Characterization of a High Sensitivity Composite Silicon Bolometer

G. Eppeldauer, A. L. Migdall and C. L. Cromer

Abstract. We have measured the electrical and radiometric properties of a cryogenic bolometer/amplifier which is intended for use as a transfer standard in an infrared spectral comparator facility under development at the NIST. We have found its sensitivity to be ~20 pW, instability <1%, responsivity $\sim 1{,}7 \times 10^6$ V/W, spatial nonuniformity <1 % and nonlinearity <1 % over five decades. These results show that this device can be used for its intended purpose as an IR detector transfer standard.

1. Introduction

A facility to characterize detectors in the 2 μm to 20 μm spectral region is currently under construction at the NIST. This facility requires a transfer detector which can be calibrated against an absolute device such as the High Accuracy Cryogenic Radiometer at the NIST [1]. The desired properties of such a transfer standard detector are wide dynamic range, good linearity, high stability and a relatively flat spectral response. Since we also intend to use this detector with a Fourier transform spectrometer, we need a relatively high frequency response to shorten measurement times. A bolometer [2] was chosen to fill these needs. We have measured the above properties to determine the accuracy with which radiometric measurements can be made using this bolometer.

2. Description of the Bolometer Design

A bolometer consists of an absorber attached to a thermal sensor. Incident radiant energy heats the absorber and is detected as a temperature rise. The bolometer we describe here [3] was designed to have low heat capacity and low noise allowing for large detector area, high frequency response, and high sensitivity. The absorber is a 5 mm diameter by 0,05 mm thick sapphire disk with its front surface coated with gold black for high absorption and spectral flatness [4]. A doped Si chip is bonded to the back of the sapphire disk. Temperature changes are seen as resistance changes of the Si chip. The electrical leads of the Si chip also provide the thermal link between the bolometer and the cold plate.

The bolometer package is attached to a liquid He cooled gold-coated Al plate inside a vacuum Dewar, so the temperature of the bolometer detector and its surroundings is near 4,2 K. A cold 4 mm aperture is positioned in front of the absorber. As shown in Figure 1, the silicon sensor is biased with a current I_B, determined by the bias voltage V_B, the load resistance R_L, and the resistance of the silicon element R_D (at the operating temperature). Thus, a change in R_D will yield a change in the detector voltage V_D. The cooled JFET and amplifier package, which are built into the bolometer Dewar, are also shown in the circuit diagram.

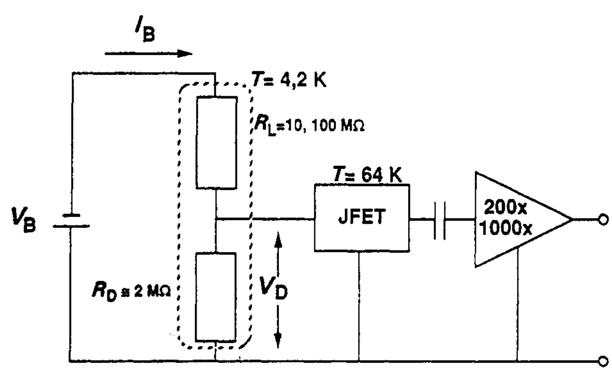

Figure 1. Electronic schematic of the bolometer.

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The dc operating point of the bolometer determines its linearity, sensitivity and responsivity. The bias voltage and detector voltage can be written as

$$V_B = I_B (R_L + R_D),$$
$$V_D = I_B R_D = V_B R_D/(R_L + R_D). \quad (1)$$

The bolometer electrical circuit is linear for $R_L \gg R_D$. In that case, the change of the detector voltage is

$$\Delta V_D = I_B \Delta R_D = I_B \alpha R_D \Delta T, \quad (2)$$

where $\alpha = \Delta R_D / R_D \Delta T$ is the temperature coefficient of the bolometer resistance. Equation (2) shows that the bolometer responsivity and sensitivity can be increased by increasing the R_D and I_B (or V_D).

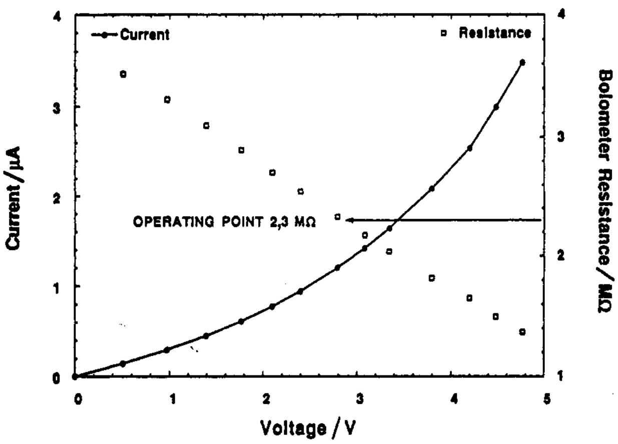

Figure 2. Bolometer I/V curve: the bias current and resistance of the Si chip are shown versus voltage. The 1 σ uncertainty for these curves is estimated to be 1 % as determined from short-term stability measurements.

