

# High-accuracy room temperature planar absolute radiometer based on vertically aligned carbon nanotubes

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**Abstract:** We have developed a planar absolute radiometer for room temperature (PARRoT) that will replace the legacy C-series calorimeter as the free-space continuous-wave laser power detector standard at the National Institute of Standards and Technology (NIST). This instrument will lower the combined relative expanded measurement uncertainty (k = 2) from 0.84 % to 0.13 %. PARRoT's performance was validated by comparing its response against a transfer standard silicon trap detector traceable to NIST's primary standard laser optimized cryogenic radiometer (LOCR) and against the C-series calorimeter. On average, these comparisons agreed to better than 0.008 % and 0.05 %, respectively.

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# 1. Introduction

Bolometers measure optical power via thermal rise of absorbing media. The first bolometer was developed by Langley [1] in 1881 for stellar radiometry with advances following in-turn. In the 1960's the first lasers [2] became commercially available and the National Institute of Standards and Technology (NIST, West *et al.* [3,4]) introduced laser calorimetry to meet the needs of laser-power meter calibrations. A notable milestone in radiometry was the development of a cryogenic radiometer in 1985 [5] that remains the most accurate primary standard in the field [6–10], offering (k = 2) uncertainty under 0.05 %.

Although cryogenic radiometers offer lower uncertainty than room temperature radiometers, they are costly, bulky, and not user-friendly. To achieve high accuracy, a bolometer in a cryostat cannot be allowed to heat beyond its linear range of operation which sets an upper limit for measurable laser power. This means that the dynamic range in these instruments is limited, and if higher laser powers are measured one has to use a transfer standard detector traceable to the cryogenic radiometer or some other absolute detector. Maintaining long calibration chains require time and work force, and measurement uncertainties are accumulated in these chains. To reduce the calibration chains and make absolute radiometers affordable and more accessible, the Predictable Quantum Efficient Detector (PQED) was developed in 2013 and it can be operated either at cryogenic temperatures [11,12] or at room temperature [13]. Quantum detectors, however, saturate at 1 mW, so their measuring range is similar to that of most cryogenic radiometers. An international EUROMET Comparison on Radiant Power of High Power Lasers performed in 2010 [14] revealed that 1 W – 10 W laser power measurements between the national metrology institutes agreed only at ~1 % level. As such, there remains a need for

room-temperature operated high-accuracy absolute thermal detectors for higher laser power measurements, or when spectrally flat response is required.

Absolute room-temperature radiometers with power measuring capabilities up to hundreds of mW shorten calibration chains and are relatively inexpensive to build and easy to operate. For these reasons, the C-series reference calorimeter [3,4] has been used for the free-space continuous-wave (CW) optical scale realization at NIST against which customer detectors have been calibrated for the past 46 years [15,16]. The C-calorimeter has been compared frequently against the Laser-Optimized Cryogenic Radiometer (LOCR) [9,17] at NIST and confirmed to perform well-within the stated uncertainty of 0.84 % (k = 2) during its long service life. Recently, applications such as the Laser Interferometer Gravitational-wave Observatory (LIGO) [18,19] and earth-observation missions from space such as the Compact Spectral Irradiance Monitor (CSIM) [20] and the Compact Total Irradiance Monitor (CTIM) [21], have indicated need for an order of magnitude lower calibration uncertainty at power levels in the 30 mW to 1 W range. Therefore, NIST has endeavored to design a new generation of absolute radiometers operating at room temperature.

In this paper, we introduce a Planar Absolute Radiometer for Room Temperature (PARRoT) that will replace the C-series reference calorimeter. Properties of the preceding C-calorimeter sets the design criteria for PARRoT: dynamic range must be from 100  $\mu$ W to 250 mW, spectral range from 300 nm to 2300 nm, and the absorber must be 20 mm in diameter so that various beam diameters up to 11 mm (1/e<sup>2</sup>) can be measured. In order to replace the C-calorimeter, PARRoT's electro-optical inequivalence must be less than 0.05 % and spatial nonuniformity within the central 4 mm less than 0.1 %, and it must be faster than the C-calorimeter.

In PARRoT, we use microfabricated silicon chips as bolometers [22] and vertically aligned carbon nanotube (VACNT) forests as planar absorbers grown on the microfabricated silicon chips. VACNTs offer greater than 0.999 absorptivity [23] which approaches that of cavity structures while allowing significant reduction in heat capacity. PARRoT's response is actively background-compensated with closed-loop control and a second identical bolometer chip which is illuminated only by background heat-flux. To achieve accurate closed loop control, low-noise and high-resolution electronics is used.

The mechanical and electrical designs of PARRoT are introduced in Section 2. Corrections needed to obtain true laser power from PARRoT's measured response are discussed in Section 3. PARRoT's uncertainty budget is presented in Section 3.6. We compared PARRoT against a silicon trap detector whose responsivity is traceable to LOCR, and against the C-series reference calorimeter. The comparison measurements presented in Section 4 validate that PARRoT achieves a combined relative expanded uncertainty of 0.13 % (k = 2) at optical powers from 2 mW to 250 mW and 3 measurement cycles. At optical powers less than 2 mW, PARRoT's combined relative expanded uncertainty increases due to measurement noise. For example, at a laser power of 100  $\mu$ W and 10 measurement cycles, PARRoT achieves a combined relative expanded uncertainty of 0.6 %.

