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# Optical power scale realization using the predictable quantum efficient detector

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# Optical power scale realization using the predictable quantum efficient detector

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**Abstract**. We report realization of scales for optical power of lasers and spectral responsivity of laser power detectors 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 optical power of a laser that is further used in calibration of the responsivities of a working standard trap detector at four distinct laser lines, with an expanded uncertainty of about 0.05%. We present a comparison of responsivities calibrated against the PQED at Aalto and the cryogenic radiometer at RISE, Sweden. The measurement results support the concept that the PQED can be used as a primary standard of optical power.

## 1. Introduction

The predictable quantum efficient detector (PQED) provides traceability of optical power to the SI system of 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) [3,4,5]. 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 [1] as a primary standard of optical power over the spectral range of 400 nm – 800 nm. The PQED, shown in figure 1, consists of high-quality photodiodes with minimal losses of internal charge carriers, arranged in a wedged trap configuration to minimize the effects of reflectance correction [6,7]. PQEDs are compact in size and operate at room temperature. They show excellent repeatability of ~0.0016% [1]. The stability of the PQEDs is also excellent as reported in [8], where no change in responsivity is observed over 8 years within the measurement uncertainty of about 0.01%.

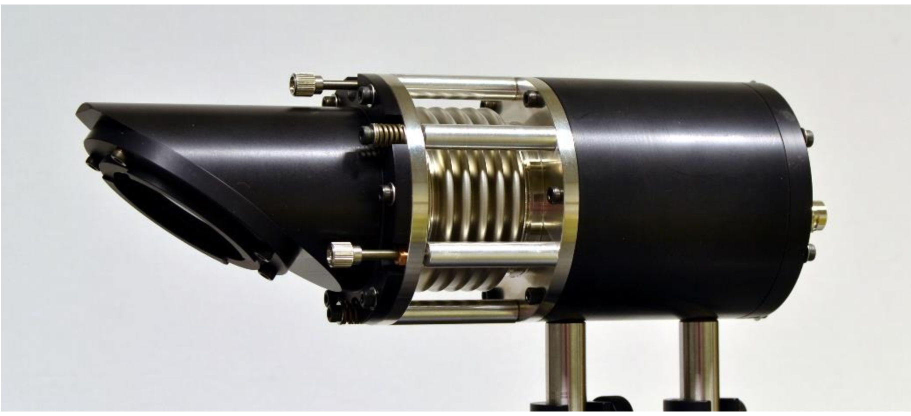


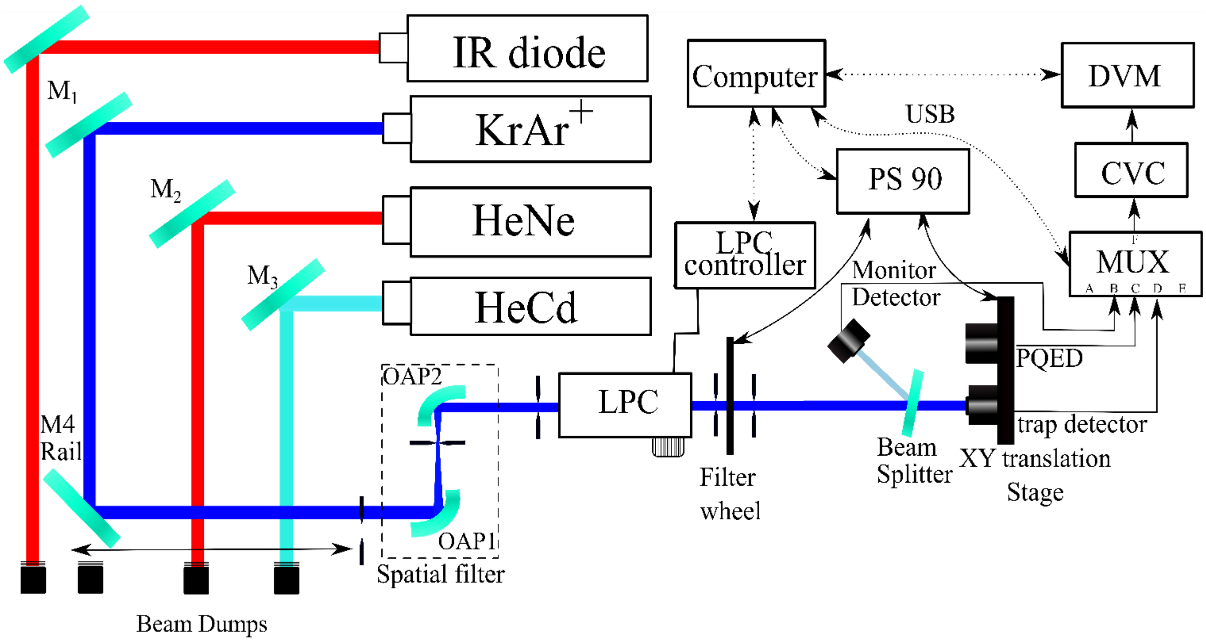
**Figure 1.** Predictable quantum efficient detector (PQED) with a Brewster window [1].

