CRYO-COOLED SAPPHIRE OSCILLATOR WITH MECHANICAL COMPENSATION

RABI T. WANG and G. JOHN DICK
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109-8099, U.S.A.

Abstract

We present test results for a short-term frequency standard, 40K Compensated Sapphire Oscillator (CSO). Included are measured resonator Q values, cryocooler vibration data, silver spacer construction process, and copper wall sensitivity. The 40K CSO design goals are a frequency stability of 1×10^{-14} (1 second $\leq \tau \leq$ 100 seconds), a year or more continuous operation, and a compact rack-mount configuration. The 40K CSO[1] bridges the gap of two previous technology 10K CSO[2] and 77K CSO[3]. In particular, the 10K CSO incorporated a Gifford-McMahon type of cryocooler with no cryogens, while the 77K CSO developed thermo-mechanical compensation operating at 80 K. The 40K CSO can serve as an independent oscillator or as a "slaved" local oscillator controlled by atomic standards like Hg ion trap, enabling their inherent performance.

Introduction

Ultra-stable cryogenic oscillators have been developed at JPL for many years[4]. The goal shifted from demonstration of best stability to end-to-end design for user application. In design of an ultra-stable oscillator the quality factor is the most crucial element. Therefore cryogenic temperature was the integrated element for RF resonator: lower the temperature, higher the Q. At the same time, other issues will need attention, such as compensation of frequency to temperature or from operation stand point using only cryocooler without cryogens.

A number of promising compensated sapphire resonator technologies have already been demonstrated. These include the following:

- Thermomechanical, for a $Q \approx 2\times10^{6}$ at 85K and a frequency stability of 8×10^{-14} [3,5].
- Dielectrics, such as Rutile, showing compensated Q's up to 10^{7} at 65K [6,7].
- Orthogonal Modes, at higher temperature in sapphire with turnover temperature at –20 deg C and a curvature of $8\text{x}10^{-8}$ K^{-2} [8].
- Paramagnetic impurities;
  - Incidental impurity compensation for $Q > 10^{9}$, $T \leq$ 6K and stability better than 10^{-15} [9].
  - External ruby compensation with $Q > 10^{9}$ below 10K and stability of 2×10^{-15}, 10K CSO,[10].

So far, these efforts fall short of reaching the needed capability in one way or another. For example, cryocoolers for the "10K CSO" frequency standards with external ruby compensation dissipate 5kW of line power, and substantially add to the size and expense of operation. Oscillators with compensation by thermal expansion have so far showed a relatively low quality factor of 2×10^{6}, and large frequency drift of $\delta f/f = 10^{-8}$/day, precluding long-term frequency locking to an external source.

The 10K CSO is presently the only available continuously operating short-term frequency source with ultra-high stability [10,11,12]. A smaller cryocooled oscillator with short-term stability of 1×10^{-14} or better (1 second $\leq \tau \leq$ 1000 seconds) at easily reached cryogenic temperatures represents a break-through technology. Mated with JPL's LITS trapped ion standards, a 40K CSO would offer inexpensive long-term operation and replacement of hydrogen masers in NASA's Deep Space Network (DSN) [13]. It also offers the L.O. performance required by the new generation of laser-cooled frequency standards. With a cryocooler drawing 100-300 W, a 40K CSO can provide a needed performance with much lower cost and power than previously available for both ground and flight capabilities. This compares to 5kW required by the 10K CSO cryocooler [10].

Figure 1 illustrates two approaches to bridge the gap between the capabilities of two previously developed JPL-developed technologies--the 10K CSO and the 77K CSO. The 10K CSO, presently being implemented in the DSN for the Cassini Ka-band experiment, represents the first cryogenic oscillator to provide ultra-high short term stability together with long-term cryocooled operation. It provides a frequency stability of 2-4 parts in 10^{15} at measuring times (1 second $\leq \tau \leq$ 1000 seconds) without the use of liquid helium and the frequent maintenance required by previous technologies. With a short term stability 25× better than the hydrogen maser, the 10K CSO is making possible a significant upgrade of DSN frequency stability as required by the Cassini Ka-band experiment. The technology of the 10K CSO was based on our previously developed 77K CSO, which showed a stability of 8×10^{-14} with a Q of 2 million. We now ready to infuse what has been learned during the

10K development into a second generation thermomechanically compensated CSO, the 40K CSO.

