IR Detector Spectral Responsivity Calibration Facility at NIST

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ABSTRACT

The National Institute of Standards and Technology (NIST) is developing a facility to provide absolute responsivity calibrations of detectors in the 2 to 20 µm spectral region. The goal is to tie the measurements to NIST's primary radiometric scale with a 1σ uncertainty of ~5%. The system uses chopped thermal IR sources, a room temperature prism/grating spectrometer for spectral selectivity with 1-2% spectral resolution and a cryogenic bolometer as a transfer standard detector. The composite design bolometer has an absorbing surface 5 mm in diameter, a nonlinearity <1% over 5 decades and a responsivity of $\sim 1\times10^4$ V/W without amplification. This bolometer is being calibrated against the High Accuracy Cryogenic Radiometer, the nation's primary standard for optical radiometric measurements. The bolometer's spectral response will also be measured using the Low Background Infrared facility at NIST, the nation's primary blackbody calibration facility.

1. INTRODUCTION

A facility to characterize detectors in the 2 to 20 µm spectral region with a 1σ uncertainty goal of 5% is currently being developed at the National Institute of Standards and Technology (NIST). This facility requires a bright, stable IR source, a high rejection spectrally selective element and a transfer standard detector which can be calibrated against absolute devices available at NIST, such as the High Accuracy Cryogenic Radiometer (HACR) [1] and the absolute radiometer in the Low Background Infrared (LBIR) facility [2] (see Fig. 1). The IR radiation is chopped and detected using a lockin amplifier system and recorded by computer. Two radiation sources have been tested, a fairly common ceramic thermal IR source and a source new to IR work, an Ar arc discharge source originally developed for the UV. A prism/grating spectrometer constructed specially for this project is used for wavelength selectivity. The device uses a KRS-5 prism to cover the entire spectral range. The design specifications were 1% spectral resolution, f/4 optics, and high rejection of out of band radiation. The transfer standard detector, a composite type silicon resistance bolometer, was designed to have wide dynamic range, good linearity, good stability and a relatively flat spectral response. Since we also intend to use this detector with a Fourier transform spectrometer, we require a relatively fast response time.

This project was motivated by the fact that it has been difficult to provide spectral response calibrations for detectors in the IR because of the relatively low spectral intensity output of thermal sources. This problem has become more important as solid state detectors that need to be calibrated for spectral response are becoming more available for the IR range. Until recently, most IR calibrations have involved spectrally flat detectors and broad band sources where a Planckian output distribution is assumed and the temperature is determined independently. The development of higher temperature blackbodies with temperatures fixed to the freezing point of metals such Al at 933 K, Ag at 1235 K and Au at 1337 K and even higher temperature variable temperature black bodies [3,4] has improved the problem of low spectral output somewhat, but spectral calibrations in the IR still suffer from low signal to noise ratio. Our work attacks this problem from both ends. First, we make use of recent advances in cryogenic detector technology which have resulted in significantly increased detector sensitivities. Second, we use even higher temperature sources. To make use of the improved signal to noise ratio, higher accuracy standards are required. Since we have very high accuracy absolute cryogenic detector standards in-house (such as the HACR and the LBIR), and it has been demonstrated recently that detector standards can be more accurate than source based standards [5], we have chosen to tie our calibrations to standard detectors rather than standard sources. To our knowledge, only two other facilities have set up detector based spectral IR scales [6,7]. Both of these facilities employ pyroelectric detector transfer standards which have less sensitivity than the bolometer used in our facility.

