Precision Microwave Frequency Measurements for Testing Fundamental Physics

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Abstract

We describe the current design and performance of a microwave frequency cryogenic sapphire oscillator with a fractional frequency stability of parts in 10^{-16} for short integration times. Such a device has been used to perform the most precise laboratory based measurement of the isotropy of the speed of light, allowing us to test the fundamental concept of Lorentz invariance with remarkable sensitivity.

1. Introduction

Microwave frequency standards and associated precision measurement techniques and technologies serve as an excellent toolset for probing fundamental aspects of physics. For example, high quality microwave cavities can be used in searches for hypothesized dark sector particles [1]. In this work, we shall focus on the current status and advances made in developing the Cryogenic Sapphire loop Oscillator (CSO) [2], an ultra-stable microwave frequency source, and how this device can be used to search for deviations in the isotropy of the speed of light.

2. Cryogenic Sapphire Oscillator

The performance of a CSO is ultimately derived from the cryogenic properties of high-purity sapphire. The sapphire is HEMEX grade and is cut in to a cylinder with diameter 51 mm and height 33 mm, with a spindle protruding from the central axis. The spindle is used to clamp the crystal inside a copper cavity which is then cooled to cryogenic temperatures in a low vibration pulsed tube cryostat. Loop probes are used to excite and couple to "Whispering Gallery" standing wave patterns, where the majority of the electromagnetic energy is confined within an outer ring of the sapphire (see Fig. 1). The combination of highly confined fields and a low loss tangent enables electrical quality factors on the order of 10^9 for the Sapphire Loaded Cavity (SLC). Despite the high purity of the sapphire there are still small concentrations of paramagnetic ions present which create an overall magnetic susceptibility. The resonance frequency of a chosen whispering gallery mode depends upon the susceptibility and the permittivity of the dielectric; at cryogenic temperatures the magnitude of these dependencies is similar but the sign is opposite. The end result of these competing effects is a frequency-temperature turning point where the resonance frequency of the sapphire loaded cavity is first order insensitive to fluctuations of temperature [2]. A temperature sensor and resistive heater are embedded in the copper post of the cavity so the temperature of the crystal can be maintained at this turning point.

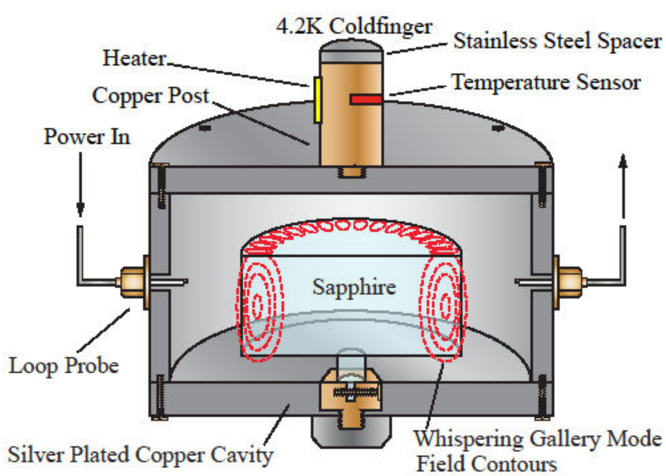

Figure 1: Cross-section of a sapphire loaded cavity. A Whispering Gallery field pattern is marked in red.

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The SLC resonator acts as a frequency discriminating element in a Pound loop oscillator circuit [3], where phase modulation is applied to the signal incident on the resonator and the reflection is demodulated and used to steer the frequency of the oscillator back to that of the resonator. Due to the imperfect nature of the voltage controlled devices used this phase modulation can induce unwanted residual amplitude modulation in the signal. This can be prevented by implementing an Armstrong phase modulator [4] with feedback to maintain suppression of undesired residual amplitude modulation [5]. It is important to prevent fluctuations in the power incident to the resonator as power shifts induce changes in the resonance frequency via two mechanisms [6]. The first arises from a change in the physical temperature and hence susceptibility and permittivity of the crystal. The second is due to a change in the radiation pressure exerted within the crystal which in turn changes the strain, creating a change in the dielectric constant of the sapphire. As such, a power detector and a voltage controlled attenuator is used to minimize power fluctuations incident on the resonator. The effectiveness of this system can be limited by the intrinsic noise of the power detector.

