Evaluation of dome-input geometry for pyroelectric detectors

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ABSTRACT

Dome-input pyroelectric radiometers with different black coatings were developed to extend the spectral responsivity scale from near infrared (NIR) to 20 µm. The reflective dome with shiny gold-coating has been known to be an efficient light trap to enhance the detector absorptance and to minimize spectral responsivity variation. The enhancement of spectral responsivity using reflective dome relies on optical characterization of black coating on detector, reflectance of dome reflector, and input aperture dimension, etc. We report a comparison of spectral responsivity of dome-input pyroelectric radiometers measured with/without dome-trap from 2.4 µm to 14 µm using the Infrared Spectral Comparator Facility (IRSCF) at NIST. The results show 4 % to 8 % gain of responsivity for two dome-input pyroelectric detectors, with reduced structure of spectral responsivity. The uncertainty of dome-input pyroelectric radiometer calibrations is approximately 2 % (k = 2).

Keywords: Spectral responsivity, dome-input pyroelectric radiometer, specular and diffuse reflectance, absorptance, organic black coating, trap efficiency, noise-equivalent-power (NEP)

1. INTRODUCTION

Reflective hemispherical mirrors (dome) were used early to improve the absorptance of black coating on pyroelectric radiometers to establish a relative spectral responsivity scale without spectral variation [1, 2]. Dome-input pyroelectric radiometers with gold black and organic black coatings have been developed at NIST to extend the spectral responsivity scale from near infrared (NIR) to 25 µm [4, 5, 10]. Some efforts have been made to optimize the light-trap mechanism, to lower NEP, and increase sensitivity [3, 5, 9]. The gold-coated reflective dome is designed for specular reflection to increase the detector absorptance and to minimize spectral structures in the responsivity, and to obtain spectrally constant responsivity. The trap efficiency mainly depends on the geometry of dome reflector, and the optical properties of the black coating on the detector, such as the reflectance and distribution of the reflected light in the wavelength range of interest. It can be evaluated by measuring the reflectance with/without dome using the Complete Hemispherical Infrared Laser-based Reflectometer (CHILR), which covers several individual wavelengths from 1.56 µm to 10.6 µm. The spectral absorptance of detector can also be determined from the spectral reflectance measurement using the Fourier Transform Infrared Spectrophotometry (FTIS) facility [8]. However, with use of the efficient dome light-trap, the absorptance of the dome-input detector approaches unity. It leads to the technical challenge to measure the weak reflected light leaving the 3.5 mm − 4.5 mm diameter aperture on the dome. Even though a witness sample of the black coating is used, variations of reflectance caused from alignment of the dome and the witness sample, low signal, and high power threshold, etc. have to be addressed to determine the absorptance of the dome-input detector. Three facilities at NIST have been used to perform direct responsivity calibrations in the infrared spectral regime [4, 5, 11], which are the Infrared Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (IRSIRCUS) facility [6, 7], the Circular Variable Filter (CVF) spectrometer, and the Infrared Spectral Comparator Facility (IRSCF) [5, 11]. In the paper, we report a comparison of spectral responsivity of dome-input pyroelectric radiometers measured with/without dome trap from 2.4 µm to 14 µm using the Infrared Spectral Comparator Facility (IRSCF) at NIST. It is the first measurement for us to verify the responsivity enhancement comparing the spectral responsivity with/without dome, and to observe the improvement of the structures of spectral responsivity. The results show 4 % to 8 % gain of responsivity for two dome-input pyroelectric detectors, and a structure of spectral responsivity is reduced. The uncertainty of the dome-input pyroelectric radiometer calibration is approximately 2 % (k = 2).

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1.1 Dome-input pyroelectric radiometers

