Miniature force sensor for absolute laser power measurements via radiation pressure at hundreds of watts

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Abstract

We present a small power meter that detects the radiation pressure of an incident high-power laser. Given its small package and non-destructive interaction with the laser, this power meter is well suited to realizing a robust real-time, high-accuracy power measurement in laser-based manufacturing environments. The incident laser power is determined through interferometric measurement of displacement of a 20 mm diameter high reflectivity mirror, mounted at the center of a dual element spiral flexure. This device can measure laser power from 25 W to 400 W with a 260 mW / Hz noise floor and ≤ 3.2% expanded uncertainty. We validate our device against a calibrated thermopile with simultaneous measurements of an unpolarized 1070 nm laser and report good agreement between the two systems. Finally, by referencing to an identical mechanical spring that does not see the incident laser, we suppress vibration noise in the power measurement by 14.8 dB over a 600 Hz measured bandwidth. This is an improvement over other radiation pressure based power meters that have previously been demonstrated.

1. Introduction

Radiation pressure and the force it imparts continues to interest experimentalists for its flexibility and extraordinary range from zeptonewtons with optical traps [1] to hundreds of micronewtons with high power lasers often designed for directed energy applications [2]. For continuous wave lasers with power ranging from 1 W to 100 kW, the optical forces due to laser reflection off highly reflective mirrors (5 nN to 500 μN) coincide with the lower edge of forces relevant to SI mass metrology [3]. It is in this range that a balance between optical power metrology and small mass metrology enables a metrological exchange, where SI masses can be used to calibrate optical power or SI optical power can be used to calibrate small mass measurements. In contrast to traditional techniques for measuring optical power (e.g. thermal and quantum detectors), radiation pressure based techniques allow for truly in...
situ real-time monitoring without absorption of the laser beam or need for pick-off techniques that reduce measurement precision [4]. In effect, this radiation pressure based power measurement system has the unique ability to embed SI traceability into a laser source. This traceable source does not need to be measured by an external detector because its output power would always be known absolutely. For these reasons, photon pressure based force metrology is of interest to the metrology community.

Optical power meters derived from the detection of radiation pressure have been demonstrated by multiple groups over two distinct power ranges. Demonstrations have been made at continuous wave (CW) power levels below 1 W (0.1 – 1 mW [5], 0.4 mW [6], 0.5 W [7], 0.8 W [8], and 1 W [9]) or at power levels above 500 W (500 W [10], 10 kW [11], and 50 kW [2]). In this paper, we demonstrate radiation pressure based power measurements in the unexplored middle range from 25 W to 400 W. This middle range in power is applicable to laser based manufacturing, particularly in metal additive manufacturing.

A multitude of force sensing architectures, from pendulums to various flexures, address the optical power measurement problem, each with their own pros and cons. At low power, the systems require stable laboratory environments, and even vacuum chambers, to resolve the small forces imparted by the light beams. At high powers, compact and portable systems have been developed using commercial precision scales. Some take advantage of the additive nature of radiation pressure with multiple reflections to amplify the signal, as was demonstrated by Vasilyan, et al. [8] and recently by Shaw, et al. [9]. Each system uses different techniques for calibrating force. Shaw et al. [9] directly compare the optical force to an electrostatic force reference, while Williams, et al. [11] calibrate against the gravitational force of milligram masses traceable to the kilogram.

Here, we detail the performance of a radiation pressure based optical power meter from 25 W to 400 W with comparison to a calibrated thermopile. This radiation pressure based power meter uses optical interferometry to measure the displacement of a highly reflective mirror mounted in a dual-spring flexure, which was originally presented by Ryger et al. [12] as part of a capacitive sensing-based power meter. This flexure’s dual spring architecture allows it to be used in environments with higher levels of vibrational noise and in a package that is more compact (5 cm cube) than the aforementioned radiation pressure power meters. Employing external optical interferometers to quantify the radiation force provides two key advantages over capacitive sensing in this system. First, interferometric measurements are immune to light-induced change in the capacitor fringe field caused by the photoconductivity of the silicon flexure. Second, this technique does not require us to coat the delicate flexure elements with thin metal films, which give rise to heat-induced deformations due to coefficient of thermal expansion mismatch. The interferometers used are all commercial off-the-shelf systems, and though the flexure is fabricated in-house, its simple design could easily be replicated by a microfabrication foundry and the high reflectance mirror deposited commercially.