In this work, we present an optical power and spectral responsivity scale realization based on a PQED. A silicon trap detector is calibrated with the new scale and compared to calibration at RISE, Sweden. RISE uses an ACR as a primary standard of optical power measurements. The comparison of the responsivities measured at Aalto and RISE supports the concept that a PQED can be used as a primary standard of optical power.

## 2. Measurement Setup

The new scale is based on a PQED and a multi-wavelength laser setup for comparing detectors developed at Aalto [9], used earlier in transmittance measurements of polymer samples [10]. The PQED photodiodes used are based on p-type silicon wafer and have been described in detail in [1,6,7]. The mechanical structure of the PQED is as described in [1]. Figure 2 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. PS 90 is the position controller which controls the movement of the filter wheel and the XY translation stage as commanded by the computer. The whole setup is computer controlled.

**Figure 2.** Multi-wavelength setup used for the optical power measurement with the PQED [9]. For abbreviations, see text.




In the PQED, two photodiodes are arranged in a wedged light trapping configuration. Seven specular reflections take place between the photodiodes before the light is reflected out of the PQED. The structure and calculation of the reflectance of a p-type PQED are discussed in detail in [1, 6, 7]. In the current setup, the PQED is operated without a Brewster window in an ordinary laboratory room. Instead of window, dry nitrogen purging is used to avoid dust and moisture contamination of the photodiodes through the open entrance aperture [11]. The dry nitrogen enters the detector at the back, flows through the detector and then leaves via the entrance aperture of the PQED which is 10 mm in diameter. Some of the Hamamatsu trap detectors used as working standards allow a similar nitrogen flow purging as used for the PQED. A flow rate of 0.5 l/min is used for both types of detectors.

With the incoming light beam, the optical power $P$ is calculated from the photocurrent $I_p$ of the PQED as

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

where $\lambda$ is the vacuum wavelength of the laser used, $\rho(\lambda)$ is the reflectance of the PQED, $[1 + g(\lambda)]$ is the quantum yield in silicon, $\delta(\lambda)$ is the internal quantum deficiency of the photodiodes, estimated to be approximately 0.0008% [6], $e$ is the elementary charge, $h$ is Planck's constant, and $c$ is the speed of light in vacuum. The specular reflectances of the PQED are measured at the respective wavelengths using the method described in [1,6]. In low-uncertainty measurements, the quantum yield may start to contribute at wavelengths below 500 nm [12], although its deviation from 1 was earlier thought to be significant only at wavelengths below 400 nm. The optical power of Eq. (1) is used to calculate the responsivity of trap detectors as $R = I_{DUT} / P$, where $I_{DUT}$ is the measured photocurrent of the trap detector under test. The PQED is used once a year to calibrate Hamamatsu silicon trap detectors serving as working standards.