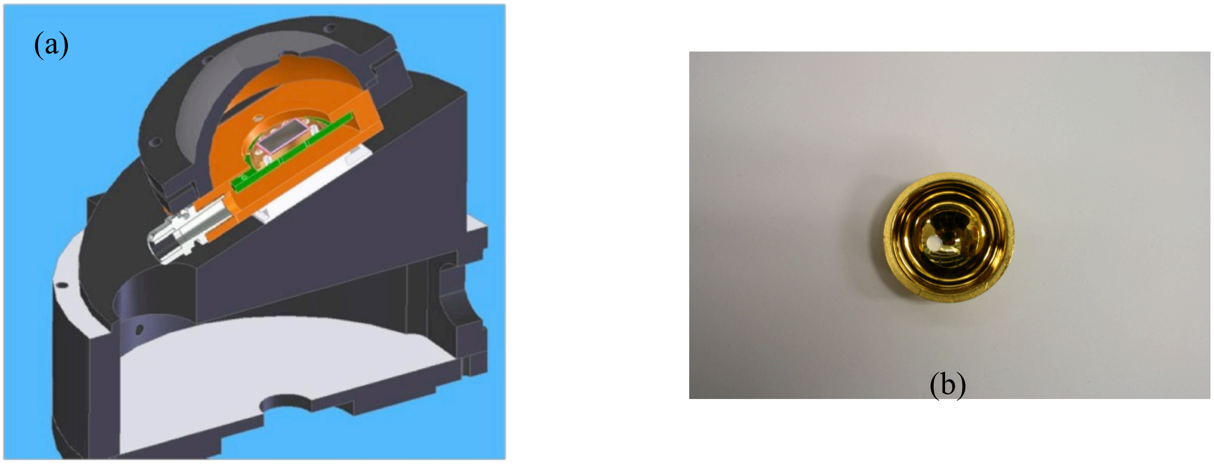

Figure 1. The cross-section of the dome-input pyroelectric radiometer head (a), and the photo of the reflective dome (b).

The hemispherical light trap concept was originated from G. W. Day et. al. at NIST in 1976 [1]. The modular design has been improved constantly with the development of material and coating [2, 5, 10, 11]. On the basis of the development of low NEP single-element pyroelectric radiometers [3], further improvement was made using a dome-trap design. As shown in the cross-section of Figure 1(a), the pyroelectric detector is enclosed in a cylindrical housing of anodized aluminum with the thermoelectric cooler (TEC) on the back to control the detector temperature. The pyroelectric detector is made of the $LiTaO_3$ crystal with a 10 mm × 10 mm and 50 µm thick. The surface of the detector is coated with organic black coating about 50 µm, and the detector element of 7 mm diameter active area left is mounted on a plane at an angle of 20° to the axis of the cylindrical house. The reflective hemispherical mirror (dome) is gold coated with reflectance as high as 99 %. A 33 mm diameter reflecting dome optic with a 4.5 mm diameter opening is shown in Figure 1(b). The geometry of the detector element and the dome opening along the optical axis can accept an f/4 incident beam or a 3.5 mm to 4.5 mm diameter collimated beam. Because of the multiple reflections of the incident radiation between detector and the dome, most of the input-radiation is absorbed by the detector coating. Figure 2 shows two photographs of the dome-input pyroelectric detector with/without dome. The dome is interchangeable using the positioning marks on dome and holder. The following experiments of calibration were performed in both with and without dome configurations as shown here. In the right photo of Figure 2, the surrounding area of the detector is covered by an aluminum ring and detector package. If the reflected light couldn't be captured completely by the detector element, it can eventually be lost on that area to cause uncertainty.

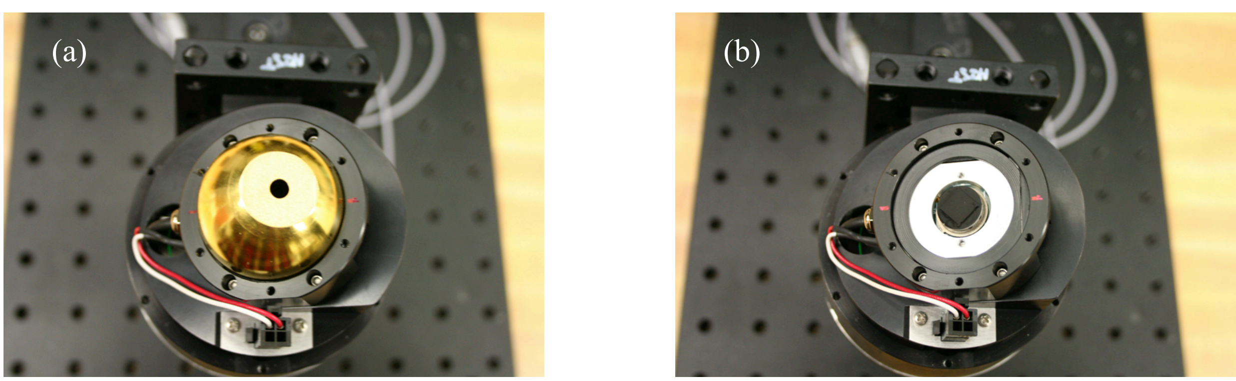

Figure 2. Photographs of the dome-input pyroelectric radiometer with (a)/ without (b) dome.

Table 1. Characteristics of dome-input pyroelectric radiometers.

