Cryocooled Sapphire Oscillator Operating Above 35 K

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We present preliminary design features for a second-generation thermomechanically compensated sapphire resonator. Developed a few years ago, the 77 K compensated sapphire oscillator (CSO) resonator showed a quality factor of $Q = 2 \times 10^6$ *at an operating temperature of 85 K, enabling a frequency stability of* $\delta f/f < 1 \times 10^{-13}$*. The new design promises a frequency stability of parts in* 10^{15} *with cooling provided by a cryocooler consuming several hundred watts or less. Optimization of the resonator design for a temperature of 40 K results in a mechanical tuning-rate requirement (MHz/mm) reduced by a factor of 8, allowing for reduced electromagnetic (EM) fields at the surface of the sapphire and reduced sensitivity to mechanical deformation. This optimized EM design is implemented in a self-assembling mechanical design that allows easy disassembly for cleaning, together with a first-order cancellation for expected mechanisms of physical creep. The new design is expected to share the very short thermal time constants characteristic of the 10 K and 77 K CSO resonators, thus allowing effective compensation of rapid temperature fluctuations.*

I. Introduction

An important new ultra-stable oscillator technology is promised by the very high inherent quality factor of whispering gallery sapphire resonators at temperatures achievable by the use of single-stage cryocoolers [1–4]. With quality factors of $Q \geq 10^8$ at temperatures above 35 K, such a resonator could support an oscillator with frequency stability better than $\delta f/f \leq 3 \times 10^{-15}$ with cooling provided by a small single-stage Stirling or pulse-tube cryocooler. However, thermal fluctuations, together with a very substantial variation of sapphire's dielectric constant with temperature, limit stability to much lower levels. If the thermal variations could be effectively canceled or compensated, the inherent promise of the sapphire resonators could be realized. The technical challenge is to provide a relatively quick compensation process without impairing the quality factor of the resonator and without otherwise limiting its stability.

The 10 K CSO is presently the only available continuously operating short-term frequency source with ultra-high stability [5–7]. A smaller cryocooled oscillator with short-term stability of 1×10^{-14} or better ($1\ s \leq \tau \leq 1000$ s) at easily reached cryogenic temperatures represents a breakthrough technology. Mated with JPL's linear ion trap standard (LITS), a 40 K CSO would offer inexpensive long-term operation

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and replacement of hydrogen masers in NASA's Deep Space Network (DSN) [8]. It also offers the local oscillator (LO) performance required by the new generation of laser-cooled frequency standards. With a cryocooler drawing from 100 to 300 W, a 40 K CSO can provide the needed performance with much lower cost and power than previously available for both ground and flight capabilities. This compares with 5 kW required by the 10 K CSO cryocooler [5].

A short-term oscillator with 10^{-14} stability offers the DSN nearly all of the performance advantages of the 10 K CSO, but with much lower cost and upkeep. In particular, short-term performance is 10 times better than the present hydrogen masers and 5 times better than near-term spacecraft ultra-stable oscillator (USO) performance. Additionally, this performance is an ideal mate as LO to the JPL LITS and linear ion trap extended (LITE) ion standards, allowing their inherent performance to be realized.

II. Background

Figure 1 shows frequency stabilities and operating temperatures for previously demonstrated short-term frequency standard technologies with stabilities of 1×10^{-13} or better. The figure shows a very large gap between the ultra-high stability available from very low temperature ($T \leq 10$ K) oscillators and the approximately 1×10^{-13} stability available at more easily reached temperatures. It also outlines a region of presently needed capability with stability better than 1×10^{-14} while using the cooling available from single-stage cryocoolers. Of the capabilities shown, those at 10 K and higher represent continuously operable frequency standards, with cooling provided by available cryocoolers.

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 finding a mechanism with sufficiently low loss that sapphire's quality factor is not degraded. This problem

