A practical optical power detector directly linked to the SI through fundamental constant ratio e/h

Marit S. Ulset[1*], Trinh Tran[1], Eivind Bardalen[2], Geiland Porrovecchio[3] and Jarle Gran[1]
[1]Justervesenet - The Norwegian Metrology Service, Kjeller, Norway
[2]University of South-Eastern Norway, Borre, Norway
[3]Czech Metrology Institute, Prague, Czech Republic
*mas@justervesenet.no

***Abstract*—We present a self-calibrated, self-assured room temperature optical power detector, which works both as a photoelectric detector and as a thermal detector. The thermal measurement mode can be used as a reference to calibrate the spectrally dependent internal losses of the photodiode. 3D charge-carrier simulations are used to model the photodiode response, and combined with experimental IV curves the simulations provide an independent method for determining the internal losses. Combining thermal measurements and simulations allow for the extraction of the fundamental constants ratio e/h. This provides a direct link from radiometric measurements to the SI, thus self-assuring the detector response.**

***Index Terms*—Fundamental constants, International System of Units, photodiodes, radiometry, self-calibration.**

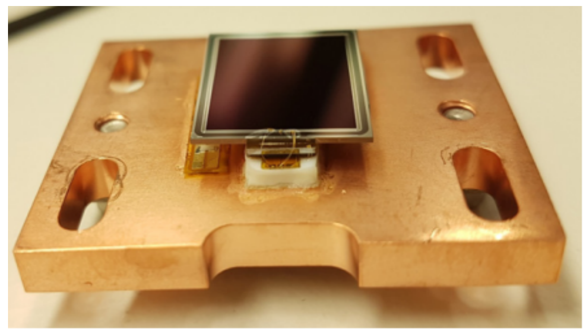

Fig. 1. The dual-mode detector module.

I. Introduction

For optical power measurements, the cryogenic radiometer has been a reliable and well-established primary standard for several decades, with measurement uncertainties in the order of 200 ppm [1]. However, the advantage of the low measurement uncertainty is usually lost when the scale is transferred to silicon trap detectors, and 0.1 % uncertainty is typical at the application level.

The dual-mode optical power detector, developed in the chipS·CALe project, combines the practicality of photodiodes with the thermal electrical substitution measurement of the cryogenic radiometer [2]. Also, it provides a primary standard to be used directly in applications, eliminating a long traceability chain. Operation at room temperature leads to a sacrifice in the measurement uncertainty compared to the cryogenic radiometer. However, by incorporating the thermal primary standard into the detector itself, and thereby eliminating uncertainty contributions usually involved with external references, such as window effects, moving parts, and differences in reflectivity and absorbance, we are able to reach a measurement uncertainty approaching that of the cryogenic radiometer even at room temperature.

The detector offers self-assurance by linking radiometric measurements to the SI through fundamental constants ratio e/h, making the usually elaborate procedures of inter-comparisons obsolete.

II. Dual-mode Self-calibration

The dual-mode detector consists of an induced-junction photodiode in combination with a thermal sensor. The photodiode is used as the absorber in both modes. By using thermal mode as a built-in reference, the internal losses of the photodiode can be determined without the need of an external reference. Once this is done for the desired radiation, temperature and optical power level, the detector can be operated as a normal photodiode to do quick and easy optical power measurements.

The absorbed optical power Φ_a of the photodiode can be calculated from the photocurrent i_{photo} as:

$$\Phi_a = \frac{hc}{e\lambda}\frac{i_{\text{photo}}}{(1-\delta(\lambda))} \quad (1)$$

where h is Planck's constant, c is the speed of light, e is the elementary charge and λ is the vacuum wavelength of the incoming radiation. The spectrally dependent $\delta(\lambda)$ represents the internal loss of the photodiode. This loss term must be determined before the photodiode can be used to make high-accuracy optical power measurements. As we use the same absorber in both the photocurrent measurement and thermal measurement, the reflectance will be the same and can hence be disregarded. For application purposes, when the absolute beam power is of interest, the reflection loss must be taken into account and can be reduced by placing the detector in a multi-reflection trap structure. Here the quantum yield, which is of most concern in the UV range, has been included as part of $\delta(\lambda)$ [4].

During measurements, the dual-mode detector module (Fig. 1) was placed in a copper trap structure inside a vacuum chamber, at a 45° angle to the incoming beam above a horizontal mirror, creating a three-reflection trap detector.

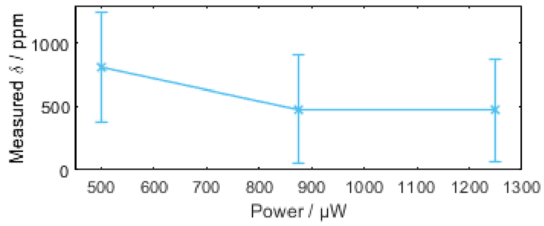

Fig. 2. Internal losses δ measured with the dual-mode self-calibration method at room temperature, as a function of absorbed optical power, with 488 nm radiation.

