The design of an ultra-stable cavity with crystalline mirror coatings for atomic optical clock

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***Summary*—We present the design of the room temperature, 30 cm ultra-stable cavity system with crystalline mirror coatings for atomic optical clock.**

Keywords*—*cavity; stability; FEM; Vacuum chamber; Thermal limit, optical cavity

I INTRODUCTION

An indispensable part of an atomic clock is an ultra-stable laser ready to measure clock transition frequency of atoms [1]. Locking the clock laser to the resonance of a rigid high-finesse ultra-stable optical cavity allows transferring the cavity's length stability to the frequency stability of the laser [2]. Therefore, to obtain 10^{-15} of relative frequency instability $\Delta\nu/\nu$ we need to stabilize length L with the same precision ($\Delta L/L = -\Delta\nu/\nu$). Hence, it is essential to isolate the system from all external noises and perturbations, e.g. acoustics and seismic noises, pressure and temperature fluctuations.

The major and ultimate limit of the cavity performance is set by thermal processes of the coating layers [3, 4]. We can mitigate this limit by lowering the temperature or finding new component's material with better inner properties, such as mechanical losses or Young modulus. Crystalline AlGaAs coatings provide tenfold reduction of the thermal noise [5], compared to dielectric coatings, because of lower mechanical losses in room temperature. The goal of our work is to achieve Brownian noise floor for wider frequency spectra by proper design of the cavity system.

II METHODS/RESULTS

Cavity's sensitivity to vibration can be initially mitigated by careful design of its geometry [6-8]. Therefore, we performed Finite Element Method (FEM) calculation to find the so called Airy and Poisson points, i.e. the supports where the ends of the mirrors remain parallel and length do not change, in 1 g acceleration (Fig. 1.). The cavity is supported by the Viton spheres or cylinders with the area of contact with the spacer of ~1.5 mm. FEM calculation shows that any change of the spacer or mirrors size or shape yields to a significant shift of the optimal point's position. Cut-outs' positions and sizes are designed for manoeuvring of the supports in the case of any inaccuracy of calculation, manufacturing or non-perfect alignment. Considering the worst case scenario, we performed additional FEM simulations which show that carefully positioned external Teflon rings change the cavity geometry (mass distribution) and effectively gives another place for manoeuvring and optimizing the Airy points. Optimal geometry together with the active anti-vibration platform and seismometers should allow achieving the thermal limit.

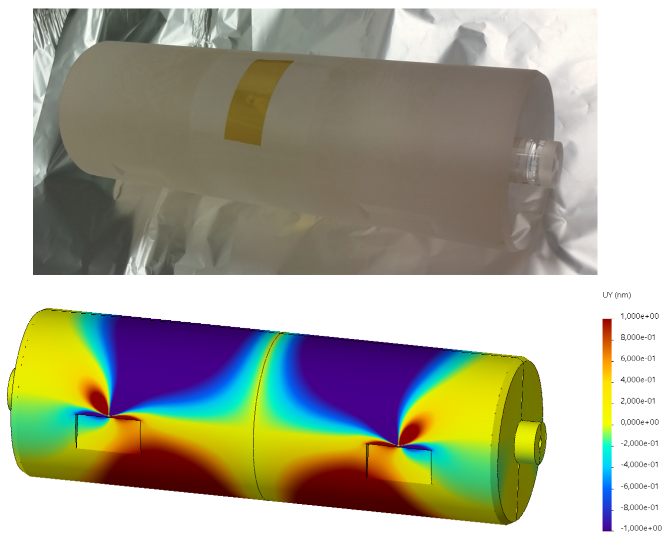

Fig. 1. A photo of manufactured ULE cavity (top) and FEM simulation results of a longitudinal displacement under a vertical 1 g acceleration (bottom).

Significant reduction of the temperature fluctuation noise is provided by the cavity's housing (Fig. 2.). The most external layer guarantees the ultra-high vacuum (UHV) regime by indium sealing wire connection and constant pumping, performed by 20 l/s ion pump. In addition, the Peltier modules are attached to the walls of the external chamber to set and control conditions for ULE's zero-crossing temperature T_0. Since the ULE's coefficient of thermal expansion is 10^{-8}/K in room temperature [3], the fractional instability on the level of $\delta L/L = 10^{-17}$ with temperature ofsetted from T_0 by $\Delta T = 0.1$ mK, requires stabilization of the temperature on the level of $\delta T < 1$ μK. Therefore, the three consecutive passive shields (Fig. 2) lower down the frequency and amplitude of the temperature fluctuations, and work as a low-pass filter. The calculated time constant of temperature setting is on the order of days.

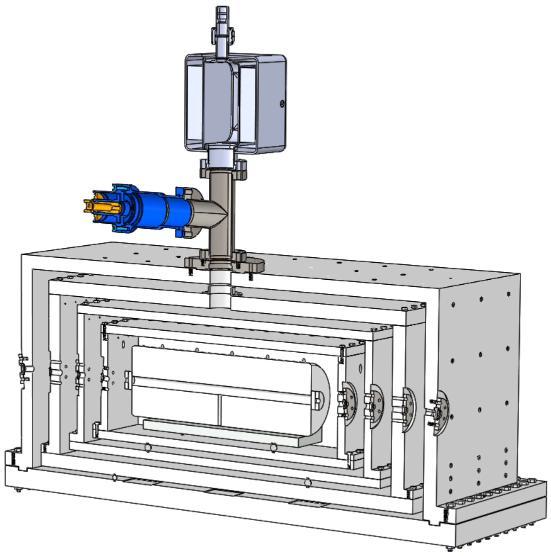

Fig. 2. Cross section of the vacuum chamber housing for the ultra-stable cavity.

When each of the layers lies on glass balls, the heat is transferred mainly by radiation. Therefore, the chamber's material must provide high thermal capacitance, high thermal conductivity, highly polished surface i.e. low emissivity, and vacuum compatibility.

III Conclusions

We presented a design of the room temperature 30 cm long ultra-stable cavity to mitigate mechanical vibrations and temperature fluctuations. By using several passive layers of the chamber and active seismic isolation, we expect to receive the thermal floor limit for wide averaging time spectra. In addition, non-perfect geometry of the cavity can be corrected by careful positioned external Teflon rings.

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