# VHDL-AMS Behavioural Modelling of a CMUT Element

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# Overview

- Introduction
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- Modelling
- Simulation
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# Introduction

- Capacitive Micromachined Ultrasonic Transducer (CMUT)

- Replacement for piezoelectric transducers in ultrasonic imaging

# Introduction

- Ultrasonic imaging
  - large and growing area of medical imaging
  - transducer elements emit and receive ultrasonic pressure waves
  - received echoes are converted to electrical signals and displayed
  - reflections at tissue boundaries allow imaging of anatomy
  - delaying signals to and from elements of array allow focusing

- Piezoelectric Transducers
  - fabricated in lead zirconate titanate (PZT)
  - highly resonant
  - backing and matching layers used to increase bandwidth

# Introduction

- CMUT advantages
  - wide bandwidth and high sensitivity
  - high frequency operation
  - integration with CMOS electronics on IC

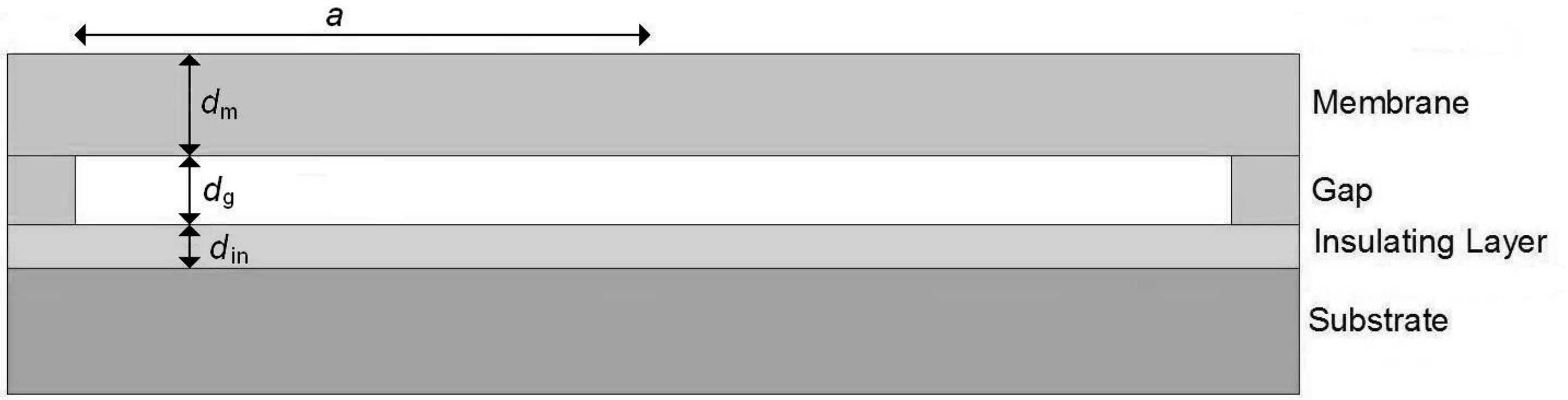
- Aim of this work
  - develop behavioural model to aid CMUT design and optimisation
  - make model compatible with other software platforms to facilitate simulation in different environments

# Background

- Ladabaum et al., 1998
  - small-signal linearisation of electro-mechanical relations about a DC bias point
  - mechanical impedance obtained from work of Mason, 1948
- Caronti et al., 2002
  - extended above approach to include damping due to gap layer
- Our approach
  - non-linear model of electro-mechanical relations
  - 2nd order system for mechanical-acoustic interactions
  - implemented in VHDL-AMS

