Greetings from

Georgia Tech

NEXTFLEX

Power Delivery and Management in Flexible Substrates for IoT Applications

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C3PS Center for Co-design of Chip, Package, System

Georgia Tech | Institute for Electronics and Nanotechnology

Outline

- ❑ Power Delivery for IoT
- ❑ Architecture
- ❑ Modeling
- ❑ Fabrication & Characterization
- ❑ PDK & Machine Learning
- ❑ Summary

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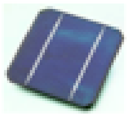
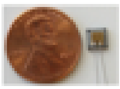
Overview

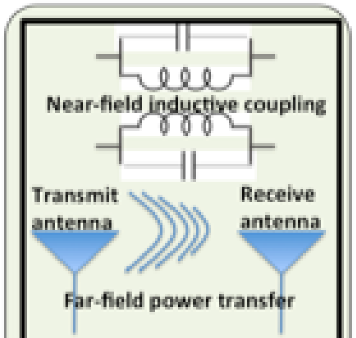
PV Cells

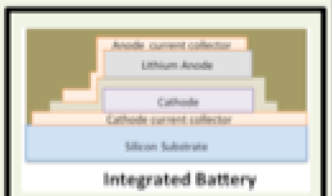


Thermoelectric



Piezoelectric





A: Energy Sources

Low-power/Low-Voltage Voltage Regulators

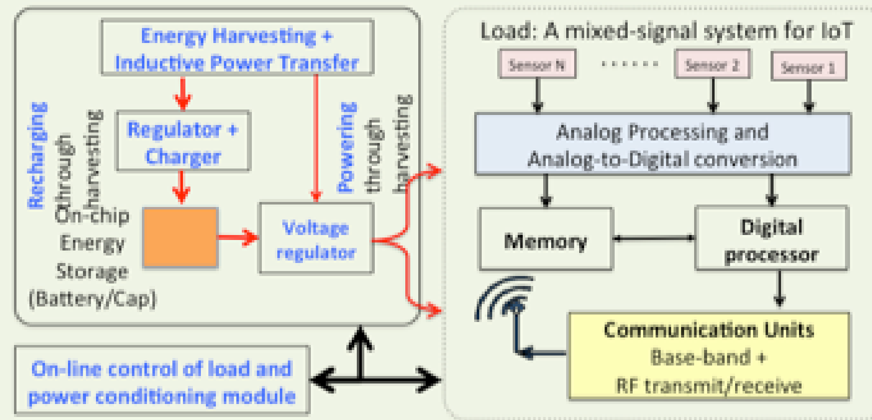
- Inductive Buck
- Inductive Boost
- Inductive Buck-boost with autonomous mode switching

Features
- PFM architecture
- Ultra-low-power with bias gating
- High-duty-cycle oscillator
- Low-voltage (subthreshold) design
- Low-load efficiency management
- Fast on-off response

Single Inductor Cascaded Stages Regulators for wide conversion ratio

Efficient RF-DC conversion & Rectifierless Boosting

B: Integrated Voltage Conversion/Regulation



- Energy from multiple sources including recharging of on-chip battery
- Maximum power/energy transfer from source to load
- Energy delivery to RF/digital/analog loads – multiple power domains with widely varying power demands
- On-line control for system level maximum energy efficiency

C. Power Delivery and Conditioning System with On-line Management

Courtesy: PDES Consortium, GT

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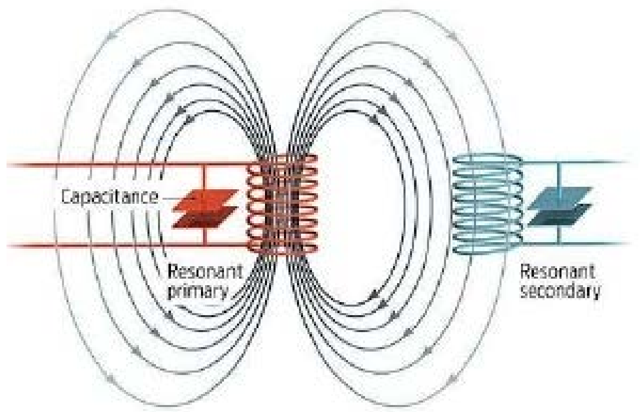
RF Energy Source

