Cryogenic primary standard for optical fibre power measurement

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Abstract

NIST has completed commissioning a new, state-of-the-art cryogenic primary standard for optical fibre power measurement and calibration. It establishes for the first time, a direct traceability route between the device under test and primary standard. Two silicon micro-machined planar detectors, with vertically aligned carbon nanotube absorbers, thin film tungsten heaters and superconducting resistive transition edge temperature transducers, form the basis of the radiometer. Magnetic phase change thermal filters ensure noise-free operation at 7.6 K. Measurement repeatability below 50 ppm is routinely achieved during a measurement cycle of 30 min. The system operates at a nominal radiant power level of 200 \(\mu\)W (\(-7\) dBm). The expanded measurement uncertainty at \(k=2\) is 0.4\%, a 20\% improvement on NIST’s current optical fibre power Calibration and Measurement Capability.

The performance of the new standard was established by comparing it to our current standard, using four transfer detectors, at nominal wavelengths 850 nm, 1295 nm and 1550 nm. The comparison agreed within the combined expanded measurement uncertainty of 0.6\%. Whilst the new standard is intended primarily to service the telecommunications industry, it is limited in use only by available sources and optical fibre.

Keywords: carbon nanotube detector, fibre coupled cryogenic radiometer, optical fibre power measurement, optical fibre power meter, planar black detector

(Some figures may appear in colour only in the online journal)
incorporated the new primary standard into our traceability chain and quality system. In doing so we have established a measurement facility that is entirely fibre coupled, which demonstrates a path forward in high accuracy measurements for fibre sensing and optical communications.

The technology behind this development is not only applicable to optical fibre power measurement, but also to radiant power measurement in general, across the broad wavelength spectrum from the ultraviolet to THz region. The measurement process compares optical and electrical heating of a cooled detector, known as electrical substitution radiometry. Traceability is assured by electrical measurement standards [12]. We have recently demonstrated the first planar cryogenic detector employing carbon nanotube absorbers grown directly onto the working substrate [13, 14].

Several key enabling technologies are instrumental in the success of this work; namely silicon micro-machining, carbon nanotube growth and thermal filtering by means of magnetic phase change material. Specific lanthanide elements exhibit a characteristic increase in volumetric heat capacity at low temperature due to magnetic ordering processes [15]. For this reason, they are used as the regenerator in mechanical cryo-coolers operating below 10 K [16]. In our case we use HoCu2 as a thermal capacitor in an $RC$ thermal filter, which is explained further in section 2.3.

In general terms we calibrated four transfer standards, two silicon, one InGaAs and one germanium with our current working standard, an electrically calibrated pyroelectric radiometer (ECPR) at three wavelengths; 850 nm, 1295 nm and 1550 nm. The ECPR is directly traceable to the laser optimised cryogenic radiometer (LOCR). Subsequently, we calibrated these transfer standards with the new fibre radiometer and compared the results.

An important aspect of the measurement is the determination of the fibre beamsplitter ratio between the device under test (DUT) and radiometer, which is measured at room temperature. It is well known that the refractive index of optical fibre is temperature dependent, and thus we determine the magnitude of this effect and apply a correction by measuring the optical return loss (ORL) of the fibres as they are cooled from room temperature to 5 K in the cryostat [17, 18]. To facilitate this measurement, we used a physical contact (FC/PC) ferrule at the 5 K end of the fibre. The measurement of ORL is defined in IEC standard 61753-1 [19].

It is apparent as we move forward, that lessons from the present study are relevant to fibre coupled superconducting nanowire single-photon detector calibration facilities that calibrate photon-counting detection efficiency [20].

In the following sections we describe the cryogenic and optical systems, the absolute reflectance measurement of the chip detector, the beamsplitter ratio measurement and the ORL measurement. Finally, we present an uncertainty analysis and discuss the contributors.

2. Experimental setup

2.1. Introduction

The measurement facility consists of independent, fibre-coupled, laser sources and detector sub-systems that are mechanically integrated and managed by data acquisition and control software that runs autonomously during the course of a measurement. This layout particularly favours the characterisation of the optical components for polarisation and temperature dependent attributes. Figure 1 schematically illustrates the layout of the facility.

