Design and calibration of a radiation-pressure based laser power meter and force sensor

Jonathan Cripe[1], Matthew Spidell[2], and Gordon Shaw[1]

[1]*National Institute of Standards and Technology, Gaithersburg, USA*
[2] *National Institute of Standards and Technology, Boulder, USA*
Corresponding e-mail address: jonathan.cripe@nist.gov

Photons impart a back-action force when they reflect from a surface. When combined with simple interferometry the radiation pressure force can be used to calibrate an optomechanical sensor. We describe the design and calibration of a radiation-pressure based laser power meter and force sensor. We propose calibrating the optomechanical sensor in two ways, with photon momentum and with the force of gravity using calibrated masses and comparing the results. Once calibrated the sensor will provide a metrological link between mass & force and laser power at the 1 W and 10 nN scales with a goal of 1 % uncertainty and provide traceability to the kilogram.

INTRODUCTION

Traditional means of measuring laser power require the light to be absorbed. For example, thermal power meters absorb photons and measure the increase in temperature. The drawback of absorptive power measurements is that one cannot directly measure the power without introducing a beamsplitter to sample the light, which in turns adds uncertainty to the measurement.

An alternative to absorptive power measurements is using radiation pressure or photon momentum. When light reflects off a mirror, the change in momentum provides a radiation pressure force given by

$$F_{RP} = \frac{2P}{c} r \cos\theta \tag{1}$$

where P is the power, c is the speed of light, r is the reflectivity of the surface, and θ is the angle of incidence with respect to the normal. By attaching the mirror to a spring-like transducer, the radiation pressure force creates a displacement, as seen in Figure 1, that can be measured using interferometry shown in Figure 2. NIST has previously developed this approach for measuring kilowatt [1] and milliwatt [2] level laser powers. Here we describe the design and calibration for measuring power on the order of 1 W and force on the order of 10 nN.

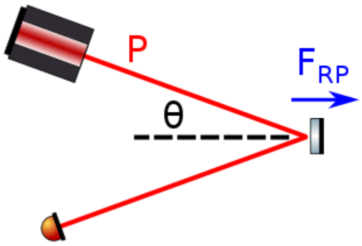

Figure 1. Schematic of radiation pressure force on a movable mirror.

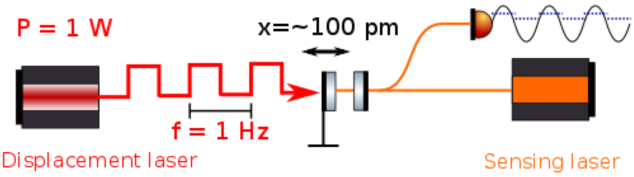

Figure 2. Schematic of radiation pressure force and displacement readout. The displacement laser causes a length change, *x*, in the Fabry Perot cavity which is read out using as separate sensing laser as a change in voltage on a photodiode in reflection of the cavity.

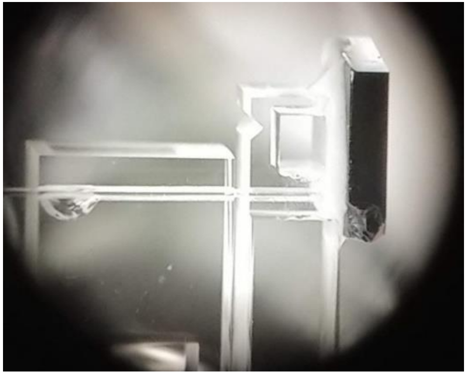

Figure 3. Image of the optomechanical sensor. The sensor consists of a reference (left) and flexible cantilever (right). A highly reflective mirror is attached to the flexible cantilever. A cleaved fiber is attached to each side to create a low finesse Fabry Perot cavity for measuring displacement.

CALIBRATION USING RADIATION PRESSURE

To calibrate the sensor using radiation pressure, we use a 1 W laser to provide a radiation pressure force which causes a 100 pm displacement of the sensor. The laser light will pass through a switch to modulate the radiation pressure force exerted on the mirror with a frequency of approximately 1 Hz. We collect the light reflected by the sensor with a calibrated integrating sphere to serve as a record of the amount of force applied to the sensor.

We measure the displacement of the sensor using a second sensing laser and a low finesse Fabry Perot cavity made up of two optical fibers. The intensity and frequency of the sensing laser is stabilized with feedback control loops to reduce the influence of intensity and frequency noise in the displacement measurement. The radiation pressure force from the displacement laser cause the cavity length to change, which in turn affects the optical interference within the cavity. We calibrate the cavity voltage signal detected in reflection by sweeping the wavelength of the widely tuneable sensing laser. Relating the calibrated force from the integrating sphere measurement to the displacement measurement allows us to calibrate the mechanical response or stiffness of the sensor and is traceable to a NIST standard laser absorption calorimeter.

CALIBRATION USING THE FORCE OF GRAVITY

A second approach to calibrating the sensor's low frequency response is to use the force of gravity from a calibrated mass to create a displacement. This method of calibration is traceable to the kilogram. By using a mass robot to load and unload the mass, we can generate a large number of repeatable trials to reduce the uncertainty of the measurements. The displacement readout is the same as described in the previous section.

Using a similar but stiffer sensor as that shown in Figure 1, we conducted 10 separate trial sets consisting of between 200 and 700 individual measurements each. Figure 4 shows a histogram of an example set of trials consisting of 300 measurements using a 200 mg mass. Using the mass robot and conducting the measurements in a stable, temperature-controlled environment allow us to achieve a population standard deviation of approximately 1 % for each set of measurements.

Having developed this method of calibration and provided a proof of principle, we will repeat the process with a smaller mass for the more flexible radiation pressure-based sensor shown in Figure 3. Calibrating the sensor using both the radiation pressure method and the mass method will allow us to compare results and create a metrological link between optical power and mass and provide a calibrated and portable sensor for measuring optical powers on the order of 1 W and forces on the order of 10 nN.

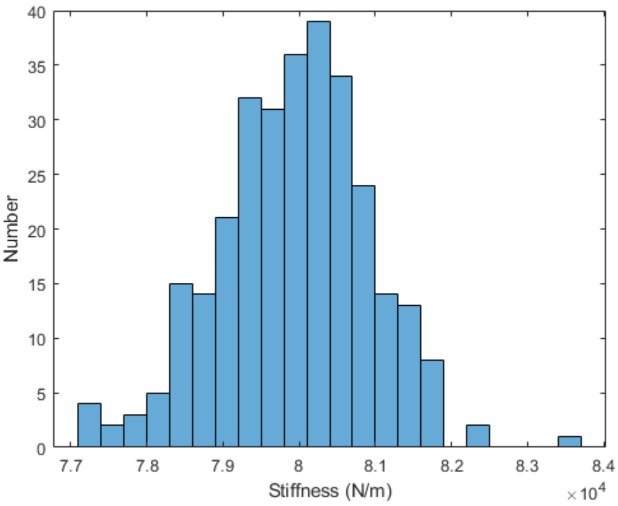

Figure 4. Histogram of results of the static stiffness using the force of gravity calibration method. The mean of the data is 79,900 N/m with a population standard deviation of 1000 N/m.

REFERENCES

1. P. Williams, et al. Portable, high-accuracy, non-absorbing laser power measurement at kilowatt levels by means of radiation pressure, Optics Express, **25**, 4382-4392, 2017.
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