Frequency Stability of 1 x 10^{-13} in a Compensated Sapphire Oscillator Operating Above 77 K

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We report on tests of a frequency-stable temperature-compensated sapphire oscillator (CSO) at temperatures above 77 K [1]. Previously, high stability in sapphire oscillators had been obtained only with liquid helium cooling. The current resonator quality factor (Q) of $\mathrm{Q} \approx 2 \times 10^{6}$ *together with recent improvements in frequency lock circuitry yield a frequency stability approximately the same as the very best quartz oscillators available. The apparent CSO flicker noise floor is* 7.5×10^{-14} *for measuring times between 3 and 10 s, with stability better than* 2×10^{-13} *for all measuring times between 1 and 100 s. We project a stability of* 2×10^{-14} *for a resonator Q of* 10^{7}*, a value about one-third of the intrinsic sapphire Q at this temperature. A local oscillator with this performance would allow new trapped-ion and cesium fountain frequency standards to realize their ultimate potential.*

I. Introduction

Newly developed atomic and ionic frequency standards are presently limited in performance by the available local oscillators. Sequentially interrogated passive standards, which include mercury ion traps and cesium fountains, rely on an ancillary local oscillator (LO) that is periodically corrected by the atomic interrogation process [2,3]. In order for the standards to achieve their potential performance, a local oscillator with stability of a few times 10^{-14} is required.

Up to now, LO requirements for passive frequency sources such as cesium and rubidium standards were easily met by available quartz oscillators. The general characteristics of quartz oscillators are an excellent match to LO requirements: Quartz oscillators are relatively inexpensive and show their best stability for measuring times that are approximately equal to the required interrogation times. However, even the best "super-quartz" oscillators with stability of approximately 1×10^{-13} do not meet LO requirements for the new standards.

Active hydrogen masers and superconducting or sapphire oscillators cooled by liquid helium [4–6] do achieve the desired performance but are roughly as expensive as the standards themselves. While such a combined standard may be very attractive when the ultimate in performance is needed, the expense is prohibitive for most applications. A sapphire oscillator cooled by liquid nitrogen (LN_2) could be a simpler and less expensive solution. The available quality factors (Q's) for whispering gallery sapphire resonators at temperatures above the 77 K boiling temperature of LN_2 are in fact high enough to allow the required performance. However, thermally induced variations of the dielectric constant are not frozen out at 77 K, as they are at LHe temperatures, and prevent high stability from being attained.

We have developed a compensated sapphire resonator that reduces the effects of thermal fluctuations. This resonator incorporates a mechanical compensation process driven by the difference in expansion coefficients for the component materials (copper and sapphire). Previously reported stability of from 2 to 4×10^{-13} [7] for the compensated sapphire oscillator (CSO) based on this resonator is now substantially improved, achieving a flicker floor of 7.5×10^{-14}.

II. Methodology

A detailed description and analysis of the operation of the compensated sapphire resonator has been given elsewhere [1,7,8]. This approach was anticipated by Tsarapkin et al. [9] in a room-temperature resonator with low phase noise. Our previous work analyzes a tunable resonator constructed with a gap between two sapphire parts excited in a $\mathrm{WGH}_{\mathrm{n}11}$ whispering gallery mode that has its magnetic field primarily transverse to the cylindrical axis and a relatively large azimuthal mode number ($n \approx 10$). The analysis shows that for this mode family the sensitivity of the resonator frequency to gap spacing is sufficient to compensate the inherent thermal frequency variation in the sapphire resonator at temperatures above 77 K if the parts are separated by a material such as copper, which has a coefficient of expansion somewhat greater than that of sapphire. However, the sapphire must be made substantially reentrant, so that the effective length of the copper spacer can be larger than the gap separating the sapphire parts. When these conditions are met, the difference between the thermal expansion coefficients of copper and sapphire adjusts the gap between two sapphire parts and cancels frequency variation due to thermal expansion in the sapphire and, more importantly, that due to temperature-induced variation in sapphire's dielectric constant.

