COMSOL CONFERENCE
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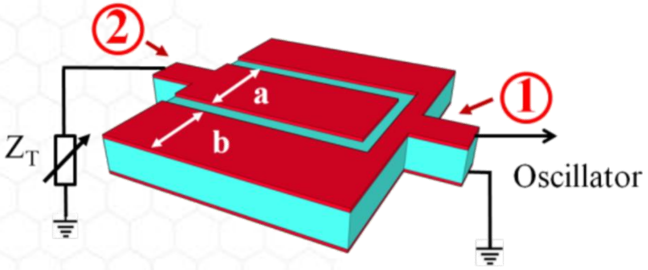
Active Control of MEMS Resonator Parameters via Electromechanical Feedback

Mojtaba Hodjat-Shamami and Farrokh Ayazi
Integrated MEMS Laboratory
Georgia Institute of Technology

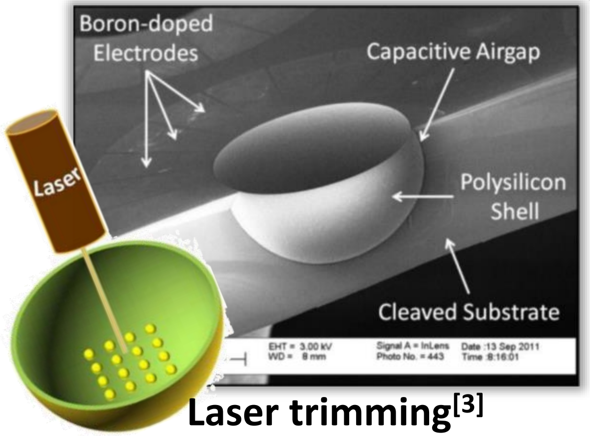
Creating the Next®

Resonance Frequency and Q control

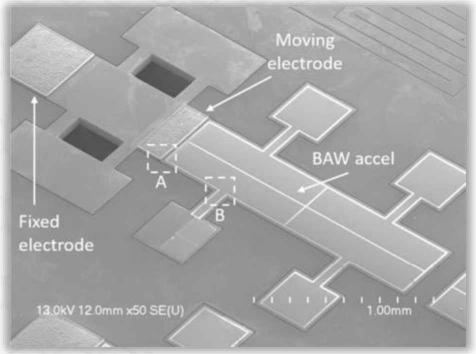
- Control of resonance parameters
  - High-precision resonant sensors[4-7]
    - Mode-matched gyroscopes
    - Resonant accelerometers
  - Tunability of timing elements
    - Mechanical oscillators and filters
  - Fast response time in actuators[2]
    - Atomic force microscopes



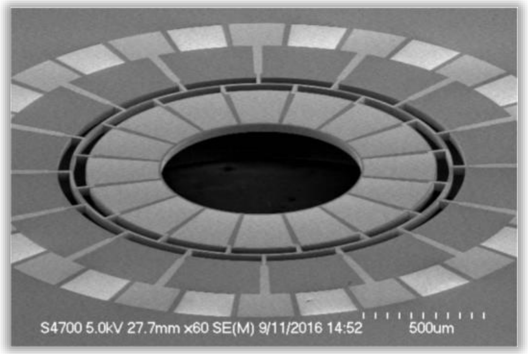
Termination impedance Tuning[1]



Laser trimming[3]



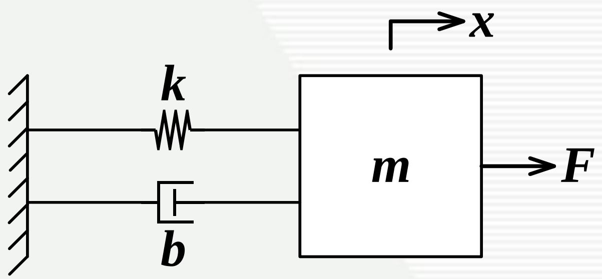
Electrostatic tuning[4]

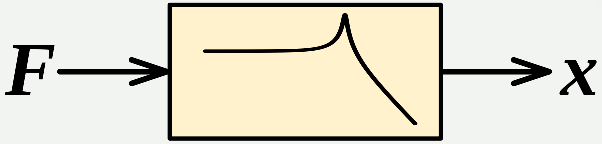


Dynamic feedback tuning[7]

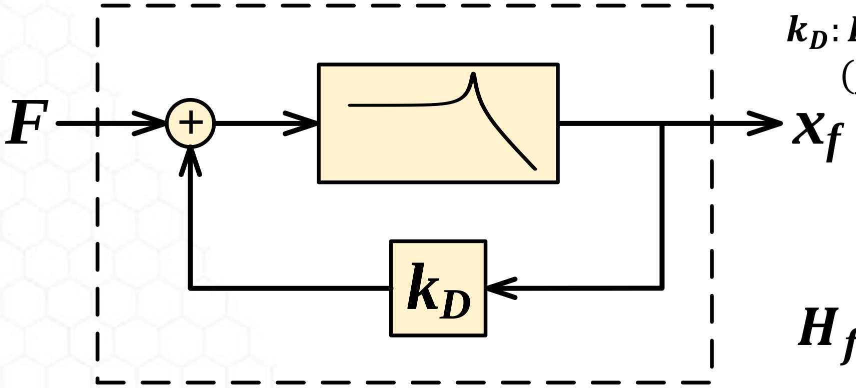
Dynamic electromechanical feedback enables bidirectional real-time tuning of both the resonance frequency and quality factor regardless of transduction mechanism

