Low-NEP pyroelectric detectors for calibration of UV and IR sources and detectors

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ABSTRACT

Pyroelectric radiometers with spectrally constant response have been developed at NIST with the cooperation of a few detector manufacturers. The new devices have noise-equivalent-power (NEP) values less than 1 $nW/Hz^{1/2}$ sufficiently low for use at the output of regular monochromators. Their response flatness is an order of magnitude better than that of filtered Si detectors and can be used to realize simple and low-uncertainty responsivity scales for the UV and IR wavelength ranges. For the first time, the UV irradiance responsivity of a pyroelectric detector has been determined. Based on spectral reflectance measurements of the black coating of the pyroelectric detector, the relative spectral response was determined between 0.25 µm and 30 µm. The relative response was then converted into spectral power and irradiance responsivities using absolute tie points from a silicon-trap-detector in the VIS range. In addition to the UV irradiance responsivity scale realization, the flat response between 1.6 µm and 2.6 µm was utilized and a constant irradiance responsivity was realized and applied as a reference scale for the Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) facility of NIST. The spectral power responsivity of the low-NEP pyroelectric detector is the internal standard of the NIST VIS-IR detector calibration facility for the 0.6 µm to 24 µm wavelength range. The pyroelectric standard is used to calibrate other types of detectors for spectral responsivity using detector substitution. The flat-response interval of the pyroelectric standard, calibrated for irradiance responsivity, was also used to measure the integrated irradiance from UV LED sources without using any source standard. The broadband radiometric measurements can be applied to IR LEDs emitting low fluxes between 750 nm and 4300 nm. All pyroelectric detector based calibrations were performed with expanded uncertainties of about 2 % (k=2).

Keywords: flat-response UV detector, pyroelectric detector standard, spectral irradiance responsivity, UV responsivity scale, broadband radiometric measurement, broadband UV LED measurement, UV-VIS-IR integrated irradiance, flat-response IR detector

1. INTRODUCTION

Low noise-equivalent-power (NEP) pyroelectric detectors with close to constant spectral response have been developed with the cooperation of a few detector manufacturers to extend the NIST responsivity scale from the visible (VIS) to the ultraviolet (UV) and infrared (IR) regions [1], and to perform broadband measurements of UV and IR sources (including LEDs). The low-NEP was needed to obtain high signal-to-noise ratios at the output of the regular monochromator of the NIST VIS-IR detector calibration facility and to measure the integrated irradiance from sources with weak output flux (like deep-UV LEDs). The spectral reflectance-based [2, 3] irradiance responsivity determination of the pyroelectric detectors in the IR range makes it possible to significantly decrease the responsivity calibration-time at the SIRCUS tunable-laser applied responsivity-calibration facility [4]. The relative response curve obtained from the spectral reflectance measurements is converted into a spectral responsivity function using absolute tie point(s) traceable to the primary standard cryogenic radiometer [4].

The low-NEP made it possible to make a first-time irradiance responsivity measurement with a pyroelectric detector. The realization of a low-uncertainty irradiance responsivity scale is described here that extends the Si trap

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detector implemented [4] irradiance responsivity scale simply and fast into the UV and IR. Using the newly developed pyroelectric detector standards, the spectral range of two NIST spectral responsivity calibration facilities (the VIS-IR detector calibration facility and the SIRCUS) could be extended. Based on the new pyroelectric detector standards, these facilities can be used for the calibration of UV, VIS, and IR test detectors. Using the low-NEP pyroelectric irradiance meter with the flat spectral response, a simple and accurate broadband measurement procedure has been introduced for the measurement of UV and IR sources including LEDs.

2. FLAT SPECTRAL RESPONSE SELECTION

The response flatness of selected pyroelectric detectors can be an order of magnitude better than that of filtered Si detectors and can be used to extend the reference responsivity scale of a silicon-trap-detector to both the UV and IR ranges. The recently developed new-generation pyroelectric detectors have low NEPs and flat response functions and they can be used at the output of regular monochromators. The low-NEP is also important for broadband measurement of low-output-flux sources like deep-UV LEDs.

The here discussed radiometric quality pyroelectric detectors with flat spectral response and low-NEP were developed with NIST cooperation using two different research agreements. First, the NEP of organic-black coated hybrid pyroelectric detectors was decreased by Gentec-EO USA to an average of 5 $nW/Hz^{1/2}$ [5]. This detector does not have any protecting (sealing) window. The response flatness of the 1st generation organic-black coated pyroelectric detectors is shown in Fig. 1. The responsivity changes are close to +/- 1 % relative to the linear-fit made for the seven spectral responsivity functions between 2 μm and 14 μm.

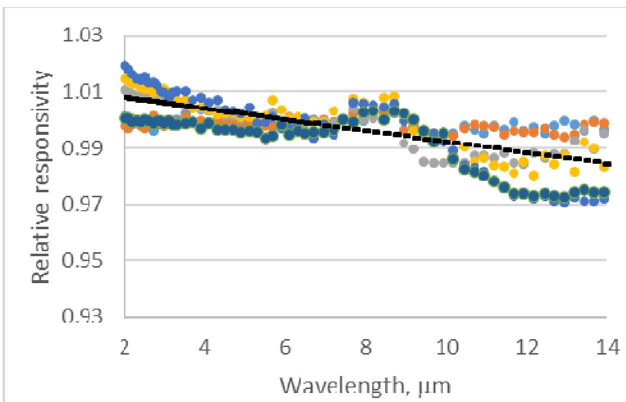

Fig. 1. Variation of spectral responsivity (normalized) for seven organic black coated pyroelectric detectors. The dotted black line represents a least-square linear fit.

