Room Temperature Laser Power Standard Using a Microfabricated, Electrical Substitution Bolometer

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Abstract

The design and performance of a room temperature electrical substitution radiometer for use as an absolute standard for measuring continuous-wave laser power over a wide range of wavelengths, beam diameters and powers is described. The standard achieves an accuracy of 0.46 % (k = 2) for powers from 10 mW to 100 mW and 0.83 % (k = 2) for powers from 1 mW to 10 mW and can accommodate laser beam diameters ($1/e^2$) up to 11 mm and wavelengths from 300 nm to 2 µm. At low power levels the uncertainty is dominated by sensitivity to fluctuations in the thermal environment. The core of the instrument is a planar, silicon microfabricated bolometer with vertically aligned carbon nanotube absorbers, commercial surface mount thermistors, and an integrated heater. Where possible, commercial electronics and components were used. The performance was validated by comparing it to a National Institute of Standards and Technology (NIST) primary standard through a transfer standard silicon trap detector and by comparing it to the legacy 'C-series' standards in operation at the U.S. Air Force Metrology and Calibration Division (AFMETCAL).

I. INTRODUCTION

Electrical substitution radiometers (ESRs) serve as primary standards for optical power at national metrology institutes around the world.[1-6] At NIST, calibrations of laser power meters at continuous-wave (CW) powers ranging from 100 µW to 2 W are performed using 'C-series' calorimeters.[7] These calorimeters operate at room temperature and provide calibrations with an expanded uncertainty of 0.6 % – 0.8 %, (k = 2).[8] Nearly identical calorimeters are in use at the AFMETCAL. The C-series calorimeters have been in continuous operation for nearly 50 years. While they have proven their reliability, as they age a need has arisen to replace them with faster, more accurate, and more portable standards based on newer, more maintainable technologies.

Radiometers that operate at cryogenic temperatures have traditionally provided the highest accuracy (expanded uncertainties of 0.02 % – 0.05 %)[9] for laser power measurements of powers below 1 mW. The higher thermal diffusivity, superconducting wires, and lower radiation losses achievable at cryogenic temperatures reduce the inequivalence between electrical and optical power.[10] Low temperature operation with well-designed cold shields reduce radiative coupling to background radiation.[10] Superconducting wires eliminate parasitic heating from electrical heater leads.[10] And finally, better thermal diffusivity of high-mass (e.g. copper) conical geometries provides high optical absorptivity without loss of sensitivity at cryogenic temperatures.[10]

For some applications, however, accuracy can be relaxed in order to extend the range of optical power, reduce the cost, and increase the speed and ease of the calibration. This is the case for the CW laser power meter calibrations performed with the 'C-series' calorimeters. This paper describes the first extension of silicon microfabricated bolometer technology to a room temperature primary laser power standard.

Silicon microfabricated, electrical substitution bolometers and vertically aligned carbon nanotube (VACNT) absorbers offer improved speed, accuracy, and portability at both room and cryogenic temperatures.[11-15] These technologies show promise of achieving accuracies at room temperature for laser powers in the 1 mW to 1 W range that are close to the accuracies currently available only at cryogenic temperatures for laser powers below 1 mW.[14,16] The high absorptivity of the VACNTs[17-21] permits a planar geometry that delivers three advantages. First, high-mass, conical geometries are no longer necessary in order to achieve high optical absorption. This, in turn, reduces the mass and size so that even at room temperature a highly absorbing bolometer can be fabricated with a short time constant and high sensitivity, enabling a bolometric power measurement rather than a calorimetric energy measurement. Second, the planar geometry is compatible with lithographic fabrication. Microfabrication is an extremely precise process that allows careful tuning of the thermal conductance of the bolometer and, in conjunction with numerical thermal analysis, enables the design and fabrication of room temperature devices with very low optical and electrical inequivalence (i.e. the mismatch between the bolometer response to power deposited by an optical source and by an electrical source). Third, multiple,

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identical devices are produced in a single fabrication run. Not only does this mean that many bolometer standards with similar performance can be manufactured reliably, but more importantly it provides an opportunity to fabricate a background-compensated standard with two nearly identical detectors integrated into a single standard. In that configuration, one of the detectors can be used to monitor and subtract the background thermal fluctuations.[14,16]

II. INSTRUMENT DESIGN

A. Operating Principle

In a bolometric power measurement, laser radiation is absorbed and converted to heat. The thermal rise of the absorbing medium is controlled by a heat link with a known thermal conductance, *G* (W/K*)*. The rise in temperature can then be related to the incident laser power. In an electrical substitution measurement, the laser power is replaced with a calibrated electrical power via a heater close to the absorber. An equivalent temperature rise equates electrical power to optical power and provides a power measurement traceable to the international system of units (SI) through the calibration of the voltage measurement.

In the radiometric standard described in this paper, VACNTs are used as absorbers on a silicon microfabricated bolometer, as shown in Fig. 1. A tungsten thin film heater is located around the circumference of the absorber. The heat link is fabricated from the silicon wafer. The length and width of the heat link control the thermal conductance. Low-noise, commercial thermistors measure the temperature of the absorber at the top of the heat link and the temperature at the base of the heat link.