The sapphire–copper composite structure is shown in Fig. 1. Increasing temperature, which would tend to *decrease* resonant frequency, causes the length of the central copper post to increase, thus separating the sapphire elements, increasing the gap, and thereby *raising* the resonant frequency. At a certain operating temperature, these effects completely cancel and, therefore, compensate the resonator frequency against the effects of temperature variation. In our tests, the WGH_{811} mode at 7.23 GHz is excited and shows a frequency turnover temperature of 87 K, in agreement with finite element calculations [10].

Thermal integrity of the sapphire–copper–sapphire resonator part is crucial to its frequency stability. The copper and sapphire elements are bonded using pure indium solder and an evaporated gold coating on the sapphire joint surface. This, together with the very high thermal conductivity of both sapphire and copper at LN_2 temperatures, enables a low thermal time constant. The much longer time constants for the sapphire–can mounting and the can–nitrogen bath attachment allow excellent short-term temperature control of the copper/sapphire resonating element and very low thermal gradients. The internal thermal time constants for the composite resonator are <5 s, allowing effective operation of the compensation mechanism. Thermal time constants of 300 s and 1500 s isolate the sapphire element from the can and nitrogen bath, respectively.

The design of the can thermal isolation, as shown by the stainless steel parts identified in Fig. 1, is reentrant to minimally affect the resonator's placement in the cryostat. The original bottom plate with the copper center that sits in the LN_2 bath is spaced approximately 8 mm from the copper can, but the thermal path length is approximately 6.5 cm. The thermal isolation stage is composed of a stainless steel "deep dish" in which a copper cylinder is attached. On top of the copper cylinder is a stainless steel plate that only makes contact to the copper can with a ~0.5-cm-width ring at its outer radius. The copper cylinder has thermistors and a heater element that allow the temperature of the stage to be controlled.

The relatively conventional frequency lock circuitry is shown in Fig. 2. A Pound circuit locks the 100 MHz crystal quartz voltage-controlled oscillator (VCO) to the sapphire resonator. Earlier versions

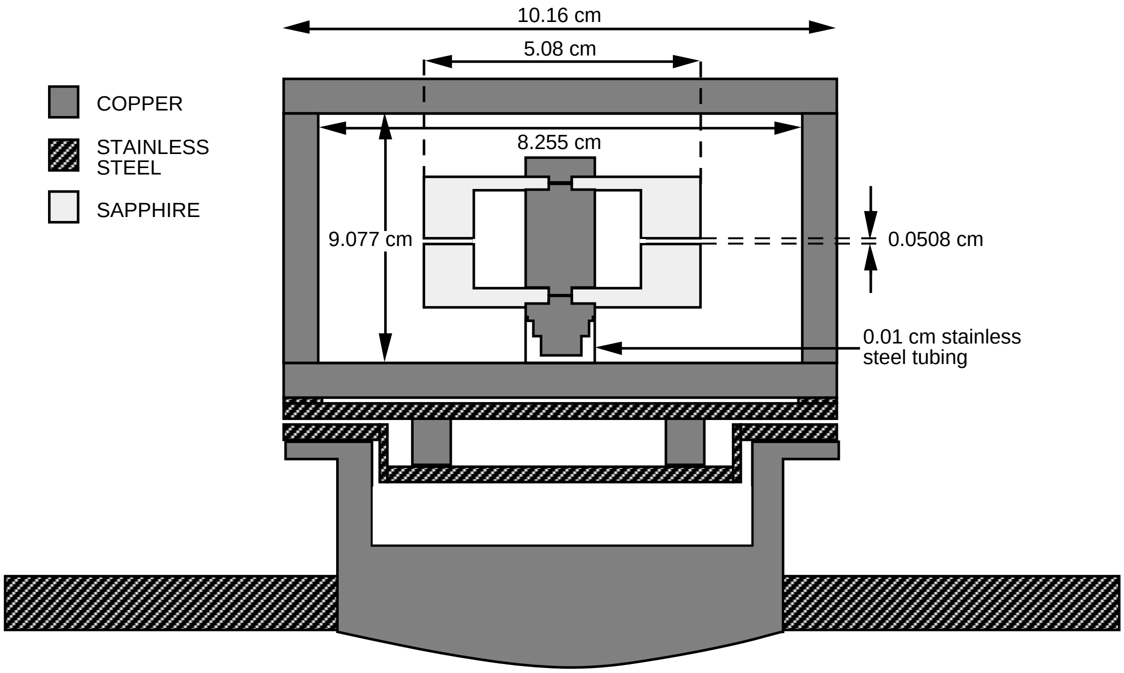

Fig. 1. The compensated sapphire resonator with a frequency turnover temperature of ~87 K. Expansion of the copper center post with increasing temperatures increases the gap spacing between the sapphire elements, counteracting an increase in dielectric constant in the sapphire. The stainless steel thermal isolation assembly reduces the effect of LN_2 temperature fluctuations.

