HIGH PERFORMANCE MATCHED-MODE TUNING FORK GYROSCOPE

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ABSTRACT

This paper presents the perfect matched-mode operation of a type I non-degenerate z-axis tuning-fork gyroscope (i.e., 0 Hz frequency split between high-Q drive and sense modes). The matched-mode tuning fork gyroscope (M^2-TFG) is fabricated on 50-µm thick SOI substrate and displays an overall rate sensitivity of 24.2 mV/º/s. Allan Variance analysis of the mode-matched device demonstrates an angle random walk (ARW) of 0.045 º/√hr and a measured bias instability of 0.96 º/hr. Temperature characterization of the M^2-TFG verifies that mode matching is maintained over a temperature range of 20-100 ˚C.

1. INTRODUCTION

The automotive and consumer electronics industries have embraced MEMS gyroscopes as attractive replacements to conventional macro-mechanical and optical gyroscopes, owing to their small size, low power and relatively inexpensive mass production potential. The most popular class of MEMS gyroscopes are the Coriolis vibratory gyroscopes (CVG) which are based on transfer of energy between two vibration modes of the microstructure in response to a rotation signal. Vibratory microgyros operate under matched-mode or split-mode condition as explained in [1]. The resulting quality factor amplification increases sensitivity and resolution and lowers bias drift in devices that are operated under matched-mode conditions.

Current commercial vibratory MEMS gyros are employed in applications where extreme resolution and precision are not critical. MEMS gyros have yet to break into the high-precision market such as the defense, navigation and space industries where rate resolutions and bias stabilities of 0.1-1º/hr are required. The lack of mass, restricted drive amplitude, low quality factors or a combination of the above have been the limiting factors in the past. In [2] the authors introduced a novel type-I vibratory gyroscope, the M^2-TFG design, which incorporated all the necessary features required to achieve inertial grade performance – large drive amplitude (employing comb-drives), maximum mass/unit area (made possible by an innovative fabrication process that facilitates proof-mass release without perforations), and high-Q resonant operating modes (through efficient flexural designs). However, excessive quadrature error prevented matched-mode operation of the device. Mode-matching enables unprecedented improvement in sensitivity and noise floor of vibratory gyros at the expense of reduced bandwidth. This paper presents experimental results under matched-mode and split-mode operation of the TFG, and examines the temperature and drift characterization data of the device.

2. THE MATCHED-MODE TFG

Figure 1 shows an SEM image of the M^2-TFG fabricated on a low resistivity 50µm thick SOI substrate using the fabrication process outlined in [2]. The M^2-TFG is comprised of two proof-masses anchored at a central post and supported by flexural springs. The flexural designs ensure minimal support loss and thermoelastic damping in flexures to result in high-Q in-plane drive and sense resonant modes, as well as minimal coupling and frequency separation between the two modes (Fig. 2).

