Design and Simulation of an Orbiting Piezoelectric MEMS Gyroscope Based on Detection of Phase-Shift Signals

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Abstract

MEMS vibratory gyroscopes are based on excitation of a primary vibration mode of a mass on springs, and detection of the mass motion due to the Coriolis force in the direction orthogonal to the primary mode. MEMS gyroscopes typically rely on electrostatic actuation to excite the primary mode, however piezoactuation is an attractive alternative because the electromechanical coupling is stronger, and no DC-bias or narrow gaps are required. Furthermore, the piezoelectric actuators can be processed directly on top of mechanical supporting springs thus reducing the form factor of the device. By using differential piezoactuation (Figure 1) linear motion of the proof mass in the wafer plane can be achieved.

In a two degrees of freedom system, driving both identical and orthogonal modes into resonance with harmonic excitations having $\pi/2$ rad phase difference results in the proof mass performing a motion along a circular path about its centre of mass. External rotation of such a resonance system modifies its mechanical response which is manifested as a phase-shift that is nearly proportional to the angular rate [1]. The device, therefore, can operate as a phase-sensitive gyroscope with potentially greater sensitivity and simplified read-out electronics compared to conventional MEMS gyroscopes relying on amplitude-signals.

In this study the feasibility of phase-sensitive detection of angular rates using bi-directional orbiting piezoresonators suspended by thick annular springs with thin-film aluminium nitride (AlN) piezoactuators processed directly on top of them (Figure 2) was investigated using Piezoelectric Devices interface of COMSOL Multiphysics® software. The ring-shaped flexures were found to be more suitable for supporting the orbiting motion due to their angle-dependent spring constant (Fig. 2c,d). The performance of the resonators was simulated in a variety of drive-sense configurations (e.g., one- or two-port) in frequency domain by applying harmonic voltages with appropriate phases to the corresponding piezolayers (Figure 1 and 2). The equations of motion were modified to account for the action of the Coriolis force on the proof mass. The response of the orbiting resonators to the angular rates was obtained from the phase-shift at the resonance frequency of the motional current that was derived by integration of the current density from corresponding piezolayers' boundaries (Figure 3).

The analytical and derived from simulations sensitivity in terms of phase-shift per degree/s of angular rate for different quality factors of the system having identical X- and Y-modes is shown in Figure 4. The good agreement between the theoretical and simulated sensitivity of the orbiting piezo-gyroscopes validates the applicability of simulation to model more complex behavior of the system not easily treatable analytically, e.g., response to the angular rates of the system having a mismatch between the resonance frequencies of the orthogonal modes, effect of the structural non-idealities leading for non-symmetric driving/sensing between the modes, as well as verifying various driving and read-out schemes. The results of this study are important for understanding the design trade-offs in the phase-sensitive orbiting piezo-gyroscope.

Reference

[1] M. Dalal, A.N. Shirazi, W.K. Sung, G. Casinovi, F. Ayazi, Novel read-out scheme for MEMS vibratory gyroscopes based on signal phase shift, Solid-State Sensors, Acuators and Microsystems Worshop (2012) 328-331.

Figures used in the abstract

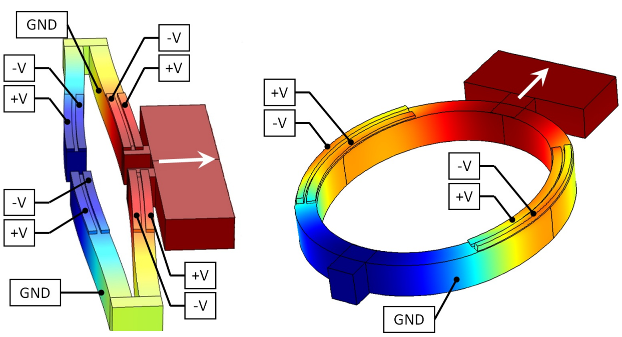

Figure 1: FEM simulation of a linear resonator with piezoactuating stripes processed directly on the Si flexures (left) straight folded beams, (right) ring-shaped beam. By applying voltage V of different polarities across the corresponding piezolayers, in-plane bending can be achieved.