The bolometer chip is mounted on a temperature-controlled copper block and wire-bonded to a flexible circuit that is also mounted on the copper block. The flexible circuit contains a custom, low-noise, AC-driven resistance bridge circuit and preamplifier for reading out the absorber thermistor. The copper block sits on top of a thermoelectric cooler (TEC) that is heat sunk to a commercial vacuum flange with flexible graphite foil, as shown in Fig. 2. The fasteners that hold the low noise bridge circuit and preamplifier to the copper block also electrically ground the copper block.

The bolometer is operated closed loop to speed up operation and maintain a linear response over the full power range. There are two thermal loops, as shown in Fig. 2. The first thermal loop maintains the base of the bolometer chip at a constant temperature near 20 °C. It uses the thermistor at the base of the heat link as the feedback sensor and the TEC underneath the copper block as the actuator. The second thermal loop maintains the absorber near 35 °C by using the thermistor at the top of the heat link as the sensor and the heater as the actuator. Details of the control loops are described in Section D.

The bolometer operates in a vacuum of about 3×10^{-5} Pa that is maintained by a 2 l/s appendage ion pump. The pump and vacuum chamber are constructed of commercially available components, as shown in Fig. 3. The laser enters the vacuum system through a commercial, uncoated UV grade fused silica window with an 8.7 mrad wedge.

Incident laser power is determined by measuring the reduction in the electrical power delivered by the temperature control loop to the bolometer heater that occurs when a laser is incident on the absorber and then making appropriate corrections for window transmission, VACNT reflectivity, and electro-optical inequivalence (discussed in Section IV). Since the laser power is absorbed and converted to heat in the absorber, a correspondingly smaller amount of electrical power is required to maintain the absorber at 35 °C. Approximately 126 mW of electrical power is required to raise the absorber temperature to 35 °C. This defines the maximum measurable laser power for the standard.

The electrical power is measured using a voltage divider and two calibrated, commercial digital voltmeters, as shown in Fig. 4. The heating current passes through a calibrated precision resistor connected in series with the heater. The precision resistor is located outside the vacuum chamber to prevent heat dissipation near the bolometer. One voltmeter measures the voltage, Vp, across the calibrated resistor, Rprec. From this one can calculate the current in the heater, i = Vp / Rprec. The second voltmeter measures the voltage across the absorber heater, Vh. These two measurements allow calculation of the electrical power in the heater

$$P = i * V_h = \frac{V_p \cdot V_h}{R_{prec}}, \qquad (1)$$

where P is the power in Watts.

B. Detector Chip

The detector chip is a silicon (Si) microfabricated bolometer with VACNT absorbers. The diameter of the laser beam varies in the calibrations performed at NIST, so the absorber diameter is 20 mm in order to accommodate the largest beam diameter. A tungsten (W) thin film heater is located around the circumference of the absorber. Commercial negative-temperature-coefficient (NTC) thermistors measure the temperature of the absorber at the top of the heat link and the temperature at the base of the heat link as shown in Fig. 1 and Fig. 5.

Three detector chips are fabricated simultaneously from a Si wafer that is 275 μm thick and 76.2 mm diameter. The wafer has a 151.3 nm layer of thermally grown silicon dioxide (SiO_2) and 1.953 μm of low-pressure chemical-vapor-deposited (LPCVD) low-stress silicon nitride (SiN_x) on both sides. These layers insulate the electrical traces from the semiconducting Si substrate and are thick enough to prevent electrical breakdown between the voltage across the heater and the substrate and to prevent shorting between the leads and the semiconductor during nanotube growth.[15]

Details of the detector chip are shown in Fig. 5. The base of the detector is 20 mm × 8 mm with two 2.2 mm diameter through-holes for mounting the detector. The through-holes are separated by 15 mm. There are 12 wire bond pads, four for the heater, four for the absorber thermistor 4-wire measurement, and four for the base thermistor 4-wire measurement. The pitch between the bond pads is 760 μm. The empty space between the pads is 60 μm.

The heat link is 2 mm × 12.5 mm with a measured conductance of G = 8.1 mW/K. The heater and leads are fabricated with tungsten because it is not affected by the 800 °C nanotube growth process.[15,22] The tungsten leads for the heater and the absorber thermistor travel up the heat link with 30 μm spacing between the traces. The traces carrying heater current are 545 μm wide and 0.200 μm thick. All other leads are 50 μm wide and 0.100 μm thick. The heat link is covered with a layer of tungsten where there are no leads to keep the emissivity uniform over the heat link. The back side of the bolometer chip is also coated with tungsten to keep the emissivity low (~0.01) to reduce radiative coupling to and from the environment.

The heater is a double ring around the outside of the absorber. VACNTs are not grown on the heater. The heater trace is 215 μm wide and 0.100 μm thick and has a resistance of a 1099.3 Ω. The traces carrying the heater current across the heat link have a resistance much less than the heater so that less than 0.4 % of the power is dissipated in the heat link.

