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

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Orbiting MEMS gyroscope: By driving identical and orthogonal modes of a mass-on-springs system into resonance with harmonic excitations having π/2 rad phase difference, orbiting motion of the proof mass can be achieved. External rotation of the system modifies its mechanical response manifested in a phase-shift at resonance that is nearly proportional to the angular rates. The motion of the proof mass can be generates using thin-film differential piezoactuators processed directly on top of supporting springs.

Thin-film in-plane piezoelectric actuation: In-plane actuation can be achieved byh using thin piezoelectric layers on top of thick linear and ring-shaped beams. By applying voltage of different polarities across the corresponding piezolayers, in-plane bending is produced. The stresses $\pm\sigma_x$ in the corresponding piezolayers are a result of applied voltages, V. The bending moment ***M*** acting on the host beam can be obtained from integration of force couples due to $\pm\,\sigma_x$.

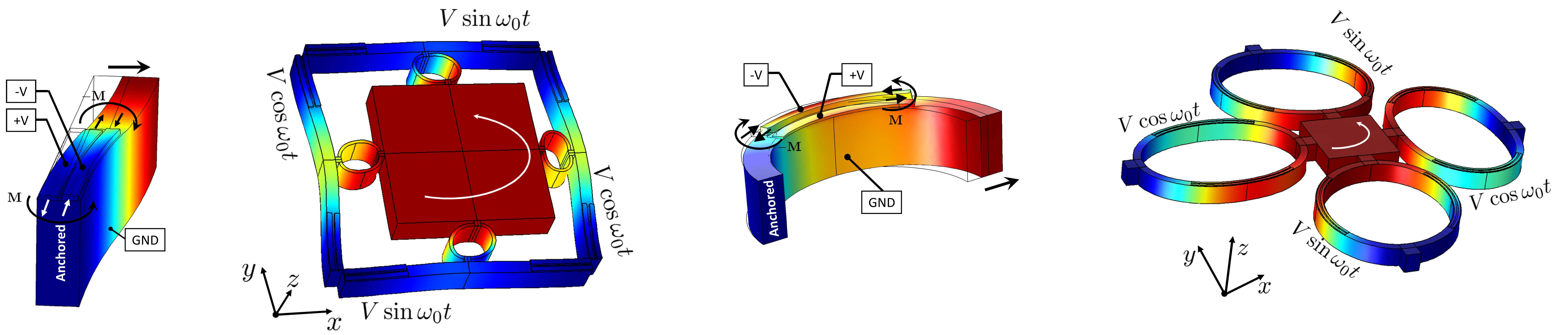


Figure 1*. Simulated displacements due to the voltages applied to the piezoactuators on straight and curved (ring-shaped, annular) beams. Orbiting resonators having two identical and orthogonal modes can be based on linear actuators with ring-shaped decouplers or on ring-shaped actuators.*

Ring-shaped springs: Annular springs' compliance have pronounced dependence on the direction of deformation allowing decoupling of the orthogonal modes. The spring constant in the primary direction of vibration (force F at 0 degrees) is ~7 higher than the "parasitic" spring constant in the "shear" deformation (force at 90 degrees to the direction of primary vibration). The ratio between the spring constants can be increased by reorienting the springs in the wafer plane.