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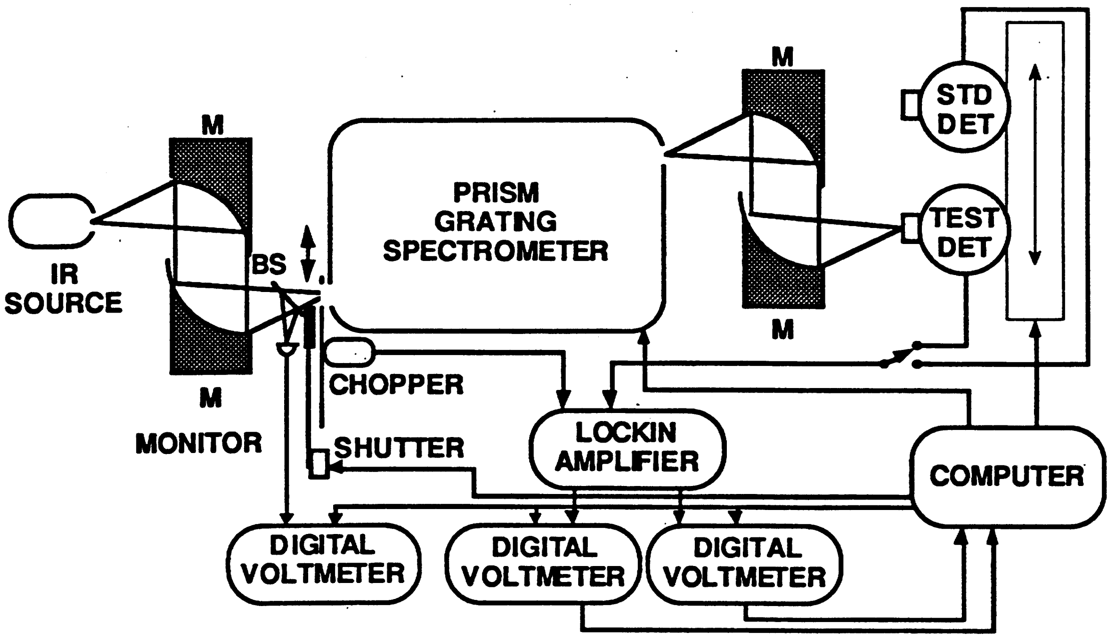

Fig. 1 Overall detector calibration facility schematic. The beam splitter and parabolic mirrors are labeled BS and M, respectively.

2. APPARATUS

2.1. IR source

Two types of thermal IR sources have been tested and their characteristics compared for use with this measurement system. The first source used was a commercial ceramic IR element consisting of a coil of wire imbedded in cement to increase spatial uniformity. The source is designed to operate at ~1500 K using 55 W of electrical power supplied by a constant current source with an output light ripple of 0.05% rms. The emissivity, according to the manufacturer, varies from ~0.1 to 0.95 over the 2 to 20 µm region. Since the source and spectrometer are just required to provide stable spectral radiation to allow comparison between the unknown and transfer standard detector, this emissivity variation is not of critical concern. Of course the emissivity should be as high as possible to improve the overall signal to noise ratio of the measurement.

The second source used was an argon plasma arc discharge [8]. The device consists of several (1 to 5) stacked electrode plates separated by insulators all with a common bore of 4 mm. The two versions that we tested, using 3 and 5 plates, are referred to as the argon mini-arc and the argon maxi-arc respectively [9]. The practical difference between these two versions is that the mini-arc can handle up to ~1 kW of electrical power, while the maxi-arc has a longer plasma discharge region and can handle up to 10 kW. In both versions, argon gas is introduced into the central region of the bore and exhausts out of both ends. (This windowless design eliminates any source spectral power variations caused by degradation of the window.) The temperature of the plasma is estimated to be between 11000 K and 14000 K [8]. Although the brightness in the IR would only approach the output of a blackbody at this temperature if the plasma were optically thick (which it is not), the source was found to be capable of higher output than the ceramic IR element. This source does contain considerable spectral line structure, but because detector calibrations require relatively low spectral resolution this structure should not affect our results. This structure and other tests are discussed later.

2.2. Spectrometer

The double spectrometer designed specially for this project, uses a prism and a grating positioned independently by motorized drives with encoders for accurate position sensing under computer control. The prism spectrometer section provides bandwidth limiting and order sorting, while the grating determines the final spectral resolution of the instrument.

Rejecting out of band radiation is important with thermal sources so that when the spectrometer is tuned to the tail of a thermal distribution, leakage of the rest of the distribution does not swamp the signal of interest.

