# Nanoscale Systems for Optical Quantum Technologies NanOQTech

Grant Agreement No: 712721
Start Date: 1st October 2016 - Duration: 36 months

## D3.7 Non-classical states in nano-resonators

| | |
|---|---|
| Deliverable: | D3.7 |
| Work package: | WP3 Opto-electrical and opto-mechanical hybrid systems |
| Task: | 3.4 Coupling of energy levels of $Eu^{3+}$ ions to the vibrations of the nanoscale mechanical oscillator via material strain |
| Lead beneficiary: | CNRS |
| Type: | Report |
| Dissemination level: | Public |
| Due date: | 30 September 2019 |
| Actual submission date: | 18 September 2019 |
| Author(s): | Signe Seidelin (CNRS-IN)<br>Yann Le Coq (CNRS-SY) |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 712721.

**Version history**

| Version | Date | Author(s) | Description |
|---|---|---|---|
| V1 | 12/08/2019 | S. Seidelin (CNRS-IN) | First draft |
| V2 | 22/08/2019 | Yann Le Coq (CNRS-SY) | Final version |

# Table of Contents

## Deliverable Description

This deliverable consists in a report on potentiality to place nano-oscillator in non-classical states (which is a part of task 3.4). The work in the report builds on and extends the work described in former deliverables, in particular D1.4, D3.1, D3.3, D3.4, D3.5, D3.6 but is also drawing on work performed in D3.8 (which will be due on September 30th 2019.)

The work towards assessing the feasibility of reaching non-classical states consists both of experimental efforts (further optimization of the resonator design relative to the resonators presented in D3.1), improvement of the measurement capacity (improvement of cryogenic setup, signal to noise ratio in the photodetector measurement), as well as theoretical considerations.

## Introduction and context

As discussed in D3.1 and D3.3, and published in Physical Review A [1], in a crystal resonator, the vibrations generate a mechanical strain. To briefly summarize, this strain influences the electronic properties of the impurity (here, rare-earth ions), as a consequence of the modification of the electronic orbital distributions. The oscillations of the crystal are mapped onto the energy levels of the impurity, which in turn gives rise to a change in the optical frequency of the photons absorbed and emitted. Alternatively, it is possible to monitor the phase change of a laser interaction dispersively with a spectral hole priorly burnt inside the inhomogeneous broadened profile. The corresponding strain mediated coupling strength is higher than what can be achieved with any realistic external forces, and the resonators can thus potentially be used to create a non-classical state (discussed in this report) or act as sensitive force sensors (also to be reported in D3.9 due on September 30th 2019).

## Experimental optimization

We have optimized several parts of the experimental setup in order to approach the quantum regime.

### New generation resonators

Since the resonators presented in D3.1, do to progress in the Focused-Ion-Beam etching and polishing techniques, we have managed to create resonators better suited for an optimal coupling. In particular, with the initial resonators, the measurements were challenging due to the presence of the bulk part of the material, which the laser had to cross, and which would add a background signal on the resonator.

A solution which circumvents this problem is shown in figure 1a. Here, we have etched a part of the bulk crystal at an angle of 45 degrees below the resonator. By coating this surface with aluminium, we have realized a mirror which allows a laser beam to be reflected onto it and pass through the resonator alone, without interacting with the bulk material of the crystal. We have chosen to position the mirror below the part of the resonator which is nearest the anchoring point in order to maximize the material strain, for an optimum coupling.

An alternative option consists in polishing the edge of the crystal down to obtain a very thin layer prior to applying the FIB. As shown in the example figure 1 b, the crystal has been polished to an angle of 3.2 degrees (measured with a DEKTAK profilometer and a calibrated microscope). This allows one to create the resonator by applying the FIB perpendicular to the surface of the crystal along a single direction. This has the advantage of allowing the laser beam to pass directly through the resonator in a straight line, without having to integrate a mirror to deviate the beam to avoid the bulk part of the crystal. Moreover, it also represents the advantage of not having to use the FIB on the top and bottom surface of the resonator, and thus conserve the initially polished surfaces. In that way, we also avoid surface effects of the FIB due a non-desired implementation of the gallium ions, although this has been shown not to represent major degradation of the coherence properties of other species of rare-earth ions in the YSO matrix [2]. If, however, the triangular shape of the resonator turns out to be a limiting factor (as it increases the resonator's stiffness) it is also possible to reshape it into a rectangular form using the FIB, by removing a much smaller amount of material than when starting out from the bulk crystal.

