A Cryogenic Radiometry Based Spectral Responsivity Scale at the National Metrology Centre

Gan Xu and Xuebo Huang

Abstract

This paper describes the spectral responsivity scale established at the National Metrology Centre (NMC) based on cryogenic radiometry. A primary standard – a mechanically pumped cryogenic radiometer together with a set of intensity-stabilised lasers provides traceability for optical power measurement with an uncertainty in the order of $10^{-4}$ at 14 discrete wavelengths in the spectral range from 350 nm to 800 nm. A silicon trap detector, with its absolute responsivity calibrated against the cryogenic radiometer is used as a transfer standard for the calibration of other detectors using a specially built spectral comparator. The relative spectral responsivity of a detector at other wavelengths can be determined through the use of a cavity pyroelectric detector and the extrapolation technique. With this scale, NMC is capable to calibrate the spectral responsivity of different type of photo detectors from 250 nm to 1640 nm with an uncertainty range from 3.7% to 0.3%.

Keywords: Photo detector. Optical power, Cryogenic radiometry, Spectral responsivity scale

1. Introduction

Photo detectors are the most critical components of any optical instruments used for quantitative measurements of optical radiation in radiometric, photometric or colorimetric applications. The accuracy of such an instrument is dependent to a large extent on the calibration of the spectral power responsivity of the photo detector used. The absolute spectral power responsivity of a photo detector is the ratio of the photo current output (in amperes) to the incident spectral power (watts). NMC has developed an absolute spectral responsivity scale based on a cryogenic radiometer – primary standard for optical power measurement with a group of intensity stabilised lasers at 14 discrete wavelengths and expanded the wavelength range of the scale to 250 nm – 1640 nm through a spectral comparator by using silicon trap detectors as transfer standards. This paper will briefly review the realisation of spectral responsivity scale at NMC, the verification of the scale through participating international comparisons, and the current capability of the calibration for spectral responsivity of photo detectors.

2. Realisation of spectral responsivity scale

The current NMC spectral responsivity scale is realised through a primary standard (cryogenic radiometer), three absolute transfer standards (silicon trap detectors), two relative transfer standards (cavity pyroelectric detectors), secondary standards (silicon and InGaAs photodiodes). Fig. 1 shows the spectral responsivity scale chain at NMC with associated uncertainties (level of confidence ~95%, coverage factor k = 2).
2.1. Primary standard – cryogenic radiometer

The cryogenic radiometer is an electrical substitution radiometer that operates at an absolute temperature about 13 kelvin. Based on thermal equivalence between optical and electrical heating, it is capable of measuring laser beam power with the relative expanded uncertainty in the order of $10^{-4}$ at about 0.5 mW provided that the laser power is stabilised to better than 0.01%.

By operating at cryogenic temperature instead of room temperature several advantages are gained [1]. Firstly, the heat capacity of copper is reduced by a factor of 1000 so as to allow the use of a relatively large cavity with a time constant about 4 min. Secondly, the thermal radiation emitted by the cavity or absorbed from the surrounding is reduced by a factor of $10^{7}$, which eliminates the radioactive effects on the equilibrium temperature of the cavity. Finally, the cryogenic temperature allows the use of superconducting wires to the heater that removes the non-equivalence of optical and electrical heating due to the heat dissipated in the wires. The largest components of the uncertainty are those due to the systematical correction for the Brewster angle window transmittance and the random error associated with the cavity temperature measurement. Fig. 2 shows the schematic diagram of cryogenic radiometer.
2.2. Absolute transfer standard – silicon trap detector

Though highly accurate, the cryogenic radiometer is not suitable for calibration of photo detectors directly as only limited number of laser wavelengths are available (see below) and calibration at each wavelength is very time consuming and may take one or more days to complete. A more practical approach is to transfer the optical power scale to silicon trap detectors which are good transfer standards since they have stable and uniform responsivity, good linearity and low noise.

