Resonant optomechanics with a vibrating carbon nanotube and a radio-frequency cavity

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In an optomechanical setup, the coupling between cavity and resonator can be increased by tuning them to the same frequency. We study this interaction between a carbon nanotube resonator and a radio-frequency tank circuit acting as a cavity. In this resonant regime, the vacuum optomechanical coupling is enhanced by the DC voltage coupling the cavity and the mechanical resonator. Using the cavity to detect the nanotube’s motion, we observe and simulate interference between mechanical and electrical oscillations. We measure the mechanical ring-down and show that further improvements to the system could enable measurement of mechanical motion at the quantum limit.

The field of cavity optomechanics exploits resonant enhancement of light-matter interaction to study mechanical motion with exquisite sensitivity, including in the quantum domain [1]. Commonly the mechanical frequency $f_M$ is much smaller than the frequency $f_E$ of the electromagnetic cavity, leading to a detuned coupling. The small zero-point motion then gives a comparatively weak optomechanical coupling, which however can be enhanced by a factor $\sqrt{n_c}$ through strong driving, where $n_c$ is the cavity photon occupation [2]. An alternative approach, which avoids the degradation of the cavity performance at low-temperatures for large $n_c$ [3], is to operate close to resonance, at $f_M \approx f_E$, with a DC voltage $V_G$ applied between the resonator and the cavity [4, 5]. In this case, the single-photon coupling is enhanced by a factor $\sim V_G/V_{2P}$, where $V_{2P}$ is the zero-point fluctuation of the cavity voltage [6]. However, for this scheme to approach the quantum regime, it requires a mechanical resonator with a frequency high enough to be thermalized close to its ground state.

Here we realize a resonant optomechanical circuit exploiting the high mechanical frequency of a vibrating carbon nanotube. Using a radio-frequency (RF) circuit as a readout cavity [7, 8], we detect nanotube motion via its changing capacitance and measure interference between electrical and mechanical resonances. We show that the cavity measurement reproduces the resonance observed in transport, but go beyond transport by measuring the ringdown even without current through the nanotube. The mechanical resonance is first studied in transport [Fig.1(c)] [9]. A hole-doped quantum dot potential is created through a combination of Schottky barriers at the contacts and a voltage $V_G$. As a function of $V_G$, a series of Coulomb peaks is evident in transport [Fig.1(c) inset]. The effect of mechanical displacement is to change the capacitance between the dot and the gates [13], shifting the Coulomb peaks in a way that leads to a rectified DC current $I$. With an RF signal applied to gate 4, this transport through the nanotube, forgoing potential for sensitivity and coherent control offered by coupling to an chip-scale cavity.

A carbon nanotube resonator [Fig.1(a)] was suspended between contact electrodes over an array of five finger gates as described in Ref. [6, 26]. For transport measurements the device is probed by applying a bias $V_{sd}$ and measuring the current $I$ through the nanotube. The doping of the nanotube, and hence its conductance, are tuned using DC gate voltages $V_{G1}$ to $V_{G5}$; these simultaneously tune the mechanical tension [9]. We define $V_G$ as the DC voltage applied to all gate electrodes. Gate 4 is connected to an RF source that can be used to excite transverse vibrations. Measurements are at 13 mK in a dilution refrigerator.

The effective RF cavity is realized using an inductor and capacitors mounted on the sample holder and coupled to gate 5. To tune cavity frequency $f_E$, we incorporate a variable capacitor $C_{S}$ controlled by a DC voltage $V_S$, giving $f_E \approx (2\pi\sqrt{LC_S})^{-1}$, where $L = 180$ nH is the circuit inductance [27]. This cavity can be driven in two ways; by injecting an RF signal to the input via a directional coupler (direct drive), and by driving via gate 4, which is capacitively coupled (gate drive). The cavity output is fed to a cryogenic amplifier and detected at room temperature. The entire setup forms a three-terminal circuit with input ports 1 and 2 and output port 3. Figure 1(b) shows electrical scattering parameters as a function of driving frequency $f_d$ for two settings of $V_S$ in both direct and gate drive. The cavity resonance is evident as a transmission minimum with quality factor $Q_E \approx 10-20$ depending on varactor losses [27].

