Simultaneous optical and electrical heating in dual-mode photodiode operation at room temperature

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In this work we investigate an alternative method for thermal detection with the dual-mode optical power detector, which combines both thermal and photocurrent detection of optical power in one device. By applying electrical heat and optical heat simultaneously, rather than in two separate steps, a closed-loop feedback control can be used to maintain the temperature while opening and closing the laser power shutter. Measurements using the new method are compared to the old method, where optical heating was done with an open circuit, with no electrical current flowing. The results demonstrate that simultaneous optical and electrical heating of the photodiode during electrical substitution is possible.

INTRODUCTION

The EMPIR project *chip*S·CAL*e* [1] aims to develop a self-calibrating optical power detector, where thermal detection of incoming radiation is used as a reference to determine the internal losses of the photodiode absorber. The incoming radiation is converted either to a photocurrent, as in a traditional photodiode, or to heat, using electrical substitution to determine the power of the absorbed radiation. The photodiode is used as the absorber in both modes.

The internal quantum deficiency (IQD) of the photodiode is found from:

$$\delta(\lambda) = 1 - \frac{i_{photo}}{\Phi_T} \cdot \frac{hc}{e\lambda} , \qquad (1)$$

where Φ_T is the absorbed optical power measured in thermal mode, i_{photo} is the measured photocurrent, λ is the wavelength of the incoming radiation and h, c and e are Planck's constant, the speed of light in vacuum and the elementary charge, respectively.

In thermal mode, all absorbed radiant energy is converted to heat, which is then compared to an equivalent amount of electrical heat with known power. In a conventional electrical substitution radiometer (ESR), the electrical heat is usually applied by an external heater attached to the absorber. However, in the dual-mode detector, the electrical heat is applied by a forward bias voltage across the photodiode. In this way, the electrical heat is dissipated inside the photodiode, and the amount of power is found from $P = IV$, where I and V are the measured current through and voltage across the photodiode.

In our previous work on the dual-mode detector, optical and electrical heating were applied separately [2]. During optical heating, the electrical circuit was open, so no current could flow. This ensures that all absorbed power is converted to heat.

In this work, we investigate the possibility of applying a forward bias voltage to the photodiode during optical heating. By applying optical and electrical power at the same time, the temperature can be maintained at a constant level, by adjusting the electrical power in a closed feedback loop. In this way, the thermal optical power measurement will be less time-consuming, since there is no need for temperature stabilisation between each time the shutter is opened or closed. The only stabilisation required after toggling the shutter is the settling of the PI control loop, which might take a few seconds.

Furthermore, in designing the thermal link, there is a trade-off between time constant and signal level. Because closed loop operation is faster than the natural time constant of the detector, this method allows the thermal link to be designed to maximise the temperature signal and hence sensitivity. In addition, the detector will be less sensitive to ambient temperature variations, as the measurement can be carried out in less time.

EXPERIMENT

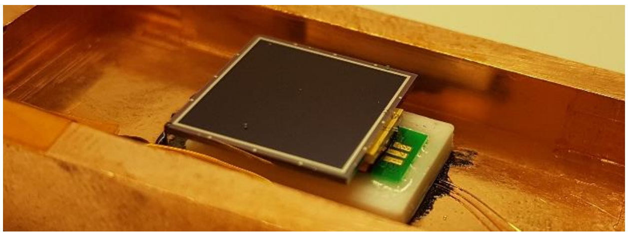

Figure 1. Photograph of the dual-mode detector, showing the 11 mm x 11 mm photodiode, the PLA heat link (white) and the copper carrier heat sink.

The dual-mode detector used in these measurements, shown in Fig. 1, is designed for room-temperature operation. The detector consists of a photodiode of 11 mm x 11 mm, mounted on a PLA heat link and placed in a copper carrier serving as the heat sink. The temperature is monitored with two germanium thermistors, one between the photodiode and the PLA heat link, and the other on the copper carrier heat sink. During measurements, the detector was screwed on to an additional copper heat sink inside a vacuum chamber at room temperature and irradiated with a 488 nm laser source. The heat sink was not temperature stabilised. Reflection losses are the same for both measurement modes and are hence irrelevant for the measurement of photodiode IQD.

In these measurements, made for demonstration purposes only, the electrical substitution was performed by switching between three levels:

i. Low electrical heating
ii. Optical + electrical heating
iii. High electrical heating

The power levels of (i) and (iii) where chosen such that the temperature was slightly below and above the temperature level at (ii), respectively. The total power level of step (ii) was calculated based on the known electrical power levels at steps (i) and (iii). The optical power was then found by subtracting the electrical power from the total power of step (ii). A complete measurement series consisted of an initial photocurrent measurement, followed by five or ten heating cycles, with a second photocurrent measurement at the end. The IQD from four different measurements were compared. In the first two measurements, a forward bias voltage was applied to the photodiode during optical heating, with the addition of 250 µW and 500 µW electrical power to the optical power of 500 µW. The last two measurements were performed with an open circuit during optical heating, the same way as in ref. 2, with an optical power of 500 µW and 750 µW.

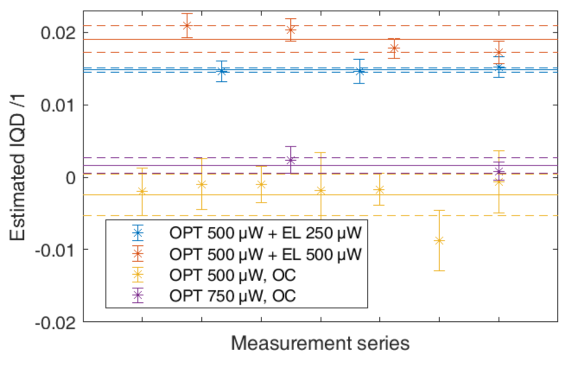

Figure 2. Estimated IQD from dual-mode measurements, with optical power of 500 µW and additional 250 µW and 500 µW electrical power, and optical heating with no additional electrical power at 500 µW and 750 µW power.

RESULTS AND FUTURE WORK

The estimated IQD for the four different measurements is plotted in Fig. 2 and summarised in Table 1. The uncertainty given is the standard deviation of the mean.

The results show a deviation between the two methods of optical heating. The IQD when using an open circuit during optical heating is close to zero, and overlapping for different optical power levels, as expected. However, when applying an additional electrical power during optical heating, the estimated IQD increases with increasing electrical power, suggesting somehow an influence on the estimate of Φ_T by unaccounted series resistance. The results vary more than expected, and a more detailed study is needed. However, this work shows that a forward biased operation of the dual-mode detector is possible.

Table 1. Estimated optical power Φ_T and internal losses δ from dual-mode measurements, with and without additional electrical heating during optical heating.

Optical heating step:	Estimated Φ_T (µW):	Estimated δ:
Opt. 500 µW + 250 µW el.	507.5 ± 0.3	0.015 ± 0.0003
Opt. 500 µW + 500 µW el.	509.5 ± 1.3	0.019 ± 0.002
Optical 500 µW, open circuit	499.2 ± 1.4	-0.0024 ± 0.0029
Optical 750 µW, open circuit	751.5 ± 1.0	0.0016 ± 0.0011

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