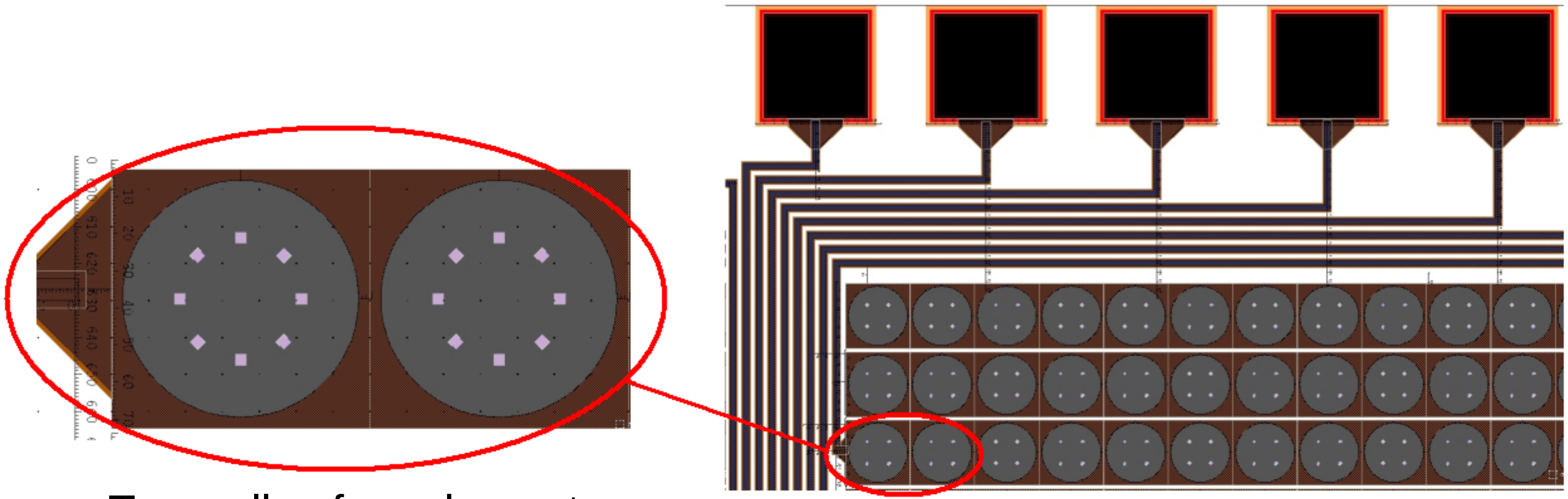
# Modelling

- General CMUT cell cross-section



# Modelling

- Many cells connected in parallel form a CMUT element
- Many individual elements form an array
- Model developed at element level

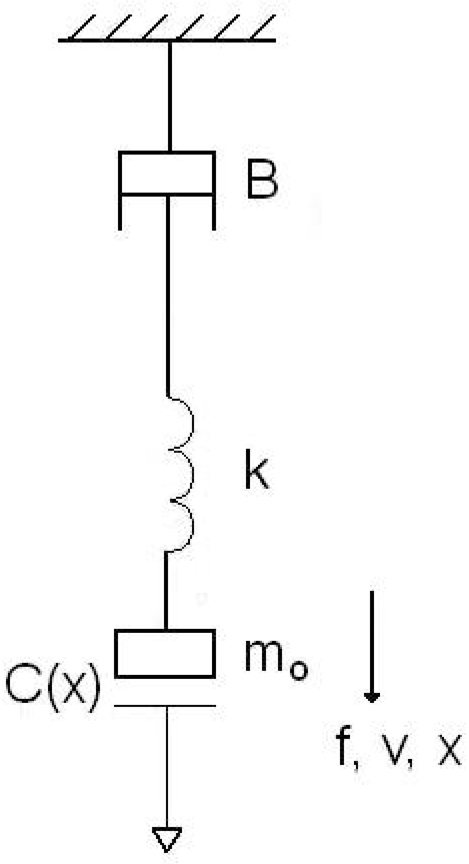


Two cells of an element

Elements of an array

# Modelling

- Assume piston movement of membrane
- Reduces model to 1-DOF: displacement at centre of membrane
- Treat as moveable plate capacitor
- Attached to mass-spring-damper system
  - $m_o$ – effective mass of membrane
  - $k$ – effective spring constant of membrane
  - $B$ – damping due to acoustic medium

