Design and Progress Report for Compact Cryocooled Sapphire Oscillator “VCSO”

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Abstract—We report on the development of a compact cryo-cooled sapphire oscillator “VCSO”, designed for operational frequency and timing systems or metrology applications requiring a higher–performance replacement for ultra–stable quartz oscillators. The VCSO matches a new Stirling cryocooler requiring only 160 Watts input power with an improved version of the thermomechanically compensated silver/sapphire resonator previously developed for the 40K CSO. We describe details of the sapphire resonator electrical and mechanical design, report on analysis of a crossover circuit that, together with an inexpensive 100 MHz quartz clean–up oscillator, reduces bright–line vibration–induced phase noise spikes by 40 dB or more, and report on cryogenic and vibration tests on a candidate cryocooler.

I. INTRODUCTION

Developments in sapphire resonator technology [1] and in long-life cryocoolers [2] now make possible an ultra-stable cryogenic sapphire oscillator with significantly improved operability and with size reduced to that of a “breadbox”. With an achieved stability of $1 \times 10^{-14}$ at 1 second, the VCSO will have multiple applications where high performance flywheel or phase noise clean up oscillators are required, such as in the NASA Deep Space Network Frequency and Timing System [3]. It is also needed for local oscillator applications to realize the full potential of state of the art microwave frequency standards such as Cesium atomic fountains, and Mercury Linear Ion Trap frequency standards [4].

Previous development of the 40K CSO established low-drift and low g–sensitivity for a “self assembling” thermo–mechanically compensated silver/sapphire resonator design that demonstrated a quality factor of $Q = 1 \times 10^8$ at its temperature turnover of about 37 K [1]. Several other compensation technologies for sapphire resonators in this temperature region are also being developed at other laboratories, including Titanium doping [5] and dual–mode excitation [6]. The VCSO is based on the 40K CSO technology, operating at 32 GHz instead of the previous 16 GHz in order to reduce resonator size to match the capabilities of a smaller cryocooler. Sizes are reduced by $\approx 50\%$ for a very small volume of about 10 cm$^3$, an ID for the shielding can of 3.55 cm (1.4 inches) and a height of 1.58 cm (0.62 inches). The VCSO design calls for a quality factor $\geq 30$ million, a specification up to two times smaller than the sapphire material Q limit at 50 K, but high enough to allow short–term frequency stability of $1 \times 10^{-14}$ or better. A significant modification is the use of the $WGE_{12,1,1}$ mode instead of the previous $WGE_{10,1,1}$ which increases the overall diameter slightly; this change allowed re-use of the 40K CSO silver spacer design without increasing RF losses due to the spacer.

A major challenge for this new technology is to reduce or eliminate the bright–line phase noise spectra that result from vibrations in the Stirling cryocooler [2] at harmonics of the 60 Hz vibration frequency. While acceleration sensitivity for the new resonator is expected to be $\leq 0.5 \times 10^{-10}/g$, a value half that measured for the previous, larger resonator, the effects of cryocooler vibrations must still be reduced by 60 dB to be essentially unobservable. We show that an appropriate clean–up oscillator with advanced crossover design, together with active cancellation of cryocooler vibrations, can give...
the required reduction with some 25 dB to spare, while still allowing short-term stability of $1 \times 10^{-14}$ for a measuring time of 1 second.

Present status is that, with the exception of the copper containing can with its waveguide coupler, nearly all the parts have been designed, ordered or are in hand. Completion of the can design and construction is the next order of business. Promising improvements to medium- and long-term stability using a new cryogenic Pound circuit methodology are discussed in a companion paper in these proceedings [7].

II. VCSO TECHNICAL DESIGN

A. Resonator

1) Electromagnetic Design: The VCSO resonator is based strongly on the previous 16 GHz design, as shown in Figure 1. In particular, the re-use of the silver spacer design allows us to use an EDM manufacturing technique that has already proven to work, and such re-use does not require that the physical tolerances required for the fitting tolerances between silver and sapphire parts be made more stringent even though the resonator itself is significantly smaller. Additionally, a higher thermo–mechanical tuning rate due to the longer length of the silver spacer relative to that of the resonator itself naturally gives a somewhat higher turnover temperature, a good match to the capabilities of the single-stage Stirling cooler.

