U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
PHYSICAL MEASUREMENT LABORATORY
Boulder, Colorado 80305

Report of Calibration (42110C/42111C)

LASER POWER METER KIT "TSA" NIST ID 686284
LIGO PCal photodetector, Model Number D1300101-V1, **S.N.** 034
Labsphere integrating sphere, Model Number 3P-LPM-040-SL, **S.N.** 0917216885
LIGO PCal photodetector satellite box, Model Number D1300368-V3, **S.N.** N/A
Keithley digital multimeter, Model Number 2100, **S.N.** 1424247

LASER POWER METER KIT "TSB" NIST ID 686285
LIGO PCal photodetector, Model Number D1300101-V1, **S.N.** 106
Labsphere integrating sphere, Model Number 3P-LPM-040-SL, **S.N.** 0917216884
LIGO PCal photodetector satellite box, Model Number D1300368-V3, **S.N.** N/A
Keithley digital multimeter, Model Number 2100, **S.N.** 1148750

Submitted by

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Table 1. Calibration results

Transfer Standard	Wavelength (nm)	Nominal input power (mW)	n	Calibration factor (V/W)	Standard deviation (%)	Expanded uncertainty (*k*=2) (%)
TSA	1047	302	5	4.35462	0.013	0.14
TSB	1047	302	5	4.26916	0.052	0.14

NIST ID: 686284, 686285
Order Number: O-0000043908, 02-DEC-2022
Date of Calibration: 4-NOV-2022 to 5-NOV-2022
Date of Report: 6-DEC-2022

Calibration summary

The Transfer Standard [1] Laser Power Meters were compared to a NIST standard radiometer [2] at a wavelength of 1047 nm (DPSS Laser). The laser beam had a $1/e^2$ diameter of approximately 4 mm at the entrance aperture which was centered and normal to the incident beam. A beam splitter ratio was determined by concurrently measuring the power incident on the standard radiometer and monitor radiometer. The power impinging upon the transfer standard was then measured concurrently with the monitor (see Figure 1). Afterward, the beamsplitter ratio was evaluated again. With the beamsplitter ratio and monitor's power measurement, the power incident on the transfer standard was inferred. The calibration factor was found by dividing the transfer standard reading by the inferred incident power. The standard radiometer is traceable to the SI through NIST representations of the Volt and Ohm.

A summary of the measurements is given in Table 1. If the readings of the transfer standard are **divided** by the appropriate calibration factor listed in the table, then, on the average, the resulting values will agree with those of the NIST measurement system.

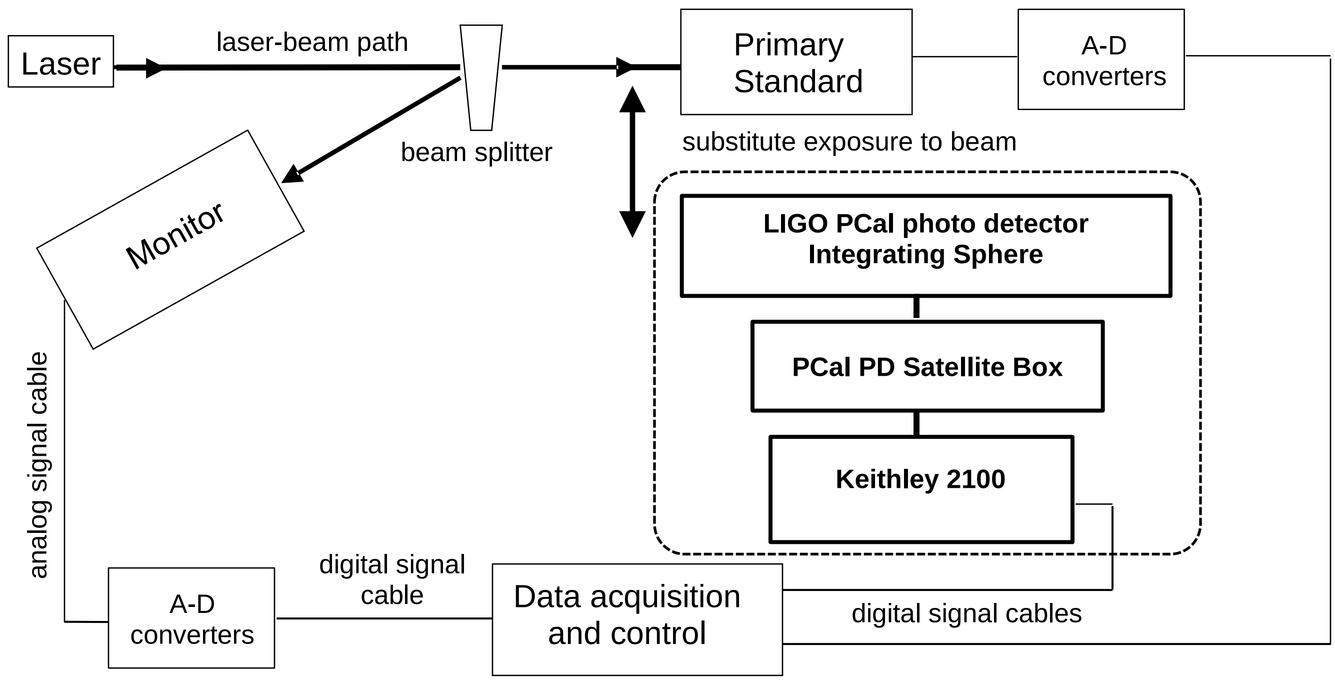

Figure 1. Measurement setup

Before the measurements began, the transfer standard was at thermal equilibrium with the laboratory environment over 1 day before measurements were performed. The ambient temperature during these measurements was 22.0 ± 1 ºC and the relative humidity was 25 ± 5 %.