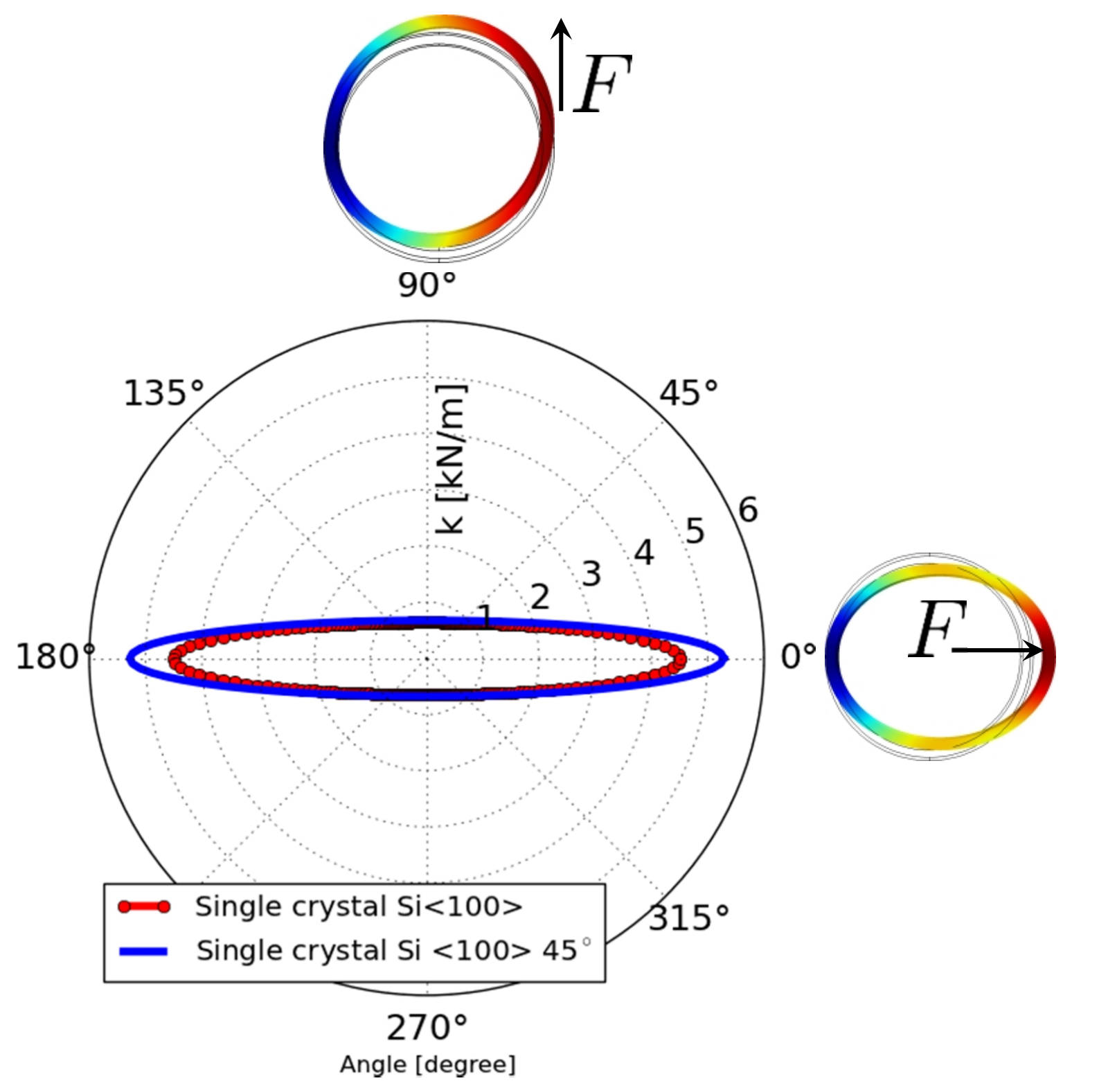


Figure 2*. Angle-dependent compliance of a ring-shaped spring.*

Simulation of sensitivity to angular rates: Phase shifts for angular rates derived from simulation for systems with different resonance frequencies and Q-factors are compared with analytical values $\varphi = \tan^{-1}\frac{-\omega_0^2}{2Q\Omega}$. The sensitivity to angular rates for a given system is linear in a certain range of angular rates.

