



DYNAMIC FEM ANALYSIS OF MULTIPLE CMUT CELLS IN IMMERSION

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Outline

- Motivation
- FEM model of an infinite CMUT
- Dynamic FEM analysis
- FEM and experimental results
- Conclusion

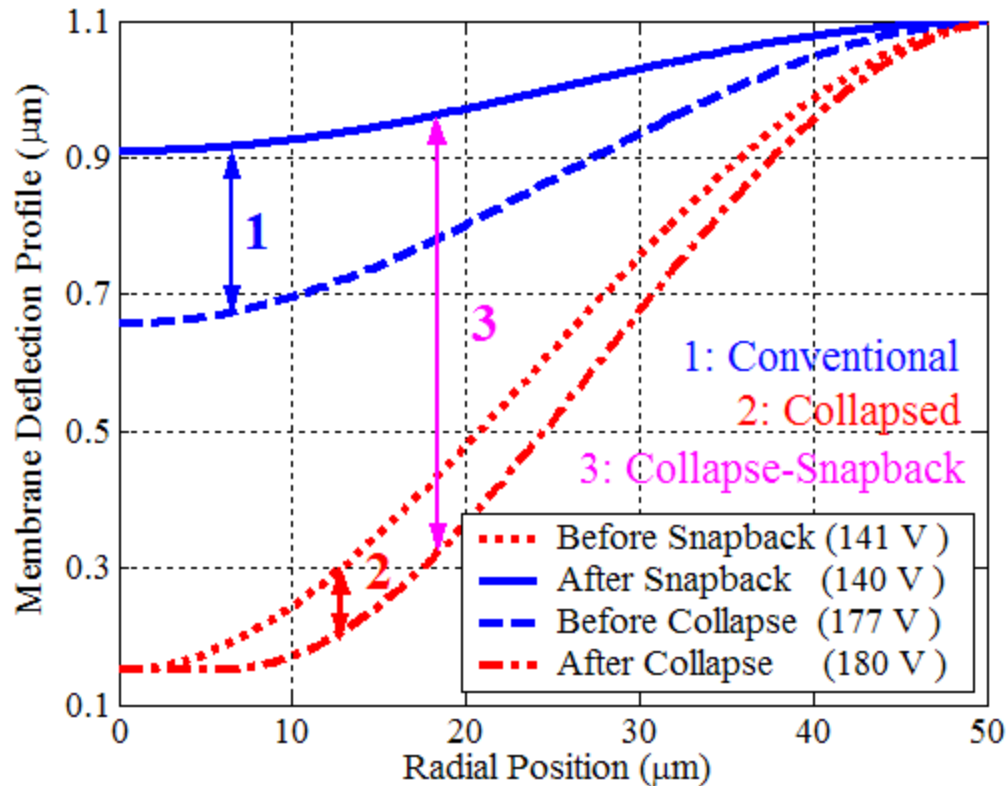


Motivation

- Goal: To accurately model the cMUT dynamics in “linear” and nonlinear operation regimes using time-domain, finite element method (FEM)
- Test: Operate in different regimes:
 - Conventional (no contact)
 - Collapsed (always in contact)
 - Collapse-snapback (intermittent contact)



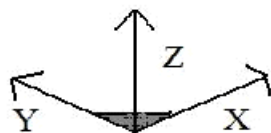
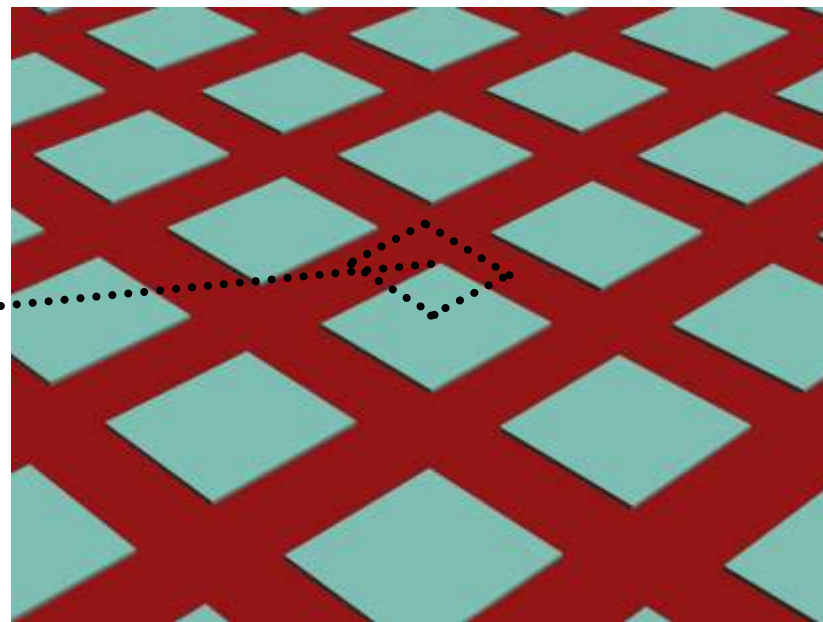
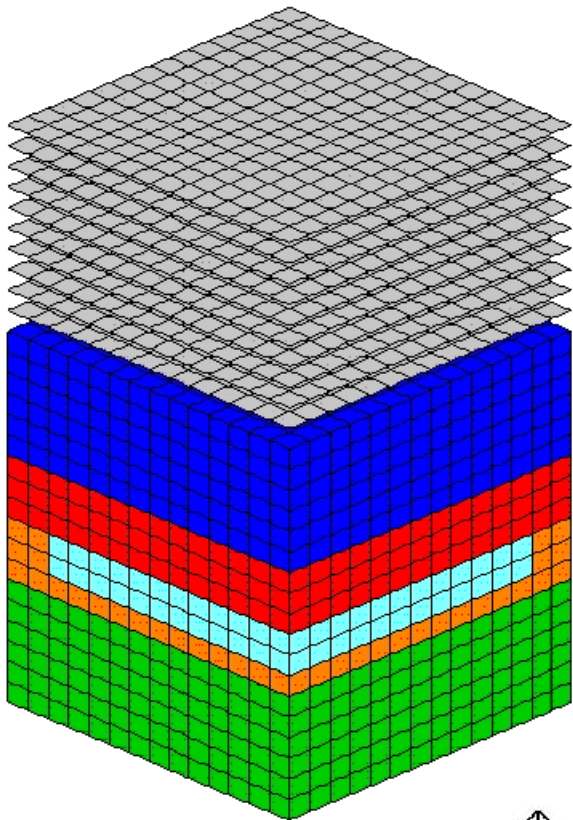
Different Operation Regimes