2.2. Planar chip detector

The chip detectors are fabricated from commercial, 375 $\mu$m thick, 76.2 mm diameter silicon wafers. The design encompasses a circumferential tungsten thin film heater, and two Nb superconducting resistive temperature sensors deposited at the top of the heatlink (figure 2(a) and 2(b)). To mitigate joule heating, the leads to the sensors and heater along the weak silicon thermal link (thermal conductance $G \sim 1$ K mW$^{-1}$) are fabricated from superconducting thin film vanadium.

The vertically aligned carbon nanotubes (VACNT) are grown in a PECVD furnace at 800 °C, which yields near unity absorption (0.999 55 visible and NIR), wideband (0.3 $\mu$m to 500 $\mu$m) radiant power absorbers with height of approximately 200 $\mu$m—see appendix A: ‘Recipes’, section 2 ‘Summary of PECVD recipe’ [21]. A chip detector has a 5.5 mm diameter absorber, is relatively fast (50 Hz) and is cheap to produce.
Material compatibility issues, caused by growing VACNTs directly onto a functioning chip detector, were overcome by characterizing multiple candidate superconducting thin film metals congruent with high temperature VACNT growth. Figure 3(a) shows two chip detectors wire bonded to the thermal reference and isothermal shield, while figure 3(b) shows the position of the shield atop the thermal filter stack of the cryogenic radiometer.

We use vanadium (V) passivated with a silicon nitride (SiN) layer for the superconducting wiring along the micro-machined silicon heat link to the thermal reference. Due to diffusion of the two materials V and SiN, during the high temperature VACNT growth, the wiring has an elevated critical temperature \( T_c \) of 12 K and critical current \( I_c \) of 51 mA. Elemental V transitions at 5.3 K. Niobium was chosen for the thin film superconducting transition edge sensor (TES), which operates as an extremely sensitive resistive transducer. It is compatible with the VACNT growth process; however, the \( T_c \) is depressed from 9.2 K to 7.5 K, again due to material diffusion during the high temperature growth period. This elevation and depression of the critical temperatures of V and Nb enables the chip detector to function correctly, given the wiring transitions to zero ohms (which is what we want) at a higher temperature than the operating point of 7.6 K, which is the steepest or most sensitive region of the TES transition.

A thin film tungsten heater is deposited around the periphery of the chip detector and this is used as the electrical substitution heater during a measurement cycle. It has been shown that VACNT post-growth plasma treatment with O2 and subsequently CF4, enhances the absorptivity and produces super-hydrophobic growths [22, 23]. The reflectance of such films was measured to be less than 0.02%.

2.3. Cryogenic detection system

The cryostat is evacuated to a base pressure of \( 1 \times 10^{-5} \) mbar with a standard dry roughing pump and 50 l s\(^{-1}\) turbo-pump. The two chip detectors are mechanically cooled to a base temperature of 3 K. We have incorporated a passive two-pole thermal RC filter, designed for the region 4 K to 8 K and constructed from readily available magnetic phase change material (HoCu2) to dampen the 1.4 Hz periodic temperature oscillations of the mechanical cryocooler (figure 3(b) above).
This approach is particularly effective with more than 50 dB isolation, resulting in a thermal noise floor of 5 µK at the chip detector. Small long-term drifts in the temperature of the thermal reference are actively controlled by a weakly coupled proportional integral (PI) feedback loop, maintaining the set temperature of the thermal reference at 7.5 K.

During the course of a measurement the chip detector, which runs in open loop mode, operates at 7.6 K. During setup a nominal operating point is established with optical heating and then an electrical heating span determined, which is dependent upon the stability of the laser sources. This was set at $\pm 350$ nW for the three diode lasers. For comparison an intensity stabilised red HeNe laser requires a span of $\pm 100$ nW.

