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Ultra-Stable Cryogenic Optical Sapphire Resonators for Tests of Fundamental Physics

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Abstract: We present a design for an ultra-stable cryogenically cooled sapphire optical cavity system, with fractional frequency stability better than 10^{-16} at one second integration. We plan to use the ultra-stable cavities to perform a test of the isotropy of light propagation at the 10^{-20} level.

1. Motivation

Many experimental and technical applications, e.g. optical atomic clocks, demand ultra-stable cavity systems for laser frequency stabilization. Nowadays, the main limiting factor in frequency stability for room temperature resonators has been identified to be the displacement noise within the resonator substrates and mirror coatings due to thermal noise. Different approaches are being proposed right now to lower the influence of thermal noise, such as using higher order modes, longer cavities, or new types of coating materials. A straightforward method is to cool down the resonators to cryogenic temperatures. Following this approach, we will set up an ultimate cryogenic optical resonator system using specially designed sapphire cavities with the goal to reach a relative frequency stability of better than 10^{-16} up to long integration times.

2. Preliminary Work

We experimentally analyzed the thermal noise floor of an optical resonator made of Zerodur at different temperatures (room temperature, 77K, and 4.2K). The results (see Figure 1) were in good accord with the theory of Numata et. al except for deviations at 4.2K likely caused by an imperfect measurement setup.

Furthermore, we cooled down to liquid helium temperatures a monolithic sapphire resonator where the light is propagating within the crystal [1]. Prior operation at room temperature revealed a limit in the obtainable relative frequency stability with a flicker floor like behaviour between 4 s and 100 s (see Figure 1). The overall frequency performance of this particular monolithic sapphire resonator (finesse 10 000; 200 kHz linewidth) is strongly affected by its low coupling efficiency of less than 0.3% due to flawed coatings.

We assume thermal noise to be the origin of the observed flicker floor. Although to our knowledge no complete theoretical description for the thermal noise limit of a monolithic resonator exists yet, it can be expected that it will be higher than for evacuated cavities due to additional noise in the index of refraction. The observed improvement in frequency stability at cryogenic temperatures supports the assumption that thermal noise effects are the performance limiting factors (see Figure 1).

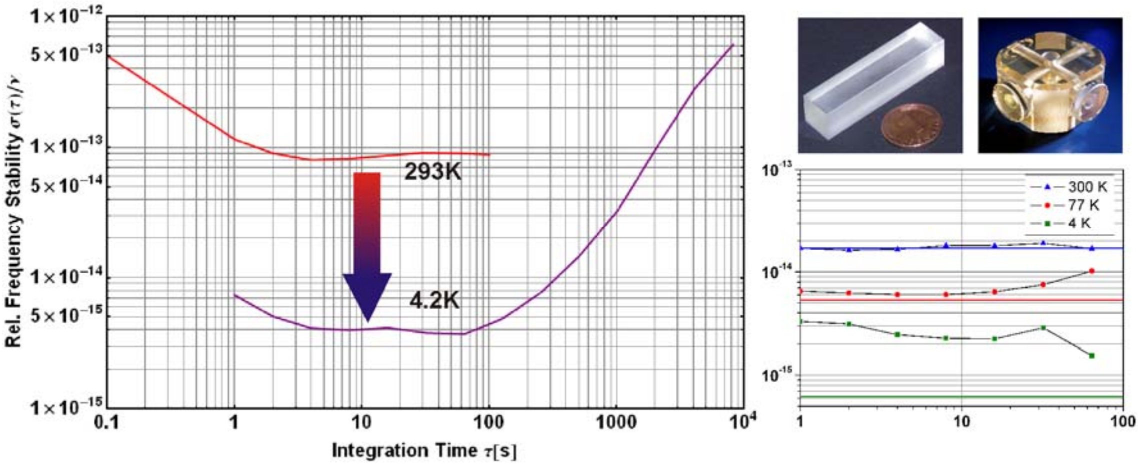

Figure 1: *Left* Measured rel. freq. stability of a monolithic sapphire resonator at room temperature and liquid helium temperature. *Lower Right* Measured rel. freq. stability of a 5.5-cm long Zerodur resonator at various temperatures. Solid colored lines display predicted displacement noise caused by thermal noise. *Upper Right* Pictures of the monolithic sapphire resonator (left) and of the crossed Zerodur resonators (right) implemented in these tests.

3. Next Generation Cryogenic Optical Cavity System

Two normally opposing requirements need to be matched in designing a cryogenic resonator and its mounting structure: high thermal conductivity towards the liquid helium bath and low mechanical coupling of the optical path length to vibrations. We used FEM computations to optimize the design for a resonator made of sapphire that reduces the influence of vertical and horizontal vibrations in combination with large thermal contact areas for the mounting structure (see Figure 2).

