Radiation Pressure Laser Power Meter for Industrial Laser Machining

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Abstract: Demonstration and validation of a linear radiation pressure-based high-power laser power meter is presented. To date, this device is the most promising real-time, absolute power meter for laser material processing where power monitoring is crucial.

1. Introduction

Laser additive manufacturing (AM) and laser welding are exciting technologies that promise to transform many sectors like medical and aerospace [1]; however, widespread adoption has been limited. This, in large part, is due to the technical difficulties in producing high quality parts [2]. A solution is to embed monitoring instrumentation with feedback control to maintain desirable part outcomes. For example, many researchers track the temperature of a part as a means to probe the highly dynamic laser-material interaction processes that ultimately impact part quality [3]. Even more fundamental to these interaction processes, though, is the incident laser beam power, on which all subsequent probe parameters like temperature depend. AM and laser weld tools are not instrumented with absolute, real-time, high accuracy feedback of laser power leaving operators to make assumptions about power level and stability on every build.

Currently in laser-based manufacturing, laser power is measured by either direct substitution or by in situ sampling. Direct substitution, the process of placing a calorimeter in the beam path prior to processing, is capable of high accuracy power measurements, but excludes the laser from other use. In situ sampling, typically executed with a beam splitter having a high splitting ratio that passes a small fraction of the beam to a fast photodetector, is much less accurate, but provides real-time information. Radiation pressure detecting power meters have the potential to provide both high accuracy and real-time information about beam power because they measure the momentum transfer of the laser to a highly reflecting mirror with minimal disruption to or absorption of the laser beam.

Radiation pressure-based optical power meters have been demonstration by multiple groups [4–8], but none offer a practical solution for power monitoring in laser-based machining systems, especially those implemented in industrial environments. Some have demonstrated that it is possible to simultaneously weld and measure total beam power [9]. We recently developed a flexure design that affords a more compact radiation pressure detection device while minimizing its sensitivity to orientation changes and suppressing vibration noise making it an attractive device for embedded absolute power monitoring in industrial environments. Here we present laser power measurements using this dual-spring flexure design and commercial optical interferometers. After careful calibration of the spring stiffness, we demonstrate good agreement in power measurement to a calibrated thermopile, validating our device.

2. Experimental Results

A diagram of our radiation pressure power meter based on the dual spring flexure is given in Fig. 1(a). The device package (excluding the laser, receivers, and electronics of the fiber coupled interferometers) fits in a 4 cm x 4 cm x 2 cm box. At this size, integration with laser delivery optics in a AM or laser weld system is possible.

Upon laser illumination of a the mirror (reflectivity greater than 0.9999), the front chip deflects relative to the back chip by Δh. This deflection is measured with a set of Michelson interferometers, where the difference in position of the two chips before laser injection (h_0) and after laser injection (h) defines the spacing change ($\Delta h = h_0 - h$). The force of radiation pressure is directly related to total beam power incident on the mirror. Therefore, by balancing the spring restoring force of the front chip with the radiation pressure force, we determine the laser power from $P = k\Delta hc((2R + (1 - R)\alpha)\cos\theta)$, where $k = 74.50 \pm 0.05$ N/m is the calibrated stiffness of the front chip, c is the speed of light, R is the mirror reflectivity, α is the fraction of non-reflected light that is absorbed, and θ is the laser incidence angle with the mirror.

The dual spring architecture suppresses spurious signals due to rotation of the device with respect to gravity (Fig. 1(b)) and ambient vibrations (Fig. 1(c)). By design, the back chip provides an inertial reference such that

