Acoustic-mechanic modeling of polydimethylsiloxane in the MHz regime for metamaterials applications

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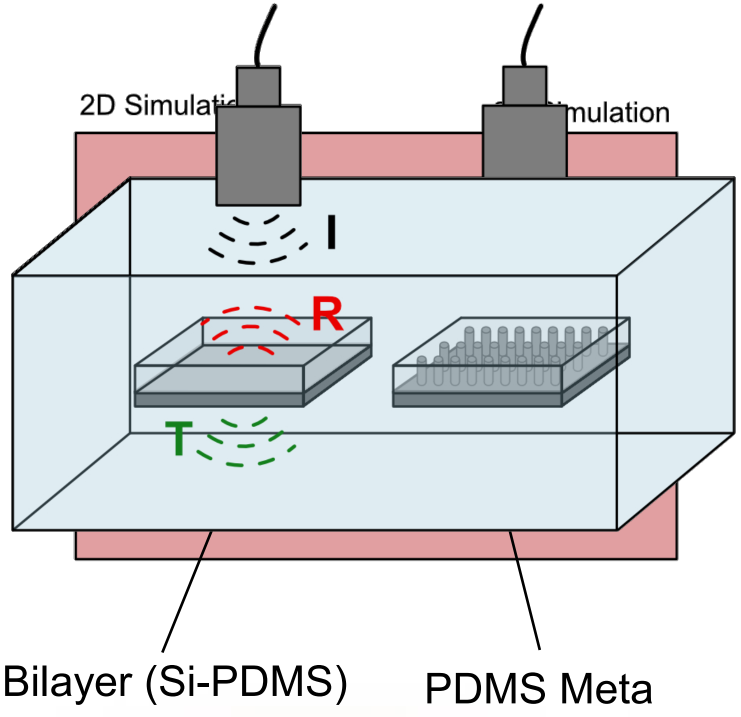
Simulation reference: bilayer

Bilayer used as **reference** to compare simulation with analytical solution

2D simulation:

- Multiphysics (Solid Mechanics & Pressure Acoustics)
- Parametric (***f***) frequency domain