The ability to measure laser power contemporaneously to its use compels the consideration of a radiation pressure power meter for real-time, high-accuracy power measurement. The power meter described here is the latest step to realizing this possibility. This work is
particularly relevant to the laser-based manufacturing environment (laser welding, additive manufacturing, directed energy deposition, etc.) where outcome quality is intimately related to input optical power [13]. The measurement technique described below represents a significant improvement in isolation from the types of environmental processes that pose challenges to other forms of radiation pressure metrology [11], and provides a model for future radiation pressure power metrology designs.

2. Device design and fabrication

Our radiation pressure power meter - the “Smart Mirror” - consists of two nearly-identical crystalline silicon spring elements (Fig. 1). The front chip is coated with a high reflectivity mirror and is displaced under the force of the reflected high-power laser to be measured. The back chip is used as a vibration reference to cancel environmental sources of disturbance that are common to both chips. Our signal is derived by measuring a change in the interplate spacing, that is the difference in position of the central disks of the front and back chips. A hole at the center of the back chip gives optical access to measure displacement of the front chip with a Michelson interferometer. Simultaneously, two additional Michelson interferometers measure the displacement of two off-center points at ±4 mm on the back chip. The interplate spacing is then the difference in position of the front chip from the mean of the two back chip measurements.

When a laser illuminates the mirror, the light’s momentum causes a step force acting on the front spring. A steady state is reached when the spring’s restoring force balances this radiation pressure force,

\[
k \Delta h = \frac{P}{c} \left[ 2 R(\theta) + \alpha (1 - R(\theta)) \right] \cos(\theta) \cos^2(\Phi/2).\]

The left side of this force balance equation is the spring force given by \( k \), the spring stiffness determined by mass calibration (see Sec. 3.1), and \( \Delta h = h_0 - h \), the change in interplate spacing from the initial spacing \( h_0 \) to the steady state spacing \( h \). The right side of Eq. (1) is the laser force dependent on the total beam power, \( P \), the speed of light in air \( c \), and scaling terms that depend on the mirror and orientation of the device with respect to the incident beam. The reflectance of the mirror \( R(\theta) \) depends on the angle of incidence \( \theta \) as determined by the geometry of its dielectric stack. We denote the absorptance of the mirror according to \( \alpha \), the fraction of non-reflected photons that are absorbed. Reflected photons impart two units of momentum to the mirror, while absorbed photons impart one unit of momentum, both scaled by \( \cos(\theta) \) for the projection of momentum along the direction of motion. The last term, \( \cos^2(\Phi/2) \) is a correction factor that accounts for the cone of converging rays incident on the mirror due to a focusing lens in the laser path, where \( \Phi \) is the divergence angle of the beam [14]. This is obtained by integrating the imparted force over the beam area. For a beam with uniform intensity distribution, integrating over the beam area returns a total force \( F = (2PC) \cos(\theta) \cos^2(\Phi/2) \). By numerical integration, a Gaussian distribution agrees with this closed-form solution to within 0.1% when the divergence angle (defined at the full extent of the uniform beam or \( 1/e^2 \) width of the Gaussian beam) is less than 25°.
From Eq. (1), we solve for the incident power \( P \) to convert from measured displacement \( \Delta h \) to measured laser power. All other terms in Eq. (1) are either constants of nature, depend on the setup geometry, or must be measured separately as is the case for the spring stiffness and mirror reflectance.