The prism section uses a KRS-5 prism with a gold coat on the back surface to double pass the radiation for double dispersion. KRS-5 was chosen for the prism because it could provide the necessary dispersion and cover the entire spectral region without requiring a prism change. Also, since it is not hygroscopic, it does not require protection from humidity.

Two gratings with groove spacings of 75 lines/mm and a 150 lines/mm are used to cover the intended spectral range. While only one mm diameter entrance and exit apertures have been used so far, apertures as small as 0.1 mm are available to give the best match to the active areas of the detectors to be calibrated. The radiation is imaged within the spectrometer using 4 gold coated off-axis parabolic mirrors. The radiation can be imaged into and out of the apertures with either ZnSe lenses or a reflective system made of two gold coated off-axis paraboloids. These optics match the f/4 acceptance angle of the spectrometer and transfer standard detector. The spectral resolution, wavelength accuracy, repeatability, throughput and slit width of the spectrometer have been tested. The spectrometer is enclosed to allow dry air purging.

2.3. Transfer standard

A bolometer was chosen for the transfer standard detector after considering the many competing requirements for this application. The early design and development of this bolometer is described elsewhere[10,11], so here we give an overview of that work, and concentrate more on the latest modifications and tests. This facility requires a transfer standard detector that can cover the 2 to 20 μm spectral range with high efficiency, relatively flat spectral response and good stability of response. It must be able to accurately measure the output of the spectrometer system which ranges from a maximum of about 1 μW to signals less than 1 nW. It must be able to operate at power levels compatible with the primary standards to which it must be tied, the LBIR facility's radiometer and the HACR. The former requires power at about the 1 μW level, while the latter has a 1σ uncertainty of ~0.004% at the milliwatt level [12]. This results in a 1σ uncertainty of ~0.4% at ~10 μW, which is acceptable for this work.

Since we also intend to use this detector with a Fourier Transform Infrared (FTIR) spectrometer, the response speed must be fast enough to allow spectral scans within reasonable periods of time. To achieve this, a minimum design speed of 100 Hz was chosen.

To meet these requirements, a low thermal mass composite bolometer design was chosen. A bolometer consists of a radiation absorber attached to a thermal sensor. Incident radiant energy heats the absorber and is detected as a temperature rise. The bolometer we describe here was supplied by a commercial vendor and subsequently modified by us [10,11]. It has 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 .05 mm thick sapphire disk with its front surface coated with gold black for high absorption and spectral flatness [13]. Gold black was selected for the absorbing coating, as opposed to black paints or resistive metal films because it has an extremely high ratio of absorptivity to thermal mass, so that a coating can be put down which is thick enough to allow most of the incident radiation to be absorbed without increasing the thermal mass too much. 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 (subsequently referred to as a silicon resistance thermometer, SRT) 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 Fig. 2, 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 AC amplifier package which are built into the bolometer dewar are also shown in the circuit diagram.

Since the temperature of the bolometer can affect its responsivity, it was monitored in two different ways. First, a carbon resistance thermometer was glued to the bolometer mounting bracket. The second method directly monitored the bolometer temperature by measuring the voltage drop across the SRT, enabling the SRT resistance to be determined. This was done by measuring the difference in the DC output of the JFET as the connection to V_B was opened and closed. This method allows not only temperature variations caused by the changes in the dewar cold plate to be seen, but also variations caused by changes in the thermal radiation background seen by bolometer. This latter effect can be very

