4.1 Final publishable summary report

Description of the project context and objectives

Interferometric measurements are by far the most sensitive displacement measurements with sensitivities better than 10^{-20}m/√(Hz) either for large-scale gravitational-wave interferometers (GWI) or table-top interferometers. Progress in low-loss mirrors, laser sources and low-noise detection electronics has been so important over the last twenty years that these experiments are about to be limited by quantum radiation-pressure noise (QRPN).

In such a measurement, there are two quantum limits one has to deal with, even after the classical noise has been substantially lowered: quantum phase noise (QPN) and quantum radiation-pressure noise. Quantum phase noise (also called shot noise) is the dominant noise source at low power but decreases as the optical power is increased. It currently limits the sensitivity of optical measurements away from mechanical resonances. Quantum radiation pressure noise is due to (quantum) intracavity intensity fluctuations: radiation pressure converts these fluctuations into mirror displacement fluctuations that may blur a displacement signal.

As these two noise sources do not have the same dependence with the optical power (with QRPN obviously increasing with power), it has been known for a while that at a given frequency, there is a limit to the displacement sensitivity that one can achieve with a coherent laser beam given by the standard quantum limit (SQL). Going beyond the SQL requires squeezed light and even though such a sub-SQL experiment was clearly beyond reach at the time, this was the driving force for the squeezing experiments performed with nonlinear optical media in the mid 80s.

The situation has now dramatically changed. The currently operated gravitational-wave interferometers are limited by quantum phase noise at high frequency and the second generation (Advanced LIGO and Advanced Virgo), scheduled for the middle of the decade, will also be limited by quantum-radiation pressure noise at low frequency.

The objective of this project is to develop an optomechanical resonator where quantum radiation-pressure noise prevails over thermal noise. The goal of this project is also to fabricate a small optomechanical resonator while sticking to the benefits of the large-scale mirrors, namely low-loss mirrors, which allows for a high optical finesse and increases the intracavity effects of radiation pressure.

Description of the main S&T results/foregrounds

Experimental setup for the observation of quantum optomechanical correlations

The ratio between QRPN and thermal noise spectra gives insights into what has to be done to reach the objectives of this project:

$$\frac{S_x^{\mathrm{rad}}}{S_x^{\mathrm{T}}} \approx 2\left(\frac{F}{300000}\right)^2\left(\frac{800\,\mathrm{nm}}{\lambda}\right)\left(\frac{P_{\mathrm{in}}}{1\,\mathrm{mW}}\right)\left(\frac{1\,\mathrm{mg}}{M}\right)\left(\frac{Q}{10^6}\right)\left(\frac{1\,\mathrm{MHz}}{\Omega_{\mathrm{M}}/2\pi}\right)\left(\frac{1\,\mathrm{K}}{T}\right)$$

Here, F is the cavity finesse, λ the laser wavelength, P_{in} the optical power; M the mass of the optomechanical resonator, Q its mechanical quality factor, Ω_M its resonance angular frequency and T

the environment temperature. All the quoted numbers have already been achieved in several experiments. The main challenge is to gather them in the same experimental setup.

The dedicated optomechanical resonator should fulfil three criteria:

- **A high mechanical resonance frequency** is required in the experiment to be immune to technical noise (either mechanical vibrations or frequency noise of the laser source). A resonance in the MHz regime is ideal, as it is high enough to be immune to technical noise but still low enough to easily operate the low-noise detection system
- **A low mass** is of course desirable because it increases radiation pressure effects and the overall displacements of the resonator, thereby relaxing the constraints over the displacement sensitivity of the global setup
- **A high Q** is needed in order to be able to decrease thermal noise

Our experimental setup is based on a high-finesse Fabry-Perot optical cavity, with a 1-inch fused silica cylindrical input mirror. The end mirror is coated on a plano-convex 34-mm diameter and 2.5-mm thick substrate, which exhibits Gaussian internal vibration modes. In our experiment we consider a mechanical mode with the following characteristics deduced from the thermal noise spectrum observed at room temperature:

- Resonance frequency of 1 MHz
- Motional mass M close to 0.1 mg
- Mechanical quality factor around 1 000 000.

