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Portable, high-accuracy, non-absorbing laser power measurement at kilowatt levels by means of radiation pressure

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Abstract: We describe a non-traditional optical power meter which measures radiation pressure to accurately determine a laser's optical power output. This approach traces its calibration of the optical watt to the kilogram. Our power meter is designed for high-accuracy and portability with the capability of multi-kilowatt measurements whose upper power limit is constrained only by the mirror quality. We provide detailed uncertainty evaluation and validate experimentally an average expanded relative uncertainty of 0.016 from 1 kW to 10 kW. Radiation pressure as a power measurement tool is unique to the extent that it does not rely on absorption of the light to produce a high-accuracy result. This permits fast measurements, simplifies power scalability, and allows high-accuracy measurements to be made during use of the laser for other applications.

OCIS codes: (040.1880) Detection; (250.0040) Detectors; (120.4800) Optical standards and testing; (120.5630) Radiometry; (140.3295) Laser beam characterization.

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1. Introduction

Accurate measurement of laser power output at the multi-kilowatt level is important for many commercially significant applications. This is difficult, however, because current primary standard power meters are large and require significant operating infrastructure. (A "primary standard" is a device whose measurement accuracy is established without reference to any secondary device measuring the same quantity). The implementation of such infrastructure by a detector manufacturer or in an industrial manufacturing environment would be costly and inconvenient if not impossible at the point of use. In the past, Williams et al. [1] introduced the idea of a portable force sensor for measuring radiation pressure (photon momentum transfer). Other groups have demonstrated optical power measurements by photon momentum transfer [2–8] but at much lower power levels and implementations that are impractical for commercial use or routine calibrations. In the present work, we document the uncertainty of a primary-standard power-measurement approach by means of photon momentum that is uniquely traceable to the optical watt through the kilogram and demonstrate excellent agreement with traditional electrically-traceable standards. For the first time, this is a standard-grade absolute radiometer for industrial use that can be easily deployed where the laser application is undertaken.

Every traditional method and means of measuring optical power is exclusive, meaning a photon must be absorbed for it to be measured. For example, semiconductor-based detectors and photocathode devices (photomultipliers) absorb photons to increase the availability of charge carriers and measure optical power as the flow (current) or quantity (voltage) of this charge. Thermal power meters absorb photons to produce phonon modes and measure optical power as a temperature increase. In the most fundamental sense, this means one cannot measure exactly how much optical power is being used in a particular application because measurement of the light and its useful operation are mutually exclusive. This apparent conundrum is typically solved by direct substitution or by sampling the light. For example, a light beam incident on a beamsplitter could have 90% of its power directed to its intended use and the other 10% toward an optical power meter. With sufficiently accurate knowledge of the beam splitting ratio, the power in one arm can be inferred from the power measured in the other. Variations of this principle are used for all conventional high-accuracy measurements of laser power [9–11]. However, semiconductor and photomultiplier devices are limited in operable power level (milliwatts for semiconductors and much less for photomultipliers). So, their use in measurements of high laser powers would require very high beam splitting ratios (or attenuators) that cannot be characterized with sufficient uncertainty to support a desired power measurement accuracy of 1-2%. So, until now, thermal power meters have been the only approach for high-accuracy, kilowatt-level, primary-standard optical power measurements.

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Thermal power meters, however, also have limitations for primary standard multi-kilowatt applications. Absorbing all the incident light means that thermal power meters must have high heat capacity, forcing the volume and mass of the meter to scale with its optical power capacity and increasing the thermal response time. For example, a primary standard calorimeter developed by NIST with a 1% uncertainty and a 100 kW capacity has a 3-4 m^3 volume, a mass of a couple hundred kilograms, and a response time of 1-2 minutes [12]. A reduction in size is achieved with a flowing water power meter approach where the temperature change and flow rate of the cooling water determine the input optical power to a 1% uncertainty from 1 kW to 100 kW with a response time of tens of seconds [13]. However, the absorber head, water tanks, and electrical and mechanical equipment are still on the order of a few cubic meters.

