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Observation of thermal feedback on the optical coupling noise of a microsphere attached to a low-spring-constant cantilever

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A silica microsphere on a low-spring-constant cantilever (pendulum) is fabricated and evanescently coupled to a tapered optical fiber. The motion of the pendulum is detected as variations in the transmitted laser power through the tapered fiber. The optical coupling noise created by the pendulum motion is recorded by taking a fast Fourier transform of the transmitted laser power and the fundamental mechanical mode of the pendulum at 1.16 kHz is observed. The thermal damping and amplification of the coupling noise is investigated and the effect of the thermal feedback on the noise spectrum is examined. The response of the thermo-optical feedback to small transient and driven variations in the taper-pendulum separation for different values of laser detuning is demonstrated. Preliminary results on the optical force between the pendulum and the tapered fiber are also presented. Microspherical pendulums, with low mechanical spring constant, could be used for studying nanoscopic optical and mechanical forces, or optical cooling.

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I. INTRODUCTION

The field of optomechanics has expanded rapidly in the last decade due to the development of optical devices which are small enough to react to the minute forces created by photon radiation pressure [1,2] or intense optical gradients (i.e., dipole forces) [3–7]. Microscopic optical devices, such as whispering gallery resonators [8–11], tapered optical fibers [12], and photonic crystal cavities [13], enhance the strength of the electric field gradient due to high-optical-Q factors and small mode volumes [14,15]. These devices are also small enough that optical forces can alter the behavior of the resonator and even distort their shape. Light may be coupled into a microresonator via evanescent fields generated by total internal reflection (TIR) at, typically, a glass-air interface such as a prism [16], or a specially prepared optical fiber [17–19]. The evanescent field coupler can also act as a useful transducer for the microresonator's motion [20,21].

Light traveling in a whispering gallery resonator, such as a microsphere, is trapped by the process of continuous TIR. At each reflection point the photons impart some force on the surface of the resonator and this photon pressure causes the resonator wall to "wobble" at its natural mechanical resonance frequencies. The surface displacement in a microsphere supporting a whispering gallery mode (WGM) is a few tens of picometers [1]. This displacement can be detected since the radiation pressure-induced wobble alters the shape of the resonator, thereby changing the resonant frequencies of the WGMs in the resonator. The varying coupling condition changes the amplitude of the transmitted power through the coupler and these changes in the transmission can be detected by a photodiode. A spectral analysis of the photodiode's electrical signal reveals the mechanical resonances of the microcavity which are typically in the MHz or GHz range [1,2].

Microresonators also generate intense electromagnetic field gradients at their surfaces. When another dielectric device, such as another microresonator or waveguide, is brought into this intense field both devices feel a force due to the interaction of the dipoles in the material [3–7]. The sign of this force depends on the phase relationship between the electromagnetic fields connecting the two devices. The phase can be adjusted by simply varying the gap between the devices, or by optically pumping the appropriate coupled cavity resonance, i.e., a symmetric (attractive dipole force) or antisymmetric mode (repulsive dipole force) [6]. The dipole or gradient force from one microresonator can be used to amplify or dampen the mechanical motion of another microscopic device, such as a nanostring [21] or a microdisk [22], as well as provide a way to precisely control the gap between them [3,4,6,7]. For example, Eichenfield *et al.* [23] have shown how the cavity-enhanced optical dipole force from a microdisk can be used to control the relative position of a movable, tapered optical fiber. Povinelli *et al.* [3] discussed the possibility of observing both positive and negative optical forces between two evanescently coupled microspheres, sometimes termed a "photonic molecule." To date, both positive and negative forces have been observed in some optical microcavity systems [22], but not between microspheres. To observe the optical forces between two microspheres the supporting stem of at least one of the spheres must have a suitably low mechanical spring constant. We call this microsphere on a flexible stem a micropendulum, which is essentially a low-spring-constant microcantilever with a microsphere on one end. A micropendulum with a stem spring constant of 10^{-3} N/m has been proposed [3] to observe an optical force displacement of 1 μm between two similarly sized spheres with Q factors of 10^6. It has

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been suggested that microsphere pendulums with very low mechanical spring constants could prove to be useful tools for studying nanoscopic optical and mechanical forces, or optical cooling [24–26]. For example in previous papers, the possibility of trapping a movable microcavity in a photonic molecule was discussed [6,7]. With the photonic molecule there is the possibility that the position of the movable cavity may be controlled by exciting both the symmetric or antisymmetric modes of the coupled cavity system.

In this paper, the fundamental mechanical resonance frequency of a micropendulum due its center-of-mass motion is observed by evanescent coupling of the micropendulum to a tapered optical fiber. The motion is assumed to be the thermal, random movement of the pendulum and/or its displacement due to background vibrations of the system. The mechanical motion of the pendulum creates coupling noise as seen in the transmitted laser power. Here we see how the thermal optical feedback in the microsphere affects the amplitude of this coupling noise. Preliminary experiments on the optical forces between the pendulum and a tapered optical fiber are also presented.

II. EXPERIMENTAL DETAILS AND RESULTS

In this section, the results obtained on the thermo-optical feedback in a taper-coupled micropendulum system are presented and a description of the processes involved is included.