Figure 2 shows the dc load characteristic of the bolometer with R_D ranging from 1 MΩ to 3,6 MΩ. The operating point was chosen for convenience of a battery supply and to reflect the competing requirements of (1) which requires that R_D must be smaller than R_L to maintain linearity, and (2) which shows that R_D must be large to maximize sensitivity. For all of our tests, the bolometer was operated with $I_B = 1{,}3$ μA yielding a resistance of 2,3 MΩ. (The sensitivity, which is proportional to $R_D \times I_B$ or V_D, might be improved somewhat by increasing the bias, although self-heating and battery drain could become problems. This will be the subject of future work.) A 10 MΩ load resistor with $V_B = 15{,}5$ V was used for most of the measurements.

3. Measurements

We measured the following properties of the bolometer: dc output stability, ac frequency response, ac stability, noise equivalent power (NEP), responsivity and spatial uniformity. We also measured the linearity of the entire measurement system as well as the linearity of various subsets of the system. For these tests, the Dewar was prepared for operation as follows. First, the Dewar was pumped to $\sim 3 \times 10^{-4}$ Pa, then both the He and N_2 reservoirs were filled with liquid nitrogen (LN_2) for initial cooling. Once the Dewar was precooled, the LN_2 in the He reservoir was replaced with liquid He and left for ~ 12 h to equilibrate. The LN_2 reservoir was then topped off before measurements began.

The dc stability of the detector was measured by recording the output of the cooled JFET (see Figure 1) with respect to time. For this measurement the only input was the room background radiation. After an initial 20 min period, the voltage varied by less than 1 % over 1 000 min. At the end of this time the cryogenic fluid was nearly gone, causing a sharp change in output. With the detector window shielded to block room radiation, the detector voltage was larger and its variation was smaller, 0,4 % over the same 1 000 min period.

The frequency response of the bolometer below 111 Hz was found to be flat to within the 2 % resolution of this particular measurement. The 3 dB upper rolloff point is at 250 Hz. The ac stability of the

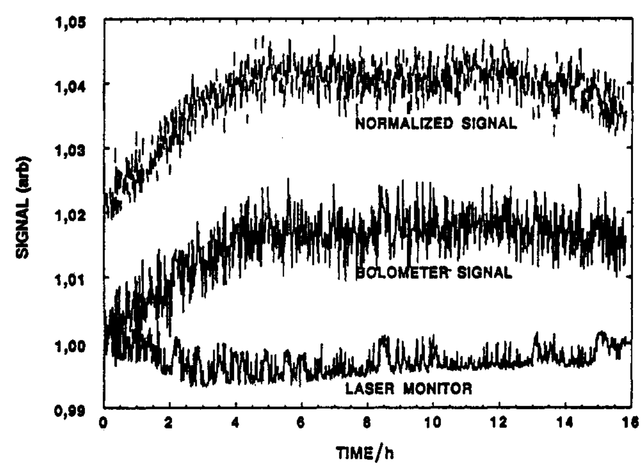

Figure 3. AC stability after LN_2 fill: bolometer output versus time with chopped 633 nm light incident on detector.

bolometer is shown in Figure 3 for a 632,8 nm laser beam chopped at 100 Hz. A silicon photodiode monitor detector, positioned upstream of the chopper, was used to monitor beam changes and normalize the results to the input laser power. The bolometer/amplifier required 4 h to reach equilibrium, after which the signal varied less than ±0,25 % for 11 h.

The linearity of the entire system was measured. The system was also measured with a silicon photodiode radiometer substituted for the bolometer, allowing the linearity of the bolometer itself to be extracted. In addition, the linearity of the bolometer's built-in amplifier was tested separately.

