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Modeling of Power and Thermal Characteristics of Piezoelectric Transformers

Safakcan Tuncdemir[1]

W. Michael Bradley[2]

[1] Solid State Ceramics, Williamsport, PA 17701 USA
[2] QorTek, Williamsport, PA 17701 USA

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Outline

- Piezoelectric Transformer Background
- Piezoelectric Transformer Operating Principle
  - Equivalent Circuit and Drive Conditions
  - Material Properties and Loss
- Common Issues
  - Motivation for Model Development
- COMSOL Model Details
- Results
- Future Work

Piezoelectric Transformer Background

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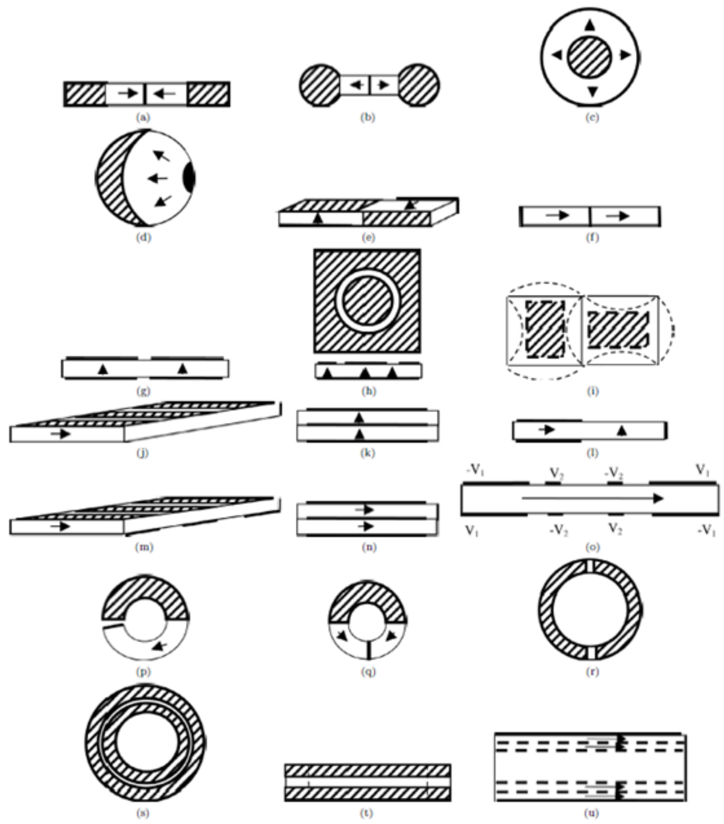
Merits

- Solid State Devices
- Efficient and High Power Density
- Low-Profile Form Factor
- Low EMI Emission
- No Magnetic Susceptibility

Applications

- Computer LED/LCD Backlights
- Florescent Ballast
- Portable Electronic Chargers
- Ignition of Gas-Discharge Lamps
- Compact AC/DC and DC/DC Converters

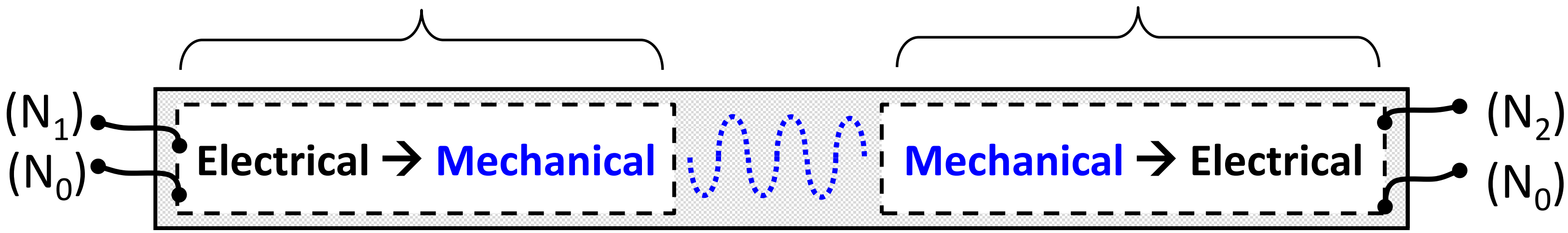
PT Designs in Literature[1]