Dynamic Frequency Tuning





$$H(s) = \frac{x(s)}{F(s)}$$



k_D: *Dynamic stiffness (feedback gain)*

$$H_f(s) = \frac{x_f(s)}{F(s)}$$

$$H(s) = \frac{1/k}{\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\frac{s}{\omega_o} + 1}$$

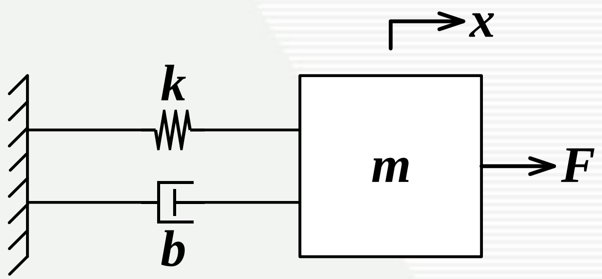
$$H_f(s) = \frac{1/k}{\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\frac{s}{\omega_o} + \left(1 - \frac{k_D}{k}\right)}$$

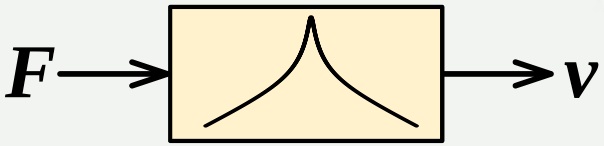
$$\omega_{90^\circ} = \omega_o$$

$$\omega_{f,90^\circ} = \omega_o\sqrt{\left(1 - \frac{k_D}{k}\right)}$$

Displacement-proportional force changes the effective stiffness!

Dynamic Quality Factor Tuning

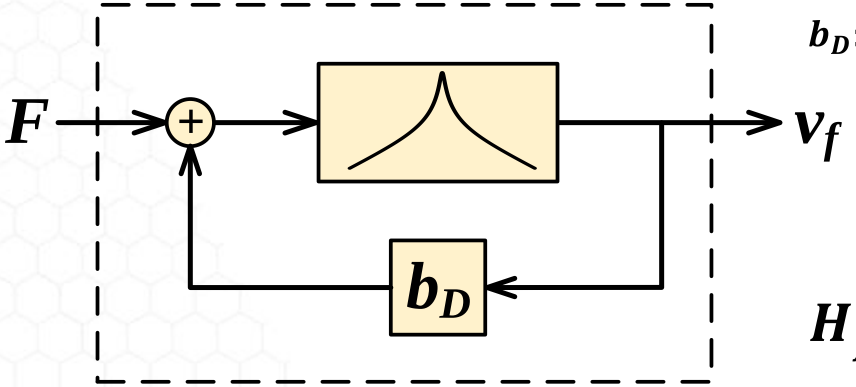




$$H(s) = \frac{v(s)}{F(s)}$$

$$H(s) = \frac{s/(b\omega_o Q)}{\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\frac{s}{\omega_o} + 1}$$

$$Q_{0^\circ} = Q_o$$



b_D: *Dynamic damping (feedback gain)*

$$H_f(s) = \frac{v_f(s)}{F(s)}$$

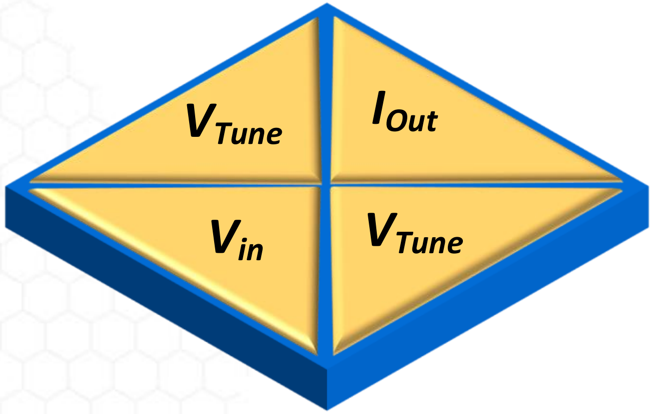
$$H_f(s) = \frac{s/(b\omega_o Q)}{\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\left(1 - \frac{b_D}{b}\right)\frac{s}{\omega_o} + 1}$$

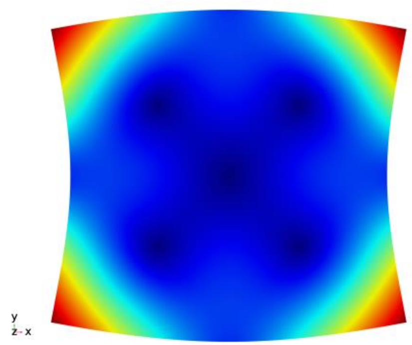
$$Q_{f,0^\circ} = \frac{Q}{1 - \frac{b_D}{b}}$$

