A Miniaturized Ultrasonic Power Delivery System

Tzu-Chieh Chou, Ramkumar Subramanian, Jiwoong Park, and Patrick P. Mercier

10/23/2014

UC San Diego

Motivation: Powering Medical Implants

- Medical implants are fundamentally size constrained by anatomy.
  - Size is often limited by power systems.
- Three options to deliver power:
  - **Embedded battery** – suitable only for ultra-low-power applications with generous available volume (e.g., pacemaker)
  - **Energy harvesting** – has not yet been demonstrated for chronic applications
  - **Wireless power transfer (WPT)** – suitable for higher-power applications, as a large battery can be placed outside of the body

Pacemaker, Medtronic

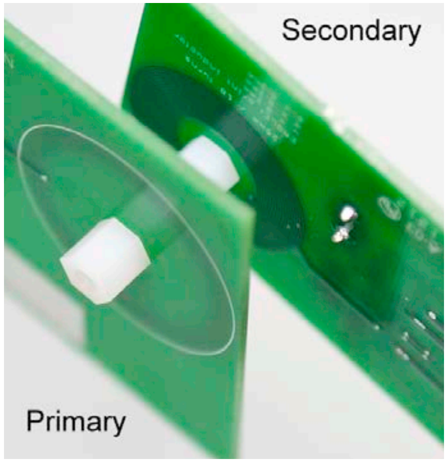
Spinal Cord Stimulator,
Boston Scientific

Retinal Implant,
Boston Retinal Implant Project

Cochlear Implant, Advanced Bionics

Transcutaneous power transfer via inductive coupling

- Most implants that employ WPT are a few cm in size
  - Employ (resonant) inductive coupling for power transfer
  - Operate at 0.1-50 MHz due to higher dielectric losses at higher frequencies
  - Efficiency can exceed 90%



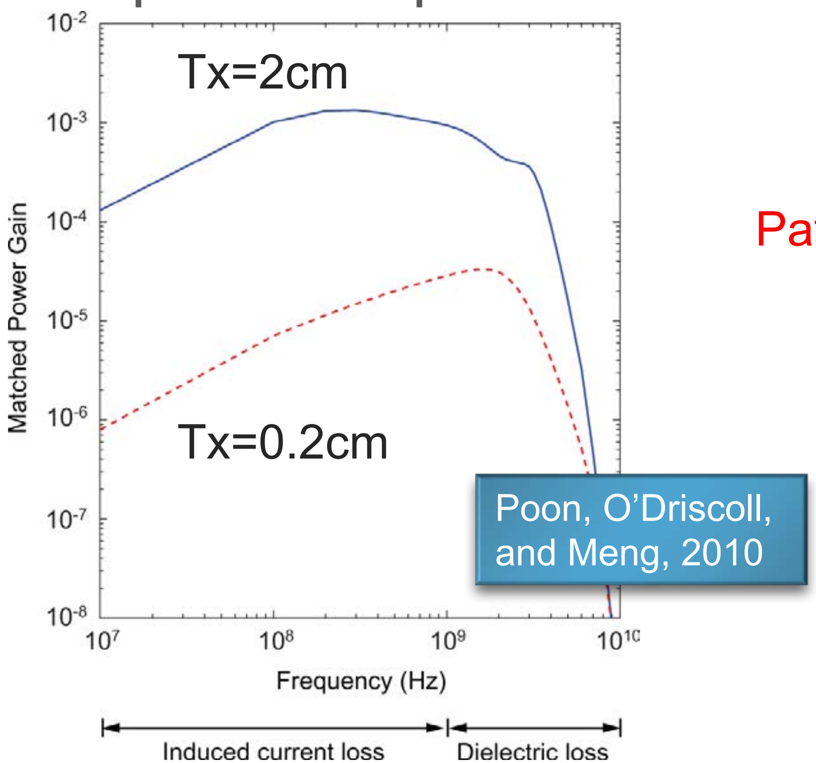
- **Problem:** there are many emerging applications that cannot employ large coils
  - E.g., smart pills, injectable sensors, etc.
  - **Requirement:** efficient transcutaneous power transfer with small (mm-sized) receive antennae

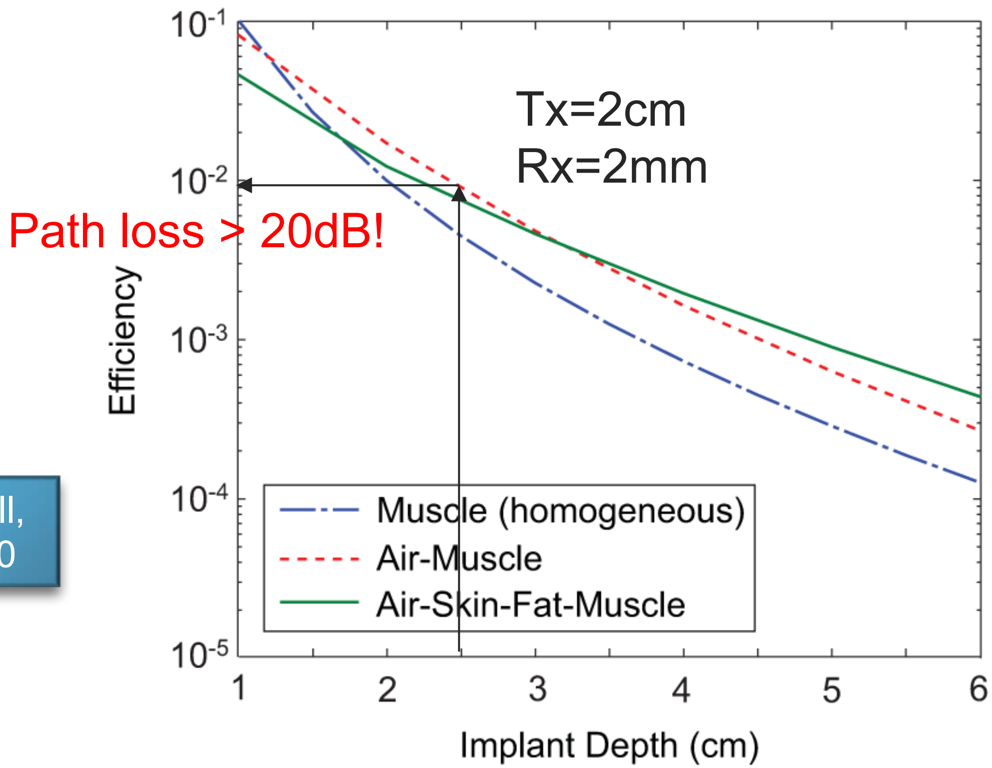
Pill Camera, PillCam

Leadless Pacemaker, St. Jude Medical

Solution 1: mid-field electromagnetics

- Full-field EM analysis shows that GHz frequencies are optimal for power transfer to mm-sized devices