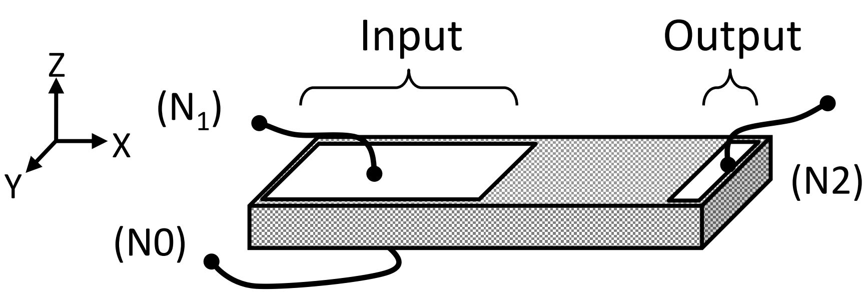
1. J. Yang, "*Piezoelectric Transformer Structural Modeling – A Review*", IEEE Trans on UFFC, 54, 6, 1154-70 (2007).

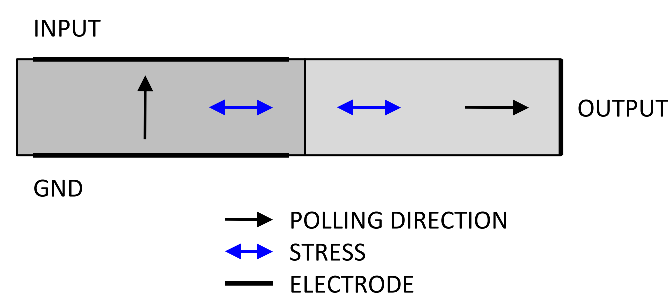
Piezoelectric Transformer Operating Principle

Combination of Converse Piezoelectric Effect, Vibration and Direct Piezoelectric Effect



Rosen[1] Type Piezoelectric Transformer





1. C. A. Rosen, "Ceramic transformers and filters", *proc. Electronic Comp. Symp.,* 205-211 (1956)

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Equivalent Circuit Model & Resonant Drive Conditions

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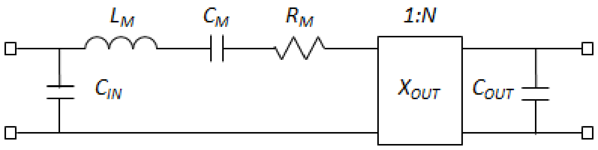
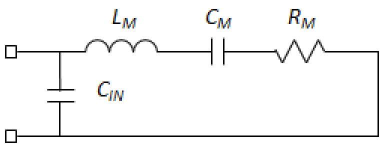
PIEZOELECTRIC TRANSFORMER EQUIVALENT CIRCUIT

(Piezoelectric Transformer with Output Opened)



PIEZOELECTRIC ELEMENT EQUIVALENT CIRCUIT

(Piezoelectric Transformer with Output Shorted)



OPTIMAL LOAD OF PIEZOELECTRIC TRANSFORMER

(Purely Resistive Load)

