Ultra-stable and tunable Fabry-Perot cavity for an ytterbium based superradiant laser

Martin Hauden, Martina Matusko, Jana El Badawi, Yann Kersalé, Francisco Ponciano-Ojeda and Marion Delehaye
Time and frequency department
FEMTO-ST, CNRS, UFC, ENSMM
26 rue de l'Epitaphe, 25000 Besançon, France
martin.hauden@femto-st.fr

***Summary*— Active optical atomic clocks are emerging as a new promising tool for time and frequency metrology. Such clocks have the potential to reach a fractional frequency instability in the 10^{-18} range at one second [1]. These references are based on the superradiant emission of an ensemble of atoms coupled to a single mode of the electromagnetic field [2]. For *optical* references, this coupling is achieved through a resonant high-finesse Fabry-Perot cavity that therefore plays a crucial role to reach superradiant lasing. Specific characteristics are required to permit superradiant emission in a metrologically relevant regime: tunability of the cavity resonant frequency, ability to accommodate atoms and low fractional length fluctuations, in the order of 10^{-13}. This work shows the conception, through simulation, assembly and preliminary characterization of this Fabry Perot cavity.**

***Keywords*— Ultrastable laser, superradiance, cold atoms, optical cavity, ytterbium**

I. Introduction

Optical atomic clocks are nowadays the most precise tool to measure time. A fractional frequency instability of 6×10^{-17} at one second has been reached [3]. Classical optical clocks start to reach their theoretical limits and new designs are investigated. Therefore, a new generation of clocks based on superradiance of atoms is emerging with the potential to reach fractional frequency instability in the order of 10^{-18} at one second [1]. The clock signal is here directly the collective spontaneous emission of atoms which are coupled to a Fabry Perot cavity [2]. Superradiant lasers strongly releases the stringent constraints on optical Fabry Perot cavities stability imposed by classical optical clocks. For instance, an instability of about 10^{-18} at one second for the clock would typically requires a relative frequency instability of 10^{-13} for the Fabry Perot cavity. However, the cavity has to present new features such as tunability or the ability to accommodate atoms. Here we show a new cavity design suitable for an ^{171}Yb based superradiant laser to be operated on the $^{171}\mathrm{Yb}\ {}^1S_0 \rightarrow {}^3P_0$ 7 mHz linewidth clock transition at 578 nm. The scheme of the cavity is indicated in Fig. 1.

II. Methods/Results

Favorable parameters for superradiant emission can be obtained with a cavity linewidth κ of about 20 kHz and a single-atom cavity coupling in the Hz range. For this, we target a finesse of 30 000, a length of 50 mm and a waist of 150 µm. The cavity spacer features large holes, in addition to the cavity axis, for good optical access and atom transport. The different accesses are required for optical transport, trapping, imaging and repumping of the atoms.

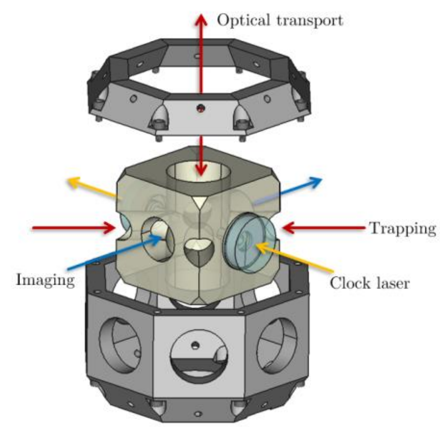

Figure 1 Fabry-Perot cavity design with the different optical accesses. The cavity holder is shown in grey.

Length tunability will be ensured using piezo-electric actuators located between the spacer and the mirrors. Special care has been taken to maintain a fractional length instability for the cavity below 10^{-13}. The cavity spacer is based on a variation of the NPL cubic cavity spacer [4]. Finite-Element Methods were used to adjust the cavity parameters to maintain its good insensitivity to acceleration despite the large optical accesses as shown in Fig. 2.

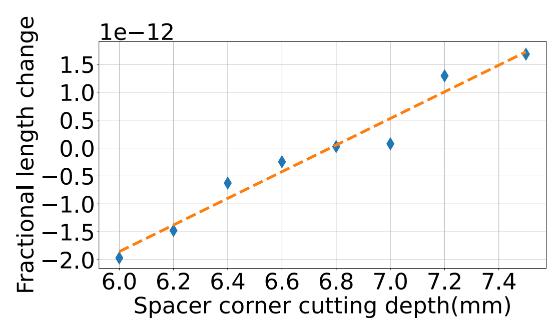

Figure 2 Fractional length fluctuation along the cavity axis for a 1N force applied to the spacer.

Tetrahedral mounting will ensure minimal sensitivity to holding forces. Thermal noise has been evaluated to 3×10^{-15}. Low-noise voltage amplifiers for the piezoelectric actuators should lead to a length instability of about 10^{-14} [5]. Sensitivity to temperature fluctuations will be dominated by the piezoelectric actuators. However, piezoelectric actuators present a negative CTE. Therefore, such fluctuations can be reduced using a kovar washer with the appropriate thickness for CTE compensation.