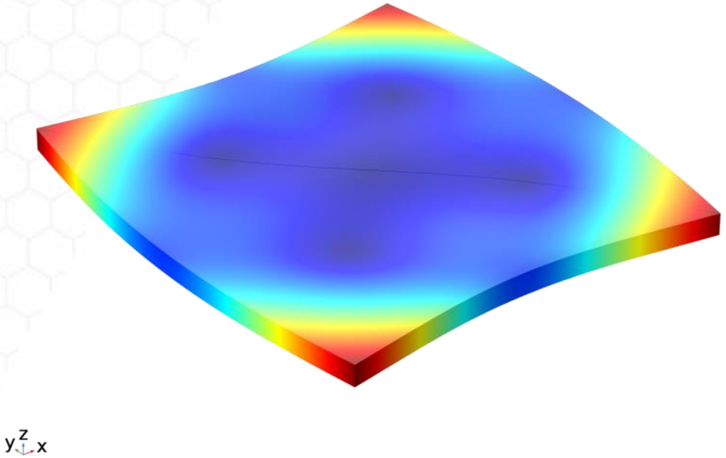
Velocity-proportional force changes the effective damping!

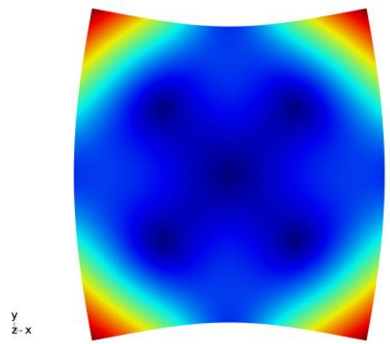
COMSOL Simulation Setup

- Multiphysics simulation for the AlN-on-Si MEMS resonator with feedback
  - Solid Mechanics Interface: Solve equations of motion in both the AlN and Si domains
  - Electrostatics Interface: Solve Gauss's law in the AlN domain
  - Global ODEs and DAEs Interface: Store the output current value to implement feedback
- Eigenfrequency and Parametric Frequency Domain studies
- Square structure to support the second-order in-plane flexural vibration mode







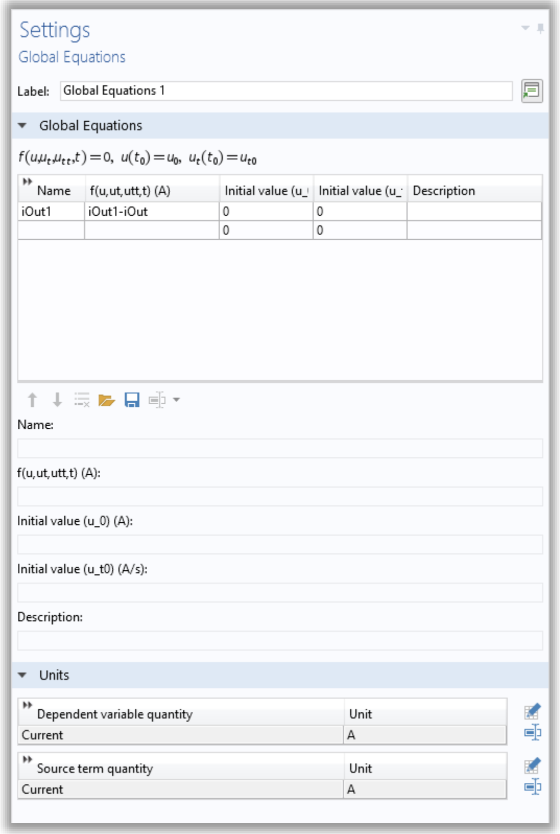


Feedback Implementation in COMSOL

- Output current signal $(iOut)$ is defined by surface integration of the current density on the output electrode.
- Global ODEs and DAEs interface is used to store the output current value which is in turn used to compute the displacement/velocity feedback signal.
- The nojac() operator must be applied to the stored solution to avoid changing the Jacobian matrix.

$$V_{tune,\,f} = nojac(iOut1) \times 1j \times gain$$

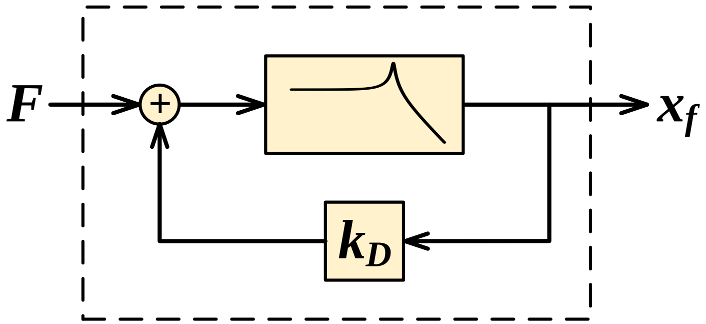
$$V_{tune,\,Q} = nojac(iOut1) \times gain$$

