Electrostatic Stabilization of Thermal Variation in Quality Factor using Anchor Loss Modulation

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***Abstract*—We report an ultra-low energy dissipation silicon MEMS tuning fork resonator with a Q-factor of over 2 million at 570 Hz, with the ability of Q-factor stabilization throughout a temperature range of over 100 °C. This stabilization approach relies on the controlling of energy dissipation through regulating the stiffness misbalance of the tuning fork resonator. Without Q-factor regulation, the resonator demonstrates a Q-factor with a 25% drift from 2.14 million to 2.67 million, over a temperature range from □40 °C to +60 °C. With implementation of the proposed stabilization method, the experimental characterization reveals a stable Q-factor of 2.14 million within 0.3% (+1σ) variation for an identical temperature range (□40 °C to +60 °C).**

Keywords—Quality factor; electrostatic tuning; thermal variation; temperature self-sensing; tuning fork.

I. INTRODUCTION

The parameter drifts due to changes of temperature are important design considerations in the development of high performance devices. Typically, either a temperature-stable environment or a thermal-compensation scheme must be created. While most studies of thermal compensation address the stability of resonance frequency over temperature by reducing the Temperature Coefficient of Frequency (TCF), designing temperature-insensitive structure, or implementing a compensation algorithm [1], herein, we focus on the stabilization of Q-factor, a fundamental parameter of resonance devices. For ultra-high Q-factor resonators, Q-factor strongly depends on temperature [2]. The thermal drift of Q-factor can induce performance deterioration. For example, frequency stability of a resonant device, and in the case of Coriolis Vibratory Gyroscopes (CVG), Scale Factor (SF) [3] and Bias drift, are proportional to Q-factor. Thus, a stable high Q-factor and high time constant (τ) are desirable.

In our previous study, we explored an idea of using the device itself as a thermometer, namely, temperature self-sensing [4]. In the effort of stabilizing resonance frequency, Q-factor of the same device was proposed to serve as an indication of temperature shift (with a resolution limited by Q-factor) [5]. In other situations, as in our study, the resonance frequency shift of the device itself can be used as an excellent thermometer.

Herein, we demonstrated a method of stabilization of the Q-factor over a wide temperature range using electrostatic tuning, with the simultaneous temperature monitoring by integrating in the algorithm the concept of temperature self-sensing, Fig. 1 This method has been experimentally validated using a specially designed tuning fork MEMS resonator, after applying the algorithm, demonstrating a Q-factor stability of 0.3% at 2.14 million over a 100 °C temperature change, compared with a 25% drift (from 2.14 million to 2.67 million) before applying the algorithm.

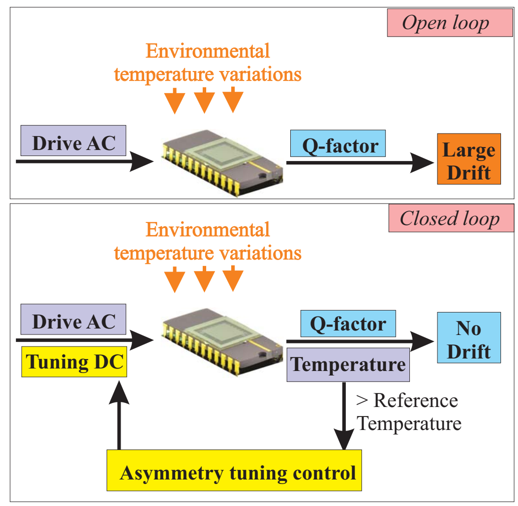

Fig. 1 Functional diagram of the proposed compensation method.