Here we discuss a new paradigm for high-power, high-accuracy, primary standard optical power measurement based on radiation pressure for which measurement exclusivity does not apply and response time, size, and scalability are significantly improved. When light reflects from a mirror, it imparts a force on the mirror. If a quantity of light has energy E, its momentum is $|\boldsymbol{p}| = E/c$, where c is the speed of light, and the force it imparts is given by $\boldsymbol{F} = \mathrm{d}\boldsymbol{p}/\mathrm{d}t$ with magnitude $F = \left(2P/c\right) r \cos(\theta)$, where P is the optical power and θ is the angle of incidence. Inversely,

$$P = cF / 2r \cos(\theta), \tag{1}$$

where $r = R + (1-R)\alpha/2$ accounts for the fact that an absorbed photon imparts all its momentum and a reflected photon imparts twice its momentum. R is the mirror reflectivity and α is the fraction of non-reflected light absorbed by the mirror. Equation (1) describes a maximum power-to-force conversion factor of $2/c = 6.67 \times 10^{-9}$ N/W for normal incidence on a perfectly reflecting mirror.

The concept of radiation pressure has been understood for centuries [14] and was experimentally demonstrated over 100 years ago [15]. To date, measurements to relate the force of radiation pressure to optical power have been heroic efforts to detect mirror deflections due to tiny forces from relatively low-power (milliwatts) incident light. The mechanisms have been predominantly torsion balances [2–4] and more recently pendulum-style [5, 6] and cantilever-based sensors [7, 16]. The measurements were made for modulated (pulsed) light in a vacuum environment (with the exception of [6] and [7]) and uncertainty claims ranged from 1% to 6%, but were not always validated.

None of these approaches will work for our goal of a robust, portable optical power meter for use as a primary standard for high-accuracy multi-kilowatt laser power measurement. The torsion and pendulum devices are not truly portable and their limitation of horizontal force sensing means they cannot be calibrated by simply weighing a reference mass. Cantilever mirror sizes are too small (ranging from 10 µm to 2 mm) and while the torsion and pendulum mirrors had diameters as large as 3 cm, further enlargement would require scaling the entire apparatus proportionally. We instead developed a radiation pressure power meter (RPPM) based on a commercial force sensor, designed as a truly portable device targeting optical powers from 1 kW to 100 kW [1] with measurement uncertainty traceable to the kilogram, and applicable for *in situ* high-accuracy measurements of laser power during laser processing operation [17]. Here we detail the design, operation, and measurement uncertainty and establish its traceability as a NIST primary standard for laser power above 1 kW and demonstrate 1.6% measurement uncertainty (coverage factor k = 2) for 20 s evaluation times.

2. Radiation pressure power meter design and operation

Figure 1 schematically views the RPPM from the top so that the incident and exiting laser beam travel in a horizontal plane. A highly-reflective mirror attached to the force sensor

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allows the momentum change from the reflected light to be measured as a force with minimal heat absorption. The mirror is contained in a protective housing (air shield) to screen external air currents. The RPPM takes up a cubic volume of approximately 30 cm on each side.

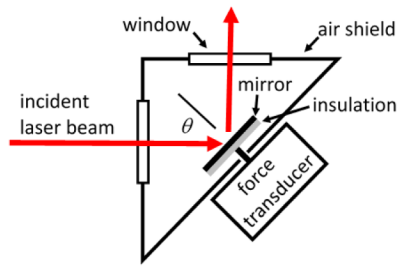

Fig. 1. Schematic of radiation pressure power meter (RPPM). The complete meter fits within a cube of roughly 30 cm on each side.

2.1 Force transducer

We use a modified commercial scale for force measurement. The scale used in this work is manufactured by Scientech, Inc., and is from the 'Zeta' series. The manufacturer and series are identified here solely to specify the details of the scale and are not in any way an endorsement of the product. Nor is the radiation pressure power meter described here identical with the Scientech product. The scale has a 100 nN readability (readout precision) and 50 mN range. It uses a "direct-load" flexure-based force sensor [18], which is capable of measuring either vertically- or horizontally-directed forces with the addition or removal of a compensating spring. The scale measures force with a null approach where a magnetic compensating force is generated to cancel out mirror deflection from the radiation pressure force. Thus, the scale measures the applied force as equal to the magnetic compensating force without need to quantify the spring constant of the apparatus.

