Power measurement standards for high-power lasers: comparison between the NIST and the PTB

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Abstract. We report the results of the first laser high-power measurement comparison between the Physikalisch-Technische Bundesanstalt (PTB, Germany), and the National Institute of Standards and Technology (NIST, USA). Laser power transfer standards were calibrated at both national standards laboratories between 82 W and 127 W at 1.06 μm and between 85 W and 554 W at 10.6 μm. Relative agreement between the standards of the two laboratories was demonstrated to lie between 5×10^{-3} and 7×10^{-3}, which is well within the combined uncertainties.

1. Introduction

High-power infrared lasers are frequently used in industry to cut, weld, and process various types of material. Although laser power measurements have been performed for more than twenty-five years, the growth of new industrial laser-based systems over the past five years has increased the need for accurate, internationally consistent measurement services.

In support of the high-power laser industry, a comparison of laser high-power measurements was conducted by the PTB and the NIST. The comparison consisted of two phases. In phase 1 a NIST scientist took two high-power laser transfer standards to the PTB for measurements, and in phase 2 a PTB scientist took a PTB transfer standard to the NIST for measurements.

The transfer standards used in this comparison were carefully selected, commercial thermopile-based probes, which had shown very good repeatability and spatial uniformity. Each of these thermal detectors consists of an absorbing disc with a thermopile attached. The laser-induced temperature rise in the absorbing disc is proportional to the power in the laser beam, and the thermal energy generated flows from the absorber assembly to either a fan or a water-cooled radiator for heat dissipation.

2. NIST measurement system

The NIST high-power laser measurement system consists of two primary standards (K-series calorimeters) and a laboratory standard (see Figure 1). The K-series calorimeter [1] is an electrically calibrated thermal detector that measures energy in the range 300 J to 3000 J at wavelengths in the range 0.4 μm to 22 μm. Since the K-series instruments measure total energy, average laser power is found by dividing the total energy by the exposure time interval. This calorimeter has been in constant use as a primary standard over the past twenty-five years and has shown little or no change in response characteristics during this time [2]. The laboratory standard used in these comparison measurements, PM150-50C, is a commercial, water-cooled, thermopile-based probe with excellent repeatability and spatial uniformity.

The laboratory standard was compared with the K-series calorimeter by simultaneously exposing them to laser beams from a beam splitter (see Figure 2).

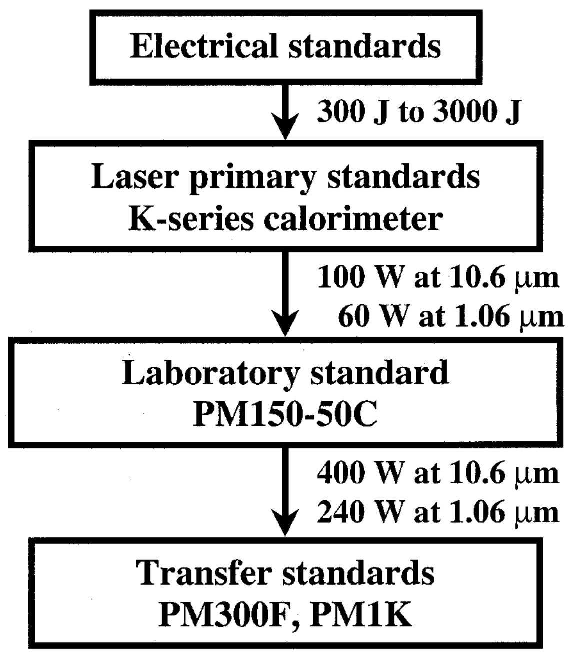

Figure 1. NIST high-power laser traceability chain.

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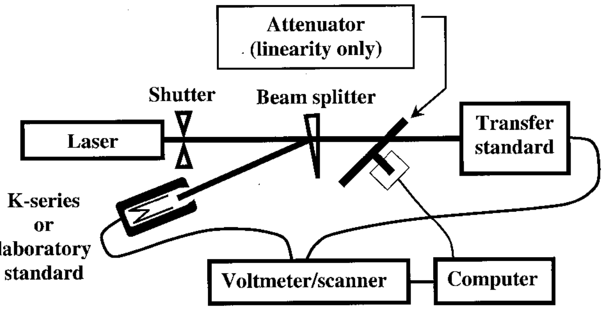

Figure 2. Basic NIST laser power measurement system.

