UF Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Electrodynamic Wireless Power Transfer for Charging through Conductive Media

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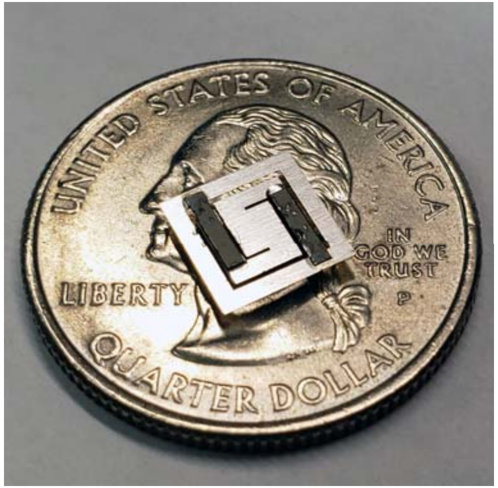
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Outline

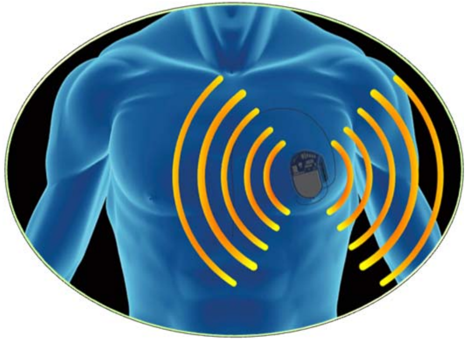
- Wireless Power Transfer (WPT) Background
- Electrodynamic WPT (EWPT)
  - Principle and Advantages
  - Prior Works
- Miniature EWPT Receivers
  - Electrodynamic, Piezoelectric, & Dual-transduction
- Summary & Comparison



Wireless Power Transfer

Kilowatts

Watts

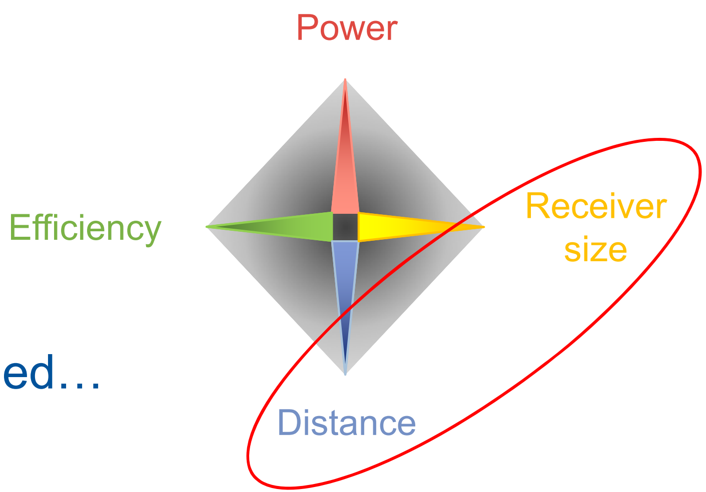


Microwatts

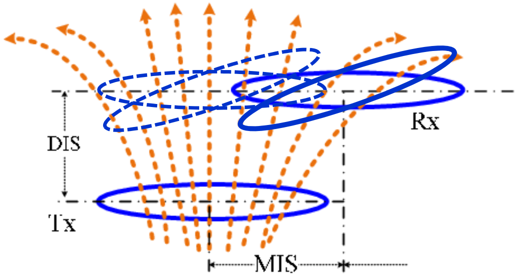
Deterministic
Higher Power Density

WPT Utopia

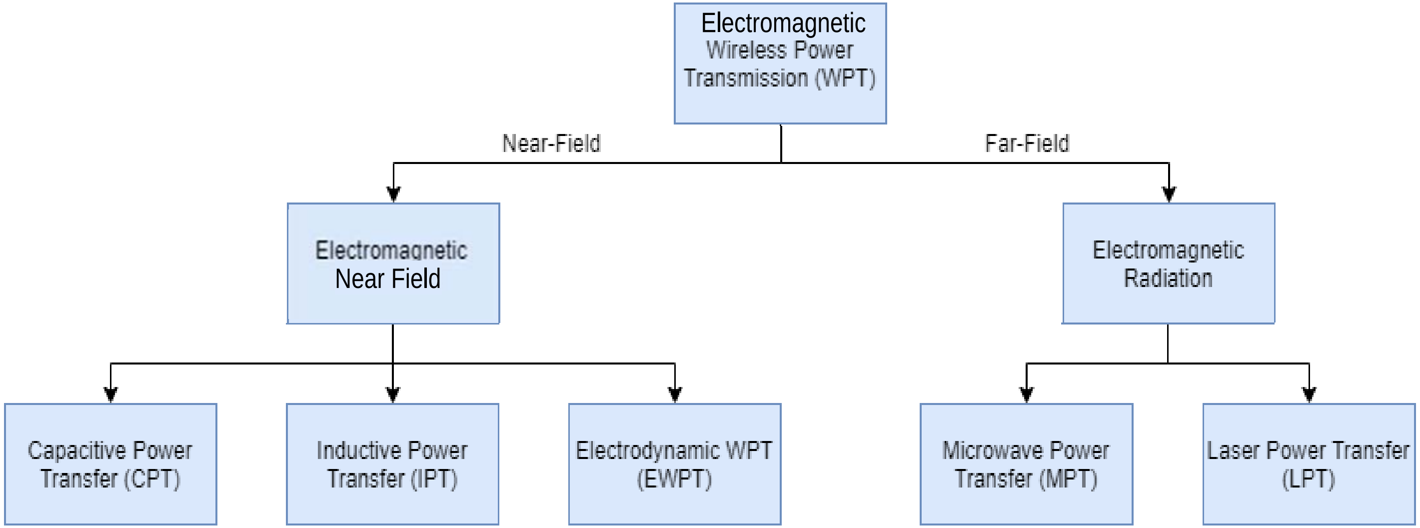
- The "Quadrilemma"
  - useful power levels
  - with relatively good efficiency
  - to compact receivers
  - over extended distances



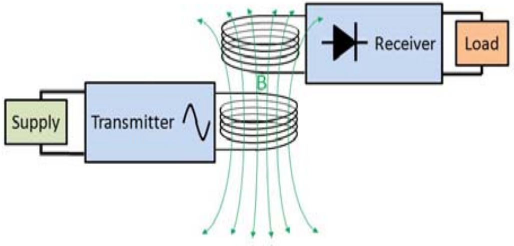
- Once charging at a distance is obtained…
  - Safety limits / human EM exposure
  - "Cluttered" environments
  - Position & orientation independence



WPT Methods



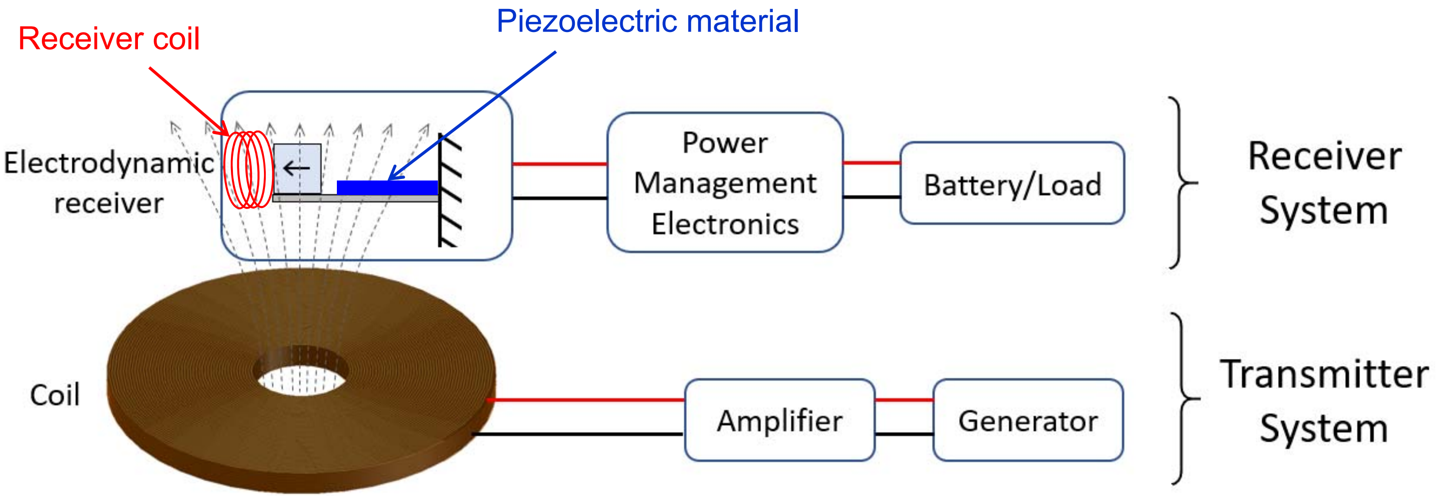
Electromagnetic Wireless Power Transmission (WPT)
Near-Field
Far-Field
Electromagnetic Near Field
Electromagnetic Radiation
Capacitive Power Transfer (CPT)
Inductive Power Transfer (IPT)
Electrodynamic WPT (EWPT)
Microwave Power Transfer (MPT)
Laser Power Transfer (LPT)