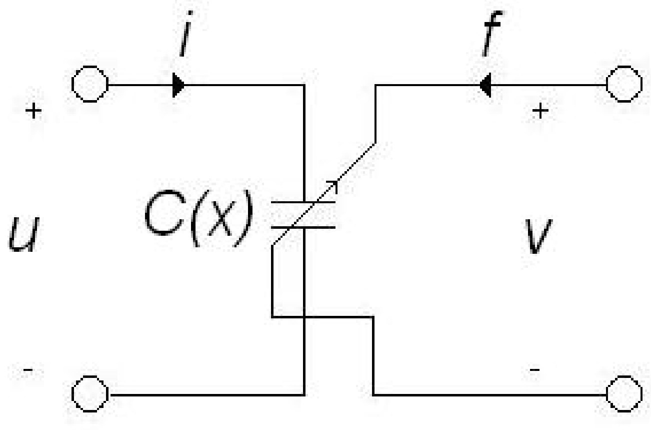


# Modelling

- Effective mass $m_o = 0.613\rho_m d_m A$
- Spring Constant $k = \dfrac{16\pi Y_m {d_m}^3}{3a^2(1-{\sigma_m}^2)} N$
- Damping $B = Z_0 A$
- Effective area $A = \pi a^2 N$
- Effective gap $d_0 = d_g + \dfrac{d_{in}}{\varepsilon_{in}}$

# Modelling

- Two-port model equations for moveable plate capacitor:



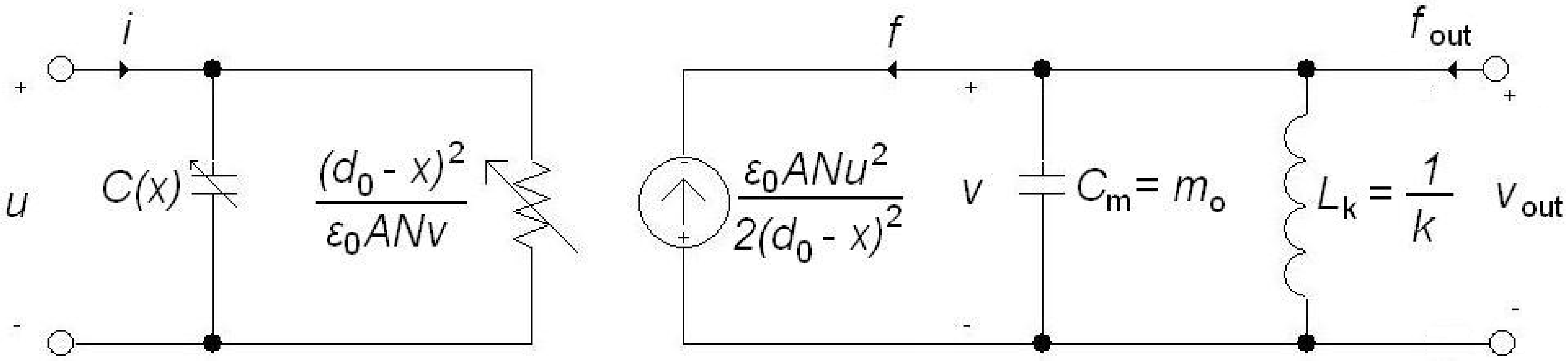
$$C(x) = \frac{\varepsilon_0 A}{d_0 - x}$$

