Optical detection of radio waves through a nanomechanical transducer

T. Bagci,[1] A. Simonsen,[1] S. Schmid,[2] L. G. Villanueva,[2] E. Zeuthen,[1] J. Appel,[1] J. M. Taylor,[3] A. Sørensen,[1] K. Usami,[1] A. Schliesser,[1] and E. S. Polzik[1]

[1]*Niels Bohr Institute, University of Copenhagen, Denmark*

[2]*Department of Micro– and Nanotechnology, Technical University of Denmark, DTU Nanotech, 2800 Kongens Lyngby, Denmark*

[3]*Joint Quantum Institute/NIST, College Park, Maryland, USA*

Abstract

Low-loss transmission and sensitive recovery of weak radio-frequency (rf) and microwave signals is a ubiquitous challenge, crucial in radio astronomy, medical imaging, navigation and communication, including those of quantum states. Efficient upconversion of rf-signals to an optical carrier would allow transmitting them via optical fibers instead of copper wires dramatically reducing losses, and give access to the mature toolbox of quantum optical techniques, routinely enabling quantum-limited signal detection. Research in cavity optomechanics[1,2] has shown that nanomechanical oscillators can couple strongly to either microwave[3–5] or optical fields[6,7]. Here, we demonstrate a room temperature opto-electro-mechanical transducer accommodating both these functionalities following a recent proposal[8] utilizing a high-Q nanomembrane. A voltage bias ($V_{\mathrm{dc}} < 10\,\mathrm{V}$) is sufficient to induce strong coupling[4,6,7] between the voltage fluctuations in an rf resonance circuit and the membrane's displacement, which is *simultaneously* coupled to light reflected off its surface. The rf signals are detected as an optical phase shift with quantum-limited sensitivity. The corresponding half-wave voltage is in the microvolt range, orders of magnitude below that of standard optical modulators. The noise of the transducer — beyond the measured $800\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$ Johnson noise of the LC circuit — consists of the quantum noise of light and thermal fluctuations of the membrane, dominating the noise floor in potential applications in radio astronomy and nuclear magnetic imaging. Each of these contributions is inferred to be $60\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$ when balanced by choosing an electro-mechanical cooperativity $\mathcal{C}_{\mathrm{em}} = 150$ with an optical power of 1 mW. The noise of the membrane has a temperature of $300\,\mathrm{K}/\mathcal{C}_{\mathrm{em}}$. For the highest observed $\mathcal{C}_{\mathrm{em}} \approx 6800$ this leads to a projected $40\,\mathrm{mK}$ noise temperature and a sensitivity limit of $5\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$. Our work introduces a new approach to all-optical, ultralow-noise detection of classical electronic signals, and sets the stage for coherent upconversion of low-frequency quantum signals to the optical domain[8–11].

Opto- and electromechanical systems[1,2] have gained considerable attention recently for their potential as hybrid transducers between otherwise incompatible (quantum) systems, such as photonic, electronic, and spin degrees of freedom[2,10,12]. Coupling of radio-frequency or microwave signals to optical fields via mechanics is particularly attractive for today's, and future quantum technologies. Photon-phonon transfer protocols viable all the way to the quantum regime have already been implemented in both radio- and optical-frequency domains separately[7,13,14].

Among the optomechanical systems that have been considered for radio-to-optical transduction[8–10,15], we choose an approach[8] based on a very high $Q_{\mathrm{m}} \approx 3{\cdot}10^5$ nanomembrane[16,17] which is coupled capacitively[18] to a radio-frequency (rf) resonance circuit, see Figure 1. Together with a four-segment gold electrode, the membrane forms a capacitor, whose capacitance $C_{\mathrm{m}}(x)$ depends on the membrane-electrode distance $d+x$. With a tuning capacitor C_0, the total capacitance $C(x) = C_0 + C_{\mathrm{m}}(x)$ forms a resonance circuit with a typical quality factor $Q_{LC} = \sqrt{L/C}/R = 130$ using a custom-made coil wired on a low-loss ferrite rod, yielding an inductance $L = 0.64\,\mathrm{mH}$ and loss $R \approx 20\,\Omega$. The circuit's resonance frequency $\Omega_{LC} = 1/\sqrt{LC}$ is tuned to the frequency $\Omega_{\mathrm{m}}/2\pi = 0.72\,\mathrm{MHz}$ of the fundamental drum mode of the membrane. The membrane-circuit system is coupled to a propagating optical mode reflected off the membrane.