PROS: enables interesting mm-sized implants with *optimal* efficiency from electromagnetics

CONS: wavelength in tissue is large → focusing energy is difficult; tissue losses limit efficiency

Solution 2: ultrasonic power transfer

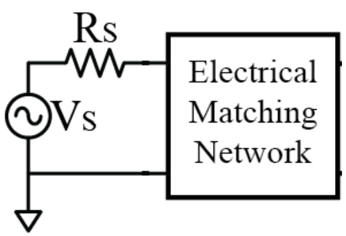
- Ultrasonic waves decay more slowly than mid-field EM waves in most tissue
  - Acoustic attenuation coefficient of *soft* tissue usually ranges from 0.6 to 3.3dB/MHz·cm
  - Mid-field EM decays at 2.6dB/cm
  - Opportunity for deeper implants
- Ultrasound has a much shorter wavelength than mid-field EM
  - 1.5 mm at 1MHz (US) compared to ~30 mm at 1GHz (EM) in most tissues
- Ultrasonic waves suffer less from mismatch loss
  - Acoustic impedance of *soft* tissue is typically between $1.38 \cdot 10^6$ and $1.99 \cdot 10^6$ kg/sec·m^2

PROBLEM: Ultrasonic power transfer has, at the time of paper submission, only been experimentally validated in cm-sized systems.

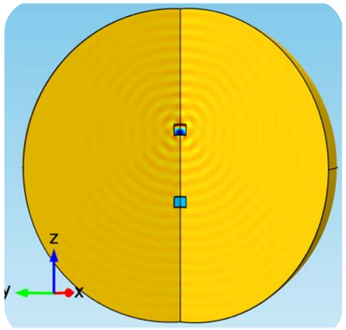
GOAL: Experimentally validate in a mm-sized system.

Finite Element Analysis Modeling

- Ultrasonic
  - COMSOL 4.4
  - Tissue model: linear elastic material with attenuation
  - Output: pressure and electric potential fields



$$\begin{bmatrix} \boldsymbol{S} \\ \boldsymbol{D} \end{bmatrix} = \begin{bmatrix} \boldsymbol{s}^E & \boldsymbol{d}^t \\ \boldsymbol{d} & \boldsymbol{\epsilon}^T \end{bmatrix} \begin{bmatrix} \boldsymbol{T} \\ \boldsymbol{E} \end{bmatrix}$$



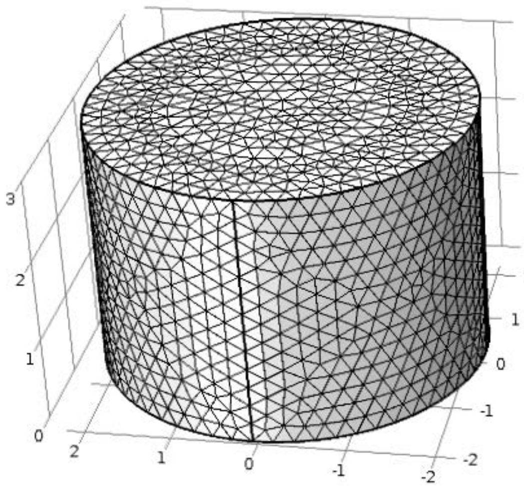
Lumped circuit
- AC voltage source
- RLC matching network

Piezoelectric constitutive eq.
- Determine electric field & strain

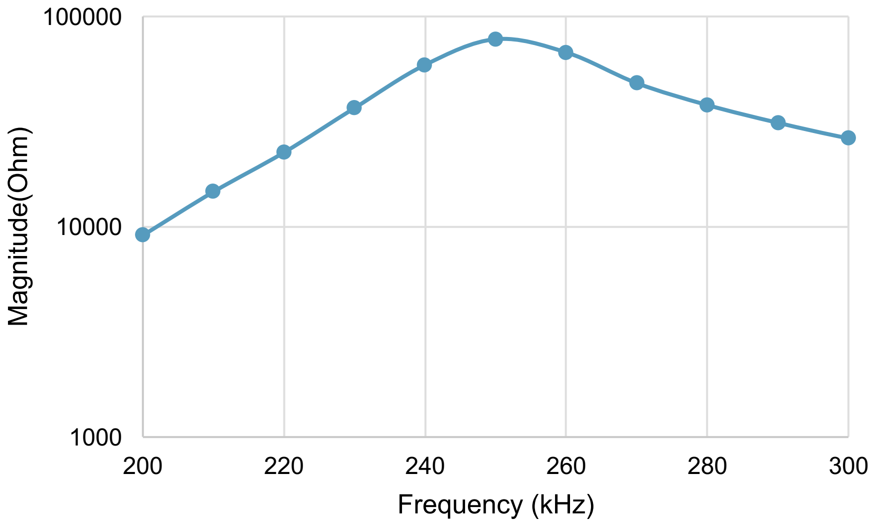
Helmholtz eq.
- Pressure field
- Attenuation caused by tissue

