A Method to Minimize Resonant Frequency Drift of CMUTs Due to Fluid Loading

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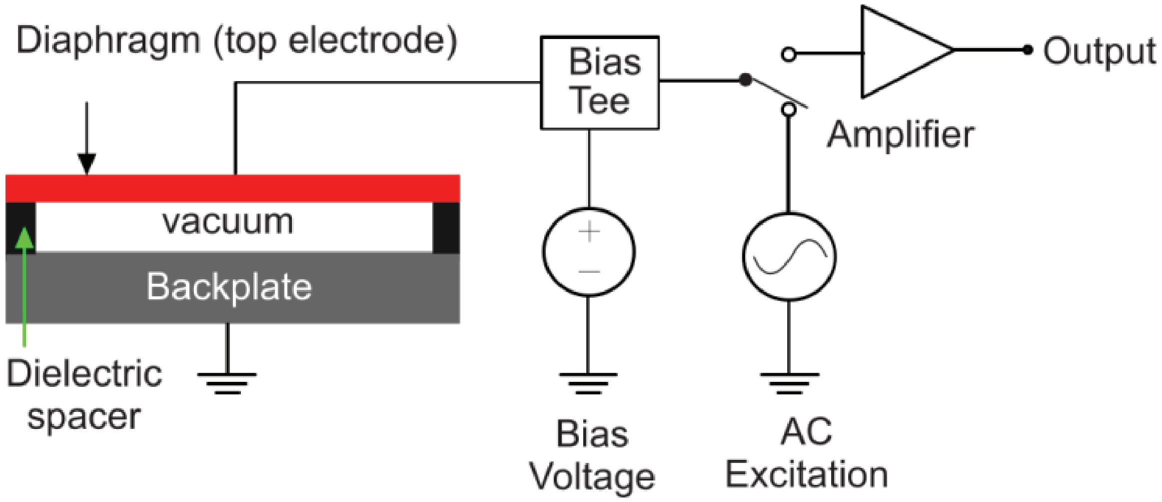
Sazzadur Chowdhury Bio

- Sazzadur Chowdhury is a professor and director of the MEM lab in the department of Electrical and Computer Engineering in the University of Windsor, Windsor, Ontario, Canada
- The MEMS Lab is dedicated to develop microsystems to provide advanced healthcare, automotive safety, and security
- His current research interests include: Electrostatic sensing and actuation, Solid state radars, Ultrasonic transducers, Microfabrication, and 3-D heterogeneous integration
- He was awarded 10 USA and Canadian patents in the areas of MEMS based ultrasonic transducers, radars, and heterogeneous integration
- He published 70+ peer reviewed research papers

Abstract

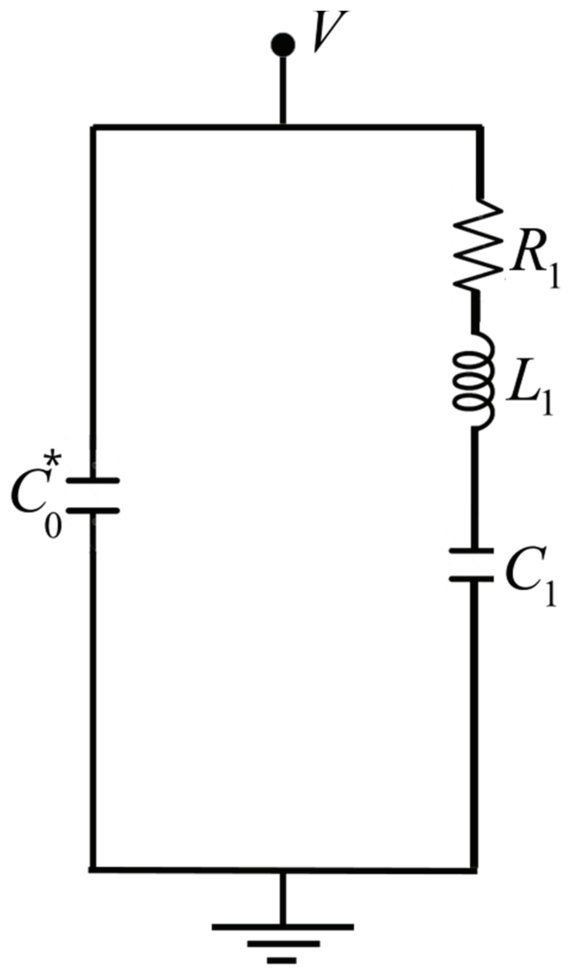
- Resonant frequency drift of Capacitive Micromachined Ultrasonic Transducers (CMUTs) due to fluid loading compromises imaging quality
- A method to minimize this resonant frequency drift has been presented
- The method involves dynamic adjustment of the DC bias voltage to modify the stiffness of a CMUT diaphragm that offsets the effects of fluid loading
- Analytical and COMSOL-based 3D Finite Element Analysis (FEA) results show the efficacy of the method in minimizing the drift of the resonant frequency
- Quantitatively, the drift in the resonant frequency of a 6 MHz CMUT in water can be compensated for by adjusting the bias voltage by 2% from its 75% pull-in voltage value to improve the axial and lateral imaging resolution by 4%
- A bias voltage adjustment of 9% of the 75% pull-in voltage value is necessary to achieve a resolution improvement of 20.74% in glycerol
- Physical implementation of the proposed scheme is in progress

CMUT Operating Principle



- A typical CMUT geometry is built to have a square or circular diaphragm separated from a fixed back plate by a small air gap or vacuum
- Basically, a variable capacitor
- When an AC voltage of desired frequency is superimposed in addition to the bias voltage, the diaphragm vibrates to generate ultrasound
- When the biased CMUT is exposed to an incoming ultrasound field, the diaphragm deforms to change the capacitance that generates a voltage
- A control circuit controls the switch to affect mode switching