Commercial surface mount end-banded chip thermistors were bonded onto the detector with epoxy and then wire-bonded. This thermistor was chosen for two reasons. First, the metallized end bands allow for wire bond connections that are more stable and less electrically noisy than other contact techniques such as electrically conductive epoxy. Second, the measured noise is lower than other commercially available surface mount thermistors. The absorber thermistor is epoxied over the heater leads with thermally conductive, electrically insulating epoxy. The bond pads for wire bonding are on the side of the heat link next to the thermistor. Note that thermal modelling shows that this configuration contributes slightly to the inequivalence of the detector.

The temperature measured by the thermistors is calculated from the measured resistance using Steinhart-Hart coefficients that were derived by fitting the manufacturer's resistance vs. temperature data to the Steinhart-Hart equation[23]

$$\frac{1}{T} = A + B \times \ln(R) + C \times \ln(R)^3 \,, \qquad (2)$$

where T is the temperature in kelvin and R is the resistance in ohms. The fitted values were $A = 7.941\times10^{-4}$, $B = 2.648\times10^{-4}$, and $C = 1.569\times10^{-7}$.

The heat link conductance and the bolometer time constant were measured in the following way: the detector was placed in a vacuum pressure of less than 0.07 Pa. The base copper block temperature was controlled so that the temperature at the base of the heat link was held constant at 20 °C. The absorber thermal control loop was left open, and the resistance of the absorber thermistor was measured using a commercial resistance bridge. The current to the heater was stepped up in increments. After each step, when the temperature of the bolometer had stabilized the resistance of the absorber thermistor was measured, converted to temperature using the Steinhart-Hart equation, and recorded, as shown in Fig. 6. The steady state temperature, $T = P/G$, where P is the electrical power and G is the total thermal conductance. G = 8.1 mW/K, was obtained with a linear fit. The measured data are compared to modelled values.

Radiative losses, the conductance of the tungsten leads, and the conductance of the SiO_2 and SiN_x layers are part of the total thermal conductance. The thermal conductance of the silicon is uncertain because the thermal conductivity depends on the doping of the wafer it was fabricated from, so it was calculated from the measurement. It was determined to be 135 W m^{-1} K^{-1} by using $G = \frac{wh}{L}\kappa$, where w is the width of the heat link, h is the thickness, L is the length and κ is the silicon thermal conductivity. Table I shows contribution of each term, calculated from a numerical model.

TABLE I. Contributions to bolometer chip conductance.

Thermal conductance contribution	G (mW/K)
Si heat link	6.0
Radiative losses	2.1
SiN_x layer on heat link	0.0013
W traces on heat link	0.0012
SiO_2 layer on heat link	0.000034

The time constant was measured by raising the absorber temperature to 35 °C with electrical power and then making a 0.2 mW step change in the electrical power and measuring the change in temperature. The 1/e time constant, τ, in s, of the detector depends on the total thermal conductance, G in W/K, and the heat capacity, C in J/K, of the detector,

$$\tau = \frac{C}{G} \,. \qquad (3)$$

A 23.6 s 1/e time constant in the decay is calculated using 135 W m^{-1} K^{-1} for the Si thermal conductivity and measured values for the Si and VACNT volumetric heat capacity at 35 °C.[15] After correcting for the measured drift due to room temperature, he measured time constant was 23.0 s, as shown in Fig. 7.

The VACNT absolute directional-hemispherical (d = 0°/h) reflectance was measured using a technique described elsewhere.[12,24] The VACNT height was measured using a micrometer attached to an optical microscope, as shown in Table II.

TABLE II Physical and operating properties of the standard.

Property	Value
VACNT height	45 μm
VACNT reflectance	270 ppm at 657.5 nm
VACNT reflectance	110 ppm at 1550 nm
Electrical power, no laser	0.1265 W, at 21.8 °C
Absorber operating temp.	35.6 °C, base at 21.8 °C

C. Electronics

The electronics consist of commercial units where possible.

A block diagram is shown in Fig. 8. There are two custom items. First, a custom flexible circuit in the vacuum system that includes a resistance bridge and preamplifier circuit for the absorber thermistor and pass-through wiring for the base thermistor and the heater. The flexible circuit, along with the TEC wires are integrated into a DB-25 connector that connects to a vacuum feedthrough. Second, a “breakout box” that receives the output signals from the vacuum system and sends them to the external commercial electronics. The breakout box also amplifies and sends the TEC and heater current into the vacuum system. The breakout box also contains the power supplies required for the bridge/preamplifier on the flexible circuit and for the power amplifier for the heater.

D. Control Loops

The TEC controller in a commercial diode laser controller is used to stabilize the base temperature to 20 °C. The controller has an autotune mode that was used to optimize the PI parameters in the control loop. Using these parameters, the stabilization time of the closed base loop is approximately 120 s, as shown in Fig. 9. This dominates the stabilization time of the radiometric standard.

