Carbon Nanotube Radiometer for Cryogenic Calibrations

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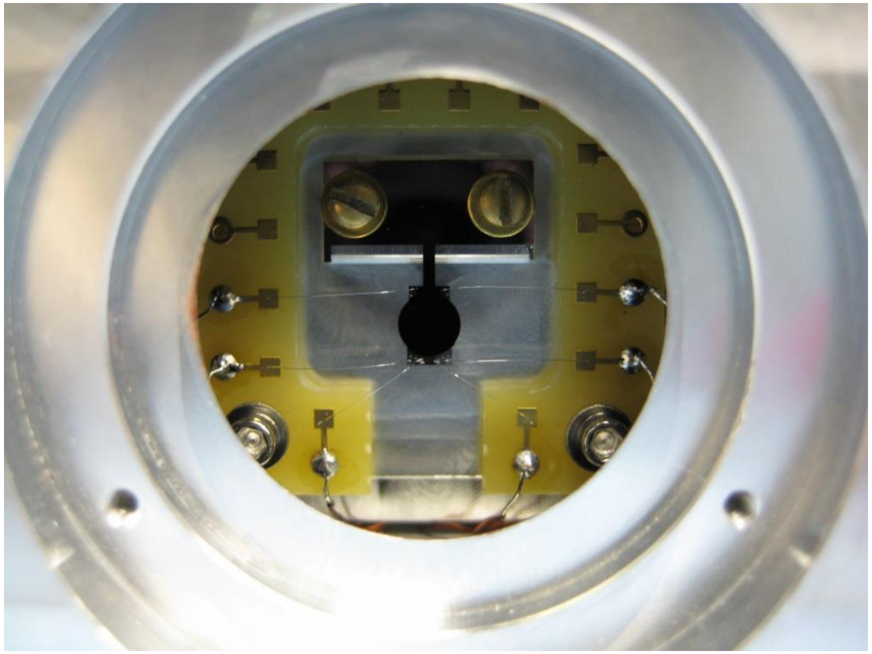

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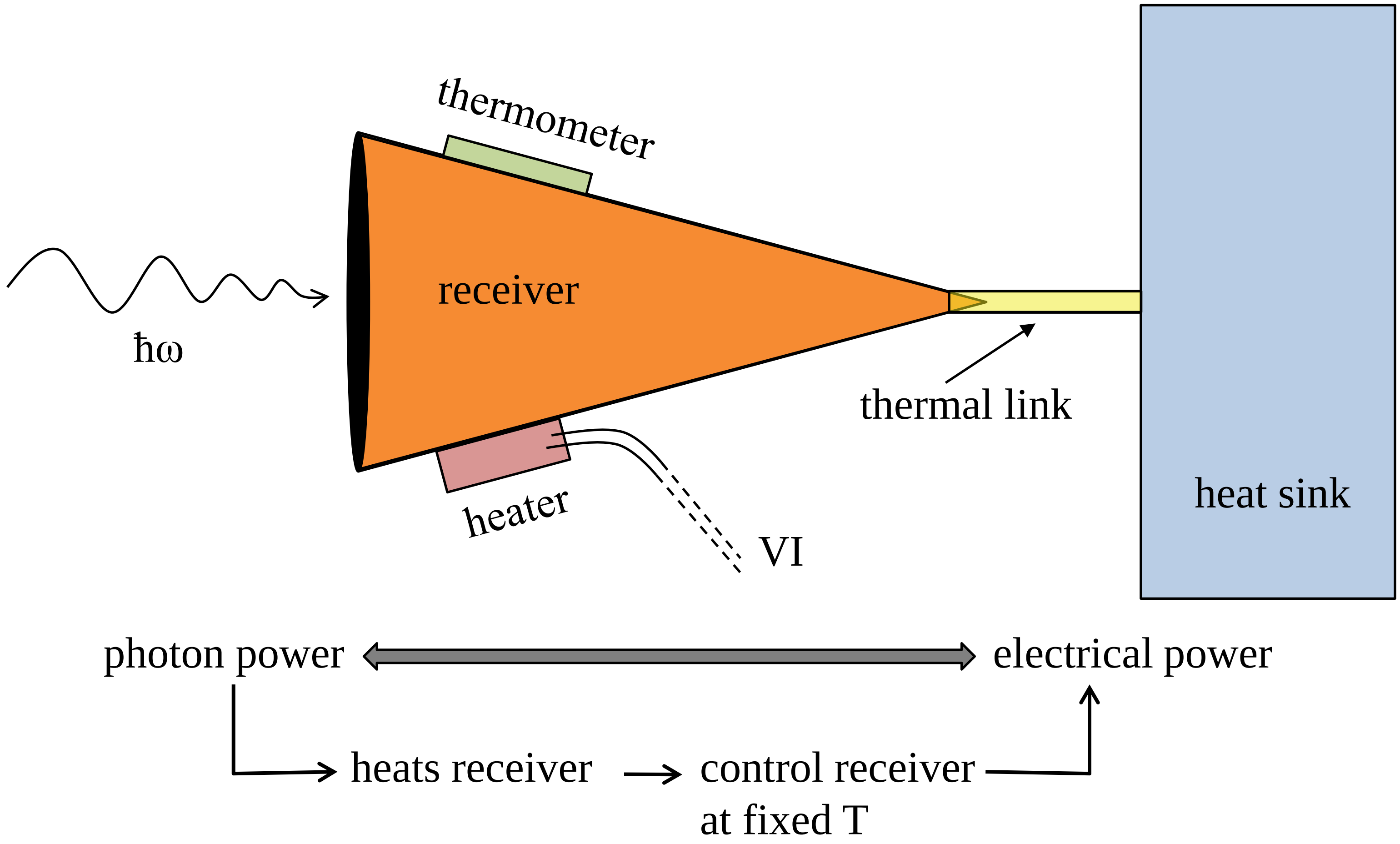
Talk Outline

- Background on the Absolute Cryogenic Radiometer (ACR)
- Design of the Carbon NanoTube Radiometer (CNTR)
- Comparing the CNTR with the traditional ACR
- Fabrication details of the CNT radiometer
- Preliminary reflectance and response data from the CNT radiometer
- Future tests and design developments