To minimize the response deviation from a constant value, the gold black coatings of the pyroelectric detectors were studied. The coatings were deposited on thin glass plates. First, the effect of the coating thickness to the response change was analyzed. Figure 2 shows the measured spectral reflectance factors of the organic black coatings of 30 μm, 40 μm, and 50 μm thicknesses. The measurements were made using a commercial spectrophotometer fitted with an integrating sphere. Each sample was mounted on the sample port of the sphere, so that the incident beam illuminated the sample (at an 8-degree angle with respect to the sample normal) and the reflected flux was collected within the integrating sphere where it was detected. The reflectance factor for this total reflectance measurement is the ratio of reflected flux to incident flux relative to the ratio of a perfectly reflecting diffuser. A flat reflectance was obtained above 1200 nm when the thickness of the coating was at least 50 μm. The reproducibility of the measured reflectance factor values was 6 % and the reproducibility of thickness comparison was 3 %.

Figure 3 depicts the spectral diffuse transmittance of the organic black coatings. These measurements were collected by mounting each sample at the entrance port of the integrating sphere of the spectrophotometer. The incident beam illuminated the sample (at a 0-degree angle with respect to the sample normal) and the transmitted flux was collected within the integrating sphere where it was detected. The diffuse transmittance is the ratio of the transmitted flux to the incident flux. The figure shows that the thickness of the organic black coating must be close to 50 µm to get a negligible diffuse transmittance for the measured overall wavelength range. The negligible transmittance means that any light that's reflected is being absorbed, so Eq. 1 below, A=1-R is valid. It wouldn't be valid for the 30 µm and 40 µm coatings.

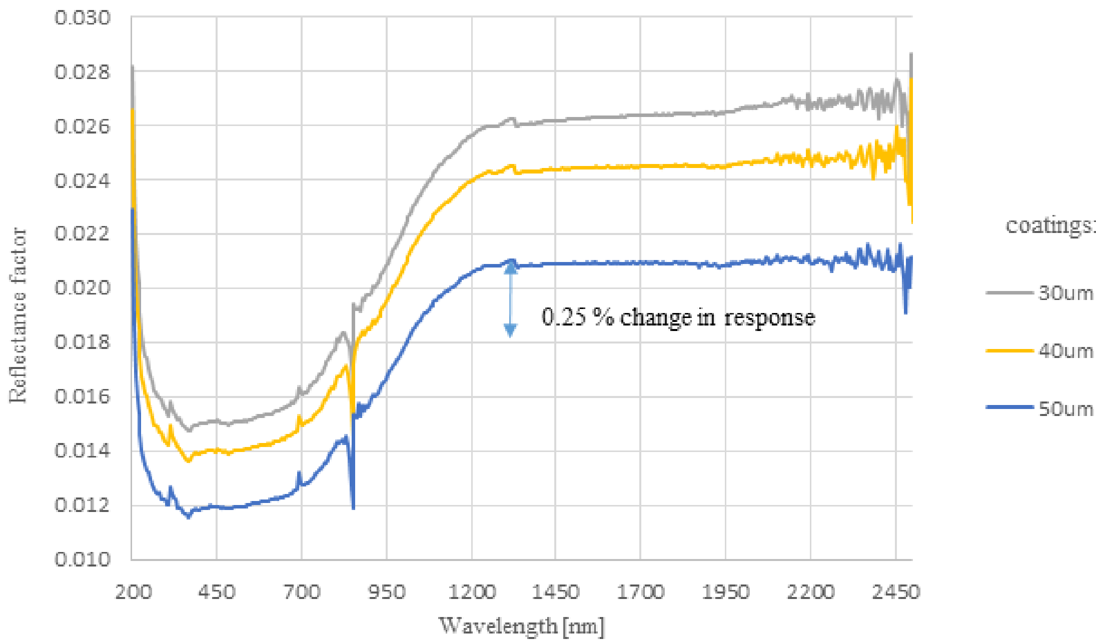

Fig. 2. Reflectance factor versus wavelength of organic-black coatings of different thickness in the wavelength range from 200 nm to 2500 nm.

