Calibration of Ultra-Low Infrared Power at NIST

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ABSTRACT

The Low Background Infrared (LBIR) facility has developed and tested the components of a new detector for calibration of infrared greater than 1 pW, with 0.1 % uncertainty. Calibration of such low powers could be valuable for the quantitative study of weak astronomical sources in the infrared. The pW-ACR is an absolute cryogenic radiometer (ACR) employing a high resolution transition edge sensor (TES) thermometer, ultra-weak thermal link and miniaturized receiver to achieve a noise level of around 1 fW at a temperature of 2 K. The novel thermometer employs the superconducting transition of a tin (Sn) core and has demonstrated a temperature noise floor less than 3 $nK/Hz^{1/2}$. Using an applied magnetic field from an integrated solenoid to suppress the Sn transition temperature, the operating temperature of the thermometer can be tuned to any temperature below 3.6 K. The conical receiver is coated on the inside with infrared-absorbing paint and has a demonstrated absorptivity of 99.94 % at 10.6 µm. The thermal link is made from a thin-walled polyimide tube and has exhibited very low thermal conductance near 2×10^{-7} W/K. In tests with a heater mounted on the receiver, the receiver/thermal-link assembly demonstrated a thermal time constant of about 15 s. Based on these experimental results, it is estimated that an ACR containing these components can achieve noise levels below 1 fW, and the design of a radiometer merging the new thermometer, receiver and thermal link will be discussed.

Keywords: infrared, radiometry, absolute cryogenic radiometer, traceability, cryogenic, low power, LBIR, NIST

1. INTRODUCTION

The Low Background Infrared (LBIR) facility at the National Institute of Standards and Technology (NIST) operates reference detectors that are used to maintain the national standard for low power infrared radiation in the range from 1 nW to 10 mW. LBIR shares this standard with the user community through two primary methods: calibration of customer sources at our facility against our primary standards and by calibration of infrared testbeds at customer sites against our secondary standard transfer radiometers. The primary standard reference detector used is an absolute cryogenic radiometer (ACR), an electrical substitution device which provides a direct physical connection between the optical watt and the electrical watt [1-3]. The transfer radiometers contain our secondary standard detectors, which are Si:As blocked-impurity-band (BIB) detectors which have been calibrated against the ACR standards [4-6]. The Si:As BIB detectors display significant responsivity from 2 µm to 30 µm and noise floor near 1 fW.

Presently, the ACRs operated at NIST attain a noise level near 10 pW and can be used to calibrate powers as low as 1 nW with an uncertainty of 1 % ($k = 3$). Although the BIB detectors can make measurements with sensitivity on the level of 1 fW, the direct traceability of their response to the ACR-based standard is limited to powers on the order of 10 pW. Once the secondary standard BIB detectors have been calibrated by the ACR primary standards at power levels greater than 10 pW, it is technically possible to use the BIB detector scale down to the 1 fW noise floor of the BIB detectors, given an estimate of the linearity of BIB detector response as a function of power. This BIB detector scale is only directly traceable down to 10 pW, however, and extrapolation to lower power can lead to unacceptably large uncertainties for the end user. To address this problem the LBIR Facility at NIST has been developing a low-power ACR with noise floor near 1 fW, which will be used to disseminate IR power calibrations down to 1 pW with a combined uncertainty of about 0.1 %. Designed for calibrations of pW power levels, the new ACR has been named the “pW-ACR” [7].

High Energy, Optical, and Infrared Detectors for Astronomy IV, edited by Andrew D. Holland, David A. Dorn
Proc. of SPIE Vol. 7742, 77421P · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857911

Infrared measurement systems requiring a low-background environment include ground and space-based astronomical telescopes and space-based sensors designed to detect ballistic warheads coming over the Earth's horizon. To achieve the calibration requirements of these sensors, the pW-ACR must be operated in a cryogenic environment at liquid helium temperatures. Once the pW-ACR has been used to calibrate our secondary standard BIB detectors, however, the BIB detectors can be used for calibrations at temperatures up to 15 K.

