Optical power scale realization using the predictable quantum efficient detector

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We report realization of an optical power scale based on a predictable quantum efficient detector (PQED) over the spectral range of 400 nm – 800 nm. The PQED is characterized and used to measure the responsivities of a trap detector at four distinct laser lines, with an expanded uncertainty of 0.05%. The measurement results support the concept that the PQED can be used as a primary standard of optical power. We present a comparison of responsivities calibrated against the PQED at Aalto and the cryogenic radiometer at RI.SE, Sweden.

INTRODUCTION

The PQED provides traceability of optical power to SI units [1,2]. Such traceability route is tempting, because the operation of PQEDs is as easy as that of other silicon trap detectors. In most national metrology institutes, the optical power is measured with an absolute cryogenic radiometer (ACR) [3]. These devices can achieve an uncertainty below 0.01%. However, they are expensive to obtain and maintain as they are operated at cryogenic temperatures. Aalto has taken into use a compact PQED [2] as a primary standard of optical power over the spectral range of 400 nm – 800 nm. The PQED consists of high-quality photodiodes with minimal losses for internal quantum deficiency, arranged in a wedged trap configuration to minimize the effects of reflectance correction [4,5]. PQEDs are compact in size and operate at room temperature. They show excellent stability and repeatability of ~0.0016% [2].

In this work, we present an optical power scale realization based on a PQED. A silicon trap detector is calibrated against the new scale and compared to calibration at RI.SE. RI.SE uses an ACR as a primary standard of optical power measurements.

MEASUREMENT PROCEDURE

The new power scale is based on a PQED and a multi-wavelength setup for comparing detectors developed at Aalto [6]. Figure 1 presents a simplified drawing of the setup. Various lasers have been installed in the setup. Lasers available include KrAr+, Ar+, HeCd, red and green HeNe, and a couple of diode lasers. The laser beam to be used is selected with a computer-driven mirror on a rail. Unused beams are terminated in beam dumps. The measurement beam is cleaned with a spatial filter based on two off-axis parabolic mirrors (OAP), and a laser power controller (LPC) stabilizes the beam intensity. The PQED and the trap detectors to be calibrated are mounted on a precise XY translation stage, and their photocurrents are recorded with a current-to-voltage converter (CVC) and a digital voltmeter (DVM). A multiplexer (MUX) is used to read various detectors with one set of electronics. The whole setup is computer controlled.

The optical power P is calculated from the

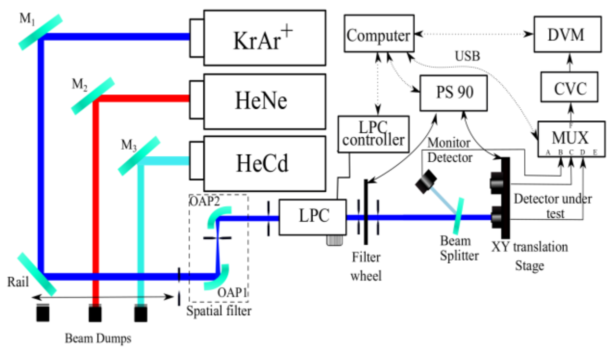

Figure 1. Multi-wavelength setup used for the optical power measurement with the PQED [6]. For abbreviations, see text.

photocurrent I_p of the PQED as

$$P = \frac{I_p\, h\, c}{e\, \lambda\, [1-\rho(\lambda)]\, [1-\delta(\lambda)]} \quad , \tag{1}$$

where λ is the wavelength of the laser used, $\rho(\lambda)$ is the reflectance of the PQED, $\delta(\lambda)$ is the internal quantum deficiency of the photodiodes, estimated to be approximately 0.0008% [4], e is the elementary charge, h is Planck's constant and c is the speed of light in the same medium as the wavelength – air or vacuum. The specular reflectances of the PQED are measured at the respective wavelengths using the method described in [2,4].

The PQED is used once a year to calibrate Hamamatsu silicon trap detectors with nitrogen flow serving as transfer standards. The nitrogen flow of

0.5 l/min through the trap detectors reduces the contamination of the photodiodes due to dust.

UNCERTAINTY BUDGET

The uncertainty budget of the new optical power scale is presented in Table 1.

Table 1. Uncertainty budget of spectral responsivity measurement of a trap detector against PQED.

Component	Standard uncertainty, %			
	458 nm	515 nm	543 nm	633 nm
Responsivity of PQED	0.011	0.011	0.011	0.011
Repeatability of results	0.007	0.003	0.003	0.008
Calibration of DVM	0.001			
Calibration of CVC	0.003			
Alignment of detectors	0.001			
Trap's spatial nonuniformity	0.023			
Combined standard uncertainty	0.026	0.026	0.026	0.027
Expanded uncertainty ($k = 2$)	0.053	0.052	0.052	0.054

The responsivity measurements have an expanded uncertainty of 0.052% – 0.054% depending on the wavelength. The highest component of uncertainty is the spatial nonuniformity of the trap detector, 0.023%. Repeatability is the standard deviation of 10 averaged measurements. The error in alignment of detectors was obtained by tilting the detectors by a few degrees and calculating the change in the signal due to a change of 0.5° in the angle.

COMPARISON MEASUREMENT

One silicon trap detector was measured both at RI.SE, Sweden, and at Aalto using the new power scale. Table 2 shows the responsivities measured at the wavelengths of 458 nm, 515 nm, 543 nm, and 633 nm, along with the difference between the two responsivities. The expanded uncertainties presented in the table are the quadratic sums of the uncertainties of RI.SE and Aalto. The results are only partially in agreement within the uncertainties.

Table 2. Comparison of spectral responsivities of a trap detector measured at Aalto and at RI.SE.

Wave-length / nm	Responsivity A/W		Difference %	Expanded uncertainty ($k = 2$)
	Aalto	RI.SE		
458	0.36446	0.36478	-0.088%	0.080%
515	0.41207	0.41204	0.007 %	0.082%
543	0.43553	0.43555	-0.005 %	0.086%
633	0.50793	0.50798	-0.010 %	0.077%

CONCLUSIONS

Aalto has taken into use a new optical power scale based on the PQED. The PQED is used annually to measure the responsivities of Hamamatsu silicon trap detectors with nitrogen flow working as transfer standards. Comparison with RI.SE using a silicon trap detector showed an agreement between the two scales within the uncertainties of 0.077% – 0.086% for the wavelength range 515 nm – 633 nm. The results indicate the usability of the PQED as a primary standard of optical power.

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Acknowledgement: The authors are grateful to Stefan Källberg of RI.SE, Sweden, for measuring the trap responsivities with ACR.