The electromechanical dynamics is described most generically by the Hamiltonian[8]

$$H = \frac{\phi^2}{2L} + \frac{p^2}{2m} + \frac{m\Omega_m^2 x^2}{2} + \frac{q^2}{2C(x)} - qV_{\mathrm{dc}} \tag{1}$$

where ϕ and q, the flux in the inductor and the charge on the capacitors, are conjugate variables for the LC circuit; x and p denote the position and momentum of the membrane with an effective mass m. The last two terms represent the charging energy $U_C(x)$ of the capacitors, which can be offset by an externally applied bias voltage V_{dc} (Fig. 1). This energy corresponding to the charge $\bar{q} = V_{\mathrm{dc}}\,C(\bar{x})$ leads to a new equilibrium position $\bar{x}$ of the membrane. Furthermore, the position-dependent capacitive force $F_C(x) = -\frac{dU_C}{dx}$ causes spring softening, reducing the membrane's motional eigenfrequency by $\Delta\Omega_{\mathrm{m}} \approx -C''(\bar{x})V_{\mathrm{dc}}^2/2m\Omega_{\mathrm{m}}$.[19]

Much richer dynamics than this shift may be expected from the mutually coupled system (1). For small excursions $(\delta q, \delta x)$ around the equilibrium $(\bar{q}, \bar{x})$, it can be described by the linearised interaction term[8] (see SI)

$$H_{\rm I} = G\delta q\delta x = \hbar g_{\rm em}\frac{\delta q}{\sqrt{\hbar/2L\Omega_{LC}}}\frac{\delta x}{\sqrt{\hbar/2m\Omega_{\rm m}}}, \tag{2}$$

parametrized either by the coupling parameter $G = -V_{\rm dc}\frac{C'(\bar{x})}{C(\bar{x})}$ or the electromechanical coupling energy $\hbar g_{\rm em}$. This coupling leads to an exchange of energy between the electronic and mechanical subsystems at the rate $g_{\rm em}$; if this rate exceeds their dissipation rates $\Gamma_{LC} = \Omega_{LC}/Q_{LC}$, $\Gamma_{\rm m} = \Omega_{\rm m}/Q_{\rm m}$, they hybridise into a strongly coupled electromechanical system[4,6,7]. Our system is deeply in the strong coupling regime ($2g_{\rm em} = 2\pi\cdot 27\,{\rm kHz} > \Gamma_{LC} = 2\pi\cdot 5.5\,{\rm kHz} \gg \Gamma_{\rm m} = 2\pi\cdot 20\,{\rm Hz}$) for a distance $d = 1\,\mu$m and a bias voltage of $V_{\rm dc} = 21\,$V (Fig. 1c). Here, for the first time, we detect the strong coupling using an independent optical probe on the mechanical system.

We have performed an experimental series, in which the bias voltage is systematically increased, with a different sample and a larger distance $d = 5.5\,\mu$m and lower mechanical dissipation $\Gamma_{\rm m}/2\pi = 2.3\,$Hz. The system is excited inductively through port '2' (Fig. 1b), inducing a weak radio wave signal of (r.m.s) amplitude $V_{\rm s} = 670\,$nV, at a frequency $\Omega \approx \Omega_{LC}$. The response of the coupled system can be measured both electrically as the voltage across the capacitors (port '1' in Fig. 1b) and optically by analyzing the phase shift of a light beam (wavelength $\lambda = 633\,$nm) reflected off the membrane. Both signals are recorded with a lock-in amplifier, which also provides the excitation signal.