The chips that form the flexure of the Smart Mirror are fabricated from micromachined silicon. We start with a double-side polished, 150 mm diameter silicon wafer that is 400 \( \mu \text{m} \) thick. Both the front chip and the back chip can be patterned from a single wafer. A high reflectivity dielectric Bragg stack coating (alternating layers of SiO_2 and Ta_2O_5 optimized for light at a wavelength of 1070 nm incident at 45° with random polarization) is ion-beam sputtered on both sides of the wafer. Though the mirror is only needed on one side of the front chip, both sides are coated because the strong compressive stress of the \( \sim 9.5 \mu \text{m} \) thick dielectric stack will strain the spring and bow the central disk \[15\]. It is crucial for the two chips to be balanced in mass to adequately reject common vibrations. Therefore, to prevent mechanical nonlinearities and the risk of two chips touching, we coat both sides of the full wafer such that the compressive stress of the film is balanced on both chips. This also makes the wafer easier to handle in subsequent lithography steps. The high reflectivity coatings on both sides of the silicon substrate create an etalon that would be problematic for measuring lasers with narrow linewidth (smaller than the free spectral range of the etalon, 0.8 nm in our case). In such cases, antireflection coatings of similar material and thickness can be used on all surfaces but the laser-facing front chip. Our laser, however, is quite broad, with a linewidth of 4 nm. Along with the loss of 1070 nm light in the silicon substrate, this leads to a negligible change in the effective reflectivity of the front surface mirror.

After the mirror coatings, small pads of gold are electron-beam evaporated and patterned by the lift-off method. These pads increase the reflectivity of the back surfaces of each chip for the 1550 nm wavelength interferometer beams used to measure deflection of both central disks. Next, the mirror coatings are reactive ion etched to expose the silicon substrate, leaving only 20 mm circular islands on the central disk of each chip. The final lithography step is deep reactive ion etching of the silicon substrate, cutting three Archimedean spirals that form three-legged spring supports of each central disk. This deep reactive ion etching step also cuts the access hole in the back chip, five smaller holes in the front chip to balance mass, three alignment holes on the annulus of each chip, and the perimeter of each chip, thus cutting them out of the wafer. Cross-section views of the two chips with dielectric and gold films are shown in Fig. 2.

Once the chips are released and washed, we bond one front chip to one back chip with several droplets of thermally conductive epoxy. The epoxy cures overnight while a weight forces the chips together. Removable Kapton flags are used to define the chip separation of 50 \( \mu \text{m} \). Lastly, we use the same epoxy to rigidly mount the back chip of the bonded pair to an aluminum plate that can be easily bolted to standard optical mounts (see Fig. 2).

### 3. Measurements

We report measurements from a sample Smart Mirror with two different commercial interferometer systems to demonstrate the performance of this device as a power meter for a
high power 1070 nm wavelength laser. To our knowledge, this is the first report of radiation pressure based measurements of laser power between 20 W and 500 W with comparison to a calibrated thermopile. The mirror coating used in this paper was deposited commercially with a quoted reflectivity greater than 0.9999. We therefore use a reflectivity value of 0.99995 with rectangular bounds at 0.9999 and 1.0. Throughout this paper, we will consistently express the standard error of a fit parameter preceded by “±” and use the usual expanded uncertainty notation \( U = k u \) to indicate when a coverage factor, \( k \), is applied. Specifically \( k=2 \) reflects an interval having a level of confidence that is approximately 95% (a “2\(\sigma\)” uncertainty when the distribution is normal).

3.1. Spring stiffness

The spring constant of the front chip is a critical scaling factor in the conversion from spring displacement to measured power and must be measured accurately in order to obtain reliable power measurements. We calibrate the spring stiffness by placing a series of masses from 6.7 mg to 144.8 mg on the central disk of the front chip and measuring the vertical displacement due to the gravitational force interferometrically. The upper limit of this range is determined by the maximum deflection the silicon spring withstands before the spring stiffness is clearly nonlinear. The measurement is performed on the bonded pair of chips and displacement \( \Delta h \) of the front chip is measured through the access hole in the back chip. Alignment to gravity is determined with a bubble level.