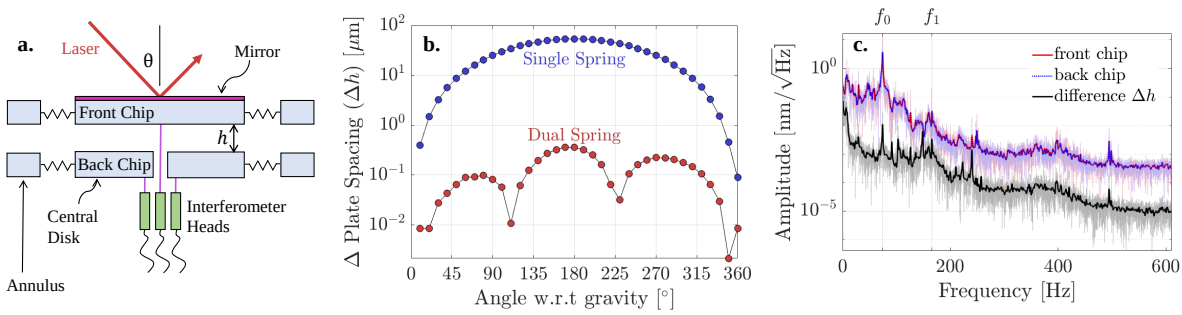

Fig. 1: (a.) Cross-section view of dual-spring flexure power meter (front and back chips have circular geometry in plane perpendicular to page). A high reflectivity mirror coats the central disk of the front chip where the laser is incident at an angle θ (in our case 45°). (b.) Response to gravity orientation change from 0°. Angle defined between plane normal of the chips and gravity vector. A fixed plate replaces the back chip in the single spring measurements. (c.) Power spectral density of vibration noise for each single chip and their plate spacing difference showing noise suppression. Fundamental out-of-plane oscillation mode is at $f_0 = 74.4$ Hz and first tilting mode at $f_1 = 165.8$ Hz.

those signals do not show up in the differential measurement of Δh. Our preliminary measurements indicate -50 dB suppression of the static signal due to rotation of the device with respect to gravity and -14.6 dB suppression of the vibration noise in a 600 Hz bandwidth. This inertial referencing is a unique value of our radiation pressure power meter that benefits the device operation in noisy industrial environments.

A sample measurement trace of a 400 W laser is given in Fig. 2(a). Using the nonexclusivity of our radiation pressure power meter, we placed a calibrated thermopile after our device to measure the power of the reflected beam. We then compared the power measured by our device to that measured by the thermopile. Percent discrepancy is calculated as $100 \times (P^* - P_0)/P_0$, where P^* is the power measured by our device and P_0 is the power measured by the thermopile. We repeated the comparison for a range of laser powers from 25 W to 400 W and found the two devices to be in agreement to within their combined expanded uncertainty (Fig. 2(b)).

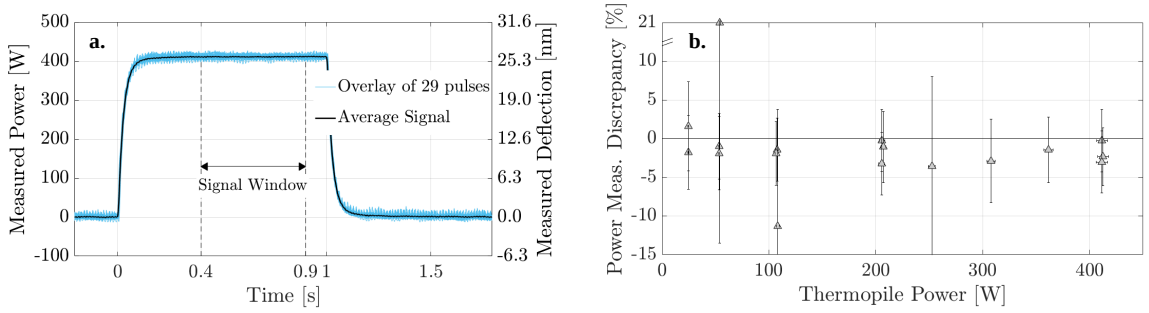

Fig. 2: (a.) Measurement trace of a 400 W 1070 nm unpolarized CW laser modulated at 0.5 Hz with the average of 29 modulation cycles. The average laser power (for comparison with the thermopile) is determined in the window from 0.4 s to 0.9 s. (b.) Percent discrepancy in simultaneous power measurements between our device and a calibrated thermopile showing agreement within the expanded uncertainties.

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