# 2. Design of the radiometer

# 2.1. Mechanical and thermal design

PARRoT's structure is presented in Figs. 1 and 2. PARRoT has two identical bolometer chips that are operated in closed loop control, so that the radiative coupling between ambient environment and the bolometer's absorber can be actively compensated. The heater of the reference bolometer is driven by constant power of 290 mW, and the measuring bolometer's temperature is forced to follow that of the reference bolometer by varying the heating power. Both bolometer chips are referenced to the temperature-controlled base plate at 22 °C via weak thermal links. The active background compensation was first developed by the Laboratory for Atmospheric and Space Physics (LASP) for their room-temperature radiometers of which heating was controlled

by pulse width modulation (PWM) [21]. We use constant heating instead of pulsed heating to avoid ground plane instability arising from changing loop areas and signal interference due to harmonics of the square pulses. Another advantage of the closed loop control over open loop operation is that thermal load to the base plate stays nearly constant, meaning that the settling time of the response is faster and independent of the laser power.



Fig. 1. Front side of the radiometer developed (a) and view inside the vacuum chamber (b).



**Fig. 2.** Microfabricated silicon bolometer chip connected to PARRoT's aluminum frame linking the chip to base temperature via weak thermal links made of stainless steel 304 (a) and PARRoT's model assembly (b). The bolometer chip is attached to the aluminum frame by vacuum compatible Spectralon washers and stainless steel nuts (not shown).

Bolometric sensing of laser power is sensitive to air convection and to eliminate it, PARRoT is operated in a 15 cm cube vacuum chamber. Optical access inside the vacuum chamber is provided by an uncoated UV fused silica window with a wedge angle of 0.5°. A small wedge eliminates any interference effects between transmitting and reflecting beams within the window

while minimizing any sensitivity in PARRoT's response to light polarization. The measurements with PARRoT presented in this paper were performed at a vacuum level of approximately  $10^{-5}$  Torr using a dry vacuum pump and a turbomolecular vacuum pump connected in series. For the long term use we will improve the vacuum level suitable for an ion pump shown in Fig. 1(a).

The geometry of the bolometer chip was optimized by thermal modeling based on the Finite-Element Method (FEM) in Ref. [24]. Based on the thermal model, four thermistors placed symmetrically near the edges of the circular bolometer chip results in better spatial uniformity and smaller electro-optical inequivalence compared to the less symmetrical case with one thermistor [25]. Another factor affecting the inequivalence is the shape and location of the heater; electrical and optical heating should originate from the same location to minimize the inequivalence. The VACNT absorber cannot be grown on metal without shorting [22], and for that reason the heater spiral with a Gaussian spatial profile was placed at the center, on the opposite side of the bolometer chip.

Four bolometer chips were simultaneously microfabricated from one 76.2 mm diameter silicon (Si) wafer with a thickness of 1 mm. The spiral heater described in Ref. [24] and electrical contacts for the thermistors are tungsten and deposited before the VACNT growth at 800 °C since tungsten can withstand high temperatures [22]. The unused surfaces of the chips were also coated with tungsten to reduce radiative coupling with ambient environment. Growing the VACNT absorber on top of the silicon chip was the last microfabrication step. Four negative temperature coefficient (NTC) thermistors were wired in parallel and mounted using vacuum-compatible epoxy on the same side with the spiral heater, symmetrically around the edges of each chip. Two bolometer chips were mounted to the heat link frame made of aluminum according to Fig. 2. The thermistors and spiral heater were electrically connected to the control and measurement circuit via wirebonds. Since a symmetrical structure improves spatial uniformity, we designed the heat link to have three solid posts made of stainless steel 304.

The thermal link in Fig. 2(a) protects the brittle silicon chip, making the radiometer more robust and portable compared to designs where the chip and heat link are all silicon [10,25]. Thermal conductivity of aluminum  $k_{Al} \approx 240$  W/(m·K) [26] near room temperature is significantly higher than thermal conductivity of silicon  $k_{Si} \approx 130$  W/(m·K) [27], which helps to improve the spatial uniformity of the electro-optical inequivalence. A major disadvantage of the aluminum frame is that it increases mass and heat capacity of the bolometer, increasing the closed loop settling time. In each measurement cycle of 400 s, the dark signal is measured for 200 s after which laser power is switched on and measured for 200 s. The last 30 s at the end of each pulse is averaged to obtain a measurement point.

The total thermal conductance, G, of a bolometer is defined as

$$G = \frac{P}{\Delta T},\tag{1}$$

where P is the total power loss and  $\Delta T$  is the temperature rise of the bolometer chip. Since convective cooling is negated by operating PARRoT in a vacuum, the only significant heat loss mechanisms are conductive and radiative cooling. The corresponding total thermal conductance is

$$G = G_{\rm con} + G_{\rm rad},\tag{2}$$

where  $G_{con}$  is the thermal conductance of the heat link structure and  $G_{rad}$  is the radiative conductance of the bolometer chip that is operated near room temperature. The radiative cooling power follows the Stefan–Boltzmann law

$$P_{\rm rad} = \sigma \epsilon A \left( T_1^4 - T_2^4 \right),\tag{3}$$

where  $\sigma$  is the Stefan–Boltzmann constant,  $\epsilon$  is the emissivity of the surface, A is the surface area of the bolometer chip, and  $T_1 \approx 325$  K and  $T_2 \approx 295$  K refer to the chip and ambient

temperatures. The radiative conductance is a derivative of Eq. (3):

$$G_{\rm rad} = 4\sigma \epsilon A T_1^3 \tag{4}$$

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and it is the mechanism for heat transfer from the bolometer to the ambient environment, which causes baseline drifts.

Traditional laser calorimeters' high sensitivity has been achieved by minimizing thermal paths in structural links, and thus they are vulnerable to overheating. Overheating may degrade the absorber's coating causing change in absorption which would lead to systematic error in laser power measurement. PARRoT has a low risk of overheating due to stronger thermal link than in laser calorimeters. In addition, the VACNT forests and the silicon substrate can withstand refractory temperatures when in a vacuum [23].

