Low-Power Ovenization of Fused Silica Resonators for Temperature-Stable Oscillators

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***Abstract*—In this paper, we report on temperature-stable operation of silica MEMS oscillators on an ovenized fused silica platform. Temperature servo-control circuits are implemented using an on-chip RTD-based temperature sensor and a resistive heater. A wide-range linear analog controller has been implemented to reduce the effective TCF of the fused silica resonator by an order of magnitude. Digital calibration method is used to mitigate offset errors caused by non-ideal temperature sensing. By effectively removing the offset errors, the frequency drift of an oscillator using a silica micromechanical resonator is reduced to less than 11 ppm over 105 °C of external temperature change. The power consumption to ovenize the entire platform consisting of four resonators is lower than 15.8 mW.**

Keywords—MEMS, micromechanical, resonator, oscillator, temperature compensation, ovenized MEMS, thermal isolation.

I. Introduction

Quartz crystal oscillators are most commonly used as timing units in consumer electronics. In recent years, the performance of more compact integrated oscillators based on silicon resonators have exceeded that offered by their quartz-based counter parts [1]. Compared to silicon, fused silica has the advantage of having smaller thermal and electrical conductivity, allowing for implementation of sensors and timing elements in a single-material fused silica package. However, unlike quartz, fused silica has a high temperature coefficient of elasticity (TCE); thereby, fused silica resonant structures require temperature compensation techniques for stable operation. In this work, we take advantage of the low thermal conductivity of fused silica to ovenize a large silica device layer consisting of multiple micro-devices at low power levels. We further analyze the thermal design of the system and present circuits for realizing closed-loop temperature control. The ovenized fused silica platform significantly improves temperature stability of resonators as well as oscillators built using the MEMS resonators.

II. Ovenized Fused Silica Platform

Fused silica MEMS resonators exhibit a high temperature coefficient of frequency (TCF) of ~ +89 ppm/K [2], owing to the high TCE of silica. While passive material compensation can be employed to reduce the TCF of MEMS resonators [3], the high TCE of fused silica makes material-based passive compensation challenging. Seeking active temperature compensation methods as a solution, ovenization is employed in this work to reduce the temperature-induced frequency instability of the silica resonators. While ovenized MEMS resonators have been demonstrated before with power consumption as low as tens of milli-Watts [4], most reported approaches were specific to a single resonator and not directly applicable to a multi-device system such as a sensor fusion platform.

In this work, we demonstrate an ovenized fused silica layer (platform) that can stabilize multiple MEMS devices over a wide external temperature range. The platform active area is 3.5 mm × 3.5 mm and includes four MEMS resonators. A scanning electron microscope (SEM) image of the fabricated fused silica platform is shown in Fig. 1. A resistive temperature detector (RTD) is co-fabricated on the silica device-layer using a 1000 Å-thick platinum (Pt) layer. A Pt resistive heater ring is placed on the edge of the active area and is used to heat the platform to a fixed oven set temperature to counter external temperature changes. During temperature measurements, the fused silica die is mounted in a package (Fig. 2) and placed in a vacuum chamber with pressure of less than 10 mTorr. The chamber temperature can be set to any value between 7 K and 400 K with +/-0.1 K accuracy.

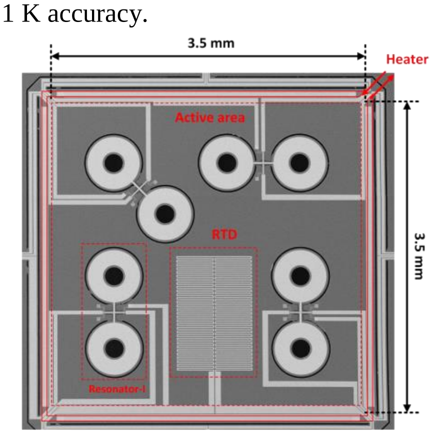

Fig. 1. A SEM image of a fused silica platform with multiple devices in the active area, an integrated RTD, a heater, and thermal isolation legs.