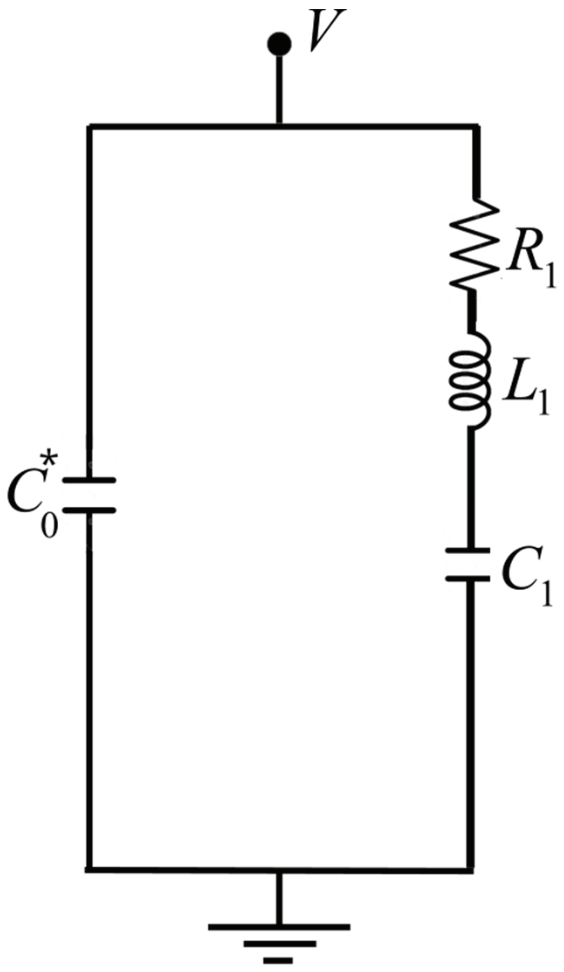
Equivalent Circuit of a CMUT



- The Butterworth-Van Dyke (BVD) model can be used to represent an analog equivalent circuit of the CMUT
- The equivalent circuit includes both electrical and equivalent mechanical lumped element circuit parameters

- C_0^* – Electrical capacitance
- L_1 – Electrical equivalent of diaphragm mass, m
- C_1 – Electrical equivalent of diaphragm stiffness, k
- R_1 – Electrical equivalent of damping, b
- V – Voltage

Equivalent Circuit of a CMUT (cont.)

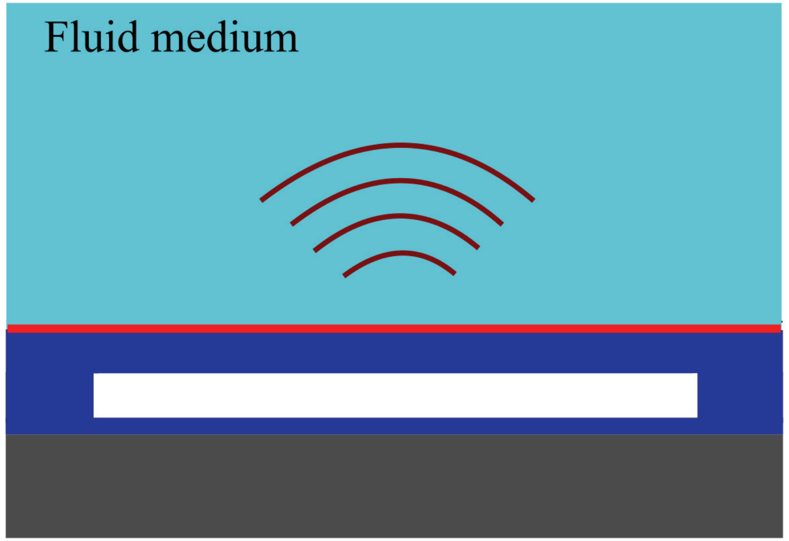


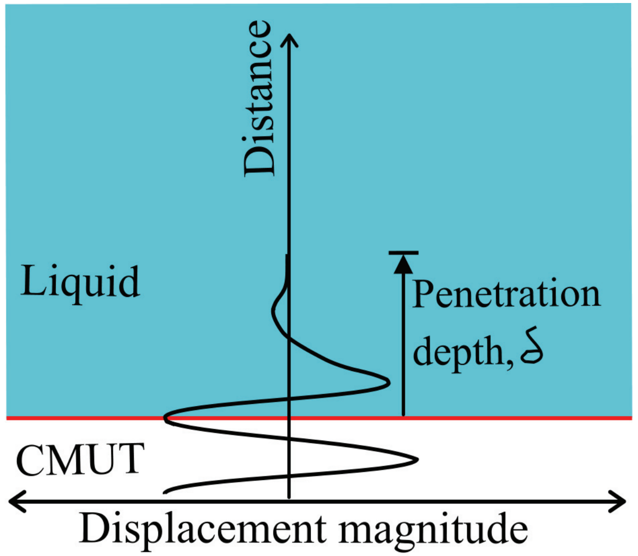
$$\left.\begin{aligned} C_1 &= \frac{n^2}{k} \\ L_1 &= \frac{m}{n^2} \\ R_1 &= \frac{b}{n^2} \end{aligned}\right\}$$

Motional impedance parameters at zero bias

- n – electromechanical transformation ratio

Effect of Fluid Loading on a CMUT





$$f_{\text{res}} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

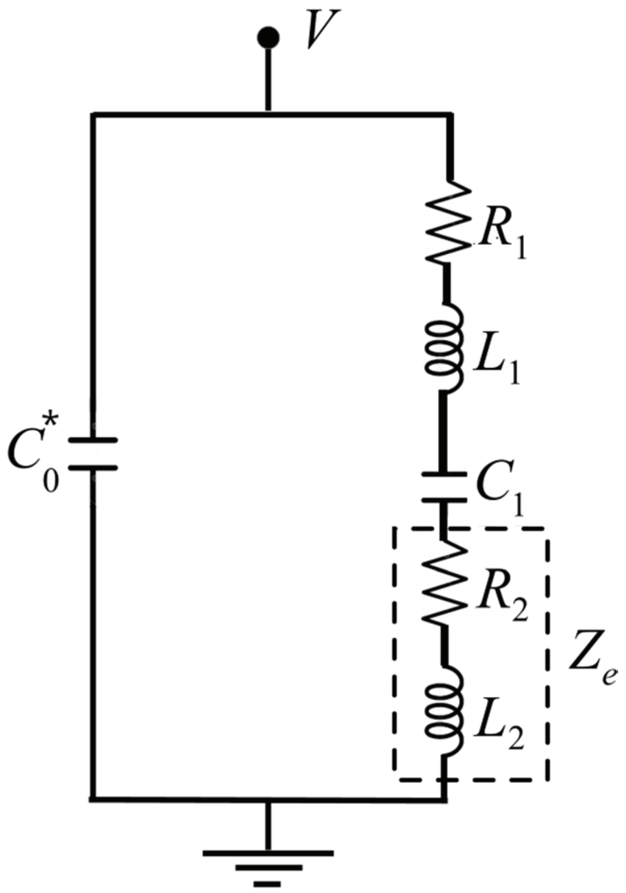
k - diaphragm stiffness
m -diaphragm mass