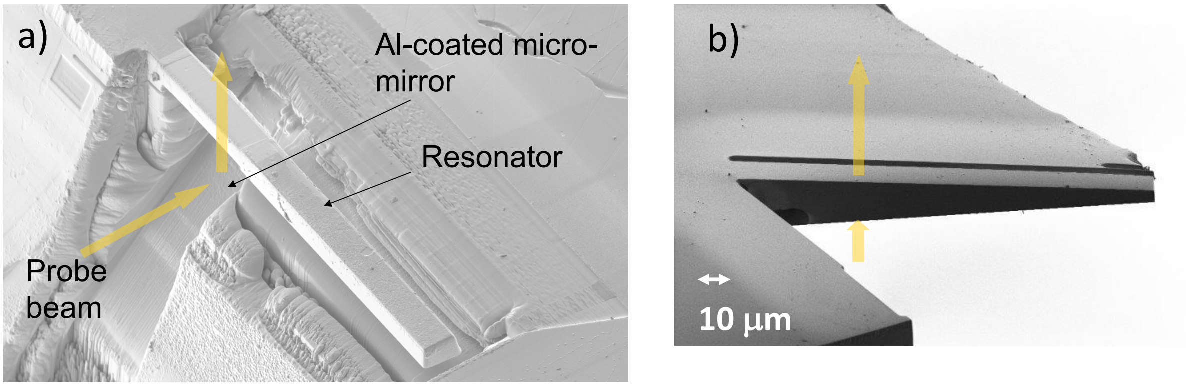
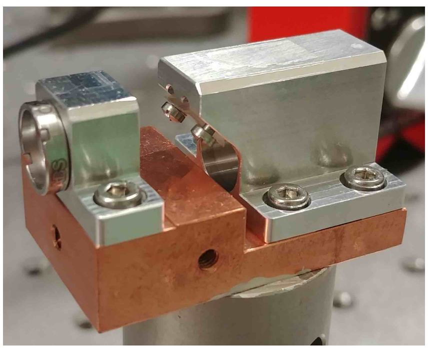



*Figure 1 New resonator geometries optimized for better coupling and read-out efficiencies. The yellow line indicated the laser probe beam. In a) we show the SEM image of the resonator etched on the corner of the crystal. A mirror at an angle of 45 degrees is integrated in order to make the laser beam cross only the resonator and thus avoiding the bulk part of the crystal. In b) the edge of the crystal has been polished so thin that the resonator is formed by a single vertical cut with the FIB. The scale indicated in b) applies to both images. The images are part of an article to be published in Journal of Modern Physics.*

An article co-authored by CNRS-IN, CNRS-SY and CNRS-CP which describes the recent progress on resonator geometries and the optical environment has recently been accepted for publication in Journal of Modern Physics [3].



## Improvements of experimental setup

In addition to work on resonator geometries, progress has been made on the optical setup, and in particular the detection schemes. Avalanches photo-diodes with high efficiencies for detection of the laser have been installed, which have improved the signal to noise ratio with more than 10 dB. Moreover, a dedicated mount has been created in order to better focus the light on the resonator and extract the signals from the resonators. The photo is shown to the left, the full length of the mount is approximately 4 cm, with the resonator (not shown) being positioned on the edge of the copper block in the middle of the mount. Finally, further work has been done in order to eliminate the vibrations of the cryostat (an active feedback mechanism has been implemented) and a publication describing the technique is currently being written.

### Improvements of strain-sensitivity measurement

We have also continued and improved the measurements of the strain coupling efficiency (the initial measurement being reported in D3.3). In particular, we have improved on the way in which we apply the pressure to the crystal. As before, we add masses on the top of the crystal to apply strain, but we have recently added a piezo translation stage which allows us to control the horizontal position of the masses, in addition to the vertical position. This has greatly improved the results (less distortion of the spectra, etc.). These measurements constitute an important input for the simulations presented in this report. An article is co-authored by CNRS-IN, CNRS-SY and CNRS-CP is currently being finalized.

## Theoretical considerations

Based on the work discussed above, we have been able to perform simulations using the best physical system achievable (resonator geometry, signal-to-noise ratio etc.). These simulations have been performed in close collaboration with Aarhus University (AU).