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In order to reduce the power consumption of ovenization, it is critical to thermally isolate the active area from the external environment. To thermally isolate the active area, thermal isolation legs are used. The low thermal conductivity of fused silica allows for having relatively wide isolation legs (100 μm). Such a design improves the platform mechanical robustness by avoiding long and meandered supporting legs usually seen in silicon MEMS [4]. Also, the wide legs allow for wiring of multiple low-resistance electrical routings to external pads using a thin-film metal layer, which favors integration of multiple devices on the platform. Using COMSOL FEM simulation, the thermal resistance of the isolation structure is extracted to be 28 K/W if heat conduction through solid structures dominates heat transfer (Fig. 2). Heat losses from convection and radiation are further included in the FEM simulation. To take into account the typical vacuum condition in a hermetic MEMS package, a heat transfer coefficient (*h*) of 0.05 W/m^2•K is assumed for modeling the convection heat loss, which amounts to mTorr pressure level typically seen in a MEMS package. The radiation effect is simulated as surface-to-ambient radiation with surface emissivity of 0.9, accounting for the material property of fused silica. With an ambient temperature of 233 K (-40 °C), the temperature increase at the center of the silica active area relative to ambient is simulated as a function of the heating power, and results are also plotted in Fig. 2 for comparison. It can be seen that the effective thermal resistance is reduced by more than four times compared to the results that only consider conduction heat transfer.

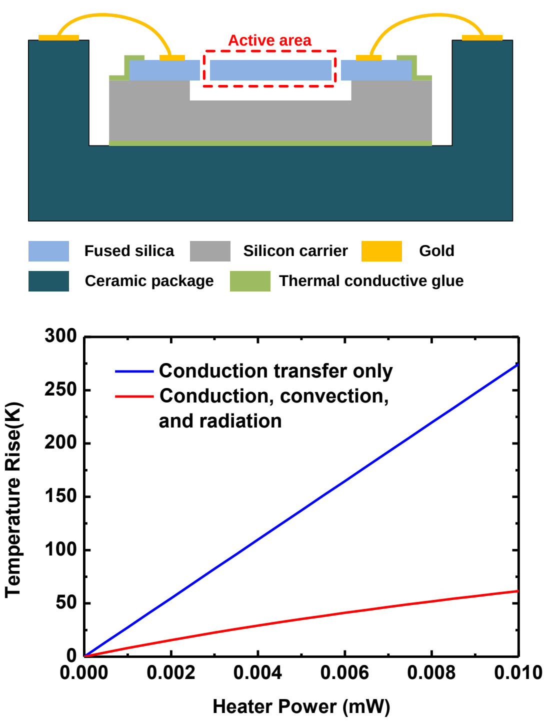

Fig. 2. (Top) Cross-sectional view showing the fused silica die mounted in a ceramic package for temperature stability measurement. (Bottom) Temperature increase of the fused silica device-layer (platform) versus heater power from COMSOL FEM simulation.

Another adverse effect is the temperature non-uniformity across the platform and between different devices on the platform. A realistic study should consider the working condition of a MEMS resonator. When a MEMS resonator is operated in a reference oscillator or a resonant sensor circuit, it is beneficial to apply high drive power to the resonator to improve the phase noise [5]. Fig. 3 plots the simulated temperature distribution when a heater power of 4.3 mW is applied to the Pt heater to heat up the platform when ambient temperature is 233 K. As shown in Fig. 3, one of the fused silica resonators on the platform is operated in an oscillator and is sustaining a driving power of 400 μW. The body of the vibrating resonator is heated up when connected in an oscillator circuit, and a higher temperature on the resonator is observed. The vibrating resonator has a high power density of 16×10^6 W/m^2. Such self-heating effect is more pronounced in miniature MEMS resonators than in conventional devices with macroscopic scales. On the other hand, the other resonators that are left static show lower temperature than the outer boundary (Fig. 3). As high-*Q* MEMS resonators typically use long and narrow supporting tethers to reduce anchor loss [2]; the large thermal resistance of these tethers makes it harder to balance the temperature between the resonator body and the rest of the platform. Considering these practical situations, the resonators on the platform experience large temperature offsets compared to the region where the RTD is placed, and it is very challenging for the RTD to accurately sense the real temperature of all devices.

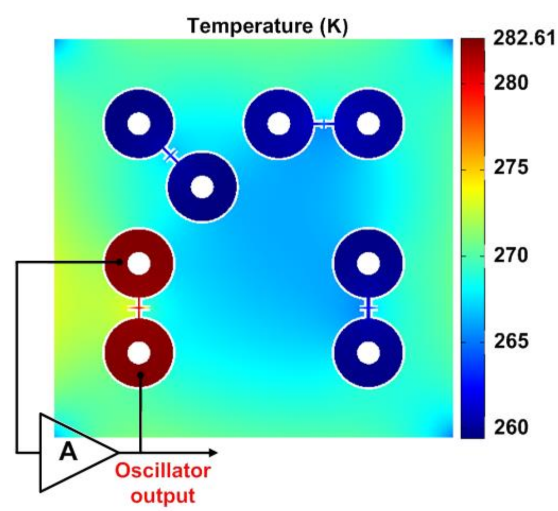

Fig. 3. Temperature distribution map of the active area with a heater power of 4.3 mW and a resonator driving power of 400 μW (in an oscillator loop) at an external temperature of 233 K.