Simulation cases

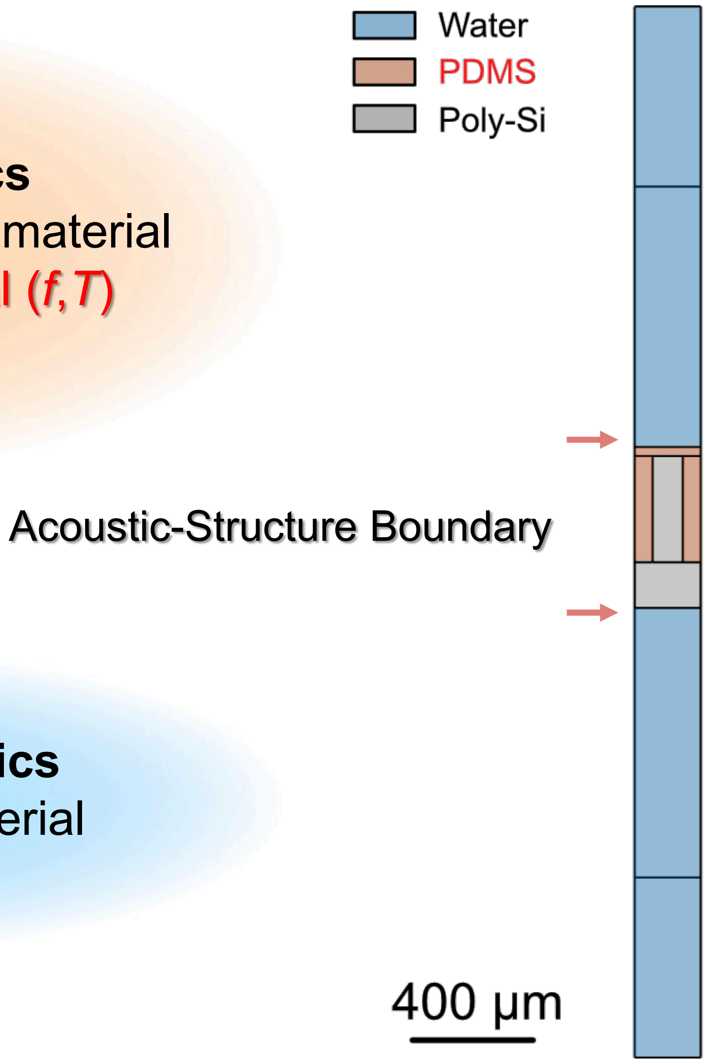


$$R = \prod_{j=1}^{n} (Z_{in}^{j} + Z_j)/(Z_{in}^{j} + Z_{j+1}) e^{i\varphi_j}$$

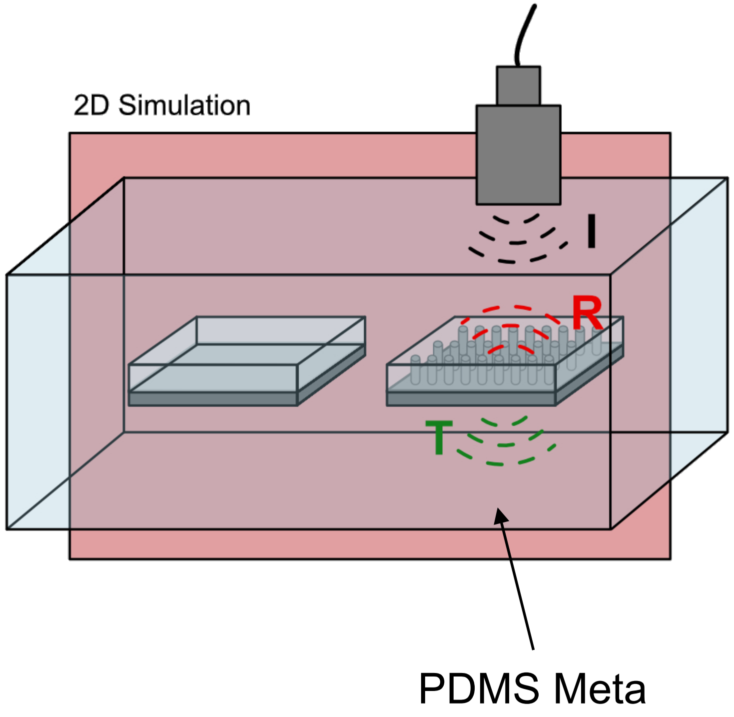
LM Brekovski, *Waves in Layered Media*, 1980, Academic Press

Solid Mechanics
- Poly-Silicon: built-in material
- PDMS: experimental (*f*,*T*)