With high power bolometers, the heat link design is a compromise between sensitivity and maximum power measuring capability. We designed PARRoT's heat link in Fig. 2 to heat the bolometer chip to approximately 325 K, which is  $\Delta T \approx 30$  K higher than the base plate. This temperature difference can be achieved with various geometries, but in order to keep the bolometer simple and reasonably symmetric with respect to its center, our heat link structure consists of three stainless steel cylinders with the thermal conductance

$$G_{\rm con} = N_{\rm cyl} \cdot \frac{\pi r^2}{l} k_{\rm ss},\tag{5}$$

where  $N_{\rm cyl} = 3$  is the number of solid cylinders, r = 1 mm is the radius and l = 15 mm is the length of a cylinder, and  $k_{\rm ss} \approx 15.1$  W/(m·K) [28] is the thermal conductivity of stainless steel 304 at the average temperature of 310 K. The thermal conductance of the heat link  $G_{\rm con} \approx 9.49$  mW/K and radiative conductance of the bolometer chip  $G_{\rm rad} \approx 2.45$  mW/K at 325 K, meaning that 1  $\mu$ W raises the chip temperature by 84  $\mu$ K.

# 2.2. Electrical control and measurement design

PARRoT's control and measurement diagram is illustrated in Fig. 3. The constant heating power of the reference bolometer is achieved by a closed-loop digital proportional-integral (PI) controller. The measuring bolometer's heater is operated in a closed loop to match the measuring bolometer's temperature with that of the reference bolometer. The thermistors of the two bolometers were connected to one branch of an AC Wheatstone bridge and the bridge output was measured with a digital lock-in amplifier. The base plate providing the reference temperature to the bolometer chips was stabilized to 22 °C. All the controllers and the lock-in amplifier have been implemented using a field programmable gate array (FPGA) board. The FPGA enables true parallelism, exact timing, and high sampling rates, which makes FPGA a more reliable option compared to microcontrollers. To achieve low noise and high accuracy laser power measurement, two external 20-bit digital-to-analog converters (DACs) and two external 32-bit analog-to-digital converters (ADCs) were connected to FPGA via serial peripheral interface (SPI) with custom-programmed low-level drivers.

The output of an AC driven Wheatstone bridge is

$$V_{\rm b}(t) = G_{\rm ina} \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_{\rm t,ref}}{R_{\rm t,ref} + R_{\rm t,meas}}\right) \cdot V_{\rm sine}(t), \qquad (6)$$

where  $G_{\text{ina}} = 200$  is the gain of the instrumentation amplifier. Ideally, the bridge is balanced when the average temperature of the measuring chip thermistors matches that of the reference chip  $R_{t,\text{meas}} = \frac{R_2}{R_1} \cdot R_{t,\text{ref}}$ . This circuit configuration compensates for the effect of parasitic capacitance of wires and thermistors on the bridge output. However, noise and nominal value tolerances limit temperature matching. At 25 °C, the nominal resistance of the NTC thermistors has a



**Fig. 3.** Simplified block diagram of the radiometer's control and measurement electronics. Acronyms DVM, TEC, and MUX refer to a digital volt meter, thermoelectric cooler, and multiplexer.

tolerance of  $\pm 5$  % and the parasitic capacitance is unspecified. Nominal resistance and parasitic capacitance variations among the thermistors result in different heating powers of PARRoT's paired bolometer chips. For instance, when the reference bolometer heating is set to 270 mW, the balanced electrical heating power of the measuring detector is 284.5 mW when no laser power is applied. Since the closed loop maintains the differential bridge voltage at 0 V and the chips remain at constant temperature (on average), an offset in the resistance of bridge quadrants from the nominal design value does not directly cause systematic error, provided the offset is constant. However, an offset in the bridge quadrant resistance may degrade the performance of active background compensation, which is discussed in Section 3.1. During the measurements of this work, the reference power was set to 270 mW, and changed later to 290 mW to slightly extend the PARRoT's dynamic range so that laser powers around 250 mW can be measured without saturation of the measuring bolometer's control signal.

The digital lock-in amplifier used for measuring the bridge output precisely has a sample frequency of 7.2 kHz. To reduce the impact of 1/f noise of the thermistors and electronics, the Wheatstone bridge is excited by a 100 Hz reference sine wave. In the lock-in amplifier, both the reference and the bridge output signals are first filtered by a 4<sup>th</sup> order Butterworth high-pass filter with a cut-on frequency of 5 Hz so that the signals experience similar phase shifts. Then, the two signals are multiplied and the result is filtered using a 4<sup>th</sup> order Butterworth low-pass filter with a cut-off frequency of 1 Hz. The resulting voltage is DC.

We determine the electrical heating power of each bolometer chip by measuring the voltage across the standard resistor  $V_{\text{std}}$  with a calibrated resistance  $R_{\text{std}} = 10.007 \ \Omega \pm 0.002 \ \%$  and the voltage across the heater  $V_{\text{h}}$  as

$$P_{\text{elec}} = i_{\text{h}} \cdot V_{\text{h}} = \frac{V_{\text{std}} \cdot V_{\text{h}}}{R_{\text{std}}}.$$
(7)

The modest resistance value of the standard resistor was selected to keep the supply voltage requirements reasonably low and to reduce the overall power consumption of PARRoT.

Figure 4(a) shows PARRoT's response when a 12.59 mW laser beam hits the absorber of the measuring detector. PARRoT's response is balanced when the thermistor bridge output in Fig. 4(b) reaches 0 V. In PARRoT, a thermal load to the base plate stays nearly constant when switching between signal and dark measurements. This can be seen Fig. 4(c), where the base temperature varies within  $\pm 500 \ \mu$ K and does not change significantly at the transition points.

