SEVENTH FRAMEWORK PROGRAMME

Grant Agreement number: **248095**

Project acronym: **Q-ESSENCE**

Project title: **Quantum Interfaces, Sensors, and Communication based on Entanglement**

Funding Scheme: **Collaborative Project (Large-Scale Integrating Project)**

DELIVERABLE REPORT

Deliverable no.:	**D1.3.3**
Deliverable name:	***Report on quantum state transfer and analysis of quantized motion below the SQL***
Workpackage no.	**WP1.3**
Lead beneficiary	**OEAW**
Nature	**R = Report**
Dissemination level	**PU = Public**
Delivery date from Annex I (proj month)	**30/04/2013**
Actual / forecast delivery date	**30/04/2013**
Status	**Submitted**

D1.3.3

Report on quantum state transfer and analysis of quantized motion below the SQL

Progress towards quantum state transfer and analysis of the mechanical resonator motion has been achieved in two respects. Concerning continuous quantum state transfer and readout we have been developing new and experimentally feasible protocols. In particular, we developed a method for state readout that is capable of the analysis of the created mechanical states. In addition we have developed a completely new experimental scheme based on pulsed optomechanics that allows sub-SQL readout of mechanical motion via back-action evading measurements. This scheme further enables quantum state tomography. In the following we will summarize the results achieved within Q-Essence in both directions. The focus of this report will be the state transfer between light and general motional states and their analysis, while quantized motional states still remain a challenge for the future.

1. Quantum State Transfer and Analysis with continuous light-mechanics interaction

Coherent state transfer between light and mechanical motion is an important ingredient for full quantum control of micromechanical motion. The main idea is to utilize an effective beamsplitter interaction between optical and mechanical excitations [1] to implement a full Rabi-swap. The necessary conditions for such an operation to be successful are: (1) operation in the sideband-resolved regime (cavity linewidth $\kappa <$ mechanical frequency ω_m), (2) operation in the strong coupling regime (optomechanical coupling rate $g > \kappa$, mechanical damping γ), and (3) Rabi frequencies Ω that are larger than both g and κ in order to drive a coherent state swap.

Some time ago we have already demonstrated requirement (2), i.e. the strong coupling regime between a micromechanical resonator and an optical cavity field [2]. In this work, the strong coupling regime manifests itself in form of (optomechanical) normal mode splitting, which we observe via direct spectroscopy of the optical field emitted by the cavity. In case of a driven optomechanical cavity, emission of a cavity photon can in general be understood as a transition between dressed states of the optomechanical system, that is, between mechanical states that are dressed by the cavity radiation field. The structure of the optomechanical interaction only allows for transitions that lower or raise the total number of normal mode excitations by one (see Supplementary Information of [2]). Photons emitted from the cavity therefore have to lie at sidebands equal to the dressed state frequencies. Homodyne detection provides direct access to the optical sideband spectrum (see Figure 1). For small optical pump power, that is, in the regime of weak coupling, the splitting cannot be resolved and one obtains the well-known situation of resolved sideband laser cooling, in which Stokes and anti-Stokes photons are emitted at one specific sideband frequency. The splitting becomes clearly visible at larger pump powers, which is unambiguous evidence for entering the strong coupling regime. At a maximum optical driving power of 11 mW, we obtain a coupling strength $g/2\pi = 325$ kHz, which is larger than both $\kappa/2\pi = 215$ kHz and $\gamma/2\pi = 140$ Hz.

In a follow-up experiment we are investigating the correlations between mechanical and optical quadratures. We used a setup similar to the one used in [2] (FIG. 2 a). The generalized optical and mechanical quadratures $Xc(\varphi, t)$ and $Xm(\theta, t)$ are obtained from two independent, time-synchronized homodyne measurements of the driving and the locking beam, respectively. Electronic demodulation of the homodyne currents at the mechanical frequency provides access to the slowly varying sideband components of the optical fields. The phase angles θ and φ are varied by scanning both the optical local oscillator phase of the driving beam homodyne and the electronic phase of the lock beam demodulation. For our measurements the local oscillator phase φ of the drive beam homodyne measurement was scanned at a rate of 0.1 Hz while independently storing the real time data for both homodyne detectors with a high- speed analogue-to-digital converter (14 bit, 10 MSample sec^{-1}). Each 2π-interval of the traces is divided into 36 equidistant time bins, in which φ is assumed to be constant. After electronic demodulation, in which the phase θ is only varied for the mechanical quadrature, i.e. the data of the resonant field, we therefore obtain data pairs $\{Xc(\varphi, t), Xm(\theta, t)\}$. The correlation function$<Xc(\varphi)\ Xm(\theta>$ is obtained by calculating the normalized co-variances $C(\theta, \varphi)=<(A-<A>)(B-<B>)>/(<(A-<A>)^2><(B-<B>)^2>)$for data sets measured within the same time window. Here A (B) is the demodulated and low-pass filtered signal for the weak (strong) field and <·> denotes the mean for data pairs measured at different times t at a fixed electronic and optical phase θ and φ, respectively. By changing both phases over 2π density plots of the correlation function $C(\theta, \varphi)$ can be obtained. In the weak coupling regime, where the rotating wave approximation is valid and where the interaction between the optical and the mechanical mode is effectively given by a "beam splitter" Hamiltonian $H_{bs}=g(a_c\ a\dagger + a\dagger a_m)$, the observed correlations obey the specific symmetry $C(\varphi, \varphi)$ = const., independent of φ. This implies in particular $<Xc\ Xm> = <Pc\ Pm>$. This symmetry demonstrates that in this regime the mechanical quadratures are directly mapped onto the optical quadratures, an effect that is actually required by the interaction Hamiltonian H_{bs} itself, which is invariant under a change of phases $a_m \rightarrow a_m e^{i\varphi}$ *and* $a_c \rightarrow a_c e^{i\varphi}$ imposing this symmetry also for the steady state of the system, and therefore also on the observed correlations.