Conventional, Collapsed and Collapse-Snapback Operations



FEM model of an infinite CMUT



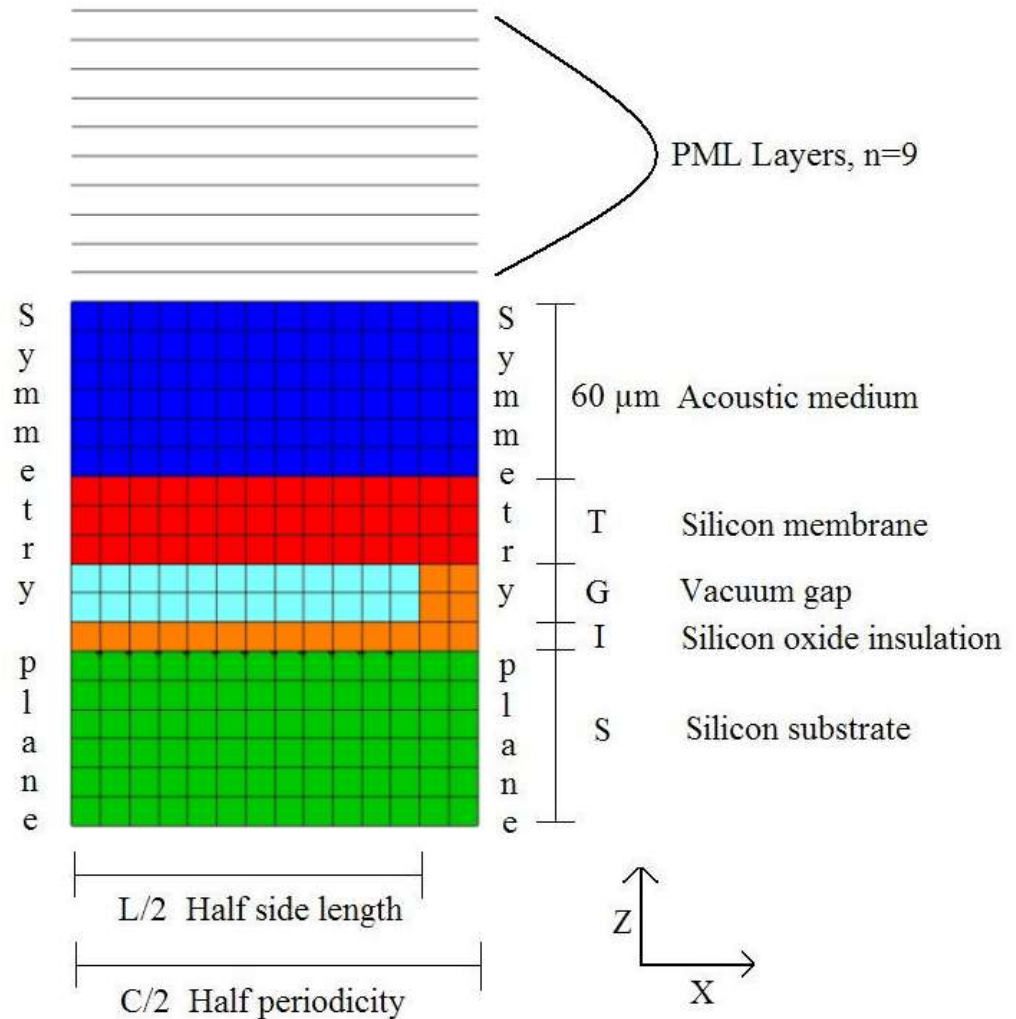
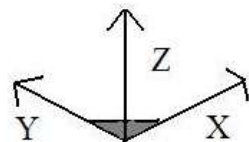
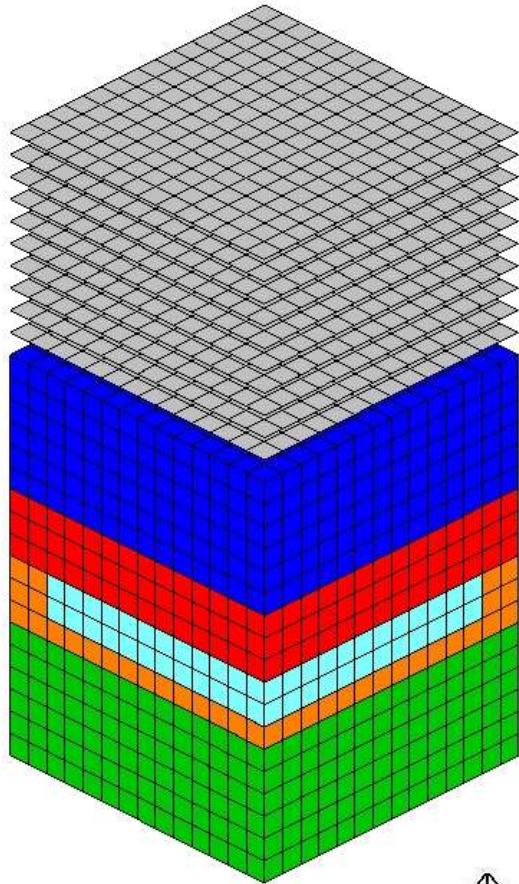
¼ of a square cMUT cell.