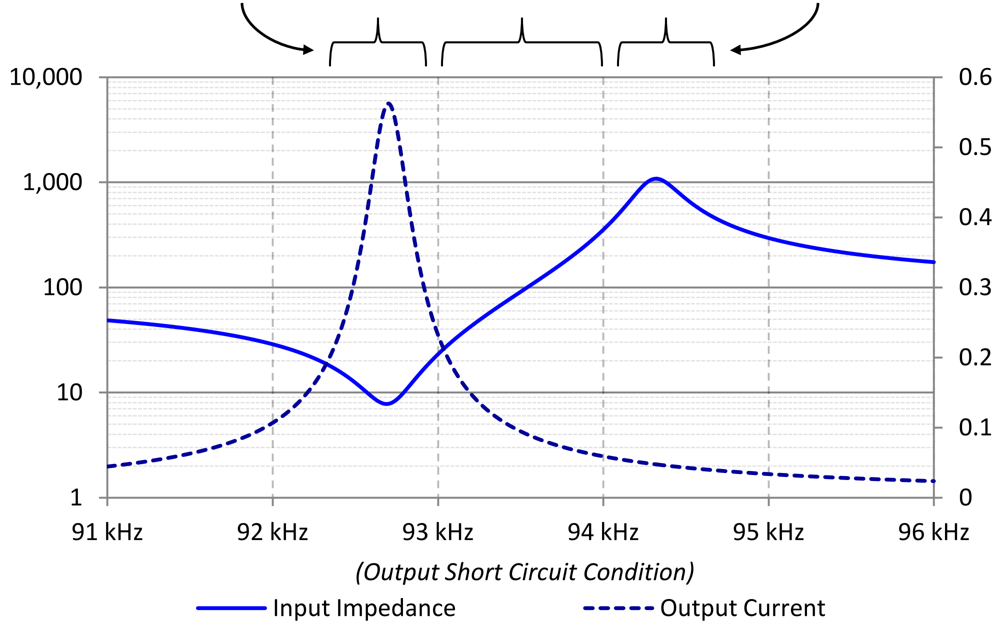
$$R_{opt} = \frac{1}{2\pi f_{opt} C_{OUT}}$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_M L_M}} \qquad f_{opt} \approx \frac{(f_p - f_s)}{2} + f_s \qquad f_p = \frac{1}{2\pi}\sqrt{\frac{C_{OUT} + C_M}{C_M C_{OUT} L_M}}$$

OPERATION AREA
(Maximum Efficiency)

Resonance Frequency
(Series Resonance)

Anti-Resonance Frequency
(Parallel Resonance)



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Material Properties & Loss

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Electromechanical Coupled Physics

$$T_i = c_{ij}^{E} S_j - e_{mi} E_m$$

$$D_i = e_{mi} S_j + \varepsilon_{ik}^{S} E_k$$

Losses

$$s^{E*} = s^{E}(1 - j\tan\phi')$$

$$d^{*} = d(1 - j\tan\theta')$$

$$\varepsilon^{T*} = \varepsilon^{T}(1 - j\tan\delta')$$

Material properties and losses are nonlinear at:

- High Frequency (Resonance)
- High Power
- Elevated Temperatures

Elastic Stiffness

$$\underline{s^E} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{55}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E \end{bmatrix} = \left(\underline{c^E}\right)^{-1}$$

Piezoelectric Charge Constant

$$\underline{d} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} = \left(e^T\right)^{-1}$$

Dielectric Permittivity

$$\underline{\varepsilon^T} = \begin{bmatrix} \varepsilon_{11}^T & 0 & 0 \\ 0 & \varepsilon_{11}^T & 0 \\ 0 & 0 & \varepsilon_{33}^T \end{bmatrix} = \left(\underline{\beta^T}\right)^{-1}$$

Common Issues

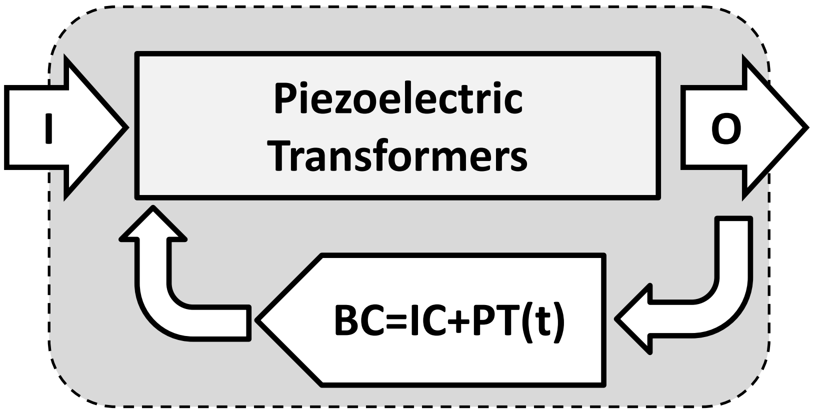
- Nonlinear Device
- Dependent on:
  - Excitation Frequency
  - Excitation Voltage and Current
  - Ambient Temperature
  - Mechanical Loading
  - Electrical Loading

A fully coupled device model that includes thermal, electrical and mechanical loads is an ideal tool for Piezoelectric Transformer design.