- ❑ Known Energy Source

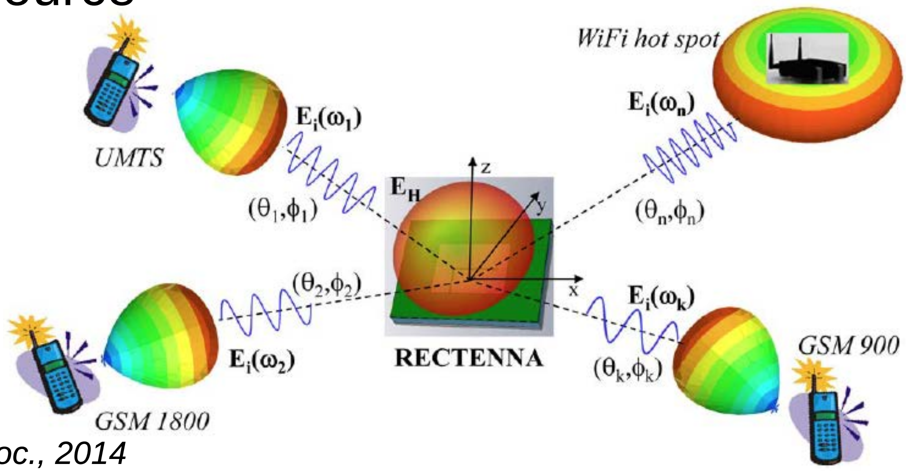


Near Field

Courtesy: PDES Consortium, GT

Far Field

- ❑ Ambient Energy Source



Courtesy: Costanzo et al, IEEE Proc., 2014

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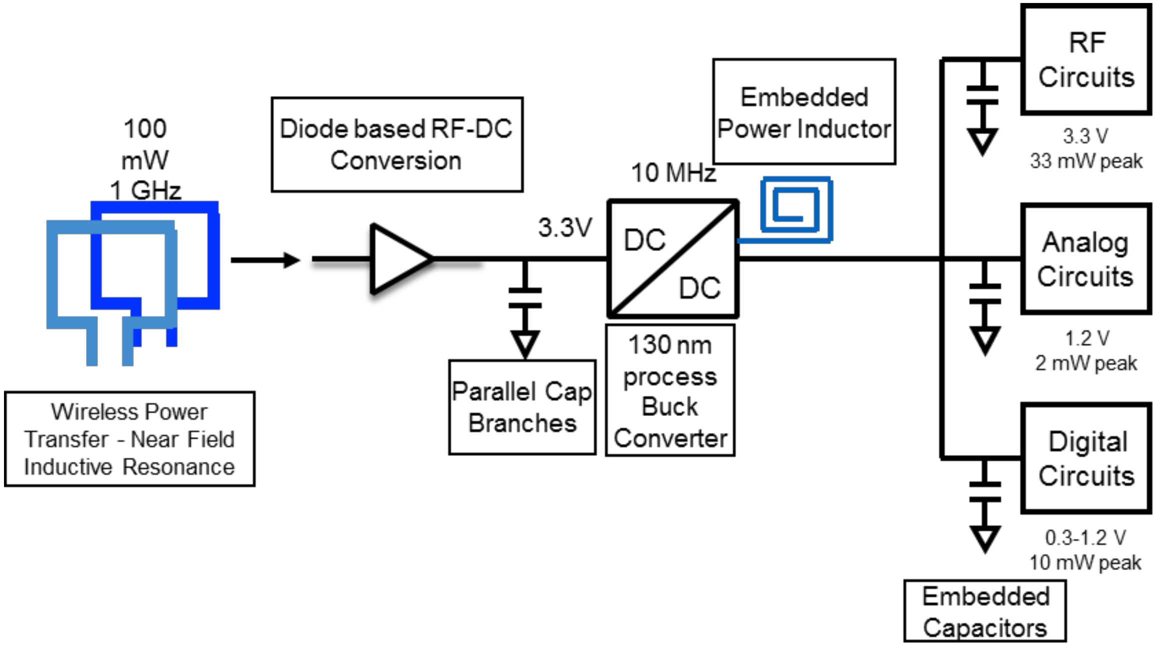
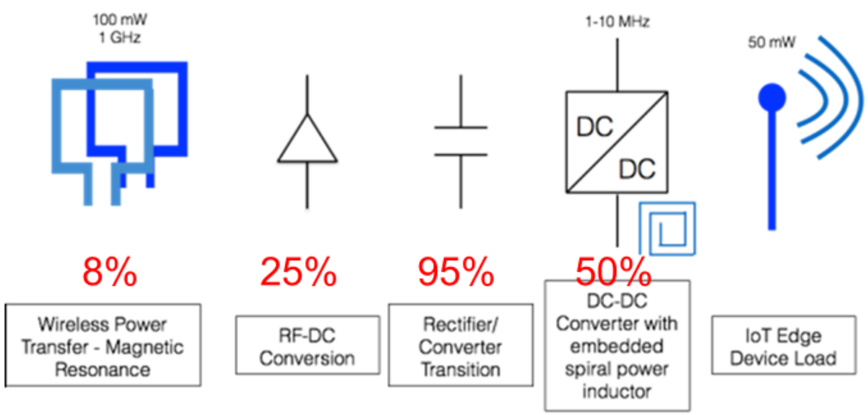
Architecture

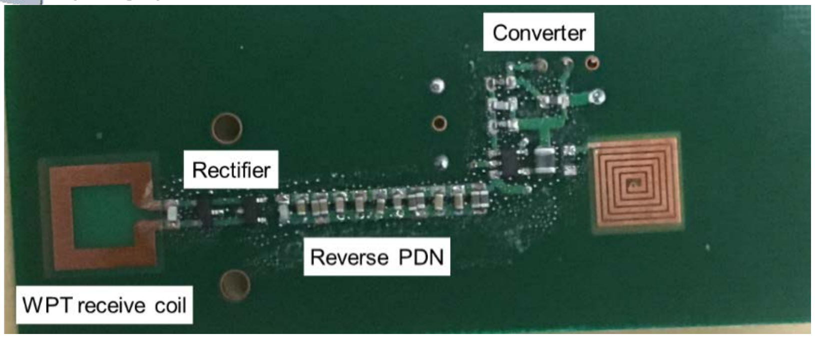


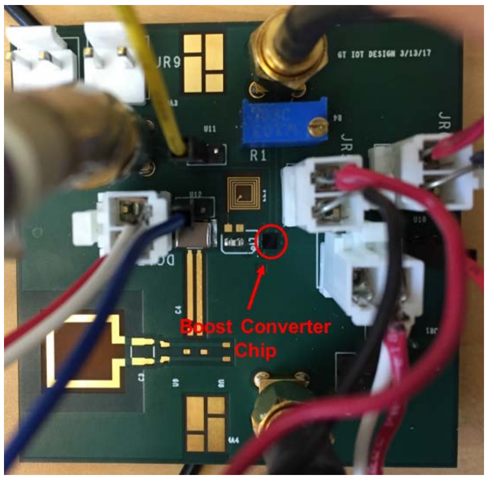
❑ 70mm Distance



- Efficiency ~ 1%
- Distance: 70mm
- ✓ RF Coils
- ✓ Matching Network
- ✓ PDN Network
- ✓ Charge Storage
- ✓ Boost Converter
- ✓ Power Inductor

Rigid Substrates





Author	Receive Element Type	Frequency	Receive Element Area	PMU	Load Power	Efficiency
This work	WPT Coil	1.025 GHz	100 mm^2	Yes	14 mW	51.1%
Nariman, 2017	Rectenna	60 GHz	.01 mm^2	No	1.22 mW	32.8%
Kuo, 2016	WPT Coil	4.7 GHz	.01 mm^2	No	0.1 mW	1%
Cabrera, 2016	WPT Coil	986 MHz	2.25 mm^2	Yes	73 µW	7.3%
Kim, 2015	Antenna	900 MHz	8100 mm^2	Yes	200 µW	20%

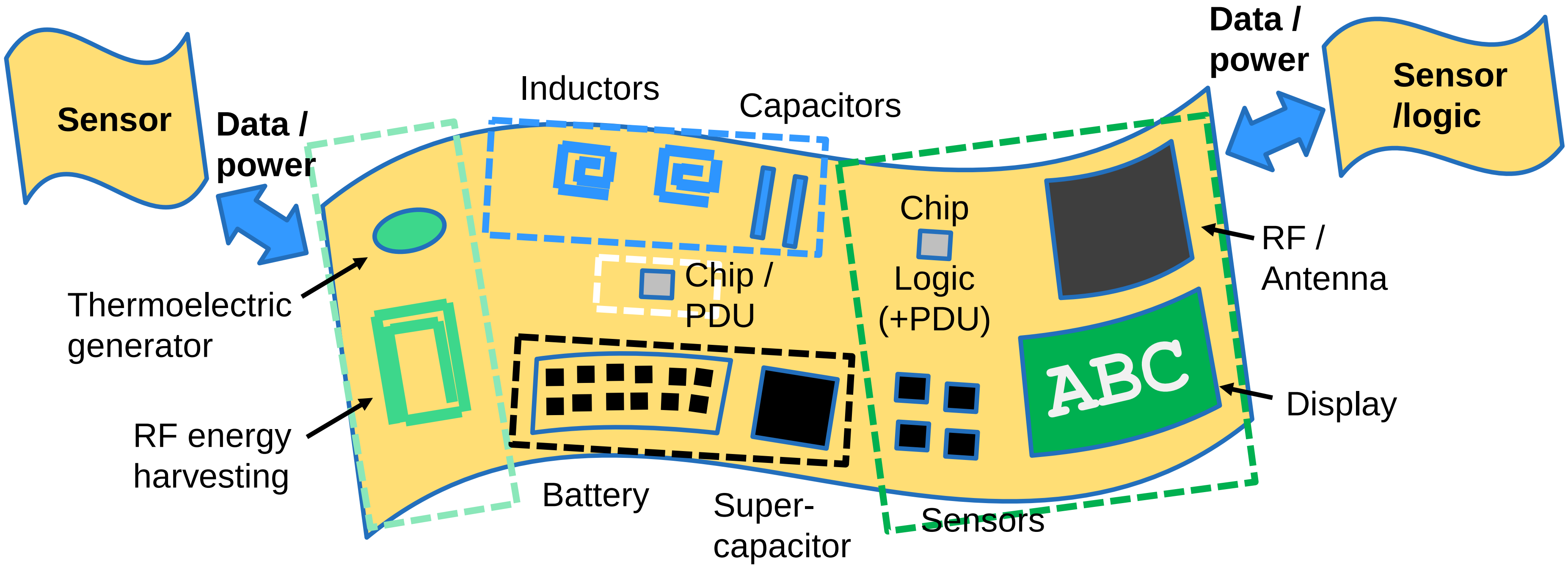
Courtesy: PDES Consortium, GT

- ❑ New buck converter based architecture for mixed signal load (2mm distance)
- ❑ Boost converter (Design: 60X conversion ratio with low bias current GF: 130nm)
- ❑ Power Delivery Efficiency: 41% – 51% (450Ω – 1500Ω variable load)
- ❑ Reverse Power Delivery Network (PDN) to maximize efficiency
- ❑ Integrated inductor (NiZn ferrite composite core) to increase inductance density
- ❑ ~1GHz & mW power transfer