	DLNO2	PT1000	DTP2	DTP3	DTP6	DTP6M	DTP7
Freq 3dB roll-off, Hz	76	49	122	67	47	6	74
NEP $nW/Hz^{1/2}$	74	8	11.6	11	10.6	6.4	8.7
Resp V/W @ 1.56 µm	762.5	14826	12353	15458	11726	85500	12295
Coating	Gold-black	Organic black	Organic black	Organic black	Organic black	Organic black	Organic black
Optical property	Diffuse	Specular	Specular	Specular	Specular	Specular	Specular
Mechanical property	Fragile	Robust	Robust	Robust	Robust	Robust	Robust

Table 1 summarizes the characteristics of different dome-input pyroelectric radiometers. It includes the detectors with gold-black and organic black coatings. The improvement of responsivity is from 20 to 100 times, and the NEP also is lowered a decade. Two dome-input pyroelectric radiometers selected from the table, DTP3 and DTP6M, are used to measure the spectral responsivity with/without dome for comparison. One dome-input pyroelectric radiometer, s/n DTP3, has a 3.5 mm diameter aperture on the dome, and its NEP is about 11 $nW/Hz^{1/2}$. The other dome-input pyroelectric radiometer, DTP6M, was recently modified by widening the aperture on the dome to 4.5 mm diameter, improving the spatial uniformity of response. Its responsivity is also increased about a factor of 7. The bigger aperture on the dome is favorable to underfill the aperture, however it degrades the performance on light trap. The high gain of DTP6M also requires the attenuation of input flux using small apertures on the monochromator to decrease signal for the reference detector.

2. EXPERIMENTS

The emergence of low-NEP pyroelectric radiometers makes the traditional monochromator-based method reusable for routine calibration. The IRSCF was constructed for the calibration service, currently covering the 1.5 µm to 14 µm range and being extended up to 25 µm. The setup is similar to the existing NIST visible to NIR Spectral Comparator Facility (SCF). Figure 3 shows the schematic diagram of main components, consisting of a blackbody or a broadband lamp source, input/output optics, a four-grating turret monochromator, and three-axis heavy-duty translation stages. The radiation from a blackbody source or a broadband source (tungsten-halogen lamp) is introduced by the spherical mirror as an f/4 beam into the entrance aperture of the monochromator through order sorting filters and a chopper. The incoming radiation is dispersed by four gratings following the order sorting filters. The outgoing beam from the monochromator is re-focused to about 2 mm diameter through a pair of off-axis paraboloid mirrors, and underfilled on the dome-input pyroelectric radiometers and the reference standard using X-Y-Z translation stages for centering them. The calibration of the radiometers against the reference standard is conducted in a substitution fashion. The four dispersive gratings on the turret can cover the spectral range from 1.7 µm to 20 µm with resolution from 20 nm to 120 nm. They are motorized with an absolute encoder for precision control. The X-Y-Z translation stages for the detectors are utilized to underfill/position detectors and measure their spatial non-uniformity. Figure 4 shows the photographs of the measurement configuration of pyroelectric radiometer with/without dome and the reference standard on the stages. The spectral responsivity was measured with/without dome by maintaining the same spot size on the detector in order to reduce the discrepancy of responsivity produced by the spatial non-uniformity of response and beam geometry.

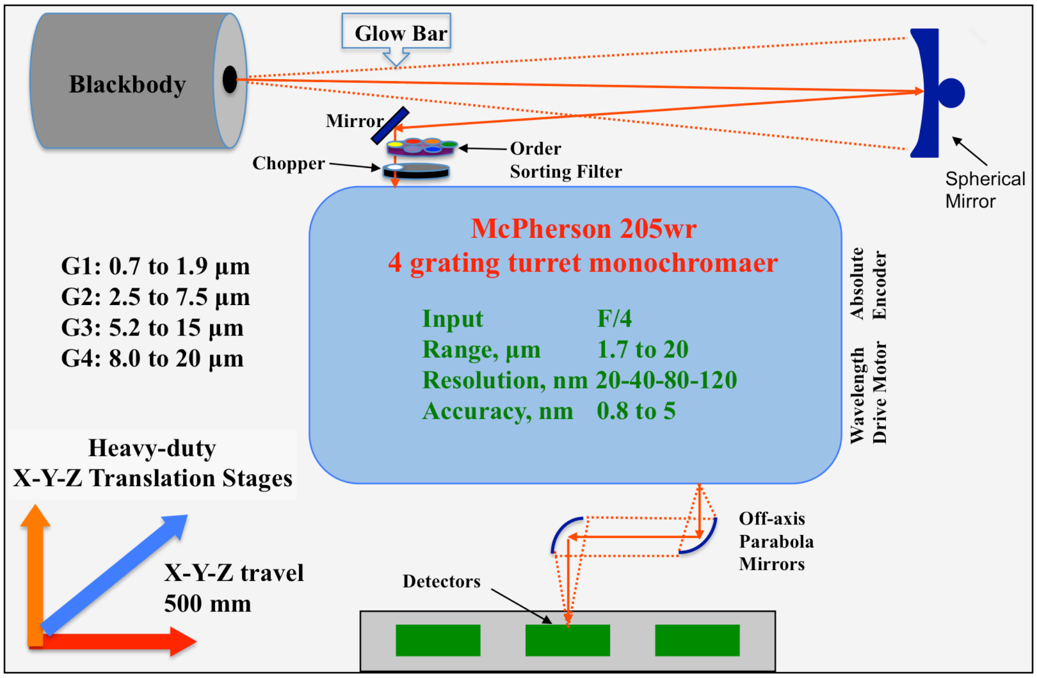

Figure 3. Schematic diagram of the IRSCF.