II. RESONATOR DESIGN

A tuning fork silicon MEMS resonator is employed to demonstrate the proposed concept. As shown in Fig. 2, the resonator consists of differential excitation port, differential detection port, and two sets of parallel plate ports for electrostatic tuning. The left and right parts of the device are designed to be symmetric and driven in opposite directions (anti-phase motion). This coupling, according to the finite element modeling, will greatly mitigate the anchor loss, as the dynamic reaction forces resulting from the anti-phase motion will cancel each other, leading to the minimization of the net reaction force and reaction moments across the structure, and thus a reduction in the energy loss through anchors. The resonator is fabricated using 100 μm SOI wafer, and then hermetically sealed to maintain a sub-mTorr vacuum level over a long period of time [6], and hence minimize the air damping.

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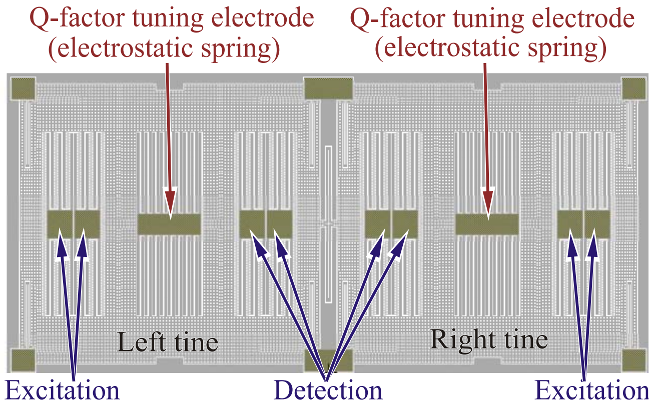

Fig. 2 Structural schematics of a tuning fork MEMS resonator for experimental validation of Q-factor stabilization

The theoretical limit of Q-factor was estimated by accounting for two major damping mechanisms – anchor loss and Thermo-Elastic Damping (TED). After minimizing the dissipation via the substrate as described above, the Q-factor limit set by anchor loss is theoretically calculated to be 5.8 million. The individual contribution of TED is also designed to set the Q-factor limit to be 5.8 million. The two numbers are designed to be equal, so that when combining these two terms, the overall limit of Q-factor is maximized at 2.87 million, as calculated by

$$\frac{1}{Q_{limit}} = \frac{1}{Q_{TED}} + \frac{1}{Q_{Anchor}}$$

For the purpose of this work, we are interested in modulating the Q-factor of the structure. This is done by controlling the energy dissipation due to asymmetry. The two sets of non-differential parallel plate capacitors, which act as electrostatic springs, can tune the individual stiffness of the left and right tines of the structure through the negative electrostatic spring effect, which offers the capability of regulating the dynamic structural misbalance using a mismatch in stiffness.

III. THERMOELASTIC DAMPING ANALYSIS

Q-factor of a vacuum-packaged, dynamically balanced tuning fork structure was calculated using finite element modeling, predicting the influence of the thermo-elastic damping over temperature. This was completed through modal analysis coupled with thermo-elastic dissipation using COMSOL Multiphysics software at different temperatures, over a range from -40 °C to +100 °C. The entire device was modeled with a density of 2,330 kg/m^3 and a constant Young's Modulus of 170 GPa, revealing a resonant frequency of 570 Hz for the anti-phase mode of vibration. The thermo-elastic limit of this vibratory mode was determined using the same 3-D model and resulted in a Q-factor of 5.6 million at room temperature. Further simulations predicted Q-factor variations from 6 million to 4.4 million for a temperature (T) range from 0 °C to +100 °C, revealing the dependence $Q_{TED} \sim 1/T$, thus defining a characteristic of thermo-elastic dissipation.

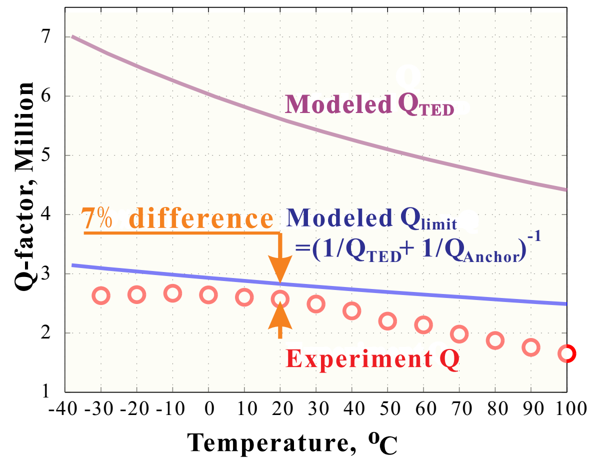

Fig. 3 Experimental result of Q-factor compared with theoretical limit of Q-factor. At room temperature, the experimental data is 7% less than the estimation, which is in a good agreement with estimation.

