SUB-DEGREE-PER-HOUR SILICON MEMS RATE SENSOR WITH 1 MILLION Q-FACTOR

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ABSTRACT

We report characterization of a silicon MEMS rate gyroscope with measured sub-deg/hr bias stability, enabled by the quality factor (Q) of 1.1 million. The rate sensor utilizes degenerate, dynamically balanced Quadruple Mass Gyroscope (QMG) design, which suppresses substrate energy dissipation and maximizes Q-factors. We demonstrated a 0.9 °/hr in-run bias stability and a 0.06 °/√hr rate noise density for the 0.1 mTorr vacuum packaged QMG with a 0.2 Hz mode-mismatch between drive- and sense-modes. This level of noise allowed detection of azimuth with 150 mrad precision, showing feasibility of a QMG for gyrocompassing.

KEYWORDS

MEMS gyroscope, north-finding, gyrocompassing.

INTRODUCTION

High sensitivity silicon MEMS rate sensors are desired for inertial navigation and north-finding applications. An optimal architecture of a high resolution vibratory rate gyroscope comprises a symmetric mechanical structure with combination of high Q-factors, high Coriolis coupling, drive- and sense-mode degeneracy, and frequency tuning capability [1]. One approach is to utilize a continuous structure, such as a disk or a ring, in a balanced wine-glass mode. However, optimization of the performance parameters for such architectures is challenging due to the inherent coupling of the natural frequency, Q-factor, and drive amplitude. Frequency trimming is also not trivial for solid structures as both mass and stiffness are collocated.

An alternative approach investigated in this paper is to use a lumped, four quadrant symmetric QMG architecture [2], Figure 1. It comprises four symmetrically decoupled tines synchronized by anti-phase lever mechanisms, providing a unique combination of low energy dissipation and isotropy of both the resonant frequency and damping. The QMG is expected to demonstrate high Q-factors and enable high precision rate measurements.

QMG SENSOR AND ELECTRONICS

In this section we analyze rate sensor dynamics and identify key parameters for achieving high resolution.

Rate Sensitivity Analysis

The operating principle of a vibratory z-axis angular rate gyroscope is based on energy transfer between two vibratory modes. The drive-mode, x-axis, is continuously excited at resonance, and the sense-mode, y-axis, is used for rate detection. The amplitude of the sense-mode (y) motion is proportional to the angular rate (Ω_z), with the angular gain factor ($k \leq 1$) and the drive amplitude (x) [3]:

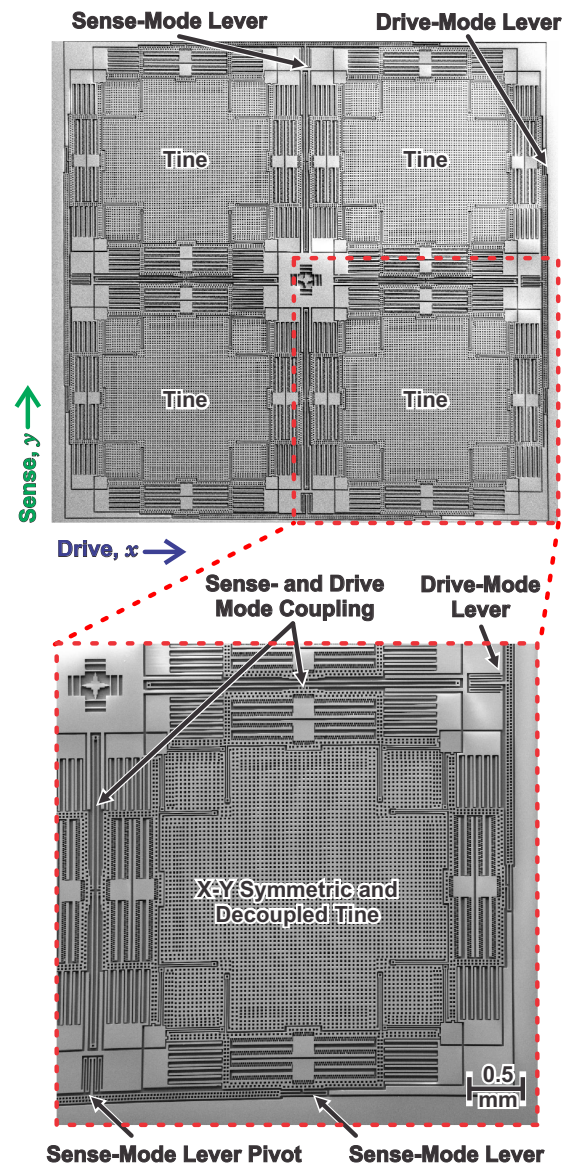Figure 1: SEM image of a fabricated SOI quadruple mass gyroscope (QMG). Die size is 8.6 ×8.6 mm.