Receiver
Load
B
Supply
Transmitter

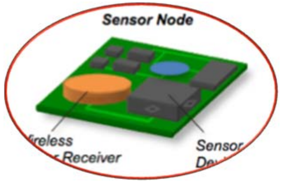
EWPT Principle

- The receiver magnet is excited by time-varying magnetic field generated by a transmitter
  “*Electrodynamic Transduction*” <--> Interaction between permanent magnet and coil
- Mechanical energy → Electrical power at receiver by one or more electromechanical transduction schemes e.g., Electrodynamic and Piezoelectric



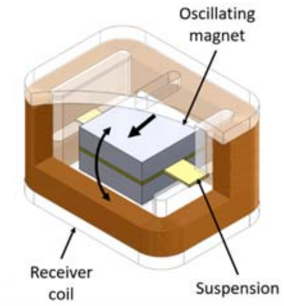
EWPT Solves Key Problems

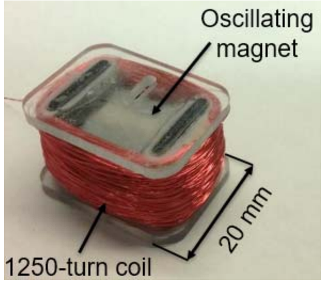
Inductive Coupling	EWPT
High frequency WPT (10's of kHz to 10's of MHz)	**Low** frequency WPT (10's to 100's of Hz)
Limited to fields ≪ 1 mT_{rms} if transmitting near humans	**Safe** to transmit fields up to 2 mT_{rms} around humans
Field **attenuated** by conductive media (metals, humans etc.) --> **heat**	Travels virtually **unimpeded** through conductive media
Generates **huge** EMI	Almost **no** EMI



Prior Works

- Macroscale EWPT receiver
  - $13.5\ cm^3$ prototype
  - Few volts (open-circuit) at 21 Hz





Relative independence of position and orientation (even with clutter)

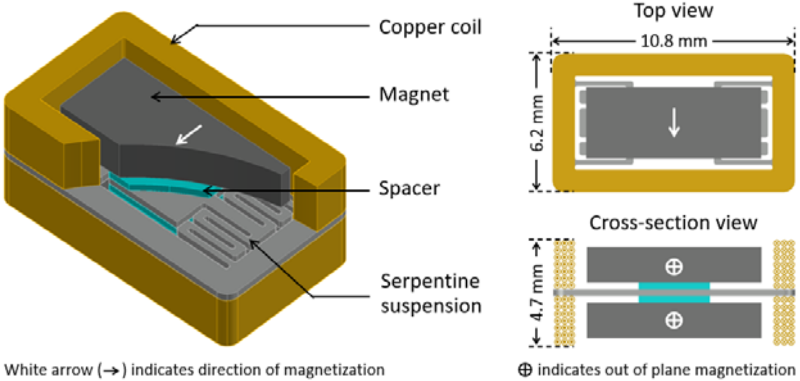
Prior Works

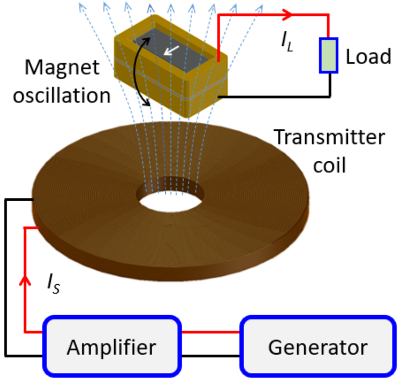
- Transmission through body using rotating magnet transmitter

- Transmission through desktop computer using coil transmitter

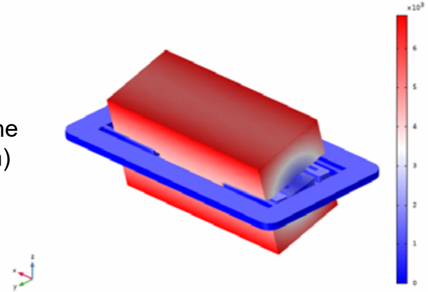
Electrodynamic EWPT Receiver

- Micro-fabricated electromagnetic EWPT receiver
  - Serpentine silicon suspension
  - Volume-efficient design
  - Two magnet-coil pairs
  - Torsional operation at 821 Hz



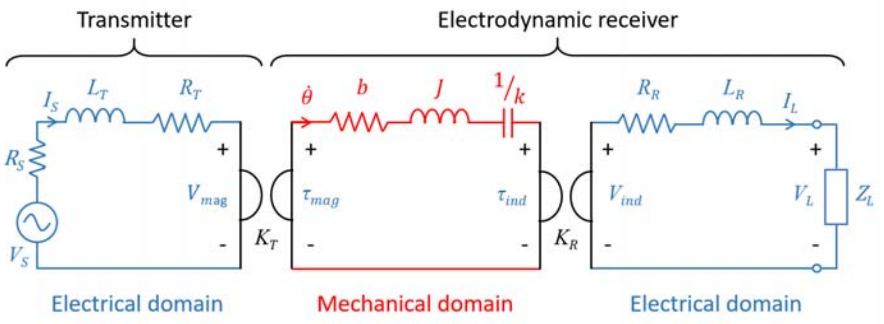


Torsional oscillation of the magnets (no coil shown)



Electrodynamic EWPT Receiver

- Lumped Element Modeling (LEM)
  - Equivalent electrical circuit model



b = torsional damping coefficient
J = mass moment of inertia
k = torsional stiffness

- Tx electrodynamic transduction coefficient

$$K_T = \frac{\tau_{mag}}{I_S} = \frac{V_{mag}}{\dot{\theta}}$$ N.m.A^{-1} or V.s.rad^{-1}

- Rx electrodynamic transduction coefficient

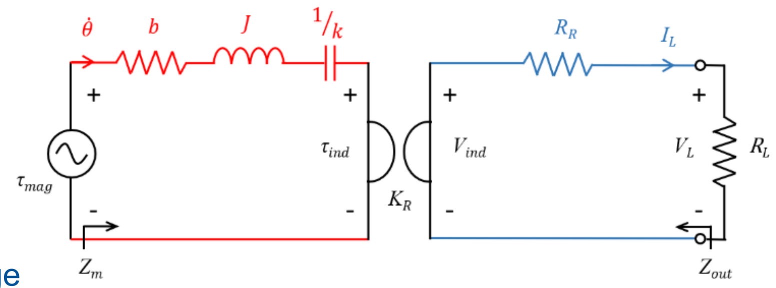
$$K_R = \frac{\tau_{ind}}{I_L} = \frac{V_{ind}}{\dot{\theta}}$$ N.m.A^{-1} or V.s.rad^{-1}

- Torque on the Rx magnets

$$\tau_{mag} = \left|\vec{m} \times \vec{B}_z\right| = \frac{B_r}{\mu_0} v_{mag} B_z$$

Electrodynamic EWPT Receiver

- Receiver system performance analysis using LEM
  - Simplified equivalent circuit
    - Assumed an ideal (controlled) torque source
    - Rx coil inductance is neglected ($\omega L_R \ll R_R$)
    - Complex Z_L is replaced with resistive load R_L
  - Using standard circuit analysis, frequency-dependent load voltage



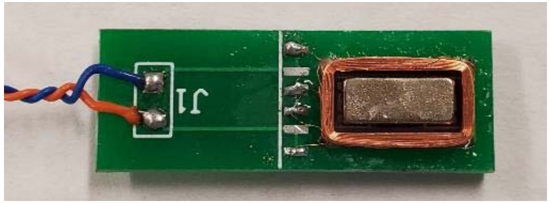
$$V_L = \frac{\tau_{mag} K_R}{\left(b + j\omega J + \frac{k}{j\omega}\right)(R_R + R_L) + K_R^2} R_L$$