The scale's operational details are proprietary to its manufacturer, but we have empirically characterized the relevant parameters. The rise time between the application of a force and the scale reaching its final equilibrium value to within the measurement noise is 5 s. The manufacturer calibration of the scale was performed with a calibrated 1 g mass and linearity characterization up to 20 g to specify the 100 nN readability. However, the forces generated by kilowatts of optical power correspond to much smaller masses. We have performed validating measurements of the scale by orienting it for vertical force measurement and repeatedly measuring known masses of nominal values 200 µg, 300 µg, 500 µg, 1 mg, and 50 mg (providing the forces experienced by the scale for optical powers from approximately 400 W to 104 kW). Figure 2 shows the agreement between the scale measurement and the calibrated mass values. For the range corresponding to 600 W and above, we assign an uncertainty for scale calibration as the standard deviation of the four 300 µg to 50 mg masses $u_{\text{scale}} = 0.0024$.

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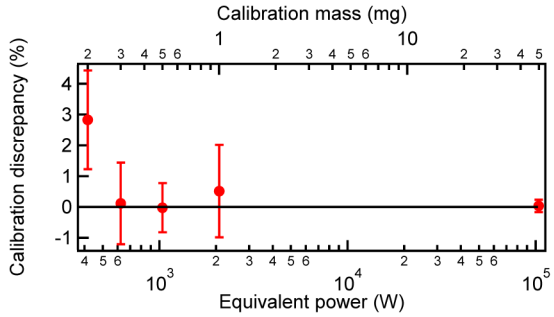

Fig. 2. Calibration discrepancy (disagreement between the mass measured by the scale and the mass's calibrated value). The mass is reported in mg and the equivalent optical power in watts. Error bars are dominated by measurement repeatability and not by mass artifact calibration uncertainty.

The force calibration has the scale in a vertical-force orientation, but laser power measurements are generally made for horizontally travelling laser beams. To verify that the scale reports the same value for a force whether horizontally- or vertically-directed, we replaced the scale's mirror with a small cylinder of magnetic steel and mounted an electric coil a few millimeters away to provide a variable magnetic force to the scale. With the electromagnet fixed to the scale housing, we rotated the electromagnet and scale simultaneously to operate in a horizontal- or vertical-force mode without changing the applied force. We recorded the electrical drive current and the force measured by the RPPM for a range of forces in both horizontal and vertical orientations. We did not need to know the scaling factor between electrical current and the resulting force since we measured only relative force changes between the horizontal and vertical orientation. The electrical current value was used to normalize fluctuations in measured force. For forces from 2.6 μN to 200 μN (equivalent of 550 W to 42.4 kW of optical power at 45°) we detected a disagreement between horizontal and vertical force measurements on the order of the measurement standard deviation itself 0.21%. We assign this as the relative uncertainty $u_{\text{H-V}} = 0.0021$.

The scale's internal magnetic compensation force is also generated by an applied current. The temperature dependence of the force generated by this current has been mitigated by the scale manufacturer through deadweight measurements performed over a 10 °C – 30 °C temperature range. Correction coefficients are implemented real time in the scale using an embedded temperature sensor. To minimize residual temperature effects, the scale is in place and powered on at least one hour prior to performing critical measurements. Laser power measurements by the RPPM are made differentially taking the difference between the laser on and laser off conditions. This "tare" operation is equivalent to that of high-precision force measurements and thermal-based optical power measurements [9].

We have also considered potential measurement errors due to air buoyancy and variations in the acceleration due to gravity g with geographic location. The relative error on our mass calibration due to air buoyancy is given by the ratio of the densities of air and aluminum (the material comprising the calibration mass). This ratio has a negligibly small value of 0.0004 and can be ignored. Variations in g do not have an effect because the sensor measures force directly (not mass). Therefore, we only require an accurate local value of g during calibration (when relating measured force to a reference mass). The radiation pressure force measured anywhere in the world does not depend on gravitational force.

2.2 Mirror and windows

Mirror choice is based on several factors:1) maximizing diameter to accommodate the largest beams to be measured, 2) minimizing mass to enable the fastest scale response times, and 3) maximizing reflectivity to limit thermal effects due to transmitted light heating the scale

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(causing measurement errors or damage). For this work we used GaAs/AlGaAs distributed Bragg reflector (DBR) mirrors grown in-house by molecular beam epitaxy on 625-µm thick, 76-mm diameter GaAs wafers. Resulting reflectivities of our various mirrors have been measured to range from 0.996 to 0.9998 for a 45° angle of incidence. The reflectivity spectrum yields usable bandwidths of +/– 20 nm. The thinness of these mirrors leads to a tradeoff between mirror flatness and light-weight operation. We interferometrically measured convex distortions as large as a 14 m radius of curvature. However, we expect this can be improved through low-stress mirror fabrication.

