OPTOMECHANICAL MOTION SENSORS

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INTRODUCTION

Low-loss mechanical oscillators are a unique interface to observe the physics governing the dynamic interactions of light with matter and its environment, yielding sensors of unprecedented resolution. The reflection spectrum of an optical cavity is exquisitely sensitive to motion-driven frequency changes which, when combined with mechanical oscillators, can provide outstanding observation resolution and bandwidth.

Furthermore, a coherent low-noise optical source coupled to a mechanical oscillator provides an optimal observable in its wavelength/frequency, which faithfully reflects the motion of a test mass and the underlying phenomena driving it. The displacement-resulting frequency changes of the light are directly traceable to the International System of Units (SI), resulting in the decisive measurement accuracy capabilities coveted in reference standards.

Based on this premise, we have directed efforts to the development of high sensitivity optical microcavities for metrology applications. These cavities consist primarily of fiber-optic micro-mirrors that we have merged with low-loss mechanical oscillators. The main goal of these efforts is to build highly sensitive traceable displacement, force, and acceleration sensors.

This article presents our results on novel and highly compact optomechanical devices that offer both high sensitivity and direct SI-traceability, outlining a path for reference measurements. We show our results on low and high finesse Fabry-Pérot fiber micro-cavities, and the achieved measurement performance.

FIBER-CAVITY DISPLACEMENT SENSOR

Our optical detection scheme is based on two fiber-optic facets facing each other[1, 2] and separated by a short distance, typically between 40–200 μm.

We have further developed these displacement sensors into two types: (a) a low-finesse fiber cavity consisting of two flat fiber end mirrors, and (b) a high-finesse plano-concave fiber cavity with highly reflective dielectric coatings as depicted in Figure 1(a) and (b), respectively.

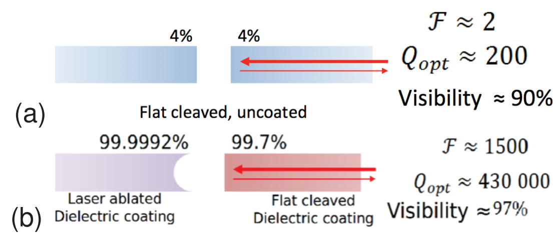

FIGURE 1. Schematics of fiber-optic Fabry-Pérot cavities of (a) low and (b) high finesse.

While the high-finesse cavity certainly provides greater sensitivity to cavity length changes, the dynamic range is significantly lower than the low-finesse counterpart due to its narrow linewidth.

We have been able to achieve displacement sensitivities at levels of $10^{-14}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ with low-finesse fiber sensors. High-finesse fiber sensors have demonstrated displacement sensitivities at levels of $10^{-16}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Figure 2 shows typical displacement sensitivities that can be measured with these systems in our laboratory.

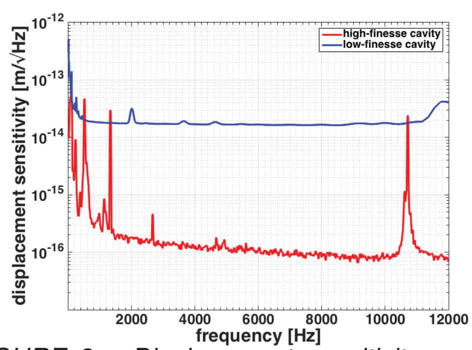

FIGURE 2. Displacement sensitivity measurements with low (blue) and high (red) finesse fiber-optic Fabry-Pérot cavities.

Fiber-based Fabry-Pérot micro-cavity sensors operating in reflection have been incorporated onto fused-silica mechanical oscillators that are equipped with collinear V-grooves as alignment canals for the fibers, as shown in Figure 3. As a reference on the physical dimensions of these systems, the thickness of the optical fiber is 125 μm, and cavity lengths are in order of 100 μm. The upper row is a high-finesse cavity with a dielectrically coated injection fiber on the right side and a gold coated concave mirror on the left. The lower row shows a low-finesse cavity consisting of two flat-cleaved uncoated optical fibers.