Figure 2 shows a cross section view of the mechanical resonator design.

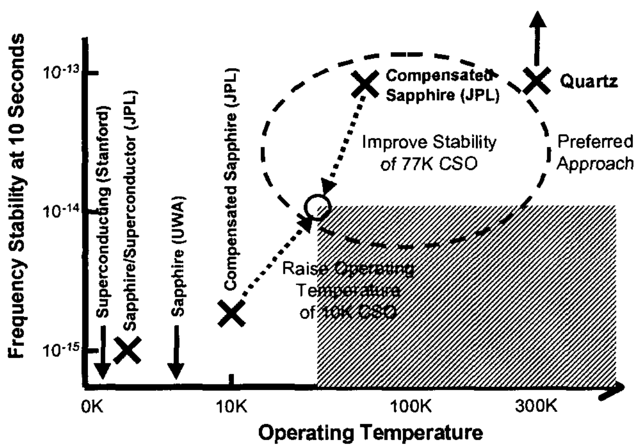

Figure 1 Approaches to the needed capability based on demonstrated compensated sapphire technologies

Background

The main purpose of 40K CSO is to build an oscillator for local oscillator application. The following requirements were crucial for project success: compact size, reliability, high stability, low cost, and long maintenance cycle. Therefore the best frequency stability was not the only reason. Most of the technical design was presented in the previous publication[1]. To narrow down our focus, we identify the general design requirements for a compensated sapphire resonator to achieve parts in 10^{-15} stability as:

1) Quality factor of 4×10^{7} or greater
2) Drift rate of 1×10^{-16}/second or less
3) Thermal time constants of 3 seconds or less coupled with an appropriate external time constant
4) Acceleration sensitivity of 10^{-9}/g or less.

Details will be discussed through out this paper.

Since the 40K CSO stemmed from two previous JPL sapphire oscillators, 10K CSO and 77K CSO, comparison is made with each system individually.

Comparison of 40K CSO and 10K CSO is listed in Table 1. The main common factor is the use of a cryocooler. At the same time, the 10K CSO required a gas buffer system to isolated the vibration from cryocooler while the 40K CSO will be able to avoid that. Consequently 40K CSO cryogenic design can be greatly simplified.

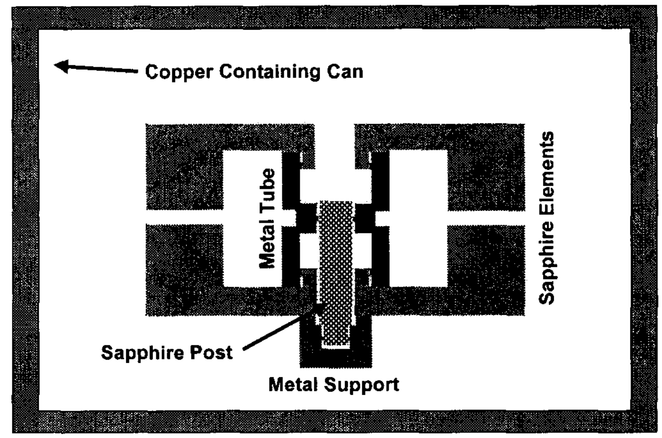

Figure 2 Cylindrical cross section of self-assembling resonator design. Upon cool-down, thermal contraction causes metal spacer and support to grip sapphire parts and then retract from other contacts.

Table 1 Comparison of 10K CSO and 40K CSO

	10K CSO	40K CSO
Coldhead	Gifford-McMahon	Pulse Tube
Cooling stages	Two stages	Single stage
RF electronics	Commercial subsystem	Integrated element
Designed stability	2×10^{-15} @1S	1×10^{-14} @ 1S
Service Period	One year	Three Years <

Comparison of 40K CSO and 77K CSO shows following advantages: (1) Lower temperature also reduces creep rates. (2) Metal spacer made of silver with its Debye temperature of 225K gives larger thermal expansion rate at low temperatures compared to copper at 330K—reduce tuning rate by 2.93×. (3) Use of WGE mode with its reduced sapphire dielectric thermal sensitivity further reduces tuning rate by 1.68×. (4) Overall reduction of tuning rate requirement is 8.33×--contributes to higher Q, reduced mechanical sensitivities by this same factor. Figure 3 shows optimization for a turnover at 40K with a silver spacer.