As can be inferred from Eq. (1), power measurement uncertainty depends directly on mirror reflectance uncertainty, which was measured to be u_{mirror} = 0.00043. Reflectance measurements were undertaken by reflecting 500 W off the mirror at a 45° angle of incidence and measuring the light transmitted through the mirror to determine the transmittance T and reflectance $R = 1-T$. This is complicated by the fact that the GaAs mirror substrate is etched (unpolished) on the back side and the transmitted light is scattered. Fortunately, for highly reflecting mirrors, large relative uncertainties in transmission or scattering translate into small uncertainties in reflectance. We estimated worst-case errors in the measured radiation force due to scattered light and found it had a negligible effect on our stated uncertainty.

It is known that semiconductor mirror transmittance and reflectance can depend on incident power through multi-photon absorption processes [19]. The DBR geometry mitigates the effect [20]. We conservatively estimate two-photon absorption to affect the reflectivity of our mirrors by less than 0.00004 for power densities as high as 10 kW/cm^2. Under our measurement conditions, this is a negligible effect.

The enclosure's entrance and exit windows are 1-mm thick, 15-cm in diameter fused silica glass coated on both sides with a dielectric stack anti-reflection coating with a reflectance of R_w = 0.0009 per side. The RPPM's power measurement must be corrected depending on whether it is reporting the light power entering the RPPM or exiting. The slight difference between the two is due to the reflectivity of the entrance and exit windows and the reflectivity R_m of the measurement mirror itself. For a power P measured by the radiation pressure power meter, the estimated power at the entrance will be $P_{entrance} = P/(1-2R_w)$ and the power at the exit will be $P_{exit} = PR_m(1-2R_w)$. These are small (< 0.1%) corrections for the mirrors and windows used.

The DBR mirror's reflectance is a function of the angle of incidence of the light but this effect is negligible compared to the cosine dependence of the radiation force projection onto the force transducer (Eq. (1)). This means that for a horizontally-directed incident laser beam, the measured force is strongly sensitive to rotational errors of the scale about a vertical axis (deviation from 45°) but weakly sensitive to rotation about a horizontal axis (deviation from 0°). Most high power lasers include a visible alignment beam which can be used to establish the 45° angle of incidence. We find we can easily achieve <0.0017 rad alignment errors, which yield a fractional standard uncertainty due to angle of incidence of u_{angle} = 0.002.

2.3 Mirror housing

The scale housing (air shield in Fig. 1) protects the mirror against noise from air currents or acoustics and shields the scale against heat delivered by the incident laser beam. The back of the mirror is fixed to a 1-mm thick thermal insulator polyetheretherketone (PEEK) of the same diameter to diffuse the heat from any unreflected light. A 6-mm thick aluminum plate barrier is situated between the scale and the mirror (the mirror shaft protrudes through a 12-mm diameter hole in the plate) to diffuse the heat link between the mirror and the scale. Residual heat transfer is dominantly along the mirror shaft, made of the glass-cloth-reinforced epoxy G10. The scale itself has a 2-mm thick layer of non-static thermally insulating foam between the inner mechanical parts and a 1.5 mm aluminum outer shell to further reduce heat transfer.

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In spite of the various heat barriers, we still observe thermal effects caused by heat from the laser beam. Upon injection of the laser light onto the mirror, the scale reads a step increase in force to the expected level within the scale's 5-s time constant, but then the reported force linearly increases with time until the laser power is turned off. We have found that this injection slope is primarily thermal in origin; due to minute distortions of the RPPM's housing with the heating by absorbed laser light. These distortions cause the scale to tilt slightly as a function of injected energy changing the nominally-zero pull of gravity. We have mitigated but not eliminated this effect through proper mounting of the housing.

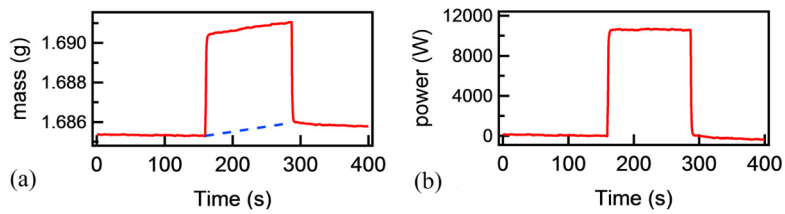

Fig. 3. (a) Raw scale response (in mass units) for a 125 s laser injection at nominally 10 kW power. The mass offset on the scale reading is arbitrary. Heating of the scale and its housing cause the upward slope visible and indicated by the blue dashed line. (b) Corrected measurement from (a) scaled to units of optical power using Eq. (1).