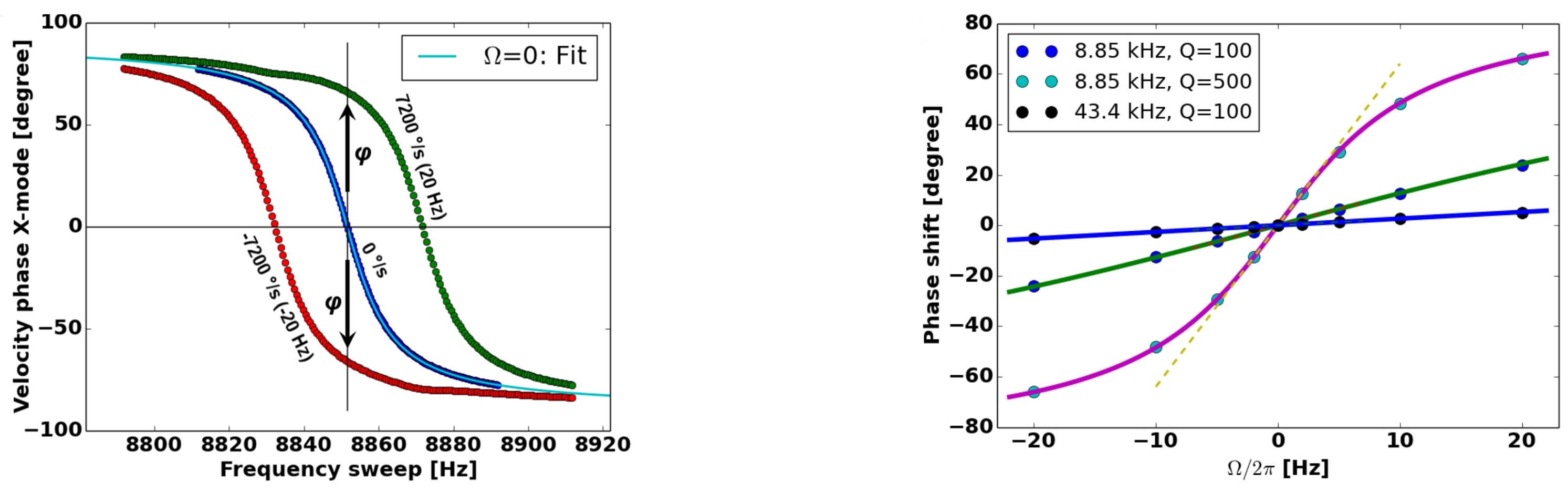


Figure 3*. Sensitivities of different orbiting piezogyroscopes.*

Frequency mismatch: Microfabrication imperfections and geometrical non-idealities in actual devices often lead to mismatch of the orthogonal modes' frequencies. The impact of the resonance frequency mismatch on the sensitivity of orbiting piezogyroscope was investigated. The system has the highest sensitivity at Δf=0, that decreases rapidly to zero as Δf increases. This decrease of the sensitivity is associated with the reduced mechanical amplitude of the Y-mode when the system is driven into orbiting motion at the resonance frequency of the X-mode.

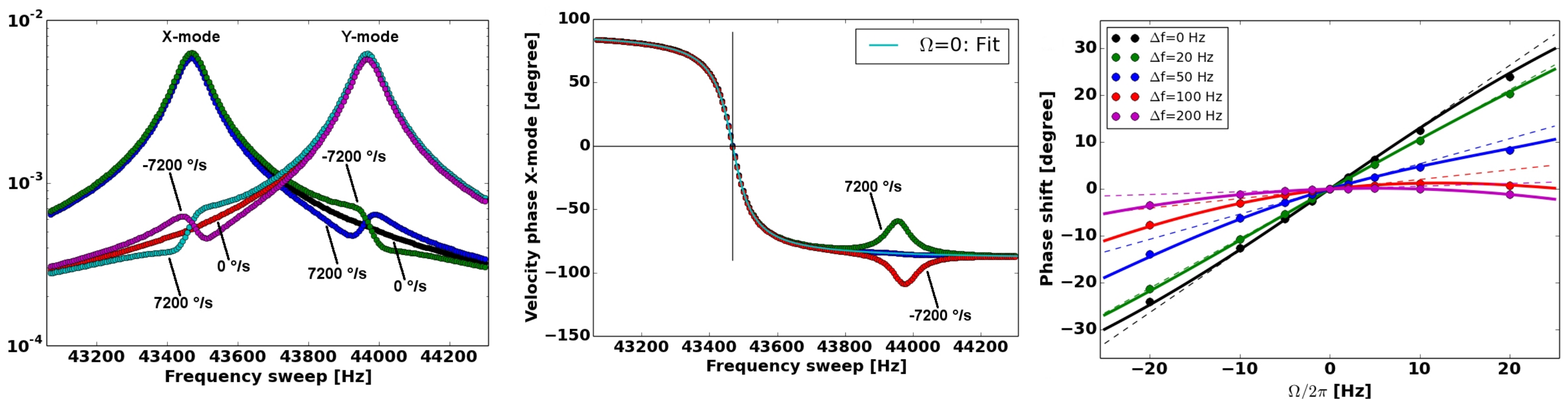


Figure 4*. Amplitude, phase and sensitivity in gyroscope with frequencies mismatch.*

Amplitude matching: Reduced Y-amplitude compared to the X-amplitudes implies that the proof mass orbits about an elliptical rather than circular path. Driving the Y-mode at higher voltage increases the Y-amplitude to the same level with the X-amplitude at resonance enabling circular orbiting motion of the mass and increasing the sensitivity.