We have recently published a second article in Physical Review A [4] in which we demonstrate that is possible to cool the resonator down to near the quantum ground state (T=0.7 mK, average phonon number n=23) by applying a feedback mechanism (to be discussed in detail in D3.8).

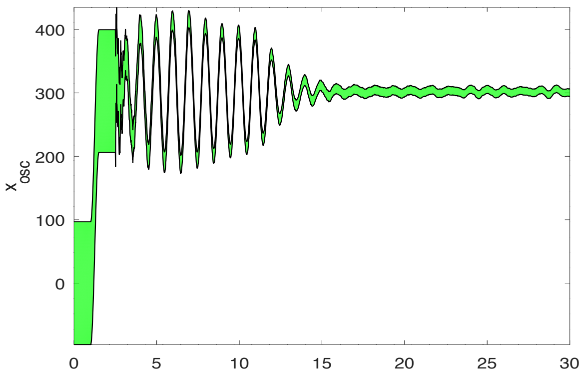



*Figure 2 The position of the resonator in units of zero-point motion as a function of time in microseconds. At time t=0 the probe laser is turned off, and the uncertainty equals 200, as reflected by the broad width of the curve. At t=2 the probe laser is turned on, which has the effect of quickly localizing the position (the oscillatory motion). At t=10 microseconds the feedback is turned on, which has the effect of cooling the resonator, indicated by rapid decrease in the oscillation amplitude. This cooling mechanism will be discussed in detail in deliverable D3.8.*

The cooling is shown in figure 2, and it is a prerequisite for proceeding to create non-classical states, and the state obtained in figure 2 will serve as our initial state for further simulations.

## Squeezed quantum states

One relatively simple possibility for creating a non-classical state, consists in generating a squeezed state, in which the position and momentum variables are squeezed and anti-squeezed respectively (and vice versa).

This is in principle possible to do by applying short square pulses (0.1 times the mechanical oscillation period). Such a pulse has the effect of measuring position X (or momentum P, according to when in the cycle it is measured) which squeezes this degree of freedom (that is, decreases its uncertainty below the Heisenberg limit), and leaves the non-measured variable anti-squeezed (increased uncertainty, in such a way that the product of uncertainties fulfill the Heisenberg uncertainty relation).

If one applies such a pulse two times per mechanical cycle, it should be possible to periodically squeeze and anti-squeeze the position and momentum, as the squeezed ellipse in phase space rotates with respect to the X and P quadrature. We have run the simulations for this system, and the results are shown in figure 3. The two curves are related to the variances of X and P. More precisely, we plot $2\sigma$, where $\sigma$ is the square root of the variance:

$\sigma^2(X)= \langle X^2 \rangle$ and $\sigma^2(P)= \langle P^2 \rangle$.

The two curves clearly indicate the alternate increase and decrease of these two parameters (as can be seen on the zoom to the right in figure 3).

However, in order to obtain a truly squeezed state in the quantum mechanical sense, the variance of one of the variables X or P needs to go below ½ (according to Heisenberg's uncertainty relation). This means that $2\sigma$ needs to be lower than 2 times $1/\sqrt{2}= \sqrt{2}$. For realistic experimental parameters, this is not the case in the numerical simulation we have performed. As a matter of fact, it can be seen in fig 3 (left) that with a thermal bath temperature of 10 mK (n=234), the minimum value reached by the plotted quantity is always greater than 2, even for long times (up to 300 microseconds).