Characteristics of the Traditional ACR

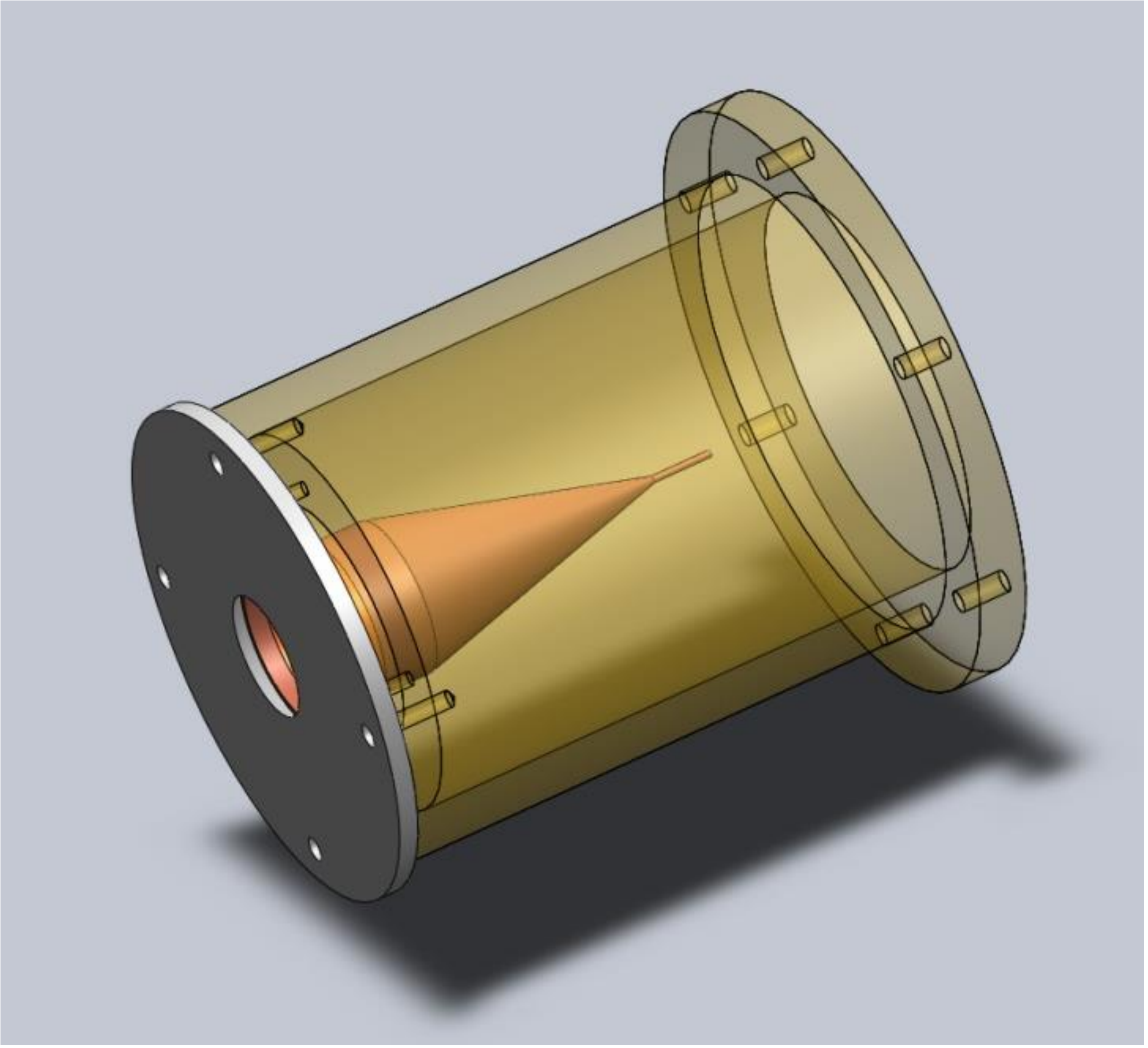
- The (Absolute Cryogenic Radiometer) ACR is a primary standard optical detector where optical power over a large spectral range can be traced to electrical power by the method of electrical substitution.
- Cryogenic operation allows high sensitivity operation with time constant on the order of 10 seconds
- The ACR is a trapping detector which typically depends upon a conical receiver cavity to achieve absorptance near unity. Traditional coatings cannot achieve near 100% absorptance over a broad spectral range.
- Due to sensitivity and speed limitations of the traditional ACR, generally secondary standard detectors calibrated by ACRs are used for practical applications.

ACR Schematic (Electrical Substitution Radiometer)



Typical performance specifications from the NIST LBIR Facility:
absorptance: 99.93 %, responsivity: 210 K/mW, time constant: 17 s, noise floor: 8 pW

Traditional ACR Construction – An "Art Form"



Click for 3D view of ACR

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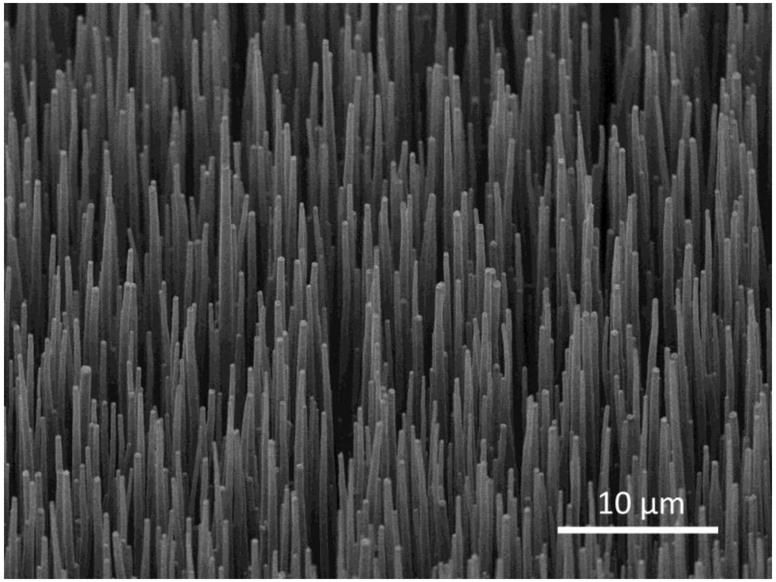
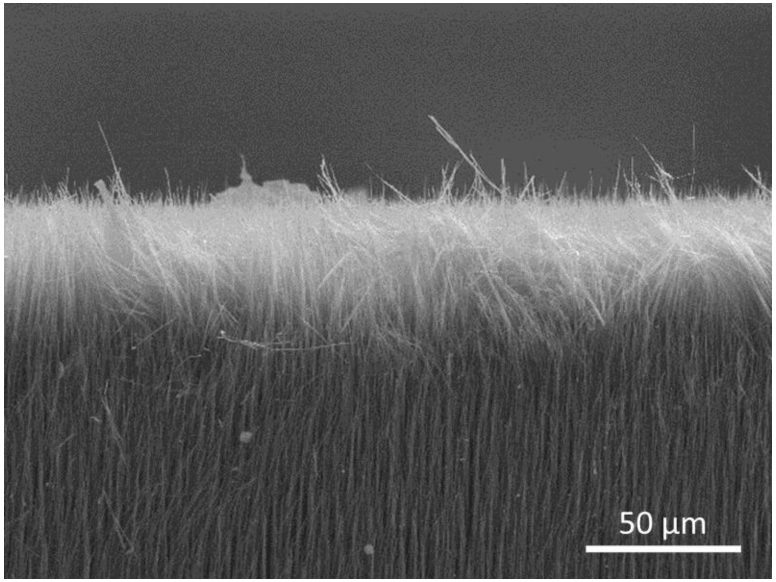
Carbon Nanotubes – A “Game-Changer” for IR Absorption