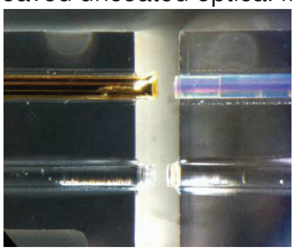

FIGURE 3. Photograph of fiber-optic Fabry-Pérot micro-cavities affixed to the V-grooves of the optomechanical devices.

The fused-silica mechanical oscillators have been designed using slightly different geometries for optimal operation in applications of force or acceleration sensing.

The following sections describe the two types of optomechanical motion sensors that we have developed for such metrology applications and their present performance.

OPTOMECHANICAL FORCE SENSOR WITH FEMTONEWTON RESOLUTION

We have developed an ultrasensitive optomechanical force sensor[3] designed to improve the accuracy and precision of measurements in atomic force microscopy. The sensors reach quality factors of 4.3×10^6 and force resolution on the femtonewton scale at room temperature. Self-calibration of the sensor is accomplished using radiation pressure to create a reference force. Self-calibration enables in situ calibration of the sensor in extreme environments, such as cryogenic ultra-high vacuum. The sensor technology presents a viable route to force measurements at the atomic scale with uncertainties below the percent level.

Figure 4 provides an overview of the self-calibrating optomechanical force sensor.

The sensors are laser machined from a fused silica wafer. The sensor geometry is a parallelogram flexure mechanically grounded at the base with a proof mass at the distal end. It has been

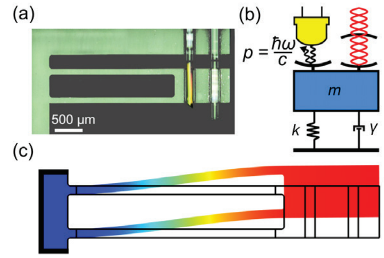

FIGURE 4. Self-calibrating optomechanical sensor. (a) Optical image and (b) schematic of the sensor indicating a high-reflectivity mirror for actuation via radiation pressure and Fabry-Pérot cavity for interferometric displacement measurement. (c) The fundamental flexure eigenmode predicted by a finite element model showing rectilinear displacement of the proof mass.

designed to approximate the behavior of a single-degree-of-freedom (SDOF) oscillator where the transverse displacement of the proof mass in the fundamental eigenmode is approximately rectilinear (see Figure 4(c)), which allows determination of the sensor stiffness through addition of a relatively large mass. In this case, the added mass can easily be as large as 100 μg, making it possible to calibrate with a precision microbalance. There are two optical cavities between the proof mass and the support. On the left, low-coherence light from a superluminescent diode is supplied by an injection fiber. The opposing face is a high-reflectivity mirror consisting of a cleaved, gold-coated fiber that actuates sensor oscillations through radiation pressure. On the right is a low- finesse, Fabry-Pérot optical cavity, formed by cleaved, uncoated optical fibers that are used to measure the displacement of the proof mass. The fibers are axially aligned and affixed to integrated v-grooves. The optical power circulating in the cavity is approximately 20 μW, therefore the optical spring effect can be neglected. The displacement noise floor of this low finesse fiber cavity is $20\,\mathrm{fm}/\sqrt{\mathrm{Hz}}$.

Calibration of the sensor can be accomplished through the direct application of a known reference force, such as radiation pressure from light incident on the test mass. A fiber-optic cavity provides a mechanism for actuation, where the injection fiber is affixed to the base of the sensor, and the opposite fiber mirror is rigidly mounted onto the test mass. Calibration of the force sensor is then accomplished by a ring-down, ring-up sequence. The resonance frequency ω_o and quality factor Q are determined from the ring-down response. Subsequently, the oscillator is self-excited by the modulating light intensity with a phase-locked loop (PLL), and the sensor stiffness is determined from the steady-state amplitude of the resulting limit cycle.

