ULTRA-STABLE MEMS OSCILLATOR WITH 42 PPT FRACTIONAL FREQUENCY STABILITY AT 85 SECONDS

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ABSTRACT

We demonstrate an ultra-stable MEMS oscillator achieving unprecedented stability can be constructed using simple temperature control alone, without complex compensation methods. We demonstrate that macro-scale ovenization of a Lamé Mode Resonator along with a sustaining oscillator loop enables a new record frequency stability of 42 parts-per-trillion (ppt) up to 85 seconds while maintaining sub-ppb stability for up to 4800 seconds.

KEYWORDS

Ultra-stable MEMS clocks, MEMS oscillators, Lamé mode resonators.

INTRODUCTION

Recent advancements in wafer-level encapsulation technology have resulted in significant enhancement of the stability of MEMS resonators for timing and sensor applications. In particular, the Epi-Seal wafer-level encapsulation process [1,2] has been shown to provide an exceptionally stable physical environment for electrostatic MEMS with only environmental temperature and control voltages requiring any further stabilization.

In a broader view, the temperature dependency of Young's modulus is a critical variable that affects stability for frequency reference applications. Prior research has focused on addressing this through various temperature compensation strategies, both passive (e.g., material adjustments and orientation changes) and active (e.g., on-die Joule heating or external ovenization). Passive compensation techniques have included changes to resonator orientation with respect to the silicon crystal [3], doping variations in the silicon [4,5] and the use of composite materials to modify the net temperature coefficient of elasticity [6,7], all of which in turn can improve the temperature coefficient of frequency (TCf). Active compensation, on the other hand, has often employed ovenization techniques similar to those used for oven-controlled quartz oscillators (OCXOs) [8-10]. This technique has been adapted for encapsulated MEMS using built-in micro-ovens and heaters within the encapsulation and device layers [11-13]. Other resonators nearby can additionally serve as thermometers, potentially with f1-f2 locking [14,15], to enable temperature stabilization feedback control loops.

In this study, we leverage Epi-Seal to develop a hermetically sealed near-vacuum environment for a Lamé Mode Resonator (LMR) device operating as a frequency reference (Fig. 1). Since the device is sealed at approximately 1100°C, all contaminants are removed or gettered within the silicon, and sidewall roughness is smoothed through annealing [16,17]. Additionally, these bulk-mode resonators are fabricated without release etch-holes [18] which decreases the thermoelastic dissipation, thus maximizing its quality factor. To date no intrinsic aging effects have been observed in these resonators [19,20]. Notably, the LMR-based oscillator we show here integrates both passive and active temperature compensation. The passive approach uses near-degenerate doping to stabilize the Lamé mode's TCf, while active compensation includes a copper chuck with a wire heater for external temperature management via an feedback system. The large heat capacity helps mitigate temperature fluctuations, enhancing stability.

The choice of Lamé mode itself imparts additional stability benefits for a frequency reference. Its mechanical rigidity makes it less vulnerable to the spring-softening effect, thereby enhancing its stability against bias voltage fluctuations [21]. Moreover, the mode exhibits a unique, inherently isochoric strain pattern, which means its quality factor is not constrained by thermoelastic dissipation. Instead, it is primarily limited by the Akhieser effect [22]. This is advantageous for developing self-sustaining oscillators as the mode achieves very high quality factor.

In previous work [14], a LMR encapsulated using Epi-Seal reached a record of sub-parts-per-billion (ppb) fractional frequency stability using the dual-mode "f1-f2" temperature compensation technique [15] with a device level heater. Surprisingly, using the same LMR, we find in this study that significantly better MEMS frequency references are possible by simply ovenizing the device with an external heating chuck in air, but at the cost of increased volume and power consumption.

EXPERIMENTAL SETUP

Our experiments were performed using a 26.8 MHz silicon 2nd order LMR built within the Epi-Seal encapsulation [14] as shown in Figure 1a. The resonator has a square body (300 x 300 µm) and is produced on a 40 µm thick silicon device layer which is boron-doped with 1e20 cm^{-3} concentration. Four drive electrodes and four sense electrodes are operated differentially. The body is fixed at the center point of each edge onto a frame structure that is itself connected to a single-ended suspension. Figure 1b shows the vibrational mode shape.