Linearity was determined by measuring the transmittance of a single neutral density filter at dif-

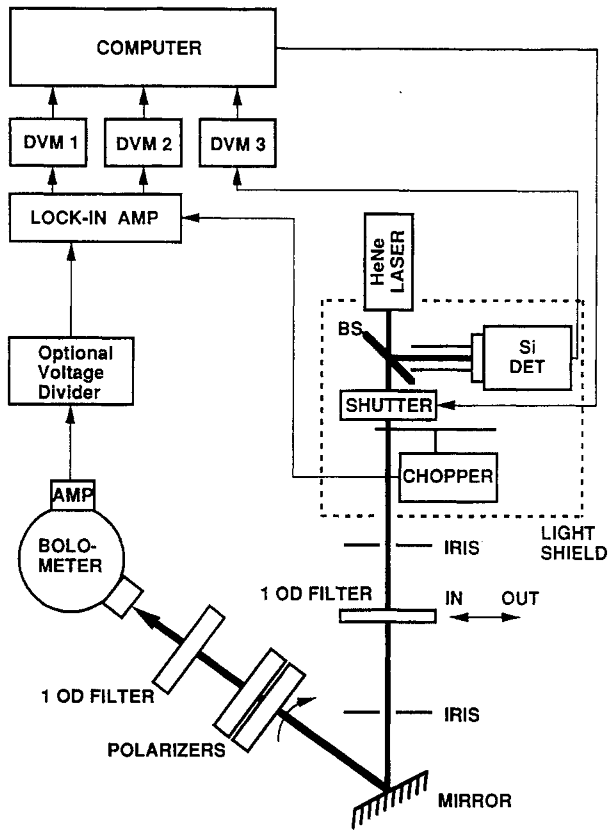

Figure 4. Linearity measurement setup.

ferent incident optical power levels. Figure 4 shows the measurement setup. The chopped laser beam underfilled the 4 mm limiting aperture in front of the bolometer detector. The neutral density filter (nominal transmittance of 10 %) was moved into and out of the chopped beam at various laser power levels. The power levels were set using a pair of polarizers and an additional neutral density filter located in the beam in front of the bolometer. The upstream polarizer was varied while the downstream polarizer remained fixed so that the polarization of the beam at the bolometer did not change. The laser power was monitored with a silicon photodiode radiometer via a beam splitter. A shutter was located between the beam splitter and chopper. Since all chopped radiations are measured by the bolometer, the chopper was located close to the laser and shielded with a light-tight box which also covered the shutter, the beam splitter, and the monitor detector. The output voltage of the bolometer was connected to a lock-in amplifier, either directly or through a voltage divider. The analogue output of the lock-in amplifier and the output voltage of the monitor radiometer were converted into digital signals using HP3456A voltmeters and recorded by a computer data system.

Using the above scheme, the linearity of the electronic portion of the measurement system was checked by replacing the bolometer with a silicon photodiode radiometer of excellent linearity [5]. Using this configuration, filter transmittance was measured as the incident power was varied over a three-decade

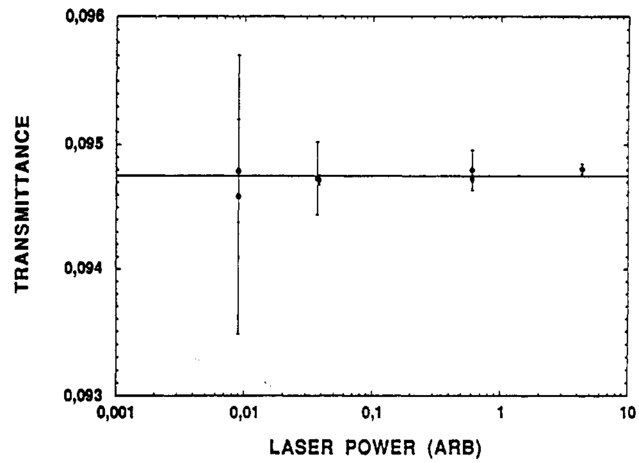

Figure 5. Linearity of system using the Si detector substituted for the bolometer. The transmittance of a filter was measured at various input laser levels. The error bars are the standard deviation of sets of repeated measurements. The double points are two data sets taken at different times. The average of all of the data is 0,094 74 with $\sigma = 0{,}000\,08$.

range. The result, seen in Figure 5, shows a high end nonlinearity of less than 0,1 %. This means that the entire measurement system (other than the bolometer) has good linearity as the incident power at the silicon detector varies over at least four decades. The results of the linearity measurements using the bolometer are

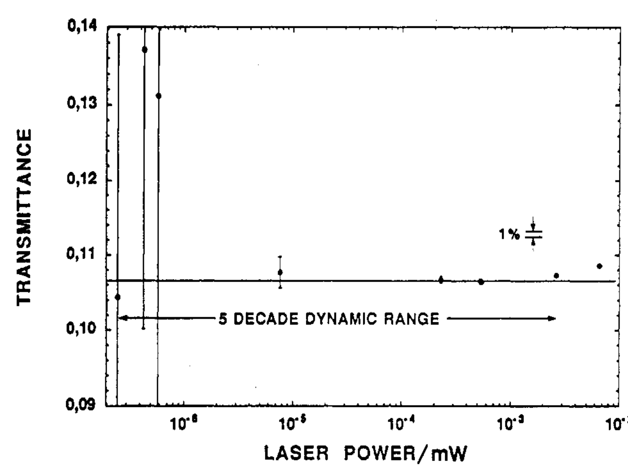

Figure 6. Linearity of the bolometer as input laser power varies over five decades (equals four decades at 1 OD filter).

