EIGENMODE OPERATION AS A QUADRATURE ERROR CANCELLATION TECHNIQUE FOR PIEZOELECTRIC RESONANT GYROSCOPES

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ABSTRACT

This paper presents a quadrature error cancellation technique based on the virtual alignment of the gyroscope excitation and readout electrodes to the actual direction of vibration mode shapes in the presence of fabrication non-idealities. The proposed method which is herein referred to as eigenmode operation, enables modal alignment of all-piezoelectric resonant gyroscopes and along with dynamic frequency matching via displacement feedback obviates the need for submicron capacitive gaps and relatively large DC voltages that are otherwise required for electrostatic mode matching. We demonstrate gyroscopic operation of a 3.1 MHz AlN-on-silicon annulus resonator, which utilizes a pair of high-*Q* degenerate in-plane vibration modes. The piezoelectric gyroscope shows a large operation bandwidth of ~150 Hz with a scale factor of 1.6 nA/°/s while operating in air, which greatly relaxes packaging requirements. Eigenmode operation results in ~35 dB reduction of the quadrature error at resonance.

INTRODUCTION

Resonant MEMS gyroscopes operate based on the transfer of energy between two vibration modes of the device due to Coriolis effect. The device is excited at the resonance frequency of the primary drive mode, and the rate-proportional Coriolis-induced signal is picked off along the secondary sense mode. If the resonance frequency of the sense mode matches that of the drive mode, the mechanical *Q*-amplification of the sense signal significantly improves the overall signal-to-noise ratio and relaxes the specification requirements of the interface circuitry.

To achieve high performance, it is crucial to ensure mode-matched operation of the gyroscope. However, mode-matching imposes a constraint on the maximum operation bandwidth of high-*Q* devices. The capacitive bulk acoustic wave (BAW) gyroscopes [1] circumvent this problem by increasing the resonance frequency of the device by taking advantage of stiff bulk vibration modes of the structure. The BAW gyroscopes have also proven to offer superior performance with shock and vibration immunity paving the way towards realization of short-range inertial navigation systems [2].

The recent advances in thin film deposition technology, along with inherent linearity and efficient in-air piezoelectric transduction [3, 4] have facilitated the design and implementation of piezoelectric gyroscopes. Thin-piezoelectric-on-substrate gyroscopes [5, 6] benefit from the advantages of capacitive BAW gyroscopes such as large resonant bandwidth and immunity to shock and vibration by using high-frequency degenerate vibration modes of the structure yet without the need for submicron gaps or large DC voltages that are required for electrostatic transduction. However, mode matching and alignment of these devices is challenging because of the lack of an electrostatic tuning and alignment mechanism.

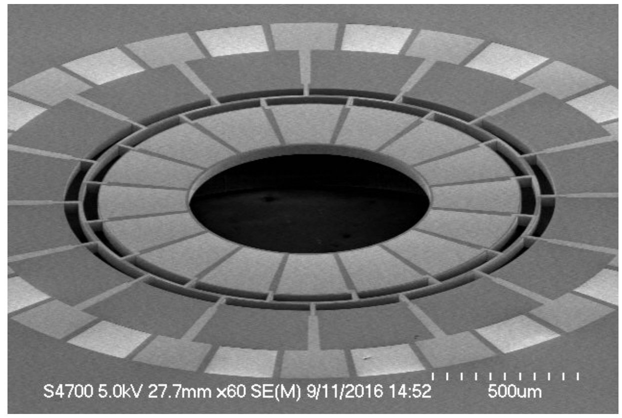

Figure 1: SEM image of the annulus piezoelectric resonant gyroscope, fabricated using a simple 4-mask AlN-on-Si process.

Dynamic frequency matching of piezoelectric gyroscopes has been demonstrated [6] based on the application of electromechanical displacement feedback [7, 8] to adjust the effective stiffness of the drive mode without the need for electrostatic tuning. Complete mode matching, however, also requires modal alignment to guarantee no intermodal coupling between the drive and sense modes. The present work introduces an alignment technique based on the virtual rotation of excitation electrodes to enable modal alignment of all-piezoelectric gyroscopes. The effectiveness of the proposed technique is verified by aligning the modes of a piezoelectric-on-silicon annulus resonator.

