SI traceable electrostatic balance to measure laser power

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We have built an electrostatic balance that can insitu measure laser power traceable to the SI in the range of 10 W to 100 kW. The photon pressure force on a mirror attached to the balance is compensated by an electrostatic force transducer. The balance is capable of measuring the force equivalent to photon pressure from a 100 kW laser with a relative uncertainty of approximately 10^{-4}.

INTRODUCTION

In normal incident reflection, a laser beam with optical power *P* will exert a force of *2P/c* on the mirror with *c* denoting the speed of light. Measurement of this force has become a tool for measurement of laser power [1,2]. A laser beam with 100 kW optical power produces a force of 667 µN, so to achieve a relative uncertainty of 10^{-4}, the force needs to be measured with an absolute uncertainty of 67 nN. In this abstract we focus on the mechanics and electrostatics of the system. The optical layout is designed by our colleagues at the NIST Boulder laboratories [3].

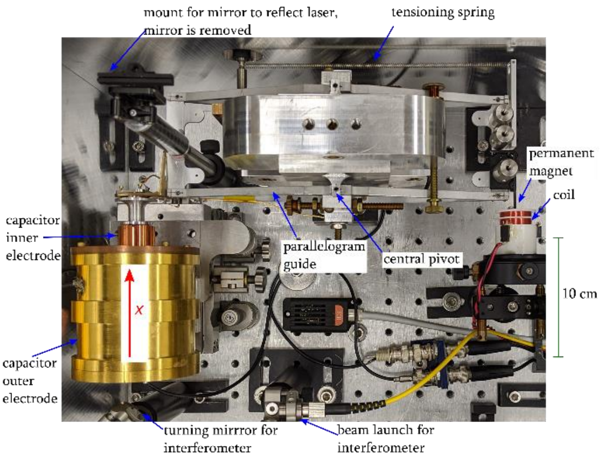

Figure 1. Photo of the electrostatic balance from the top.

A photograph taken from the top of the balancing mechanism is shown in Fig. 1. A four-bar linkage provides nearly parallel movement of the mounting platforms on the left and the right side of the balance along the x-axis (indicated by the red arrow in the photograph). The light reflects off a mirror mounted on the short arm on the left of the balance mechanism. On the same arm, the inner electrode of a concentric cylinder capacitor is affixed. The balance and outer electrode are mounted to an optical table and a commercial fiber interferometer is used to measure the position of the inner electrode. During force measurements, the balance position is held at a nominal zero position by a digital feedback controller that changes the output of a high voltage amplifier connected to the inner cylinder. The force generated by the electrostatic attraction is given by

$$F = \frac{1}{2}\frac{dC}{dx}V^2, \tag{1}$$

where *V* is the difference in potential between the cylinders forming the capacitor. The capacitance gradient (d*C*/d*x*) is calculated from measurements of the capacitance as a function of position *C(x)*. A second order polynomial $f(x)$, shown in Fig.2, is fitted to the data. The derivative of the polynomial with respect to *x* gives the capacitance gradient with an average value of -1.12 nF/m.

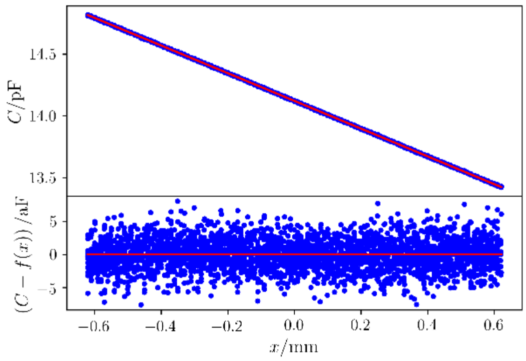

Figure 2. The measured capacitance as a function of position of the inner electrode. The lower graph shows the absolute differences of the measured values from a second order polynomial.

