Cryogenic Primary Standard for Optical Fibre Power Measurement

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Introduction

Experimental Setup

Results

Introduction – Why?

- *to establish traceability for optical fibre power directly to a purely fibre coupled primary standard;*
- *we validate this approach by comparing the new standard to our existing standard (LOCR) using four transfer detectors calibrated at 850 nm, 1295 nm and 1550 nm.*

M.G.White, Z.E.Ruiz, C.S.Yung, I.Vayshenker, N.A.Tomlin, M.S.Stephens, J.H.Lehman, submitted Metrologia June 2018

Introduction – How?

Introduction – Measurement Equation

$$R_{DUT} = \frac{I_{mA}}{[P_{meas}/A_{corr}] \cdot BS_{ratio} \cdot ORL_{corr}} A/W$$

R_{DUT} : is the responsivity of the device under test

I_{mA} : is the measured output current of the DUT

P_{meas} : the measured electrical power dissipated in the chip detector

A_{corr} : is the nanotube absorptance correction factor (0.99955)

$[P_{meas}/A_{corr}]$: is the measure of radiant power output from the fibre (7 K)

BS_{ratio} : Beam splitter ratio between DUT and primary standard fibres

ORL_{corr} : is the optical return loss correction (0.9992)

Setup – Complete System

- Optical System

- Cryogenic System

Setup – Optical System

Setup – Cryogenic Detection System

Setup – Cryogenic Detection System

- 850 nm
- 1295 nm, 1550 nm

Setup – Patterning of Chip Detector

Position of Nb TESs and Vanadium superconducting leads

2.0 mm long x 0.4 mm wide

Setup – Sensor & Superconducting Wiring

Setup – Supplementary Measurements

Reflectance

Radiometric Assessment

Beam Splitter Ratio

Optical Return Loss

Source Spectral Dependence

DUT Measurement

Setup – Absolute Reflectance Measurement

Photo courtesy Karl Hueurman, LASP

Laser based reflectometer - measure absolute total hemispherical reflectance from 406 nm to 1625 nm and 10.6 μm

Can raster scan the sample

Results – Absolute Reflectance Scan @ 1310 nm

830 nm 393 ppm
1310 nm 302 ppm
1625 nm 274 ppm

No post growth treatment

Results – Nanotube Absorptance Uncertainties

Uncertainty components for radiant power absorptance correction factor

Component of Uncertainty	¹ δ_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 ($N = 2$) ²	0.0003	normal	A	0.0002
Combined Standard Uncertainty:				0.007
Expanded Uncertainty ($k = 2$):				0.013

¹ $\pm\delta_i$ represents the limits of the estimated uncertainty of the measurand

²Standard uncertainty expressed as $\delta_i/\sqrt{N}$ = standard error of the mean (SEOM)

Setup – Radiometric Assessment of Chip Detector

Photo courtesy Montana Instruments

Trap Detector

Photo courtesy L-1 Standards & Technology

Chip Detector

Radiometrically compare to primary standard via trap detector

Setup – Radiometric Assessment @ 200 μW Radiant Power

Results – Chip Detector Radiometric Assessment Uncertainties

Uncertainty components for chip detector radiometric comparison measurement @ 633 nm

Component of Uncertainty	$^1\delta_i$ (%)	Distribution	Type	Std Unc (%)
Electrical heating inequivalence	0.005	rectangular	B	0.003
✓ Detector absorptance correction factor	0.013	normal	B	0.007
Brewster window transmittance correction	0.005	normal	A	0.003
Beam scatter loss correction	0.005	rectangular	B	0.003
Electrical power measurement	0.005	rectangular	B	0.003
NIST 6 traceability to primary standard	0.030	rectangular	B	0.017
Changes in background radiation	0.005	rectangular	B	0.003
Measurement repeatability ($N = 9$) ²	0.003	normal	A	0.001
Combined Standard Uncertainty:				0.02
Expanded Uncertainty ($k = 2$):				0.04