Depending on the laser wavelength, either a Zn-Se wedge or an optical chopper wheel with reflecting blades was used as the beam splitter. The beam-splitter ratios (approximately 4:1) between the transmitted and the reflected power were calibrated using two K-series calorimeters. The transfer standard was then compared with the laboratory standard using the same beam-splitter-based system. In these measurements, the power incident upon the laboratory standard was kept at the same level used during the earlier calibration against the K-series. The transfer standard calibration measurements were performed at power levels of 400 W at 10.6 µm and 250 W at 1.06 µm.

Using a linearity measurement technique [3], the responsivity (s_1) of the transfer standard was obtained over the desired power range. These measurements were performed by taking pairs of readings (five at each power level) from the transfer standard with an attenuator placed in and out of the beam in front of the transfer standard (see Figure 2). A rotating chopper wheel was used as the attenuator and had a transmittance of around 70%. The power incident on the transfer standard was varied in appropriate steps that covered the required power range. A thermopile-based detector monitored the laser power during the ratio measurement process. Since the attenuation value of the chopper wheel was known and constant, the actual relative power incident upon the transfer standard was also known. A polynomial curve fit was performed on the data and the resulting curve was normalized to the calibration values obtained in the single-power calibrations described above.

The relative expanded uncertainty $(k = 2)$ of the NIST high-power laser calibration measurement for the comparison is 0.01.

3. PTB measurement system

The PTB high-power laser measurement system consists of two laboratory standards, HLR500 and SCT391, a beam splitter, and a monitor detector [4]. The HLR500 standard contains a flat absorbing disc with an electrical heater attached, enclosed in a water-cooled housing. It is calibrated against the PTB standard LM7 at 1.06 µm and 10.6 µm at power levels of 10 W and 5 W [5]. With additional correction factors determined by electrical calibration, the HLR500 can be used up to 120 W.

The LM7 standard, used for low- and medium-power levels in the range 3 mW to 10 W, is an electrical-substitution radiometer calibrated optically against a silicon trap detector at 632.88 nm and a power level of 5 mW. The trap detector is calibrated against a cryogenic radiometer, which serves as the PTB primary standard for low radiant power (see Figure 3). The non-linearity of the LM7 is characterized for powers up to 10 W by electrical calibrations, and spectral responsivity ranging from 350 nm to 10.6 µm is determined by measuring the reflectivity of the absorber.

The SCT391 meter, a modified commercial water-flow calorimeter, is calibrated against the HLR500 at 10.6 µm at a power level of 100 W. With an additional correction factor for non-linearity from electrical calibrations, the SCT391 can be used for measuring powers up to 1000 W.

The beam splitter is used to obtain two simultaneous beams. The transmitted beam is directed on to the standard meter or the transfer standard, which

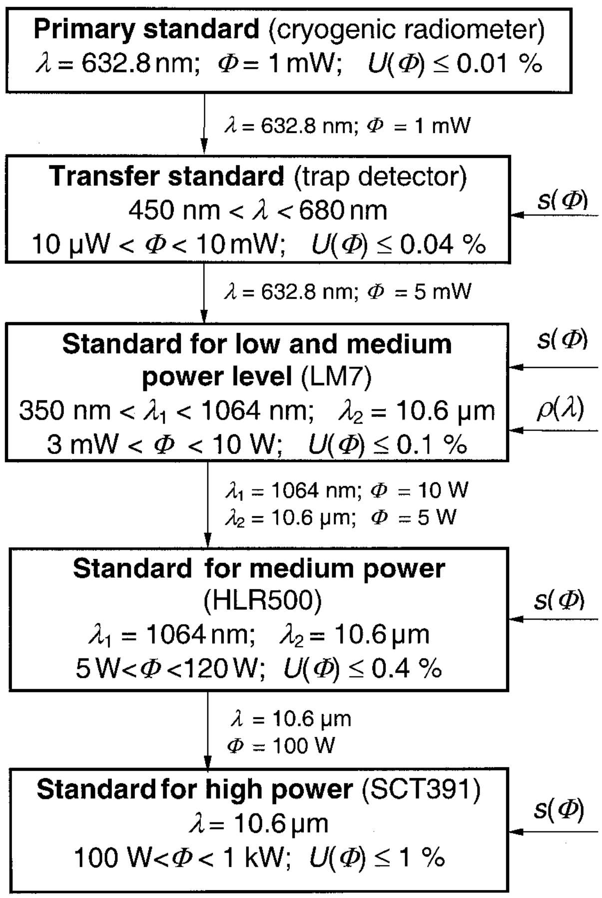

Figure 3. Transfer of laser power from 1 mW at 632.8 nm to 1 kW at 10.6 µm at the PTB. For the different standards the dependence of the responsivity on the power $s(\Phi)$ and the reflection losses $\rho(\lambda)$ of LM7 at different laser wavelengths are measured additionally.