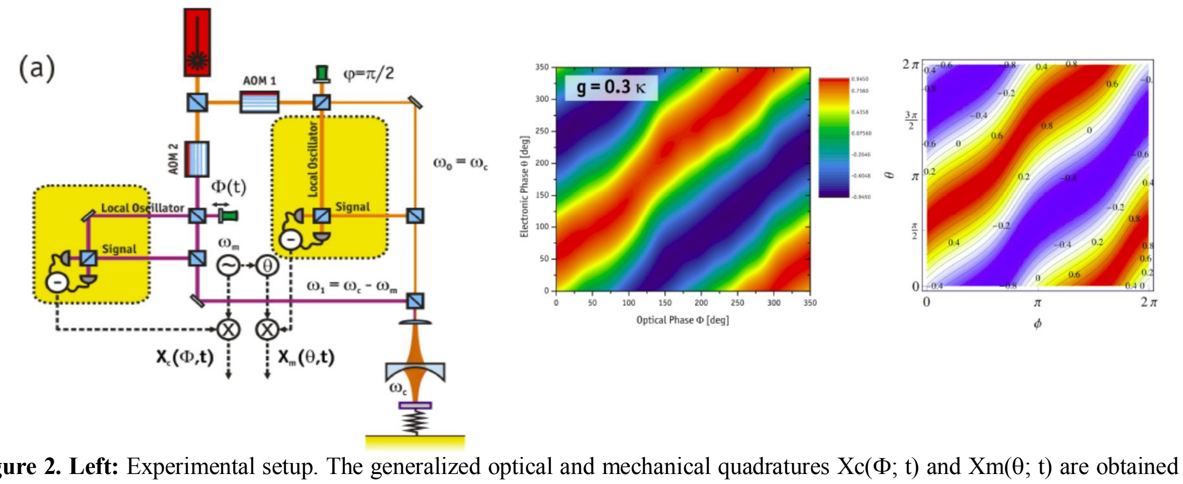

Figure 2. Left: Experimental setup. The generalized optical and mechanical quadratures Xc(Φ; t) and Xm(θ; t) are obtained from two independent, time-synchronized homodyne measurements of the driving and the locking beam, respectively. Electronic demodulation of the homodyne currents at the mechanical frequency ω_m provides access to the slowly varying sideband components of the optical fields. The phase angles Φ and θ are varied by scanning both the optical local oscillator phase of the driving beam homodyne and the electronic phase of the lock beam demodulation. **Right:** Optomechanical correlations. The correlation measurements were performed close to resonant coupling. To achieve the mechanical readout with minimum disturbance we operate in a regime where strong adiabaticity in the coupling of the lock beam is fulfilled. For weak driving power the symmetry between optical and mechanical quadratures is present.