- Fluid loading alters the mass of the diaphragm to alter the resonant frequency of a CMUT
- Entrained liquid layer of height $\frac{\delta}{2}$ is used to calculate the mass of the loading fluid

$$\delta = \sqrt{\frac{2\eta}{\omega_s \rho}}$$

- η - shear viscosity of liquid
- ω_s - series resonant frequency in rad/s
- ρ – density of the liquid

CMUT Equivalent Circuit With Fluid Loading



- Coupling of CMUT diaphragm with fluid medium alters motional impedance
- The adjacent liquid layer contributes
  - An additional equivalent damping:

$$R_2 = \frac{\pi}{4k_s^2 C_0}\left(\frac{\rho\eta}{2\omega_s \mu_q \rho_q}\right)^{\frac{1}{2}}$$

  - An additional equivalent fluid mass:

$$L_2 = \frac{\pi}{4k_s^2 \omega_s C_0}\left(\frac{\rho\eta}{2\omega_s \mu_q \rho_q}\right)^{\frac{1}{2}}$$

- k_s^2 - coupling coefficient
- μ_q - shear stiffness of diaphragm
- ρ_q - mass density of diaphragm

Diaphragm Stiffness and Spring Softening

- For a square shape CMUT diaphragm the stiffness can be expressed as:

$$k = C_r \frac{t_d \sigma_0}{(L/2)^2} + C_b \frac{12 D_{eff}}{(L/2)^4}$$

- C_r = 3.45
- C_b = 4.06
- D_{eff} - effective flexural rigidity
- L - sidelength of CMUT diaphragm
- σ_0 - residual stress of CMUT diaphragm
- t_d - thickness of diaphragm

- Assuming the small signal model of a CMUT, the spring softening effect due to the applied DC bias voltage reduces the effective stiffness by a factor

$$k_{soft} = \frac{\varepsilon A V_{DC}^2}{d_{eff}^3}$$

- ε - relative permittivity
- A - coupling area of electrodes
- V_{DC} - applied DC bias voltage
- d_{eff} - effective electrode gap

Resonant Frequency Drift Mechanisms

- The spring softening effect causes a downshift in the resonant frequency

$$f_{\text{res-ss}} = \frac{1}{2\pi}\sqrt{\frac{k - k_{\text{soft}}}{m}}$$

- When CMUT is operated immersed in a fluidic medium, the adjacent fluid layer manifests as an inertial mass, m_{f} onto the diaphragm
- The resonant frequency of the diaphragm subject to both spring softening and fluid loading effects can be expressed as the following:

$$f_{\text{res-ss-fl}} = \frac{1}{2\pi}\sqrt{\frac{k - k_{\text{soft}}}{m + m_{\mathrm{f}}}}$$

Effect of Fluid Loading on CMUT for Imaging

- The decrease in resonant frequency modifies the wavelength λ that affects the following parameters:
  - Lateral resolution
  - Axial resolution
  - Beam directivity pattern
- The imaging resolution degrades

➢Axial resolution

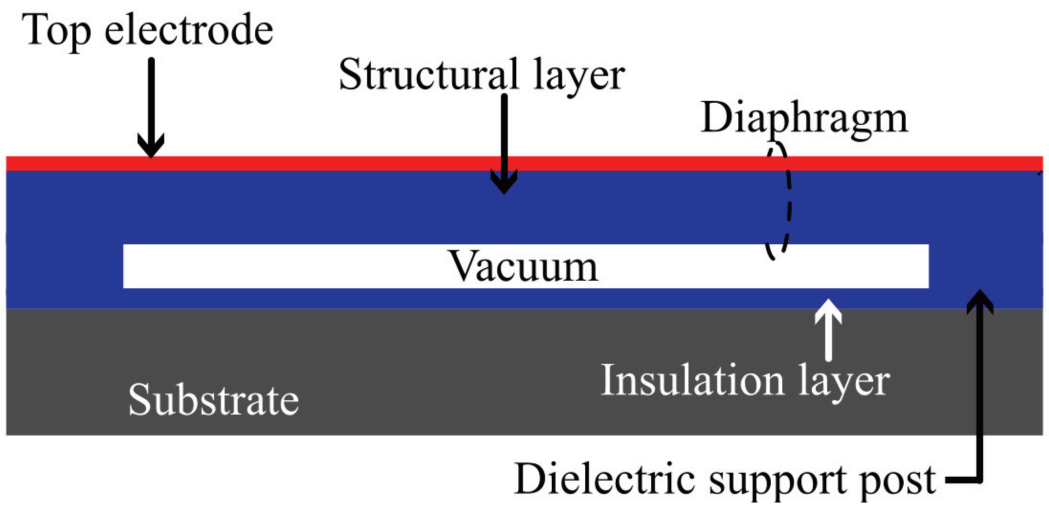
$$\Delta x = \frac{n\lambda}{2}$$

➢Lateral resolution

$$\Delta y = \left(\frac{1.22\lambda}{A_{\mathrm{a}}}\right) S$$

- n – number of scanning pulses
- A_a - Array aperture
- S – distance between focus and array surface at center of the array

CMUT Cell – Design and Material Specifications



- Structural Layer – Bisbenzocyclobutene
- Top electrode – Gold
- Dielectric support post – Bisbenzocyclobutene
- Substrate – Low resistivity Silicon

CMUT Material properties

Material	Young's modulus (GPa)	Poisson's ratio	Density (kg.m^{-3})	Residual stress (MPa)
BCB	2.9	0.34	1050	28
Gold	70	0.44	19300	106
Silicon	165.9	0.26	2329	55

