Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

THE PROGRESS IN THE DEVELOPMENT OF A SOLID NITROGEN COOLED DUAL-MODE FREQUENCY-TEMPERATURE-COMPENSATED SAPPHIRE-RESONATOR OSCILLATOR

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Abstract - **A dual-mode single crystal sapphire resonator with a frequency-temperature turning point at approximately 50.6 K has been designed (patent pending). It utilizes the inherent anisotropy of the temperature coefficient of frequency of two orthogonally polarized quasi-TE/TM modes separated by approximately 3.5 GHz as the oscillator output. The Q-factors of both modes have been measured to be both around 10^8. The dual mode oscillator was constructed as two individual loop oscillators, each connected to the cryogenic resonator via separate coaxial cables and coupling probes in transmission. The probes were oriented to maximize coupling to the design mode and minimize coupling to the other orthogonally polarized mode. The loop oscillators were operated with Pound locked servos. The beat frequency between the oscillators was measured against a HP8673 synthesizer referenced to an Oscilloquartz 8600 OCXO stable reference. A fractional frequency Allan Deviation of about $7 \times 10^{-13}/\tau^{1/2}$ was obtained from 1 s to 26 s. Above 26 s the measurement was limited by the noise floor of the measurement system.**

Keywords - **sapphire, whispering gallery modes, resonator oscillator**

I. INTRODUCTION

The Whispering gallery (WG) modes have been utilized in liquid helium cooled single crystal sapphire resonator oscillators to achieve the most highly stable microwave frequency sources. These oscillators have Allan Deviations of the order of 10^{-16} to 10^{-15} over 1 s to 300 s [1-3]. To operate an atomic oscillator at the quantum limit requires a local oscillator (LO) with stability of order 10^{-14} at 1 s [4]. The desire to also implement such high stability clocks in space and specifically on the International Space Station (ISS) [5] has motivated the development of an LO that could operate in the ambient radiation cooled environment (around 50 K) on the ISS palate where the Atomic Clock Ensemble (ACES) will be positioned. The main problem achieving this goal was to build an oscillator that could operate on a resonator frequency-temperature compensated turnover point at around 40 K – 80 K, yet have a stability sufficient for an LO of about 10^{-14} at 1 to 10 s.

The design of a resonator that has a null in the frequency-temperature dependence around 40 – 50 K and yet still exhibits a high Q-factor has been the goal of a few research groups [6-11]. One such design, that is based on the fact that modes of orthogonal polarizations in an uniaxial anisotropic crystal, such as sapphire, have different frequency-temperature dependences was presented at IFCS last year [12]. This fact, it was shown, allows the existence, with an appropriate chosen pair of modes, of a null in the frequency-temperature dependence of the difference frequency. Using the same resonator as described in [12, 13] we have constructed such an oscillator. This paper discusses the implementation of that dual-mode oscillator at a turnover temperature of about 50.6 K using solid nitrogen as the coolant [14]. Also we present the first fractional frequency measurements.

II. METHODOLOGY

1*) The resonator*: The resonator is approximately 50.00 mm in diameter with a tapered height ranging from 24.50 mm in the center to 20.27 mm at the diameter. It has two spindles at either end of the sapphire cylinder and it was supported in a silver-plated copper cavity by the bottom spindle only. The inner diameter of the cavity was nominally 80 mm and 50 mm high. The chosen mode pair was the $WGH_{12,0,0}$ mode with a frequency of 9.086 GHz (unloaded Q-factor of 1.3×10^8) and the $WGE_{15,0,0}$ with a frequency of 12.605 GHz (unloaded Q-factor of 0.94×10^8) both measured at 50 K.

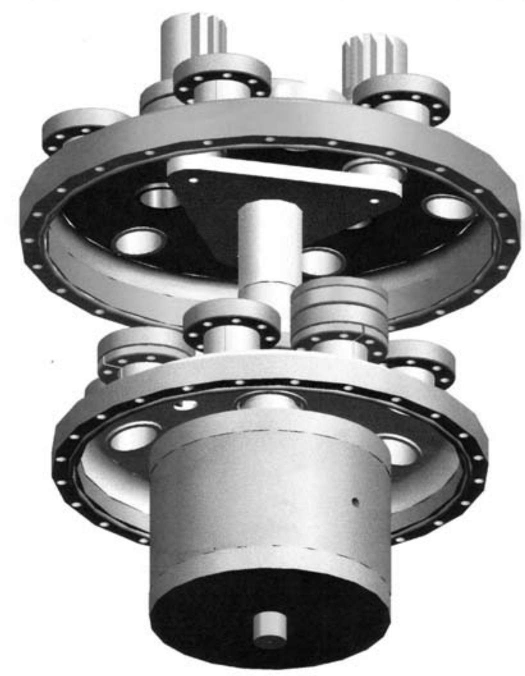

Fig 1. Open view of vacuum insert used to house the cavity (bottom) which was then inserted into the cryostat. The two stainless-steel cylinders (not shown) were attached to the flanges shown, one inside the other. Two microwave coaxial coupling lines are inserted horizontally into the cavity (see small hole) while two were inserted from the top.