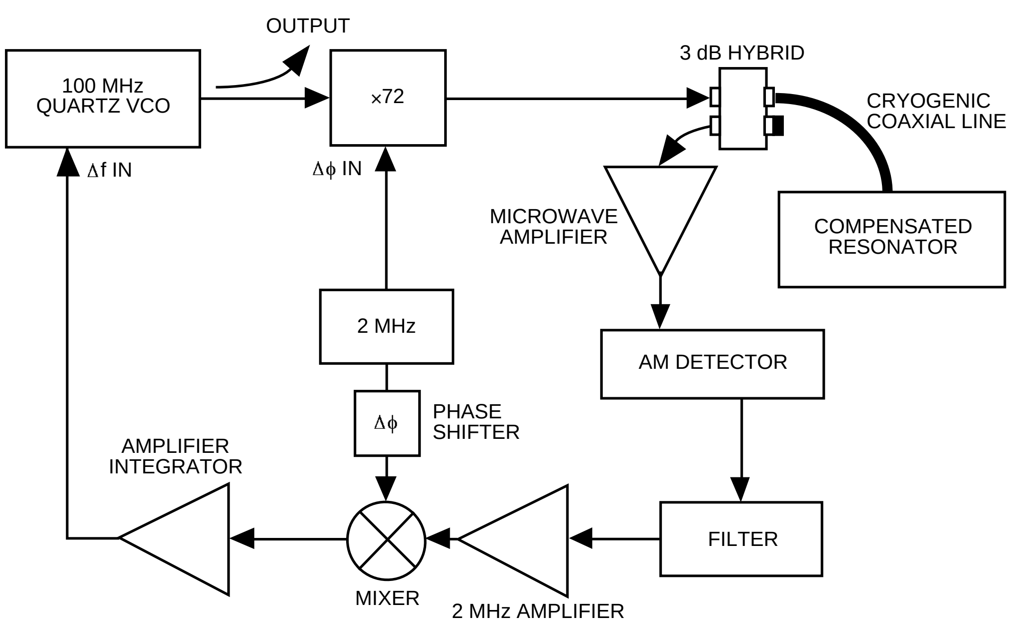

Fig. 2. A Pound (frequency lock) circuit with a 2 MHz modulation frequency. Not shown is the frequency offset circuitry associated with the ×72 multiplier that derives the exact resonator frequency at 7.226 GHz.

used a 50 to 200 kHz modulation frequency injected into the VCO input. However, sufficient loop gain could not be attained without instabilities to effectively eliminate VCO frequency fluctuations. Therefore, we modified the $\times 72$ multiplier to allow injection of a higher 2 MHz modulation frequency into its L-band (1.2 GHz) internal power oscillator. The increase in loop gain in the frequency lock circuitry greatly improved short-term stability performance.

Because flicker noise in the rf system components is a limiting factor in the system performance, we employ the lowest noise components available. Additionally, we generally design for the shortest microwave path lengths possible.

III. Experimental

A number of significant sources of frequency instability were uncovered during the development process. Early performance (June 1994 in Fig. 3) was found to be limited by thermal stability of the resonator containment can. The copper can cavity housing the resonator had been well anchored to the LN_2 bath, and changes in room temperature and pressure as well as the LN_2 level affected the temperature of the liquid nitrogen bath.

First tests with a second thermal stage showed greatly improved long-term performance. With the resonator operating at its turnover temperature of 87 K, the new isolation stage was a few degrees above the LN_2 temperature. When the stability of the current sources used to drive the heaters was found to be poor, they were replaced with more stable diode-laser current supplies (current noise $\leq 8\ \mu$A) for subsequent experiments.