We use two similar optical sub-systems for each of the two cryogenic chip detectors (figure 3(a)), one for 850 nm and one for 1310/1550 nm. For each optical sub-system, the 50% output fibres of the two-independent three-way beamsplitters are fusion spliced to the single-mode input fibres of the cryogenic radiometer. A separate fibre runs to each of the two detectors. Since the VACNT absorber is sensitive to optical radiation out to wavelengths of 500 µm, it is imperative to ensure the fibre and fibre tip are thermally anchored very well. To this end, 20 turns of fibre is wrapped around the thermal filter to ensure adequate heat sinking and to thermally anchor the fibre tip at 7.5 K. The zirconia ferrule is anchored at the heat-sink reservoir. The end of the fibre is polished flat and is positioned 2 mm in front of the chip detector. The flat polish facilitates ORL measurements, which are required to correct for the change in refractive index, and thus output power of the fibre, with temperature. The other two legs of the beamsplitter are connected to a photodiode monitoring channel and the device under test.

A Stanford Research Systems CS580 current source supplied current to the 13.4 kΩ detector heater via a 999.979 ± 0.010 Ω calibrated resistor. Calibrated voltmeters measure the voltage across the resistor and heater, thus giving a measure of the applied electrical power. Commercial alternating current resistance bridges were used to monitor the heatsink sensor for PI feedback control, and the TES transducer, which was operated at 4.5 Ω, the steepest point of its’ resistance-temperature response curve. Only one detector is operated at a time.

**2.3.1. Detector absolute reflectance measurement.** The absolute reflectance of the VACNT chip detectors was measured using a diode laser-based reflectometer, configured to measure normal incidence directional-hemispherical (0°/h) reflectance. The system consists of a 150mm diameter

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**Figure 4.** Absolute directional-hemispherical (0°/h) reflectance measurement setup, top view and side view. Not shown is a small 1 mm thick square black aluminium reducing mask placed between the sphere port and the VACNT sample to facilitate measurement. A small correction to the measured reflectance is made to account for the thickness of the mask.

**Figure 5.** Spatial uniformity of reflectance over central 3 mm diameter portion of detector PBR8.4V-17 at 660 nm. The raster scan is limited by the 1 mm beam spot size and the ability to position the beam at the centre of the chip detector. The step size is 0.5 mm.
spectraflect coated integrating sphere and a suite of temperature-controlled diode lasers spanning the wavelength range 406 nm to 1625 nm. The laser beam is directed sequentially by a rotating mirror to two input ports, irradiating the sample and reference (figure 4). A phase sensitive detection technique with pre-amplifier was used to optimise the signal-to-noise ratio during a measurement.

The chip detector reflectance measurement is difficult to perform due to the size of the absorber (5.5 mm), and the positioning and size of the laser beam. In order to bound the uncertainty, larger VACNT witness samples 17 mm diameter, were centrally positioned to overfill the 15 mm diameter sample port and measured. These measurements were very reliable and repeatable and thus the maximal spread about the average of these measurements is used to bound the uncertainty of a specific detector reflectance measurement. A correction is applied to the electrical substitution power measurement for each detector at each wavelength.

The fibre tip is centrally located 2 mm from the detector surface and thus the beam-spot size on the detector is approximately 0.5 mm diameter, given a numerical aperture of 0.12. Thus, the small reflectance non-uniformity observed around the edge of the absorber will not affect performance, figure 5.

For reference chip detector PBR8.4V-17 is used at 850 nm and chip detector PBR8.4V-20 is used at 1310/1550 nm. VACNT growth times were 36 and 40 min respectively, with measured heights of 170 µm and 250 µm. Growth conditions were 800 °C, $P_{\text{Ar}} = 2.413$ kPa (gas flow: 452.5 sccm), $P_{\text{H}_2} = 0.227$ kPa (gas flow: 42.5 sccm), $P_{\text{C}_2\text{H}_4} = 0.027$ kPa (gas flow: 5 sccm), 900 watts RF power at 2.45 GHz. The chip detectors were not subjected to O2 or CF4 plasma etching.