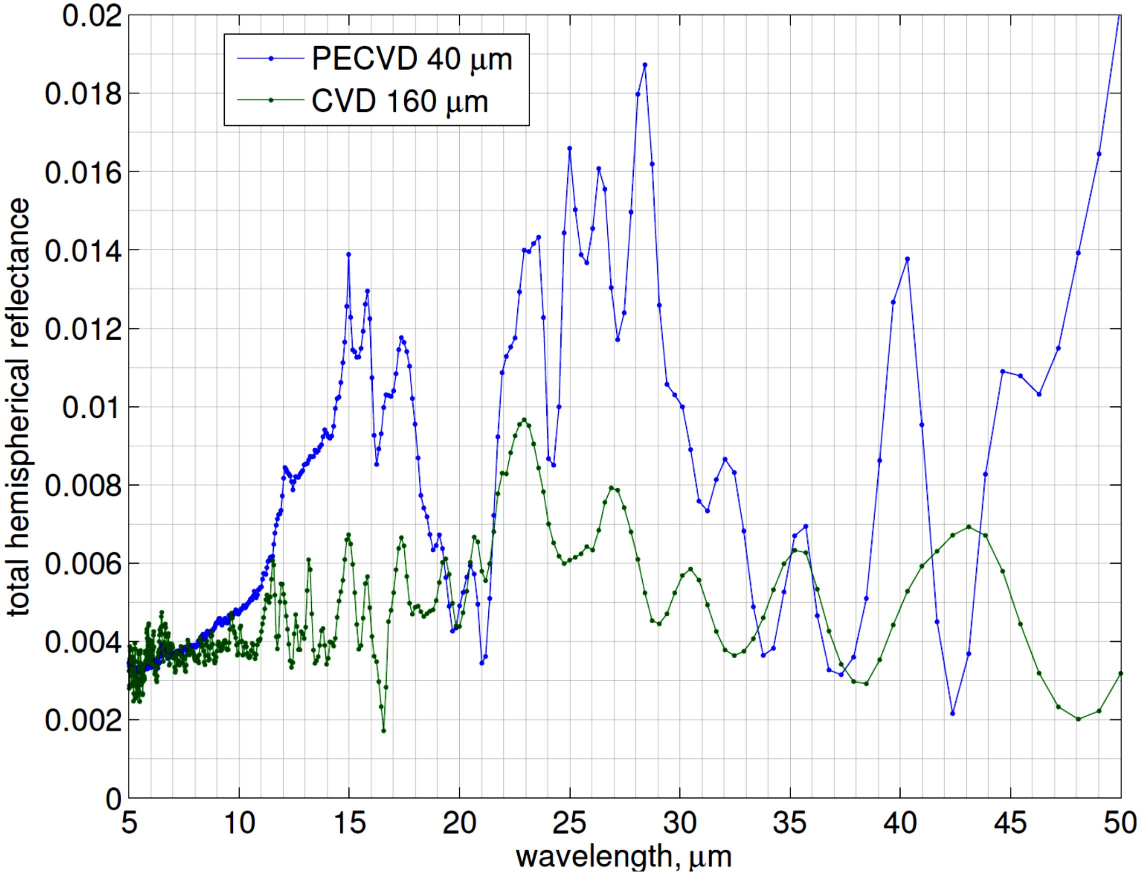
VACNT & SEM image courtesy of Nanolab

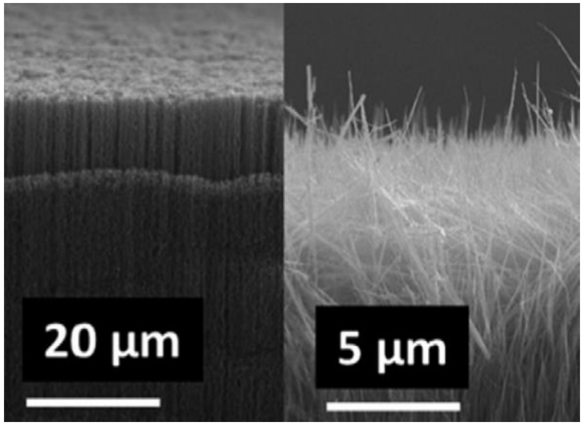


VACNT courtesy of Nanolab
SEM image courtesy of Precision Imaging Facility, Aric Sanders

VACNT = Vertically Aligned Carbon NanoTubes

IR Reflectance of Vertically Aligned Carbon Nanotubes





CVD PECVD

Chunnilall, C.J., Lehman, J.H., et al. *Carbon* **50**, 5340 (2012).

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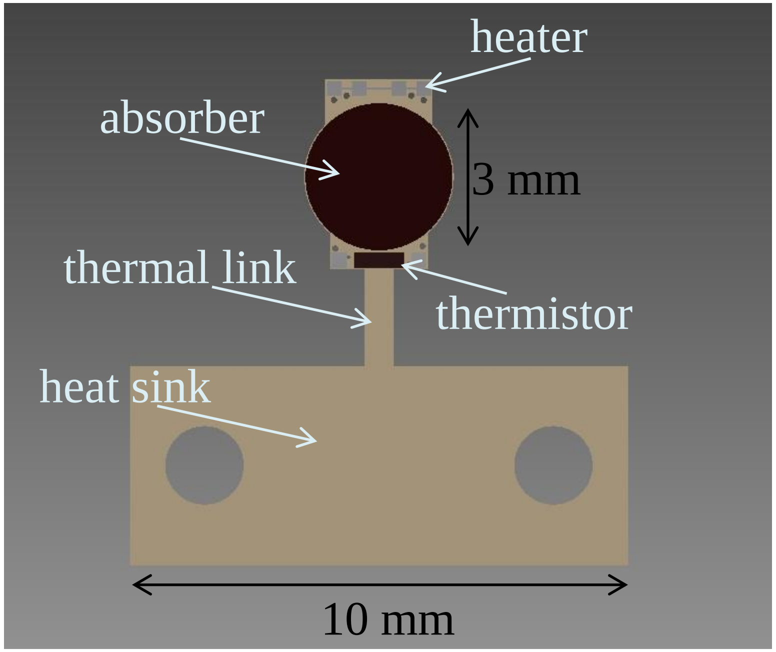
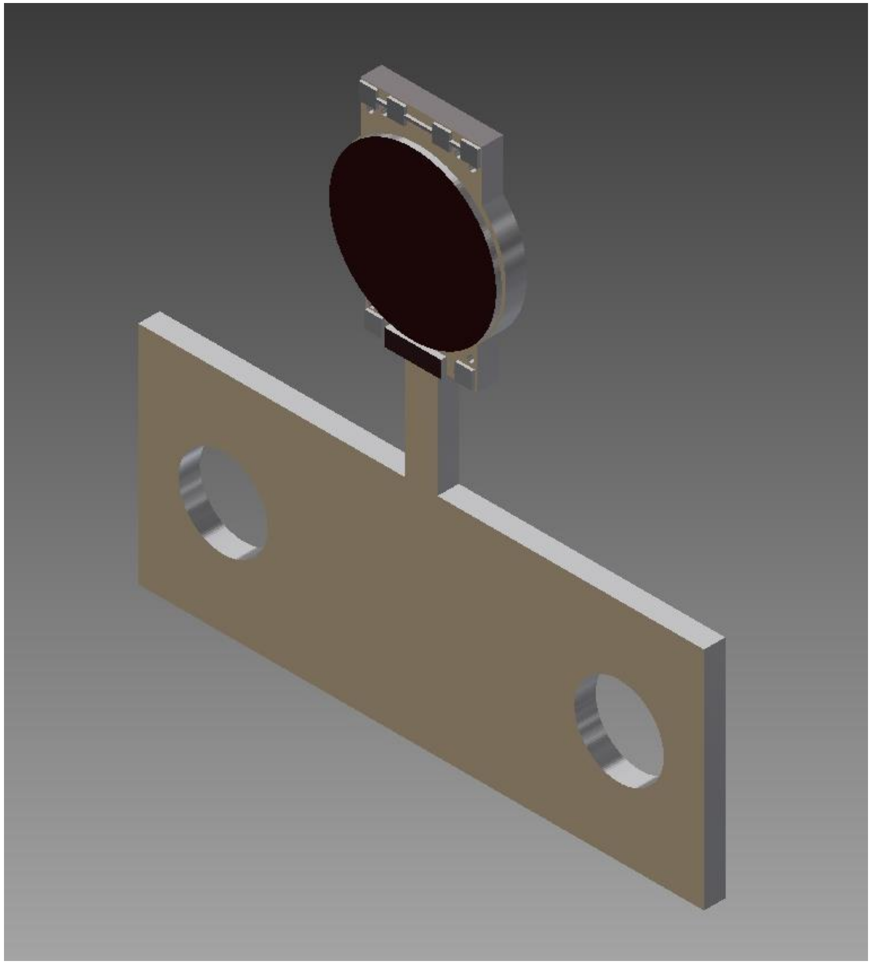
Design of the Carbon Nanotube Radiometer (CNTR)