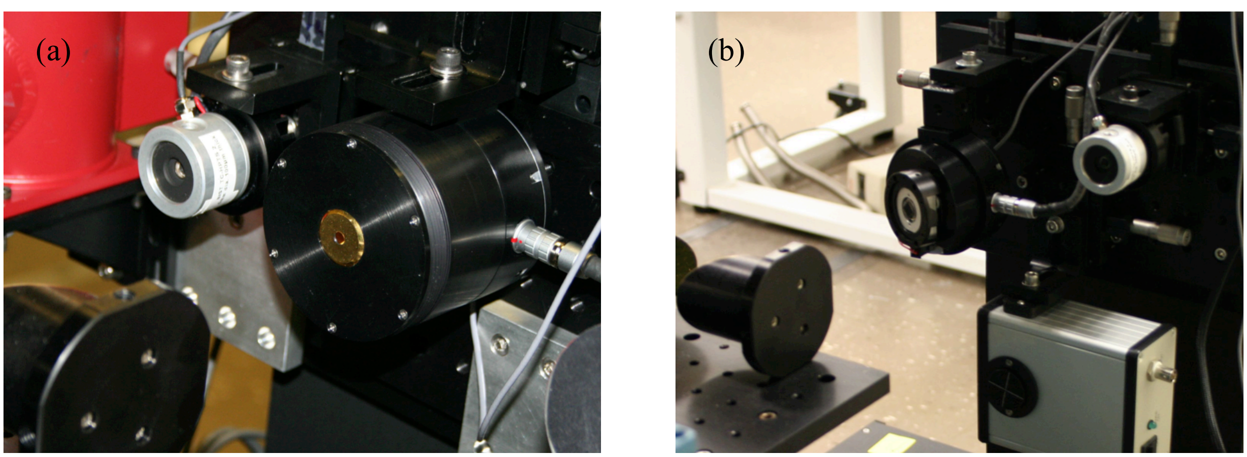

Figure 4. Photographs of dome-input pyroelectric radiometers with (a)/without dome (b) on the IRSCF.

The characterization of spatial non-uniformity of responsivity for radiometers provides useful information about the detector surface, and helps estimate the calibration uncertainty by knowing the calibration area. The surface coatings of different detectors may also be wavelength dependent, so the spatial non-uniformity can vary at different wavelengths. In Figure 5 (a), the spatial profiles of a single-element reference standard pyroelectric radiometer with an active area of 5 mm diameter are illustrated. It reveals a central plateau area from ± 1 mm, to ± 2 mm with use of different apertures on the monochromator from 2.5 mm to 4.5 mm, and the associated signal level change is about one decade. The spatial non-uniformity of the reference standard also demonstrates the optimized beam size, which can be used to underfill any radiometer of size > 5 mm diameter (without dome). The spatial profiles of the single element radiometer are not beam geometry dependent as long as the beam is underfilled on the element surface. However, the dome-input pyroelectric radiometer requires the beam geometry from f/2 to f/4. In the right graph of Fig. 5, the spatial profiles of the dome-input pyroelectric radiometer DTP3 with a 3.5 mm diameter aperture show narrow plateau area within ± 0.5 mm diameter area in both cases (with/without dome). By optimizing the spatial profile of the radiometer with dome, the beam distance from end of off-axis paraboloid mirror to detector is determined and the same spot size is maintained on the radiometer for with/without dome measurements. The spatial profiles of the radiometer with dome show similar trend to those of the radiometer without dome, and the signal output from the radiometer with dome is about 4 % larger than that without dome. It also verified that the beam geometry and alignment are good enough to see the enhancement of responsivity with dome. A small difference of width on the x-y spatial profiles can be seen in the right graph of Figure 5 due to the 20° tilt of detector surface along the vertical axis. It means the width of the spatial profile in x direction is smaller than that in y direction since the 20° tilt of detector surface only affects the spatial profile in x direction.

