Nanoscale Systems for Optical Quantum Technologies

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D3.3 Effect of strain on Eu^{3+}

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Version history

Version	Date	Author(s)	Description
V1	29/05/2018	S. Seidelin (CNRS-IN) Y. Le Coq (CNRS-SY)	First draft
V2	08/06/2018	S. Seidelin (CNRS-IN) Y. Le Coq (CNRS-SY) and Philippe Goldner (CNRS-CP)	Submission to EC

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Deliverable Description

The coupling between the motion of the resonator (described in deliverable 3.1) and the Eu^{3+} ions (task 3.4) strongly relies on the sensitivity of the ions' energy levels on the mechanical uniaxial strain. The measurements of this uniaxial strain sensitivity, presented in the form of a report, constitutes the deliverable 3.3.

Introduction and context

As described in deliverable 3.1, the studies of mechanical resonators belongs to the field of optomechanics [1]. A way to study the resonators in or close to the quantum ground state, is to couple it to a two-level system, and interact with the resonator via this system. One particularly interesting way to achieve this is to use "strain-coupling", first demonstrated in 2014 with a semi-conductor nanowire [2]. This strain-coupling can also be used in a rare-earth crystal resonator: in such a resonator, the vibrations, which can be induced deliberately by means of a piezo actuator or result from the Brownian motion due to a finite temperature (or even from the zero-point energy position fluctuations), generate a mechanical strain. 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 therefore 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.

Before the beginning of the NanOQTech project, only the so-called "isotropic" strain-sensitivity had been measured to be 200 Hz/Pa for the crystal site 2 [3]. This corresponds to applying a uniform stress to all sides of the crystal simultaneously which can be obtained by increasing the pressure of the background gas surrounding the crystal, which is technically relatively easy to do.

However, when a resonator vibrates, the corresponding strain applied to the europium ions (in the ideal case) is uniaxial, and thus it is necessary to quantify this value as well. This corresponds to a much more elaborated measurement, as it is challenging to apply a well-calibrated uniaxial force on the crystal inside the cryostat, and measure the response of the energy of the transition of the europium ions.

Measurement techniques

As the atomic structure makes it very challenging to observe single ions, we use the technique of spectral hole burning (as discussed in deliverable 3.1), and we study the influence on strain of the spectral position of the hole (the hole shifts according to the strain applied). The measurements are performed using the following protocol: a bulk crystal (4x4x4 millimeters) is cooled down to 4K, and a spectral hole is burned and recorded. Then a calibrated, uniaxial force is applied to the crystal, and the spectral hole is again recorded. This last step is repeated for several different values of the force. The challenge has been to obtain a uniform (and calibrated) force and has required to explore several different solutions in terms of equipment, before arriving at a suitable solution.

More precisely, to obtain a well-known force, the solution adopted has been to position, with the help of an advanced piezo-actuator setup (functioning at 4K) different masses on the crystal. The first actuators turned out not to be compatible with the cryogenic temperatures (in contrast to what has been promised by the company fabricating these).

The 2 months' delay in the report is essentially due to the waiting time in order to obtain a new actuator system that functions smoothly at low temperatures.

Moreover, in the initial stages of the measurement, static charges building up due to the presence of the piezo-actuators added spurious frequency shifts, and several modifications were necessary to eliminate these artifacts.

Strain measurement setup

The setup inside the cryostat is shown in figure 1. The crystal is situated on the circular copper plate which is cooled down to 4K, by means of thermal contact by connecting copper threads.