Assuming that Q_{anchor} is constant at 5.8 million over temperature, Q_{limit} set by TED and anchor loss can be calculated theoretically.

Experiments have been performed to validate this theoretical estimation. Fig. 3 shows the Q-factor versus temperature relation obtained by theoretical estimation and experiment. A maximal anti-phase Q-factor of 2.67 million at 570 Hz is found, ~7% less than the theoretical prediction, 2.85 million, probably due to other unmodelled energy loss mechanisms such as asymmetry, residual gas, and electrical damping. For more details on device design and characterization, see [7].

IV. ENERGY DISSIPATION VIA ASYMMETRY

A. *Description of tuning mechanism*

As described in Section II, when the two coupled tines are in perfect symmetry, energy is conserved in the anti-phase motion. When asymmetry is introduced, the unbalanced forces lead to leakage of energy through the substrate, hence lowers the time constant and Q-factor of the device. The introduction of asymmetry can be realized due to fabrication imperfection or asymmetric electrostatic stiffness modulation. For the resonator under investigation, experiments demonstrated that the influence of fabrication imperfection on symmetry is negligible. Furthermore, even if the imperfections of fabrication are significant, the asymmetry of the structure can be controlled using electrostatic tuning. For a detailed theoretical description of the effect, and its application on Q-factor maximization, see [10].

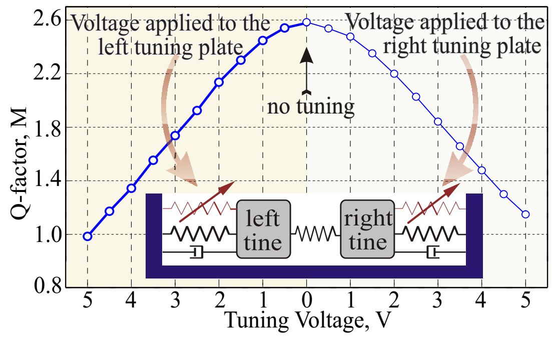

Fig. 4 Experimental characterization of the stiffness matching effect on the resonator's energy dissipation by measuring Q-factor of the anti-phase motion versus tuning voltage applied to the left or right electrodes.

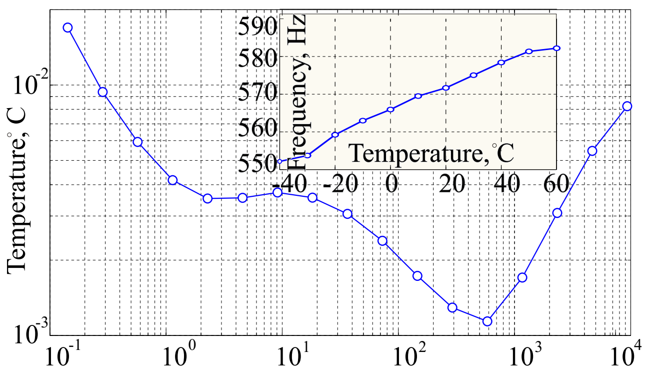

Fig. 5 Temperature sensitivity calculated from measured Allan deviation of frequency using TCF, revealing a temperature stability up to 10^{-3} °C. Insert: frequency versus temperature.

B. Experimental results

Fig. 4 illustrates the experimental data when the as fabricated resonator is initially symmetric and no electrostatic tuning is applied. When voltage is applied to one of the two non-differential parallel plate capacitors, energy dissipation increases and Q-factor decreases. Tuning via the left and right plates leads to the same decreasing trend in Q-factor, with a slightly different slope. This can be due to small variations in capacitance gaps between the left and right tuning electrodes, as well as due to fabrication tolerances.