$$y = 2Q_{eff} k\Omega_z x / \omega_y , \qquad (1)$$

where ω_y is the sense-mode natural frequency. Here, Q_{eff} is gain of the sense-mode at the drive-mode frequency ω_x [3]:

$$Q_{eff} = Q_y / \sqrt{1 + 4Q_y^2 (\Delta\omega / \omega_y)^2} , \qquad (2)$$

which reaches maximum Q_y for zero frequency mismatch between ω_x and ω_y ($\Delta\omega = 0$).

It follows from (1) that the rate sensitivity is enhanced by maximizing the Q-factor and reducing the resonant frequency. Q-factor above 100,000 was previously realized for both continuous and lumped type MEMS gyroscopes [2,4]. In contrast to continuous structures, lumped, mass-spring type devices, operate at lower frequencies, and thus, promise superior rate sensitivity.
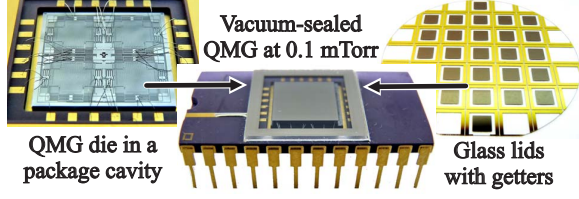
Figure 2: Photograph of a vacuum packaged QMG used in the experiments. Insets: die before sealing; glass lid wafer.
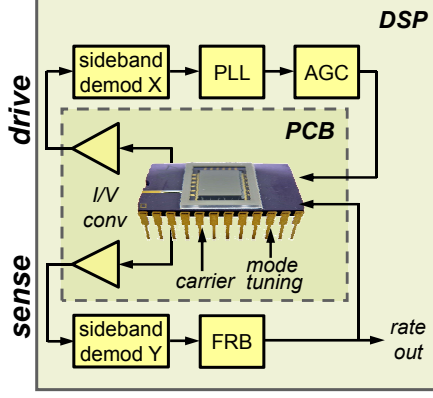

Figure 3: Block diagram of QMG signal processing for rate measurements, showing drive- and sense-mode control loops.

For instance, the scale factor improves by 60 dB for a 1 kHz operational sensor compared to a 1 MHz sensor. The trade-off between frequency and sensitivity is a limited bandwidth, which can be resolved by operating in a closed loop, or force-rebalance (FRB) mode. In addition, mass-spring, lumped architectures can provide high Coriolis coupling ($k \sim 1$) and large amplitude of motion (several microns), which also increase the rate sensitivity. Based on these considerations, we investigate a lumped design approach in this paper.

Mechanical Architecture Symmetry

Mode-matched operation over a wide temperature range is desired for high-Q MEMS gyroscopes. Frequency mismatch induced by fabrication imperfections is typically compensated by electrostatic tuning, which often requires high voltages and active controls. In this paper, we evaluate a design-level solution, where structural symmetry of the lumped mechanical element provides closely matched drive and sense temperature coefficients of frequency (TCFs) for increased robustness to the temperature-induced drifts [2].

The recently introduced lumped quadruple mass gyroscope architecture [2], Figure 1, comprises four identical tines, four linear coupling flexures, and a pair of lever mechanisms for synchronization of the anti-phase drive- and sense-mode motion. Momentum and torque balance in both x and y directions are expected to provide ultra-low dissipation of energy through the substrate, leading to a high resolution and equal high Q-factors, $Q_x = Q_y > 1$ million. Symmetric lever mechanisms and flexures ensure low operational frequency (~ 2 kHz), as well as the common mode rejection of input accelerations, both required for high precision rate measurements.
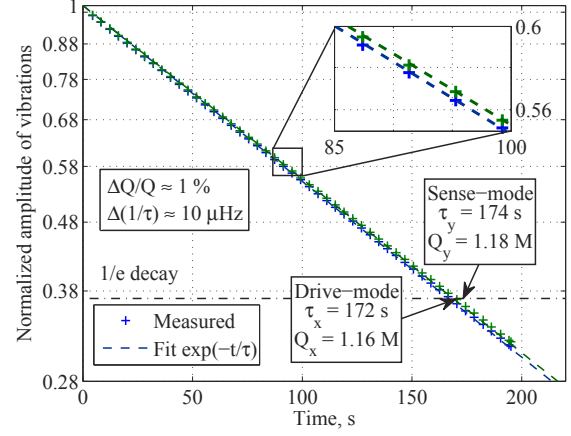