$$i = \frac{\varepsilon_0 A}{(d_0 - x)^2} uv + C(x) \frac{du}{dt}$$

$$f = -\frac{\varepsilon_0 A}{2(d_0 - x)^2} u^2$$

# Modelling

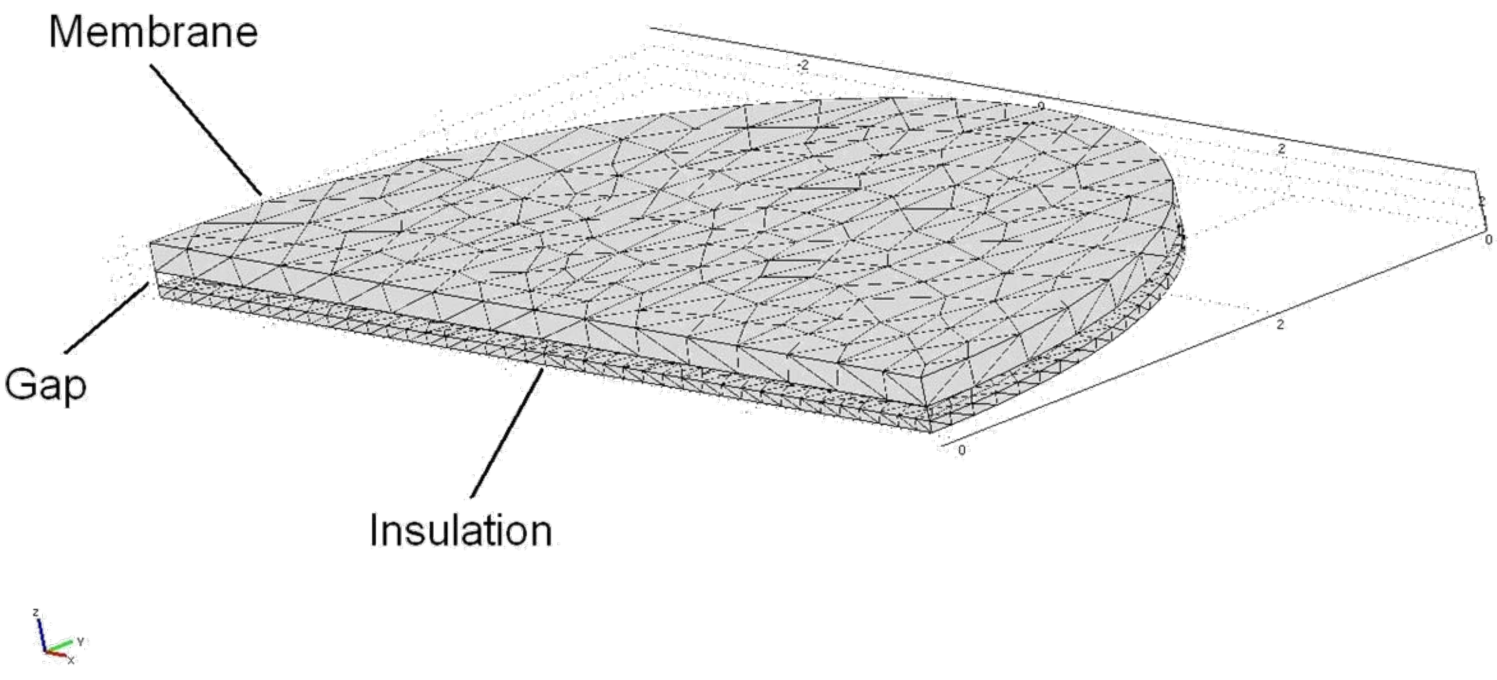
- Equivalent circuit



- Non-linear
- Implement in VHDL-AMS

# Modelling

- FEM Model developed using COMSOL *Multiphysics*



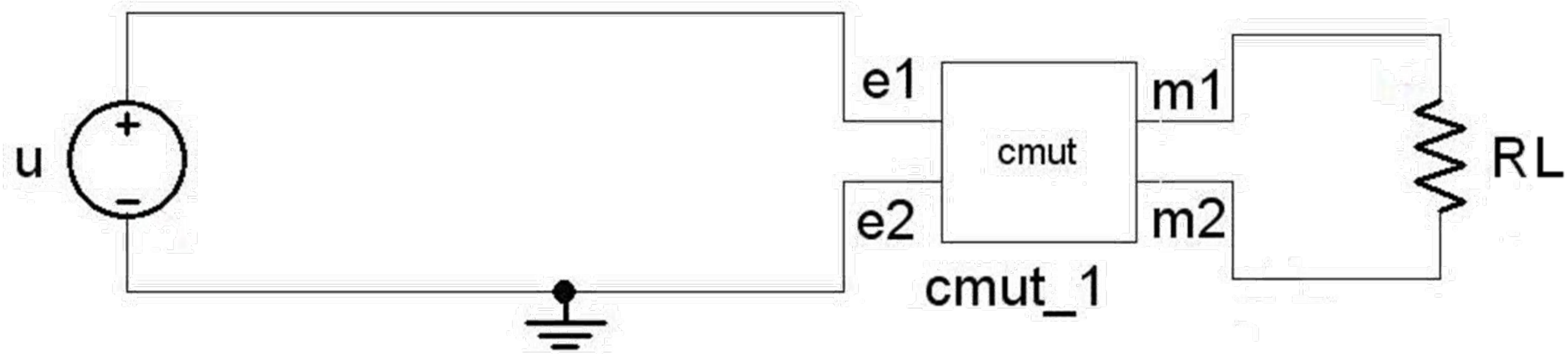
# Simulation

- Designed CMUT compatible with MEMSCAP *PolyMUMPs* fabrication process

| Parameter | Value |