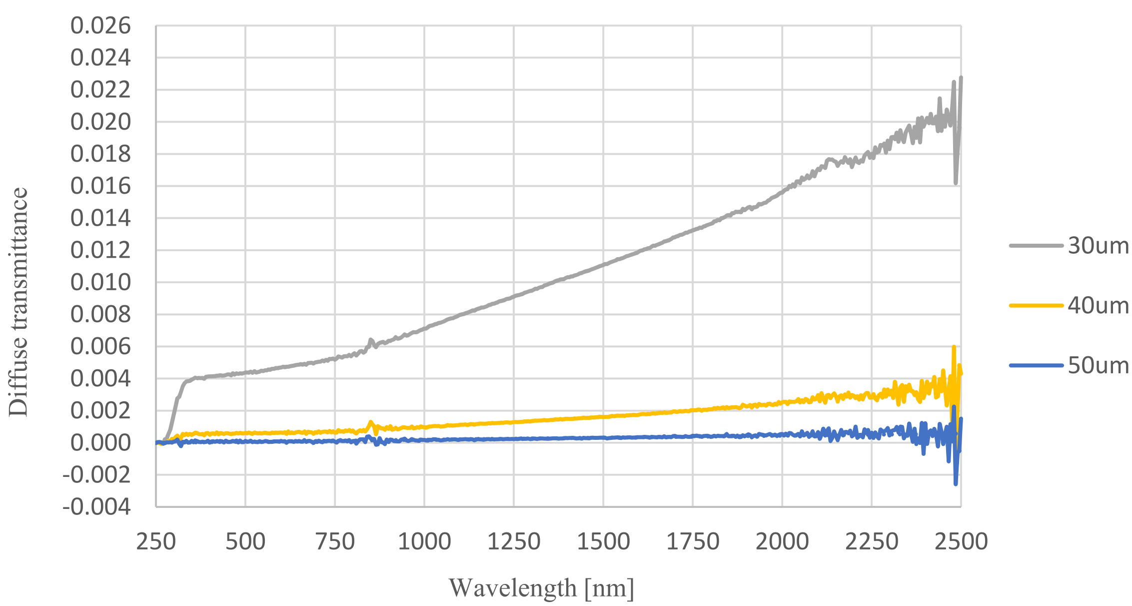

Fig. 3. Spectral diffuse transmittance for organic black coatings of three different thickness.

The spectral responsivity of the pyroelectric radiometer can be given in V/W for radiant power measurements and in V cm^2 / W for irradiance measurements. The here discussed hybrid pyroelectric detectors are connected to 10^{10} V/A (fixed) gain current-to-voltage converters. In this hybrid design, both the detector and the converter are located in the same shielded metal can. On the detector surface, the diameter of the spot produced by the incident radiation in power mode measurements is 2.4 mm. The spot is positioned into the center of the 5-mm detector. The total power in the incident beam can be measured with low uncertainty if the spatial nonuniformity of the detector-response is low. Figure 4 shows response scans along the orthogonal X and Y axes in the detector plane at a wavelength of 1.32 µm. The response change within the plateau is close to 1 % which is comparable to the expanded uncertainty of the power responsivity determinations of the discussed pyroelectric detectors. The spatial non-uniformity of response may be larger in irradiance mode measurements where the detector is overfilled by the uniform field of the incident radiation.

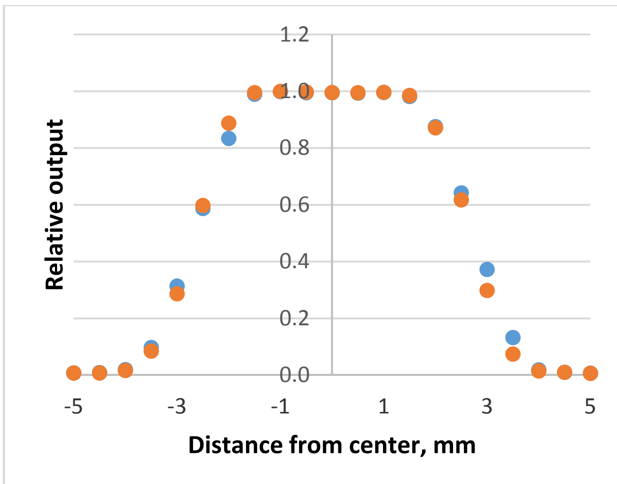

Fig. 4. Spatial uniformity of response of a 5-mm diameter organic-black-coated pyroelectric detector at 1.32 µm. The blue and orange markers represent orthogonal X and Y scans through the detector center taken with 0.5 mm increments. The scanning spot size was 2.4 mm.

A UV-VIS-NIR irradiance responsivity scale as realized using an organic-black coated pyroelectric detector between 250 nm and 2000 nm is shown in Fig. 5. The deviation from a constant responsivity value is +/- 0.68 % in this wavelength range. The uncertainty of the irradiance responsivity tie point at 660 nm (derived from a Si trap-detector) was combined with a few additional uncertainty components as discussed earlier [16]. Such components are distance measurement, wavelength error, target spot spatial nonuniformity, and signal (ratio) measurement errors. The response deviation from constant (0.18 %) was included for the 250 nm to 750 nm wavelength range. The spectral reflectance R of the black coating was measured with a few percent uncertainty. As shown in Fig. 2, R is between 0.02 and 0.03 (for the close to flat reflectance values), resulting in a spectral absorptance of

$$A = 1 - R \qquad (1)$$

with an uncertainty of ~0.1 %. The overall 0.5 % (k=2) irradiance responsivity uncertainty (see Table 6 below) was utilized in the above UV-VIS range. This irradiance responsivity uncertainty, which is a few times smaller than the uncertainties obtained with traditional spectral responsivity calibrations (as discussed in Section 3), can be propagated to 2500 nm.

For power responsivity calibration of the pyroelectric detector, the tie point can be derived from the power responsivity of the same Si trap-detector (where the irradiance responsivity was derived from) also at 660 nm but both detectors are to be underfilled by the incident-beam from the 660 nm LED.