When the laser beam hits the measuring detector, electrical power is reduced so that the temperatures of the two bolometer chips match. Optical power is determined from the difference in the electrical powers measured when the laser is switched off  $P_{\text{elec, dark}}$  and when the laser is on  $P_{\text{elec, light}}$ :

$$P_{\text{opt}} = \frac{P_{\text{elec, dark}} - P_{\text{elec, light}}}{c_{\text{ineq}} \cdot c_{\text{abs}}(\lambda) \cdot c_{\text{window}}(\lambda) \cdot c_{\text{lead}}}$$
(8)

To obtain the correct optical power  $P_{\text{opt}}$ , the modeled electro-optical inequivalence  $c_{\text{ineq}}$ , finite absorption of the VACNT absorber  $c_{\text{abs}}(\lambda)$  and transmittance of the wedged window  $c_{\text{window}}(\lambda)$ that both depend on the laser wavelength  $\lambda$ , and the parasitic resistance of wirebonds  $c_{\text{lead}}$  must be corrected from electrical power difference. To achieve high accuracy, all the correction factors should be as close to unity as possible. This holds for the corrections of the VACNT absorber that at the wavelength  $\lambda = 633$  nm has absorption of  $c_{\text{abs}}(633 \text{ nm}) = 0.99932$  and for the electro-optical inequivalence correction  $c_{\text{ineq}} = 1 - I_{\text{ineq}} = 0.99993$ . Transmittance of the wedge window  $c_{\text{window}}(633 \text{ nm}) = 0.93312$  is the largest correction and it also has the largest contribution to the total expanded uncertainty in PARRoT's laser power measurements. Finally, we correct the resistance of wirebonds,  $c_{\text{lead}} = 1.0001$ , connecting the heater electrically to the flexible circuit. This correction is obtained by theoretical resistance calculations of the aluminum-alloy wirebonds. The correction factors listed are discussed in more detail in Section 3.

Quantization due to limited resolutions in ADCs and DACs can be a problem in a closed-loop bolometer. The severity of quantization depends on the electrical heating power through  $V_{\text{std}}$ ,  $V_{\text{h}}$  and  $R_{\text{std}}$ , and resolution  $\delta V$  of an instrument:

$$\delta P_{\text{elec}} = \frac{V_{\text{std}}}{R_{\text{std}}} \delta V + \frac{V_{\text{h}}}{R_{\text{std}}} \delta V + \frac{\delta V^2}{R_{\text{std}}}$$
(9)

We reduced the effects of signal quantization in PARRoT's response by selecting 20-bit DACs for the control side and 32-bit ADCs for the measuring side. Equation (9) applies also to noise; increased driving power results in increased noise in electrical power measurements.

Figure 5 shows PARRoT's response to different laser powers. PARRoT can measure laser powers from 100  $\mu$ W to 250 mW. Measurement noise is a dominant uncertainty component at laser powers less than 2 mW.



**Fig. 4.** PARRoT's response (a) is balanced when thermistor bridge output (b) reaches 0 V. A significant advantage of PARRoT's closed-loop control is that thermal load to the base plate stays nearly constant. For example, 12.59 mW laser power does not deviate the base temperature as seen in (c).



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**Fig. 5.** PARRoT's closed-loop response to different laser powers. The shape of the response stays similar across the entire dynamic range.

# 3. Measured properties of the radiometer

# 3.1. Long-term drift

**Research Article** 

Though dark signals are measured before and after each laser power measurement, moderate longperiod changes in background radiation (following a 1/*f* distribution attributable to environmental controls) would cause systematic error in measured optical power. The drift is rarely perfectly linear meaning that simple dark signal averaging causes systematic error if the drift is large compared to the laser power measured. To reduce this uncertainty contribution in PARRoT, we use active closed-loop compensation of the radiative coupling with background using a second identical bolometer chip.

Figure 6 shows typical long term drift of the baseline that follows unstabilized room temperature when PARRoT views the laboratory thermal scene through the instrument's window. PARRoT's baseline drift is 48  $\mu$ W/K which is a factor of 24 improvement when compared to a bolometer with a similar size absorber that does not have a background compensation [25]. A typical comparison takes 4.5 measurement cycles and 30 minutes, which is short compared to the time scale in Fig. 6, meaning the long-term drift does not cause systematic error in PARRoT's response.

# 3.2. Spectral transmittance of the wedge window

The laser beam enters the vacuum chamber though a 12.7 mm thick uncoated UV fused silica window with a wedge angle of  $0.5^{\circ}$ . The window provides a clear aperture of 60 mm, and it is mounted so that both the measuring and background bolometer chips sees the same environment.



Fig. 6. Long-term drift of PARRoT's baseline monitored over 54 hours.

We align the wedge window in a similar manner as the wedge window of the C-calorimeter [4], so that the reflected beam orders -1 and +1 [29] make equal angles with the incoming laser beam.

Performing a direct measurement of the wedge window transmittance is nontrivial due to higher order beams produced by the wedge along with the back-reflection, back-scatter, and spatial non-uniformity of typical optical detectors one might conceivably employ. We infer window transmittance using Fresnel equations with the material parameters of optical-grade UV fused silica established in Ref. [30]. We have validated this approach by comparing the theoretical transmittance with the measured value as presented in Fig. 7. These measurements



**Fig. 7.** Theoretical transmittance of uncoated UV fused silica window with a wedge angle of  $0.5^{\circ}$  as solid curve and measured transmittance values with k = 2 uncertainty bars as circles. Dashed curves depict k = 2 uncertainties used in PARRoT's laser power measurement uncertainty budget.

were performed using a polarization-independent, large-area transmission trap detector that does not have a back reflection. The agreement of the theory and measurement is well within k = 2uncertainties plotted as dashed curves in Fig. 7. Due to a 71 mm distance between the back surface of the 0.5° wedge window and the PARRoT's absorbers, the higher order transmitted beams +2, +4, and +6 were determined to hit 1.8 mm, 3.6 mm, and 5.4 mm off from the main beam using the model in Ref. [29]. When the main beam is aligned to the center of PARRoT's absorber, these three higher orders are absorbed along with the main beam.

