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Quantum Thermometry in Optomechanics

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Abstract: We describe a method to control the cavity detuning in optomechanics experiments. This helps accurate measurements of the asymmetry in the motional sidebands, that testify the quantum behavior of the oscillator and quantifies its occupation number.

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1. Introduction

A crucial outcome of cavity optomechanics [1] is the observation of peculiar quantum features in the behavior of macroscopic mechanical oscillators. The most relevant indicator of the achieved mechanical quantum domain is the so-called motional sidebands asymmetry. The optomechanical interaction generates spectral peaks around the carrier frequency of a probe field, at distances equal to the mechanical oscillation frequency Ω_m. Their amplitudes are generally different according to quantum theory. Different interpretations have been proposed to explain such asymmetry, all agreeing in recognizing it as a non-classical signature of the mechanical oscillator [2], as soon as spurious experimental features are avoided. A particularly elucidating explanation considered that the anti-Stokes (blue) sideband implies an energy transfer from the oscillator to the field (frequency up-conversion of photons), and vice versa for the Stokes (red) sideband. Since the quantum oscillator cannot yield energy when it is in the ground state, the anti-Stokes process is less favored. It turns out that the blue and red sideband strengths are proportional respectively to $\bar{n}$ and $(\bar{n}+1)$, where $\bar{n}$ is the mean occupation number of the oscillator.

In this work we experimentally investigate the sidebands asymmetry as signature of quantum performance, and we compare it with a further indicator, i.e., the oscillator displacement variance measured form the area of the corresponding peak in the probe phase spectrum. Furthermore, we demonstrate a method for correcting the measured sidebands asymmetry for non-null probe detuning, exploiting the spectral features of the device oscillating modes that are weakly coupled to the cavity field ("heavy" modes).

2. Experimental results

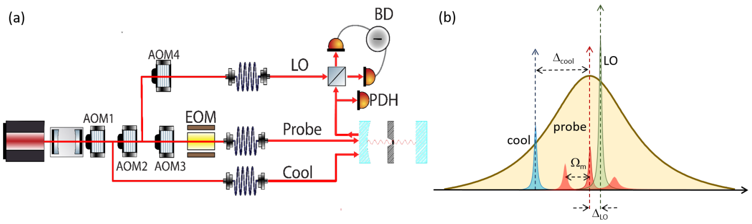

Fig. 1. (a) Simplified scheme of the experimental setup. (b) Scheme of the beam frequencies. The LO is placed on the blue side of the probe and detuned by $\Delta_{\mathrm{LO}} << \Omega_m$, therefore the Stokes lines are on the red side of the LO, while the anti-Stokes lines are on the blue side. In the heterodyne spectra, they are located respectively at $\Omega_m + \Delta_{\mathrm{LO}}$ (Stokes) and $\Omega_m - \Delta_{\mathrm{LO}}$ (anti-Stokes).

The measurements are performed on a circular SiN membrane with a thickness of 100 nm and a diameter of 1.64 mm, supported by a silicon ring frame [3–5]. The resonance frequencies of the drum modes are given by the expression $f_{mn} = f_0\,\alpha_{mn}$ where α_{mn} is the n-th root of the Bessel polynomial J_m of order m. For $m > 0$ we expect couples of quasi-degenerate modes. The oscillator is placed in a Fabry-Perot cavity of length 4.38 mm, in a "membrane-in-the-middle" setup. The cavity optical axis is displaced from the center of the membrane, so that the optomechanical coupling and readout are much more efficient for one of the modes in each quasi-degenerate couple. In this work we mainly focus on the (1,1) modes at 370 kHz, having a quality factor of 8.9×10^6 at cryogenic temperature. The optomechanical cavity is cooled down to ~ 7 K. The light of a Nd:YAG laser is split into several beams, whose frequencies are controlled by means of acousto-optic modulators (AOM) (Fig. 1a), that are used to cool optically cool the mechanical modes and to probe their displacement spectrum in heterodyne and homodyne setups.

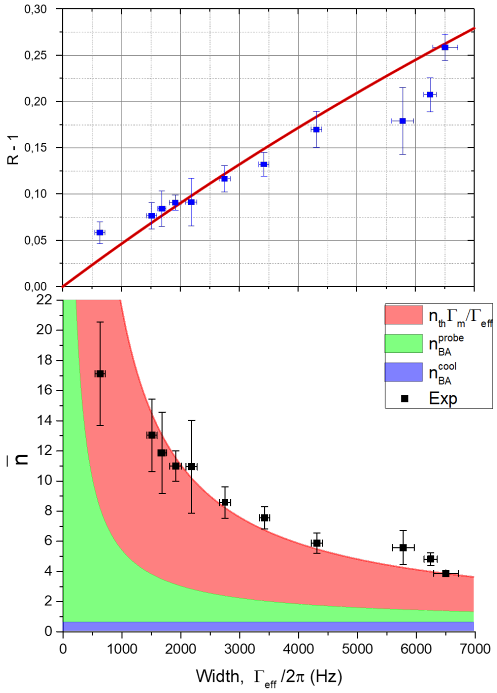

Fig. 2. Close symbols report the occupation number $\bar{n}$ calculated from the corrected values R of the sideband ratio for the "light twin" mode, according to $\bar{n} = 1/(R-1)$. The red solid curve represents the occupation number $\bar{n}$ calculated according to a theoretical model using independently measured parameters. Red, green and blue areas represent respectively the contributions of the thermal noise, the probe beam back-action, and the cooling beam back-action.

The occupation number $\bar{n}$ calculated from the corrected sideband ratio is shown in Figure 2 as a function of the width Γ_{eff} of the mechanical resonance, obtained at increasing values of cooling power. Filled solid curves reflect the expected $\bar{n}$ and its different contributions, calculated according to a theoretical model. without any free fitting parameters: all the contributions to $\bar{n}$ are calculated on the basis of independent measurements. The agreement with the experimental data is excellent, considering the experimental statistical uncertainty, suggesting the absence of non-modeled extra noise. Each single data point can thus be exploited to extract the occupation number, using as experimental error its statistical uncertainty.

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