With the capability of controlling the asymmetry loss, we are now able to regulate the total loss to maintain a constant Q-factor over temperature. When temperature decreases, energy dissipation due to TED decreases as well. Without any regulation, this causes Q-factor to drift upwards. By applying a voltage for stiffness tuning, the loss via asymmetry increases. This increases the total energy dissipation, which helps to maintain a constant Q-factor over temperature.

V. CONCEPT OF TEMPERATURE SELF-SENSING

To properly and automatically compensate the parameter drift due to thermal variation, we first require a precise measurement of the device temperature. This can be done indirectly using the fact that resonance frequency is dependent

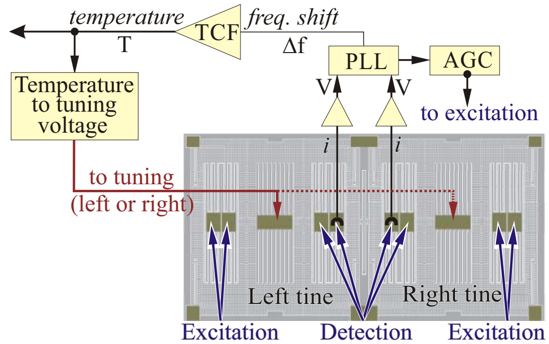

Fig. 6 Electro-mechanical schematic of Q-factor stabilization over temperature by temperature self-sensing. Temperature is measured using temperature self-sensing, and corresponding tuning voltage is applied.

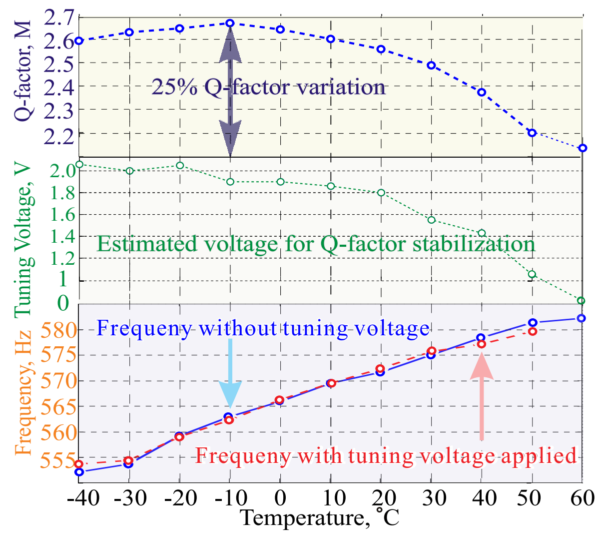

Fig. 7 Q-factor versus temperature, showing a 25% drift of Q-factor from 2.14 million to 2.67 million over a 100 °C temperature variation (top), required tuning voltage to compensate for the Q-factor drift over the same temperature range (middle), and frequency versus temperature plot with and without the tuning voltage applied (bottom).

on temperature through the Temperature Coefficient of Frequency (TCF). Therefore, by monitoring the frequency shift of the resonator, we can measure the temperature of the structure. This leads to the temperature self-sensing concept, which has two major advantages: high performance and no time lag due to direct measurement of the device temperature.

This concept is validated by measuring the frequency shift over temperature and its long-term stability. The former is used to calculate the TCF, and first measured from the frequency shift over temperature. Using the measured TCF and the Allan deviation of the frequency, both shown in Fig. 5, the frequency stability was translated to temperature self-sensing precision of 0.003 °C at 10 s and 0.001 °C at 600 s.

