Ultra Compact Reference ULE Cavity

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***Abstract*—In this paper, we present a new Fabry-Perot cavity design that will be used as a compact reference. The mechanical and thermal simulations that led to the design of the cavity are described. The vacuum chamber and thermal shields around the cavity are also presented.**

I. Introduction

Cavity stabilized lasers are promising devices that could overcome the fractional frequency stability limits of current secondary frequency references. Some ultra-stable lasers already display stabilities over the range of 10^{-16} at short term for cavity lengths superior or equal to 10 cm [1]–[3] and for cryogenic cavities [4]. This very high performance is obtained at the expense of a total set-up volume around 1 m^3. Our project purpose is to use the high frequency stability offered by this technology in order to build a compact and transportable ultra-stable laser with lesser performances. Several design have been already tested [5]–[9] for cavity lengths equal to or longer than 5 cm and frequency stability around 10^{-15} at 1 s.
Our goal is to develop a frequency source with relative frequency stability that overcomes the current performances of best quartz crystal oscillators. For that purpose we have designed a compact ULE cavity with length of 2.5 cm and a total chamber volume of 1.1 L. Mechanical and thermal simulations led to a new spacer geometry with acceleration sensitivity lower than 10^{-12}/(m.s^{-2}) in all directions and temperature inversion around 11 $^\circ$C. The thermal noise of this cavity has been calculated to be 1.5×10^{-15}, which would make it a valuable challenger for the current most stable quartz oscillator.

In this paper, we describe the choice of a spacer design, with small acceleration sensitivities. This choice is based on mechanical and thermal finite element modeling. A custom designed ultra-high vacuum chamber is then presented. It is specially designed to reduce thermal fluctuations on the cavity. The future optical set-up is also described and its components will allow to have a total system volume under 40 L.

II. Cavity Design

A Fabry-Perot cavity is extremely sensitive to the relative length variation between its two mirrors, as it is equal to its relative frequency variation. Mechanical acceleration sensitivity, as well as thermal expansion, are therefore two key parameters when designing a Fabry-Perot cavity.

A. Choice of the spacer geometry

Mechanical simulations with COMSOL Multiphysics (Structural Mechanics module, Solid Mechanics physic, Stationary study) have been performed in order to find an effective ULE spacer shape with low acceleration sensitivities.
A global force is applied on the whole cavity, in order to simulate the effect of a 1 m/s^2 acceleration. The axial displacements are then measured at the center of the mirrors, and at a 1 mm distance from the optical axis in all transverse directions. This allows us to estimate the relative displacement and angle of the mirrors.
The aim was to keep as much symmetries as possible around the optical axis. Cavity spacers such as cylinders [2] or spheres [6] have good symmetries but are not easy to hold. We tested other geometries in order to find a better mounting of the cavity with good acceleration sensitivities. These simulations were performed for several spacer shapes of 25 mm length. They allowed us to find spacer shapes that minimized the tilt of the mirrors under accelerations (a result of one simulation is depicted on figure 3).
An octahedral cavity displayed very low acceleration sensitivities, as well as a "double tetrahedral" cavity, with respectively four and three support points. The four-points holding of a cavity in its middle plane seems to exhibit few problems. The three-points holding allows self equilibrium of the resulting forces if the finger that holds the cavity is too tight. In the case of a four-point holding, this unbalance in the forces leads to a bad holding of the cavity, as well as possible effects over the acceleration sensitivities.
In addition, a three-points holding matches more a real holding with a machined support, as errors of machining will not have as much effect as with a four-points holding, as the machining tolerances of an hyperstatic four-points support have to be very small.

