NMI-on-a-chip" for optical power measurements.

## Need

The use of radiometry, photometry and spectrally resolved measurements through filter radiometry is increasing in climate monitoring, medical treatment, health and photonic industries, energy saving illumination (LEDs), across science and in many more applications. Common for all applications is that the traceability to the SI is achieved through the calibrated spectral responsivity of detectors. By far, the majority of these calibrations is within the spectral range covered by silicon detectors, serving customers' needs over a wide dynamic range from the few photon regime to several watts. Provided by the best laboratories in the world, the current state-of-the-art spectrally dependent uncertainty of around 0.1 % is limited by the properties and stability of current silicon transfer standard detectors.

Previous projects have developed the Predictable Quantum Efficient Detector (PQED), which has proven to have an extremely low internal quantum deficiency (IQD) of around 0.01 % and an undetectable drift over 6 years. These properties makes the PQED a very attractive calibration standard detector and complies well with the low-cost, high-accuracy, transfer standard requested by CIPM's Consultative Committee for Photometry and Radiometry (CCPR). However, the low availability and lack of experimental techniques to extract the PQEDs internal quantum deficiency has to date prevented it from being exploited as a stand-alone primary standard.

Furthermore, CCPR and EURAMET expresses the need to measure fundamental constants ratio e/h radiometrically as the ultimate comparison of the two accepted radiometric primary standard detectors, with no preference for either of them, as a contribution to a strengthened and coherent SI system defined by fundamental constants.

## Objectives

The overall objective of the project is to develop new experimental techniques for optical power measurements over a wide spectral and dynamic range by the production of an "NMI-on-a-chip" detector developed as a self-calibrating silicon photodiode.

The specific objectives are:

1. To develop improved and validated 3D charge-transfer models to predict the PQED internal quantum deficiency. The target prediction uncertainty is 10 % of the internal quantum deficiency value.
2. To develop the best possible PQED photodiodes for cryogenic operation by using the improved 3D models and evaluation of passivation layer materials, passivation strategies and charge increasing techniques. To manufacture a batch of optimised PQED photodiodes and to acquire bare-chip photodiodes for room temperature operation.
3. To develop instrumentation and packaging enabling self-calibration of photodiodes. The photodiodes should be operated in both photocurrent and electrical substitution mode with sufficient sensitivity and equivalence between optical and electrical heating over a temperature range from 20 K to 300 K.

4. To provide traceability of the self-calibrating photodiodes to the revised SI by measuring the fundamental constant ratio *e/h* to 1 ppm uncertainty at cryogenic temperatures and to 0.05 % uncertainty at room temperature for wavelengths from 400 nm to 850 nm over a dynamic range from 10 nW to 10 mW.
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by engaging standardisation bodies and international organisations (CCPR, CIE, EURAMET and other RMO TC-PR), the measurement supply chain (accredited laboratories, instrument manufacturers) and end users (photonics industry).

**Progress beyond the state of the art and results**

Radiometric measurements of radiant power at discrete laser wavelengths are possible with cryogenic radiometers (CR) with an uncertainty down to 0.005 %. Cryogenic radiometers are accurate for most applications, but are bulky, expensive and require a high skill level to operate. Dissemination outside discrete wavelengths is carried out with silicon trap detectors and interpolation functions. The trap detectors' properties and insufficient stability is limiting the comparison agreement at the NMI level to a spectrally dependent dispersion around 0.1 %.

Objective 1 aims to improve the predicted values of PQED response with 3D simulation software. The aim has two purposes: i) Improve the uncertainty in the responsivity to go beyond the IQD losses and ii) use the model in a new experimental technique to independently extract the photodiode model parameters.

The aim of objective 2 is to develop the best possible PQEDs with lower internal losses at cryogenic temperatures. The IQD in the PQED is limited by surface recombination velocity (SRV) and fixed oxide charge ($Q_f$). These parameters are found from standard material characterisation techniques as capacitance voltage (C-V) and charge carrier lifetime measurements. The passivation material / process giving the best PQED is effectively found by standard material characterisation techniques combined with improved 3D models without going through a full photodiode manufacturing process. The surface characterisation will be performed both at room and cryogenic temperatures.

In objective 3, we aim to develop the needed instrumentation and packaging to operate PQED type photodiodes also as a cryogenic electrical substitution radiometer (CESR). This will realise a self-calibrating dual-mode detector, which can be operated as both primary standards with the same absorber. Heat equivalence and signal to noise ratio (SNR) at sufficient accuracy for cryogenic and room temperature operation to meet the target uncertainties in objective 4 will be studied. Developing the PQED also as a CESR will eliminate present calibration limiting errors such as optical window and photon absorption differences from geometry or imperfect blackness. In this dual mode detector the same number of absorbed photons will generate the signal in either mode of operation.