It could possible to have a direct observation of the QRPN if thermal fluctuations weren't higher than the mirror position fluctuations due to the QRPN ($S_x^{rad} > S_x^T$). However, this is not the usual case and the thermal fluctuations are much higher than the QRPN. In order to overcome this limitation we used a setup where we create correlations between two light beams that are sent into the cavity (see Fig. 1). A pump beam drives the mirror and we use a second beam to probe the position of the mirror. We have developed a double injection scheme where the two laser beams are simultaneously resonant with the cavity. Then it is possible to demonstrate the effects of QRPN by monitoring correlations between the intensity of the first beam and the phase of the probe beam.

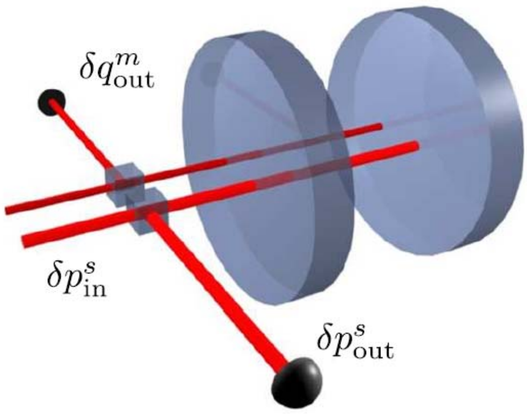

Figure 1: Pump-probe experimental approach. The plano-convex mechanical resonator is driven by the QRPN of the intense beam and the motion is probe with a second beam.

Figure 2 shows the complete setup for the experimental observation of radiation-pressure effects. A Ti:Sa laser working at 810 nm provides the two cross-polarized beams used to lock and to probe the cavity. The two beams are detuned using two acousto-optic modulators. The Ti:Sa laser source provides a quantum-noise limited beam up to 1 mW. For this reason we use a mode-cleaner cavity to filter the laser classical noise in order to have a 10 mW beam at the shot noise level. The overall resonance is controlled by locking the laser frequency via a Pound-Drever-Hall technique.

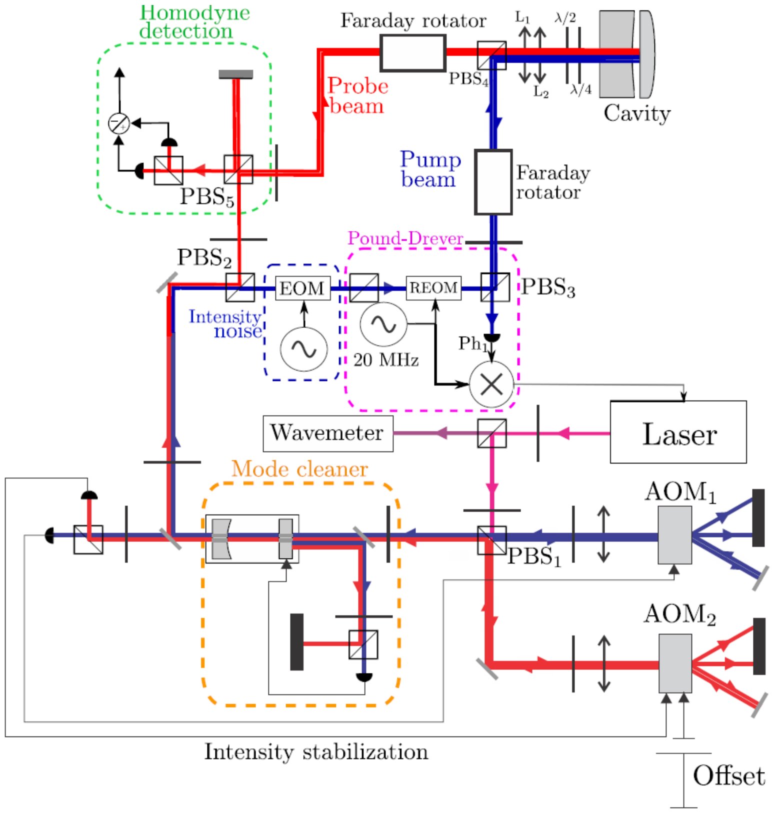

Figure 2 Experimental setup.