2. DESIGN OF THE PICOWATT-ACR COMPONENTS

To design a higher sensitivity absolute cryogenic radiometer, it is necessary to optimize each component in the ACR to maximize responsivity and minimize noise. Figure 1 presents an ACR schematic, with the major components of such an electrical substitution radiometer labeled. In the schematic, light enters from the left and is incident upon the receiver. The receiver cavity is designed to absorb and trap as much of the incident radiation as possible. Typically, this cavity is coated on its inside with a black, infrared-absorbing paint and has a conical shape, allowing no incident light to escape without multiple reflections from the cavity walls. The receiver temperature is monitored by an attached thermometer, and the receiver heater can be used with this thermometer in a closed feedback loop to maintain the cavity at a constant temperature during operation. The electrical substitution method works as follows: first the receiver is brought to a fixed equilibrium temperature using closed loop feedback in the absence of incident light; then the incident light to be measured is directed to the receiver (e.g., by opening a shutter) and the receiver is allowed to equilibrate under the closed loop feedback of thermometer and heater to the same fixed temperature. In the absence of incident light, the receiver heater will require a certain power to maintain the receiver at the chosen temperature; with the incident light striking and heating the receiver, less power will be required from the heater to maintain the receiver at the same temperature. In a well-designed ACR, there is near equivalence between the power of the incident light and the difference in heater power required in the light/no-light measurements.

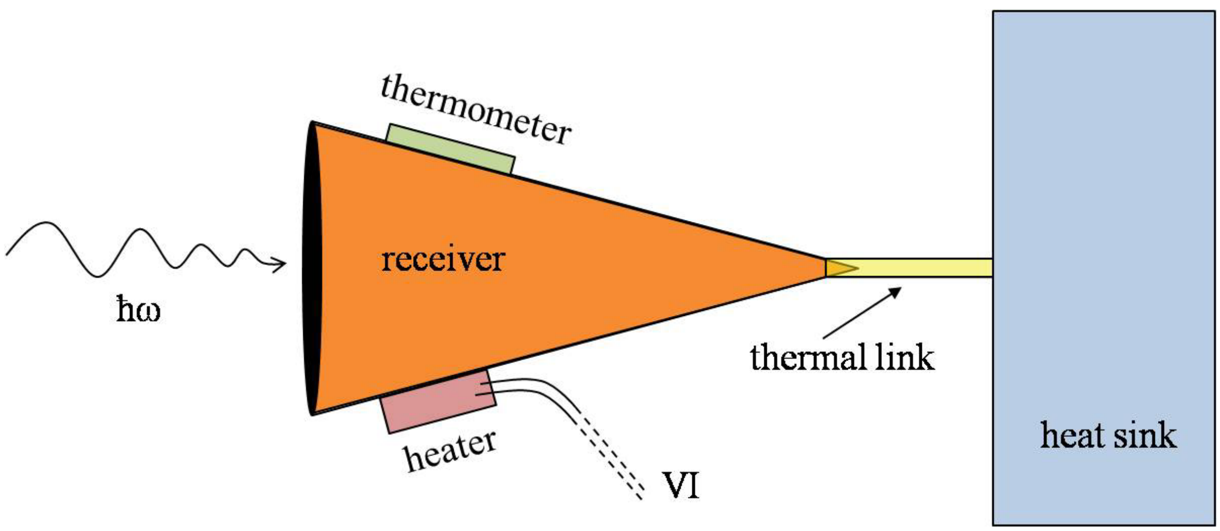

Figure 1. Schematic of an absolute cryogenic radiometer, with significant components labeled. Light is incident from the left on the receiver, which is maintained at a constant temperature during measurements.

