Development of a cryogenic silicon cavity stabilized laser

B. Marechal, S. F. Tetsing Talla, J. Millo, C. Rocher, P.-Y. Bourgeois, G. Goavec-Mérou,
C. Lacroûte, E. Rubiola, Y. Kersalé
FEMTO-ST, Univ. Bourgogne Franche-Comté, CNRS, ENSMM, 26 Rue de l'Épitaphe, 25030 Besançon cedex, France

***Abstract*—In this paper, we present the current development status of a cavity stabilized laser at 1550 nm. The expected thermal noise limit of the silicon Fabry-Pérot cavity is 3×10^{-17} at 17 K in terms of fractional frequency instability. We cooled it to its thermal expansion turning point, measured at 18.1 K, with a pulse-tube based cryocooler. Thanks to the thermal filtering and the temperature control of the cavity, the temperature induced fractional frequency instability is below the thermal noise up to 1000 s of integration time. We also discuss the vibration induced limitations, the thermal characterization of the cryocooler and the digital servo implementation and performances.**

I. INTRODUCTION

Cavity stabilized lasers have reach outstanding short term frequency stabilities and are used as local oscillators in optical frequency standards [1]. Their ultimate performances are limited by the thermal noise of the Fabry-Pérot cavity onto which they are stabilized. Performances in the range of 10^{-17} have been demonstrated [2, 3, 4] in the recent years. The thermal noise comes from the Brownian thermomechanical noise of the cavity. Using well-chosen materials for spacer, substrates and coatings and decreasing temperature are key points to improve the performances of these lasers [5].

II. SILICON CAVITY AND SENSITIVITIES

The optical cavity is made in mono crystalline silicon, which has a higher mechanical quality factor than other conventional materials like ultra low expansion glass or fused silica [4, 6]. The 140 mm long optical axis is perpendicular to the $< 111 >$ orientation to gain stiffness and to have a better rejection of the longitudinal strains. The cavity is placed in a pulse-tube based cryocooler to reach its lowest thermal turning point, working near 17 K [7]. The major benefit of the 17 K turning point is a lower thermal noise due to the coatings of the mirrors compared to 124 K. The cavity is held in three points in its middle plane to be isostatic and symmetrically constrained. We measured the thermal turning point at 18.1 K with a second order thermal sensitivity of -3.9×10^{-10} K^{-2} (fig. 1). The mismatching with values published at 17 K could be due to the calibration of the temperature sensors.

We have also estimated the temperature to frequency transfer function of the three-layers thermal insulation chamber by $\frac{F(s)}{T(s)} = \frac{-3.858\cdot10^{-10}\times\epsilon_T}{1+6600s}$. With a static temperature error ϵ_T of 10 mK, we estimate that the thermally induced frequency instability is below the thermal noise of the cavity up to few thousands seconds (fig. 2).

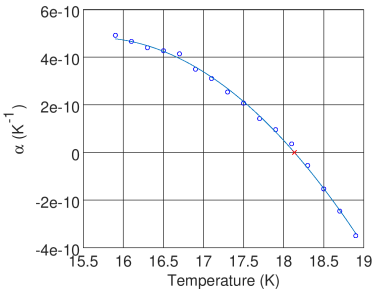

Fig. 1. Evolution of the coefficient of thermal expansion (CTE) with the temperature (blue circles) with a parabolic fit (blue line). The zero CTE is at 18.1 K (red cross)

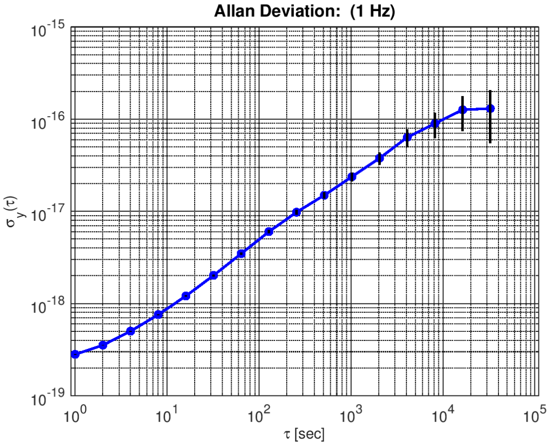

Fig. 2. Allan deviation of the temperature fluctuations of the heating system converted to fractional frequency instability

The power to frequency sensitivity has also been measured with a value of 7.8×10^{-9} W^{-1}. Without power stabilization of the laser source, we are limited at the level of 3×10^{-16} at 1 s with a 0.3 mW incident power.