Both thermo-mechanical and electromagnetic aspects of the resonator were designed using finite element tools. The excited resonator mode is $WGE_{10,1,1}$ at 16 GHz with expected Q $\approx10^{8}$. Stable operation can only be achieved near a preferred "turnover temperature" at which frequency sensitivity to temperature fluctuation is zero. Frequency compensation is from two competing effects: one is the dielectric constant and the ther-

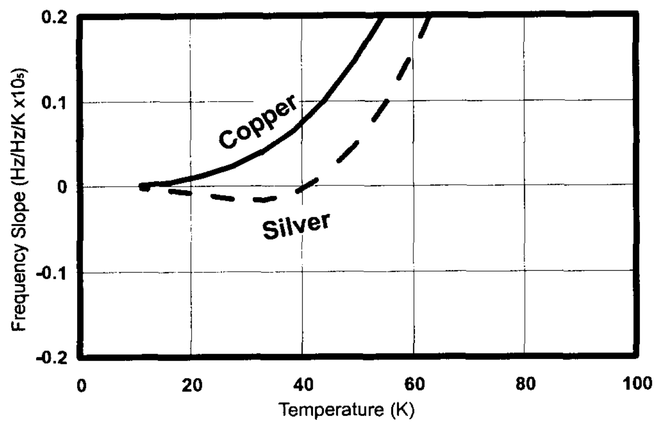

Figure 3 Optimization for a turnover at 40K with a silver spacer and WGE mode is achieved by reducing the tuning rate by 8.33×. Such resonator with a copper spacer would be under-compensated at all temperatures.

mal expansion of sapphire and the other is the thermal expansion of silver post. Creep-free mechanical design enables low frequency drift rates and simplified element cleaning and assembly.

Figure 3 shows calculated frequency slopes for the thermomechanically compensated oscillator. The model is based on Debye temperatures of 900K, 550K, 330K, and 225K for sapphire expansion, sapphire dielectric constant, copper and silver expansion, respectively. At the lowest temperatures, all the curves scale as T^3. Fig 4 shows the frequency dependence for example WGH and WGE modes

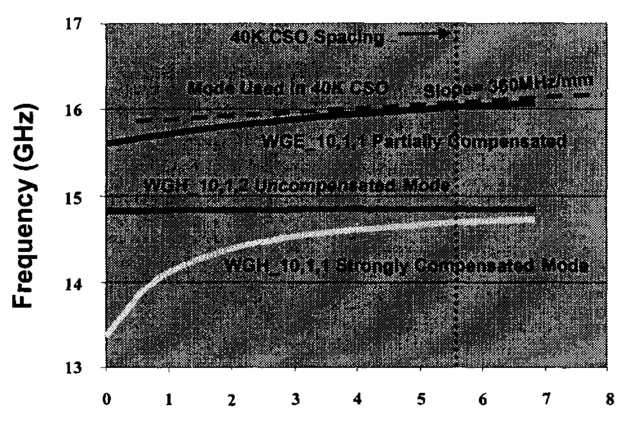

Figure 4 Finite element calculation of frequency dependence on the gap between sapphire elements for 40K CSO resonator. Reduced slope requirement now allows use of WGE mode with its higher Q, lower temperature coefficient for epsilon.

While the short thermal time constants of sapphire and other materials in this temperature range give rise to a host of possible compensating methodologies, a primary difficulty so far has proven to be in finding a mechanism with sufficiently low loss that sapphire's quality factor is not degraded. This problem becomes progressively more severe with increasing temperature due to a T^4 dependence for sapphire's dielectric constant. Additionally, severe constraints are placed on any mechanical motion, such as those that might be due to external vibrations or internal creep and on internal thermal time constants.