Feature	Material
absorber	VACNT
heater	Mo
thermistor	VACNT
thermal link	silicon



Sensitivity/Speed Tradeoff for ACRs

- Largest noise source is typically thermal fluctuations in thermal link, which depends on the thermal conductance (G) of the thermal link and temperature:

$$S_{phonon} = (NEP)^2 = 4k_B G T^2$$

- Time constant is determined by the thermal conductance (G) of the thermal link and the heat capacity (C) of the receiver:

$$\tau = \frac{C}{G} \quad \Rightarrow \quad \tau = \frac{4k_B T^2 C}{S_{phonon}}$$

- Thus the time constant and approximate noise spectral density are inversely related.

Comparing Cryogenic CNTR with the Traditional ACR

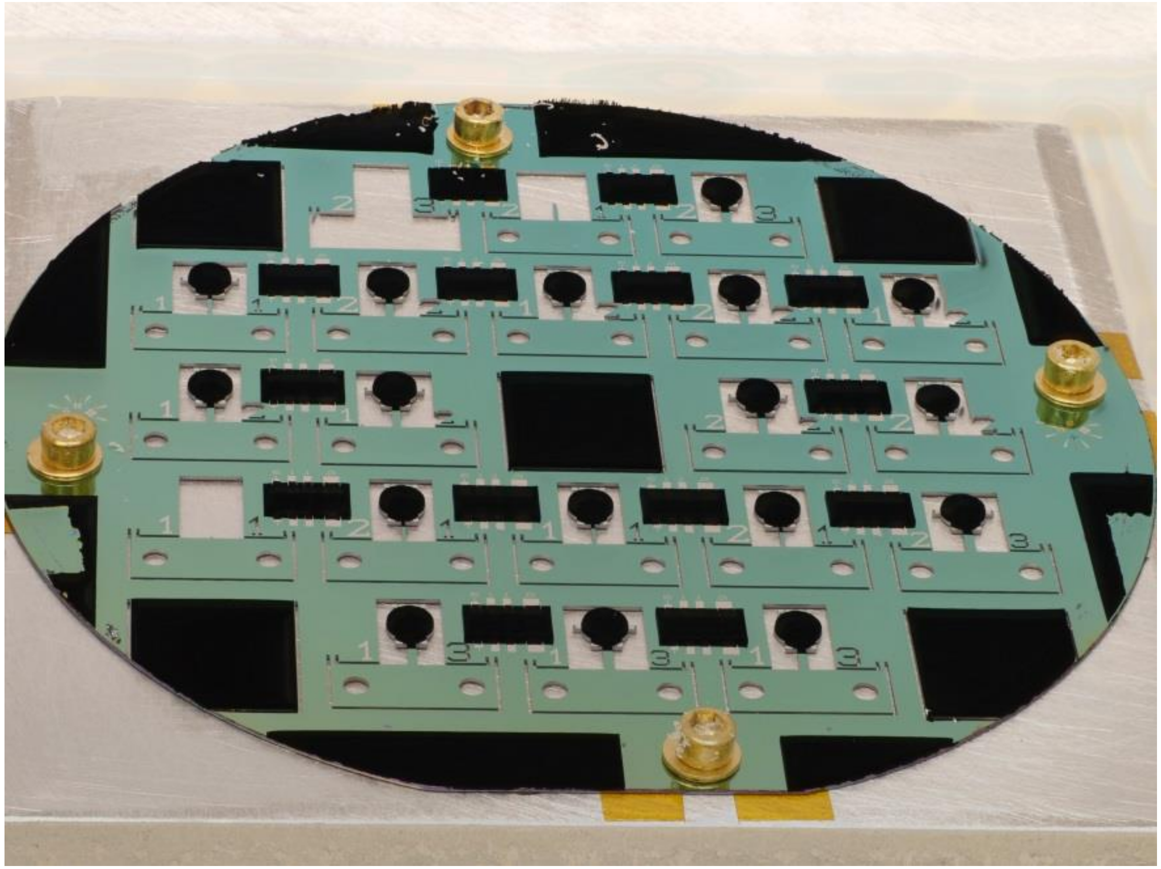
- Fabrication is a "2D" process on silicon rather than a 3D assembly. The manufacture of identical devices and the miniaturization of devices is straightforward.

- Absorptance near 99.9 % at a single surface is possible for the VACNT absorber, allowing calibrations without the use of a trapping arrangement.

- Time constant near 1 kHz is feasible for CNTR designs with sensitivity better than 1 nW, enabling its use for rapid scan Fourier-transform spectroscopy of low power signals.

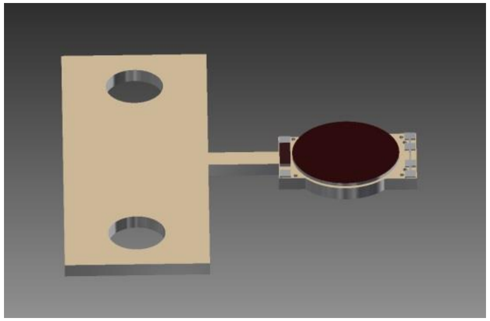
- The cryogenic CNTR and traditional ACR share the same basic components (receiver, heat sink, thermal link, heater, thermometer) but the CNTR allows heat capacity of the device to be readily reduced, improving the sensitivity/speed profile.