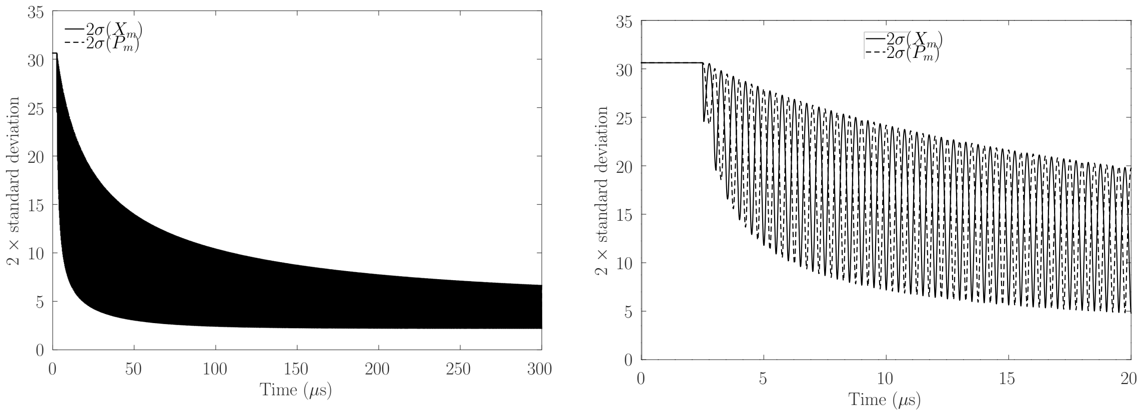



*Figure 3 Simulations on squeezed states (initial temperature of 10 mK). To the left, the full timescale (the oscillations are so fast that they appear as a black surface), and to the right, a zoom on the first 20 microseconds, allowing to visualize the oscillations.*

By assuming the initial temperature to be equal to 1 mK, it is possible to reach a state with a very modest squeezing (2σ=1.38) within a few hundreds of micro-seconds. This is shown in figure 4.

It should be noted at this point that the theoretical prediction for the lowest achievable temperature of the resonator achievable by active feed-back mechanism presented in ref. [4] is predicted to be slightly below 1 mK, starting from a thermal bat at 400 mK. In these conditions, obtaining a modest squeezing factor seems therefore achievable, provided that 1) initial temperature lower than 400 mK is experimentally achieved in a cryostat and 2) active cooling mechanism works experimentally as good as expected theoretically. The associated experimental challenges will need to be addressed in the future.

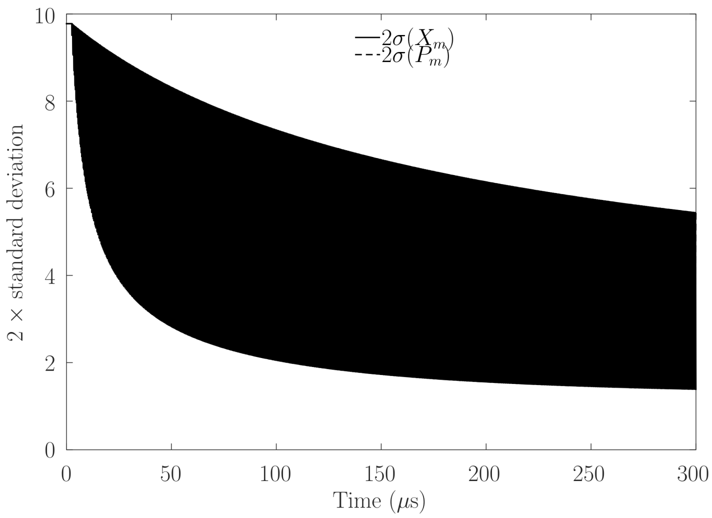



*Figure 4 Modest squeezing with an initial temperature of 1 mK.*

Finally, by assuming n close to 0 (zero temperature bath) is it possible to obtain large squeezing factors using the measured values of the strain coupling strength (D3.3). In figure 5, we have shown a simulation which assumes that we start with an initial photon number of n=0. Here, the minimum value of 2σ is below √2 after only 20 microseconds, allowing the efficient creation of squeezed states. This experimentally unrealistic situation (null bath temperature) is however a demonstration that the method of synchronous pulsed dispersive probing of the resonator can lead to significant levels of squeezing in the physical system studied here.