Correlations induced by the "downconversion" Hamiltonian in the strong coupoling regime should break this symmetry. However state analysis as described above assumes the mechanical resonator to act as a single harmonic oscillator – an assumption that is not valid in the strong coupling regime. Therefore, OEAW has developed a method to reconstruct the full optomechanical state in any coupling regime (weak or strong) that is based on the so-called Kalman filter [4]. The scheme therefore can be used in the above discussed protocols. The Kalman filter is a signal processing method used for state estimation that is valid forGaussian systems. Optomechanical systems are such physical systems, when the intra-cavity light field is strong enough (mean cavity occupation >> 1). Prior knowledge is required as input to the Kalman filter, namely the description of the full optomechanical system dynamics and all noise contributions. Then, appropriate measurements (in our case homodyne detections of optical fields that have interacted with the optomechanical system) are used to reconstruct the optomechanical state via a Kalman filter. The result is the full knowledge of the system's state variables (mechanical and optical quadratures) with filter-determined error variances. This can then be used to calculate the covariance matrix of the optomechanical system, the Wigner function and many quantities derived thereof. Hence, OEAW has now a tool at hand to reliably verify prepared optomechanical states, which is not restricted to any specific coupling regime for a linearized optomechanical interaction [4].
Towards quantum state transfer we have further developed a novel scheme for time-continuous quantum state transfer which combines two concepts [5]: Bell measurements, in which two systems are projected into maximally entangled states and continuous measurements, which concern the evolution of a continuously monitored quantum system. This effectively realizes a time-continuous Bell measurement, which, among other things, can be used to realize quantum teleportation of general (squeezed) Gaussian states onto a mechanical oscillator. We have analyzed the feasibility of the scheme for the case of a Fabry-Perot cavity with an oscillating mirror and found that the experimental requirements (in terms of optomechanical coupling and decoherence rates) are essentially the same as for optomechanical ground-state cooling and ponderomotive squeezing, which both have already been demonstrated experimentally. This demonstrates the feasibility of the scheme for experimental implementation of quantum state transfer protocols. As another interesting application of time-continuous Bell measurements one can use our scheme to prepare two mechanical oscillators in an entangled state (which approximates a two-mode-squeezed state).

In a similar direction we have analyzed entanglement generation and teleportation in a pulsed scheme which utilizes the "downconversion" dynamics described above and have shown its experimental feasibility [3].

2. Quantum State Tomography by Pulsed Optomechanics

Within the timeframe of Q-Essence a completely new approach to sensing and state preparation via back-action evading measurements has been developed. Amongst others, this resulted in a new scheme that allows quantum state reconstruction of mechanical states based on pulsed interactions [6]. The essence of quantum state tomography is to make measurements of a specific set of observables over an ensemble of identically prepared realizations. The set is such that the measurement results provide sufficient information for the quantum state to be uniquely determined. One such method is to measure the marginals $\left\langle X \middle| e^{-i\theta n} \rho e^{i\theta n} \middle| X \right\rangle$, where n is the number operator, for all phase-space angles θ. Our pulsed scheme provides a means for precision measurement of the mechanical quadrature marginals, thus allowing the mechanical quantum state to be determined. Specifically, given a mechanical state ρ_{in}^{M}, harmonic evolution of angle $\theta = \omega_M t$ provides access to all the quadratures of this mechanical quantum state which can then be measured by a subsequent pulse. Thus, reconstruction of any mechanical quantum state can be performed. The optical phase distribution, including the harmonic evolution, becomes a convolution between the mechanical marginal of interest and a kernel that is dependent upon χ and the quantum phase noise of light. The effect of the convolution is to broaden the marginals and to smooth any features present. For the specific example of a mechanical resonator in a superposition of two coherent states, i.e., $|\psi_\delta\rangle \propto |i\delta\rangle + |-i\delta\rangle$, the X_M marginal of this mechanical Schrödinger-cat state contains oscillations on a scale smaller than the ground state, which can be resolved by our scheme (see [5] for details). Shown in Fig. 3 are marginals of the mechanical state $|\psi_\delta\rangle$ and the optical phase distributions that would be observed.

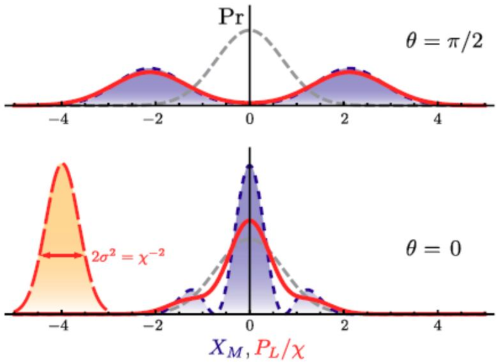

FIGURE 3. Shown are complementary quadrature marginals of the mechanical coherent state superposition $|\psi_\delta\rangle \propto |i\delta\rangle + |-i\delta\rangle$, for $\delta = 1.5$ (blue dashed lines with fill, plotted with X_M). The mechanical ground state is shown for comparison in gray dashed lines. For the quadrature angle $\theta = \pi/2$ the two population components are seen and for $\theta = 0$ the quantum interference fringes. The scheme presented here provides an experimentally feasible means to obtain direct access to these marginals of a quantum state of a mechanical resonator: A coherent optical pulse is used to probe the mechanical state where its phase quadrature becomes the convolution between the intrinsic phase noise and the mechanical marginal (red solid lines, shown for a specific measurement strength χ). The convolution kernel can be observed by using a fixed length cavity, shown in the $\theta = 0$ plot (red dashed line with fill), which allows for accurate recovery of the mechanical marginals.