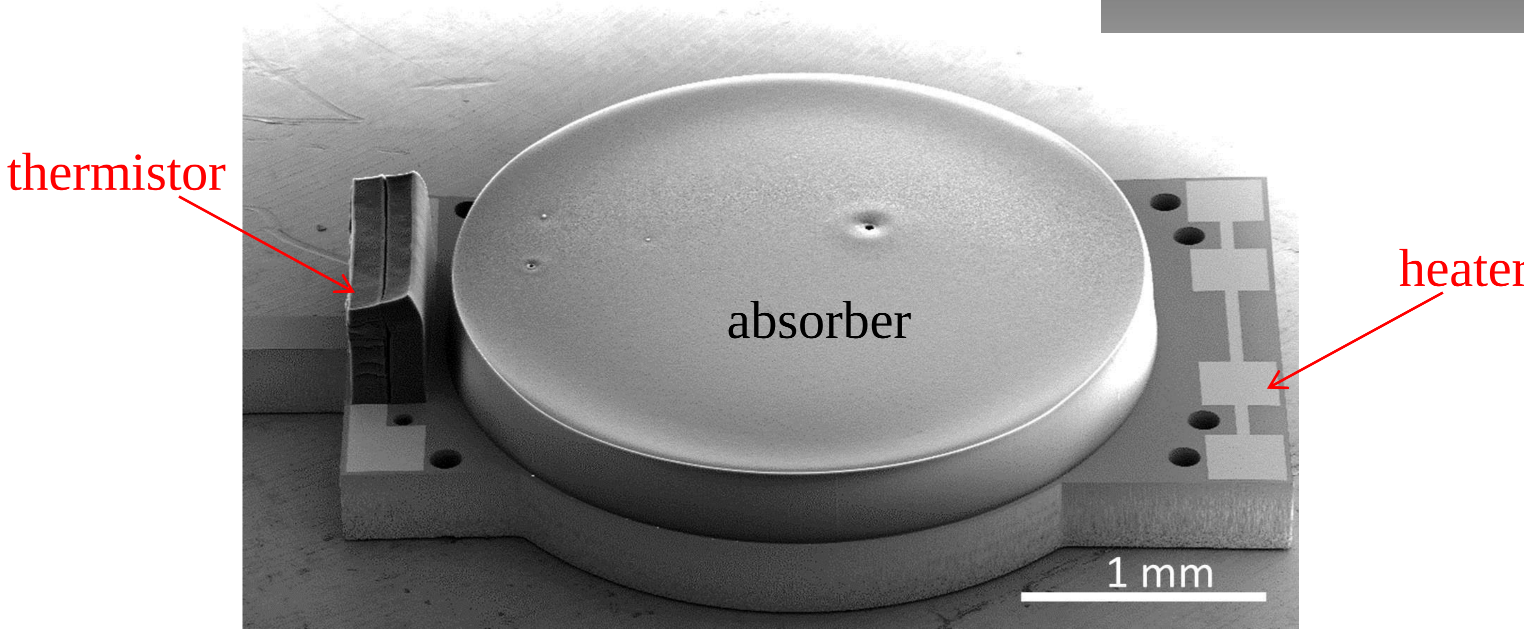
Wafer of Carbon Nanotube Radiometers



** 3” silicon wafer contains 20 radiometers of 12 varying designs, as well as reflectance witness samples.

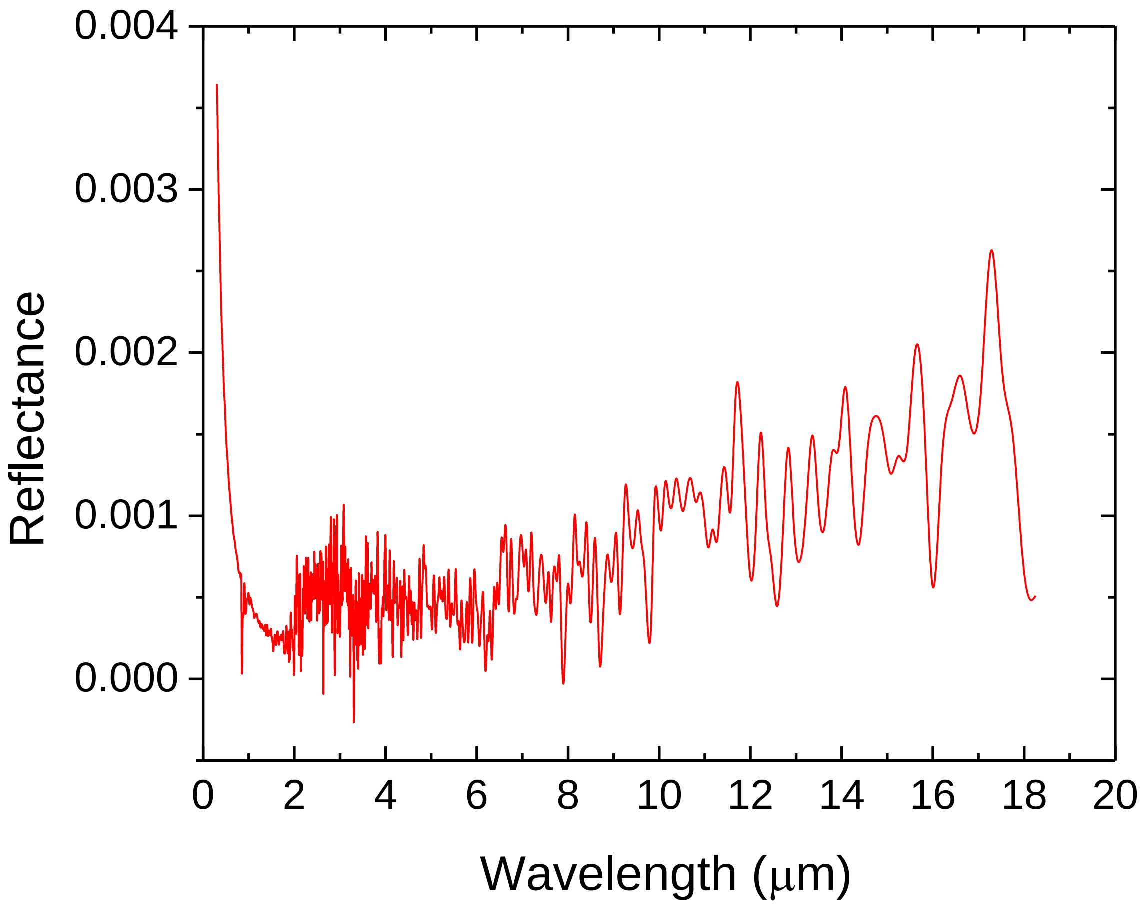
VACNT Fabrication on the CNTR Device





VACNT for absorber and thermistor deposited by FirstNano
SEM image courtesy of Precision Imaging Facility, Aric Sanders

