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High-Frequency Dissipative Optomechanics

André G. Primo[*,1], **Pedro V. Pinho**[*,1], **Rodrigo Benevides**[2], **Simon Gröblacher**[3], **Gustavo S. Wiederhecker**[1], **& Thiago P. M. Alegre**[1]

1 - Photonics Research Center, Gleb Wataghin Physics Institute, University of Campinas, Campinas, SP, Brazil
2 - Department of Physics, ETH Zürich, 8093 Zürich, Switzerland
3 - Kavli Institute of Nanoscience, Department of Quantum Nanoscience, TUDelft, Delft, The Netherlands
agprimo@ifi.unicamp.br, ppinho@ifi.unicamp.br, alegre@unicamp.br

Abstract: We demonstrate dissipative optomechanical transduction and backaction in coupled nanobeams. Compared to previous demonstrations, our system corresponds to a hundredfold increase in mechanical frequency and displays a record-high dissipative optomechanical coupling.

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The ability to swap information between highly confined electromagnetic modes, in the telecom band, and mechanical modes, in microwave frequencies, puts cavity optomechanics as a strong candidate for interfacing radio-frequency and optical photons. This could benefit future distributed quantum computing and long-range quantum communications. On the one hand, the efficiency of these systems is limited by the heating arising from the absorption of photons circulating in the optical cavity. This generates thermal phonons colocalized to the mechanical mode, causing the decoherence of nonclassical mechanical states. On the other hand, relatively large intracavity fields are required to enhance the optomechanical interaction. Attempts at reducing photonic absorption were made by refining microfabrication processes, however, this is still the most important limiting factor in current experiments [1,2].

Typically, the optomechanical coupling is dispersive ($G_\omega = \frac{d\omega_c}{dx}$), i.e. mechanical motion (displacement x) modulates the frequency of the optical resonator (ω_c). As a consequence, only photons circulating in the cavity can be scattered. In a dissipative optomechanical system ($G_{\kappa_e} = \frac{d\kappa_e}{dx}$, where κ_e is the loss rate to a driving channel), acoustics affect the coupling between an excitation/dissipation channel e.g. waveguide, and the cavity [3–5]. In this case, one gets waveguide-to-cavity instead of cavity-to-cavity scattering. This replaces the requirement of large intracavity fields for large waveguide fields. Since absorption is now delocalized from the cavity, the aforementioned problems are minimized. Although dissipative optomechanical systems have been previously demonstrated [4,5], they never reached the sideband resolved regime, where the mechanical frequency surpasses the total optical losses. This is a required step for enabling quantum optomechanics experiments with dissipative interactions [7].

Here we demonstrate the first dissipative optomechanical system working in the sideband-resolved regime [7]. Our device consists of two evanescently coupled silicon nanobeams periodically patterned to simultaneously confine optical ($\lambda \approx 1562$ nm) and mechanical modes ($\Omega/(2\pi) \approx 5.5$ GHz). As shown in Fig. 1**a)**, one of the nanobeams is laterally coupled to a waveguide, used for the optical excitation and readout of the device.

The system operates as follows: if the two resonators share the same optical frequencies, an anti-crossing occurs and symmetric and antisymmetric optical supermodes are formed, as identified in the optical spectrum in Fig. 1**b)**. In this case, photons are equally distributed between both cavities, as depicted in the toy model of Fig. 1**c1)**. Mechanical motion perturbs the optical frequency of one of the cavities, causing the supermodes to assume a different spatial distribution within the timescale of mechanical oscillations, that is, energy becomes more confined in either of the cavities, as illustrated in Fig. 1**c2)**. In our device, this arises from mechanical modes confined in each individual nanobeam. Since the cavities interact with the waveguide/excitation channel differently, a mechanically induced asymmetry in the supermodes' losses is generated, giving rise to dissipative optomechanics [6]. Naturally, a modification in the frequencies of the supermodes is also observed, i.e. dispersive coupling.

We measure the simultaneous existence of the dissipative and dispersive optomechanical couplings by monitoring the mechanical spectrum (Fig. 1**d)**) for a range of laser-cavity detunings (Δ) with respect to both optical modes. Due to fabrication imperfections, the mechanical frequencies of the nanobeams' (breathing) modes are slightly different, allowing for their individual analysis. In Figs. 1**e1)-e2)**, we plot the amplitude of the reflected field photocurrent spectral density $S_{II}(\Omega)$ at the frequency of one of the mechanical modes $\Omega = \Omega_1$. Dynamical backaction is avoided by keeping low input powers.

In both optical modes, a large difference is observed between the signals at blue ($\Delta \approx \Omega_1$) and red ($\Delta \approx -\Omega_1$) detunings. In a purely dispersive optomechanical system without backaction, only one scattering channel is available, and these curves are necessarily symmetric. On the other hand, if both dispersive and dissipative couplings are present, the different scattering mechanisms interfere. Whether this interference is constructive or destructive depends on the detuning used, as the phase of the cavity photons, which are dispersively scattered, depends on Δ. This is not true for the dissipatively-scattered waveguide photons, which keep the same phase irrespective of Δ.