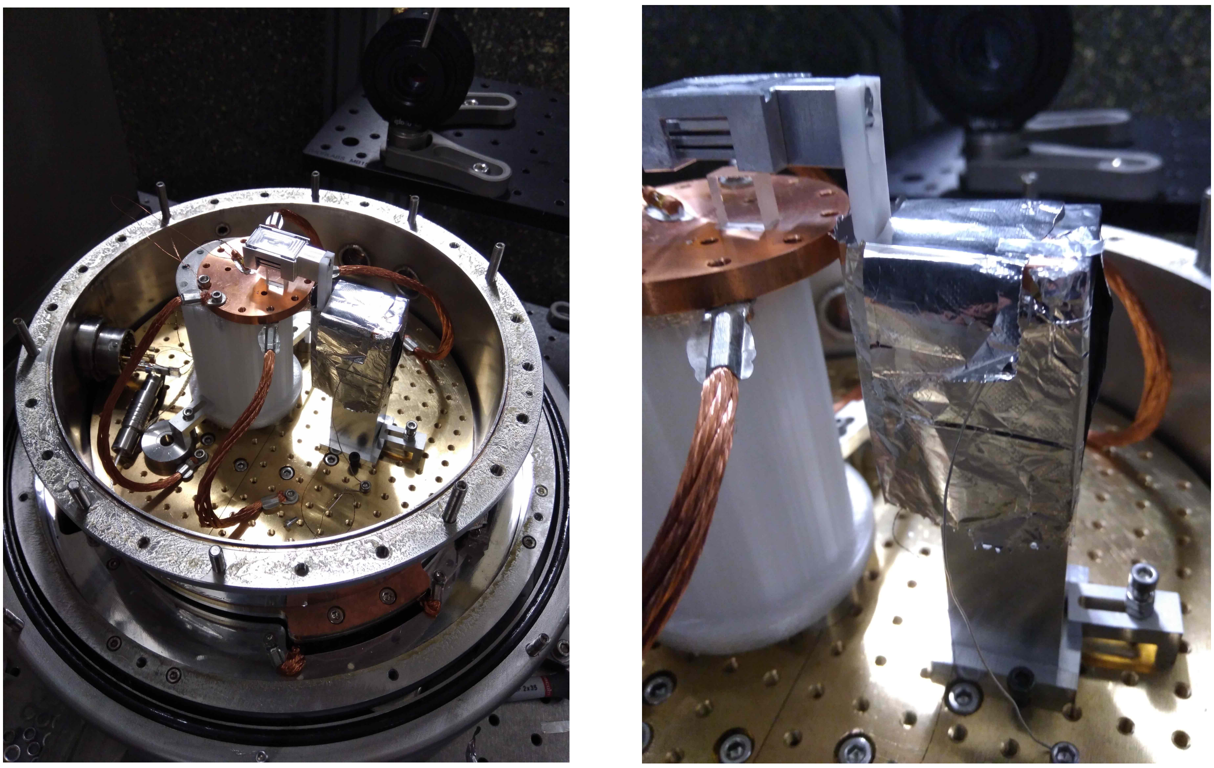

Figure 1 To the left, a global view on the strain measurement setup inside the cryostat, and to the right, the piezo-actuator stage allowing to add a calibrated force to the crystal.

Strain measurement results

The Eu^{3+} ions have two non-identical crystallographic sites, which are likely to have different strain sensitivities, and the measurements have been carried out independently for both sites. Moreover, in order to eliminate the possibility of artifacts, and estimate uncertainties, the measurements have been carried out both by measuring the effect of progressively adding more and more weight on the crystal and measuring the shifts, but also by starting out by adding a weight. The results of these measurements are shown in figure 2 and 3 for site 1 and in 3 and 4 for site 2. In order to achieve the best signal-to noise ratio, the probe light is polarized along the D2 crystal axis, and the force is applied along the D2 axis.