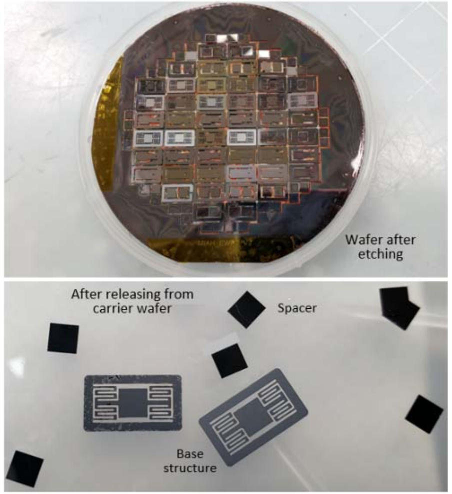
Case I: Open-circuit	Case II: Resonance	Case III: Resonance + R_{opt}
$V_L\Big\vert_{R_L=\infty} = \frac{\tau_{mag} K_R}{\left(b + j\omega J + \frac{k}{j\omega}\right)}$	$V_L\Big\vert_{\omega=\omega_r} = \frac{\tau_{mag} K_R}{b(R_R + R_L) + K_R^2} R_L$ $P_L\Big\vert_{\omega=\omega_r} = \frac{V_L^2}{R_L}$	$V_{opt} = V_L\Big\vert_{\substack{\omega=\omega_r \\ R_L=R_{L\_opt}}} = \frac{\tau_{mag} K_R}{2b}$ $P_{max} = P_L\Big\vert_{\substack{\omega=\omega_r \\ R_L=R_{L\_opt}}} = \frac{\tau_{mag}^2 K_R^2}{4b^2 R_{L\_opt}}$

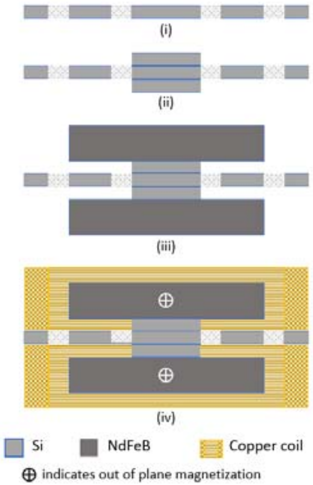
Key parameters

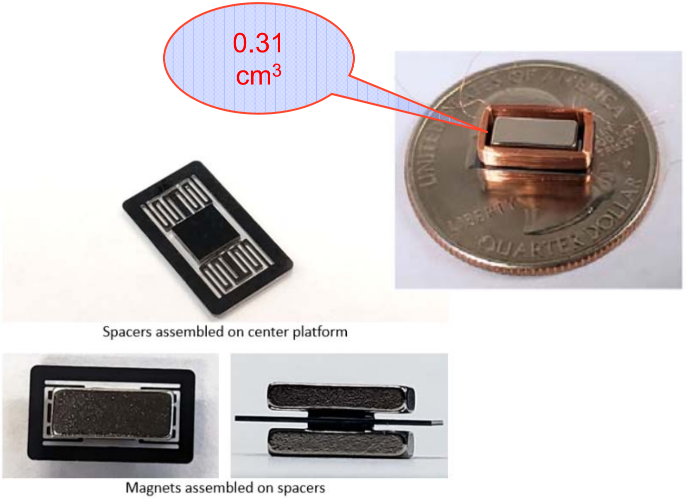
Electrodynamic EWPT Receiver

- Microfabrication of silicon suspension
  - Through-etching a 300 µm-thick 4-inch Si wafer via DRIE
- Prototype assembly
  - NdFeB magnets magnetized after assembly using pulse magnetizer
  - Assembled within a PCB for characterization





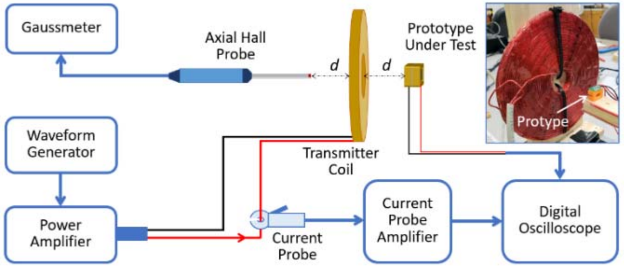




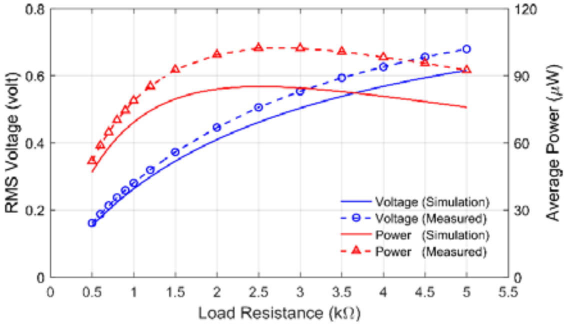
Electrodynamic EWPT Receiver

- Characterization and model validation

Experimental setup

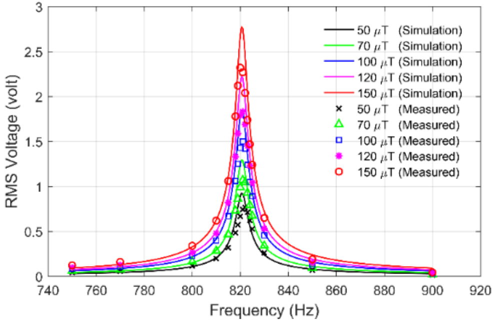


Load voltage & Power vs. load @ resonance



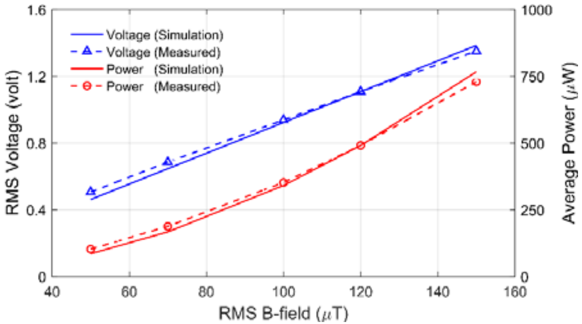
- Strong electrodynamic coupling
- Coupling strength $\gamma = 9$

Frequency response @ 4 cm



- 821 Hz resonance
- Underdamped 2nd-order system
- High Q (= 165 in air)

V & P vs. B-field @ resonance w/ $R_{L\text{-opt}}$

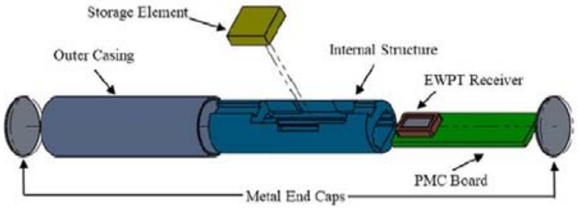


- Power increases quadratically
- Nonlinearity observed from > 120 μT_{rms}

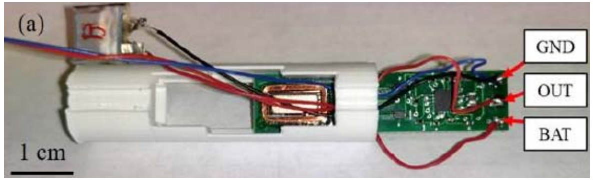
EWPT System Demo

- Wirelessly Rechargeable AA Battery

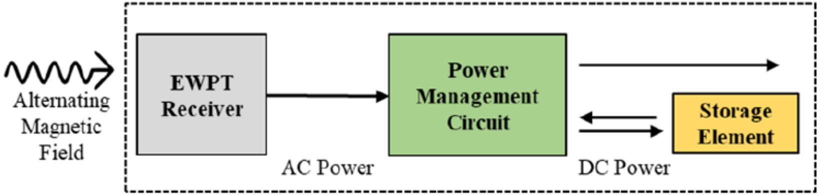
Exploded view of the AA battery prototype



Photographs of the system

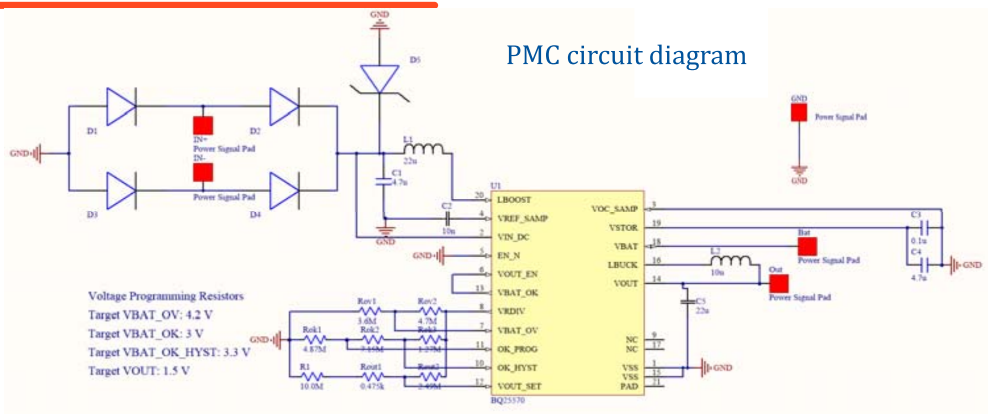


- System-level integration

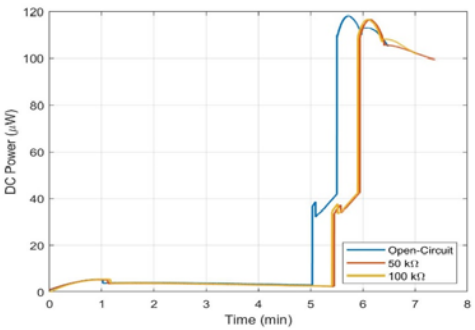


EWPT System Demo

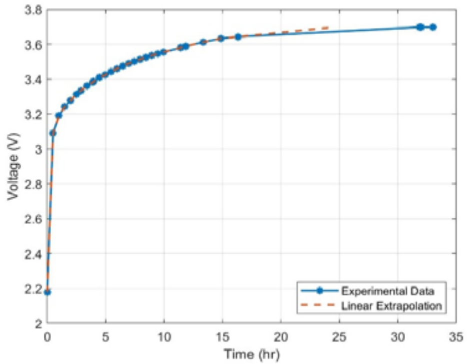
- Power Management Circuit
  - Diode Bridge Rectifier
  - TI BQ25570 energy-harvesting chip