Infinite cMUT

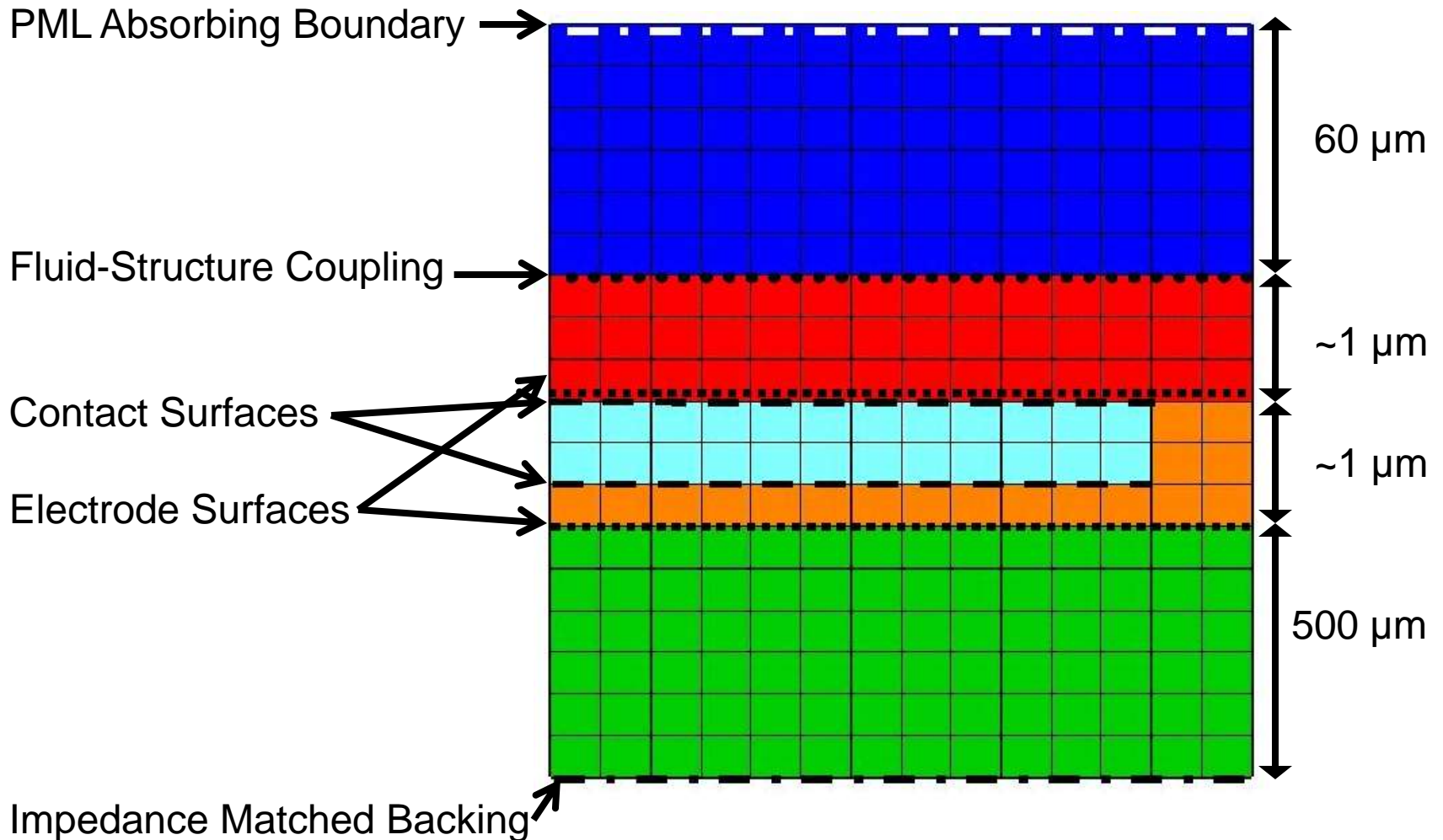


FEM model of an infinite CMUT





FEM model of an infinite CMUT





Dynamic FEM Analysis

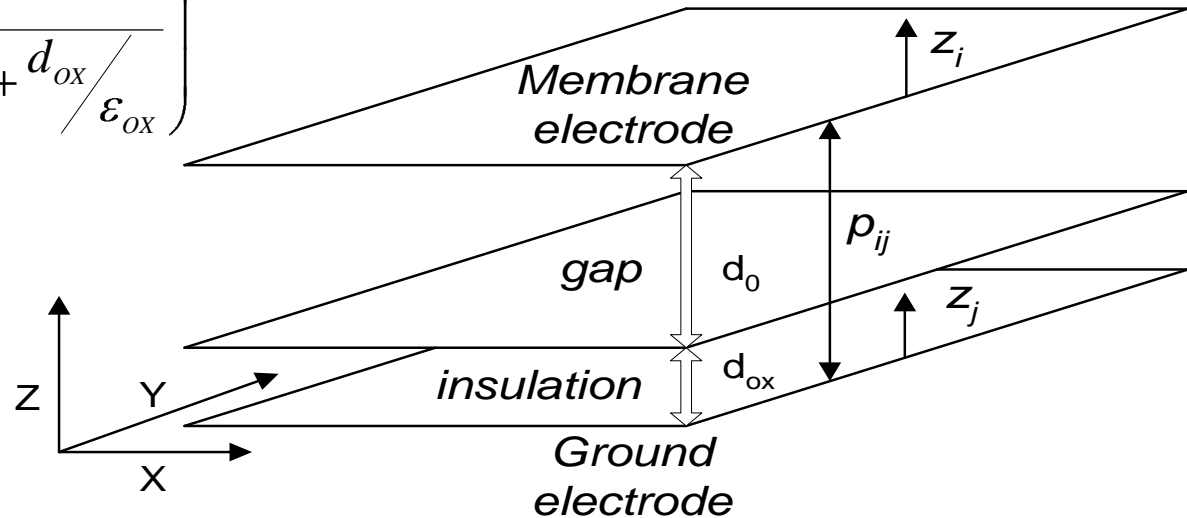
- Commercially available software (*LS-DYNA 970*)
 - Explicit, time-domain solver
- LS-DYNA built-in features
 - Fluid-structure coupling
 - Contact capability
- LS-DYNA user-defined features
 - Electrostatic-structural coupling
 - Berenger's Perfectly Matched Layer (PML) absorbing boundary
- Large Signal Characterization
 - Biasing + Pulse excitation
 - Acoustic Output Pressure



