A Cryogenic High-Finesse Optical Cavity to Improve the Stability of Yb Optical Lattice Clocks

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***Abstract*—We report on the implementation of a high-finesse sapphire optical cavity operating in a closed-cycle cryostat at 4 K. Operation at cryogenic temperature allows suppression of thermal noise and potential for laser frequency stabilization at the low 10^{-17} fractional frequency stability level. However, it complicates controlling technical sources of noise. Solutions for minimizing the impact of acceleration noise, temperature fluctuations, and residual amplitude modulation will be presented, as well as laser frequency stability characterization and preliminary results in applying the improved clock laser to the interrogation of the NIST Yb optical lattice clocks.**

Keywords—laser frequency stabilization; high-finesse optical cavities; cryogenics; optical lattice clocks.

I. Introduction

The periodic interrogation of the electronic transition frequency, inherent in the operational principle of atomic clocks, results in unavoidable aliasing of the local oscillator frequency noise [1]. Techniques for rejecting this source of frequency noise in clock comparisons [2] and for synthesizing an effective zero-dead time clock from the interleaved interrogation of two atomic ensembles [3] have been demonstrated. However, the quest for optical clocks with better stability is still dominated by the development of laser sources with longer coherence times.

State-of-the-art laser stabilization techniques rely on the Pound-Drever-Hall technique [4] to stabilize the optical wavelength to a length reference realized with a Fabry-Pérrot optical cavity. After the suppression of all technical noise sources, the ultimate limit of this technique is thermal noise: the stochastic motion of the atoms in the spacer due to the finite temperature causing length fluctuation and thus frequency noise.

Thermal noise can be suppressed using materials with lower mechanical losses [5] or lowering the temperature [6]. We experimentally investigate this second option realizing a high-finesse sapphire optical cavity operating at a temperature of about 4 K in a closed-cycled cryostat.

II. Design

Operation at cryogenic temperature presents two main challenges for the implementation of an ultra-stable optical cavity.

First, the closed-cycle cryocooler generates significant vibration. This acceleration noise, coupled with finite rigidity, results in deformation of the cavity spacer and thus frequency noise. To suppress acceleration noise, the cavity is mounted on an original passive vibration isolation stage in the cryostat vacuum chamber. Sapphire is chosen for its high Young modulus and thus higher rigidity resulting in smaller deformation for a given acceleration noise spectrum. The geometry of the spacer is optimized via finite element modeling to minimize acceleration sensitivity. Further acceleration sensitivity suppression is realized by experimentally tuning the orientation of the sapphire crystalline axis with respect to the mounting structure [7]. Results of the experimental characterization of the acceleration sensitivity will be presented.

Second, the specific heat of most materials vanishes with decreasing temperature, thus it is difficult to efficiently filter thermal fluctuations in a cryogenic environment. Our design employs a triple polished stainless-steel passive thermal shield, an actively stabilized copper thermal shield, and a superinsulation layer to minimize temperature. Results from the experimental characterization of the temperature fluctuations will be presented.

The volume of the cryostat vacuum chamber is defined by the target temperature and by the finite closed-cycle cryocooler cooling power. The size of the vacuum chamber and the space occupied by the necessary thermal shields and vibration isolation stage in turn constrain the cavity length to 7 cm. For realistic reflectivity and optical losses in the cavity mirror this results in a finesse in the few hundred thousands range. This accentuates the role played by residual amplitude modulation imposed by the electro-optical phase modulator required for Pound-Drever-Hall operation and of electonic noise. The residual amplitude noise suppression scheme employed will be presented.

Finally, preserving the painstakingly realized laser frequency stability for the atomic interrogation requires optical-path length stabilization from the cavity to the atoms reference frame in the optical lattice. The solution implemented for the Yb clocks will be described.

III. Results

We will present laser frequency stability results from three-corner-hat and beatnote phase noise cross-correlation analysis [8].

Preliminary results from interrogation of the Yb clocks with the improved clock laser will also be presented as well as the technical detection noise minimization techniques implemented to improve the clocks stability closer to the quantum projection noise limit.

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