A block diagram of the absorber proportional-integral (PI) control loop is shown in Fig. 10. The thermistor read-out and servo feedback are realized with a low-noise resistance bridge excited by a 1 kHz sinusoidal voltage and a preamplifier located on the flexible circuit in the vacuum system that feeds a signal into a commercial lock-in amplifier. The signal from the lock-in amplifier is filtered through an analog commercial controller. The feedback signal is sent to the heater through a custom, low-noise power amplifier located in the breakout box.

The P and I terms of the feedback loop were tuned by measuring the open loop step response of the absorber loop while the base control loop was closed, as shown in Fig. 11, and implementing a graphical analysis first order plus dead time (FOPDT) model[25] to obtain the controller tuning constants.

III. MEASUREMENT

During a laser power measurement, the thermal control loops are closed. In a ‘dark’ configuration, with no light incident on the bolometer, the electrical power dissipated by the heater, $P_{elec,h}$, is approximately 126 mW and maintains the absorber temperature at approximately 35.6 °C. In a ‘light’ configuration, with the laser incident on the bolometer, the thermal control loops will adjust the heater power to maintain the absorber temperature at 35.6 °C in the presence of the optical power. Therefore, the electrical power will be reduced by the value of the optical power that is absorbed by the bolometer, as shown in Fig. 12. If the electrical-optical inequivalence is zero, the optical power incident on the bolometer is equal to the difference between the closed loop electrical power with the laser incident on the detector, $P_{elec,l}$, and the baseline electrical power without the laser incident on the detector, $P_{elec,h}$:

$$P_{opt} = P_{elect,h} - P_{elect,l} \ , \qquad (4)$$

where P_{opt} is the optical power in W.

However, since it is necessary to wait for the control loops to settle between the ‘light’ and ‘dark’ measurements, drift in the baseline ‘dark’ measurement due to thermal coupling with the vacuum chamber leads to an offset in the estimated optical power, as shown in Fig. 13. Therefore, it is necessary to correct for any baseline drift and then apply a correction for the inequivalence. The time to wait after a shutter transition before recording the laser power is determined by the time required for the base loop to stabilize.

To correct for the drift in the ‘dark’ signal we interpolate linearly between the ‘dark’ signal before and after the ‘light’ signal measurement to estimate the ‘dark’ electrical power at the time of the ‘light’ measurement, $P_{elec,dark}$, and use the interpolated value, $P_{elec,dark} = P_{elec,h}$ in Eq. (4).

Furthermore, the electrical-optical inequivalence is not zero for this detector. This is discussed further in IV.

Finally, the optical power absorbed by the bolometer is not the optical power incident on the vacuum system. There are losses due to the transmittance of the wedged vacuum window and the hemispherical reflectance of the VACNTs as well.

We correct for the drift in the ‘dark’ signal and apply correction factors, namely: the inequivalence between the electrical and optical powers when the laser beam hits the center of the VACNT absorber, C_{ineq}; the VACNT absorptance, C_{abs}; and the window transmittance, C_{trans}. The laser power incident on the vacuum chamber, can then be calculated using

$$P = \frac{(P_{elec,dark} - P_{elec,l})}{C_{ineq} * C_{abs} * C_{trans}} \ , \qquad (5)$$

where P is the laser power in W.

The next section discusses the determination of the values of the correction factors and the associated uncertainties.

IV. MEASUREMENT UNCERTAINTY

The measurement uncertainties include the electrical-optical heating inequivalence uncertainty, uncertainty in the correction for the coupling of thermal background to the bolometer, uncertainty in the window transmittance, uncertainty in the VACNT absorber reflectance, and other uncertainties such as the impact of bolometer spatial nonuniformity and alignment accuracy of the laser beam on the bolometer, electrical noise, thermistor noise, and fundamental thermal noise. This section describes the assessment and evaluation of the measurement uncertainties.

The two largest uncertainties are in the correction applied for changes in the background radiation during the measurement time and the window transmittance. Because the sensitivity to changes in the thermal environment dominates, the expanded uncertainty varies for laser power.

Table III summarizes the expanded uncertainty expected for different laser powers. These uncertainties assume a measurement procedure identical to those performed at NIST and uses NIST’s uncertainties for the parts of the measurement that are not inherent to the standard, for example beamsplitter uncertainty and laser power stability.

Table III Expanded uncertainty for laser power measurements.

Laser Power	Expanded Uncertainty (k = 2)
10^{-4} W ≤ P ≤ 10^{-3} W	7.0 %
10^{-3} W < P ≤ 10^{-2} W	0.83 %
10^{-2} W < P ≤ 10^{-1} W	0.46%

Table IV shows the uncertainty budget for a 1 mW laser power measurement. The residual power variations after correcting for the thermal sensitivity of the standard are constant, so the relative uncertainty will decrease with increasing laser power. In contrast, the uncertainties related to the inherent inequivalence of the chip do not change with laser power, and therefore become the dominant uncertainties at higher powers, as shown in Table V. Type A refers to uncertainties which are evaluated by statistical methods, and Type B refer to uncertainties evaluated by other means. For the Type B uncertainties, the distributions are identified.[26]

The following sections describe the terms of the uncertainty budget and the origins of the three correction factors that are applied to the measurement – the electrical-optical heating inequivalence, the window transmittance, and the chip detector absorptance correction.