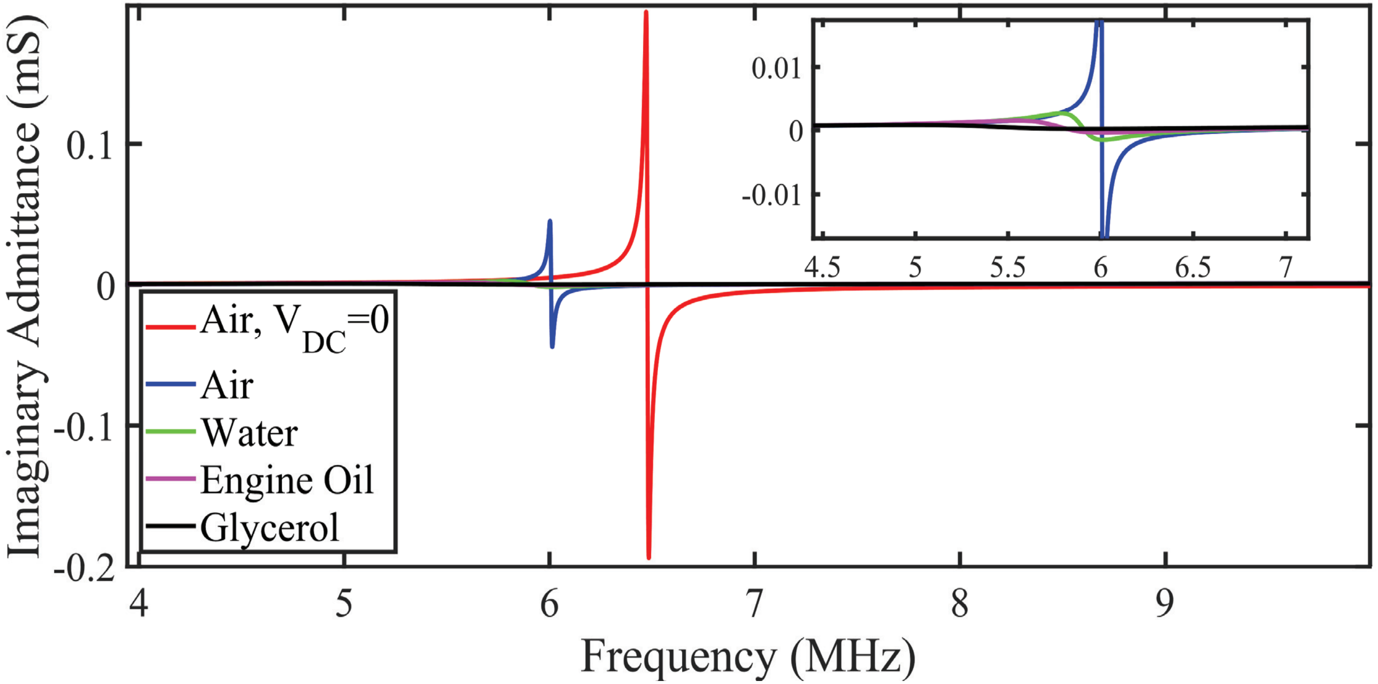
CMUT Cell Specifications

- A CMUT with square-shaped diaphragm and having the following specifications was investigated as a test case

Design specification	Value
Width of cavity (sidelength)	28 μm
Thickness of diaphragm	1.5 μm
Thickness of top electrode	0.1 μm
Cavity height	0.75 μm
Pull in voltage	395 V
DC bias voltage	295 V
Resonant frequency	6 MHz

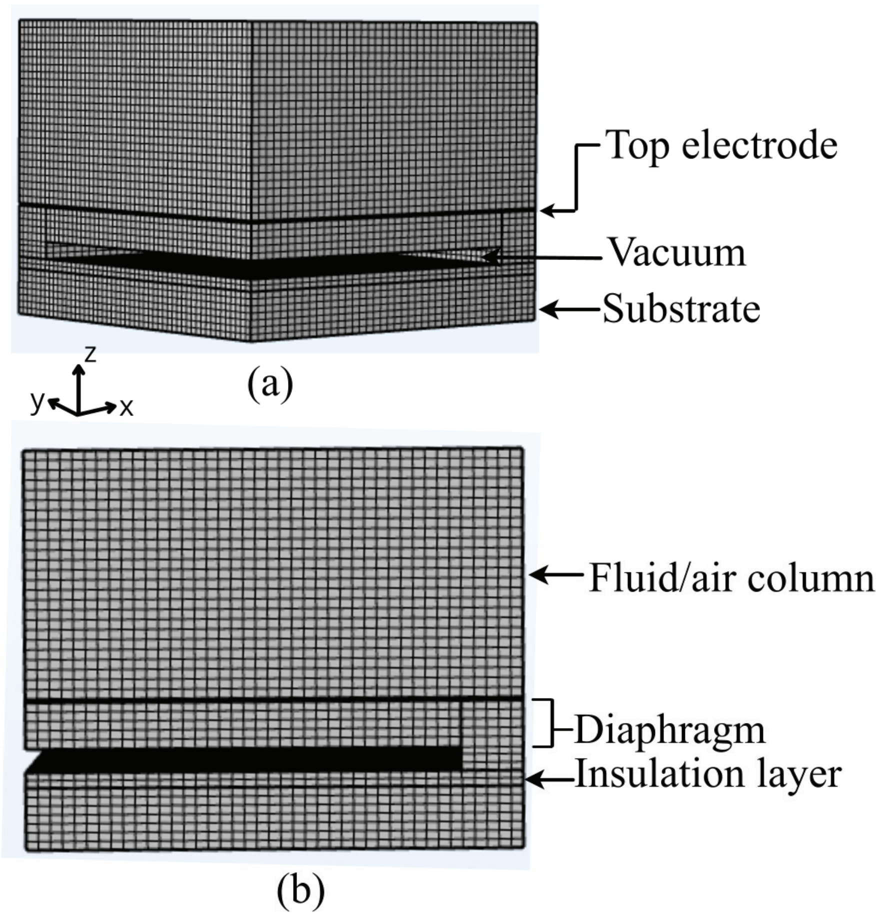
Effect of Fluid Loading on CMUTs

Fluid type	Fluid Physical Properties		Resonant frequency (MHz)
	Viscosity (mPa/s)	Density (g/cm^3)	
Air	0.01825	0.001204	6.002
Water	1.0016	0.998	5.783
Engine oil	287.23	0.8787	5.422
Glycerol	1412.8	1.2608	4.975



Resonant frequency drift of the CMUT cell with bias voltage (V_{DC}=0.75 V_{PI}) for unloaded (air) and loaded (water, engine oil, glycerol) conditions. (Inset y-axis unit is in μS)