A. Thermo-optical feedback

For a fiber-coupled, silica, microcavity resonator, such as a microsphere, thermal effects on the optical modes of the microsphere are readily observed [8,27–30]. The thermal effects arise since the laser light coupled into the resonator generates heat through absorption, causing the resonator to expand and the refractive index to change, thereby resulting in a redshift of the microsphere resonances. When the laser is tuned near to the microsphere resonance any small disturbance which causes a change in the optical coupling—such as a variation in the laser power or frequency, ambient temperature, or movement of the sphere—will trigger the thermal shift on the sphere's WGMs. For example, any motion of the microsphere can alter the optical coupling and change the circulating power and temperature inside the microsphere resulting in a thermal shift of the WGMs.

The steady state equation describing the net heat flow in (q_{in}) and out (q_{out}) of the microsphere is given by [28]

$$C_p \Delta \dot{T}(t) = \dot{q}_{\text{in}} - \dot{q}_{\text{out}}, \tag{1}$$

where $q_{\text{in}} = I_h\{1/([\Delta\lambda_p(1+\alpha\Delta T)/\Delta\lambda/2]^2+1)\}$, $q_{\text{out}} = K\Delta T(t)$, and $I_h = I\eta Q/Q_{\text{abs}}$.

C_p is the heat capacity, K is the thermal conductivity, Q_{abs} is the quality factor due to absorption, I is the pump power, η is the coupling efficiency, α is a coefficient that describes the shift rate of the optical modes due to changes in the temperature and/or the refractive index, $\Delta\lambda$ is the cavity linewidth, and $\Delta\lambda_p$ is the difference between the pump wavelength and the cold cavity resonance wavelength. Equation (1) describes the heat flow from the cavity into the surrounding medium, but not from the mode volume into the surrounding sphere, and has three solutions, two of which are stable and one of which is unstable.

When the laser is blue-detuned relative to resonance the microsphere is said to be in a warm stable equilibrium [28] because negative thermal feedback works to stabilize the microsphere resonator against small variations in the internal energy of the sphere. When the laser is red-detuned relative to a resonance the microsphere is said to be in an unstable warm equilibrium because positive thermal feedback works to destabilize the microsphere's thermal equilibrium and to increase the small variations in the internal energy of the sphere. In the unstable warm equilibrium regime the positive thermal feedback may either (i) continue to heat the sphere forcing it over to the warm stable equilibrium, or (ii) continue to cool the sphere into a cold stable equilibrium far away from the resonance condition [28]. The thermal feedback also produces a hysteretic behavior (bistability) in the transmitted pump power and in the internal energy of the sphere as a function of pump-cavity detuning [8,28–30].

The thermal feedback with regards to the motion of the pendulum works as follows: If the laser is blue-detuned relative to the microsphere resonance, and the pendulum motion causes a change in the coupling which decreases the temperature inside the sphere, then the resonance will be blueshifted towards the pump; see Fig. 1(a). The approaching resonance condition increases the coupling and the temperature which counteract the decrease caused by the pendulum motion. Now if there is, instead, a small increase in the temperature in the sphere due to the pendulum motion (i.e., increased coupling) then the microsphere resonance is redshifted away from the pump, as illustrated in Fig. 1(b). This reduces the internal energy of the sphere and, again, counteracts the power change caused by the pendulum movement.

Conversely, when the laser is red-detuned relative to the sphere resonance, and there is a small decrease (or increase) in the temperature inside the sphere caused by the pendulum's motion, i.e., decreased (increased) coupling, the resonance will be blueshifted (or redshifted) away from (or towards) the laser, thus reinforcing the decrease (or increase) in the internal energy of the sphere; see Figs. 1(c) and 1(d). Note that when the laser power is so low the optical gradient force can be neglected, the thermal feedback, no matter whether the laser is blue- or red-detuned from the WGMs in the microsphere, will only change the transmitted power through the taper and will not affect the motion of the pendulum.

B. Pendulum details

A microspherical resonator is typically formed by melting the tip of a tapered optical fiber with a CO_2 laser. The remaining section of fiber forms the stem, which supports the microsphere and facilitates its manipulation during experiments. The stem is usually very rigid and provides a stable platform to perform extremely sensitive experiments [31,32]. In contrast, in the work reported here the microsphere is on a flexible stem, i.e., a pendulum. The pendulums are made in the same way as normal microsphere resonators except that the stem is longer and thinner, thus lowering the mechanical spring constant (κ_c) of the stem. The spheres are typically made with diameters between 20 and 200 μm while the stems are 5–10 μm in

