Enhanced radio frequency sensing with an optoelectromechanical transducer

Najmeh Eshaqi-Sani[1,2], **Stefano Zippilli**[1], **David Vitali**[1,3,4]

1. *Physics Division, School of Science and Technology, University of Camerino, Camerino, MC I-62032, Italy*
2. *School of Physics, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran*
3. *INFN, Sezione di Perugia, via A. Pascoli, Perugia, Italy*
4. *CNR-INO, L.go Enrico Fermi 6, Firenze I-50125, Italy*

Abstract: We investigate enhanced sensitivity in detecting perturbations of an optoelectromechanical system by detecting its response at radio frequencies. We demonstrate enhanced signal to noise ratio due to impedance matching and suppressed thermal noise.

The precise control and sensitive detection of rf signals are essential for a wide range of modern technologies, including communication, sensing, and highly sensitive astronomical metrology. However, thermal noise represents a fundamental challenge for quantum operations at these frequencies.

Here, we study an optoelectromechanical system in which one or two vibrational modes of a mechanical element mediate the interaction between the optical field of a cavity and the rf field of an LC resonator (see Fig. 1) [1]. In the impedance-matching regime, where rf input fields experience no reflection, thermal noise is redistributed among system elements, and the rf output noise approaches the quantum vacuum level. By leveraging this mechanism, we show that a rf probe field reflected from this system, exhibits reduced noise. Consequently, detecting variations in a system parameter using this probe field achieves significantly enhanced sensitivity, characterized by an improved signal-to-noise ratio (SNR). In particular, here we analyze this effect to probe small perturbations in the capacitance of the rf resonator [1]. The performance is compared with the signal-to-noise ratio of a simple rf resonator (SNR_0), and the enhancement is quantified in terms of the relative signal-to-noise ratio $r=SNR/SNR_0$ (Figs. 2 and 3).

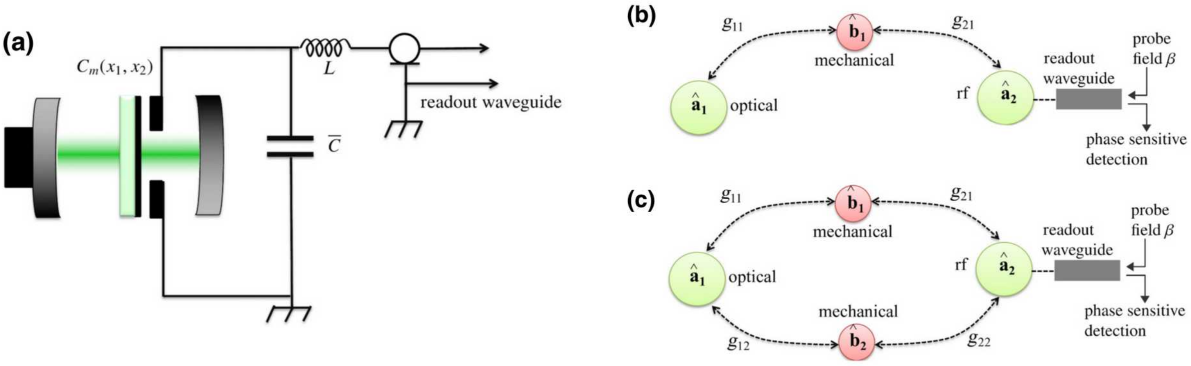

Fig. 1 (a) The optoelectromechanical system, where a mechanical elemement interact with the light of an optical cavity and to LC resonator via the capacitance C_m. The capacitance is influenced by external factors, causing a small perturbation that we aim to detect. (b),(c) Schematic representation of the system with one (b) and two (c) vibrational modes. The transmission between the optical and rf ports is mediated by the mechanical resonators. The system response is analyzed by injecting a probe field (of amplitude β) through the readout waveguide attached to the LC resonator.

We analyze two configurations of the system: one involving a single mechanical resonator (three-mode model) and the other with two resonators (four-mode model), see Fig. 1 (b) and (c). The performance of both setups are investigated across various parameters, such as cooperativity (Γ), temperature (T), and detection efficiency (η), and under various operational regimes (see Figs. 2 and 3), revealing that impedance matching is critical for achieving noise suppression and enhanced sensitivity. Specific parameter regimes are identified where each model achieves optimal performance based on the relative frequencies of the mechanical and rf modes.