Pressure Acoustics
- Water: built-in material

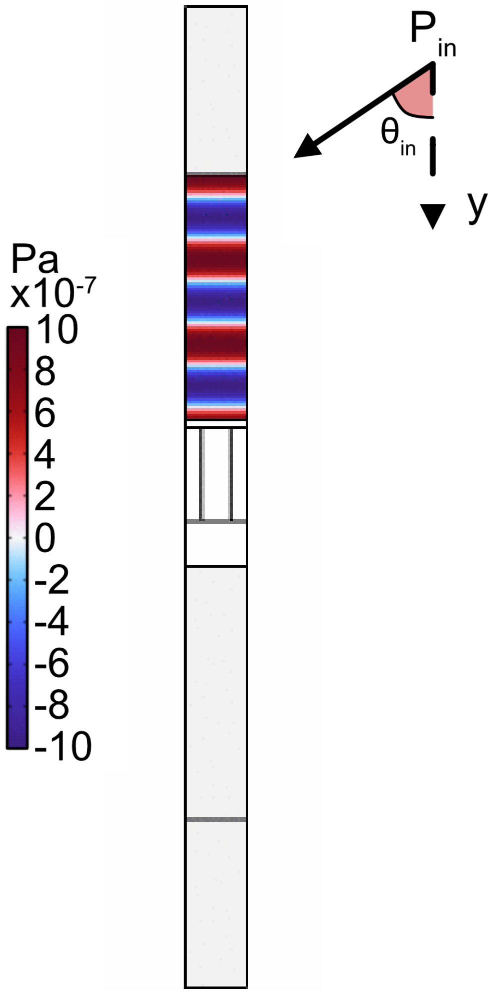


Simulation cases



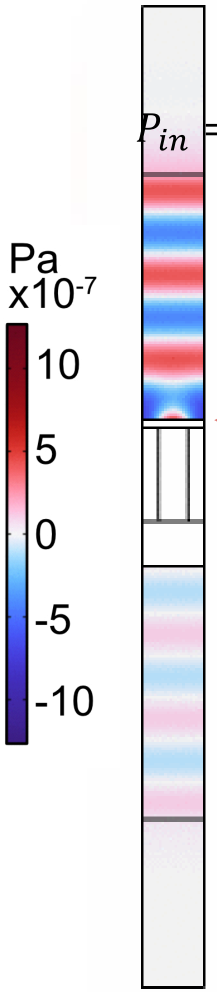
Simulation: PDMS Meta

Incoming pressure



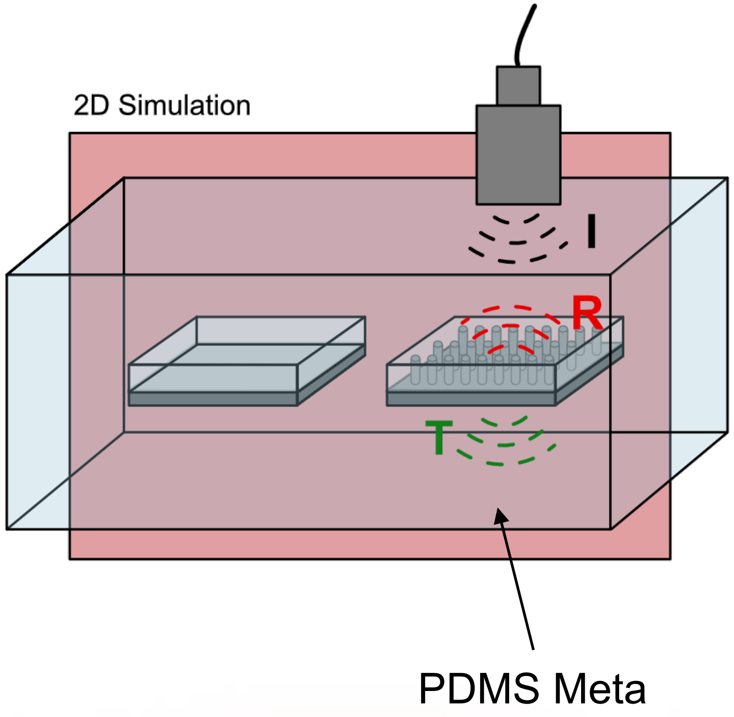
Scattered pressure

$$P_{in} = 10^{-6}[Pa] \cdot e^{-i \cdot k(f) \cdot \cos(\boldsymbol{\theta_{in}}) \cdot y}$$



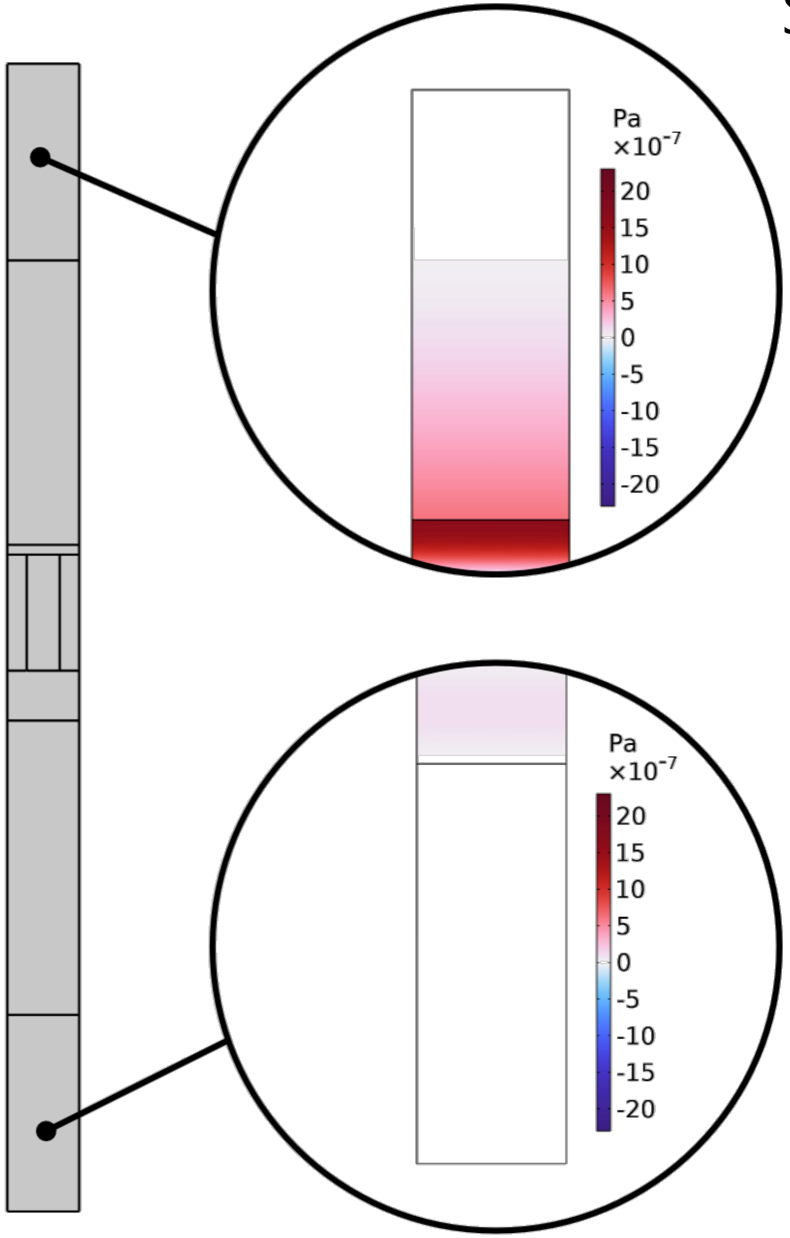
Reflected pressure

Simulation cases



$$|R_{dB}| = 20 \cdot log_{10}\left(\left|\frac{P_s}{P_{in}}\right|\right)$$

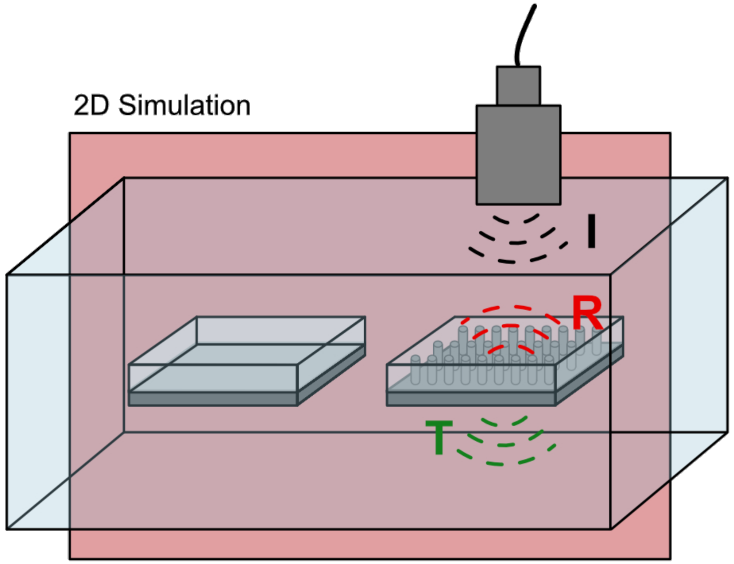
Simulation: PDMS Meta



Perfectly Matched Layers:

- Coordinate stretching type: Rational
- Type: Cartesian (unitary scaling factor)

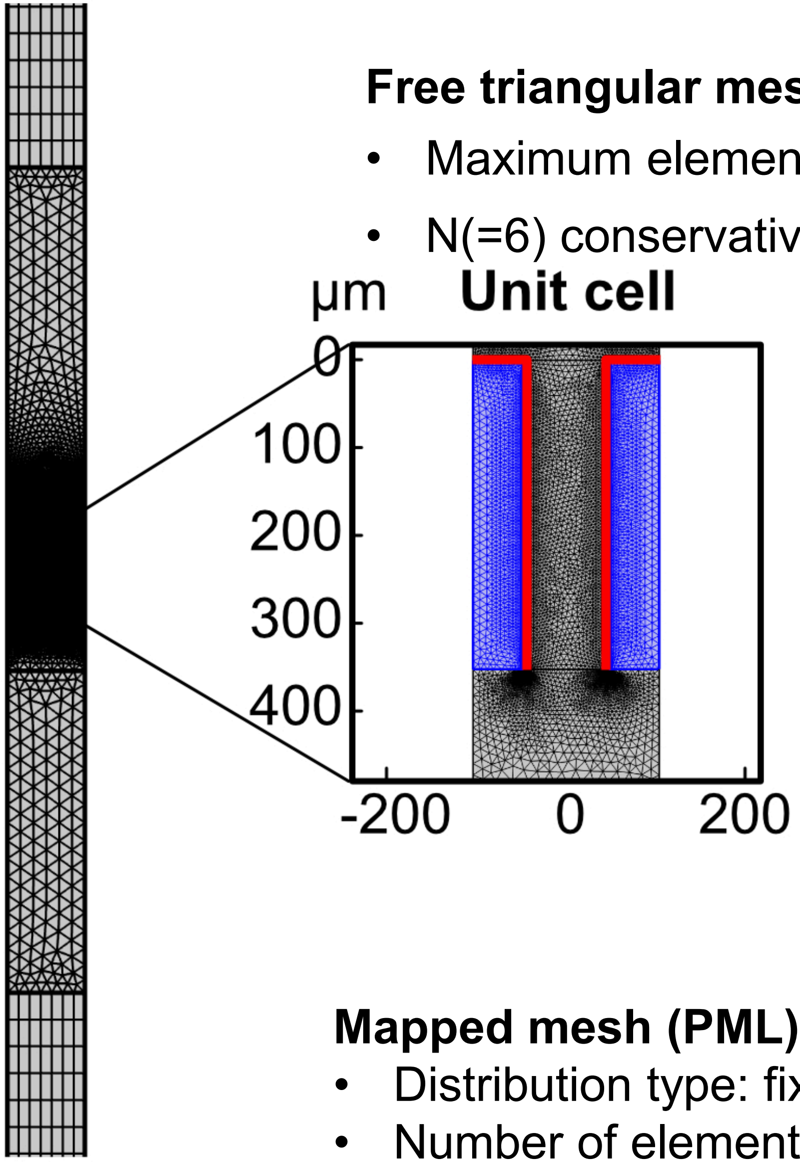
Simulation cases



Boundary conditions:
Floquet periodicity

Simulation: PDMS Meta

Free triangular mesh:
- Maximum element size: $\left(\frac{c_{L,water}}{f}\right) \cdot \frac{1}{N}$
- N(=6) conservative factor

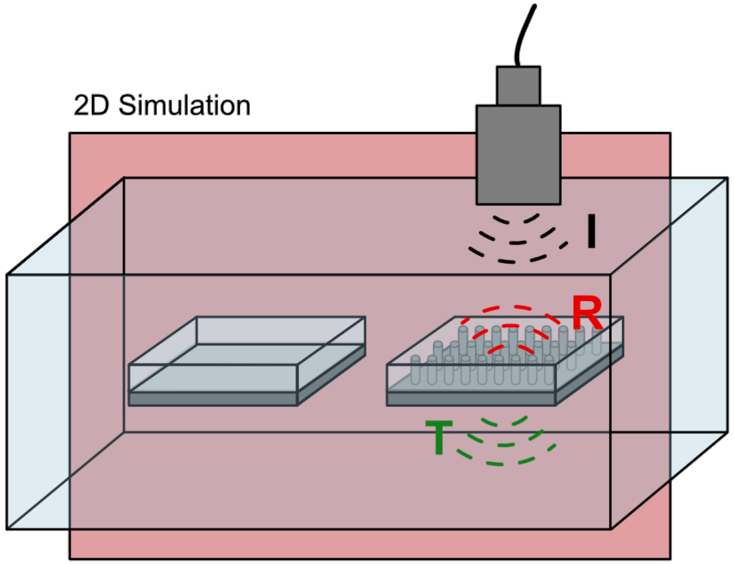


PDMS domain mesh:
- Edge mesh
- Maximum element size: $\left(\frac{c_{s,PDMS}}{f}\right) \cdot \frac{1}{N}$
- Boundary layers: 20