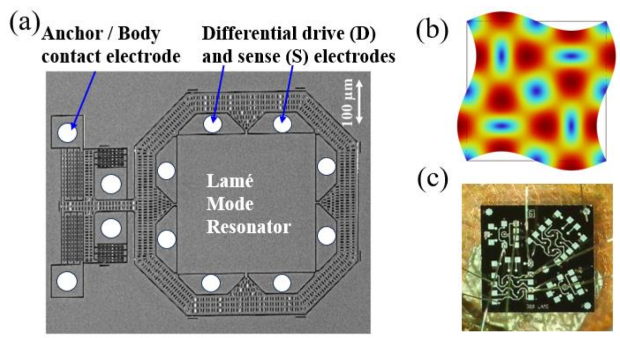

Figure 1. (a) Microscope view of the EpiSeal encapsulated electrostatic Lamé mode resonator (LMR) used in this study. Image from [14]. (b) Vibrational mode shape of the 2nd order Lamé mode at 26.8 MHz for the tested device. (c) Photo of the EpiSeal encapsulated and wirebonded LMR.

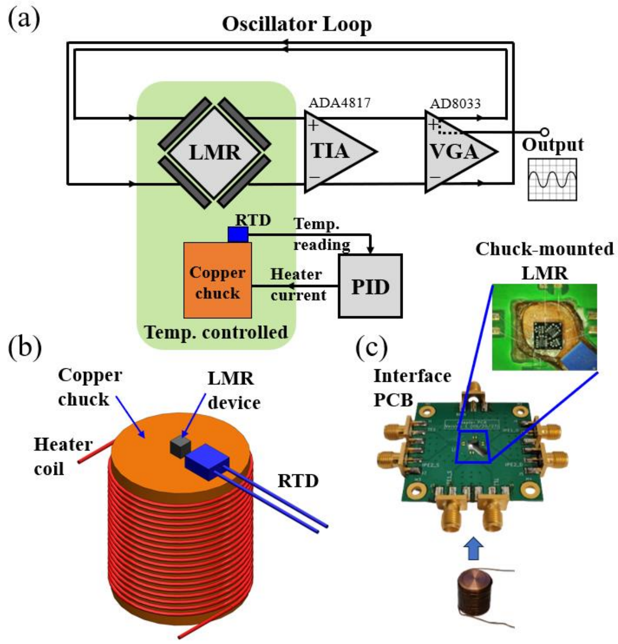

Figure 2. (a) Schematic of the self-sustaining oscillator loop using a differential trans-impedance amplifier (TIA) and variable gain amplifier (VGA) stages, with a PID-based temperature control system. (b) The LMR and RTD (PT-1000) are mounted together on a copper chuck with a nichrome wire coil for temperature control. (c) Photo of the mounted LMR device and the interface PCB assembly.

We constructed a self-sustaining differential oscillator loop around the LMR (Fig. 2a). The setup includes a custom trans-impedance amplifier (TIA, ADA4817) circuit and a variable gain amplifier (VGA, AD8033) chain. Power and control voltages for the TIA and the VGA are supplied by Agilent E3631a power supplies, while the resonator bias voltage is provided by a Stanford Research Systems DC205 voltage source.

The LMR device die is mounted on a copper thermal chuck (cylindrical shape with 10 mm diameter x 11 mm height). An RTD temperature sensor is also attached next to the die. Both the LMR and RTD are wire-bonded to an interface PCB, as shown in Figures 2b and 2c. A nichrome wire is wound around the chuck and heating current is regulated via a computer-based PID controller so that the temperature registered by the RTD is held constant. The entire setup was placed inside a sealed chamber to minimize the effects of air flow, enabling precise chuck temperature regulation.

A frequency counter (Tektronix FCA3020) measures the oscillator frequency in real time, receiving its input from a buffered output port of the VGA. A Stanford Research System FS740 GPS/GNSS system is used to generate a GPS-based timing reference for the counter. We simultaneously monitor the ambient air temperature near the device and the thermal chuck temperature throughout the experiments.

EXPERIMENTAL RESULTS

Initially, the temperature coefficient of frequency (TCf) of the device was characterized (Fig. 3) using an oscillator and a frequency counter. The TCf exhibited a quadratic curve, achieving a frequency stability lower than 8 ppm over the entire temperature range, thanks to passive compensation achieved through near-degenerate doping. To optimize temperature stability, the operating temperature was set at the turn-over point of the TCf curve, which was found at 71.902°C.