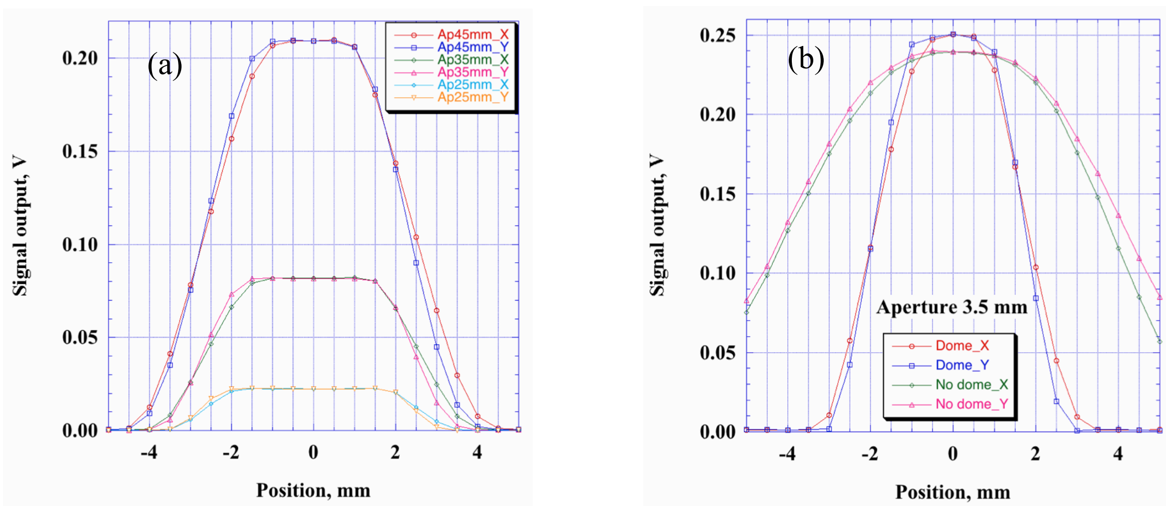

Figure 5. Spatial profiles of a standard detector at 2.4 µm using three apertures on monochromator (a), and the spatial profiles of dome-input pyroelectric radiometer DTP3 with/without dome using an aperture of 3.5 mm on the monochromator (b).

The geometry of the detector element and dome opening along the optical axis requires a typical f/2-f/4 input beam. The schematic diagram of beam geometry on the dome-input detector is illustrated in Figure 6, where the 7 mm diameter detector, the 33 mm diameter dome, and 4 mm diameter aperture are used. The input beam passes through the plane of the 4 mm diameter aperture in order to ensure underfilling of the active element of the radiometer. The dome trap geometry could modify the ultimate spatial non-uniformity of the detector if the unabsorbed radiation is reflected from the dome optics back to the detector element. The spatial reflectance and the BRDF of the coating is necessary to fully understand the resulting spatial non-uniformity with dome effect. The light-trap dome plays a role to obtain complete absorption, which is also advantageous to reduce the effect of the spatial non-uniformity of the black coating. The different input beam geometries are also associated with the angular dependence of radiometer, such as the optical properties of the organic-black coating for s-p polarizations. As shown in Figure 6, the maximum angle of view can be 38.7° (f/1.25) if the focus is placed at an optimum position between the entrance aperture and the detector element in order to underfill its detector element. If the focus is right on the plane of the entrance aperture, the maximum viewing angle is 26.6° (f/2). If the focus spot is outside the dome, the view angle should be less than 11° (f/5.1). To focus at the element surface, the maximum viewing angle is limited to 14.4° (f/3.9). It is possible to use beams in the range from f/1.25 to f/5, while the output beam of the monochrometor is about f/3-f/4. The challenge of alignment is how to determine the optimum position to ensure beam underfilling of detector without loss.

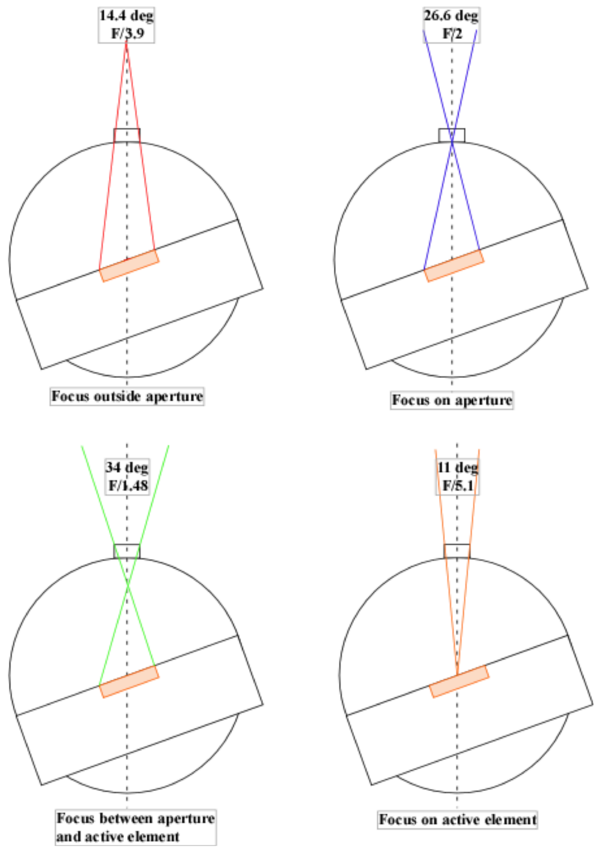

Figure 6. Schematic diagram of different beam geometries for the dome-input detector.