Figure 5 shows the ring-down test and frequency stability measurement for the sensor at room temperature in high vacuum (10^{-4} Pa). The sensor achieves a quality factor of 4.32×10^6, which represents a 100-fold improvement over state-of-the-art quartz tuning fork sensors. The high quality factor arises from use of low-loss materials, such as fused-silica, and by careful mounting of the sensor to minimize support loss.

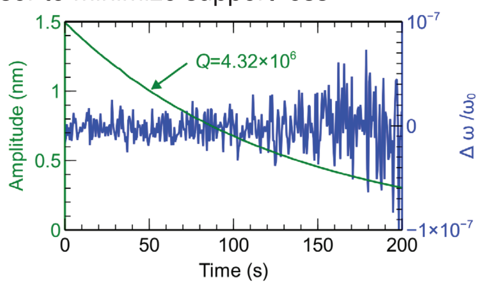

FIGURE 5. Ring-down test showing the amplitude decay and frequency stability the sensor. $Q = 4.32 \times 10^6$ is obtained from a least-squares fit to the amplitude decay. The test was performed at room temperature in high vacuum (10^{-4} Pa)

Assuming the stiffness value from the added mass calibration, we instead use the sensor to measure the radiation force. Thus, the light source is modulated at ω_o by the PLL. The modulation amplitude is then alternated between a pair of discrete, closely spaced RMS intensities. The radiation force is then measured by repeatedly switching the source intensity. From this procedure, we obtained a standard deviation of 67 fN and a force resolution of 14 fN. The resulting distributions are plotted in Figure 6.

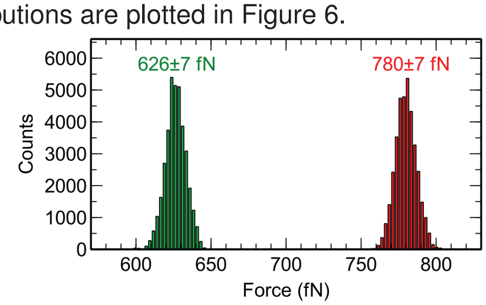

FIGURE 6. Measurement of the radiation force for an alternating source intensity. The standard deviation of the distributions is 67 fN and an estimated force resolution is 14 fN.

HIGH SENSITIVITY REFERENCE OPTOMECHANICAL ACCELEROMETERS

Here, we described our results on optomechanical reference accelerometers that consist of a low-loss fused-silica oscillator, incorporating fiber-optic Fabry-Pérot microcavities to measure the test mass displacement. We have developed acceleration sensors that operate with the two types of fiber cavities described above, low[4] and high[5] finesse.

Assuming a simple harmonic oscillator response for the mechanical resonator, acceleration can be obtained from a direct displacement measurement of the test mass by

$$\frac{X(\omega)}{A(\omega)} = -\frac{1}{\omega_o^2 - \omega^2 + i\,\frac{\omega_o}{Q}\omega}, \qquad (1)$$

where $X(\omega)$ is the relative displacement given an input acceleration $A(\omega)$ at an angular frequency ω, with a harmonic oscillator response of the mechanics determined by its natural frequency ω_o and quality factor Q.

Our devices provide measurement traceability to the SI, since the test mass displacement measurement is directly linked to the laser wavelength. Moreover, the mechanical oscillator translates external accelerations into displacement of its test mass through two parameters only, its natural frequency ω_o and quality factor Q. The parameters can be obtained from series of ring down measurements and spectroscopy analysis that are referred to a frequency standard. The mechanical fused-silica oscillator is shown in Figure 7. This material was chosen for its compatibility with fiber optics and its inherent low loss characteristics.