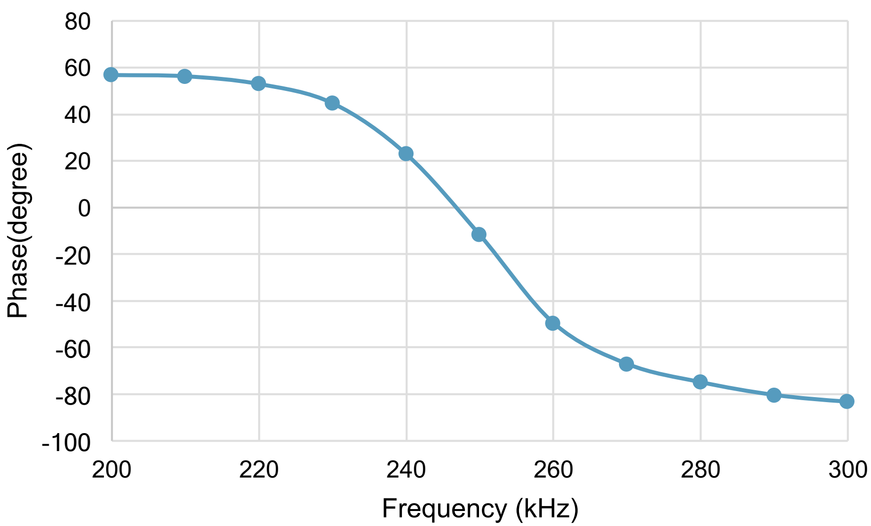
Finite Element Analysis Modeling

- PZT model
  - Validation of the parameters for the constitutive eqn.
    - Part from manufacturer
    - Others from least-square optimization process of electrical impedance



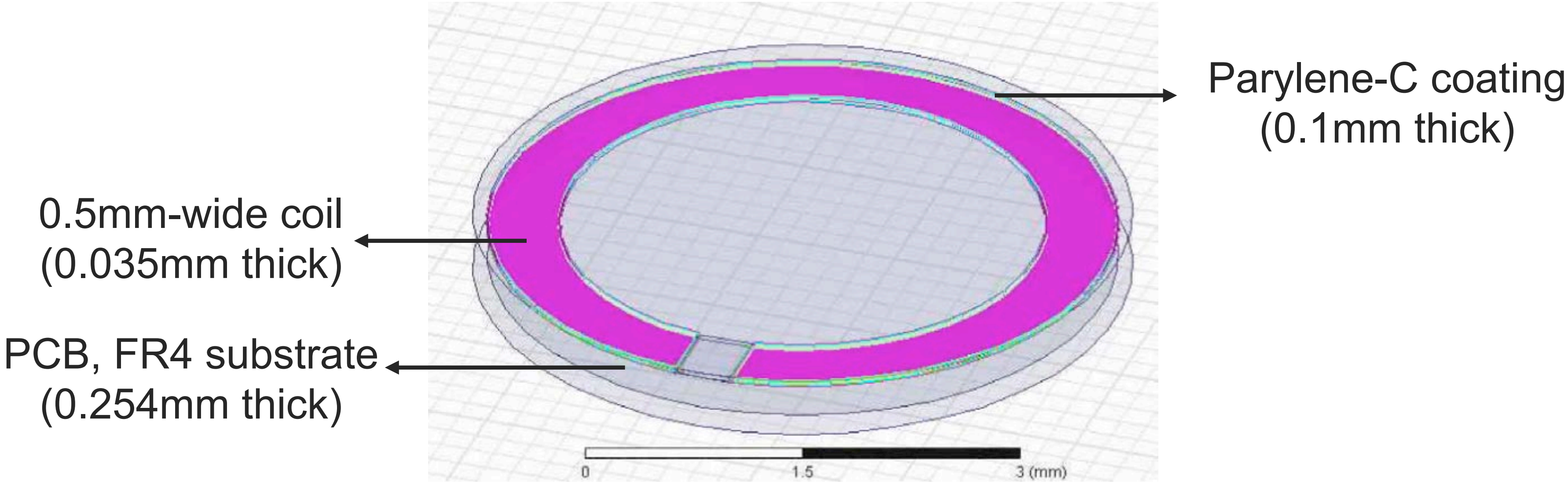
4.4mm (diameter)
3.0mm (height)





Finite Element Analysis Modeling

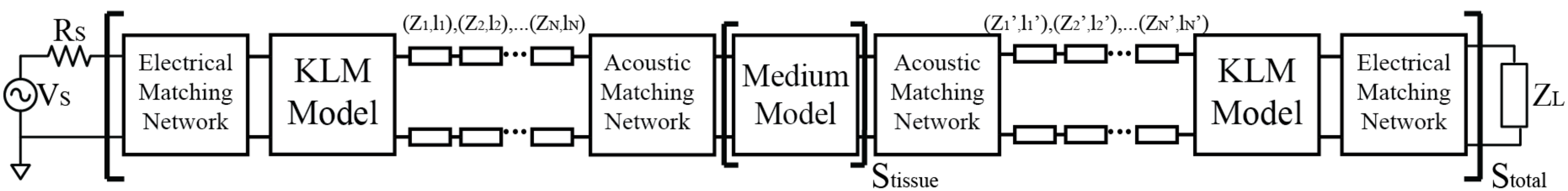
- EM coupling
  - Ansys HFSS
  - Tissue model: water and muscle with dielectric properties
  - Optimal frequency tuned to around 400MHz (MICS band)
  - Circular coil with the same diameter of PZT receiver



UC San Diego

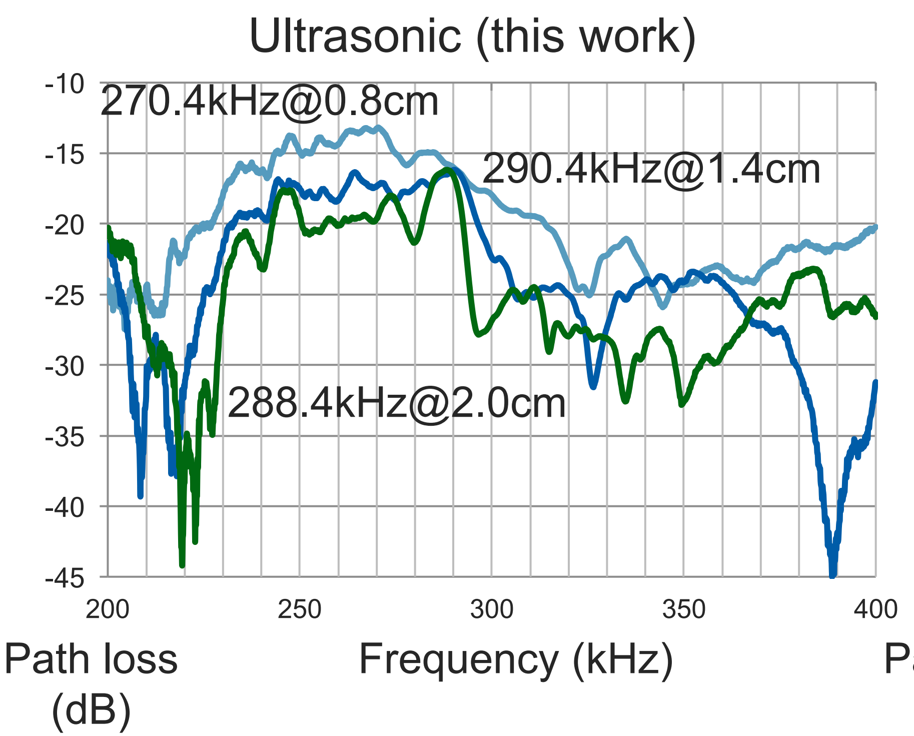
Maximum available gain (MAG)

