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Efficient Anchor Design for Quality Factor Enhancement in a Silicon Nitride-on-Silicon Lateral Bulk Mode Resonator

Udit Rawat, V. V. Pasula, D. R. Nair, A. DasGupta

Presenter: **Udit Rawat**

Microelectronics and MEMS Laboratory
Department of Electrical Engineering
Indian Institute of Technology Madras

Outline

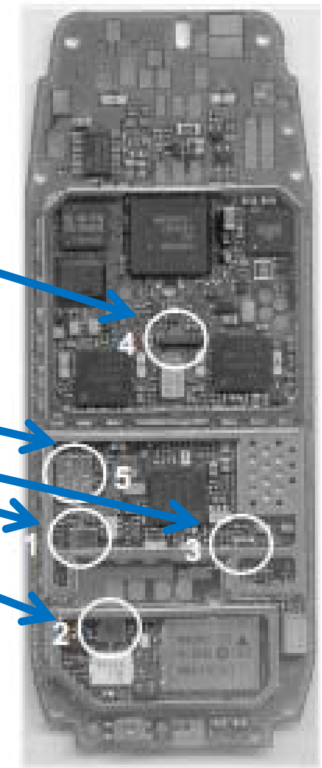
- **Introduction**
- **Resonator Design**
- **Analysis**
- **Simulation Results**
- **Conclusion**

Introduction

- **Off-chip** passives in modern day wireless transceivers:
  - oTuning fork (quartz crystal) for standby clocking
  - o**TCXO** clock reference
  - oThe RF and IF SAW Filters

- Features:
  - o **High Quality Factor**
  - o Stable over a wide temperature range
  - o Low phase noise

- Drawbacks:
  - o Ultimate **bottleneck in device miniaturization and portability**
  - o Quartz is **incompatible with modern day VLSI technology processes**



Piezoelectric Components in a Typical Dual-Band GSM Handset*

Solution: **On-chip silicon based micromechanical signal processors**

*C.S.Lam ," **A Review of the Recent Development of MEMS and Crystal Oscillators and Their Impacts on the Frequency Control Products Industry**," IEEE Int'l Ultrasonics Symposium, Beijing, Nov. 2~5, 2008

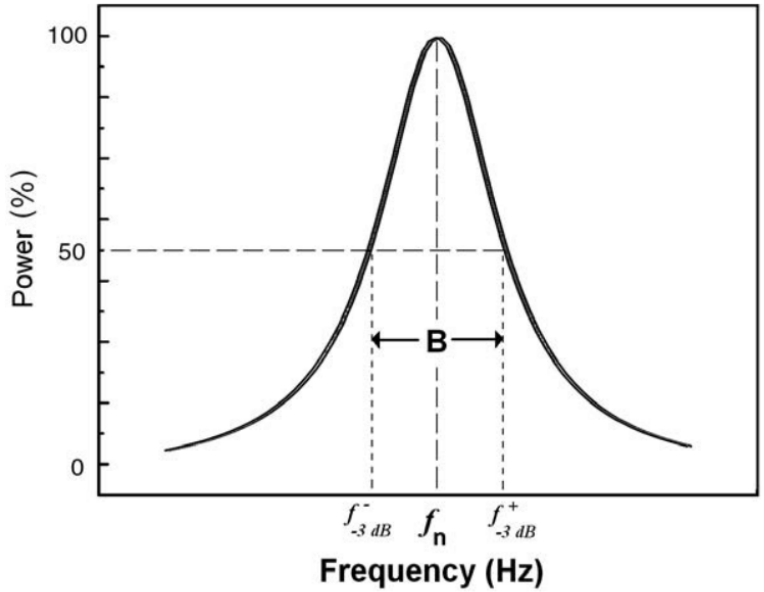
Quality Factor of MEMS Resonators

- Important design metrics: Operating frequency, motional impedance and **Quality Factor**

- Mathematically:-

$$Q = 2\pi \cdot \frac{\text{max. energy stored in one period}}{\text{energy dissipated per period}}$$

- **The Q-Factor is directly related to the energy retaining capability of a resonator in the presence of different loss mechanisms**



f_n : resonant frequency
B : bandwidth
f^+_{-3dB} f^-_{-3dB} : 3dB frequencies

- Reasons for wanting a high Q-Factor*:-
  - o Low power operation and high force sensitivity
  - o Low insertion loss
  - o High frequency selectivity

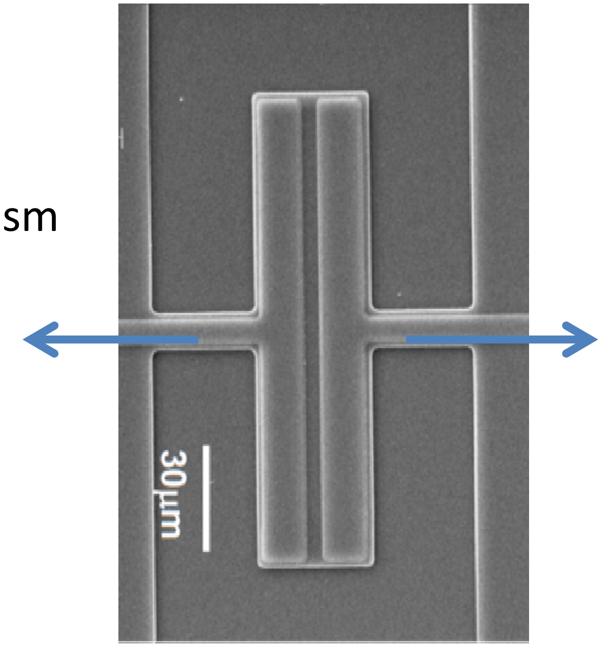
Very important for RF Applications

*C. T.-C. Nguyen, "**Advances in RF MEMS and MEMS-Based RF Front-End Architectures**," TAPAS'06, 8/5/06

Anchor Loss in MEMS Resonators

- Anchor Loss is prominent in high frequency Micromechanical resonators
- The source of this loss mechanism is the **acoustic energy leaking from a vibrating resonator through its anchors and into the substrate**
- Appropriate anchor design is of paramount importance in resonators where anchor loss is the dominant loss mechanism

Wave Propagation
(Mechanical energy loss)

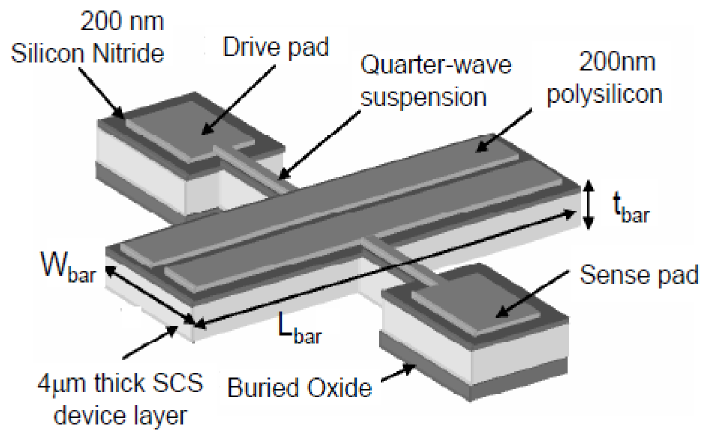


SiN on Si Lateral Mode Bulk Resonator*

- The **Perfectly Matched Layer (PML) Method** is the one that is used to model the energy loss through the anchors

