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

CRYOGENIC WHISPERING GALLERY SAPPHIRE OSCILLATOR USING 4 K PULSE-TUBE CRYOCOOLER

Ken-ichi Watabe[1], Yasuki Koga[1], Shin-ichi Ohshima[1], Takeshi Ikegami[1], and John G. Hartnett[2]

[1]National Metrology Institute of Japan / AIST, AIST Tsukuba Central 3, Tsukuba, Ibaraki 305-8563, Japan
[2]School of Physics, University of Western Australia, 35 Stirling Hwy, Crawley, WA, 6009, Australia

Abstract – A **cryogenic Whispering Gallery sapphire resonator oscillator has been investigated using a 4 K pulse-tube cryocooler. The turnover temperature of the chosen mode in the sapphire crystal was 9.169 K with an unloaded Q-factor of 7 × 10^8. The prototype SLC oscillator was designed to oscillate at 9.195 GHz and exhibited a fractional frequency stability of 2 × 10^{-13} at integration times of 10 s. We project a fractional frequency stability better than 1 part in 10^{-14} for integration times of 1 s to 100 s with a better temperature stabilized housing and with improved vibration isolation.**

Keywords - **Sapphire, whispering gallery mode, 4 K pulse-tube cryocooler, oscillator**

I. INTRODUCTION

Microwave oscillators based on cryogenic sapphire resonators operating below about 10 K has been implemented with the highest possible short-term stability of any frequency source [1], [2]. Due to the exceptional frequency stability the oscillators have been used as local oscillators (LO) for a Cs atomic fountain [3] and for a trapped mercury ion frequency standard [4]. The excellent performance of this system is primarily due to the high-Q factor of the sapphire resonator, which operates on a Whispering Gallery mode [5]. The sapphire resonators have been cooled below 10 K in a cryostat with liquid helium or with a cryocooler, which does not require liquid helium. Since atomic standards require practically a continuous operation of the LO, it is essential to use a cryocooler, which can be operated continuously for periods of a year or more.

Cryocoolers have been used to cool the sapphire resonators by a couple of authors [4], [6]. Pulse-tube cryocoolers are attractive tools due to their intrinsically higher durability and lower level of vibrations than other regenerative coolers, e.g., Gifford-McMahon or Stirling coolers. Since the pulse-tube cryocoolers have no moving piston, this reduces the mechanical complexity, increases durability, and reduces induced vibrations. Therefore we implemented a cryogenic sapphire oscillator with a 4 K two-stage pulse-tube cryocooler, which allows operation at temperatures down to 4.2 K.

At the National Metrology Institute of Japan / AIST, a Cs atomic fountain has recently become operational. For this standard, we plan to use the cryogenic sapphire oscillator as an LO. Our performance target is a stability below 10^{-14} (1 s $\leq \tau \leq$ 100 s) at 9.192 GHz, which is sufficient to operate an atomic clock at the quantum projection noise limit [3].

II. OSCILLATOR DESIGN

Fig. 1 shows the configuration of the cryogenic sapphire oscillator (CSO). The sapphire-loaded cavity (SLC) in the cryocooler is the primary frequency-determining element of the free-running loop oscillator. The circuit losses are compensated by the gain of the two microwave amplifiers (JCA Technology, JCA711-323 and JCA910-4153). A bandpass filter with a loaded Q-factor of 7 × 10^2 was used to select the required sapphire resonator mode. The loop electrical length was adjusted by a phase shifter to tune the oscillation frequency to the resonance of the SLC. Fig. 2 shows a diagram of the cryogenic system based on a 4 K two-stage pulse-tube cryocooler manufactured by Sumitomo Heavy Industries, Ltd. The cryocooler has a specified cooling power of 16 W at 50 K at the first stage and 0.45 W at 4.2 K at the second stage. The SLC is suspended by oxygen-free copper from the 4 K stage. A heater was placed on the copper cavity, and a temperature sensor was mounted on the side of the cavity. The sapphire cylinder placed in a copper cavity has a diameter of 45.3 mm and a height of 30.0 mm, with two 15.08 mm-diameter and 11.83 mm-long support spindles all machined from a single piece of sapphire. Coupling to the resonator was accomplished with a straight probe at the input cavity port and a magnetic field loop probe at the output port. A Whispering Gallery mode, $E_{11,1,\delta}$ (quasi-transverse magnetic polarization) of 9.195 GHz around 9 K was chosen due to its small frequency difference from the Cs transition frequency of 9.2 GHz.