2.4. Optical system

A temperature stabilised Fabry–Pérot laser diode is coupled to an enclosed three-way fibre beamsplitter via a variable optical attenuator, either an HP 8157A or JDS Uniphase HA9, which incorporates an optical switch (figure 6). The three arms of the beamsplitter are in turn connected to the device under test (DUT at 25% of total optical power), monitor (25%) and the primary standard (50%, 200 µW). The lasers were measured to have a linewidth $\Delta \lambda$ of approximately 1.5 nm. Single-mode fibre (SM) is used throughout the system with the low temperature end of the fibres terminated with an FC/PC zirconia ferrule with stainless-steel stem. The cryogenic system includes two fibres, each irradiating nearly identical chip detectors, (figure 3(a)). The monitor channel was used to track small beamsplitter ratio changes during the course of a measurement. Note that one beamsplitter is used for both 1310 nm and 1550 nm wavelengths.

The three lasers were characterised using an optical spectrum analyser (OSA) with 0.02 nm resolution. Mode-hopping was observed in the 850 nm laser along with wavelength variations of ±0.25 nm. Care is taken to minimise mode-hopping regions during operation by selecting the most appropriate operating temperature of the diode laser. The 1310 nm and 1550 nm lasers were stable in both intensity (<±0.02%) and wavelength (<±0.02 nm). The OSA was calibrated using a hybrid wavelength reference as described in [24].

2.4.1. Beam splitter ratio measurement. The beamsplitter ratio is required to relate the power measured by the cryogenic chip detector to that measured by the DUT. The ratio between all pairs of the three arms of the beamsplitter was measured using fibre-coupled InGaAs and silicon photodiodes. The short-term ratio is stable and precise ±0.03%; however, temperature dependent polarisation effects manifest as a rate of change in the beamsplitter ratio of 0.1% °C$^{-1}$. During the course of our measurement campaign ambient room temperature varied as 24 °C ± 2 °C.

In an ideal single-mode fibre two degenerate orthogonal polarisation modes propagate along the fibre, maintaining the initial state of polarisation. However, core asymmetry and stress induced birefringence, for example from bending, leads to a phase difference between the two orthogonal propagation states due to a change in the refractive indices of each state, resulting in a change in polarisation at the output of the fibre. The uncertainty in the beamsplitter ratio determination is the largest contributor to the DUT responsivity measurement uncertainty as shown in section 3.

We used a simple automated Mueller–Stokes method with a polarization controller to investigate polarization dependent
losses (PDL) of the beamsplitters. Four well defined polarization states were applied in sequence to the beamsplitters, whilst simultaneously measuring the output power, from which the PDL was ascertained.

### 2.4.2. Optical return loss measurement

The power output from the fibre was indirectly observed to increase as the system was cooled and thus a correction to the DUT responsibility was required. The reflection at the fibre/vacuum interface changes because the index of refraction of the fibre changes with temperature. The ORL correction is of the order 0.08% changes because the index of refraction of the fibre changes from room temperature to 5 K was measured at each of the wavelengths reported and a correction applied to the measurement states were applied in sequence to the beamsplitters.

Where:

\[ \text{ORL (dB)} = 10 \log_{10} \left( \frac{P_r}{P_i} \right) \]  

where:

- **ORL (dB)**: is the value of the optical return loss in dB
- **P<sub>i</sub>**: is the incident power
- **P<sub>r</sub>**: is the reflected power

### 3. Uncertainty assessment and evaluation

#### 3.1. Introduction

The performance of the tungsten electrical substitution heater of the chip detector was extensively assessed across many detectors, to determine potential electrical-optical heating inaccuracy. The reflectance of the VACNT planar absorbers has also been extensively measured across a range of growth conditions, tube heights and temporal conditions. The change in optical fibre return loss in cooling the fibre from room temperature to 5 K was measured at each of the wavelengths reported and a correction applied to the measured power. The beamsplitter ratio was measured at each wavelength and monitored as the room temperature changed, in order to apply a correction factor. An estimate of polarisation dependent losses, within the optical fibre delivery system, was determined from polarisation synthesis measurements. Further, each diode laser was evaluated with an OSA to determine mode-hopping and wavelength drift characteristics.

### 3.2. Chip detector reflectance measurement

The reflectance of each chip detector was measured at 300 K to 4 K. A commercial ORL meter was used for this purpose (figure 6). We assumed the FC/APC connectors of the DUT and monitor channel did not contribute to the ORL measurement.