The window transmittance correction  $c_{\text{window}}(\lambda)$  is the largest correction to be applied to obtain correct laser power in Eq. (8) and it also has the largest uncertainty contribution of ±0.1 % (rectangular distribution). These uncertainty limits were estimated by varying refractive indices in the Fresnel equations and by checking how much spatial uniformity varies across a clean wedge window. For instance, at the laser line of 633 nm, the window transmittance is  $c_{\text{window}}(633 \text{ nm}) = 0.93312$ . Surface roughness of the window causes some reduction in transmittance due to scatter, but this effect is negligible, on the order of 0.01 % when the window is clean. We noted that scattering increases drastically when dust or residual contamination from inappropriate cleaning agents is present. Vacuum grease applied to window seals will sputter into the optical path, over extended time periods. We have linked measurement inequivalence approaching 1 % to such deficiencies. We achieved the best cleaning result with optical grade 95 % ethyl alcohol dropped on an optical lens paper and dragging the paper slowly across the surface.

# 3.3. Spatial nonuniformity of the electro-optical inequivalence

Selected materials, geometry and placement of thermistors in a thermal detector determine the inequivalence between optical and electrical heating modes. The bolometer chip geometry and heat link of PARRoT were optimized previously in Ref. [24] using thermal modeling so that the electro-optical inequivalence defined by

$$I_{\text{ineq}} = 1 - \frac{P_{\text{opt,modeled}}}{P_{\text{opt,true}}}$$
(10)

is nearly 0 when the laser beam is aligned to the absorber's center. PARRoT's thermal model predicts the electro-optical inequivalence of 0.00007 when the laser beam hits the absorber's center, meaning the correction to be applied to Eq. (8) is  $c_{\text{ineq}} = 1 - I_{\text{ineq}} = 0.99993$  [24].

We show the measured spatial nonuniformity of PARRoT with respect to the center position at which the electro-optical inequivalence is nearly 0, across the horizontal and vertical axes in Fig. 8, obtained using a monitor detector and beamsplitter ratio where the spatial nonuniformity is determined as

$$I_{\text{spatial}} = \left(1 - \frac{R_{\text{opt}}}{R_{\text{opt, center}}}\right) \cdot 100 \%.$$
(11)

The parameter  $R_{opt} = P_{opt}/s$  is the beam ratio between PARRoT's laser power measurement  $P_{opt}$  and the monitor detector's uncorrected signal *s* when the laser beam hits off-center, and  $R_{opt,center} = P_{opt,center}/s_{center}$  is the beam ratio when the laser beam is aligned to the center of the PARRoT's absorber.

PARRoT's spatial nonuniformity in Fig. 8 was measured at 100 mW, 10 mW, and 1.7 mW laser powers with a wavelength of 532 nm and beam diameter of 1.2 mm ( $1/e^2$ ). Uncertainty bars in Fig. 8 take into account the repeatability of 4 measurement cycles and the uncertainty related to the spatial nonuniformity of the wedge window. We can align a laser beam within a 2 mm radius from the absorber's center, which corresponds to ±0.05 % uncertainty limits of the spatial nonuniformity (dashed lines in Fig. 8) to PARRoT's laser power measurement uncertainty.

The spatial nonuniformity is nearly constant with laser power, and not symmetric along x and y-axes arising from the geometry of bolometer chip and heat link. The bolometer chip is not



**Fig. 8.** Measured spatial nonuniformity of PARRoT across *x*-axis (a) and *y*-axis (b) with a beam diameter of 1.2 mm  $(1/e^2)$ . An alignment uncertainty of the laser beam is small in these measurements. 4<sup>th</sup> order (a) and 2<sup>nd</sup> order (b) polynomial functions (solid curves) were fitted to 10 mW measurement data using the least squares method weighted by uncertainties. Uncertainty bars are plotted with a coverage factor of k = 2. Dashed lines depict uncertainty limits of the spatial uniformity to PARRoT's laser power measurement arising from a laser beam alignment uncertainty.

perfectly rotation symmetric and there are only four thermistors attached. Since the silicon chip and aluminum frame have a limited thermal conductivity and diffusivity, relatively strong heat flow through the three heat link legs causes thermal gradients across the chip.

The spatial uniformity is a factor of 10 worse than the predicted spatial inequivalence obtained from the thermal FEM model in Ref. [24]. Figure 9 shows a close-up of the thermal map obtained from the FEM model that is operated in closed loop so that the average temperature of four thermistors is controlled to 325 K and the base plate is controlled to 295 K. While we can not verify the exact reason for the discrepancy between the model and measurement, we suspect it is attributable to differences in the thermal contacts to the heat link structure, and differences in the resistance and parasitic capacitance among the thermistors of each bolometer chip and differences in the it temperature dependence affecting the output of the lock-in amplifier that were not accounted for in the thermal model. Aforementioned factors become significant only when the thermal distribution changes with respect of the electrical heating, which is the case when the laser beam is not centered on the absorber. PARRoT's spatial uniformity is favorable when compared to other room temperature thermal detectors, whose nonuniformity can be several percent [4,25,31], and comparable to some cryogenic bolometers reported previously [32,33].

