FREQUENCY STABILITY OF 1×10^{-13} IN A COMPENSATED SAPPHIRE OSCILLATOR OPERATING ABOVE 77 K

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Abstract*

We report on tests of a compensated sapphire oscillator (CSO) which shows frequency-stable operation at temperatures above 77 K[1]. The frequency stability for this oscillator shows an apparent flicker floor of 7.5×10^{-14} for measuring times between 3 and 10 seconds, and stability better than 2×10^{-13} for all measuring times between 1 and 100 seconds. These values are approximately the same as for the very best available quartz oscillators. Previously, high stability in sapphire oscillators had only been obtained with liquid helium cooling. Recent improvements include a more careful analysis of the ac frequency-lock "Pound" circuitry that now enables the oscillator to reliably attain a stability 6 million times better than its fractional resonator linewidth. Measurements to date have been made with a resonator quality factor $Q\approx2\times10^6$. Frequency stability of 2×10^{-14} is projected for a resonator Q of 10^7, a value about one third of the intrinsic sapphire Q at this temperature.

Introduction

Newly developed atomic and ionic frequency standards are presently limited in performance by available local oscillators. Sequentially-interrogated passive standards, which include mercury ion traps and cesium fountains, rely on an ancillary local oscillator (L.O.) which 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, L.O. 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 L.O. requirements: They are relatively inexpensive and show their best stability for measuring times approximately equal to the required interrogation times. However, even the best "super-quartz" oscillators with stability of approximately 1×10^{-13} do not meet L.O. 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 77K 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 77K 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 $2\text{-}4\times10^{-13}$[7] for the compensated sapphire oscillator (CSO) based on this resonator is now substantially improved, achieving a flicker floor of 7.5×10^{-14}.

The presently observed $Q\approx2\times10^6$ is very much lower than the intrinsic value of 30 million for sapphire at 77K, and is also below the value of 20 million we observed for other, uncompensated, modes in the same resonator. A redesign is presently underway 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 $1\text{-}2\times10^{-14}$ for a resonator with $Q = 10^7$. Based on this achieved and projected performance, the CSO approach promises to meet new passive standard L.O. requirements in a compact and inexpensive cryogenic package.

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 tuneable resonator constructed with a gap between two sapphire parts.

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The analysis shows that, for the WGH_{n11} mode family, the sensitivity of resonator frequency to gap spacing is sufficient to compensate the inherent thermal frequency variation in the sapphire resonator at temperatures above 77K 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 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 Figure 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 turn-over temperature of 87 K in agreement with finite element calculations[10].

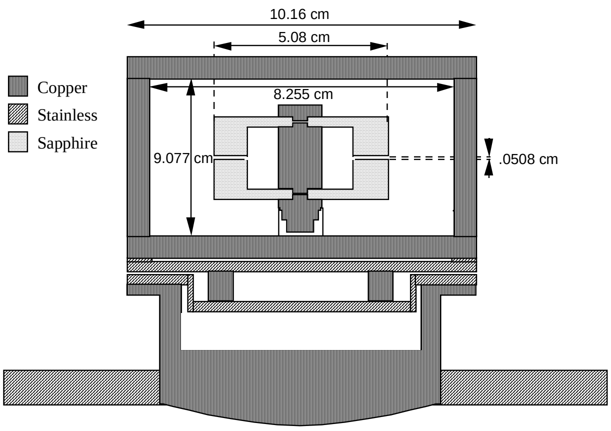

Figure 1. Compensated sapphire resonator with frequency turn-over temperature of ~87K. Expansion of the copper center post with increasing temperature increases the gap spacing between the sapphire elements, counteracting an increase in dielectric constant in the sapphire. Stainless steel thermal isolation assembly reduces the effect of LN_2 temperature fluctuations.

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 seconds, allowing effective operation of the compensation mechanism. Thermal time constants of 300 seconds and 1500 seconds 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 Figure 1, is re-entrant to minimally effect 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 which 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 which allow the temperature of the stage to be controlled.

The relatively conventional frequency lock circuitry is shown in Figure 2. A Pound circuit locks the 100 MHz crystal quartz VCO to the sapphire resonator. Earlier versions used a 50-200 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 ×72 multiplier to allow injection of a higher 2 MHz modulation frequency into its L-band internal power oscillator. The allowed increase in loop gain in the frequency lock circuitry greatly improved short-term stability performance.