Figure 4: Experimental characterization of the packaged QMG using ring-down tests, revealing identical drive- and sense-mode Q-factors of 1.17 million (with ΔQ/Q of 1 %).
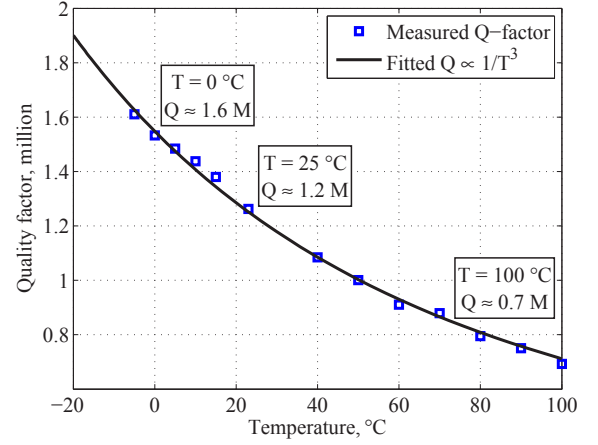

Figure 5: Measured Q vs. temperature for a packaged QMG. The $1/T^3$ dependence is attributed to the thermoelastic dissipation. Q-factors > 0.7 M were observed up to 100 °C.

Sensor Fabrication and Vacuum Packaging

Stand-alone prototypes of the QMG were fabricated using an in-house 100 μm SOI process with 5 μm minimal gap size [5]. The rate sensor was packaged using custom technology for robust vacuum sealing of the high-Q gyroscopes [5], Figure 2. First, the QMG die was attached to a ceramic 24-pin package using eutectic solder and wire bonded. Finally, the device was sealed at sub-mTorr vacuum, preceded by the getter activation on a glass lid.

Interface and Control Electronics

All experiments were performed using a custom PCB connected to a FPGA-based DSP unit. The vacuum packaged sensor was mounted on a PCB with front-end electronics and installed on a 1291BR Ideal Aerosmith rate table inside the thermal chamber. Electrostatic capacitive actuation and detection were employed along with the EAM technique for the parasitic feedthrough elimination. All control and signal processing were realized using a LabView programmable, FPGA-based, HF2 unit from Zurich Instruments.

Figure 3 depicts drive- and sense-mode control loops used for precision angular rate measurements. The PLL-based drive-loop sustained oscillation at resonance
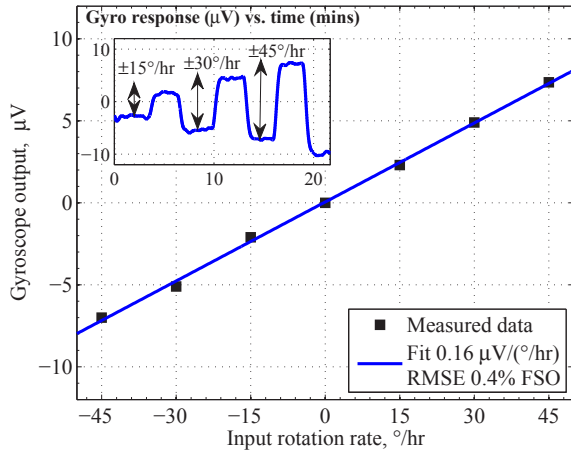
Figure 6: Measured linear rate response in ±45 °/hr range. Inset: time history of a gyro output with 15 °/hr increments.

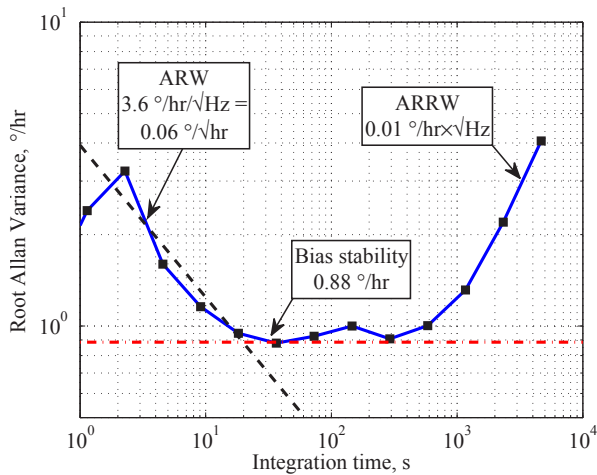*Figure 7: Root Allan variance of measured zero rate output, revealing a 0.06 °/√hr ARW, and a 0.88 °/hr bias stability.*

and provided reference for the sideband demodulations. The AGC stabilized the amplitude of drive-mode motion. Rotation was detected by demodulating the sense-mode signal. Rate was proportional to a feedback force used to null the Coriolis induced motion (FRB loop). The rate measurements were performed at a 0.2 Hz separation between drive- and sense-mode frequencies.