|---|---|
| Membrane material | Crystalline silicon |
| Membrane radius | 32 µm |
| Membrane thickness | 1.5 µm |
| Gap thickness | 0.75 µm |
| Insulation material | Silicon nitride |
| Insulation thickness | 0.6 µm |
| No. cells per element | 118 |

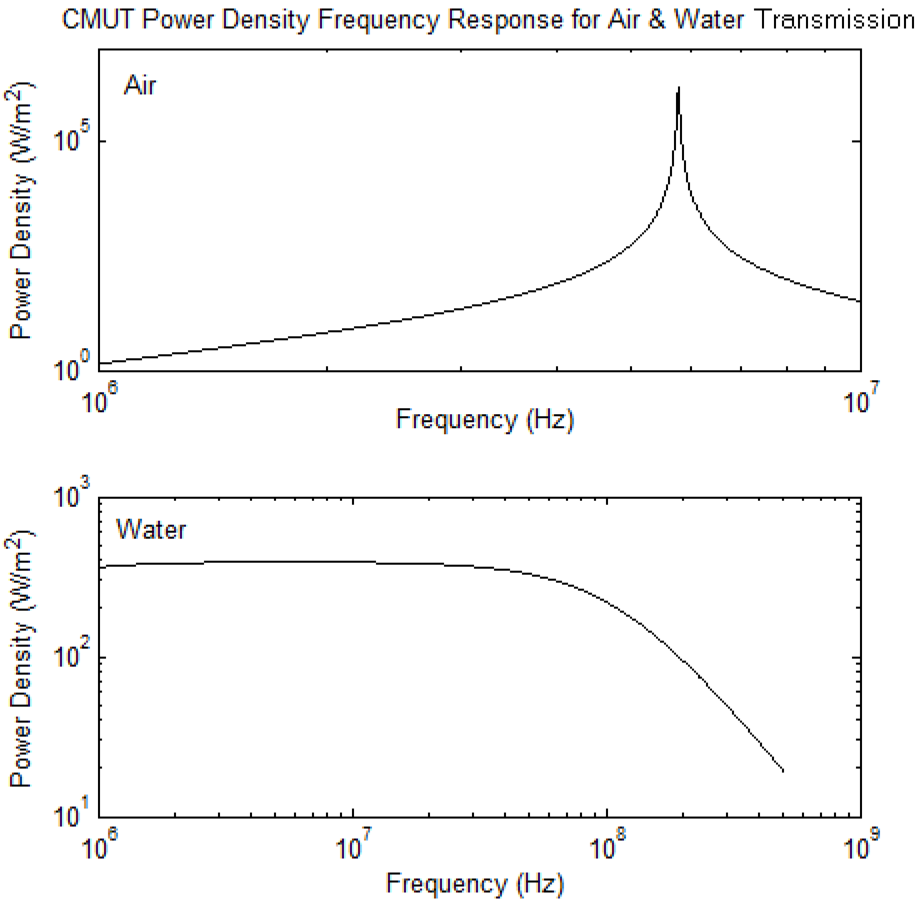
# Simulation

- Ansoft *Simplorer* for simulation
  - allows combination of VHDL-AMS and SPICE components
  - transmission circuit used for simulations:



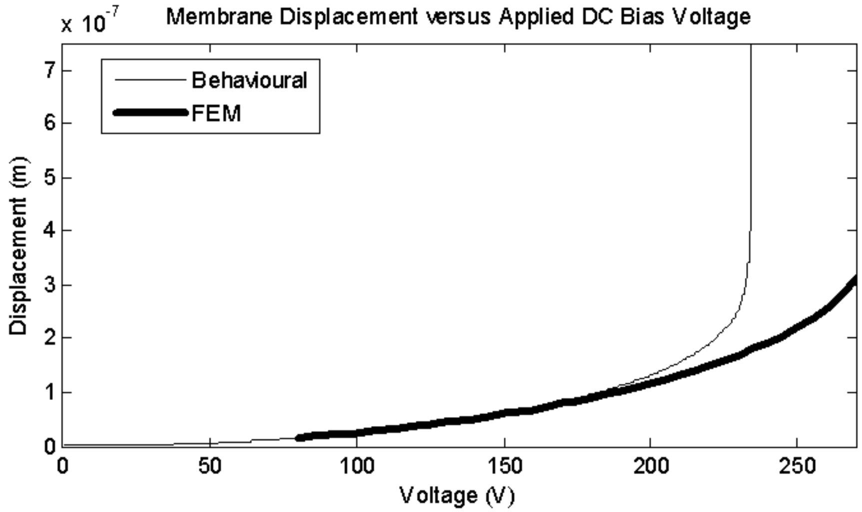
# Simulation

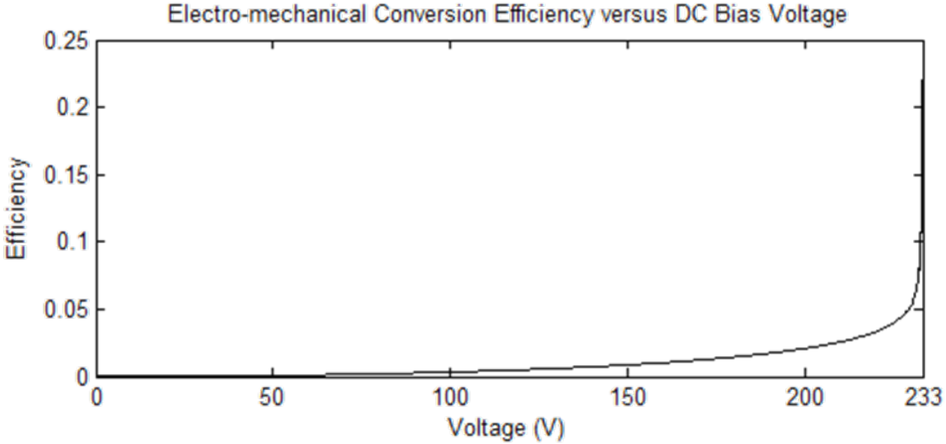
- Frequency response
  - 90 V DC bias
  - 20 V AC excitation
- Air: $f_{res} = 5.78$ MHz
- Water: $BW = 115$ MHz
- FEM: $f_{res} = 5.85$ MHz
  - (Eigenfrequency analysis)