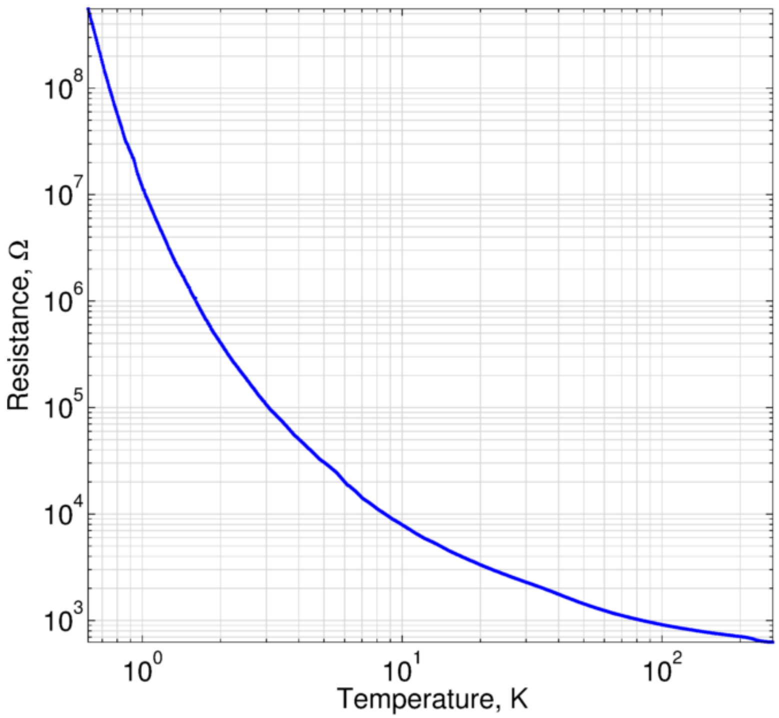
Reflectance of VACNT Witness Sample



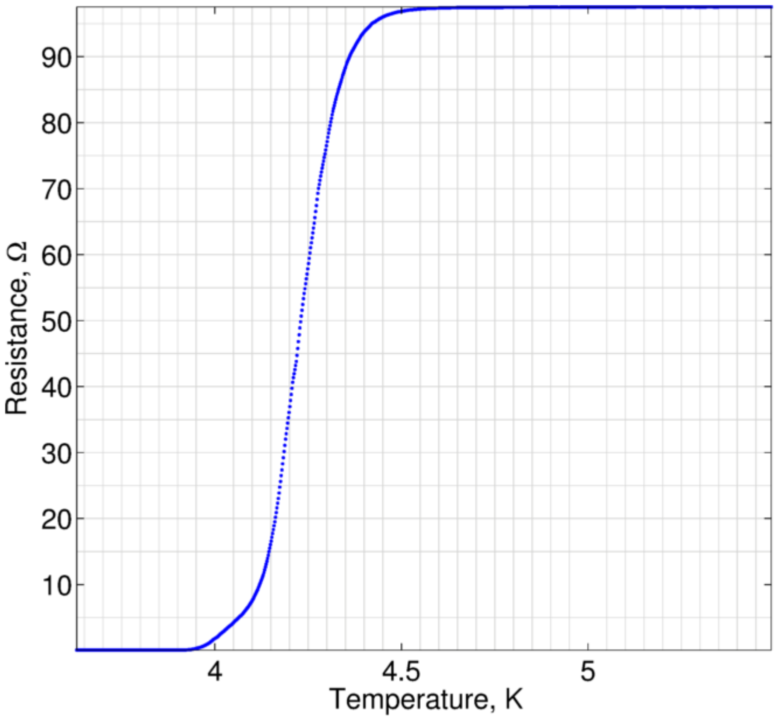
** Average reflectance is less than 0.2 % from 500 nm to 18 μm.
Acknowledgement to Leonard Hanssen for assistance with NIR/MIR data.

Thermistor and Heater Characteristics

VACNT thermistor resistance



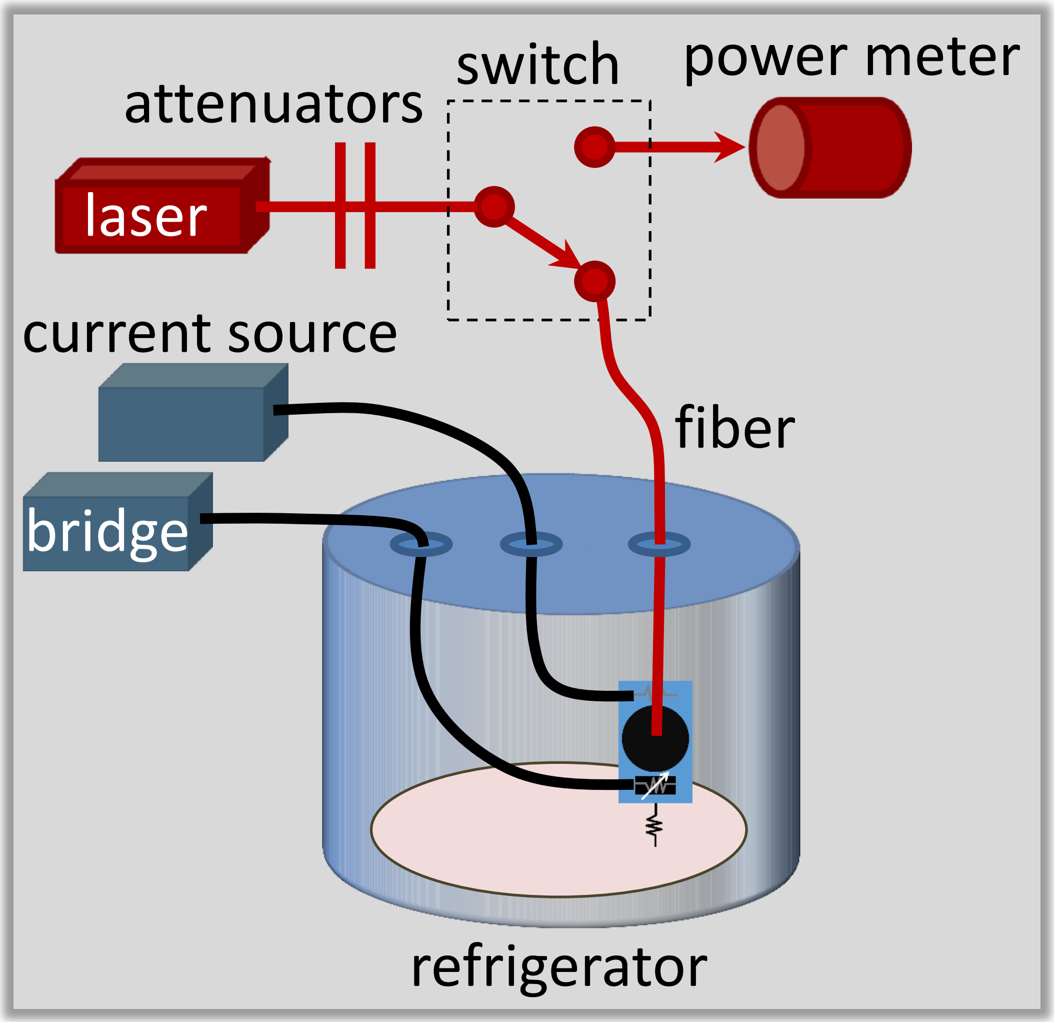
Mo heater resistance



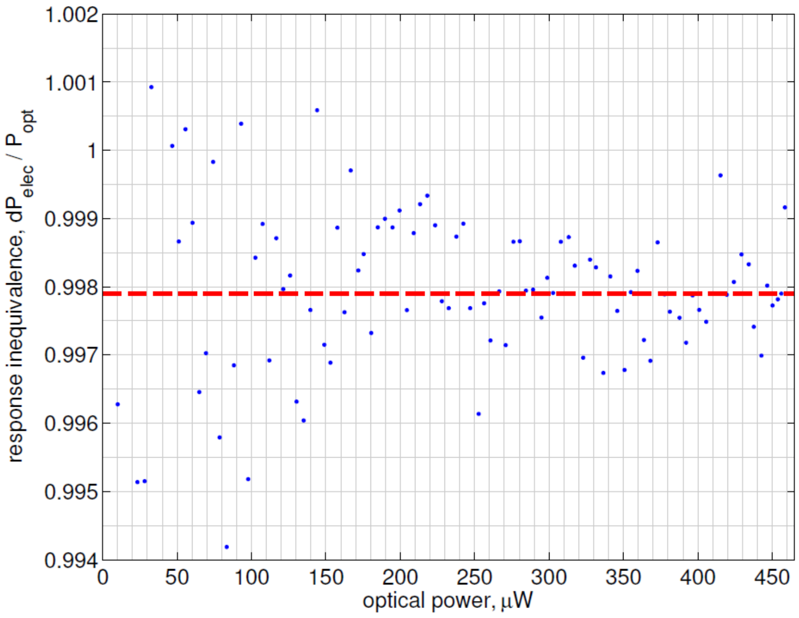
Dimensionless sensitivity of the thermistor is comparable to Cernox thermometers at 4 K.

Alloy of Mo with Si or C is superconducting. Operated above 5 K, the heater has resistance near 100 Ω.