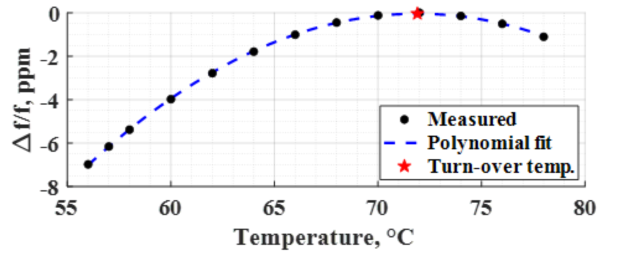

Figure 3. Measured temperature coefficient of frequency (TCf) obtained using the oscillator and frequency counter. The turn-over temperature is found at 71.902 °C.

Long-duration continuous measurements of the 26.8 MHz oscillator are presented in Figure 4. The oscillator shows a minimal frequency drift, approximately 1 ppb per hour, despite daily temperature fluctuations of up to 3 degrees Celsius around the resonator, and chuck temperature control maintained within about 2 millidegrees of the device's turnover temperature. We currently suspect that the drift may originate from two potential sources. Firstly, the gradual delamination of the attachment between the RTD and the copper chuck could contribute to the drift, as the RTD measures only its own temperature. Secondly, variations in the supply voltages provided to the self-sustaining oscillator circuit may also play a significant role in the observed frequency drift.

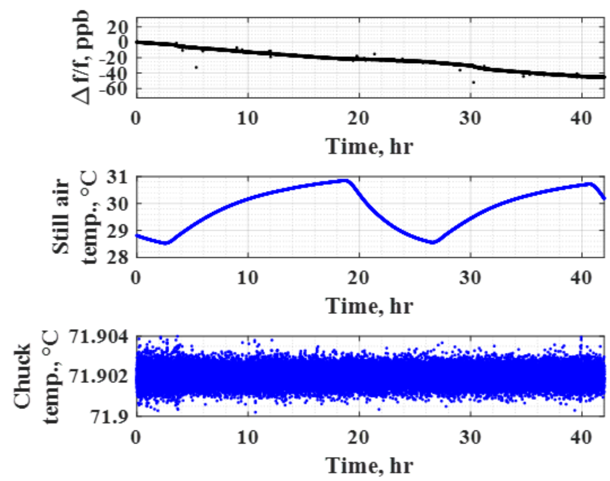

Figure 4. Long-duration observation of the 26.8 MHz oscillator fractional frequency drift, ambient temperature, and chuck temperature. ppb = parts-per-billion

In Figure 5, we present an Allan deviation analysis of the oscillator frequency data. For short time scales, we observe very low frequency instability, following the expected $\tau^{-1/2}$ trend due to white frequency noise in the oscillator. Frequency drift becomes noticeable after approximately 100 seconds, and best-case stability of 42 ppt (parts-per-trillion) is achieved at 85 seconds—representing a roughly 20-fold improvement over the previous record [14]. The oscillator's frequency stability remains better than 1 ppb for up to 4800 seconds, underscoring its suitability as a short-term timing reference and for holdover applications.

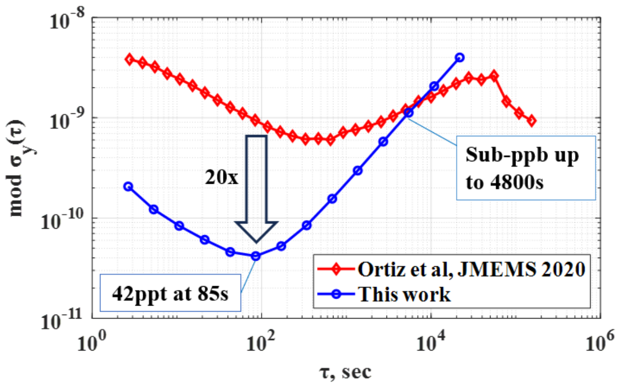

Figure 5. Measured modified Allan deviation (MDEV) for the oscillator, with comparison to the previous record from [14].

CONCLUSION

This study demonstrates that ultra-stable MEMS oscillators can be constructed using simple macro-scale temperature controls, in the style of an OCXO, without the need for more complex compensation methods. However, we do observe some amount of frequency drift since the RTD-based thermometry approach does not accurately track the device temperature. For next steps, we believe that further improvements in stability may be achievable by implementing the dual-mode "f1-f2" tracking, e.g. by simultaneous monitoring and locking to a second mode of the LMR as was previously used in [14], or by incorporating an additional on-die resonator as a temperature sensor. Further improvements may be possible by invoking the in-device heater for rapid temperature feedback. Even without these additional innovations, the experimental results presented in this work set a new record and benchmark of MEMS oscillator stability by significantly improving on past results. Further improvements in frequency stability will be important for holdover applications in GPS-denied environments.

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