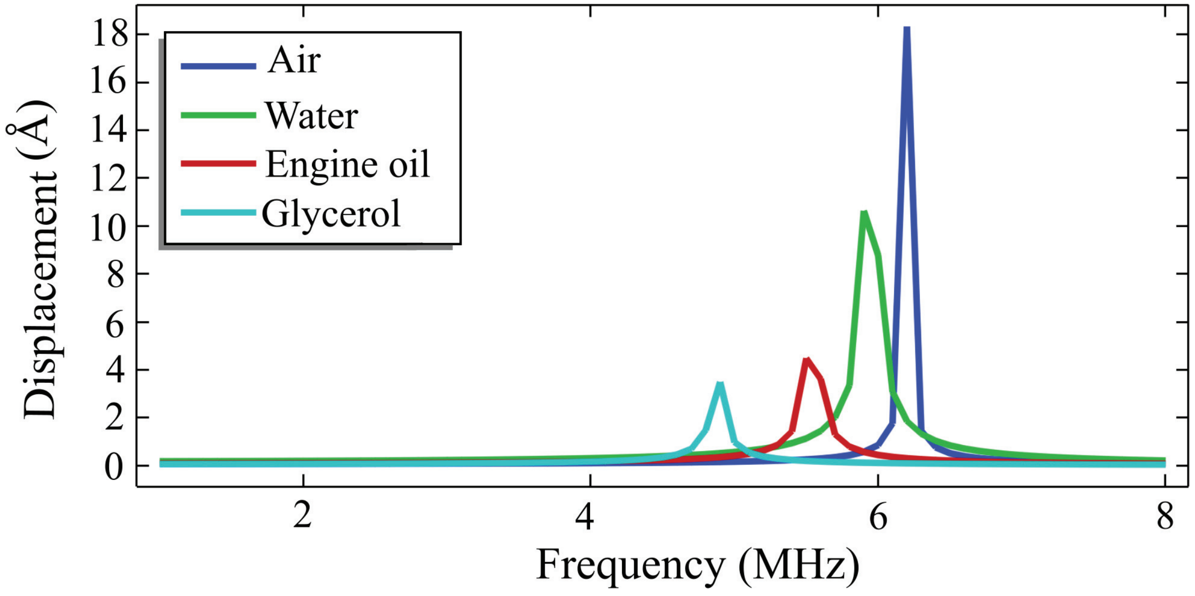
FEA Modelling of CMUT with Fluid Loading



3D model of the CMUT in COMSOL

- The CMUT diaphragm was set as a linear elastic material
- The boundary between the electro-mechanics and pressure acoustics domains was defined as a fluid-solid coupled boundary that acts as a pressure load on the electro-mechanics domain
- The maximum mesh size was set to one-sixth of the smallest wavelength
- An AC perturbation signal superimposed with DC bias voltage was applied to the CMUT cell to conduct a frequency domain modal analysis in COMSOL

FEA Modeling Result Validation



COMSOL-based 3D FEA simulation results showing CMUT resonant frequency drift due to fluid loading for different fluids

Analytical and FEA Resonant frequency Comparison with Fluid Loading

Medium	Resonant frequency (Analytical) (MHz)	Resonant frequency (FEA) (MHz)	Percentage deviation between analytical and FEA (%)	Drift from the resonant frequency in air (FEA)(%)
Air	6.002	6.19	3.1	-
Water	5.783	5.945	2.8	3.9
Engine oil	5.422	5.545	2.3	10.42
Glycerol	4.975	4.8788	1.9	21.18

Approach to Minimize Resonant Frequency Drift

- The resonant frequency including the spring softening effect and fluid loading effect is represented as:

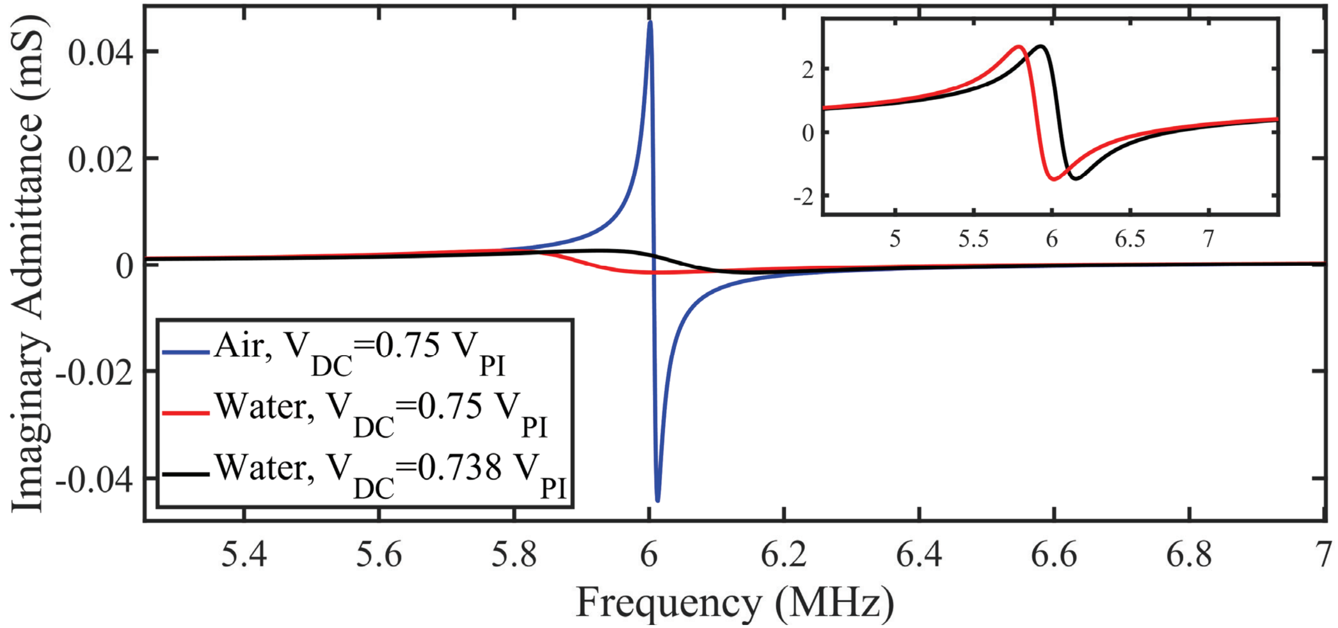
$$f_{\text{res-ss-fl}} = \frac{1}{2\pi}\sqrt{\frac{k - k_{\text{soft}}}{m + m_{\text{f}}}}$$

$$k_{\text{soft}} = \frac{\varepsilon A V_{\text{DC}}^2}{d_{\text{eff}}^3}$$

- Drift in resonant frequency due to fluid loading can be compensated by adjusting the bias voltage

