Cryogenic properties of optomechanical silica microcavities

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We report the study of the optical and mechanical properties of high-Q fused silica microtoroidal resonators at cryogenic temperatures (down to 1.6 K). A thermally induced optical multistability is observed and theoretically described, originating from the reverse thermally induced optical frequency shift. Moreover the influence of structural defect states (two level fluctuators) on their mechanical properties is observed and probed at an unprecedentedly achieved low phonon number. The resulting implications for cavity optomechanics and studies of mechanical decoherence are also discussed.

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I. INTRODUCTION

Cavity optomechanics is an emerging thematic in physics motivated, in particular, by the possibility of observing signatures of quantum phenomena with mechanical resonators [1,2]. A variety of experimental approaches has been recently developed, sharing the common goal of reducing the resonator mean phonon number below unity, by means of traditional cryogenic and optical cooling techniques [3,4]. Among them, due to their ability to combine advantageous optical and mechanical properties in one and the same device, toroidal optomechanical microcavities [5,6] represent a promising system. In particular, they support high-frequency (~60 MHz) and low mass (~10 ng) mechanical eigenmodes whose clamping losses can be strongly suppressed with a suitable geometric design [7]—as well as ultrahigh finesse (10^9) optical resonances. It allows us to enter deeply into the resolved sideband regime [8], a prerequisite for cooling the radial breathing mode (RBM) down to its ground state. While earlier work studied silica-based microcavities [9,10] at low temperatures, here we present for the first time the optomechanical properties of silica microcavities at cryogenic temperatures. A hereto unobserved multistability is reported that produces distinct features in the optical cavity response at high power, qualitatively different from the thermal bistability observed at room temperature [11]. It has its origin in the reversal of the temperature-induced refractive index change. Moreover, the parametric coupling of optical and mechanical modes allows observation of phonon coupling to structural defects states of glass. Importantly, the study of mechanical decoherence is carried out in a new regime of low occupancy in contrast to earlier studies, i.e., without driving the oscillator to large displacement amplitudes but by mean of an ultrasensitive and low perturbative measure of its Brownian motion. Our results have implications for future cavity optomechanical experiments using optical microcavities from dielectric material [12] and, equally important, represent a powerful tool for probing mechanical decoherence at low temperature and phonon number [13].

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II. THERMOMETRY

Starting point of our experiments is a cryogenically cooled optical microresonators using a 4He exchange gas cryostat. To verify the proper thermalization of the sample, we perform thermometry on the Brownian motion of the RBM as an internal thermometer of the microcavity. A tunable 1550 nm diode laser is coupled by means of a tapered fiber to an optical resonance of the microcavity, whose mechanical noise is imprinted on the phase of the transmitted beam and read out via a Pound-Drever-Hall technique, providing a high sensitivity measurement of its displacement noise [16,17]. No significant modification of its optomechanical properties was observed when working with laser intensities below 1 μW. To overcome the photodetector dark noise, it is possible to take advantage of a low noise erbium doped fiber amplifier, which when combined with a low noise fiber laser yields a typical displacement sensitivity of 3×10^{−18} m/√Hz at 60 MHz achieved with 1 μW of light injected in a 10^5 finesse optical resonance. In this manner, the resonator’s Brownian motion at 1.6 K (corresponding to an average occupancy of 600 phonons) can be monitored with a high signal-to-noise ratio (>10 dB at 1.6 K) sufficient for determining the mechanical quality factor Q, the resonance frequency ω_m/2π, and the effective temperature of the RBM. The latter was compared to the cryostat temperature determined with semiconductor sensors, and no differences (at the level of 0.5 K) could be observed, indicating that the displacement readout does not induce any significant temperature increase via light absorption or dynamical back action. The proper thermalization of the toroid—even for a microstructures weakly coupled to its silicon substrate [7]—requires a helium gas pressure of approximately 5 mbar, sufficiently low for not increasing its mechanical losses by gas damping.