The electrically measured response (Fig. 2a) clearly shows the signature of a mechanically induced transparency[20] indicated by the dip in the LC resonance curve. Independently, we observe the rf signal in the LC circuit optically via the membrane mechanical dynamics (Fig. 2b). In particular, the electromechanical coupling leads to broadening of the mechanical resonanceto a new effective linewidth $\Gamma_{\rm eff} = (1+\mathcal{C}_{\rm em})\cdot\Gamma_{\rm m}$, where $\mathcal{C}_{\rm em}$ is the electromechanical cooperativity

$$\mathcal{C}_{\rm em} = \frac{4g_{\rm em}^2}{\Gamma_{\rm m}\Gamma_{LC}}. \tag{3}$$

The width of the induced transparency dip and the mechanical linewidth grow in unison, and in agreement with our expectations as $\Gamma_{\rm eff} \propto V_{\rm dc}^2$ (inset). Both these features also shift to lower frequencies as the bias voltage is increased, following the expected $\Delta\Omega_{\rm m} \propto -V_{\rm dc}^2$ dependence[19]. Note that in each experiment we have tuned the LC resonance frequency to $\Omega_{\rm m}$.

Using the model based on the full Langevin equations (SI), derived from the Hamiltonian (1), we fit the electronically and optically measured curves, and obtain fit parameters Ω_{m}, Ω_{LC}, Γ_{LC}, and G which for the two curves agree typically within 1%. Together with the intrinsic damping determined independently from thermally driven spectra, the system's dynamics can be quantitatively predicted. Our data analysis allows us to quantify the coupling strength in three independent ways, by (i) analysis of the mechanical responses' spectral shape, (ii) comparison of the voltage and displacement modulation amplitudes, and (iii) the frequency shift[19] of the mechanical mode. Finally we compare these experimental values with (iv) a theoretical estimate accounting for the geometry of the electromechanical transducer. For $V_{\mathrm{dc}} = 125$ V we find $G = 10.3\,\mathrm{kV/m}$ following the first method, and similar values using the three others (SI), corroborating our thorough understanding of the system.

In another experimental run ($d = 4.5\,\mu$m, Fig. 3), we have characterised the strong electromechanical coupling[3,4,14] via the normal mode splitting giving rise to an avoided crossing of the resonances of the electronic circuit and the mechanical mode, as the latter is tuned through the former using the capacitive spring effect[19]. In contrast to earlier observations[4,6,7] we can simultaneously witness the strong coupling through the optical readout, in which the recorded light phase reproduces the membrane motion (Fig. 3c,e). Again, the predictions derived from the Langevin equations are in excellent agreement with our observations, yielding a cooperativity of $\mathcal{C}_{\mathrm{em}} = 3800$ for these data with $m = 24\,\mathrm{ng}$, $\Gamma_{\mathrm{m}}/2\pi = 3.1\,\mathrm{Hz}$.

We now turn to the performance of this interface as an rf-to-optical transducer. A relevant figure of merit for the purpose of bringing small signals onto an optical carrier is the voltage V_π required at the input of the series circuit in order to induce an optical phase shift of π. Achieving minimal V_π requires a tradeoff between strong coupling and induced mechanical damping. For the optimal cooperativity $\mathcal{C}_{\mathrm{em}} = 1$ we find

$$V_\pi = \frac{1}{2}\sqrt{mL\Gamma_{\mathrm{m}}\Gamma_{LC}}\lambda\Omega_{\mathrm{r}} \approx 140\,\mu\mathrm{V} \tag{4}$$

at resonance ($\Omega_{\mathrm{r}} \equiv \Omega_{\mathrm{m}} = \Omega_{LC} = \Omega$), orders of magnitude below commercial modulators optimised for decades by the telecom industry, but also explorative microwave photonic devices[21,22] based on electronic nonlinearities. It is interesting to relate this performance to more fundamental entities, namely the electromagnetic field's quanta that constitute the signal. Indeed it is possible to show that the *quantum* conversion efficiency, defined here as the ratio of optical sideband photons to the rf quanta extracted from the source $V_{\mathrm{s}}I/\hbar\Omega_{\mathrm{LC}}$

for $C_{\rm em} \gg 1$, is given by (see SI)

$$\eta_{\rm eo} = 4(kx_{\rm zpf})^2 \frac{\Phi_{\rm car}}{\Gamma_{\rm m}}. \tag{5}$$