LS-DYNA User-defined Features

– Electrostatic-structural coupling

$$p_{ij} = \frac{1}{2} \epsilon_0 \left(\frac{V}{d_0 + (z_i - z_j) + \frac{d_{ox}}{\epsilon_{ox}}} \right)^2$$



| Operation Regime | Bias voltage (Volt) | Average Deflection (Å) using | | Percentage Difference |
|------------------|---------------------|------------------------------|---------|-----------------------|
| | | ANSYS | LS-DYNA | |
| Conventional | 83 | -148 | -145 | 2.1 % |
| Collapsed | 83 | -649 | -632 | 2.6 % |
| Collapsed | 101 | -755 | -752 | 0.4 % |



LS-DYNA User-defined Features

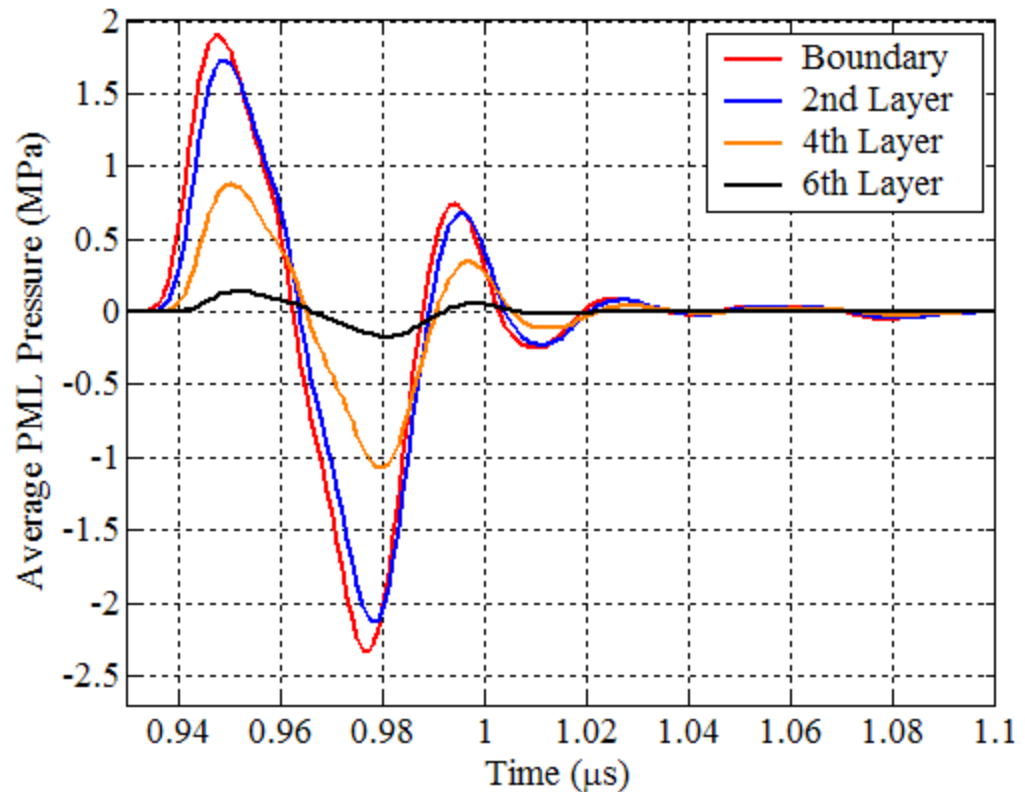
– Berenger's Perfectly Matched Layer (PML)

Attenuation profile:

$$\alpha_{zi} = \alpha_{z_{\max}} \times \left(\frac{n-i}{n} \right)^2; n=9$$

Reflection (dB):
-40 dB

Stability (# of t_{STEP}):
300,000

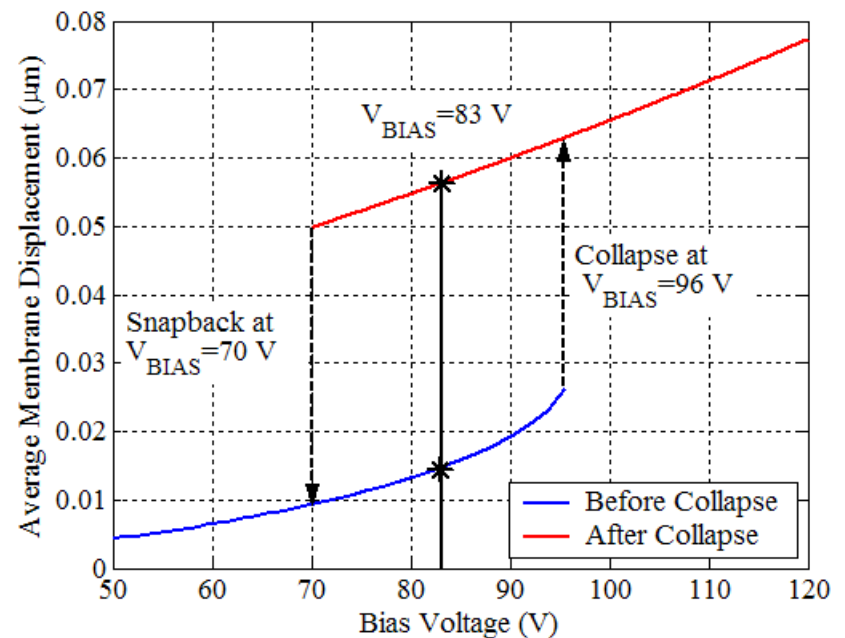




Static FEM Results

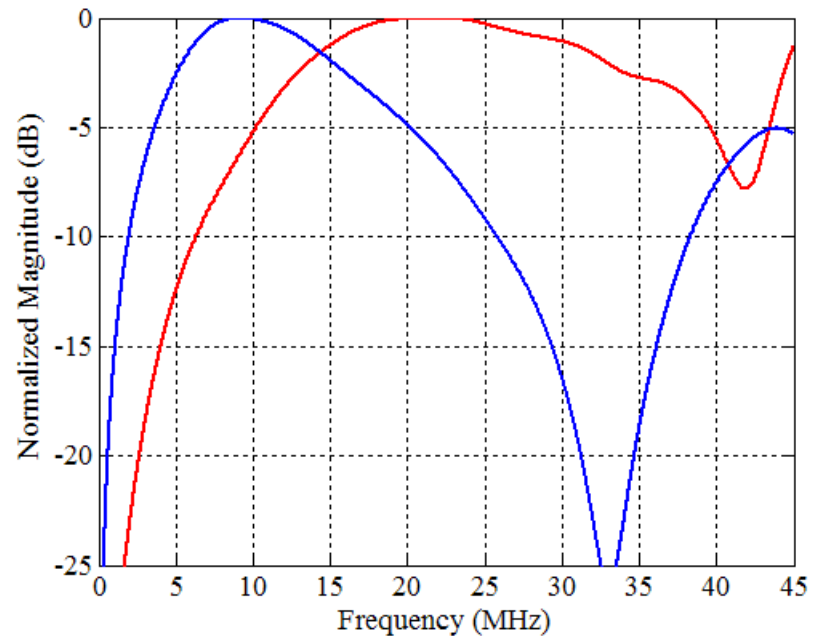
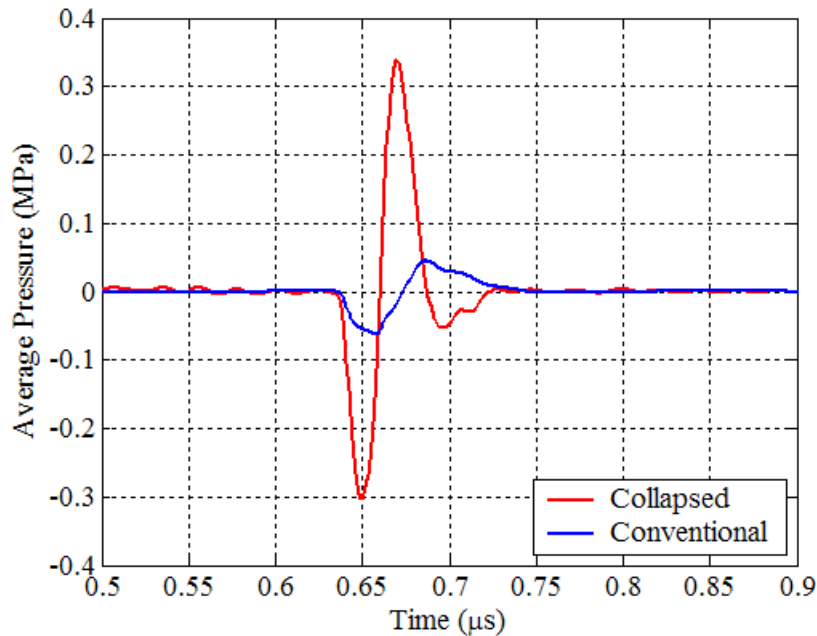
■ CMUT Dimensions

| | |
|--|-------------|
| Side length (L) (μm) | 30 |
| Membrane thickness (T) (μm) | 1.2 |
| Gap thickness (G) (μm) | 0.18 |
| Insulating layer thickness (I) (μm) | 0.10 |
| Cell periodicity (C) (μm) | 35 |
| Substrate (S) (μm) | 500 |





Dynamic FEM Results



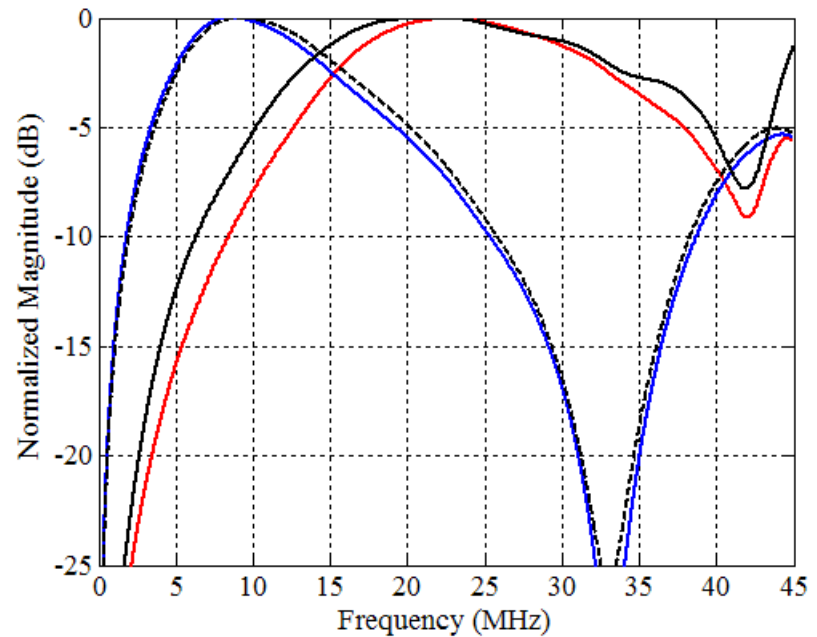
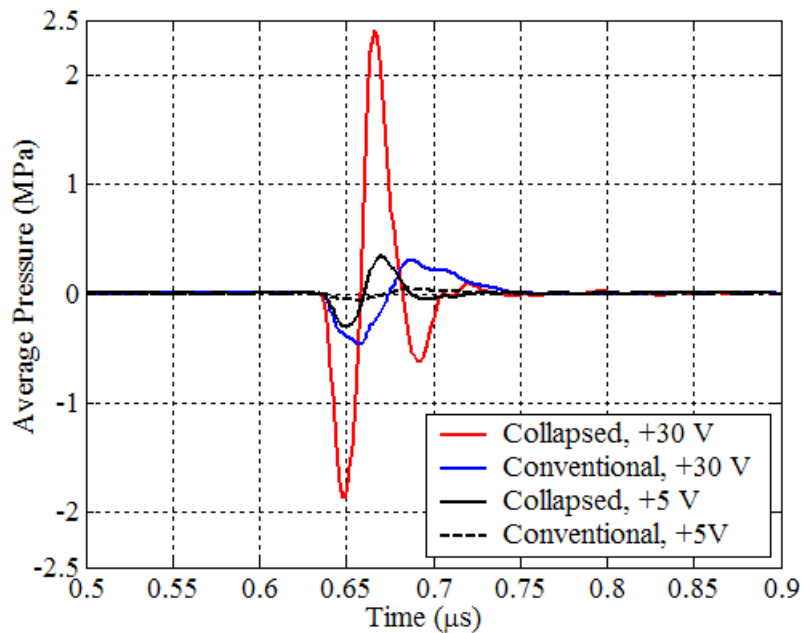
| | | |
|----------------|-----------------|------------------|
| V_{BIAS} (V) | V_{PULSE} (V) | t_{PULSE} (ns) |
| 83 | +5 | 20 |