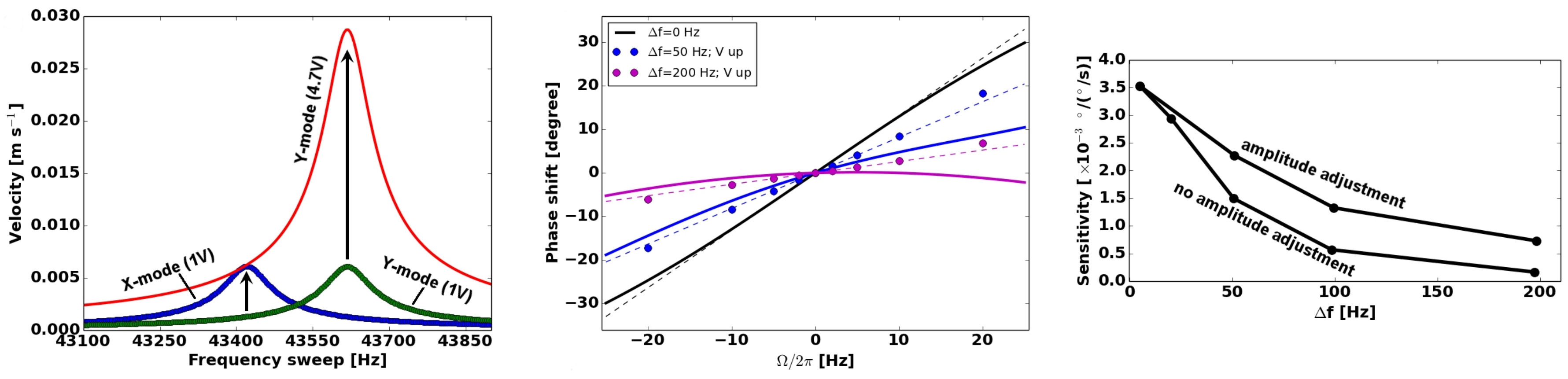


Figure 5*. Amplitude-matching improves the sensitivity in gyroscope with mismatch in resonance frequencies of the orthogonal modes.*

Experiment: Experimentally, the devices have high Q-factors (up to 20,000) in vacuum. Higher sensitivities are expected due to the high Q-factors, however, at the expense of the linearity.