This corresponds to the squared effective Lamb-Dicke parameter $(kx_{\rm zpf})^2 = (2\pi/\lambda)^2\hbar/(2m\Omega_{\rm m})$ enhanced by the number of photons sampling the membrane during the membrane excitations' lifetime ($\Phi_{\rm car}$ is the photon flux and k the wavenumber). For the experiments shown in fig. 2, we deduce a conversion efficiency of 0.8% from the independently measured RF voltage and optical phase modulation. While this result is limited by the optical power in this interferometer, we have tested that the membranes can support optical readout powers of more than $\Phi_{\rm car}hc/\lambda = 20\,\rm mW$ without degradation of their (intrinsic) linewidth and thus project that conversion efficiencies on the order of 50% are available. Note that this transducer constitutes a phase-insensitive amplifier, and can thus reach conversion efficiencies above one—at the expense of added quantum noise.

For the recovery of weak signals, the sensitivity and bandwidth of the interface is of greatest interest. The signal at the optical output of the device is the interferometrically measured spectral density of the optical phase φ of the light reflected off the membrane,

$$S_{\varphi\varphi}^{\rm tot} = (2k)^2 \left|\chi_{\rm m}^{\rm eff}\right|^2 \left(\left|G\chi_{LC}\right|^2 S_{VV} + S_{FF}^{\rm th}\right) + S_{\varphi\varphi}^{\rm im}. \tag{6}$$

The voltage V_s at the input of the resonance circuit (denoted here as its spectral density S_{VV}) is transduced to a phase shift via the circuit's susceptibility χ_{LC}, the coupling G, the effective membrane susceptibility $\chi_{\rm m}^{\rm eff}$ and the optical wavenumber k (see SI). The sensitivity is determined by the noise added within the interface. This includes in particular, the imprecision in the phase measurement ($S_{\varphi\varphi}^{\rm im}$), but also the random thermal motion of the membrane induced by the Langevin force ($S_{FF}^{\rm th}$). The former depends on the performance of the employed interferometric detector and can be quantum-limited ($S_{\varphi\varphi}^{\rm im} \sim \Phi_{\rm car}^{-1}$).

We demonstrate the sensitivity and the noise performance of the transduction scheme by measuring the noise as a function of the input circuit resistor and its temperature (Fig. 4). As the high-Q homemade inductor is too sensitive to the ambient rf radiation (see SI), we use a shielded commercial inductor (Picoelectronics) resulting in a lower $Q_{\rm LC} = 47$ for these measurements. Fig. 4a and Fig. 4b present optically measured noise spectrum and corresponding to it voltage noise, respectively (red). On resonance the dominant contribution is the Johnson noise ($S_{VV}^{\rm J} \approx (800\,\rm pV)^2/Hz$) of the circuit (violet). Off resonance optical quantum (shot) noise (yellow) limits the phase sensitivity to $S_{\varphi\varphi}^{\mathrm{im}} = (18\,\mathrm{nrad})^2/\mathrm{Hz}$, corresponding to membrane displacements of $(1.5\,\mathrm{fm})^2/\mathrm{Hz}$. In this experiment, we use a home-built interferometer operating at $\lambda = 1064\,\mathrm{nm}$ and with a light power of $\sim 1\,\mathrm{mW}$ returned from a membrane with $m = 64\,\mathrm{ng}$ and $\Gamma_{\mathrm{m}}/2\pi = 20\,\mathrm{Hz}$. $\sqrt{S_{\varphi\varphi}^{\mathrm{im}}}$ can be translated to a voltage sensitivity limit by division with the transfer function $|\chi^{\mathrm{tot}}| \equiv |2k\chi_{\mathrm{m}}^{\mathrm{eff}} G \chi_{LC}|$ of the transducer. With the cooperativity $\mathcal{C}_{\mathrm{em}} = 150$ chosen here, this corresponds to a voltage noise level of $60\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$ within the resonant bandwidth of this proof-of-principle transducer, but higher powers, and more sensitive optomechanical transduction[16,23] could readily improve this number. From our model, we furthermore deduce that the contribution of the thermal motion of the membrane adds an equal amount of voltage noise (green line in fig. 4b), so that, at this cooperativity, these noise contributions are balanced and their sum minimised to $84\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$.