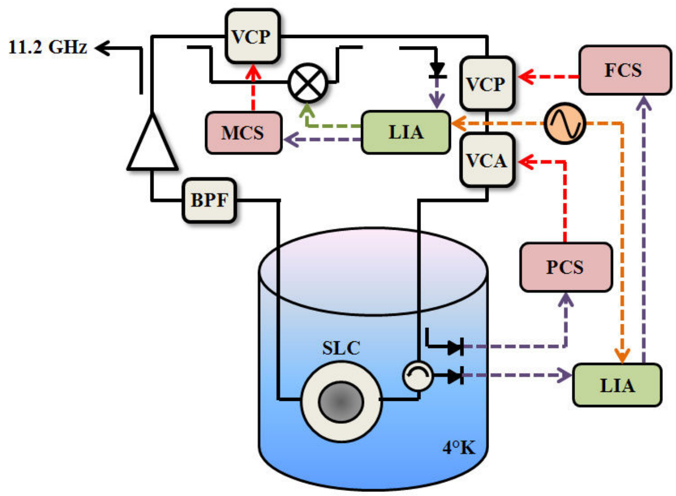

Figure 2: Schematic of a Pound loop oscillator circuit with an Armstrong phase modulator locked to a Sapphire Loaded Cavity (SLC) resonator. VCP = Voltage Controlled Phase Shifter, VCA = Voltage Controlled Attenuator, BPF = Band Pass Filter, LIA = Lock-In Amplifier, FCS = Frequency Control System, MCS = Modulation Control System, PCS = Power Control System.

The current design of the CSO results in an output frequency of ~11.2 GHz. In order to characterize the frequency stability of a CSO a second unit is needed to compare against as the short term stability of, for example, a hydrogen MASER is insufficient. Due to minor differences between sapphire crystals the beat frequency of nominally identical CSOs is typically on the order of hundreds of kHz. The fractional frequency stability of two CSOs is shown in Fig. 3. For integration times up to 10 seconds, the stability is limited by the Pound lock control electronics. The observed "white" noise floor from 10 to 10^3 seconds arises from fluctuations of power incident on the SLC, while long term instability is due to random walk noise and ambient temperature cycles. A CSO can be used to synthesize different frequencies ranging from 10 MHz [7] to 100 GHz [8] with minimal degradation in performance.

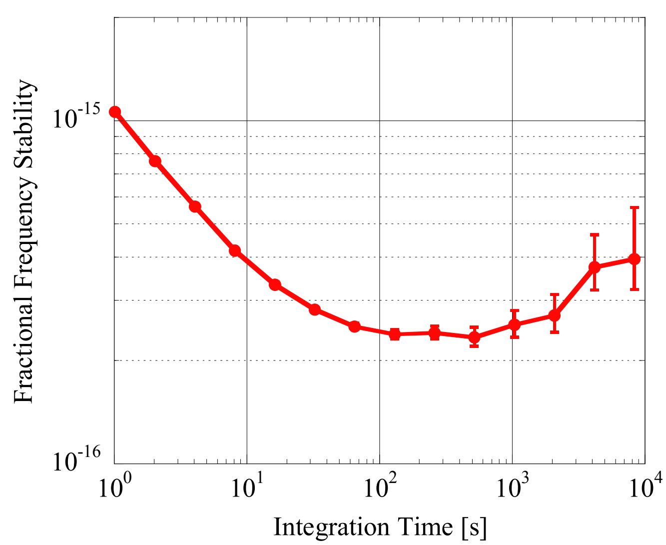

Figure 3: Allan deviation of fractional frequency stability of an individual CSO with linear drift removed.

3. Testing Speed of Light Isotropy

Einstein's theories of Special and General relativity are integral to modern physics and everyday applications. One of the most important consequences of relativity is the concept of Lorentz invariance which implies that the speed of light, *c*, should be isotropic in terms of both direction and velocity. However, various theories of quantum gravity predict that Lorentz invariance could be violated at some energy level. There is a real need for experimental searches for possible violations in order to help inform and refine theory. The CSO is an ideal tool for testing speed of light isotropy due to its remarkable short term frequency stability.

The general arrangement of the experiment is shown in Fig. 4. Two sapphire loaded cavities are aligned with their crystal c-axes orthogonal to each other. Anisotropies in the speed of light will manifest as orientation and rotation dependent changes in the beat frequency of the two cavities. Both cavities are used to form independent loop oscillators and the entire experiment is actively rotated in the laboratory to increase the rate of useful data collected and improve the overall sensitivity of the measurement. The period of rotation is chosen to correspond with the maximum level of frequency stability, typically on the order of 100 seconds as demonstrated in Fig. 3. In order to reduce the influence of systematic noise a precision air-bearing rotation table is used, which is mounted on three aluminum supports that are cooled and heated in order to actively stabilize the tilt of the experiment.

