Using small mass and force metrology for laser power measurement

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Abstract — Precision measurement of photon pressure by various methods has been ongoing for over a century, but without a metrological comparison between optical power and mass or force standards. The work summarized herein describes metrological methods for use of radiation pressure forces to interconvert between mass, force and laser power. These experiments have the potential to allow the accurate measurement of laser from a calibrated mass or force and vice versa in a fashion traceable to the International System of Units (SI). New results show potential improvements in both small force and laser power measurement uncertainties using these methods.

Index Terms — Photon pressure, radiation pressure, photon momentum, small force, small mass, atomic force microscopy (AFM), scanning probe microscopy (SPM), metrology, International System of Units (SI).

I. INTRODUCTION

Starting with the classic experiments of Nichols and Hull [1], the precision measurement of macroscale photon pressure forces has remained a challenge to experimentalists. The difficulty of the measurement stems from the small magnitude of the forces caused by the reflection, absorption, or scattering of light from the surface of an object. This force, F_p , can be quantified using

$$F_p = \frac{2P \cos \theta}{c} (R + A/2 + S)$$

where P is laser power incident at angle θ relative to the surface normal, R is surface reflectance, A is surface absorbance, S is a scattering factor, and c is the velocity of light. This relation can be used to merge measurements of mass, force and laser power. Several recent experiments illustrate how this paradigm can be applied to measurement of force from femtonewtons to micronewtons, and laser power from microwatts to kilowatts.

This range of force and power is important in a variety of applications. The calibration of femtonewton to piconewtons forces has been a challenge in atomic force microscopy (AFM), kilowatt laser powers are important in laser welding processes, and average powers at the watt level are employed in precision laser machining processes. Importantly, using reflection to calibrate laser power means that the calibrated laser is available downstream for use in a final application. This circumvents one of the difficulties encountered with the use of conventional detectors relying on light absorption for power measurement.

In addition, much of the current instrumentation used in laser power and small force measurement standards relies on electrical metrology to realize a derived unit. In laser power

metrology, the primary standard is a cryogenic radiometer that uses the balance between electrical power and laser to control the temperature of an absorbing surface. Likewise, the NIST Electrostatic Force Balance (EFB) and Watt Balance both use electrical measurements to obtain measurements of mass and force. The development of force-based standards for laser power measurement and vice-versa has significant implications for electrical metrology as well.

II. EXPERIMENTAL

A. Femtonewton force measurements for atomic force microscopy

Atomic force microscopy (AFM) uses a sharp probe tip to measure force at the level of nanonewtons and lower to characterize material properties at the nanometer scale. A “NIST-on-a-chip” device has been constructed that allows the use of a calibrated laser power as an internal force standard in an AFM probe [2]. Fig. 1 shows this device, and a measurement of a dynamic force such as might be used in a noncontact-AFM (NCAFM) or frequency modulated-AFM (FMAFM) experiment.

Figure 1. Microfabricated NIST-on-a-chip AFM probe. On the left is a picture of a device showing the interferometer, photon pressure force cavity and flexures. On the right is experimental data showing histograms of repeated dynamic force measurements. Fitting a Gaussian curve to the histograms shows a standard deviation of 7 femtonewtons. Excerpted from [2].

The device consists of a microfabricated fused silica parallelogram flexure attached to a proof mass at its end, and incorporates two fiber optic-based optical cavities. One is a low-reflectivity cavity that acts as a Fabry-Perot interferometer to measure the probe displacement, and the other has a gold-coated fiber mirror on the moving end where photon pressure force is exerted by reflection of the calibrated laser power. A

dynamic photon pressure force is introduced by modulating the power of the calibrated laser and measuring the resulting displacement using the interferometer. The histogram of measured forces show that forces separated by 14 femtonewtons can be clearly resolved when operating in vacuum, as in many atom-scale AFM measurements.

Because the sensor has a very high quality factor (above 1 million in vacuum), the sensor is potentially useful for frequency modulated-AFM experiments. The accurate calibration of force in these type of AFM has been an ongoing problem, and the inclusion of an internal force reference is a possible solution. The inclusion of an interferometer in the device also allows the amplitude of oscillation to be accurately determined and controlled. New results showing the imaging capabilities of these sensors will be presented.

B. Micronewton forces for measurement of kilowatt laser power

While the lower uncertainty available in laser power calibration at the milliwatt level enhances the force metrology in AFM, it is possible to use lower uncertainty available in the calibration of micronewton forces with mass artifacts to enhance calibration of kilowatt laser power [3]. For this work, a commercial balance was calibrated with mass artifacts and a high-reflectivity multilayer dielectric mirror was attached to the balance pan, as illustrated in Fig. 2. This allowed the measurement of kilowatt-scale laser power as the force applied to the balance. New work including the incorporation of the sensor into a laser welding head and the comparison to a radiometer standard will be presented.

Figure 2. Measurement of kilowatt-scale laser power using photon momentum force. The experimental schematic on the left shows the general measurement principal. Experimental data on the right shows the correspondence between the force measured at the balance and the reflected laser power. Excerpted from [3].

C. Comparison between electrostatic force balance and laser power

The NIST Electrostatic Force Balance (EFB) uses a concentric cylinder capacitor to generate a traceable force using the electrical measurements of capacitance and voltage and displacement from a laser interferometer. An experiment carried out on the EFB tests the metrological equivalence of laser power at the 1-Watt scale to the electrostatic forces measured by the balance. Representative experimental data from a nanonewton force measurement is shown in Figure 3.

Methods for performing this type of experiment accurately will be discussed. Preliminary results indicate that an order of magnitude improvement in laser power measurement precision relative to previously published work is feasible using force-based methods. A cross-check between radiometric laser power calibration and the EFB measurements will also be reported.

Figure 3. Representative data showing photon pressure force measured with the electrostatic force balance for a 1 W laser source. Force is increased by multiple reflections.

VI. CONCLUSION

This summary outlines metrological methods for interconversion of mass, force and laser power within the SI. Through measurement of photon pressure, force from femtonewtons to micronewtons (corresponding to laser power from microwatts to kilowatts) can be used as a calibration reference for measurements that have previously been difficult to calibrate, such as force measurements in cryogenic atomic force microscopes, and laser power in high-power laser welding and machining apparatus. More generally, this type of measurement may be well suited to embedded standards approaches where a calibration reference is included in a particular instrument or machine as part of the design, minimizing the need for frequent calibrations to be performed in order to achieve optimum performance while significantly decreasing uncertainties available in femtonewton-level force metrology and kilowatt-level laser power calibration. The addition of the new EFB work to the methods outlined allow SI-traceable measurement of force and laser power over a range of 12 orders of magnitude, and improve the relative precision of previously published metrology results by a factor of ten.

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