IOP Publishing Metrologia
Metrologia **46** (2009) S155–S159 doi:10.1088/0026-1394/46/4/S04

Extension of the NIST spectral responsivity scale to the infrared using improved-NEP pyroelectric detectors

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Received 22 October 2008, in final form 26 November 2008
Published 2 June 2009
Online at stacks.iop.org/Met/46/S155

Abstract
Routine NIST spectral responsivity calibrations are needed for the infrared range. Low-NEP pyroelectric radiometers have been developed for traditional monochromator applications to extend the responsivity scale to the infrared. After NEP tests, the best pyroelectric detectors were converted to transfer-standard radiometers. The relative spectral responsivities were determined from spectral reflectance measurements of the organic black detector coatings. The absolute tie points were measured against a domed pyroelectric radiometer standard and a sphere-input extended-InGaAs transfer-standard radiometer. The infrared spectral power responsivity scale has been extended for the 2 µm to 14 µm wavelength range. A single-grating monochromator has been adapted to the calibration facility and used to characterize and calibrate infrared detectors.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since responsivity calibrations at the National Institute of Standards and Technology (NIST) Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) [1] facility are slow and expensive, a revisit of the traditional monochromator source applications was necessary. However, the noise-equivalent-power (NEP) of traditionally used pyroelectric detectors is too high for wide-wavelength-range measurements at the outputs of regular monochromators. Also, application of low-NEP cryogenic bolometers is complicated, slow and expensive [2]. Instead, improved-NEP pyroelectric detectors with 5 mm detector diameter have been developed to obtain high signal-to-noise ratios (SNRs) at the output of regular monochromators [3]. The low-NEP pyroelectric detectors were extended to user-friendly transfer-standard radiometers that can extend the responsivity scale to the long-wave IR with low measurement uncertainty. Though the improved NEPs are about one order of magnitude lower than that of traditional pyroelectric detectors, they are still high enough not to obtain any measurable signal contribution from the background radiation and the stray light of the monochromator. Traditionally used InSb, HgCdTe and other IR detectors can be calibrated with low responsivity uncertainty against the new pyroelectric transfer standard in the 0.3 µW to ~1 µW radiant power range of traditional monochromators. While the calibrations are performed in this limited power (signal) range, the traditionally used (very low-NEP) IR detectors (such as quantum detectors) will extend the spectral responsivity calibrations to low signal levels.

Since the atmospheric windows are at 2 µm to 2.5 µm, 3 µm to 5 µm and 8 µm to 12 µm, the wavelength coverage of the planned routine infrared responsivity calibrations has been limited between 2 µm and 14 µm.

2. Transfer-standard pyroelectric radiometer

For spectral responsivity scale extension to the infrared and monochromator use, eight low-NEP pyroelectric hybrid detectors have been characterized and selected. They were built from 100 µm thick $LiTaO_3$ crystals and utilized a frequency compensation method [3]. The 5 mm diameter active area of the detectors was coated with organic black paint. The paint introduced a differentiating time constant that cancelled the large integrating time constant of the

Figure 1. A temperature-controlled pyroelectric transfer-standard radiometer head[1].

photocurrent-to-voltage converter (attached to the pyroelectric detector) [3]. The paint also introduced an integrating time-constant which is much smaller than the original (cancelled) integrating time constant. As a result, the upper 3 dB roll-off frequency could be extended by a factor of five (to about 100 Hz) at a signal gain of 10^{10} V A^{-1}, which is an order of magnitude higher than the maximum signal gain without this frequency compensation. Most of the tested pyroelectric detectors were extended to radiometers where the temperature of the detectors was monitored. One pyroelectric detector was extended to a radiometer where the detector temperature is stabilized at 26 °C using thermoelectric heating/cooling. The picture of this transfer-standard radiometer head is shown in figure 1.

3. Tests of the pyroelectric transfer-standard radiometer

The output beam power of a single-grating monochromator together with the output SNR of the pyroelectric transfer-standard radiometer was tested to evaluate the achievable responsivity uncertainties. The arrangement of the monochromator-based setup is shown in figure 2.

An alignment laser, a blackbody source for single beam operation, a ceramic glower and a tungsten–halogen lamp can be alternately selected with a rotating mirror. The selected beam is imaged to the entrance slit of the monochromator through order sorting filters. The total power in the output beam of the monochromator is measured by the reference and test detector using the detector substitution method.