Power Delivery – Flex Substrates

Integrate components that are:

- ❖ Cost effective
- ❖ Safe for human contact and usage
- ❖ Flexible



- ➢ RF Coils
- ➢ Thinned Silicon (Buck/Boost Converter)
- ➢ Embedded Super Capacitor
- ➢ Transmission lines
- ➢ Embedded Inductors
- ➢ Battery

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Multi-physics Modeling

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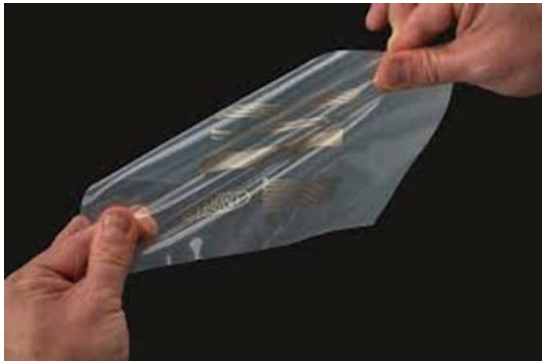
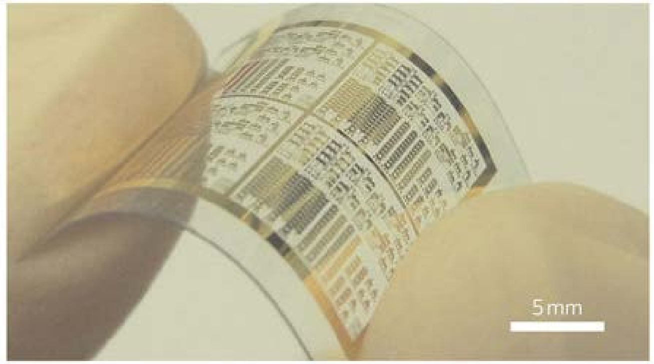
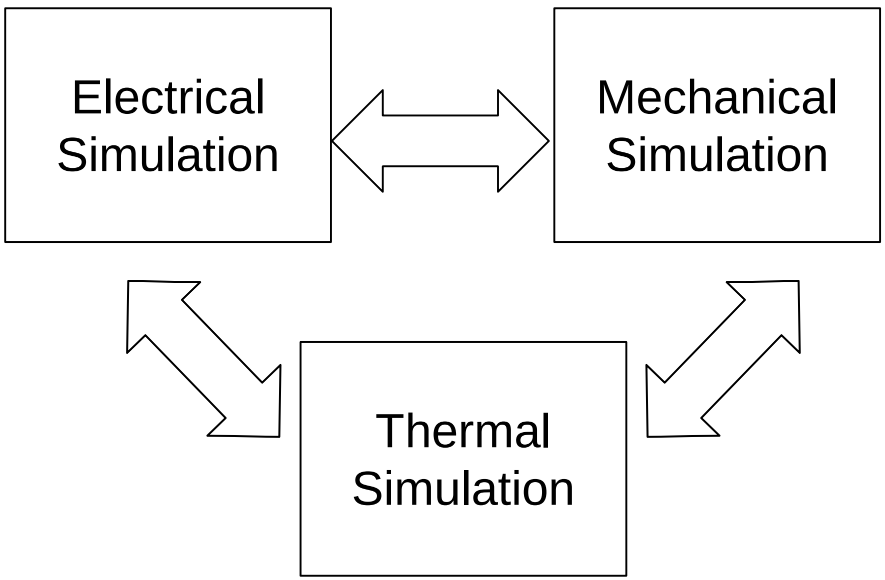
Stretching



Bending



Twisting



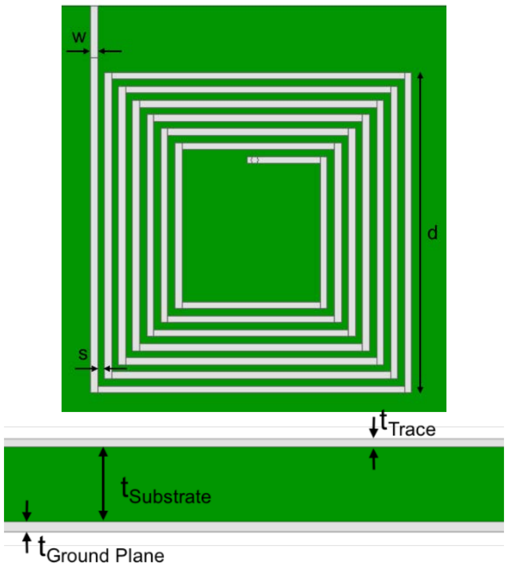
- ❑ Modeling operating conditions important
- ❑ Possible scenarios:
  - ▪ Mechanical loading changes electrical response due to geometry
  - ▪ Mechanical loading changes electrical properties

  ……
- ❑ How do you model the electrical response in such scenarios?
- ❑ Are the commercially available tools adequate?
- ❑ How complex are such simulations?

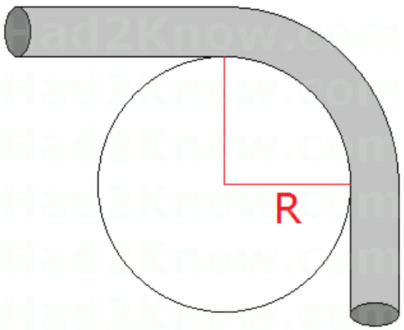
Inductors - Bending

- ❑ Substrate: Kapton Polyimide
- ❑ Conductor: PE 410 (Ag) & Cu (Etch)
    - Resistivity: 5 mΩ/□/25µm (PE410)
      1 mΩ/□/25µm (Cu)