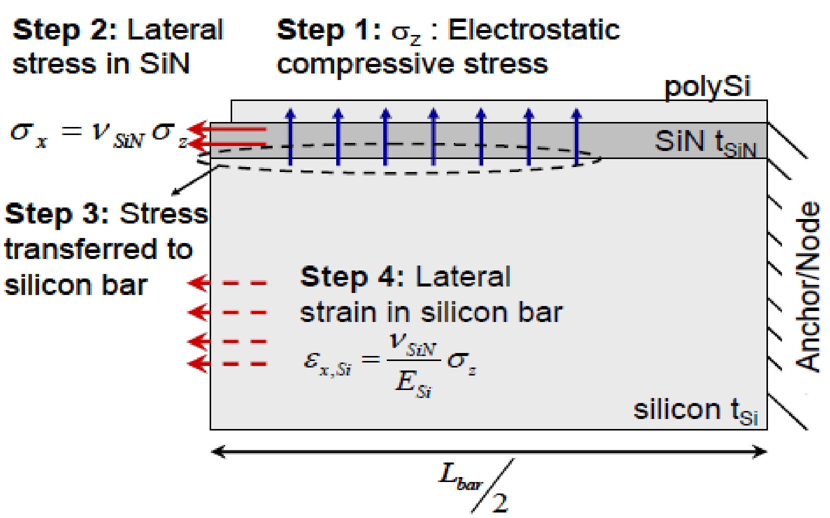
*S.A.Bhave, R.T.Howe **," Silicon Nitride-on-Silicon Bar Resonator Using Internal Electrostatic Transduction**," The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005

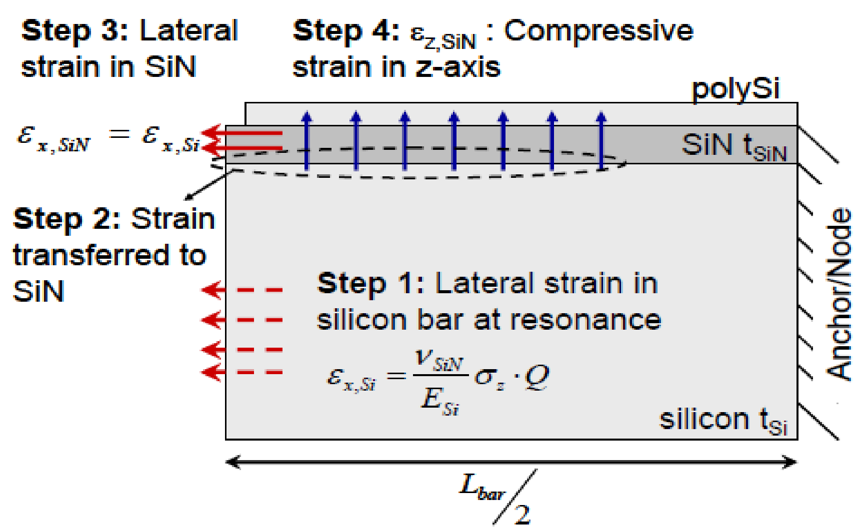
Silicon Nitride on Silicon Bar Resonator



Dimensions:-

- L_{bar}= 100µm
- W_{bar}= 30µm
- t_{bar}= 4µm

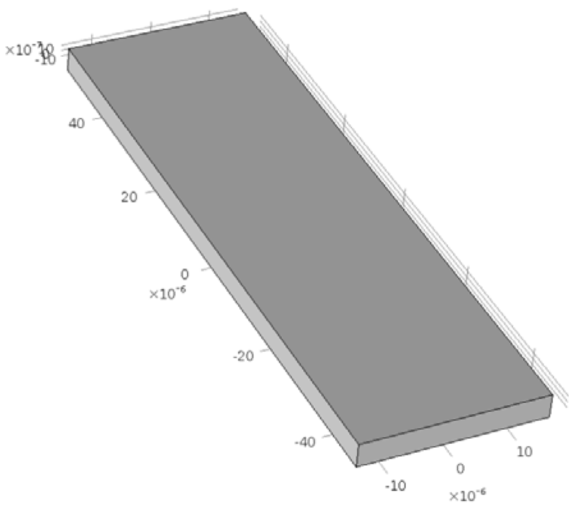




S.A.Bhave, R.T.Howe ,” **Silicon Nitride-on-Silicon Bar Resonator Using Internal Electrostatic Transduction**,” The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005

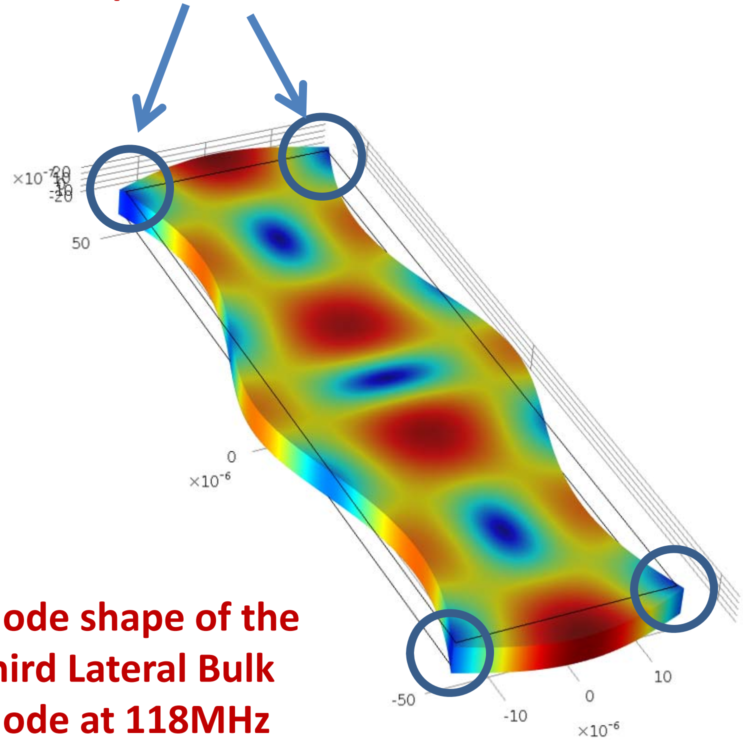
Modal Analysis

- Modal analysis was performed on the resonator body using the Eigenfrequency analysis of the Solid Mechanics module

