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

Report of Calibration (42170SA)

LASER POWER METER
Detector model number D1300101-V1, **S.N.** 038, **NIST ID** 686193
Labsphere integrating sphere 3P-LPM-040-SL, **S.N.** N/A
LIGO transimpedance amplifier D1300368, **S.N.** N/A
Keithley digital multimeter 2100, **S.N.** 8002111

Submitted by
LIGO Hanford Observatory
127124 North Route 10
Richland, WA
99354

Table 1. Calibration results

Wavelength (nm)	Nominal input power (mW)	N	Calibration factor (V/W)	Standard deviation (%)	Expanded uncertainty (*k*=2) (%)
1047	296	10	-8.0985	0.0142	0.63

Page:	1 of 4
NIST ID:	686193
Folder Number:	291902-19
Date of Calibration:	10-DEC-2018
Date of Report:	11-DEC-2018
Reference:	01-AUG-2018, 75-S388075

Calibration summary

The laser power meter was compared to NIST standard calorimeters at a wavelength of 1047 nm (Diode Pumped Solid State 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. The power impinging upon the test instrument was measured concurrently using a calibrated beamsplitter and a NIST standard calorimeter (see Figure 1). The primary standard is traceable to the SI through NIST representations of the Volt and Ohm. The beamsplitter ratio was calibrated for each data set using two NIST standard calorimeters.

Before the measurements began, the test instrument was allowed to reach equilibrium with the laboratory environment. Readings were recorded from the test meter via USB interface to 'KI Tools' software. The instantaneous power was integrated for full injection period for both the calorimeter and device under test, negating laser instability contributions to uncertainty (table 2) and this report is issued as a special test as such an uncertainty assessment differs from the method outlined for a standard test. The calibration factor was found by dividing the integrated test instrument power readings by the calculated incident power as measured by the standard calorimeter. By customer request, the laboratory temperature set to 20 °C ± 1 °C and the relative humidity followed ambient conditions of 23 % ± 5 %.

A summary of the measurements is given in Table 1. If the readings of the test instrument 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.

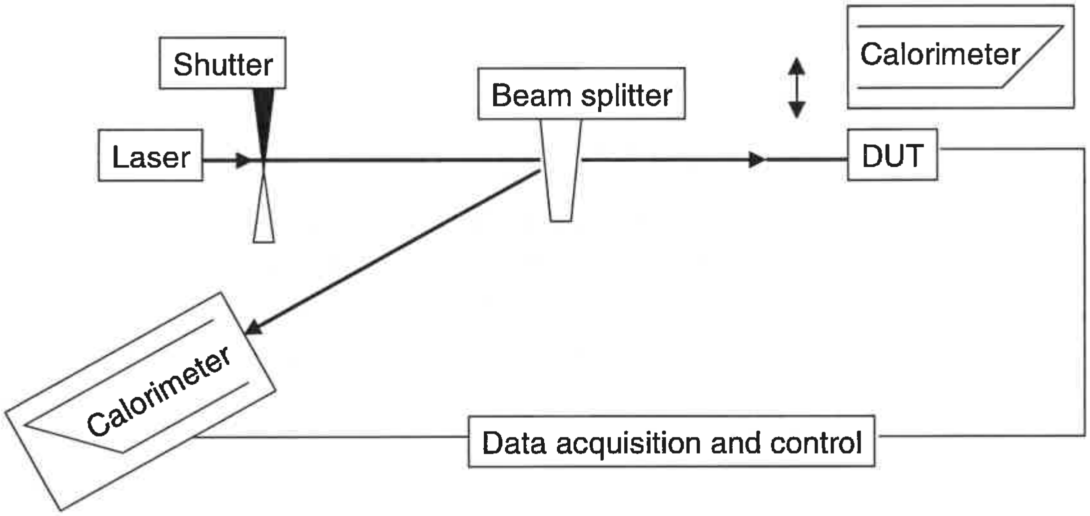

Figure 1. Measurement setup

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

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

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

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

Relative uncertainties used to calculate the relative expanded uncertainty of the calibration factor are listed in Table 2. The number of decimal places used in reporting the mean value of the calibration factor listed in Table 1 was determined by expressing the total NIST uncertainty to at least two significant digits.

Table 2. Calibration uncertainties

Source	**Standard Uncertainty**	**(type)**
Inequivalence	0.087 %	$(u_{rel,\ Type\ B})$
Absorptivity	0.0058 %	$(u_{rel,\ Type\ B})$
Electronics	0.058 %	$(u_{rel,\ Type\ B})$
Electronics	0.0033 %	$(u_{rel,\ Type\ A})$(N=30)
Heater Leads	0.0058 %	$(u_{rel,\ Type\ B})$
Window Transmission	0.064 %	$(u_{rel,\ Type\ B})$
Window Transmission	0.0033 %	$(u_{rel,\ Type\ A})$(N=30)
Inject time	0.029 %	$(u_{rel,\ Type\ B})$
Standard meter ratio	0.29 %	$(u_{rel,\ Type\ B})$
Standard meter ratio	0.0050 %	$(u_{rel,\ Type\ A})$(N=20)
Test meter ratio	0.0045 %	$(u_{rel,\ Type\ A})$(N=10)

For the Director,
National Institute of Standards
and Technology

Nate Newbury, Acting Chief
Applied Physics Division

Report reviewed by:

Igor Vayshenker

Igor Vayshenker, Technical Reviewer
Sources and Detectors Group
Applied Physics Division

Report prepared and calibration performed by:

Matthew Spidell

Matthew T. Spidell, Calibration Leader
Sources and Detectors Group
Applied Physics Division