## 3. Uncertainty Budget

The uncertainty budget of the new optical power and spectral responsivity 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 | 543.5 nm | 633 nm |
| **Responsivity of PQED** | 0.015 | 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 | | | |
| **Spatial nonuniformity of trap detector** | 0.023 | | | |
| **Combined standard uncertainty** | 0.029 | 0.026 | 0.026 | 0.027 |
| **Expanded uncertainty (*k* = 2)** | 0.057 | 0.052 | 0.052 | 0.054 |

The responsivity of the PQED has a standard uncertainty of 0.011% – 0.015%. This uncertainty value consists of the main components due to reflectance (0.001%), non-uniformity (0.008%), repeatability (0.001%), internal quantum efficiency (0.008%) and quantum yield (0.010% at 458 nm, zero at other wavelengths) of the PQED. The quantum yield is $[1 + g(\lambda)] = 1.0001 \pm 0.0001$ at 458 nm and zero at other wavelengths [12]. Uncertainty due to repeatability of results has been obtained by calculating 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. The alignment error also accounts for the repeatability error of the linear translator. The uncertainties in the calibrations of the DVM and the CVC include all uncertainty components from the national standards of electricity to the measuring instruments. The DVM is calibrated by feeding the multimeter with a known current and voltage from a Keithley calibrator. The sensitivity of the CVC is calibrated by measuring the output voltage of the CVC with a calibrated DVM, when supplying a known current to the input with the Keithley calibrator. The trap detector has been scanned at a wavelength of 488 nm with a laser beam, having a diameter of 1.2 mm, in order to check for the uniformity of the detector. The same spatial uniformity is expected to be valid at all wavelengths. The uncertainty due to the spatial nonuniformity of the trap detector is 0.023%, which is the largest component of the uncertainty budget.

The uncertainty of the optical power scale contains all listed components except the spatial nonuniformity of the trap detector. The expanded uncertainty of optical power is thus 0.024% – 0.034%. The uncertainty of the spectral responsivity scale, measurements of a trap detector against the PQED, includes all the components. The expanded uncertainty is 0.052% – 0.057% at the wavelength range of 458 nm – 633 nm, depending on the wavelength.

## 4. Comparison Measurement

One silicon trap detector was measured both at RISE, Sweden, and at Aalto using the new spectral responsivity scale. Table 2 shows the responsivities measured at the wavelengths of 458 nm, 515 nm, 543.5 nm, and 633 nm, along with the differences between the two responsivities. The expanded uncertainties presented in Table 2 are quadratic sums of the uncertainties of RISE and Aalto. The results are in agreement within the uncertainties ($k$ =2) of 0.077% to 0.086% at all wavelengths as seen in Table 2. However, the difference between the two responsivities is somewhat higher at 458 nm than at other wavelengths.

**Table 2**. Comparison of spectral responsivities of a trap detector measured at Aalto and at RISE.

| **Wavelength in vacuum / nm** | **Responsivity / A W$^{-1}$** | | **Difference** | **Expanded uncertainty ($k$ = 2)** |
|---|---|---|---|---|
| | Aalto | RISE | | |
| **458.07** | 0.36450 | 0.36478 | -0.077 % | 0.083 % |
| **514.68** | 0.41207 | 0.41204 | 0.007 % | 0.082 % |
| **543.51** | 0.43553 | 0.43555 | -0.005 % | 0.086 % |
| **632.99** | 0.50793 | 0.50798 | -0.010 % | 0.077 % |

## 5. Conclusion

Aalto has taken into use a new optical power scale based on a PQED. The PQED is used annually to measure the responsivities of Hamamatsu silicon trap detectors, used as working standards. Comparison with calibrations performed against an ACR at RISE using a silicon trap detector showed an agreement between the two scales within the expanded uncertainties of 0.077% – 0.086% for the wavelength range 458 nm – 633 nm. The comparison results deviate more at the wavelength of 458 nm than at 514 nm, 543.5 nm, or 633 nm. This may be because of high temporal instability of the Hamamatsu trap detectors at wavelengths below 476 nm [8]. Overall, the results indicate the usability of the PQED as a primary standard of optical power.

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