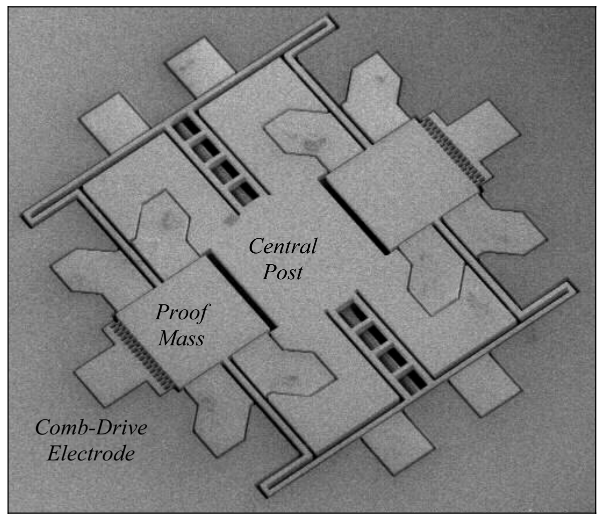


Figure 1: SEM image of a M2-TFG on SOI substrate

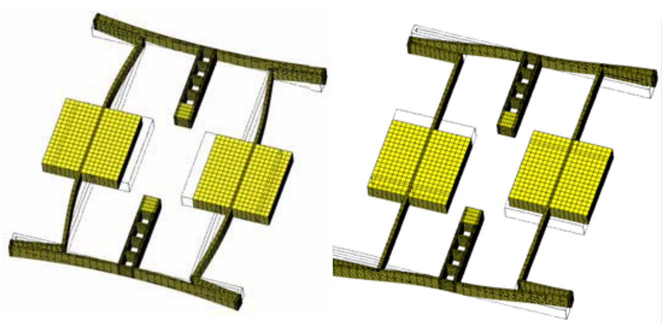
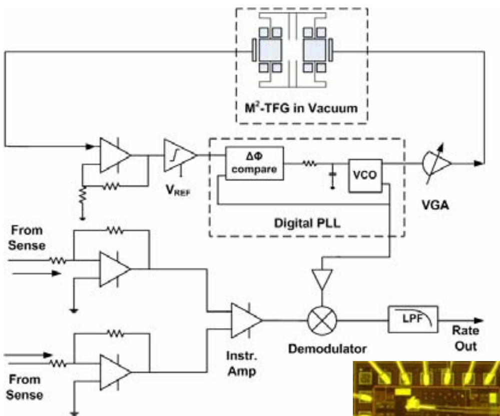


Figure 2: Resonant in-plane operating modes of the M2-TFG: (Left) Drive mode and (Right) Sense mode.

The operating principle of the device is based upon a standard tuning fork's response to rotation. The proof-masses are driven at resonance along the x-axis using comb-drive electrodes, and the Coriolis acceleration induced by rotation about the z-axis is sensed capacitively along the y-axis. The in-plane drive and sense resonant modes are illustrated in Fig. 2.

3. EXPERIMENTAL RESULTS

The M^2-TFG was interfaced to front end read-out amplifiers implemented in a 0.5µm 2P3M CMOS process, available through MOSIS (see inset Fig. 3). The device is driven to the drive-mode resonance using a PLL-based drive loop. The rotation signal is obtained by synchronous demodulation. The signal processing circuits were implemented using discrete electronics. A schematic overview of the gyro-system is displayed in Fig. 3.



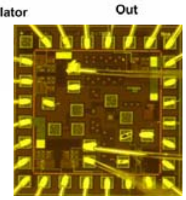


Figure 3: Schematic of the interface electronics (Inset) IC implementation of the read-out circuitry.

Figure 4 shows the open-loop measured quality factors of the drive and sense resonant modes in vacuum. Such high quality factors are essential to achieve inertial grade performance in a small bandwidth [3]. Larger bandwidth can be obtained by operating the device in closed loop at the expense of sensitivity.

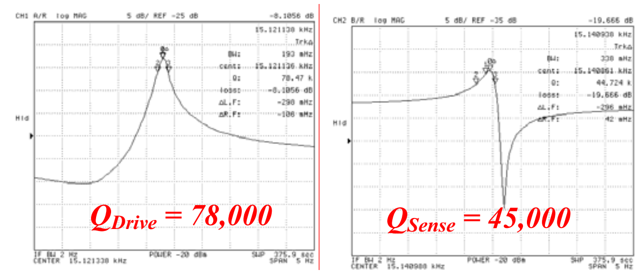


Figure 4: Measured drive and sense resonant mode Q observed at the respective drive and sense monitoring electrodes.

From an initial separation of 150 Hz, the drive and sense frequencies were matched by the application of the proper tuning voltages. Despite an optimized, mechanically decoupled design, in practice, fabrication imperfections can lead to non-zero off-diagonal elements in the spring stiffness and damping coefficient matrices resulting in an undesirable zero-rate output (ZRO). Only through the compensation of this quadrature error is the perfect matching of the drive and sense resonant modes possible [4]. The matched-mode quality factor of the device was recorded to be 40,000 as shown in Fig. 5.