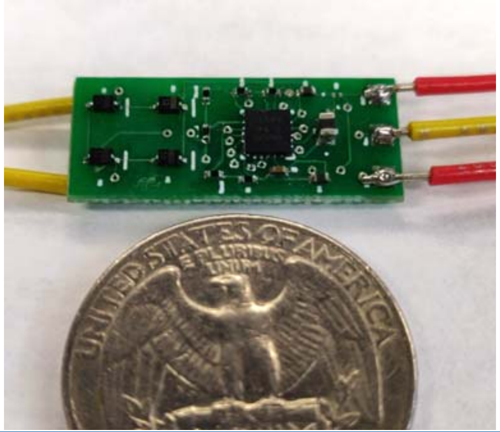
PMC circuit diagram



DC power across the capacitor vs time
for various resistive loads

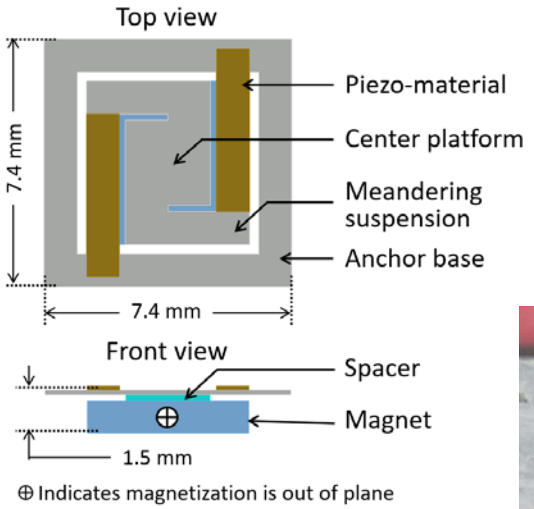


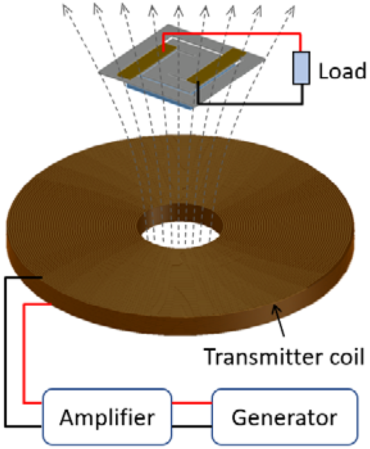
Charge cycle for the lithium polymer battery



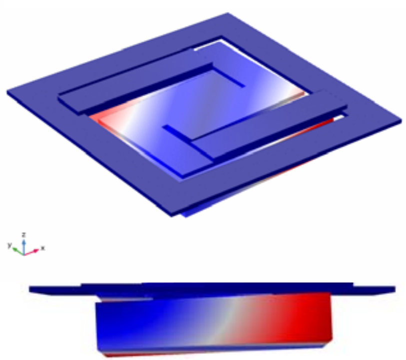
Piezoelectric EWPT Receiver

- Laser micro-machined EWPT receiver
  - Meandering suspension
  - Two Piezoelectric transducers in series
  - Torsional operation 724 Hz

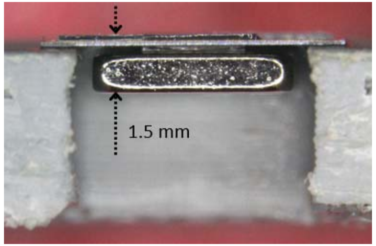




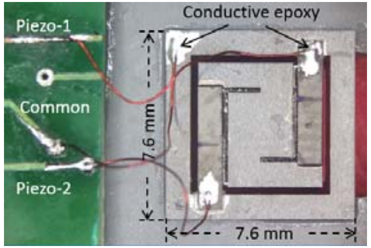
Torsion mode resonance



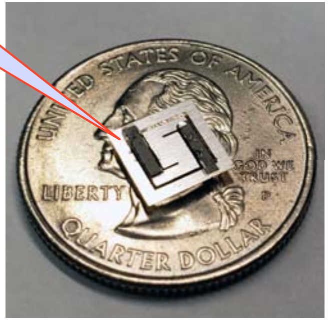
Side view



Top view

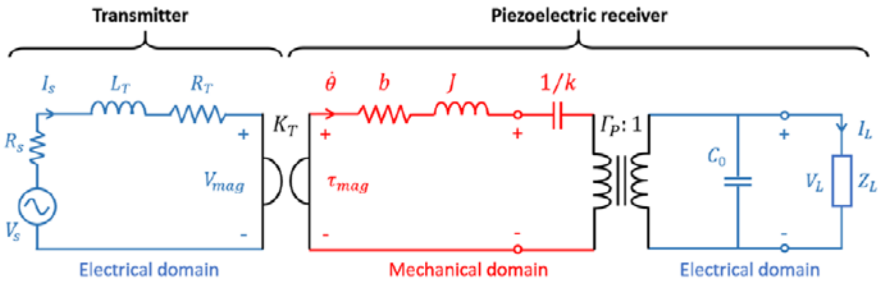


0.08 cm^3



Piezoelectric EWPT Receiver

- Lumped Element Modeling (LEM)
  - Equivalent electrical circuit model

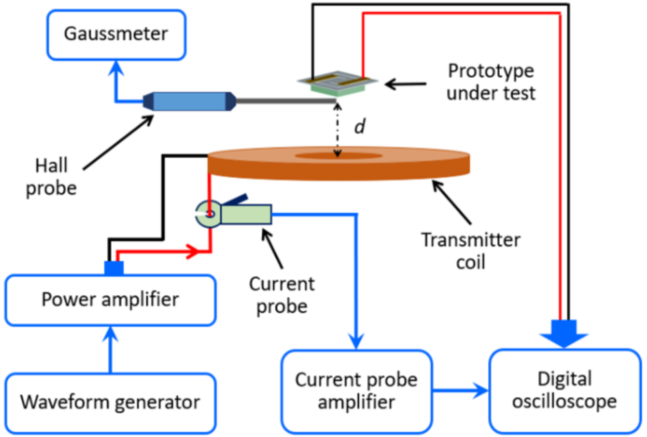


b = torsional damping coefficient
J = mass moment of inertia
k = torsional stiffness (short-circuit)

  - Frequency-dependent load voltage

$$V_L = \frac{\Gamma_P \tau_{mag}}{\left(b + j\omega J + \frac{k}{j\omega}\right)(1 + j\omega C_0 R_L) + \Gamma_P^2 R_L} R_L$$

