

Non-Absorbing, Point-of-Use, High-Power Laser Power Meter

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Abstract: We have developed a compact, high-power laser power meter in the form of a folding mirror, precluding the need for beam splitters that considerably increase measurement uncertainty. Furthermore, our symmetric design inhibits responsivity to gravity.

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1. Introduction to radiation pressure power meters

Absolute laser power meters in the high-power regime (≥ 100 W) traditionally require slow (tens of minutes) calorimetric measurements that exclude the beam under test from use downstream [1]. With the rise in industrial use of high-power laser processing, a need has arisen to develop high-accuracy point-of-use laser power meters that do not perturb the beam for its downstream use. This would facilitate desired quality control across platforms and over time for many commercially significant applications. Recently, Williams et al. [3] introduced an alternative primary standard laser power meter [4] that measures power from radiation pressure and traces its calibration of the optical watt to the kilogram. Derived from a commercial precision scale, this radiation pressure power meter (RPPM), while allowing use of the beam for processing throughout a measurement, is yet a relatively slow and bulky system filling a cube 30 cm on a side and having a response time of 5 s.

Smaller, faster, and more sensitive devices are needed to meet the measurement requirements of commercial systems. We, therefore, have improved upon and miniaturized the RPPM for convenient integration by incorporating microelectromechanical systems technology. To this end, we devised a capacitor-based force transducer that merged the optical elements (a high reflectivity mirror) and sensing elements into a compact, 4 cm on a side, package. In doing so, we increased the sensitivity by a factor of 100, decreased the response time of the detector by a factor of 50, and mitigated static sagging errors that arise when the device orientation changes with respect to gravity.

2. The “Smart Mirror” laser power meter

Our “Smart Mirror” capacitor-based compact RPPM sensor design is depicted in Fig. 1(a). The silicon micromachined force transducer consists of an Archimedean spiral planar spring supporting a circular plate with a high reflectivity mirror (reflectance >0.999 at 1070 nm) on one side and an electrode on the back side. An identical silicon spring is placed in close proximity to the first such that the two electrodes face each other forming a variable capacitor [5]. This dual spring configuration reduces the sensor response to sagging under gravity by an average factor of 22 dB over its single spring counterpart (see Fig. 1(b)). Mitigating sensor response to changes in orientation with respect to gravity is important for operating an embedded sensor at the end of a robotic arm, i.e. where a laser weld head may be placed – a constraint the bulk RPPM cannot meet.

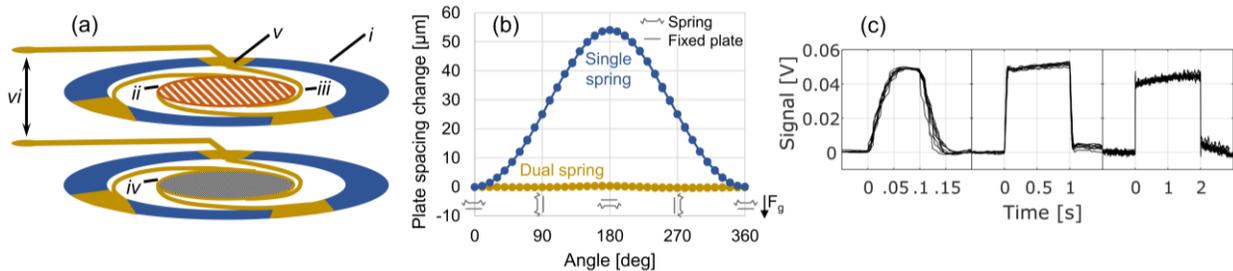


Fig. 1. (a) Depiction of dual spring sensor including mirror coated 10 mm diameter silicon disk *ii* attached to supporting silicon annulus *i* through 125 μm wide spring legs *iii* following an Archimedean spiral. Plate spacing is detected by measuring capacitance between two electrodes: *iv* and on the back side of *ii*. Electrical connection *vi* is provided through contact pads *v*. Springs are then clamped together in a mount with a plastic insulator providing a predefined spacing of 25 μm . (b) Measured change in static electrode spacing due to rotation of the sensor with respect to gravity (F_g) comparing a single spring and fixed plate electrode to the dual spring configuration. (c) Open-loop signal output of a single-spring prototype sensor upon 20 W CW 1070 nm laser injection at 45° incidence, square-wave modulated with (left to right) 0.1 s, 1 s, and 2 s periods. Each injected pulse was repeated six times and overlaid to show repeatability of sensor response to constant input. Standard deviation between repeated sensor response is 1 mV, or equal to the noise.

The spring-based sensor is integrated with capacitive bridge electronics to convert the fractional change in sensor capacitance to an electrical voltage. The bridge output is then amplified and synchronously demodulated in a digital lock-in amplifier. This approach allows suppression of $1/f$ preamplifier noise and low frequency interference. A detailed review of the electronics and sensitivity optimization for this system is outlined in Ref. [6]. In prototype tests tracing the open-loop output of a single spring sensor, we measure noise levels below $1 \text{ W}/\sqrt{\text{Hz}}$, which agree with our expected value of $0.44 \text{ W}/\sqrt{\text{Hz}}$. We also observe noise-limited repeatability of the sensor response to a modulated CW laser impulse as seen in Fig. 1(c). Furthermore, we measure an 80 ms response time in open-loop. This response time is given directly by the natural resonance of the spring filtered by a 10 Hz noise bandwidth-limiting filter.

4. Calibrating lasers with embedded RPPMs

The “Smart Mirror” compact RPPM, as studied in these sensitivity and open-loop prototype tests, demonstrates improved measurement capability over its bulk predecessor. We find a low 1% single-to-noise ratio of the open-loop readout at 100 W laser power with a response time far faster than any other absolute power meter for high-power lasers. Like any folding mirror, this small, absolute power meter can be incorporated into laser optical systems for point-of-use laser calibration eliminating the need for beam splitters or pick-off techniques, which are sources of large uncertainty. The dual spring architecture for this sensor minimizes its response to static changes in the inertial reference frame. This adds flexibility to its use by allowing the sensor to be placed in additive manufacturing (AM) and laser welding systems where the laser head will move and rotate over the build time of a part. An absolute laser power meter of this type, embedded in laser processing systems, will facilitate process qualifications suitable for any so-equipped system. Currently, each individual AM or weld tool must be qualified for a particular process. RPPM technology offers a simple method for laser power calibration. By embedding these sensors into laser heads, we may look forward to systems where “calibrated lasers” can be exploited.

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