Vacuum Sealed and Getter Activated MEMS Quad Mass Gyroscope Demonstrating Better Than 1.2 Million Quality Factor

Sina Askari, Mohammad H. Asadian, Kasra Kakavand, Andrei M. Shkel

MicroSystems Laboratory, University of California, Irvine, CA, USA

Email: { sina.askari, asadianm, kasrak, andrei.shkel } @uci.edu

Abstract— This paper presents the in-run bias stability of a high Q-factor Quad Mass Gyroscope (QMG), vacuum sealed with getter activated in Leadless Chip Carrier (LCC) package. Quality factors of 1.2 and 1.1 Million were measured along the layout-defined drive and sense modes. As-fabricated, frequency mismatch of 35Hz was electrostatically tuned to 200mHz, for a device with 2kHz center frequency. A performance improvement of 4X in Angle Random Walk (ARW) and 15X reduction in in-run bias stability were achieved after the electrostatic frequency matching between drive and sense modes, resulting in below 0.1 deg/hr bias stability. The results showed a strong dependency of the in-run bias stability of the gyroscope due to quality factor and frequency mismatches.

I. INTRODUCTION

The noise performance of degenerate mode MEMS gyroscopes are limited by the quality factor (Q-factor), as well as by the frequency and damping mismatches between the drive and sense modes (X- and Y- axis for a z-axis gyroscope). In the mode matched, or nearly-matched, MEMS gyroscopes, the scale factor is amplified by the quality factor of the sense mode, thus offering a higher rate-sensitivity and a reduced thermally-induced noise [1]. A Quad Mass Gyroscope (QMG) is a two degree-of-freedom resonator with four mechanically coupled proof-masses that operates in the dynamically-balanced anti-phase degenerate mode [2]. The coupling mechanism between masses provides the phase synchronization, whereas the internal negative stiffness widens the frequency separation between anti-phase and in-phase modes, improving the immunity of gyro to the linear acceleration and reducing mode conversion losses [3].

Fabrication imperfections in QMG cause a frequency separation between drive and sense modes. Therefore, a post-fabrication frequency tuning is necessary to improve the scale-factor and bias stability of high Q-factor mode-matched devices.

II. VACUUM SEALING WITH GETTER ACTIVATION

QMGs were fabricated using $100\mu m$ SOI process with $7\mu m$ minimal gap size. The sensors were attached to LCC packages using AuSn (80/20) eutectic alloy and wire-bonded. Then, the devices were vacuum sealed at < 0.1mTorr in SST 3150 furnace using an in-house sealing process, Figure 1. Ceramic packages were dehydrogenated in vacuum at $400°$C for 3
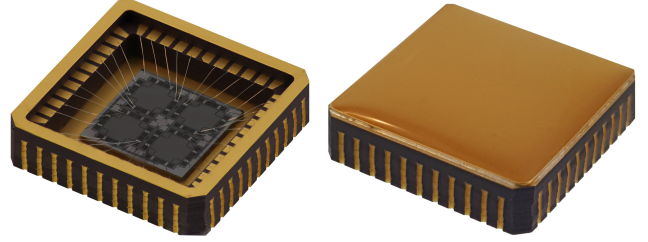

Fig. 1. 8.6 mm footprint Quad Mass Gyroscope (QMG) is die attached and wire bonded in an LCC package, and vacuum sealed with activated getter.