Calculations on the shot noise and thermal noise level show that the theoretical frequency stability at a temperature of 4.2K is in total an order of magnitude better than the best ever value obtained with an optical resonator system (see Figure 2). We will also implement novel measures to enhance the long term performance of the optical cavity system in order to maintain the potential relative frequency stability below 10^{-16} up to long integration times.

As a future perspective, we plan to exchange the Ta_2O_5/SiO_2 coatings, which is the thermal noise limiting source for the here presented cryogenic optical sapphire resonators, with monocrystalline coatings composed of $Al_xGa_{1-x}As$. Those crystalline coatings will further reduce the stability limiting effects of thermal noise for the here presented cryogenic resonators by more than an order of magnitude.

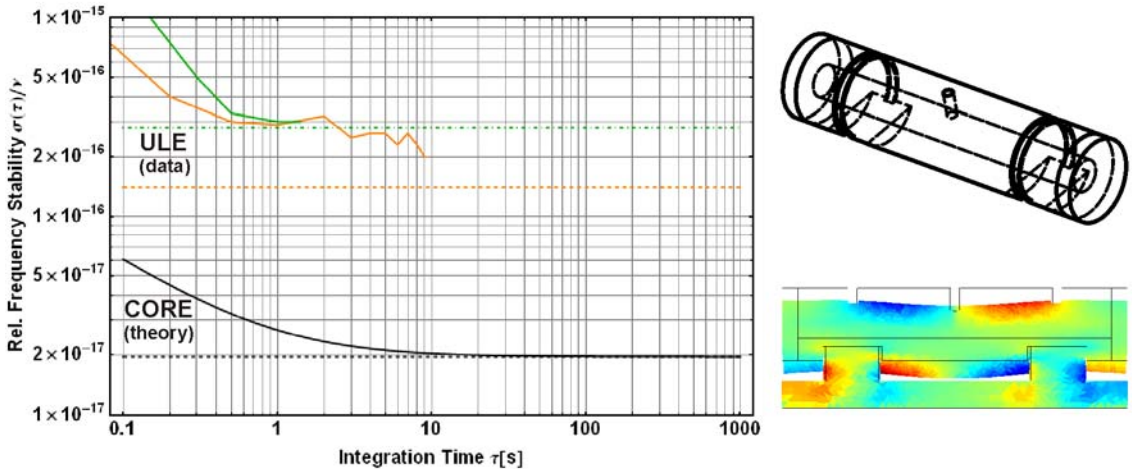

Figure 2: *Left* Comparison of measured and predicted rel. freq. stability of the best room temperature (ULE, Young et. al [NIST 1999] green line and Jiang et. al [NIST 2010] orange line) and proposed cryogenic optical resonators (CORE, black line). The dashed lines show the theoretical thermal noise limit. *Upper Right* Sketch of an optimized design for a CORE. *Lower Right* FEM simulation of vertical vibration (gravitational) induced bending (deformation scaled up by a factor of 10^{10}).

4. Our Application: Testing Lorentz Invariance

We plan to use the ultra-stable cavities to perform a laboratory-based test of Lorentz invariance – a basic principle of the theories of special and general relativity. While both theories developed by Einstein play an integral part in modern physics and in today's ordinary life, there have been claims that a violation of Lorentz invariance might arise within a yet to be formulated theory of quantum gravity.

The cavities will be arranged in a Michelson-Morley configuration and continuously rotated for more than one year using a custom-made high-precision low noise turntable system made of granite. The sensitivity of this setup to violations of Lorentz invariance should be in the 10^{-19} to 10^{-20} regime. This corresponds to more than a 100-fold improvement in precision of modern Michelson-Morley type experiments [2].

Furthermore, ultra-stable cryogenic microwave whispering gallery resonators will be added to the experiment in collaboration with the University of Western Australia. With this co-rotating microwave and optical resonator setup we will be able to search for additional types of Lorentz violating signals.

[1] M. Nagel, K. Möhle, K. Döringshoff, S. Herrmann, A. Senger, E.V. Kovalchuk, and A. Peters, " Testing Lorentz invariance by comparing light propagation in vacuum and matter," in Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, V.A. Kostelecký, (World Scientific, Singapore, 2010), pp. 94-102.

[2] S. Herrmann, A. Senger, K. Möhle, M. Nagel, E. V. Kovalchuk, and A. Peters "Rotating optical cavity experiment testing Lorentz invariance at the 10^{-17} level," Phys. Rev. D **80,** p. 105011 (2009).