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Liquid-Nitrogen-Cooled High T_c Electrical Substitution Radiometer as a Broadband IR Transfer Standard

J. P. Rice and Z. M. Zhang

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Radiometric Physics Division
Physics Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-0001

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J. P. Rice and Z. M. Zhang

Radiometric Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

Abstract

A requirement exists for broadband radiometers that can be used to transfer NIST infrared radiometric scales to calibration laboratories elsewhere. We discuss the design of a liquid-nitrogen-cooled transfer standard radiometer that represents a practical tradeoff between room-temperature and liquid-helium-cooled radiometers. The detector utilizes high-T_c superconductors as temperature sensors for increased sensitivity. Such sensors have already been shown to enable temperature regulation of 100 μK peak-to-peak at 85 K, and have the potential for further improvements by three orders of magnitude. Electrical substitution is used to linearize the response over the dynamic range and to remove susceptibility to sensor aging effects. A reflective light trap is used in conjunction with a gold-black coating on the sensor to enable flat spectral response over a broad infrared band. Ultimately, the radiometer could have a noise-equivalent power of 10 pW/Hz$^{1/2}$, which is sufficient sensitivity to perform 1% uncertainty scale transfers over the milliwatt to nanowatt power ranges.

Keywords

infrared, radiometer, electrical-substitution, high-T_c superconductors, temperature control

1. INTRODUCTION

Currently there are several infrared transfer radiometers that have been developed or are being developed at NIST for various purposes, as shown in Figure 1. Although all these radiometers can be used to transfer a radiometric scale (i.e., radiant power, irradiance, or radiance) they differ in many other respects. Wavelength coverage, temperature of operation, power range, and projected uncertainties in the transfer of radiometric scale are some of the differences. In Figure 1 we have grouped the IR transfer radiometers according to wavelength and temperature of operation. This is a simplified way of demonstrating where requirements are being fulfilled and where there is important need for more development. Electrically calibrated pyroelectric detectors, originally developed at NIST during the 1970's and now commercially available, are the least sensitive but most convenient because they operate at room temperature [1]. At the other extreme are blocked impurity band (BIB) detectors and silicon bolometers. Custom-made BIB detectors are currently being characterized as transfer standards for low-background infrared detection [2]. A silicon bolometer device has been characterized recently as a transfer standard for the IR detector comparator facility at NIST [3]. BIB detectors and silicon bolometers are the most sensitive but must be cooled to temperatures near that of liquid helium. At liquid-nitrogen temperatures (77K), transfer radiometers based on InSb are being developed at NIST [4], but they are limited to wavelengths less than 5 μm. The radiometer proposed here would fulfill the need for a broadband radiometer at 77 K for wavelengths from 5 μm to 20 μm, with the required sensitivity level for most radiometric applications.

2. ABSOLUTE ELECTRICAL-SUBSTITUTION RADIOMETERS

Electrical-substitution radiometers (ESR) are commonly used to establish absolute detector-based radiometric scales [5,6]. They operate by heating a thermally isolated optical absorber with radiant power and then with electrical power in alternate cycles. Using precision thermometry to ensure that an equivalent temperature rise is attained by the two heating methods, a measurement of the electrical power provides an accurate measurement of the radiant power. While some ESR's have been designed to work at ambient temperatures, the most sensitive instruments are cryogenic radiometers cooled with liquid helium. At liquid-helium temperatures (< 4.2 K) the heat capacity of materials such as copper is very low. Thus the optical absorber can be made as a high emissivity cavity while the time constant can be kept short enough to complete a measurement cycle in a reasonable time. Such radiometers, often called active-cavity radiometers, are absolute radiometers since essentially all of the radiative power is converted to heat which is measured by comparison to electrical power. Since they require liquid helium for their operation, however, their use as portable transfer standard radiometers for transferring radiometric scales is fraught with difficulties of using bulky expensive equipment and bearing associated costs.

