

Onsite multikilowatt laser power meter calibration using radiation pressure

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We have demonstrated the calibration of a thermal power meter against a radiation pressure power meter in the range of 20 kW in a manufacturing test environment. The results were compared to a traditional calorimeter-based laboratory calibration undertaken at the National Institute of Standards and Technology. The results are reported, and the effects of nonideal conditions typical of measurements in low-stability environments are discussed.

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1. INTRODUCTION

Accurate measurements of laser power from multikilowatt CW lasers are important for their effective operation in manufacturing (welding [1,2], cutting, additive manufacturing [3], and materials processing), as well as in research and defense. In general, accurate measurement of laser power requires a calibrated power meter. Such a meter is typically calibrated through a comparison performed at a calibration laboratory to a more accurate power meter. This process establishes traceability to the International System of Units (SI) with ultimate comparison to a “primary standard” power meter. A primary standard power meter has its measurement accuracy established without comparison to any other laser power meter (its traceability is through a different parameter). For multikilowatt CW lasers, this calibration process is complicated by limited laser availability. For example, many manufacturing facilities have multikilowatt lasers, but the cost of purchasing and maintaining such a laser is typically prohibitive for calibration laboratories. Therefore, if a multikilowatt-laser user requires a calibration of a power meter, the calibration laboratory might not have a suitable laser. The calibration laboratory could ship its primary standard power meter to the laser user for an onsite “point of use” calibration of the user’s power meter with the user’s laser, but multikilowatt primary standard power meters are typically large and not easily portable. Furthermore, complex calibration procedures associated with high-power calibrations often make onsite calibration in a manufacturing environment impractical.

However, a solution comes by implementing a novel primary standard power meter based on radiation pressure [4]. A radiation pressure power meter (RPPM) measures the laser

power by reflecting the light from a mirror and using the light’s pushing force on the mirror as a direct measure of the incident laser power. Since this technique does not absorb the laser light, it allows for the design of a much smaller power meter than is typical for a conventional thermal-based primary standard, and it simplifies the measurement setup, enabling practical, onsite, primary-standard calibration of a multikilowatt test meter.

Here we describe and demonstrate such a calibration. We performed an example calibration of a thermal power meter for a “customer” onsite at its manufacturing test facility using our primary-standard RPPM and its laser over the power range from 1 kW to 20 kW (a factor of 2 increase in range over that previously reported for RPPM [4]). This calibration was also carried out using the traditional approach of shipping the customer’s thermal power meter (referred to as the device under the test, or DUT) to the National Institute of Standards and Technology (NIST) high-power calibration laboratory for a measurement comparison to our traditional “K-series” calorimetric primary standard [5]. A small but significant disagreement between the two calibration approaches was found. Since the RPPM and K-series power meter have already been shown to agree within their measurement uncertainty [4,6,7], this disagreement is an indication of how changes in environmental conditions between the manufacturing floor and a calibration laboratory can affect the DUT’s performance (specifically its calibration factor). We found that critical measurement conditions, which can often go unnoticed by a customer, can have a significant effect on the accuracy of their laser power measurements. This illustrates an advantage of onsite calibration in that it allows the power meter to be calibrated under the conditions of its operating environment.

2. EXPERIMENTAL DESCRIPTION

Laser power measurements above 1-kW CW are predominantly thermally based. Primary standards based on thermal measurements are either isoperibol calorimeters [8–11] or heat transfer techniques using flowing water power meters [7,12]. Both techniques measure a temperature rise in response to absorbed laser energy. Coupled with the time dependence of the rise, this yields the injected laser power.

However, radiation-pressure-based power measurements offer a new approach. It has been understood for decades that photon momentum and its resulting radiation pressure can be measured as a direct indicator of incident laser power [13–16], and recent demonstrations have shown that for laser powers in the kilowatt range, commercial-quality force balances can be used for highly accurate and portable laser power meters [4]. Such an RPPM enables portable, primary standard power measurements with traceability to the kilogram, a quantity that can be easily measured with better relative accuracy than the equivalent laser power [17].