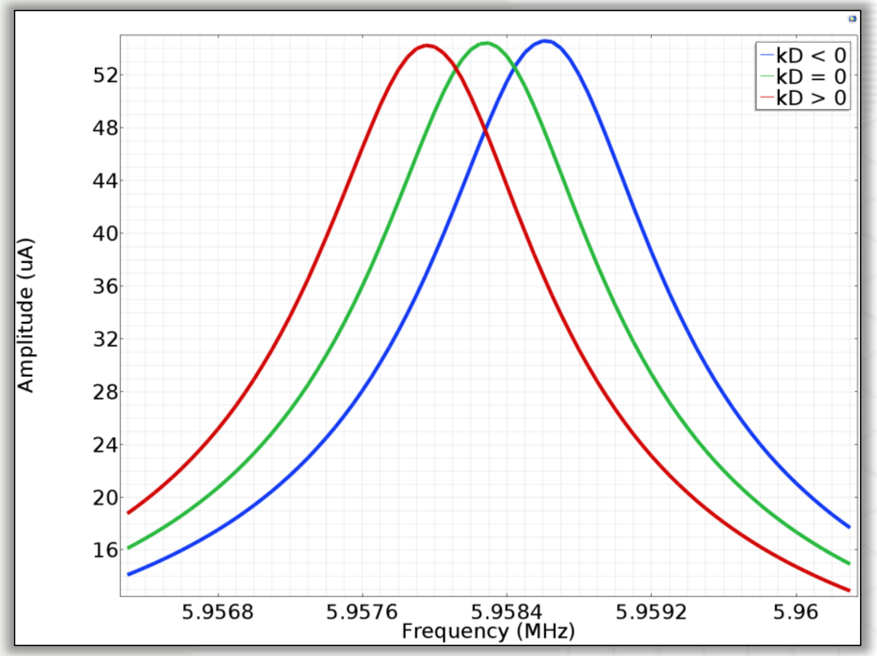


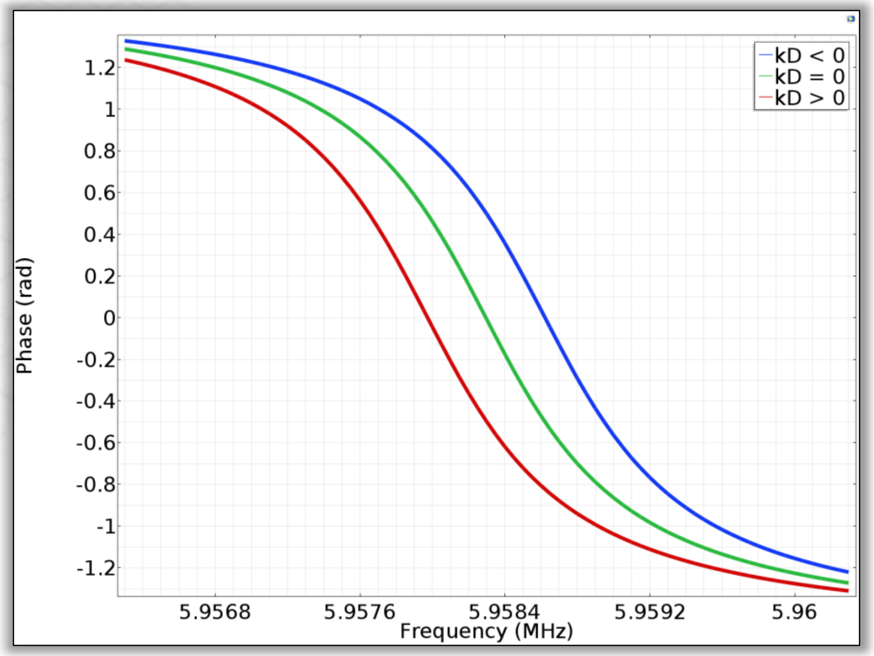
Global ODEs and DAEs interface and the nojac() operator are key additions to the Piezoelectric Multiphysics for implementation of the feedback channel.

FREQUENCY TUNING – SIMULATION RESULTS

- Displacement feedback applied by phase shifting the output current signal by 90°
- Resonance frequency is controlled by changing the displacement feedback gain parameter