### 3.4. Electrical connections between the bolometer chip and circuit board

There is a trade-off between parasitic resistance of the bolometer chips' electrical connections to the rest of circuitry, causing a systematic error in the power measurement and parasitic thermal conductance impacting thermal distribution and therefore an uncertainty in the spatial non-uniformity. To heat the bolometer chip and measure the temperature, the chips were electrically connected to the flexible circuit board by aluminum alloy wirebonds. The wirebonds create an alternative heat path from the bolometer chips to the base plate. Each wirebond conducts heat by

$$G_{\rm w} = \frac{\pi r_{\rm w}^2}{l_{\rm w}} k_{\rm w},\tag{12}$$

where  $r_w = 12.7 \ \mu\text{m}$  is the radius and  $l_w = 3 \ \text{mm} \pm 1 \ \text{mm}$  is the length of the wirebond, and  $k_w = 230 \ \text{W/(m\cdot K)} \ [34]$  is the thermal conductivity of the aluminum alloy (99 % aluminum, 1 %



Fig. 9. 3D thermal model of PARRoT.

silicon). The corresponding thermal conductance of one wirebond is  $G_w = 0.0376$  mW/K. There are 24 wirebonds per bolometer chip so, the total thermal conductance of the alternative heat path to base plate via two posts similar to heat link cylinders is

$$G_{\rm w, \, tot} = \frac{1}{\frac{1}{24 \cdot G_{\rm w}} + \frac{1}{2/3 \cdot G_{\rm con}}} \tag{13}$$

when the thermal conductance of the flexible circuit board made of Kapton is ignored. The alternative heat path of  $G_{w, \text{ tot}} = 0.79 \text{ mW/K}$  is 6.6 % from the intended total thermal conductance.

Reducing the number of wirebonds between the chip and flexible circuit would reduce the unwanted heat path. However, it would result in larger systematic error in electrical power measurement. Connecting both ends of the heater with eight aluminum alloy wirebonds with resistivity of  $2.53 \cdot 10^{-8} \Omega \cdot m$  [34] to the flexible circuit results in 38.7 m $\Omega$  parasitic resistance and 0.01 % higher systematic error in electrical power measurement. We correct  $c_{\text{lead}} = 1.0001$  in Eq. (8) and add an uncertainty of  $\pm 0.01$  % (rectangular distribution) to the uncertainty budget of PARRoT's laser power measurement. This uncertainty arises from varying lengths of the wirebonds ( $l_w = 3 \text{ mm} \pm 1 \text{ mm}$ ).

# 3.5. Reflectance of the VACNT absorber

The VACNTs in PARRoT's absorbers are 55  $\mu$ m ±10  $\mu$ m long. Figure 10 shows the total hemispherical spectral reflectance  $R(\lambda)$  of a VACNT witness sample grown on the same day using the same fabrication process and settings as for growing PARRoT's absorbers. The VACNT absorptance  $c_{abs}(\lambda) = 1 - R(\lambda)$  depends on the laser wavelength and is corrected in Eq. (8). While an oxygen-plasma treatment has been noted to reduce the total hemispherical reflectance on VACNTs to a few 0.0001 level [35], we elected not to apply such a treatment in order to avoid possible long-term degradation that may occur with functionalized VACNTs.

Since PARRoT's measuring bolometer chip was not directly measured for its total hemispherical spectral reflectance, the VACNT absorptance correction may leave a systematic error in the corrected optical power. To account for this, we include  $\pm 0.03$  % rectangular uncertainty in PARRoT's uncertainty budget.



**Fig. 10.** Measured total hemispherical reflectance of a typical VACNT forest sample similar to the PARRoT's absorber. Lorentzian function with *a*, *b*, *c*, and *d* as free parameters is used for interpolation between measured values. Dashed curves depict k = 2 uncertainties used in PARRoT's laser power measurement uncertainty budget.

# 3.6. PARRoT's uncertainty budget

An example of PARRoT's uncertainty budget at a laser power of 12.59 mW is presented in Table 1. At laser powers  $\geq 2$  mW, the transmittance correction of the wedge window is the largest uncertainty contribution. The uncertainty in measured laser power due to the alignment uncertainty and the spatial nonuniformity of PARRoT's absorber is the second largest uncertainty component. The third largest component arises from VACNT absorptance correction. Since the VACNT absorbers in PARRoT have diffuse reflection from ultraviolet to near-infrared wavelengths, a large reflecting dome with a small opening for a laser beam would reduce the total hemispherical reflectance by an order of magnitude, and thus the corresponding uncertainty would also reduce. We did not use the reflecting dome since one of the design criteria for PARRoT was a 20 mm diameter absorber, so the reflecting hemispherical dome would have to be at least 40 mm in diameter, which would have increased PARRoT's overall dimensions excessively and would not have led to a significant reduction in the combined relative expanded uncertainty because it is dominated by the window transmission. Electrical uncertainties have small contributions to PARRoT's combined measurement uncertainty. Repeatability of measurement due to noise becomes a dominating uncertainty component at laser powers less than 2 mW.

Figure 11 visualizes how 0.9  $\mu$ W<sub>rms</sub> baseline noise, limited by PARRoT's electronics, affects PARRoT's combined relative expanded measurement uncertainty (k = 2) as a function of laser power. Although each measured point ( $P_{elec,dark}$  and  $P_{elec,light}$ ) is averaged over 25 points (30 s), there are residual fluctuations attributable to limits of the background compensation provided by the monitor chip and bridge electronics. Therefore, we use a conservative estimate for PARRoT's repeatability (k = 1):

$$u_{\text{repeatability}} = \frac{0.9 \ \mu\text{W}}{P_{\text{opt}} \cdot \sqrt{N}},\tag{14}$$

where  $P_{opt}$  is the measured laser power and N is the number of measurement cycles. PARRoT's combined relative expanded uncertainty reaches 0.13 % at laser powers  $\ge 2$  mW when the

Table 1. Uncertainty budget of 12.59 mW laser power measurement with PARRoT. The combined relative expanded uncertainty with a coverage factor k = 2 corresponds to the confidence level of approximately 95 %. Each uncertainty component is related to a symbol in Eqs. (7) and (8).