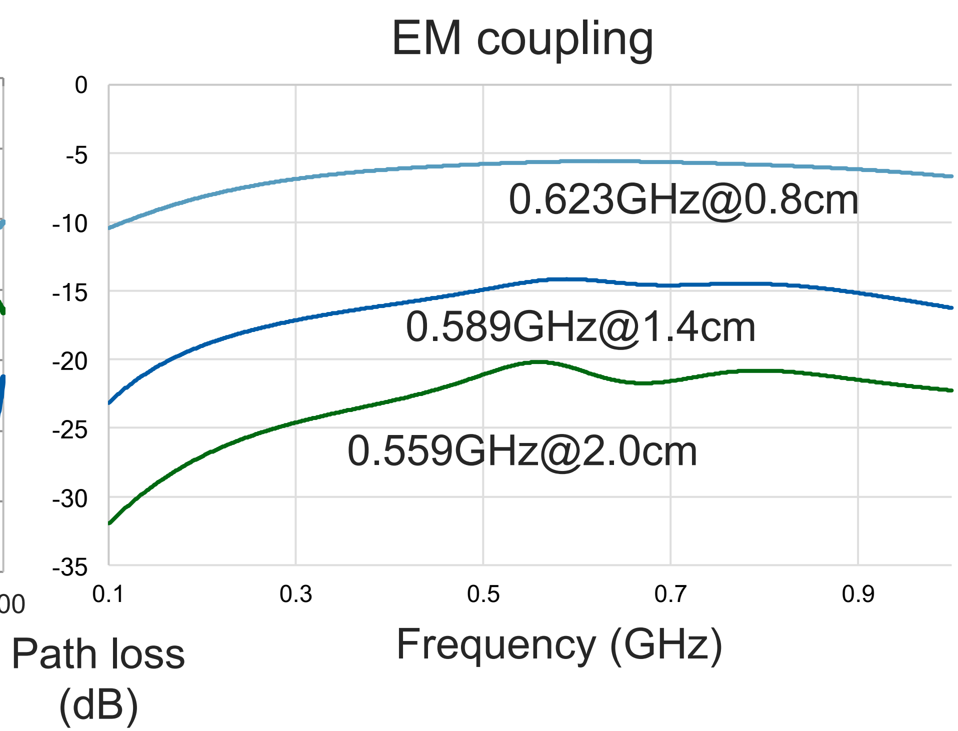
- System-level path loss set by path loss through medium and matching performance
  - **Problem:** difficult to adjust matching network at every frequency
  - **Solution:** measure two-port s-parameters, calculate MAG assuming optimal matching network at all frequencies
  - Simulation:
    - Calculated by parametric sweeping the RLC values
  - Experiment:
    - Measured by connecting the PZT pair to a network analyzer
- In order to physically achieve the MAG, electrical matching networks at both ports are required



Maximum available gain (MAG)

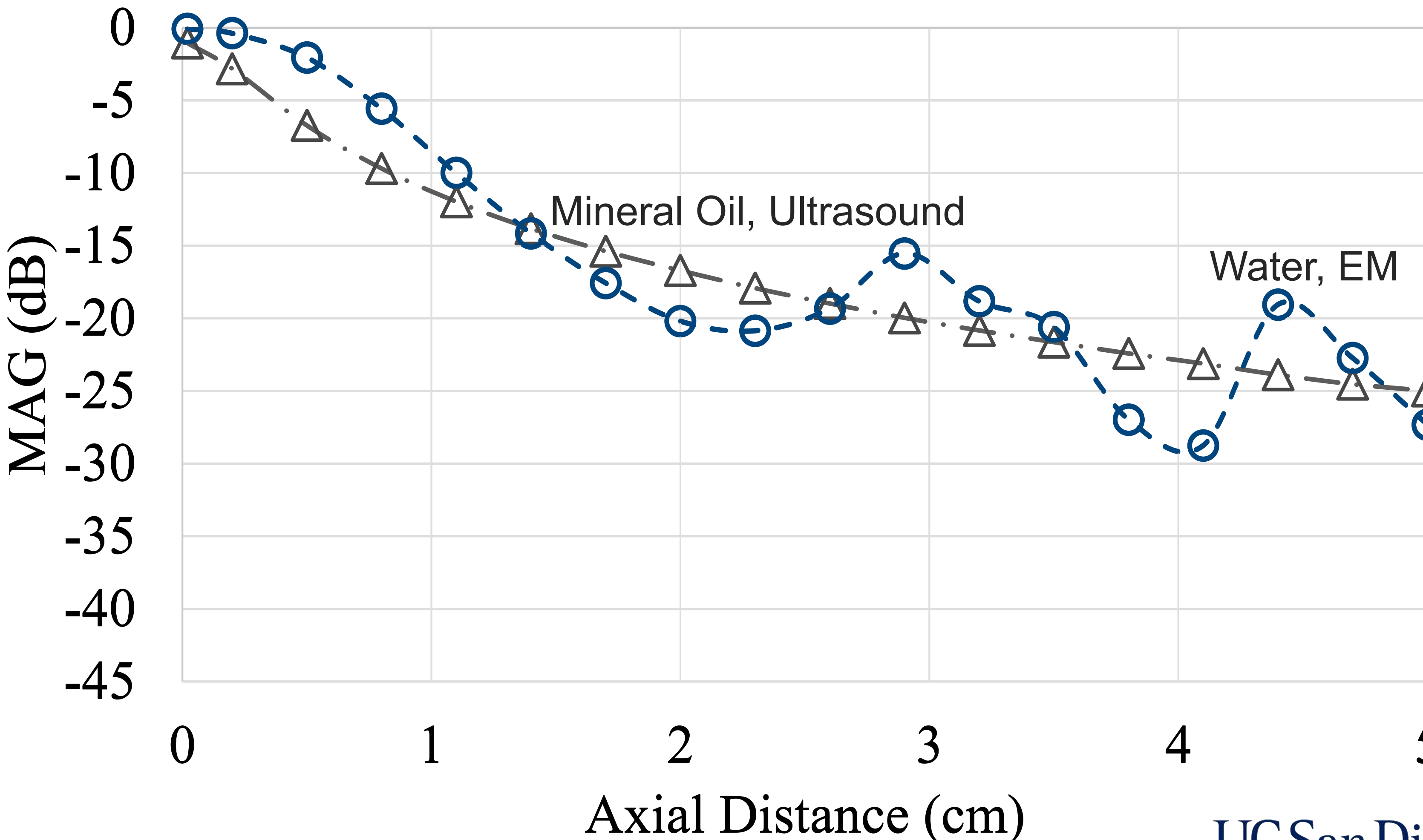
- MAG vs. optimal frequency
  - The optimal frequency is defined as the frequency at which the minimum path loss occurs
  - The figures below show the comparison between EM coupling and ultrasonic for the medium water