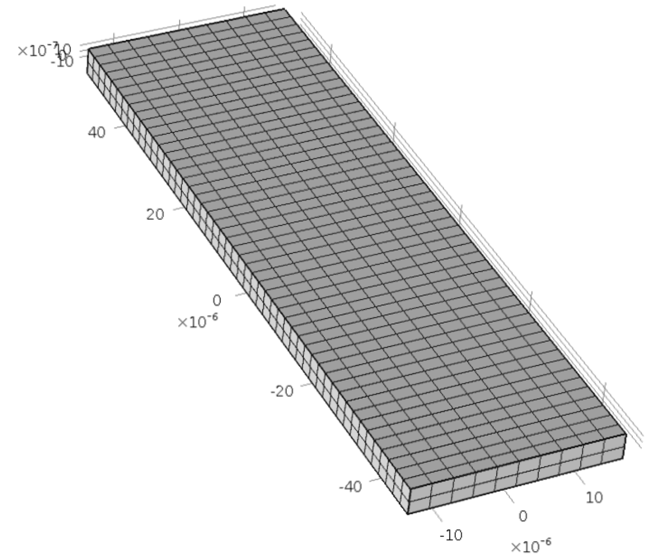


Geometric Model

Areas of minimum displacement



Mode shape of the Third Lateral Bulk Mode at 118MHz



Meshed Model

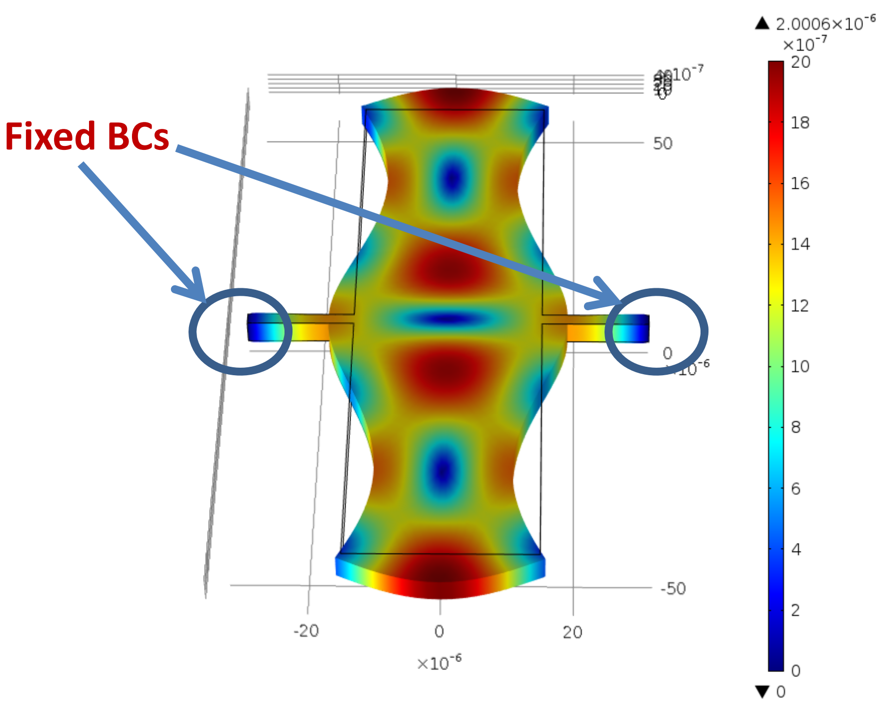
Udit Rawat, Department of Electrical Engineering, IITM

Anchoring Strategies

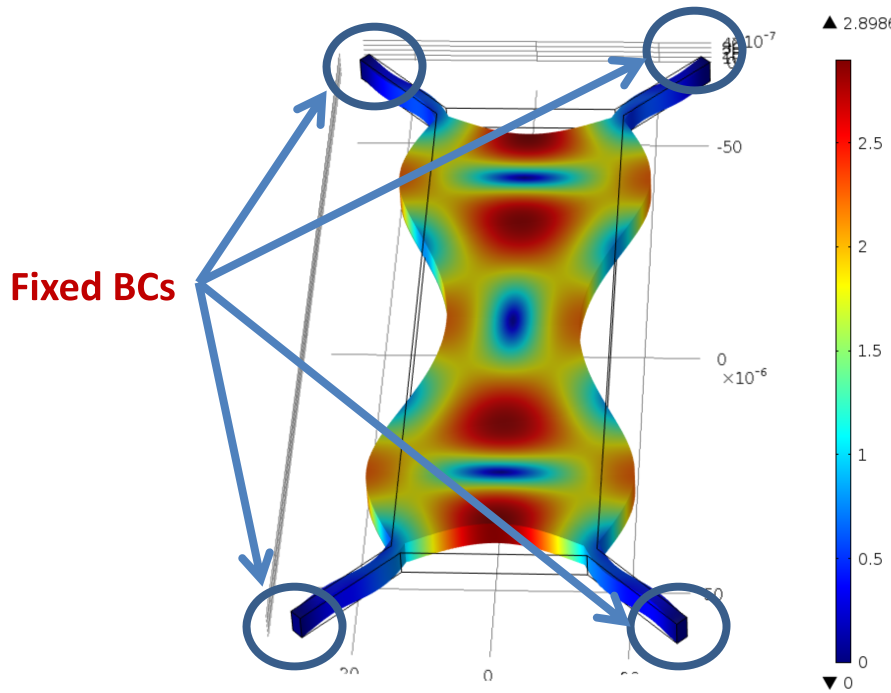
- In the Anchor Type I the anchors are attached using the central part of the structure as the anchor point