QMG EXPERIMENTAL CHARACTERIZATION

Structural and Thermal Characterization

The damping and frequency symmetry of the stand-alone QMG prototype with a 2 kHz operational frequency was evaluated using ring-down tests in a TestEquity 107 thermal chamber. Figure 4 shows measured time-domain amplitude decays of both mechanical modes at the room temperature. Exponential fits revealed identical drive- and sense-mode Q-factors of 1.17 million with $\Delta Q/Q$ variation of 1 % before tuning or compensation, confirming the complete structural symmetry. The measured Q value of 1.17 million is within 90% of the 1.3 million thermoelastic limit estimated by finite element modeling for the QMG design. The ultra-high Q-factor translates into the fundamental mechanical-thermal
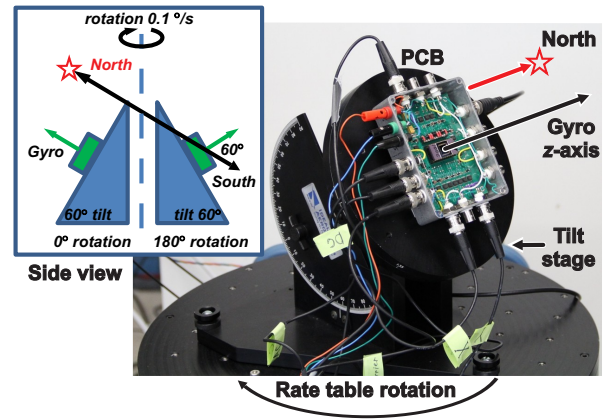

Figure 8: Photograph of a carouseling setup for north-finding experiment. Inset: gyro orientation for each 180 ° turn.

resolution limit of 0.01 °/hr/√Hz for a mode-matched case.

The temperature sensitivity of frequency and Q-factor were characterized in the range from −5 °C to 100 °C. Isotropic Q-factors above 0.7 million were experimentally observed up to 100 °C for a packaged QMG, Figure 5. The fit to the $Q(T)$ data revealed $1/T^3$ dependence, suggesting that the dominant energy loss mechanism is thermoelastic dissipation [6]. Frequency symmetry of the QMG design was previously evaluated in [2], and confirmed closely matched TCFs of −22.6 ± 0.2 ppm/°C for both modes.

Rate Resolution Characterization

The low dissipation QMG design and closed loop operation of the QMG are expected to provide low noise rate performance. Figure 6 shows rate response of the packaged QMG sensor performed under a 0.2 Hz frequency mismatch in the input angular rate range of ±45 °/hr, demonstrating the linearity and ability to measure rates on the order of Earth's rotation.

The QMG noise performance was evaluated using the root Allan variance analysis of a zero rate output recorded for 4 hours at a sampling rate of 28 Hz, Figure 7. Fit to the $\tau^{-1/2}$ slope (white noise) at the short integration time revealed a 3.6 °/hr/√Hz = 0.06 °/√hr Angle Random Walk (ARW). The flicker noise reached for integration times between 20 and 500 s indicated a 0.88 °/hr bias stability. For times longer than 1000 s the output was dominated by the $1/f^2$ random walk. Fit to the $\tau^{1/2}$ slope revealed a 0.01 °/hr×√Hz Angular Rate Random Walk (ARRW). Next, we demonstrate that the low level of noise and the long-term bias stability of the QMG allow detection of the true North based on the Earth's rotation measurements.