The slope of this residual linear drift with time is approximately 0.1%/s independent of injected power [Fig. 3(a)]. This linear drift is removed by performing a baseline measurement before and after laser power injection. The baselines are extrapolated to the point of the injection start and stop (allowing for the scale's 5 s rise and decay time). The pre- and post-injection zero-power points are used to find the slope of the scale's linear increase (dashed line in Fig. 3(a)). This slope is removed from the raw scale reading (in mass units, g), the mass reading is converted to optical power with Eq. (1) and the injection start point is shifted to be zero power. The measured power is then reported as the average of this drift-corrected laser power [Fig. 3(b)] over a time interval Δt.

As our apparatus improves, we expect to eliminate the thermal drift but might uncover other smaller sources of drift. We have investigated these potential drifts through the following means. We have operated the RPPM in a vacuum to test for convective effects. We have applied forces magnetically (rather than optically) as described in Section 2.1 to demonstrate that there is no drift in force reading due to scale self-heating. And, we have examined the possibility of static charge buildup on the mirror due to optically induced free charge. Though the 1070 nm laser wavelength is below the GaAs bandgap, some charge may be generated through sub-bandgap pathways. We expect this contribution is small particularly given the nanosecond carrier lifetimes of the material. Further, multiphoton absorption will be negligible at these kW/cm^2 power densities.

As with all precision scales, the measurement is affected by both air currents and vibration. Passive vibration mitigation (mounting the scale on vibration-dampening material) showed no improvement at the frequencies of interest. We therefore rely solely on averaging over the laser injection time in order to reduce vibrational noise effects. The uncertainty due to vibrational noise is estimated below but is best characterized by statistical methods during measurement.

3. Measurement uncertainty

The uncertainty of the RPPM laser power measurements is a combination of the inferred measurement uncertainties mentioned above ("Type B") and the statistical uncertainties dominated by vibrational noise and nonlinear thermal drifts ("Type A") [21]. The vibrational noise σ_P is independent of laser power and so its contribution to total relative uncertainty will be greatest at lower powers. A second statistical error source γ_T is the deviation from linearity

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of the thermal drift slope exemplified in Fig. 3. Errors due to the nonlinear part of this drift will be proportional to the measured power and will dominate the statistical uncertainty at higher powers. The fractional standard deviation u_{stat} for these uncorrelated statistical effects is

$$u_{stat} = \sqrt{\left(\frac{\sigma_p}{P}\right)^2 + \gamma_T^{\,2}} \ . \tag{2}$$

σ_p is the standard deviation of the RPPM's measured average laser power (over time interval Δt) in units of W, laser power P also has units of W, and γ_T is unitless.

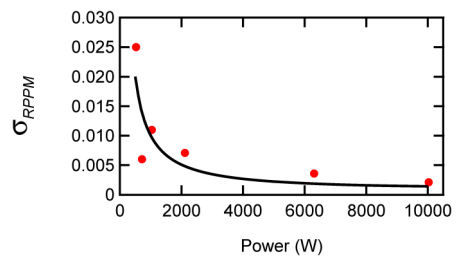

Fig. 4. Standard deviation of repeated RPPM measurements of CW laser power (circles). Solid line is Eq. (3) with σ_p = 10 W and γ_T = 0.001. The low value of the 750 W point (second from left) is attributed to quiet measurement conditions. Removing this point does not significantly alter the fitting coefficients.