#### 3.2.1. ORL measurement

The performance of the tungsten electrical substitution heater of the chip detector was extensively assessed across many detectors, to determine potential electrical-optical heating inaccuracy. The reflectance of the VACNT planar absorbers has also been extensively measured across a range of growth conditions, tube heights and temporal conditions. The change in optical fibre return loss in cooling the fibre from room temperature to 5 K was measured at each of the wavelengths reported and a correction applied to the measured power. The beamsplitter ratio was measured at each wavelength and monitored as the room temperature changed, in order to apply a correction factor. An estimate of polarisation dependent losses, within the optical fibre delivery system, was determined from polarisation synthesis measurements. Further, each diode laser was evaluated with an OSA to determine mode-hopping and wavelength drift characteristics.

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### Table 1. Uncertainty components for radiant power absorptance correction factor.

| Component of uncertainty | \( \sigma_i \) (%) | Distribution | Type | Std unc. (%) |
|--------------------------|---------------------|--------------|------|-------------|
| Total VACNT absorber reflectance spread | 0.0110 | rectangular | B | 0.0064 |
| Small sample mask displacement | 0.0005 | rectangular | B | 0.0003 |
| Two beam intensity difference | 0.0009 | rectangular | B | 0.0005 |
| Reproducibility, 9 month period, 1310 nm | 0.0004 | rectangular | B | 0.0002 |
| Measurement repeatability (\( N = 2 \)) | 0.0003 | normal | A | 0.0064 |
| Combined standard uncertainty: | | | | 0.013 |

### Table 2. Measured directional-hemispherical (0°/h) reflectance of chip detectors PBR8.4V-17 and PBR8.4V-20 as a function of wavelength.

| Det. designation | 660 nm/ ppm | 830 nm/ ppm | 1310 nm/ ppm | 1625 nm/ ppm |
|------------------|-------------|-------------|--------------|--------------|
| PBR8.4V-17       | 386         | 393         | 287          | 274          |
| PBR8.4V-20       | 597         | 605\*       | 440\*        | 425\*        |

\* Extrapolated.

\[ R_{DUT} = \frac{I_{mA}}{[P_{meas}/A_{corr}] \cdot BS_{ratio} \cdot ORL_{corr}} \cdot AW^{-1} \] (2)

where:

- **R<sub>DUT</sub>**: is the responsivity of the device under test
- **I<sub>mA</sub>**: is the measured output current of the DUT
- **P<sub>meas</sub>**: is the measured electrical power dissipated in the primary standard chip detector
- **A<sub>corr</sub>**: is the VACNT absorptance correction factor
- **[P<sub>meas</sub>/A<sub>corr</sub>]**: is the measure of radiant power output from the fibre
- **BS<sub>ratio</sub>**: is the beamsplitter ratio which includes the beamsplitter temporal drift correction
- **ORL<sub>corr</sub>**: is the optical return loss correction (0.9992)

In the sections described below, tables 1, 2 and 4 record the uncertainty components associated with the above evaluations, which are then included in table 5 which lists the uncertainties of a DUT responsivity measurement.
reflectance of our chip detectors. This uncertainty component dominates the radiant power absorptance correction factor uncertainty of 0.013%.

A small black 25 mm square, 1 mm thick aluminium reducing mask was placed between the sample and the sphere port to facilitate measurement. This displacement of the VACNTs effectively reduces the reflectance by 1%, which is corrected for. Further, there remains a small displacement between the sample and the sphere mask for which we estimate a further uncertainty of 1% (of 0.045%). The difference in laser beam intensity between the sample and reference paths contributes an estimated uncertainty of 2% (of 0.045%).

A sphere calibration procedure is used to monitor drifts within the system and over a nine-month period, this was observed to maximally change the reflectance by 0.8% at 1310 nm, and is included in the uncertainty budget as a reproducibility term.

Table 1 records the radiant power absorptance correction factor uncertainty due to the measured reflectance of the VACNT absorber.

