RECENT DEVELOPMENTS IN CRYOGENIC COMPENSATED SAPPHIRE OSCILLATORS

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Cryogenic microwave oscillators offer the highest short term stability of any frequency sources[1,2,3]. This stability and accompanying ultra-low close-in phase noise are made possible by the high quality factors (Q's) available with cooled sapphire or superconducting resonators, and by advantageous thermal properties (low expansion coefficients and small time constants) for solid materials at low temperatures. The capability offered by these oscillators is crucial to several advanced technology areas; notable among these being NASA radio science applications and local oscillator (L.O.) requirements for a new generation of laser-cooled frequency standards. However, until recently cryogenic oscillators were restricted to research laboratories due to the requirements of liquid-helium cooling. A new generation of sapphire resonators is changing that by offering a much broader range of operating parameters than before. With the addition of external compensation, the new resonators make possible ultra-high frequency stability at higher (and much more easily reached) temperatures than previously required. Today, cryocooled compensated sapphire oscillators (CSO's) are being installed in NASA's Deep Space Network[4] (10K CSO) and work is going on many laboratories around the world to develop an even higher temperature version, one that can be cooled by a single stage cryocooler. This would meet L.O. requirements for the new laser-cooled frequency standards in a small and economical package. We describe these developments and analyze some of their technical aspects in the sections that follow.

1 Background

The first ultra-stable cryogenic oscillators used liquid helium to cool monolithic superconducting[2] or sapphire resonators[3]. Superconducting niobium resonators require a temperature well below 2K in order to achieve the required $Q \geq 10^9$ and frequency insensitivity to temperature. Sapphire resonators improve on this in two ways. Sapphire's high Q is not due to a phase transition, but is part of a rapid "freezing out" of thermal energy, a process that is enhanced by sapphire's high Debye temperature. These combine to give a Q increase immediately upon cooling from room temperature with an approximate T^4 dependence[5]. Additionally, incidental paramagnetic impurities in typical sapphire samples typically give a $1/T$ compensating effect that cancels the T^4 low temperature Debye variation[6] (see Fig. 1), for an advantageous frequency turnover at temperatures of 4K - 6K.

Continuous long-term operation is crucial to the applicability of short-

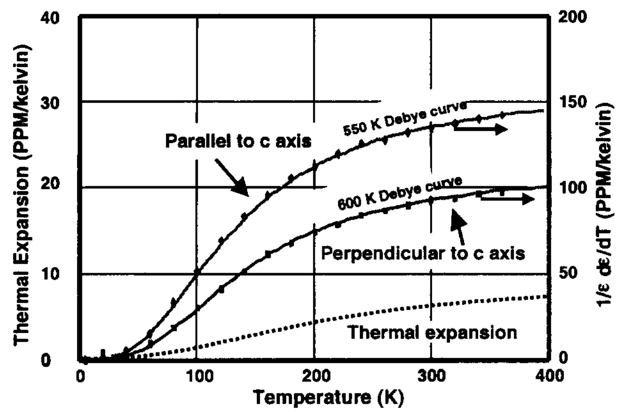

Figure 1. Thermal variation of sapphire's dielectric constant shows a typical Debye temperature dependence. Variation of a resonator's frequency would be just 1/2 of the values shown. Sapphire's thermal expansion coefficients, smaller by an order of magnitude, are indicated by the dotted line.

term frequency standards since they are typically are used to "clean up" the short-term variations of an atomic standard, the combined output being then distributed to various users. Furthermore, cryogenic oscillators provide the local oscillator (L.O.) performance required by a new generation of passive atomic standards. These include the laser-cooled and trapped-ion standards presently being developed at many laboratories around the world, and whose potential is presently thwarted by the lack of available L.O. performance[1,7]. Long-term operation is required for these absolute frequency standards.

