Detector Responsivity by Fibre Coupled Cryogenic Primary Standard at 0.1 %

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**Introduction – Outline**

**Optical Return Loss (ORL)**
- Fresnel reflection
- Rayleigh backscatter

**Beam-Splitter**
- Ratio measurement

**Environmental Chamber**
- PDL measurements

**OSA Measurements**
- Spectral power distribution
Introduction – Calibration Assurance

Environment Chamber
- PDL measurements

OSA Measurements
- Spectral power

Beam-Splitter
- Ratio measurements

Laser source (A) → Variable optical attenuator (B) → Beam splitter (C) → Cryogenic detector (E)

Primary Standard

Environmental Chamber

Optical Return Loss (ORL)
- Fresnel reflection
- Rayleigh backscatter
**Introduction – Cryogenic System; Reality Check**

Carbon nanotubes absorb 99.95% of incident radiation

- 850 nm
- 1310 nm, 1550 nm

Photo courtesy Nathan Tomlin, NIST
Introduction – Measurement Facility Operation

Primary Standard

Laser source (A) → Variable optical attenuator (B) → Beam splitter (C) → Cryogenic detector (D) → 1 kΩ heater – electrical SI traceability → fibre coupled cryogenic detector

- 850 nm
- 1310 nm
- 1550 nm

1 kΩ heater – electrical SI traceability

ferrule FC / PC Cryostat

1 x 3

25 % DUT

50 % RAD

25 % MON
### Component of Uncertainty

<table>
<thead>
<tr>
<th>Component of Uncertainty</th>
<th>$\delta_i$ (%)</th>
<th>Type</th>
<th>Std Unc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant power measurement</td>
<td>0.013</td>
<td>B</td>
<td>0.006</td>
</tr>
<tr>
<td>Beam splitter ratio at room temp</td>
<td>0.060</td>
<td>B</td>
<td>0.035</td>
</tr>
<tr>
<td>PDL of beam splitters &amp; fibre connector</td>
<td>0.050</td>
<td>B</td>
<td>0.030</td>
</tr>
<tr>
<td>Fresnel reflection correction at 5 K</td>
<td>0.010</td>
<td>B</td>
<td>0.006</td>
</tr>
<tr>
<td>Rayleigh scatter losses in fibre on cooling</td>
<td>0.005</td>
<td>B</td>
<td>0.003</td>
</tr>
<tr>
<td>Laser spectral power density, ± 0.02 nm @ 1549 nm</td>
<td>0.002</td>
<td>B</td>
<td>0.001</td>
</tr>
<tr>
<td>Trans-impedance amplifier calibration</td>
<td>0.010</td>
<td>B</td>
<td>0.006</td>
</tr>
<tr>
<td>DVM calibration</td>
<td>0.004</td>
<td>B</td>
<td>0.003</td>
</tr>
<tr>
<td>Measurement repeatability($N=3$)</td>
<td>0.015</td>
<td>A</td>
<td>0.009</td>
</tr>
</tbody>
</table>

**Combined Standard Uncertainty:**

**Expanded Uncertainty ($k = 2$):**

\[ 0.05\% \quad 0.10\% \]

$^{1}\pm\delta_i$ represents the limits of the estimated uncertainty of the measurand.
**ORL – Fresnel Reflection & Rayleigh Backscatter**

**Fresnel Reflection**

- Transmitted Light: $P_1$
- Reflected Light: $P_r$
- $n_1$ and $n_2$

**Rayleigh Backscatter**

- Transmitted Light
- Rayleigh scattering due to minute fluctuations in refractive index
- Reflected Rayleigh backscatter

**Optical Return Loss (ORL)**

- Fresnel reflection
- Rayleigh backscatter

Swept-wavelength (OFDR) reflectometer can measure both
ORL – Fresnel Reflection & Rayleigh Backscatter; Investigated 3 Fibre Types

SMF-28

PM single mode PANDA

PM15/13-U25D

PM-1550-01

Courtesy NKT Photonics
ORL – Fresnel Reflection & Rayleigh Backscatter at 1310 nm & 1550 nm; Technique

8 deg. angle initially
ORL – Fresnel Reflection & Rayleigh Backscatter at 1310 nm & 1550 nm; Setup

- Fibre attached to cold plate;
- Increase in backscatter of 0.06 ± 0.02 %
- Fresnel reflection calculated from change in reflected signal level, backscatter change
We want to use the OFDR at 1550 nm to confirm beam-splitter measurement of Fresnel reflection and backscatter.
ORL – Refractive Index Change of Fibres at 1550 nm; Room Temp. & 6K

**Graph:**
- **SMF-28**
  - $0.11 \pm 0.01 \%$
- **PM Fibre**
  - $0.15 \pm 0.01 \%$
- **PM PCF Fibre**
  - $0.30 \pm 0.02 \%$
Result – OFDR & Beam-Splitter Techniques Equivalent at 1550 nm

✓ • Confidence in beam-splitter measurements of Fresnel reflection at other wavelengths
Result – Correction to Beam-Splitter Ratio as Measured at Room Temperature

- PM 13-U25A $\Delta N_{\text{eff}}$ reduces 0.13 % @ 1310 nm;
- PM 15-U25D $\Delta N_{\text{eff}}$ reduces 0.15 % @ 1550 nm;

Rayleigh backscatter increases at 5 K; reduces output power

- 0.01 %
- 0.005 %
Beam-Splitter Ratio Between DUT & RAD at Room Temperature; Setup

**Laser source 1310 nm**

**Variable optical attenuator**

**Beam splitter 1 x 3**

InGaAs Photodiodes

- M₁ DUT
- M₂ RAD
- MON

**BSR**

\[
BSR = \sqrt{\frac{M_1 \text{DUT}}{M_2 \text{RAD}}} \times \frac{M_2 \text{DUT}}{M_1 \text{RAD}}
\]

0.06 %

**Primary Standard**

Cannot measure ratio at low temperatures – no access!!
PDL – Testing Temperature Effects on Output Power of Beam-Splitter

Mueller matrix analysis method
PDL – 1310 nm, 1550 nm PM PANDA Style; Results

PDL results show a temperature dependence, but operate at 20 °C, 1 % PDL
Spectral Power Distribution – 1550 nm Fabry-Pérot laser diode source (OSA)

- $\lambda_c = \frac{\sum P_i \lambda_i}{\sum P_i} = 1549.43 \pm 0.02$ nm,
- output power 210 µW (max pk height 28 µW)

$$\Delta \lambda = 2.82 \text{ nm}$$

$$\Delta \lambda = K \left( \frac{\sum P_i (\lambda_i - \lambda_c)^2}{\sum P_i} \right)^{1/2}$$
Calibration Assured at

0.1 %
THANK YOU

Thanks to Esther Baumann for lots of help with these measurements


Fresnel Reflection of PM PCF Fibres at 1550 nm

- Plane cut end face - each fibre connectorised (FC / APC) at one end only with modal adaptation of 10 mm fused SMF-28 fibre.
- Inset: time of flight (ns) for approx. 4 m of PM-1550-01 PM, high index, solid core, photonic crystal fibre at room temp., 77 K and 5 K showing reflection nodes of slow and fast axes as the fibre is cooled.