hours prior to die attachment. After the die attachment, a long (> 24 hours) vacuum bake-out step at $220°$C was performed to effectively eliminate moisture and adsorbed water molecules on interior surfaces of the package and the device. A thin film getter material (SAES PageLid®) was deposited on the Kovar lids and activated during the sealing process, to maintain the high vacuum inside the sealed cavity and enable a long-term stability. Finally, the eutectic AuSn (80/20) solder preform was reflowed at $350°$C to bond the Kovar lids to the ceramic package. Above 1 Million Q-factor was repeatedly achieved on QMGs using the developed sealing process.
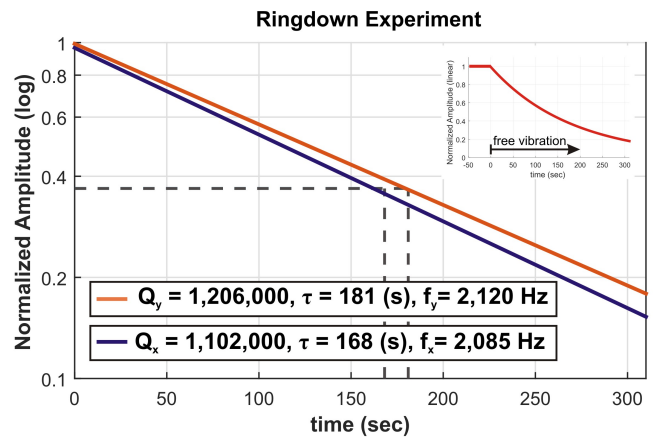

Fig. 2. Experimental results of ring-down of the vacuum sealed QMG device under test. The exponential fit to the data revealed the energy decay time at (1/e) normalized amplitude.

III. Experimental Results

The tested device was electrostatically excited to the resonance frequency under a narrow bandwidth condition in the drive loops (X- and Y-modes, subsequently). The decay time (τ) was extracted; this is the time it takes for the settled drive amplitude to drop down under the free vibration to 37%. From the measurement, the quality factor along the X-mode was $Q_x = 1,102,000$, which corresponded to $\tau_x = 168(s)$ at $f_x = 2,085Hz$, and along the Y-mode $Q_y = 1,206,000$, which corresponded to $\tau_y = 181(s)$ at $f_y = 2,120Hz$, Figure 2. Without tuning voltages, the Δf was measured at $35Hz$.

The X-Y frequency mismatch was tuned electrostatically down to $0.2Hz$ using 14.4 Volts DC bias, which in-turn improved the scale factor of sensor. After tuning, Q_y dropped to $397,000$ with $\tau_y = 60.5(s)$, and Q_x dropped to $296,000$ with $\tau_x = 45.1(s)$, all at the center frequency $f_x = 2,085Hz$, Figure 3. As the tuning voltage increased, we observed higher cross-coupling between orthogonal axes of the quad mass gyroscope on the sense electrodes (X-Y modes). Due to the presence of anisoelasticity in a non-ideal gyroscope, the tuning along X-Y axes would presumably result in a larger unbalanced reaction force at the anchor, leading to the energy dissipation through the substrate.

The rate mode characterization was performed in an open-loop architecture with only two main loops operational, including phase-locked loop (PLL) and amplitude gain control (AGC). Due to electro-mechanical symmetry of the device, a high symmetry of phase synchronization was observed across two modes in readout electronics. For example, during the rate mode characterization, the maximum demodulated amplitude was observed when the phase difference between drive and sense signals was near $90°$, as predicted.

Two independent experiments were conducted under the same environmental condition for both as-fabricated and electrostatically tuned cases. The experiment was performed without any calibration or compensation loops. After the electrostatic tuning, from $f_y = 2,120Hz$ to $f_y = 2,085Hz$, the bias stability improved from 1.6175 to $0.0733(°/hr)$ and ARW improved from 0.1858 to $0.045(°/\sqrt{hr})$, respectively. For comparison, the performance of a QMG with the quality factor of $Q = 1,000$ in both modes with the frequency mismatch of $\Delta f = 4Hz$ and without self-calibration loop has been independently verified, the result is shown in Figure 4. A performance prediction for a QMG with $Q = 1M$ and $\Delta f = 1Hz$ was estimated to be $0.0005(°/\sqrt{hr})$, [4]. Figure 4 summarizes the current status and projected performance of high Q-factor, and X-Y symmetric quad mass gyroscopes.