¹ $\pm\delta_i$ represents the limits of the estimated uncertainty of the measurand

²Standard uncertainty expressed as $\delta_i / \sqrt{N}$ = standard error of the mean (SEOM)

Setup – Beam Splitter Ratio Measurement

$$BSR = \sqrt{\frac{M_1 O_1}{M_2 O_2}} \times \frac{M_2 O_1}{M_1 O_2}$$

Results – Beamsplitter Ratio Uncertainties

Uncertainty components in determining the beamsplitter ratio				
Component of Uncertainty	¹ δ_i (%)	Distribution	Type	Std Unc (%)
Beamsplitter ratio (short term noise)	0.03	rectangular	B	0.02
Beamsplitter temporal drift correction	0.10	rectangular	B	0.06
Polarisation dependent losses	0.20	rectangular	B	0.12
✓ 7 K fibre ferrule dependence	0.10	rectangular	B	0.06
Repeatability ($N = 4$) ²	0.10	normal	A	0.05
Combined Standard Uncertainty:				0.16
Expanded Uncertainty ($k = 2$):				0.32

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Setup – Optical Return Loss Measurement

$$ORL (dB) = 10 \log_{10} \frac{P_i}{P_r}$$

P_i : is the incident power
 P_r : is the reflected power

Results – Optical Return Loss Correction Uncertainty

- Output power from fibre at 4 K increases due to decrease in refractive index of fibre - correction
- SMF 28 Ultra N_{eff} 1.4682 @ 1550 nm

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

$$\text{Correction} = 0.9992 \pm 0.0005$$

Results – Source Spectral Dependence

- Use optical spectrum analyser to characterise source

Uncertainty = 0.15 %

Setup – DUT Measurement

Results – DUT Measurement Uncertainties

DUT responsivity measurement uncertainty components using optical fibre radiometer

Component of Uncertainty	¹ δ_i (%)	Distribution	Type	Std Unc (%)
✓ Chip detector radiometric assessment	0.040	normal	B	0.020
Electrical power measurement	0.005	rectangular	B	0.003
✓ Beam splitter ratio	0.320	normal	B	0.160
✓ Optical return loss correction at 7 K	0.050	rectangular	B	0.030
InGaAs temp correction at 1550 nm	0.050	rectangular	B	0.030
✓ Spectral dependence of source	0.150	rectangular	B	0.100
Pico-ammeter calibration	0.100	rectangular	B	0.060
Measurement repeatability($N=32$) ²	0.030	normal	A	0.005

Combined Standard Uncertainty:

0.20

Expanded Uncertainty ($k = 2$):

0.40

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²Standard uncertainty expressed as $\delta_i/\sqrt{N}$ = standard error of the mean (SEOM)

Highlights & the Future

- ❖ Demonstration of a planar detector that is efficient, fast, and versatile with specs at least equal to that of cavity detectors
- ❖ Establishment of a new facility for Optical Fibre Power Measurement at 0.4 % ($k = 2$)
 - CMC at 0.5 %
- ❖ Capability to be further developed using polarisation maintaining fibre → 0.1 %

Photo courtesy Nathan Tomlin, NIST

THANK YOU

M.G.White, Z.E.Ruiz, C.S.Yung, I.Vayshenker, N.A.Tomlin, M.S.Stephens, J.H.Lehman, submitted Metrologia June 2018

Chip Design – side view

Side view of lithographic pattern

CNT catalyst: 10 nm Al₂O₃ + 1 nm Fe

Chip Design – side view of lithographic pattern

Layers:

- Silicon substrate: 375 μm
- SiO_2 insulator: 150 nm
- W heater: 44 nm
- Nb TES sensor: 93 nm
- V wiring: 146 nm
- SiN_x passivation layer: 170 nm
- Catalyst: 10 nm Al_2O_3 + 1 nm Fe
- Si deep etch
- VACNT growth: 400 μm

Results – beamsplitter ratio @ 1310 nm

Std dev < 0.01 % over 12 hours, monitoring output with InGaAs detectors, airside