A. Correction for fluctuations in background radiation

Temperature changes in the window couple to the detector and result in drifts in the steady state electrical power. Fig. 14 shows an example of the drift in the electrical heater power and how it correlates to the change in the temperature of the window. As the window warms, the thermal coupling to the detector increases, so the electrical power decreases to keep the detector at a constant temperature. As the window cools, less energy is radiatively coupled to the detector, so the electrical power increases to keep the detector at a constant temperature. A 1 mK drift in window temperature causes a drift in the electrical power of 20 μW.

The drift can be corrected using the methodology described in III. The residuals are typically on the order of a few μW over the measurement time but vary with the laboratory environment. We model this as a Type B uncertainty with a rectangular distribution and use ±6 μK as the limits of the distribution.

B. Correction for window transmittance

The window transmittance correction, C_{trans}, of the wedged, fused silica window was measured by measuring the laser power incident on a calibrated, carbon nanotube-coated pyroelectric radiometer having a low (~0.05 %) diffuse back-reflection, with and without the window in the laser beam. The beam was aligned to be at normal incidence to the air-side surface of the window. The effect of the window wedge on the transmittance of s- and p-polarization was calculated using the Fresnel equations for UV fused silica and deemed negligible for the 8.7 mrad wedge. Measurements were performed at 632.8 nm and 1550 nm. The window transmittance at other wavelengths was determined by using vendor-provided spectral transmittance data of the UV fused silica scaled to match the

Table IV. Uncertainty budget for a 1 mW laser power measurement

Uncertainty	δ_i[a] (%)	Distribution	Type[26]	u[b] (%)	Comment
Correction for changes in background radiation	0.60 %	Rectangular	B	0.35 %	Measurement
Window transmittance correction	0.30 %	Rectangular	B	0.17 %	Measurement
Correction factor for electrical and optical heating power inequivalence	0.18 %	Rectangular	B	0.10 %	Measurement
Spatial nonuniformity of the inequivalence and laser alignment	0.15 %	Rectangular	B	0.09 %	Assumes centered to ± 0.75 mm
Trap traceability to primary standard	0.03 %	Rectangular	B	0.02 %	
Repeatability of measurement (N = 50)	0.20 %	Normal	A	0.03 %	Measurement
Chip detector absorptance correction	0.02 %	Normal	B	0.01 %	Measurement
Electrical power measurement, DVMs	0.01 %	Rectangular	B	0.00 %	Vendor specification
Beamsplitter ratio uncertainty	0.10 %	Rectangular	B	0.06 %	NIST C calorimeter calibration[7]
Electrical power measurement, precision resistor	0.00 %	Normal	B	0.00 %	Measurement
Laser power fluctuations over measurement time	0.01 %	Rectangular	B	0.01 %	
Combined standard uncertainty, u_c				0.42 %	
Expanded uncertainty, U, (k = 2)				0.83 %	

[a]$\pm\delta_i$ represents the limits of the rectangular distribution or the standard deviation of the normal distribution of the measurand
[b]Standard uncertainty

Table V. Uncertainty budget for a 10 mW laser power measurement

Uncertainty	δ_i[a] (%)	Distribution	Type[26]	u[b] (%)	Comment
Correction for changes in background radiation	0.06 %	Rectangular	B	0.03 %	Measurement
Window transmittance correction	0.30 %	Rectangular	B	0.17 %	Measurement
Correction factor for electrical and optical heating power inequivalence	0.18 %	Rectangular	B	0.10 %	Measurement
Spatial nonuniformity of the inequivalence and laser alignment	0.15 %	Rectangular	B	0.09 %	Assumes centered to ± 0.75 mm
Trap traceability to primary standard	0.03 %	Rectangular	B	0.02 %	
Repeatability of measurement (N = 50)	0.02 %	Normal	A	0.00 %	Measurement
Chip detector absorptance correction	0.02 %	Normal	B	0.01 %	Measurement
Electrical power measurement, DVMs	0.01 %	Rectangular	B	0.00 %	Vendor specification
Beamsplitter ratio uncertainty	0.10 %	Rectangular	B	0.06 %	NIST C calorimeter calibration[7]
Electrical power measurement, precision resistor	0.00 %	Normal	B	0.00 %	Measurement
Laser power fluctuations over measurement time	0.01 %	Rectangular	B	0.01 %	
Combined standard uncertainty, u_c				0.23 %	
Expanded uncertainty, U, (k=2)				0.46 %	

[a] $\pm\delta_i$ represents the limits of the rectangular distribution or the standard deviation of the normal distribution of the measurand

[b] Standard uncertainty

absolute transmission measurements performed at 632.8 nm and 1550 nm, as shown in Fig. 15.

The window is a commercial-grade UV fused-silica window. It is wedged but is not superpolished or anti-reflection coated. As a result, at the few tenths of a percent level, the transmittance measurement is strongly influenced by the relatively large amount of scattered light and spurious reflections. While the uncertainty due to repeatability of each transmission measurement is ~0.04 %, the reproducibility leads to a greater uncertainty. In addition, one must account for uncertainties in the scaled spectral responsivity. Therefore, we estimate the uncertainty arising from the window transmittance correction as a Type B uncertainty with a ±0.3 % rectangular distribution.