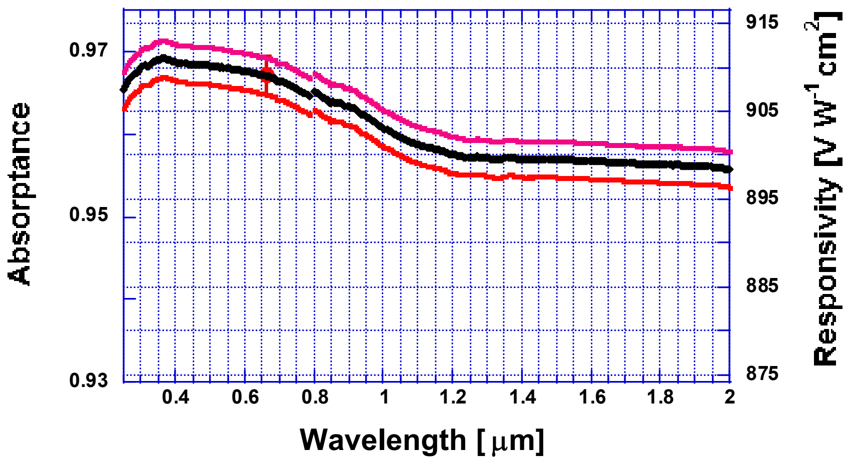

Fig. 5. Absorptance and irradiance responsivity of an organic-black-coated hybrid pyroelectric detector. The 0.5 % (k=2) irradiance responsivity uncertainty is propagated here to 2000 nm.

The flat response was extended to the long-wave IR using 2nd generation low-NEP organic-black-coated pyroelectric detectors. As shown in Fig. 6, the spectral power responsivity of the calibrated two pyroelectric detectors (#1 and #2) is close to constant between 0.85 μm and 21 μm. The applied linear curve fits are shown with solid lines. The change in the flatness is 0.2 % for the shown wavelength range. The 2.1 % (k=2) responsivity error bars obtained from the power responsivity calibrations are larger than the max-to-min (individual) responsivity deviations from the constant value. The advantage of the constant response is that the relative spectral response calibrations (the spectral reflectance measurements) will not be needed when the detector to be calibrated is taken from the same batch where the measured (flat) detector was taken from.

Also, the integrated irradiance (discussed below) of infrared LEDs with peaks between 750 nm and 4300 nm needs to be measured. When using pyroelectric detectors with flat (relative) response function, only one or two absolute tie points are needed for both the near-IR and the SW-IR ranges. The tie points applied here were derived from sphere-input InGaAs [6] and sphere-input extended-InGaAs transfer standard detectors [7] calibrated against the cryogenic radiometer. The low-NEP for the pyroelectric detector is important because the output radiant flux is a few mW in the near-IR and 0.2-0.3 mW in the SW-IR.

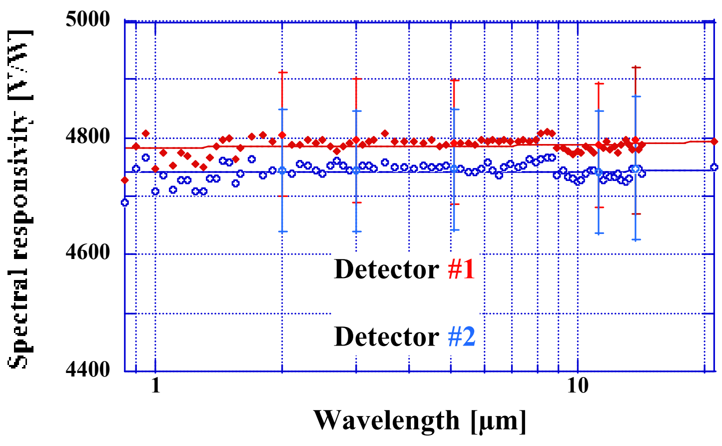

Fig. 6. Flat spectral power responsivity of 2nd generation organic black coated pyroelectric detectors. in the 0.85 μm to 21 μm wavelength range. Linear curve fits are shown with solid lines.

The main characteristics of two Gentec-EO organic-black-coated pyroelectric detectors are shown in Table 1. The responsivity primarily depends on the crystal thickness and the value of the feedback resistor. The applied feedback resistor of the current-to-voltage converter (inside of the hybrid package) was 10 GΩ for all organic-black coated detectors. The feedback capacitance was between 0.1 pF and 0.2 pF. The 3dB upper roll-off frequency was tuned to about a decade higher than the applied signal chopping frequency (which was selected between 10.5 Hz and 4 Hz). As a result of the above described pyroelectric detector improvement with the NIST cooperation, Gentec EO has introduced a new hybrid pyroelectric detector, model STEP-45 [8]. This model was built with a 100 μm thick $LiTaO_3$ crystal. The detector was covered with an organic-black paint coating. This 5-mm detector has similar characteristics to the above discussed low-NEP hybrid pyroelectric detectors of flat-response.

Table 1. Main characteristics of two Gentec-EO organic-black-coated pyroelectric detectors.

