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HIGH STABILITY 40 KELVIN CRYO-COOLED SAPPHIRE OSCILLATOR

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Abstract

We present initial test results for a new short-term frequency standard, the 40K Compensated Sapphire Oscillator (40K CSO). Included are measurements of resonator quality factor, operational frequency, turn-over temperature, acceleration (g) sensitivity, frequency drift, and preliminary frequency stability tests. Long-term operation is facilitated use of a small cryo-cooler (1KW wall power) with no moving cryogenic parts, and thus no preset service interval for the cold head. Initial tests with this single-stage pulse-tube cooler show a stability of 3×10^{-14} (1 second $\leq \tau \leq$ 10 seconds) and a flicker floor of 2×10^{-14}.

Introduction

The 40K CSO [1] development builds on JPL capabilities demonstrated in the successful development of the 10K CSO[2] and 77K CSO [3], short term frequency standards which achieve stability in the 10^{-14}'s and 10^{-15}'s without the use of liquid helium. The 40K CSO bridges the gap between, and builds upon the capabilities of two previous technologies; the 10K CSO and 77K CSO. In particular, the 10K CSO incorporates a two-stage Gifford-McMahon type of cryocooler to achieve a stability of a few times 10^{-15} with paramagnetic spin compensation, while the 77K CSO first developed the idea of thermo-mechanical compensation, achieving a stability of about 1×10^{-13} at an operating temperature of 80 K. The 40K CSO is designed to provide most of the capability of the 10K CSO in a small, low power package.

40K CSO design goals are a frequency stability of 1×10^{-14} or better (1 second $\leq \tau \leq$ 100 seconds), a year or more continuous operation, and a compact rack-mount configuration. Both 10K CSO and 40K CSO were developed for the purpose of JPL Mission support. The two main applications are local oscillator for atomic clocks like the LITS [4], or as an ultra-stable oscillator for verifying performances of other lower stability oscillators. 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). It also offers the L.O. performance required by the new generation of laser-cooled frequency standards. Potentially operable with a cryocooler drawing only 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.

A previous publication [1] listed a number of compensated sapphire oscillators range from thermal-mechanical at 77 Kelvin to paramagnetic tuning at 1.6 Kelvin. [5-11]. Other 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.

Recent advances in pulse-tube cryocoolers have the potential to substantially enhance long term CSO operation. Compared to a few weeks of operation with liquid helium cooling, the cryocooler allows one to three years of uninterrupted operation. In addition to the JPL CSO's, other groups are also incorporating cryocoolers to extend cryogenic oscillator run time. [12-14]

Design

In the design of an ultra-high stability oscillator, we were tackling the issues in an inter-connected fashion. Traditionally one can focus on each element individually: resonator Q, temperature, vibration, cryogen/cryocooler, frequency compensation, resonator g-sensitivity, resonator modes, resonator frequency, size/continuous operation period, electronics, and cost. The 40 K CSO has been a product of integrated factors:

- **Operational Temperature** and **Q**: Sapphire Q is a function of temperature: Q(77) ~ 10^{7} , Q(4)~ 10^{9}. It's possible to reach frequency stability in a few parts in 10^{-16} with the sacrifice of lower temperature operation. Compromise can be reached when a lower stability level and a higher operational temperature are needed.
- **Temperature** and **cryocooler**: Operational temperature will dependent on the turnover temperature of sapphire resonator, the base temperature of cryo-cooler, and its cooling power. Single stage pulse tube coolers can reach a base temperature of 33 K.[15] A single stage coldhead was chosen for reliability and lower cost, compared to a two stage cooler, while pulse-tube technology provides improved service periods and vibration levels, compared to a G-M coldhead.

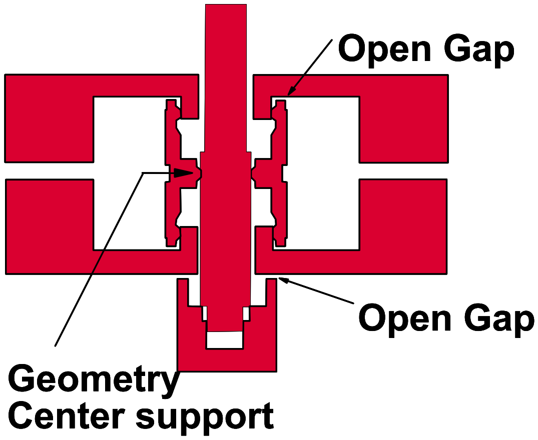

Figure 1: Cylindrical cross section of self-assembling resonator design. Upon cool-down, thermal contraction causes metal spacer and support to grip sapphire parts and then retract from other contacts. Final assembly will support the resonator from the geometry center providing g-sensitivity of less than 10^{-10}/ g.