2) *Vacuum cryostat:* The resonator was placed inside a small stainless steel vacuum cylinder, which was sealed with

Mylar gaskets. The air was pumped out and sealed off. The resonator was coupled to the loop oscillator (in the room temperature environment) with stainless steel coaxial lines. Fig. 1 shows a schematic of the cavity on the cryogenic insert. The flanges are shown but not the vacuum cylinders. The small vacuum cylinder was sealed inside a large stainless steel cylinder that was supported by the insert inside the dewar.

Each mode acts both as a high-Q filter/frequency determining element in the loop oscillator as well as a frequency discriminator in the Pound control servo. Therefore 4 coaxial lines enter the outer cylinder, but 6 enter the inner cylinder. The double vacuum provides thermal insulation to the sapphire loaded cavity.

By pumping continuously on the liquid nitrogen, transferred into the dewar, we were able to solidify the liquid and cool to 49.6 K, just a little below the turnover point.

The cavity is thermally connected to the bath via a copper post that joins a stainless steel post connected to a triangular plate (see Fig 1.) This plate is connected to the solid nitrogen bath by three cooling fins that protrude into the cryogen. The stainless steel post provides some thermal filtering of bath temperature fluctuations. These temperature fluctuations from the solid nitrogen were previously shown to be more than an order of magnitude smaller than from those the liquid [14].

A foil heater and platinum resistance thermometer (PRT) were attached to the copper post just above the cavity to control the set point of operation. The temperature controller used was a Neocera LTC-21, with nominal mK stability. No temperature sensors (or any microwave components) were placed inside the inner vacuum cylinder, to avoid contamination of the sapphire crystal. This meant the temperature was controlled at the copper posted above the cavity, outside the inner vacuum cylinder.

3) *Coupling:* The coupling to each mode was achieved via straight antenna probes. For the WGH mode they we placed in the top lid of the resonator and positioned on opposite sides on the cavity but at 90 degrees to the position of the probes for the WGE mode. The coupling on all ports was set at room temperature, which resulted in couplings for the WGH mode of 0.34 and 0.04, and for the WGE mode of 0.58 and 0.11 at the turnover temperature. Ideally, they should respectively, be 1 (for maximum discriminator conversion efficiency) and about 0.1 (so not to load the Q-factor too much but minimize insertion loss) for optimum operation [15]. (A circulator is used to reflect back the incident microwave signal, which then forms part of the control loop. See fig. 2). For each transmission line a triple series of isolators was used to reduce frequency pulling effects of the Teflon lining in the transmission lines resulting from the changing level of the solid nitrogen coolant. Therefore these components were all placed in the space above the inner vacuum cylinder but inside the outer cylinder.

