

Recent Developments in Cryogenic Compensated Sapphire Oscillators

G. John Dick and Rabi T. Wang
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109-8099, USA

Cryogenic microwave oscillators using resonant elements made with high-purity single crystal sapphire now make possible a new range of capabilities for ultra-stable short-term frequency standards. The addition of compensation makes possible ultra-high frequency stability at much higher temperatures than the $\approx 1\text{K}$ that would otherwise be required. Presently operational compensated sapphire oscillators (CSO's) include an oscillator with thermomechanical compensation with stability better than 1×10^{-13} , a cryo-cooled oscillator using paramagnetic impurities in an external compensating element (ruby) with a stability of 2×10^{-15} , and oscillators with using incidental paramagnetic impurities with stabilities from 1×10^{-15} to 2×10^{-16} . The compensating elements or features in these resonators enable high stability by providing zero thermal sensitivity of frequency at resonator temperatures of 85K, 8K, and 1.5K-6K, respectively. Two properties of sapphire—losses that reduce as $\approx T^4$ as temperatures are reduced below 300 K, and a thermal conductivity that reaches values greater than 70 W/cm/K at 80 K enable ultra-high stability at easily reached cryogenic temperatures. Sapphire's X-band Q of $\approx 250,000$ also has application for ultra-low phase noise at room temperature where its relatively poor thermal conductivity prevents high stability. As the temperature is reduced below 100 K a thermal conductivity higher than copper makes for short thermal relaxation times. This, together with Q's from 3×10^7 to $> 1 \times 10^9$ and low noise RF electronic techniques, makes possible ultra-high stability operation. An important application for the performance enabled by CSO's is to provide the local oscillator (L.O.) performance required by a new generation of atomic frequency standards. Available quartz oscillators have frequency fluctuations that are aliased to near zero frequency by the sequential interrogation processes used in these new frequency standards, thus degrading their performance. However, the new CSO's provide a practical L.O. capability that allows full performance to be achieved. The JPL-developed cryo-cooled "10K CSO" is the first oscillator to provide long-term operation with stability of $3\text{-}4 \times 10^{-15}$ for times ($1 \text{ second} \leq \tau \leq 300 \text{ seconds}$), and is presently being installed in stations of NASA's Deep Space Network in support of the Cassini Ka-band Experiment. A new generation of promising new resonator technologies will also be described that promise roughly comparable stability at temperatures of 40K – 50K, making possible a much smaller and lighter unit capable of being cooled by a single-stage Stirling or pulse-tube cooler with a dissipation of 300 W or less.