The output beam power of the monochromator changed between 0.3 µW and 1.6 µW within the 900 nm to 2600 nm wavelength interval of a grating blazed at 1250 nm. The standard deviation changed between 0.2% and 0.4% between 1000 nm and 2500 nm. This is equivalent to an SNR between 500 and 250 in the output signal of the radiometer [3]. This is the radiant power range where traditionally used InSb, HgCdTe and other IR detectors can be calibrated against the pyroelectric transfer standard.

For the best pyroelectric detectors, less than 4 nW Hz$^{-1/2}$ NEPs were measured, which is an order of magnitude smaller than the NEP of our earlier developed (traditional) pyroelectric detector standard [4]. The NEPs of the eight tested pyroelectric radiometers ranged between 3 nW Hz$^{-1/2}$ and 10 nW Hz$^{-1/2}$ [3]. The test results of the temperature-controlled transfer-standard pyroelectric radiometer are shown in table 1. The NEP was calculated as the ratio of the standard deviation (noise) of the output voltage (from twenty data points) to the radiometer responsivity. The responsivity value includes the 10^{10} V A^{-1} gain of the current meter attached to the pyroelectric detector. A 785 nm responsivity tie point was made against a silicon trap detector and a 10.6 µm tie point was derived from our previously developed and calibrated dome-input pyroelectric radiometer [4]. These tie-point derivations were made at a chopping frequency of 10.5 Hz. The frequency-dependent responsivity of the pyroelectric transfer standard has been measured to determine the upper 3 dB roll-off frequency and to apply responsivity corrections for different signal frequencies in different applications. The result of the frequency-dependent responsivity measurement for the transfer standard is shown in figure 3. A three time-constant curve fit [4] was applied to the measured data after normalizing the data at low frequencies. The 3 dB upper roll-off frequency is about 100 Hz, a decade higher than the suggested chopping frequency.

4. Calibration of the pyroelectric transfer-standard radiometer

The spectral directional-hemispherical reflectance of the organic black coated transfer-standard detector was measured on the NIST FTIR Spectrophotometry Facility. The spectral reflectance of this paint-coated detector is structured versus wavelength. The relative spectral responsivity of the detector was determined first. The spectral reflectance measurement results are shown in figure 4. The reflectance varied from 3.5% to 5.5% between 1.5 µm and 14.5 µm. The expanded uncertainty ($k = 2$) of the spectral reflectance measurements is shown in the same graph. This reflectance uncertainty includes the structures, the noise and the signal loss due to the detector can. The reflectance structures in the measured absolute reflectance curve are material characteristics of the organic black paint-coating. The loss is a systematic uncertainty component which will have a minimal contribution to the responsivity uncertainty budget since an absolute tie point to the relative spectral reflectance curve will take care of this problem. Since the responsivity is proportional to the absorptance (which is equal to 1 − reflectance), the expanded responsivity uncertainty component from the relative spectral reflectance is 0.5% ($k = 2$) between 2.5 µm and 13 µm. The 10.6 µm tie point was derived from the previously developed domed pyroelectric radiometer [4]. The expanded uncertainty of the 10.6 µm tie points is 0.8% ($k = 2$).

[1] Certain commercial equipment, instruments or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment is necessarily the best available for the purpose.