| | |
|----------------------|----|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

| | Conventional | Collapsed |
|-----------------------|--------------------|---------------------|
| Pressure (p-p) | 107 kPa (21 kPa/V) | 641 kPa (128 kPa/V) |
| f_{CENTER} , BW (%) | 9.2 MHz, 130 % | 21.6 MHz, 108 % |



Dynamic FEM Results



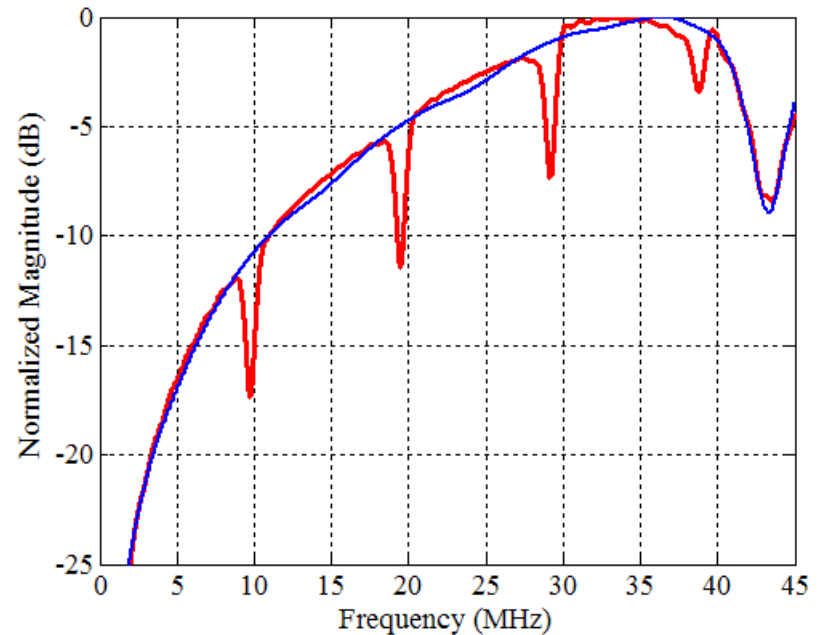
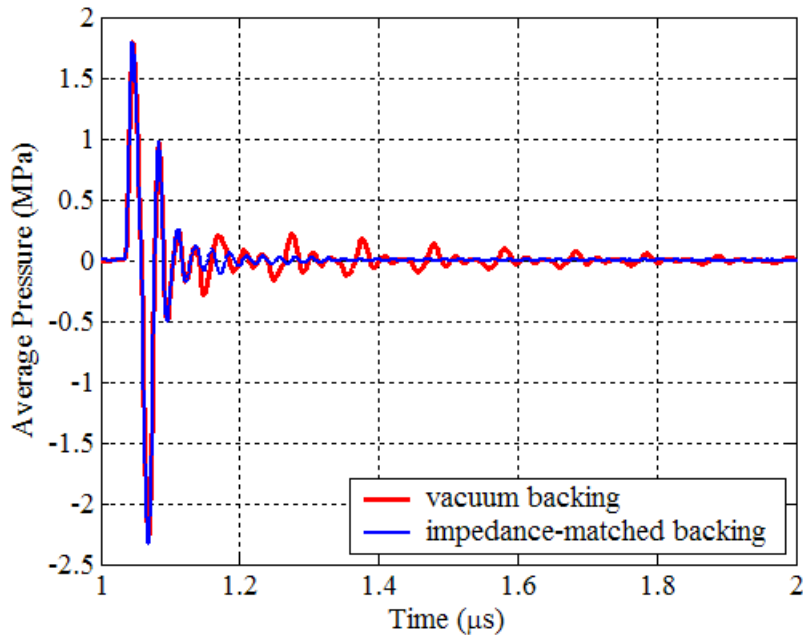
| | | |
|---------------|----------------|-----------------|
| $V_{BIAS}(V)$ | $V_{PULSE}(V)$ | $t_{PULSE}(ns)$ |
| 83 | +30 | 20 |

| | |
|----------------------|----|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

| | Conventional | Collapsed |
|-----------------------|--------------------|----------------------|
| Pressure (p-p) | 770 kPa (25 kPa/V) | 4260 kPa (142 kPa/V) |
| f_{CENTER} , BW (%) | 8.6 MHz, 132 % | 22.7 MHz, 84 % |



Dynamic FEM Results



| V_{BIAS} (V) | V_{PULSE} (V) | t_{PULSE} (ns) |
|----------------|-----------------|------------------|
| 120 | -30 | 20 |

| | |
|----------------------|----|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

- Vacuum backing causes reflections from the bottom of the substrate.