Simulation results – Mineral Oil & Water

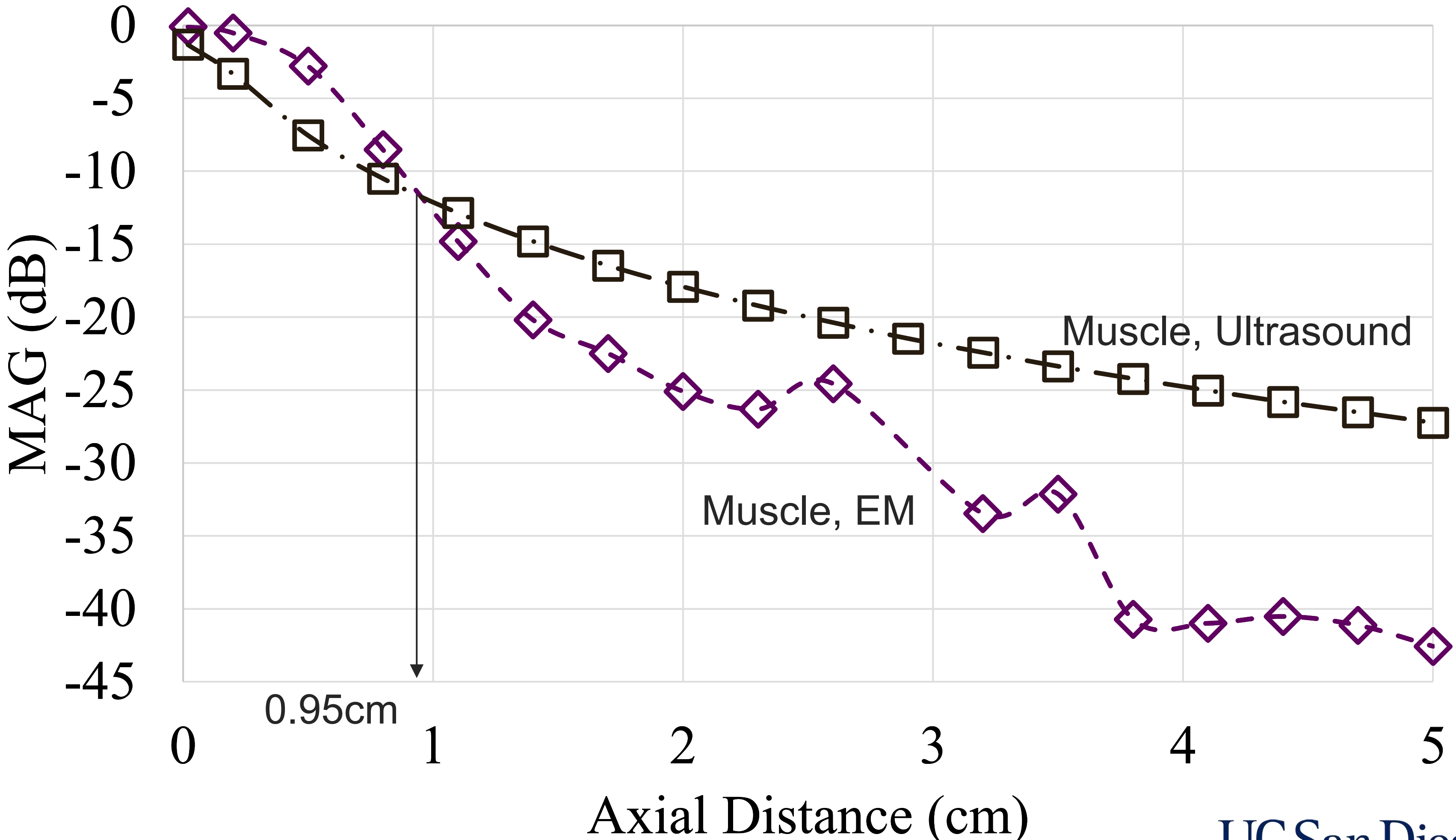
- MAG vs. axial distance



UC San Diego

Simulation results - Muscle

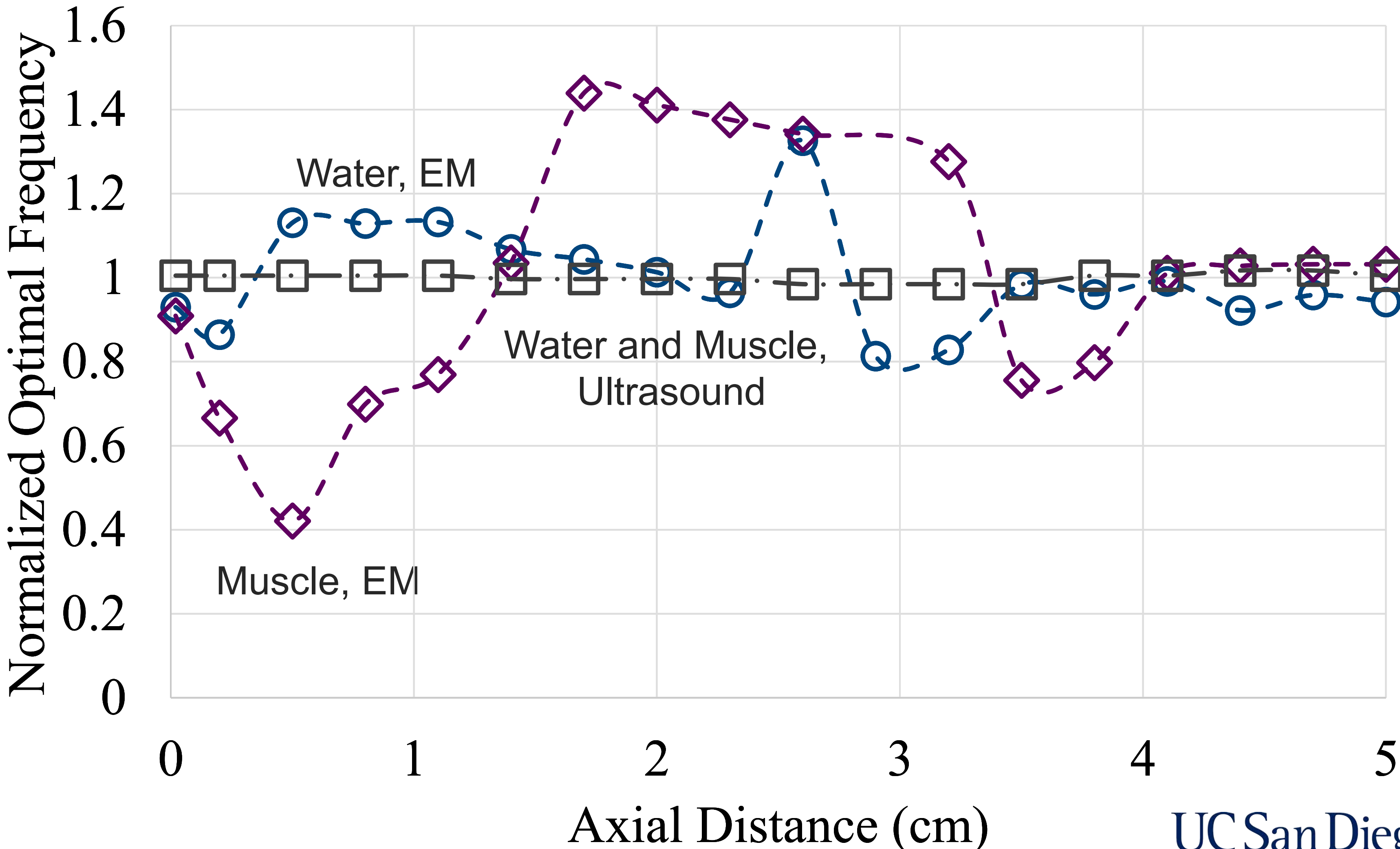
- MAG vs. axial distance



UC San Diego

Simulation results

- Normalized optimal frequency vs. axial distance



UC San Diego

Simulation results

- Slope of MAG curve slowly converges to acoustic attenuation coefficient
  - 0.28dB/cm for mineral oil
  - 0.64dB/cm for muscle