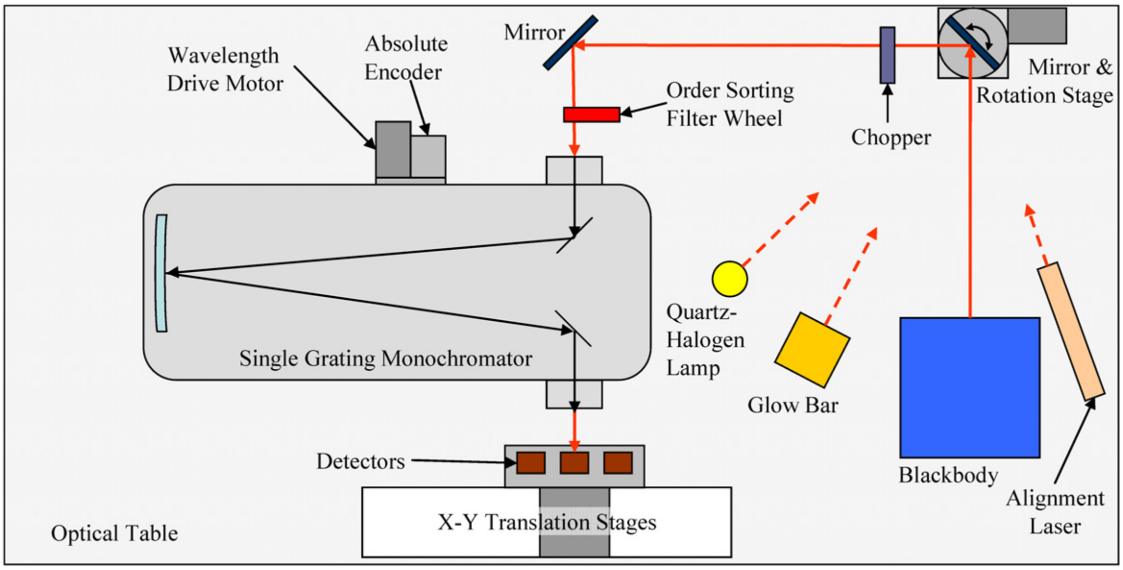

Figure 2. Monochromator-based detector responsivity calibrator.

Table 1. Test results of the transfer-standard pyroelectric radiometer.

Standard deviation in dark	9.4×10^{-6} V
NEP (with 1 s time constant)	4.7 nW
3 dB upper roll-off frequency	100 Hz
Responsivity, 785 nm, 10.5 Hz	5059 V W^{-1}
Responsivity, 10.6 µm, 10.5 Hz	4995 V W^{-1}

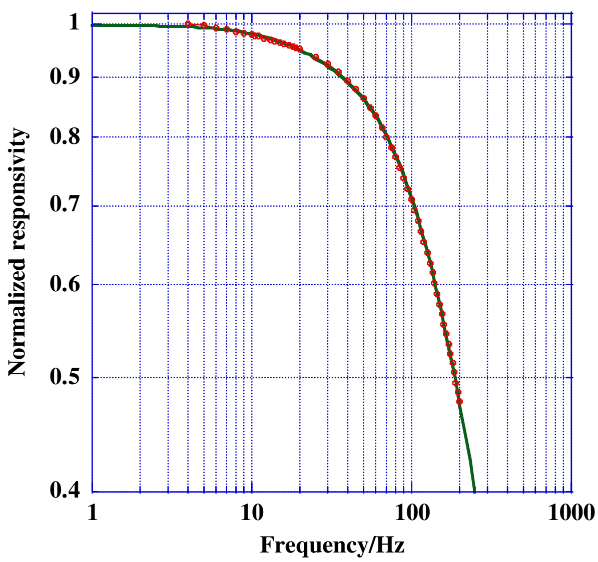

Figure 3. Frequency-dependent responsivity of the pyroelectric transfer standard.

The monochromator-based tie point was made against a sphere-input extended-InGaAs (EIGA) radiometer. The EIGA radiometer was calibrated against an electrical substitution cryogenic radiometer using the detector substitution method [5]. Both radiometers measured the same radiant power from intensity-stabilized tunable lasers. Since the laser power levels were high, the EIGA radiometer was operated in a dc signal measurement mode. The calibrations were made between 1 µm and 2.5 µm with an expanded uncertainty of 0.4%

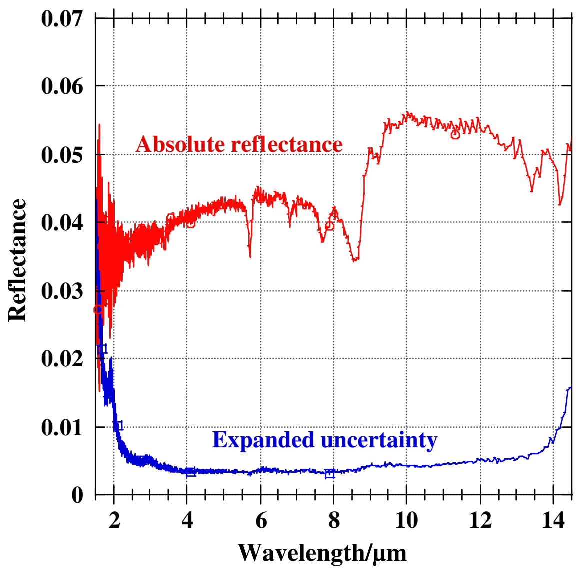

Figure 4. Spectral reflectance of the pyroelectric transfer-standard detector.

($k = 2$). The tie point at the monochromator-based facility was at 1790 nm. This tie-point calibration was made at 0.5 µW radiant power output radiation of the monochromator to avoid non-linearity errors in the calibrations of the pyroelectric detectors. The other (longer wavelength) tie points from the monochromator-based spectral measurements were not used because of the smaller SNRs. The radiation was chopped with 12 Hz and the radiometer (both reference and test) output signals were measured by a sine-wave measuring lock-in amplifier.