The three-points holding is therefore suitable for a compact holding system, as it allows fixing two feet and apply a maintaining force with the last one.
The last advantage of the "double tetrahedral" cavity over the octahedral one is its smaller volume. All of these advantages led us to choose a "double tetrahedral" shape for the spacer

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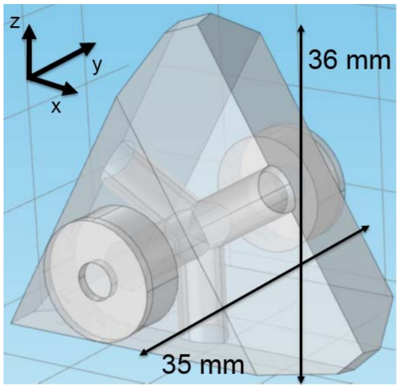

Fig. 1. Double tetrahedral spacer, SiO_2 substrates and ULE rings.

of our compact cavity (see figure 1).

The spacer dimensions were then optimized in order to exhibit small acceleration sensitivities (see subsection II-C).

B. Thermal simulation

The spacer of the cavity is made of ULE glass, as it significantly reduces the length fluctuations due to small thermal fluctuations. The ULE glass displays indeed a temperature inversion point, where its coefficient of thermal expansion vanishes at the first order [10]. Using fused silica as mirror substrates decreases the contribution of the mirror substrates to the thermal noise limit of the cavity [11], but shifts the inversion point to lower temperatures. This could be problematic in a vacuum chamber, as condensation might occur on the optical viewports. It would also lead to higher current consumption from the Peltier. This shift can be partially compensated with the addition of ULE rings attached to the backside of the mirrors [12].

Thermal simulations with COMSOL Multiphysics were performed to estimate the inversion temperature of the whole cavity regarding rings thickness and inner diameter (see figure 2).

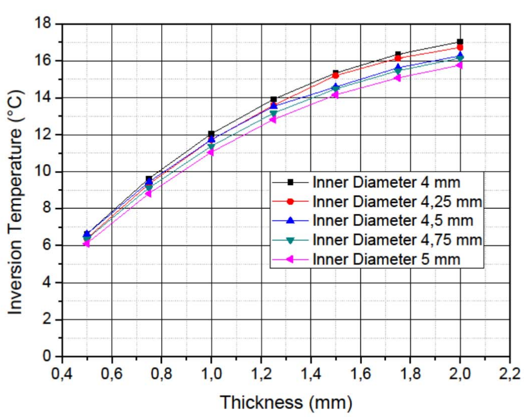

Fig. 2. Inversion temperature versus ring thickness, for several ring inner diameters.

Nevertheless, the mass addition at each side of the cavity led to increased acceleration sensitivities, as our cavity is maintained in its middle plan. The spacer dimensions corresponding to low acceleration sensitivities have therefore to compensate for the dimensions of the rings.

A compromise had to be found between the thermal inversion temperature and the spacer's dimensions. We chose ULE rings of 1 mm thickness and inner diameter of 5 mm, in order to have an 11 ˚C inversion temperature (see figure 2).

C. Final design

The final cavity has to be optimized regarding the chosen ULE rings dimensions. The acceleration sensitivity of a cavity is strongly linked to its spacer dimensions. The optimization consisted of changing several geometric parameters, such as the basis edge of its middle plan *ar*, as depicted on figure 3. The relative length variation is evaluated for several values of the basis edge, between the mirrors' centers and transverse or crossed length variations from points at 1 mm distance from the centers in all transverse directions. The a_x acceleration corresponds to 1 m/s^2 acceleration in the *x* direction (see figure 1).