Increasing the loop gain proved to be the most significant factor in achieving the May 1995 performance indicated in Fig. 3, but several other factors contributed to the improved stability. The resonator is the only component of the system contained in the cryostat, while the external microwave components are exposed to the environment of our open laboratory. These mixers, hybrids, amplifiers, connectors, and cable lengths are sensitive to temperature fluctuations and, in combination, greatly contribute to the

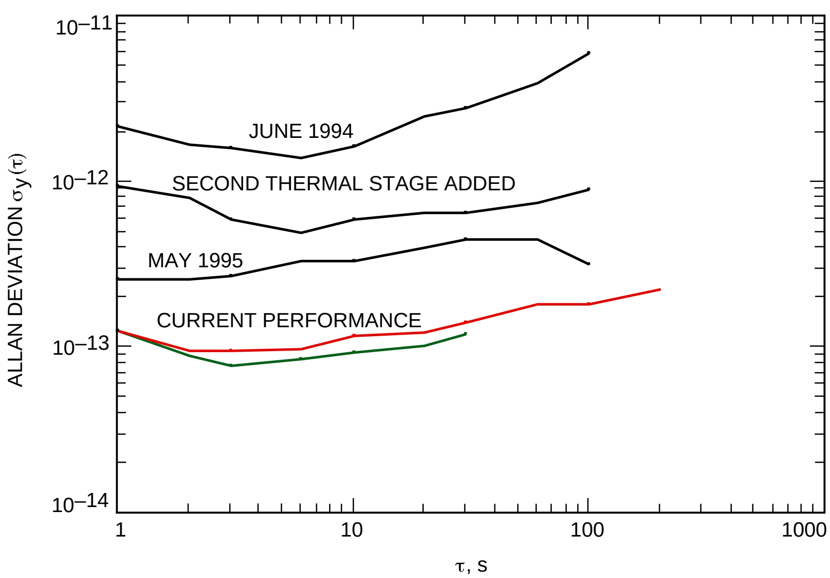

Fig. 3. The Allan deviation of CSO frequency stability, showing performance at various stages of development.

instability of the system. Medium- and long-term performance were improved by thermally insulating the microwave components with foam. More important sources of instability are temperature fluctuations and gradients on the relatively long coaxial line that feeds the resonator in the cryostat. This cable is cooled to LN_2 temperature at the resonator and held at room temperature at the cryostat's input, thus making it sensitive to both LN_2 and room temperature fluctuations. This instability was reduced by better isolating the line from the cryostat wall and maintaining a more stable LN_2 surface temperature and level. This improvement also contributed to the May 1995 stability shown in Fig. 3.

By monitoring various temperatures in the system, we found that the sapphire temperature followed the outer can as well as showing its own temperature fluctuations. This indicated a thermal "leak" in the resonator. The thermal path was a combination of a small vacuum leak and thermal radiation. Sealing the leak and adding radiation shielding significantly improved short-term stability, as seen in the current performance curve in Fig. 3.

An additional concern is vibration sensitivity because of the multiple-element structure of the resonator. No quantitative testing has been performed to determine vibration sensitivity, but during initial tests, the system was subjected to deliberate mechanical impulses. Several mechanical resonances were observed in the range 1 kHz $< f <$ 10 kHz, with ringing times of a few tenths of a second. Such resonances are unlikely to degrade frequency stability performance and, in a frequency-locked condition, the apparent sensitivity of the resonator cryostat to applied vibration and shaking was less than that of the associated microwave components or of the 100 MHz crystal quartz oscillator.

It was then appropriate to demonstrate the CSO's intended use and capability as an LO for a passive ionic standard. A combined ultrastable microwave signal was generated from the CSO and linear ion trap standard (LITS) [11]. The present performance of the LITS, which serves as a long-term standard, is $6.4 \times 10^{-14}/\tau^{1/2}$. The LITS, using a superquartz oscillator with stability of approximately 1×10^{-13} as the LO in a conventional control loop, obtains a stability of 1.0×10^{-14} at a 1000 s measurement time. This closed-loop performance can be improved with better software techniques as well as by improving the LO.