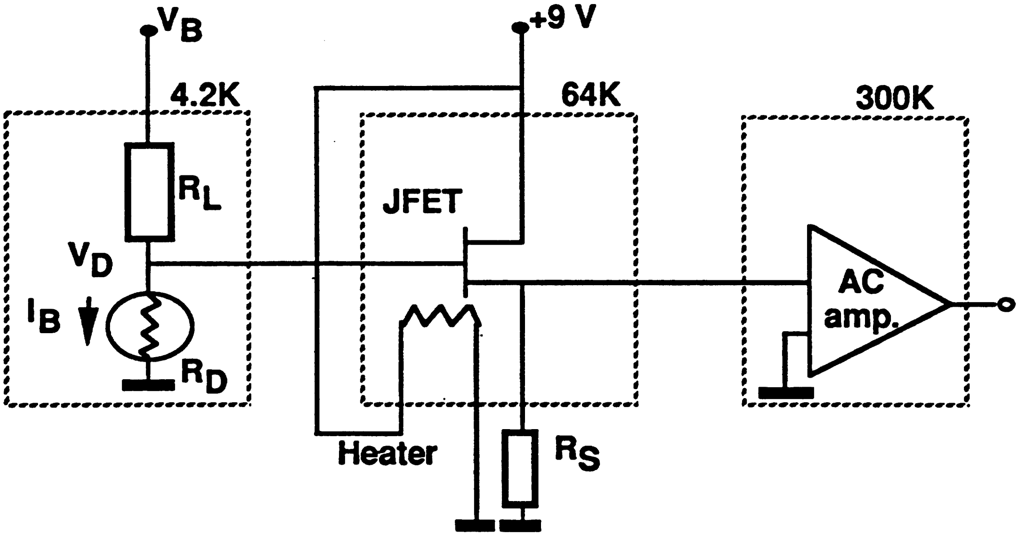

Fig 2. Bolometer bias circuit

important, since we intend to use the bolometer in an ambient background as well as in the LBIR facility which has a 20 K background.

2.4. Electronics

Since the incident radiation is chopped, a lockin amplifier is used to measure the amplified AC signal. We found that to achieve the highest accuracy, it was best to send the analog outputs of the lockin amplifier to high quality digital voltmeters (DVMs) rather than to use the lockin's internal analog-to-digital converters. The in-phase and quadrature outputs are read simultaneously by two DVMs and the magnitude is calculated digitally by the computer. A zero can be taken while an optical shutter is closed and then subtracted vectorially from the signal by the computer. The electrical bandwidth can be limited by either the integration time constant of the lockin amplifier or the DVMs. Our tests were bandwidth limited by the DVMs to about 0.3 Hz.

3. TESTS OF SYSTEM

3.1. IR source tests

The signal strengths of the two types of IR sources were compared using the prism/grating spectrometer and a HgCdTe detector operated at 77 K. The ceramic element was run at 55 W producing a temperature of about 1500 K. Since operation at higher output significantly shortens the source lifetime, 55 W is the practical limit of this device. Both versions of the Ar arc source, the Ar mini-arc and the Ar maxi-arc, were tested. The relative outputs of the two versions of the Ar discharge arc source and the ceramic element are shown in Fig 3. The comparison shows that the mini-arc running at 1.2 kW produces about the same amount of signal at the detector as the ceramic element, while the maxi-arc run at 6.3 kW (near the limit of our power supply) produces over 6 times more signal.

Spectral scans of the arc source performed on our spectrometer show some line structure but this should not adversely affect its use as a source for spectral calibrations, since both unknown and standard detectors will see the same structure. Spectral measurements on a higher resolution (~1 nm) instrument between 1 and 4 μm show that the output is mainly composed of many spectral lines [14]. The density of lines is such that they appear as a pseudocontinuum on lower resolution instruments. We expect that the maxi-arc with its increased brightness will be very useful for detector calibrations. While we have not yet measured the IR stability of the arc, we expect it will be similar to the <1% variation measured in the UV [8].

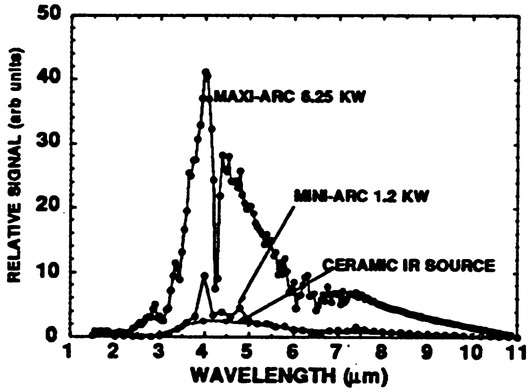

Fig. 3 Relative spectral radiant power of the ceramic source and arc sources.