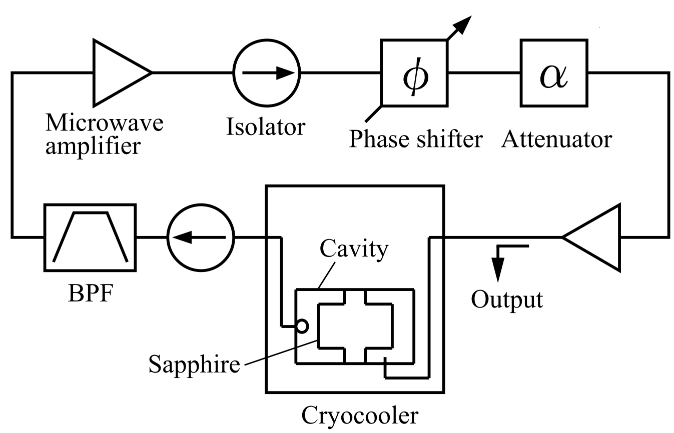

Fig. 1. Layout of the 9.195 GHz free-running loop oscillator incorporating a cryogenic SLC.

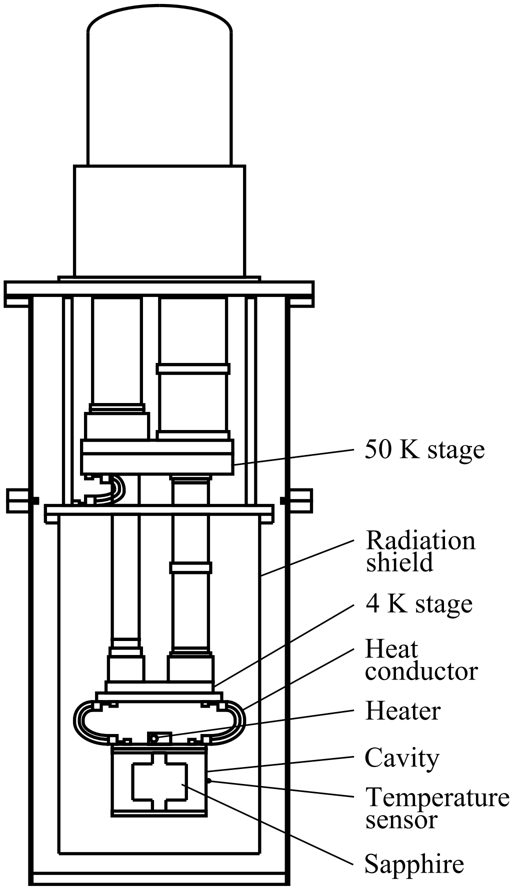

Fig. 2. Schematic of our cryogenic sapphire-loaded cavity and the cryogenic system based on 4 K two-stage pulse-tube cryocooler.

III. EXPERIMENTAL RESULTS

The temperature turnover and unloaded Q-factor for the SLC are shown in Fig. 3. An unloaded Q-factor as high as 1×10^9 at 9.195 GHz was measured at 5.4 K. The 4 K stage achieved a temperature of 3.76 K. Turnover temperature was 9.169 K with unloaded Q-factor of 7×10^8 and the couplings measured were $\beta_1 = 0.31$ and $\beta_2 = 0.45$. The frequency stability of the CSO was measured by a 15.29 MHz beat between the CSO and the reference signal from a hydrogen maser as shown in Fig. 4. The Allan standard deviation was calculated to be 2×10^{-12} at 1 s and 2×10^{-13} at 10 s as shown in Fig. 5. The oscillator exhibited a fractional frequency drift of about 10^{-10}/day during the course of the measurement. We attribute this to the insufficient temperature control of the sapphire resonator. It is most likely that the degradation of stability around $0.2 \text{ s} \leq \tau \leq 1 \text{ s}$ is due to vibrations of the cavity caused by expansion and contraction of helium gas at the cryocooler cycle frequency of 1 Hz. We project a frequency stability of 10^{-14} for this oscillator with an improved temperature stabilized housing and with the implementation of vibration isolation techniques.