Sensitivity Analysis

The device (including the interface system) was mounted on a rate table (Ideal Aerosmith Model 1256) and the sensor output voltage was measured at different angular speeds. The rate sensitivity response of the M^2-TFG under matched-mode operation is presented in Figure 6 and the inset shows the signal at one sense electrode.

The overall sensitivity of the M^2-TFG is directly proportional to the effective quality factor of the sense resonant mode (Q_{EFF}) at the drive frequency. With other parameters such as drive amplitude, operating frequency and initial sense gap constant, any variation in the Q_{EFF} can lead to considerable fluctuation in the sensitivity of the micro-gyro.

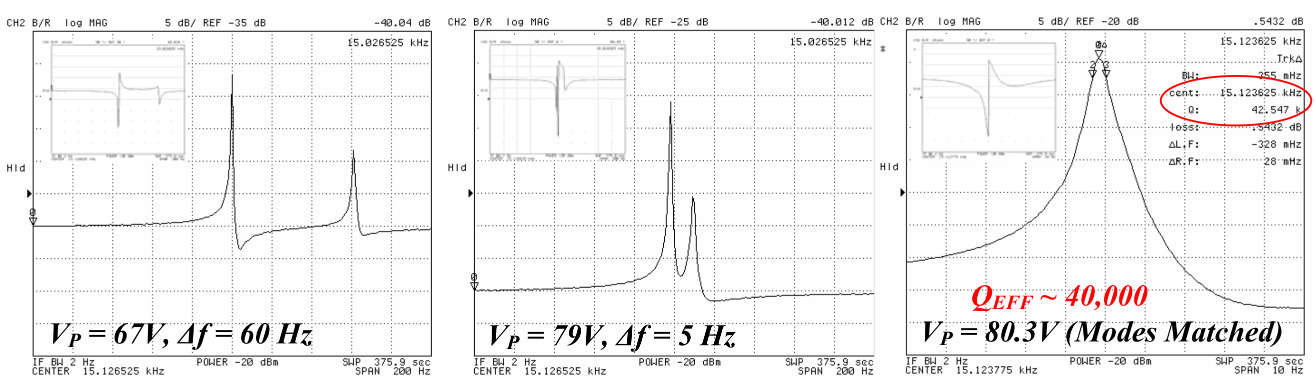


Figure 5: Collection of plots showing perfect mode-matching of the M2-TFG (Inset shows the phase information). The matched-mode effective sense quality factor of the device was recorded to be 40,000 at the sense monitoring channel.

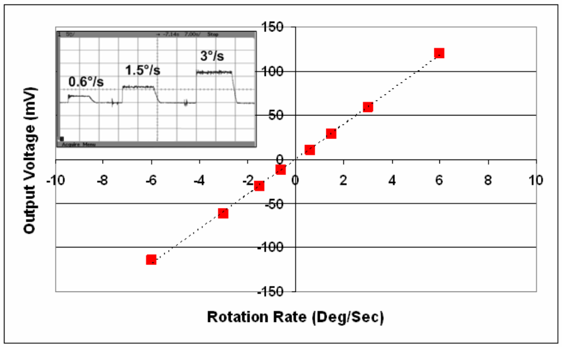


Figure. 6: The rate sensitivity plot for the M2-TFG under matched-mode operation (Inset) Signal at one sense electrode

Mode-mismatch, even of the order of a few Hz, can lead to drastic Q reduction as illustrated in Fig. 7 for a second TFG sample operated with a 2 Hz mismatch.

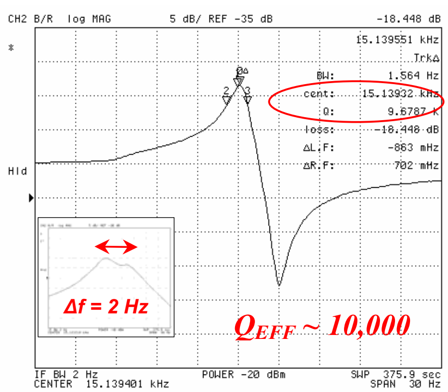


Figure 7: Near matched-mode operation (Inset) Frequency split of 2Hz. Effective sense Q is measured at 10,000.