- Ultrasonic scheme starts to take the lead beyond certain depth threshold
  - 1.4cm for mineral oil
  - 0.9cm for muscle
- Optimal frequency for ultrasonic scheme does not dramatically change over distance
  - Less re-tuning is needed compared to EM coupling

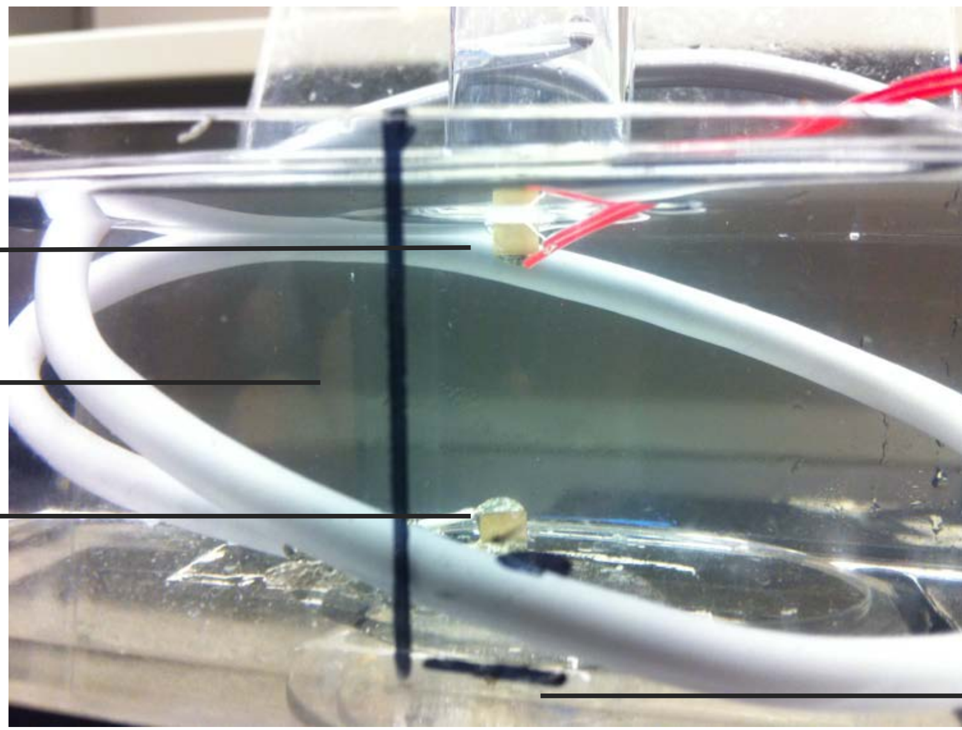
Experimental setup

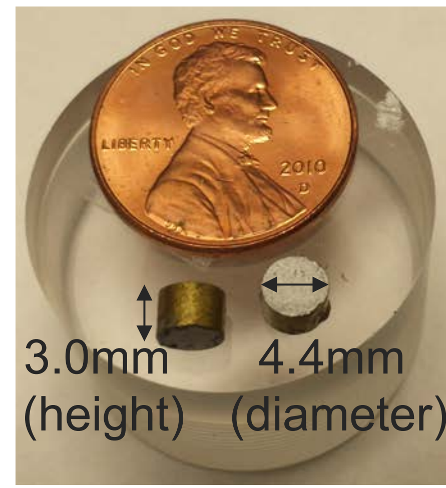
- Frequency range: 200 to 400kHz (containing the fundamental and a few harmonic vibration modes)
- Medium: mineral oil

