An electrically substituted bolometer as a transfer-standard detector

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Abstract. An electrically substituted bolometer (ESB) has been developed at the National Institute of Standards and Technology (NIST) to serve as a portable transfer-standard detector over the wavelength range 200 nm to 20 µm. The ESB is designed to provide a direct transfer of the optical power scale from the NIST High Accuracy Cryogenic Radiometer (HACR) to the NIST spectral-comparator facilities in the infrared region, where silicon-photodiode trap detectors cannot be used and where the noise of pyroelectric detectors currently limits the uncertainty. The noise floor of the 8 mm diameter active-area ESB approaches 10 pW/Hz$^{1/2}$ at 15 Hz, corresponding to a detectivity of the order of 10^{11} cm Hz$^{1/2}$/W. This is an improvement by a factor of almost 1000 on that attainable from a similar-sized room-temperature electrically calibrated pyroelectric radiometer (ECPR). The ESB is linear from the noise floor to 1 mW (the power range of the HACR), whereas previous helium-cooled bolometers developed at the NIST have a similar noise floor but are non-linear above about 10 µW and so cannot be directly calibrated against the HACR. Because of its low noise, linearity over a wide dynamic range, and the spectral and spatial flatness of its response, the ESB is finding other applications beyond that which motivated its development.

1. Introduction

Absolute-detector-based radiometry using cryogenic electrical-substitution radiometers has allowed national standards laboratories such as the NIST to establish and maintain high-accuracy primary radiant power scales at power levels near 1 mW [1]. However, many applications, such as power measurements at the output of a monochromator, require measurements of much smaller power levels, near 1 µW or even lower. In such cases, the transfer detector must be linear enough to maintain high accuracy while transferring the scale over this dynamic range. Silicon trap detectors are useful in solving this problem in the limited ultraviolet, visible, and near-infrared spectral ranges where they operate. For longer-wavelength infrared and shorter-wavelength ultraviolet regions, however, thermal detectors are often preferred over quantum detectors because thermal detectors can be made to have a spectrally flat response over a wide wavelength range. For example, the NIST has calibrated pyroelectric detectors against the HACR at 10.6 µm in order to transfer the scale to an Infrared Spectral Comparator Facility (IR SCF) that operates over the spectral range 2 µm to 20 µm [2, 3]. The problem with this approach is that room-temperature thermal detectors, such as pyroelectric detectors, tend to have a noise floor of the order of 10 nW (for a typical 1 cm diameter active area in a 1 Hz bandwidth), which is too high for uncertainties of less than 1 part in 10^2 to be achieved in power measurements of 1 µW or lower.

Helium-cooled bolometers have a much lower noise floor, but the inherent non-linearity resulting from resistance versus temperature of the thermistor begins to be a problem at high power levels. In the case of the silicon bolometer that currently serves as the reference standard at the NIST IR SCF, this non-linearity becomes a problem at power levels higher than about 10 µW [4, 5]. Thus, for example, the scale transfer from the HACR to the IR SCF could not be accomplished through a single transfer radiometer, but required a complex chain involving several detectors and several calibration steps [6].

This motivated us to develop a single transfer radiometer having specifications that would allow a one-step transfer from a relatively high-power primary standard (such as the NIST HACR) to lower-power facilities such as the NIST IR SCF. The response of such a detector must be spectrally flat, preferably from the visible to 20 µm, be spatially flat over an active area approaching 1 cm in diameter, have a noise floor below 50 pW, be able to measure radiant power up to 1 mW, and have linearity over this dynamic range. As the detector is to be used in a room-temperature environment, its response must be fast enough to allow the source to be chopped at a reasonably high frequency (e.g. 15 Hz) so that background subtraction can be carried out. This paper describes the design and basic performance of such a detector: an electrically substituted bolometer (ESB).

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The ESB can be considered as a combination of two existing technologies: (i) the type of liquid-helium-cooled silicon bolometer described in [3-6]; (ii) the type of chopper-synchronized electrical substitution described in [7-8] and previously used in ECPRs. Thus, the ESB is basically a low-noise silicon bolometer with the addition of electrical substitution to provide stability and linearity over an extended power range.