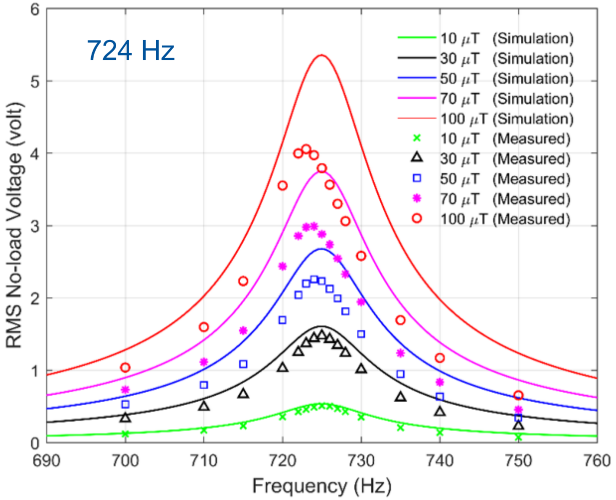
- Experimental validation



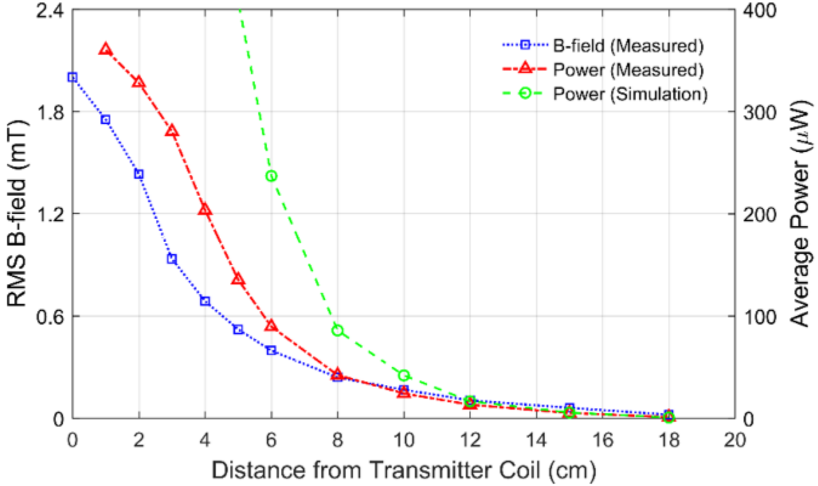
Electrodynamic EWPT Receiver

- Characterization and model validation

Frequency response @ 4 cm

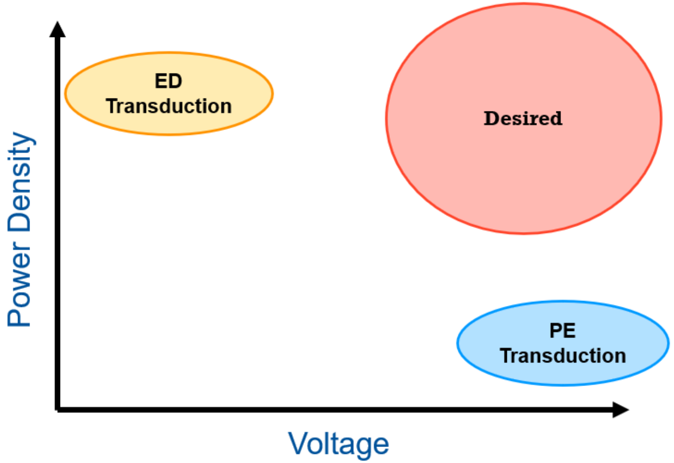


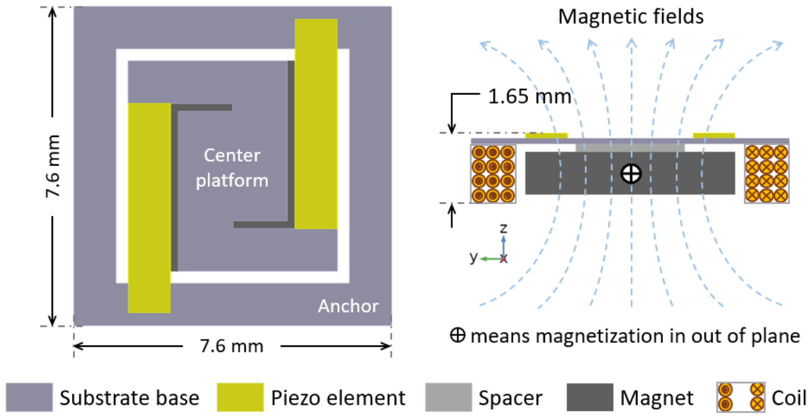
Power vs. distance @ resonance w/ $R_{l\text{-}opt}$



Dual-transduction EWPT Receiver

- Combined with ED and PE transducers
  - Two piezoelectric transducers (series connected)
  - One electrodynamic transducer
  - Both transducers operate simultaneously
  - Torsional operation at ~ 744 Hz





Lumped Element Model (LEM)

- Equivalent electrical circuit
  - Torque source is either a Helmholtz coil pair or multi-turn single solenoid coil
  - Transformer couples the PE transducer
  - Gyrator couples ED transducer

$$\tau_{mag} = \frac{B_r}{\mu_0} v_{mag} B_z \qquad k = (1-\kappa^2)k_0$$

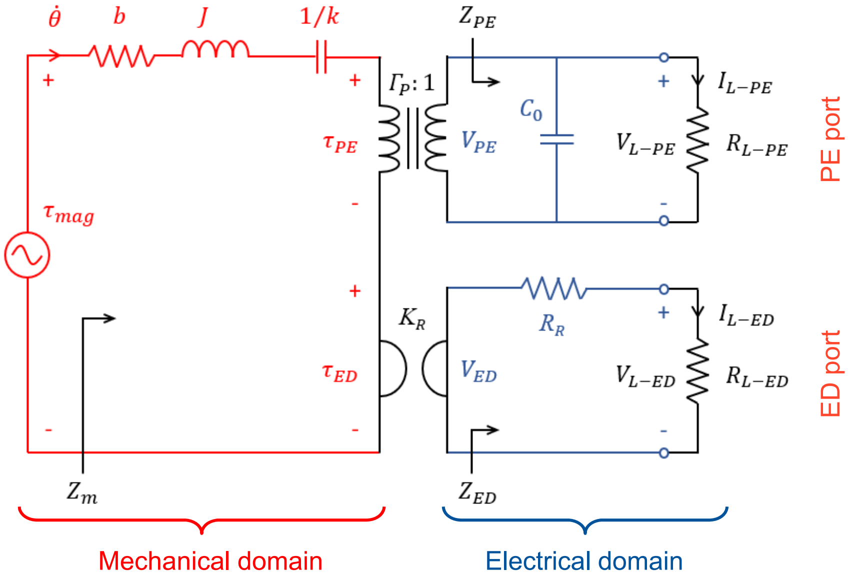
$$K_R = \frac{V_{ED}}{\dot{\theta}} \qquad C_0 = (1-\kappa^2)C$$

$$\Gamma_P = \sqrt{\kappa^2 k C} \qquad \kappa^2 = 1 - (f_{r-sc}/f_{r-oc})^2$$

  - The voltages across corresponding load resistances

$$V_{L-PE} = \frac{\tau_{mag}\Gamma_P R_{L-PE}}{(1+j\omega C_0 R_{L-PE})\left[\left(b + j\omega J + \frac{k}{j\omega}\right) + \frac{\Gamma_P^2 R_{L-PE}}{1+j\omega C_0 R_{L-PE}} + \frac{K_R^2}{R_R + R_{L-ED}}\right]}$$

$$V_{L-ED} = \frac{\tau_{mag} K_R R_{L-ED}}{(R_R + R_{L-ED})\left[\left(b + j\omega J + \frac{k}{j\omega}\right) + \frac{\Gamma_P^2 R_{L-PE}}{1+j\omega C_0 R_{L-PE}} + \frac{K_R^2}{R_R + R_{L-ED}}\right]}$$



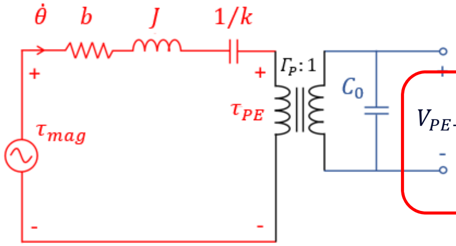
$$P_{PE} = \frac{V_{L-PE}^2}{R_{L-PE}}$$

$$P_{ED} = \frac{V_{L-ED}^2}{R_{L-ED}}$$

Lumped Element Model (LEM)

- Four special cases under various harmonic excitation and load conditions

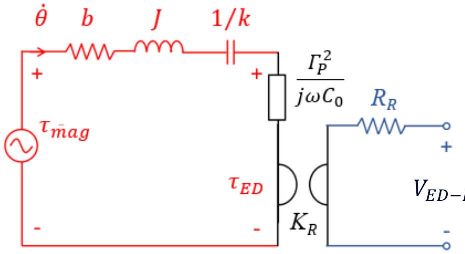
Case I: PE open-circuit with ED open



$$V_{PE-I} = \frac{\tau_{mag}\Gamma_P}{j\omega C_0\left[\left(b + j\omega J + \frac{k}{j\omega}\right) + \frac{\Gamma_P^2}{j\omega C_0}\right]}$$

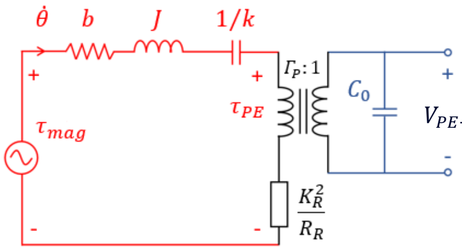
Pure PE response

Case III: ED open-circuit with PE open



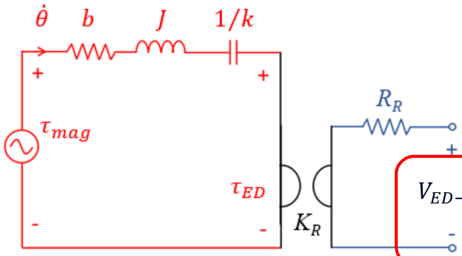
$$V_{ED-III} = \frac{\tau_{mag}K_R}{\left(b + j\omega J + \frac{k}{j\omega}\right) + \frac{\Gamma_P^2}{j\omega C_0}}$$