PIEZOELECTRIC GYROSCOPE DESIGN

It has been demonstrated that the degenerate in-plane flexural vibration mode shapes of square and disk structures [3, 4] are good candidates to provide gyroscopic functionality while enabling effective thin-film piezoelectric transduction. The same vibration mode shape can also be transduced in an annulus structure for gyroscopic operation and is used in this work to implement a thin-film-piezoelectric-on-silicon gyroscope. Figure 1 shows the SEM image of the annulus piezoelectric gyroscope introduced here. The device is comprised of a 1.3 µm thin film of AlN deposited in between 50 nm top and bottom molybdenum (Mo) electrode layers and stacked on top of a 35 µm thick (100) silicon structural layer. The annulus structure has an outer radius of 700 µm and inner radius of 400 µm and is anchored to the substrate through a network of 32 circularly symmetric T-supports to

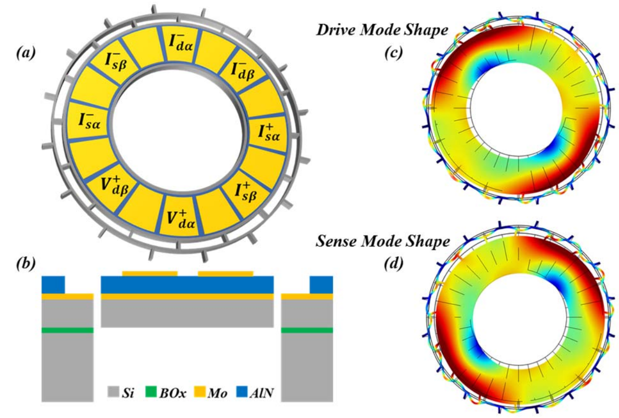

Figure 2: (a) schematic view of the annulus gyroscope with drive and sense signaling required for eigenmode operation, (b) cross-sectional view of the AlN-on-Si structure based on a 4-mask fabrication process, (c, d) in-plane flexural gyroscopic mode pair of an annulus structure provides an orthogonal path for the detection of Coriolis signal with efficient piezoelectric transduction.

ensure structural symmetry of the drive and sense modes. The support structure is also used for routing the electrical signals to the metal electrodes attached to the structure.

The schematic of the gyroscope structure and the cross-sectional view of the fabrication process are depicted in Figure 2a and 2b. The device is transduced using 16 identical top electrodes. The bottom Mo layer is used as common terminal between input and output ports. Because of the specific configuration of the interfacing technique, pairs of adjacent Mo electrodes are connected together to form an 8-terminal device. To implement eigenmode operation terminals that are spatially 45° apart are used for excitation and readout of the gyroscope signals. The device was fabricated using a simple 4-mask process similar to the one described in [4]. The pair of in-plane flexural gyroscopic mode shapes is shown in Figure 2c and 2d. The orthogonality of the two mode shapes provides a means for detection of Coriolis-induced signal for measurement of angular rate of rotation and the efficient transduction of this particular mode shape ensures low motional resistance, large scale factor and low level of mechanical noise of the device.

EIGENMODE OPERATION

Ideally, the proportional-to-rate Coriolis force is the only source of coupling between the drive and sense modes of resonant gyroscope. However, in reality, the misalignment of the natural vibration modes (eigenmodes) with respect to the location of the drive and sense electrodes gives rise to additional undesired coupling between the two resonance modes. This undesired coupling which causes the quadrature error in gyroscopes is modeled by considering stiffness terms in the drive and sense equations of motion of the gyroscope that cross-couple force and displacement of the two resonance modes. Assuming small damping, we can write the equations of motion as given in Equation 1.

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} k+\Delta k & k_{12} \\ k_{12} & k-\Delta k \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} f_1 \\ 0 \end{bmatrix} \qquad (1)$$

In the above equation, q_1 and q_2 are the generalized coordinates defined in the direction of the drive and sense electrodes, f_1 is the excitation force in the drive direction, m is the effective mass, k is the effective stiffness coefficient Δk represents the stiffness error in the drive and sense modes, and k_{12} is the cross-coupling stiffness coefficient. Using modal analysis, we can find the eigenfrequencies ($\omega_{1,2}$) and eigenmodes ($\boldsymbol{\varphi}_{1,2}$) corresponding to the above system of equations as follows.

$$\omega^2{}_{1,2} = \frac{k \pm \sqrt{\Delta k^2 + {k_{12}}^2}}{m} \qquad (2)$$

$$\boldsymbol{\varphi}_{1,2} = \begin{bmatrix} 1 \\ \dfrac{\Delta k \pm \sqrt{\Delta k^2 + {k_{12}}^2}}{k_{12}} \end{bmatrix} \qquad (3)$$

Quadrature error cancellation is concerned with the elimination of the cross-coupling stiffness terms from the equations of motion as modeled along the physical direction of transduction electrodes and hence aligning the modes to the direction of electrodes. It is achieved either by permanent trimming of the device structure [9] or by real-time electrostatic adjustment of the direction of transduction.