IV. Conclusion

We demonstrated a high performance Quad Mass Gyroscope (QMG) with measured $0.0733(°/hr)$ bias stability and a $0.045(°/\sqrt{hr})$ ARW in the open-loop rate operation mode. The QMG was vacuum sealed with activated getter at the pressure $< 0.1mTorr$, showing a stable vacuum over time. Higher quality factor and lower frequency mismatch are projected to result in an improvement in ARW and bias stability.
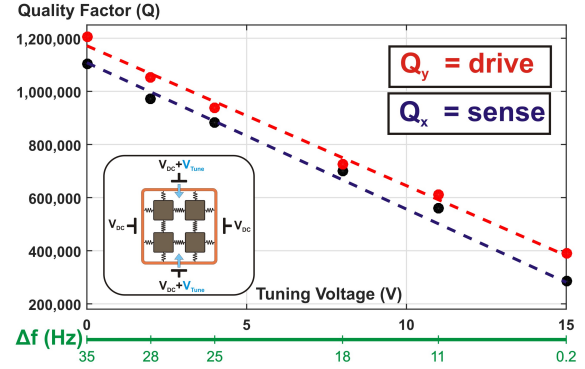

Fig. 3. Experimental characterization of the quality factor at different tuning voltages. The measured result demonstrated the Q-factor of an as-fabricated device at 1.2 Million with the frequency mismatch of $\Delta f = 35Hz$ at center frequency of $f = 2,120Hz$.

We estimate that the integral noise level corresponding to the navigation grade performance will be achieved on QMG gyroscopes with frequency mismatch of $\Delta f = 1Hz$ and the qualify factor of $Q = 1M$. We believe the electrostatic tuning along the principal axis of stiffness is a necessary condition to maintain high Q-factor while matching frequencies of the drive and sense axes.
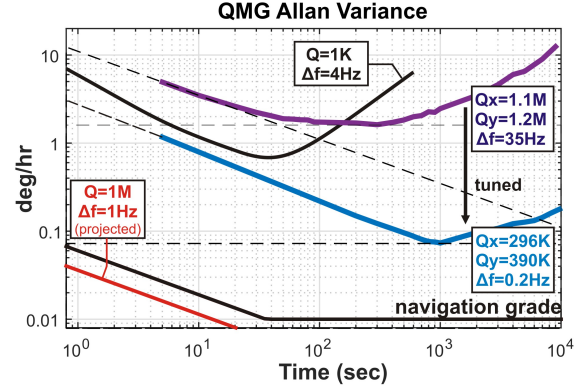

Fig. 4. Performance of QMG without self-calibration algorithm ("disabled"). Independent verification of a QMG ($Q = 1K, \Delta f = 4Hz$) revealed ARW=$0.0562(°/\sqrt{hr})$, vacuum sealed QMG with getter ($Q = 1.2M$, $\Delta f = 35Hz$) revealed ARW=$0.1858(°/\sqrt{hr})$, vacuum sealed QMG with getter after tuning ($Q = 390K$, $\Delta f = 0.2Hz$) revealed ARW=$0.045(°/\sqrt{hr})$. Lower frequency mismatch and higher Quality factor allowed to reduce the in-run bias stability.

References

[1] Igor P. Prikhodko et al. Sub-degree-per-hour Silicon MEMS Rate Sensor with 1 Million Q-factor. In *Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS)*, pages 2809–2812, 2011.

[2] Brenton R. Simon et al. Mode Ordering in Tuning Fork Structures with Negative Structural Coupling for Mitigation of Common-mode g-Sensitivity. In *Sensors, IEEE*, pages 626–629, 2015.

[3] Alexander A. Trusov et al. Ultra-High Q Silicon Gyroscopes with Interchangeable Rate and Whole Angle Modes of Operation. In *Sensors, IEEE*, pages 864–867, 2010.

[4] Alexander A. Trusov et al. Flat Is Not Dead: Current and Future Performance of Si-MEMS Quad Mass Gyro (QMG) System. In *Position, Location and Navigation Symposium-(PLANS), IEEE/ION*, pages 252–258, 2014.