Case II: PE open-circuit with ED short



$$V_{PE-II} = \frac{\tau_{mag}\Gamma_P}{j\omega C_0\left[\left(b + j\omega J + \frac{k}{j\omega}\right) + \frac{\Gamma_P^2}{j\omega C_0} + \frac{K_R^2}{R_R}\right]}$$

Case IV: ED open-circuit with PE short

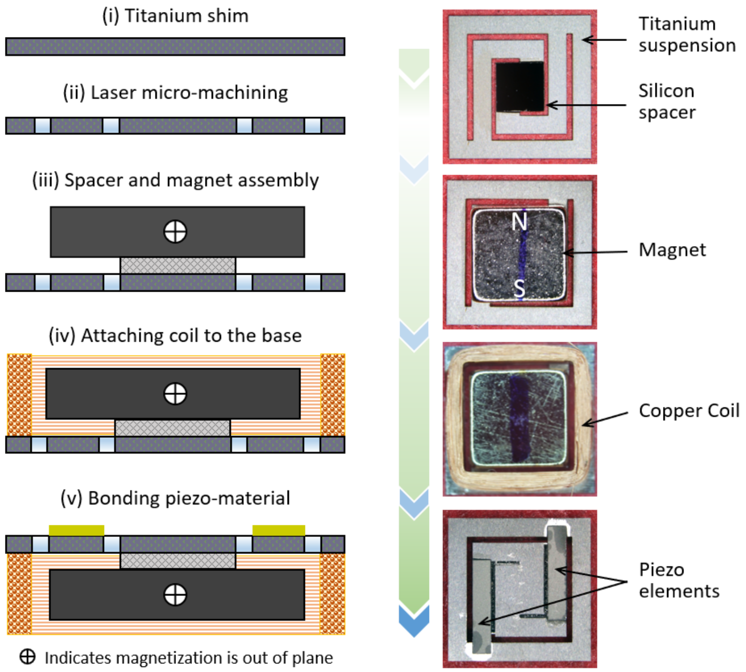


Pure ED response

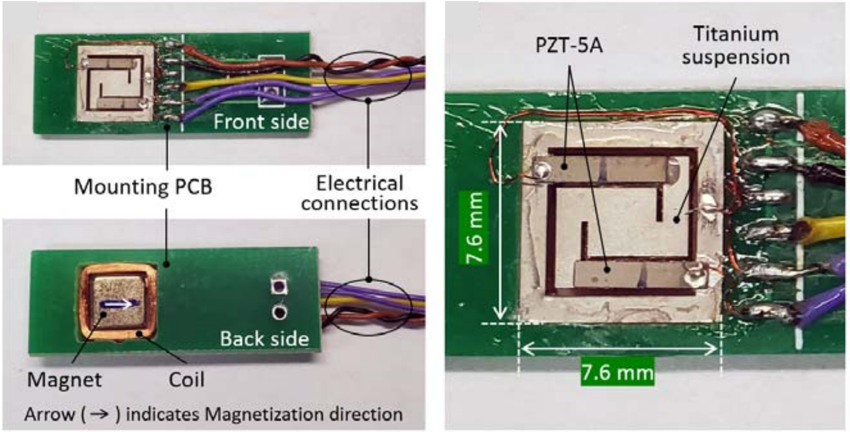
$$V_{ED-IV} = \frac{\tau_{mag}K_R}{\left(b + j\omega J + \frac{k}{j\omega}\right)}$$

Prototype Fabrication

Fabrication process flow

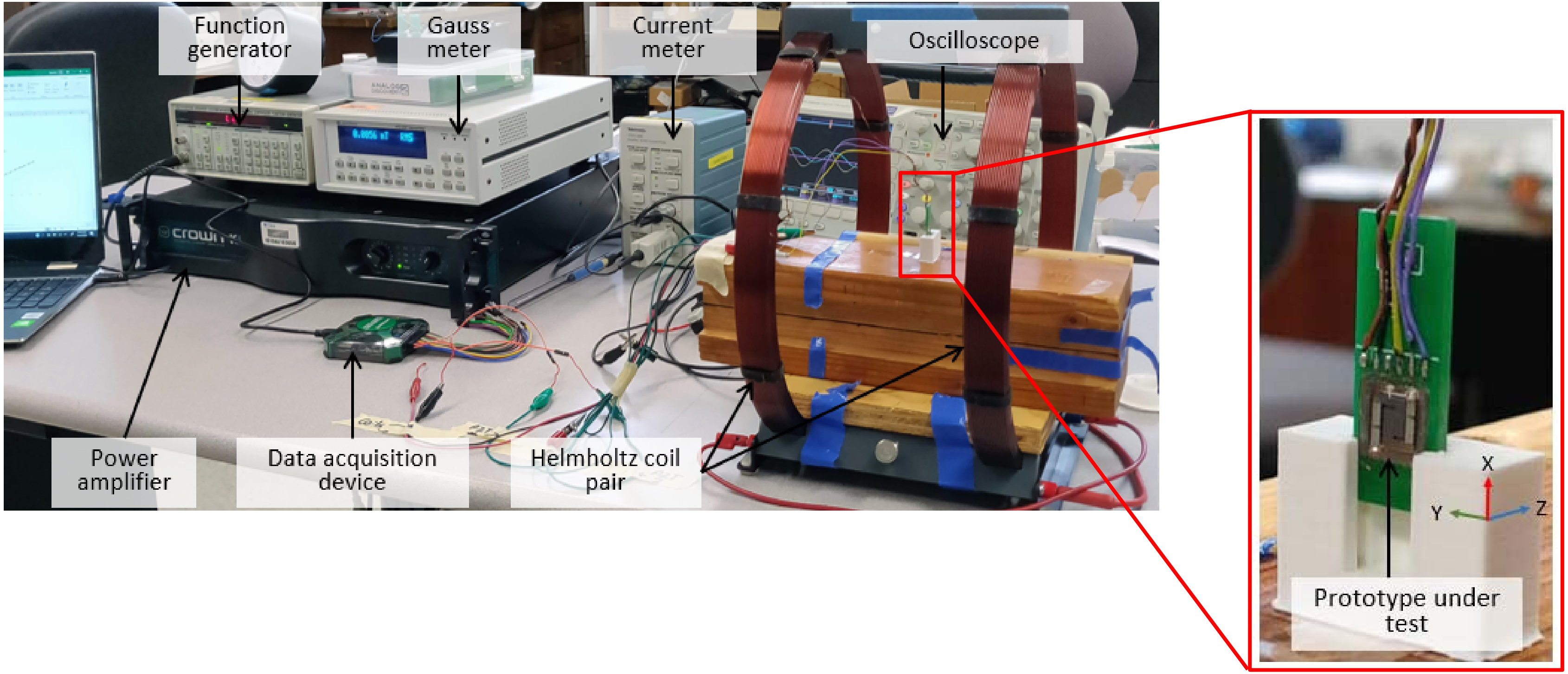


Fabricated and assembled prototype



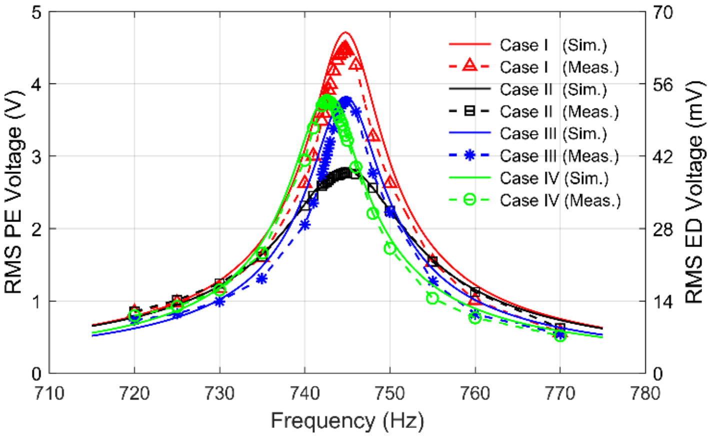
Magnet (NdFeB, N50) dimension	5 × 5 × 1 mm^3
Piezo (PZT-5A) dimension	5 × 1 × 0.127 mm^3
Center platform (Ti) and spacer (Si)	2.6 × 2.6 mm^2
Suspension base (Ti) thickness	0.125 mm
Receiver coil (Cu) inner dimension	5.6 × 5.6 × 1.4 mm^3
Coil resistance	71 Ω