Fig. 15 shows that the window transmittance correction, C_{trans}, is wavelength dependence. To perform a measurement at a wavelength besides 632.8 nm and 1550 nm, where the transmission was measured, the value of the scaled vendor data was used.

C. Correction factor for electrical-optical heating power inequivalence

There is an inequivalence between the electrical heating alone and when a portion of the electrical heating is replaced with optical heating by a gaussian laser beam aligned to the center of the absorber. This is attributable to the asymmetrical geometry of the bolometer chip, placement and number of the absorber thermistors, the difference in the location of the applied electrical and optical powers (the circumference of the absorber for the electrical heater and the center of the absorber for the laser), and the radiative losses across the large, VACNT absorber that is operated at room temperature.

A thermal model of the bolometer was developed using a finite-element method (FEM). The thermal model was operated in closed loop similarly to the real bolometer so that the electrical power was reduced when laser power was switched on in the model and the laser power was obtained from the difference in electrical powers when the laser is switched on and when it is off. Fig. 16 shows the temperature profile in the detector at steady state with electrical heating only.

Table VI shows the predicted inequivalence when the beam is centred on the bolometer chip for different beam powers and diameters. This inequivalence includes any parasitic heating from the leads. The inequivalence is nearly insensitive to beam diameter and power for diameters less than 10 mm. The inequivalence is, however, sensitive to the location of the beam on the detector; this will be discussed in the following section. The model doesn't include an additional inequivalence created by secondary reflections from the wedged window hitting a different spot on the detector since the effect is estimated to be less than 0.002 %.

Table VI. Model prediction of the electrical-optical heating inequivalence as a function of beam diameter ($1/e^2$) and beam power for a gaussian laser beam centered on the VACNT absorber.

$1/e^2$ beam diameter (mm)	Predicted inequivalence (%)		
	0.8 mW	3.0 mW	100.0 mW
0.85	0.76	0.76	0.77
2.0	0.76	0.77	0.77
4.0	0.74	0.76	0.76
6.1	0.74	0.75	0.75
9.4	0.72	0.73	0.73

The inequivalence is

$$I_{ineq} = \left(1 - \frac{P_{measured}}{P_{trap}}\right) \times 100\ \% \ , \qquad (6)$$

where I_{ineq} is the inequivalence in percent. I_{ineq} was measured to be 0.74 % ± 0.16 % (1-sigma) by alternating laser power measurements between the radiometric standard and a silicon trap detector (referred to as NIST-6) calibrated by the NIST Laser Optimized Cryogenic Radiometer (LOCR).[9] Twenty measurements were performed at 799 μW, 633 nm, with a beam diameter of 0.85 mm. The repeatability of the measurements is limited by the correction in the thermal drift. The related correction factor, C_{ineq}, in Equation 5 is then calculated to be C_{ineq} = 1 - 0.0074 = 0.9926, when the laser beam is centered on the VACNT absorber.

Fig. 17 shows the results of the measurements. The uncertainty bars on each individual point are the expanded uncertainties (k = 2) calculated from uncertainties in the electrical power measurement, the window transmittance correction factor, the chip detector absorptance correction factor, and the trap detector calibration. The remaining scatter in the plot is due to the residuals in the thermal drift correction and dominates the measurement at 799 μW.

We model the uncertainty as a Type B with a rectangular distribution and use ±0.18 %, the minimum and maximum variation measured in the data run in the NIST lab, as the limits.

D. Uncertainty arising from the spatial nonuniformity of the inequivalence and the alignment of the laser.

The inequivalence of the detector changes with the location of the beam on the bolometer chip. Therefore, there is an uncertainty associated with the location of the laser on the bolometer chip. An alignment fixture is used to align the laser to within 0.75 mm of the center of the chip. To estimate the uncertainty in the inequivalence of the detector as the location varies, the inequivalence was measured at the center and at the top and bottom of the detector and compared to the predictions of the COMSOL model, as shown in Fig. 18. The model predicts no significant difference with beam power or beam diameter, so a single correction can be applied to all measurements.

Since the measurements match the model well, we use the model to predict the maximum change in inequivalence for a 0.75 mm offset. We model the uncertainty as a Type B with a ±0.15 % rectangular distribution.

E. NIST-6 traceability to primary standard

The NIST-6 silicon trap detector used to validate the model predictions is a calibrated, polarization-independent, three-element Si reflection trap detector transfer standard.[27] The responsivity was calibrated at 632.8 nm against the optical power scale of LOCR.[28] The uncertainty on its responsivity calibration is a Type B rectangular distribution of ±0.03 %.

F. Repeatability of measurement

The "repeatability of measurement" uncertainty captures the uncertainty associated with the measured statistical noise of the heater power amplifier and out-of-band servo noise. This is a Type A uncertainty.