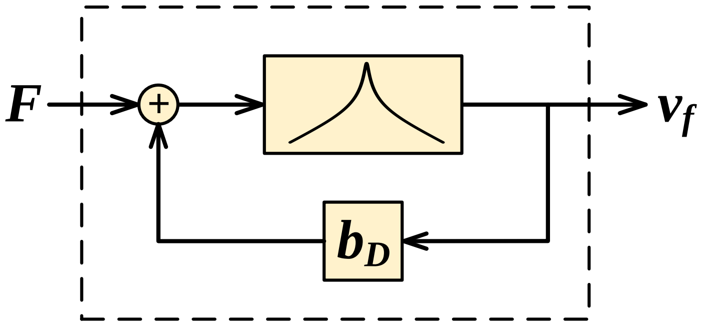


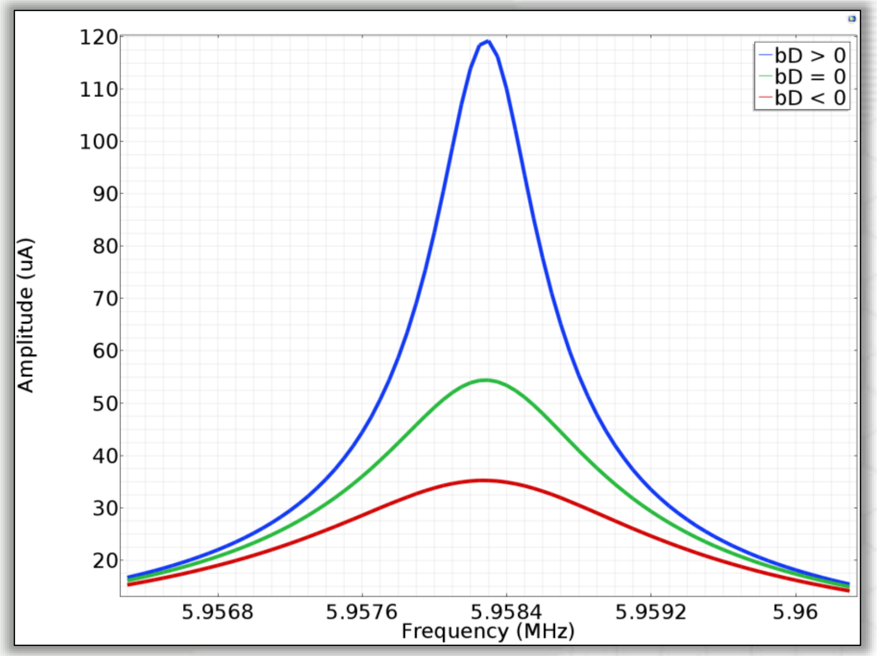


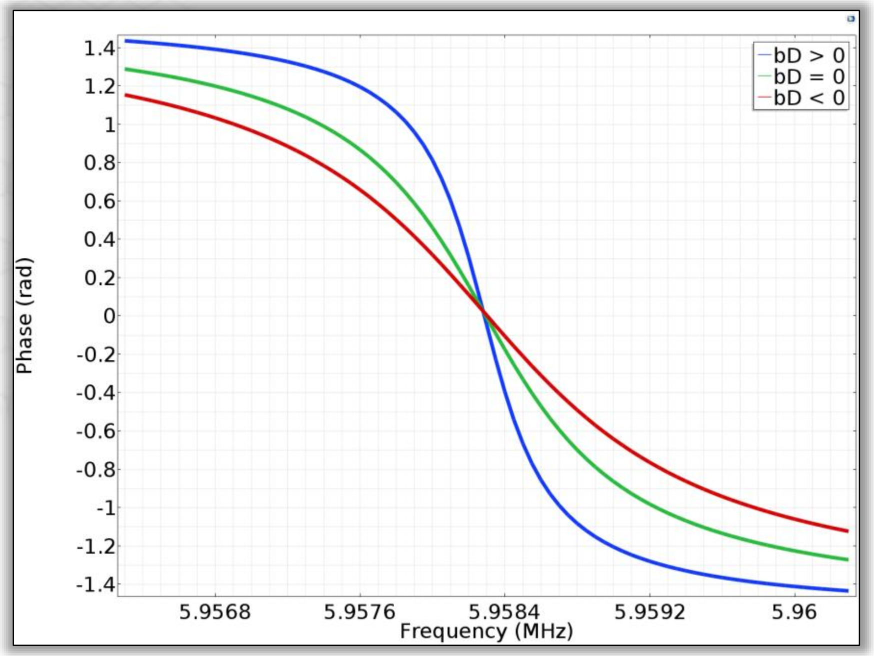


Q Tuning – Simulation Results

- Velocity feedback applied as a signal proportional to the output current signal
- Quality factor is controlled by changing the velocity feedback gain parameter

