A NEW LOW POWER MEMS DUAL MODE CLOCK WITH PPB STABILITY OVER TEMPERATURE

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ABSTRACT

In this paper, we demonstrate a novel dual-mode clock with an in-chip device layer micro-oven which operates at 10X reduced power consumption and provides more than 30X improved stability when compared to a recent result with a micro-oven embedded in the cap [2]. The decrease in the thermal time constant and in the micro-oven power dissipation improves compensation for ambient temperature variations and allows for significant improvements in the stability. This device layer micro-oven enables correction for ambient temperature fluctuations and achieves long-term stability over temperature in ppb, which is better than the stability of TCXOs and competes with state-of-the-art OCXOs, while requiring much less power.

BACKGROUND AND DEVICE DESIGN

A combination of passive and active temperature compensation methods can significantly improve the stability of encapsulated MEMS clocks [1-4]. Active compensation has been achieved previously with the use of a micro-oven embedded in the encapsulation lid of the die; while this method is successful in compensating for temperature changes (+/- 0.9ppb/^{o}C), it requires substantial power (approximately 3mW/^{o}C) [2]. The dissipated heat can affect the stability and performance of the device due to temperature gradients and thermal stresses. Previous work has shown that a micro-oven isolated within the device layer of the die can significantly reduce thermal stresses and the power required to ovenize [4, 9].

Here, we extend these efforts by combining the low-power of the device-layer planar suspension with the high-Q and high-linearity of a temperature-compensated Lamé-mode resonator. As shown in Figure 1A, micro-oven structures provide support and thermal isolation for a frame that contacts the dual-mode MEMS resonator at nodes of both vibrational modes.

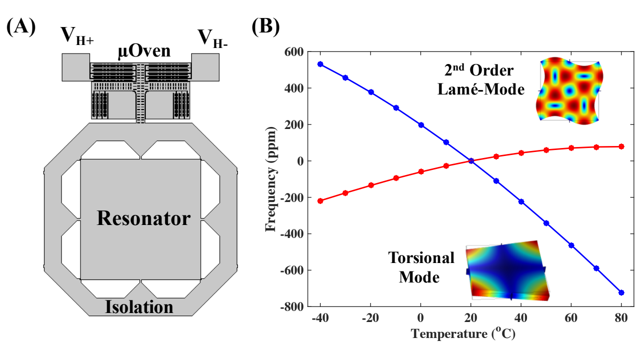

Figure 1: Schematic of dual mode clock: (A) dual Lamé-mode clock, (B) temperature dependence of frequency for each mode using closed loop frequency sweeps.

The devices are fabricated on p-type SOI wafer with a 40µm device layer using commercially-available, high-volume epitaxial thick film encapsulation processes. The temperature dependence of frequency for both modes was determined within a range of -40^{o}C to 80^{o}C, as shown in Figure 1B. Each mode was excited with a Zurich Instruments digital lock-in amplifier and transimpedance amplifiers to amplify the resonators' signal as shown in Figure 2.

Table 1: Summarized clock properties and measurements.

Properties		***Lamé-Mode Clock***
Doping		P-type: 1e20cm^{-3}
Geometry		400µm x 400µm
Mode 1	f_1	20.16MHz
	Q_1	950k
Mode 2	f_2	1.19MHz
	Q_2	770k
µOven Power		0.18mW/^{o}C
Temperature Stability		**< +/- 1.5ppb**

By simultaneously exciting a pair of modes in the same structure, we can continuously determine temperature and provide a frequency reference using a control scheme that is common for quartz OCXOs [5]. The frequency for both modes was tracked with phase lock loops and the frequency difference was regulated by application of voltage across the micro-oven terminals using proportional and integral control.

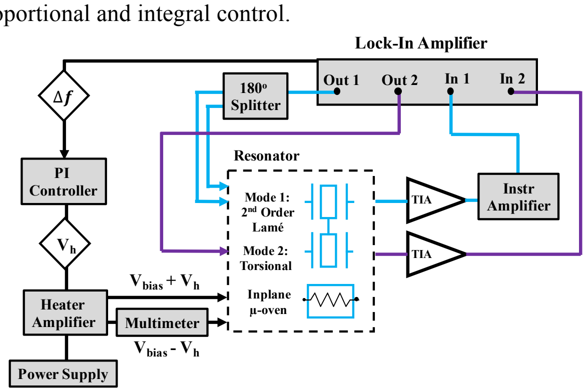

Figure 2: Schematic of experimental set up: a phase locked loop was used to simultaneously track the frequencies of two modes in one resonator. A PI controller was used to control the micro-oven voltage and maintain a constant turnover temperature of 80^{o}C.

RESULTS

This dual-Lamé-mode clock was operated at steady state at -40^{o}C over 12 hours, where 22mW of micro-oven power is required to bring the resonating element to its turnover temperature of 80^{o}C. The Allan Deviation corresponding to this data indicates a minimum of <0.2ppb at 1000s.