- The modified anchoring attaches the anchors to the corners of the structure

- **The main idea is to anchor the resonator at places of minimum displacement**



Mode shape for the Anchor Type I

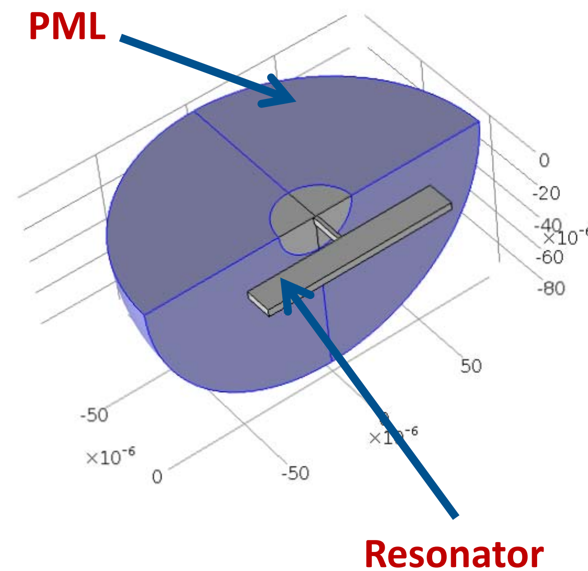


Mode shape for the Anchor Type II

Matched Layers

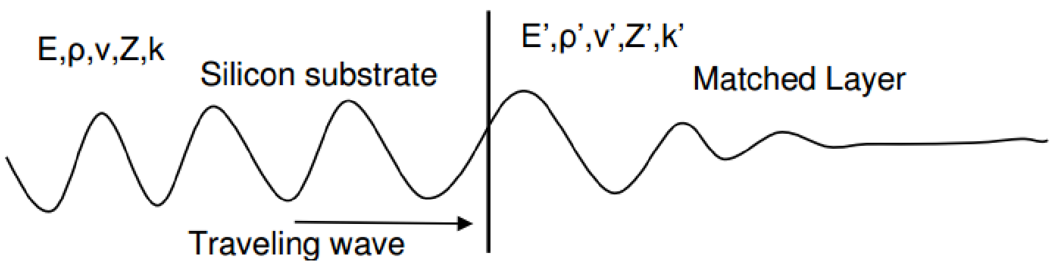
- **Anchor loss** is **modeled using matched layers** (**ML**s) that emulate the large expanse of the substrate

- The ML material parameters:-



Young's Modulus	Density	Poisson's Ratio
$E' = jE/\alpha$	$\rho' = -j\alpha\rho$	$\nu' = \nu$

(E, ρ and ν : parameters of the resonator material)

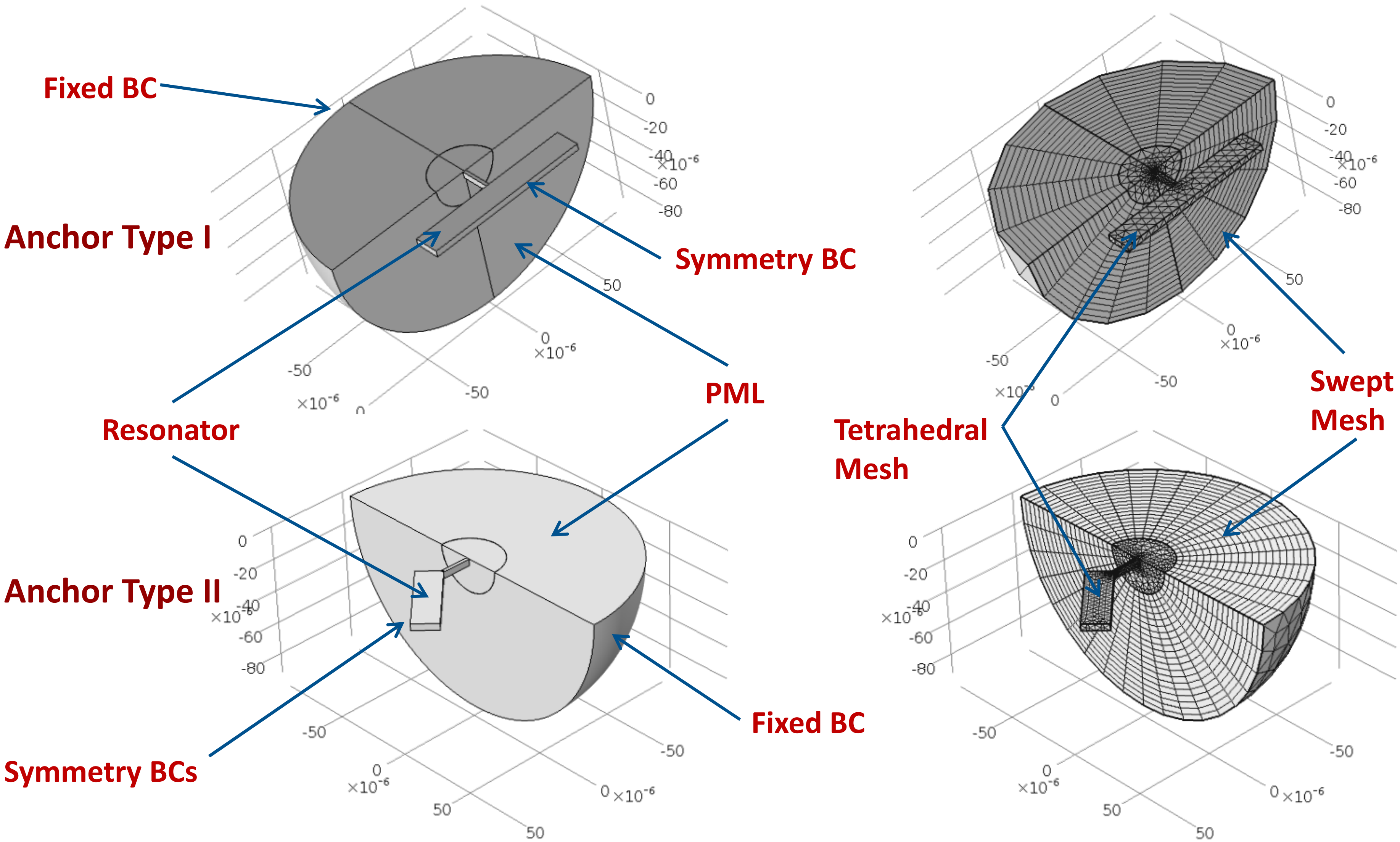


- COMSOL implements **Perfectly Matched Layers** through complex co-ordinate stretching:-

$$t' = \left(\frac{t}{\Delta_w}\right)^n (1 - i)\lambda F$$

* P.G.Steeneken et al. ," **Parameter Extraction and Support-Loss in MEMS Resonators**," Proc. Comsol Conf. 2007 10/2007.

FEM Models of the two Resonator Types



Stored Energy Density Analysis

- Stored energy density within the resonator is a measure of the vibrational energy being confined within the resonator

- A higher value of the stored energy Density automatically translates to a higher value of the Quality Factor

- The resonator with the **Anchor Type I** is attached to the substrate at the points of high displacement which results in **a larger amount of acoustic energy leaking into the substrate**

- Conversely in the resonator with **Anchor Type II** the points of anchorage have minimum displacement resulting **in lower leakage of acoustic power**