3. TRANSFER STANDARD ESR AT 77 K

As transfer standards, the operation of an ESR near the temperature of liquid nitrogen (77 K) would offer many advantages. Here the purpose of electrical substitution is not to establish an absolute scale, but rather to provide linearity of the radiometer over a wide dynamic range to enable an accurate transfer of a radiometric scale from a primary facility to a secondary facility. The advantage over a liquid-helium-cooled radiometer is ease of use and operating cost. The heat of vaporization per volume of liquid nitrogen is 59 times higher than that of liquid helium [7], and the price per volume of liquid nitrogen is typically about 60 times lower. Thus the total cryogen cost during operation is thousands of times cheaper for liquid nitrogen operation than for liquid helium operation. The advantage over an ambient temperature radiometer is that cooling from 300 K to 77 K reduces the background radiance by of factor of 230. Thus as a transfer radiometer in the thermal infrared, where the precision of a liquid-helium-cooled radiometer is often not necessary but room-temperature background is not acceptable, a liquid-nitrogen-cooled radiometer would be a welcome addition to satisfy the needs.

3.1 DESIGN

A simplified design for a liquid-nitrogen-cooled ESR to be developed is illustrated in Figure 2. It consists of a temperature sensor and a heater integrated onto a thin sapphire (or silicon micromachined) disk thermally isolated from a heat sink. The disk is coated with a low-mass-density infrared absorbing coating such as gold-black. The temperature sensor is a thin film of $YBa_2Cu_3O_{7-\delta}$ (YBCO) grown on the sapphire with a buffer layer of CeO_2. The heater is a thin film of a resistive alloy such as Ni-Cr. Both the YBCO sensor and the heater are patterned as four-wire resistors.

The operation of the radiometer is as follows. YBCO is a high-T_c superconductor having a sharp resistive superconducting transition near 90 K, as shown in the inset. Thus it provides a very sensitive temperature sensor if its temperature is held near the midpoint of the resistive transition, which we call the operating point. A feedback circuit is used to supply the appropriate power to the heater to keep the sensor, and hence the thermally isolated disk, at the operating point. The feedback electronics consist of an ac bridge to monitor the four-wire resistance of the YBCO sensor, a lock-in amplifier to demodulate the ac signal into a dc signal, and a dc amplifier to drive the heater. The electrical power supplied to the heater is measured as the product of the voltage across the heater and the current through it. With the radiometer shutter closed, a certain amount of electrical power is required to keep the sensor at the operating point. When the shutter is opened, the radiant power illuminating the disk will change, and hence the electrical power supplied to the heater will change in order to keep the sensor at the operating point. The difference in electrical power supplied to the heater is then a measure of the difference in radiant power absorbed by the disk between the shutter open and shutter closed conditions. This balancing between radiant and electrical power provides an inherently linear measure of the radiant power over the full dynamic range of the instrument.

Heat capacities of materials are relatively high at liquid nitrogen temperatures, so it is necessary to minimize the sizes of components which potentially heat and cool during measurements. Thus in the design above we have incorporated a gold-coated reflective light trap in conjunction with the gold-black coating on the disk. In this design, only the disk heats. The radiation enters through a hole in the reflective light trap and most rays are absorbed by the gold-black. The reflective light trap redirects scattered rays toward the gold-black, thus increasing the chances that they will ultimately be absorbed on the disk. It has been shown that the spectral response of gold-black in such a reflective light trap is much flatter than that for gold-black alone [8].

3.2 THEORETICAL PERFORMANCE ANALYSIS

As a first example, consider a design where the disk is at 90 K and the heat sink is held at 77 K by good thermal contact with the nitrogen bath. The maximum power P_{max} that can be measured is determined by

$$P_{max} = G\Delta T, \tag{1}$$

where G is the thermal conductance between the disk and heat sink and ΔT is the maximum allowable temperature difference between the disk and heat sink. Assume that $G = 10^{-4}$ W/K (a practical value) and $\Delta T = 10$ K. Then $P_{max} = 1$ mW, which corresponds roughly to the typical laser power routinely used for calibrations in the High Accuracy Cryogenic Radiometer (HACR), a liquid-helium ESR which serves as the primary standard for optical power in the Radiometric Physics Division at NIST.

The time constant for temperature changes is given by

$$\tau = C/G, \tag{2}$$

where C is the heat capacity of the thermally-isolated components. Assuming that the sapphire disk is 5 mm in diameter, 25 μm thick, and dominates the heat capacities of the thin films, $C \approx 0.15$ mJ/K at 90 K. This gives $\tau = 1.5$ s, which is a practical value.