The sensitivity improvement as a function of mode matching is clearly evident from the scale factor comparison shown in Fig. 8. The device with a 2Hz mode-mismatch (Q ~ 10,000 and larger bandwidth) yields a 7.2mV/˚/s rate sensitivity. In contrast, the perfectly mode-matched device (Q~40,000) demonstrates a rate sensitivity of 24.2 mV/˚/s.

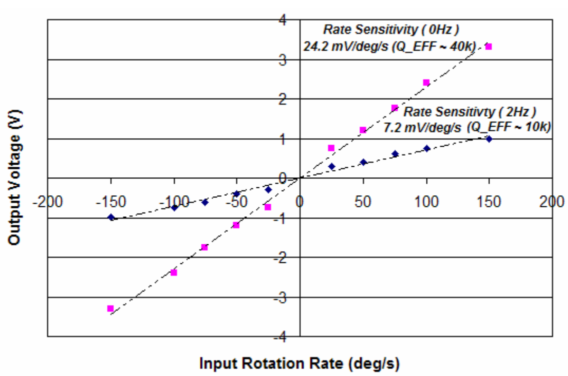


Figure. 8: The z-axis angular-rate input versus voltage output plot for two different matched conditions.

Bias Drift Estimation

Gyro Scale Factor stability and bias drift are essential performance gauging parameters in any inertial measurement unit (IMU). The scale factor stability is a directly affected by the stability of the matched-mode Q (Q_{EFF}) over time. It was observed that the measured Q_{EFF} remained constant over a period of 24 hours at a fixed room temperature and pressure. The zero rate output (ZRO) of the device was sampled every 100ms for a period of 12 hours (at room temperature and vacuum). Using the collected ZRO data an Allan variance analysis was performed to characterize the long-term stability of the matched-mode device – interfaced with the discrete electronics. A time-slice of the ZRO from one electrode is shown in Fig. 9. The ZRO level may be decreased through proper vibration isolation and elimination of other extraneous common-mode noise. The root Allan Variance plot of the M^2-TFG is shown in Fig. 10.

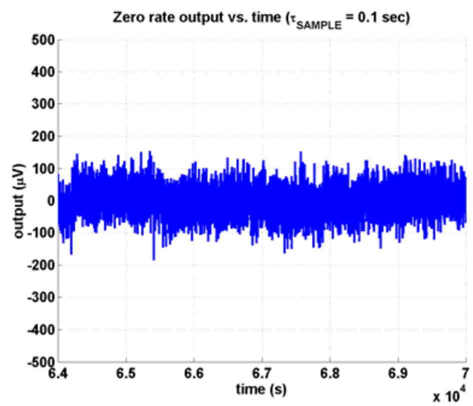


Figure 9: A section of the time domain plot of the ZRO.

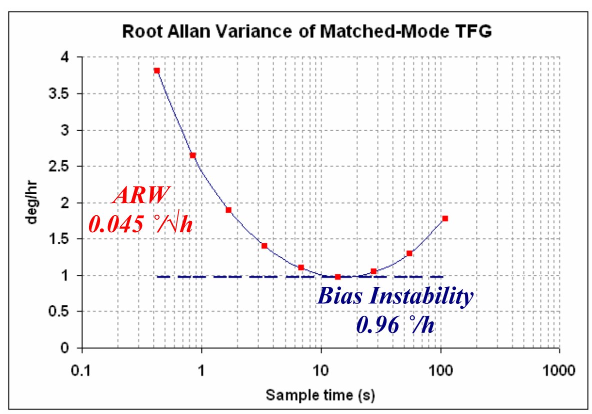


Figure 10: Root Allan Variance plot of the M2-TFG under perfectly matched operating condition.

From the Allan Variance graph, the measured bias instability of the system, without applying any pre-whitening or filtering [5], is 0.96 º/hr. The bias instability of the system degrades to 5.4 º/hr when operated under a 2Hz frequency split. From the Allan Variance curve, the measured angle random walk (ARW) is 0.045º/√hr. This is higher than the theoretical Brownian noise floor of 0.5º/hr and is attributed to the flicker noise of the interface electronics and common-mode interference.