Before the tie-point calibration, the frequency-dependent responsivity of the EIGA sphere-detector was measured. Also, the signal attenuation of the pyroelectric transfer standard was checked between 12 Hz and 10.5 Hz. The signal attenuation of the EIGA sphere-radiometer was 0.3% overcompensated by the increased signal responsivity of the

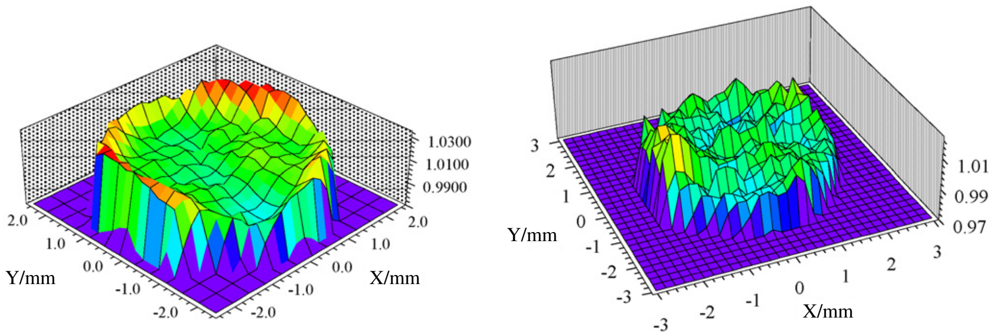

Figure 5. Spatial uniformity plots of the transfer standard at 785 nm (left) and 10.6 μm (right).

Table 2. Expanded uncertainty ($k = 2$) budget of spectral responsivity for the pyroelectric transfer standard at 10.5 Hz from 2.5 μm to 13 μm.

Uncertainty factor	Type A/%	Type B/%	Combined/%
Tie-point absolute responsivity calibration			
Sphere-EIGA radiometer responsivity	0.4		
Pyroelectric radiometer gain		0.04	
Pyroelectric temperature dependence		0.04	
Pyroelectric radiometer frequency dependence		0.08	
Pyroelectric spatial non-uniformity of responsivity		0.5	
Pyroelectric noise dominated repeatability		0.5	
Expanded combined uncertainty			0.82
Relative responsivity calibration			
Spectral reflectance measurement	0.5		
Overall expanded ($k = 2$) uncertainty			0.96

pyroelectric radiometer at 10.5 Hz (compared with 12 Hz) where the spectral responsivities are reported. The 0.3% ($k = 2$) overcompensation has been corrected and this uncertainty component is not included in the overall uncertainty budget. The reading of the sine-wave measuring lock-in amplifier was multiplied by 2.221 (the reciprocal of the lock-in 0.9003 conversion factor multiplied by two) to obtain the correct (equivalent dc) responsivity value for the tie point. From three repeats of the absolute tie-point measurements of the pyroelectric transfer standard, an expanded measurement uncertainty of 0.5% ($k = 2$) was obtained. This uncertainty component is noise dominated.

Figure 5 shows the measured spatial uniformities of the pyroelectric transfer standard at two different wavelengths. The roughly 2% maximum-to-minimum non-uniformity in the centre area at 785 nm increased by about 50% at 10.6 μm. The increase in the spatial non-uniformity is associated with the ~50% higher reflectance at 10.6 μm. According to figure 5, the uncertainty component that originates from the spatial non-uniformity of responsivity is wavelength dependent. If the detector centre area is used and the incident beam diameter is between 1 mm and 2 mm and positioned into the detector centre, the spatial non-uniformity uncertainty component can be decreased to 0.5% ($k = 2$).

The responsivity uncertainty budget of the pyroelectric transfer-standard radiometer at 10.5 Hz signal frequency from 2.5 μm to 13 μm is shown in table 2. The expanded uncertainty (not shown in the table) at 2 μm is 1.3% ($k = 2$) because of the increased noise in the spectral reflectance measurements (see figure 4). For the same reason, the expanded uncertainty at 14 μm increased to 1.2% ($k = 2$).