Bending radius:
2 cm, 2.5 cm, 4 cm, 6 cm, 8 cm and flat

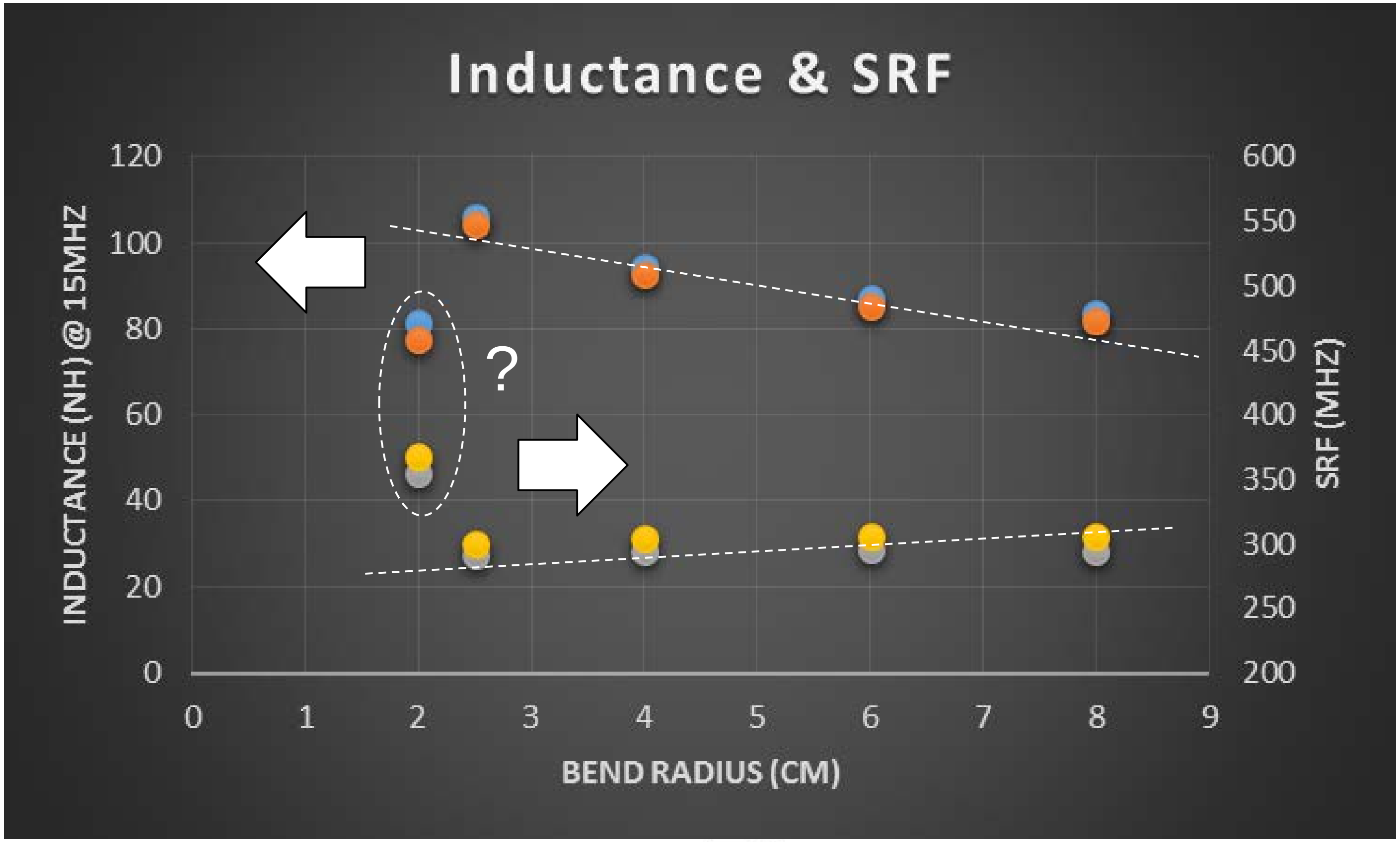


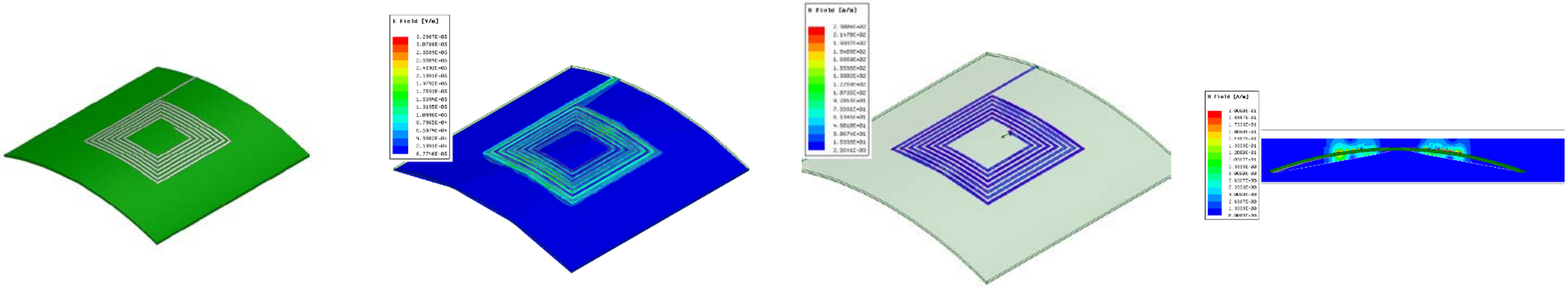
Dimension	Size (mm)
d	6.85
s	.15
$t_{Ground\ Plane}$	.018
$t_{Substrate}$	.125
t_{Trace}	.018
w	.15



- ❑ We will focus on the Electrical Response
    - ▪ Inductance, Q & SRF Vs Bend radius

Inductors – Bending





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Inductors – Bending (cont.)

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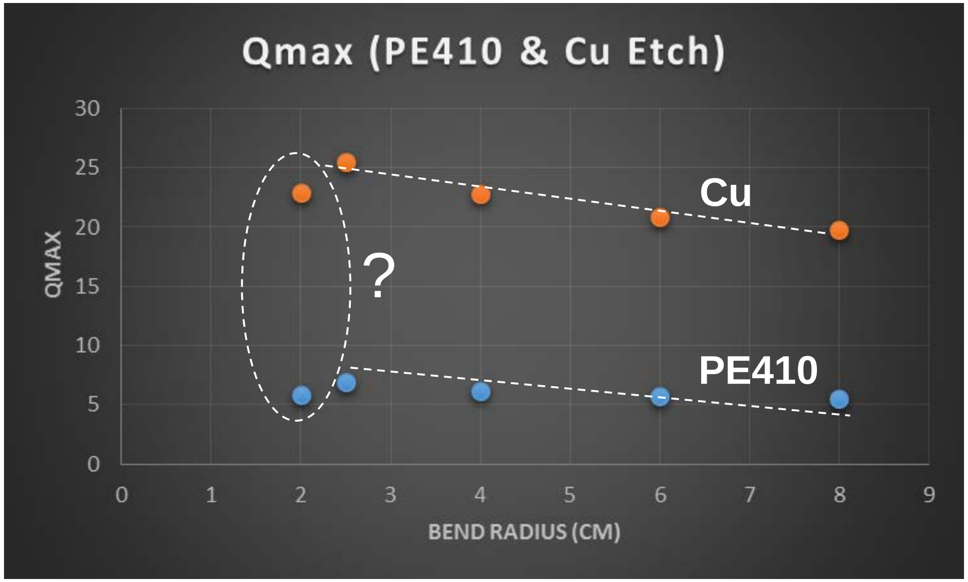