The mechanical resonance is first studied in transport [Fig.1(c)] [9]. A hole-doped quantum dot potential is created through a combination of Schottky barriers at the contacts and a voltage $V_G$. As a function of $V_G$, a series of Coulomb peaks is evident in transport [Fig.1(c) inset]. The effect of mechanical displacement is to change the capacitance between the dot and the gates [13], shifting the Coulomb peaks in a way that leads to a rectified DC current $I$. With an RF signal applied to gate 4, this
is evident when $dI/df_d$ is plotted as a function of $V_G$ and $f_d$ [13, 14, 16]. A resonance feature is seen at the mechanical frequency $f_M$ [Fig. 1(c)]. The measured $f_M$ is consistent with similar nanotube resonators [9–13, 15, 16]. The mechanical nature is clear from the dependence on $V_G$ due to electrostatic tensioning.

We now detect this motion via the readout cavity. The dependence of gate capacitance $C_{CNT}$ on mechanical displacement $u$ leads to a cavity coupling $dI/df = f_dC_{CNT}du/dt$ [6]. In a detuned optomechanical setup with $f_M \ll f_E$, this coupling allows the motion to be monitored via the phase shift of the cavity transmission $[1, 3]$. We use a different scheme that takes advantage of the fact that $f_M$ and $f_E$ can be tuned into resonance. With the DC voltage on gate 5 set to $V_G$, the mechanical motion induces a current $I_G = -V_G\frac{dC_{CNT}}{du}du/dt$ onto the gate electrode. This current excites the cavity, leading to an output signal

$$V_{out} = Z_{trans}I_G,$$

where $Z_{trans}$ is a transimpedance set by the circuit parameters [6]. The transimpedance, and hence the sensitivity, is maximal close to degeneracy ($f_M \approx f_E$). In contrast to detuned readout (at least outside the resolved-sideband regime), the signal arises from velocity $du/dt$ rather than displacement.

We demonstrate this coupling with the cavity tuned to $f_E = 304$ MHz and with $V_G = −7$ V. Drive and detection are provided by a scalar network analyser (SNA), which monitors the time-average transmission $|S_{31}|^2$ from port 3 to port 1. A challenge of this scheme is that the drive used to actuate motion also couples directly to the cavity via a parasitic capacitance $C_G$ between gates 4 and 5. This gives rise to a non-resonant background that in our unoptimized circuit overwhelms the mechanical signal. (This is why a mechanical signal is not seen directly in
Fig. 1(b)). We can largely reject this contribution using the pulsed driving scheme of Fig. 2(a), which separates the times of driving and detection using RF switches to gate the input and output signals. With the output decoupled, gate 4 is first driven for time $t_d = 300$ ns, exciting both the mechanical motion and the cavity voltage. After a wait interval $t_w$ from the end of this drive burst, the output is coupled for a detection interval of duration $t_r = 300$ ns. For each data point, the detected power was averaged over $\sim 8$ ns during which this cycle was applied with a period of $t_w + 610$ ns. By choosing $t_w$ intermediate between the cavity and mechanical ringdown times ($Q_M/2\pi f_E$ $\approx 11$ ns > $t_w$ > $Q_M/2\pi f_M$ $\approx 370$ ns), the mechanical contribution to $V_{out}$ is largely isolated.

Figure 2(b-c) shows transmission as a function of $f_d$ and $\overline{V_G}$ for two different values of $t_w$. To highlight the signal due to the nanotube, data are plotted after subtraction of the average $|S_{31}|^2$ at each frequency, giving the excess signal $\Delta|S_{31}|^2$. The mechanical resonance is evident, with a similar dependence of $f_M$ on $\overline{V_G}$ as measured in Fig. 1(c). However, it now appears as a pattern of bright and dark fringes whose alignment depends on $t_w$. This is attributable to a classical interference effect between the ringdown of mechanical and electrical signals. Both the nanotube and the cavity are set ringing during the drive burst with phases that depend on the difference between their corresponding resonance frequencies and $f_d$. Subsequently each evolves at its own frequency. The two signals therefore add constructively or destructively in a way that depends on $t_w$, $f_d$, $f_E$, and $f_M$ (tuned by $\overline{V_G}$). Superimposed on this pattern are sidebands separated by the gating repetition frequency.