3.2. Spectrometer tests

The spectral calibration, spectral resolution, slit function and wavelength repeatability of the spectrometer were measured. The wavelength scale was determined for the grating by scanning it across laser lines at 0.633, 1.15, 1.52 and 3.39 µm at a number of grating orders. To calibrate the prism scale, a thermal IR source was used and the grating was set for a particular wavelength after it had been calibrated. With this set up, the prism calibration was determined by scanning the prism for optimum signal. This was repeated at a number of wavelengths to complete the prism wavelength calibration.

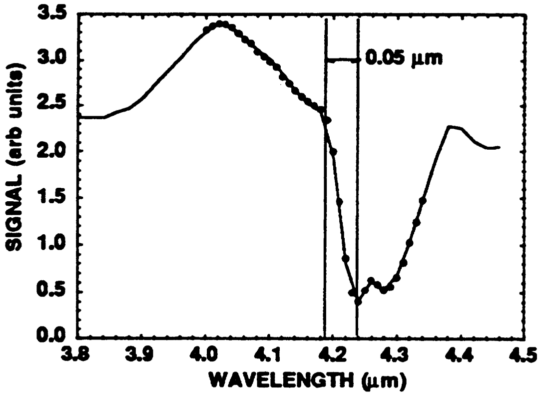

Fig. 4a Two repeated spectrometer scans (indicated by the line and dots) across an absorption line at 4.2 µm using a thermal source.

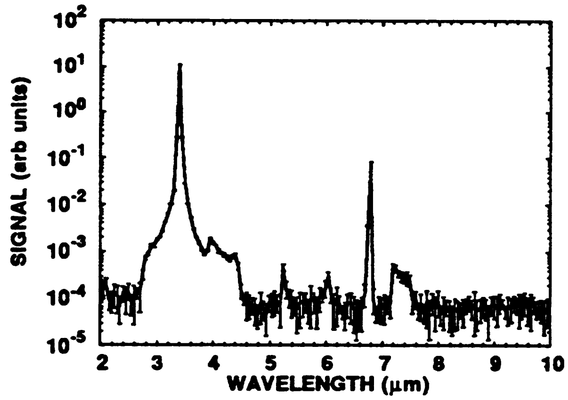

Fig.4b Spectrometer scan using 3.39 µm HeNe laser as a source. The error bars are standard deviation of 8 individual measurements.

The spectral resolution was determined from an observed atmospheric CO_2 absorption line edge and a laser linewidth. The spectrometer was scanned across a sharp absorption line at 4.2 µm as shown in Fig 4a. The width of the edge of the line gives an upper limit of 0.05 µm to the spectral resolution. Repeated scans show that the wavelength scale does not shift by more than 0.01 µm. Scans across the 3.39 µm laser line (Fig 4b) also show a FWHM of 0.05 µm, which is consistent with the CO_2 absorption line edge result. The scan across the laser line shows the degree of rejection of out of band radiation in the neighborhood of the laser line. The signal drops by five decades approximately 1 µm away from line center. The second order peak seen at 6.8 µm is reduced by about two and a half decades. Most of this reduction is due to the prism section out-of-band rejection, as the grating efficiencies for first and second order are roughly comparable at this wavelength.

3.3. Bolometer tests

A great deal of the effort of this project involved the development of the bolometer into a transfer standard. Initial tests characterized the original bolometer while later work centered on modifications for improvement and subsequent recharacterization. The initial measurements of the bolometer included the spectral reflectance of the absorbing coating and the overall absolute spectral response at some wavelengths, chop frequency response, dynamic range and linearity. Later measurements have dwelt on characterizing and improving response stability.

The measurements of the spectral reflectance of the gold black absorbing coating showed the reflectivity rising from less than 10% at 2 μm to greater than 70% at 15 μm. Improvements to the coating procedure, based on a literature search [13,15,16], were tried on a second bolometer. This resulted in reducing the peak reflectance to 30%. (A recoat of the first bolometer achieved even lower peak reflectance than 30%.) The absolute spectral response of the bolometer was measured between 400 and 900 nm, where NIST has an absolute spectral response scale [17]. The result showed a variation of 2% across this region, which is consistent with the increase in reflectivity observed in the IR. Spatial uniformity maps were also performed with this calibration facility at 900, 1200 and 1550 nm with a scan resolution of 1.1 mm. The variations were less than 0.3% over the entire 10 mm^2 aperture area.