III. TEMPERATURE CONTROLLER DESIGN

A. Analog Control with High Thermal Gain

For active temperature compensation, a servo-control system is implemented to monitor the RTD response and generate a feedback power control signal. The performance of the conventional analog servo-control system is studied. As shown in the circuit schematic in Fig. 4, the RTD is connected in a Wheatstone bridge configuration along with three other low-TCR and precision resistors. The RTD and other resistors have a nominal resistance of 7 kΩ. The Wheatstone bridge is biased with a stable voltage reference (V_B) of 1.2 V and interfaced to an instrumentation amplifier (IA) for pre-amplification. The IA (AD8553) provides a very low input offset voltage of 20 μV and a high voltage gain of 10,000. Having an RTD with measured temperature coefficient of resistance (TCR) of 0.26%, the low IA input offset voltage translates to a temperature sensing error of 13 mK. The signal generated from the IA is filtered to increase the signal to noise ratio. The heater driver is implemented using an analog square-root generator based on BJT translinear circuits [6], as shown in Fig. 5. The square-root generator linearizes the transfer function from the input control voltage to the output heater power. Fig. 6 plots the normalized power gain versus input voltage of the square-root generator extracted from measurement. Compared to an earlier work that employed a linear amplifier to generate a heater current proportional to the sensor signal [4], the heater driver design in this work performs linearization and ensures a near constant thermal loop gain across a wide input range. Therefore, sufficient power gain can be ensured even at low heater power levels. Using the square-root driver, the oven temperature can be set close to the maximum device working temperature without degrading the control performance, thus minimizing the power consumption of ovenization [7].

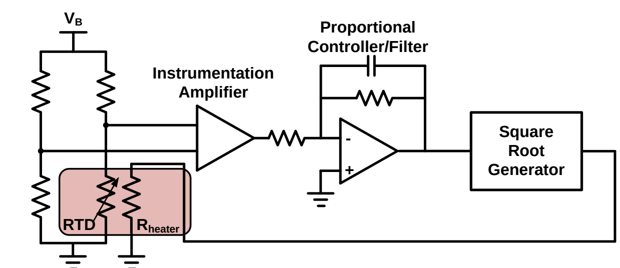

Fig. 4. Circuit schematic of the resistive temperature detector (RTD) interface and analog oven-control system.

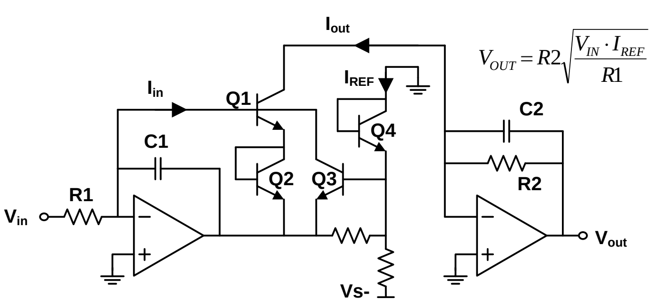

Fig. 5. Circuit schematic of the square-root generator as the heater driver.

The temperature stability of a resonator on the platform (Resonator I in Fig. 1) is measured over external temperature changes. While the analog temperature controller is used to provide a servo-control, the frequency drift of the resonator is monitored using a network analyzer, and the results are plotted over a chamber temperature of -40 °C to +75 °C in Fig. 7. Using oven-control with a thermal loop gain of ~1900, the effective TCF of the fused silica resonator has been reduced to +10 ppm/K, as compared to +89 ppm/K for an uncompensated silica resonator. Although the active compensation has reduced the uncompensated TCF of a fused silica resonator by almost an order of magnitude, a significantly smaller drift is expected due to a large thermal loop gain of the servo-control system. Yet, there is an overall frequencies drift of 1163 ppm over -40 °C to +75 °C. This is mainly due to the temperature gradient within the active area as analyzed in the previous section. Since the temperature sensor (RTD) is not sensing the true resonator temperature, further increase in the thermal loop gain is ineffective in improving the temperature control accuracy (compare the results with loop gain of ~5,000 against loop gain of 1,900 in Fig 7).