The silicon trap detector we built is a reflection type which consists of three single silicon photodiodes electrically connected in parallel while oriented in such a way shown in Fig. 3 so that the incoming laser beam is reflected by the surfaces of the photodiodes five times before leaving such a “light trap”. This unique structure enables the detector absorb nearly 100% of incoming laser power, i.e., a near unity quantum efficiency within its band gap over a wide spectral range (400 nm – 900 nm). Within this range, assuming negligible surface reflection loss, the spectral responsivity $s(\lambda)$ of a trap detector can be directly calculated by

$$s(\lambda) = \frac{\varepsilon \cdot \lambda \cdot e}{h \cdot c}$$

where $\varepsilon$ is the external quantum efficiency, $\lambda$ is the vacuum wavelength and $h$, $c$, and $e$ are fundamental constants. In our lab, the trap detectors are calibrated by the cryogenic radiometer at five wavelengths between 476.2 nm and 799.3 nm from a krypton ion laser and a He-Ne red laser, both intensity stabilised with relative expanded uncertainty (confidence level ~95% with coverage factor $k = 2$) between 0.03% and 0.06%. As the spectral responsivity of a silicon trap detector is proportional to wavelength within the wavelength range (400 nm – 900 nm), its values at other wavelengths can be obtained by interpolation or extrapolation using linear regression method.

![Fig. 3 Schematic 2 – D diagram of a trap detector](image)

2.3. Relative transfer standard – cavity pyroelectric detectors

To extend the scale to UV range from 250 nm to 400 nm and NIR range from 900 nm to 1640 nm, two relative transfer standards - cavity pyroelectric detector (CPD) (Al-coated for UV and Au-coated for NIR) together with the silicon trap detectors are used to calibrate three secondary standards (silicon photodiode in the range from 250 nm to 1050 nm, and InGaAs photodiode in the range from 900 nm to 1640 nm). As the CPD is a spectrally flat detector i.e., its spectral responsivity is independent of wavelength, once calibrated at a specified wavelength, its spectral responsivity values at other wavelengths are all known with a very low uncertainty (0.2%).

2.4. Secondary standard – silicon/InGaAs photodiodes

The absolute spectral power responsivities of each secondary standard in the range from 400 nm to 900 nm are determined by comparison with that of the silicon trap detector, using the following measurement equation:
\[
    s_i(\lambda) = s_s(\lambda) \cdot \frac{V_t(\lambda)}{V_m(\lambda)} \cdot \frac{G_s}{G_t}
\]

where \(s_i(\lambda)\) and \(s_s(\lambda)\) are the absolute spectral power responsivities of photodiode and trap detector respectively; \(V_t(\lambda)\) and \(V_s(\lambda)\) are the signals from photodiode and trap detector respectively; \(V_m(\lambda)\) and \(V_m(\lambda)\) are the signals from the monitor simultaneous with \(V_t(\lambda)\) and \(V_s(\lambda)\) respectively; \(G_t\) and \(G_s\) are the calibrated amplifier gains for the photodiode and trap detector respectively.

The spectral power responsivities of both UV and NIR CPDs are determined by comparison with that of the calibrated secondary standards in the ranges (400 nm – 450 nm for UV CPD and 850 nm – 900 nm for NIR CPD) respectively. The absolute spectral power responsivity values of each secondary standard in the ranges (250 nm – 400 nm and 900 nm – 1640 nm) are then determined by comparison with that of both calibrated CPDs in UV and NIR ranges respectively.

### 2.5. Spectral responsivity calibration facility

The spectral responsivity calibration facility allows the calibration of spectral responsivity of photo detector through a comparison with a detector standard with known spectral responsivity. The facility consists of a double grating monochromator (CVI DK242) with wavelength accuracy of 0.1 nm, a light source chamber and a detector chamber as shown in Fig. 4.