Fig. 6 illustrates a proposed schematic to integrate the temperature self-sensing concept into the thermal variation stabilization algorithm. With pre-calibrated TCF, the frequency shift is monitored, translated into temperature

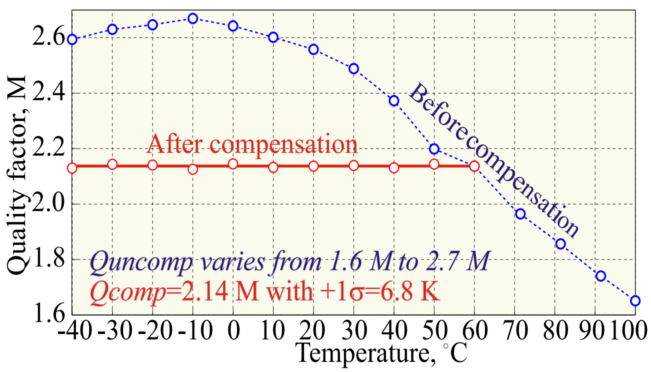

Fig. 8 Measured Q-factor versus temperature for a vacuum sealed tuning fork MEMS resonator. Before compensation, Q-factor thermal drift is significant. After compensation, Q-factor stays at 2.14 million with 6,800 (+1σ) variation from -40 °C to +60 °C, compared with 53,000 variation before compensation.

variation, which in turn is used to determine the tuning voltage applied to one of the electrodes and modulate the degree of asymmetry to compensate the thermal drift properly. The automatic and real-time control is ensured by the instantaneous feedback.

VI. EXPERIMENTAL DEMONSTRATION

The experiment was conducted using a thermal chamber with both device and circuit board inside. The setup was first isothermally treated for over one hour to reach thermal equilibrium. Q-factor was then calculated by observing the amplitude decay of the resonator over time and static conditions.

Fig. 7 (top) shows the characterization of Q-factor for temperature, from −40 °C to +60 °C. A maximum Q-factor of 2.67 million for temperatures below 20 °C is obtained, while this value changes to 2.14 million at +60 °C, revealing 25% Q-factor drift over this temperature range (−40 °C to +60 °C). To stabilize the Q-factor to 2.14 million (corresponding to 60 °C), different tuning voltages were applied to the left tuning electrode at different temperatures, Fig. 7 (middle). While the operational frequency is influenced by temperature, it is not significantly affected on the level of 1 Hz by the tuning voltages, Fig. 7 (bottom). Therefore, the frequency response at each temperature point can be estimated with high accuracy and compensated alone using a pre-calibrated frequency-versus-temperature curve even with the Q-factor stabilization algorithm implemented. When the compensation is large (where Q-factor is drifting upwards significantly), higher level of asymmetry is required to allow more energy dissipation via substrate. Accordingly, the tuning voltage required follows the same trend of Q-factor versus temperature. After implementing the compensation method with appropriate tuning voltage, we experimentally demonstrate a stable Q-factor at 2.14 million with variation of 6,800 (+1σ) or 0.3% for a temperature range from □40 °C to +60 °C, Fig. 8.

VII. CONCLUSIONS

This paper proposes a compensation scheme to stabilize Q-factor over temperature by controlling energy dissipation via structural asymmetry using electrostatic tuning electrodes. A temperature self-sensing concept that utilizes the frequency shift of the same device to monitor the temperature variation is also utilized. This method is experimentally validated by use of an ultra-high Q-factor tuning fork silicon MEMS resonator. Before applying the compensation scheme, the resonator experiences 25% Q-factor drift from 2.14 million to 2.67 million over a temperature range from -40 °C to +60 °C. After implementing the algorithm for the same temperature range, the Q-factor is stabilized to the +60 °C level (2.14 million) and only 0.3% (+1σ) variation is observed. Stabilization to other temperature levels can also be realized by controlling the tuning voltage.

This method demonstrates a tradeoff between high Q-factor and stable performance for operations over a wide temperature range. While impossible to maintain a stable Q-factor at a maximum value over all temperatures, it provides the option of maintaining a constant Q-factor at relatively lower level which accommodates the maximum operation temperature, particularly for devices requiring high stability but not high Q-factor.

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