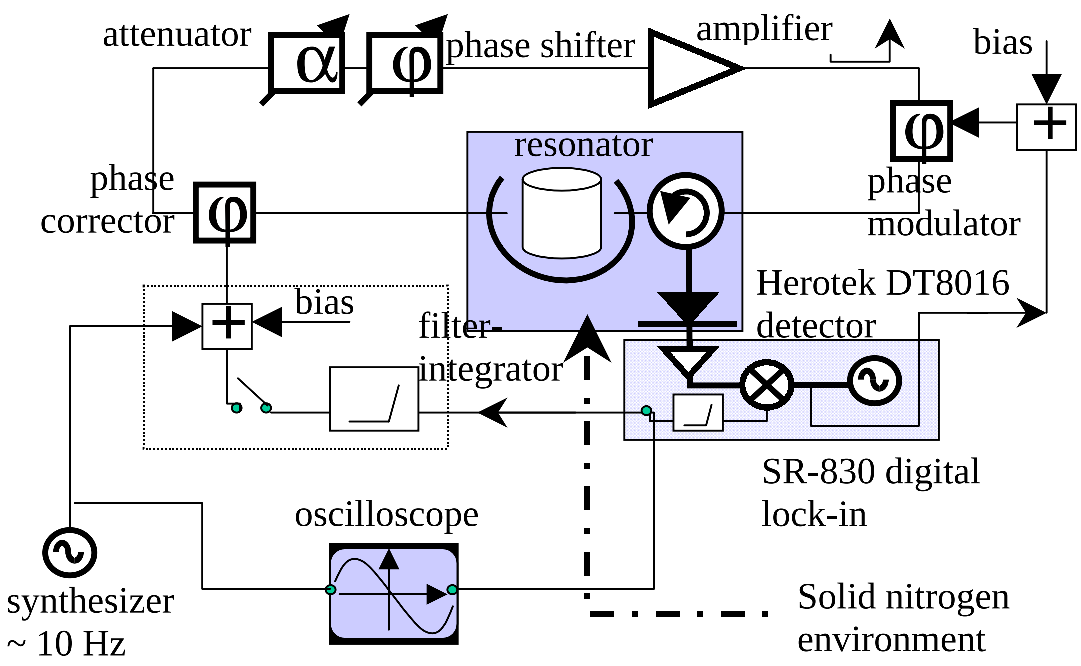

Fig. 2: Schematic of one of the two Pound-servo-locked loop oscillators based on a solid nitrogen cooled sapphire dual mode resonator. Initially the loop is interrogated open loop using the 10 Hz synthesizer. When the resonance error curve (on oscilloscope) is centered using the mechanical phase shifter, the loop is closed. This procedure is repeated on both oscillators and then the beat frequency is taken from a mixer as the output frequency. The phase modulator is driven by the internal source of the lock-in, and the error signal is recovered at the output of the lock-in and sent to the phase corrector. The isolators used in the loop are not shown.

4) *Loop Oscillator:* Fig. 2 shows only one of the loops used in the measurements. This was repeated for each of the two chosen operational modes with a relative frequency difference of 3.5188 GHz. Both loop oscillators were Pound lock with frequency servos taking their error signals from Stanford Research SR830 lock-ins, as shown. The phase modulators were operated at a few bias volts and close to a turning point in their insertion loss characteristic.

III Results

The first observation to make is that a significant amount of common-mode rejection was observed. In fig. 3 the two mode frequencies are shown as normalized frequency offsets as a function of time. Curve 1 is the fractional frequency of the WGE mode, curve 2 for the WGH mode and curve 3 is their beat frequency. The latter is offset from zero for clarity. Notice the common rejection of the frequency excursion seen in curves 1 and 2 but not shown in curve 3. This is one of the primary advantages of the technique. The fractional frequency drift, shown in curve 3, was about 10^{-10}/day.

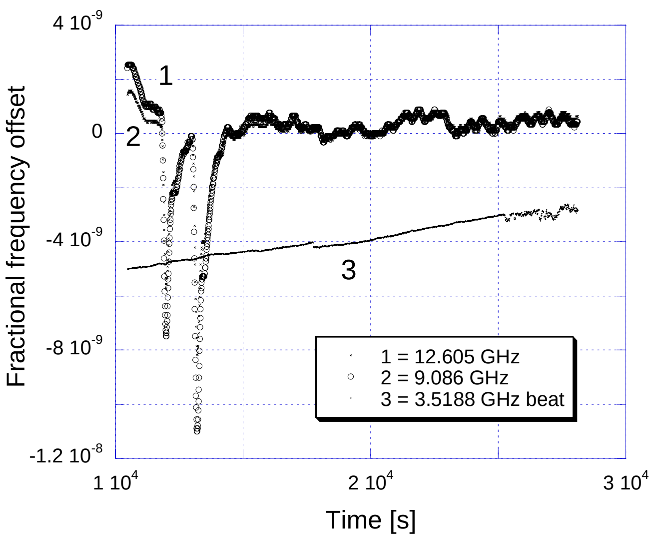

Fig 3. A sample of the frequencies recorded simultaneously over half a day while both oscillators were Pound locked and the temperature of the resonator controlled near the turnover temperature for the beat frequency.

Using an HP8673 synthesizer locked to a very stable (8600 Oscilloquartz OCXO) reference oscillator we were able to measure a 20 kHz difference frequency between the dual mode oscillator and the synthesizer. From this the Allan Deviation [16] was calculated. The noise floor of the measurement system was also calculated and subtracted. See broken line in fig. 4. From this, it is apparent at short integration times, the measured stability is only slightly above the noise floor. In this region it fits a power law of about $7 \times 10^{-13}/\tau^{½}$. At integration times longer than 20 seconds it appears to meet the noise floor. The quartz reference rises up according to the long dashed line.