Poly-Si domain mesh:
- Free triangular
- Maximum element size: $\left(\frac{c_{L,Si}}{f}\right) \cdot \frac{1}{N}$

Mapped mesh (PML):
- Distribution type: fixed number of elements
- Number of elements: 8

Simulation cases



Shear waves at the interface PDMS-Si due to BCs

c_s = shear wave speed
c_L = longitudinal wave speed

Frequency dependency of PDMS

Solid Mechanics

$$\begin{pmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{pmatrix} = \begin{pmatrix} \boldsymbol{C_{11}} & \boldsymbol{C_{12}} & \boldsymbol{C_{12}} & 0 & 0 & 0\\ \boldsymbol{C_{12}} & \boldsymbol{C_{11}} & \boldsymbol{C_{12}} & 0 & 0 & 0\\ \boldsymbol{C_{12}} & \boldsymbol{C_{12}} & \boldsymbol{C_{11}} & 0 & 0 & 0\\ 0 & 0 & 0 & \boldsymbol{C_{44}} & 0 & 0\\ 0 & 0 & 0 & 0 & \boldsymbol{C_{44}} & 0\\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{C_{44}}\end{pmatrix}\begin{pmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{pmatrix}$$

Hypothesis: isotropic material

L- and S-waves velocities related to elastic constants:

$$C_{11}(f) = \rho_P\, \boldsymbol{\hat{c}_L}^2, \qquad C_{44}(f) = \rho_P\, \boldsymbol{\hat{c}_s}^2$$

$$\hat{c}_i(f) = \frac{2\pi f}{2\pi f / c_i + j\alpha_i} \quad \text{with} \quad i = L \text{ or } S$$

Elastic constants relation:

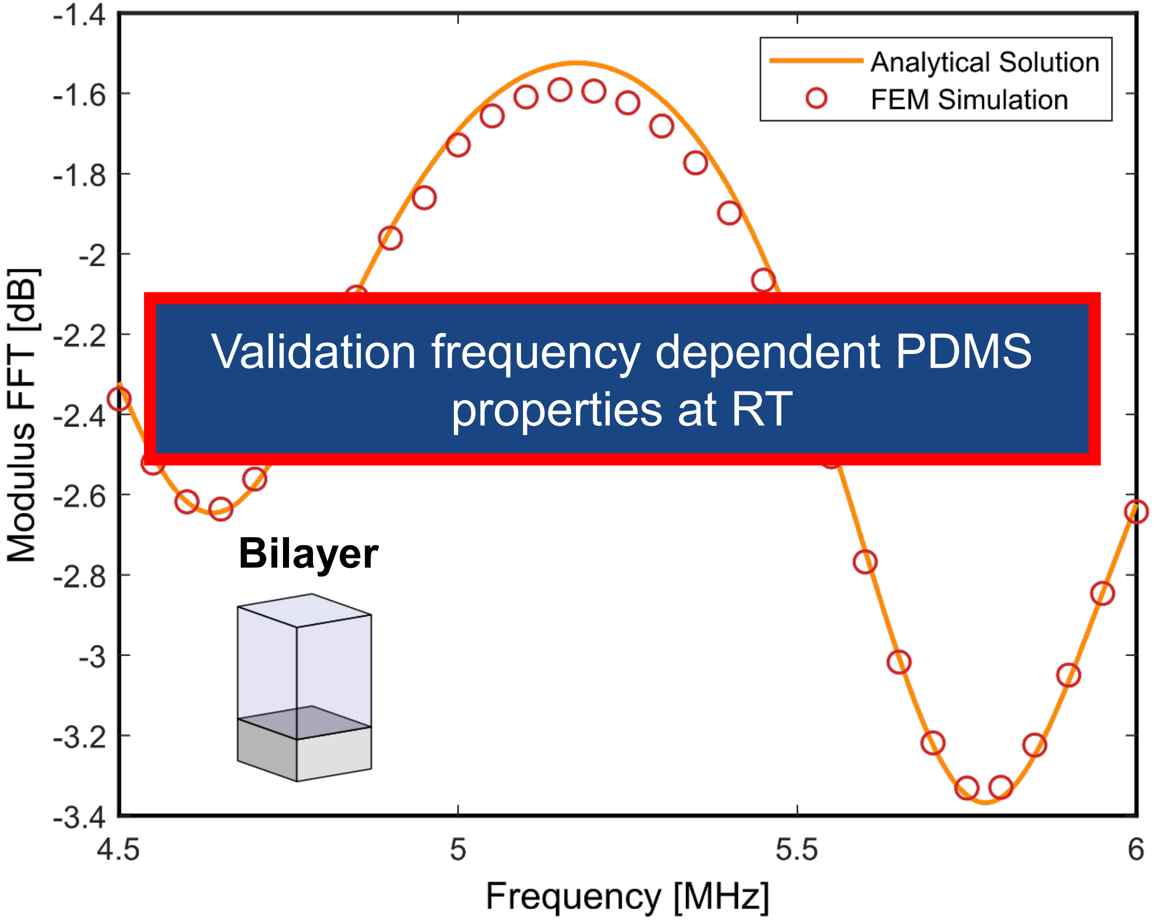
$$C_{12}(f) = \boldsymbol{C_{11}(f)} - 4\boldsymbol{C_{44}(f)}$$