Motivation for Model Development

- *Because of the thermal-electrical-mechanical coupled physics of Piezoelectric devices we need to build models considering all the peripheral effects.*

- ***System Level***
  - ***Input (I)***
  - ***Output (O)***
  - ***Initial Conditions (IC)***



- ***Coupled Physics***
  - ***Piezoelectric***
  - ***Electrical***
    - *Driving*
    - *Load circuit*
  - ***Mechanical***
    - *Device holder (fixture)*
  - ***Thermal***
    - *Ambient temperature*

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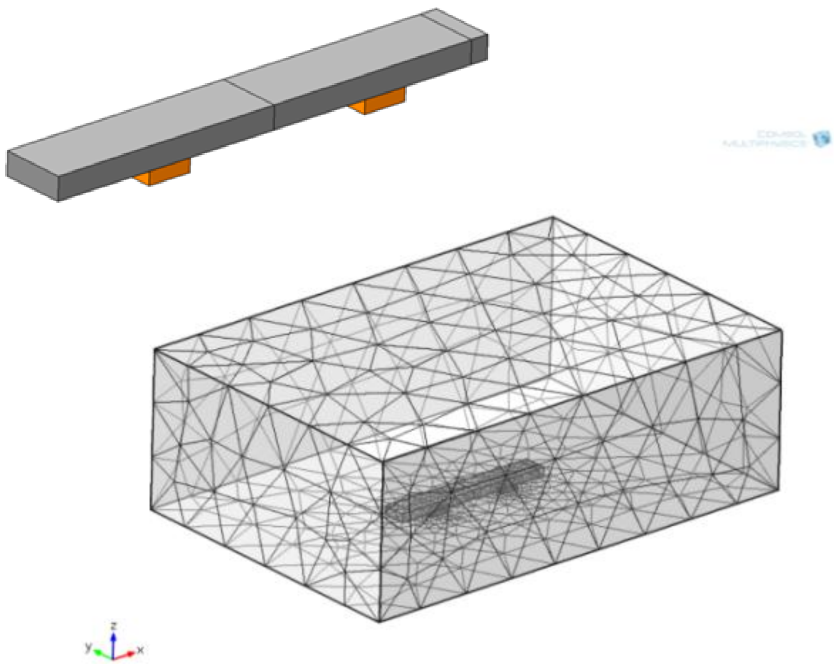
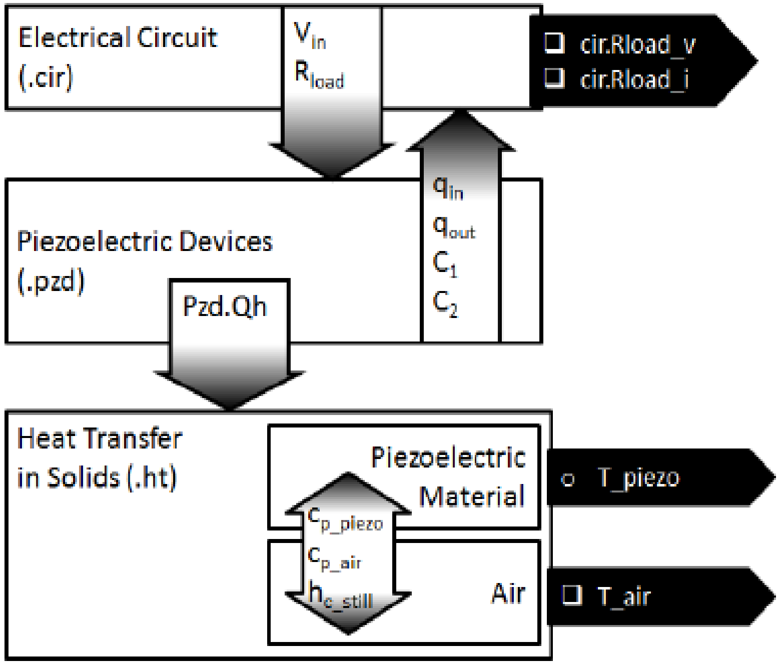
COMSOL Model Details