To estimate P_{min}, the minimum power that can be calibrated at the desired accuracy, we need to know the noise floor power P_{nf}. A typical measurement cycle would take place over a time interval on the order of 100 time-constants. The ability to control temperature over this time interval plays a role in determining P_{nf} according to

$$P_{nf} = G\sqrt{(\delta T_d)^2 + (\delta T_h)^2}\,, \tag{3}$$

where δT_d and δT_h are the temperature stability of the disk and heat sink, respectively. As discussed below, we estimate $\delta T_d \approx \delta T_h \approx 100$ μK over several minutes. Thus Equation (3) yields $P_{nf} = 1.4 \times 10^{-8}$ W. To allow for a relative expanded uncertainty of 1%, $P_{min} = 100 P_{nf} = 1.4$ μW. Thus, this transfer radiometer would enable a scale comparison from milliwatt power levels to microwatt power levels at the 1% relative expanded uncertainty level. This assumes, of course, that other considerations do not degrade the accuracy. This level of sensitivity is roughly equivalent to that quoted for commercially available room-temperature electrically calibrated pyroelectric radiometers [9]. If temperature stability can be made even better, as we discuss below, P_{min} will likewise be lower and the dynamic range will increase.

3.2.1 TEMPERATURE STABILITY

We now consider the temperature stability attainable using YBCO sensors. Peak-to-peak temperature stability of 100 µK over several minutes has recently been achieved by the group of D. Robbes using a YBCO strip and heater in a temperature control feedback loop [10]. The stage being controlled was a cold finger made of an aluminum alloy having C = 0.49 J/K in thermal contact with a liquid-nitrogen bath by a G of 50 mW/K. This stage is akin to what would be the heat sink in our radiometer above. The stability under temperature control was several times better than that achieved by having the cold finger in contact with nitrogen and without controlling the temperature. This suggests that a design involving independent temperature control for both the disk and the heat sink, with a superconductive sensor on both disk and heat sink, would be superior, since by controlling the temperature of the heat sink the fluctuations of liquid nitrogen temperature from effects such as atmospheric pressure fluctuations would be greatly reduced. The change in the boiling point of liquid nitrogen with pressure is about 83 µK/Pa (11 mK/Torr) [7]. Since the disk is further isolated, we would expect to attain as good or better stability for the disk temperature. Thus the assumption of 100 µK temperature stability for both disk and heat sink is conservative.

3.2.2 OPERATING POINT

In the discussion above, we have assumed that the operating point for each sensor is at the midpoint of the YBCO resistive transition. In order to maintain a temperature difference of ΔT = 10 K between heat sink and disk, the two superconductive sensors must have T_c's that differ by 10 K. This presents a challenge, since pure YBCO films typically have a 1 K wide transition at 90 K. The heat sink sensor, which would require T_c

near 80 K, would need to be made from either YBCO doped with impurities to reduce T_c or another high T_c material. An alternative solution is suggested by the experiments of Robbes, where the temperature dependence of the critical current just below T_c is used as a thermometer [10]. The critical current (I_c) is the current that drives the sensor from the superconducting to the normal state. It is a strong function of temperature just below T_c, dropping to zero at T_c. Using a bias reversal technique and the appropriate compensation electronics, Robbes' group demonstrated a method for using this sensitive variation of I_c with temperature to measure temperature over a range of about 5 K below T_c in YBCO. The 100 μK temperature stability quoted above was achieved using this technique a few Kelvin below T_c. Thus, since the operating point does not have to be at T_c, YBCO sensors having identical values of T_c may be useable as both the disk and heat sink sensors.

3.2.3 ULTIMATE LIMITS OF SENSITIVITY

From a consideration of the minimum detectable temperature fluctuation, or noise equivalent temperature (NET), we can determine the ultimate limits on temperature stability and sensitivity. The lowest values of NET measured until now on YBCO sensors are below 1×10^{-7} K/$\sqrt{\mathrm{Hz}}$ [11,12]. This is close to the so-called phonon noise contribution to the NET, which is a result of thermodynamic temperature fluctuations:

$$\mathrm{NET}_{ph} = \sqrt{\frac{4k_B T^2}{G}} \qquad (4)$$

With $G = 10^{-4}$ W/K and $T = 90$ K this is 7×10^{-8} K/$\sqrt{\mathrm{Hz}}$. Thus, for a bandwidth of 1 Hz the ultimate temperature stability is about 70 nK, so it is feasible that we could improve on the 100 μK stability used in our estimate above by more than three orders of magnitude [13]. A temperature stability of 70 nK would lead to a P_{nf} of 10 pW, surpassing the sensitivity of the electrically calibrated pyroelectric detectors by a factor of 1000. At this level of performance, scale comparisons at the 1% relative expanded uncertainty level could be made between milliwatt power levels and nanowatt power levels.