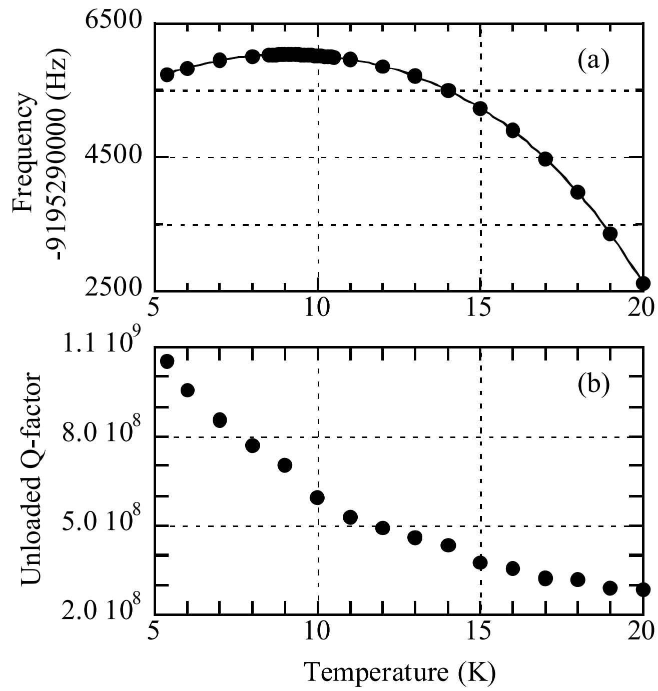

Fig. 3. Frequency (a) and unloaded Q-factor (b) as a function of temperature for the sapphire resonator for the $E_{11,1,\delta}$ mode. This resonator shows a turnover temperature of 9.169 K by using a curve fit.

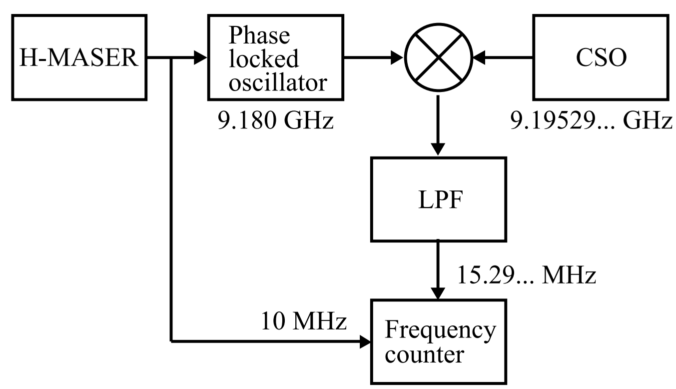

Fig. 4. Arrangement for measuring the frequency stability of the CSO by counting the IF signal.

IV. CONCLUSION

A cryogenic-sapphire microwave oscillator using a 4 K pulse-tube cryocooler was implemented. Unloaded Q-factors of 1×10^9 at 5.4 K and 7×10^8 at the turnover temperature of 9.169 K were measured for the $E_{11,1,\delta}$ mode in the SLC. Our first tests of the CSO exhibited an Allan standard deviation of 2×10^{-13} at 10 s integration time. We are currently working to reduce vibrations at the cavity induced by the cryocooler and to improve temperature control. A further two orders of magnitude improvement in performance should be possible.

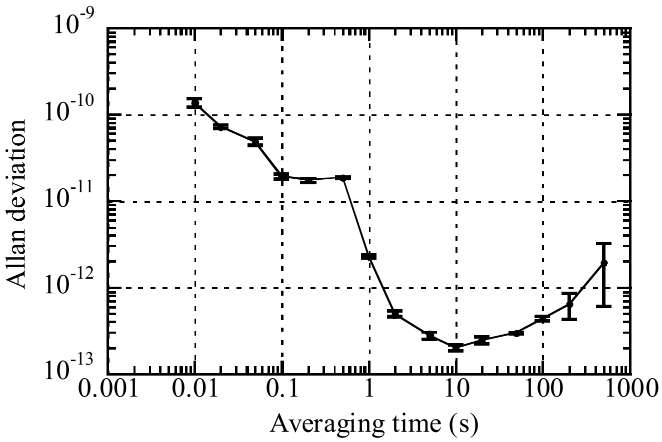

Fig. 5. Measured frequency stability for the CSO against a hydrogen maser.

REFERENCES

[1] S. Chang, A. G. Mann, and A. N. Luiten, "Cryogenic sapphire oscillator with improved frequency stability," *Proc. Int. Freq. Contr. Symp.*, 2000, pp.475-479.

[2] G. J. Dick and R. T. Wang, "Stability and phase noise tests of two cryo-cooled sapphire oscillators," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 47, pp. 1098-1101, 2000.

[3] G. Santarelli, P. H. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon, "Quantum projection noise in an atomic fountain: a high stability cesium frequency standard," *Phys. Rev. Lett.*, vol. 82, pp. 4619-4622, 1999.

[4] R. T. Wang and G. J. Dick, "Cryocooled sapphire oscillator with ultrahigh stability," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 528-531, 1999.

[5] A. N. Luiten, A. G. Mann, A. J. Giles, and D. G. Blair, "Ultra-stable sapphire resonator-oscillator," *IEEE Trans. Instrum. Meas.*, vol. 42, pp. 439-443, 1993.

[6] M. Winter, N. Klein, L. Hao, and J. C. Gallop, "Cryogenic composite whispering-gallery mode resonators for low-phase noise frequency standards," *Proc. Int. Freq. Contr. Symp.*, 2000, pp.500-505.