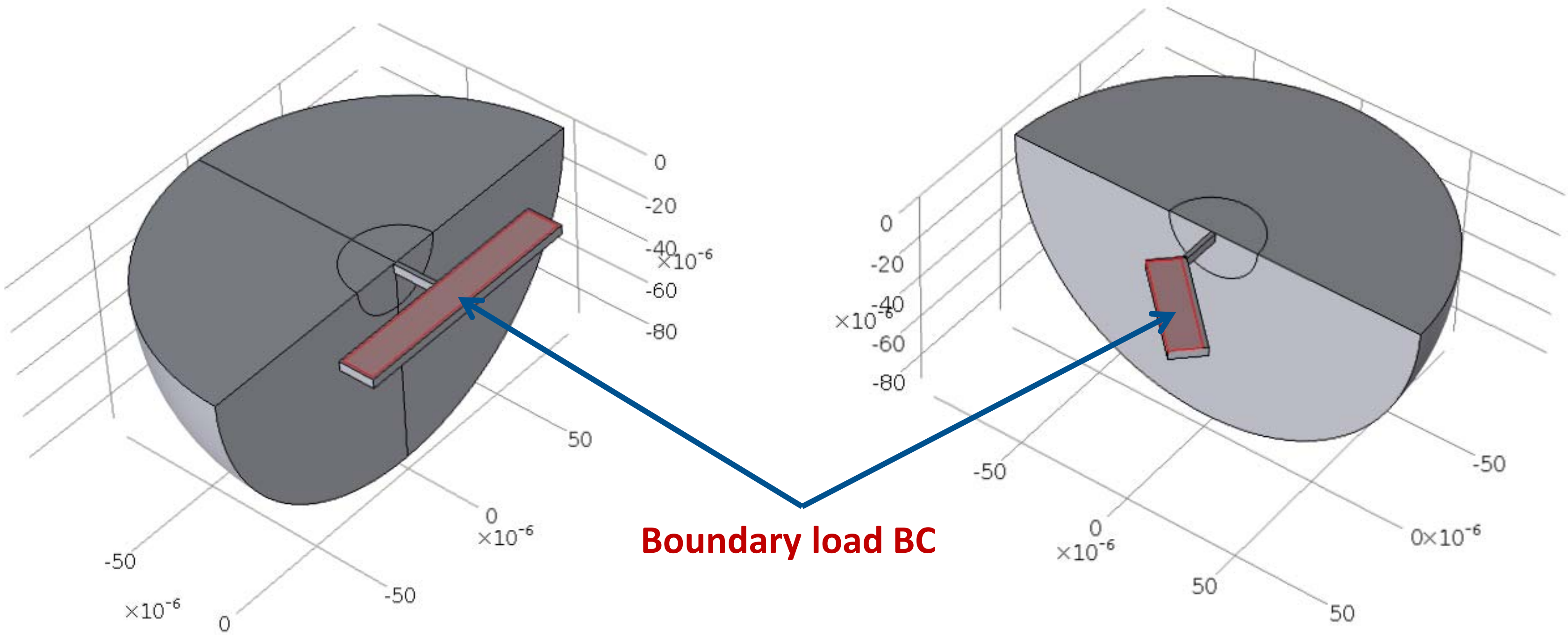
- The efficacy of Anchor Type II over Anchor type I in terms of the Stored Energy Density is established through simulation

Stored Energy Density Analysis

- The lateral drive force acting on the resonator is estimated using the relation:-

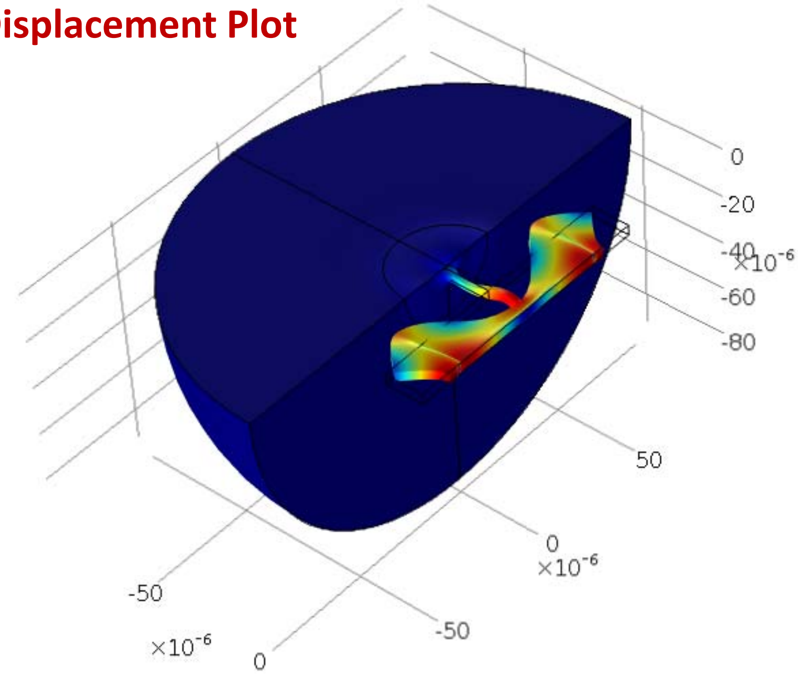
$$f_{drive} = \nu_{SiN} \cdot V_{DC} \cdot \frac{\varepsilon_0 \cdot \kappa_{SiN} \cdot A_{electrode}}{t_{SiN}^2} \cdot v_{ac}$$

- The Boundary Load boundary condition is then applied to the resonator body to get the frequency response of the resonator