North-Finding Experiment

The experimental setup for north-finding consists of a rate table and a tilt stage, Figure 8. The true North was detected by changing the orientation of a QMG sensitive axis relative to the Earth's axis [7]. The sensor was 57 ° titled relative to the local vertical (33 ° N latitude in Irvine, CA) in order to maximize the output. The 0.1 °/s carouseling rate resulted in periodic rotation of the QMG sensitive axis and modulation of the Earth's constant rate
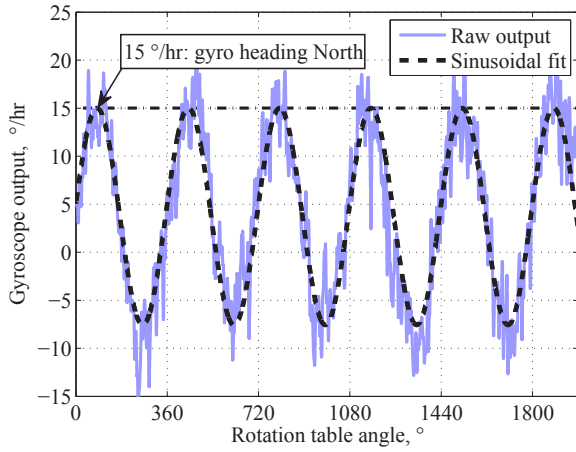
Figure 9: Carouseled gyro output produced by the Earth's rotation. The output is +15 °/hr when gyro is pointing North.
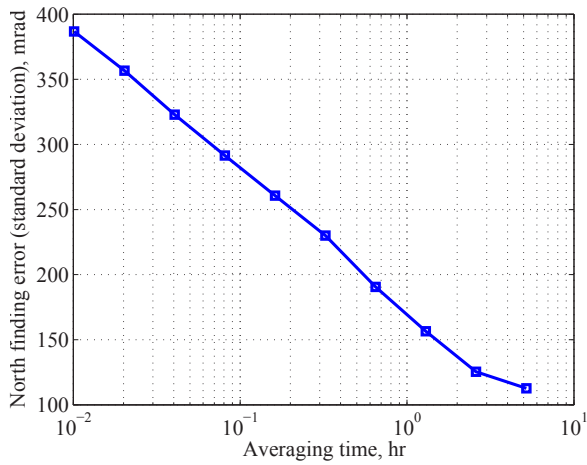

Figure 10: Azimuth error vs. averaging time, revealing 150 mrad precision for 1 hour integration (from Fig. 9 data).

with a 1 hr period, Figure 9. The data shown in Figure 9 represents a raw gyro output for a 6 hr run without postprocessing or temperature compensation. For each 180 ° turn of the rate table, the orientation of the QMG sensitive axis was changing from North to South, as explained in Figure 8. This effectively changed the gyroscope output from +15 °/hr to −7.5 °/hr.

The azimuth angle (relative to the 0 ° position of the rate table) was derived from the phase of the sinusoidal fit. To estimate the precision of azimuth measurements, the fit residuals (RMS errors) were computed for different averaging times, Figure 10. The azimuth precision of the 0.2 Hz mismatched QMG was 150 mrad after 1 hr average.

CONCLUSIONS

We demonstrated a high resolution silicon MEMS z-axis rate gyroscope with measured 0.9 °/hr bias stability and a 0.06 °/√hr rate noise density enabled by the fully symmetric QMG design with unprecedented ultra-high Q-factors. Characterization of a 0.1 mTorr vacuum sealed quadruple mass gyroscope confirmed identical Q-factors of 1.17 million with $\Delta Q/Q$ variation of 1 %. The north-finding experiments relying on the Earth's rotation demonstrated a 150 mrad precision of azimuth detection.
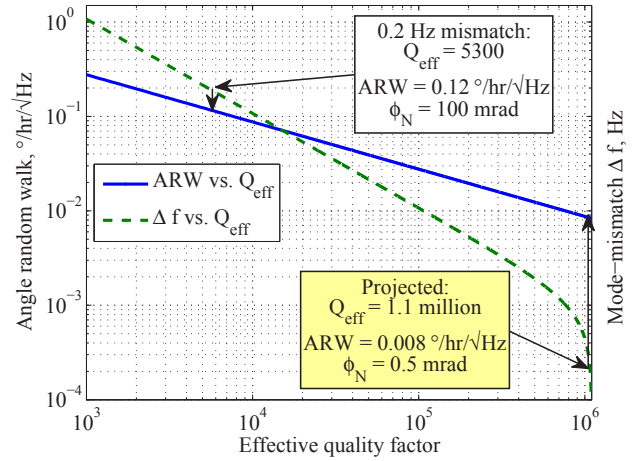

Figure 11: Projected performance of a QMG. Expected rate noise is 0.01 °/hr/√Hz and azimuth precision is 0.5 mrad.

Based on the measurement data and noise modeling [8], we expect the rate noise for mode-matched operation to be 0.01 deg/hr/√Hz, which translates to 0.5 mrad azimuth precision, Figure 11. Our experimental results and analysis illustrate the feasibility of the QMG rate sensor for north-finding applications, requiring a highly sensitive detection.

ACKNOWLEDGMENTS

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