- **Acceleration sensitivity** and **cryocooler**: Due to the low vibrational level of new pulse tube coldhead[1], the sapphire resonator can be mounted directly on the coldhead. This configuration simplifies the design compared to the 10K CSO and provides a longer operation period. A mechanical FEM program was used to design a configuration with 100x lower g-sensitivity with a center support geometry that gives better results than is achieved with end support. (see figure 1)
- **RF frequency** and **resonator mode**: Resonator frequency is calculated from sapphire size and mode configurations. FEM calculation can be used to determine these parameters, see figure 2. Sapphire whispering gallery modes provide higher Q, limited only by sapphire inherent performance. Output frequency at 16 GHz will provide low phase noise signal to users without additional frequency multiplier. Higher frequency at 16GHz for WGE(10,1,1) results in a small resonator with a smaller copper can but it does increased the complicity of the silver spacer design.
- **Frequency compensation** and **frequency drift**: Stable operation can only be achieved near a preferred “turnover temperature” at which frequency sensitivity to temperature fluctuation is zero. Without a frequency compensation, the burden on the temperature control increase by 1000x. Temperature controllers are commercial equipments which lower the overall cost of the system. With a silver spacer (see figure 3) a "preferred" temperature is selected. Frequency drift has historically been a substantial problem in thermo-mechanical CSO operation. To address this issue, an interference fit design and selection of a low creep material at low temperature were folded into the sapphire resonator design. Silver was selected for its thermal properties and also for ease of machining. An Electrical Discharge Machining (EDM) process was chosen for its lower cost, faster delivery, and possible lower chance of contamination.

Therefore the 40 K CSO is an integrated and complex oscillator. Any change of parameter will change other configurations. For example the turnover temperature changes from 36 K to 30 Kelvin, the coldhead will need a two stage system in stead of a single stage then the reliability requirement and total cost will be impacted.

Problems associated with cryogens are refilled disturbances and large frequency drift due to liquid level drop. Using cryocooler will minimize that problem, at the cost of vibration caused by the coldhead. With advances in pulse tube coolers, this difficulty can be tolerated with matched g-sensitivity of sapphire resonator.

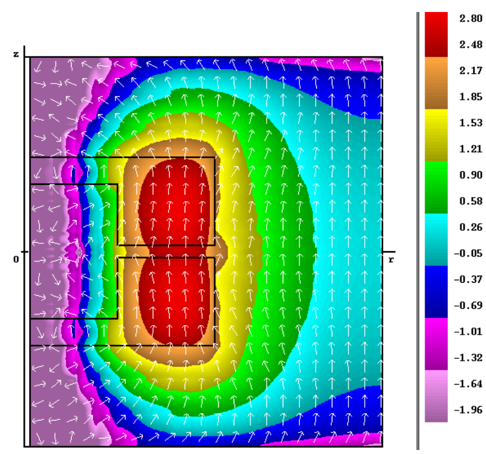

Figure 2 Compensated sapphire resonator showing details of electromagnetic design. Electromagnetic field intensity varies approximately one order of magnitude per color band calculated by the finite element program.

While the short thermal time constants of sapphire and other materials in this temperature range enable 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 on the expansion coefficient but also on the creep rate. The creep rate can be directly related to frequency drift because spacer size changes directly the gap space between sapphire parts. Silver was selected for its low creep rate at cryogenic temperature which is nearly two orders of magnitude lower than copper at 40 K.[16,17]

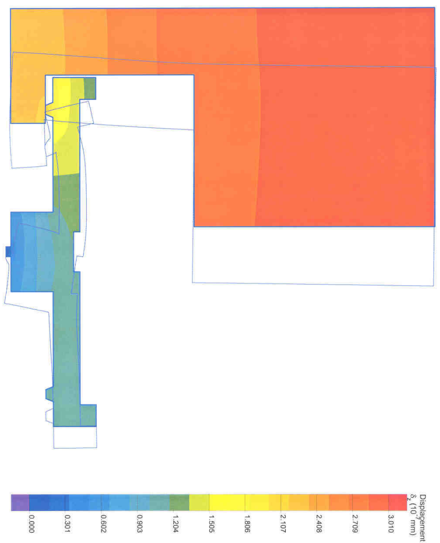

Figure 3 Mechanical finite element calculation was used to aid the design of silver spacer. Due to the three grip area, motion-canceling design was necessary to eliminate gap motion and associated frequency creep when contact force relax with time.

Results

We are reporting progress on the measured turnover temperature, resonator g sensitivity, frequency stability, and drift rate. Results of measured sapphire Q, cryocooler vibration data, and interference fits design were presented in a previous publication [1]. A low power cryocooler (1KW wall power) was incorporated in this test. Vibration level was measured and it showed the same low vibration level as 3KW system.