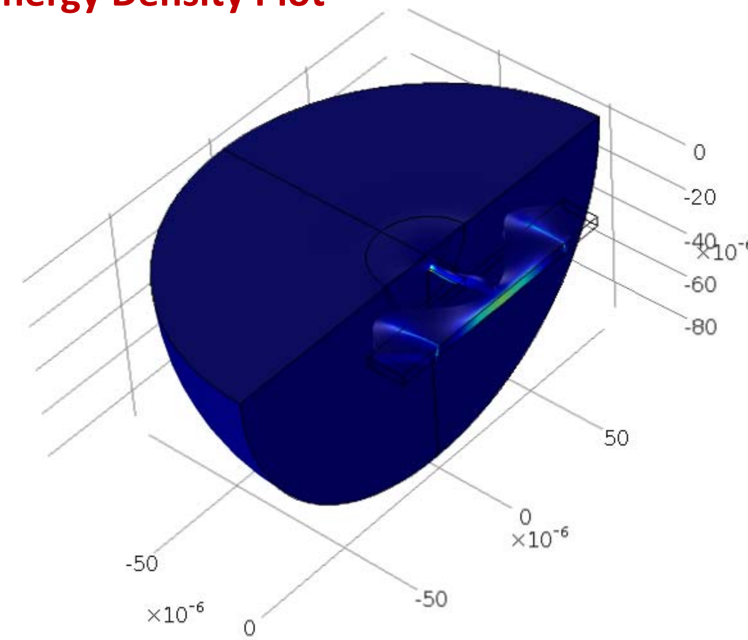


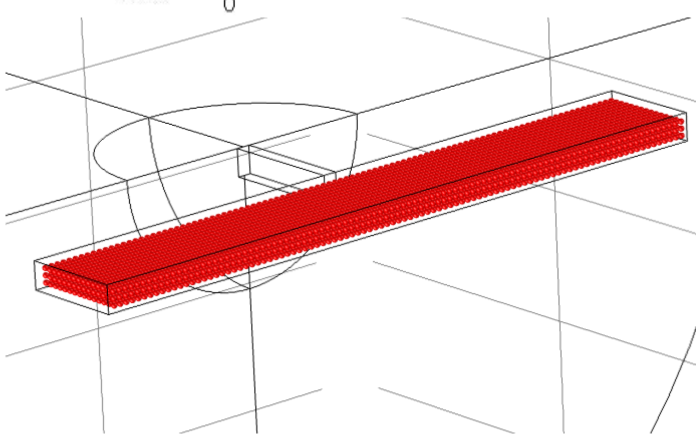
Stored Energy Density Analysis

Displacement Plot



Stored Energy Density Plot



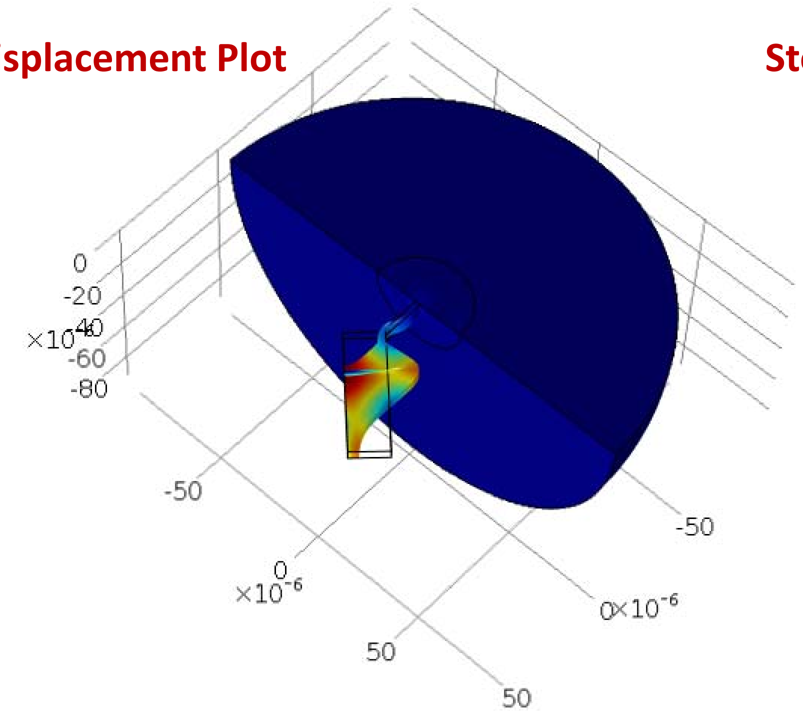


- A new data set with the point grid is created within the resonator volume
- The value of the stored energy density was averaged over these points

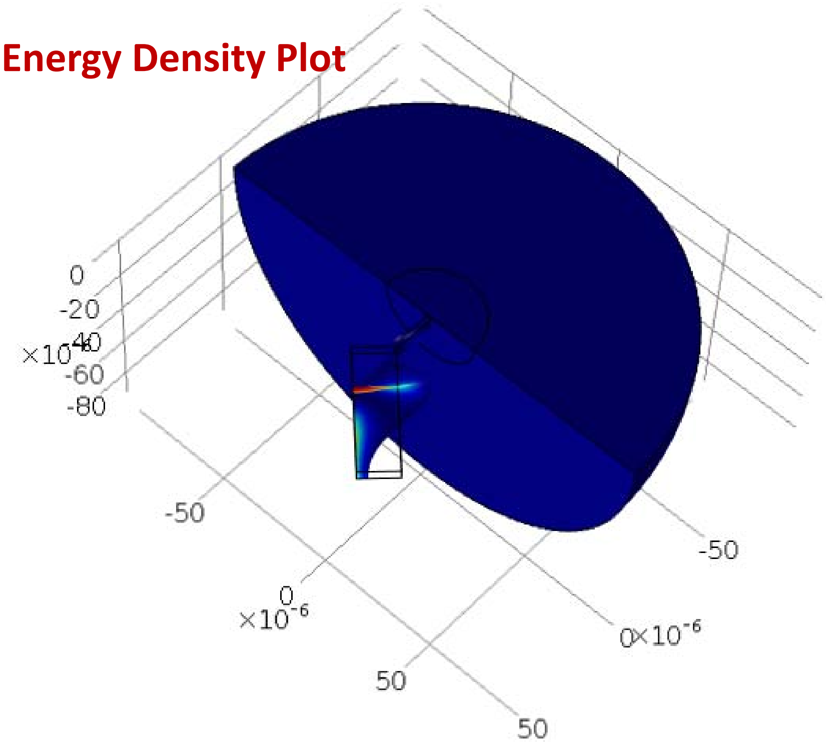
Stored Energy Density= 9.025x10^{-4} J/m^{3}

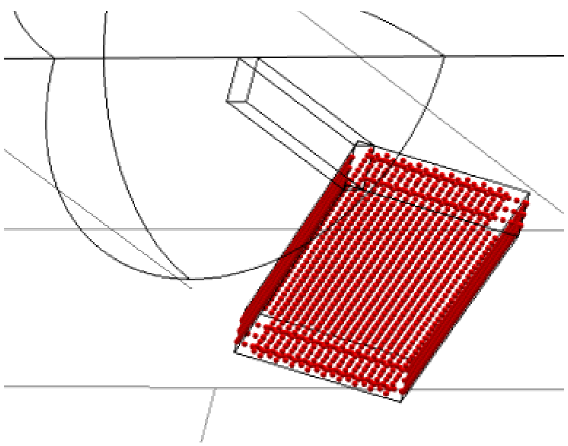
Stored Energy Density Analysis

Displacement Plot



Stored Energy Density Plot





- The same procedure is followed for the Anchor type II as the Anchor type I

Stored Energy Density= **188.9x10^{-4} J/m^{3}**

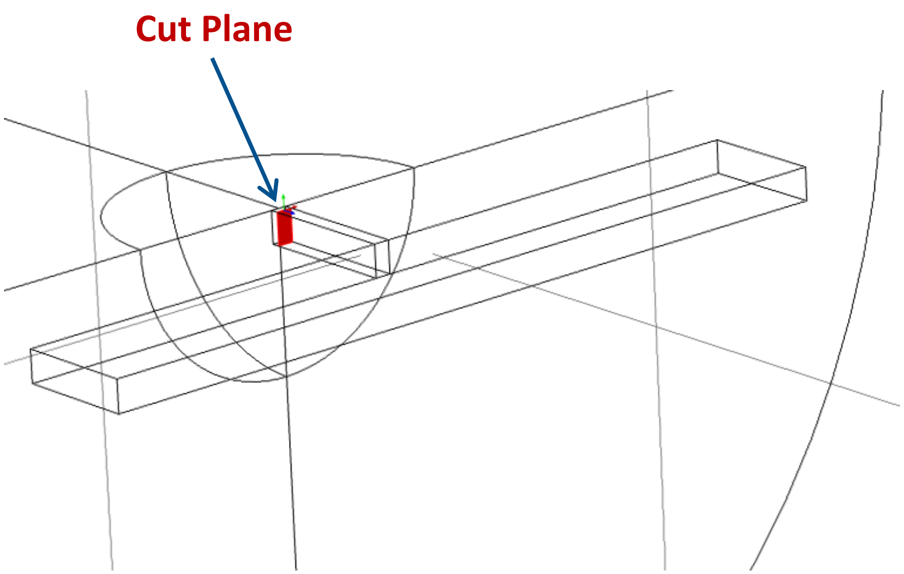
Leaky Power Analysis

- Leaky Power is used to estimate the **flux of the acoustic energy radiating from the resonator** to the substrate through the anchors