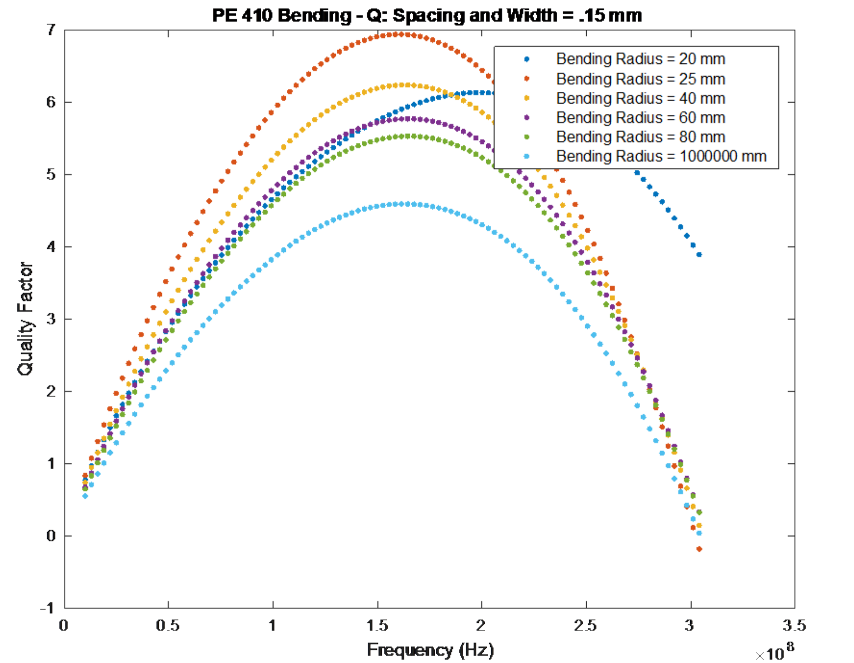

- 10% - 50% change in inductance due to bending (large)
- Q(PE410): 5 – 7; Q(Cu): 20 - 25
- 4X higher Q with Cu due to lower resistivity
- PE410 too lossy
- Monotonic reduction in L & Q with increasing radius (except 20mm radius)

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Inductors - Stretching

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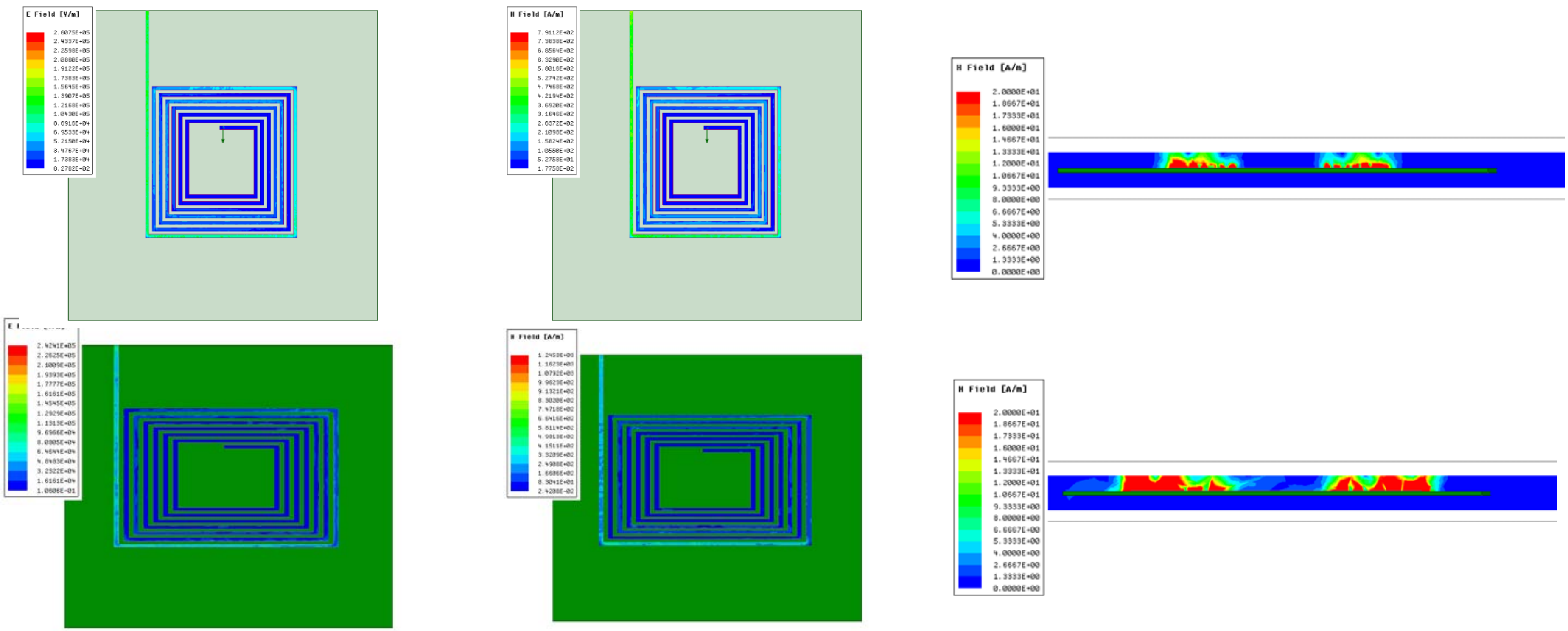
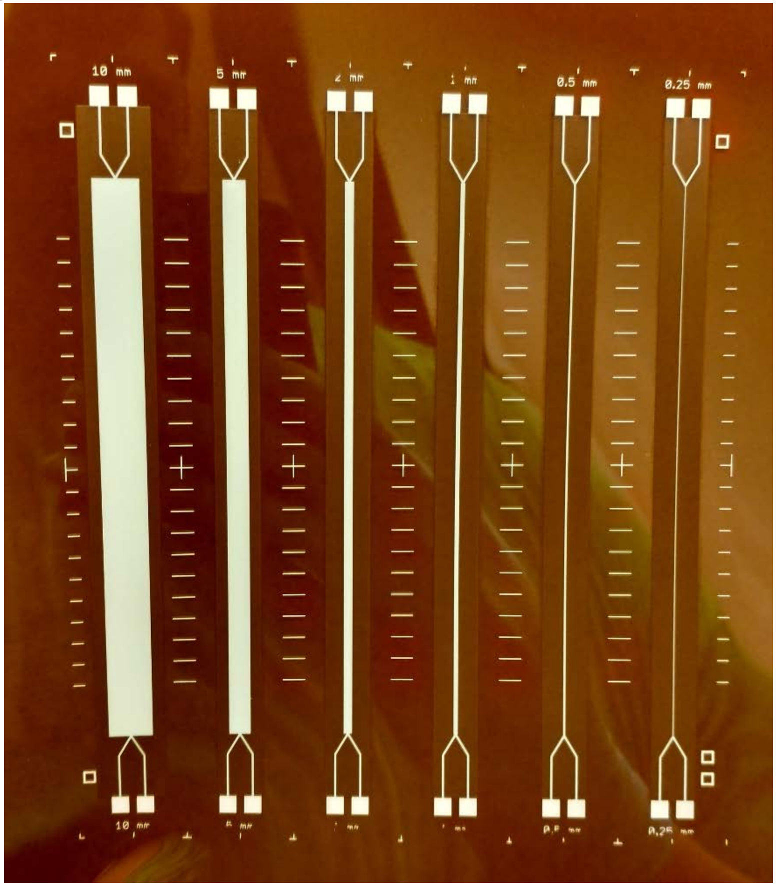
- ❑ Substrate: Kapton Polyimide
- ❑ Conductor: Screen Printed (SP) Ag-Flake
  - Resistivity: 15 mΩ/□/25µm
  - Trace Thickness: 12 µm to match empirical data

E-Field H-Field



- ❑ 0%, 5% & 10% Stretch

Inductors – Stretching (cont.)