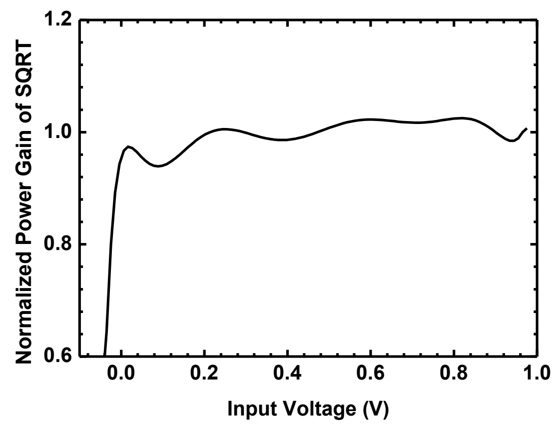

Fig. 6. Normalized power gain vs. input voltage of the square-root generator.

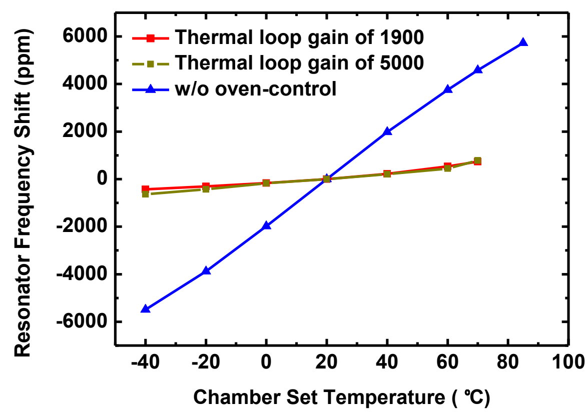

Fig. 7. Measured effective TCF of ovenized silica resonator compared to that of an uncompensated fused silica resonator . As shown, increasing the thermal loop gain does not improve the effective TCF due to the offset between the actual temperature of the resonator and the temperature sensed by the RTD.

B. MEMS Oscillator Implementation

A MEMS oscillator is implemented using Resonator I on the platform. Following the design presented in [5], a self-biased CMOS inverter amplifier is interfaced to the resonator at the board level (Fig. 8). A supply voltage of 1.2 V is used for the oscillator circuit, which determines the voltage that drives the MEMS resonator. Due to a low motional resistance of ~400 Ω [2], the resonator sustains a high driving power of above 400 μW at 1.2 V of supply voltage, which helps reduce the phase noise. The measured output signal of the oscillator is also shown in Fig. 8.

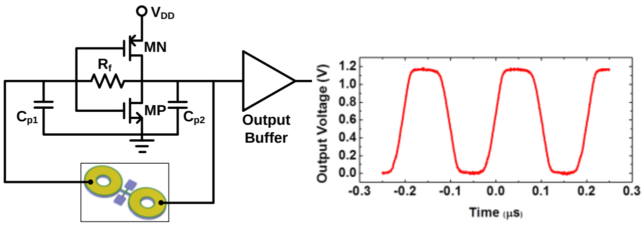

Fig. 8. Schematic of the MEMS Pierce oscillator; the measured output waveform of the fused silica MEMS oscillator is also shown.

C. Stability Improvement with Digital Calibration

The RTD-based temperature compensation method mainly suffers from offset errors due to a non-uniform temperature distribution in the active area. The offset error can be compensated using digital calibration in the temperature controller design; as plotted in Fig. 9, after the RTD response is pre-amplified and filtered, the output voltage is digitized for further processing. A digital calibration table is used to store the offset errors across the RTD output range. After the data is converted back to the analog domain to generate a heater control signal, the offset errors are effectively removed in the servo-control system. The square root function from control voltage to heater driver voltage can also be performed in a digital calibration look-up table to simplify the analog implementation.

To study the properties of the digital calibration method, the temperature control system is operated by setting the control bits (instead of using closed-loop operation) to control the heater power for stable oscillator output. Meanwhile, the output frequency of the MEMS oscillator is monitored using a frequency counter. The output voltage from the RTD is also monitored using a digital multimeter (Fig. 9). From the sensor output voltage measurement, the resistance change of the RTD is back calculated. The oven set temperature for the silica device layer is near 70 °C.

