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Quadrature-Resolved Dissipative Optomechanical Measurement

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Abstract: We present a homodyne detection scheme to reliably measure the dissipative coupling in optomechanical systems. Our method is validated on silicon devices yielding $G_{\kappa_e}/G_{\omega} = -0.007 \pm 0.001$.

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The bulk of research performed towards the understanding of the interplay between optical cavities and their mechanical degrees of freedom has been carried out by focusing only on the so-called dispersive coupling [1], $G_\omega = -\frac{d\omega_c}{dx}$. This interaction emerges from the cavity resonance frequency (ω_c) dependency on the position of a mechanical oscillator (lumped displacement x). However, there are constraints to this interaction: optomechanical ground-state cooling, which is theoretically and experimentally founded on dispersive coupling, requires an optical cavity operating in the sideband-resolved regime, where the optical decay rate, κ, is smaller than the mechanical oscillation frequency, Ω_m [2]. Such constraint breeds demanding requirements for an optical cavity while limiting the usage of low frequencies (10-100 MHz) mechanical oscillators as quantum memories. A new manifestation of the optomechanical interaction, where the motion of the mechanical oscillator modulates the optical decay, was introduced in the last decade [3]. This interaction, coined dissipative coupling, $G_\kappa = \frac{d\kappa}{dx}$, renders optomechanical ground-state cooling possible even for the sideband-unresolved regime ($\kappa > \Omega_m$). This new route considerably expands the realm of opportunity for optomechanics in studying quantum phenomena in systems progressively closer to the macroscopic. Recent work was able to bridge the gap between theoretical frameworks and computational simulations towards devices optimization [4]. However, the development of efficient dissipative optomechanical systems has been hampered by the lack of reliable experimental methods to characterize G_κ and G_ω simultaneously.

When a purely dispersive optomechanical system ($G_\kappa = 0$) is driven at resonance ($\Delta = \omega_l - \omega_c = 0$; ω_l is the laser frequency) the mechanical oscillator motion is imprinted into a phase modulation of the optical field leaving the cavity. However, considering the same detuning for a purely dissipative system, mechanical motion generates fluctuations in the amplitude of the cavity's optical field as illustrated in Fig. 1**a)**. In realistic devices however, both effects take place concomitantly. Due to the distinct nature of these phenomena, their effects operate independently in different quadratures - phase and amplitude - of the electromagnetic field. To profit from this insight, we introduce a novel approach to gauge the dissipative optomechanical coupling through a quadrature-sensitive measurement based on homodyne detection.

The optomechanical system employed in this work comprises a pair of coupled cavities placed laterally to an integrated waveguide, as can be observed in Fig. 1**b)**. The cavities, manufactured on a Silicon-on-Insulator (SOI) platform, consist of periodically-patterned silicon beams. An adiabatic defect in their central region allows for highly confined, low-loss, optical modes. The beams' electromagnetic response interacts to hybridize into symmetric and anti-symmetric supermodes. For this work, we shall focus, without loss of generality, on the symmetric mode, shown in Fig. 1**c)**. In addition, the beams are physically coupled at their extremities, enabling the existence of a "zipper" mechanical mode (Fig. 1**d)**). The mechanical motion then modulates both inter-cavity and waveguide-cavity distances, giving rise to dispersive and dissipative coupling as both the resonance frequency and waveguide coupling rate, κ_e, are modulated.

In this work, the dissipative coupling was gauged through a homodyne measurement in which the weak cavity signal, containing the information of the mechanical oscillator, is combined with a stronger local oscillator and fed to a balanced homodyne detector. The photocurrent power spectral density at the detector, $S_{\text{II}}(\Omega)$, was measured as a function of the relative phase ϕ, between the local oscillator and the cavity optical signal in order to acquire information about different quadratures of the optical field. Fig. 1**e)** contains an example of the RF spectrum of the homodyne detector and a fit of the mechanical spectrum for the "zipper" mode at $\Omega/(2\pi) \approx 20$ MHz with quality factor $Q \approx 10^4$ at room temperature. The analyzed optical mode has a coupling rate $\kappa_e/(2\pi) \approx 20$ MHz and linewidth $\kappa/(2\pi) \approx 130$ MHz thus placing the system in the sideband-unresolved regime. The quadrature-resolved mechanical amplitude, $S_{\mathrm{II}}(\Omega_m)$ is shown in Fig. 1**f)** together with a fit yielding $G_{\kappa_e}/G_\omega \approx -0.007 \pm 0.001$.