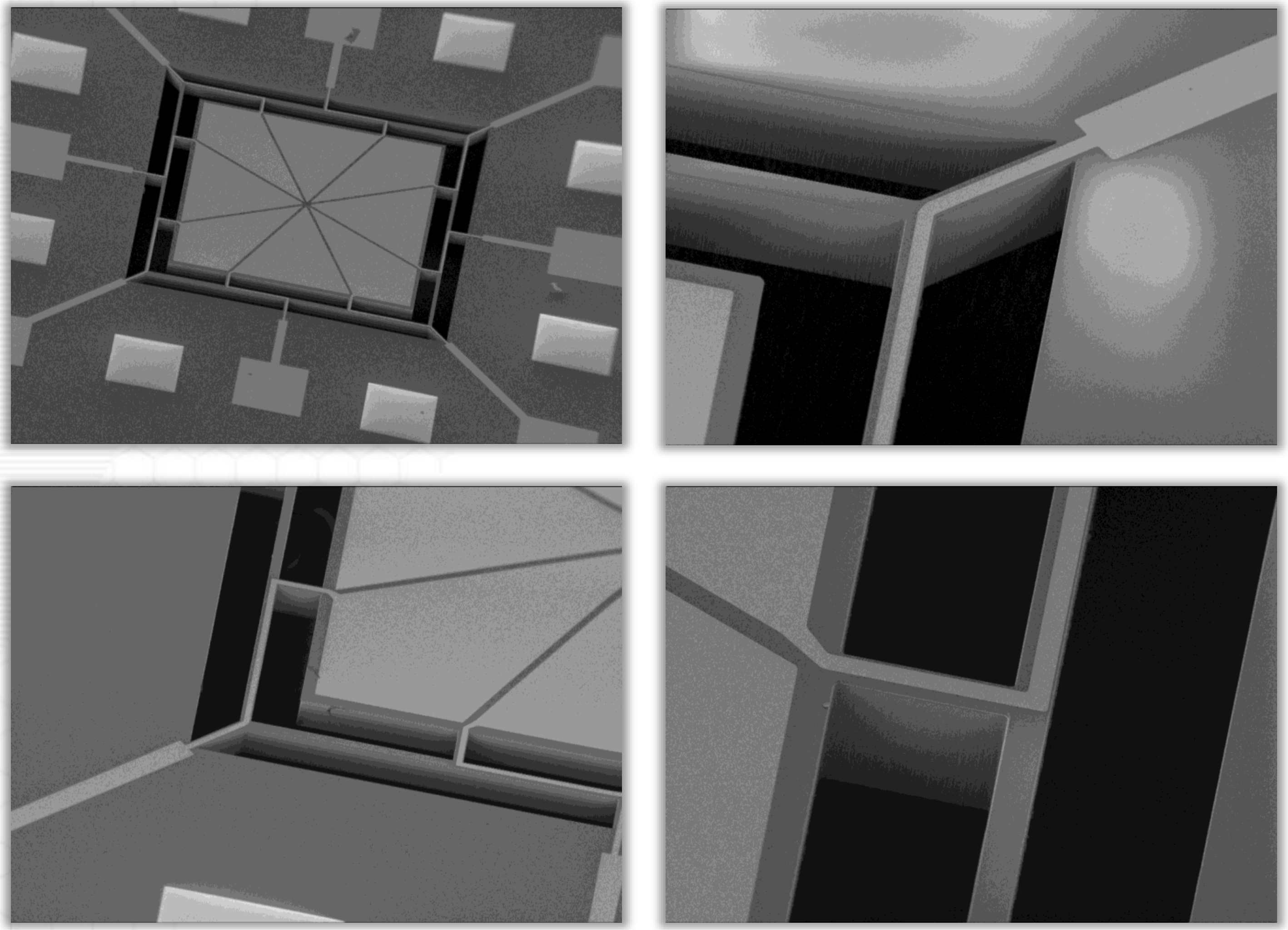




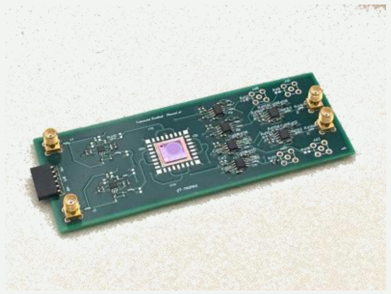


AlN-on-Si MEMS Resonator

- Square resonator with a network of side-supporting tethers for electric signal routing
- Aluminum Nitride sandwiched between top and bottom Molybdenum electrodes and stacked on top of the Silicon device layer
- Second order in-plane flexural vibration mode at ~5.9 MHz with a Q of ~2900 and IL of ~40 dB



Digital Interface Architecture

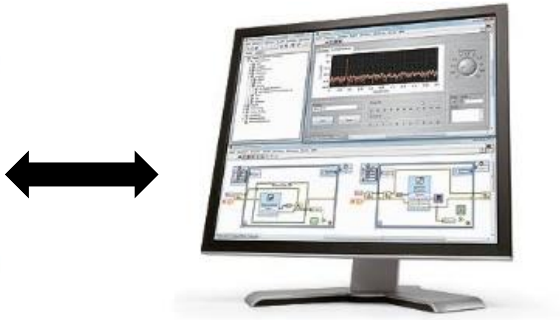


PCB (MEMS and Analog)