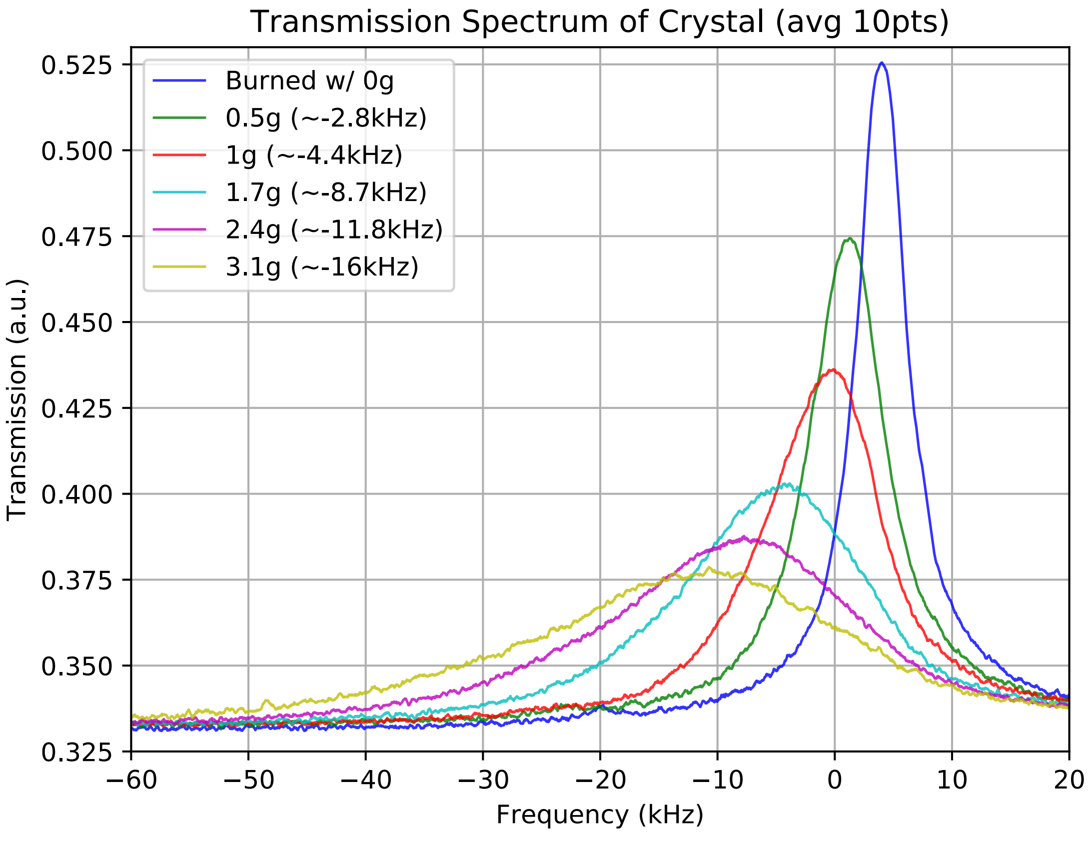

Figure 2 Crystal site 1, the spectral hole burned with zero weight. We then monitor the spectral hole by progressively adding weights.

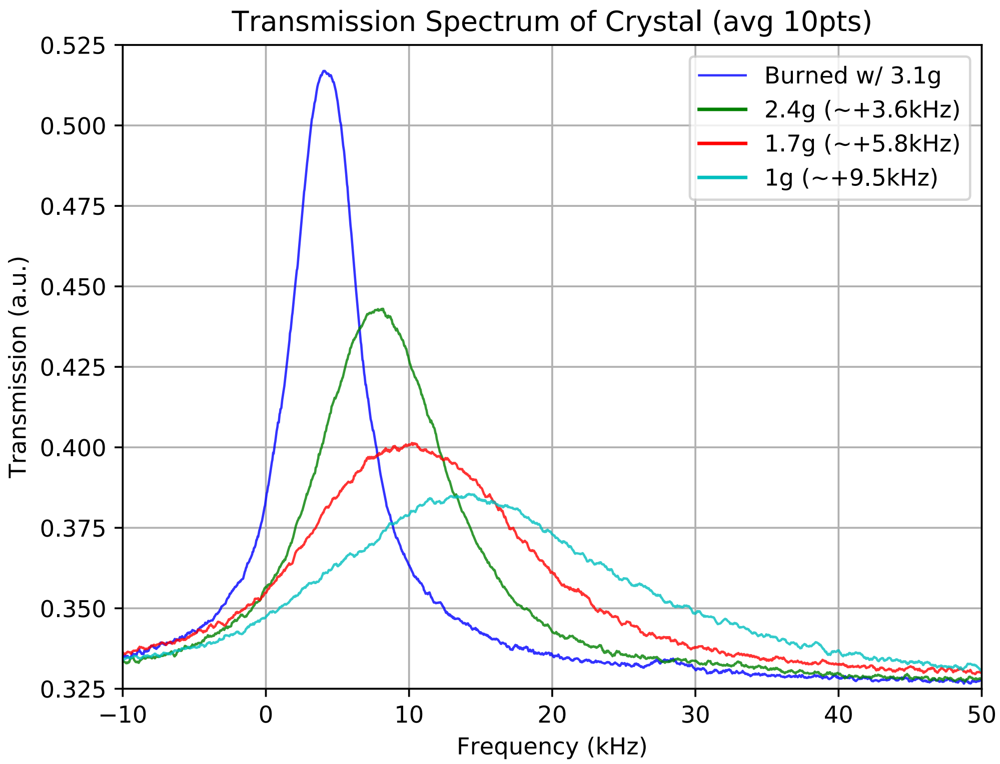

Figure 3: Crystal site 1, spectral hole burned with a non-zero weight, monitoring the spectral hole by progressively removing weights.