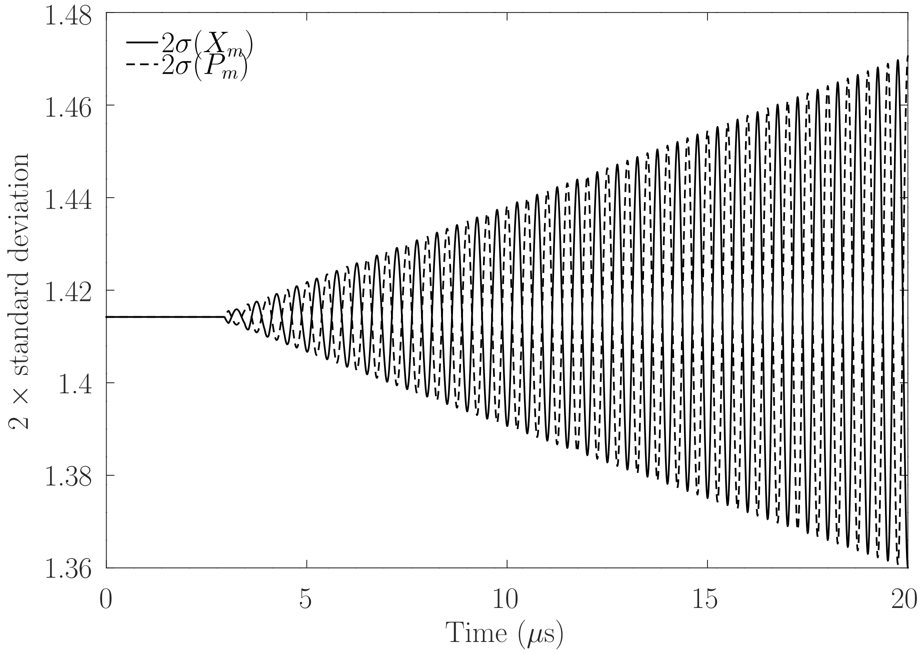



*Figure 5 Squeezed state, obtained by choosing an initial temperature equals to zero (n=0).*

## Entangled quantum states

By extension, with the current parameters of the systems, it seems unrealistic at present time to be able to entangle 2 separate resonators. As a matter of fact, the condition for entangling two resonators 1 and 2 can be seen as a development upon the condition necessary to squeeze the quadratures of a single resonator. Using the equations from reference [5], we define the variables

$X_{\pm}=1/\sqrt{2}(X_2 \pm X_1)$

$P_{\pm}=1\sqrt{2}(P_2 \pm P_1)$,

where the subscript 1 and 2 referring to the oscillator 1 and 2 respectively. In this notation, the criterion for entanglement of the 2 resonators can be written as [5]

$\langle X^2_+ \rangle + \langle P^2_- \rangle < 1.$

In order to be able to fulfil this condition, along with the Heisenberg's principle for both resonators, it is necessary (but not necessarily sufficient), that, $\langle X_{1,2}^2 \rangle$ or $\langle P_{1,2}^2 \rangle$ can be made close or smaller than 1. Therefore, the previous discussions about the conditions necessary to establish squeezing of the quadratures of a single resonator also hold here, and it will be sound to first demonstrate squeezing of the quadratures of a single resonator before trying to entangle two systems.

## Conclusion

Several improvements towards creating non-classical states in resonators have been made, both concerning the resonators themselves (new geometries), the optical setup (optics and detections) and the cryostat, as well as an improvement on the accuracy on the strain-coupling measurements.

All these efforts have allowed us to define experimentally the optimal parameters for the system, which we have then used to assess, based on simulations, the feasibility of reaching the quantum regime with the resonators. The conclusion of these simulations is that the initial value of the minimum resonator phonon number attainable and/or the minimum rate of the heat transfer from the surroundings currently are too high to create squeezed or entangled states, as our cryostat cannot go below 4K. In order to reach such quantum states, a dilution refrigerator (which can be used to achieve thermal bath temperatures as low as a few mK for the most advanced versions) would be of great benefit, ideally in combination with a resonator having a higher vibration frequency, allowing to have a lower phonon-number for a given temperature. Whereas the modification of resonator geometry can be done rapidly, the modifications of the cryostat would require some time to be implemented and a significant extra equipment budget. The team at SYRTE has recently ordered (from the company MyCryoFirm) a dilution refrigerator stage for its existing pulsed-tube based cryostat, that should allow reaching temperatures as low as 30 mK and will be installed in 2020 (it is currently under development and in earlier stage testing by the company). This will be a first prerequisite for the furthering of the studies of rare-earth doped resonators, which we are convinced hold great promise for applications in the field of quantum technologies.

## Bibliography

[1] K. Mølmer, Y. Le Coq and S. Seidelin, Physical Review A **94**, 053804 (2016)

[2] T. Zhong, J. M. Kindem, E. Miyazono, and A. Faraon, Nat. Commun. **6**, 8206 (2015)

[3] J. F Motte, N. Galland, J. Debray et al., Journal of Modern Physics, accepted.

[4] S. Seidelin, Y. Le Coq and K. Mølmer, Physical Review A **100**, 013828 (2019)

[5] C. F. Ockeloen-Korppi, E. Damskägg, J.-M. Pirkkalainen, M. Asjad, A. A. Clerk, F. Massel, M. J. Woolley & M. A. Sillanpää, Nature, **556**, 478–482 (2018)