<u>Approximate Thicknesses</u>

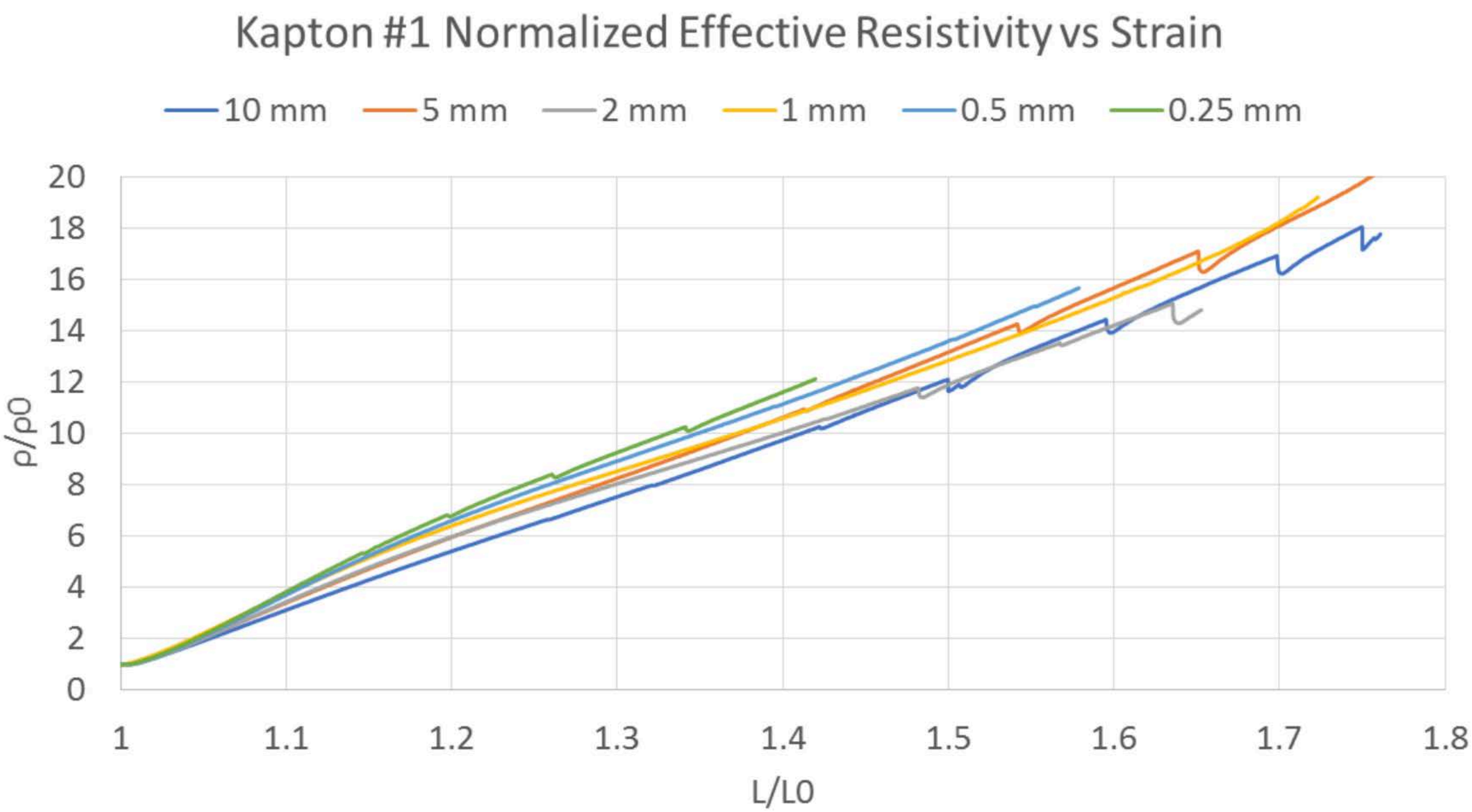
- Substrate: 128 µm (~5 mil)
- Ink: 12 µm
- Encapsulant: 26 µm

Courtesy: Prof. S. Sitaraman, GT

<u>Test Parameters</u>

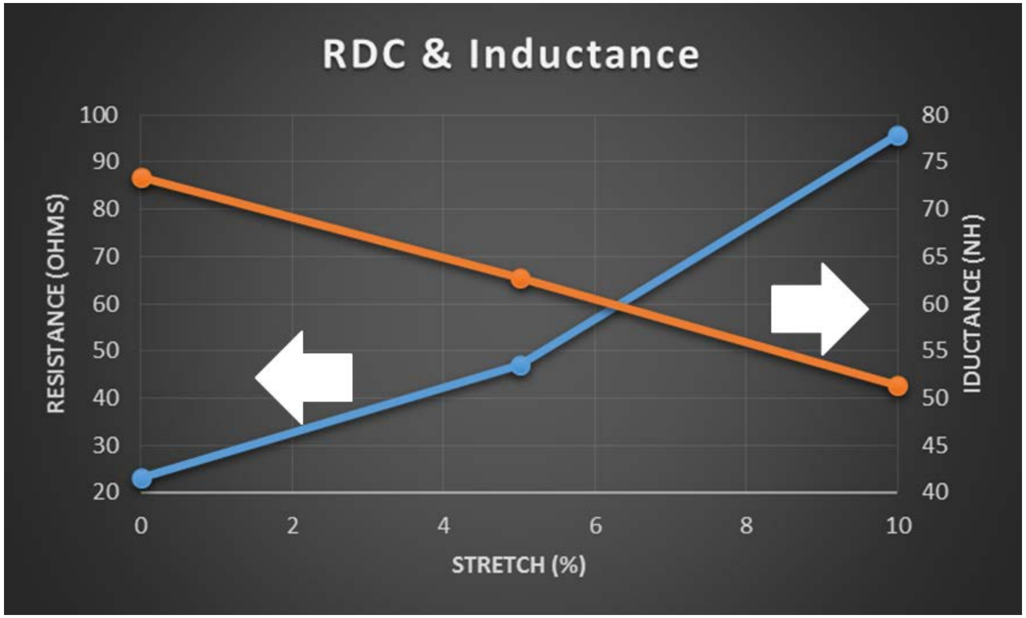
- Monotonic Tension until Break
- 4-Wire In-Situ Resistance Measurements
- Load Rate: 10 mm/min
- Initial Grip Separation: 100 mm
- Sample Width: 25 mm