Table 2 lists the measured reflectance as a function of wavelength. Chip detector PBR8.4V-20 was only measured at one wavelength to ensure functionality. A correction factor \( A_{\text{corr}} \) for the chip detector reflectance at each wavelength, 850 nm, 1295 nm and 1550 nm was applied to the measured electrical power (equation (2)). The reflectance measurements of PBR8.4V-17 were interpolated, whilst the required reflectance’s for PBR8.4V-20 were extrapolated.

### 3.3. Chip detector radiometric performance assessment

The chip detectors are firstly compared with LOCR, our laser optimised cryogenic radiometer primary standard, to ensure functionality. In order to assess the radiometric performance of the two chip detectors, PBR8.4V-17 and PBR8.4V-20, they were sequentially mounted in a cryostat fitted with a Brewster window and configured to operate as an open-beam cryogenic radiometer. The responsivity of NIST 6, a calibrated transfer standard silicon trap detector, was determined at 632.8 nm and compared with the established calibration by LOCR [25]. In essence we are comparing primary standards via the transfer standard, with a comparative expanded uncertainty of 0.04%. This measurement was repeated at regular intervals over a three-week period to investigate and confirm short term performance. No radiometric drift was detected in the performance of the two chip detectors over this period of time.

Occasionally a chip detector picked at random from a production run of twenty would display anomalous behavior, which we attribute to a combination of joule heating in the vanadium superconducting leads on the heatlink and amorphous carbon buildup during nanotube growth manifesting as a high impedance short (>1 M\( \Omega \)) between the heater and temperature transducer. On these chip detectors it was observed that the vanadium leads did not fully transition to zero ohms. As a consequence, we screen all chips using a physical properties measurement system.

Table 3 records the uncertainty components of a radiometric comparison measurement. The beam scatter loss term accounts for the uncertainty in the correction for the difference in scatter between the focal plane of the transfer standard and the cryogenic detector, which are 70 cm apart. The correction was 0.010% ± 0.005%.

The uncertainties listed in table 3 are typical for this type of measurement and align with those reported previously in the literature [26–28].

#### 3.4. Beamsplitter ratio measurement

The beamsplitter ratio was determined at room temperature. The uncertainty in the measurement dominates the DUT responsivity measurement uncertainty at 0.32%. Fibre-coupled single element silicon and InGaAs detectors were used for this purpose. Table 4 lists the uncertainty components in the measurement of the beamsplitter ratio. For reference, the corrected ratio between the DUT and radiometer fibres was 0.459(2), 0.550(2) and 0.672(2); at 850 nm, 1295 nm, 1550 nm respectively. The ratio has been corrected for temporal drift and optical return loss.

The short-term noise observed in a 5 min interval, in the splitter ratio, was 0.03%. A slow but perceptible temporal drift was observed in the beamsplitter ratio throughout the day of 0.1% °C\(^{-1}\). The room temperature was noted and a correction applied to the ratio, with an estimated uncertainty of 0.1%. This is attributed to polarisation dependent loss (PDL). We chose to use single mode (SM) fibre aware that PDL could be troublesome. In particular, changing from purely vertical linear polarisation to horizontal using a General Photonics PSY 101 polarisation synthesizer, produced upwards of 5% change in the splitter ratio. For this reason, the SM fibre was wrapped and anchored around 50 mm diameter spools. We estimate the uncertainty associated with PDL as 0.2%.
The 5 K fibre ferrule is not keyed into the chip detector receptacle used for the measurements and thus an uncertainty arises due to the positioning of the ferrule within the receptacle. As the VACNTs are spatially uniform in reflectance and insensitive to polarised light, they maximally respond to the incident radiation. Therefore, during alignment the fibre-coupled photodiode was rotated about the ferrule to maximise the signal from the photodiode, and marked. It was rotated approximately ±5° in order to ascertain a bounded uncertainty attributed to the ferrule location. This was estimated as 0.1%.

3.5. Optical fibre return loss measurement

The refractive index of a single mode fibre decreases as it cools from room temperature to 5 K leading to an increase in output power. As the beamsplitter ratio is determined at room temperature this change is accounted for and a correction of 0.9992 ± 0.0005 applied at all wavelengths to the measured radiometric power. A commercial optical fibre return loss meter was used to measure the change in reflected laser intensity from the plane-cut fibre tip. Measurements were recorded at all wavelengths as the fibres cooled, and on average showed a change from 14.5 dB return loss to 14.6 dB, with an uncertainty of 0.05 dB.