3. RESULTS AND DISCUSSION

The main purpose of this paper is to evaluate the enhancement of responsivity using the reflective dome-mirror, and the improvement of the variation of spectral responsivity, and the dependence of trap effect on the optical property of black coating by comparing the spectral responsivity results with/without dome. In previous work on dome-input pyroelectric radiometer calibration, the improvement of spectral responsivity of a dome-input pyroelectric radiometer has been demonstrated by comparing with a single element standard detector. Since the reflectance/absorptance of the black coating is highly dependent on coating process, it is still unknown how much the enhancement of responsivity could be achieved in different conditions, whether spectral features of responsivity are improved, and what kind of black coating works better with the dome-trap geometry.

The theory of dome light trap operation is dependent on inherent characteristics of the black coating, assuming its reflection $\rho(\lambda)$ is specular. Without the dome trap, the black coating only absorbs the incoming light once, and reflects the rest of light back to environment. It results in the spectral responsivity depending on the spectral reflectance/absorptance of the black coating, which can vary from several percent to several ten percent as shown in Figure 7.

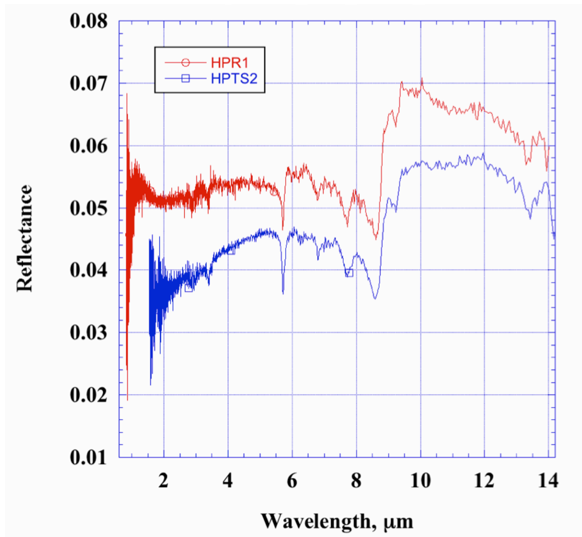

Figure 7. Results of spectral reflectance from two pyroelectric radiometers with organic black coating.

A reflective dome mirror with reflectance $R(\lambda)$ is introduced on top of the detector to decrease the reflectance. The radiant power is first absorbed with an absorption fraction of $1-\rho(\lambda)$ by the black coating. Then the reflective dome redirects part of reflected light back to the black coating again with a fraction of $R(\lambda)\rho(\lambda)$ each time, and a complete absorption can be approached in multiple times. The total absorbed power by the black coating on dome-input pyroelectric detector is given as follows:

$$\Phi_{abs}=\Phi_i\left[1-\rho(\lambda)\right]\left[1+R(\lambda)\rho(\lambda)+R^2(\lambda)\rho^2(\lambda)+......+R^n(\lambda)\rho^n(\lambda)\right]=\Phi_i\left[1-\rho(\lambda)\right]\frac{1-R^n(\lambda)\rho^n(\lambda)}{1-R(\lambda)\rho(\lambda)} \quad (1)$$

where Φ_i and Φ_{abs} are input power and absorbed power.

If $n\to\infty$, the total absorptance α_T of the black coating is simplified to be:

$$\alpha_T=\frac{1-\rho(\lambda)}{1-R(\lambda)\rho(\lambda)} \quad (2)$$

In the ideal case, $R(\lambda)=1$, the total absorptance will be unity no matter how much the reflectance of coating is.

If a black coating of 4 % – 6 % reflectance as shown in Figure 7 is used, and the reflectance of the dome reflector is assumed to be 99 %, the total absorptance can reach to 99 % through two absorptions. The simple evaluation shows the coating with specular reflection works well in the trap geometry.

Two dome-input pyroelectric radiometers with different apertures, and different coating processes were selected to compare the spectral responsivity with/without dome. The reflection distribution of the black coating on two detectors is considered to have specular and diffuse reflections, which is also wavelength dependent. The two spectral responsivity curves with/without dome from 2.4 µm to 14 µm for DTP6M are presented in Figure 8 (a), which is a factor of 8 higher than that of the other radiometer, DTP3, in Figure (b). The enhancement of responsivity has been demonstrated in the results of spectral responsivity for both of them, comparing lower and upper curves in each graph. The result without dome for the upgraded dome-input pyroelectric radiometer, DTP6M, shows the spectral flatness within a variation of 1 %

in the measured wavelength range. The spectral variation of responsivity with dome remains about 1 %. The enhancement of responsivity is roughly 4 %. The spectral responsivity curve without dome for DTP3 shows a slope from 2.4 µm to 14 µm with a spectral variation of 2 % to 4 %. When the reflective dome is used, the slope of spectral responsivity is reduced. It is attributed to the increasing contribution of specular reflection with changing from NIR to Mid IR. The spectral responsivity curves without dome also shows a feature around 8.5 µm, which corresponds to the structure of spectral reflectance on the organic black as seen in Figure 7. This feature is removed from the spectral responsivity curves using with the dome. The 2 % to 3 % uncertainty of the spectral responsivity is also presented in Figure 8.

