Stimulated raman adiabatic passage in optomechanics
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Summary

The work presented in this thesis is the continuation of a long-term research program towards the investigation of macroscopic quantum superpositions. At the start of the presented PhD research, optomechanics with trampoline resonators holding a DBR mirror had been investigated [78, 87]. Although a state transfer of a classical state between two mechanical modes coupled by two detuned light fields was achieved [12] the operation in the quantum regime remained elusive. Two main complications were found. Light absorption in the DBR stack resulted in significant heating of the device: 300 nW resonant readout probe laser light (after mode matching taken into account) resulted in an increase of the device temperature from 200 mK to 1 K [78]. We find it not a prohibitively large heating which might limit the operation in the quantum regime. A more significant drawback of this optomechanical system was a limited mechanical quality factor of $Q = 0.4 \times 10^6$ at cryogenic temperatures [87] for modes with frequency $\omega_m \sim 0.5$ MHz. Clamping losses at the points where the trampoline meets the DBR stack and bending losses in the DBR stack itself were identified as the main sources of mechanical dissipation. Such a modest mechanical quality factor results in the quantum coherence time $\tau \leq \frac{Q\hbar}{k_B T} = 4\ \mu$s at 1 K being approximately equal to the mechanical oscillation period of the device. Coherent optomechanical manipulation would require multiphoton optomechanical coupling of $g \gtrsim 1$ MHz. The methods for high-fidelity state transfer between mechanical modes [12, 75] require the sideband-resolved regime $\kappa \ll \omega_m \sim 1$ MHz and weak optomechanical coupling $g \ll \kappa$, these requirements cannot be satisfied for the trampoline devices.

Another complication was maintaining optical alignment during cooling down. The cryogenic setup for the trampoline devices was highly asymmetric and had 7 low temperature actuators to compensate for the misalignment effects during cooling down. When cold, the set up had a modest mode coupling of 0.33 and it was challenging to lock the probe laser to the cavity resonance even with a fourth order mechanical low-pass filter installed in the cryostat [79].

To address these limitations we started with building an axisymmetric room temperature membrane-in-the-middle setup, described in Chapter 2. Using this setup and a commercially available SiN membrane we achieved a strongly squeezed thermal state of a mechanical mode. One of the quadratures was cooled by the parametric driving. This is a well known technique possessing a limit of 3 dB squeezing due to divergence of the other quadrature. Our contribution was to apply a viscous damping force to this diverging quadrature via electrostatic interaction which allowed to reach 8.5 dB squeezing.

At room temperature the quality factors of commercially available SiN membranes are reaching 50×10^6 [88] when special care is taken to properly clamp these devices. In [88] it was reported that the major source of dissipation is through radiation losses from the membrane to the substrate. To avoid the radiation losses together with the bending losses at at the interface between the membrane and the substrate we adopted the idea of localizing the mechanical mode far away from the membrane-substrate boundary by creating a defect in the phononic crystal patterned on the membrane [7]. We observed quality factors as high as 40×10^6 for a 1.3 MHz mode at room temperature which allowed us to demonstrate optomechanical Stimulated Raman Adiabatic Passage (STIRAP) between two mechanical modes [75] described in Chapter 3. We didn't pick the best device out of tens of devices which might increase the quality factor to approximately 100×10^6 according to [7].

In Chapter 4 we investigate the possibility to create and transfer a single phonon mechanical Fock state between two high-Q modes using STIRAP at cryogenic temperatures. We found it feasible with state-of-the-art membranes under the assumption that the STIRAP pulses do not heat the membranes above 1 K. The state preparation and read out requires filtering out the driving pulses and high fidelity detection of the Stokes and anti-Stokes single photons. We also explored the possibility to create and detect entangled mechanical states via fractional STIRAP.