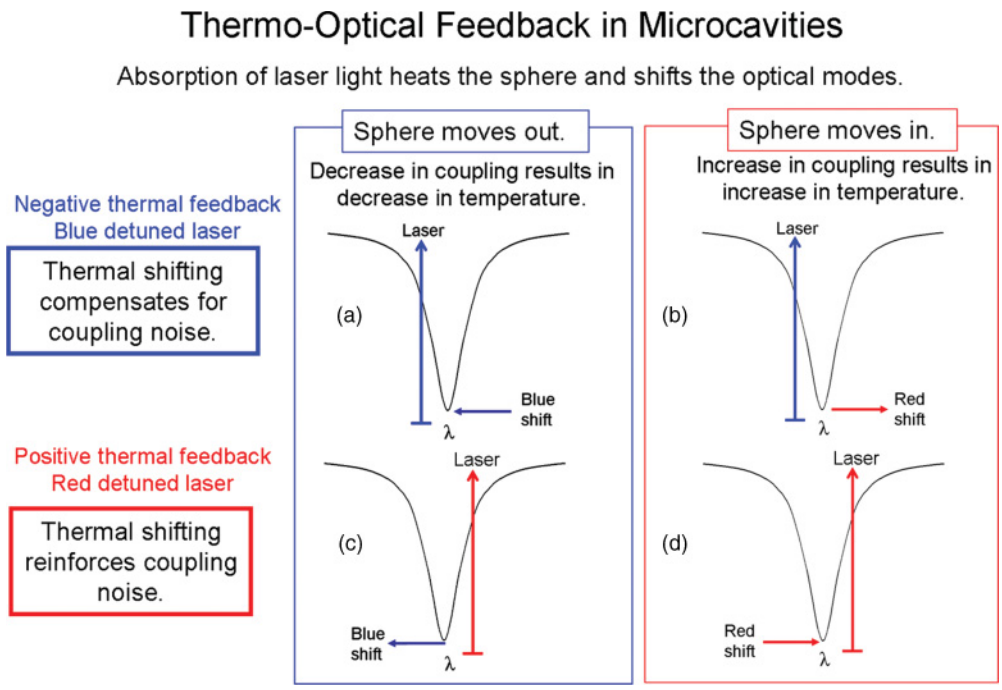

FIG. 1. (Color online) The Lorentzian shaped line represents the microsphere resonance. (a) and (b): Negative thermal feedback (warm stable equilibrium). A decrease in laser power, temperature, or coupling is compensated for by a blueshift of the resonance towards the pump laser. An increase in power, temperature, or coupling is compensated for by a redshift away from the pump laser. (c) and (d): Positive thermal feedback (unstable equilibrium). A decrease in laser power, temperature, or coupling is further decreased by a blueshifting of the resonance away from the pump laser. An increase in laser power, temperature, or coupling is further increased by redshifting away from the pump laser.

diameter and can be up to a few millimeters long. By making the stem diameter less than 5 μm, or by making the stem longer, it is possible to fabricate pendulums with mechanical spring constants as low as 10^{-6} N/m. However, these devices are difficult to control in our current experimental setup due mainly to air currents and electrostatic forces, so instead we use pendulums with a more rigid spring constant of approximately 10^{-2}–10^{-3} N/m. At these low mechanical spring constants the motion of the spherical tip is still relatively large so that the coupling between the sphere and the tapered optical fiber is altered. As described earlier, the pendulum can be treated as a flexible cantilever with a sphere on one end. The pendulum used in these experiments has a cantilever length of $\sim$1.7 mm with a radius a of 5 ± 1 μm next to the sphere. After 1.7 mm the diameter of the cantilever starts to increase to 14 μm over a length of about 300 μm and beyond this point the diameter increases to 125 μm over another 300 μm length. The sphere diameter is 100 ± 2 μm and, from optical measurements, the estimated mass m of the sphere plus the cantilever (for a length of 1.7 mm) is $2.2(\pm 0.3) \times 10^{-9}$ kg. The mass of the sphere is approximately equal to that of the cantilever.

The spring constant of the cantilever can be calculated from [6]

$$\kappa_c = \left(\frac{3\pi}{4}\right)\left(\frac{Ea^4}{L^3}\right), \tag{2}$$

where $E = 73.1$ GPa is Young's modulus for silica. For example, given a cantilever with a length $L = 1.7$ mm and a uniform radius of $a = 6$ μm, κ_c equals 0.045 N/m. The natural resonance frequency, $\Omega/2\pi$, of such a cantilever with a sphere attached can be estimated from

$$\Omega = \sqrt{\left(\frac{\kappa_c}{m}\right)}, \tag{3}$$

where $m = 1.2 \times 10^{-9}$ kg is the mass of the sphere. This yields a resonant frequency of 1000 Hz, which corresponds to an estimated thermal displacement, δx, of the microsphere [6]:

$$\delta x = \sqrt{\left(\frac{2k_bT}{m\Omega^2}\right)} = 0.4\text{nm}, \tag{4}$$

where k_b is Boltzmann's constant and T is the temperature, i.e., 300 K. Equations (2)–(4) provide reasonable approximations for the basic characteristics of the pendulum.