Detector #	Diameter [mm]	Crystal thickness [μm]	3 dB roll-off frequency [Hz]	Responsivity [V/W]
1	5	100	100	5059 (at 785 nm)
2	5	50	109	16985 (at 1.32 μm)

As an alternate solution for flat-response pyroelectric detector based calibrations, InfraTec GmbH [8] developed the very-low-NEP Model LIE-651 custom pyroelectric detector with NIST cooperation. The characteristics of this detector were evaluated [9]. Using a 25-μm thick pyroelectric chip and a feedback resistor of 100 GΩ, the NEP was decreased to about 0.3 $nW/Hz^{1/2}$. This detector had a silver-black coating with a diffuse reflection of less than 1 % from about 2 μm to 25 μm due to the repeated coatings. Sealing windows of ZnSe, AgBr, KBr, or CaF_2 can modify the spectral coverage of the detector. The window behind the 5-mm aperture was also needed to protect the metal black coating and to decrease the noise pickup. A low-loss feedback capacitor of 1.2 pF was used against excessive noise and gain peaking. The upper roll-off frequency was about 1 Hz. At the 4 Hz to 10.5 Hz chopping frequencies the signal and the noise changed in the same extent versus frequency.

The spectral power responsivity is shown in Fig. 7 between 1.6 μm and 15.5 μm when the detector is equipped with a ZnSe window. The flat irradiance responsivity is utilized as a reference scale between 1.6 μm and 2.6 μm at the NIST SIRCUS facility where tunable laser sources are used for spectral responsivity calibration of detectors, instead of using a monochromator. The close to constant responsivity was important for the SIRCUS facility to avoid the long and expensive tunable-laser used spectral irradiance responsivity calibrations. Instead, the fast and accurate monochromator based spectral reflectance calibrations with the flat pyroelectric response are utilized. The selected flat responsivity of the SIRCUS reference pyroelectric detector, equipped with a CaF_2 window, is shown in Fig. 8 between 1.6 μm and 2.6 μm. The response change in this interval was less than +/- 0.35 %.

The responsivity uncertainty of a pyroelectric detector from a monochromator-based responsivity calibration is typically 3 times higher (about 2 %, k=2) than the peak-to-peak change in the shown spectral responsivity function. Utilizing the lower uncertainty of the flat relative spectral response determination from spectral reflectance measurements and using an irradiance responsivity tie point from an InGaAs reference detector at about 1.6 μm, the spectral irradiance responsivity uncertainty can be significantly decreased in this SW-IR wavelength range.

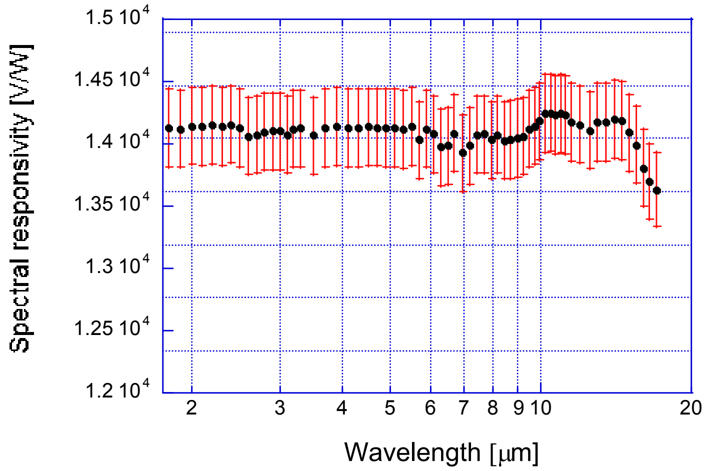

Fig. 7. Flat response of the InfraTec custom Model LIE-651 pyroelectric detector between 1.75 µm and 15.5 µm when the detector is equipped with a ZnSe window.

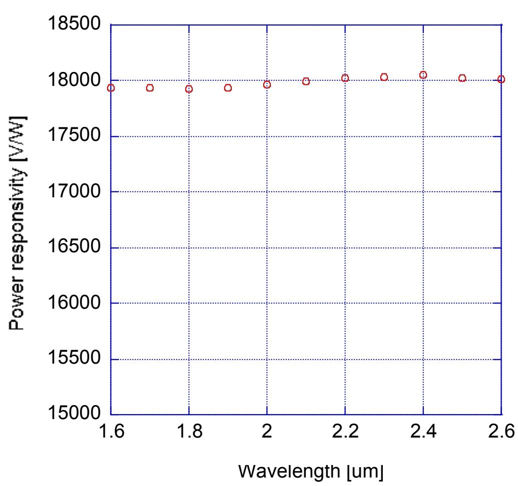

Fig. 8. SW-IR responsivity of a custom InfraTec pyroelectric detector when equipped with a CaF_2 window. The response change is +/- 0.35 % between 1.6 µm and 2.6 µm.

The NEPs of custom InfraTec LIE-651 pyroelectric radiometers measured with different time constants of a lock-in amplifier are shown in Table 2.

Table 2. NEPs of a 5-mm diameter InfraTec LIE-651 custom pyroelectric meter using different lock-in time constants.