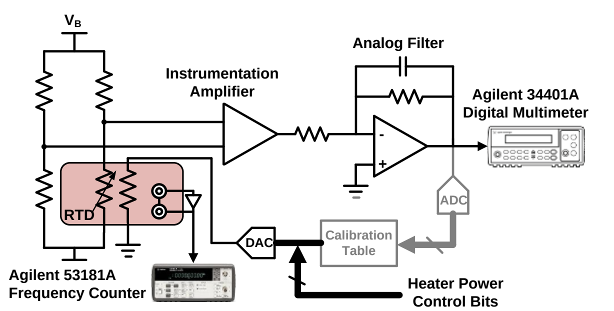

Fig. 9. Circuit schematic of the RTD interface and oven-control system with digital calibration to reduce sensor offset.

During measurements, the heater power is controlled digitally to stabilize the output frequency of the MEMS oscillator. The frequency drift of the oscillator is plotted in Fig. 10 over the chamber set temperature of -40 °C to +65 °C. The overall frequency drift of the oscillator has been reduced to 11 ppm. The output voltage from the RTD front-end is also recorded, and the extracted RTD resistance change is plotted in Fig. 10. It can be seen that the RTD resistance increases at lower chamber set temperature. This indicates the RTD is experiencing a temperature increase at lower external temperature, if the system tries to stabilize the oscillator frequency. Therefore, an upper shift of the heater control voltage needs to be performed in the digital calibration table for stabilizing the oscillator frequency, as plotted in Fig. 11. The difference in the heater control voltage shown in Fig. 11 is what needs to be calibrated and stored in the look-up table during the initial calibration process. The power consumption of the heater is plotted in Fig. 12.

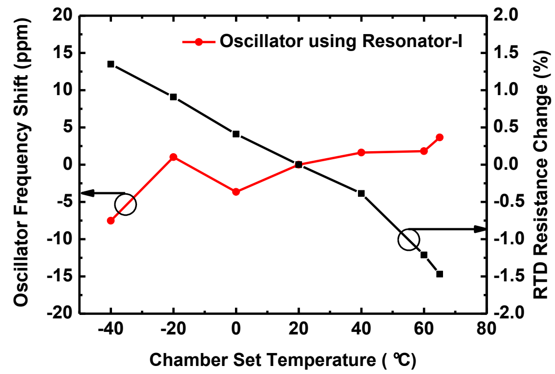

Fig. 10. Frequency drift of the MEMS oscillator using Resonator I on the platform with controlled heater power to maintain a stable oscillator frequency (RTD resistance change is plotted).

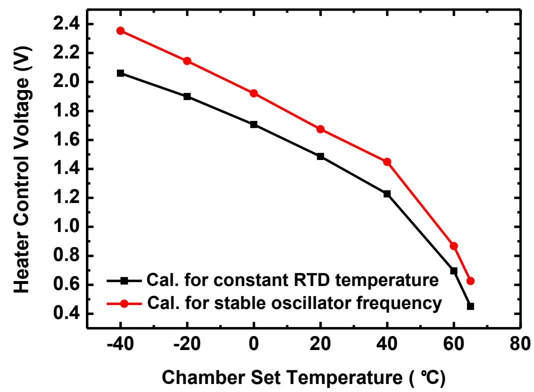

Fig. 11. Heater control voltage calibrated for constant RTD temperature and stable oscillator frequency over chamber temperature range.

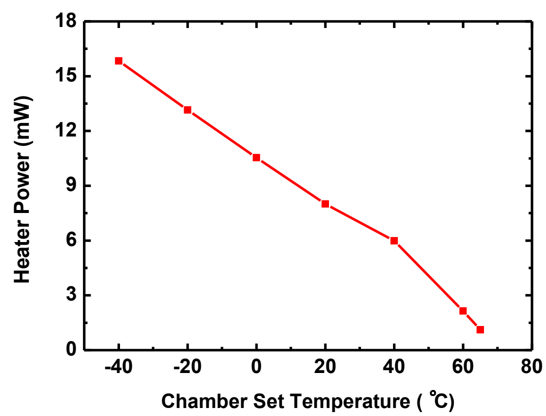

Fig. 12. Extracted power consumption of the heater vs. chamber set temperature to stablize the MEMS oscillator.

IV. CONCLUSION

In this work, a fused silica platform is implemented for integrating multiple resonators on a single-die. Thermal properties of the device platform are analyzed, showing a low-power consumption for ovenization. Temperature sensing and closed-loop servo-control is demonstrated as an effective active compensation method. Non-ideal properties of RTD-based temperature sensing are also studied, and digital calibration method is introduced to drastically reduce offset errors in the servo-control. An ovenized oscillator is demonstrated showing an overall frequency drift of 11 ppm across -40 °C to +65 °C. Benefited from low thermal conductivity of fused silica material, the power consumption of the ovenized device is less 15.8 mW across a wide external temperature range.

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