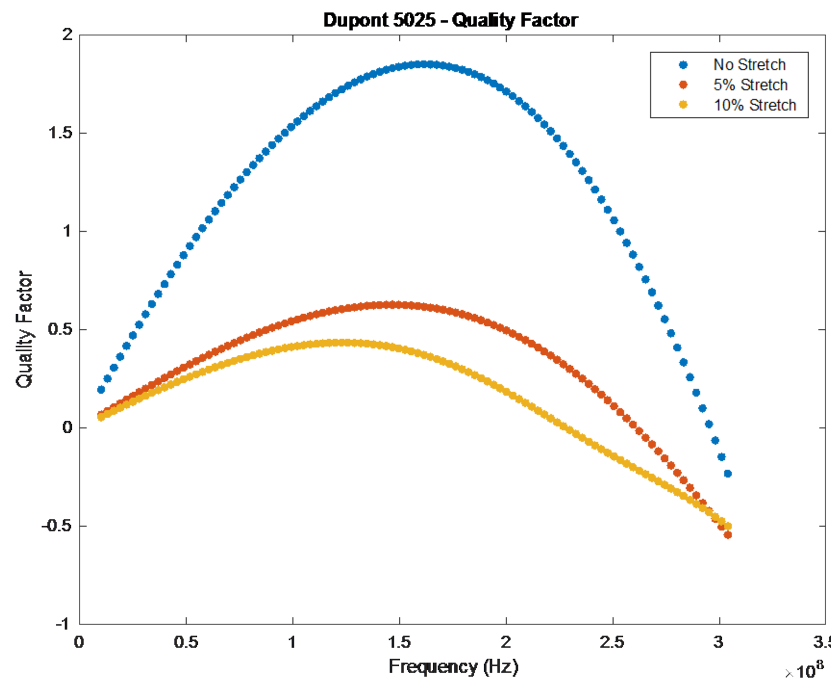
Resistivity Vs Stretching



- Effective resistivity changing with stretching

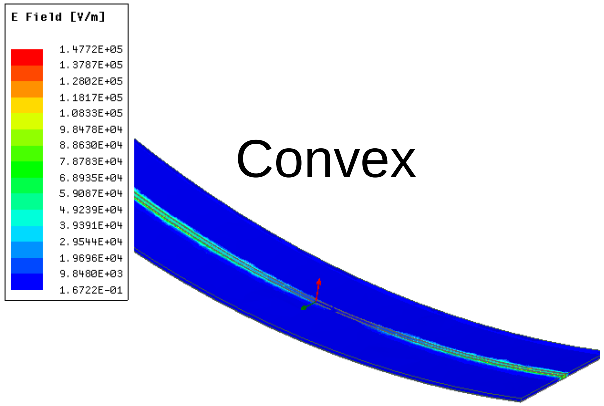
Electrical Results - Stretching

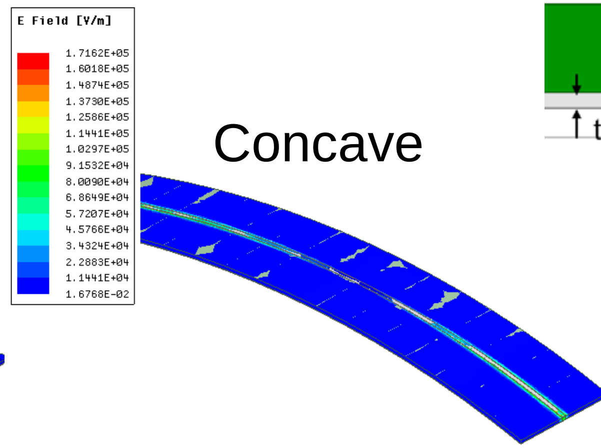


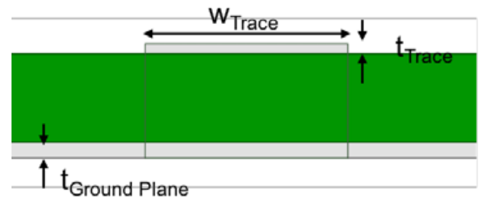


- ❑ Resistivity of Ag-Flake high
- ❑ Very resistive – 23Ω for 0% Stretch
- ❑ Resistance increases by 4X for 10% Stretch
- ❑ 30% reduction in inductance for 10% stretch
- ❑ Q decreases from 2 to 0.5 (4X) for 5% stretch
- ❑ Too lossy!

Transmission Lines - Bending

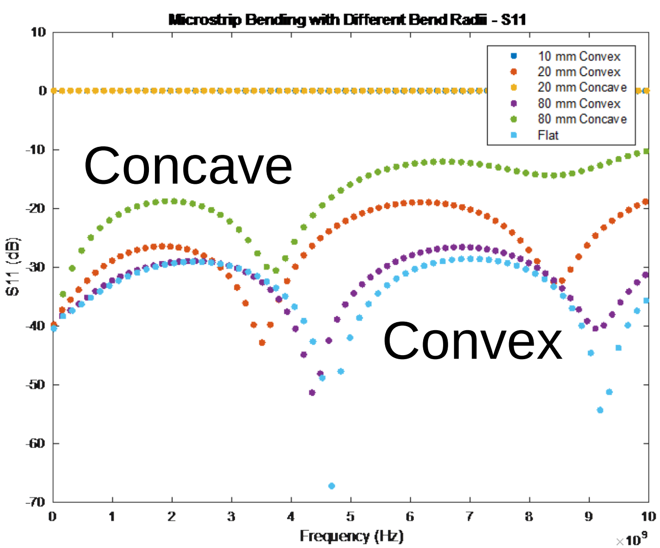


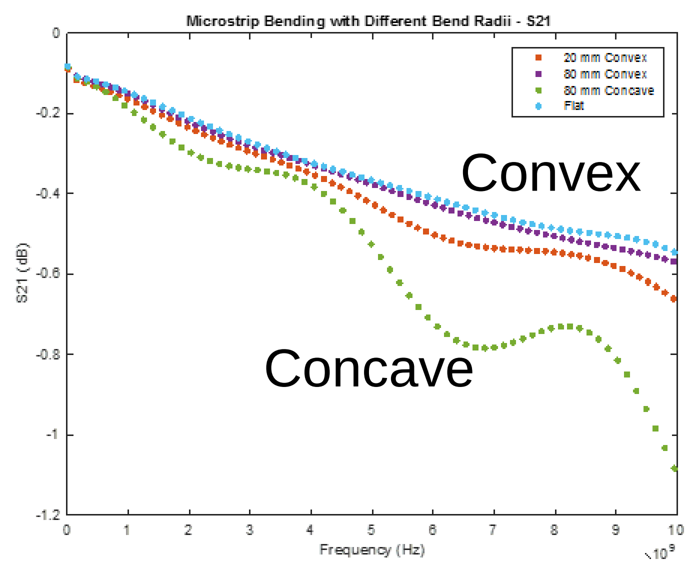




Dimension	Size (mm)
l	20
$t_{Ground\ Plane}$	.018
$t_{Substrate}$	.100
t_{Trace}	.012
$w_{Substrate}$	2.4
w_{Trace}	.23