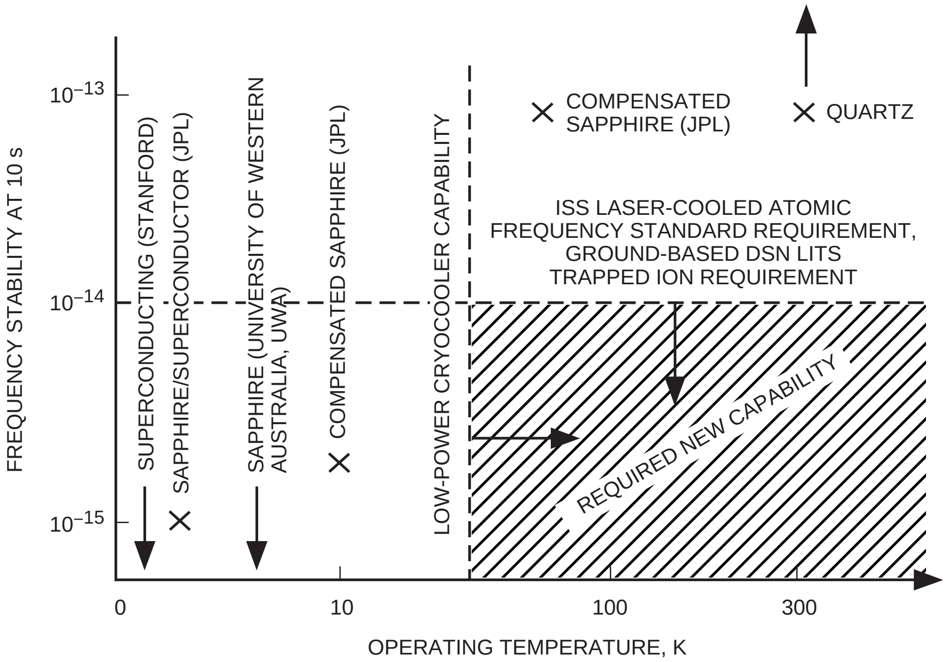

Fig. 1. Scatter plot of short-term frequency standard capabilities below 10^{-13}. Parameters for a new capability, meeting the requirements of laser-cooled atomic frequency standards now being developed for the International Space Station (ISS), are also indicated.

becomes progressively more severe with increasing temperature, T, due to a T^4 dependence for sapphire's dielectric constant and, consequently, for the resonator frequency as well. 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.

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

(1) Thermomechanical, for a $Q \approx 2 \times 10^6$ at 85 K and a frequency stability of 8×10^{-14} [1,2].

(2) Dielectrics, such as rutile, showing compensated Q's up to 10^7 at 65 K [3,4].

(3) Paramagnetic impurities: (a) incidental impurity compensation for $Q > 10^9$, $T \leq 6$ K, and stability better than 10^{-15} [9] and (b) external ruby compensation with $Q > 10^9$ below 10 K and stability of 2×10^{-15} [10].

So far, these efforts fall short of reaching the needed capability in one way or another. For example, cryocoolers for the 10 K CSO frequency standards with external ruby compensation dissipate 5 kW 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.

Figure 2 illustrates two methods for bridging the gap between the capabilities of two previous JPL-developed technologies—the 10 K CSO and the 77 K CSO. The 10 K 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 to 4 parts in 10^{15} at measuring times of 1 s $\leq \tau \leq 1000$ s without the use of liquid helium and the frequent maintenance required by previous technologies. With a short-term stability 25 times better than the hydrogen maser, the 10 K CSO is making possible a significant upgrade of DSN frequency

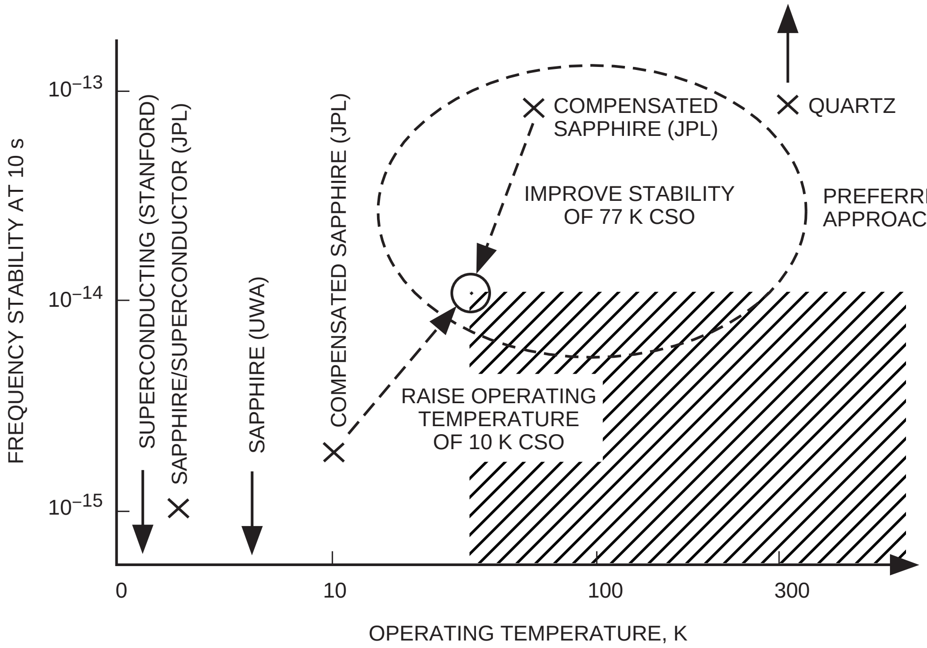

Fig. 2. Approaches to the needed capability based on demonstrated compensated sapphire technologies.

stability as required by the Cassini Ka-band experiment. The technology of the 10 K CSO was based on our previously developed 77 K CSO, which showed a stability of 8×10^{-14} with a Q of 2 million. We now propose to infuse what has been learned during the 10 K development into a second-generation thermomechanically compensated CSO.