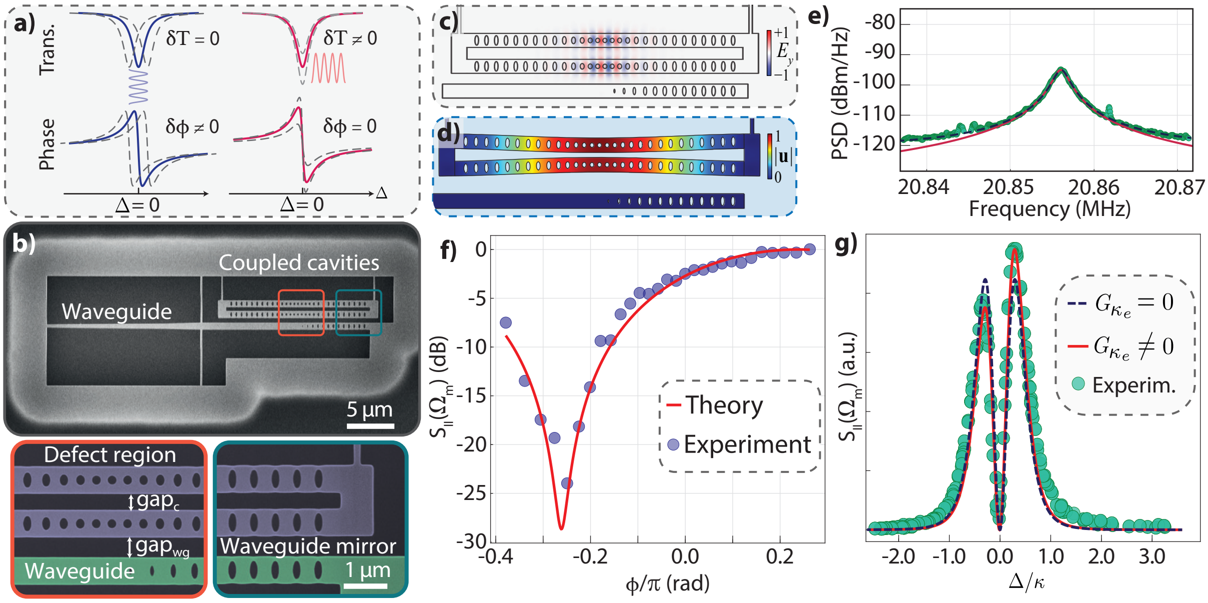

Fig. 1. **a)** Dispersive and dissipative effects on optical field quadratures for an optomechanical system driven close to resonance. **b)** Scanning electron microscopy image of the fabricated device. Green: tapered waveguide used for coupling and collecting light; Blue: silicon photonic crystal coupled cavities. **c)** Finite Element Method simulations for the coupled nanobeams showing the fundamental symmetrical optical mode E_y. **d)** Finite element simulations for the low frequency "zipper" mechanical mode. **e)** In green, mechanical power spectral density for the "zipper" mode near 20 MHz with a fit in red yielding $Q \approx 10^4$. **f)** Normalized measured signal of the homodyne detection for the mechanical mode as a function of the relative phase ϕ between the local oscillator and the cavity output field and theoretical fit yielding $G_{\kappa_e}/G_\omega \approx -0.007 \pm 0.001$. **g)** Mechanical transduction as a function of detuning. Measured experimental data is in green and the theoretical curves for the dispersive (dissipative) case in black (red).

Our measurement of the dissipative coupling is further compared with results employing a different methodology [5]. As can be noted in Fig. 1**g)**, an apparent asymmetry is observed between a detuned blue ($\Delta > 0$) and red detuned ($\Delta < 0$) laser. Considering that optical powers were held sufficiently low to prevent dynamical backaction effects, such asymmetry can only be explained by a model that encompasses both G_κ and G_ω. The theoretical curves in Fig. 1**g)** were obtained using the values from the fit in Fig. 1**f)**.

In conclusion, we propose a reliable approach for measuring the relative strength between dispersive and dissipative coupling in optomechanical systems. In our talk, we will present additional data demonstrating this method's ability to improve the measurement uncertainty when benchmarked against previous techniques. The framework presented in this work overcomes the constraints in previous experiments in which complex, multi-variable fits were employed to estimate G_κ, hence leading to considerable uncertainties. This work is an important step towards the engineering of the next generation of optomechanical cavities with large dissipative couplings.

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