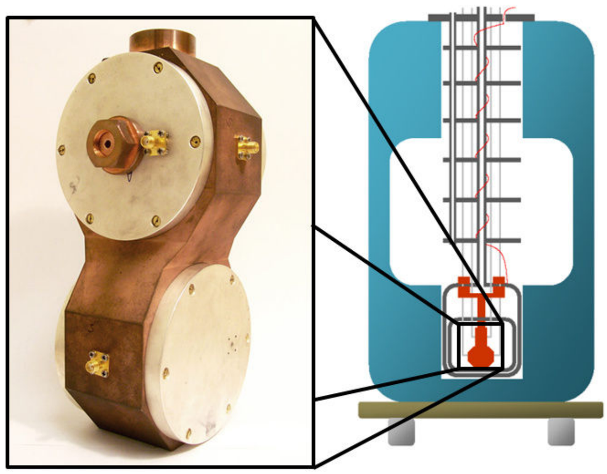

Figure 4: Photograph of the orthogonal sapphire loaded cavity mount (insert, left) and cross-section of the cryogenic liquid helium dewar and rotation platform.

Data has been collected over the course of a year (see Fig. 5), with interruptions to refill the liquid helium and perform maintenance. Active rotation will inevitably introduce some level of systematic noise, identifying and minimizing these noise sources is an experimental challenge. Some of the dominant contributors include helium pressure fluctuations, rotation speed variations, ambient temperature changes and induced magnetic field modulation due to active rotation through the Earth's stationary field.

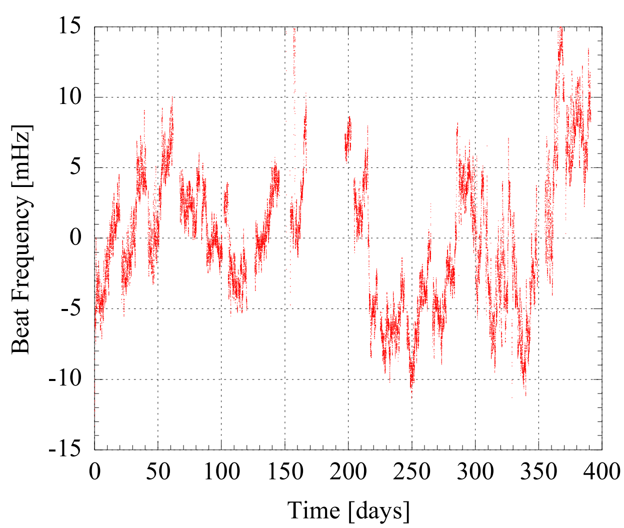

Figure 5: Beat frequency of the rotating Lorentz invariance experiment with linear drift and an offset removed.

Once all the data has been collected it is analyzed in the context of the Standard Model Extension framework [9], whereby bounds are placed on multiple coefficients to describe a variety of potential violations of Lorentz invariance. Of particular interest are statistically significant frequency shifts corresponding to modulations on the order of the laboratory turntable rotation (ω_R), Earth's sidereal and orbital period, and various combinations of these factors. It is advantageous to first demodulate the data around the turntable rotation frequency and then proceed to search for daily and annual variations,

$$\frac{\Delta v}{v} = A + Bt + C(t)\cos 2\omega_R t + S(t)\sin 2\omega_R t, \tag{1}$$

$$C(t) = C_0 + \sum_i C_{C,\omega_i}\cos\omega_i t + C_{S,\omega_i}\sin\omega_i t, \tag{2}$$

$$S(t) = S_0 + \sum_i S_{C,\omega_i}\cos\omega_i t + S_{S,\omega_i}\sin\omega_i t, \tag{3}$$

Where ω_i represents the frequency component of interest. One can calculate the experiment-dependent relationship between these cosine and sine amplitudes and different combinations of Lorentz violating coefficients of the Standard Model Extensions. As such, from a measurement of the beat frequency we are able to place bound on various coefficients, which can be easily compared to results from other experiments.

As work on this experiment comes to a conclusion we have begun planning the next generation of oscillator-based Lorentz invariance tests. Future plans and ideas will be discussed, such as the possibility of combining microwave cavities with optical cavities, which would enable us to probe different regions of the Standard Model Extension.

4. Acknowledgments

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