Further analysis of the transducer noise has been performed by measurements with an additional, "source", resistor R_{s} in series with the inductor of the circuit (Fig. 4c). The input to the circuit thus consists of the Johnson noise of both resistors, $(S_{VV}^{\mathrm{J}})' = 2k_{\mathrm{B}}(RT_R + R_{\mathrm{s}}T_{\mathrm{s}})$. We cool the source resistor using liquid nitrogen, and optically measure the displacement of the membrane both at room ($T_{\mathrm{s}} = 300\,\mathrm{K}$) and nitrogen temperature ($T_{\mathrm{s}} = 77\,\mathrm{K}$). We can thus determine the amount of noise added by the transducer using the Y-factor method[24]. From eq. (6), we expect to find a noise temperature of (see SI)

$$T_{\mathrm{n}} = \left(\frac{1}{\eta_{\mathrm{e}}} - 1\right) T_R + \frac{1}{\eta_{\mathrm{e}}}\left(\frac{1}{\mathcal{C}_{\mathrm{em}}} T_{\mathrm{m}} + \frac{(1+\mathcal{C}_{\mathrm{em}})^2}{\mathcal{C}_{\mathrm{em}}} T_{\mathrm{L}}\right) \tag{7}$$

at resonance, where the three summands are due to the Johnson noise of the circuit's loss $R = 60\,\Omega$ at $T_R = 300\,\mathrm{K}$, the membrane's thermal fluctuations ($T_{\mathrm{m}} = 300\,\mathrm{K}$), and the noise in the optical readout ($T_{\mathrm{L}} \approx 50\,\mathrm{mK}$), respectively. Note that both the circuit's loading $\eta_{\mathrm{e}} = \frac{R_{\mathrm{s}}}{R_{\mathrm{s}}+R}$ and the cooperativity $\mathcal{C}_{\mathrm{em}} = \frac{R}{R_{\mathrm{s}}+R} \cdot \mathcal{C}_{\mathrm{em}}(R_{\mathrm{s}} = 0\,\Omega)$ are now a function of the source resistance. In this experiment, we vary the cooperativity by varying the source resistor from $\mathcal{C}_{\mathrm{em}}(R_{\mathrm{s}} = 0\,\Omega) = 550$ to $\mathcal{C}_{\mathrm{em}}(R_{\mathrm{s}} = 2\,\mathrm{k}\Omega) = 18$, and find a noise temperature overall consistent with eq. (7), with the lowest measured value reaching down to 24 K (Fig. 4c).

The challenge of engineering a low-loss, overcoupled electronic resonance circuit ($\eta_{\mathrm{e}} \to 1$) aside, the transducer itself adds only very little noise (green and yellow lines in Fig. 4c, representing the second and third terms in eq. (7), respectively). For example, at a cooperativity of $\mathcal{C}_{\mathrm{em}} = 70$ achieved with $R_{\mathrm{s}} = 400\,\Omega$, subtracting the Johnson noise from the total noise yields respective noise temperatures of 4 K. Remarkably, the membrane contribution, which can usually only be suppressed by cryogenic cooling, is strongly reduced by the cooperativity parameter ($\propto T_{\mathrm{m}}/\mathcal{C}_{\mathrm{em}}$). The highest cooperativity we have obtained is $\mathcal{C}_{\mathrm{em}} = 6800$, by applying eq. (3) to the data of Figure 1c. This implies that membrane noise temperatures down to 40 mK can be expected, corresponding here to a voltage noise level of $5\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$.