III. OPTICAL MULTISTABILITY

Importantly, the high optical finesse (>10^9) are preserved at low temperatures. When probing the optical resonances at high power (as relevant e.g., for achieving appreciable optomechanical cooling) the heating of the resonator due to light absorption distorts the optical resonance, but...
the induced temperature increase is strong enough to reach
oscillating at 63 MHz. The rms amplitude of its Brownian motion
\( T_{\text{rms}} \). The presence of two turning points in the cavity transmission

This inversion is of relevance for optomechanics as it renders
the gas contribution will give access to silica’s optical refractive
index at low temperatures, which has not been measured
below 30 K (note that the temperature dependence of silica’s
microwave dielectric constant is known to reverse \([18]\)).

To model the observed multistability, it is important to
take into account the coupling between the optical field \( a \) and
the effective resonator temperature \( T \). The normalized
complex intracavity optical field \( \tilde{a} = a / \sqrt{I_{\text{max}}} \),
where \( I_{\text{max}} = \eta_{n} K_{\text{e}} T_{\text{th}} \) is the maximum intracavity photon flux expected
for an input flux \( I_{\text{in}} \) and coupling efficiency \( K (K = 1\) in
case of critical coupling), follows the dynamical equation:
\[
\frac{d \tilde{a}}{dt} = - \frac{i \eta}{\pi} R \tilde{a} + \frac{1}{2} \frac{\partial n_{R}}{\partial T} \frac{dT}{dt} + \frac{1}{2} \nu_{c}(T) \tilde{a} + 1,
\]
where the laser to cavity detuning \( \nu \) is normalized to the cavity bandwidth
\( \Omega_{c} / 2 \pi = c / (4 \pi n_{R} R) \) and can be written as \( \nu_{c}(T) = \nu_{c}(0) - \frac{1}{2} \frac{\partial n_{R}}{\partial T} \nu_{c}(T_{0} + \Delta T(t)) \),
where \( \nu_{c} \) stands for the laser
frequency detuning at low excitation flux and \( \Delta T \) is the
effective temperature increase induced by light absorption.
The dynamical equivalent temperature response depends on the mechanism considered (expansion or refraction), and we define here a global thermal response function \( \chi_{\text{th}} \) for the effective temperature increase, \( \Delta T(t) = h \nu n_{\text{th}} \int_{-\infty}^{t} \chi_{\text{th}}(t') dt' \),
where \( I_{\text{in}} = I_{\text{in}} \) is the normalized intracavity intensity. The static working point of the
system is then solution of \( 1 + \nu_{c}(0) - \frac{1}{2} \frac{\partial n_{R}}{\partial T} \nu_{c}(T_{0} + \Delta T) \tilde{a} + 1/I = 0 \),
with \( \mu = h n_{\text{th}} \) being the maximum light-induced heating
expected, \( \chi_{\text{th}} = \int_{-\infty}^{t} \chi_{\text{th}}(t') dt' \), in units of K/W representing
the induced static heating per intracavity power. It fits (with a
seventh-order polynomial) of the experimental \( \nu_{c}(t) \) is used
for numerically solving the nonlinear equation. It allows us
to calculate the normalized intracavity intensity for each laser
detuning \( \nu_{c} \) and for various input intensities \( I_{\text{in}} \) by varying
the parameter \( \mu \). The results of the simulation are shown
in Fig. 2 and show a remarkable agreement with experimen-
tal traces. The dynamically unstable branches are marked
with dashed lines. Compared to higher-temperature behavior,
the upper stable branch does not exhibit the typical triangular
shape \([11]\) (also observed for Kerr or radiation pressure non-
linearities) but is progressively curved as the temperature
approaches \( T * \) (a, b). When the input intensity is sufficient
for heating the resonator beyond \( T * \), two new branches
appear, allowing the onset of a multistability (c). At even
higher intensities, the upper branch can be found at a laser
detuning lower than the “blue side” lower turning point \([cf.
Fig. 3(c) inset], inducing a characteristic double turning
point feature when reducing the laser frequency.