The operation of an RPPM is simple. As light is reflected from a mirror, the momentum of the photons generates a force on the mirror. This force F is directly proportional to laser power P as [4]

$$P = cF/(2r \cos \theta), \quad (1)$$

where c is the speed of light, $r = R + (1 - R)\alpha/2$ is related to mirror reflectivity R , α is the fraction of nonreflected light that is absorbed by the mirror or its mounting assembly, and θ is the angle of incidence of the laser light with respect to the mirror normal. In a radiation-pressure-based power measurement, the light does not need to be absorbed to be measured. This is novel and contrary to all other high-accuracy laser power measurement techniques. We refer to this property as “nonexclusive” power measurement, meaning the power can be measured accurately while the laser light is being used for other purposes (e.g., allowing accurate measurement of laser power during a laser weld [18]). The design of our RPPM is shown in Fig. 1. As with all sensitive force transducers (scales), small air currents pushing on the mirror will increase the noise floor of the measured power. An air shield with input and output windows reduces this effect. The windows are antireflection-coated, and their residual reflectivity is accounted for when determining the measured laser power.

The nonexclusive nature of radiation pressure power measurement means that an RPPM and a second conventional (thermal, absorbing) power meter can measure the same laser’s power at the same time [4]. This greatly simplified the calibration. Using a thermal-based power meter as the standard

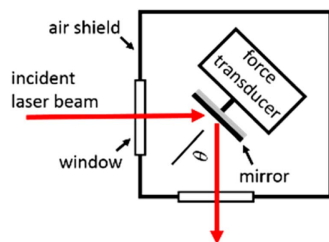


Fig. 1. Radiation pressure power meter (RPPM) design.

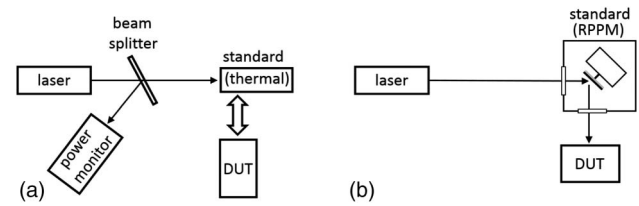


Fig. 2. (a) Typical configuration for a traditional laser power meter calibration by comparison to a thermal “standard” power meter—the device under test (DUT) power meter is compared to the standard by alternately inserting each into the laser beam while a power monitor measures source power fluctuations. (b) The simplified setup afforded by using RPPM as the standard power meter, enabling the DUT to be measured simultaneously.

typically requires a setup as shown in Fig. 2(a). The DUT and the standard power meter are alternatively inserted and aligned in the beam while a beam splitter picks off a fraction of the light to normalize away power fluctuations between when the DUT or the standard is measuring the laser. This requires additional precision alignment to stably sample the beam. For such a measurement in a calibration laboratory, this setup is straightforward. But if the calibration is to be performed onsite at the location of the laser, the setup and operation can be complicated. High-power primary standard power meters can be large and not easily portable, and the conditions in, for example, a laser-manufacturing environment might not be conducive to careful alignment and positioning of multiple components. The nonexclusivity of the radiation pressure power measurement allows the much simpler setup of Fig. 2(b). Here, the laser beam reflects off the RPPM’s mirror and the exit light is incident on the DUT for simultaneous measurement.

Our onsite calibration was performed in a manufacturing test facility on the campus of EWI (formerly the Edison Welding Institute, a facility for development and implementation of laser joining processes) using its 20-kW Yb-doped fiber laser (1.07- μm wavelength). The RPPM approach can work for other laser wavelengths with a suitable choice of mirror and window coatings and a highly transmissive window material. We used our RPPM to perform calibrating measurements from 1 kW up to 20 kW of a thermal-based laser power meter. Operation of this meter followed the prescriptions of [4]. This comparison provided the test meter with a calibration factor C , where

$$C = P_{\text{DUT}}/P_I \quad (2)$$

with P_{DUT} being the power reported by the thermal power meter (DUT) and the incident power P_I as measured by the primary standard RPPM. The use of such a calibration factor is to assign a correction factor to the power measurement reported by the DUT such that the true laser power is given as P_{DUT}/C .