Experimental Test Setup



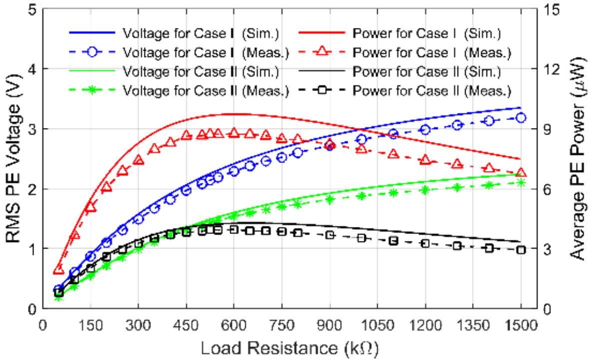
Experimental Results

No-load voltage vs. frequency @ 50 μT_{rms}



- Linear behavior with Q = 90 (in air)
- 744.8 Hz for Cases I, II & III
- No effect on resonance for ED loading condition
- 742.6 for Case IV (while PE shorted)

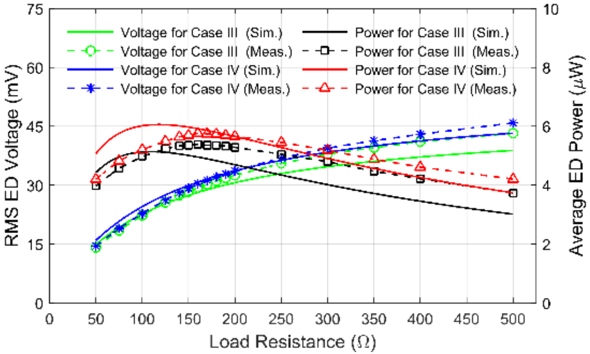
Load voltage & Power vs. load resistance @ resonance



Cases I & II

Optimum $R_{L\text{-}PE}$

600 kΩ



Cases III & IV

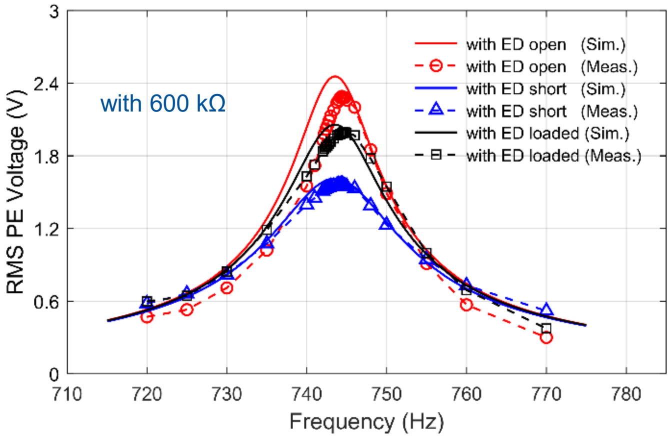
Optimum $R_{L\text{-}ED}$

115 Ω (sim)

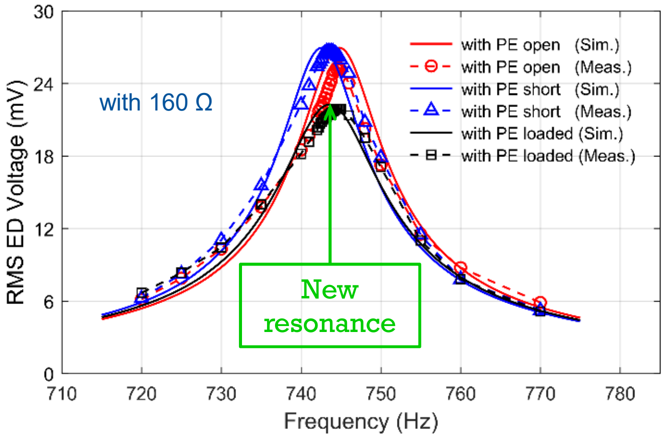
160 Ω (meas)

Experimental Results

PE load voltage vs. frequency @ 50 μT_{rms} w/ $R_{L\text{-}PE\text{-}opt}$



ED load voltage vs. frequency @ 50 μT_{rms} w/ $R_{L\text{-}ED\text{-}opt}$

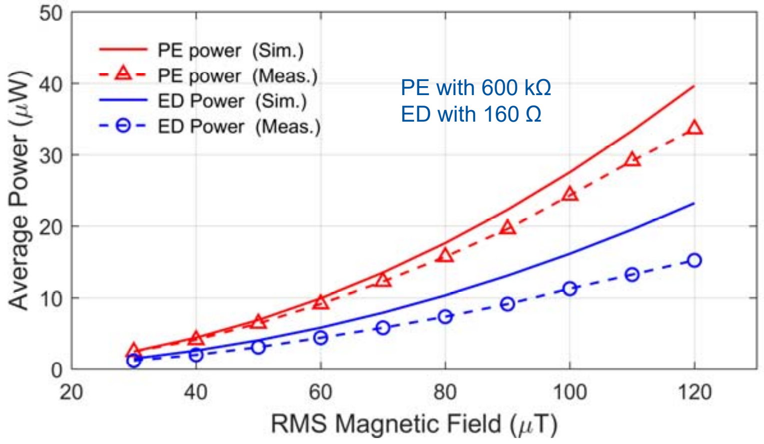


- ED loading does not affect the resonance
- However, controls the PE amplitude

- PE loading controls the resonance
- New resonance is obtained when both transducers are at their respective $R_{L\text{-}opt}$

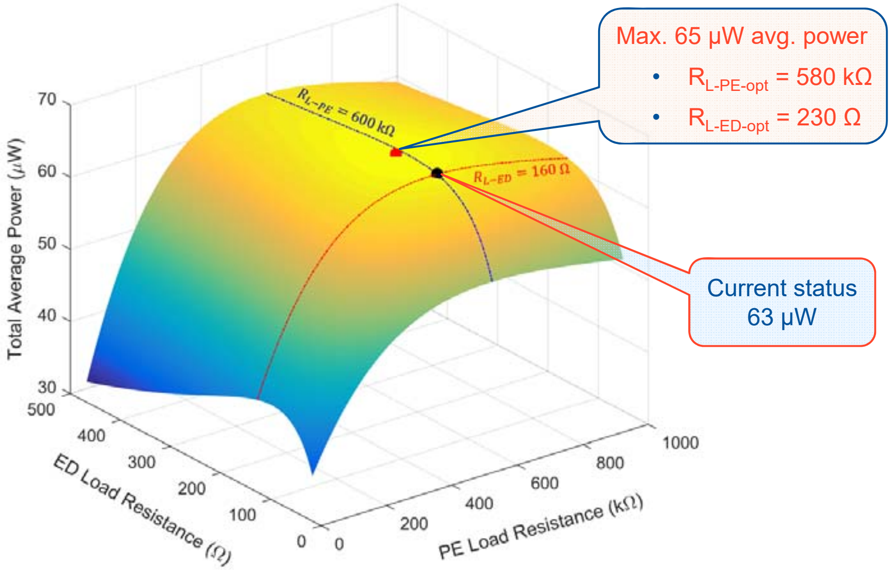
Experimental Results

PE and ED load power vs. magnetic field @ resonance



- Power increases with magnetic fields
- Nonlinear behavior at higher fields due to
  - Spring stiffening effect
  - Nonlinear piezoelectric effect
  - Non-constant K_R

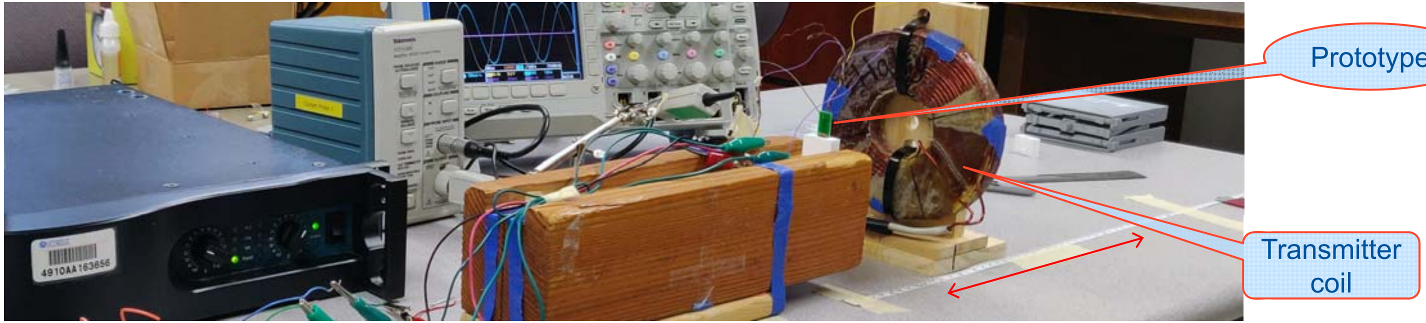
Simulated total (PE+ED) power vs. load @ 120 μT_{rms} & 743.6 Hz