4. CONCLUSION

We have outlined the design and estimated the performance level for a liquid-nitrogen-cooled high-T_c superconductive infrared radiometer that offers a practical tradeoff between cost, convenience, and sensitivity. It will be a broadband detector, will have an ultimate sensitivity of as low as 10 pW, and will be capable of measuring radiant power levels up to 1 mW.

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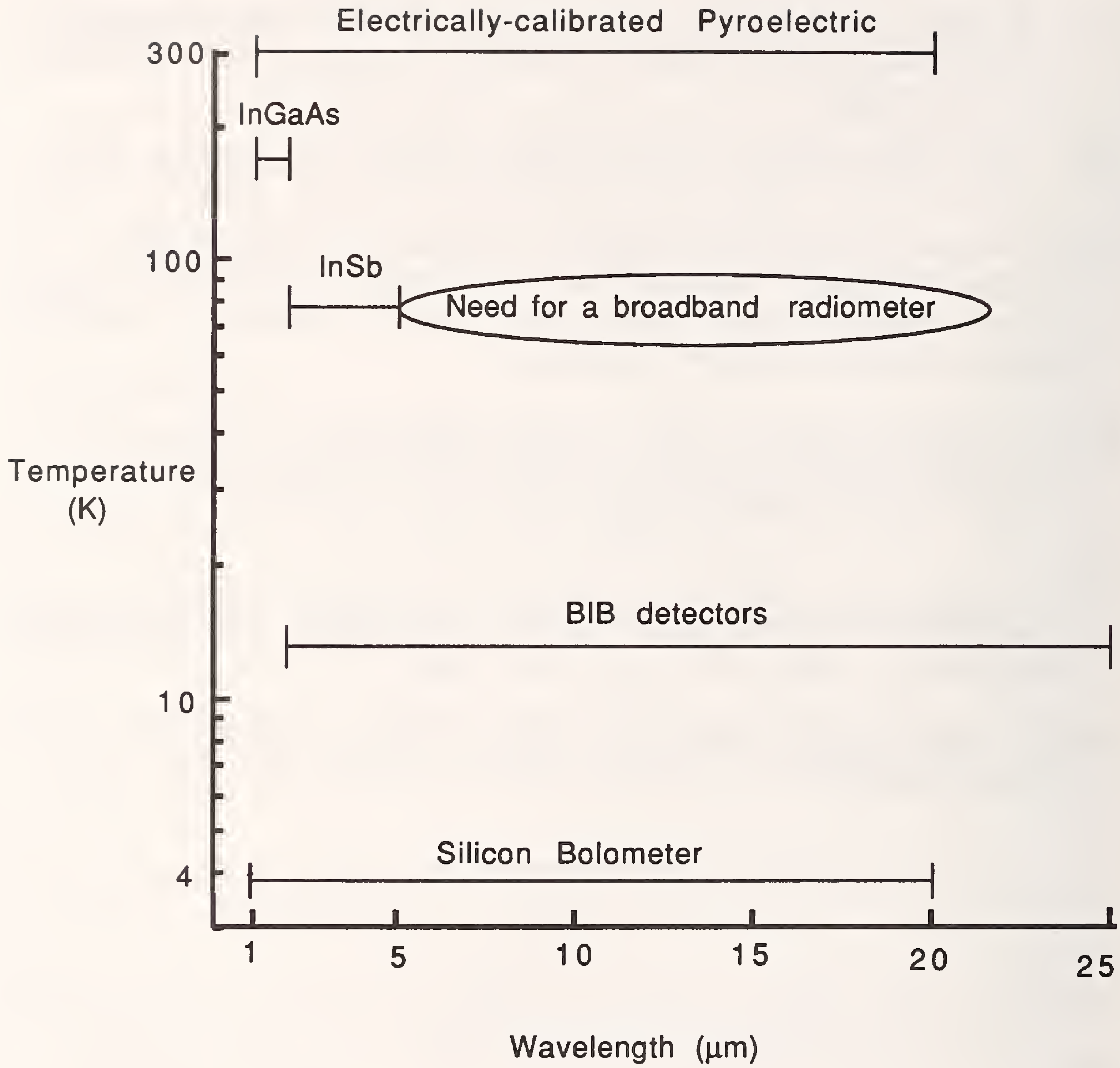

Figure 1. A map of infrared transfer standard radiometers that exist or are being developed at NIST, showing where the proposed broadband radiometer would fit in.