Electromagnetic fields calculated for the $WGE_{12,1,1}$ mode for the sapphire resonator are shown in Fig. 2. Such calculations allow optimization of the resonator parameters such as balancing can diameter against losses, establishing appropriate RF magnetic field values at the coupling port. The positions of the walls of the can have been adjusted to give a copper can–limited quality factor of $Q_{can} = 4 \times 10^8$ and so to allow critical coupling with a waveguide port for the expected sapphire quality factor of $Q \approx 3 – 6 \times 10^7$.

Choice of an azimuthal mode number of $n_{\phi} = 12$ instead of the previously used $n_{\phi} = 10$ was made because RF losses due to In Phase magnetic fields as shown in Fig. 2 reduced the quality factor $Q_{can}$ to an unacceptable value.

The somewhat odd resonator shape as shown in Fig. 1 resulted from sequences of electromagnetic field calculations as plotted in Fig. 3. First attempts without the “cut–out” region at the resonator corners resulted in a low tuning rate and consequent low value for its “turnover temperature”, the temperature where the net sensitivity of frequency to temperature passes through zero, and near which the resonator is operated for high–performance.

The thermo–mechanical compensation process operates due to variation with temperature of the gap between sapphire disks for the assembled resonator; this variation is primarily due to the thermal expansion coefficient of the silver spacer. This temperature dependence allows the effect of the thermal variation of sapphire’s dielectric constant to be cancelled by a proper choice of tuning rate for the resonator and so to achieve a zero net variation (i.e. turnover) at the desired operational temperature.

2) Mechanical Design: Early thermo-mechanically compensated sapphire resonators suffered from excessive frequency drift, showing values as high as $10^{-7}$/day [8], [9]. For this reason we use a design that reduces frequency drift due to mechanical creep in several ways. First, the use of a silver spacer instead of copper as previously used provides much lower cryogenic creep values [10]. Secondly, as shown in Fig. 4 and Fig. 5 a design is used for which the primary loading forces are radial and for which the crucial longitudinal dimensions can be somewhat isolated from the effects of radial creep by an appropriate design. These radial loading forces result from the “self–assembling design” in which the silver spacer grips both the sapphire disks and the central sapphire support rod as the parts are cooled, resulting in small but
Cyclical mechanical vibrations from Giffard–McMahon cryocoolers and other such coolers operating with low mechanical frequencies of 1–2 Hz must be effectively isolated in order to achieve high frequency stability in a sapphire oscillator [11]. However we show here that vibrations at 50–60 Hz characterize small Stirling- or Pulse Tube coolers can be filtered by means of a clean–up oscillator without degrading ultra–high short–term stability performance. In particular, Figures 6 and 7 show the phase noise and frequency stability performance for several example clean–up oscillators and for a crossover design that provides highly–tuned rejection at the fundamental of the cryocooler vibration frequency and its first two harmonics.

Choice of the unity gain or crossover frequency for the crossover circuit balances the need for the clean–up oscillator to be effective at high frequencies (favoring a low crossover–frequency), while effectively ignoring its higher noise at lower frequencies (favoring a higher crossover–frequency), higher noise that would otherwise degrade the frequency stability of the combined system. With an optimal crossover frequency of only 25 Hz as determined by this trade–off, rejection of the vibration harmonics is largely up to the notch filters. We find that these filters require a Q value of \( Q \approx 5 - 10 \) to minimize their impact on lower frequencies and on the phase margin of the loop. However, such filters will have a substantial sensitivity to component variation with temperature, and so a software method was developed to evaluate non–ideal “balanced tee” notch filter performance. Based on these calculations we have determined that 40 dB reduction for the harmonics can be held for a 1 deg. C variation of the crossover electronics interior. See the figure captions for further details.

C. Cryocooler

1) Cryogenic Tests: The CryoTel cryocooler from Sunpower, Inc. has a rated lifetime of 40,000 hours and requires an input power of \( \approx 160 \) Watts. The availability of such coolers now makes possible their inclusion in equipment with very much improved useability compared to previously available coolers. The cooler itself, power electronics and a control laptop computer are shown in Figure 8. The cooler is available with passive balancer and active balancer purchase options to reduce vibration levels. The passive balancer reduces vibrations by \( \approx 10 \) dB to approximately 0.3 g RMS, a reduction that is enhanced by addition of an electrical voice–coil mechanical driver and user–supplied electronics. We have operated the cooler for 5 months so far without failure or degradation.