[*] These authors contributed equally to this work.

Analyzing the optomechanical transduction of the antisymmetric optical mode, we verify that constructive interference between dispersive and dissipative channels is obtained when $\Delta \approx \Omega_1$, leading to larger signals. This contrasts with the symmetric case, where constructive interference is observed at $\Delta \approx -\Omega_1$. This is understood using the described mechanism underlying the optomechanical response of our device. During the mechanical motion, if the extrinsic loss of one of the supermodes is increased, it is necessarily decreased for the other one, generating dissipative couplings G_{κ_e} with opposite signs for each mode. As a consequence, for a given detuning, constructive interference in the antisymmetric mode necessarily implies destructive interference in the symmetric mode.

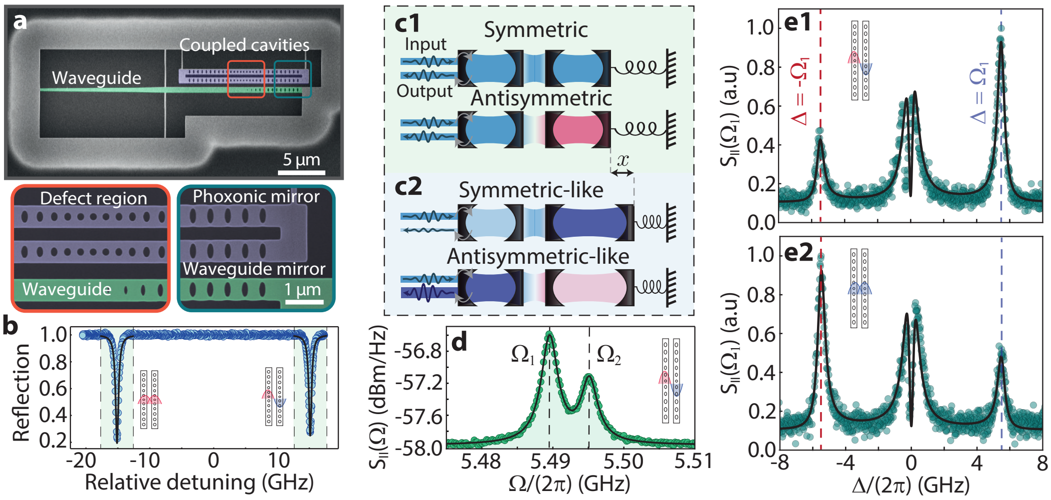

Fig. 1: **a)** Colorized scanning-electron microscopy image of our device. Blue: coupled optical cavities, green: waveguide. **b)** Optical spectrum of our device. Modes are split by ≈ 30 GHz, indicating hybridization. Symbols represent if modes are symmetric or antisymmetric. **c1)** Idealized scheme for coupled resonators for the case where they are identical. Different colors represent opposite phases of the optical field. **c2)** After a small displacement x, the energy is redistributed between resonators. Darker colors indicate larger energy densities. The external losses of the symmetric-like (antisymmetric-like) modes are decreased (increased). **d)** Example of the mechanical power spectral density, showing the two mechanical breathing modes. Optomechanical transduction at the mechanical frequency for **e1)** the antisymmetric and **e2)** symmetric optical modes. Input powers are kept low enough to avoid dynamical backaction.

Fitting the data in Figs. 1**e1)-e2)** and analyzing optically-induced modifications in the mechanical linewidth (dynamical backaction – not shown), we are able to extract the values of both dispersive and dissipative couplings. For the symmetric (antisymmetric) optical mode we get $G_{\kappa_e}/(2\pi) \approx 1.16$ GHz/nm ($G_{\kappa_e}/(2\pi) \approx -0.98$ GHz/nm) and $G_{\omega}/(2\pi) \approx 130$ GHz/nm ($G_{\omega}/(2\pi) \approx 121$ GHz/nm). Notice that the sign of G_{κ_e} is flipped between both optical modes, in agreement with our discussion.

Our demonstration represents a one order of magnitude [4] increase in the dissipative coupling at a frequency two orders of magnitude [5] higher than previous demonstrations. Despite the two-order-of-magnitude difference between G_{ω} and G_{κ_e}, we still verified strong signatures of dissipative coupling. This is rooted in the waveguide-cavity scattering previously discussed. This mechanism is far more efficient than the dispersive interaction that scales with the number of photons in the cavity, which is largely suppressed for off-resonant excitation.

In conclusion, our results show the feasibility of using dissipative optomechanics in future quantum optomechanics experiments to drastically reduce the heating in optical cavities. In our talk, we will present data for dynamical backaction and optomechanically induced transparency that provide further evidence of the relevance of this interaction.

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