Planar Detectors as Radiometric Standards using Carbon Nanotube Absorbers

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Calcon 2017
Logan, Utah
Motivation – new radiant power standards

- open beam
- 850 nm
- 1310, 1550 nm
Chip Design – close up of patterning

Position of Nb TESs and Vanadium superconducting leads

- CNT Absorber
- W Heater
- Nb TES
- V Leads

5.5 mm

2.0 x 0.375 x 0.4 mm wide
Layers:
- Silicon substrate: 375 µm
- SiO₂ insulator: 150 nm
- W heater: 44 nm
- Nb TES sensor: 93 nm
- V wiring: 146 nm
- SiNₓ passivation layer: 170 nm
- Catalyst: 10 nm Al₂O₃ + 1 nm Fe
- Si deep etch
- VACNT growth: 400 µm
Chip Design – nanotube growth
Chip Design – post growth processes

As grown

THR / ppm

Wavelength / nm

300 600 900 1200 1500 1800

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Chip Design – post growth processes

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**As grown**

**200 W @ 60 s**

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**Graph:**

- **As grown**
- **O₂ plasma**

**Plot:**

- **X-axis:** Wavelength / nm
- **Y-axis:** THR / ppm

**Legend:**

- Blue line: As grown
- Orange line: O₂ plasma
Chip Design – post growth processes

- As grown
- 200 W @ 60 s
- 30 W @ 40 s

![Graph showing THR/ppm vs. Wavelength/nm for different treatments: As grown, O₂ plasma, and O₂ + CF₄ plasma.](image)

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

Can raster scan the sample
Chip design – absolute reflectance scan @ 1310 nm

$O_2$, 200 W, 60 s, don’t break vacuum $CF_4$, 30 W, 40 s

830 nm 102 ppm
1310 nm 197 ppm
1625 nm 304 ppm
Chip design – sensor & superconducting wiring

Integration – fibre radiometer (ESR)

- Operation at 300 µW
- 850 nm
- 1310, 1550 nm
Integration – open beam radiometer (ESR)

- Operation at 200 µW
Integration – RC filters & thermal stability

Example: the 3 dB cutoff frequency $f_c$ for a filter with an RC of 180s is 0.88 mHz. This attenuates the 1.4 Hz temp. fluctuation of the cryocooler by 1000 x or 30 dB.

$$f_c = \frac{1}{2\pi RC} = 0.884 \text{ mHz} \Rightarrow 10 \times \log \left( \frac{1.4 \text{ Hz}}{8.84 \times 10^{-4}} \right) = 32 \text{ dB}$$
For a periodic time dependent thermal fluctuation $\Delta T(x) = \Delta T(0) \exp(-x/\delta_{th})$, where $x =$ distance, $\delta_{th}$ the thermal penetration depth; that depth at which the amplitude has dropped to $1/e$ of its initial value, defined as:

$$\delta_{th} = \sqrt{\frac{\alpha}{\pi f}}$$

$\alpha =$ thermal diffusivity of the material and $f$ the frequency of the driven temp. oscillation.
Thermal stability achieved with 2 pole Butterworth filter, 20 dB / decade - optimised design

\[ f_c = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}} \]
Integration – effectiveness of filtering

- Temperature and Resistance noise spectrum of thermal system
- Commercial AC resistance bridge, sampled at 5Hz, 10 mV excitation, constant current

Effectively 50 dB of attenuation of the 1.4 Hz signal; from 200 mK pk-pk to 2 uK (5 µK)
Integration – thermal profile @ 1 mW

1 mW input power: 0.55 K temp rise across 1st stage RC filter, 0.2 K across 2nd stage
Results – uncertainties
Results – offset

- 0.1 % offset in power

• Reflectance measured at room temp but used at 4 K. Morphological change? Have seen R increase by 10 %
• FC / APC fibre – tip heating up at 4 K and being absorbed by chip detector
• Refractive index of fibre changes at 4 K - typically 0.2 % increase

+ 0.4 % offset in power
Results – actual setup

- Chip detectors’ reflectance measured at LASP
- Offset measured in cryogenic radiometer, detector mounted in fibre system
- Beam-splitter ratio determined
Results – actual setup

beamsplitter
Results – beamsplitter ratio @ 1310 nm

Std dev < 0.01 % over 12 hours, monitoring output with InGaAs detectors, airside
### Results – CNT detector offset uncertainty