Cryocoolers offer the needed long-term operability, but while high quality monolithic sapphire resonators show quality factors of $Q \geq 10^9$ at temperatures up to 10K, stable operation can only be achieved near a preferred "turnover temperature" which is typically too low to be reached by cryocooler. Furthermore, this temperature varies from resonator to resonator depending on the concentration of incidental ($\approx$ 1 PPM) paramagnetic impurities. In order to be used with a cryocooler, the impurity levels would need to be very accurately controlled so that the resonator's turnover temperature is in the relatively narrow temperature band between that which can be achieved with available cryocoolers and the point at which the Q is degraded.

The CSO approach solves this problem by the addition of external elements which can be varied in configuration to achieve just the right amount of compensation. Additionally, it offers a variety of different mechanisms, some

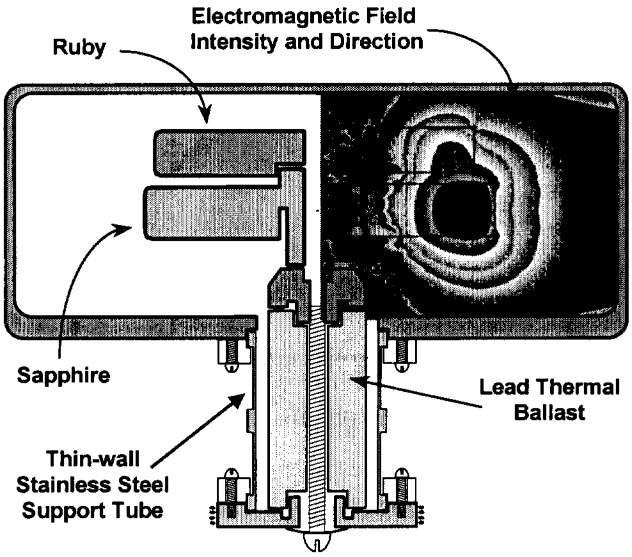

Figure 2. Spin-compensated sapphire resonator with external ruby element as used in the 10K CSO. The thin-walled tube thermally isolates the resonator elements while providing good rf confinement. Electromagnetic field intensity varies approximately 1 order of magnitude per color band as calculated by finite element software.

of which are much stronger than paramagnetic impurity tuning, and so can raise the turnover temperature significantly.

2 Introduction

CSO development has been fueled in part by recent advances in cryocoolers. In particular, new 2-stage Giffard-McMahon cryocoolers opened a window of opportunity–for the first time a cryocooler could credibly promise effective cooling well below the 10K required to reach $Q \approx 10^9$ in sapphire. And, developments in small single stage pulse-tube and Stirling coolers are now driving new CSO technologies that promise 10^{-14} stability at temperatures of 40K – 60K.

Two different CSO approaches have so far resulted high or ultra–high stability, and a third shows much promise, with demonstrations of high Q's together with very attractive turnover temperatures. Thermomechanical tuning was the first to be developed[8] and has been the subject of several stability demonstrations[9,10]; the "77K CSO" showing short-term frequency stability of

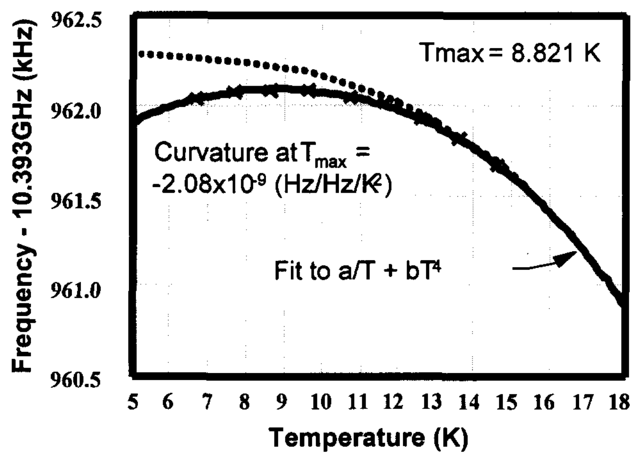

Figure 3. Measured turnover temperature for the 10K CSO, Configuration corresponds to weaker compensation option(lower turnover temperature). Dotted line shows uncompensated sapphire temperature dependence.