Time constant [s]	**NEP [W]**
0.1	3.1E-10
0.3	1.9E-10
1	9.9E-11
3	6.5E-11

The spatial nonuniformity of response of the 5-mm diameter custom InfraTec pyroelectric detector was measured with a 2-mm diameter scanning beam. As shown in Fig. 9, the max-to-min change of response during the orthogonal XY scans was 1.5 % within a 2-mm diameter spot around the center.

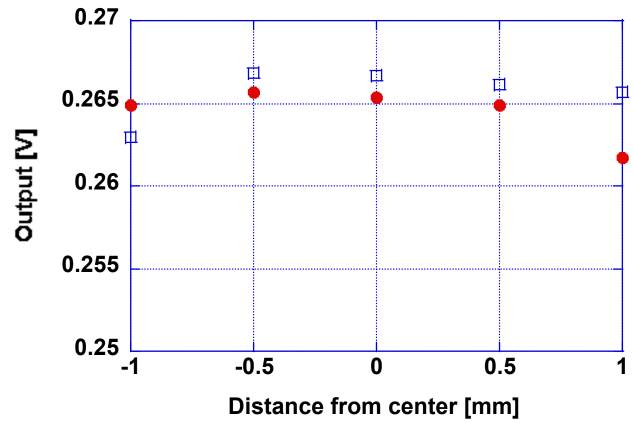

Fig. 9. Spatial nonuniformity of response of a custom LIE-651 pyroelectric detector from orthogonal XY scans around the detector-center using a 2-mm scanning beam.

3. SPECTRAL CALIBRATIONS BASED ON LOW-NEP PYROELECTRIC DETECTORS

While the flat spectral response can make spectral responsivity calibrations faster and more accurate than use of traditional calibrations, the flat-response for spectral responsivity calibrations is not a must. In traditional responsivity calibrations, the test detector is substituted for the standard detector (of known spectral responsivity) and the responsivity from the standard detector is transferred to the test detector while measuring the output signal from both detectors for the same incident radiation. Figure 10 shows the non-flat spectral power responsivity of an organic-black coated hybrid pyroelectric detector standard. The tie points were derived from a sphere-input ext-InGaAs transfer standard [7] at 2 µm and a dome-input pyroelectric standard [10] at 10.6 µm. The uncertainty budget is shown in Table 3.

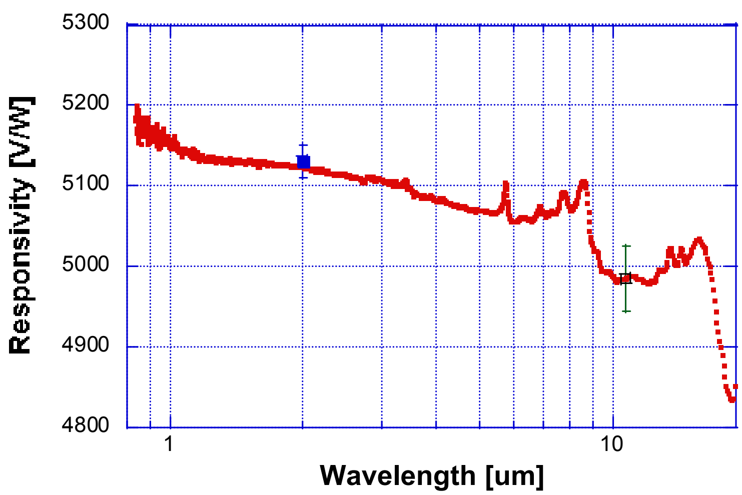

Fig. 10. Reference power responsivity scale of an organic-black coated hybrid pyroelectric detector standard.

Table 3. Spectral power responsivity uncertainty budget for the hybrid 5 mm OB-coated pyroelectric standard.

Uncertainty components	**Type A, %**	**Type B, %**	**Combined, %**
Sphere Ext-InGaAs (2 μm)	0.4		
Dome pyro (10.6 μm)	0.8		
Pyroelectric radiometer gain		0.04	
Pyroe. temperature dependence		0.04	
Radiometer frequency dependence		0.08	
Spatial non-uniformity of resp.		0.5	
Pyroe noise dominated uncertainty		0.5	
Expanded combined uncertainty (2 μm)			0.82
Expanded combined uncertainty (10.6 μm)			1.06
Relative response from reflectance data	0.5		
Overall expanded (*k*=2) at 2 μm			1.0
Overall expanded (*k*=2) at 10.6 μm			1.2

When the test detector has a flat response it may not need a traditional spectral calibration. If the response deviation from a constant value is equal to or less than the uncertainty of the relative spectral response determination, the calibration of the flat-response detector can be simplified. It is enough to derive a few absolute responsivity tie points from a standard detector. However, as discussed below, the flat detector-response is required when an integrated radiometric quantity (like the broadband irradiance) from a source (with broad spectral distribution) is to be measured.

Table 4 shows a summary of traditional spectral responsivity calibrations of large area IR detectors. The large area is needed for power-mode calibrations to underfill the test-detector with the incident beam. Small area or spatially nonuniform detectors should be calibrated in irradiance measurement mode to obtain low responsivity uncertainties. In irradiance mode, the detectors are overfilled with the uniform field of the incident radiation.