♦ Turnover temperature:

Figure 4 shows the measured turnover temperature at 36.6K with a quadratic coefficient of $3.09x10^{-8}$ K^{-2}. The typical variation of turnover temperature is plus or minus 0.5K when cycling between 33K and 300K. The excited $WGE_{10,1,1}$ mode was designed for operation at 16.0 GHz and showed values 16.113 GHz plus or minus 6 MHz and a Q of $1.4x10^{8}$. Other modes also show turnover temperatures ranging from 30 to 60 K around 16GHz.

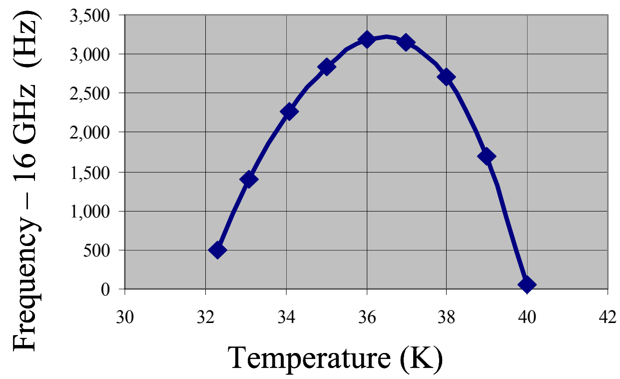

Figure 4 Turnover temperature was measured at 36.6 K with quadratic coefficient of $3.09x10^{-8}$ K^{-2}. Silver spacer is firmly attached to sapphire resonators providing good thermal contact and frequency compensation.

♦ Resonator g sensitivity:

Vibration sensitivity is a critical element in our design since the resonator is directly mounted to coldhead for the reason of simplifying cryogenic configuration. Therefore the level of acceleration and g-sensitivity should be measured. Measurement shows a vibration sensitivity of $1x10^{-10}$/ g. This measured maximum acceleration is $6x10^{-5}$ at 4Hz which translated to stability of $6x10^{-15}$, well below of our design goal of $1x10^{-14}$. We have verified not only the interference fit design is working properly but also g-sensitivity has been reduced. The key element is the center support of the 3-part compensated resonator as in figure 1. This advanced mechanical design gives first order cancellation of axial motion due to relaxation of radial stress.

♦ Frequency Stability and drift rate:

Figure 5 shows the Allan Deviation plot of 40K CSO verses 10K CSO. A good short term stability of $3x10^{-14}$ at 1S was measured. Measurement was performed at turnover temperature with 1mK variation using a commercial temperature controller. After 3 weeks of operation the drift rate is 2.2×10^{-11} per day, reduced from its initial value by almost 10x. The present value is 100× lower than was shown by the 77K CSO.

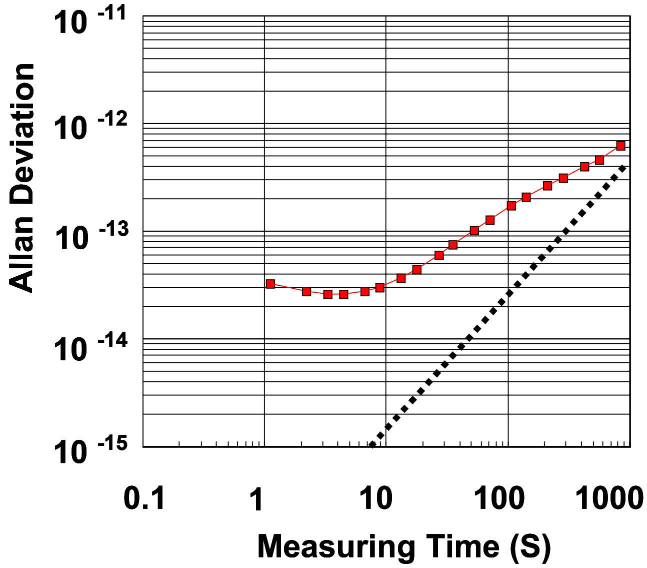

Figure 5 Stability measurement between 40K CSO and 10 K CSO shows 3x10 $^{-14}$ at 1S and a floor of 2.6x10 $^{-14}$. Drift rate was settled after 3 weeks of operation at 2x10 $^{-11}$/ day.

Conclusions/Acknowledgment

We have presented experimental test results of a 40 Kelvin compensated sapphire. Demonstrated stability between 40K CSO and 10K CSO was 3x10^{-14} at 1S and a floor of 2.6x10^{-14}. We have demonstrated the design success of the interference fit. The sapphire resonator shows a Q of 1.4x10^{8} at 16 GHz with a turnover temperature of 36.6 K. A new pulse tube coldhead was incorporated in this test and it shows a low vibration level and a base temperature of 33K. Future work includes improving stability by removing AM noise on the RF input and improving reliability by integrating all electronics for field testing. 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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