Alternatively, it is possible to cancel the quadrature error by adjusting the direction of transduction to the eigenmode direction or in other words, by applying a rotation to the equations of motion such that the coupling terms are removed in the new rotated system. By definition, there is no coupling between the equations of motion as defined in the direction of the eigenmodes (Equation 3). This method of operating the gyroscope based on the natural modes of vibration is herein referred to as eigenmode operation.

Since the eigenmode direction is only determined post

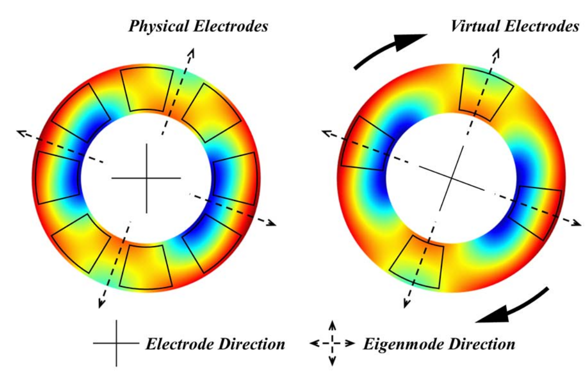

Figure 3: Schematic illustration of the eigenmode operation. The natural vibration modes are misaligned with respect to electrodes as fabricated (left), by applying scaling factors to electrode pairs that are spatially apart, we can virtually control the location of the effective excitation and readout electrodes to align them with eigenmodes (right).

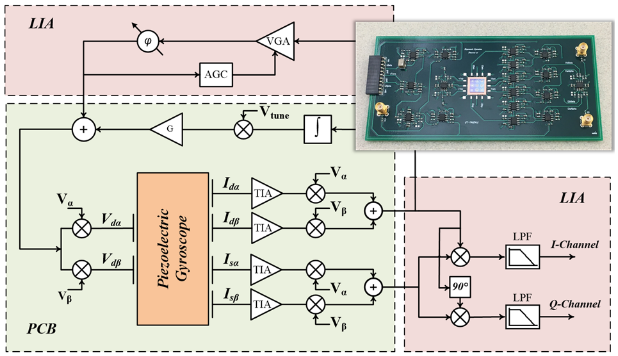

Figure 4: Interface architecture for eigenmode operation. The board is interfaced with an HF2LI lock-in amplifier from Zurich Instruments. The inset shows the system implemented on a prototype PCB.

fabrication, it is not possible to assign dedicated electrodes in the direction of eigenmodes. However, by using two electrodes that span the 2D subspace and by applying scaling factors α and $(1-\alpha)$ to the transduction of the two electrodes, where α is swept from 0 to 1, it is possible to create a virtual electrode and electronically control its effective location. Quadrature cancellation can now be achieved simply by adjusting the value of α to align the effective direction of transduction to the eigenmodes. In theory, the misalignment angle between the electrode location and the direction of eigenmode could be as large as 90°, as can be inferred from Equation 3, but in practice the misalignment angle is usually much smaller. In this work, electrodes that are 45° apart are used for virtual electrode alignment to the direction of eigenmodes.