$$C_{11}(f) = \boldsymbol{K} + \frac{4}{3}\boldsymbol{G}$$

$$C_{44}(f) = \boldsymbol{G}$$

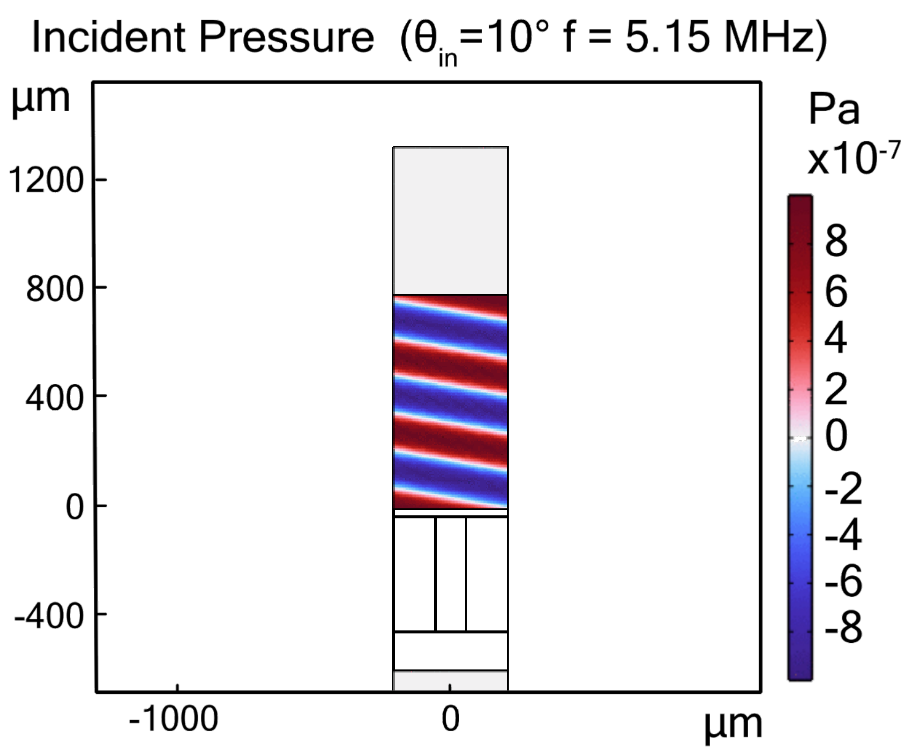
- Linear elastic material
- Specify: Bulk and Shear Modulus

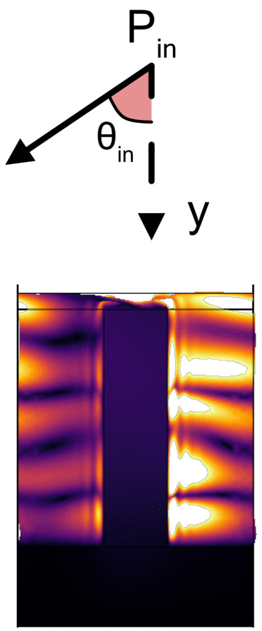
- Experimental elastic constants **@RT** (interpolated from [1])
- Analytical solution vs FEM simulation with complex PDMS material properties