The displacement sensitivity of a microsphere on a cantilever under microaccelerations was demonstrated in [26]. In the work reported here, it is assumed the pendulum is free to move for the following reasons: (i) It has thermal energy which gives rise to Brownian motion, (ii) air currents are present, and (iii) low-frequency noise from nearby roads and heavy machinery is present. This low-frequency noise changes over time, e.g., from day to night [33–37]. The Peterson noise model [34,37] gives the lowest vertical noise observed for the seismic frequency band. The minimum vertical displacement at 100 Hz is about -150 dB (relative to 1 m/s^2), horizontal displacements are typically a few dB less. Urban noise can bring the amplitude to -100 dB (10 μm/s^2), i.e., 50 dB above the minimum noise level. Other local environmental factors can also be present [33–37] which can increase this noise level. The displacement of a cantilever with a sphere on the

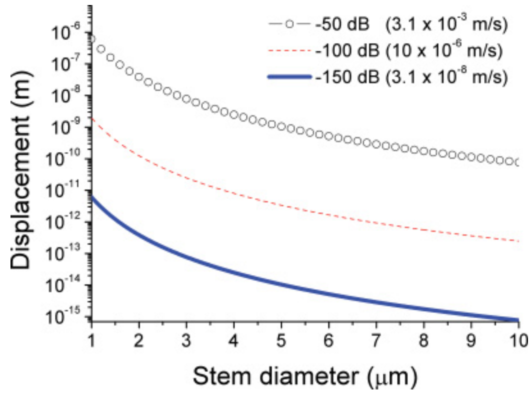

FIG. 2. (Color online) Calculated displacement of a pendulum with a sphere diameter of 100 μm and a length of 1.7 mm as function of cantilever diameter (1–10 μm) for accelerations of 3.1×10^{-3} m/s^2 (circles), 10×10^{-6} m/s^2 (dashed line), and 3.1×10^{-8} m/s^2 (solid line).

end due to acceleration is given in Ref. [26] and is plotted in Fig. 2 as a function of cantilever diameter for accelerations of -50 dB, -100 dB, and -150 dB (relative to 1 m/s).

It is clear that there is a large increase in the displacement (due to a large decrease in κ_c) when the cantilever diameter is reduced below 4 μm. The displacement for a 10 μm/s^2 acceleration of our microsphere would be around 1 pm [26]. From this analysis it is possible to see that increased sensitivity can be achieved by reducing the diameter of the cantilever (and/or by making it longer) but at the cost of a higher noise floor. However, for trapping and cooling, a thin cantilever provides improved thermal isolation and reduces the mechanical trap potential.

Eigenfrequency analysis using a structural mechanics software package was also used to visualize the mechanical modes of the pendulum; see Fig. 3.

The cantilever in the model is a cone with a minimum (maximum) diameter of 10 μm (14.5 μm) and a length of 1.7 mm after which it increases gradually up to 125 μm over 300 μm. The first mode at ~1.1 kHz gives the largest displacement of the tip, while the other modes produce hardly any movement of the sphere, but give oscillations along the cantilever. The third mode, at 30.2 kHz, is a torsion mode that appears to produce a radial distortion of the sphere. The frequency of a torsion mode can be calculated from [6]

$$\frac{\Omega_\phi}{2\pi} = \sqrt{\frac{\kappa_\phi}{I}}, \tag{5}$$

where $I = 2/5MR$ is the moment of inertia, M is the mass, and R is the radius of the sphere. The spring constant for a torsion mode, κ_ϕ, is defined by the shear modulus of the silica cantilever, G, the cantilever radius, a, and the length of the cantilever, L, such that $\kappa_\phi = a^4G/2L$. The angular displacement (azimuthally) is of the order of microradians and the resulting radial distortion is expected to be negligible compared to the swinging motion at 1.1 kHz. Figure 3 also shows that, for the higher-frequency modes, the tip displacement is negligible compared to the oscillations along the stem.

The software was also used to simulate the displacement of the pendulum under a static point load. When a force of 10 pN is applied to the spherical end of the pendulum the resulting displacement of the pendulum is 0.17 nm. The force relationship, $F = \delta x \kappa_c$, yields a spring constant of $\kappa_c = 0.05$ N/m, which is close to the value determined from Eq. (2).

C. Experimental setup and results

The pendulum is glued to a metal post and is then mounted so that it hangs downward. The metal post is attached to a three-dimensional (3D) piezo-activated nanopositioning stage. The spherical end of the cantilever, i.e., the microspherical resonator, is brought into the evanescent field of a tapered optical fiber. The tapered fiber is made from standard optical fiber that has been heated and adiabatically stretched in an oxybutane torch; the taper waist has a diameter of 1 μm. The pendulum and the tapered fiber are inside an enclosure to isolate against air currents. The enclosure is supported on top of eight posts, each of which is fixed on an elastomer cradle (Isonoe Audio Isolation) in a rigid metal hub and each hub is fitted with sorbothane boots [38]. The entire setup is sitting on a pneumatically isolated optical table. In fact, it is not necessary to eliminate all vibrations, but rather the vibration noise should