First, the detector was operated as a photodiode, by measuring the photocurrent i_{photo} while applying a reverse bias voltage across the photodiode. Then a thermal measurement was carried out, by cycling through five electrical substitution measurements.

The photodiode itself was used as the electrical heater, by applying a forward bias to the photodiode. The thermal design ensures heat equivalence between optical and electrical heating, such that equal optical and electrical power will give the same temperature rise.

When the optical power Φ_a has been determined using thermal mode, rearranging equation (1) gives the internal losses $\delta(\lambda)$. Fig. 2 shows experimental results for the internal loss δ from room temperature dual-mode measurements at different power levels, with 488 nm radiation.

III. Charge-Carrier Simulations

Predictable, low-loss induced-junction photodiodes [5] provide a second calibration method in the dual-mode detector, as 3D charge-carrier computer simulations can be used to predict the internal losses of the photodiode with high accuracy [3]. An experimental IV curve of the photodiode is acquired by measuring the photocurrent while gradually varying the reverse bias voltage across the photodiode. Fig. 3 shows experimental IV curves for different power levels at 647 nm, as well as simulation data from a 3D simulation model that has been fitted to the experimental data. The experimental data is plotted as $1 - I/I_{\max} + \xi$, where $I_{\max}$ is the maximum measured current and ξ is an offset parameter.

By fitting the simulation parameters to the experimental data, parameters, such as the surface recombination velocity and oxide charge, can be extracted from the model. When the photodiode defining parameters are known, the model can be used to determine the internal losses for any wavelength or power level.

IV. Self-Assurance

Even with a self-calibrated detector, it is necessary to check for drift in the detector response. This assurance of detector responsivity of primary standards is usually carried out by inter-comparisons between different metrology institutes. However, for the dual-mode detector, the charge-carrier simulations allow the assurance to be done internally - without removing the detector from its position. This makes it ideal for operation in remote locations, such as on a satellite.

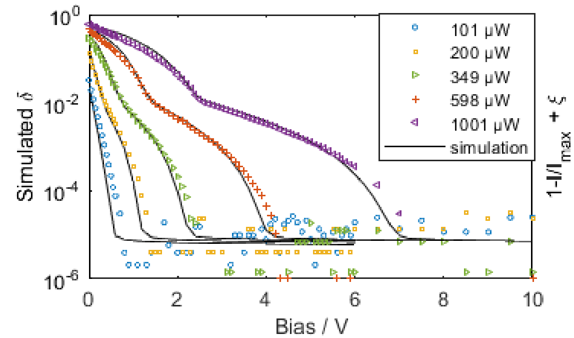

Fig. 3. Fitted simulated internal losses δ (solid lines, left axis) with experimental data, $1 - I/I_{\max} + \xi$ (right axis), of an induced-junction photodiode at 647 nm.

By using thermal mode to determine the absorbed optical power Φ_a, and using a charge-carrier simulation model fitted to experimental IV curves to determine the internal losses $\delta(\lambda)$, all terms in equation (1) are known. Consequently, we can tie our radiometric measurement of Φ_a directly to the SI through the fundamental constants ratio e/h. A consistency between the extracted value and the tabulated value provides self-assurance of the detector.

At cryogenic temperature, where both photodiode and thermal properties improve the signal-to-noise ratio, a low-uncertainty version of the method can be performed [6].

V. Conclusion

We present a room temperature self-calibrated optical power detector. In combination with charge-carrier simulations, the detector response is self-assured through a measurement of e/h, and thus provides a direct link between radiometric measurements and the SI. Our work shows promising results with room temperature dual-mode measurement uncertainties around 400 ppm (k = 2), and excellent agreement between a fitted 3D simulation model and experimental IV curves.

Acknowledgement

This project 18SIB10 chipS·CALe has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

References

[1] T. Varpula *et al.* "Optical power calibrator based on a stabilized green He-Ne laser and a cryogenic absolute radiometer" *IEEE Transactions on Instrumentation and Measurement* 38, 2, Apr 1989.

[2] M. S. Ulset *et al.* "Dual-mode room temperature self-calibrating photodiodes approaching cryogenic radiometer uncertainty" *Metrologia* 59 035008, 2022.

[3] T. Tran *et al.* "Determination of the responsivity of predictable quantum efficient detector over a wide spectral rangeb based on a 3D model of charge carrier recombination losses" *Metrologia* - Accepted manuscript, 2022.

[4] L. Werner "Quantum Yield in Induced Junction Silicon Photodiodes at Wavelengths around 400 nm", *14th Int. Conf. on New Developments and Applications in Optical Radiometry (NEWRAD 2021)* 2021.

[5] O. Koybasi *et al.* "High performance predictable quantum efficient detector based on induced-junction photodiodes passivated with SiO_2/SiN_x" *Sensors* 21 7807, 2021.

[6] T. Tran and J. Gran "Simulation of Predictable Quantum Efficient Detector Responsivity with Temperature" *These proceedings*, 2022.