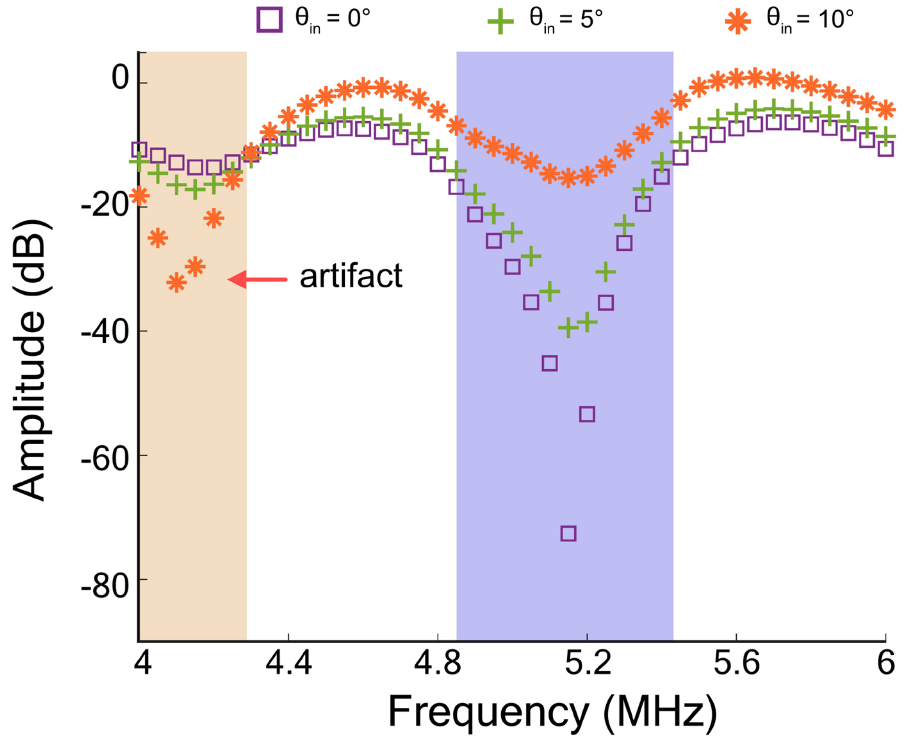


[1] NR Skov et al., *Physical Review Applied* 12, 2019
[2] G Xu et al., *Physical Review Applied* 13, 2020

Application: incidence angle







Asymmetric stress distribution in the PDMS generating spurious peaks and **artifacts** in the reflection spectrum

Outlooks and conclusions

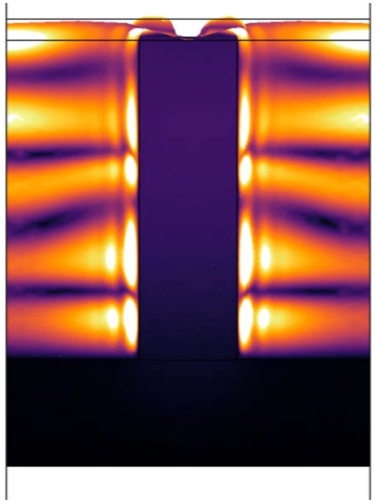
✓ Successful implementation of **temperature** and **frequency** dependent acoustic properties of **PDMS** (MHz regime)

✓ Validation with simpler **analytical** models and **experiments**

✓ Material definition can be used for other bio-applications

- Investigation of artifacts potentially arising in our experiments (incoming pressure field misalignment)

- Investigation of fabrication process variation (not shown in this presentation)



− 3D implementation **computationally limited**

- Investigation of **cluster-based** solutions

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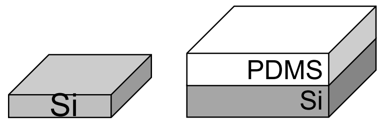
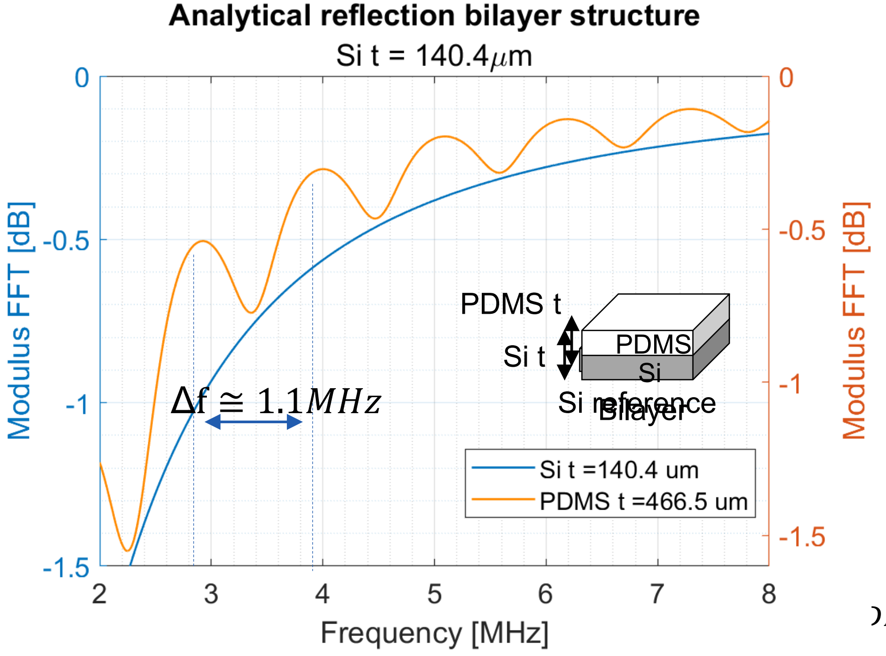
Silicon reference vs bilayer





$$R_{dB} = 20log_{10}\left(\alpha \cdot \frac{i \cdot \tan(\boldsymbol{k_0} d) \cdot (Z_0{}^2 - Z_1{}^2)}{i \cdot \tan(\boldsymbol{k_0} d) \cdot (Z_0{}^2 + Z_1{}^2) - 2Z_0 Z_1}\right)$$