The remaining ACR components in Figure 1, the thermal link and heat sink, allow for controlled release of thermal energy from the receiver during measurements. The only physical connection between the receiver and the external environment is through the thermal link to the heat sink, a heat reservoir maintained at a fixed temperature slightly colder than the receiver. Two simple relations can be used to estimate the thermal behavior of an ACR and place constraints on its design. The first relates the temperature difference between the receiver and heat sink (ΔT) to the thermal conductance of the thermal link (G) and power applied to the receiver (P) and is given by: $\Delta T = P/G$. In order to enable a large change in temperature for a given power, G should be made small (i.e., the receiver must be somewhat thermally-isolated from its environment). The second relation provides an estimate for the time constant of the ACR (τ) as a function of the thermal conductance of the thermal link (G) and the heat capacity of the receiver (C) and is given by: $\tau = C/G$. It can be noted that if G is made arbitrarily small, the thermal time constant of the ACR will become arbitrarily large, but that by making the heat capacity of the receiver smaller (e.g., by decreasing the mass of the receiver) it is possible to make the time constant smaller.

The pW-ACR design is based on the ACRII model radiometer that is currently in use at the LBIR Facility [3], with various improvements to increase radiometer sensitivity. Table 1 shows the most relevant differences between the currently used ACRII and the pW-ACR under development. Direct improvements in sensitivity are made by employing a more sensitive thermometer on the ACR receiver cavity, weakening the thermal link from the receiver cavity to the heat sink and operating at lower background temperature. The smaller cone size, which reduces the pW-ACR receiver mass by a factor of about 40 from that of the ACRII (although the receiver heater and thermometer also add significant mass to the pW-ACR), allows the time constant to remain nearly unchanged even though the thermal conductance of the thermal link is more than 20 times smaller for the pW-ACR than for the ACRII.

Table 1. Comparison between key parameters for the currently operated ACR model (ACRII) and the new low power ACR under development (pW-ACR).

Receiver Cavity Property	ACRII	pW-ACR
Cone Diameter (cm)	2.5	0.4
Cone Absorptivity	0.9993	0.9994
Responsivity (K/mW)	210	~ 4700
Time Constant (s)	17	~ 15
Noise Floor (pW)	> 8	~ 0.001
Maximum Power (nW)	~ 10^5	~ 20

An ultra-sensitive superconducting transition edge sensor (TES) thermometer made from a high purity Sn core monitored by a Superconducting QUantum Interference Device (SQUID) will measure the temperature of the pW-ACR receiver cavity. The physical basis of such a thermometer is demonstrated in Figure 2. The tin core is closely surrounded by a superconducting pickup coil which transmits signal to the SQUID. Above the superconducting transition of the Sn core, magnetic flux lines from the applied field can pass freely through the core, and the magnetic flux through the pickup coil is maximal. As the temperature is lowered and the core becomes superconducting, magnetic flux is expelled from the tin by the Meissner effect and the flux through the pickup coil is reduced. The SQUID is an extremely sensitive magnetometer, and small changes in flux through the pickup coil with temperature can generate significant signal changes at the SQUID output.

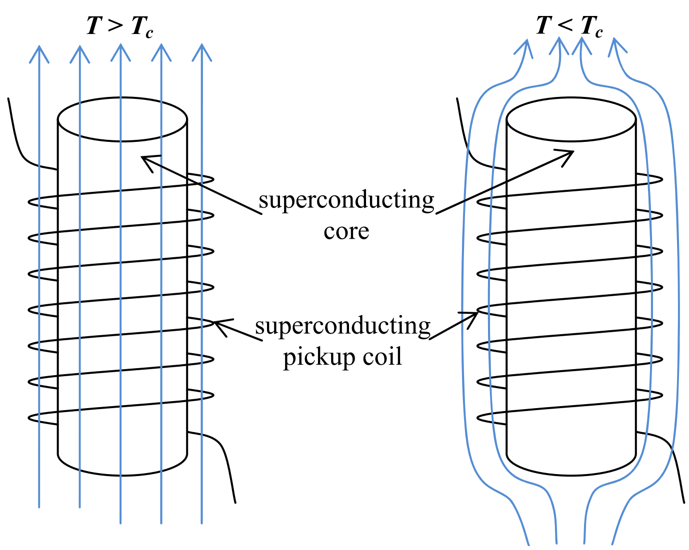

Figure 2. Schematic depicting the physical basis of the TES developed for the pW-ACR. Above the transition temperature (T_c) of the core (left), the flux lines of the applied field (blue) pass freely through the core. Below the T_c of the core (right), the flux lines are expelled from the core, lowering the total flux passing through the pickup coil.