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1 As the laser power meters will be used to compare primary standards, they qualify as Transfer Standards (TS) as defined by Joint Committee for Guides in Metrology (JCGM) 2012 International Vocabulary of metrology" (3rd edn) bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

2 A. Vaskuri, et. al. "High-accuracy room temperature planar absolute radiometer based on vertically aligned carbon nanotubes", Optics Express 29, 14, (2021). https://doi.org/10.1364/OE.427597

A supplemental thermometer, paired with the transfer standard kit, was placed beneath the integrating sphere and the indicated temperature recorded at the start of the measurement activity. Also, the voltage reported by the AD590 temperature-to-voltage transducer circuit located inside the photodetector enclosure was recorded. Environmental conditions as reported by these sensors are indicated in Table 2.

Table 2. Environmental conditions reported by various sensors.

Transfer Standard	AD590 onboard temperature sensor voltage (V)		Paired thermometer (°C)	Laboratory temperature (°C)
	Min	Max		
TSA	3.015	3.021	21.9	22 ± 1 ºC
TSB	3.026	3.027	22.1	22 ± 1 ºC

Uncertainty assessment

The uncertainty estimates for the NIST laser power and energy measurements are assessed following guidelines given in NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results" by Taylor and Kuyatt, 1994. Uncertainty is separated into uncorrelated components ascribed to either Type A or Type B sources in current measurement process. Neither correlated nor unidentified uncertainty sources are significant in comparison to the identified Type A and Type B uncertainties.

Type A uncertainty components are assumed independent and normally distributed. Consequently, the relative standard uncertainty, $u_{rel,\ Type\ A}$, for each component is

$$u_{rel,\ Type\ A} = \frac{1}{\bar{x}\sqrt{n}}\sqrt{\frac{1}{n-1}\sum_{h=1}^{n}(x_h - \bar{x})^2} \ ,$$

where x_h represents the individual measurements of a value, $\bar{x}$ the average of measurements, and n is the number of measurements made.

Type B uncertainty components are assumed independent, typically with a uniform distribution. Consequently, the relative standard uncertainty, $u_{rel,\ Type\ B}$, for each component is typically

$$u_{rel,\ Type\ B} = \frac{\delta_{rel}}{\sqrt{3}} \ ,$$

where the value has an equal probability of being within the region, $\pm\delta_{rel}$, and zero probability of being outside that region.

Certain uncertainty sources arise from both Type A and Type B uncertainty components. Consequently, the relative standard uncertainty, $u_{rel,\ c}$, for each combined component is

$$u_{rel,\ c} = \sqrt{\sum u_{rel,\ Type\ A}^2 + \sum u_{rel,\ Type\ B}^2} \ .$$

The relative expanded uncertainty U_{rel} combines relative standard uncertainties u_{rel} in quadrature, multiplying this result by a coverage factor $k = 2$ where such an expansion supports a 95% confidence interval. The expanded relative uncertainty, U_{rel}, is then

$$U_{rel} = 2\sqrt{\sum u_{rel}^2}\ .$$

Relative uncertainties used to calculate the relative expanded uncertainty of the calibration factor are listed in Tables 3 to 5. The number of decimal places used in reporting the mean value of the calibration factors listed in Table 1 was determined by expressing the total NIST uncertainty to at least two significant digits.

Table 3. Shared Calibration Uncertainties

Source	Standard Uncertainty	(type)
Standard Resistor Calibration	0.0010 %	$(u_{rel,\ Type\ B})$
Standard Resistor Voltage Measurement	0.0005 %	$(u_{rel,\ Type\ B})$
Heater Voltage Measurement	0.0005 %	$(u_{rel,\ Type\ B})$
Heater Leads	0.0058 %	$(u_{rel,\ Type\ B})$
Inequivalence	0.0058 %	$(u_{rel,\ Type\ B})$
Spatial Nonuniformity	0.058 %	$(u_{rel,\ Type\ B})$
Absorptivity	0.017 %	$(u_{rel,\ Type\ B})$
Window Transmission	0.029 %	$(u_{rel,\ Type\ B})$

Table 4. Calibration Uncertainties NIST ID 686284

Source	Standard Uncertainty	(type)
Monitor to Standard Radiometer Ratio	0.0051 %	$(u_{rel,\ Type\ A})$(n=10)
Transfer Standard to Monitor Ratio	0.0056 %	$(u_{rel,\ Type\ A})$(n=5)

Table 5. Calibration Uncertainties NIST ID 686285

Source	Standard Uncertainty	(type)
Monitor to Standard Radiometer Ratio	0.0071 %	$(u_{rel,\ Type\ A})$(n=8)
Transfer Standard to Monitor Ratio	0.023 %	$(u_{rel,\ Type\ A})$(n=5)

For the Director,
National Institute of Standards and Technology

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