This mechanism also allows us to quantify the tempera-
ture increase induced by light absorption (i.e., the parameter
change in the effective refractive index \( n_{\text{eff}} \) of the resonator to
which both silica and the surrounding medium contribute:
\( n_{\text{eff}} = (1 - \eta)n_{S} + \eta n_{\text{ex}} \), where \( \eta \) is the evanescent fraction of
the optical mode and ranges between 0.1–10 \% depending
on the spatial shape of the mode. The inferred variation
in the effective refractive index \( \frac{dn_{\text{eff}}}{dT} \), represented in Fig. 1(d),
is in agreement at high temperature (30 K) with measurements
reported in Ref. [15] and becomes negative below 7 K.
Additional measurements performed at 20 mbar resulted in
an increased negative shift, of \(-520 \text{ MHz/K at 2 K, indi-
}

cating the non-negligible surrounding helium contribution
at low temperatures (bellow 4 K). A quantitative study of the
gas contribution will give access to silica’s optical refractive
index at low temperatures, which has not been measured
below 30 K (note that the temperature dependence of silica’s
microwave dielectric constant is known to reverse \([18]\)).

To model the observed bistability, it is important to
contrast to room temperature experiments \([cf. Fig. 2(a)]\) and
leads to a blueshift of the resonances with increasing power.
This inversion is of relevance for optomechanics as it renders
the cooling side of the resonance thermally stable \([11]\). At
higher power, the resonances further distort and exhibit
hereto unreported higher-order multistability underlined by
the presence of two turning points in the cavity transmission
scans, first for increasing laser frequencies \([cf. Fig. 2(c)]\) and
even for decreasing frequency scans at higher input powers
\([cf. Fig. 3(c)]\).

To understand this behavior, we studied the temperature
dependence of the microcavity optical resonance frequency
\( \nu_{c}(T) \). Measurements were performed at low laser intensity
\(<100 \text{ nW} \) in order to avoid inducing any thermal or optical
(Kerr \([9]\), radiation pressure) nonlinearities and at a pres-
ture of 10 mbar ensuring a good thermalization. These
experiments showed a \(-135 \text{ MHz/K shift at 30 K that reverses}
\([10]\) around \( T_{c} = 13.3 \text{ K and reaches } +100 \text{ MHz/K at 2 K}
\([cf. Fig. 1(c)]\). Contrary to the room temperature case, the
“red bistability” can only be observed for resonances whose
half linewidth is smaller than the optical frequency shift
between the cryostat temperature \( T_{0} \) and \( T * \) (i.e., \( F > 10000 \text{ at}
4 K for a radius of 30 \text{ \mu m} \)). The multistability appears when
the induced temperature increase is strong enough to reach
the inversion temperature (\( T * \)).

The optical frequency shift originates both from a
mechanical expansion (thermal expansion coefficient \( \alpha \) and a
\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{(Color online) (a) Experimental setup. FPC: fiber polariza-
tion controller and EDFA: erbium doped fiber amplifier. (b) Typical
displacement noise spectrum obtained at low temperature (1.6
K, 4 mbar) for the radial breathing mode of a 30-\mu m-radius toroid
oscillating at 63 MHz. The rms amplitude of its Brownian motion
(approximately 4 fm) serves as measure of the toroid temperature,
proving its proper thermalization ensured by the exchange gas. (c)
Optical resonance frequency \( \nu_{c}(T) \) vs temperature. The solid line
represents a polynomial fit of the data. (d) Relative optical fre-
quency shift with temperature: i: \( \frac{d \nu_{c}}{dT} \); ii: silica’s thermal expan-
sion coefficient \( \alpha \) \([14]\); iii: inferred effective refractive index con-
tribution, \( \frac{1}{2} \frac{\partial n_{R}}{\partial T} \alpha \); iv: measured contribution of silica’s
refractive index, from Ref. \([15]\), and extrapolation to lower
temperatures.
\end{figure}
A simple estimation can be obtained by measuring the injected power $P_{\text{in}}$ required for observing the multistability (or $\mu = T - T_0$) and the cavity optical parameters (coupling and cavity loss rate). A value of $\chi_{\text{int}} = 4.5$ K/W is extracted for an exchange gas pressure of 5 mbar. For lower pressures, it increases up to 8.6 K/W at 0.5 mbar (assuming the same static optical shift), emphasizing the crucial role of Helium for thermalization. Note that the heating of the resonator is of particular relevance in the context of ground-state cooling that requires high optical cooling power (up to approximately 1 mW) since it competes with the laser cooling. However, it can be circumvented in the resolved sideband regime where the laser is far detuned from the optical resonance. For completeness, it is important to mention that at higher exchange gas pressure (approximately 20 mbar), it is possible to enter the superfluid phase of the thin helium film appearing on the microcavity surface. A clear signature of this phenomenon is imprinted on the microcavity’s optical resonance frequency shift [see Fig. 3(d)] showing an additional slope inversion below 1.8 K, as expected from the temperature dependence of liquid and gaseous helium refractive index below the lambda point [19]. The study of the film properties will be presented elsewhere.