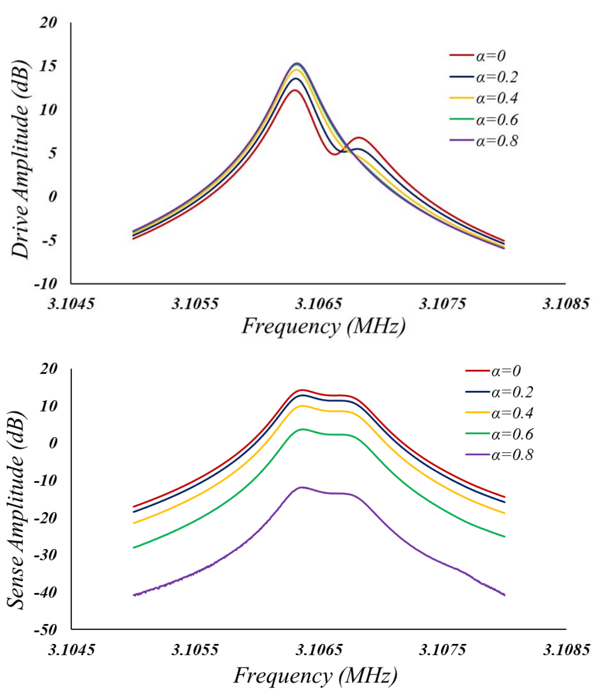

Figure 5: Drive and sense mode response of the gyroscope for different levels of the weighting factor α. For α=0.8, the resultant transduction direction is closest to the eigenmode direction; the sense-mode peak disappears from the drive response and the sense-mode amplitude is significantly reduced.

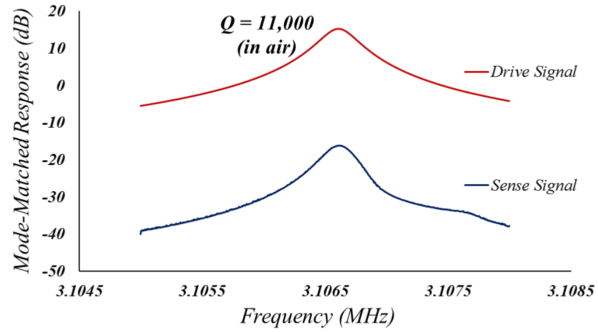

Figure 6: Drive and sense mode frequency response at perfect mode-matched conditions. The sense response is minimized and the drive and sense frequencies are matched by iterative adjustment of the factor α for modal alignment and the level of displacement feedback for frequency matching.

EXPERIMENTAL RESULTS

Eigenmode operation circuitry for the piezoelectric annulus gyroscope was implemented on a printed circuit board, and the device was interfaced with a lock-in amplifier to realize the drive loop and sense channel. The excitation electrodes of the gyroscope were scaled using two input multipliers to apply the coefficients of α and $1-\alpha$ with proper normalization factors. The same scaling factors were used to scale the drive output and the differential sense output signals to generate the effective drive and sense currents from the pickoff electrodes. The effective drive current is used in a feedback loop after integration to provide the displacement signal necessary for dynamic frequency tuning. The level of frequency tuning is adjusted by an external signal to control the amplitude of the displacement feedback.

Drive and sense mode response of the gyroscope for different levels of the weighting factor α are shown in Figures 5. For α=0.8, the direction of the virtual transduction electrode is closest to the eigenmode direction causing the sense-mode peak to disappear from the drive frequency response and the sense-mode response to be reduced significantly, showing the effectiveness of this method in canceling the quadrature error in vibratory gyroscopes.

Perfect mode matching, where the sense mode response is minimized and the drive and sense frequencies are equal, is achieved by iterative adjustment of the factor α and matching the drive and sense frequencies by adjusting the level of the displacement feedback as shown in Figure 6.

The Coriolis response of the annulus piezoelectric gyroscope to applied external rotation rate was measured using a rate table and a large scale factor of 1.6 nA/°/s was recorded (Figure 7). Allan deviation plot for the annulus gyroscope, showing a bias instability of 270 °/hr and an ARW of 1.6 °/√hr is given in Figure 8. The bias stability of device

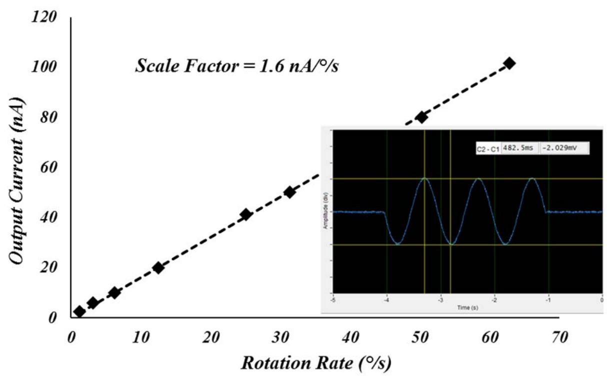

Figure 7: Measured Coriolis response of the annulus piezoelectric gyroscope to external rotation. The device shows a large scale factor of 1.6 nA/°/s. the inset shows the output signal for three cycles of sinusoidal rotation.