The onsite calibration was set up as shown in Fig. 3. The laser’s output (process) fiber was connected to a nonrefractively focusing laser weld-head with an effective focal length of 32.5 cm. To allow for space between the power meters, the beam first was incident on an off-axis parabolic copper mirror placed beyond the beam’s focal point to reduce the divergence

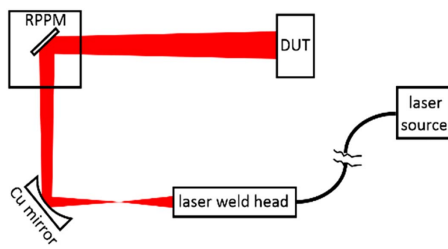


Fig. 3. Layout of RPPM-based onsite laser power meter calibration. The laser weld-head focused the light 32.5 cm from its exit, and a concave copper mirror was used to provide a slower expansion of the beam for incidence on the RPPM and then the DUT.

of the beam. The light was incident on the mirror of the RPPM with a beam diameter of roughly 2.5 cm. The beam was presumed to have a typical nominal “flat-top” profile with edge diffraction effects. This is the behavior of similar focusing optics but was not specifically characterized for this setup. The DUT was placed 126 cm away from the RPPM’s mirror. The beam made a larger 3.5-cm-diameter spot on the input aperture of the DUT. The RPPM was approximately 2 m from the laser’s fiber exit, coupled with the slightly-off-from-normal alignment of the RPPM’s windows to avoid any retroreflected light back into the laser.

The DUT was a thermopile, water-cooled by the laser’s cooling water loop with the DUT downstream of the laser. The flow rate was chosen to match the DUT’s specification for a 20-kW injection (17 lpm). This single flow rate was held constant for all injected laser power levels. The cooling water’s initial temperature was 20.5°C, but since it was downstream of the laser, the temperature rose by as much as 5°C during the injection. This temperature rate of change was outside the DUT’s specification but unavoidable. The ratio of the powers measured by the DUT and the RPPM were taken according to Eq. (2) to yield the calibration factor of the DUT. The RPPM power measurement considers the 0.1% transmission loss per window surface due to imperfect antireflection coatings.

To compare to this onsite calibration, the DUT was then shipped to NIST for calibration at 10 kW (the maximum power of our laser) by means of our conventional high-power calorimeter (K-series [5]) with a configuration described by Fig. 4. The resulting calibration factor obtained at NIST

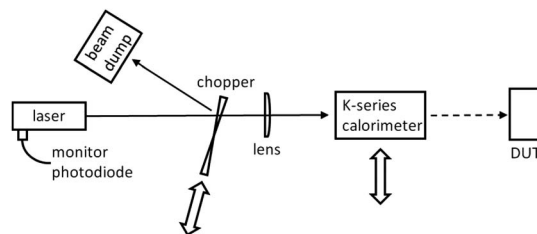


Fig. 4. Measurement setup for the calibration performed at the NIST high-power calibration laboratory. The primary standard K-series calorimeter standard is inserted and removed from the beam path in tandem with the optical chopper to switch between the standard and DUT measurements. A characterized monitor photodiode internal to the fiber laser was used to correct for any source power fluctuations.

was then compared to the calibration factor obtained by the RPPM during the onsite measurement.

