Development of a stable cryogenic silicon cavity

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***Abstract*— A laser frequency locked to an ultra-stable cryogenic silicon cavity is presently under-development at FEMTO-ST. The laser will target a remarkable low fractional frequency stability defined by the low thermal noise limit of the Fabry-Perot cavity of 3×10^{-17}. We are presenting the status of development of this experiment.**

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

I. INTRODUCTION

Lasers that are locked to ultra-stable Fabry-Pérot cavities using the Pound-Drever-Hall technique [1] have reached remarkable frequency instabilities surpassing $\sigma_y(\tau)=10^{-16}$ in fractional value [2]. These ultra-stable cavities are widely used in metrology and fundamental physics experiments [3]. To improve the frequency instability, perturbations like laser power fluctuations, vibrations, residual amplitude modulation, and temperature fluctuations must be compensated or controlled, ensuring that their contribution to the fractional frequency instability remains lower than the limit set by the thermal noise of the cavity.

We present the status of development of the ultra-stable cavity developed at FEMTO-ST. The thermal limit fractional frequency stability of the cavity is at $\sigma_y(\tau) = 3\cdot10^{-17}$, defined by the Brownian motion of the atoms composing the Fabry-Pérot cavity, and other sources of instabilities have to be reduced below this thermal noise limit.

II. METHODS

Our silicon cavity, of biconic shape, made of two amorphous dielectric mirrors optically contacted to a 14 cm horizontal spacer, has a finesse of 78000. The cavity is cooled to 18.1 K to null out the first-order thermal expansion coefficient, using a pulse tube cryocooler.

The temperature fluctuations contribution to the frequency instability is maintained below the thermal noise limit from 1 to 100s [4]. Fluctuations of the optical power have also been reduced by controlling the amplitude of the signal driving the acousto-optic modulator AOM1 shown in Fig.2. Preliminary measurements of the sensitivity of the frequency to the optical power indicate a sensitivity coefficient of 12 Hz/μW, therefore, the contribution of the optical power on the frequency instability should then be below $\sigma_P < 5\cdot10^{-4}$ μW.

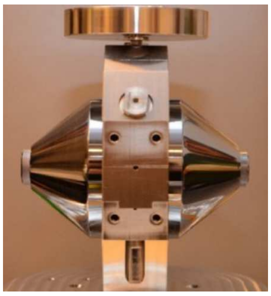

Figure 1: The horizontal cavity spacer has a biconic shape with specific cut angles to reduce the sensitivity to accelerometric noise.

The residual amplitude modulation induced frequency fluctuations have also been reduced to $\sim5\cdot10^{-19}$ [5], contribution that is lower than the thermal noise limit. This has been done by stabilizing the temperature of the EOM, locking the optical power and implementing a DC lock on the EOM, as seen in Fig.2.

As for vibrations, both seismic and acoustic vibrations are a major constraint on the stability of the ultra-stable laser. Therefore, the acoustic noise, notably the one coming from the pulse tube, has been minimized by enclosing the entire setup within a box and the next step will be to implement an active compensation setup for the seismic vibrations

III. STABILITY MEASUREMENTS

In order to estimate the frequency instability of the laser, a frequency beatnote is done with another ultra-stable laser locked to a spherical ULE cavity present in our laboratory, as seen in Fig.1. Preliminary results indicate a frequency instability of $7\cdot10^{-15}$ at 1 s with a long-term drift of $\sim 10^{-16}$ s^{-1}.

IV. PERSPECTIVES

We have noticed that the performances of our ultra-stable laser are comparable to the ULE-cavity-stabilized laser, therefore, we plan to implement a beatnote between the silicon cavity and a cryogenic sapphire oscillator having a frequency instability of $\sim 10^{-16}$ [6], through a fully stabilized optical frequency comb.

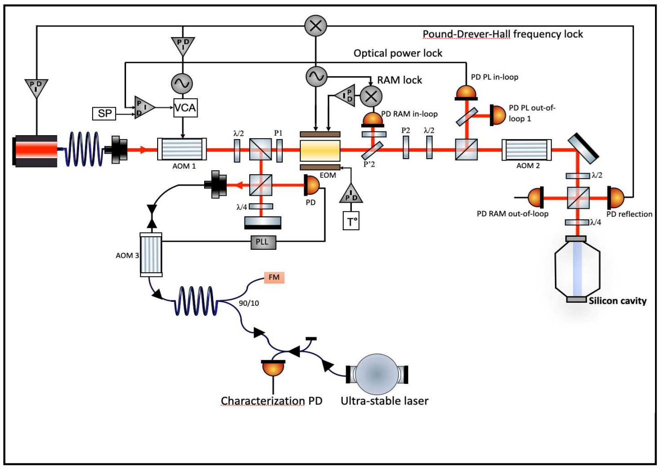

Figure 2: Set-up for stabilizing the frequency of the laser to the Fabry-Perot cavity. EOM: electro-optical modulator, AOM: acousto-optic modulator, λ/2: half-wave plate, λ/4: quarter-wave plate, PBS: polarizing beam splitter, FM: Faraday mirror, C: collimator, P: polarizer, PLL: phase-locked loop, PD: photodiode, PL: power lock, SP: setpoint, VCA: voltage-controlled attenuator.

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