Typically, TES thermometers employ a resistive measurement of the superconducting element [8,9], but for the pW-ACR the sample will be placed in a uniform magnetic field and its magnetization measured using the SQUID. The pW-ACR contains an integrated solenoid that can be used to apply a magnetic field of any strength up to the critical magnetic field of the Sn core (2.4×10^4 A/m). There are a number of important benefits in using this non-contact measurement technique with a variable magnetic field. First, the power dissipation in the temperature sensor will be negligible. Second, the temperature resolution for the lowest power measurements can be improved by increasing the applied magnetic field. Third, the operating temperature and power of the receiver cavity can be changed by varying the magnetic field, as this field can be used to tune the tin superconducting transition to any temperature below 3.7 K. One more important design element related to the superconducting pickup coil improves the noise performance of the TES. The pickup circuit has a gradiometer geometry containing two oppositely-wound coils, one surrounding the Sn core and the other a copper wire. External magnetic noise will produce cancelling contributions to the signal in the two coils and will allow the radiometer to be operated in electromagnetically noisy lab environments.

For the pW-ACR, the receiver is a conical cavity with base diameter of about 4mm, and its inside is painted with IR-absorbing black paint to maximize absorption. To maximize thermal conductivity and minimize heat capacity, the cone is made from 50 µm thick electroformed copper, plated with gold. The thermal link connecting the receiver cavity to the heat sink has the dual purpose of setting an appropriate level of thermal isolation between these two elements and providing a rigid framework for holding the receiver in place. Thin-walled polyimide tubing allows for enough strength to hold the receiver cone while providing very low thermal conductance. Figure 3 shows a photograph of the receiver cavity held in place by a thin insulating polyimide tube in a configuration used for thermal impedance measurements.

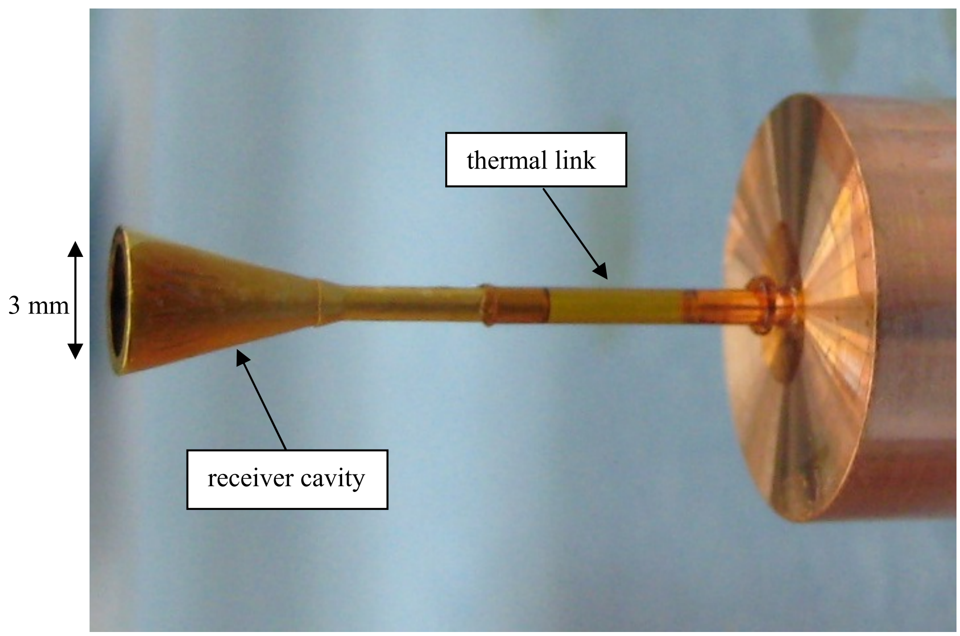

Figure 3. Photograph of the pW-ACR receiver cavity attached to a copper block by a thin-walled polyimide thermal link.

