Radiation Pressure-based Laser Metrology Implementing an Electrostatic Force Balance

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***Abstract* — A primary standard force sensor and laser power meter are combined to achieve laser power traceability to Planck's constant by means of radiation pressure. We assess the measurement noise for approximate laser powers of 1 kW, 2 kW, and 5 kW using an electrostatic force balance as the force sensor in our high amplification laser-pressure optic (HALO). This is the first demonstration of a primary force standard in a kW-level radiation pressure-based power meter. Our initial findings over this laser power range show statistical noise levels of 0.04% - 0.13%, with lower values achieved at the higher laser power. This is consistent with previous measurements using commercial force sensors requiring mass artifact calibration.**

***Index Terms* — Electrostatic force balance, high-power lasers, laser radiometry, mass metrology, radiation pressure**

I. Introduction

High-power laser radiometers benefit when based on radiation pressure (RP) rather than thermal measurements. We describe the status of our effort to improve the measurement uncertainty and shorten the traceability path to the International System of units (SI) for RP-based measurements at kW power levels. Traditional thermal techniques achieve SI traceability through the volt, ohm, and second (defined by the constants of electronic charge, Planck's constant, and Cs hyperfine splitting frequency). For powers from 2 W to 10,000 W, calorimetric approaches typically have expanded uncertainties (k=2) near 1%. Our first RP power meter had a minimum expanded uncertainty of 1.6% above 1 kW, decreasing at greater powers with demonstrations beyond 50 kW [1].

Multiple reflection RP power meters have been recently demonstrated at 10 W and 10 kW with relative uncertainties of 2.3% (standard, k=1) [2] and 0.26% (expanded, k=2) [3], respectively. The 10-kW high amplification laser-pressure optic (HALO) [3] uses a ring mirror geometry to reflect laser light back onto the same force sensor 14 times, increasing the signal-to-noise ratio of the force measurement. This initial instance of the HALO utilized a commercial force sensor with traceability through the kilogram using mass calibration standards. In this work, this is replaced with a purpose-built electrostatic force balance (EFB), removing the need for mass artifact calibration. Furthermore, this is the first demonstration of a kW-level RP laser power meter utilizing a primary force standard with direct traceability through Planck's constant.

II. Electrostatic Force Balance Power Sensor

A. EFB Design

Radiation pressure forces F_L due to laser irradiation on a mirror, are calculated according to

$$F_L = \frac{P \cos \alpha}{c}(2R + A) \quad (1)$$

where P is the laser power, α is the angle of incidence, c is the speed of light, and R and A are the reflectivity and absorptivity of the mirror, respectively. For laser powers of 10 kW at a 45-degree angle of incidence, a single reflection delivers 47 µN of force. Since HALO forces are nominally 14 times larger, the net force is 660 µN, equivalent to 67 mg of mass. There are two types of primary standard force balances: the electro-magnetic force balance (EmFB), commonly known as the Kibble balance, and the EFB [4]. These are traceable to the definitions of Planck's constant, the speed of light, and the Cs hyperfine transition frequency. We chose an EFB based on its lower achievable uncertainty in the relevant force range [4].

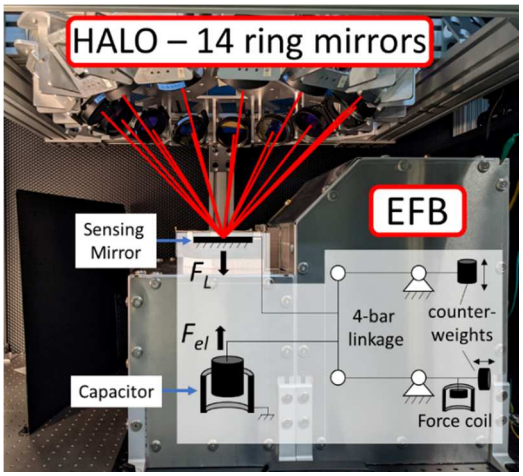

Fig. 1. Image of the EFB in the HALO system. The inset shows a diagram of the EFB mechanism including the four-bar linkage balance flexure, cylindrical capacitor, and the inductive force coil.