By linear regression we solve for \( b = 1/k \) in the relation \( \Delta h = bmg \) (Fig. 3), where \( m \) is the mass of a small object as measured with a precision scale and \( g \) is gravitational acceleration. We weigh each mass multiple times and calculate the mean and standard deviation of each of eleven objects. For example, the mean mass of the lightest object is 6.7 mg, with a standard deviation of 0.001 mg, which corresponds to a fractional uncertainty of 0.03% (\( k=2 \)). The fractional uncertainty in the deflection measurement is significantly higher, at 13% (\( k=2 \)). Across all the masses used, the uncertainty in the mass measurements is orders of magnitude smaller than the uncertainty in the deflection measurements. We are, therefore, able to use a simple linear regression model where the uncertainty in the mass measurements is not propagated; this is in contrast to an error in a random variable regression model. We find the spring stiffness of our device is 74.49 ± 0.02 N/m (from 598 measurements).

3.2. Signal response

Knowing the spring stiffness and mirror reflectance and applying Eq. (1), we evaluate the performance of this Smart Mirror using laser injection. A 400 W laser modulated at 0.5 Hz with 50% duty cycle illuminates the mirror at 45°. The Smart Mirror response to the pulse train is plotted in Fig. 4 (with 29 cycles and each modulation period overlaid) showing excellent repeatability. Fitting an exponential of the form \( P_0(1 - \exp(-t/\tau)) \) to the rising edge of the average signal of 29 pulses, we find \( P_0 = 410.3 \pm 0.1 \) W and \( \tau = 30 \pm 0.1 \) ms. Air between the two closely-spaced chips acts as a strong dampener, so we see no ringing of the spring. This is known as the squeeze-film effect \([16]\). The squeeze number of our system is 0.05 \( \ll 1 \), indicating the trapped gas is not compressed and viscous damping of the air dominates over elastic damping as the gas slowly leaks out from between the two chips. From the fit time constant of 30 ms, we determine the damping ratio of the system is 7 and
the force damping coefficient is 2.24 kg/s, which agrees within a factor of 3 with the circular plate squeeze film damping model in Ref. [16] (Eq. 3.31) where the plates are not perforated as is the case for our device.

Each laser injection lasts 1 s with a measurement window defined between 0.4 s and 0.9 s. The amplitude of each pulse signal is defined as the average signal over this window and the noise (deviation from average signal) root mean square is calculated. The RMS noise of the 29 pulse average is 4.3 W (the RMS noise of a single pulse is ≤ 7.6 W), describing an RMS displacement noise of 0.27 nm. After about 5 pulses, or 10 s of measurement time, the noise on the averaged signal is dominated by continuous oscillations of the springs (driven by ambient sources of vibration) and is non-Gaussian; thus, the improvement from averaging 29 pulses is only a factor of 0.5 rather than $1/\sqrt{29}$. A low-pass filter with cutoff frequency at 277 Hz was applied in the data collection; therefore, the average noise equivalent power of these measurements is 260 mW / $\sqrt{\text{Hz}}$ (maximum of 459 mW / $\sqrt{\text{Hz}}$).

3.3. Noise sources

3.3.1. Vibrations—The dual spring architecture reduces vibration noise. We confirm this by analyzing the spectral density of displacement noise for each of the individual springs and compare with the spring difference (Fig. 5). Again, a low-pass filter was applied to the data with a cut-off frequency of 277 Hz and the data sample frequency was 1220.7 Hz. The fundamental resonant frequency of each spring in our system is at 74.4 Hz, this motion corresponds to out-of-plane displacement of the central disk with respect to the annulus and a clear resonant peak marked by $f_0$ can be seen in Fig. 5. Excited by only background sources of vibration noise (e.g. chillers, fans in power supplies, etc.) the displacement amplitude of a single chip at $f_0$ is about 17 nm / $\sqrt{\text{Hz}}$. This compares to the amplitude of the difference signal at this frequency of only 0.03 mm / $\sqrt{\text{Hz}}$. By taking the ratio of the single chip amplitude and the difference amplitude, we calculate the noise suppression factor of −27.5 dB at $f_0$. The next dominant oscillation mode is a tilting mode, where we may expect the common mode rejection to perform less well due to the location differences of our interferometer probes. This tilting resonant frequency is at $f_1 = 165.8$ Hz. Here, the noise suppression factor is −9.1 dB. Over the full range of measured frequencies, the total ambient vibration noise suppression factor of the dual spring architecture is −14.8 dB.