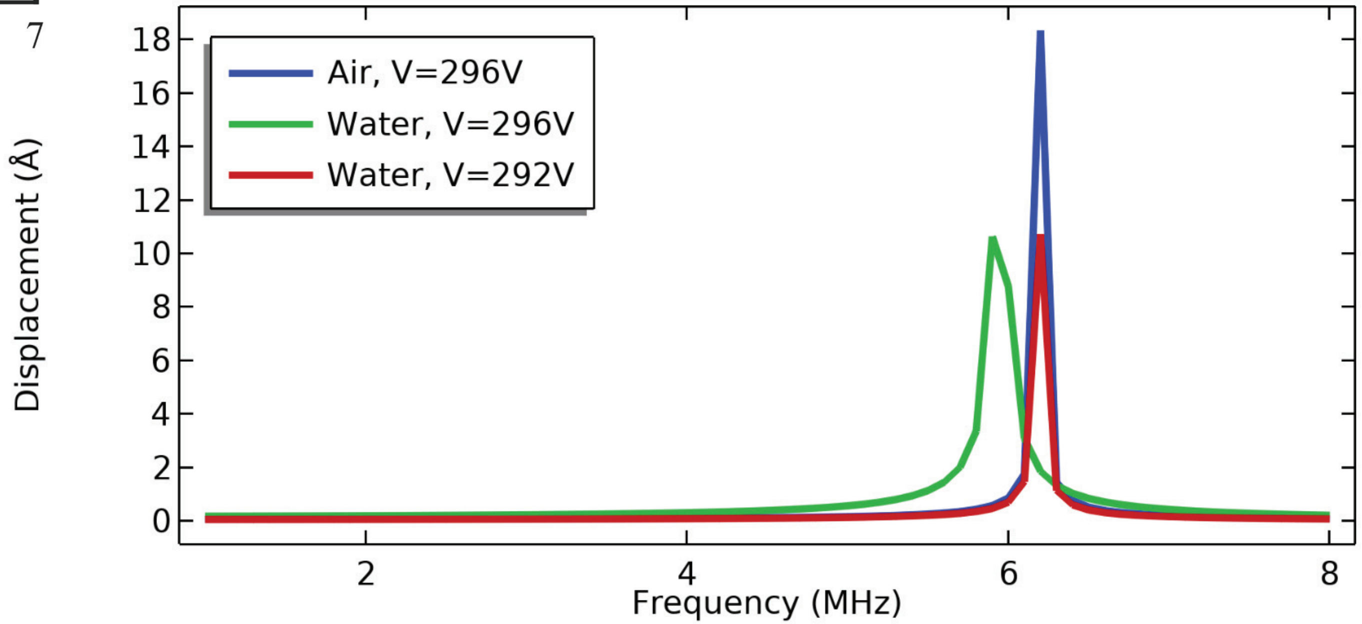
- The spring softening parameter varies with change in applied DC bias voltage, thus minimizing the resonant frequency drift

Drift Minimization Result -Water

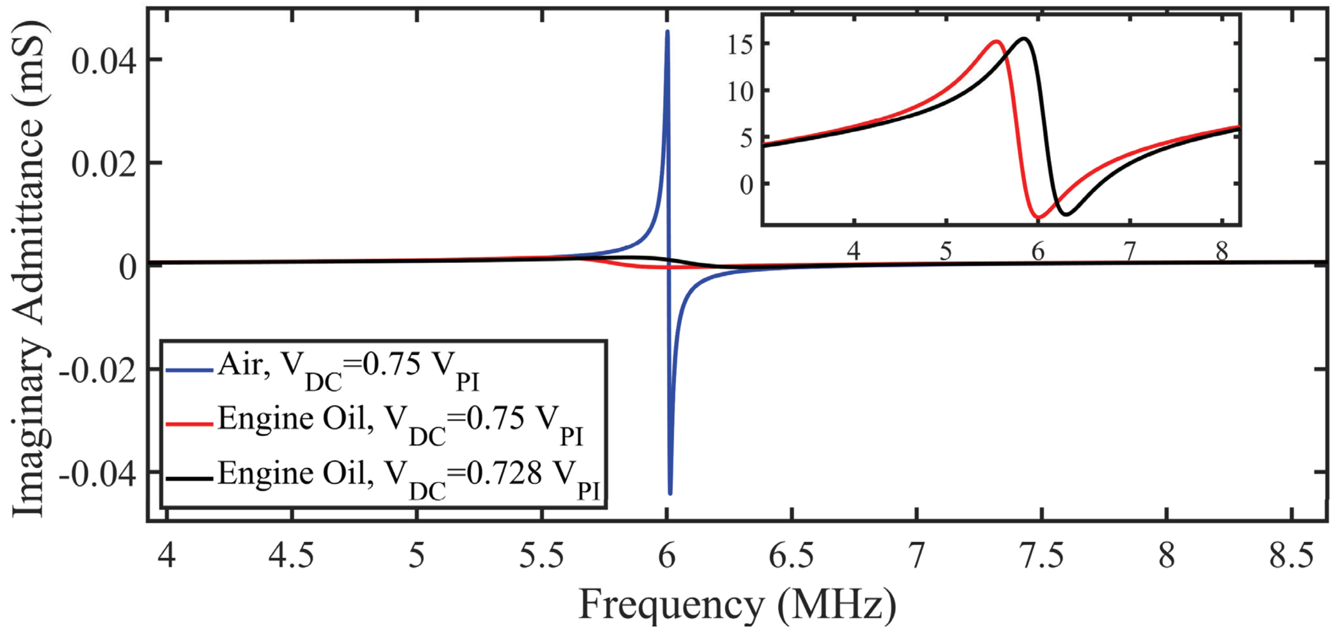


Matlab simulation result of CMUT small-signal analysis for frequency compensation in water. (Inset y-axis unit is in µS)