III. Resonator Design

We identify general design requirements for a compensated sapphire resonator to achieve parts in 10^{-15} stability as

(1) A quality factor of 4×10^7 or greater
(2) A drift rate of 1×10^{-16}/s or less
(3) Thermal time constants of 3 s or less coupled with an appropriate external time constant
(4) An acceleration sensitivity of 10^{-9}/g or less.

Table 1 provides a comparison of these requirements with capabilities actually achieved in the previous design. It is clear the primary challenge for a new design is to increase resonator quality factor and reduce frequency drift rate and that a strength of the previous design was the low thermal time constant.

An intermediate figure of merit of considerable import is the required mechanical tuning rate for the electromagnetic resonator, typically measured in MHz/mm. A challenge for the original design was to achieve a large 660 MHz/mm tuning rate, required for compensation at temperatures above 77 K, while using only materials (copper, sapphire) with excellent thermal properties in this temperature range (see Fig. 3). This requirement is considerably relaxed in the new design. Lower values for the mechanical tuning rate allow smaller surface electrical fields in the resonator for reduced surface losses, a more open resonator design, and reduced sensitivity to all types of mechanical deformation.

Figures 3 through 5 show a progression of calculated frequency slopes for the thermomechanically compensated oscillator. The model is based on Debye temperatures of 900 K, 550 K, 330 K, and 225 K

Table 1. Requirements versus 77 K CSO capability.

77 K CSO	Needed now	How to accomplish
$Q = 2 \times 10^6$	$Q = 4 \times 10^7$	– Post-polish anneal of sapphire parts decreases surface losses by 4 times or more – Optimize design for 40 K—allows 8 times less energy at surface – Self-assembly (cleaning ease)
Drift $= 1 \times 10^{-13}$/s	Drift $= 1 \times 10^{-16}$/s	– Motion-canceling design – Lower stress – Symmetric transverse stress – Lower temperature
Thermal $\tau = 5$ s	Thermal $\tau = 3$ s	– Utilize same general design—metal to sapphire joint inside inner caustic where RF fields are small – Lower temperature gives improved thermal conductivity, reduced heat capacity
$\delta f/f = 1 \times 10^8$/g	$\delta f/f = 1 \times 10^{-9}$/g	– Center-mount resonator design

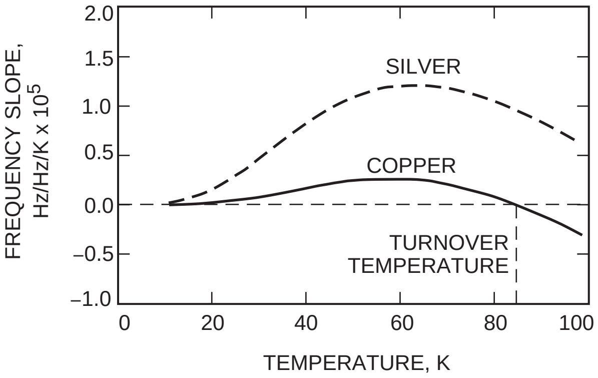

Fig. 3. A high tuning rate of 660 MHz/mm enabled a turnover of 85 K with a copper spacer and WGH mode orientation in the 77 K CSO.

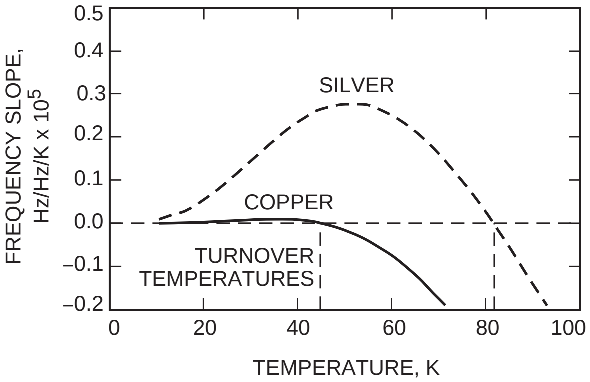

Fig. 4. Use of the WGE mode and a 2.84 times lower tuning rate gives a turnover of 45 K for the copper spacer, together with nearly complete compensation at lower temperatures; a silver spacer would show an 82 K turnover.