3.3.2. Thermal effects—When making radiation pressure measurements, it is important to evaluate the significance of radiative heating. To confirm that the deflections we measure are due to radiation pressure and not a result of heating of either the mirror, the springs, or the air around them, we completed two tests. Mirrorless chips identical to those used in our high power laser tests were fabricated without the high reflectivity mirror coatings. The bare polished silicon then serves as a high absorbing, low reflecting component. We directed 500 mW of optical power from a 1064 nm laser onto the mirrorless chip and measured 165 mW of reflected power indicating that 335 mW of power was absorbed by the silicon. Figure 6 shows the measured deflection of this mirrorless chip during a 440 s laser injection. Radiation pressure deflection at this power level for the bare silicon reflector is well below detection levels at 14 pm. Therefore, the deflection of Fig. 6 is completely due to heating effects.
Thermal effects in our power measurements are identified by a slow exponential drift. This is due to temperature differentials in the mounted structure. By averaging the results of four of these low-power mirrorless injections, we find the thermal drift time constant is 329 ± 2 s and estimate 17 mW/s initial drift rate per milliwatt of absorbed optical power (worst case as the system thermalizes). This thermal drift is present in all Smart Mirror measurements.

With the 0.99995 reflectivity mirror and 400 W input power, 20 mW of power is absorbed by the device. From the results of Fig. 6, this should contribute a drift rate of approximately 340 mW/s. We remove this slow drifting from the signal data by modulating the injecting laser and subtracting off a moving average of the raw data (this was done in Fig. 4, for example). The averaging window is set to two times the laser modulation period, to not affect the step height measurement. This slow drift correction also removes some of the slowly varying disturbance due to air currents.

3.3.3. Angular dependence—We further confirm that the signal measured in Fig. 4 is radiation pressure by demonstrating the cosine dependence of the signal on laser incidence angle with respect to the mirror. If we plot the measured power over a range of incidence angles and omit the \( \cos(\theta) \) term in Eq. (1), the resulting curve is well fit by a cosine (Fig. 7), with the amplitude as the only free parameter.

4. Validation

We validate the Smart Mirror measurements by simultaneously measuring power with a calibrated thermopile as reference. A schematic of the measurement setup is shown in Fig. 8. A lens prior to the Smart Mirror reduces the laser beam size to under-fill the Smart Mirror mirror and increases the beam size at the thermopile to fill the absorber area. An aperture stops scattered light from illuminating outside the mirror area. An anti-reflection (AR) coated window can be placed between the Smart Mirror and thermopile to seal the air current reducing box; however, it is usually left out. When the window is in place, the thermopile power measurement is scaled up to account for 0.24% power loss due to both surfaces of the AR coated window. The air current reducing box is oriented such that the window is not perpendicular to the optical path and back reflections are directed away from the Smart Mirror.

4.1. Linearity

We test the linearity of the Smart Mirror by fitting a straight line to the Smart Mirror power as a function of thermopile power. In its calibration procedure, the thermopile response is linearized and therefore provides a reliable reference of linearity to within its expanded uncertainty. A separate linear fit is calculated for three separate measurement series and fit residuals, reported as percent relative to the thermopile measured power, are given in Fig. 9. These residuals are randomly dispersed around zero with no clear non-linear trend. A weighted average of these residuals, where \( w_i = 1 / u_i^2 \) is the weighting factor of the \( i \)th measurement and \( u_i \) is the combined uncertainty of the measurement, is used to determine if a bias is present in the measurement. We calculate a residual baseline of 0.4%, which is small relative to the measurement uncertainty. Thus, the Smart Mirror shows good linearity over the range 25 W to 400 W.
4.2. Calibrated comparison

Next, we evaluate the accuracy of the Smart Mirror power reading by again comparing with the calibrated thermopile. The results of the comparison are reported in Fig. 10. Percent discrepancy is defined as $100 \times (P_{SM} - P_{Th})/P_{Th}$, the measured power of the Smart Mirror $P_{SM}$ minus that of the thermopile $P_{Th}$ normalized by the thermopile power. Taking the weighted average of all measured power levels, the average percent discrepancy is $-1.6\%$. The combined expanded uncertainty of each of the Smart Mirror power measurements in Fig. 10 is between 2.8\% and 34\% depending on exact measurement conditions and laser power level (see Sec. 5.). With the 1.2\% expanded uncertainty of the thermopile detection and 0.02\% added expanded uncertainty of the window transmittance when used, we can confidently say the $-1.6\%$ discrepancy between these two devices is well within their respective uncertainty bounds. A detailed discussion of the uncertainty in the Smart Mirror measurements follows.

