Voltage-Controllable Center Frequency

- Quadrature force \( \Rightarrow \) voltage-controllable electrical stiffness:
  \[ k_e = \frac{d^3}{d^2} \frac{A_e}{L^2} \]
  
- Electrical overlap area
  \[ A_e = 88 \mu m^2 \]
  \[ d = 100 \mu m \]
  \[ \Delta f = 1.1\% \]

Microresonator Thermal Stability

- Thermal stability of poly-Si micromechanical resonator is 10X worse than the worst case of AT-cut quartz crystal.

Geometric-Stress Compensation

- Use a temperature dependent mechanical stiffness to null frequency shifts due to Young's modulus thermal dep.

- Problems:
  - Stress relaxation
  - Compromised design flexibility

Voltage-Controllable Center Frequency

- Quadrature force \( \Rightarrow \) voltage-controllable electrical stiffness:
  \[ k_e = \frac{d^3}{d^2} \frac{A_e}{L^2} \]
  
- Electrical overlap area
  \[ A_e = 188 \mu m^2 \]
  \[ d = 100 \mu m \]

- Controllable center frequency
  \[ \Delta f = 1.1\% \]
Excellent Temperature Stability

Top Electrode-to-Resonator Gap

Elect. Stiffness compensation

Frequency due to temp. dependence

Counteracts reduction in frequency due to Young’s modulus temp. dependence

On par with quartz!

Excellent Temperature Stability

Measured Δf/f vs. T for k_e-Compensated μResonators

Design/Performance:

f_0 = 10MHz, Q=4,000

V_p=8V, h=4μm
d_1=1000Å, h=2μm
W'=8μm, L=40μm

Can One Cancel k_e w/ Two Electrodes?

* What if we don’t like the dependence of frequency on V_p?
* Can we cancel k_e via a differential input electrode configuration?
* If we do a similar analysis for F_{d2} at Electrode 2:

Subtracts from the F_{d1} term, as expected

F_{d2,|d=0} = -V_{p}^{2} \frac{C_{a2}}{d_{2}} |v_{2}| \cos \omega_{0} t

+ V_{p}^{2} \frac{C_{a2}}{d_{2}} |x| \sin \omega_{0} t

Add to the quadrature term \rightarrow k_e's add, no matter the electrode configuration!

Problems With Parallel-Plate C Drive

* Nonlinear voltage-to-force transfer function
  - Resonance frequency becomes dependent on parameters (e.g., bias voltage \( V_p \))
  - Output current will also take on nonlinear characteristics as amplitude grows (i.e., \( x \) approaches \( d \))
  - Noise can alias due to nonlinearity
* Range of motion is small
  - For larger motion, need larger gap ... but larger gap weakens the electrostatic force
  - Large motion is often needed (e.g., by gyroscopes, vibromotors, optical MEMS)
Electrostatic Comb Drive

- Use of comb-capacitive transducers brings many benefits
  - Linearizes voltage-generated input forces
  - (Ideally) eliminates dependence of frequency on dc-bias
  - Allows a large range of motion

Comb-Driven Folded Beam Actuator

Typical Drive & Sense Configuration

Comb-Drive Force Equation (2nd Pass)

* In our 1st pass, we accounted for
  - Parallel-plate capacitance between stator and rotor
  - But neglected:
    - Fringing fields
    - Capacitance to the substrate
  - All of these capacitors must be included when evaluating the energy expression!