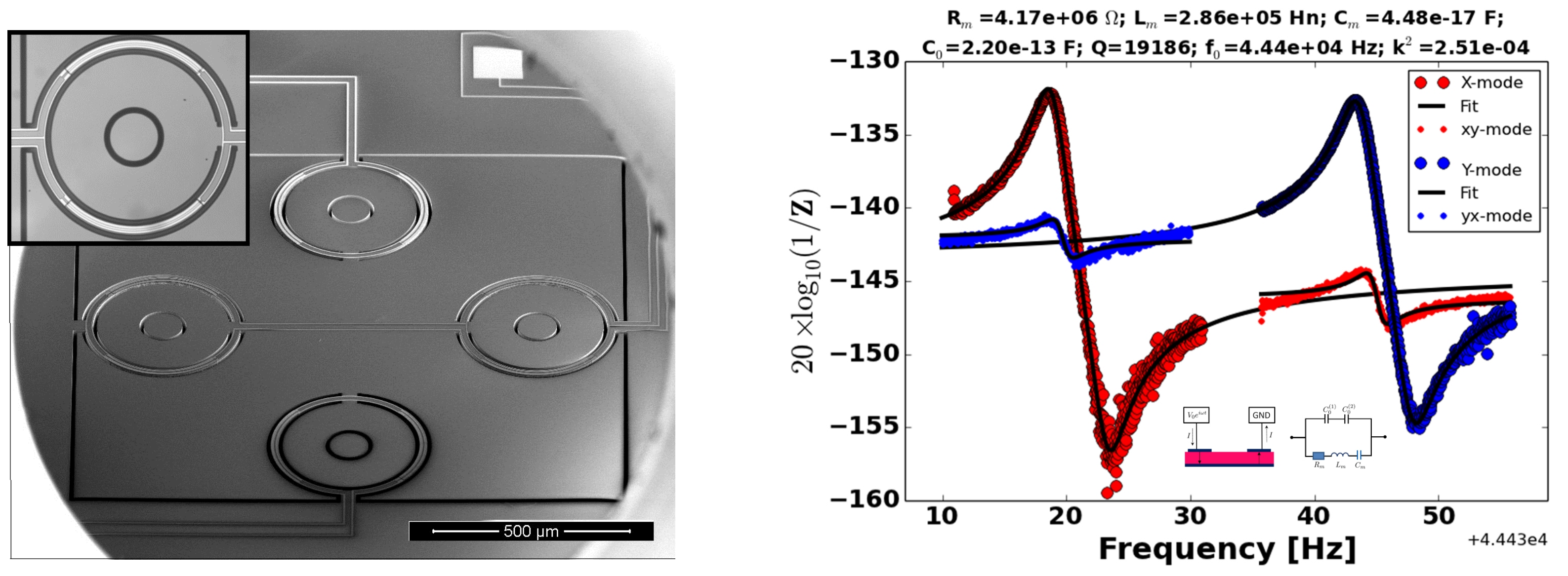
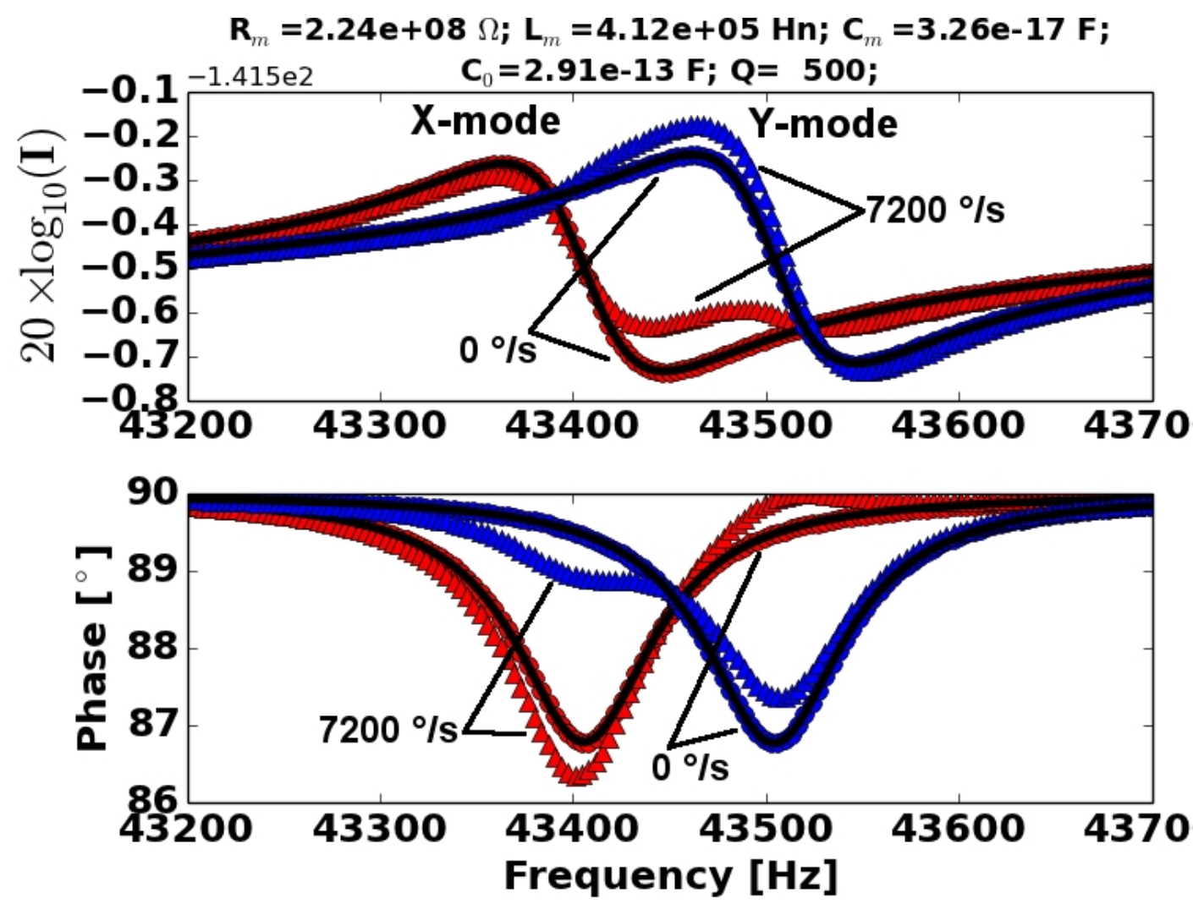


Figure 5*. Fabricated device and its electrical characterization (mode mismatch is 25 Hz).*

Equivalent circuit parameters: The electrical performance of devices can be simulated and equivalent circuit parameters fitted ($R_mL_mC_m$-$C0$) for comparison with the experimental performance



Conclusions:

- Orbiting gyroscopes actuated by means of thin-film piezoelectric layers were simulated and their sensitivities to angular rates evaluated
- Effect of modes frequencies mismatch can be mitigated by amplitude-matching of the modes
- Electrical performance can be directly obtained from the simulation and various drive-sense scenarios can be easily compared

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