Validation of a compact radiation pressure power meter at hundreds of watts

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We report on the operation of a small-package radiation pressure laser power meter and detail its measurement uncertainties. Given the small package of this device and its non-destructive interaction with the laser, this power meter is attractive for real-time, high-accuracy power measurements in industrial applications. We measure laser power from 25 W to 400 W with a 260 mW/√Hz noise floor and 3.1-4.6 % expanded uncertainty. We validate our device against a calibrated thermopile by simultaneous measurements of an unpolarized 1070 nm laser and report good agreement between the two.

INTRODUCTION

In recent years, radiation pressure-based laser power metrology has developed significant interest from the metrology community. In contrast to traditional thermal and quantum techniques for measuring optical power, radiation pressure-based techniques allow for real-time, full beam, in situ monitoring. This offers a unique opportunity to embed SI traceable detectors into laser sources producing what effectively becomes a traceable source system.

Radiation pressure laser power meters have been demonstrated by multiple groups measuring power levels below 1 W [1-5] and above 500 W [6-8]; however, there exists a gap in demonstrated measurements at the few hundred watts level. This middle range in power is applicable to laser-based manufacturing processes like metal additive manufacturing. For this reason, we report on laser power measurements from 25 W to 400 W using our recently developed compact, room temperature, ambient radiation pressure force transducer.

DETECTOR DESIGN

Our compact radiation pressure power meter is diagrammed in Fig. 1. The device consists of two identical spiral flexures made from micromachined crystalline silicon (like the flexures introduced by Ryger [9]) and three fiber-coupled interferometer heads for position detection. The full package (excluding the interferometer laser, receivers, and electronics) fits within a 4 cm x 4 cm x 2 cm box.

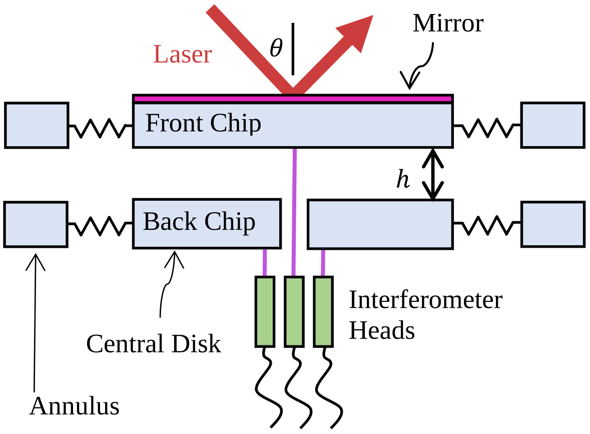

Figure 1. Cross-section view of dual-spring compact power meter (front and back chips have circular symmetry in the plane perpendicular to the page).

Upon laser illumination of the mirror coating (reflectivity greater than 0.9999), the front chip deflects relative to the back chip by Δh, where h is the inter-plate spacing determined from the position measurements of the front chip and back chips made by one interferometer tracing the front and two tracking the back (to account for off-center tilting errors). The power of the laser is directly related to the force of radiation pressure on the front chip and is calculated by balancing this optical force with the restoring spring force of the front chip:

$$P = {}^{\Delta hkc}\big/_{[2R + \alpha(1-R)]\cos\theta}\,, \qquad (1)$$

where $k = 74.5 \pm 0.2$ N/m is the calibrated stiffness of the front chip, c is the speed of light, R is the mirror reflectivity, α is the fraction of non-reflected light that is absorbed, and $\theta = 45°$ is the laser incidence angle with the mirror surface normal.

MEASUREMENTS AND UNCERTAINTY

To overcome small baseline drifting of the measurement signal from air current disturbances and differential heating of the flexure, we modulate the incident laser at 0.5 Hz with 50 % duty cycle and perform a baseline correction. Squeezed air damping between the two chips over-damps ringing of the spring and results in an exponential time constant of 30 ms on the rising edge of the measurement. Figure 2 shows the baseline corrected power measurement from our compact device. Twenty-nine modulation cycles are overlaid (blue curve) and averaged (black curve). In comparing against the calibrated thermopile, we defined the measured power as the averaged signal in a window from 0.4 s to 0.9 s. In this region, the average noise equivalent power is 260 mW/√Hz.

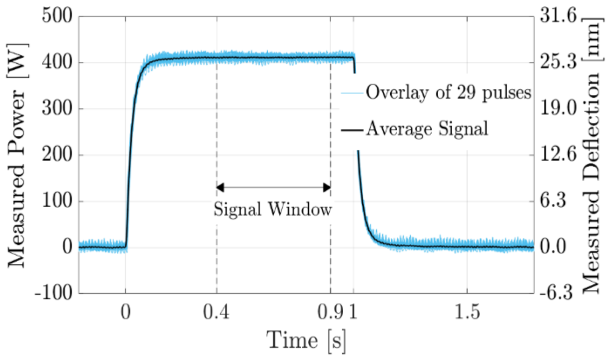

Figure 2. Measurement trace of 400 W laser modulated at 0.5 Hz with 29 cycles overlaid (blue) and averaged (black). The final power measurement is the averaged signal in the window from 0.4 s to 0.9 s.

Over a range of power levels, measured power from our device is compared to the thermopile in Fig. 3, where percent discrepancy is defined $100 \times (P^* - P_0)/P_0$, P^* is the power measured by our compact radiation pressure meter and P_0 is the power measured by the calibrated thermopile (1.2 % expanded uncertainty). Taking an uncertainty weighted average of the measured discrepancies, we find our device reads 1.6 % lower than the thermopile.

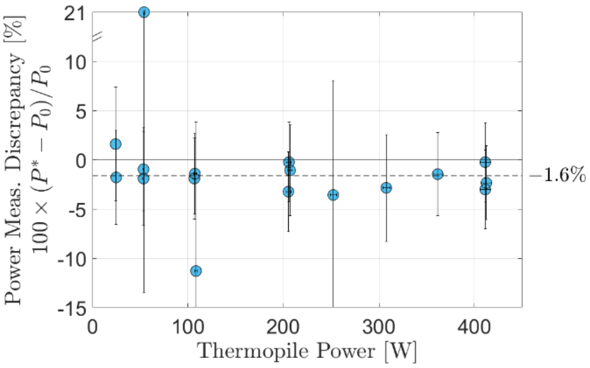

Figure 3. Percent discrepancy in simultaneous power measurements between our device and a calibrated thermopile showing agreement within expanded uncertainties (error bars represent combined uncertainty of both devices, k=2).

Fractional uncertainties of our compact radiation pressure measurements are reported in Table 1. Calibration uncertainty components (reflectance and spring constant) and set-up uncertainty components are independent of the laser power, whereas the fractional uncertainty in the measured deflection (Δh) decreases with power.

Table 1. Fractional measurement uncertainty components (k=2). Power dependent uncertainties given at two power levels as example.

Component	Dist, Type	Unc. (%)
Reflectance	rect, B	0.010
Spring constant		0.302
Fit	norm, A	0.054
Repeatability	norm, A	0.292
Alignment with gravity	rect, B	0.030
Mass decentering	rect, B	0.044
Laser incidence angle	rect, B	3.126
Laser decentering	rect, B	0.044
Interferometer alignment	rect, B	0.062
Thermal drift correction	rect, B	0.008
Meas. deflection at 25 W	norm, A	3.352
Meas. deflection at 400 W	norm, A	0.186
Combined Uncertainty at 25 W		4.626
Combined Uncertainty at 400 W		3.148

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