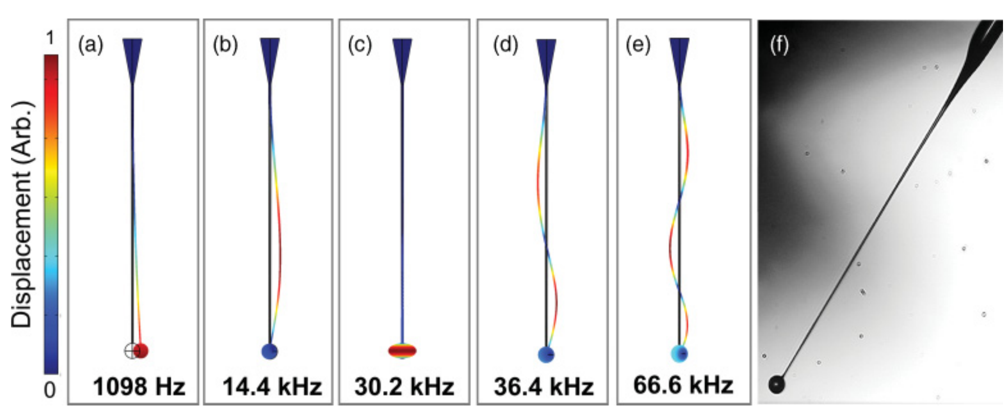

FIG. 3. (Color online) The first five fundamental modes of the pendulum as determined by a COMSOL structural model. The eigenfrequency analysis only returns frequency and shape deformations. The pendulum was modeled in vacuum with no damping, The last panel (f) is an image of the device.

be reduced to a level where the pendulum can swing without making contact with the tapered fiber.

A 1500-nm widely tunable, mode-hop-free laser (linewidth 300 kHz) is coupled into the tapered fiber and produces the evanescent field at the taper waist. To find the optical resonances in the sphere, the laser wavelength is scanned at a rate of 1 nm/s over tens of nanometers and the transmitted power from the output of the tapered fiber is monitored using a photodiode and a digital storage oscilloscope (DSO). Once a suitable mode is found the laser scan is stopped and the laser frequency is modulated by ± 60 GHz over the mode at a rate of 5 Hz. The thermal shifting threshold of the sphere's modes is determined by observing the position of an optical mode as the pump power is increased. Noticeable distortion and redshifting of the modes for this particular sphere occur for a pump power around 1 μW. The pump power, as measured at the output, shows a loss of about 20%. The laser power is kept at a level which avoids significant thermal distortion of the optical modes, which appear roughly Lorentzian at this value. After fabrication the Q factors of the spheres degrade over a long period of time and the typical Q factor used in these experiments is $\sim 10^5$.

Next the laser frequency modulation is stopped and the laser is tuned either into the red or blue side of the resonance. The laser is not side locked to the resonance but is rather left free running, and a fast Fourier transform (FFT) of the transmitted power is recorded. The resulting spectrum for a red-detuned laser is shown in Fig. 4(a). Tuning the laser to the red side of the resonance is difficult when the laser power is increased above a few tens of μW due to the combination of positive thermal feedback and taper-pendulum coupling noise.

Some of the peaks in the spectrum are believed to be due to technical noise such as laser noise [28,36], background vibrations [33–35,37], and thermorefractive and systematic noise [35], while the peak at 1.16 kHz corresponds to the fundamental mechanical resonance of the pendulum. Just as is the case for background vibrations, it is also not necessary to eliminate all sources of noise associated with the laser, e.g., frequency and power fluctuations. These sources of noise (including thermal fluctuations) also change the coupling and, therefore, the circulating power in the sphere and act as inputs for the thermal feedback loop. As shown in Fig. 4(a), the amplitude of the noise peaks in the FFT increases as the frequency decreases. The source of these peaks (below 500 Hz) is largely unknown; however, they do not appear in the transmitted power of a microsphere on a rigid stem and so are assumed to be mainly due to the pendulum's increased sensitivity to low-frequency mechanical noise and air currents (see Fig. 2). However, further investigation is needed.

For this particular pendulum, the peak at 1.16 kHz appears to be the fundamental mechanical mode; the Q factor of the mechanical mode at 1.16 kHz is 2×10^4 [see Fig. 4(b)]. The smaller oscillations of the higher-order mechanical modes shown in Figs. 3(b)–3(e) were not possible to detect do to the lack of sensitivity in our system. To show that the peak at 1.16 kHz is a mechanical mode the pendulum was vibrated in one direction (in and out from the taper) using the piezo-activated stage while simultaneously recording the transmitted power. When the frequency of the piezo modulation was adjusted to 1.16 kHz the mechanical motion of the pendulum was amplified and harmonics appeared in the transmitted power, as shown in Fig. 5. The piezo stage holding the pendulum was modulated using a sine wave with an applied voltage that corresponds to a piezo displacement of at least 30 nm (open loop control). However, on resonance, the resulting gap change is on the order of tens of micrometers. The harmonics seen in Fig. 5 are not the higher-order mechanical modes depicted in Figs. 3(b)–3(e) but features of resonance excitation with the pendulums' fundamental mode.