# Simulation

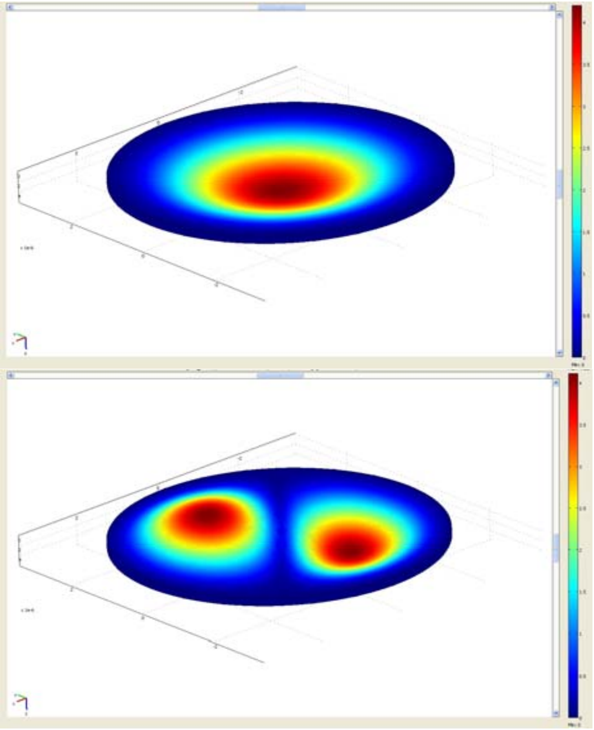
- Pull-in phenomenon
- Behavioural Model
  - $V_{PI} = 230\ V$
  - $x_{PI} = 0.265\ \mu m$
- FEM Model
  - $V_{PI} = 275\ V$
  - $x_{PI} = 0.315\ \mu m$
- Coupling efficiency increases near pull-in