3. EXPERIMENTAL RESULTS ON THE PICOWATT-ACR COMPONENTS

We have completed initial tests on a prototype TES to be used as the thermometer for the pW-ACR. Measurements of the thermometer responsivity and SQUID noise indicate the thermal noise of the thermometer to be about $T_{noise} = 2.25 \times 10^{-9}$ K/Hz$^{1/2}$ at a temperature of 3.58 K. This represents about a 10,000 times improvement in sensitivity over the germanium resistance thermometers presently used on our ACRs. Thus, the TES will be able to maintain constant temperature within a much narrower range when used along with the receiver heater in closed loop control. Tests of the gradiometer pickup coil used in the TES have verified the value of this design element in shielding the sensor from external noise. Two types of superconducting pickup coils have been tested to compare their noise performance. In one case, a single coil flux transformer was wound around a core and attached to the input of the

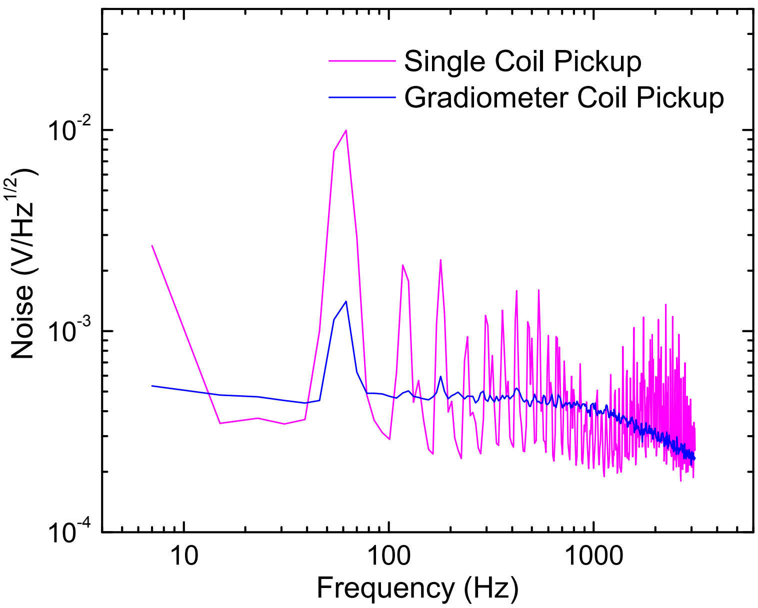

Figure 4. Comparison of the voltage noise at the SQUID output for two types of superconducting pickup coils, in the presence of applied external electromagnetic noise. The SQUID signal shows that the gradiometer coil arrangement confers significant immunity from external noise as compared to the single coil.

SQUID and in the other case a gradiometer was oppositely-wound about a pair of cores. The experimental environment was intentionally subjected to significant electromagnetic noise, and the effect of this noise on SQUID output was measured. Figure 4 shows the frequency dependent noise from the SQUID output in the presence of significant external noise for the two pickup coil geometries out to a frequency of about 1.6 kHz. It is clear from the data that the external noise creates a much larger signal at the SQUID output in the case of the single coil than in the case of the gradiometer, where there is little difference between the SQUID noise signature with or without the applied external noise.