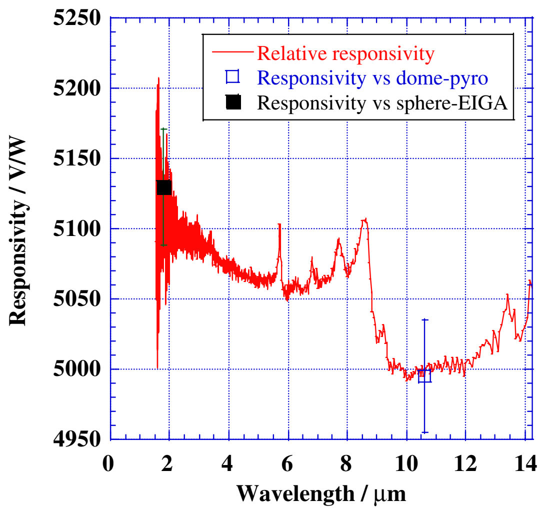

Figure 6. Spectral responsivity of the pyroelectric transfer-standard radiometer.

The spectral radiant power responsivity of the pyroelectric transfer-standard radiometer is shown in figure 6. In addition to the 10.6 μm tie point, the tie point of the sphere-input EIGA radiometer is also shown in figure 6. The individual error bars represent the expanded uncertainties ($k = 2$) of the tie points. The sphere-EIGA related error bar (filled square) illustrates the overall expanded uncertainty summarized in table 2. Table 2 includes both the absolute tie point and the relative spectral responsivity calibration uncertainties. The latter one includes the uncertainty caused by the measured structures in the spectral reflectance measurement shown in figure 4.

5. Spectral responsivity propagation from the pyroelectric transfer standard

The scale from the transfer-standard pyroelectric radiometer can be transferred to other infrared test detectors using the detector substitution method. The substitution is performed in the 0.3 μW to 1.6 μW radiant power range using a detector stage at the output of the single monochromator in figure 2. The monochromator has four gratings to continuously cover the spectral range to 24 μm for future scale extensions. The total power in the output beam of the monochromator is measured by under-filling both the reference and the test detector(s). A stable 1000 °C blackbody source is imaged to the entrance slit of the monochromator to make wide consecutive wavelength scans for both the test and the reference (transfer-standard) detectors. The measurements can also be performed in two-beam mode where the signal of the test or reference detector is simultaneously divided by the signal from a monitor detector.

Traditional IR detectors, such as InSb and MCT detectors, can be calibrated against the pyroelectric transfer standard to extend the radiant power range to low signal levels. All infrared responsivity measurements on the monochromator-based facility are performed in ac mode using individual lock-in amplifiers for the reference, test and monitor detectors.

6. Conclusions

Traditional pyroelectric detectors need high incident radiant power, such as stabilized tunable lasers to obtain high SNRs for low uncertainty measurements. The laser-used spectral responsivity measurements are time consuming and expensive. Development of low-NEP pyroelectric radiometers was needed to use traditional monochromators for routine spectral responsivity calibrations in the infrared. Characterizations and calibration of a recently developed low-NEP pyroelectric transfer-standard radiometer are described in detail. This transfer standard can be used at radiant power levels higher than 0.3 μW to obtain close to 1% ($k = 2$) responsivity uncertainties. It is operated in a limited power range (to a couple of microwatts) to avoid non-linearity errors in the pyroelectric detector. Traditional InSb, HgCdTe and other very low-NEP infrared detectors can be calibrated against the pyroelectric transfer standard at the monochromator output to extend the spectral responsivities to sub-picowatt radiant power levels. The new monochromator-based responsivity scale can be used to 14 μm.

References

[1] Brown S W, Eppeldauer G P and Lykke K R 2006 Facility for spectral irradiance and radiance responsivity calibrations using uniform sources *Appl. Opt.* **45** 8218–37

[2] Eppeldauer G, Migdall A L and Cromer C L 1994 A cryogenic silicon resistance bolometer for use as an infrared transfer standard detector *6th AIAA/ASME Thermophysics and Heat Transfer Conf. (Colorado Springs, CO, June 1994) Proc. HTD* vol 277, *Thermal Phenomena at Molecular and in Cryogenic Infrared Detectors* pp 63–7 (Book No. H00908)

[3] Eppeldauer G P, Zeng J and Yoon H W 2008 Low-NEP pyroelectric radiometer standards *Proc. SPIE* **6940** 694036

[4] Eppeldauer G P, Zeng J and Hanssen L M 2006 Development and calibration of pyroelectric radiometer standards at NIST *Proc. SPIE* **6201** 620119

[5] Eppeldauer G P and Yoon H W 2007 Short wave infrared radiometers design and characterizations *Proc. SPIE* **6542** 65420O