Development of an Ultra-Stable Cryogenic Silicon Optical Cavity

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An ultra-stable laser frequency locked on a silicon cryogenic cavity is presently under development at the FEMTO-ST lab. The laser will present a remarkable frequency stability of $\sigma_y(\tau)=3\times10^{-17}$. We are presenting the status of the development of this experiment.

Keywords— Fabry-Pérot cavity; vibrations compensation; laser power stabilization; ultra-stable laser; silicon cryogenic cavity

I INTRODUCTION

Lasers stabilized to ultra-stable Fabry-Pérot cavities are widely used devices for metrology and physics experiments like spectroscopy, gravitational waves detectors, frequency standard and tests of fundamental physics [1]. The Pound-Drever-Hall (PDH) technique [2] ensures the frequency stabilization of lasers at a high level of precision, and state of the art fractional frequency stabilities are better than $\sigma_y(\tau)=10^{-16}$ [3,4].
However, the continuous improvement of the stability of optical cavities faces several technical challenges e.g., mechanical vibrations, fluctuations in laser power or thermal noise.

Here, we present a status of a development of an ultra-stable laser at the FEMTO-ST lab and the current challenges to overcome to reach the remarkable frequency stability of $\sigma_y(\tau)=3\times10^{-17}$. This frequency stability goal is defined by the thermal noise, i.e the brownian motion of the atoms composing the Fabry-Pérot cavity. Thus, other sources of noise have to be reduced under the thermal noise.

II METHODS

The mirror substrates and the cavity spacer constituting the ultra-stable optical cavity are made from a single crystal silicon, with the optical axis cut along the [111] direction which has a greater Young modulus.
The cylindrical spacer with a length of 140 mm and a diameter of 100 mm is shown in figure 1. This optical resonator is horizontally hold by three contact points in the vertical middle plane, in a special crystalline orientation. The finesse dielectric is about 78000, for the TEM00 mode around 1542 nm, and we attribute this low value to an insufficient polishing quality of the substrates. The cavity is cooled to 18.1 K, a temperature for which the thermal expansion coefficients are nulled, with a cryostat specifically designed to reduce the vibrations. The cryogenic system used to reach this temperature works with a closed cycle helium-cooling machine from Cryomech. The pulsed tube of the cryostat generates important vibrations, and for that reason we have developed a mechanical structure shown on figure 2, that diminish the vibrations at a level of -110 dB.$(m.s^{-2})^2$ at 1 Hz [5], under the limit defined by the thermal noise. Among the effects that can deteriorate the frequency stability, the residual amplitude modulation (RAM), coming from a bad polarization orientation of light inside the electro-optic modulator or from etalon effects in optics, is a frequent issue in metrology experiments. With a fully digital architecture, we managed to reduce this noise under $\sigma_y(\tau)=10^{-18}$ [6].

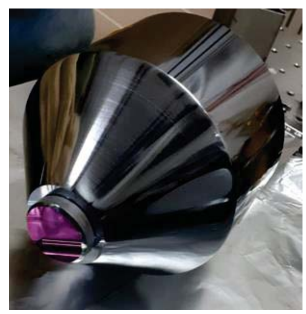

Figure 1: The horizontal cavity spacer has a biconic shape with specific cut angles to reduce the sensitivity to accelerometric noise.

III EXPERIMENTAL DEVELOPMENTS IN PROGRESS

Nevertheless, several others problems are currently limitating the frequency stability of the laser.

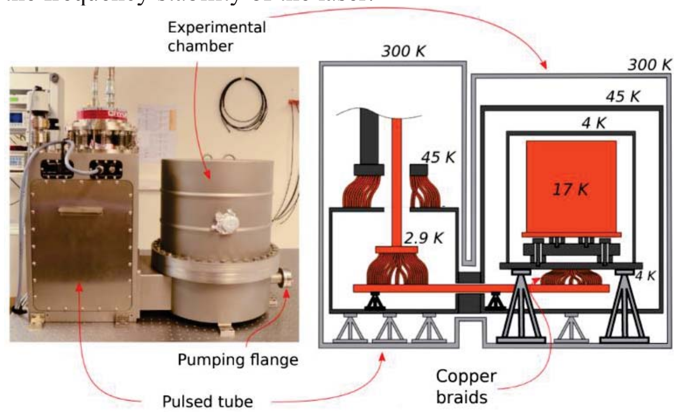

Figure 2: structure developed to passively reduce the vibrations coming from

the pulsed tube and to thermally stabilize the silicon cavity. The vibrating pulsed tube cools a highly thermically conductive copper plate which is linked to the 4 K thermal shield of the cavity by copper braids. The cavity is heated up to ≈ 17 K by thermal resistors inside the orange shield.

First of all, vibrations are still limitating the aimed performance, at low frequency near 1 Hz due to the pulsed tube, and at high frequency (hundreds of Hz) in the acoustic domain. The difficulty lies in the fact that vibrations are mainly produced on the optical table and not from the floor. As a consequence, we cannot use a basic vibrations device filtering and compensating the vibrations under the optical table. Thus, we are currently developing an active system of compensation with seismometers and tilt-meters.

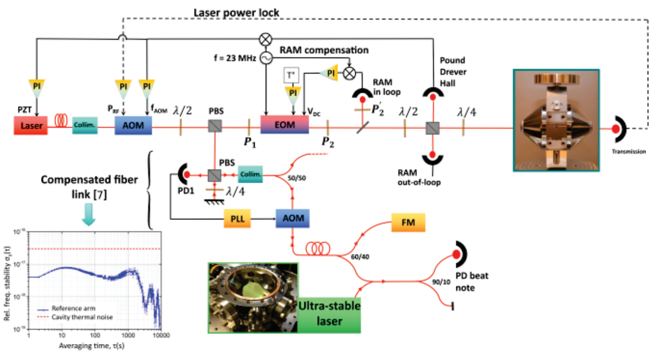

Figure 3: experimental setup including the optical setup, the servo loops for RAM, the laser power stabilization loop, the frequency beat note bench and the performances of the compensated fiber link.

The fluctuations of the laser power are also a limitation since variations of light intensity injected in the cavity change the thermal equilibrium of the mirrors [8]. We estimate that, for a dependance of 20 Hz/µW, we will need to stabilize the laser power at ΔP ≈ 300 pW. For that purpose, we are presently implementing a two stages laser power lock, based on a fine tuning of the RF power send on acousto-optic modulators.

Preliminary results indicate a frequency stability of $\sigma_y(\tau)=4\times10^{-15}$ at 1s and a good long-term drift close to $10^{-19}s^{-1}$.

IV CONCLUSIONS

We are developing an ultra-stable laser frequency stabilized on a cryogenic single-crystal silicon Fabry-Pérot cavity and we present a status about this work. Among the issues preventing us to reach the frequency stability defined by the thermal noise limit, laser power fluctuations and vibrations are crucial. Our team is currently developing an active compensation device for the vibrations and a two-stage laser power stabilization. We also suspect that the frequency stability is partially limitated by the performances of the reference laser stabilized on the ULE spherical cavity.

This experiment will constitute one of the best frequency references for the FEMTO-ST lab, as well as for the Refimeve+ network. This experiment will also be used to realize a test of detection of ultra-light dark matter [9].

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