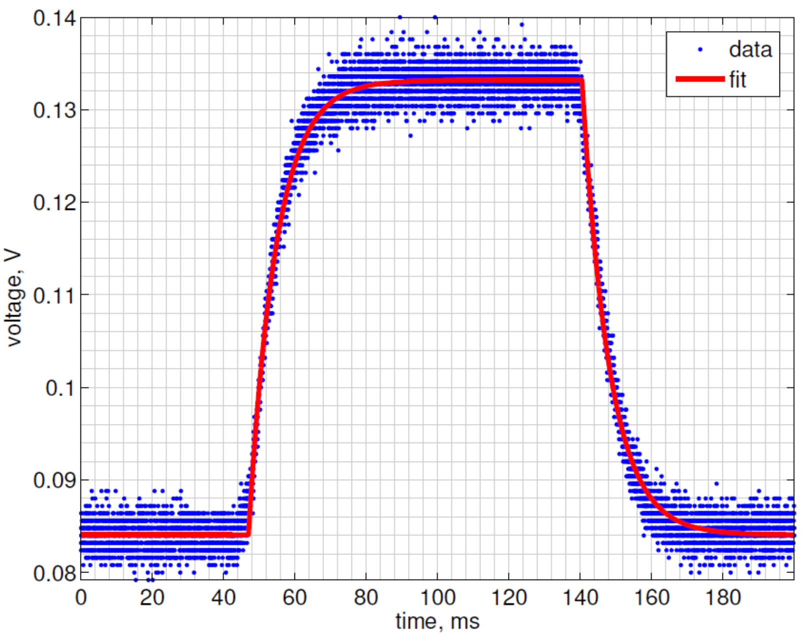
Schematic of Fiber-Coupled Experimental Arrangement



Preliminary Fiber-Coupled Experimental Results

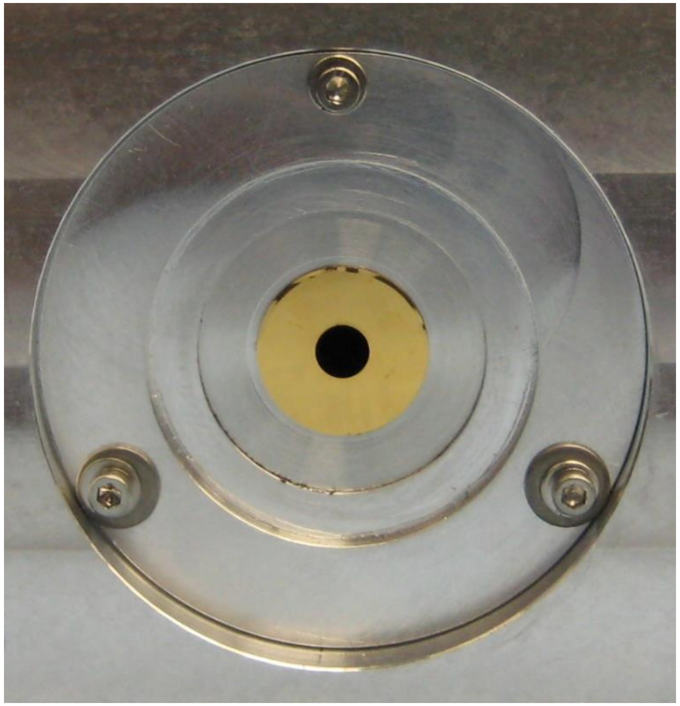


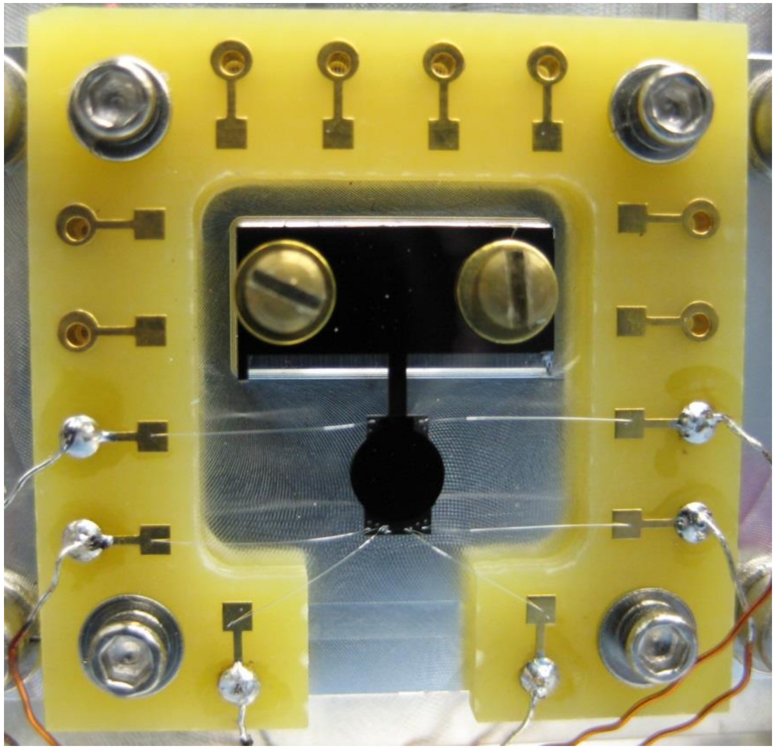
Response inequivalence < 0.5 %



τ = 7.7 ms (at T = 3.9 K)

Detector Mounting for Free-Field Experiment





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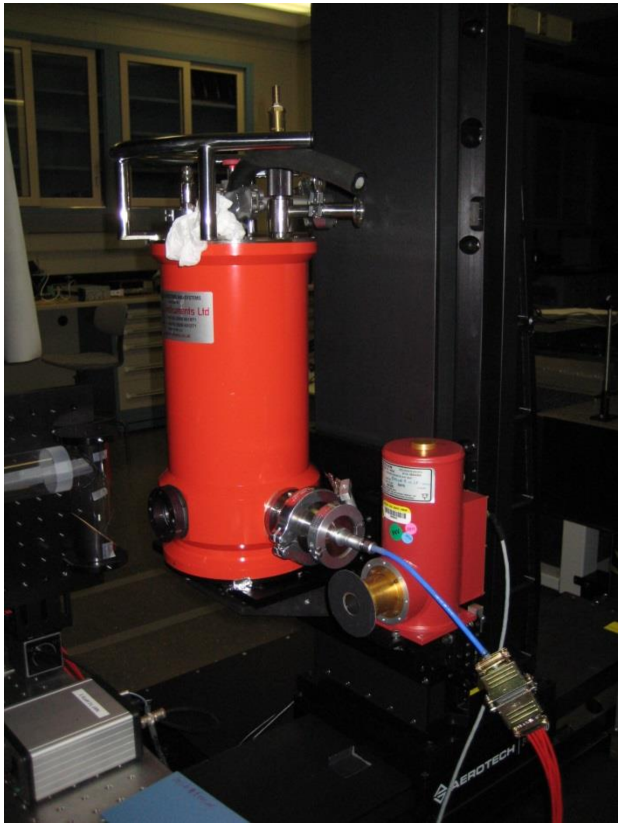
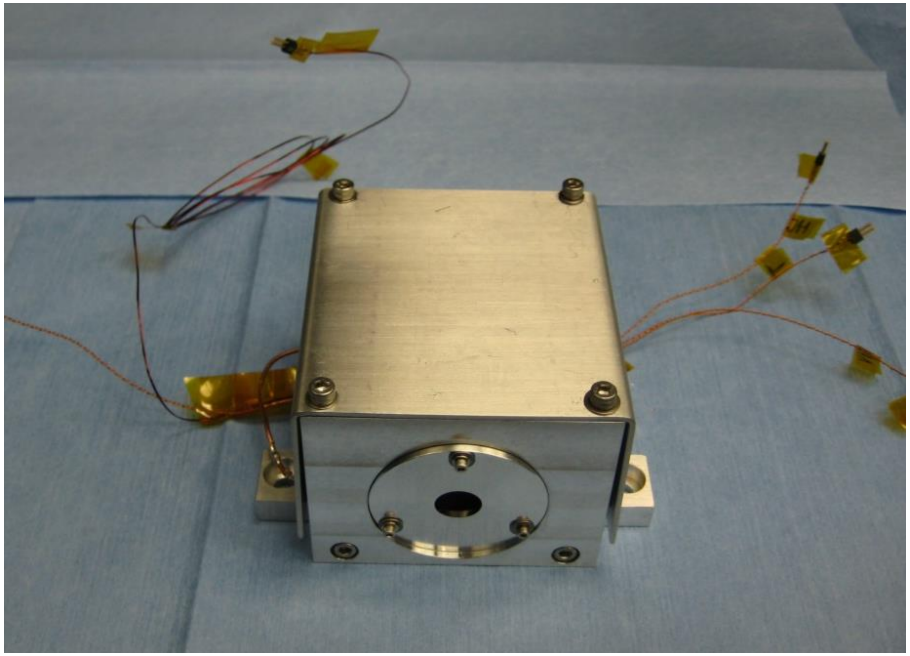
Photos of Free-Field Experimental Arrangement