Matched-Mode Temperature Characteristics

It is essential that the mode-matching is maintained over temperature. The M^2-TFG was tested under both matched and split-mode conditions to accurately determine the effects of temperature on device performance. Figure 11 shows the measured frequency variation of the individual (unmatched) resonant modes of a M^2-TFG sample as a function of temperature. Such a frequency shift is attributed to the temperature dependency of Young's modulus of SCS. The drive mode temperature coefficient of frequency (TCF) is measured to be about – 22 ppm/ºC. As seen in Fig. 11, the TCF of the drive and sense resonant modes vary by less than 1 ppm/˚C.

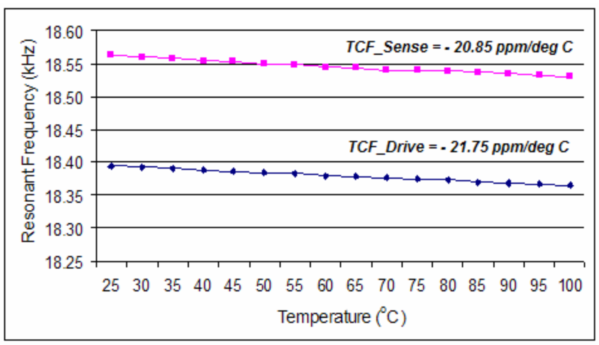


Figure 11: Temperature variation of the operating mode frequencies of a M2-TFG operating at 18.4 kHz.

The TCF data for a matched-mode device is shown in Fig. 12. It was found that the matched-mode condition is well maintained over temperature. Thermoelastic damping may be the reason why Q_{EFF} decreased at elevated temperature. The effect of degradation in Q is reflected in the Allan variance analysis at 70˚C which yielded a bias instability of 1.1 º/hr.

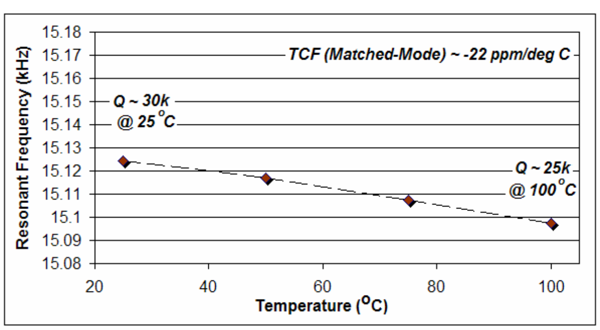


Figure 12: Temperature variation of the matched-mode resonant frequency of a M2-TFG operating at 15.1 kHz.

4. CONCLUSIONS

This paper presents the first reported demonstration of perfect mode matching in type I vibratory microgyroscopes operating with non-degenerate resonant modes. Table 1 summarizes the essential device parameters while clearly illustrating the performance advantage offered by mode-matching. Significant improvement in sensitivity, bias stability, and noise floor of vibratory microgyros is observed when the device is operated in matched-mode.

Table 1: Performance comparison of M2-TFG under two separate matching condition and basic device parameters

Device Parameter	Mismatched	Matched
Frequency split	2 Hz	0 Hz
Effective sense quality factor	10,000	40,000
Theoretical Brownian noise floor	1.1 °/h/√Hz	0.5 °/h/√Hz
Measured bias drift (at 25˚C)	5.4 °/h	0.96 °/h
Rate sensitivity	7.2 mV/°/s	24.2 mV/°/s
Effective mass	30 μg	
Drive amplitude	2.5 μm	
Temperature coeff. of frequency	-22 ppm/˚C	
Operating frequency	15 kHz	

The theoretical Brownian noise floor of the device is 0.5˚/hr with a measured bias stability of 0.96 ˚/h. By implementing the design on thicker substrates it is possible to attain 0.1˚/h resolution and bias stability performance which has been elusive in MEMS gyroscopes to date.

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