The metrological applications of the self-calibrating photodiodes at room temperature and cryogenic temperature to unprecedented uncertainties and simplicity will be demonstrated in objective 4. There are two different routes for self-calibration: i) photocurrent mode with fitted models and ii) dual-mode photodiodes. By exploiting the design of the self-calibrating photodiode, the relative measurement, and PQEDs with improved passivation and prediction models, will allow for radiometric measurement of e/h with 1 ppm uncertainty compared to the 100 ppm uncertainty normally provided by the established standard CESR. The same technology can be used to operate and build self-calibrating photodiodes into applications as an "NMI-on-a-chip" and by that removing the need to move instruments to the lab for calibration. They can calibrate themselves in their own, possibly remote, and unattended location to a lower cost.

**Impact**

*Impact on industrial and other user communities*

The production volume of the European Photonics industry accounted for € 69.2 billion in 2015. Industry in general requires accurate and cost-efficient calibration methods to maintain traceability to an SI unit of their methods and equipment. Working out an exploitation plan and making the self-calibrating photodiodes commercially available are the most important criteria for uptake of the technology developed in *chip*S·CAL*e*. Commercialisation of developed products is likely to be targeted in a follow up Support for Impact Project (SIP) project. The two planned animation videos will help users understand how the devices work and make it appealing to use the devices. The videos will also be instrumental in the promotion of the project in scientific talks, on the website and in the approach to the wider user community.

Photonics21 is one of the European Technology Platforms, supporting the Key Enabling Technologies (KET) defined by the EU, and has more than 2500 members from the photonic industry, research institutes, academia and public service. The established contact between the consortium and Photonics21 simplifies the transfer of knowledge about project outputs to this important technology platform. In Photonics21 WG5 strategic roadmap “Europes Age of Light! How photonics will power growth and innovation” for the period 2021-2027 they have already implemented the ideas of *chip*S·CAL*e* and requests “maintenance-free, self-calibrating sensors” as both a technology challenge and a research and innovation challenge for optimised value.

*Impact on the metrology and scientific communities*

The principles and methods developed in *chip*S·CAL*e* will support and strengthen the implementation of the new SI system and the radiometric community’s position within the SI. The CCPR has requested the possibility of making radiometric measurement of fundamental constants as will be demonstrated here with unprecedented accuracy by comparing two independent and inherently different primary standards in one device. With the commercialisation of the self-calibrating photodiodes the community will have a new chip-scaled device for measuring optical power with unprecedented accuracy in possibly remote operation.

The validated 3D simulation tool will be used to establish a new service for owners of PQEDs based on customer’s own relative characterisations. The new service would support laboratories to make independent realisations based on PQEDs alone. The self-calibrating device will also help a number of project partners to reduce their CMC uncertainty for in-house customer calibration service. In a perspective beyond *chip*S·CAL*e*, other European NMIs can develop their capacity based on the self-calibration technology.

*Impact on relevant standards*

CIE is the international standardisation committee for light and lighting. CIE – Division 2: Physical Measurement of Light and Radiation is particularly interested in exploiting the new experimental techniques developed in this project through the planned revision of TC2-81 Update of CIE065:1985 (Absolute Radiometers). CIE welcomes the idea of an “NMI-on-a-chip” and has agreed to join the stakeholder committee to closely follow the progress of *chip*S·CAL*e.* The technical committee leader of TC2-81, a consortium partner in *chip*S·CAL*e*, presented the project at the CIE 29$^{th}$ Quadrennial Session in Washington June 2019, and will ensure that project outputs can be effectively implemented in the new standards.

*Longer-term economic, social and environmental impacts*

Photonic sensors are key enablers in a wide range of industrial manufacturing and service sectors including: healthcare, surveillance, and automotives. The resultant leverage makes photonic metrology and sensors a multi-billion euro industry. Improved sensors and simplified traceability will contribute to an improved efficiency in the photonic sensor industry.

The fraction of the population above 65 years age is increasing and this will put more pressure on the health care system. Optical methods are used increasingly both for diagnosis and therapy. Supporting optical methods with improved and simplified calibrations will contribute both on the improved diagnosis and optically based therapy side, as they are known to be faster and less invasive compared to previous surgical methods.

About 2/3 of the Essential Climate Variables (ECV) used to monitor impact of climate change require some sort of optical measurement. SI traceable measurements over decadal timescales require new instrumentation to detect small trends in ECVs from a background of natural variability. A self-calibrating instrument making climate quality measurements in the field, ideally in an autonomous manner would meet this requirement and is mentioned as an important application of basic science in the environmental roadmap for photometry and radiometry. The self-calibration detector proposed in this project is a first step towards such an instrument, and will have a major impact on the quality of Earth Observation data.

**List of publications**

None at this stage

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| Project start date and duration: | | 01 June 2019, 36 months |
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| Project website address: http://chipscale.aalto.fi/index.html | | |
| Internal Funded Partners:<br>1. JV, Norway<br>2. Aalto, Finland<br>3. CMI, Czech Republic<br>4. CNAM, France<br>5. INRiM, Italy<br>6. Metrosert, Estonia<br>7. PTB, Germany<br>8. TUBITAK, Turkey | External Funded Partners:<br>9. IFE, Norway<br>10. SINTEF, Norway<br>11. USN, Norway | Unfunded Partners: |
| RMG: - | | |