To characterize these effects, we performed repeated RPPM measurements of laser powers ranging from 500 W to 10000 W with an injection duration of Δt = 60 s while monitoring the laser's power with an uncalibrated low-noise photodiode. The RPPM measurement's fractional standard deviation σ_{RPPM} is shown in Fig. 4. The low-noise photodiode signal verified that the noise was dominated by RPPM measurement noise and not true laser noise. At low laser powers, the measurement standard deviation displays a nominal $1/P$ behavior as expected and at high powers, the γ_T floor dominates. An approximation to Eq. (2) at these two extremes yields agreement with the data of Fig. 4 when σ_p = 10 W and γ_T = 0.001. The value for σ_p was determined in our laboratory environment, so for best estimates, σ_p should be measured for the specific operating environment. In general, for a power measurement averaging time Δt, the predicted statistical uncertainty will be given as:

$$u_{stat} = \sqrt{\left(\frac{\sigma_p}{P}\sqrt{\frac{60}{\Delta t}}\right)^2 + \gamma_T^{\,2}} \ . \tag{3}$$

Since σ_p represents the standard deviation of the measured power for a 60 second averaging time, the $\sqrt{60/\Delta t}$ factor allows scaling to other averaging times, assuming a normally-distributed noise. The inferred and statistical uncertainties mentioned above are summarized in Table 1 as standard uncertainties.

Table 1. RPPM measurement uncertainties.

	Type A	Type B
Scale calibration, u_{scale}		0.0024
Horizontal-vertical force equivalence, $u_{H\text{-}V}$		0.0021
Mirror reflectivity, u_{mirror}		0.00043
Angle of incidence, u_{angle}		0.002
Vibrational noise, σ_p	10 W	
Drift nonlinearity, γ_T	0.001	

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The full measurement uncertainty for an RPPM measurement of laser power is given from the parameters in Table 1. The relative expanded uncertainty $2U$ is given as the quadrature sum of the Type A and Type B uncertainties and includes a multiplicative coverage factor of 2

$$2U(P,\Delta t) = 2\sqrt{u_{scale}{}^2 + u_{H-V}{}^2 + u_{mirror}{}^2 + u_{angle}{}^2 + \left(\frac{\sigma_p}{P}\sqrt{\frac{60}{\Delta t}}\right)^2 + \gamma_T{}^2}, \qquad (4)$$

where P is the averaged laser power and Δt is the averaging interval for the measurement.

4. Validation

As a primary standard for laser power, the accuracy of the RPPM measurement does not rely on calibration to other means of measuring optical power. However, we performed a

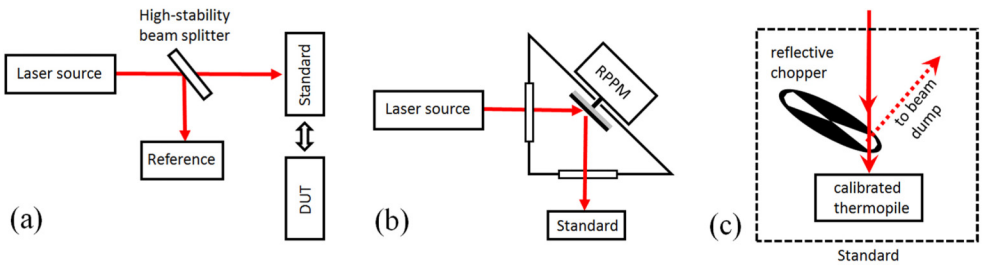

Fig. 5. (a) Traditional setup for high-accuracy laser power meter calibration. (b) Calibration scenario used for simultaneous comparison of the radiation pressure power meter. (c) expanded view of the standard used in the validation test including a reflective chopper to attenuate light before the thermopile.

measurement comparison between the RPPM and a thermopile power meter traceable to the "K-series" calorimeter (the current primary standard for high power laser measurements at NIST [22]) to validate our uncertainty analysis. The measurement setup illustrates the unique capability of the RPPM for calibration measurements. Figure 5(a) shows a conventional setup for high-accuracy calibration where the "standard" meter and the device under test (DUT) meter are measured sequentially, moving one into place and then replacing it with the other. An intermediary reference power meter must be used to measure relative changes in laser power between insertion of the standard and the DUT. In contrast, the non-exclusivity of the RPPM allows it to measure the laser power simultaneously with the standard or DUT [Fig. 5(b)]; no reference needed. In our comparison, the upper limit of the thermopile's operational range was 1000 W, so we used a calibrated reflective chopper to attenuate the beam by 97.9 ± 0.6%, which for the sake of the diagram in Fig. 5(b) is considered as a part of the standard power meter (depicted in Fig. 5(c)). Light reflected from the chopper was captured in a beam dump sufficiently removed from the rest of the experiment to avoid effects due to scattered light or residual heating, and the remaining 2.1% was transmitted to the thermopile.