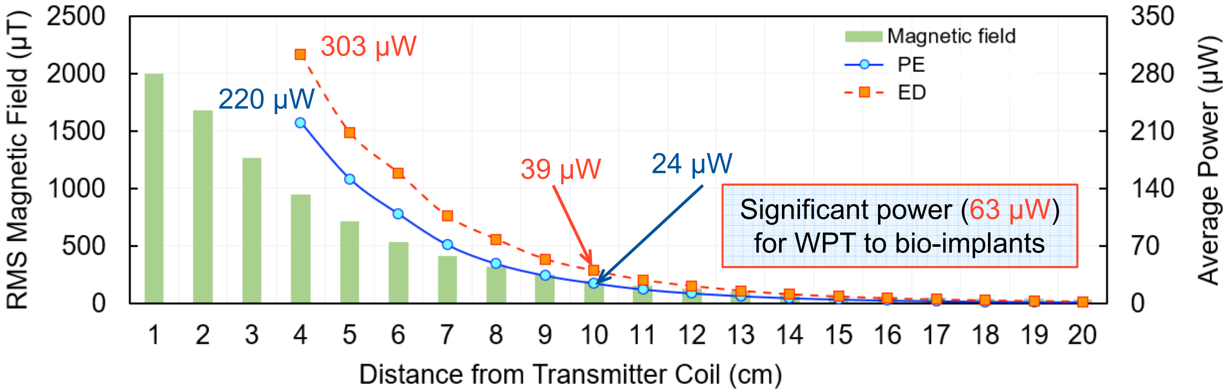


- Strongly correlated with the strength of electromechanical coupling of the transducers
- Should be carefully considered in future designs

Experimental Results

- Power vs. distance using multi-turn single solenoid coil @ resonance with $R_{L\text{-}opt}$





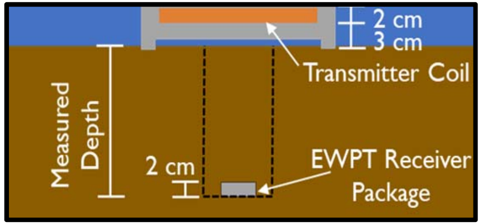
Charging through Conductive Media

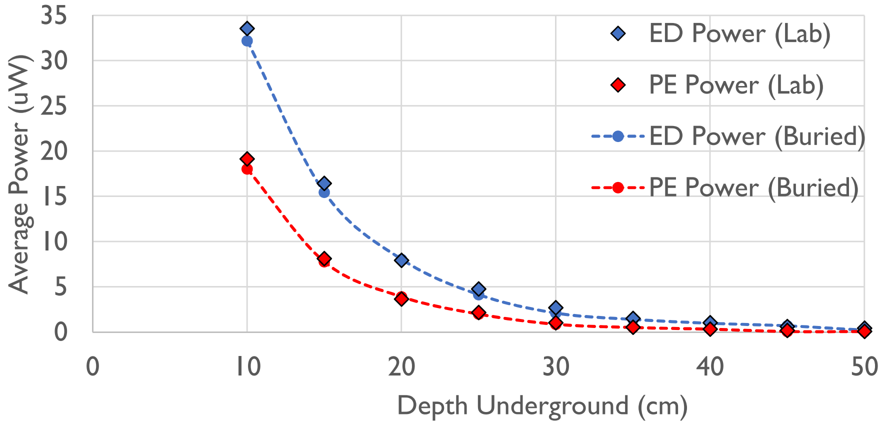
Through Metal

Through Humans

Charging through Conductive Media

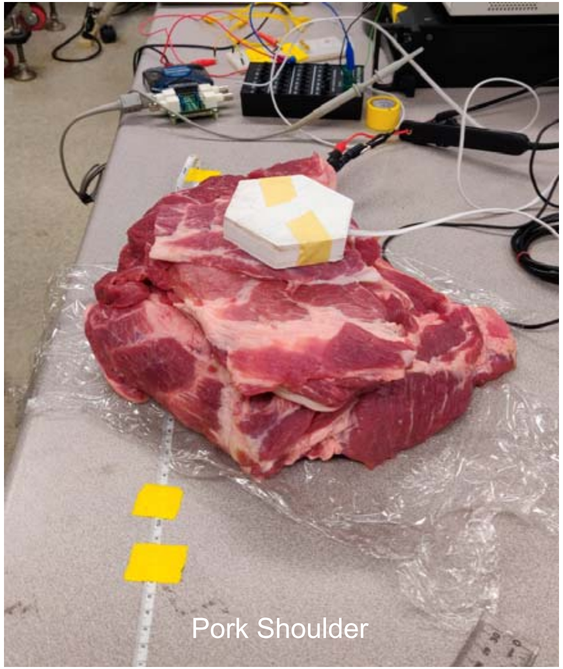
Dual Transduction Receiver for Underground WPT

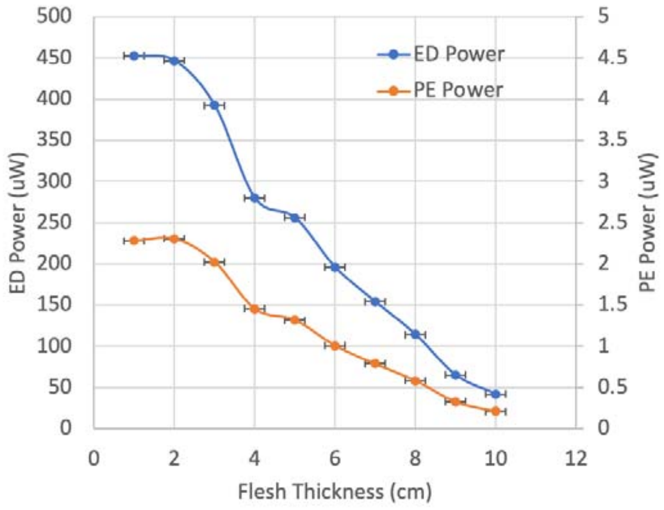




Charging through Conductive Media

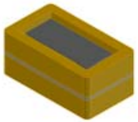
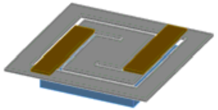
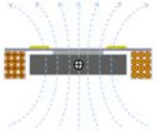
Dual Transduction Receiver charging through Tissue





Summary & Comparison

- Designed, modeled and experimentally verified various EWPT systems
- Volume-efficient, low-profile, chip-like designs
- Application in wearables and implantable medical devices

	ED receiver	PE receiver	Dual-transduction
			
Frequency (Hz)	821	724	743.6
Receiver Volume (cm^3)	0.31	0.08	0.09
Receiver thickness (mm)	4.7	1.5	1.65
Load voltage (V)	2.5	11.5	10.8 (PE) 0.25 (ED)
Max. Power (mW)	2.48	0.21	0.52
PD ($mWcm^{-3}$)	7.9	2.6	5.8
NPD ($mWcm^{-3}mT^{-2}$)	22.1	5.5	6.5

Power density (PD) = power/volume Normalized PD (NPD) = PD/B-field^2

Acknowledgements

- NSF Multi-functional Integrated System Technology (an NSF I/UCRC)

MIST CENTER

Innovating more than Moore technologies
for smart systems in the Internet of Things era.

- Internet of Things for Precision Agriculture (IoT4Ag)

IoT4Ag

The Internet of Things for Precision Agriculture
an NSF Engineering Research Center

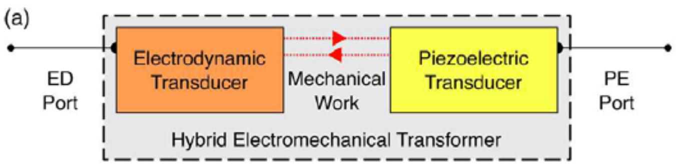
- Interdisciplinary Microsystems Group

Interdisciplinary Microsystems Group

- Dr. Arnold's group

UF

Hybrid Electromechanical Transformer



Abstract—This paper presents a hybrid electromechanical transformer that passively transfers electrical power between galvanically isolated ports by coupling electrodynamic and piezoelectric transducers. The use of these two complementary electromechanical transduction methods along with a high-Q mechanical resonance affords very large transformations of voltage at particular electrical frequencies. A chip-size prototype is designed, simulated, fabricated and experimentally characterized. The 7.6 mm × 7.6 mm × 1.65 mm device achieves open-circuit voltage gains of 31.4 and 48.7 when operating as step-up transformer at 729.5 Hz and 1015 Hz resonance frequencies, respectively. In one operational mode, the system shows a minimum power dissipation of only 0.9 µW corresponding to a power conversion efficiency of 11.8 %. A practical application of the hybrid transformer is demonstrated through an AC-DC step-up converter. When using a 1015 Hz input signal of only 209 mV_{rms} and 2.4 mA_{rms}, the step-up converter outputs 5.3 V_{DC}.