The optical cavity used in the experiments of Chapters 2 and 3 is close to concentric which makes the optical alignment very sensitive to lateral shifts of the cavity mirrors. To have the optical mode reasonably parallel to the mechanical axis the cavity mirrors should be positioned with lateral precision of $\sim 100\ \mu$m. We found that by manually shifting one of the cavity mirrors laterally it was possible to achieve the required relative position of the two mirrors. This observation inspired the design of the cryogenic cavity where the cavity mirrors are shifted laterally with precision screws to make the optical mode parallel to the mechanical axis of symmetry. In addition, instead of an asymmetric design of the periscope for coupling to a single mode fiber we used the same idea of lateral shift of the mode matching lenses instead of tilting optical elements. Keeping the whole setup axisymmetric and made of Invar we found that the cavity remained reasonably well aligned when cooled to cryogenic temperatures without any actuators. During one of the cool downs we saw a monotonic decrease of the optical coupling with decrease in temperature. During warming up of the cryostat the setup was heated ~ 5 degrees Celcius above the room temperature and the coupling went up above the room temperature coupling to our surprise. We realized that the optical alignment was suboptimal and the cavity can be pre-aligned in such a way to compensate for the misalignment during cooling down. That worked - in the subsequent cool down the optical coupling between the fiber and the cavity increased from 0.8 at room temperature to 0.96 at 130 K and then stabilized at 0.93 at 20 mK after the precompensation has been made. The cryogenic cavity allows for high collection efficiency of Stokes and anti-Stokes photons and has a stiff design. When a membrane is placed in the cryogenic cavity we didn't see a decrease in the external coupling to the linewidth ratio $\kappa_{\text{ext}}/\kappa$. A probe laser can be easily locked to the cavity with a membrane when the setup is at mK temperatures, which allowed us to measure the mechanical ring down of one of the defect modes corresponding to $Q = 200 \times 10^6$. The cryogenic cavity is discussed in Chapter 5.

In addition to high quality mechanical modes and low temperature optomechanical quantum STIRAP requires an optical filter to filter out the pump pulses while transmitting the optomechanically scattered photons to a single photon detector. In Chapter 6 we are discussing an implementation of such a filter with the design transmissivity of 0.85 on resonance and attenuation of the unwanted light $> 10^{14}$ detuned by 1 MHz from the filter resonance. The filter was adapted from [66], it consists of 4 consecutive narrow linewidth optical cavities kept on resonance by feedback loops controlled by microprocessors. We proceed by evaluating the performance of superconducting nanowire single photon detectors aimed to register the optomechanically scattered photons. The requirement of the quantum STIRAP is an overall detection efficiency of $\gtrsim 0.05$ and a dark count rate of $\lesssim 10$ Hz. Our detectors were measured to have system detection efficiency > 0.9 and dark count rate ~ 0.01 Hz.

It is still an open question how much the membrane will be heated by the STIRAP pulses which might also affect the quality factor. In Chapter 7 we are addressing this issue by proposing a thermometry technique based on measuring the anti-Stokes scattering rate $\Gamma_{\text{AS}} = \frac{k_B T}{Q\hbar}$ produced by a sideband cooling light fields. This method allows to estimate the increase of the membrane temperature when the STIRAP driving pulses are switched on. Under the assumption that the membrane is not heated by the intracavity light Γ_{AS} does not change when the intracavity photon number is varied from $\sim 10^3$ when the heating is most likely negligible to $\sim 10^7$ required to drive STIRAP. Any increase of measured Γ_{AS} with an increase of the cooling light fields intensity will signify the proportional increase of temperature of the membrane (more precisely T/Q).

At the moment of writing the thesis the complete setup for quantum optomechanical experiments is being finalized: the cryogenic cavity, high-quality membranes and single photon detectors are in place, while the optical filter setup together with its support and its vacuum chamber is produced and is in process of assembly. The control of the optical filter also requires extra attention.

We are planning to investigate membrane heating, a shot noise limited balanced detector is being produced for this purpose by our electronic department. The next step after the filter setup is ready will be preparation of a single phonon state via detection of a heralding Stokes photon and eventually STIRAP of a non-classical mechanical state between two modes of a membrane.