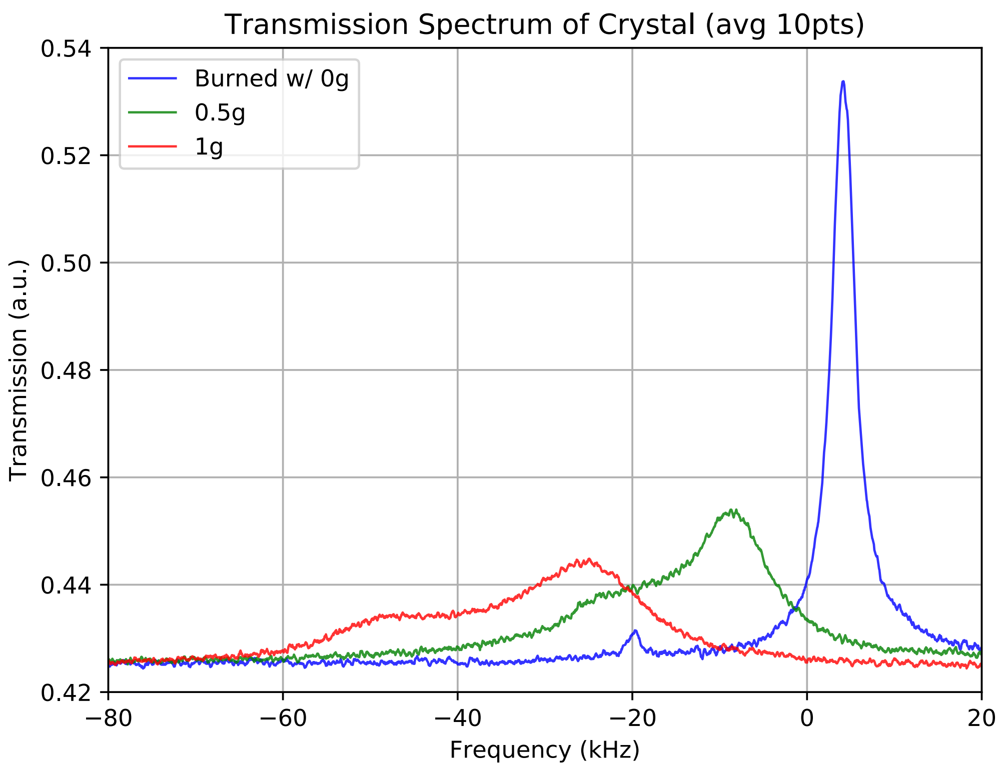

Figure 4: Crystal site 2, spectral hole burned with zero weight, then monitoring the spectral hole by progressively adding weights.

