Development of an ultra-stable cryogenic silicon cavity

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Ultra-stable lasers locked to 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, effects like laser power fluctuations, vibrations, residual amplitude modulation, and temperature fluctuations must be compensated or stabilized, 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 development of our silicon cavity at FEMTO-ST, with a thermal noise floor of 3×10^{-17}, defined by the brownian motion of atoms inside the cavity. Our silicon cavity 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 at $\sigma_y(\tau) = 3 \times 10^{-19}$. Fluctuations of the optical power have also been reduced by controlling the amplitude of the signal driving an acousto-optical modulator. Preliminary measurements indicate a sensitivity coefficient of 2 Hz/μW, therefore, the contribution of the optical power on the frequency instability is then around $\sigma_y(\tau) = 10^{-17}$.
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 pulsed 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.
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. Preliminary results indicate a frequency instability of 7×10^{-15} at 1 s with a long-term drift of $\sim 10^{-19}$ s^{-1}. We have noticed that the performances of our ultra-stable laser are comparable to the ULE-cavity-stabilized laser, therefore, we will be presenting the characterisation of the beatnote between the silicon cavity stabilized laser and a cryogenic sapphire oscillator having a frequency instability of $\sim 10^{-16}$ at 10 GHz, through a fully stabilized optical frequency comb.

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