G. Chip detector absorptance correction

The reflectance, R, of the VACNTs was measured (Table II). We use 1-R at 657.5 nm for the absorptance correction factor for all wavelengths. Based on previous measurements of VACNT reflectance[24] we define the expected uncertainty for all wavelengths.[12]

H. Electrical power measurement, voltage measurements

Digital volt meters (DVMs) were used for measuring the electrical heating power according to Eq. (1). We use the standard uncertainty for the DVMs stated in the technical specification and propagate to power using the related partial derivatives and standard uncertainty propagation methodology.

I. Electrical power measurement, precision resistor

The resistance of the precision resistor was calibrated to be R_{prec} = 999.9949 Ω ± 0.00014 Ω. We use the standard uncertainty for the precision resistor calibration (0.00014 Ω) and propagate it to an uncertainty in power using the related partial derivative of Eq. (1) and standard uncertainty propagation methodology.

J. Laser power fluctuations over measurement time

This value will vary with the measurement configuration and laser used. The value used here is the typical value currently achieved in the NIST C-lab using a power-stabilized 1 mW laser in a calibration using C-series calorimeters.

K. Beamsplitter ratio uncertainty

This value varies with the measurement configuration. The value used is the typical value currently achieved for a similar NIST optical power calibration with the C-series calorimeters.

L. Thermistor noise and heat link thermal noise

The fundamental noise sources of the system are the thermistor noise and the weak link thermal noise. In the case of this room temperature standard, these noise sources are far below the other uncertainties.

Typical thermistor noise is characterized by $1/f$ noise at low frequencies and Johnson noise at higher frequencies.[29] Using the measured thermistor noise in Ref. 29 and a peak-to-peak 0.25 V 1 kHz sinusoidal excitation across the resistance bridge we estimate a Type A standard uncertainty of 0.000076% for N = 100.

The weak link thermal noise can be calculated using

$$NET = \sqrt{\frac{4k_B T^2}{G}} \tag{7}$$

where *NET* is the noise equivalent temperature in K/√Hz, T = 308 K is the bolometer temperature, G = 8.1 mW/K is the heat link conductance, and k_B is Boltzmann's constant. The Type A standard uncertainty, u, is

$$u = \frac{1}{N}\sqrt{\frac{G4k_B T^2 B}{P_0^2}} \times 100\ \%\ , \tag{8}$$

where B = 0.9375 Hz is the noise equivalent bandwidth, N is the number of measurements, and P_o is the incident power. The standard uncertainty is less than 0.0001 % for P_o= 1 mW and N = 100.

V. Direct Comparison with Primary Standard

The new standard was transported from NIST in Boulder, CO to AFMETCAL in Heath, OH. AFMETCAL maintains C-series calorimeters as primary standards very similar in construction to those used at NIST. During the comparison, the calorimeters were operated at two wavelengths, 532 nm and 1064 nm, to measure laser powers that varied from 25 mW to 2.6 W.

In order to compare the measurements with the new standard that is limited to input laser powers around 100 mW, an optical wedge beamsplitter was used to direct a reduced amount of light into the new standard. The beamsplitter ratio was 25.715 at 532 nm and 26.839 at 1064 nm. For example, 2 W would be directed to the calorimeter while 0.078 W was directed to the new standard at 532 nm. For some measurements, the standard was also compared to a calibrated Si transfer standard detector. Table VII shows the results of the comparisons.

VI. Conclusions

A room temperature laser power standard using a microfabricated electrical substitution bolometer has been demonstrated. A thermal finite element model that accurately predicts the performance of the bolometer has been developed and validated. The new standard reduces measurement times over the existing calorimeters at powers greater than 10 mW. The cooling time of the existing calorimeters can range from 15 minutes to several hours, depending on the measured power, while the closed loop measurement time of the new standard is around five minutes for all powers. It is robust enough to be transferred between distant laboratories. At powers greater than 1 mW the accuracy meets or exceeds the accuracy of the existing calorimeters. However, the accuracy degrades at lower powers due to radiative coupling to thermal fluctuations of the surrounding environment. Also, the design of the standard limits the input power to 0.1 W, while existing standards based on calorimetric operation can operate with input powers up to 2 W. A modified version of this standard is under development that addresses these final issues.

Table VII. Results of comparison of new standard with C-series calorimeters.