For comparison, we have performed measurements with an arrangement of ultralow-noise operational amplifiers connected directly to port '1'. The amplifier is based on junction field effect transistors (JFETs) and combines low input voltage noise (nominally, $4\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$) with extremely low current noise (nominally, $2.5\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$), as required[24] for measurements on a relatively high source impedance, which here amounts to $RQ_{\mathrm{LC}}^2 \approx 140\,\mathrm{k}\Omega$ at port '1'. In practice, with a gain of 1000, the best voltage sensitivity we have obtained is only $S_{VV}^{\mathrm{oa,tot}}(\Omega_{LC}) = (130\,\mathrm{pV})^2/\mathrm{Hz}$ over the bandwidth of the LC resonance. Similar performance levels—on a par with the transducer discussed here—are expected even for ideal operation of other amplifiers described in the scientific and technical literature (SI). Beyond being competitive with standard electronics in its noise figures, our transducer provides a new functionality due to the direct compatibility with fiber optical communication lines. The presented electrooptomechanical transducer also compares very favorably with previous proof-of-principle mechanical amplifiers for radio-frequency[25] and microwave[26] radiation (SI).

As our transducer noise floor is well below the room temperature Johnson noise from the circuit's $R = 60\,\Omega$, this approach can be of particular relevance in applications where electronic Johnson noise is suppressed. For example, for direct electronic (quantum) signal transduction, the resonance circuit is overloaded ($\eta_{\mathrm{e}} \to 1$) with a cold transmission line which carries the signal of interest. In radio astronomy[27], highly efficient antennas looking at the cold sky can have noise temperatures significantly below room temperature. The usually required cryogenically cooled pre-amplifiers might be replaced by our transducer—a critical advantage for satellite missions—and extension to GHz frequencies should be straightforward using ac driving[4]. Direct and efficient conversion of rf signals into optics could save significant resources in large phased-arrays antennae. Finally, in nuclear-magnetic resonance experiments including imaging, cooled pickup circuits can deliver a significant sensitivity improvement, yet this approach is challenging current amplifier technology[28,29].

METHODS SUMMARY

The capacitor is fabricated by standard cleanroom microfabrication techniques. Electrodes made of gold (200 nm thick) are deposited on a glass substrate and structured by ion-beam etching. Each segment is 400 μm long, with 60 μm gaps between the segments. Pillars of a certain height (600 nm, 1μm) are placed to define the membrane-electrode distance. The inductor is wound with Litz wires to ensure high Q-factor. A variable trimming capacitor is used to tune the resonance frequency of the LC circuit.

The mechanical resonator consists of a 50 nm thick Aluminum layer on top of a high-stress stoichometric SiN layer with a thickness of 100 nm and 180 nm for different samples. The Al layer is deposited on top of the whole wafer after the membranes have been released. Photolithography and chemical etching are subsequently used to remove the metal from the anchoring regions and from a circle in the middle of the membrane. The metal layer on SiN typically causes a 10% decrease in the eigenfrequency of the fundamental mode.

Optical interferometry is carried out via a commercial Doppler vibrometer (MSA-500 Polytec) and a home made Michelson interferometer (for the data set in Fig.4). The home made Michelson interferometer utilizes shot noise limited balanced-homodyne detection with a high-bandwidth (0-75MHz) InGaAs receiver. The two DC outputs from the detector are used to generate the differential error signal, which is then fed to the piezo in the reference arm for locking the interferometer. The rf output of the detector is high-pass filtered and fed to a spectrum analyzer in order to record the vibrations of the membrane. Absolute calibration of the mechanical amplitude is carried out via a known modulation of the piezo at a frequency close to the mechanical peak.

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Supplementary Information is linked to the online version of the paper.

ACKNOWLEDGMENTS

This work was supported by the DARPA project QUASAR, the European Union Seventh Framework Program through SIQS (grant no. 600645) and iQUOEMS (grant no. 323924), the ERC grants QIOS (grant no. 306576) , INTERFACE (grant no. 291038) . We would like to thank Jörg Helge Müller for valuable discussions, Andreas Barg and Andreas Næsby for assistance with the interferometer, and Louise Jørgensen for cleanroom support.

CONTRIBUTIONS

T.B., A.Sim., S.S., K.U., A. Sch. performed the experiments and analyzed the data, L.G.V. and S.S. designed and fabricated the membrane and the capacitor, J. A. designed the electronic readout circuit, J.M.T., K.U., A. Sør., A. Sch., E.Z., E.S.P. developed the model, T.B., A. Sch., E.S.P. wrote the paper. A. Sch. coordinated most of the work. E.S.P. conceived and supervised the project. All authors discussed the results and contributed to the manuscript.