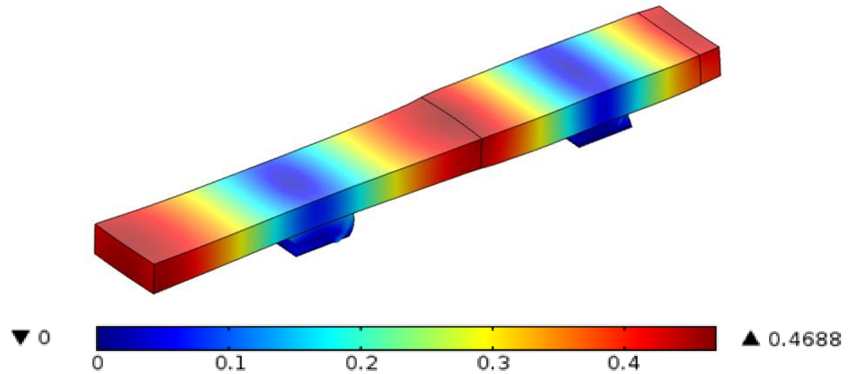
- **Model Geometry**
  - *PZT-4*
  - *Silicone Supports*
  - *Air Cavity*
- **Model Topology**
  - *Electrical Circuit*
  - *Structural Mechanics*
  - *Heat Transfer*



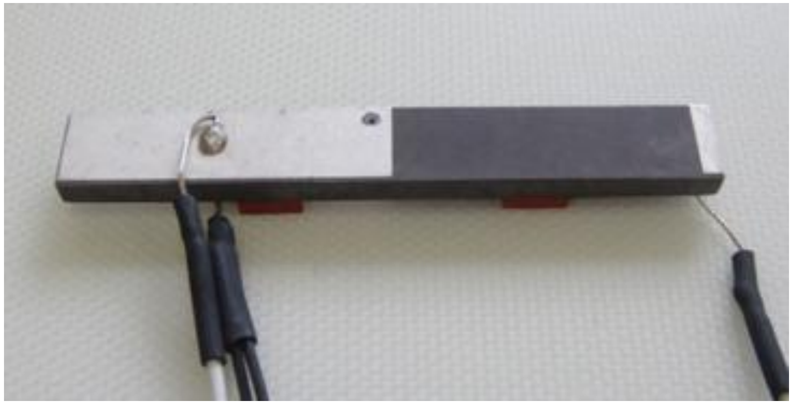


Mechanical Results

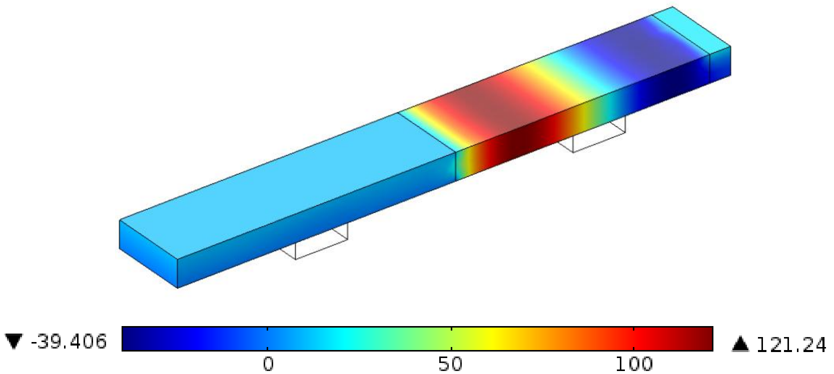
- ***Resonant Mode Shape***
  - *2nd Longitudinal Mode*
  - *Mounted at Modal Points*