The data also show a stairlike dependence of $f_M$ on $\overline{V_G}$ because Coulomb blockade modulates the electrostatic tensioning [28–30].

Both fringes and sidebands are reproduced in a simulation [6] of $V_{out}(f_M, f_d)$ by modelling the electrical and mechanical impedances between gate 4 and the cavity output [Fig. 1(c-d)]. From the sharpness of the resonance and the intensity of the interference fringes, the mechanical quality factor can be estimated as $Q_M \approx 700$, while the effective coupling is $\partial C_{CNT}/\partial u \sim 0.3 \times 10^{-12}$ F/m$^{-2}$, roughly consistent with the device geometry [6].

Coulomb blockade effects are not seen in the simulation because results are plotted as a function of $f_M$ rather than $\overline{V_G}$.

In contrast to previous electromechanical measurements of nanotubes [9–15, 19], cavity readout allows detection of mechanical motion even for device configurations where $I$ is unmeasurably small. To access such a configuration, we set $\overline{V_{G2}} = \overline{V_{G3}} = \overline{V_{G4}} = -7250$ mV and we adjust $\overline{V_{G1}} = \overline{V_{GS}} = \overline{V_{TB}}$ to tune the dot tunnel barriers. Figure 3 inset shows how, as an increased $\overline{V_{TB}}$ makes tunnel rates smaller, transport turns-off to an undetectable level ($I \ll 1$ pA) when $\overline{V_{TB}} \geq 4000$ mV. As expected, the mechanical resonance becomes correspondingly unmeasurable in transport [Fig. 3(a)]. However, it is evident in cavity readout across the entire range [Fig. 3(b)]. The oscillations of $f_M$ as a function of $\overline{V_{TB}}$ are an effect of mechanical softening on Coulomb blockade peaks [29, 30] and indicate that the sum of the dot’s tunnel rates to left and right, although not big enough to lead to a detectable current, is at least of the order of $f_M$ ($\Gamma_L + \Gamma_R \gtrsim f_M$).

We now study the mechanical decay rate for different tunnel barrier configurations by directly measuring the ringdown. A time-resolved measurement was previously performed using a fast current amplifier [15], but relied on transport through the device. Since for some barrier configurations, $Q_M$ is known to be limited by tunneling resistance [16, 17, 29, 30], it is of interest to determine the limiting $Q_M$ in an electrically pinched-off nanotube. Extracting a precise linewidth from data as in Fig. 2 is complicated by the interference fringes. We therefore sample the cavity output directly in the time domain. For this experiment, port 1 is connected to an RF source generating a fixed frequency $f_d$ gated with a function $G_m(t)$ and port 3 is connected without gating to an oscilloscope that digitizes $V_{out}$ [Fig. 4 (a-b)]. Typical traces averaged over $\sim 3500$ repetitions are shown in Fig. 4 (c-d) insets. Because the electrical ringdown is close in frequency to the mechanical one, it is not straightforward to separate them in the time domain. Instead, we take a segment of duration $t_\Delta$ from each averaged trace and transform it to give a frequency power spectral density (PSD), in which the mechanical signal appears as a separate peak. For

![FIG. 3. (a) Numerically differentiated $dI/df_d$ as a function of $f_d$ and $\overline{V_{TB}}$ for $P = -38$ dBm and $V_{dd} = 10$ mV. The inset shows $I$ for the same range of $\overline{V_{TB}}$ and same $V_{dd}$ with no microwaves applied. As $\overline{V_{TB}}$ increases, the tunnel barriers are pinched off so that $I$ cannot be detected. (b) Measured $\Delta|S_{31}|^2$ following the scheme in Fig. 2(a) and plotted as a function of $f_d$ and $\overline{V_{TB}}$. The resonance is seen even with transport pinched off. Measurement parameters were $V_S = 0.2$ V, $t_d = t_r = 300$ ns and $t_w \approx 15$ ns.](image-url)
acceptable signal-to-noise, we further average PSD over 1250 traces [Figs. 4 (c-d)].

Figure 4 (e-f) shows two-dimensional maps of PSD plotted as a function of frequency and gate voltage in two gate voltage ranges; one ‘open’ [part of the range in Fig. 2(b-c)] and one ‘closed’ [part of the range in Fig. 3]. After subtracting a background due to purely electrical resonances, the mechanical signal is evident as a gate-dependent peak or dip in PSD.