AUTHOR INFORMATION

Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to E.S.P. (polzik@nbi.dk) or A.Sch. (albert.schliesser@nbi.dk).

LEGENDS

1. FIGURE 1

Optoelectromechanical system.

(**a**) An Al-coated[30] SiN 500μm square membrane in vacuum ($< 10^{-5}$ mbar) forms a position-dependent capacitor $C_{\rm m}(x = 0) \approx 0.5\,{\rm pF}$ with a planar 4-segment gold electrode in the immediate vicinity ($0.9\,\mu{\rm m} \lesssim d \lesssim 6\,\mu{\rm m}$). The membrane electrode's potential is electrically floating. The membrane's displacement is converted into a phase shift of the laser beam reflected off the membrane. (**b**) The membrane capacitor is part of an LC-circuit, tuned to the mechanical resonance frequency by means of a tuning capacitor $C_0 \approx 80\,{\rm pF}$ (see SI). A bias voltage $V_{\rm dc}$ couples the excitations of the LC-circuit to the membrane's motion. The circuit is driven by a voltage $V_{\rm s}$, which can be injected through the coupling port '2' or picked up by the inductor from the ambient rf radiation. (**c**) For $d = 1\mu$m, the optically observed response of the membrane to a weak excitation of the system shows a split peak (dashed lines: fitted Lorentzian resonances), due to strong electro-mechanical coupling.

2. FIGURE 2

Mechanically induced transparency.

Response of the coupled system to a weak excitation at frequency Ω (through port '2' in Fig. 1b) probed through (**a**) the voltage modulation in the LC circuit (at port '1'), and (**b**) the optical phase shift. The data (coloured dots) measured for five different bias voltages agree excellently with model fits (curves) corresponding to $g_{\rm em}/2\pi = \{280, 470, 810, 1030, 1290\}$ Hz. Each curve is offset so that its baseline corresponds to the $V_{\rm dc}$ indicated between the panels. Grey points indicate $\Omega_{\rm m}$ values extracted for each set of data. A shift $\Delta\Omega_{\rm m} \propto -V_{\rm DC}^2$ is fitted with the dashed line. The inset shows the effective linewidth of the mechanical resonance extracted from full model fits to the electrically (circles) and optically (boxes) measured response and simple Lorentzian fits to the optical data (diamonds).

3. FIGURE 3

Strong coupling regime.

(**a**) Measured coherent coupling rate $2g_{\mathrm{em}}/2\pi$ as a function of bias voltage (points) and linear fit (line). The shaded area indicates the dissipation rate $\Gamma_{\mathrm{LC}}/2\pi \approx 5.9\,\mathrm{kHz}$ of the LC circuit. (**b-e**) Normalised response of the coupled system as measured on port '1' (Fig. 1c) (**b,d**) and via the optical phase shift induced by membrane displacements (**c,e**). Upon tuning of the bias voltage the mechanical resonance frequency is tuned through the LC resonance, but due to the strong coupling an avoided crossing is very clearly observed. Panels (**d,e**) show the spectra corresponding to the orange line in (**b,c**), at $V_{\mathrm{dc}} = 242\,\mathrm{V}$, where the electronic and mechanical resonance frequencies coincide. Points are data, orange line is the fit of the model.

4. FIGURE 4

Voltage sensitivity and noise.

Noise characterisation of the transducer with contributions from Johnson noise (violet), optical quantum phase noise (yellow), and membrane thermal noise (green). (**a**) Optically measured noise (red) is well reproduced by a model $\sqrt{S_{\varphi\varphi}^{\mathrm{tot}}}$ (blue). (**b**) Data and models as in (a), but divided by the interface's response function $|\chi_{\mathrm{tot}}|$, and thus referenced to the voltage V_{s} induced in the antenna. (**c**) Noise temperature of the amplifier and its standard deviation. It is determined using the Y-factor method, at the resonance frequency (dark red points), and in a 10 kHz wide band around the resonance (light red points), as a function of external loading. Lines are the model of eq. (7), broken down into contributions as in a and b. Inset shows one example of a noise temperature measurement at $R_{\mathrm{s}} = 1250\,\Omega$.