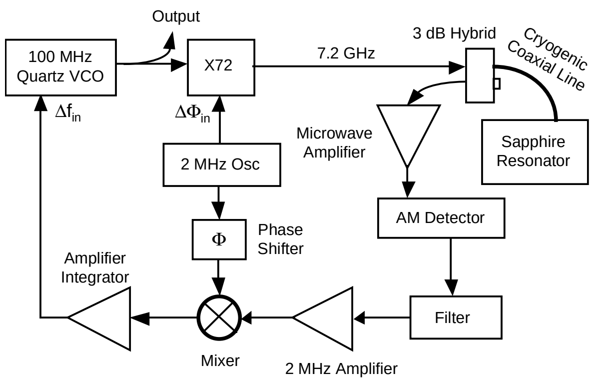

Figure 2. Pound (frequency lock) circuit with 2 MHz modulation frequency. Not shown is frequency offset circuitry associated with the x72 multiplier which derives the exact resonator frequency of 7.226 GHz.

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.

Experimental

A number of significant sources of frequency instability were uncovered during the development process. Vibration sensitivity is a concern 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. 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.

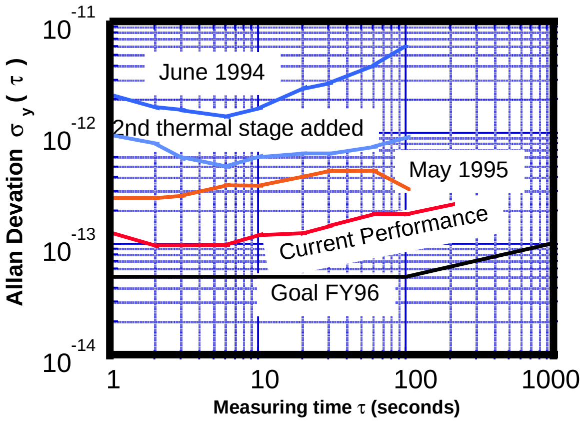

Figure 3. Allan Deviation of CSO frequency stability showing performance at various stages of development (see text).

Early performance (*June 1994* in Fig. 3) was found to be limited by thermal stability of the resonator containment can. The copper can cavity which houses the resonator had been well anchored to the LN_2 bath. Changes in room temperature and pressure as well as the LN_2 level affect the temperature of the liquid nitrogen bath.

First tests with a *2nd thermal stage* showed greatly improved long-term performance. With the resonator operating at its turnover temperature of 87K, the new isolation stage was a few degrees above the LN_2 temperature. The stability of the current sources used to drive the heaters was found to be poor, so they were replaced with more stable diode-laser current supplies for subsequent experiments.

Increasing the loop gain proved to be the most significant factor in achieving the *May 1995* performance indicated in Figure 3, but several other factors contribute to the improved stability. The resonator is the only component of the system contained in the cryostat. 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 instability of the system. Medium and long term performance were improved by thermally insulating the microwave components with foam.

An important source of instability is temperature fluctuations and gradients on the relatively long coaxial line which 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 in Figure 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 curve labelled *current performance*.

Analysis

Several additional improvements have been identified as necessary to achieve the desired oscillator stability. The resonator's thermal environment is currently free running and not actively controlled. Addition of feedback control electronics to the heater elements of the system with better than milliKelvin temperature resolution is required for the desired ultra-stable performance.

An important sensitivity of the flicker floor to the adjustment of the *Phase Shifter* identified in Figure 2 helped to identify a "false signal" in the Pound loop and a solution to the problem that this represents. It was found that 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 due to a 2 MHz signal at the output of the *AM Detector* which is phase shifted by exactly 90 degrees 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 first order the Pound methodology eliminates any dependence of oscillation frequency on coaxial line length, the false signal represents a breakdown of the method, being a signal that is not immune from changes in line length. The exact 90 degree 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 which 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 is 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 resonator Q for the compensated mode is ≈2 million, while other modes in the same resonator show Q's up to 20 million. 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. An improved sapphire polish may allow us to achieve resonator Q's of 8 million or more. Based on our experimental results this Q would make possible a stability of 2×10^{-14}. The large drift rate is likely due to relaxation of the soft metal bond in the composite sapphire/copper resonator element. This is being addressed by an improved fabrication technique.

Conclusion

We have demonstrated a new ultra-stable oscillator capability which 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 20x 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 seconds. We project a stability of 5×10^{-14} or better in FY96 with a resonator designed for improved Q.

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