shown in Figure 6. We see that the nonlinearity exceeds 1 % when the power at the bolometer exceeds $\sim 5\ \mu W$. At the low power end of the curve any nonlinearity is less than the noise as represented by the error bars. These results show a five-decade linear power range of the bolometer. Since the high power ends of both data sets (Figures 5 and 6) correspond to roughly the same signal level at the lock-in input, the nonlinearity of the bolometer measurement must originate in the bolometer/amplifier rather than the rest of the measurement system.

We separately checked the gain linearity of the bolometer's built-in amplifier using a sine wave generator. The amplifier's nominal gain was 1 000. A chop frequency of 124,6 Hz was chosen because the sine wave generator was more stable at that frequency than at lower frequencies. The results showed the actual gain was 784,23 with 0,04 % standard deviation for a range of amplifier output voltages less than 5,5 V_{rms}. Above this output level, we saw a sharp onset of saturation. The bolometer transmittance tests showed nonlinearity in the region below this amplifier saturation level. This indicates that the observed nonlinearity is inherent in the detector itself. We made one measurement using a 100 MΩ load resistor with $V_B = 130$ V to see if linearity could be improved. Consistent with the previous measurement, no significant change was seen, indicating that the bolometer's electronic circuit was not limiting the linearity.

As additional verification of the electronic portion of the measurement system, we calibrated the lock-in amplifier as a single unit against a sine wave generator. The calibrations were made over three decades, at 100 mV, 10 mV, and 1 mV full-scale ranges of the lock-in amplifier. We found that if the sensitivity range of the lock-in was matched to the output signal of the generator, the linearity error was 0,1 %.

We used the statistical noise of the transmittance measurements to determine the sensitivity of the bolometer. The NEP was calculated from the signal-to-noise ratios of the transmittance measurements and a measurement of the laser power. At very low power levels the NEP is about 20 pW. The integration time for these measurements was about 1,7 s.

The responsivity of the bolometer/amplifier was found to be $\sim 1{,}7 \times 10^6$ V/W with the bolometer's built-in amplifier gain set to 200. We measured the spatial uniformity of the bolometer by scanning a small laser spot across the antireflection-coated glass bolometer entrance window. The variation as shown in Figure 7 was less than 1 %, although there are some sharp variations visible at about the 1 % level. We believe that these are due to scratches in the gold black coating that occurred during assembly. Careful recoating should reduce this variation.

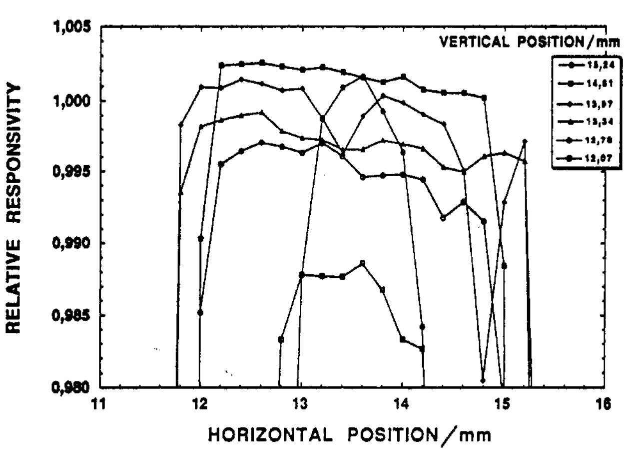

Figure 7. Spatial dependence of bolometer response using AR-coated glass window on the bolometer entrance port.

4. Conclusions

We have measured the electrical and radiometric properties of a cryogenic bolometer. We have found its sensitivity to be ~ 20 pW, instability < 1 %, responsivity $\sim 1{,}7 \times 10^6$ V/W, and spatial nonuniformity < 1 %. The nonlinearity was < 1 % over five decades and limited by the detector itself. This nonlinearity is most probably due to the variation of the detector resistance with voltage (i.e. nonlinearity in the I/V curve). We will use these results to make a number of improvements. An independent temperature sensor on the cold plate will allow better monitoring of stability. For IR work we will need to install an optical-quality infrared window. These results show that this device will be useful for its intended purpose as an IR transfer standard although there are still a number of properties to be studied, such as spectral reflectance of the gold black coating, absolute responsivity and window effects.

Note. Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

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