The spectral irradiance responsivity determination in Fig. 5, used a large (5 mm) pyroelectric detector. This realized irradiance responsivity scale covers the 250 nm to 2000 nm wavelength interval and its uncertainty is 0.5 % (*k*=2) for the overall wavelength interval. This low irradiance-responsivity uncertainty can be utilized in the UV-VIS-SWIR wavelength range in spectral responsivity (such as monochromator-based) calibrations. The range can be extended to 2.5 μm.

In broadband measurements (discussed below) where different source distributions are measured, the flat spectral response is a must. In this case, the use (extension) of the wavelength interval is limited for the response-interval where the response is constant (in the wavelength range of the emitted radiation). The wavelength limit is obtained where the response-deviation from constant becomes equal to the uncertainty of the responsivity (tie point) calibration.

Table 4. Examples for spectral power responsivity calibrations of different IR test detectors at the VIS-IR detector calibration facility [11].

Test detector	**Calibrated spectral responsivity**	**Expanded uncertainty [%]**
LN_2 cooled PC-MCT	1.7 - 12.2 μm	2.3
InSb	1.6 - 5.2 μm	1.2
Low-NEP test pyroelectric	0.6 - 24 μm	2.3; above 19 μm: 2.5

The responsivity uncertainty in irradiance mode is higher than in power mode. Table 5 shows the expanded uncertainty budget (with the dominating components) of the irradiance responsivity transfer from an extended-InGaAs transfer standard to a 7 mm InSb working standard for the 1.95 μm to 2.35 μm interval. The 2.5 % (k=2) uncertainty is roughly twice as high than the 1.2 % (k=2) power responsivity uncertainty shown in Table 4. The 2.5 % (k=2) uncertainty was extended to 5.2 μm based on the agreement of the spectral power responsivities derived from the sphere-input ext-InGaAs and the pyroelectric transfer standards [7].

Table 5. Spectral irradiance responsivity uncertainty budget for a 7 mm InSb detector.

Uncertainty factor	**Type A [%]**	**Type B [%]**	**Combined [%]**
Ext-IGA irradiance responsivity	1.23		
Distance		0.66	
Ext-IGA signal noise and drift		1.5	
InSb signal noise		1.5	
Expanded combined uncertainty (k=2)			2.5

4. FLAT-RESPONSE PYROELECTRIC STANDARD FOR BROADBAND MEASUREMENTS

The organic-black coated pyroelectric-detector-based UV-VIS-NIR irradiance responsivity scale, shown in Fig. 5 (above), was utilized in the earlier developed broadband measurement procedure [12, 13]. The output signal measured by a pyroelectric radiometer is equal to the spectral product of the source distribution and the meter response function. The requirement from the broadband measurement procedure is to obtain invariance in the measured signal (at the output of the meter) for changes in both the source (peak and spectral-width) and the spectral-shape of the meter-response. To perform uniform broadband measurements, the spectral response of the meter must be broader than the spectral distribution of the measured source(s) and the source distribution(s) must be within the spectral response function of the meter for all the expected source(s) and meter changes. This is the reason that the above discussed flat-response pyroelectric meters are excellent candidates for broadband (integrated) radiometric measurements. The measurement equation using a flat-response pyroelectric meter is:

$$i = s \int_{\lambda} E(\lambda) d\lambda$$

where s is the constant spectral responsivity of the meter, $E(\lambda)$ is the spectral irradiance of the source to be measured, λ is the wavelength, and i is the measured output signal (current) of the flat-response irradiance-meter. The integrated (broadband) irradiance (from the source) is the ratio of the measured output current divided by the constant irradiance responsivity of the meter:

$$\overline{E} = \frac{i}{s}$$

where the unit of i is A, the unit of s is A cm^2/W, and the obtained unit for $\overline{E}$ is W/cm^2.

Use of the pyroelectric irradiance-measuring detector standard with the flat-response between 250 nm and 760 nm, simplified the broadband measurement procedure and uniform integrated irradiance measurements from all kinds of UV and VIS sources (with different peaks and distributions) can be made without using any source standard. The deviation of the meter-response from constant in this spectral range was less than the responsivity uncertainty of the 660-nm irradiance responsivity (absolute) tie point (see the UV-VIS-NIR irradiance responsivity scale realization in Fig. 5). Using this flat-response pyroelectric standard, yearly spectral calibrations of the reference UV (lamp or LED) sources and irradiance meters is not needed [14]. Field UV meters (including existing commercial UV irradiance meters) can be calibrated against this irradiance measuring pyroelectric radiometer standard for integrated irradiance responsivity when both measure the same UV source. Using this calibration transfer, spectrally flat response for the field UV meters is not required. Applying the flat-response pyroelectric detector standard in the broadband measurement procedure, the UV measurement uncertainties (lamps or LEDs) were significantly decreased.

The flat-response pyroelectric detectors, in Figs. 7 and 8, with NEP ~ 0.3 nW/Hz^{½} can be used for scale transfer from sphere-InGaAs transfer standard to the flat-response pyroelectric detector or to directly measure the integrated irradiance from mid-IR LEDs that have low output flux of 0.2 mW to 3 mW between 1.55 μm and 4.3 μm [15].

4.1. UV LED measurements

The above described low-NEP pyroelectric detector with the flat-response between 250 nm and 760 nm was used to measure UV LEDs. This low-NEP detector can measure radiant power down to 1 μW with a signal-to-noise ratio (S/N) of 100 [14]. For UV LED measurements, the spectral irradiance responsivity was determined first. This is the first-time calibration of the irradiance responsivity for a pyroelectric detector.