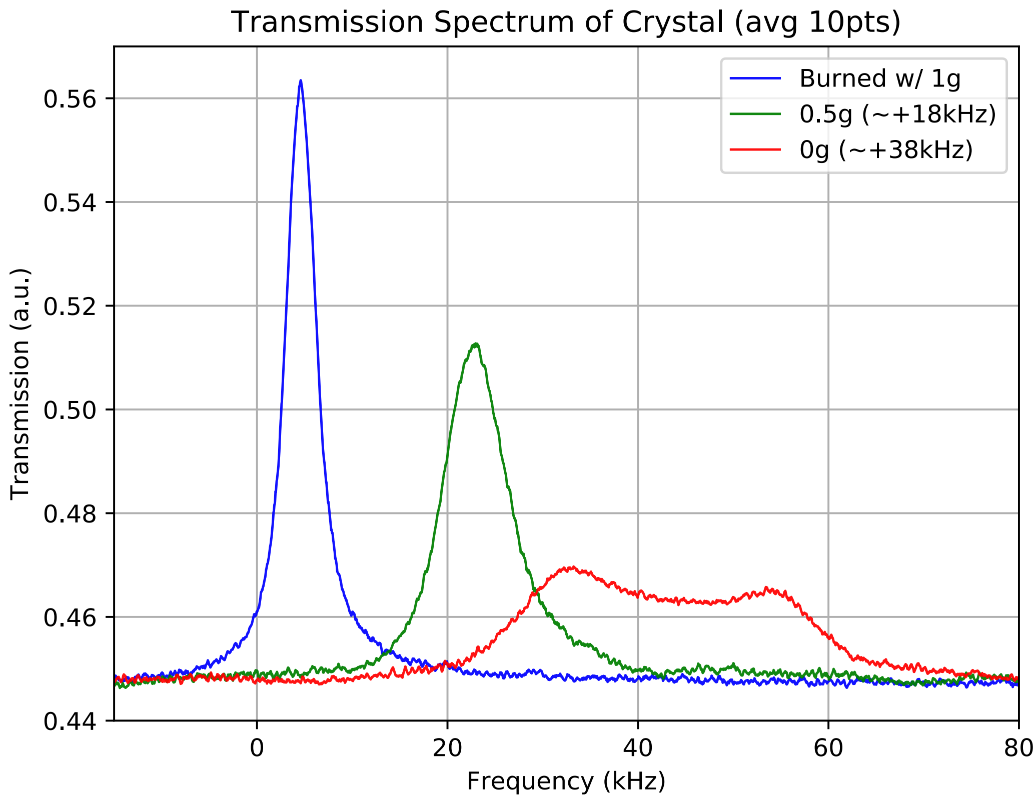

Figure 5: Crystal site 2, spectral hole burned with a non-zero weight, then monitoring the spectral hole by progressively removing weights

For all the measurements, we observe a clear shift of the centre of the spectral hole which is proportional to the weight applied. After converting weights to forces, we obtain the following shifts (in case of a splitting of the spectral hole, we use the arithmetic mean value).

Crystal site 1

- Measurement 1, adding weights (figure 2) 16.6 ± 2 Hz/Pascal
- Measurement 2, removing weights (figure 3) 14.3 ± 2 Hz/Pascal

Crystal site 2

- Measurement 1, adding weights (figure 4) 137 ± 15 Hz/Pascal
- Measurement 2, removing weights (figure 5) 124 ± 15 Hz/Pascal

Here, the error bars do not include the systematic errors discussed in the following.

For both sites, we observe a difference in the obtained value depending on whether we add or remove weights, giving rise to a hysteresis effect. We thus still suspect some minor spurious effects (permanent deformation of crystal, static charging, etc. …) but these effects give rise to errors smaller than 10 %.

Moreover, a broadening of the spectral hole, which we suspect is related to the fact that the force applied is not perfectly uniform across the crystal is observed. The shift of the centre of the peak should however correspond to the total force applied (as long as all ions in the crystal are probed) and is therefore not expected to add a significant error to the measurement.

Finally, for the site 2 we observe an additional splitting of the spectral hole as the force is applied which is not present in the case of site 1. This is possibly due to the fact that the force is not perfectly applied along the D2 axis as expected. We plan to perform additional measurement on a new crystal (in preparation at CNRS-CP) in which we are certain that the D2 crystal axis corresponds the axis of the applied force.

These yet not perfectly understood effects (hysteresis, broadening of the spectral hole for both sites, and splitting for site 2) will be investigated thoroughly in the near future, before allowing us to publish the results for uniaxial strain measurements.

Conclusion

We have completed the first measurement of uniaxial, mechanical strain sensitivity of the transition energy of the europium ions, by applying a well-calibrated force on a crystal containing a spectral hole and observing the frequency shift of this hole.

The site 2 is clearly more sensitive to strain, and will be used for the future resonator experiments. Our measurements have allowed us to confirm that the values of the shifts are large enough to be able to couple a mechanical resonator - already fabricated and described in deliverable 3.3 - by strain to the europium ions. The achievement of this resonator - ion coupling corresponds to the task 3.4, but is also a prerequisite for task 3.7, the creation of non-classical states with mechanical resonators.

In our theoretical article [4] published within the NanOQTech consortium, we assumed the isotropic strain coupling constant (as we did not yet have access to the uniaxial value) but with the newly measured values, we can now also definitively asses the feasibility of the proposal described in this article.

Bibliography

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