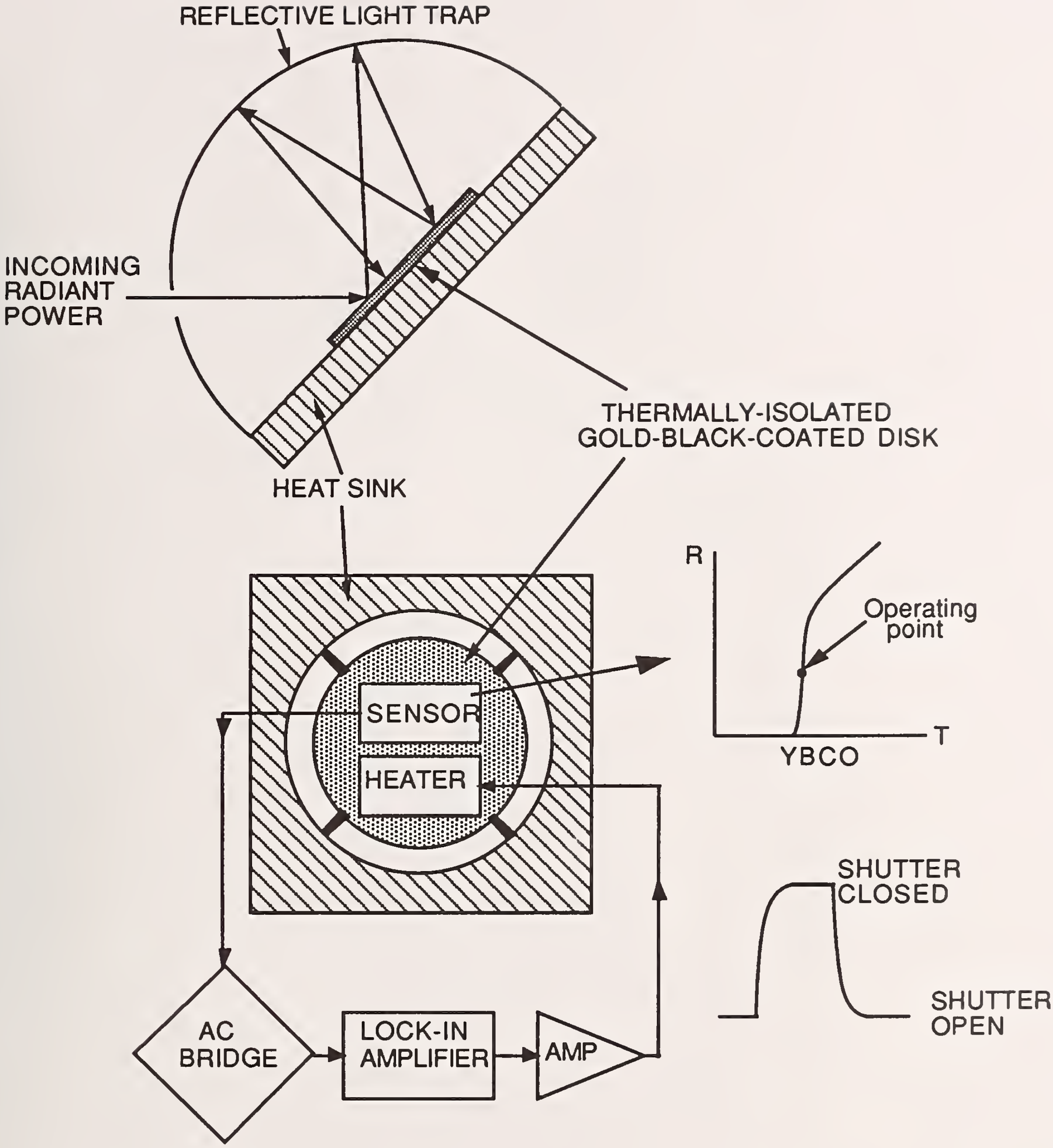

Figure 2. Proposed design for a liquid-nitrogen-cooled high T_c ESR.

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