We calculate $Q_M$ from the linewidth in this PSD. Figure 4(c-d) shows spectral densities at fixed gate voltage settings in open and closed configurations. The mechanical signal is evident as a weak but sharp peak superimposed on a broad background arising from several electrical resonances of the cryostat. The choice of $t_\Delta$ is set by a tradeoff; larger $t_\Delta$ increases the frequency resolution in the PSD and suppresses the background contribution due to the cavity, but also weakens the mechanical peak by incorporating more of the decay. This tradeoff is illustrated by traces for two choices of $t_\Delta$ [Fig. 4 (c-d)]. For an open gate configuration [Fig. 4(c)] the mechanical peak is resolved to a width of $\Delta f_M \approx 0.3$ MHz for $t_\Delta = 3.32 \mu$s, allowing the estimate $Q_M = f_M/\Delta f_M \approx 1000$. For the closed gate configuration [Fig. 4(d)] the peak’s width is not resolved and only a lower bound $Q_M \gtrsim 900$ is extracted. In this device there is therefore no evidence that $Q_M$ is limited by tunnel resistance, despite the modest value compared with other clean nanotube devices [13, 17, 29]. Since the sensitivity does not yet allow single-shot readout, this is a lower bound, incorporating dephasing as well as decoherence [15]. Interestingly, $Q_M$ is slightly higher than measured previously for a stamped nanotube [16].

To set this work in context with other implementations [1], we calculate several measures of the optomechanical interaction, using the geometrically estimated coupling capacitance [6]. The vacuum optomechanical coupling $g_0 = 2\pi f_E \sqrt{2}\eta_{\text{amp}}$, which is the cavity shift due to zero-point displacement $u_{\text{zp}} = \sqrt{\hbar/4\pi m f_M} \approx 2$ pm, is $g_0 \approx 2\pi \times 0.4$ MHz, where $m$ is the nanotube mass [6, 31]. For typical cavity drive of -38 dBm, we estimate the photon occupation as $n_c \approx 8 \times 10^8$, so that the detuned optomechanical strength is $g_D = \sqrt{n_c}g_0 \approx 2\pi \times 35$ Hz. However, the cavity-nanotube interaction near $f_M = f_E$ is parameterized by a resonant coupling $g_R = \frac{\eta_{\text{amp}}}{V_{\text{zp}}}g_0$, where $V_{\text{zp}} \approx 240$ nV is the zero-point voltage on the cavity electrode. Our parameters imply $g_R \approx 2\pi \times 12$ kHz, so that this coupling dominates [6].

This resonant enhancement might allow quantum-limited measurements in the ground state. In a continuous displacement measurement, the uncertainty principle [32–34] limits the position resolution to $\Delta u_{\text{QL}} = \sqrt{2/\ln 3} u_{\text{zp}}$. In a detuned configuration, where measurement is via phase shift to a cavity probe tone, the attainable imprecision at low temperature is typically limited by cavity nonlinearity at high drive power [3]. In our setup, the analog of the probe tone is $\overline{V}_C$, which does not directly excite the cavity. Given an amplifier voltage sensitivity $S_V$, Eq. (1) predicts a vibrational amplitude sensitivity $S_u = S_V/(2\pi f_M Z_{\text{trans}} V_C \sqrt{Z_{\text{trans}}/\eta_{\text{amp}}})$, which for our unoptimized parameters is $S_u \approx 6$ pm/$\sqrt{\text{Hz}}$ [6]. The corresponding imprecision is $\Delta u = S_u \sqrt{\Delta f_M} \approx 1700 \times \Delta u_{\text{QL}}$, limited by amplifier noise. To resolve $\Delta u_{\text{QL}}$ would require a near-quantum-limited external amplifier such as a SQUID [35, 36] as well as an increase in $Z_{\text{trans}}$, $Q_M$, or the coupling strength. With other parameters unchanged, increasing gate length to 550 nm and $\overline{V}_C$ to 65 V would give a quantum backaction imprecision of order $\Delta u_{\text{QL}}$ [6]. This would allow quantum effects to be studied in a resonator near the phonon ground state [6, 37, 38].

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