AFMETCAL Std Type	AFMETCAL Beam Power w/beamsplitter correction (mW)	AFMETCAL expanded uncertainty	NIST Beam Power (mW)	NIST expanded uncertainty	Abs difference (%)	Allowed[a] (%)	Wavelength (nm)
Calorimeter	1.166	0.90 %	1.167	0.83 %	0.08 %	1.22 %	532
Calorimeter	1.168	0.90 %	1.160	0.83 %	0.68 %	1.22 %	532
Calorimeter	5.268	0.90 %	5.259	0.83 %	0.17 %	1.22 %	532
Calorimeter	5.262	0.90 %	5.250	0.83 %	0.22 %	1.22 %	532
Calorimeter	77.856	0.90 %	77.754	0.46 %	0.13 %	1.01 %	532
Calorimeter	20.208	0.90 %	20.079	0.46 %	0.64 %	1.01 %	532
Calorimeter	20.122	0.90 %	20.088	0.46 %	0.17 %	1.01 %	532
Calorimeter	20.070	0.90 %	20.067	0.46 %	0.01 %	1.01 %	532
Calorimeter	39.716	0.90 %	39.660	0.46 %	0.14 %	1.01 %	532
Calorimeter	39.733	0.90 %	39.709	0.46 %	0.06 %	1.01 %	532
Calorimeter	77.211	0.90 %	77.239	0.46 %	0.04 %	1.01 %	532
Calorimeter	19.527	0.90 %	19.521	0.46 %	0.03 %	1.01 %	532
Calorimeter	39.688	0.90 %	39.647	0.46 %	0.10 %	1.01 %	532
Detector	103.415	1.75 %	102.996	0.46 %	0.41 %	1.81 %	532
Detector	103.606	1.75 %	102.611	0.46 %	0.96 %	1.81 %	532
Detector	103.632	1.75 %	103.144	0.46 %	0.47 %	1.81 %	532
Calorimeter	1.546	0.90 %	1.549	0.83 %	0.21 %	1.22 %	532
Calorimeter	77.084	0.90 %	77.025	0.46 %	0.08 %	1.01 %	532
Calorimeter	0.982	0.90 %	0.980	0.83 %	0.26 %	1.22 %	532
Calorimeter	5.328	0.90 %	5.305	0.83 %	0.44 %	1.22 %	532
Calorimeter	4.728	0.90 %	4.690	0.83 %	0.81 %	1.22 %	1064
Calorimeter	5.241	0.90 %	5.216	0.83 %	0.46 %	1.22 %	1064
Calorimeter	72.610	0.90 %	72.301	0.46 %	0.42 %	1.01 %	1064
Calorimeter	1.053	0.90 %	1.059	0.83 %	0.61 %	1.22 %	1064
Detector	5.090	1.75 %	5.188	0.83 %	1.93 %	1.94 %	532
Detector	5.103	1.75 %	5.195	0.83 %	1.79 %	1.94 %	532
Detector	28.179	1.75 %	28.252	0.46 %	0.26 %	1.81 %	532
Detector	90.798	1.75 %	91.721	0.46 %	1.02 %	1.81 %	532

[a]The quadrature sum of the NIST and AFMETCAL uncertainties

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Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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FIGURE CAPTIONS

FIG. 1. Silicon microfabricated detector.

FIG. 2. Mounting and thermal control of the bolometer chip. Two thermal control loops maintain the absorber at ~35 °C and the base of the detector at ~20 °C.

FIG. 3. Vacuum chamber constructed of commercially available components.

FIG. 4. Electrical power through the heater is determined by measuring two voltages: the voltage across a calibrated precision resistor, V_p, in series with the absorber heater, and the voltage across the heater, V_h.

FIG. 5. a) Drawing of the Si micromachined detector b) The leads for the heater and absorber thermistor 4-wire measurement run up the heat link. The rest of the heat link is coated with W to keep the emissivity the same across the heat link c) absorber thermistor.

FIG. 6. Bolometer temperature rise with applied electrical heating power when the base copper block is kept at 20 °C.

FIG. 7. Calculated and measured bolometer step response. The corresponding 1/e time constants are $\tau_{modelled}$ = 23.6 s and $\tau_{measured}$ = 23.0 s.

FIG. 8. Block diagram of electronics.

FIG. 9. The closed-loop step response of the base temperature loop. The absorber loop is open.

FIG. 10. Block diagram of absorber thermal control loop.

FIG. 11. Open loop step response of absorber loop with base loop closed.

FIG. 12. The change in electrical power when a shutter blocking the laser entering the standard is opened (at ~1.2 minutes) and closed (at ~4.5 minutes). The solid line is the measured power. The asterisks are the average values of the 'dark' electrical power before and after closing the shutter and allowing the temperature to stabilize. The diamond is the average value of the electrical power with the shutter open. The 'x' marker is the interpolated value for 'dark' electrical power at the time the shutter is open.

FIG. 13. Expanded plot of change in electrical power when a shutter blocking the laser entering the standard is opened. The drift in the 'dark' electrical power is evident. The markers have the same significance as Fig. 12.

FIG. 14 Example of coupling of the vacuum window temperature changes (blue) to 'dark' electrical power (black).

FIG. 15 Spectral transmittance of the fused silica vacuum window. a) The solid black curve shows the scaled vendor data, the red points indicate the measured values with k = 2 uncertainties from measurement repeatability. b) A zoomed-in version of the upper figure with the y-axis re-scaled.

FIG. 16. FEM model of the temperature profile in the detector chip at steady state with electrical heating.

FIG. 17 Twenty inequivalence measurements with their expanded uncertainties taken with a laser power of 799 □W at 633 nm and a 0.8 mm diameter beam.

FIG. 18. Inequivalence as a function of a laser beam offset along the x-axis (a) and y-axis (b) with respect to the absorber center. The blue circles are predictions of the COMSOL model, and the black circles are the measured values with their k = 2 uncertainties.