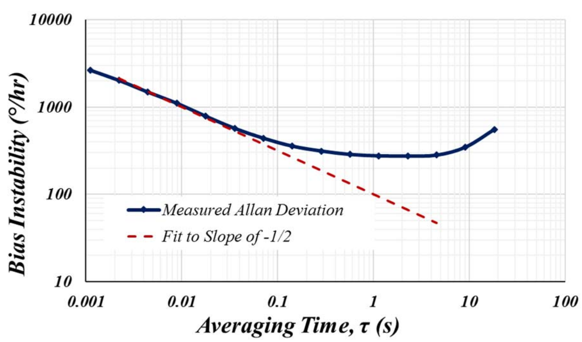

Figure 8: Allan deviation plot for the annulus piezoelectric gyroscope showing a bias instability of 270 °/hr and an ARW of 1.6 °/√hr. The bias stability is limited by the flicker noise of the scaling voltages and the mismatch between the input and output analog multipliers.

is limited mainly by the mismatch of analog components on the board and by the flicker noise of the DC voltages used for scaling the effective transduction of electrodes. Since the added noise in the scaling voltages α and $1-\alpha$ is up-converted by the input mixer to the resonance frequency of the gyroscope and then at the output is down-converted with the Coriolis signal, it is important to generate these signals with as little low-frequency noise as possible.

CONCLUSION

This work introduced eigenmode operation as a quadrature error cancellation technique to enable all-piezoelectric modal alignment of resonant gyroscopes. The gyroscopic operation of a piezoelectric annulus resonator which utilizes a pair of degenerate high-frequency in-plane flexural vibration modes was demonstrated. The effectiveness of the eigenmode operation in cancelling the quadrature signal was shown by reducing the amplitude of the indirect response of the annulus gyroscope. Frequency matching of the two modes was achieved by applying displacement feedback to control the effective stiffness of the drive mode. The 3.1 MHz annulus piezoelectric gyroscope demonstrates a large operation bandwidth of ~150 Hz with a scale factor of 1.6 nA/°/s and ARW of 1.6 °/√hr while operating in air which significantly relaxes the wafer-level packaging requirements of the device.

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REFERENCES

[1] H. Johari and F. Ayazi, "Capacitive Bulk Acoustic Wave Silicon Disk Gyroscopes," *International Electron Devices Meeting*, San Francisco, CA, 2006, pp. 513-516.
[2] F. Ayazi, "Multi-DOF inertial MEMS: From gaming to dead reckoning," *16th International Solid-State Sensors, Actuators and Microsystems Conference*, Beijing, 2011, pp. 2805-2808.
[3] R. Abdolvand et al., "Thin-film piezoelectric-on-silicon resonators for high-frequency reference oscillator applications," in *IEEE Transactions on UFFC*, vol. 55, no. 12, pp. 2596-2606, December 2008.
[4] W. Pan and F. Ayazi, "Thin-film piezoelectric-on-substrate resonators with Q enhancement and TCF reduction," *Micro Electro Mechanical Systems (MEMS), IEEE 23rd International Conference on*, Wanchai, Hong Kong, 2010, pp. 727-730.
[5] R. Tabrizian et al., "High-Frequency AlN-on-Silicon Resonant Square Gyroscopes," *J. Microelectromech. Systems,* vol.22, no.5, pp.1007, 1009, Oct. 2013.
[6] M. Hodjat-Shamami et al., "A dynamically mode-matched piezoelectrically transduced high-frequency flexural disk gyroscope," *in Proc. Micro Electro Mechanical Systems (MEMS)*, 2015, pp. 789-792.
[7] N. A. Hall et al., "Micromachined Accelerometers with Optical Interferometric Read-Out and Integrated Electrostatic Actuation," in *J. Microelectromechanical Systems*, vol. 17, no. 1, pp. 37-44, Feb. 2008.
[8] A. Norouzpour-Shirazi et al., "Dynamic tuning of MEMS resonators via electromechanical feedback," in *IEEE Transactions on UFFC*, vol. 62, no. 1, pp. 129-137, January 2015.
[9] B. Hamelin et al., "Localized Eutectic Trimming of Polysilicon Microhemispherical Resonating Gyroscopes," in *IEEE Sensors Journal*, vol. 14, no. 10, pp. 3498-3505, Oct. 2014

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