3. RESULTS

For the onsite calibration, the laser power was measured at powers ranging from 1 kW to 20 kW with three measurements at each power level (except at 1-kW and 2-kW power levels, where only two measurements were used) and a 60-s injection duration. Typical power measurement results for both the RPPM and the DUT are shown in Fig. 5. The RPPM measurement was processed as described in Ref. [4] including the prescribed removal of linear thermal drift, to yield the time-dependent power injection curves of Fig. 5(a). The 5-s rise time of the RPPM’s force sensor is seen in the rise time of the reported power. For calculation of the calibration factor in Eq. (2), the average of the RPPM-measured laser power was calculated over the last 20 s of the injection and denoted P_I . The power reported by the thermal power meter is shown in Fig. 5(b). The response includes an overshoot at the beginning and end of the laser injection that is likely due to an interaction between the DUT’s predictive algorithm and the cooling water flow rate. The most accurate value should come when the reported power has reached steady state. From the exponentially decaying power, we determined the DUT’s measurement of average injected power at the end of the injection as follows. We empirically fit an exponential function to the decay portion of the reported laser power (from approximately 10 s to 60 s) to effectively average noise fluctuations in the reported power. The value of the fitted function at the time the laser is turned off (as close as possible to the steady-state value) is taken to be P_{DUT} , the average of the DUT’s reported laser power at the end of its injection. This power is referenced to the pre- and post-injection readout values. The post-injection value includes a suitable settling time to avoid the undershoot seen in Fig. 5(b).

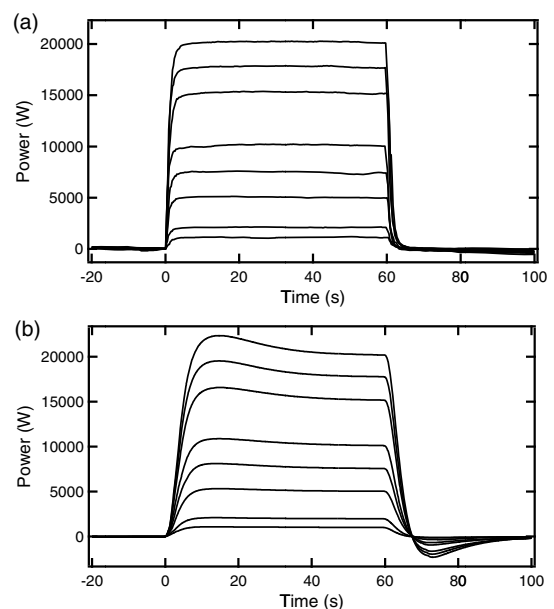


Fig. 5. Example power measurements from (a) the RPPM and (b) the DUT for laser injected powers of nominally 1, 2, 5, 7.5, 10, 15, 17.5, and 20 kW.

The resulting calibration factors are plotted in Fig. 6 over the full testing range. The error bars include a 0.8% standard uncertainty due to the RPPM, detailed in Ref. [4], added in quadrature with measurement standard deviation for the three measurements performed at each power level and expanded by a coverage factor of 2. Although only two measurement results were used at the 1-kW and 2-kW power levels, we made a conservative estimate of their measurement standard deviation by using a third measurement at 2 kW that had been excluded from the average due to an anomalous discrepancy in the thermal power meter's reported laser power.

As mentioned, this comparison was followed by a traditional calibration of the DUT at the NIST laboratories using our K-series isoperibol calorimeter [5]. A series of measurements were carried out at a single power level of nominally 10 kW. As seen in Fig. 4, during the K-series measurement only, a reflective optical chopper [19] was used to accurately attenuate the laser beam to 1.065% of the average incident power to keep the calorimeter within its calibrated range. The beam diameter on the DUT was matched to the condition of the onsite calibration. Cooling water to the DUT was provided, but the maximum achievable flow in our laboratory was 13.7 lpm. We operated at this flow rate to be as close as possible to the measurement conditions of the onsite calibration. The effects of the discrepancy between the flow rates at NIST and EWI will be discussed in the next section. The calibration factor determined by this traditional measurement at NIST is plotted in comparison to the onsite results in Fig. 6. The error bars represent the 1.4% expanded uncertainty (coverage factor of 2) for the K-series measurement at NIST. The slow variation of calibration factor with laser power is likely due to the operation of the DUT outside its specified rate of change for its cooling water but is not considered significant since it remains within the measurement uncertainty.