An EFB was designed and implemented with the HALO as shown in Fig. 1. The balance mechanism utilizes a four-bar linkage system to ensure vertical translation with minimal

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parasitic mirror rotation and corner-loading error [5]. An inverted pendulum reduces the balance stiffness, which is around 0.045 N/m. When a RP force is applied to the mirror, an electrostatic compensating force, F_{el}, is applied by a concentric-cylinder capacitor to achieve a net zero displacement. Therefore, F_L can be calculated according to the applied voltage, V, to the capacitor:

$$F_L = -F_{el} = -\frac{1}{2}\frac{dC}{dx}V^2 \quad (2)$$

The capacitance gradient, dC/dx, is determined separately using an electromagnetic coil to move the system over a range of positions while measuring capacitance; typical values of dC/dx are around 1.1 pF/mm.

B. Measurement Noise for EFB Power Measurements

Previous HALO measurements with a commercial force balance found that at 1-kW measurement noise (0.14%) dominated the combined uncertainty [3]. Measurement noise is defined as the standard deviation of the mean of laser power for multiple laser exposures under identical conditions. At 10 kW (the highest laser power previously measured with HALO), the noise improved considerably to 0.025%, making alignment errors (0.097%) dominant. By combining the EFB with HALO, we anticipate improved sensitivity and accuracy, but noise reduction techniques (control loop design and mechanical/software filters) must first be optimized. Here we present measurement noise values of the EFB-based HALO for nominal laser exposures of 1 kW, 2 kW, and 5 kW.

Laser power was measured with (1) by converting the capacitor voltage in (2) into force as a function of time before, during, and after a 50 s laser injection consisting of a 10 s power ramp up and down and 30 seconds of constant power (during which the average power was measured). A total of 81 injections were measured with results plotted in Fig. 2. Horizontal solid and dashed lines represent the mean and standard deviation of the mean, respectively. For nominal applied laser powers of 1 kW, 2 kW, and 5 kW the measured standard deviation of the means are 0.13%, 0.07%, and 0.04%. These values are comparable to those found previously [3]. We also find that the non-thermal contribution to noise is similar to other high-power RP measurements [1].

The reduction in fractional noise with increased applied laser power is consistent with the fact that the noise source is largely independent of laser power. Therefore, we expect that we should realize an additional decrease when increasing laser power beyond 5 kW. Other possibilities for decreasing noise are through improved control loop parameters, environmental noise reduction, decreased mirror size, and increasing the number of injections.

VI. Conclusion

We have successfully integrated a primary force standard into a radiation pressure-based laser power meter for measuring multi-kW lasers. This has shortened the traceability chain of the optical Watt to the kilogram by eliminating a mass calibration artifact. We have evaluated the measurement noise associated with this electrostatic force balance and have found it to be on par with the previously used commercial balance. We have also identified areas of improvement for reducing this contribution to the combined uncertainty.

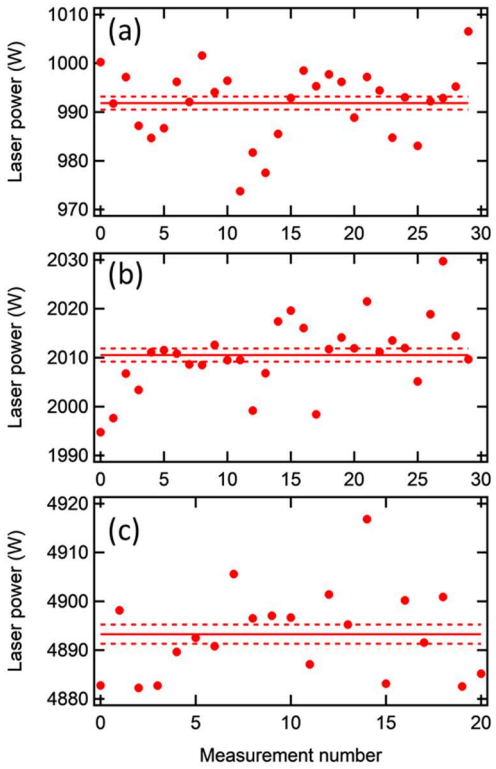

Fig. 2. EFB measured laser power for nominal powers of (a) 1 kW, (b) 2 kW, and (c) 5 kW. The average and standard deviation of the mean are the horizontal solid and dashed lines, respectively.

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