**IV. MECHANICAL PROPERTIES**

The amorphous nature of the microresonators strongly influences their mechanical behavior. The phonon propagation properties (speed of sound and attenuation) are deduced from an analysis of the microresonator’s Brownian motion (mechanical frequency and quality factor, respectively), [cf. Fig. 4]. Importantly, our approach consisting of an ultrahigh sensitivity read out of the thermal displacement noise in a micrometric acoustic resonator represents the least perturbing measurement technique of the phonon properties as it does not require external acoustic driving that can saturate the material response at lower temperatures (as detailed below). Indeed, the reported measurements thus probe the mechanical dissipation of silica in a qualitatively new regime.

The results obtained present a nontrivial temperature dependence, which is a characteristic of amorphous materials [20]. They are in good agreement with direct measurements of sound propagation in bulk material, meaning that the mechanical damping is dominated by the material properties. Indeed, most of the amorphous silica acoustic and dielectric properties, ranging from kHz to GHz frequencies, that have
been widely studied in bulk materials can be explained [20,21] by considering a coupling of the strain and electromagnetic fields to the structural defects states of glass—whose origin is still under investigation—modeled as an assembly of two-level systems (TLS) with a wide distribution of energy parameters. The mechanical damping presents a maximum at approximately 50 K, $Q \approx 500$, corresponding to a thermally activated relaxation process, that is fitted here with the parameters taken from [22]. Below 10 K the relaxation mechanism is dominated by tunneling assisted transitions between the two levels of the defects. They are responsible for both the plateau ($Q \approx 1200$ at 5 K) and the further improvement of the mechanical quality factor observed at lower temperatures and higher frequencies ($Q \propto \Omega_0/T^3$). In the context of ground-state cooling, it is important to maintain a high mechanical quality factor at low temperatures for facilitating the readout and providing an efficient temperature reduction by means of optical cooling techniques. Importantly, mechanical Q factors above 30 000 for 90 MHz oscillators can be expected at 600 mK [20], a temperature at which the $^3$He vapor pressure is still high enough (approximately 1 mbar) to ensure a proper thermalization of the resonator in the resolved sideband regime.

It is important to note that the phonon coupling to the assembly of two-level systems opens promising future perspectives for amorphous materials based optomechanical devices. Indeed, it has been shown that in addition to the relaxation mechanisms described above, there also exist processes where the phonon resonantly interacts with the TLS possessing the right energy splitting. This mechanism dominates the phonon propagation properties at lower temperatures and higher frequencies (and is responsible for the anomalous electromagnetic dispersion previously mentioned). At 1 K and 500 MHz, their contributions have similar magnitude [20,21]. Our system has the potential for entering this resonant regime since higher frequency oscillators can be obtained by reducing the toroid size [24] and working on higher-order radial breathing modes that could be still thermalized and monitored in $^3$He cryostats. The TLS density of states is finite, and it has been shown that they can be saturated at both high electromagnetic or acoustic intensities [25] ($\frac{\Delta \omega_{\text{sat}}}{\Omega_0} \approx 10^{-3}$ W/m$^2$ at 1 K). The latter would require a mechanical driving of $\Delta \omega \approx \sqrt{\frac{\Delta \omega_{\text{sat}}}{\rho c \Omega_0}} \approx 2$ nm that is experimentally feasible via radiation pressure force and well within the detection capacity observed by optical readout. Importantly, the TLS can be coupled simultaneously to strain and electromagnetic fields, and cross couplings have been demonstrated [26] at microwave intensities (20 W/m$^2$ at 1 K) that could feasibly be implemented. This would allow a possible control and read out of the resonator mechanical state by means of an external radio frequency field, a promising step toward mechanical quantum state engineering. Furthermore, this interaction has allowed to generate phonon echo phenomena [27] at temperatures and frequencies where the equivalent mechanical oscillator would be found at occupancies close to unity and could be interestingly exploited to measure mechanical decoherence at low phonon number [28].

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