Thermal impedance measurements have been completed on the pW-ACR receiver cavity and thermal link, using a standard measurement configuration described elsewhere [10]. Results show that at a temperature of 1.8 K the thermal

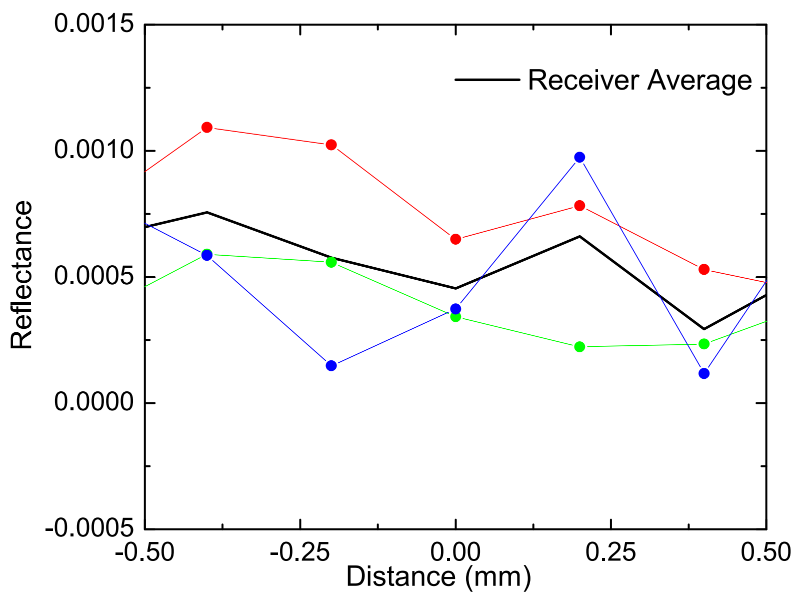

Figure 5. Reflectance from three different ACR receiver cavities (red, blue and green data) at a wavelength 10.6 µm, measured across the central 1 mm of the cavity. The solid black line shows the average of the three cavities. The average absorptivity over the central portion of the cavities is 99.94 %.

conductance of the cavity is $G = 2.13 \times 10^{-7}$ W/K and the time constant of the receiver/thermal-link assembly (including receiver heater and test thermometer) is $\tau \sim 15$ s. The thermal conductance is equivalent to an ACR responsivity of about 4700 K/mW, more than 22 times larger than that of the thermal links presently used on our ACRs. It can be estimated from the initial thermometer and thermal impedance results that the power noise floor of the pW-ACR at 3.6 K could be approximately $T_{noise} \times G = 4.8 \times 10^{-15}$ W/Hz$^{1/2}$.

Despite the reduced size of the pW-ACR receiver cavities, reflectance measurements at a wavelength of 10.6 µm demonstrate that these cavities have an average absorptivity comparable to the cavities presently used for our ACRs. Measurements were made at room temperature using the Complete Hemispherical Infrared Laser-based Reflectometer (CHILR) at NIST, the operation of which has been previously described elsewhere [11]. Data on three pW-ACR receivers is shown in Figure 5, and the average reflectance of the cavities over the relevant spatial range is 0.0006, equivalent to an average absorptivity of 99.94 %.