For the capacitance measurements, the balance position must be controlled to a specified target without using the electrostatic force transducer. Therefore, a second actuator consisting of a weak permanent magnet attached to the right mounting platform inside a stationary coil was built. The balance is controlled by supplying current to the coil using the same digital feedback control mentioned above. The dynamic range of the position control is

1.2 mm. The capacitance C was measured using a commercial LCR meter.

SENSITIVITY

The magnetic actuator gives us the opportunity to check the sensitivity of the electrostatic feedback without relying on optical power. An electrical current in a square waveform was supplied to the coil producing a force of about ± 80 nN. The feedback system maintained the balance null position by changing the voltage on the electrostatic actuator. The voltage on the capacitor cylinders is measured with a commercial voltmeter, and from it's reading and the previously measured capacitance gradient the electrostatic force was calculated. Figure 3 shows the electrostatic force for a 3.5-minute-long data taking window.

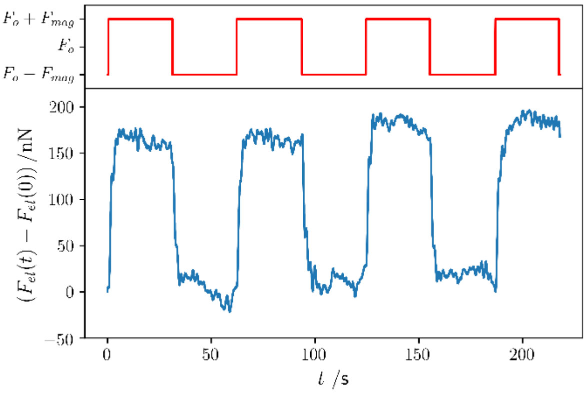

Figure 3. Compensation of the magnetic force (top) with an electrostatic force (bottom).

Figure 4 shows the amplitude of the differential electrostatic force as a function of time for a day. The mean value of the signal is 168 nN with a standard deviation of 18 nN. The data is consistent with a slight

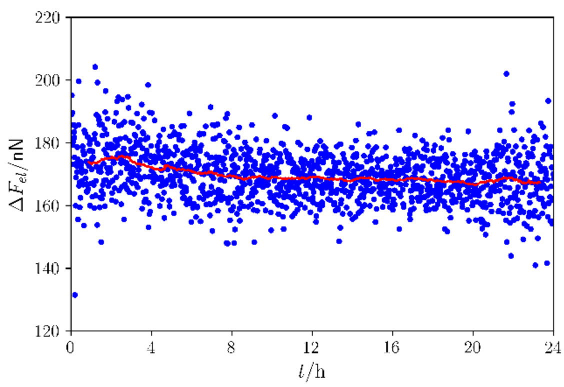

Figure 4. The measurement of the signal amplitude as a function of time (blue dots). The red line represents a moving average over 100 points.

linear drift of about -0.56 nN/h which we believe is caused by the temperature dependence of the magnetization of the permanent magnet that is used to provide the signal. The standard deviation of the signal is smaller at night, around t=12 h in Figure 4. At night time standard deviations of 7 nN are achieved. At day time, standard deviations are 50 % higher, an increase that is probably caused by vibrations in the building due to human activity.

SUMMARY AND OUTLOOK

In summary, an electromagnetic signal that represented approximately 2 x 10^{-4} of a 100 kW optical force was resolved at the 1 W level. Hence, the mechanical, electrical, and control systems are sufficient for the task. However, before the balance can be used to measure light, two important considerations need to be addressed. First, the alignment of the force axis of the balance must be made parallel to the light beam within 0.8° for a relative measurement uncertainty of 10^{-4}. Second, the thermal gradients must be managed. Any absorbed light will cause heating, which will couple into the mechanical system in two ways: (a) the elastic properties of the balance system will change causing a shift in the force required to maintain the balance at 0 and (b) thermal currents in the air surrounding the mirror can produce spurious forces on the mirror. These effects are currently under investigation.

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