3-D FEA simulation result of CMUT for frequency compensation in water

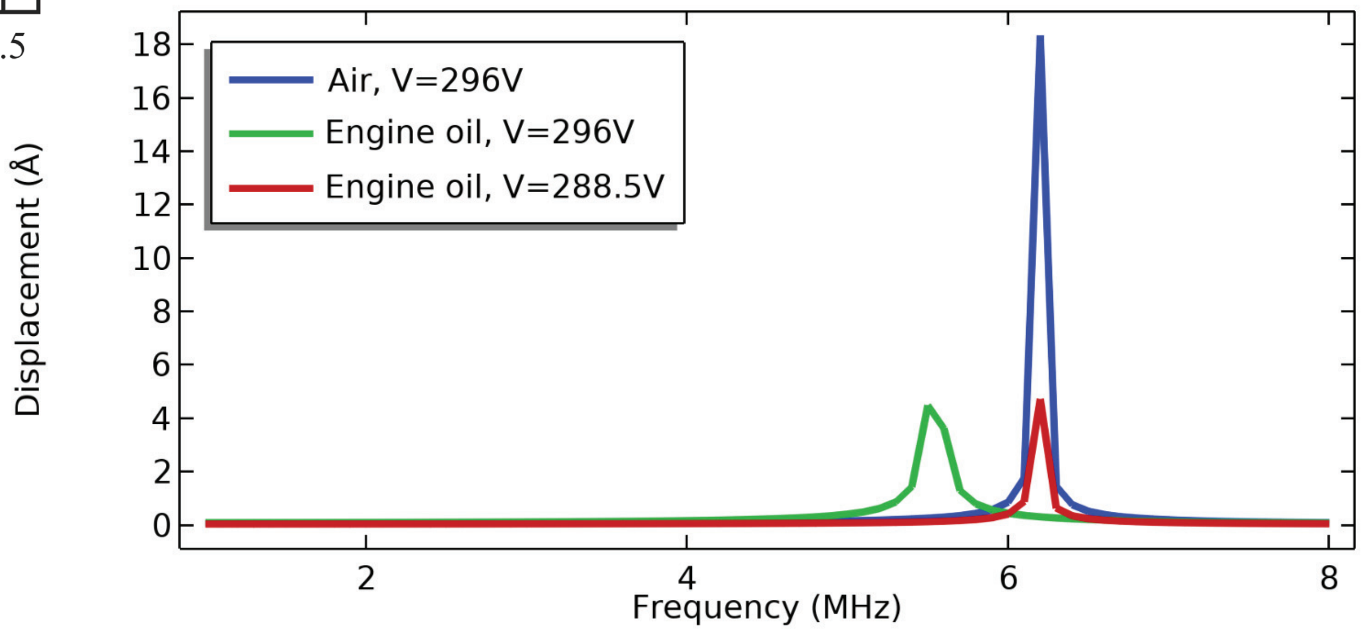


Drift Minimization Result – Engine Oil

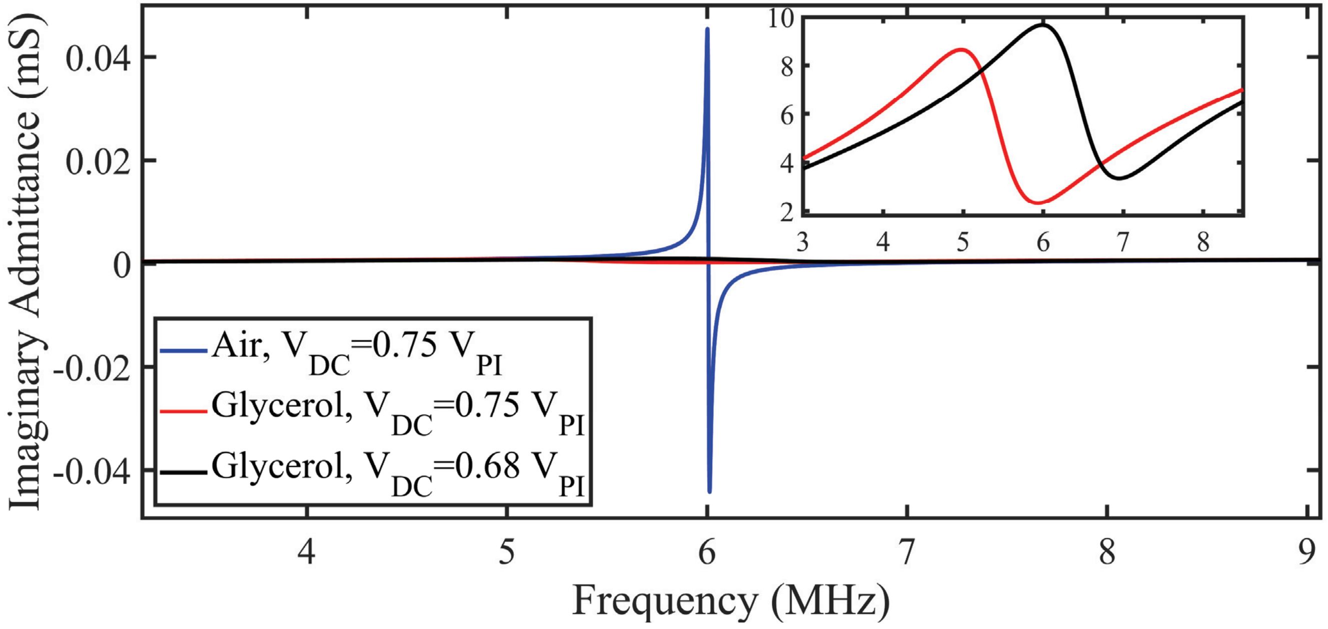


Matlab simulation result of CMUT small-signal analysis for frequency compensation in engine oil. (Inset y-axis unit is in μS)