Recently, OEAW has also demonstrated the first proof of principle experiment on state tomography with pulsed optomechanics. Currently the scheme is experimentally applied without an optical cavity [7] (see Fig. 4). We already achieve a position sensitivity of 19 pm with 10^{10} photons per pulse and a quantum limited homodyne readout. Our experimental results demonstrate that using an optomechanical microcvity [6] with reasonable parameters (Finesse=10000, $\kappa > 1/\tau$, κ: cavity decay rate, τ: puls length) provides a clear pathway towards Sub-SQL sensing.

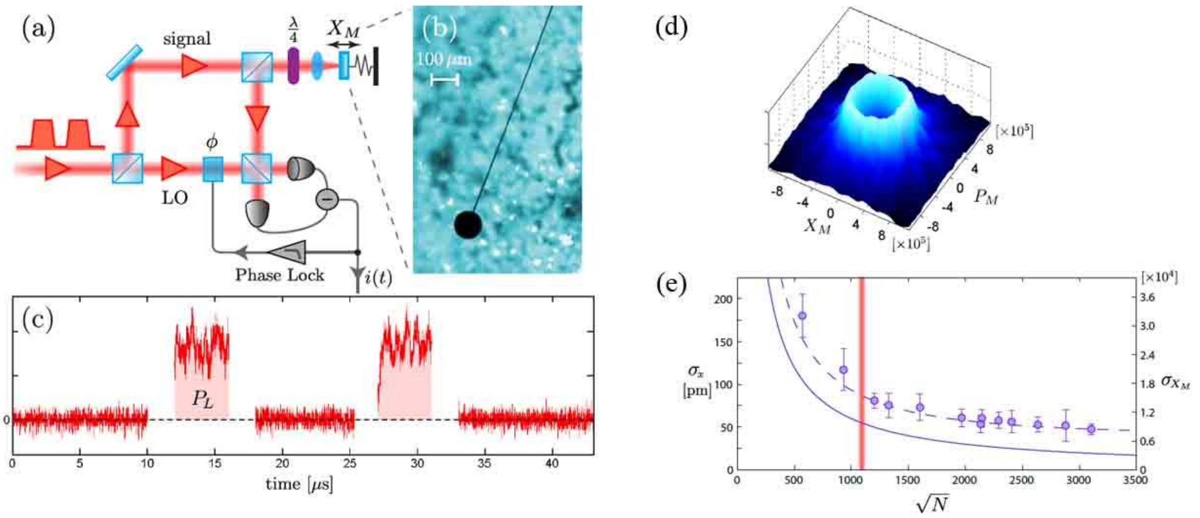

FIGURE 4. (a) Schematic of the experimental setup used to perform state tomography and state preparation of the motional state of a mechanical resonator. In addition to the optical pulses a weak continuous field is used to stabilize the interferometer phase using the homodyne output passed through a low-pass filter with cutoff frequency below the mechanical frequency. (b) Colorized optical micrograph of the high-reflectivity micro-mechanical cantilever fabricated for this experiment. The head of the cantilever, where the signal beam is focused, is 100 µm in diameter. (c) Example time trace of the homodyne output for a pair of 4 µs pulses. (For clarity, the pulse rising and falling edges are not shown.) The measurement outcome PL is the time integral of the homodyne output (indicated by the shaded region). Time resolved optical quantum noise is visible during the pulse. (d) Reconstructed State of a non-Gaussian mechanical state of motion experimentally generated by resonant sinusoidal drive. (e) Conditional mechanical width with pulse strength measured using preparation and read-out pulses separated by 5° of mechanical evolution. The dashed line is a theoretical fit with a model using the two units of optical quantum noise and the finite mechanical evolution. The solid line is the inferred conditional mechanical width immediately after the preparation pulse

[1] M. Aspelmeyer, S. Gröblacher, K. Hammerer, and N. Kiesel; Quantum optomechanics - throwing a glance; JOSA B Vol. 27, Issue 6, pp. A189-A197 (2010)
[2] S. Gröblacher, K. Hammerer, M. R. Vanner, M. Aspelmeyer; Observation of strong coupling between a micromechanical resonator and an optical cavity field; Nature 460, 724-727 (2009)
[3] S. Hofer, W. Wieczorek, M. Aspelmeyer and K. Hammerer; Quantum entanglement and teleportation in pulsed cavity optomechanics; Phys. Rev. A 84, 052327 (2011)
[4] W. Wieczorek et al., in preparation.

[5] S. Hofer et al. arXiv:1303.4976
[6] M. R. Vanner, I. Pikovski, G. D. Cole, M. S. Kim, Č. Brukner, K. Hammerer, G. J. Milburn, and M. Aspelmeyer; Pulsed quantum optomechanics; PNAS USA 108, 16182 (2011)

[7] M. Vanner et al., arXiv: 1211.7036