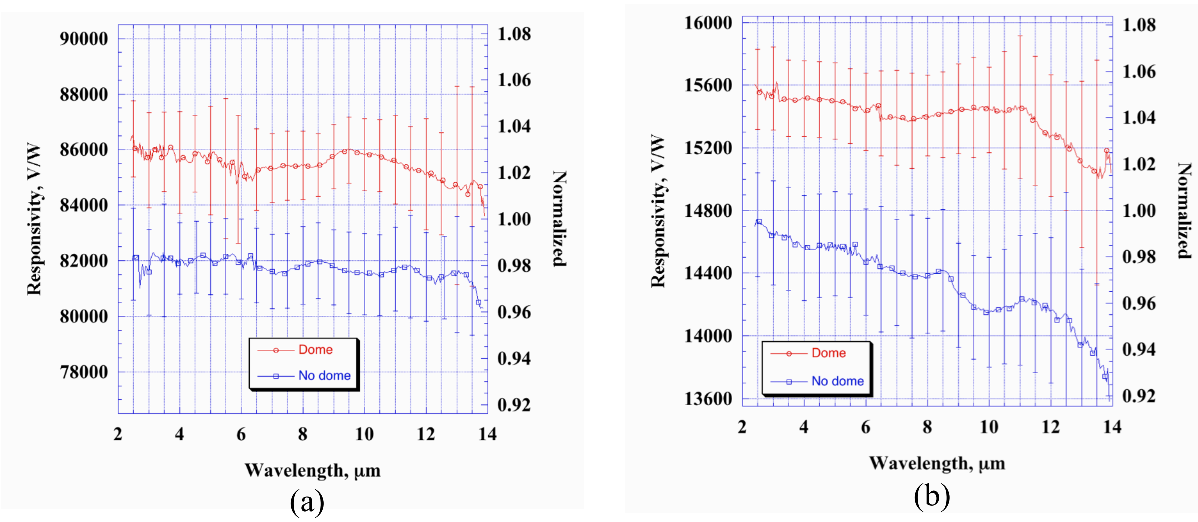

Figure 8. Comparison of spectral responsivity of two dome-input pyroelectric radiometers with 4.5 mm aperture (a) and 3.5 mm aperture (b).

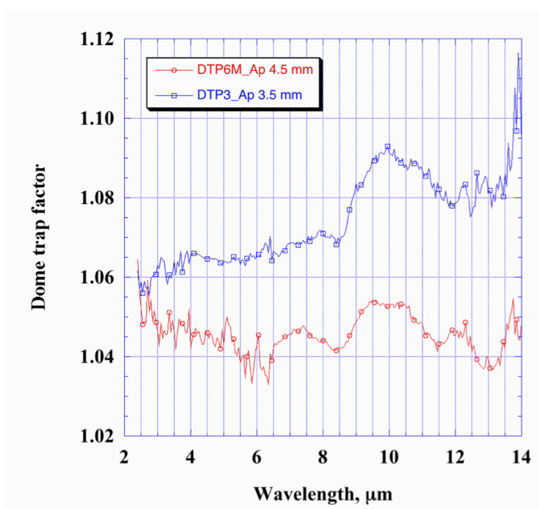

Figure 9. Comparison of light-trap efficiency of two dome-input pyroelectric radiometers.

To evaluate the light trap efficiency, a dome trap factor is introduced by simply taking the ratio of the responsivity with dome to that without dome. It is dependent on reflectance and BRDF of absorbing coating, and reflectance of reflective dome-gold coating. Two dome trap factor curves as a function of wavelength for two dome-input pyroelectric radiometers are given in Figure 9 for comparison. The circle line of the dome-input pyroelectric radiometer with the aperture of 4.5 mm diameter, DTP6M, shows about 4 % – 5% enhancement of responsivity of the dome-input detector. Its dome trap factor curve has small wavelength dependence over the spectral range from 2.4 µm to 14 µm. The square line of the other dome-input radiometer with aperture of 3.5 mm diameter, DTP3, shows bigger enhancement of responsivity roughly from 6 % to 8 %. The 2 % – 3 % difference of dome trap factors between the two dome-input pyroelectric radiometers was caused by the different dome-aperture sizes, whereby the larger aperture decreased the trap efficiency. The wavelength dependence of responsivity enhancement from 2.4 µm to 14 µm for the dome-input pyroelectric radiometer with 3.5 mm dome aperture is associated with the dependence of specularity on wavelength. As discussed before, the specular component of light can be more efficiently trapped by the dome geometry than the diffuse component of light. The increase of the dome trap factor for the dome-input detector with 3.5 mm aperture demonstrates the specular property is getting dominant in the long infrared range.