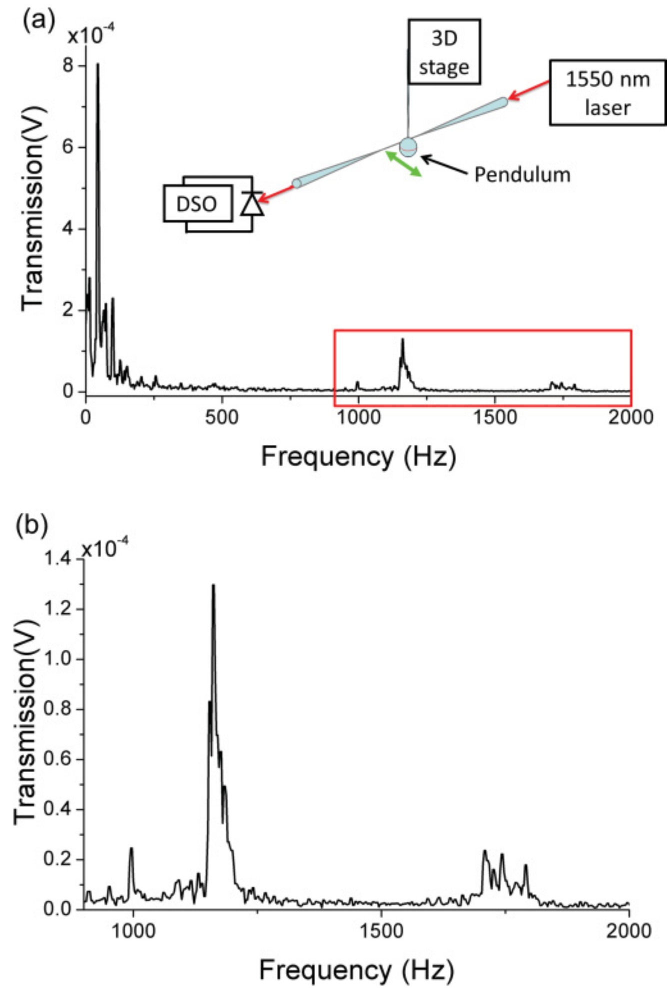

FIG. 4. (Color online) (a) Noise spectrum of the transmitted power when the pendulum is in the evanescent field of the tapered fiber and the laser is red-detuned. The peaks at 50Hz, 1 kHz, 1.16 kHz, and 1.75 kHz are due to laser noise, systematic noise, pendulum motion, and unknown, respectively. Inset: schematic of the experimental setup. (b) The fundamental mode of the pendulum at 1.16 kHz highlighted by the box in (a).

This resonant excitation is useful for discriminating the natural mechanical modes of the pendulum from other oscillations and on-resonance excitation may be valuable for sensing applications. Normally the piezo stage is used just to align the micropendulum in the evanescent field of the tapered fiber. For example, Fig. 6 shows the transmitted power noise spectrum for a pendulum positioned in the evanescent field with different laser detuning. When the transmitted powers for the red- and blue-detuned pump laser are compared we see a marked difference in the amplitude of the coupling noise,

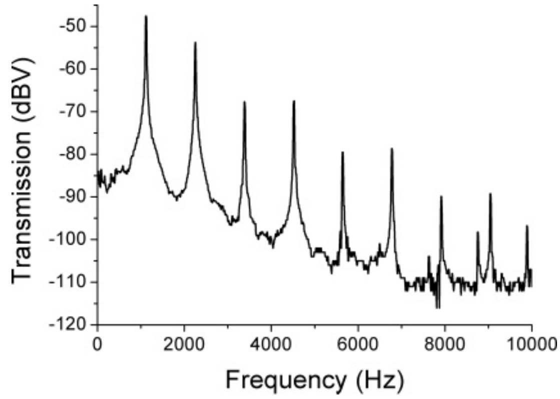

FIG. 5. Harmonics of the fundamental mechanical mode as seen in the transmitted power when the piezo stage holding the pendulum is modulated by ~30 nm at a frequency of 1.16 kHz equal to the mechanical resonance frequency of the pendulum.

i.e., the red-detuned side appears noisier than the blue-detuned side; see Fig. 6. Care is taken to ensure that the same coupling is achieved for both sides of the resonance so that the transduction gain is equal. The inset of Fig. 6 shows the corresponding transmitted power as a function of time for red, blue. and off-resonance detuning. The variation in the coupling due to the motion of the pendulum is typically around 10%.

The difference in the spectra is attributed to the thermal mechanism described in Sec. II A. The variations in the transmitted power caused by the pendulum's motion are amplified by positive thermal feedback when the laser is red-detuned relative to the cavity and damped when the laser is blue-detuned. In the red-detuned case, the thermal feedback adds to increase the noise created by small variations in the taper-pendulum coupling. The motion of the pendulum and the thermal feedback are not large enough to make the sphere drift from this unstable warm equilibrium to the cold or warm stable equilibrium unless there is a further increase in the pendulum motion, or in the laser power. Conversely, when the laser is blue-detuned, the variations in the taper-pendulum coupling are offset by negative thermal feedback. At very low pump powers (~50 nW), the damping is not as strong but is still noticeable; most likely dispersive shifting is also playing a dominant role at very low powers.

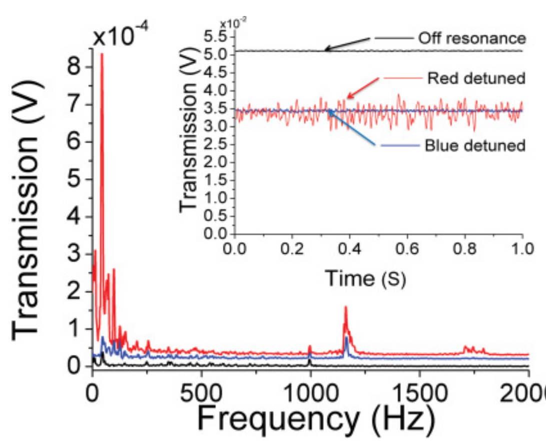

FIG. 6. (Color online) FFT of the transmitted power when the pump laser is off resonance (bottom trace), red-detuned (top trace), and blue-detuned relative (middle trace) to an optical mode. The plots have been shifted relative to each other for ease of viewing. The inset shows the corresponding time signal.