2. Design of electrically substituted bolometer

The ESB detector consists of a receiver element suspended from a copper heat sink (Figure 1). The heat sink serves as a mount for the structure, and incorporates a heater and a calibrated germanium resistance thermometer so that its temperature can be controlled independently of the receiver element. The receiver element is built on a 50 µm thick, 1 cm diameter sapphire substrate. It is composed of an optical absorber/electrical heater and a temperature sensor.

The optical absorber is a film of gold-black, about 30 µm thick, deposited on the front of the substrate. Two gold-over-chromium contacts, each about 500 µm in diameter, are deposited under the gold-black film and make electrical contact with it. Two NbTi electrical leads are soldered to each contact, allowing the gold-black film to act as a four-wire resistor. Thus the gold-black film can be used as an electrical heater (for electrical substitution) as well as an optical absorber. The NbTi leads become superconducting at a temperature below about 9 K, yet have very low thermal conductance compared with the temperature sensor leads and thermal-shunt wire discussed below.

A thin film (20 nm) of aluminium is deposited on the back of the substrate. The gold-black film absorbs most of the incident light over a wide spectral range, from ultraviolet to infrared. The small fraction of incident light transmitted through the gold-black film and the substrate is reflected by the aluminium film for a second pass through the substrate and gold-black film, thereby increasing the overall absorptance.

The temperature sensor is a heavily doped silicon-chip thermistor, approximate dimensions 300 µm × 300 µm × 300 µm. It is fixed to the back of the substrate with epoxy resin and has two electrical leads. One of these leads is electrically grounded at the heat sink; the other is electrically isolated. Both are thermally grounded to the heat sink, and act as a thermal link between the receiver element and the heat sink. However, the thermal conductance provided by these leads is not sufficient to cool the receiver element to its operating temperature (5 K to 6 K) in the presence of approximately 1 mW of ambient infrared background when the heat sink is at its nominal operating temperature of 4.2 K. Thus an additional copper wire, diameter 200 µm, was added between the receiver element and the heat sink to act as a thermal shunt. The dimensions of this thermal-shunt wire control the value of the thermal conductance from receiver element to heat sink. This is set at about 1 mW/K, a value determined by considering the trade-off between operating temperature, bolometer sensitivity and time response.

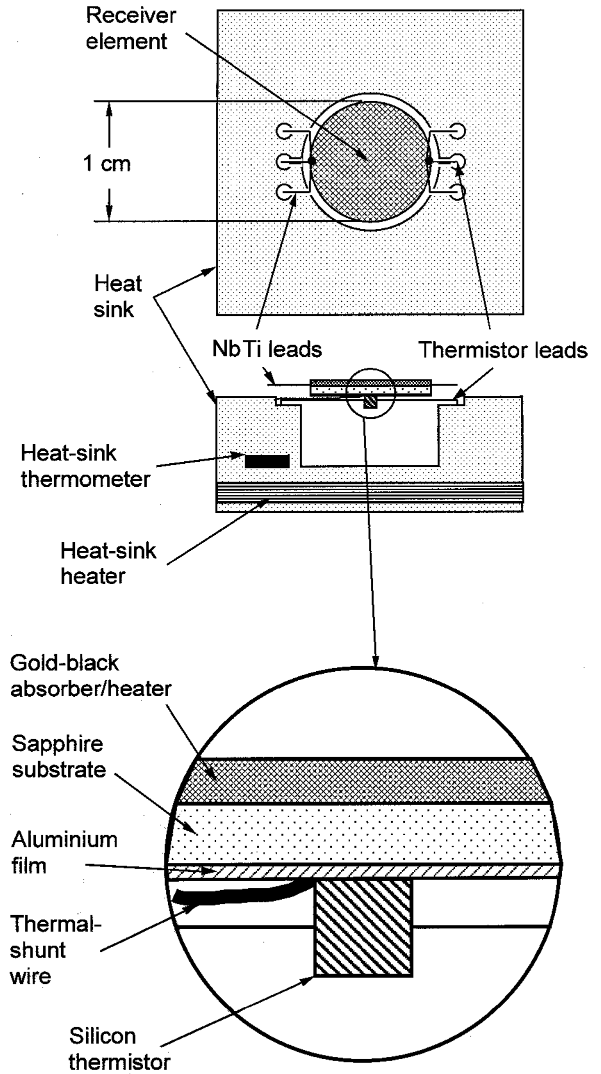

Figure 1. Schematic of the detector element of the NIST electrically substituted bolometer. Above: plan view; below: enlarged cross-section of the receiver element.