- Impedance matching condition for $f = \frac{(n+1)}{2} \cdot \frac{c}{d}$

$$f_{0,Si} \cong 28.4\ MHz \qquad f_{0,PDMS} \cong 1.1\ MHz$$

$$\prod_{j=1}^{n} (Z_{in}^{j} + Z_{j})/(Z_{in}^{j} - Z_{j+1}) e^{i\varphi_j}$$

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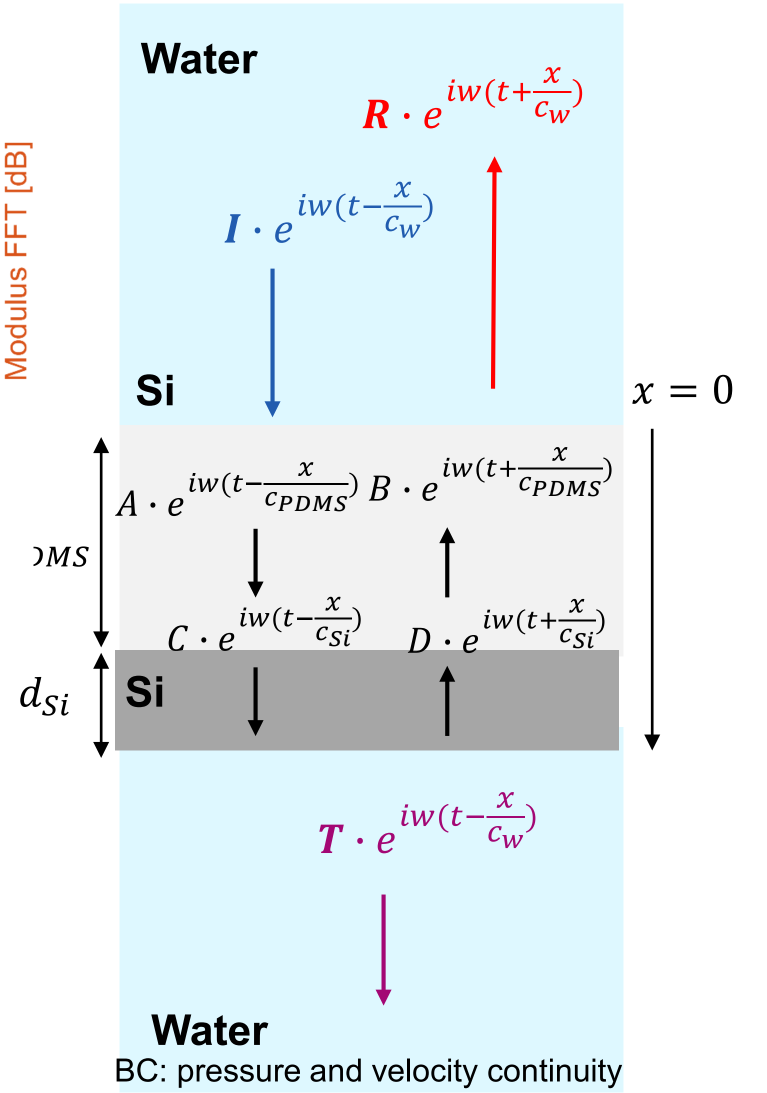

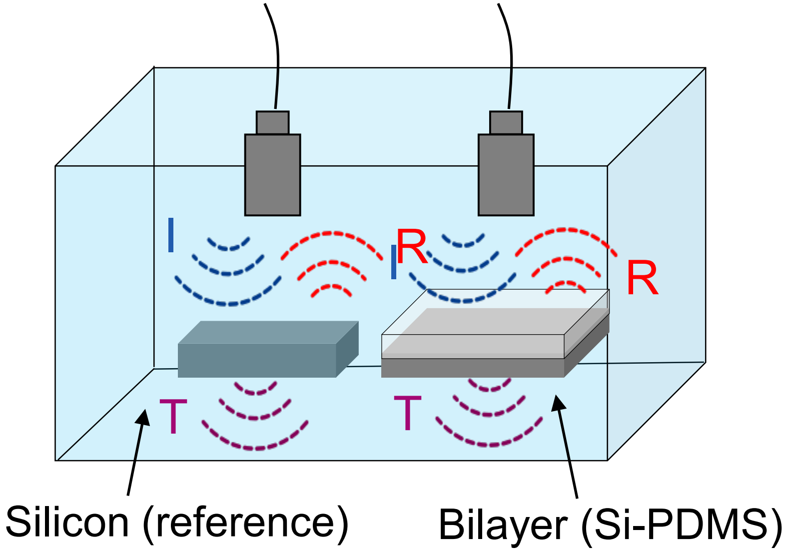

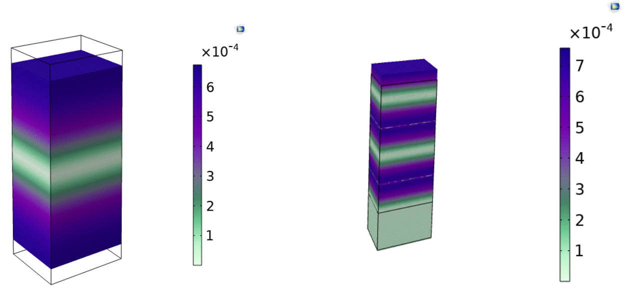

- Only longitudinal waves considered
- Neglected attenuation and dispersion

Scattered Pressure Field