Figure 3 shows the measured correlations between both beams vs the cavity detuning: a minimum is found at zero detuning. This minimum should correspond to the QRPN, however, it does correspond to a correlation level of almost 20%; some orders of magnitude greater than the expected optomechanical correlations (close to 10^{-3}).

We found a contamination effect that is present in our measurements. Several directions are taken to decrease the contamination level. We will operate the cavity in a cryostat that we have installed, reducing by two orders of magnitude the thermal noise. We have also developed a quartz micro-mechanical resonator that has a smaller motional mass and high quality factor.

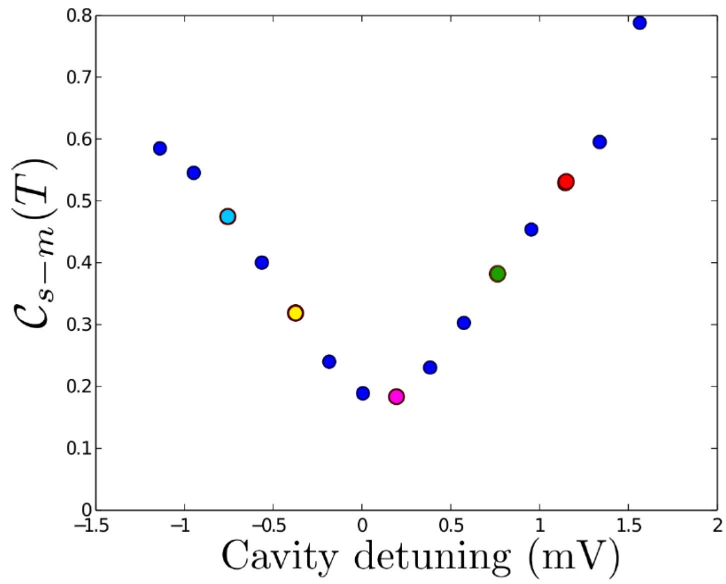

Figure 3 Correlations between the intense beam and the probe beam vs the cavity detuning. At zero detuning the contamination is minimum.

Development of the mechanical resonator

Based on previous studies, we worked in collaboration with ONERA for the development of a quartz micro-mechanical resonator (see Fig. 4). This mechanical resonator will be integrated in the setup that has been previously described. It has been designed for optomechanical experiments and has outstanding characteristics such as a very high quality factor $Q \cong 10^6$ and a motional mass of 25 µm. We chose quartz because it offers a very good mechanical behaviour at high and low temperatures. This is an important requirement in our experiment.

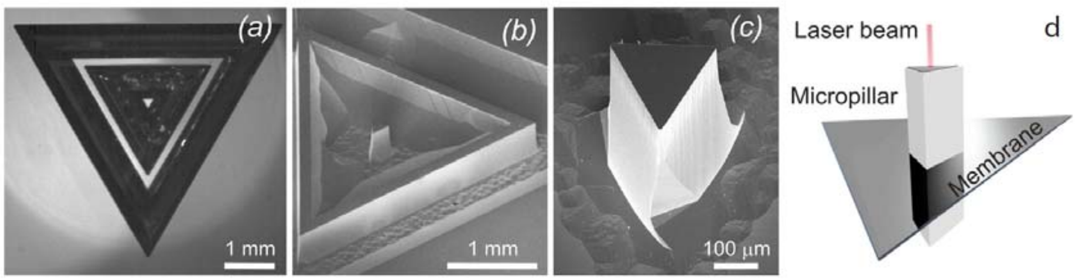

Figure 4 Quartz Micropillar. (a) Optical photograph. (b) Scanning electron microscope (SEM) image of the micropillar and the inner dynamical frame. (c) Closer view of the micropillar. (d) Schematic of the micropillar.

In addition we have developed several techniques that allow to coat a high-reflectivity mirror on top of the resonator. This part is essential for our project's approach. The high optical finesse provided by low-loss coatings dramatically increases both the displacement sensitivity and the radiation-pressure effects. We took advantage of our collaboration with the Laboratoire des Matériaux Avancés in Lyon to process the optical coating. This will allow to use the quartz micro-mechanical resonator as end mirror in our high-finesse cavity.