A stability of +/-1.4ppb was achieved while ramping temperature from -40^{o}C to 60^{o}C over 10 hours, as shown in Fig. 4. These results exceed the best performance of all previously-published MEMS-based time references. Notably, this is the first MEMS device to demonstrate single-digit ppb stability over time and temperature. Figure 6 shows this new result in the context of prior products and academic demonstrations of MEMS-based and macroscopic time references.

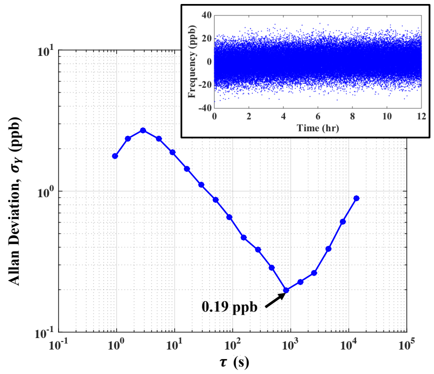

Figure 3: Allan deviation for 2nd order Lamé-mode at an ambient temperature of -40°C with +/-0.3°C temperature fluctuations.

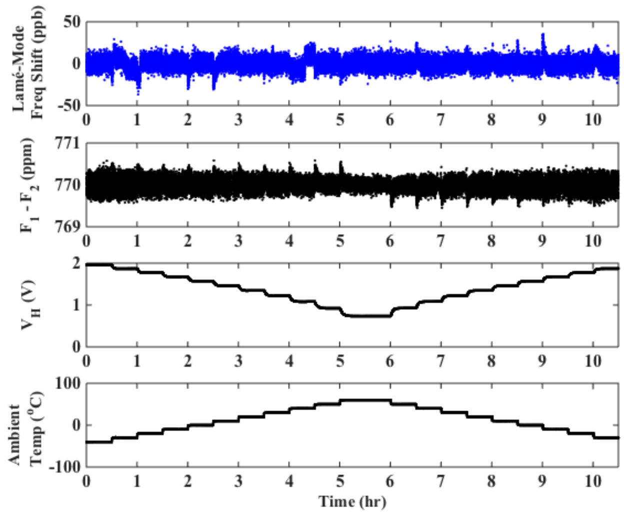

Figure 4: Frequency stability of 2nd order Lamé-mode with changes in ambient temperature. Heater voltage is applied through the micro-oven to maintain the frequency at the turnover temperature.

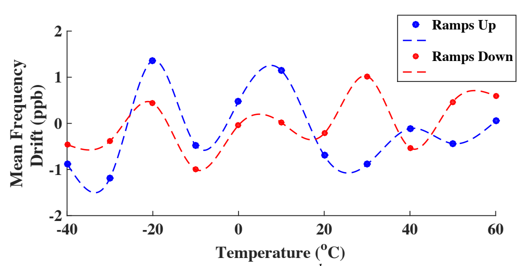

Figure 5: Mean frequency error of 2nd order Lamé-mode at steady state with changes in ambient temperature.

CONCLUSION

In this paper, we demonstrate more than 30X improvement in the stability of a dual Lamé-mode clock and 10X reduction in the power consumption. We show that stiff Lamé-mode bulk resonators are ideal candidates for ultra-precise ovenized clocks since they are less susceptible to thermal expansion nonlinearities. Our results for temperature and long-term stability are the best of any previously-published or commercially produced MEMS-based clock, while also operating with heater power far below any conventional quartz OCXO.

These devices have the potential to revolutionize applications that require ultra-stable references and low power.

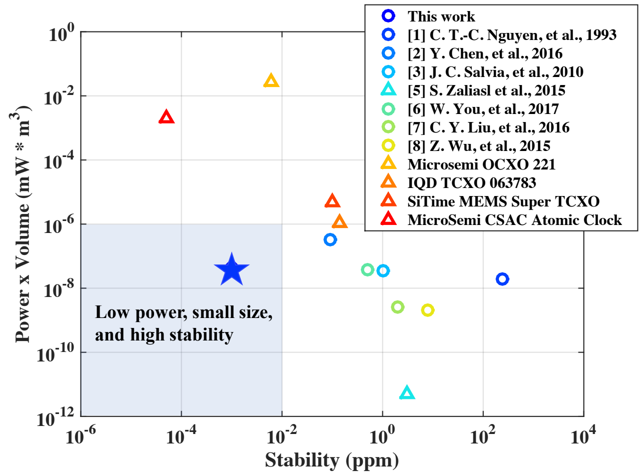

Figure 6: Comparison of clock stability over temperature (-40°C to 80°C) for range of devices shows that the dual Lamé-mode clock (starred) has better stability and power consumption than leading TCXOs and OXCOs used in industrial applications.

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