Selection of compensation material depends not only depending on the expansion coefficient but also on the creep rate. The creep rate is directly related to frequency drift because size of the spacer directly changing sapphire gap space. Silver was selected for its low creep rate at cryogenic temperature which is nearly two orders of magnitude lower than copper at 40 K.[14,15]

Results

We are reporting the test progress vibration measurements of the coldhead, sapphire resonator Q measurements, silver spacer construction process, and copper wall sensitivity.

Q measurements: Mode frequencies were measured between 14 to 17 GHz. The desired $WGE_{10,1,1}$ mode was found at 16.068 GHz. Quality factor is $1x10^8$ for many modes including $WGE_{10,1,1}$. This test was done with a copper spacer to simulate final configuration. Temperature tuning rate was measured for each mode and was used to identify mode families. The typical number was 2KHz/K while the desired mode has x5 less sensitivity. Test results verified our FEM design of frequency, thermal integrity, and the required Q performance.

Vibration tests: Vibration sensitivity is a critical element in our design since the resonator will be directly mounted to coldhead for the reason of simplifying cryogenic configuration. Therefore the level of acceleration needs to be measured. Assuming the sapphire resonator has a vibration sensitivity of $1x10^{-10}$/ g (number taken from 10K CSO with reduction factor of frequency and FEM design), the measured maximum acceleration is $6x10^{-5}$ at 4Hz which translated to stability of $6x10^{-15}$, well below of our design goal of $1x10^{-14}$. Figure 5 shows the measured data with coldhead fundamental vibration at 2.4 Hz.

Silver spacer: This spacer serves as the frequency tuning element. We have designed and made two silver testers for verifying interference fits and two silver spacers for initial test of resonator configuration.

- Design: Advanced mechanical design to give first order cancellation of axial motion due to relaxation of radial stress. Center support of the 3-part compensated resonator for reduced g—sensitivity.

- Construction process: Two processes were considered for creating the silver spacer: Electrical Discharge Machining (EDM) and electroforming. Our requirement is a tight tolerance of 0.1 mil (≈ 0.0025 mm) which can't be accomplished by standard machining. Parts were made from both processes and the EDM was selected for lower cost and faster delivery.

Copper wall sensitivity: Although majority of the RF energy is confined to sapphire resonator, a small faction is absorbed by the copper wall. Finite element method is able to calculate frequency sensitivity of the copper wall. Since the 10K CSO and 40K CSO use the same mode configuration, we can compare the can sensitivity. On the 10K CSO the measured sensitivity is $6.5x10^{-15}$/mK while the FEM calculation with the expansion coefficient give a sensitivity x10 higher. For the 40K CSO, our calculated sensitivity is $2.4x10^{-14}$/mK. With the same interpretation, we would expect overall can sensitivity to be $2.4x10^{-15}$/mK. This estimation will be verified in the near future.

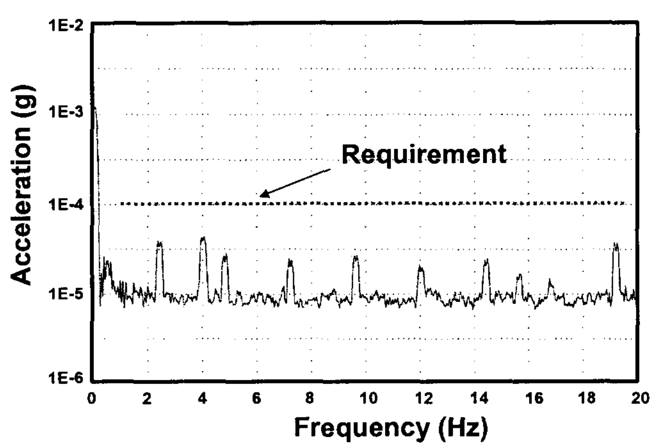

Figure 5: Vibration level measured at pulse tube coldhead. With our estimated acceleration sensitivity of $1x10^{-10}$/g, the required maximum acceleration is $1x10^{-4}$ to achieve stability of $1x10^{-14}$.

Conclusion/Acknowledgment

We have presented experimental test results of a 40 Kelvin compensated sapphire. This development builds on JPL capabilities demonstrated in the successful development of the 10K and 77K CSO's, short term frequency standards which achieve stability in the 10^{-14}'s and 10^{-15}'s without the use of liquid helium. Future work includes testing of turnover temperature and verify short term stability. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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