The cooler control system supports constant temperature and constant stroke operational modes; because of the need...
to reduce cooler vibrations by an active feedback system, we expect to use the constant stroke mode to reduce the burden on control of that system. Resonator temperature control will be accomplished instead by means of electrical heaters and the use of appropriate thermal impedances. Figure 9 shows measured values for ultimate temperature as a function of programmed stroke length.

2) Vibration Control: Figure 10 shows drive electronics for the active vibration cancellation system. The circuit is designed to cancel the first two harmonics by manual adjustment of their phases and amplitudes. Somewhat surprisingly, the 60 Hz drive for the cooler itself (and which we use as input to our circuit) consists of a PWM modulated square wave signal at 420 Hz – hence the inclusion of a 420 Hz notch filter.

The effectiveness of cancellation of the two vibration harmonics is shown in Figure 11. Requirements of 25 dB reduction at 60 Hz and 16 dB at 120 Hz are much lower than the 55 dB reduction shown in the figure. The figure is not a long-term value – nonetheless values were more typically 40 dB reduction. These values are sufficiently optimistic that it is not clear whether an adaptive system would be required for long-term operation.

Also somewhat surprisingly, varying the cryocooler stroke gave rise to some 20 dB smaller degradation than would be expected for a constant amplitude cancellation model, indicating that the variations in vibration levels in cooler and active compensator are largely compensating each other with the

Fig. 6. A clean-up oscillator can help to reduce vibration-induced phase noise spikes to negligible levels. However to achieve this without degrading the Ultra–High Stability performance of the VCSO requires a sophisticated crossover design. Shown here are phase noise plots for 5 MHz and 100 MHz candidate clean-up oscillators, example VCSO phase noise with a single 60 Hz vibration harmonic, and combined (crossed over) phase noise for the VCSO together with each candidate clean-up oscillator. Phase noise for all oscillators are scaled to MHz. The crossover design here has a unity gain frequency of 25 Hz, and includes notch filters for the first three vibration harmonics. Operating together with an active vibration–cancellation system as described in Figure 10, the combined system promises to reduce vibration harmonics by more than 60 dB.

III. Conclusions

A design has been developed for a “breadbox” sapphire oscillator with ultra–high stability and much improved usability. More than one time the number of design challenges have been met, and the configuration seems solid. Most parts are now either ordered or in hand and we expect to continue with sapphire Q-measurements at 32 GHz and resonator can design in the coming months.

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

[2] CryoTel cryocooler by Sunpower Inc. 182 Mill St. Athens, Ohio, 45701, USA
Fig. 8. Photograph of the CryoTel cryocooler as–tested with control electronics and a laptop control computer. Here the cooler itself and its vibration cancelling driver are hidden from view by a cylindrical air duct that channels air from the blower at the right through a heat exchanger at its left end. The cooler’s cold finger extends into the vacuum fittings at the left and will be replaced with somewhat larger fittings to accommodate the resonator and heat–shield; a vertical, downward hanging configuration is planned.


Fig. 9. Plot of ultimate temperature vs stroke length as measured for the cooler configuration shown in Fig. 8.

Fig. 10. Circuit diagram for feed–forward cancellation of first harmonics of the cryocooler vibrations. Because the cooler’s own 60 Hz signal is quartz–crystal generated, its phase walks significantly from that of the line over times of seconds to minutes, apparently depending on variations in load experienced by the power grid. Thus we use the cooler’s power drive as the signal – phase shifted, scaled and multiplied, to drive the voice coil in the passive/active compensator supplied by the cooler manufacturer and so to reduce the vibration levels for the two lowest (and most significant) vibration harmonics.


Fig. 11. Acceleration spectrum for the CryoTel cooler measured with and without active vibration cancellation. The first two vibration harmonics and their reduction values are indicated in the figure. Based on the crossover design described earlier, these reductions are some 25 dB higher than necessary to achieve our overall 60 dB bright–line reduction goal.