Frequency corrections were applied to the CSO using a time-to-analog converter (TAC) unit that was developed to control quartz oscillator LOs for the trapped ion standards [12]. A large frequency drift in the CSO was easily corrected with the TAC but can be a drawback for long-term operation. Frequency control software has been improved from single-loop feedback to multi-loop control in order to remove slow drift in parameters while locking the LO closer to the true performance of the LITS. This new software is much more aggressive in controlling the LO than is the typical sequential loop [11].

Preliminary stability measurements with the CSO serving as the LO for the LITS show a stability of $2 \times 10^{-13}/\tau^{1/2}$. The use of improved control software resulted in significantly increased stability for medium-term (100 to 1000 s) measuring times. The 6×10^{-15} stability at 1000 s is nearly a factor of two better than a standard configuration of VCO/LITS. As the CSO continues to improve its stability toward 2×10^{-14}, this exercise demonstrates a first step in developing a frequency source that realizes the full stability LITS ion standard in a compact package.

IV. Analysis

Several additional improvements have been identified as necessary to achieve the desired oscillator stability. The resonator's temperature is presently controlled by occasional adjustment of the heater currents. Addition of feedback control electronics to the heater elements of the system with better than millikelvin temperature resolution is required for the desired ultrastable performance.

A very large sensitivity of the flicker floor to the adjustment of the phase shifter identified in Fig. 2 helped to identify a "false signal" in the Pound loop and a solution to the problem that this represents.

It was found that if the phase shifter was adjusted to be even a few degrees from the peak of the response curve at the mixer output the performance was substantially degraded. Furthermore, ultimate performance was found to be very sensitive to the length of the cryogenic coaxial line. These effects have been identified as being due to a 2 MHz signal at the output of the amplitude modulation (AM) detector, which is phase shifted by exactly 90 deg from the true Pound signal and which is periodically dependent on the length of the coaxial line.

Analysis shows that such a false signal can be expected due to transmission line mismatches, and experiment shows that adjusting the line length to minimize the false signal gives the best possible stability. While to the first order the Pound methodology eliminates any dependence of oscillation frequency on coaxial line length, the false signal, being a signal that is not immune from changes in line length, represents a breakdown of the method. The exact 90 deg phase shift is due to the very high Q of the resonant mode. The results indicate that caution must be observed with regard to possible sapphire modes with moderate to high Q's that have frequencies near the modulation sidebands. This problem is compounded by the fact that very many lower Q modes in the whispering gallery resonator are coupled to the output as strongly as the desired mode.

Features of the achieved stability are a flicker floor of 7.5×10^{-14} and a large frequency drift of approximately 1.5×10^{-8}/day. A significant improvement in stability is expected with increased resonator Q. The presently observed $Q \approx 2 \times 10^6$ is very much lower than the intrinsic value of 30 million for sapphire at 77 K and is also below the value of 20 million we observed for other, uncompensated, modes in the same resonator. We believe the low compensated Q is due to poor surface cleanliness of the sapphire elements, most likely in the tuning gap where rf electric fields are large. A redesign is presently under way to reduce surface contamination of the tuning gap, where resonant electric fields are large. We project a stability of 5×10^{-14} or better with the improved design and calculate a noise-limited frequency stability of from 1 to 2×10^{-14} for a resonator with $Q = 10^7$. The large drift rate likely is due to relaxation of the soft metal bond in the composite sapphire/copper resonator element. This is being addressed by an improved fabrication technique. Based on this achieved and projected performance, the CSO approach promises to meet new passive standard LO requirements in a compact and inexpensive cryogenic package.

V. Conclusion

We have demonstrated a new ultrastable oscillator capability that promises to enable improvements on the best quartz technology in a small and inexpensive cryogenic package. Projected performance is well matched to the requirements of new passive atomic standards. With a 20× performance improvement over the past 18 months, continuing improvements can be expected. Present stability ranges from 7.5×10^{-14} to 2×10^{-13} for measuring times between 1 and 100 s. We project a stability of 5×10^{-14} or better with a resonator designed for improved Q. Preliminary tests in combination with the LITS have demonstrated the CSO's capacity to operate as a local oscillator for a passive ionic standard.

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