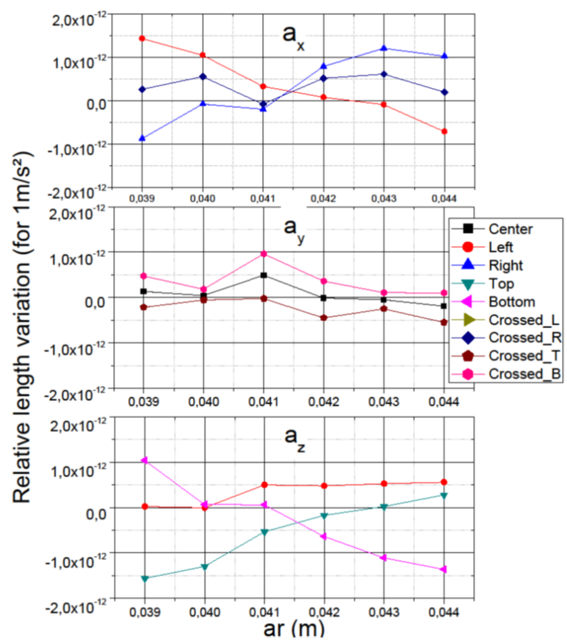

Fig. 3. Fractional length stability for 1 m/s^2 acceleration.

A 25mm length Fabry-Perot cavity was designed, with a calculated 1.5×10^{-15} fractional frequency stability. The "double tetrahedral" ULE spacer and fused silica mirrors with ULE rings display simulated acceleration sensitivities below 10^{-12} per m/s^2 in all direction (see figure 3) and an 11 ˚C inversion temperature. The cavity design is depicted on figure 1. This cavity fits in a cylinder of 64 cm^3.

III. Vacuum Chamber

A custom vacuum chamber (see figure 4) was designed in order to put the Fabry-Perot in an ultra-high vacuum environment. We chose a cubic shape to reduce the volume of the system. Indium gaskets will close the chamber, in order to reach the desired 10^{-8} mbar pressure.
The cavity will be maintained by three points in its middle plane. Inox enclosures will close a first thermal shield around the cavity. A copper thermal shield (polished and gold plated) will reduce the thermal radiation from the external environment to the cavity and allow homogeneous temperature around the cavity.

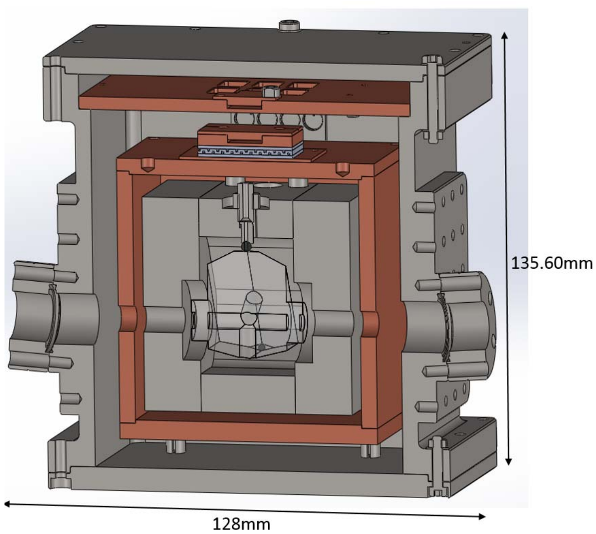

Fig. 4. Vacuum Chamber and thermal shields made of copper and inox. Threadings are available outside the chamber in order to attach components. The viewports are 4° tilted. An electrical 16CF pass-through and two 16CF gates for ion pump and turbo pump are not visible on this picture. The inox part with four holes in the background avoids thermal connection between electrical wires and the copper shield. The big copper plate on top of the picture is used to evacuate the heat from the Peltier module.

The power radiated between the vacuum chamber housing and the copper thermal shield is calculated to be 63.1 mW for a vacuum chamber temperature of 20°C and a polished and gold-plated copper shield temperature of 11°C. The conduction through the posts holding the copper shield has therefore to be at the level of this radiation. Special materials (*eg* Teflon and glass reinforced polymer) will be used for the screws holding the thermal shield, in order to provide the needed thermal resistance of 400 K/W per foot and keep small feet heights.
The thermal flux used to cool the cavity will be pumped by a Peltier module, and conducted to the external faces of the vacuum chamber. The calculated thermal resistance of 0.132 K/W between the vacuum chamber and the copper plate over the Peltier will prevent from local overheating, even with the initial transient response.