5. Measurement uncertainty

A full discussion of the uncertainty in the Smart Mirror power measurements is provided to give a complete understanding of these measurements. In evaluating this uncertainty, we define two sets of uncertainty components. The first is the power dependent statistical uncertainty in each measurement of the spring deflection. Written as a fractional uncertainty, $u_{\Delta h}(P_{Th}) = \sigma_p / (\Delta h N_p)$ is calculated from the standard deviation, $\sigma_p$ of $N_p$ pulse measurements having a mean deflection value of $\mu_{\Delta h}$. This statistical uncertainty is plotted in Fig. 11. The calibrated comparison data reported above were collected over three measurement series, where the first two differ only by the inclusion of the AR coated window located between the Smart Mirror and the thermopile (see Fig. 8). In Fig. 11, these three measurement series are denoted separately to highlight differences in measurement noise. In Series 1, with and without the window, the Smart Mirror mount was placed on 25 mm thick vibration dampening foam and deflection measurements were collected with a set of interferometers having a resolution limit of 1 pm. On the other hand, in Series 2, the Smart Mirror mount was rigidly bolted to the optical table and deflection measurements were collected with a set of interferometers having a resolution limit of 1 nm. These system differences explain the fractional uncertainty differences in Fig. 11.

The second set of uncertainty components come from the calibration of the Smart Mirror device and from the experimental conditions. These are added in quadrature to the power dependent fractional uncertainty $u_{\Delta h}(P_{Th})$ to obtain the combined fractional uncertainty:

$$u_c(P_{Th})^2 = u_{\Delta h}(P_{Th})^2 + u_R^2 + u_k^2 + u_{kr}^2 + u_{mc}^2 + u_a^2 + u_{ga}^2 + u_{ia}^2,$$

(2)

where $u_R$ is the fractional uncertainty in the mirror reflectance, $u_k = s_k/k$ is the fractional uncertainty in the fitted spring stiffness, $s_k$ is the standard error on the spring constant fit parameter $k$ obtained from the linear regression in Sec. 3.1, $u_{kr} = \sigma_k / (\mu_k N_k)$ is the repeatability uncertainty in spring stiffness from $N_k$ independent measurements with mean value $\mu_k$ and standard deviation $s_k$, $u_{ga}$ is due to the uncertainty in alignment with gravity in...
the stiffness calibration, $u_{mc}$ is uncertainty from placing the mass off center on the central disk of the chip during the stiffness calibration, $u_\theta$ is the uncertainty due to misalignment of the laser beam angle of incidence with respect to the Smart Mirror mirror, $u_{bc}$ (like $u_{mc}$) accounts for decentering of the laser beam with respect to the central disk of the front chip, $u_{ia}$ is the uncertainty due to pointing errors of all interferometer beams, and $u_t$ is a small uncertainty contribution from imperfect correction of the thermal drifting. The uncertainty of scaling factors in Eq. (1) $\alpha$ and $\Phi$ have negligible effect on the total uncertainty and are not specified in the budget that follows. The expanded combined uncertainty is $U(P_{Th}) = 2u_C(P_{Th})$ (k=2).