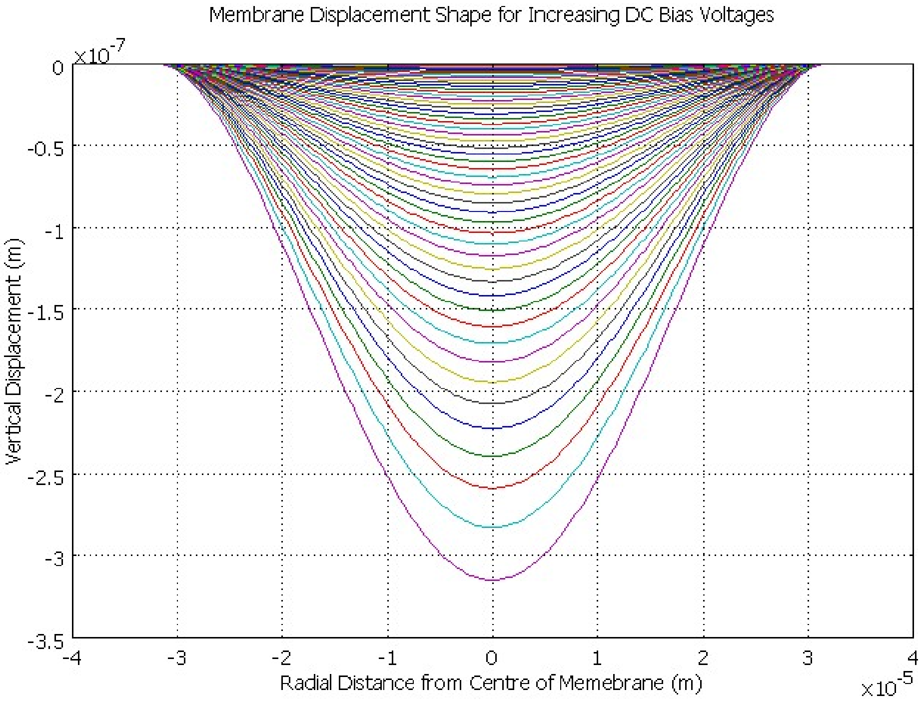


# Simulation

- FEM model shows membrane modes and shapes



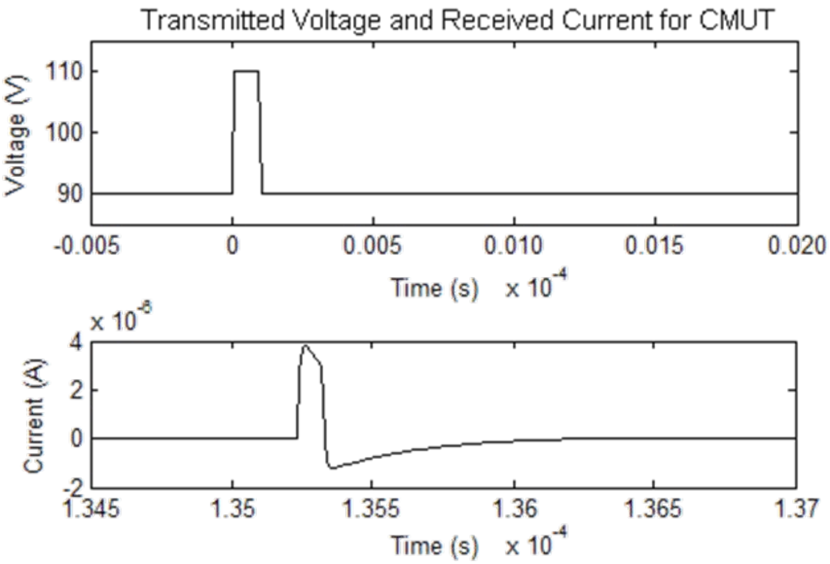
First two harmonic modes

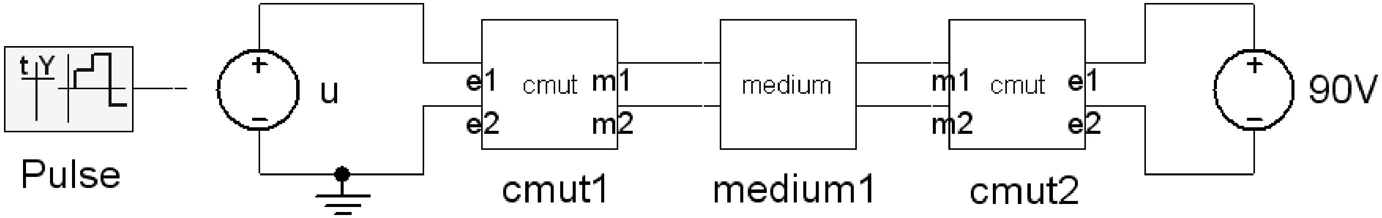


Deformation shapes with DC bias voltage

# Simulation

- Transmit and receive circuit
- Medium imposes time delay and attenuation
- 20 V input pulse gives 4 µA output pulse, delayed by 135µs





# Discussion

- Resonant frequency
  - excellent agreement between behavioural and FEM models
  - very wide bandwidth transmitting into water or tissue

- Pull-in phenomenon
  - 16% difference between behavioural and FEM models
  - likely due to assumption of parallel plate capacitance
  - higher DC bias increases coupling efficiency
  - simulations demonstrate non-linear nature of CMUT and model

- Transmit and receive
  - demonstrates model bi-directionality
  - simulation time was ~5.8 s on 2 GHz PC (FEM would be hours)

# Conclusion

- This work
  - Developed non-linear behavioural CMUT model in VHDL-AMS
  - *Simplorer* simulations of model were compared with FEM
  - Excellent agreement in resonant frequency
  - 16% error in pull-in voltage and displacement

- Future work
  - modelling of membrane deformation shape
  - incorporation of membrane-gap interaction
  - comparison of simulation results with experimental results from fabricated design

# Acknowledgements & References

- Acknowledgements
  - Natural Sciences and Engineering Research Council of Canada
  - CMC Microsystems

- References
  - Caronti et al., 2002, “An Accurate Model for Capacitive Micromachined Ultrasonic Transducers,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 49, no. 2, pp. 159-168.
  - Ladabaum et al., 1998, “Surface Micromachined Capacitive Ultrasonic Transducers,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 45, no. 3, pp. 678-690.