Transmitter

Mineral oil

Receiver

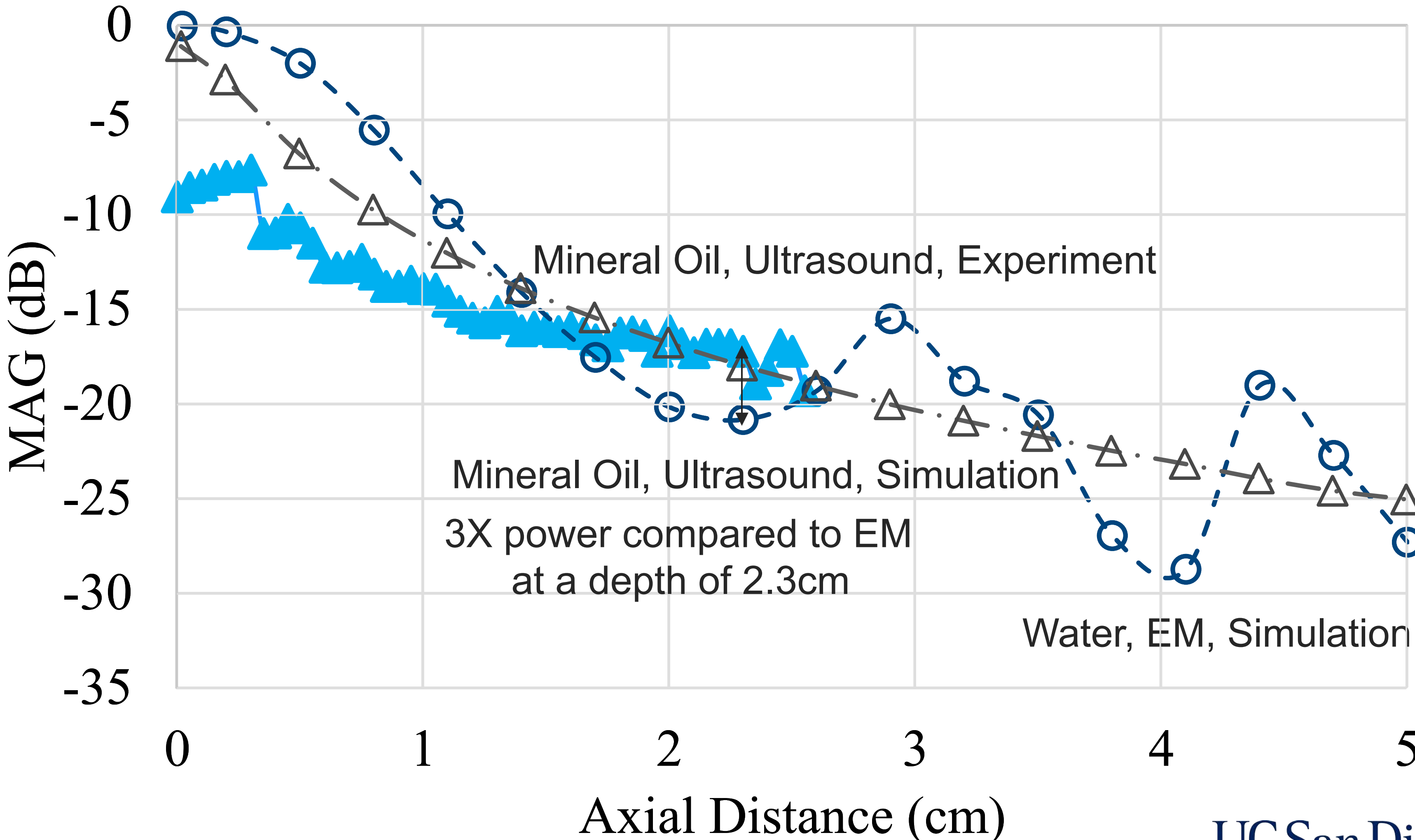




Stage and
Micromanipulators

Experimental results

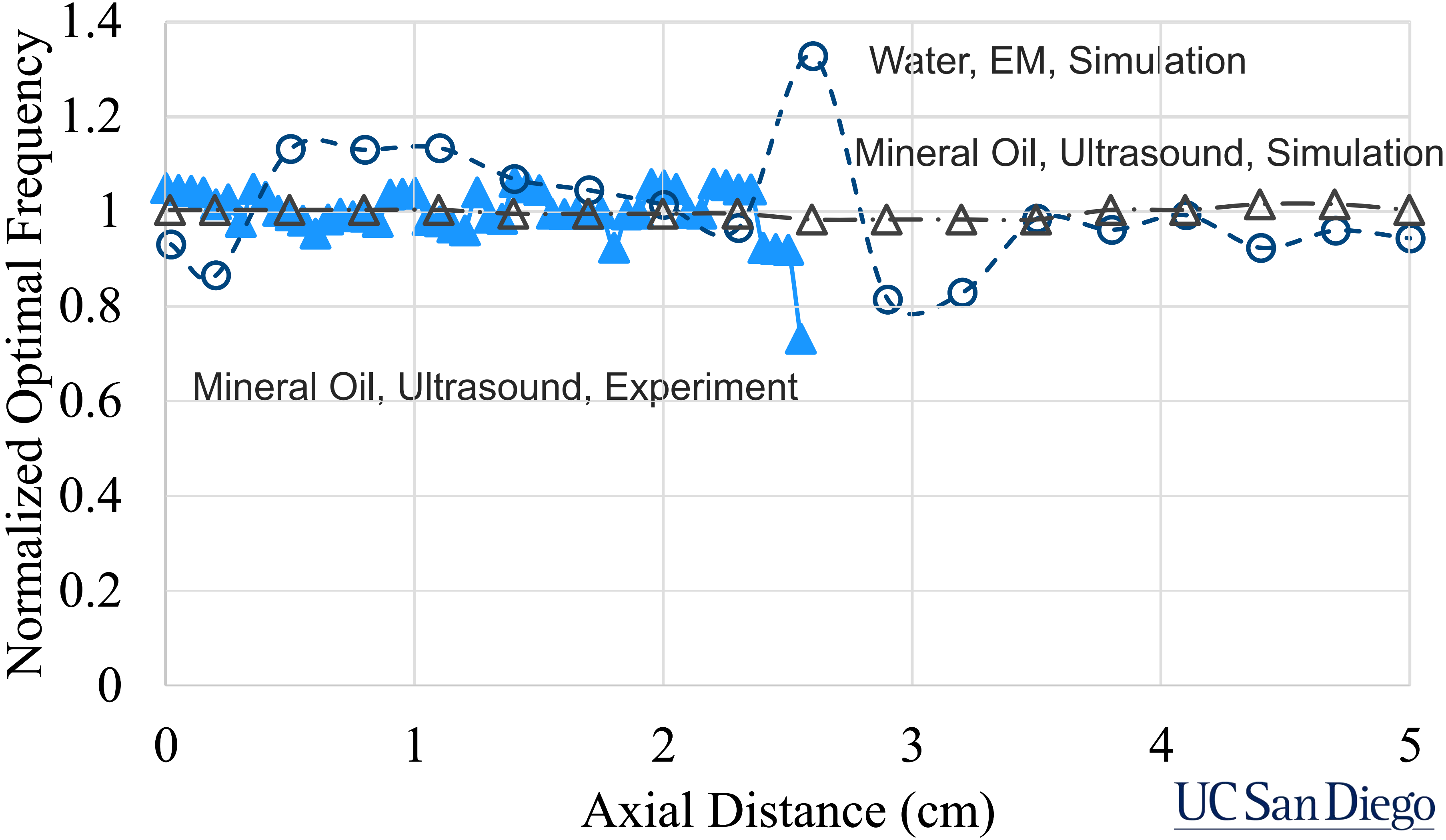
- MAG vs. axial distance



UC San Diego

Experimental results

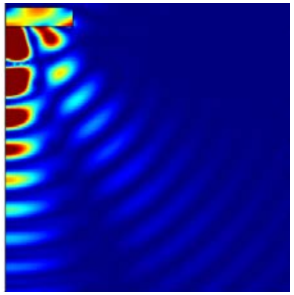
- Normalized optimal frequency vs. axial distance



UC San Diego

Experimental results

- Why MAG is -9dB even when axial distance is 0?
  - Nulls in radiation pattern
    - In both (axial and lateral) directions
    - Also explains the saw-tooth profile in the measured data



  - Reflections caused by the epoxy layer
    - Much lower acoustic impedance compared to that of PZT's
- Slope of MAG curve is -2.3dB/cm beyond 1cm
  - Comparable to previously reported -2.5dB/cm (simulation)
  - Remains competitive against mid-field EM coupling ,which decays at the rate of -2.6dB/cm

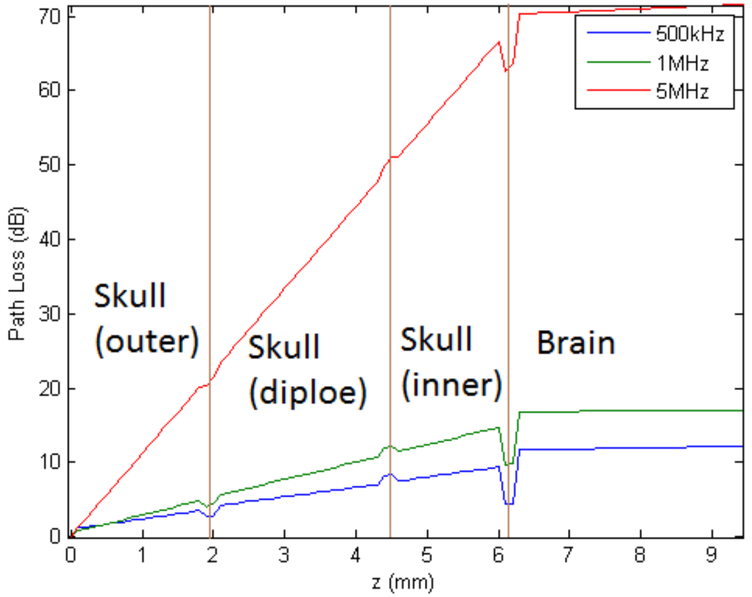
UC San Diego

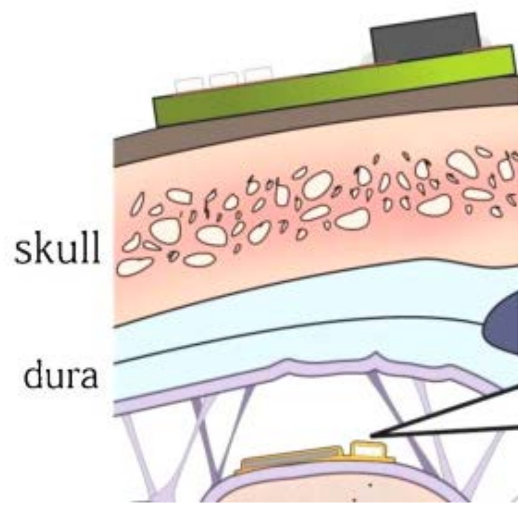
Conclusions

- Ultrasonic power delivery scheme was verified to be feasible by both simulations and experiments
  - MAG is less than -20dB at 2.5cm depth
- It has a power delivery efficiency about -2.3dB/cm with a 4.4mm-diameter transmitter-receiver pair
  - -2.6dB/cm for a 2mm-diameter EM mid-field coupled Rx
- The optimal frequency changes less dramatically over distance
  - Less re-tuning is required compared to EM coupling
- PZT receivers scale better down to even lower sizes than small antennas
  - Opportunity for even smaller implants in the future

Application note for future work

- Ultrasound decays quickly through bone and other stiff materials
  - Attenuation coefficient is about 22dB/MHz·cm for bone compared to 1dB/MHz·cm for brain
    - 100X path loss for a depth of 5cm when the frequency is 0.2MHz
  - It may not be appropriate to use ultrasound for implants that go underneath bone (e.g., neural implants)
  - Either strictly EM solutions are required here, or more invasive dual-mode solutions





D. Seo, J. Neuro. Methods, 2014