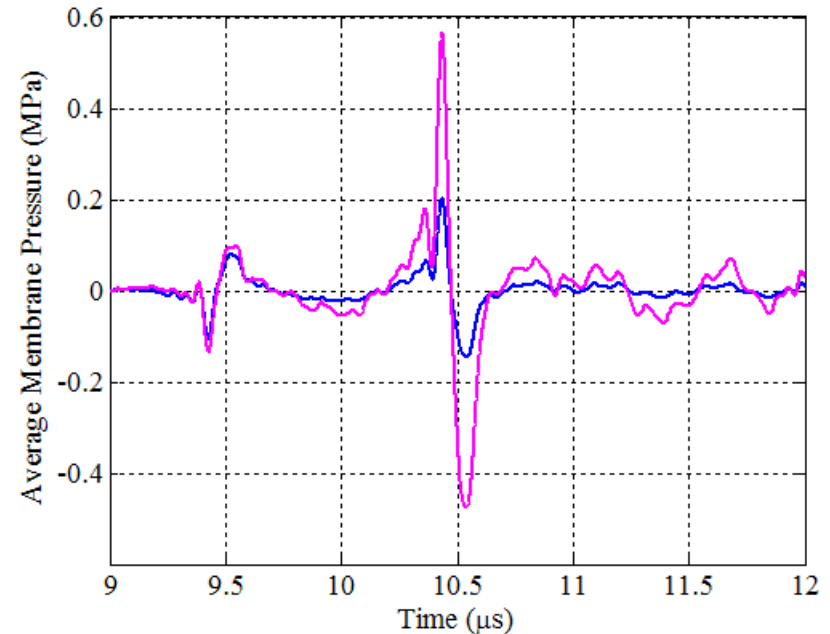


Conventional vs. Collapse-snapback

CMUT Parameters

| | |
|---|---------|
| Length of the transducer, μm | 1180 |
| Width of the transducer, μm | 280 |
| Number of cells per element | 4 x 52 |
| Cell Shape Factor | Hexagon |
| Cell radius (r_{cell}), μm | 16 |
| Electrode radius (r_{el}), μm | 8 |
| Electrode thickness (t_{el}), μm | 0.3 |
| Membrane thickness (t_m), μm | 1.06 |
| Gap thickness (t_g), μm | 0.22 |
| Insulating layer thickness (t_i), μm | 0.3 |
| Silicon substrate thickness, μm | 500 |
| Collapse voltage, V | 130 |
| Snapback voltage, V | 110 |

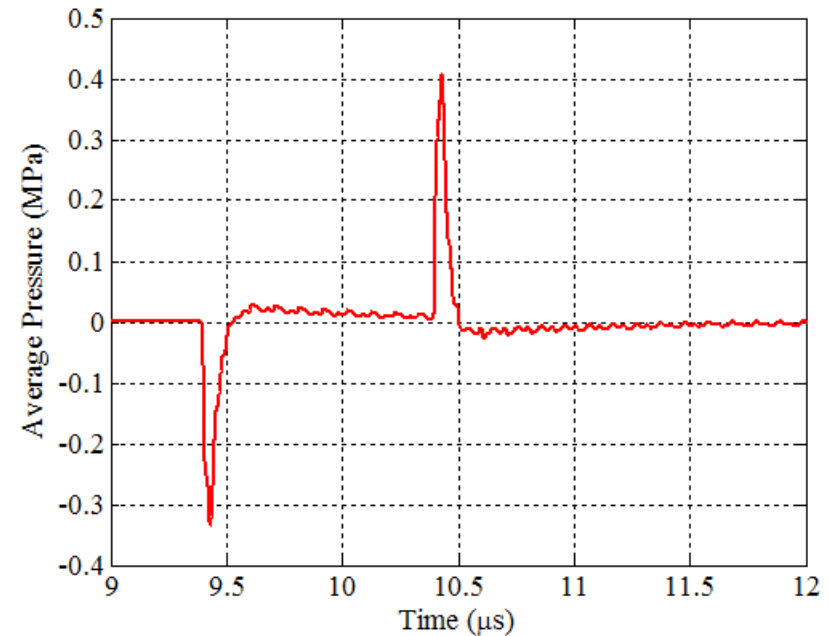
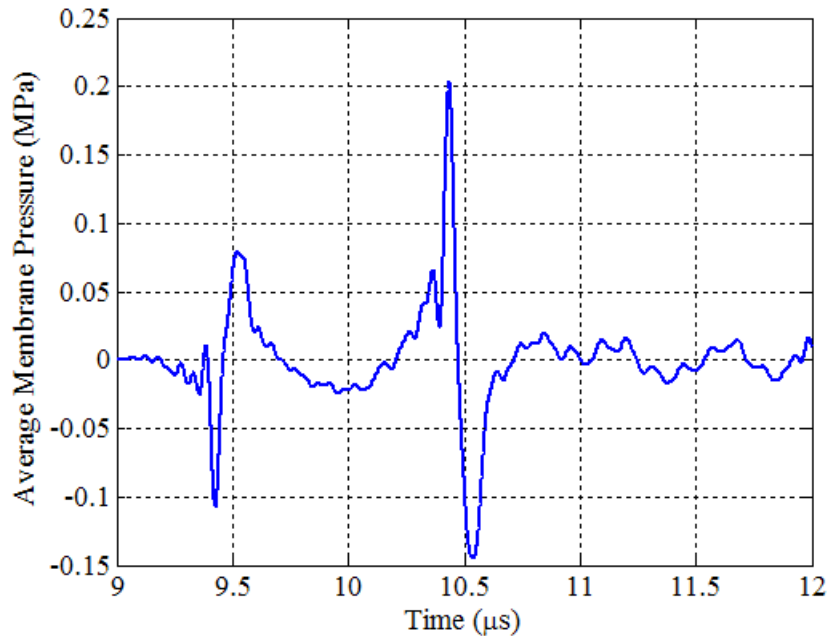
Experimental Results



| $V_{BIAS}(V)$ | $V_{PULSE}(V)$ | $t_{PULSE}(\mu s)$ |
|---------------|----------------|--------------------|
| 50 | +70 | 1 |
| 50 | +90 | 1 |