A digital temperature controller will lock the copper thermal shield temperature at a level of 1 mK fluctuations. The passive thermal attenuation as seen from the cavity has been calculated using basic simulation with Pspice (see figure 5).

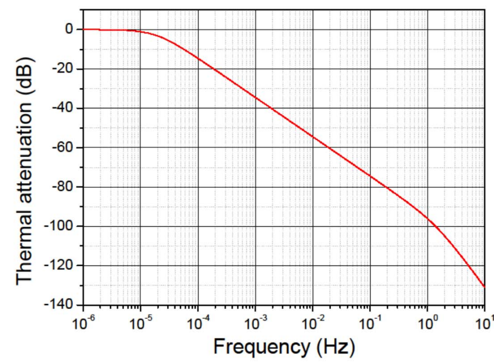

Fig. 5. Thermal Pspice simulation showing the thermal attenuation at the cavity.

The attenuation at 1Hz is suitable for fractional frequency stabilities at a 10^{-15} level.

IV. Optical set-up

Figure 6 shows an overview of the system. A RIO laser diode will be used as the laser source. In order to keep the optical set-up as compact as possible, we will use as much pigtailed devices as possible. The Doppler cancellation system is thus made of fibered components [13] including two acousto-optic modulators. This structure allows correcting the effective phase shift due to light transfer within the fiber, and to separate spurious reflections inside the fiber.

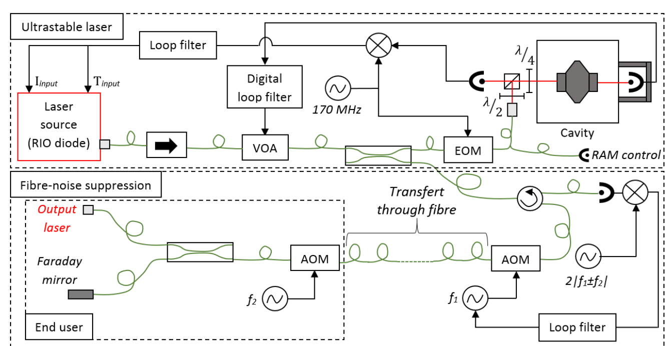

Fig. 6. Overview of the system. The Laser source is a RIO laser diode. A Variable Optical Attenuator (VOA) is controlled by a digital loop filter and stabilizes the optical power. The electro-optic modulator (EOM) creates the sidebands used by the Pound-Drever-Hall frequency stabilization. Slow stabilization is applied on the temperature of the RIO laser diode, and fast stabilization is applied on its current. A control of the Residual Amplitude Modulation (RAM) of the EOM is implemented before the free-space optical set-up. The fiber phase noise suppression is allowed by two Acousto-Optic Modulators (AOMs) with different drive frequencies. A digital temperature control of the EOM is not presented in this figure but will be implemented in the system.

Special digital PID controllers with few hundreds kHz bandwidth will be used for the optical power locking system

and for temperature controllers.
A compact version of the free-space part is under development. The calculated total volume of the system, including RIO diode controller, thermal controllers, Pound-Drever-Hall loop filter, power supplies and vacuum chamber with turbo-pump valve and ionic pump is predicted to be under 40 L.

V. Conclusions and Outlook

The design of a 25 mm length Fabry-Perot cavity has been presented. It has a calculated 1.5×10^{-15} fractional frequency stability and simulated acceleration sensitivities under 10^{-12}/(m/s^2) in all direction, for an 11 $^\circ$C inversion point.
A custom vacuum chamber design was also presented, with little heat radiated to the cavity and thermal insulation compatible with good fractional frequency stabilities.
The future optical bench was also designed in a compact way, with an all-fibered Doppler cancellation system.

The complete system will be implemented, with a compact version of the free-space optical set-up. A special vibration test set-up will be created in order to measure the actual acceleration sensitivities of the cavity.

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