The peak-to-peak response of the bolometer was measured as a function of the chop frequency of the incident radiation. The response was flat to about 175 Hz before the gold black was deposited and flat to 111 Hz after coating. Since 100 Hz was about the design frequency minimum, this was about the maximum amount of gold black that could be tolerated on the bolometer.

The upper limit to the dynamic range was determined by measuring the nonlinearity as a function of incident power. Nonlinearities of 1% and 4% were found at radiant powers of 7 mW and 20 mW respectively [11]. This high end limit is important since the HACR, which will be used to calibrate the bolometer, can be expected to achieve an uncertainty of 0.004 with 10 μW of incident power. The bolometer's spectral noise density of 30 pW/$\sqrt{Hz}$ determines the low end of the useful range. These two limits give nearly five decades of useful range for the bolometer with 1 s integration times.

Measurements of the spectral responsivity made using the visible absolute spectral response scale at NIST revealed a problem with stability. The response was found to shift within a range of about 5% from day to day. To correlate this variation with external parameters, arrangements were made to monitor the temperature of the mounting bracket which holds the bolometer, the voltage of the SRT bias battery, and the DC voltage drop across the SRT which allowed the temperature variations of the sensor itself to be recorded. Also the barometric pressure was monitored to see if temperature variations were due to liquid He boiling point changes induced by pressure changes.

The results showed that the majority of the response variations were correlated with the SRT temperature. The SRT temperature variations may be due to several causes, such as radiation load on the bolometer. One effect observed was a correlation of the SRT resistance with barometric pressure. The observed variation of 47 kΩ is consistent with the 2800 Pa change in pressure, as the coefficient for the liquid He boiling point is 11.3 mK/Pa near atmospheric pressure [18]. While the variation of the bias voltage was small so its effect could not be observed in the data, its effect can be calculated with high confidence. Another possible cause of temperature variations of the bolometer is the dewar vacuum. The vacuum degrades over about 3 days to the point where the device is no longer usable. Currently the dewar vacuum is not directly monitored.

4. IMPROVEMENTS

Stability of the bolometer response is the area where the most improvement is required. Because most of the factors that affect the responsivity do so through temperature changes of the SRT, we will pursue a plan to monitor and correct for these effects rather than try and remove them. The most important reason for doing this is that one of the factors that can affect the SRT temperature, the background radiation load, would be very difficult to correct for, in particular, because this bolometer will be used in applications where the background may range from ambient to 20 K. The development of this correction procedure should be a significant advance, which allows a much broader range of applications where bolometers may be used with high accuracy.

The vacuum dewar itself will be replaced with an improved version to increase the hold time of the cryogens. A new dewar employing UHV methods has been received which uses all metal seals instead of rubber gaskets. The new dewar incorporates a charcoal getter sunk to the liquid He reservoir to maintain the low vacuum and a vacuum gauge to monitor the dewar pressure. An effort has been made to reduce outgassing by minimizing the use of glues and adhesives which were used in the original dewar. The hold time of this improved dewar has not been measured but we expect significant improvement.

5. CONCLUSION & PLANS

We have set up a facility to calibrate the absolute spectral response of detectors in the IR. A source new to IR work has been tested and shows promise of significantly improving the signal over a conventional IR source. A room temperature spectrometer employing a prism and a grating has been constructed with a spectral resolution of 0.05 μm and a rejection of out of band radiation of as much 5 decades. This later characteristic is one of the most crucial requirements of a system using a thermal source. A bolometer is being developed into a transfer standard which will be tied to the nation's primary standard radiometer. When complete, the facility will allow users outside of NIST a means to determine the absolute spectral response and spatial response uniformity of detectors in the 2 to 20 μm region. This adds to the existing capability at NIST where calibrations are provided in the 200 nm to 1800 nm range.

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