Experimental and FEM Results



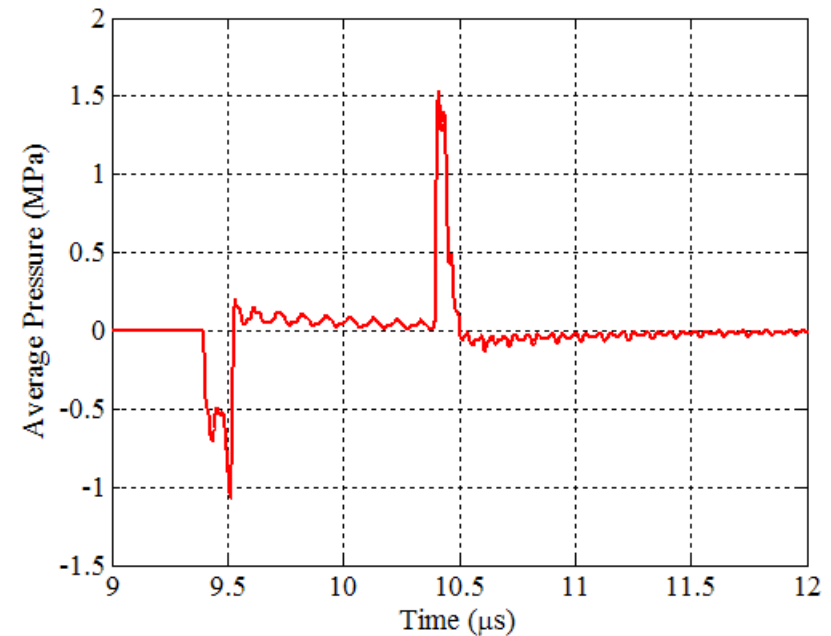
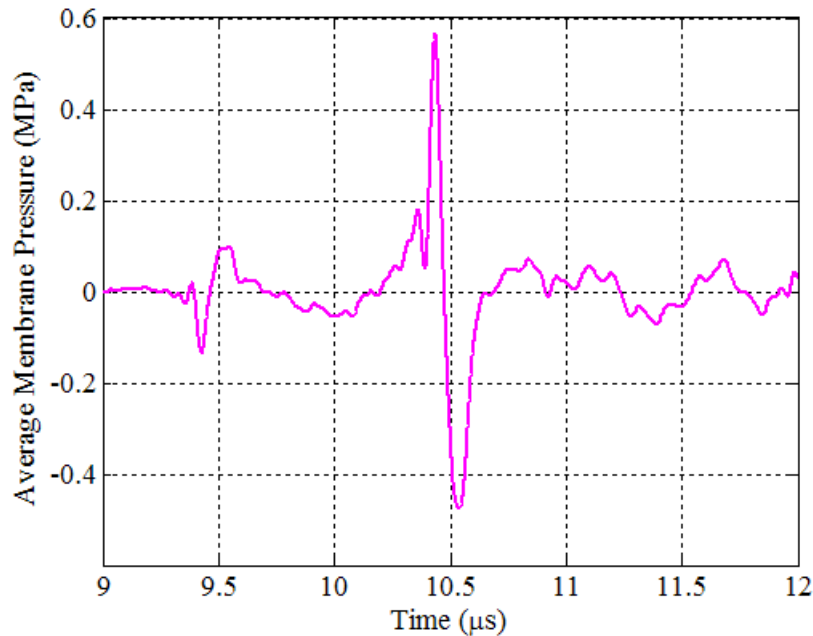
| $V_{BIAS}(V)$ | $V_{PULSE}(V)$ | $t_{PULSE}(\mu s)$ |
|---------------|----------------|--------------------|
| 50 | +70 | 1 |

| | |
|----------------------|-----|
| Collapse Voltage (V) | 130 |
| Snapback Voltage (V) | 110 |

| Conventional | Experimental | FEM |
|----------------|-------------------------------------|-------------------------------------|
| Pressure (p-p) | Rising, Falling 185 kPa, 348 kPa | Rising, Falling 366 kPa, 422 kPa |



Experimental and FEM Results



| $V_{BIAS}(V)$ | $V_{PULSE}(V)$ | $t_{PULSE}(\mu s)$ |
|---------------|----------------|--------------------|
| 50 | +90 | 1 |

| | |
|----------------------|-----|
| Collapse Voltage (V) | 130 |
| Snapback Voltage (V) | 110 |

| Collapse-Snapback | Experimental | FEM |
|-------------------|---|--|
| Pressure (p-p) | Collapse, Snapback 234 kPa, 1040 kPa | Collapse, Snapback 1270 kPa, 1580 kPa |



More Results

- **U3-D-4** High-Frequency CMUT Arrays for High-Resolution Medical Imaging: Preliminary Results.
- **U3-D-5** CMUT Ring Arrays for Forward-looking Intravascular Imaging: Preliminary Results.



Conclusion

- The cMUT dynamics modeled with time-domain, nonlinear, finite element method (FEM) using LS-DYNA explicit solver.
- Tested in linear (**conventional**) and nonlinear (**collapsed** and **collapse-snapback**) operation regimes.
- Good agreement between experimental and FEM results observed.
- High acoustic output pressure produced in nonlinear regimes.