Total Displacement (µm)
10k (Load) - 60300Hz (Resonance)



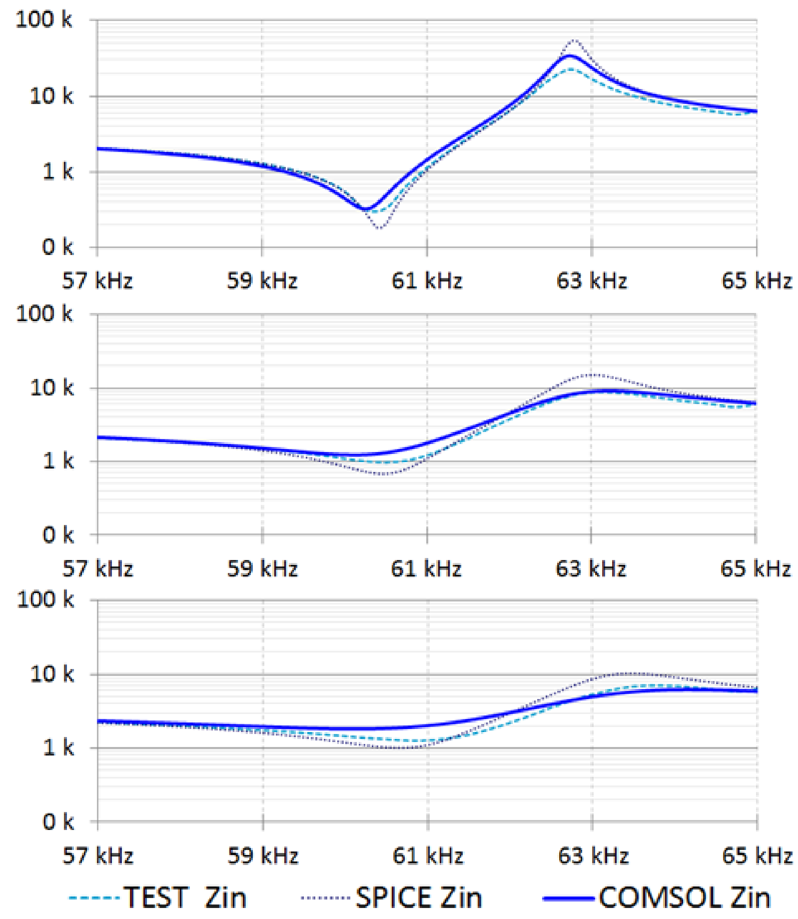
Physical Test Sample



Electric Potential (Volts)
10k (Load) – @ Resonance

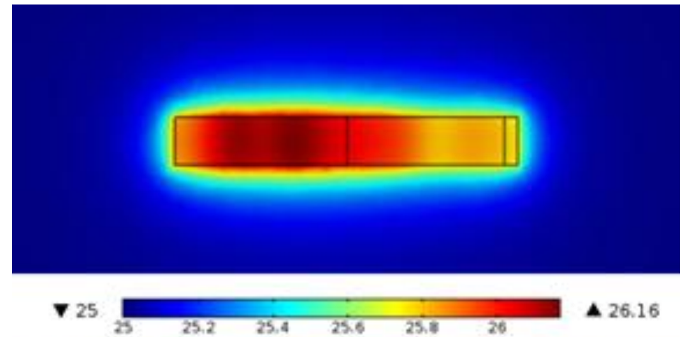
Input Impedance Results

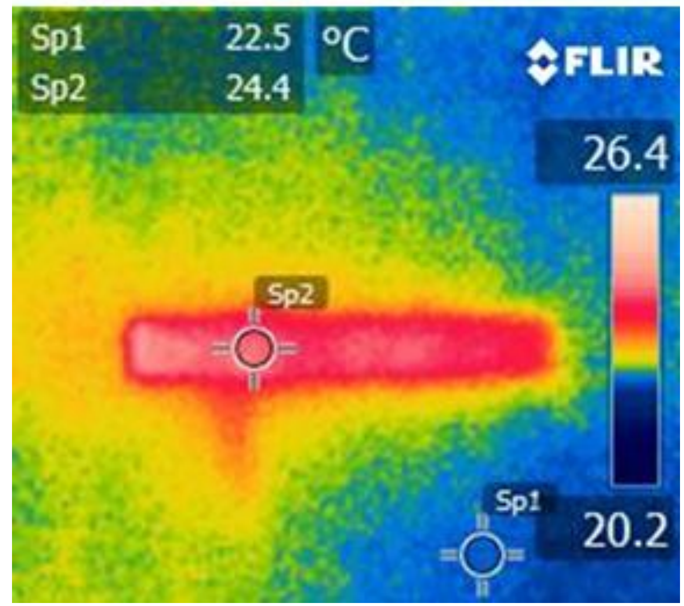
- ***Input Impedance Plot***
  - COMSOL Model
    - Derived Value
  - Electrical Test
    - Electrical Test
  - SPICE
    - Parameters Derived from Test Sample Measurement

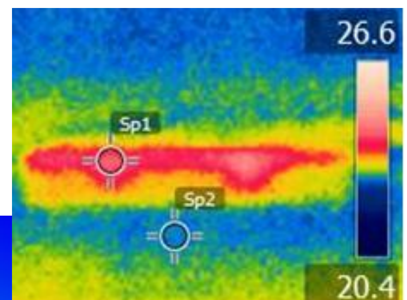


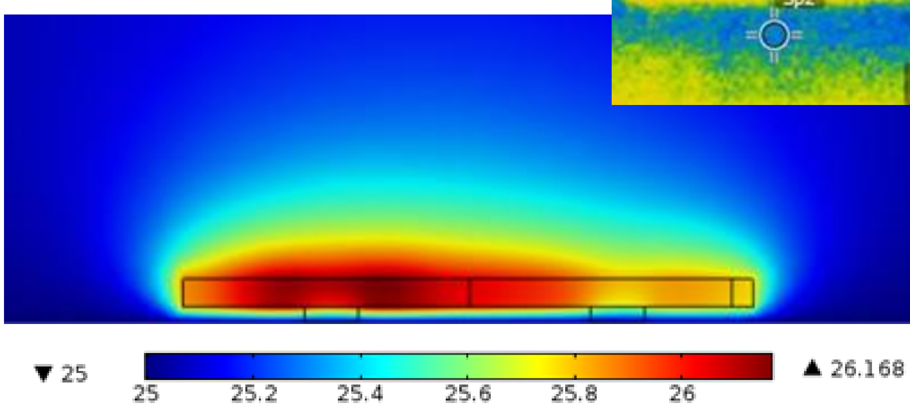
Temperature Profile Results

- ***Temperature Profile***
  - Top Surface
  - Thermal Image of Test Sample vs. Model









Future Work

- Implement Fully-Coupled Heat Transfer
  - Include Thermal Expansion
  - Include Temperature Dependence of Piezoelectric Parameters
- Include effects of Electrode Material
  - Thin Mechanical Layer
- Include Effects of Wired Connections

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References

1. C. A. Rosen, “Ceramic transformers and filters”, *Electronic Comp. Symp.,* 205-211 (1956)

2. J. Yang, “Piezoelectric Transformer Structural Modeling – A Review”, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 54, No. 6, 1154-1170 (2007).

3. S. Bronshtein, A Abramovitz, A, Bronshtein and I. Katz, “*A Method for Parameter Extraction of Piezoelectric Transformers*”, Vol. 26, No. 11, 3395-3401 (2011)

4. E. L. Horsley, M. P. Foster and D. A Stone, “State-of-the-art Piezoelectric Transformer technology”, *European Conference on Power Electronics and Applications,* 1-10 (2007)

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6. G. E. Martin, Dielectric, “Elastic and Piezoelectric Losses in Piezoelectric Materials”, *Proc. Ultrasonics Symp*, 613-617 (1974)