5.1. Uncertainty budget

Fractional uncertainties reported in Table 1 are specific to each measurement series. In all measurement series, the same bonded pair of chips are used, thus the component uncertainties pertaining to the device calibration are common to all measurements. In Series 1, the vibration dampening foam between the Smart Mirror mount and the optical table prevented us from securing the Smart Mirror in place. For this reason, we assign a larger uncertainty to the laser angle of incidence for these measurement series ($\pm 0.9^\circ$) to cover the possibility that the device moved in testing. We speculate that an unintentional angular displacement may be responsible for the discrepancy between the windowed and non-windowed Series 1 measurements, which should be identical otherwise. In Series 2, the Smart Mirror was rigidly bolted to a high quality rotation stage and extra care was taken to accurately align the detector to the incident beam. Its angle of incidence uncertainty is therefore lower; however, vibration and interferometer noise in the interplate spacing measurement (Fig. 11) of this series is higher. Interferometer alignment uncertainty describes the error that arises when the interferometer laser is not aligned with the direction of motion of the two springs. These uncertainty values are bounded by the alignment needed to obtain a strong interference signal.

The combined expanded uncertainty (k=2) of Series 1 is roughly 3% over the measured power range, while the combined expanded uncertainty of Series 2 ranges from 15% at 100 W to 2.8% at 400 W (34% at 50 W). With a better mounting technique that ensures accurate alignment of the Smart Mirror to the high power laser being measured and decouples the device from environmental vibrations, we may expect lower combined uncertainty. Designing an appropriate mount to reach these uncertainty levels would require a vibration isolation component (especially near the spring resonance of 74.4 Hz - an elastomer isolator may suffice [17]) with well defined tip-tilt control to align with the laser axis. Another way to reduce system uncertainty is to operate at a smaller angle of laser incidence with the Smart Mirror mirror; however, 45° incidence has the benefit of ease of use and optical system integration.

6. Conclusion

We report the performance of a radiation pressure detecting power meter for 1070 nm unpolarized laser measurements in the range of 25 W to 400 W. A dual-spring crystalline silicon flexure design is used in this device, with external optical interferometric detection of
position. By concerning ourselves only with the change in interplate spacing in this dual spring flexure design, we passively decrease vibration noise in the signal by 14.8 dB over 600 Hz bandwidth. Absolute force calibration of this detector is carried out by comparison to known gravitational forces from a set of masses. The stiffness of our system is found to be 74.5 N/m with expanded uncertainty of 0.2 N/m (k=2) including repeatability and Type B uncertainty components. Our optical force detector is over-damped with an estimated damping ratio of 7 and an exponential time constant of 30 ms, which is orders of magnitude faster than the heat induced drift time constant we measure of 330 s. This slow thermal drift in the signal is removed from the data by modulating the laser source at 0.5 Hz and subtracting a moving average of the data with window width of 4 s. We confirm the signal measured is from radiation pressure of the incident laser (and not radiometric effects) by empirically showing the cosine dependence of the signal with incident angle and by observing no fast signal when absorptance dominates over reflectance (as in a mirrorless system illuminated with a low power laser). In comparisons with an in-line linear thermopile, we report good linearity of our detector by evaluating linear fit residuals. In calibrated tests, we measure an average of −1.6% discrepancy between the power reported by our Smart Mirror and the power reported by the thermopile. The measurement uncertainty for the Smart Mirror is defined and the combined expanded uncertainty is about 3% (k=2). The thermopile measurement uncertainty was 1.2%. Thus, the discrepancy between the Smart Mirror and thermopile is well within their combined uncertainty.

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Fig. 1.