The uncertainty budget of the spectral irradiance responsivity for the organic black coated (hybrid) pyroelectric detector-standard is shown in Table 6. The expanded irradiance responsivity uncertainty between 0.25 μm and 0.76 μm was 0.5 % (k=2).

When measuring LEDs using the above pyroelectric radiometer, lower uncertainties can be obtained with the discussed radiometric broadband (integrated) irradiance measurements than with traditionally used V(λ)-based illuminance measurements, especially in the blue and red. Using this broadband radiometric measurement, spectral information about the measured source will not be obtained.

As a result of the introduced broadband calibration procedure, the close to 0.5 % (k=2) combined uncertainty for the reference level integrated irradiance measurement is significantly lower than the 5 % (k=2) uncertainty performed using the previously applied source and detector spectral calibrations based method [16].

The less than +/- 1 % responsivity deviations from constant up to 2 μm makes it possible to apply broadband (integrated) irradiance LED measurements for the VIS-NIR range [9] as well.

Table 6. Uncertainty budget of spectral irradiance responsivity of the flat-response pyroelectric detector from 250 nm to 760 nm.

Relative uncertainty components	**[%]**
Δλ	0.03
Distance	0.04
Target spot non-uniformity	0.10
Spectral response change	0.18
Output signal ratio	0.10
Reference Si-trap	0.10
Combined (k=1)	**0.25**
Expanded (k=2)	**0.5**

UV LEDs peaking at 265 nm, 275 nm, 285 nm, 365 nm, and 400 nm were measured for integrated irradiance using the flat-response pyroelectric standard discussed in Table 6. The high output-flux LEDs were used with forward-current control and heat-dissipation using efficient heat sinks. For the LEDs of lower output flux, a UV-lens with f-number of f /1 was attached to the LED mount for beam collimation. Table 7 shows the measured integrated irradiance from six UV LEDs measured with the flat-response organic-black pyroelectric standard at a source-to-detector separation of 40 cm. The measurement uncertainties were less than 1 % (k=2).

Table 7. Integrated irradiance form six UV LEDs measured with the flat-response organic-black coated (hybrid) pyroelectric detector at a distance of 40 cm. The measurement uncertainties are less than 1 % (k=2).

ILT E275P (1 mW flux)	$\overline{E}$ = 0.71 μW/cm^2 at 19.8 mA
Thorlabs M265L3 (10 mW)	$\overline{E}$ = 80 μW/cm^2 at 300 mA
Thorlabs M285L4 (45 mW)	$\overline{E}$ = 0.44 mW/cm^2 at 325 mA
Tenzi 365	$\overline{E}$ = 2.20 mW/cm^2 at 400 mA
LED Engin LZ1 365 (1 W)	$\overline{E}$ = 48.6 mW/cm^2 at 1.0 A
Old blue LED 400 nm	$\overline{E}$ = 0.14 mW/cm^2 at 400 mA

5. CONCLUSIONS

As a result of several-year research and development work, pyroelectric detectors with low-NEP and spectrally constant response have been developed. The low NEP was required to use the pyroelectric detectors at the output of regular monochromators with signal-to-noise ratios high enough for low uncertainty detector calibrations and measurements. The flat-response was needed to simplify spectral responsivity scale realizations for the UV and IR wavelength ranges. For the first time, pyroelectric detectors were applied for irradiance responsivity calibrations and measurements. Based on spectral reflectance measurements of the black coatings, a UV-VIS-NIR irradiance responsivity scale with an uncertainty of 0.5 % (k=2) was realized. This uncertainty is a few times lower than the uncertainty of traditional spectral responsivity calibrations. Using the flat-response of the pyroelectric irradiance-measuring detector standard between 250 nm and 760 nm, uniform integrated irradiance measurements from all kinds of UV and VIS sources (with different peaks and distributions) were performed without using any source standard. The response-deviation of the pyroelectric standard from constant in this spectral range was less than the responsivity uncertainty of the scale realization. Using the irradiance measuring pyroelectric standard, VIS, UV, and deep UV LEDs could be measured. The uncertainty of the pyroelectric detector based UV LED measurements was three times lower than that of traditional FEL lamp based spectral determinations. When measuring VIS LEDs using the constant-response pyroelectric meter, lower measurement uncertainties can be obtained than with traditionally used V(λ)-based photometric measurements, especially in the blue and red. However, the broadband measurement does not include the spectral distribution of the measured source. The flat-repose of the low-NEP pyroelectric detectors was extended to 21 μm and utilized for reference spectral irradiance responsivity calibrations between 1.6 μm and 2.6 μm where the response deviation from constant is only +/- 0.35 %. Using again spectral reflectance based irradiance responsivity scale realization, the scale realization can be accurate, short, and simple. The low-NEP pyroelectric radiometers with the flat-response were used for irradiance responsivity transfer from a sphere-input InGaAs transfer-standard radiometer and they also measured integrated irradiance from LEDs in the UV and also in the near-to-mid IR ranges.

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8. Disclaimer, C*ertain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does imply that the equipment are necessarily the best available for the purpose.*
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