IV. Discussion

A few points are worthy of note. To operate an LO for an atomic clock, a frequency stability of a few parts in 10^{14} is needed around 1 s. At best a few parts in 10^{13} was achieved near 20 seconds. The dashed line (in fig. 4) also indicates the scope for improvement of the system. Further investigation is needed to determine the source of the instability at short integration times.

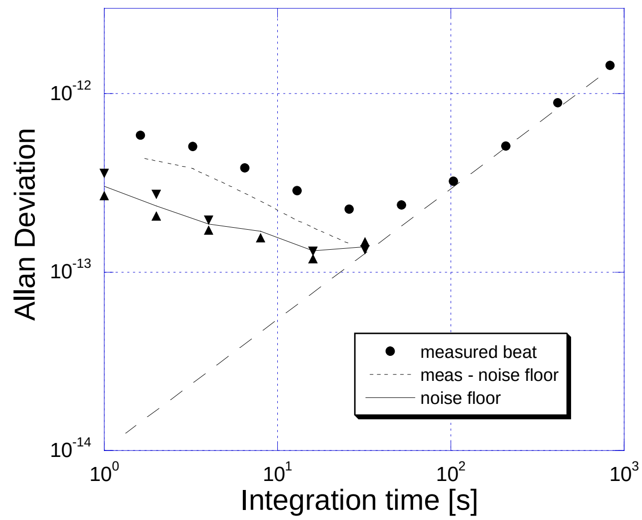

Fig 4. Allan Deviation of the dual mode beat frequency (solid circles) as a function of integration time. The beat frequency Allan Deviation is shown (broken line) after the noise floor due to the synthesizer-reference (solid triangles) was subtracted.

Also the best data were taken when the oscillator was allowed to sit at one temperature for a long period of time (a day). This indicates that there are significant thermal gradients that need to come into equilibrium.

From fig. 5 it is clear that near the turnover temperature the temperature dependence of either of the two WG modes is very linear in frequency. From curve 2, the frequency-temperature gradient near the turnover point is about 0.04 mK/Hz. This is more sensitive than the PRT used and measures the temperature directly in the crystal, not at the copper post.

It is proposed that, in order to more precisely determine the temperature of the resonator and hence get better servo control of the resonator temperature, we use one of these WG mode frequencies as a temperature sensor. Notice, also the deviation of the data points from the smooth curves in fig. 5. This results from noise in the PRT used.

Power stabilization will be introduced as an additional servo to control AM noise fluctuations in the loop oscillators.

V. Conclusion

A dual mode oscillator operating near the temperature turnover point of the beat frequency of two quasi-orthogonal modes in a high purity sapphire resonator near

50 K has been implemented and its stability measured. Further improvements planned include a novel temperature servo using one of the WG frequencies as a temperature sensor. Another is an additional servo to control power fluctuations in the loop. With these implemented it is expected that a fractional frequency stability of order 10^{14} is achievable at 50 K.

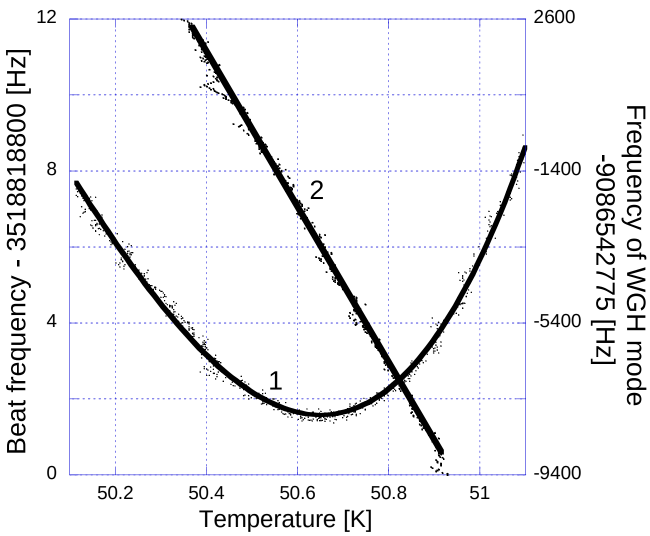

Fig 5. The beat frequency (curve 1 – left axis) of the dual mode oscillator as a function of temperature. The temperature was allowed to slowly drift across the turnover temperature while both oscillators were Pound locked. Also simultaneously sampled was the WGH (9.086 GHz) mode (curve 2 – right axis).

ACKNOWLEDGMENT

This work was supported by the Australian Research Council.

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