3.6. DUT calibration measurement

The uncertainties in the DUT calibration measurement are propagated in accordance with equation (2) and follow the guidelines outlined in NIST technical note 1297 [29]. No two variables appear more than once in the measurement equation and thus we assume no correlation exists in the determination of the final measurement uncertainty of 0.4%. The relative (fractional) measurement uncertainties are summed in quadrature as the responsibility of the DUT (R_{DUT}) is represented by a simple ratio expression.

Two calibrated 6-digit voltmeters were used to measure the electrical substitution chip heater voltage and the voltage across the 1 kΩ Vishay calibrated resistor.

We calibrated the DUTs at 850 nm, 1295 nm and 1550 nm. At 1550 nm we applied a small correction factor to account for the InGaAs temperature dependence, as these detectors were not temperature stabilised. The estimated uncertainty in this correction was 0.05%.

The Fabry–Perot laser diode sources were characterised with an OSA. A FWHM bandwidth of 1.2 nm to 1.8 nm was recorded using the rms method. The shape of the 850 nm laser diode spectrum was observed to change from day to day, due to mode-hopping and temperature effects, although the output power remained relatively constant within 0.02% of nominal during the course of a 30 min measurement run. This directly impacts the responsivity of the DUT, and thus the uncertainty associated with the diode laser output power spectrum is folded into the responsivity uncertainty, rather than being reported separately. The wavelength is recorded as the weighted mean of the source. An analysis of source spectra convoluted with the DUT wavelength responsivity yields an estimated spectral dependence uncertainty of 0.15%, which we apply across the three wavelengths. The response of the pico-ammeter was verified by the manufacturer to lie within its’ bounded specification of 0.1%, and thus we use a rectangular distribution, type B in the uncertainty budget.

4. Discussion

The expanded measurement uncertainty of the responsivity of the DUT is determined to be 0.4%, and is dominated by two components; the beamsplitter ratio uncertainty and the spectral dependence of the source. The standard uncertainty of these two components is respectively 0.16% and 0.1%.

An important aspect in going forward is consideration of the polarisation dependent losses of the optical components,
especially the beamsplitter. To minimise this problem we are developing a polarisation maintaining (PM) fibre system, which will use planar lightwave couplers and PM coupled diode lasers. To this end we are embarking on a measurement program to study temperature effects on the polarisation dependent loss of the new optical components.

The current uncertainty is limited by the optical components and not the cryogenic primary standard detector. This work illustrates a path forward to achieving our realistic goal of disseminating the fibre power scale at better than 0.1% expanded uncertainty, by replacing the lasers and beamsplitters, an improved ORL measurement, and the use of a trans-impedance amplifier in lieu of the pico-ammeter. This would represent a five times improvement on our current optical fibre power calibration and measurement capability (CMC) as recorded by the bureau international des poids et mesures (BIPM). This work will also benefit an upcoming pilot comparison, concerning optical fibre power meter calibration between National Metrology Institutes, run under the auspices of the BIPM.

5. Conclusion

A new cryogenic primary standard, for the calibration of optical fibre power meters, is operating at NIST. The instrument uses thermal filtering for unprecedented stability and noise, and planar micro-machined detectors, with carbon nanotube arrays and superconducting sensors, for optical fibre power measurement. The detectors are vacuum coupled to laser diode sources using single mode fibre anchored at 7.5 K. The system operates at a nominal radiant power level of 200 µW (−7 dBm), with an expanded uncertainty (k = 2) of 0.4%. Our measurement uncertainty is dominated by the beamsplitter ratio, its’ temporal and polarisation dependence and the characteristics of the laser sources. The detectors themselves are fast for a thermal device, efficient and cheap to produce. Commissioning of this new standard was completed in December 2017. It has replaced the laser optimised cryogenic radiometer as the new primary standard for optical fibre power measurement at NIST.

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Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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