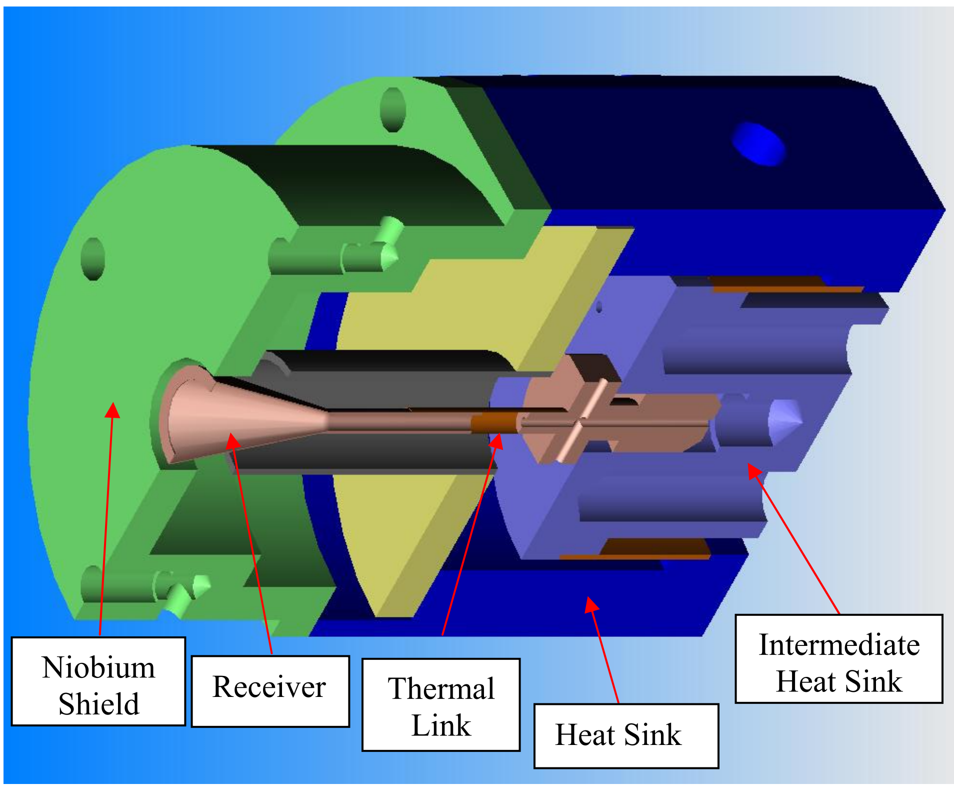

Figure 6. Schematic of the final pW-ACR assembly, with major components labeled. All component hardware for the assembly has been fabricated, but the final radiometer has not yet been built up.

4. DESIGN OF THE PICOWATT-ACR CALIBRATION HARDWARE

All the critical components of the pW-ACR have been built and their performance validated through testing. The final calibration hardware for operation of the pW-ACR has been designed and largely fabricated, but measurements with the complete radiometer and its use in calibrations have not yet begun. Figure 6 contains a schematic of the final pW-ACR design, with its primary components labeled. The receiver is contained within a niobium shield, which will be superconducting at operating temperatures and will help reduce the effect of external electromagnetic noise on the ACR measurements. The receiver thermometer (TES) and heater will be affixed to the receiver and are not shown in the schematic. A two-stage heat sink, with both stages separately temperature-controlled, will be used to buffer the receiver from temperature fluctuations of the measurement cryostat liquid helium reservoir. The receiver is attached to the intermediate heat sink by a thin-walled polyimide thermal link, and the intermediate heat sink is attached to an outer heat sink by a larger polyimide thermal link.

Once the fully assembled pW-ACR has been experimentally tested, this new radiometer will be mounted within an intercomparison assembly and used to calibrate our secondary standard BIB detectors at low powers. The hardware for this intercomparison has already been designed and fabricated, and a labeled schematic of this assembly is shown in Figure 7. The intercomparison assembly will be mounted in a test cryostat with a pumped helium reservoir which can cool all experimental components to temperatures near 2 K. The output of a monochromator source or infrared laser will be fed directly into the integrating sphere assembly using an optical fiber. The integrating sphere assembly will be used to improve the spatial uniformity of the incoming radiation and reduce the total source power. Then the beam will enter the mirror box and be directed by high reflectivity mirrors to a detector aperture. The pW-ACR and the BIB detector will be mounted next to each other on a linear mechanical stage directly behind this aperture. A direct calibration of the BIB detector can then be accomplished in the following manner: first, the detector stage can be moved so the beam from the detector aperture is centered on the pW-ACR, and then an absolute measurement of the beam power can be made; second, the detector stage can be moved so the beam is centered on the BIB detector, and then the response of the BIB to the beam can be recorded.

