Towards a photonic quantum standard for mass and force

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Abstract — **A fundamental standard for measuring small forces can potentially be realized using single photons to transfer a known number of quantized photon momenta using the process of reflection. For such an experiment, a resonant optical cavity will maximize the number of momentum transfers per photon, making it possible to scale the total force generated. We have developed and tested such a system that operates in the many photon regime as a stepping stone towards a photonic quantum force standard.**

***Index Terms* — Force sensors, measurement, optics, quantum mechanics, standards.**

I. INTRODUCTION

When photons reflect they experience a quantized change in momentum of $2\,h\nu/c$, where h is Planck's constant, ν is optical frequency, and c is the speed of light. In the limit of classic electromagnetism this change in momentum manifests itself as the radiation pressure force $F = 2P/c$, where P is the optical power incident on the mirror. If the number of photons arriving per unit time Φ can be counted then radiation pressure can be expressed as $F = 2h\nu\Phi/c$. This expression for radiation pressure can form the basis of a photonic quantum force standard as force has been represented in terms a specific number of photons, frequency, and fundamental constants.

One hundred and fifty milliwatts of optical power corresponds to 1 nN of force. One nanonewton of force is a small value of force compared to most traditional force calibrations. A photonic quantum force standard would likely operate at forces considerably less than 1 nN. This scaling makes radiation pressure forces attractive for small forces standards as reaching such small levels of force from traditional mass standards runs into the problem of increasing uncertainty during subdivision [1].

The range of the photonic quantum force standard increases if force generated per photon can be amplified. Inside of an optical resonator, photons reflect multiple times, interacting with the cavity boundaries during each reflection. This allows for magnification of the force generated per photon. Therefore, we propose that building an optical cavity resonator force standard is a starting point towards building a photonic quantum force standard.

II. MATERIALS AND METHODS

We have built a device consisting of rectilinearly translating fused silica flexure and two fiber based Fabry-Perot optical cavities, as shown in figure 1a. One of the optical cavities is used as an interferometer to measure the position of the fused silica flexure and the second optical cavity is used to apply a modulating radiation pressure force to the fused silica flexure. V-grooves are used to align the coated optical fibers ends into optical cavities and the fibers are held in place with UV-cure epoxy. Secondary flexures with attached piezoelectric actuators can be used to modulate the length of the optical cavities. Finally, the fused silica device is frit bonded to a large fused silica puck and placed on a series of isolation stages and inside of a vacuum chamber. The Pound- Drever-Hall approach [2] is used to lock the frequency of the laser to the resonance of the optical cavities.

III. THEORY AND RESULTS

If the mechanical properties of the fused silica flexure are known the radiation pressure force can be determined by measurement of the displacement of the flexure. This constitutes a direct measurement of the circulating optical power in the Fabry-Perot cavity. Alternately, if the properties of the optical cavity and the input optical power are known, the radiation pressure force can be calculated. The calibration data needed to make these calculations are shown in figure 1b and 1c. From the measurement of optical power reflected from the forcing Fabry-Perot cavity shown in figure 1b, the cavity finesse $\mathcal{F}$ and mode matching α are fit from the data. This, in combination with the incident power on the cavity P_{in} allows the calculation of cavity circulating power P_c:

$$P_r = P_{in}\left|\sqrt{R_1} - \alpha^2 \frac{1-R_1}{\sqrt{R_1}} \frac{g_{rt}e^{i\phi}}{1-g_{rt}e^{i\phi}}\right|^2, \quad (1)$$

$$P_c = P_{in}\left|\alpha \frac{\sqrt{1-R_1}}{1-g_{rt}e^{i\phi}}\right|^2, \quad (2)$$

where R_1 is the reflectivity of the first cavity mirror, g_{rt} is the round trip cavity gain and is related to the cavity finesse as $\mathcal{F} \approx$

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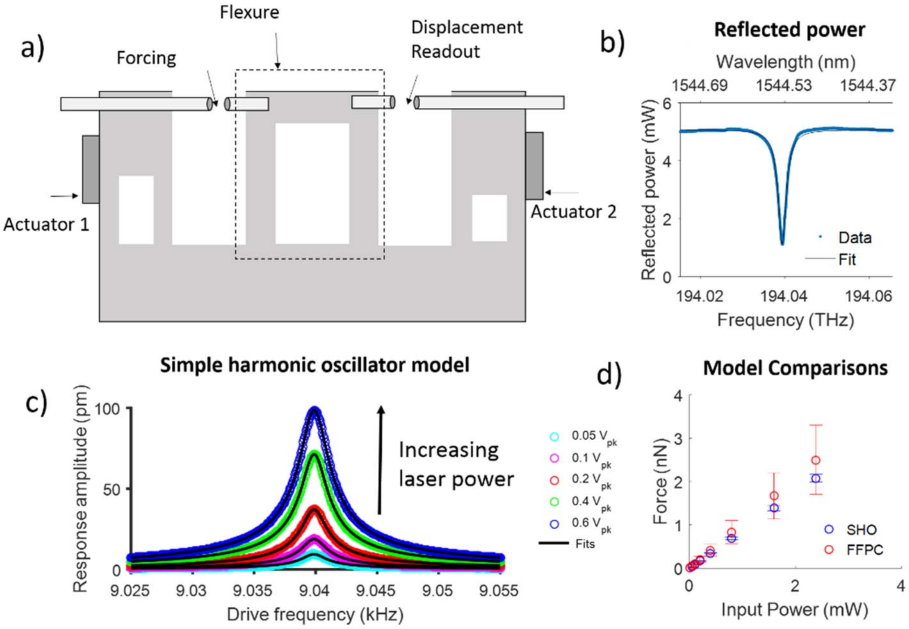

Figure 1: a) Schematic of optomechanical device. b) Reflected power signal from forcing Fabry-Perot cavity. c) Simple harmonic oscillator response near resonance read from the displacement forcing Fabry-Perot cavity. d) Comparisons of force predicted from the response of the simple harmonic oscillator and force predicted from the properties of the forcing Fabry-Perot cavity.

$\pi\sqrt{g_{rt}}/(1-g_{rt})$, ϕ is the nondimensionalized optical frequency and is given as $\phi = 2\pi\,\nu/\Delta\nu$ where ν is the optical frequency and $\Delta\nu$ is the free spectral range [3]. Figure 1c shows the flexure displacement Δx as a function of drive frequency ω of the harmonically oscillating input power. From this measurement the force on the flexure can be calculated as:

$$F_{SHO} = k\Delta x\sqrt{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2+\left(\frac{\omega}{\omega_0 Q}\right)^2}, \qquad (3)$$

where k is the stiffness of the flexure, ω_0 is the resonant frequency of the flexure, and Q is the quality factor of the flexure. The radiation pressure equation:

$$F_{FFPC} = 2P_c/c, \qquad (4)$$

can be used to convert cavity circulating power into force on the flexure and vice versa. Comparing either force or power for these two different methods provides information on the consistency of the two measurement approaches.

Figure 1d shows a comparison of forces calculated from both the simple harmonic oscillator model (3) and from the radiation pressure equation (4) combined with the fiber Fabry-Perot cavity model (1) and (2). For this test case the force produced inside the cavity is less than 1.5 nN. The agreement between the different methods of calculating force is within the uncertainty bounds (95 % CI); however, more data is needed to draw definite conclusions about the completeness and robustness of our experiment and modeling.

IV. CONCLUSIONS

These experiments represent first proof of concept modeling and measurement for creating a calibrated force inside of an optical cavity. This work is a stepping stone for creating a quantum force standard from a known number of photons.

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