- A higher Leaky Power indicates that the resonator is losing energy to the substrate at a higher rate

- The Leaky Powers of the two anchor types are compared through simulation

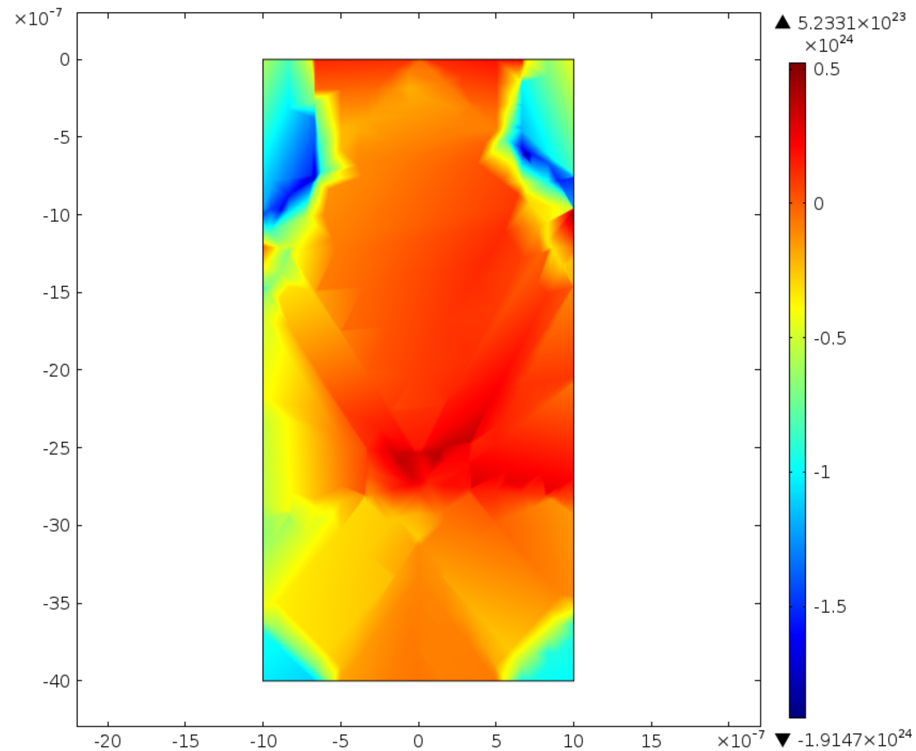
Leaky Power Analysis



- A new dataset is created as a 2D cut plane cutting the anchor at the point where it attaches to the substrate

- The surface average of the mechanical energy flux over the cut plane is evaluated

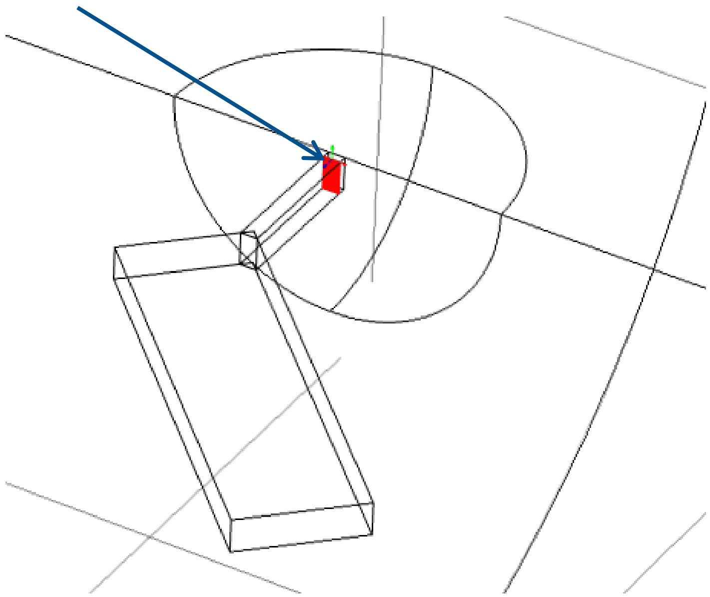
Leaky Power Flux= 0.37545 W/m²

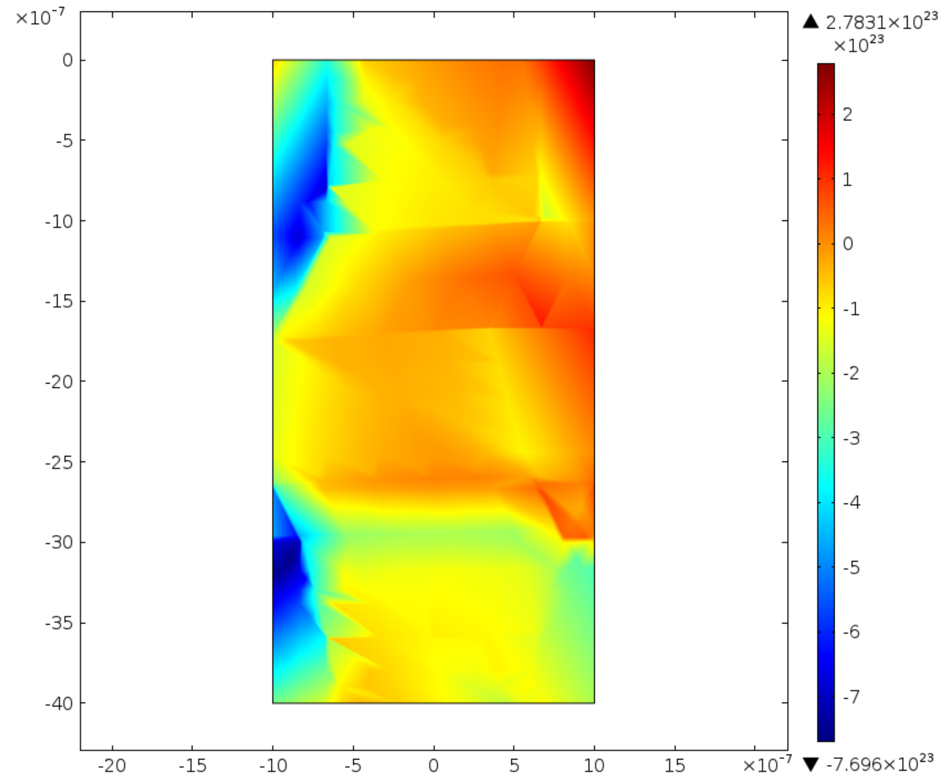


Surface plot for the normal component of the mechanical energy flux through the anchor