a. Depiction of Smart Mirror power measurement device where the laser is incident on the mirror of the front chip at an incident angle $\theta$. Each chip consists of a central disk (on which the mirror is deposited), a three-legged spring support, and an outer annulus for mounting. b. Outside view of chips drawn with dimensions. After bonding, these faces are visible as the front and back sides of the device.
Fig. 2.
Fabrication layers represented by cross-sections of each chip architecture (not drawn to scale). Photograph of a Smart Mirror device on the right.
Fig. 3.
Spring stiffness is calculated by linear regression of interferometrically measured deflection (vertical axis) due to the gravitational force of calibrated masses placed on the central disk of the spring (horizontal axis). Dashed lines indicate fit prediction bounds with 95% confidence. Data points are the mean deflection for each mass with $2\sigma$ for the error bars.
Fig. 4.
Smart Mirror measured power of 400 W laser modulated at 0.5 Hz with 50% duty cycle. Averaged RMS noise is 4.3 W in the signal window, or 260 mW / Hz.
Fig. 5.
Vibration noise suppression with dual spring architecture. Spectral density of displacement noise measured by three interferometers as outlined in Sec. 2. Ambient vibrations excite the fundamental oscillation mode of each chip, $f_0 = 74.4$ Hz, which is suppressed by a factor of $-27.5$ dB in the difference curve. For the tilting mode, $f_1 = 165.8$ Hz, the suppression factor is $-9.1$ dB.
Fig. 6. Deflection ($\Delta h$) of a mirrorless bonded pair of chips as a 500 mW (335 mW absorbed) 1064 nm laser illuminates the bare silicon (on at 0 s, off at 440 s). Exponential time constant is slow ($329 \pm 2$ s). Initial drift rate is 17 mW/s per milliwatt absorbed.
Fig. 7.
Without correcting for the incident angle of the laser beam on the surface of the Smart Mirror mirror, we confirm the cosine dependence of measured power with incident angle by injecting a 500 W laser at a variety of incident angles. Dashed lines report prediction bounds of the cosine fit with 95% confidence and error bars report the (k=2) uncertainty in each power measurement.
Fig. 8.
Comparison setup used to relate the Smart Mirror (SM) power measurement to a calibrated thermopile, track SM linearity, and validate the power measurement.
Fig. 9.
Smart Mirror response is linear with incident power as determined by a down-stream thermopile. Deviation from linearity is calculated from residuals of a linear fit with 0 W intercept to Smart Mirror power versus thermopile power. These deviations are then normalized by the thermopile power. Marker colors indicated independent measurement series, where a unique linear fit is derived for each series. Dashed line marks the weighted average of all deviations. Error bars report combined Smart Mirror and thermopile expanded uncertainties.
Fig. 10. Discrepancy between the Smart Mirror power measurement and simultaneous calibrated thermopile power measurement normalized by thermopile power. The weighted average discrepancy of all measurements is $-1.6\%$ (dashed line). Error bars report combined Smart Mirror and thermopile expanded uncertainties.
Fig. 11. Fractional uncertainty in interplate spacing measurements. Placing a window between the Smart Mirror and thermopile increased the statistical measurement uncertainty slightly. More significant was the exclusion of vibration dampening foam and use of interferometers having worse displacement resolution, leading to an order of magnitude difference between Series 1 and Series 2.
Table 1.
Smart Mirror fractional measurement uncertainty components. Power independent components are added in quadrature with power dependent uncertainties in Fig. 11 to obtain the expanded combined uncertainty for each power level ($U = 2u_C$).

| Uncertainty Component | Distribution | Type | Series 1 (%) | Series 2 (%) |
|-----------------------|--------------|------|--------------|--------------|
| Reflectance ($u_R$)   | rectangular  | B    | 0.005        | 0.005        |
| Spring Constant Fit ($u_k$) | normal     | A    | 0.027        | 0.027        |
| Spring Constant Fit Repeatability ($u_{kr}$) | normal | A | 0.146        | 0.146        |
| Alignment with $g$ ($u_{ga}$) | rectangular | B | 0.015        | 0.015        |
| Mass Decentering ($u_{ma}$) | rectangular | B | 0.022        | 0.022        |
| Angle of Incidence ($u_\theta$) | rectangular | B | 1.563        | 0.112        |
| Beam Decentering ($u_{bk}$) | rectangular | B | 0.022        | 0.022        |
| Interferometer Alignment ($u_{ia}$) | rectangular | B | 0.031        | 0.015        |
| Thermal Drift Correction ($u_t$) | rectangular | B | 0.004        | 0.004        |
| Interplate Spacing ($u_{\Delta h}$) at 107 W | normal | A | 0.380        | 7.455        |
| Interplate Spacing ($u_{\Delta h}$) at 411 W | normal | A | 0.093        | 1.405        |
| $U(P_{Th} = 107\ \text{W})$ (k=2) |                |      | 3.235        | 14.92        |
| $U(P_{Th} = 411\ \text{W})$ (k=2) |                |      | 3.148        | 2.837        |