A Yb-doped fiber laser provided 1070 nm CW collimated light (~30 mm diameter) in a nominally Gaussian spectrum (4.8-nm full width half maximum) for nominal power levels of 1000 W, 2000 W, 5000 W, and 10000 W. The thermopile required a 125 s injection (105 s to reach equilibrium followed by a 20 s rating period). The RPPM measured the power during the entire injection but only the last Δt = 20 s was averaged in order to compare with the thermopile. Sample power measurements are compared in Fig. 6 for nominally 2 kW and 10 kW. At 2 kW, the RPPM's vibrational noise is apparent but by 10 kW, it is minimal. In both cases, the RPPM response time advantage over the thermopile is evident. While the RPPM is capable of measuring more rapid changes in laser power, it also resolves unwanted vibration noise. We have discussed elsewhere the use of a fast (and uncalibrated) photodiode in

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combination with the RPPM to provide fast and low-noise measurements of laser power [23]. Further improvements could come from a dedicated force sensor optimized for response time.

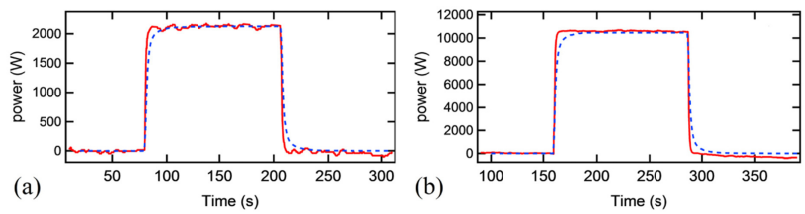

Fig. 6. Radiation pressure power meter (red solid) and thermopile (blue dashed) measurements of injected power (a) nominally 2 kW injected power and (b) nominally 10 kW.

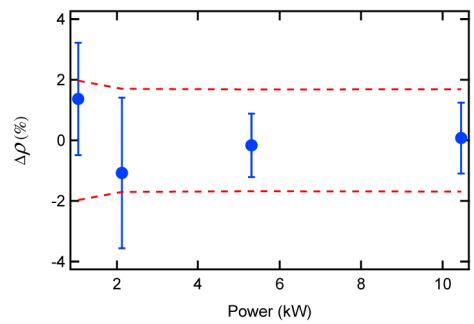

Fig. 7. Measured percent difference $\Delta\rho$ (circles) between RPPM and thermopile versus injected power. Expanded relative uncertainties are: RPPM (blue error bars) and thermopile (red dashed line).

Figure 7 illustrates the agreement between the RPPM and calibrated thermopile for the four measured powers. Each data point represents the average of 3 repeated measurements (thermopile and RPPM). The percent difference between the RPPM (P_{RPPM}) and the thermopile (P_{therm}) powers is given as $\Delta\rho = \frac{100\left(P_{RPPM} - P_{therm}\right)}{P_{therm}}$ so that zero indicates perfect agreement. The thermopile's expanded uncertainty ranges from 1.68% to 1.97%, and the RPPM expanded uncertainty includes the Type B uncertainty from Table 1 but for Type A statistical uncertainty, the repeatability (standard deviation) of these particular measurements (3 samples per power level) were used. The resulting RPPM expanded uncertainties are seen as error bars in Fig. 7 and have an average value of 1.6%.

5. Conclusion

The scale employed for this work is a modified version of a relatively inexpensive "off the shelf" instrument and it demonstrates excellent agreement with existing standards. Compared to the alternatives for high-power (multi-kW) laser power calibrations, the RPPM is highly capable and provides unique advantages as a portable primary standard allowing simultaneous power measurements rather than the traditional method of direct substitution. We have quantified and validated the sources of uncertainty for this scale-based power measurement over the range of 1 to 10 kW and expect the instrument to be operable at significantly higher power levels. While measurements up to 92 kW have been performed with this device, rigorous validations of the measurement results have not yet been possible. We expect the upper limit to measureable laser power will ultimately be due to mirror reflectivity. At some point, the non-reflected light will cause nonlinear heating of the scale which cannot be simply corrected. We have not yet determined this upper limit. The dominant

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sources of uncertainty in the measurements we have documented are vibration at low power levels and thermal heating at higher powers. Future work for this calibration method and technology will address the need for faster measurement response, smaller dimensions, and improved mirrors.

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