Uncertainty components of CNT chip detector offset compared to a trap detector @ 633 nm

<table>
<thead>
<tr>
<th>Component of Uncertainty</th>
<th>$\delta_i$ (%)</th>
<th>Distribution</th>
<th>Type</th>
<th>Std Unc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNT detector absorptance</td>
<td>0.0100</td>
<td>rectangular</td>
<td>B</td>
<td>0.0060</td>
</tr>
<tr>
<td>Brewster window transmittance</td>
<td>0.0012</td>
<td>rectangular</td>
<td>B</td>
<td>0.0007</td>
</tr>
<tr>
<td>Alignment</td>
<td>0.0017</td>
<td>rectangular</td>
<td>B</td>
<td>0.0010</td>
</tr>
<tr>
<td>Heating inequivalence</td>
<td>0.0050</td>
<td>rectangular</td>
<td>B</td>
<td>0.0030</td>
</tr>
<tr>
<td>Trap traceability to primary standard</td>
<td>0.0200</td>
<td>normal</td>
<td>B</td>
<td>0.0100</td>
</tr>
<tr>
<td>Beam scatter losses</td>
<td>0.0040</td>
<td>rectangular</td>
<td>B</td>
<td>0.0025</td>
</tr>
<tr>
<td>NIST electrical power measurement</td>
<td>0.0005</td>
<td>rectangular</td>
<td>B</td>
<td>0.0003</td>
</tr>
<tr>
<td>Repeatability of measurement (N = 9)$^2$</td>
<td>0.0100</td>
<td>normal</td>
<td>A</td>
<td>0.0033</td>
</tr>
</tbody>
</table>

**Combined Standard Uncertainty:** 0.012 %

**Expanded Uncertainty ($k = 2$):** 0.025 %

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

$^{2}$Standard uncertainty expressed as $\bar{\delta}/\sqrt{N} = \text{standard error of the mean (SEOM)}$
Results – beamsplitter uncertainty

Measurement uncertainties in determining the absolute beam-splitter ratio

<table>
<thead>
<tr>
<th>Component of Uncertainty</th>
<th>$^{1}\delta_i$ (%)</th>
<th>Distribution</th>
<th>Type</th>
<th>Std Unc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip detector offset</td>
<td>0.025</td>
<td>normal</td>
<td>B</td>
<td>0.012</td>
</tr>
<tr>
<td>NIST electrical power measurement</td>
<td>0.0005</td>
<td>rectangular</td>
<td>B</td>
<td>0.0003</td>
</tr>
<tr>
<td>Beamsplitter polarisation dependence</td>
<td>0.100</td>
<td>rectangular</td>
<td>B</td>
<td>0.058</td>
</tr>
<tr>
<td>Beamsplitter ratio stability</td>
<td>0.015</td>
<td>rectangular</td>
<td>B</td>
<td>0.010</td>
</tr>
<tr>
<td>Lab std spectral resp. 1310 &amp; 1550 nm</td>
<td>0.020</td>
<td>rectangular</td>
<td>B</td>
<td>0.012</td>
</tr>
<tr>
<td>Laser spectral bandwidth</td>
<td>0.020</td>
<td>rectangular</td>
<td>B</td>
<td>0.012</td>
</tr>
<tr>
<td>Detector calibration$^2$</td>
<td>0.380</td>
<td>rectangular</td>
<td>B</td>
<td>0.220</td>
</tr>
<tr>
<td>Repeatability (N = 9)$^3$</td>
<td>0.050</td>
<td>normal</td>
<td>A</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Combined Standard Uncertainty: 0.23 %
Expanded Uncertainty ($k = 2$): 0.46 %

$^{1}\pm\delta_i$ represents the limits of the estimated uncertainty of the measurand
$^2$Detector calibration could be improved to 0.05 % by direct cal. against cryogenic radiometer
$^3$Standard uncertainty expressed as $\delta_i/\sqrt{N}$ = standard error of the mean (SEOM)
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 family of laser power standards at NIST using planar detectors

Capability to be further developed into linear and two dimensional arrays for spectral and imaging applications

Photo courtesy Blue Canyon Technologies, Boulder

Photo courtesy Nathan Tomlin, NIST