The typical uncertainty budget of the spectral responsivity for the dome-input pyroelectric radiometer, DTP6M, is given in Table 2. The major uncertainty components come from the transfer standard, detector and reference measurements, and the spatial non-uniformity. The signal output of the radiometer without dome shows higher standard deviation than that of radiometer with dome. It is attributed to the dome structure, which can diminish the ambience influence, and acoustic pickup on the pyroelectric radiometer. The uncertainty from input beam geometry is estimated by using the underfilled mode with/without dome. The dome-input pyroelectric radiometer, DTP6M, shows the improved spatial uniformity comparing to the radiometer, DTP3. The spatial uniformity of it can also be improved by using the dome. The expanded uncertainty of the responsivity of the radiometer without dome is 2.5 % (k = 2), and 2 % (k = 2) for the radiometer with dome. All the results of spectral responsivity with uncertainty for the two dome-input pyroelectric radiometers are presented in Figure 8.

Table 2. Uncertainty budget of the dome-input pyroelectric radiometer (DTP6M).

Uncertainty Source	**Without dome**	**With dome**	**Type**
Transfer standard	**0.5 %**	**0.5 %**	**B**
Detector	**1 %**	**0.68 %**	**A**
Reference	**0.3 %**	**0.37 %**	**A**
Input beam geometry	**0.1 %**	**0.3 %**	**B**
Spatial non-uniformity	**0.5 %**	**0.25 %**	**B**
Combined	**1.23 %**	**1.00 %**	
Exp Unc (*k* = 2)	**2.5 %**	**2.0 %**	

4. CONCLUSIONS

The spectral responsivity of two dome-input pyroelectric radiometers with/without dome was calibrated from 2.4 µm to 14 µm using the IRSCF in order to understand the dome-trap efficiency, and improvement of spectral variations of responsivity. Two dome-input pyroelectric radiometers with different dome apertures of 3.5 mm and 4.5 mm, and different organic black coatings were selected for comparison. Different trap factors were obtained from 4 % to 8 %. The removal of local feature of spectral responsivity around 8.5 µm has been verified. A slope variation of spectral responsivity was reduced from 4 % to 2 % in the dome-input pyroelectric radiometer using a 3.5 mm aperture. The uncertainty of the spectral responsivity calibration from 2 µm to 14 µm was approximately 2 % to 3 % ($k = 2$) using the IRSCF.

REFERENCES

[1] G. W. Day, C. A. Hamilton, and K. W. Pyatt, "Spectral reference detector for the visible to 12-µm region; convenient, spectral flat, " Appl. Opt. **15** 1865-1868.

[2] E. Theocharous, "The establishment of the NPL infrared relative spectral responsivity scale using cavity pyroelectric detectors, " Metrologia, **43** (2006) S115-S119.

[3] G. P. Eppeldauer, J. Zeng, and H. W. Yoon, "Low-NEP pyroelectric radiometer standards, " SPIE, Proc. Vol. 6940, pp. 694035-1 to 694035-8, (2008).

[4] G. P. Eppeldauer, J. Zeng, H. W. Yoon, B. Wilthan, T. C. Larason, and L. M. Hanssen, "Extension of the NIST spectral responsivity scale to the infrared using improved-NEP pyroelectric detectors, " Metrologia 46 (2009) S155-S159.

[5] George P. Eppeldauer, Jinan Zeng, and Leonard M. Hanssen, "Increased responsivity pyroelectric radiometer with dome input and temperature control," SPIE, Proc. Vol. 8014, pp. 801419-1 to 801419-8, (2011).

[6] S. W. Brown, G. P. Eppeldauer, and K. R. Lykke, "Facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources, " Applied Optics, 45(32), 8218-8237 (2006).

[7] Jinan Zeng, Howard W. Yoon, George P. Eppeldauer, Leonard Hanssen, and Joseph Rice, "Spectral irradiance responsivity calibration of InSb radiometers using the improved IR-SIRCUS at NIST, " San Diego, CA, Aug. 3-6, (2009), Proc. of SPIE Vol. 7453, 74530N.

[8] L.M. Hanssen and S.G. Kaplan, "Infrared diffuse reflectance instrumentation and standards at NIST, " Analytica Chimica Acta 380, 289-302 (1998).

[9] J. Lehman, A. Sanders, L. Hanssen, B. Wilthan, and J. Zeng, "Very black infrared detector from vertically aligned carbon nanotubes and electric-field polling of lithium tantalite, " Nano Lett. 10 (9) pp. 3261-3266, (2010).

[10] G.P. Eppeldauer, M. Racz, and L.M. Hanssen, "Spectral responsivity determination of a transfer-standard pyroelectric radiometer," SPIE, Proc. Vol. 4818, pp. 418-216, (2002).

[11] J. Zeng, G.P. Eppeldauer, L.M. Hanssen*, V.B. Podobedov, "*Spectral responsivity calibration of two types of pyroelectric radiometers using three different methods," SPIE, Proc. Vol. 8355, 835503 (2012).