Table 1. Results of comparison of NIST transfer standard PM1K.

Wavelength/μm	Power/W	Responsivity, NIST (s_1)/(mV/W)	100 × Std dev.	Responsivity, PTB (s_2)/(mV/W)	100 × Std dev.	100 × Difference $s_2/s_1 - 1$
10.6	133 to 554	0.1615	0.09	0.1604	0.37	−0.68

Table 2. Results of comparison of NIST transfer standard PM300F.

Wavelength/μm	Power/W	Responsivity, NIST (s_1)/(mV/W)	100 × Std dev.	Responsivity, PTB (s_2)/(mV/W)	100 × Std dev.	100 × Difference $s_2/s_1 - 1$
10.6	85 to 199	0.107 0	0.07	0.106 5	0.21	−0.47
1.06	82 to 127	0.099 57	0.13	0.099 06	0.51	−0.51

Table 3. Results of comparison of PTB transfer standard OPH1500.

Wavelength/μm	Power/W	Responsivity, NIST (s_1)/(mV/W)	100 × Std dev.	Responsivity, PTB (s_2)/(mV/W)	100 × Std dev.	100 × Difference $s_2/s_1 - 1$
10.6	105	37.03	0.17	36.77	0.11	−0.71
10.6	447	35.32	0.10	35.14	0.12	−0.50
1.06	98.8	34.80	0.25	35.05	0.08	0.72

are mounted on a translation stage. The beam reflected from the beam splitter is directed on to a monitor detector (see Figure 4).

First, the outputs of the PTB standard and the monitor are measured simultaneously to obtain the responsivity of the monitor, including the ratio of the beam splitter. Next, the translation stage is moved, so that the transmitted beam goes to the transfer standard. The outputs of both meters are collected. The first step is then repeated to re-check the responsivity of the monitor. Once the responsivity of the monitor is known, the data from the transfer standard can be used to determine its responsivity (s_2).

The relative expanded uncertainty ($k = 2$) of the PTB high-power laser calibration measurement for the comparison is 0.01.

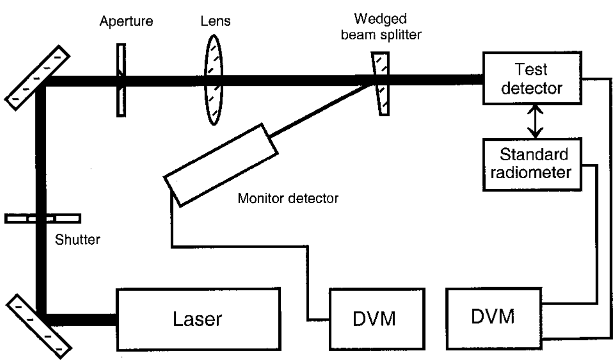

Figure 4. Principal set-up for calibration of laser power meters at the PTB. DVM: digital voltmeter.

4. Comparison results

(a) Phase 1: two NIST transfer standards, designated PM1K and PM300F, were calibrated at the NIST and taken to the PTB, where calibration measurements were performed at various power levels. Table 1 gives the average results for the PM1K comparison, and Table 2 gives the results for the PM300F.

(b) Phase 2: a PTB transfer standard, designated OPH1500, which had been previously calibrated at the PTB, was taken to the NIST for calibration measurements. Table 3 shows the comparison results.

5. Conclusion

The maximum relative discrepancy in the measurements from both phases is about 7×10^{-3}, well below either the NIST expanded uncertainty ($k = 2$) of 0.01 or the PTB expanded uncertainty ($k = 2$) of 0.01. This is the first comparison of power measurement standards for high-power lasers between the two national laboratories and the results confirm that their measurements are essentially in agreement.

References

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