Uncertainty component	Symbol	Method	$\pm\delta$ / %	Distribution	Туре	u / %
Calibration of standard resistor	R <sub>std</sub>	Experimental	0.002	Normal	В	0.001
Voltage across standard resistor	V <sub>std</sub>	Experimental	0.001	Normal	В	0.0005
Voltage across heater	$V_{\rm h}$	Experimental	0.001	Normal	В	0.0005
Parasitic resistance of heater leads	Clead	Theoretical	0.01	Rectangular	В	0.0058
Electro-optical inequivalence at	Cineq	Theoretical	0.01	Rectangular	В	0.0058
the center of the chip						
Alignment offset and spatial		Experimental	0.05	Rectangular	В	0.0289
nonuniformity of absorber						
Reflectance of VACNT absorber	$c_{\rm abs}(\lambda)$	Experimental	0.03	Rectangular	В	0.017
Window transmittance including	$c_{\mathrm{window}}(\lambda)$	Theoretical &	0.1	Rectangular	В	0.0577
its spatial nonuniformity		experimental				
Measurement repeatability $(N = 4)$		Experimental	0.007	Normal	А	0.0035
Combined relative standard uncertainty / %						0.067
Combined relative expanded uncertainty ( $k = 2$ ) / %					0.13	

number of measurement cycles  $N \ge 3$ , and is limited by an uncertainty of  $\pm 0.1$  % (rectangular distribution) due to the window transmittance correction.



**Fig. 11.** PARRoT's combined relative expanded uncertainty with respect to laser power and the number of measurement cycles *N*.

# 4. Comparison measurements against existing detector standards

We have compared PARRoT against a transfer standard silicon trap detector traceable to NIST's Laser Optimized Cryogenic Radiometer (LOCR) [9,17]. The results of this comparison measured directly using a stabilized 633 nm helium-neon (HeNe) laser with a beam diameter  $(1/e^2)$  of 1.2 mm at powers less than 1 mW are plotted as blue circles in Fig. 12. To extend the transfer

standard's measuring range, a beamsplitter (BS) ratio technique was used in comparisons at higher laser powers between 1 mW and 25 mW, and these results are plotted as red squares in Fig. 12. We used an uncoated fused silica glass window with a wedge angle of 1° as a beamsplitter. The BS ratio  $27.654 \pm 0.05 \%$  (rectangular distribution) between reflected beam order -1 and transmitted beam order +0 was measured using the trap detector and a monitor detector. In the comparison measurement, the transmitted beam was centered to PARRoT's absorber and the reflected beam was measured with the monitor detector. The monitor detector's signal was then scaled to the absolute optical power scale of the trap detector using the BS ratio measured before and after each set of comparison cycles. The laboratory room, where these comparison measurements were performed, does not have stable temperature control, so the room temperature varied between 22 °C - 25 °C during the measurement days. The transfer standard's uncertainty budget is presented in Table 2.



**Fig. 12.** Discrepancies in the optical power measured with PARRoT and the transfer standard silicon trap detector (NIST6). Beamsplitter (BS) ratio measurement was used at optical powers >1 mW to extend dynamic range of the trap detector. Uncertainty bars depict an expanded uncertainty (k = 2).

We also compared PARRoT against the C-series reference calorimeter at laser powers from 260  $\mu$ W to 200 mW, beam diameters (1/ $e^2$ ) from 1.2 mm to 3.2 mm, and wavelengths of 405 nm, 532 nm, and 1064 nm. The results are presented in Fig. 13. The comparisons were performed in a temperature stabilized laboratory room at 25 °C. C-calorimeter's typical uncertainty budget is shown in Table 3.

Since the C-calorimeter measures laser energy from which laser power is derived, it has an uncertainty arising from the injection time (200 s) of the laser pulse, listed in Table 3. The corrected temperature rise measurement relies on constant laser power during the injection. Drifts result in  $\pm 0.5$  % uncertainty (rectangular distribution) in laser power measurement with the C-calorimeter. The C-calorimeter has an electrical calibration mode where the corrected temperature rise scale of a thermopile is linked to the electrical energy/power scale. In an optical mode of the C-calorimeter, laser power is determined from the corrected temperature rise by laser injection, corrected by the electrical calibration curve. Variations in environmental

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Table 2.	Uncertainty components related to measurements with the transfer	standard trap	detector.
	BS ratio refers to beamsplitter ratio measurement.		

					Direct	BS ratio
Uncertainty component	Method	$\pm\delta$ / %	Distribution	Туре	u / %	u / %
Trap traceability to primary standard	Experimental	0.03	Rectangular	В	0.0173	0.0173
Alignment offset and spatial	Experimental	0.02	Rectangular	В	0.0115	0.0115
nonuniformity						
Beamsplitter ratio	Experimental	0.05	Rectangular	В	_	0.0289
Measurement repeatability $(N = 4)$	Experimental	0.003	Normal	А	0.0015	0.0015
Combined relative standard uncertainty / %					0.021	0.036
Combined relative expanded uncertainty $(k = 2) / \%$				0.04	0.07	



**Fig. 13.** Discrepancies in the optical power measured with PARRoT and the C-series calorimeter (C41). Uncertainty bars depict an expanded uncertainty (k = 2).

conditions, such as changes in ambient temperature between the electrical and optical modes increase systematic uncertainty (Electronics and Standard meter BS ratio in Table 3). The rest of uncertainty components: electro-optical inequivalence, absorber's absorptivity, parasitic resistance of the heater leads, window transmittance, and measurement repeatability contribute in both PARRoT's and the C-calorimeter's uncertainty budgets. An advantage in PARRoT's operating principle is that optical power is actively substituted from the absolute electrical power scale, requiring only the resistance calibration of a standard resistor and two digital volt meters calibrated across their voltage range.