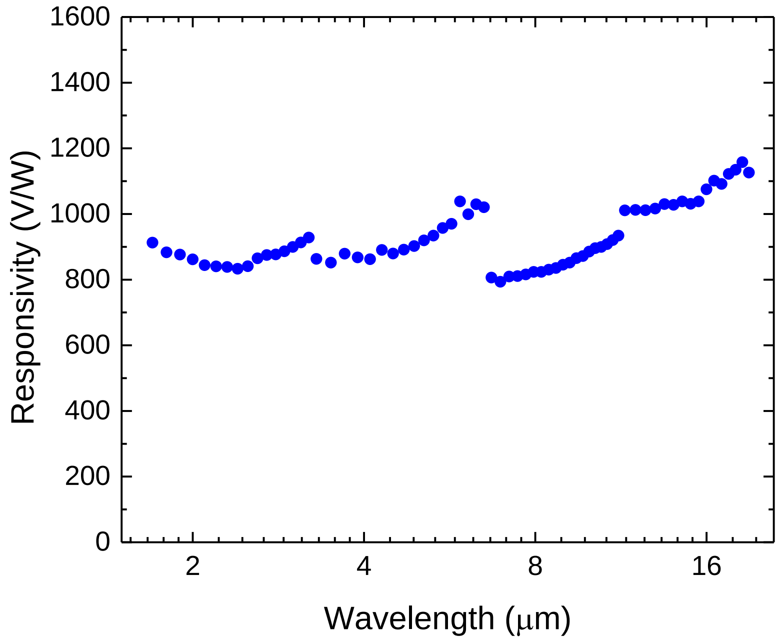
Cryostat on NIST IRSCF Monochromator



Detector 4 K Shroud

Responsivity Measurement of CNTR at the NIST IRSCF

Infrared Spectral Calibration Facility (IRSCF): Monochromator with spectral coverage from 1.7 μm to 19 μm with calibration against a standard pyroelectric detector



Signals from 150 nW to 15 μW over the spectral range from 1.7 μm to 19 μm were measured. For this free-field method, the noise floor with no signal was equivalent to approximately 5 nW.

Responsivity rise across each grating may be caused by detector spatial non-uniformity.

* Acknowledgment to Slava Podobedov from NIST IRSCF for assistance

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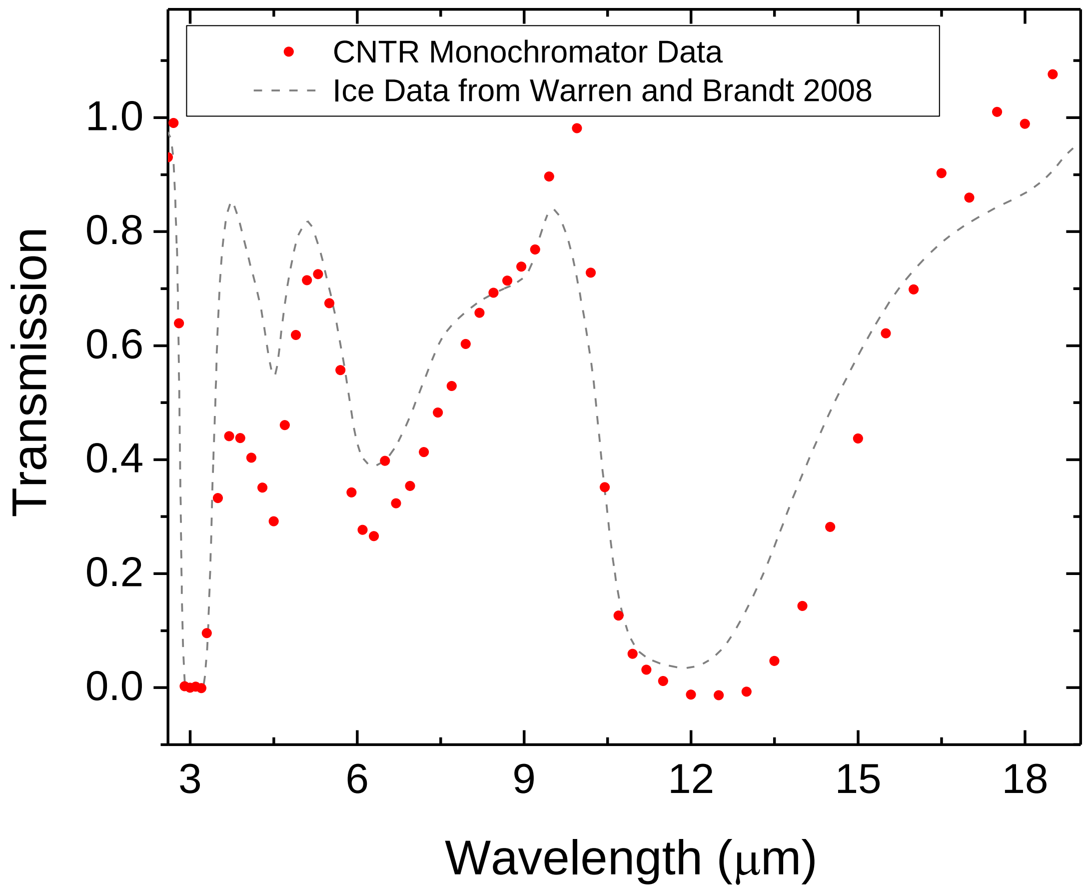
Absorption Spectra of Water Ice Taken with CNTR



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Future Plans and Design Developments

- Early versions of a carbon nanotube radiometer (CNTR) have been designed and fabricated.
- Preliminary results demonstrate the compatibility of the fabrication techniques, use of the detector in fiber-coupled and free-field measurements, and promising values for reflectance, time constant and inequivalence.
- CNTR will be intercompared with a standard ACR in one of our cryogenic calibration test chambers.
- Further modeling and redesign of the detector will address potential spatial non-uniformity of response due to direct thermistor illumination and thermal gradients across the absorber.