Regarding the assembly of the cavity, a direct monitoring of the cavity properties is implemented. An optical bench is set such that the cavity injection and finesse measurement can be performed while the mirrors are the mirrors are placed onto the space. Indeed, injection of the fundamental mode of the cavity and a consistent finesse reflects a successful assembly. Custom masks are machined in order to ensure the centering of the mirrors with respect to the spacer cavity axis. The tolerances of the masks are less than 100µm. Since optical contact is not suitable for this design, an epoxy resin with low CTE and outgassing is used (LOCTITE ABLESTIK 285 + CAT 9). One inch mirrors are used with an antireflective coating at 578nm (clock laser) and 759nm (magic wavelength) with a radius of curvature of 0.5m. Ring piezoelectric actuator are used with a thickness of 2mm, a tunable range of 3.3µm and an outer diameter of 15mm (CTS NAC2124). A 1mm thick kovar ring is used to match the mirror and piezo diameter and CTE compensation. A clean environment is required for the assembly such that no dust or foreign particles contaminate the mirror surface. The optical setup used for the monitoring is shown in Fig. 3.

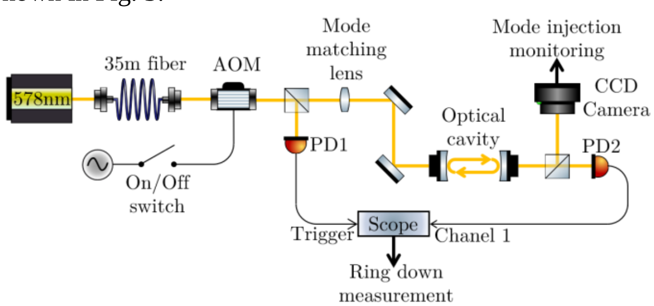

Figure 3 Optical setup for cavity characterization. The 578nm laser is sent to a 35m fiber to the clean room. An AOM is used as fast switch to perform Ring down measurement. Part of the beam is collected and sent to photodiode 1 (PD1) in order to trigger the scope. PD2 collects transmitted light from the cavity. A CCD camera is used to monitor the special mode injected in the cavity.

The 578nm clock laser is sent to the clean area using a 35m long single mode fiber. A single pass acousto optical modulator (AOM) is used as a fast shutter for the laser in order to perform rig down measurements and retrieve the finesse of the cavity [6]. The exponential decay in the transmitted intensity when the laser is turned off is collected by PD2 (Thorlabs PDA100A). A first photodiode, PD1, is used to trigger the scope. The cavity injection is done thanks to a mode matching lens and the two alignment mirrors. The spatial transmitted mode can be seen on the CCD camera in transmission.

The mode injection reflects the centering quality of the mirrors. The reliability of the centering mask is confirmed, before gluing the mirror, seeing the modes on the CCD camera. The fundamental TEM00 mode being injected successfully, as shown in Fig. 4, the mirror is subsequently glued to the spacer.

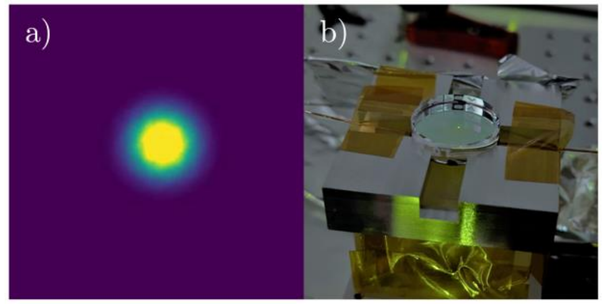

Figure 4.a Spatial profile of the transmitted light recorded on the CCD camera. Here the fundamental TEM00 mode of the cavity is injected. Arbitrary intensity units 4.b Picture of the experimental setup showing in grey the centering mask on the spacer. A yellow dot can be observed at the center of the mirror showing the transmitted light.

Finesse measurements is also a critical characteristic of the cavity which depend on the assembly quality. Experimental measurements of the finesse are performed before placing the cavity in the vacuum chamber. Since the environment is noisy regarding the clock laser frequency and ambient light, several measurements are made. The cavity presents a finesse of 22000±7000 which is consistent with the expected value. A higher value is expected in vacuum since propagation losses will become negligible.

III. Conclusions

Superradiant lasers presents a promising new active scheme for optical clocks being released from stringent constraints on optical Fabry-Perot cavities stability imposed by classical optical clocks. This work presents the design, assembly and preliminary results for a tunable Fabry-Perot cavity for an ytterbium based superradiant laser. Finite-Element Methods is used to design a cavity with low fractional length instabilities. A real time monitoring of the cavity properties is implemented during the assembly process to ensure correct sequences. Finally, good preliminary results are obtained with respect to the cavity design.

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