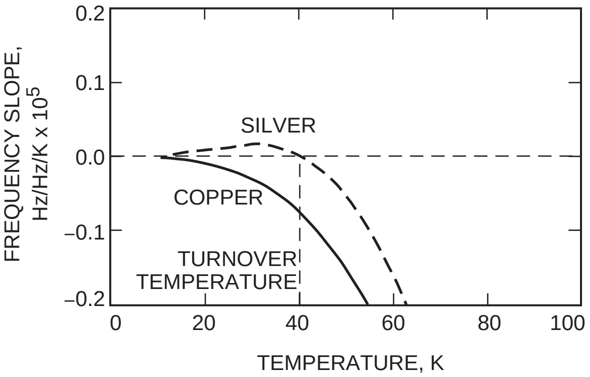

Fig. 5. Optimization for a turnover at 40 K with a silver spacer and WGE mode is achieved by reducing the tuning rate by 8.33 times. Such a resonator with a copper spacer would be under-compensated at all temperatures.

for sapphire expansion, sapphire dielectric constant, copper expansion, and silver expansion, respectively. At the lowest temperatures, all the curves scale as T^3.

Figure 6 shows the frequency dependence on gap spacing for several examples of whispering gallery transverse magnetic (WGH) and transverse electric (WGE) modes. The slope of the dashed line corresponds to the 77 K CSO tuning rate, as used in Fig. 3. Reduced slopes, as specified in Figs. 4 and 5, can be achieved by increasing the gap spacing and/or choosing a different mode.

We have identified general technical approaches to meet these requirements as follows:

Operation at 40 K instead of 85 K:

(1) Lower temperature operation alone allows a reduction of the required mechanical tuning rate by a factor of 1.69 times.

(2) Lower temperature also reduces creep rates—experience with the 10 K CSO showed greater than a 100-times reduction.

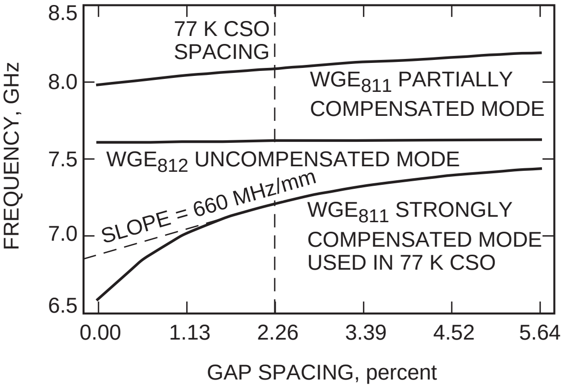

Fig. 6. Finite-element calculation of frequency dependence on the gap between sapphire elements for the 77 K CSO resonator. A lower slope requirement now allows use of the WGE partially compensated mode with its higher Q, lower temperature coefficient for epsilon.

Further optimization of resonator design for 40 K:

(1) A metal spacer made of silver with its Debye temperature of 225 K gives a larger thermal expansion rate at low temperatures as compared with copper at 330 K. It reduces the tuning rate by 2.93 times.

(2) Use of the WGE mode with its reduced sapphire dielectric thermal sensitivity further reduces the tuning rate by 1.68 times.

(3) The overall reduction of the tuning rate requirement is 8.33 times. This contributes to higher Q and reduced mechanical sensitivities by this same factor.

Post-polish anneal of sapphire parts:

(1) Experience with the 10 K CSO indicates that annealing reduces overall losses by 4 times or more. Surface losses important to tunable resonator design may be reduced even more.

Self-assembling mechanical design:

(1) Use transverse (radial) joining by differential thermal contraction on cool-down: (a) join the metal spacer to the two sapphire end parts and (b) join the spacer to internal support.

(2) Use gravity alignment at room temperature; the parts support each other but then pull away after the grips take hold.

(3) High hardness and precision of the sapphire parts prevents groove formation and allows for reassembly.

(4) Have easy recleaning of parts.

(5) A low-temperature anneal after the first assembly may reduce subsequent mechanical creep.

(6) Reduce material stress by control of mechanical clearances—0.3 mil tolerance is required.

(7) Use very short metallic contact regions to reduce sensitivity to angular misalignment upon cool-down: (a) a very long contact region would be required to prevent binding due to misalignment and (b) a short region eliminates the negative consequence of slight misalignment.