The receiver element is supported mechanically from the heat sink by the thermal-shunt wire, the two thermistor leads, and the four NbTi leads. The ESB detector is mounted in a portable liquid-helium cryostat with a wedged KBr window. The window is wedged to prevent interference effects when the ESB is used with lasers, as in calibrating it with respect to the HACR. Scattered light is minimized by a set of diffuse-black-painted baffles on the liquid-helium-cooled stage, and a similar baffle on the liquid-nitrogen-cooled stage. A high-precision aperture, diameter about 8 mm, is mounted at the end of the baffle tube on the helium stage, about 2 mm in front of the ESB receiver element. The field-of-view is designed to allow an $f/4$ converging beam to be focused on to the receiver element and to underfill the detector. An Infrared Laboratories LN6-C JFET preamplifier, with a cooled first stage, is used to amplify the signal from the silicon thermistor. A 10 MΩ load resistor, mounted on the back of the ESB heat sink, is connected in series to the silicon thermistor to set the bias current.

3. Principle of operation

The major improvement in the performance of the ESB compared with traditional bolometers is that the gold-black absorber film can also be used as an electrical-substitution heater, so the principle of operation can be fundamentally different. Traditional bolometers operate in an open-loop mode, where the chopped incident optical power causes heating and cooling of the receiver element at the chopper frequency. This temperature oscillation leads to a modulation of the thermistor resistance, which is monitored as an amplified modulated voltage signal across the biased thermistor. However, the ESB operates in a closed-loop mode, where an external servo loop attempts to keep the temperature of the receiver element constant by turning the electrical heater power on and off. The amplitude of this substituted electrical power is determined by negative feedback within the electronic servo loop that nulls the modulated signal across the silicon thermistor. When the null is achieved, the temperature of the receiver element is constant and the substituted electrical power is very nearly equal to the incident optical power.

This principle of operation is similar to that of the commercially available electrically calibrated pyroelectric radiometer developed at the NIST in the 1970s [7, 8]. The main conceptual difference is that bolometer response is roughly proportional to temperature, whereas pyroelectric response is roughly proportional to temperature changes. As the light is chopped in both cases, this makes no difference except in the relative phase between the detector response signal and the chopper reference signal. For the prototype performance tests described here, a commercial ECPR controller, the Laser Probe RS-5900, was used to control the ESB in closed-loop mode. The only modification required was that of the phase-adjustment circuit in order to allow a wider range of phase shift between detector signal and chopper signal.

As the temperature dependence of the silicon thermistor resistance is non-linear, the detector response for a traditional bolometer (or for the ESB operated in open-loop mode) is in general a non-linear function of the radiant power. Temperature drifts of the bolometer and the preamplifier circuit also affect the measured signal from the silicon thermistor, and extensive corrections for these effects have been required in previous attempts to use traditional bolometers for accurate radiometry [3-6]. The ESB operated in closed-loop mode avoids these problems, as the silicon thermistor is operated at a fixed temperature and the modulated signal is instead the electrical power applied to the gold-black heater. As this power is monitored by the product of the measured voltage across the heater and the measured current through the heater, the linearity is determined simply by the linearity (which can be quite high) of the analogue-to-digital converters used for these electrical measurements.

As with other electrical-substitution radiometers, such as ECPRs and active-cavity radiometers, there are a number of small effects that would need to be quantified and corrected in order to use the ESB as an absolute radiometer [9]. These include non-unity optical absorptance and electrical-optical non-equivalence. However, our present motivation is to use the ESB as an inherently linear transfer radiometer from an existing absolute radiometer for relatively high power levels (the HACR) to other facilities operated at relatively low power levels, rather than as an absolute radiometer.

4. Performance tests

As a demonstration of basic performance, Figure 2 shows the open-loop thermistor response of the ESB to a He-Ne laser beam (632 nm) chopped at 15 Hz. The frequency where the response is half of maximum is 30 Hz. Thus at 15 Hz the open-loop waveform shows that the bolometer temperature is modulated strongly but the frequency is still too high for the temperature of the receiver element to reach equilibrium. At lower frequencies, this waveform becomes more like a square wave, similar to the waveform seen from a traditional bolometer.