1×10^{-13}. We discuss a second-generation version of this technology in a following section. The second CSO approach to be developed used paramagnetic tuning in an external ruby compensating element. This approach gave rise to the cryocooled "10K CSO", a frequency source with short-term stability of $\approx 2 \times 10^{-15}$ and phase noise of -73dBc/Hz @ 1Hz measured at 34 GHz. 10K CSO units are presently being installed in NASA's Deep Space Network (DSN) stations around the world[1,4]. This technology is discussed in the next section. Finally, a number of studies have demonstrated sapphire resonators with dielectric compensation[11,12]. These studies show great promise, but have so far had limited success as frequency sources, with stabilities typically 10^{-11}, limited by thermal effects

The success of the CSO approach depends on keeping the compensating and compensated elements at the same temperature to a high degree of accuracy. Thermal design for the system must achieve this condition even in the face of time–varying temperature inputs from the cooling system, such as boiling cryogens or cyclic coolers. While sapphire itself has millisecond thermal equilibration times at helium temperatures, composite structures can have much longer time constants. And, since short–term frequency stability is the capability gap being filled by the CSO technology, the fact that the compensating mechanism may work poorly at short times is a crucial problem.

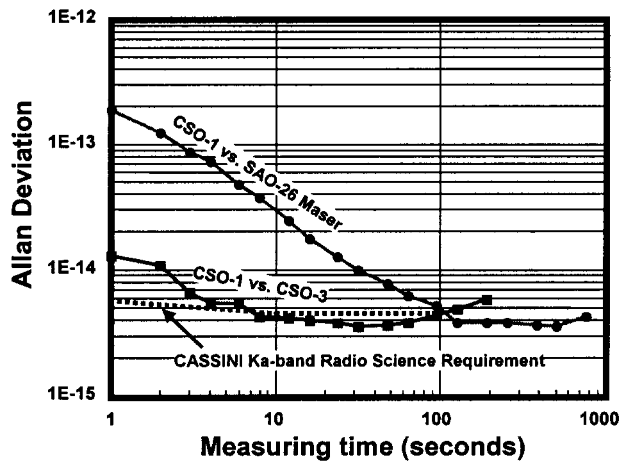

Figure 4. Frequency stability measurement between several 10K CSO units, and between one of the units and an SAO Hydrogen Maser. The CSO improves on the stability of the Hydrogen Maser at 1 second measuring time by an order of magnitude.

3 Spin-compensated CSO (10K CSO)

Figure 2 shows the physical configuration and resonant RF magnetic for the 10K CSO. RF fields were calculated using the CYRES-2 finite element software[13]. Indium foil or wire gaskets are used at all joints, both to provide a dependable thermal contact and also for low RF losses. The lead thermal ballast, together with the stainless steel support tube, provides a time constant for the sapphire elements of about 3000 seconds, while the time constant between ruby and sapphire elements is approximately 1 second. It can be seen that the ballast and the compensator have complementary functions – without the compensator, the ballast itself provides immunity to external temperature variations for times of 1 second or less, while the compensator, even without the ballast does just as well for times of 100 seconds or more.

The temperature turn-over for CSO-1 is shown in Fig. 3. A second and third CSO are now operational, with resonator turn-over temperatures of 7.907 K and 7.336K. Q's for all three resonators are greater than 10^9.