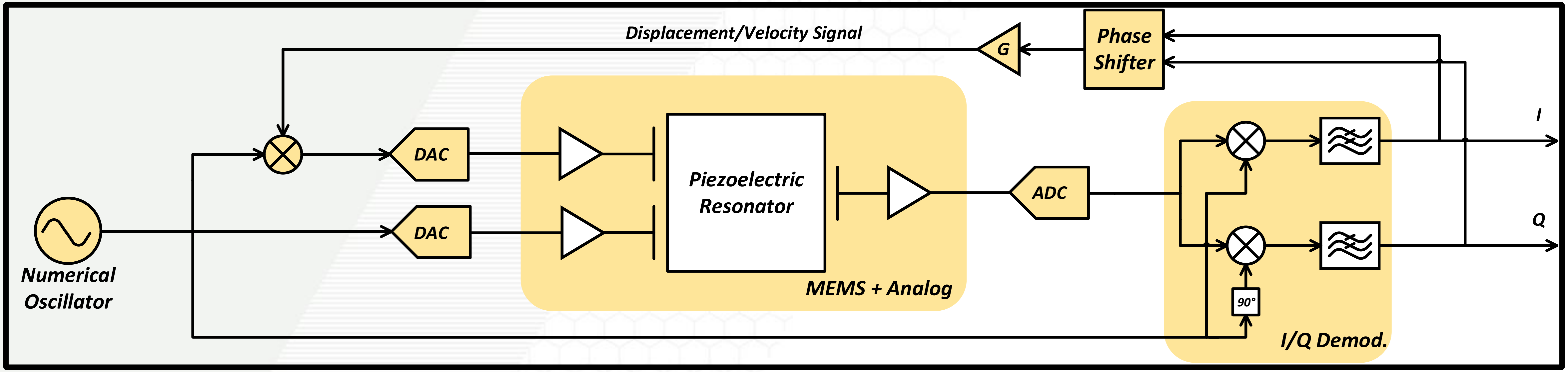
Adapter Module

FPGA

Real-Time Controller

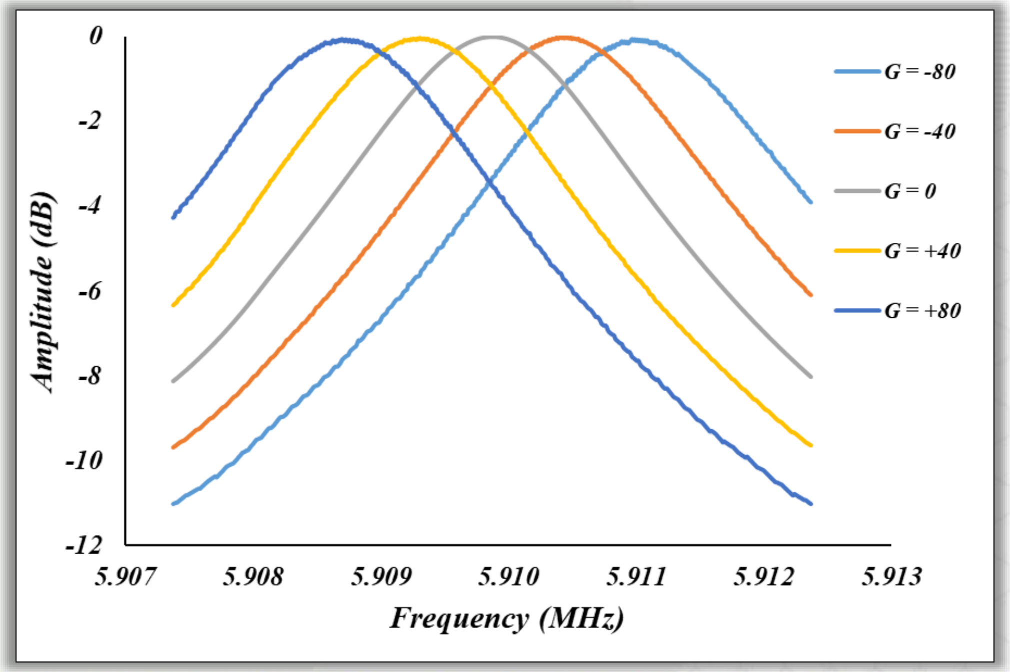


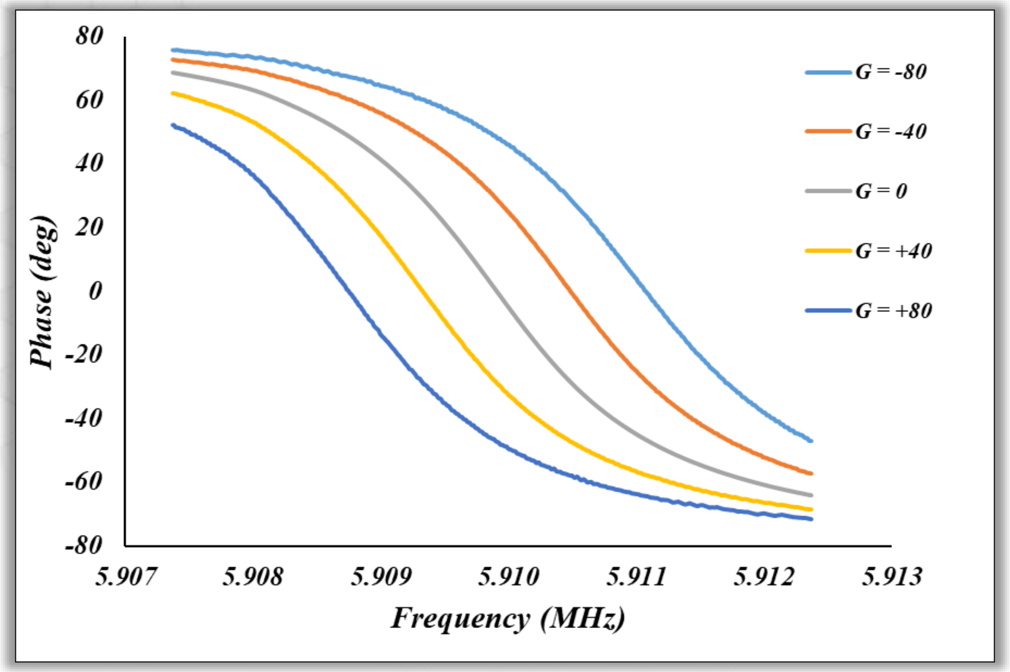
PC



Frequency Tuning – Experimental Results

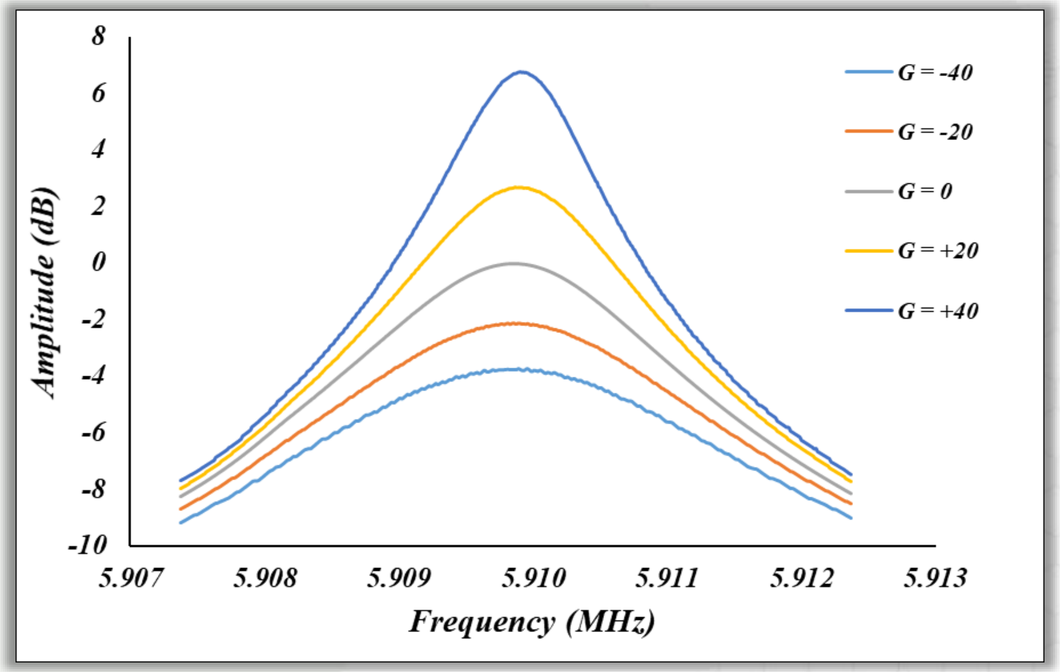
- Dynamic frequency tuning technique is verified experimentally by adjusting the displacement feedback gain.
- Resonance frequency of the piezoelectric resonator is tuned in both directions by ~400 ppm.