The closed-loop thermistor response to the same chopped He-Ne laser beam is also shown in Figure 2. The thermistor response is nearly completely nulled, as desired. Figure 3 shows the electrical power applied to the electrical-substitution heater.

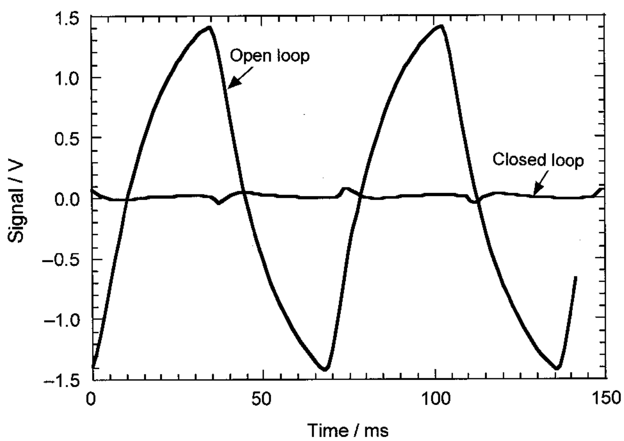

Figure 2. Open-loop and closed-loop thermistor signals.

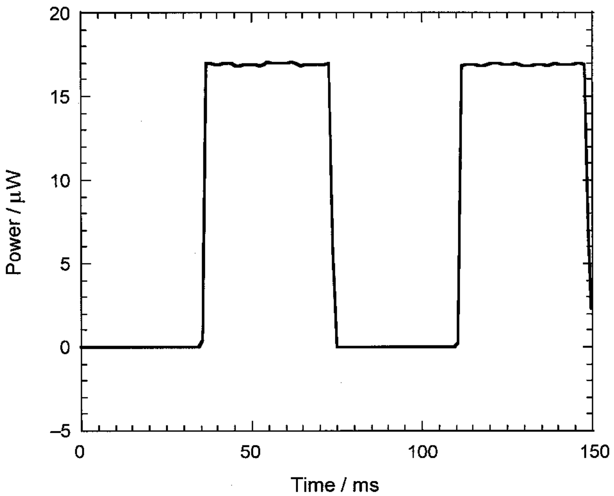

Figure 3. Closed-loop heater power with the RS-5900 controlling the ESB.

Open-loop noise performance is considered to be a benchmark for closed-loop noise performance. Preliminary open-loop noise measurements of the ESB showed a noise-equivalent power (NEP) of 32 $\mathrm{pW/Hz^{1/2}}$ at 15 Hz with a bias current of 9.4 μA. As a preliminary check of the closed-loop noise performance, the ESB was operated at the output of the IR SCF monochromator tuned to 3.7 μm using a lamp chopped at 15 Hz as the input source to the monochromator. The power measured by the ESB was of the order of 600 nW, but the read-out resolution of the RS-5900 controller is limited to 1 nW. During a 4 hour period when the lamp was believed to be sufficiently stable, the noise and drift of the power was below the 1 nW digitization-limited resolution. That is, the bolometer noise, expected to be of the order of 10 pW to 100 pW based on the open-loop measurements, could not be seen in this test. The next step in the development of the ESB will be a higher-resolution equivalent of the RS-5900 controller so that full advantage can be taken of the low noise floor of the ESB.

Spatial response uniformity and spectral reflectance measurements on the ESB have also been performed, showing spectral and spatial flatness well below the level of 1 part in 10^2 [10].

5. Conclusions

An electrically substituted, helium-cooled silicon bolometer has been developed. Preliminary measurements of open-loop noise and responsivity show that it works as expected. The bolometer was operated successfully in closed-loop electrical-substitution mode using a controller designed for ECPRs, with a noise floor consistent with the open-loop measurements. The next step is to replace the RS-5900 controller with a higher-resolution equivalent that will allow the ESB to take full advantage of its low noise. After more detailed characterization, it will then be calibrated against the HACR at a relatively high power level and will be used as a reference detector at relatively low power levels.

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Note. References are made to certain commercially available products in this paper to adequately specify the experimental procedures involved. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these products are the best for the purpose specified.

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