The lower-frequency peaks tend to show a larger enhancement or damping than the higher-frequency oscillations. This is probably due to the fact that the microsphere has a limited thermal response time in milliseconds [28,30,36]. If the period of the mechanical (or any coupling noise) oscillation is longer (i.e., the change in temperature is slower) than the thermal response time, then the thermal feedback (i.e., the shifting of the WGMs) has time to enhance or damp the variation in temperature. The thermal decay rate from (i) the optical mode volume to the rest of the silica microsphere was estimated by Schmidt *et al*. [30] to be on the order of microseconds, and (ii) from the rest of the sphere to the surrounding medium was on the order of milliseconds, whereas the thermal shift rate of a silica sphere is around 2.5 GHz/K [39]. At higher oscillation frequencies, the period of the oscillation becomes comparable or less than the thermal response time of the sphere and the thermal feedback should be cut off [30] (e.g., by the pendulum moving) before it has a chance to take effect. Therefore, higher-frequency noise may not see this slower thermal effect. This is analogous to the nonadiabatic response of a light field coupled to a high-frequency micromechanical oscillator. The above is purely a phenomenological discussion and further studies are needed to determine the limiting factors.

Next the response of the system to transient coupling noise for red and blue detuning was observed. The transient signal is generated by dropping a small metal weight next to the 3D stage holding the pendulum. A similar experiment was performed by Carmon *et al*. [28]. However, here a much lower spring constant stem was used and both amplification and damping of the coupling noise were observed.

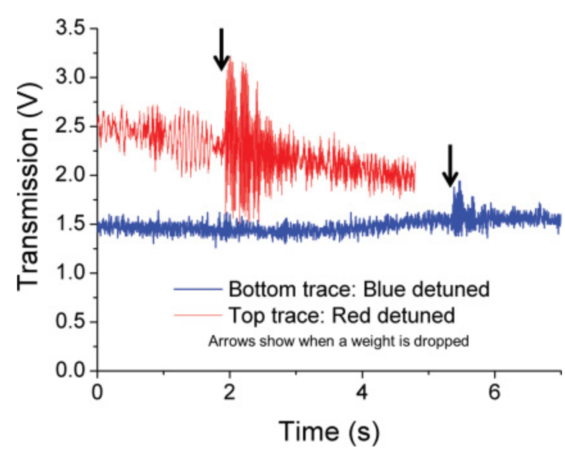

FIG. 7. (Color online) Typical response of the tapered fiber-pendulum system to transient noise. A small weight was dropped next to the 3D stage holding the pendulum when the laser was red-detuned (top trace) and blue-detuned (bottom trace). Some care is taken to ensure that the weight does not bounce and is dropped from the same height each time. The scales for red and blue detuning have not been adjusted; they have been offset for clarity. The arrows show when the weight was dropped. This experiment was performed for a different pendulum with length 2 mm, sphere diameter 45 μm, and minimum (maximum) stem diameter 8 μm (10 μm).

When the laser is red-detuned, the sphere is in the unstable, warm equilibrium and, therefore, the transient noise in the coupling (created by dropping the weight) is amplified and prolonged by the positive thermal feedback, as shown in the top trace in Fig. 7. In this case the transient noise can very easily cause the sphere resonance to jump to the cold or warm, stable equilibrium. However, when the laser is blue-detuned and the sphere is in a warm, stable equilibrium the transient noise is quickly damped; see the bottom trace in Fig. 7. The y-axis scale for the red and blue detuning has not been adjusted but the traces have been offset for clarity. Sometimes the damping for the blue-detuned case appears asymmetrical, i.e., more damping when the pendulum swings towards the taper, and the reason for this remains unclear.

It must be emphasized that in the experiments described above, and at pump powers around the thermal threshold, the pendulum motion does not appear to be affected by any optical gradient force generated by the laser light. Eichenfield *et al.* [23] used the optical gradient force between a tapered optical fiber and a microresonator to pull a movable tapered fiber towards the resonator. An input power of less than 370 μW was used to displace the tapered fiber by about 120 nm. The tapered fiber had an estimated mass of 2.6×10^{-11} kg and a spring constant of 35×10^{-6} N/m. The maximum force determined from experimental data was 20 pN/mW.