Advanced mechanical design to give first-order cancellation of axial motion due to relaxation of radial stress:

1. Three axial/radial motion transfer coefficients impact frequency creep: (a) radial relaxation of the center grip of the metal spacer onto the sapphire post can change the spacer length, (b) radial relaxation of the end grips of the metal spacer onto the sapphire parts can change the spacer length, and (c) radial relaxation of the end grips of the metal spacer onto the sapphire parts can bend the sapphire.
2. Advanced mechanical design can adjust each of these to give nominally zero axial motion due to radial relaxation of grip stress.

Center support of the three-part compensated resonator for reduced g-sensitivity:

1. Accurate center support should reduce acceleration sensitivity by 100 times or more.
2. The previous design used an end support.

Thermal contact between elements by a metal-to-sapphire joint in the low-RF-field region of the resonator:

1. The region inside the inner caustic has very low RF fields and allows the use of metallic parts.
2. Use of soft metals—possible gold-plating on the metal spacer—improves thermal contact.
3. Previous designs used an indium–sapphire joint to achieve a 5 s thermal time constant at 77 K, a 1 s one at 10 K. However, ultra-soft indium seems a likely candidate as a source for mechanical creep and is not being considered here.

Figure 7 shows a cross-sectional view of the mechanical resonator design. Figure 8 shows the results of finite-element calculation of axial motion in response to radial force at the center grip for a preliminary design candidate. One-half of the cylindrical cross-section is shown, rotated 90 deg from Fig. 7. A similar finite-element calculation is used to adjust the end grip positions in order to eliminate any axial motion induced by radial creep at the end grips.

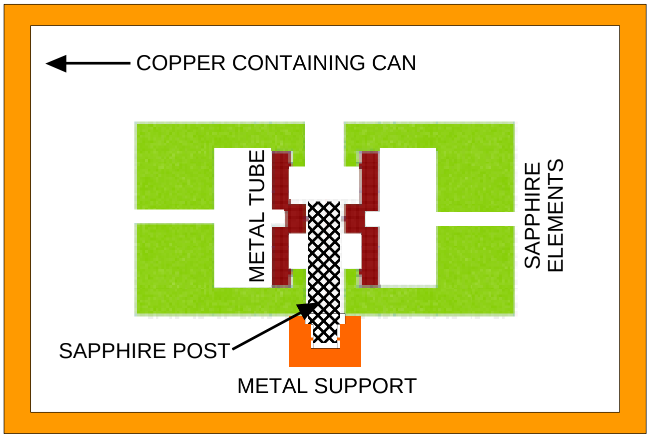

Fig. 7. Cylindrical cross-section of the self-assembling resonator design. Upon cool down, thermal contraction causes the metal spacer and support to grip the sapphire parts and then to retract from other contacts.

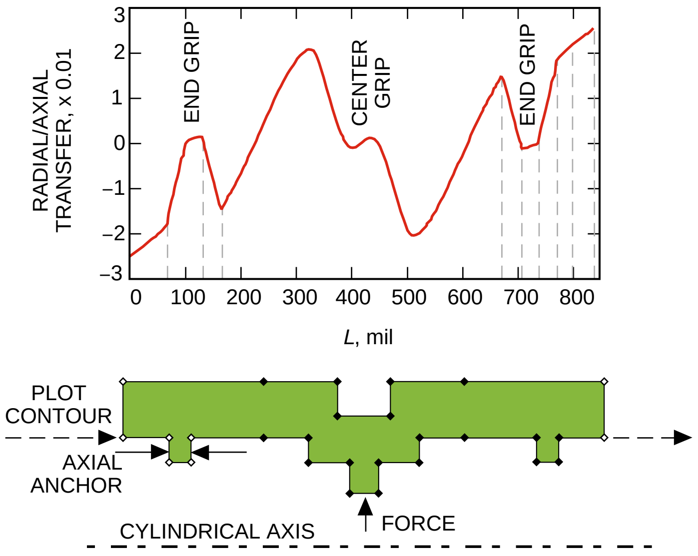

Fig. 8. Motion-canceling designs eliminate axial motion and associated frequency creep when force at either center grip or end grips relaxes with time. This example shows nominally zero motion of the end grips due to force on the center grip of the metal spacer.

IV. Conclusion

We have presented preliminary design features for a second-generation thermomechanically compensated sapphire resonator optimized for operation near 40 K. This development builds on JPL capabilities demonstrated in the successful development of the 10 K and 77 K CSOs, short-term frequency standards that achieve stability in the 10^{-14} and 10^{-15} range without the use of liquid helium.

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