3-D FEA simulation result of CMUT for frequency compensation in engine oil

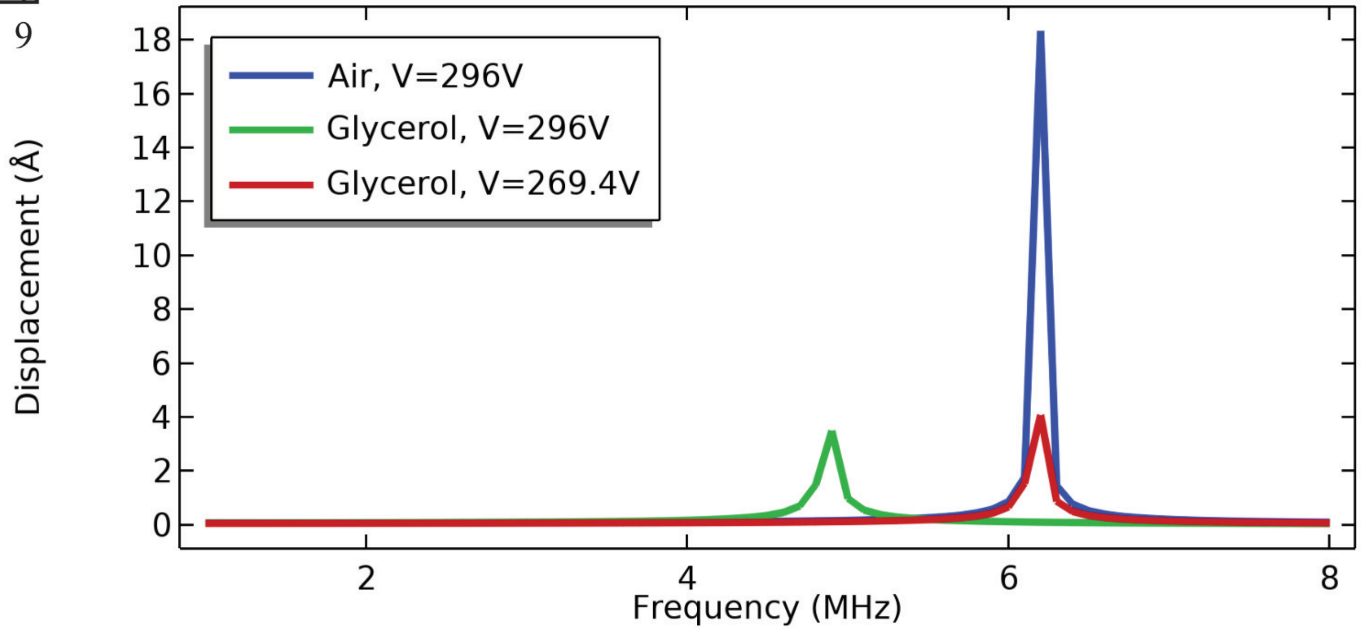


Drift Minimization Result -Glycerol



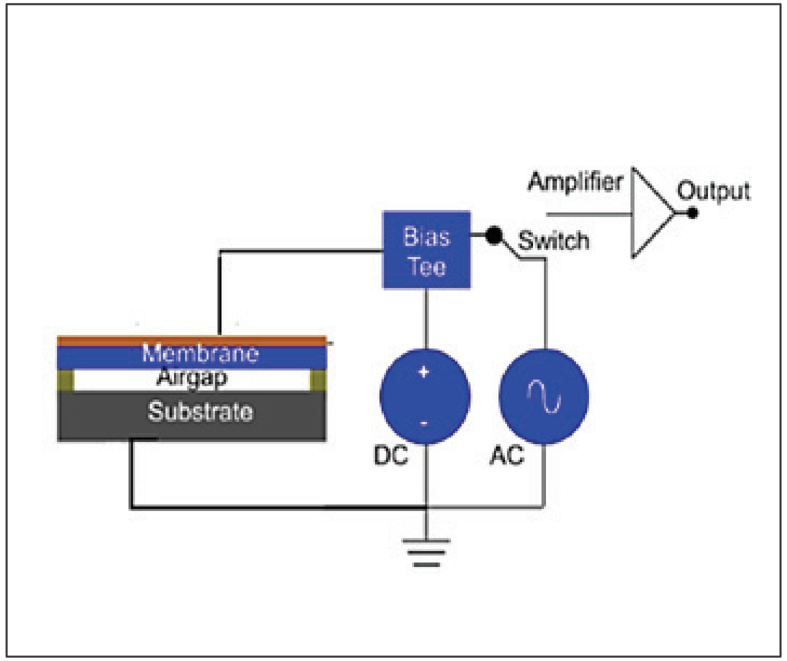
Matlab simulation result of CMUT small-signal analysis for frequency compensation in glycerol. (Inset y-axis unit is in μS)

3-D FEA simulation result of CMUT for frequency compensation in glycerol

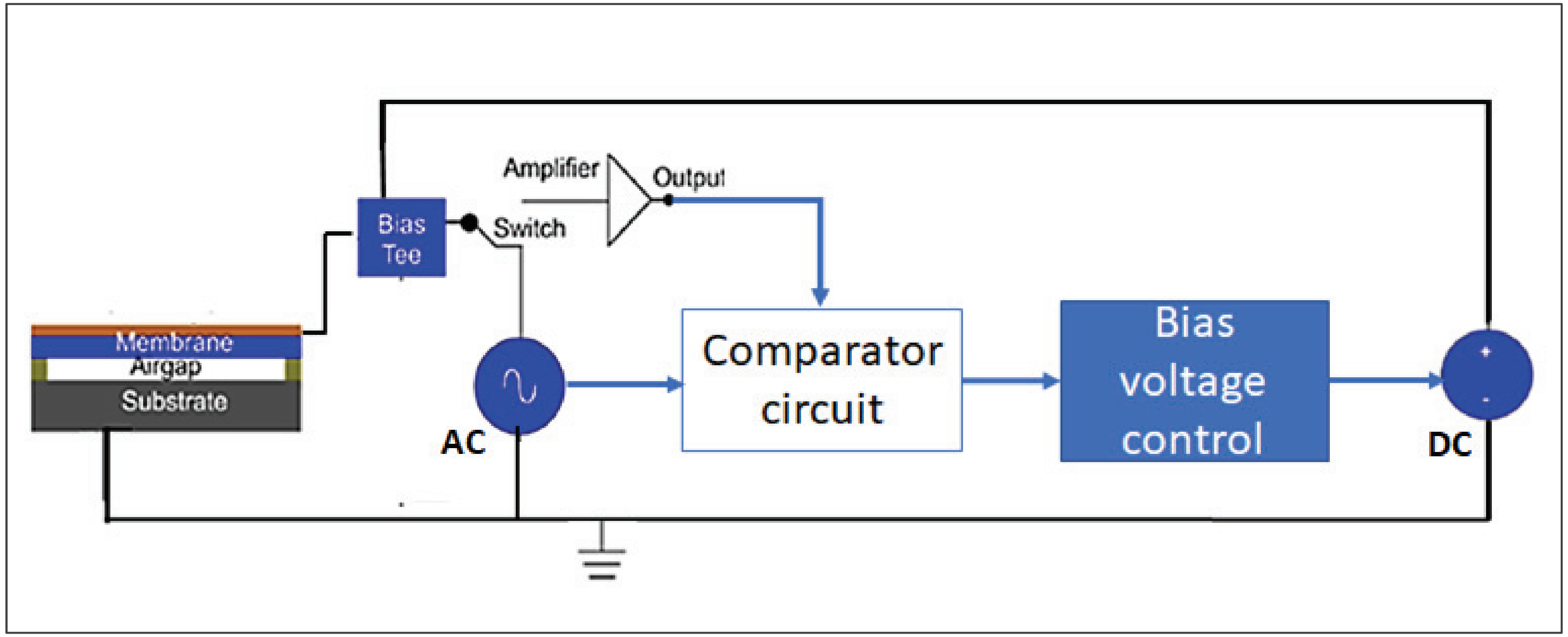


Implementation Scheme Block diagram

- Comparator circuit outputs Δf
- Depending on the magnitude of Δf, DC bias voltage is adjusted so that $\Delta f \rightarrow 0$



Current CMUT circuit



Proposed circuit model for frequency drift compensation

Work is in progress

Conclusions

- This paper presents a method to minimize the fluid loading induced resonant frequency drift of a CMUT by dynamically adjusting the bias voltage
- Analytical and 3D FEA based simulation studies revealed that the amount of change in DC bias voltage necessary to offset the resonant frequency drift is small and is not expected to affect the acoustic power/pressure output of a CMUT array
- The design of a high-speed microelectronic control circuit necessary to implement the proposed scheme is in progress

Thank You for Your Support

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