III. CONTROL SYSTEM

The laser source is locked on the cavity using the well-known Pound-Drever-Hall (PDH) technique (fig. 3) [8]. The modulation and demodulation signals are digitally generated, involving a fine adjustment of the phase between them to reject the residual amplitude modulation (RAM) of the electro-optic modulator (EOM2). The corrections are applied on four different inputs: the temperature and the piezo-electric module of the laser source, the acousto-optic modulator driving frequency (AOM1) and the EOM DC voltage (EOM1). To keep a high correction bandwidth, the demodulation part, the front-end and the EOM1 phase controller remain analogical. The single-input multiple-output PDH controller is fully digital to this day, with a measured bandwidth of $\sim$ 100 kHz. The laser is transferred between the two optical tables by a full-digital active compensated fiber link. Based on the same mechanism, we reject the phase fluctuations due to residual motion of the cavity along the beam path. We plan to complete it with the high bandwidth analog controller using the DC coupled input of the EOM1. A digital RAM control and a power control are also developed to improve the global performances of the setup.

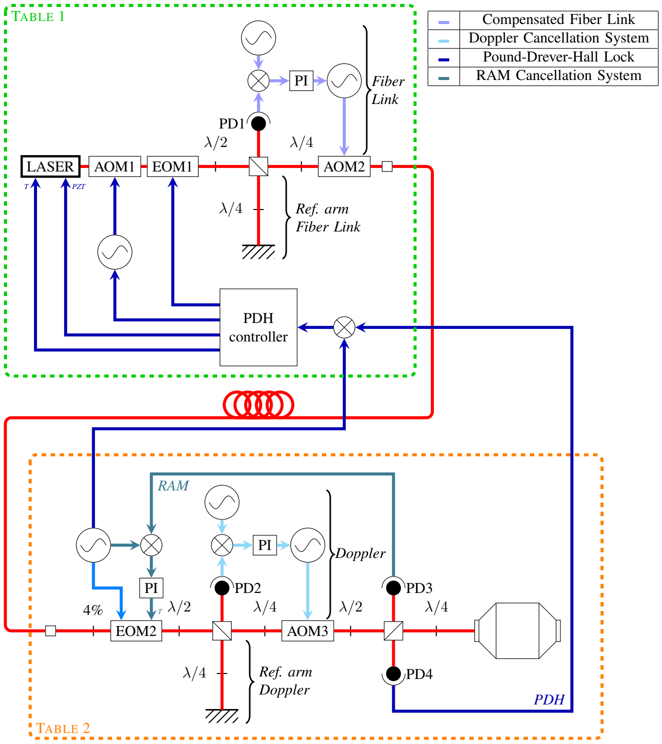

Fig. 3. Principle of the optical setup. AOM: acousto-optic modulator, EOM: electro-optic modulator, PD: photodiode, PI: proportional integrator controller

IV. CONCLUSION

We are developing a laser stabilized to an ultra-stable cavity in silicon at 17 K. We have measured the coefficient of thermal expansion and the temperature turning point of our cavity. The dynamic temperature behavior of the cryocooler has been characterized and allows us to estimate the temperature induced limitations on the cavity. We are also investigating the impact of power fluctuations on the cavity. An intensive use of digital systems took place in this setup. The last results of this work will be presented at the conference, specifically the environmental sensitivities and the control system performances. We will also show the influence of residual motion of the cavity induced by the cryocooler.

REFERENCES

[1] A. D. Ludlow et al. “Optical atomic clocks”. In: *Reviews of Modern Physics* 87.2 (2015), pp. 637–701.

[2] S. Häfner et al. “8×10^{-17} fractional laser frequency instability with a long room-temperature cavity”. EN. In: *Opt. Lett., OL* 40.9 (2015), pp. 2112–2115.

[3] D. G. Matei et al. “1.5 μm lasers with sub 10 mHz linewidth”. In: *Phys. Rev. Lett.* 118 (26 2017), p. 263202.

[4] T. Kessler et al. “A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity”. en. In: *Nature Photonics* 6.10 (2012), pp. 687–692.

[5] K. Numata, A. Kemery, and J. Camp. “Thermal-Noise Limit in the Frequency Stabilization of Lasers with Rigid Cavities”. In: *Phys. Rev. Lett.* 93.25 (2004), p. 250602.

[6] R. Nawrodt et al. “High mechanical Q-factor measurements on silicon bulk samples”. en. In: *J. Phys.: Conf. Ser.* 122.1 (2008), p. 012008.

[7] E. Wiens et al. “Silicon single-crystal cryogenic optical resonator”. In: *Opt. Lett.* 39.11 (2014), pp. 3242–3245.

[8] E. D. Black. “An introduction to Pound–Drever–Hall laser frequency stabilization”. In: *American Journal of Physics* 69.1 (2001), p. 79.