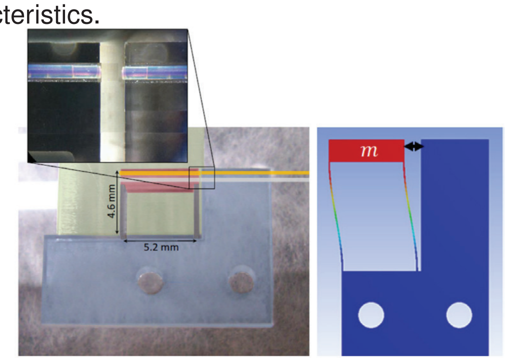

FIGURE 7. Photograph (left) and sketch (right) of the monolithic fused-silica mechanical oscillator with the integrated fiber micro-cavity (magnified in the upper left corner)

We have tested extensively both systems in our laboratory, low and high finesse accelerometers, and have been able to demonstrate acceleration noise floors at levels of 8 $\mu g/\sqrt{\text{Hz}}$ in the low finesse case, and better than 100 $\text{n}g/\sqrt{\text{Hz}}$ over 10 kHz when measuring with high finesse fiber cavities. Figures 8 and 9 show the corresponding measured performances.

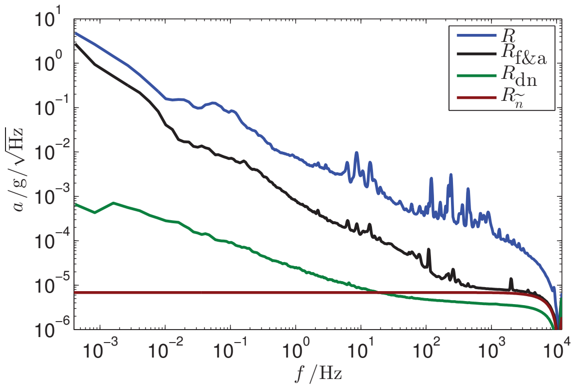

FIGURE 8. Measured acceleration spectra of a low finesse accelerometer with ($R_{f\&a}$) and without stabilizations (R) running. Shown are also the estimated shot noise level ($R_{\tilde{n}}$) and the measured dark noise (R_{dn}).

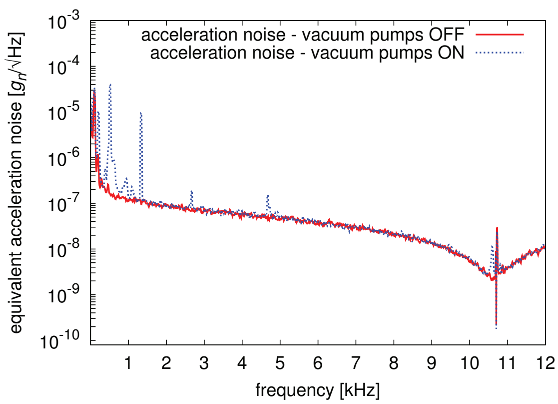

FIGURE 9. Noise equivalent acceleration of a high finesse system, demonstrating sensitivities below 100 $\text{n}g/\sqrt{\text{Hz}}$ over 10 kHz.

A thorough uncertainty analysis of these systems is provided in Reference [4]. Our analysis results estimate that both, low and high finesse systems currently achieve relative accuracies in the order of 10^{-4}. This indicates that our uncertainty levels are better than current state-of-the-art calibration capabilities at National Metrology Institutes[6].

The simplicity, compactness, and traceable high-sensitivity performance over a wide bandwidth accompanied by built-in advanced laser-interferometric detection highlight our optomechanical sensors for a wide variety of precision measurement applications. The concept of self-calibration and the exquisite performance demonstrated by our devices outline a realistic path towards developments in sensor technology where low uncertainties are crucial.

DISCLAIMER

Certain commercial equipment, instruments, processes or materials are identified in this paper for completeness. Such identification does not imply a recommendation or endorsement by the National Institute of Standards and Technology.

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