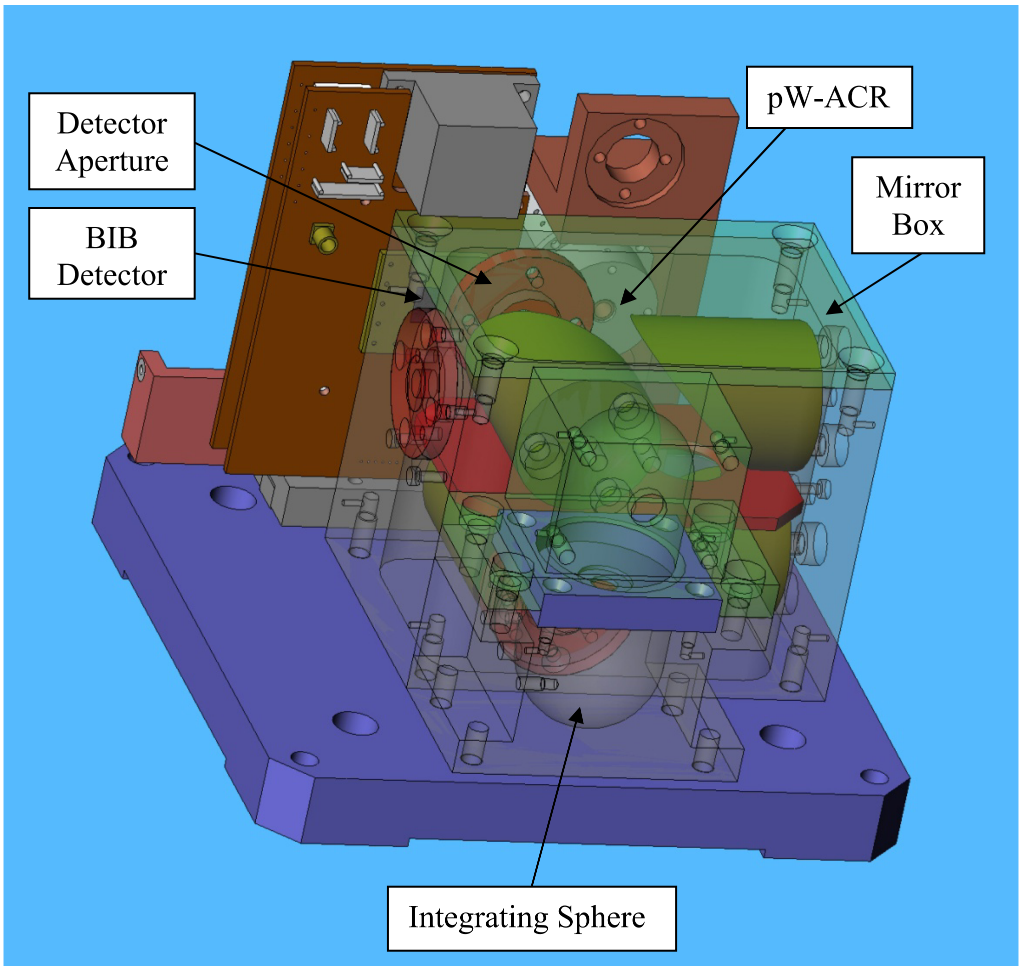

Figure 7. Schematic of the intercomparison assembly for calibrating our secondary standard BIB detectors against the pW-ACR, with all major components labeled. Most component hardware for the assembly has been fabricated, and calibrations will commence once the integrated pW-ACR has been tested and validated.

5. CONCLUSIONS

All the critical components of the pW-ACR, a new radiometer for low power infrared calibrations, have been tested and meet their performance criteria. It is estimated based on the results of these tests that the fully integrated pW-ACR could achieve the 1 fW noise floor for which it has been designed. The hardware for the final integrated pW-ACR is nearly complete, and the intercomparison assembly for calibration of other detectors using the pW-ACR in a 2 K environment has already been designed and fabricated. When operational, the pW-ACR will allow absolute traceability of infrared power down to levels more than three orders of magnitude lower than now possible at NIST.

* The authors would like to thank Jinan Zeng of NIST for reflectance measurements on the pW-ACR receiver cones.

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