Comparison results against the transfer standard trap detector and C-calorimeter confirm that PARRoT's response is linear with respect to laser power. PARRoT's average discrepancy against the transfer standard is 0.008 %, and against the C-calorimeter it is 0.05 %. These discrepancies are well within PARRoT's expanded measurement uncertainty. At laser powers of a few 100  $\mu$ W, PARRoT's repeatability limits the measurement uncertainty. At laser powers  $\geq 2$  mW, the uncertainty reaches 0.13 % (k = 2) (see Fig. 11), and is dominated by an uncertainty in the

Uncertainty component	Method	$\pm\delta$ / %	Distribution	Distribution Type	
Electro-optical inequivalence	Theoretical	0.03	Rectangular B		0.017
Cavity absorptivity	Experimental	0.01	Rectangular B		0.0058
Parasitic resistance of heater leads	Theoretical	0.01	Rectangular B		0.0058
Electronics	Experimental	0.1	Rectangular B		0.058
Electrical mode $(N = 30)$	Experimental	0.1	Normal	А	0.018
Window transmittance	Theoretical &	0.1	Rectangular	В	0.058
	experimental				
Injection time of laser pulse	Experimental	0.05	Rectangular	В	0.029
Laser power drift	Experimental	0.5	Rectangular B		0.29
Standard meter BS ratio	Experimental	0.5	Rectangular B		0.29
Standard meter BS ratio $(N = 8)$	Experimental	0.04	Normal A		0.014
Test meter BS ratio $(N = 4)$	Experimental	0.028	Normal	А	0.014
Combined relative standard uncertaint	y / %				0.42
Combined relative expanded uncertain	ty $(k = 2) / \%$				0.84

Table 3. Typical uncertainty budget of optical power measurement with the C-series calorimeter. BS ratio refers to beamsplitter ratio measurement.

wedge window transmittance correction. This measurement uncertainty achieved with less than 7 minute measurement cycles is an improvement over 0.84 % (k = 2) measurement uncertainty and 15 minute measurement cycles of the C-series calorimeter currently used in CW optical power calibrations at NIST.

# 5. Conclusions

We have developed a high-accuracy room temperature radiometer consisting of paired microfabricated silicon bolometer chips with VACNT absorbers. PARRoT is background compensated by controlling two identical bolometer chips in closed loop so that the reference chip is driven with constant electrical power and the measuring chip follows the temperature of the reference chip. With this configuration, a baseline drift of the radiometer is 48  $\mu$ W/K, which is a factor of 24 improvement compared to a similar size bolometer that does not have background compensation. PARRoT's spatial nonuniformity within a 2 mm radius from the absorber's center was measured to be within ±0.05 %. Within 6 mm radius from the absorber's center, the spatial nonuniformity did not exceed ±0.25 %. In addition, the spatial uniformity did not change with laser power.

We compared PARRoT's response against the legacy C-series calorimeter from 260  $\mu$ W to 200 mW using laser wavelengths of 405 nm, 532 nm and 1064 nm, and against a transfer standard trap detector directly at powers less than 1 mW and via beamsplitter measurements between 1 mW and 25 mW using stabilized HeNe laser at the wavelength of 633 nm. Comparison measurements validate that PARRoT can measure optical powers  $\geq 2$  mW with a combined relative expanded uncertainty of 0.13 %. At optical powers less than 2 mW, PARRoT's repeatability becomes worse due to 0.9  $\mu$ W<sub>rms</sub> baseline noise, limiting the expanded measurement uncertainty. Based on the comparison measurements, PARRoT's typical measurement uncertainty of 0.13 % (k = 2) at laser powers from 2 mW to 250 mW with less than 7 minutes measurement cycles is an improvement over C-calorimeter's typical measurement uncertainty of 0.84 % (k = 2) with 15 minutes measurement cycles. Thus, PARRoT will replace the C-series calorimeter in optical power calibrations at NIST.

Further improvements to make the radiometer faster may be achieved by using a thinner chip frame and flexible circuit pad holders. A superpolished wedge window would reduce an

uncertainty due to scatter in the transmittance correction. If PARRoT is customized to a single wavelength one could reduce the magnitude of the window transmittance correction by using a superpolished wedge window with an anti-reflection coating on both sides or a Brewster window. From these options, an anti-reflection coated wedge window is desirable for maintaining the polarization insensitivity of the radiometer. With an anti-reflection coating on both sides, the higher order transmitted beams become negligible and the transmitted order +0 that is close to unity can be measured reliably within  $\pm 0.02$  % uncertainty limits. Actually, a highly-transmitting broadband coating might reduce the higher order transmitted beams enough to allow reliable transmittance measurement across a broader wavelength range. In addition, placing a reflecting hemispherical dome over the VACNT absorber would reduce the magnitude of the reflectance correction and the related uncertainty. These changes would reduce PARRoT's combined relative expanded uncertainty (k = 2) under 0.07 %.

PARRoT's spatial uniformity was measured to be worse than what we had predicted by thermal modeling. This is attributable to imperfect thermal contacts in the heat link structure and tolerances of thermistors used. To further improve PARRoT's spatial uniformity, one could replace the silicon substrate of PARRoT's chips with diamond since it has significantly higher room temperature thermal conductivity and diffusivity than silicon.

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**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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