Leaky Power Analysis

Cut Plane





Surface plot for the normal component of the mechanical energy flux through the anchor

- Another 2D Cut Plane dataset is created for the second anchor type as depicted above
- The surface average of the mechanical energy flux over the cut plane is evaluated

Leaky Power Flux= 0.13406W/m^2

Quality Factor Evaluation

- Complex coordinate stretching of the PML domain causes the **eigenfrequencies of the of the resonator to also be complex**

- The complex eigenfrequencies reflect the exponential damping of the amplitudes of the displacement field

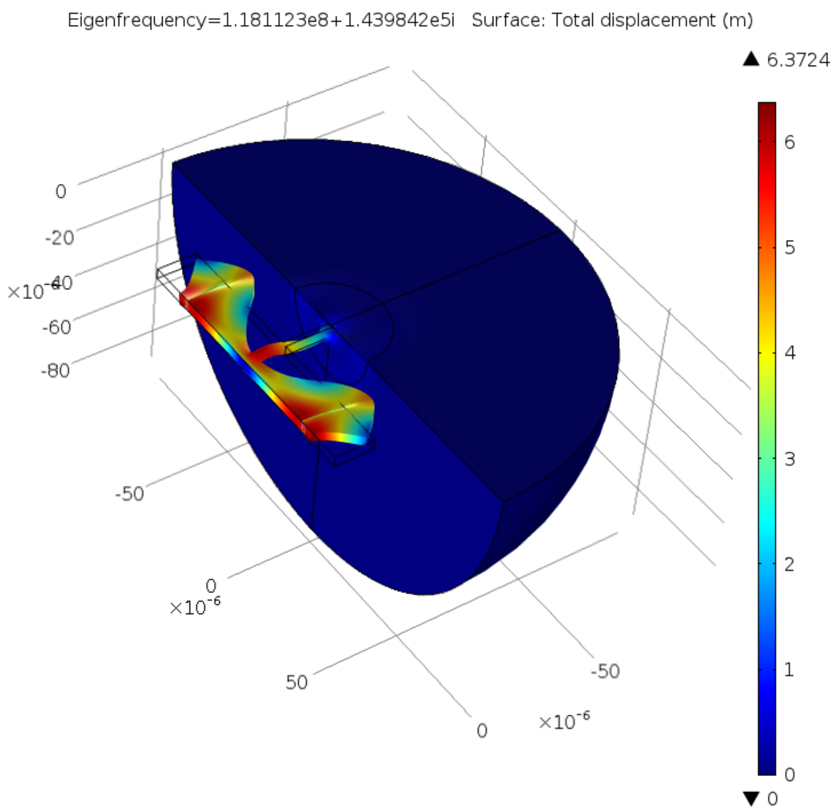
- The Quality Factor is directly inferred from the eigenfrequency analysis using the relation*:-

$$Q_i = \frac{\mathrm{Re}\,\omega_i}{2\,\mathrm{Im}\,\omega_i}$$

- The Quality Factor so evaluated is the one **taking into account only the anchor losses**

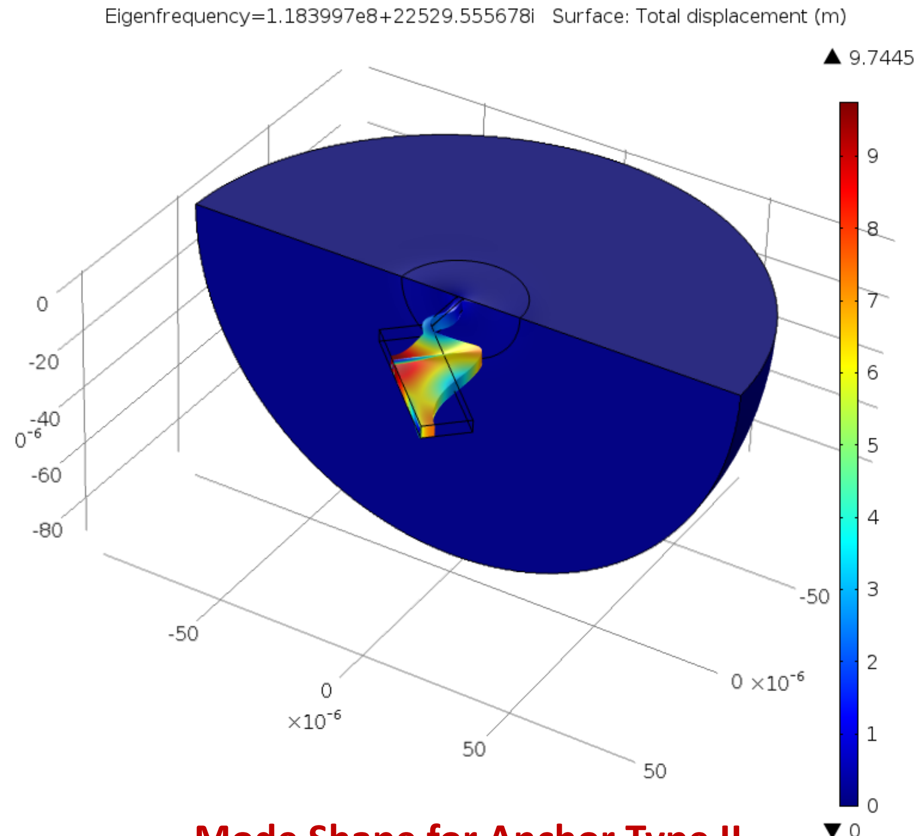
* P.G.Steeneken et al. ," **Parameter Extraction and Support-Loss in MEMS Resonators**," Proc. Comsol Conference 2007 10/2007.

Quality Factor Evaluation



Mode Shape for Anchor Type I

Q Factor = 820



Mode Shape for Anchor Type II

Q Factor = 2527

Summary

- Two different anchor arrangements for a particular target mode shape were considered for comparison

- **PML Method** was adopted to study the anchor losses in the two arrangements

- The performance of Anchor Type II (corner anchored) was found to be better than that of Anchor Type I (side anchored) in terms of the metrics such as:-
  - **Stored Energy Density** : Higher for Anchor Type II
  - **Leaky Power** : Higher for Anchor type I

- The performance disparity between the two anchor types was further verified by evaluating the **Quality Factor** from the eigenfrequency analysis results

THANK YOU