4. DISCUSSION

The measurement results of Fig. 6 indicate that there is a 3% disagreement between the DUT's calibration factor determined calorimetrically in the NIST facility and that measured onsite in the manufacturing test environment using the RPPM. Although the error bars do barely overlap, other unaccounted-for error sources are most likely involved. The most obvious culprit would be if there were a discrepancy between the RPPM and K-series primary standard power meters. However, a recent direct comparison between the two yielded

an agreement of better than 1% from 1 kW to 10 kW [4,6,7]. This means the 3% disagreement must be due to measurement instability; that is, the DUT truly had a different calibration factor during the onsite measurements than during the NIST measurements.

We suspect that differences in the cooling conditions of the DUT caused the change in its calibration factor. As mentioned, practical limitations forced different cooling water conditions for the DUT at the onsite calibration than were in place for the calibration at NIST. The DUT cooling water had a flow rate of 17 lpm during the onsite measurement, while it was 13.7 lpm during the NIST calibration laboratory measurement. We investigated the effect of this change by making power measurements with the DUT at a nominal power level of 10 kW under various flow rates. Results indicate an approximate increase in DUT-reported power of 5 W for each liter per minute of change in flow rate. This predicts that the power measured by the DUT during the onsite 10-kW measurement would be roughly 15 W higher (0.15%) than that measured by the DUT during the measurement at NIST. This explains a small fraction of the disagreement seen in Fig. 6.

The potentially bigger but less quantifiable source of error is the rising temperature of the DUT's cooling water by up to 5°C/min during the onsite calibration. In principle, a thermopile is independent of the static temperature of its environment. However, a thermopile is not immune to dynamic changes in its cooling water temperature, such as were seen during laser injection for the onsite calibration. This gradient, though unavoidable, exceeded the manufacturer's specification (less than 1°C/min) for this meter. We did not emulate temporal water temperature variation to estimate the resulting error, but we confirmed that its sign agrees with the calibration factor discrepancy of Fig. 6. Specifically, if the cooling water extracts heat from the laser-absorption area on the power meter, then as the cooling water temperature rises the temperature of the absorber will rise more quickly than expected for the injected power level and will yield an apparently higher measured laser power. Again, this is in the direction seen in our measurements.

5. CONCLUSIONS

We have demonstrated the use of an RPPM to perform an onsite high-laser-power calibration of a conventional thermal power meter. We found a 3% change between the thermal meter's calibration factor as measured at NIST and its value measured onsite at the manufacturing test facility. This difference indicates the effect that uncontrolled or unknown conditions in a manufacturing test environment can have on the laser power measurement results. If the DUT is to be used in this type of poorly known (or poorly controlled) operating environment, its calibration factor should be measured *in situ* by a technique (e.g., radiation pressure) capable of performing the calibration of the power meter under its exact operating conditions. This is the unique ability of the RPPM with its portability and non-exclusive measurement. Work is currently underway to develop an RPPM suitable for permanent implementation at the delivery point of manufacturing lasers [20]. We have illustrated the second advantage of onsite radiation-pressure-based laser power measurements that they enable power calibrations beyond the

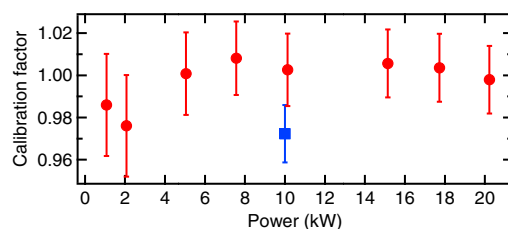


Fig. 6. Calibration factor determined by the RPPM versus DUT onsite measurement (red circles) and the calibration factor determined in the NIST laboratory between the K-series calorimeter and the DUT (blue square).

laser power levels that might be available at most calibration laboratories.

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