![Fig. 4 Schematic diagram of spectral responsivity calibration facility](image)

*(BS: beam splitter, WS: working standard, PD: photodiode, CVC: current-to-voltage converter, DVM: digital voltmeter)*

The optical radiation emitted from either a tungsten trip lamp or a 300 W xenon arc lamp in the source chamber is focused into the entrance slit of the monochromator through a concave mirror, dispersed by the grating inside and then becomes monochromatic light after emerging from the exit slit. This monochromatic beam is focused onto the surface of photo detectors to be measured in the detector chamber. A motorized translation stage is used to move the...
detectors to be compared into the optical path in a predetermined sequence. The output signals from these detectors are sent to the current-to-voltage converters and measured by high accuracy digital voltmeters. The whole system is controlled by a PC and is fully automated.

3. International comparison results

The accuracy of our spectral responsivity scale in the visible wavelength has been verified by an international comparison (CCPR-S3) while its accuracy at other wavelength ranges is being assessed through three other comparisons which are still in progress.

The CCPR-S3, a comparison of cryogenic radiometers between NMC and the National Physical Laboratory (NPL), UK, has been conducted through calibration of spectral responsivity of silicon trap detectors. The agreement at specified laser lines (356.4nm, 476.2nm, 568.2nm, 632.8nm, 647.1nm, and 799.3nm) has been assessed and a link of the scale of NMC to the international scale - CCPR-S3 comparison reference values at laser lines (476.2 nm, 568.2 nm, 647.1 nm) has been established and published in 2010 [2].

The relative difference between the NMC and NPL values \( \Delta(NMC-NPL) \), at each wavelength and the associated standard uncertainty \( u(NMC-NPL) \), are shown in Table 1 and Fig. 5.

| Wavelength/nm | 356.4 | 476.2 | 568.2 | 632.8 | 647.1 | 799.3 |
|---------------|-------|-------|-------|-------|-------|-------|
| \( 10^4 \Delta(NMC-NPL) \) | 32.5  | 6.9   | 2.3   | 0.8   | 6.3   | 10.0  |
| \( 10^4 u(NMC-NPL) \) | 7.9   | 2.0   | 1.7   | 1.3   | 1.5   | 1.7   |

Fig. 5 NMC – NPL comparison results - average value for 3 detectors
The relative difference between the NMC value and the CCPR-S3 reference value, $\Delta(NMC-\text{Ref})$, at each wavelength and the associated standard uncertainty $u(NMC-\text{Ref})$, are shown in Table 2.

### Table 2. Linkage of NMC scale to CCPR-S3 comparison reference value

| Wavelength / nm | 476.2 | 568.2 | 647.1 |
|-----------------|-------|-------|-------|
| $10^4 \times \Delta(NMC-\text{Ref})$ | 6.5   | 3.2   | 6.8   |
| $10^5 x u(NMC-\text{Ref})$     | 2.2   | 1.9   | 1.8   |

#### 4. Conclusion

A spectral responsivity scale from 250 nm to 1640 nm, traceable to SI unit through cryogenic radiometer at the NMC has been established. The scale consists of a group of secondary standards – silicon/InGaAs photo detectors which are calibrated by absolute transfer standard – Si trap detector and relative transfer standard – cavity pyroelectric detector. The international comparison results show that difference between NMC scale and CCPR key comparison reference value and associated uncertainty is in the order of $10^{-4}$ in the visible spectral range.

#### References

1. T. C. Larason, S. S. Bruce, and C. L. Cromer, 1996, *The NIST High Accuracy Scale for Absolute Spectral Response from 406 nm to 920 nm*, J. Res. Natl. Inst. Stand. Technol. 101, P. 133

2. Malcolm G White, Gan Xu and Xuebo Huang, 2010, *Final report on the bilateral supplementary comparison of cryogenic radiometers CCPR-S3 between the NPL and the NMC-A*STAR*, Metrologia, 47, (Technical Supplement 2010), 02004