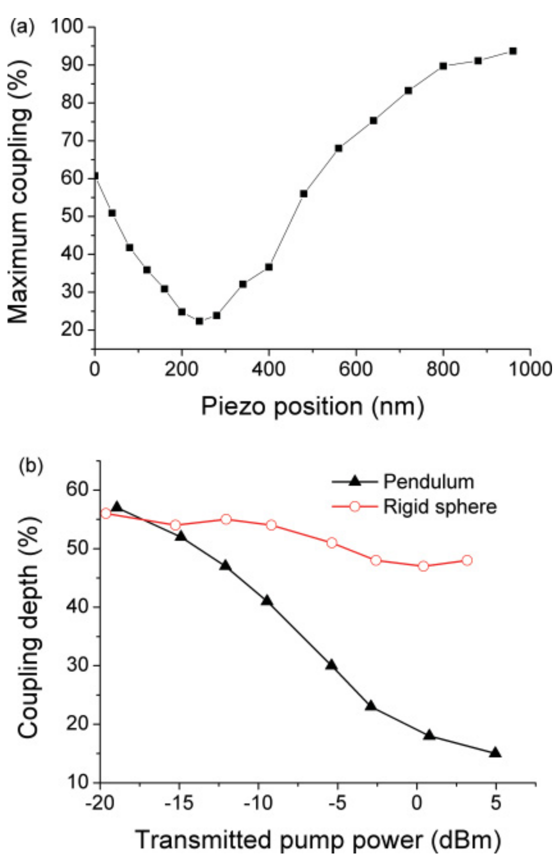

FIG. 8. (Color online) (a) Coupling strength for different taper-sphere gaps. The pendulum is moved towards the taper and the optical resonance is recorded at each step, with each point being the minimum transmitted power recorded. (b) Attractive pendulum-taper dipole force for increasing pump power (black squares). The same experiment was repeated for a rigid sphere (red circles). The pump laser is blue-detuned relative to the cavity mode.

Here, we perform a similar experiment, only the tapered fiber remains stationary and the resonator moves towards the fiber. First, the pendulum is moved towards the taper in ~30-nm steps and at each step the laser is scanned (from blue to red) across a cavity resonance while the transmitted power is recorded. The minimum transmitted power is recorded at each step. This is shown in Fig. 8(a).

Next, the pendulum tip is kept at a constant distance from the taper so that the sphere is undercoupled with a coupling strength of 50%. The pump laser is blue-detuned from the optical mode and the pump power is increased from 100 μW to 3 mW while the position of the optical mode is monitored. As the pump power is increased the pendulum is pulled towards the taper due to the attractive gradient force. Increased coupling and increased input power causes the optical mode to redshift. The power required to actuate the pendulums used in these experiments is far above the thermal threshold and, as such, there is significant thermal distortion of the optical modes [13]. By comparing Figs. 8(a) and 8(b) we can estimate the displacement of the pendulum for a pump power of 3.3 mW to be around 200 nm. For comparison, the same experiment is repeated with a 90-μm sphere on a rigid stem and the result is plotted in Fig. 8(b). The rigid sphere shows a small amount of increased coupling with increasing power. This is believed to be due to movement of the taper or a variation in the laser power.

III. CONCLUSION

A silica microspherical pendulum was fabricated and evanescently coupled to a tapered optical fiber. The motion of the pendulum was detected as oscillations in the transmitted laser power through the tapered fiber. The noise spectrum created by the pendulum was observed by taking the FFT of the transmitted power. It was shown that thermal feedback can either dampen or amplify the taper-pendulum coupling noise, depending on whether the laser is blue- or red-detuned from the optical resonances. Because of the relatively large mechanical spring constant of the pendulum (10^{-2} N/m) and the low-input laser power (less than 100 μW) the displacement of the pendulum due to optical dipole forces is negligible and the choice of pump detuning has little effect on the motion of the pendulum. For low laser power it is only the transduction of the pendulum motion in the evanescent field of the tapered fiber that is changed, i.e., only the amplitude of the coupling noise (as seen in the transmitted power) is affected by detuning the laser and not the motion of the pendulum. At higher pump powers, in the mW range, the optical dipole force is observed and the pendulum is drawn towards the tapered fiber.

For optical trapping of a microsphere in a photonic molecule setup [6], where the lasers should be blue-detuned from the symmetric (antisymmetric) modes, the thermal feedback should aid in stabilizing the system against coupling noise, laser power noise, and temperature variation. It may also be interesting to investigate Doppler cooling of a microsphere held in a weak mechanical potential. However, for Doppler cooling to take place, the laser should be red-detuned and, as a result, the thermal feedback will in fact act to destabilize the system. This should not be an insurmountable problem if the power coupled into the sphere is not too large.

In conclusion, we consider the movable microsphere pendulum to be an interesting device that warrants further study. In future work we plan to increase the sensitivity by using higher-Q modes and to reduce the spring constant of the pendulum to below 10^{-4} N/m. Rather than making the cantilever longer to achieve this, we can reduce the mass of the cantilever by reducing its length and bringing the diameter to below 1 μm. For a true spherical pendulum the mass of the cantilever should be negligible compared to the mass of the sphere. This reduces the spring constant and lowers the mechanical potential, thereby helping to reduce clamping losses and isolating the sphere. The reduced spring constant and mass of the cantilever will also allow for larger sphere displacements to occur for smaller forces, such as the optical dipole force between the pendulum and the tapered fiber and/or another microsphere. However, using a lower-spring-constant pendulum would require the pendulum to be placed in a vacuum chamber with increased mechanical isolation.

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