Pair stability measurements in Fig. 4 show an Allan Deviation of 1.3×10^{-14} at 1 second and $\approx 4 \times 10^{-15}$ for measuring times between 10 and 100 seconds. Assuming both units are similar their individual performances are 8×10^{-15} at 1 second and $\approx 2.5 \times 10^{-15}$ for 10 to 100 seconds. These results

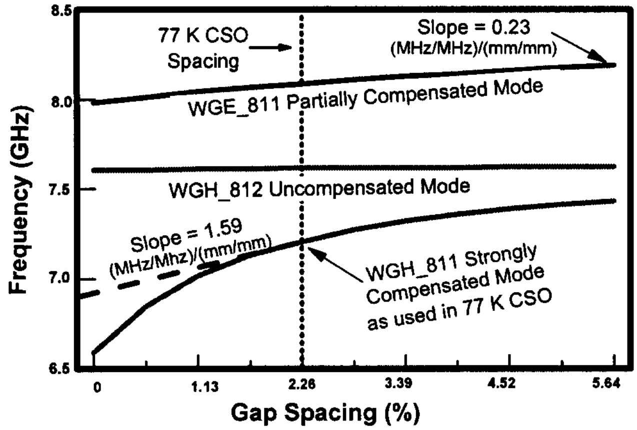

Figure 5. Frequency sensitivity to gap change for several modes of the 77K CSO resonator. The slope of 1.59 for the strongly compensated mode gave a turnover of $\approx$ 85K using a copper spacer. The 40K CSO resonator with silver spacer needs a slope of only 0.16, allowing use of the "partially compensated" mode which was observed to show a significantly higher quality factor (Q).

are approximately 10 times better than the hydrogen maser in this time range.

Excellent short-term performance could also be inferred by the success of an application of the CSO as local oscillator (L.O.) to the JPL LITS passive atomic standard[1], where medium-term stability showed no degradation due to L.O. instabilities at a level of $\sigma_y = 3 \times 10^{-14}/\tau$.

Phase noise measurements show a 24 dB improvement over the best of the masers at 1Hz offset, and verify that CSO noise performance meets the Cassini Ka-band requirement of -73dBc/Hz at 34GHz.

4 Thermomechanically compensated CSO

The thermomechanically compensated CSO uses a metallic spacer to adjust the spacing between two sapphire halves so as to compensate their inherent thermal frequency variation. The previous 77K CSO used a very strongly tuned mode (Fig. 5), a mode with large electric fields in the gap between the sapphire parts. The observed quality factor for this mode was only $Q \approx 1 \times 10^6$ compared to $Q \approx 1 - 2 \times 10^7$ for the other modes.

We are now developing a new 40K unit, designed for stability better than 1×10^{-14}. In addition to an expected higher Q due to reduced gap fields, sensitivities to all other mechanical aspects is reduced by almost a factor of

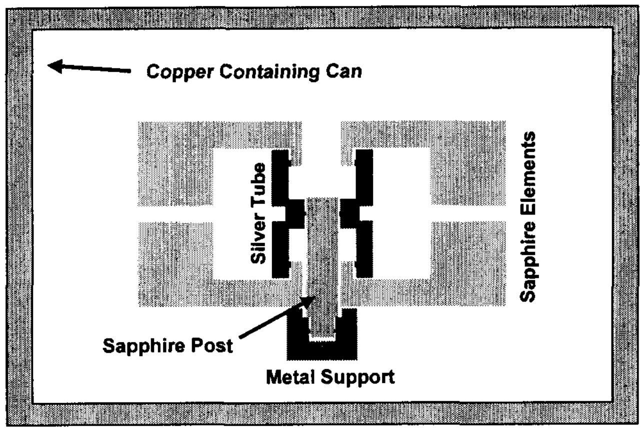

Figure 6. 40K thermomechanically compensated resonator with interference–fit joints.

10, due to the lower tuning rate requirement.

Figure 6 shows the new resonator design. Indium joints to the sapphire elements themselves are eliminated by a "self assembling" design that tightens as it cools. Other advantages of the 77K CSO also accrue–all joining inside the resonator can being done close to the axis where RF fields are small, thus allowing metallic thermal joints.

Acknowledgments

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