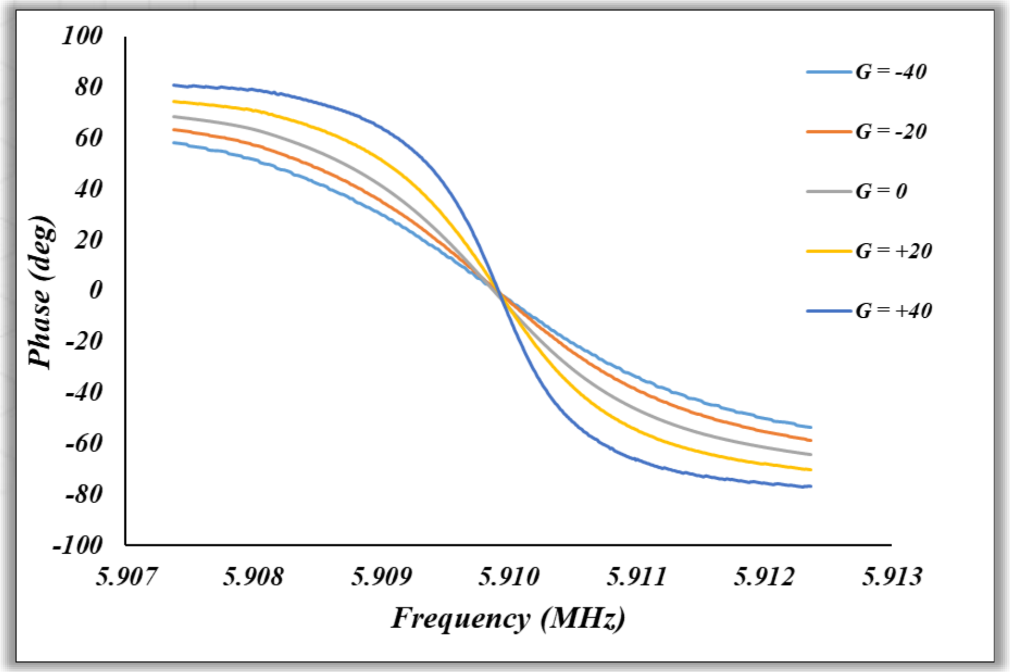




Q Tuning – Experimental Results

- Dynamic quality factor tuning technique is also verified experimentally by adjusting the velocity feedback gain.
- Quality factor is tuned from 1800 to 6300 for the piezoelectric resonator with the reference Q value of 2900.





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Contact:
shamami@gatech.edu
ayazi@gatech.edu

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