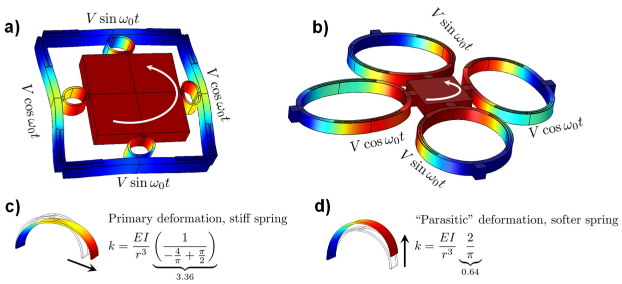

Figure 2: Simulated displacements of a proof mass due to voltages applied to the piezoactuators processed on (a) straight Si beams with circular decouplers, (b) annular, ring-shaped beams. The systems in (a) and (b) have two orthogonal resonance modes along X- and Y-axis. Driving both identical and orthogonal modes into resonance with harmonic voltages having 90 degrees phase difference results in the proof mass performing a motion along a circular path about its centre of mass (orbiting). (c, d) The ring-shaped suspension is suitable for supporting orbiting motion due to the angle-dependent spring constant. The spring constant in “parasitic” deformation is considerably smaller (factor of 5 analytically and factor of 7 from simulations) allowing decoupling of the orthogonal modes.

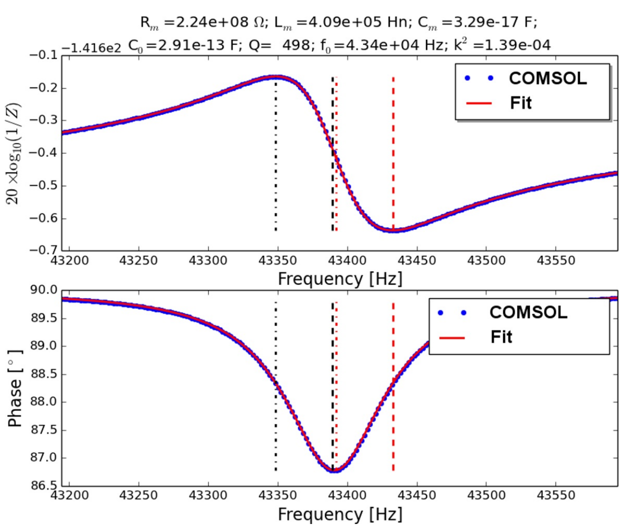

Figure 3: Figure 3. Frequency domain simulation of the AC-current per 1V excitation (admittance) through the piezoelectric layers in one-port configuration drive for a design shown in Figure 3b with the resonance frequency of 44.3 kHz and assumed quality factor of 500. In the simulation 1 V excitation in one-port configuration of both modes with 90 degrees phase difference between the X- and Y-modes excitation was applied. The current was obtained by integration of the current density over the piezoelectric boundaries. The current amplitude (top) and its phase with respect to the voltage excitation (bottom) are for the X-mode. The frequency response of the resonator can be represented as an equivalent circuit consisting of mechanical resistance Rm, inductance Lm and capacitance Cm branch connected in parallel with a static capacitance C0 of the piezoelectric layers. The results of the fit are shown in the title of the figure.

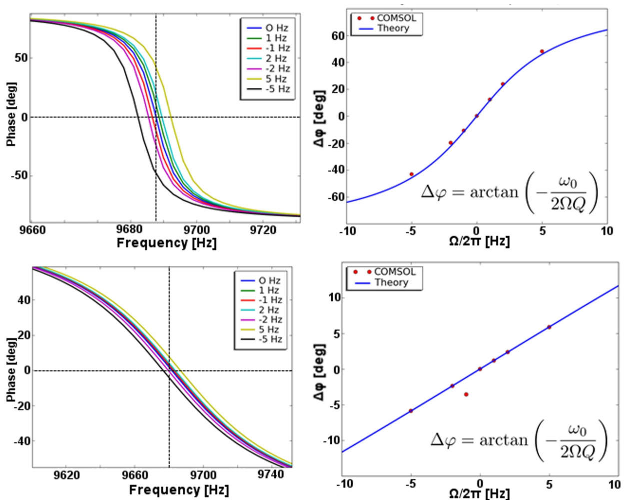

Figure 4: Figure 4. (left) Frequency domain simulation of the phase of the motional current through the piezoelectric layers in two-port configuration drive for a design shown in Figure 3a with the resonance frequency of ~10 kHz and assumed quality factors of 1000 (top) and 100 (bottom). The X- and Y-modes are identical. Due to the external angular rates and hence introduction of Coriolis force into the equation of motion of the system, the phase at the resonance frequency is shifted. (right) Phase-shifts for various external angular rates derived from simulation are compared with theoretical values according to the expression show in the plots showing very good agreement.