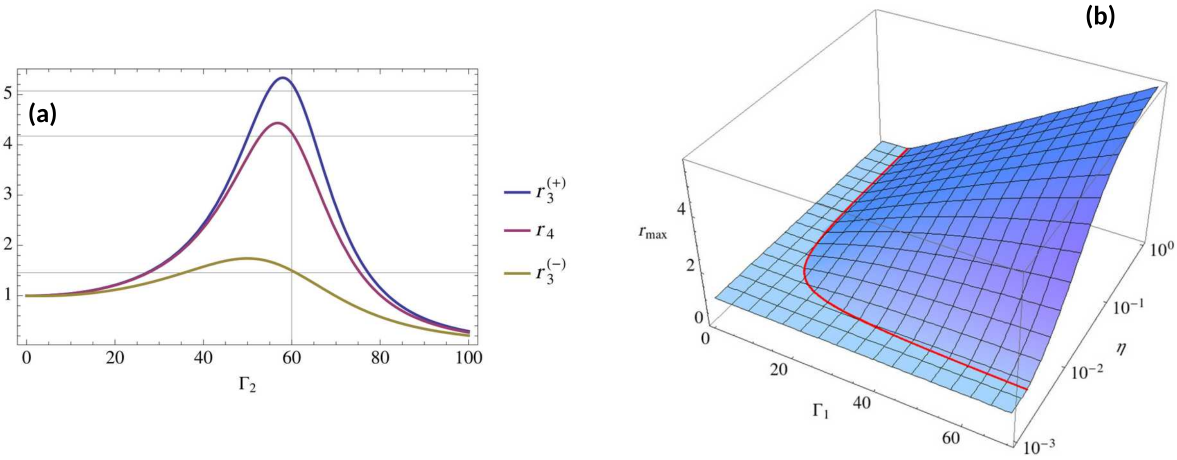

Fig. 2 (a) Relative signal-to-noise ratio as a function of the electromechanical cooperativity Γ_2=$g_1/\gamma_m\gamma_{LC}$ (with γ_m the mechanical decay rate, g_2 the electromechanical coupling and γ_{LC} the decay rate of the LC resonator), when the optomechanical cooperativity is fixed at the value indicated by the vertical thin line, Γ_1=$g_1/\gamma_m\kappa$ = 60 (with g_1 the optomechanical coupling and κ the decay rate of the optical field). The central curve (r_4) corresponds to the four-modes model. The upper ($r_3^{(+)}$) and lower ($r_3^{(-)}$) curves correspond to the three-modes models with mechanical frequency larger and smaller than the LC resonance frequency. The horizontal thin solid lines indicate the values achieved under the conditions of perfect impedance matching. (b) Relative signal-to-noise ratio for the four-modes model as a function of the optomechanical cooperativity parameter Γ_1 and the detection efficiency η, optimized over the electromechanical cooperativity Γ_2. The red line separates the region of enhanced sensnitivity (where $r_{\max} > 1$), from that of no enhancement (where $r_{\max} = 1$). The other system parameters are ω_{LC} = 5 MHz, γ_{LC} = 6 kHz, ω_{m1} = 2 MHz, ω_{m2} = 8 MHz, γ_m = 500 Hz. The temperature is T = 0.1 K.

Notably, the enhancement is observed over a wide range of temperatures, and it is effective also with noisy rf systems operating in the high-temperature regime, see Fig. 3.

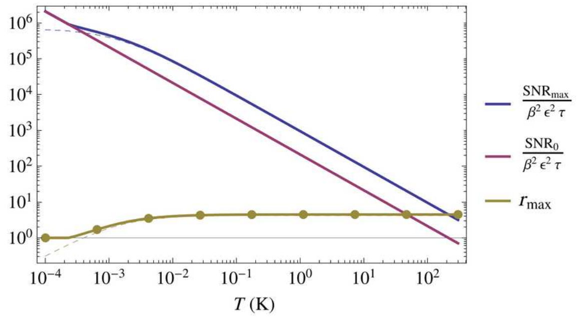

Fig. 3 Analysis of the signal-to-noise ratio as a function of the temperature T for the four-modes model. The other parameters are as in Fig. 1.

We also highlight that, while the four-mode model can operate in a nonreciprocal regime [2], and related works have shown that nonreciprocity can enhance sensitivity in similar systems [3], in the present case, nonreciprocity does not offer additional advantages.

To conclude, this work provides a comprehensive analysis of the response of an optoelectromechanical systems to a radiofrequency porbe field and explores how this response can be leveraged for quantum-enhanced sensing of variations of system parameters. The enhancement is achieved in a regime of impedance matching where rf noise is significantly suppressed.

References

[1] Najmeh Eshaqi-Sani, Stefano Zippilli, David Vitali, “Optics-assisted enhanced sensing at radio frequencies in an optoelectromechanical system”, Phys. Rev. Appl. **22**, 014003 (2024).

[2] Najmeh Eshaqi-Sani, Stefano Zippilli, David Vitali, “Nonreciprocal conversion between radio-frequency and optical photons with an optoelectromechanical system”, Phys. Rev. A **106**, 032606 (2022).

[3] Hoi-Kwan Lau, Aashish A. Clerk, “Fundamental limits and non-reciprocal approaches in non-Hermitian quantum sensing”, Nat. Commun. **9**, 4320 (2018).