- Substrate: Kapton Polyimide
- Conductor and Ground Plane: PE 410

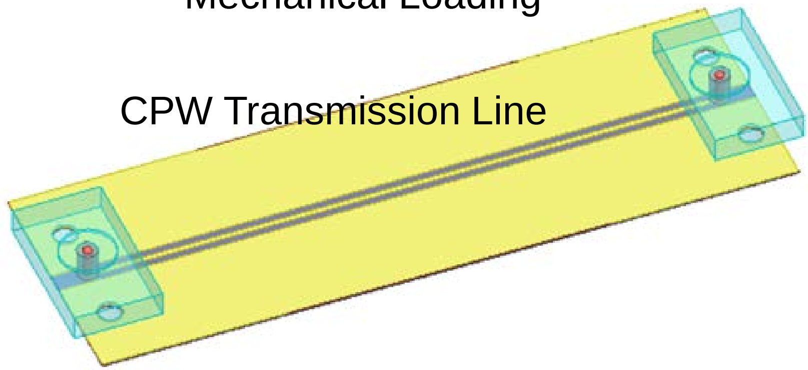




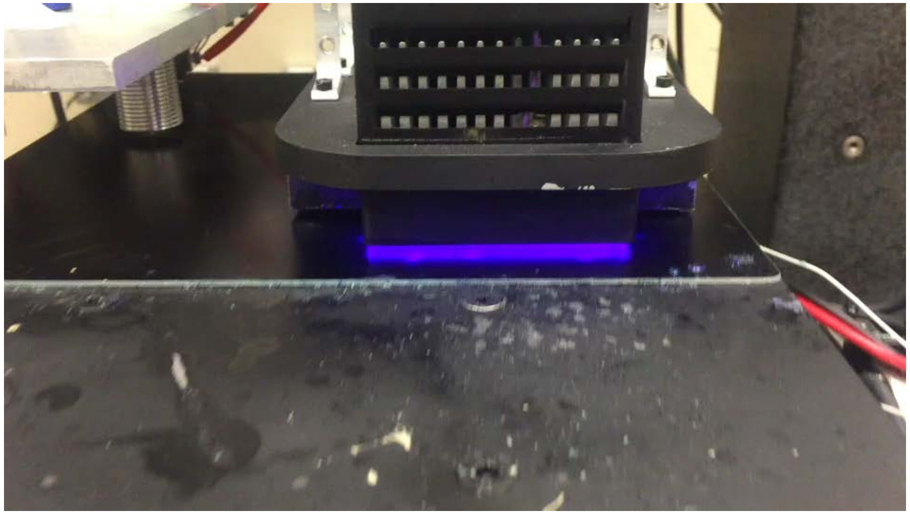
- ❑ Matching is worse for concave
- ❑ Counterintuitive!
- ❑ Need correlation with measurements

Fabrication & Characterization

Electrical Characterization under Mechanical Loading

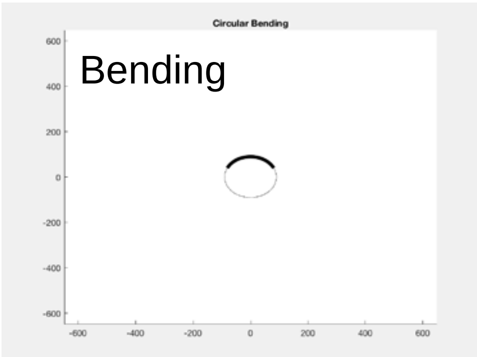


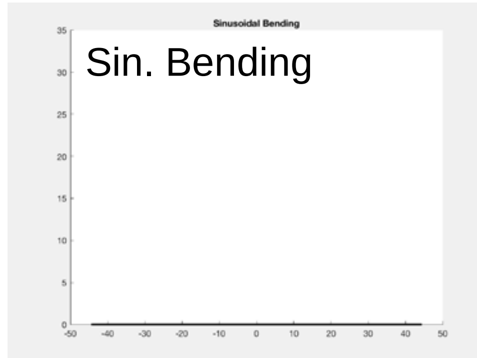
M[4] 3D Printing of a stretchable conductive stripe
Prof. J. Qi, GT

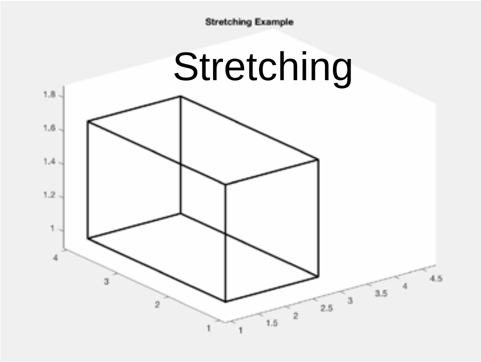


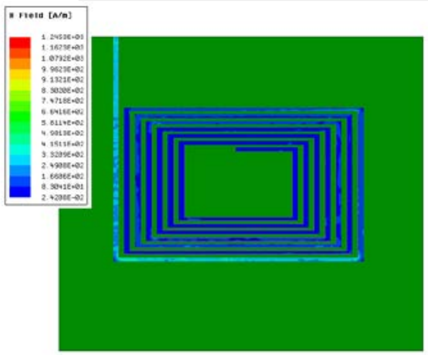
- Test Structures: Transmission line and Inductor Structures
- Substrates: Polyimide, PET, TPU
- Ink: Silver based inks
  - Screen Printed (SP) Ag-Flake
  - Aerosol Jet Printed (AJP) Nano-Ag
- Cu Etch
- Fabrication: GT & Dupont
- Test structures specially designed for electrical characterization with mechanical loading (Stretching & Bending)
- Correlate with models

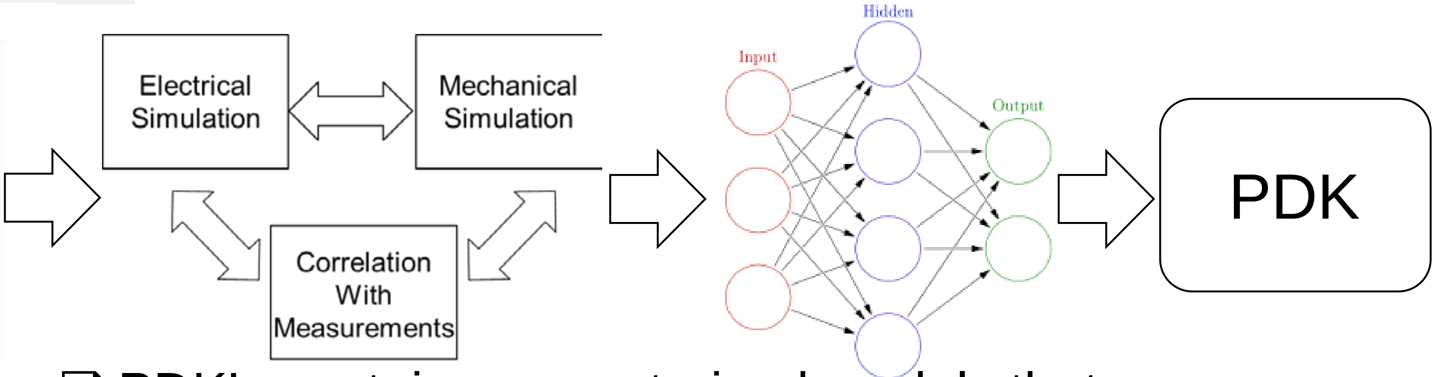
Process Design Kits

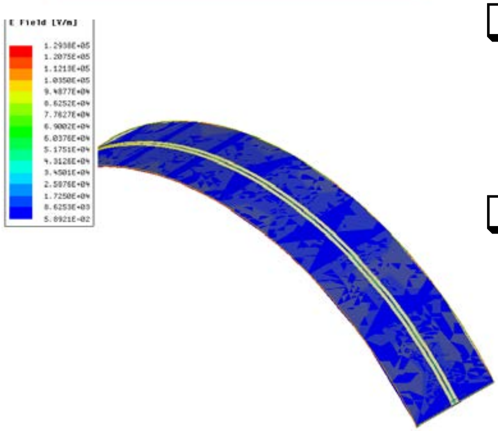






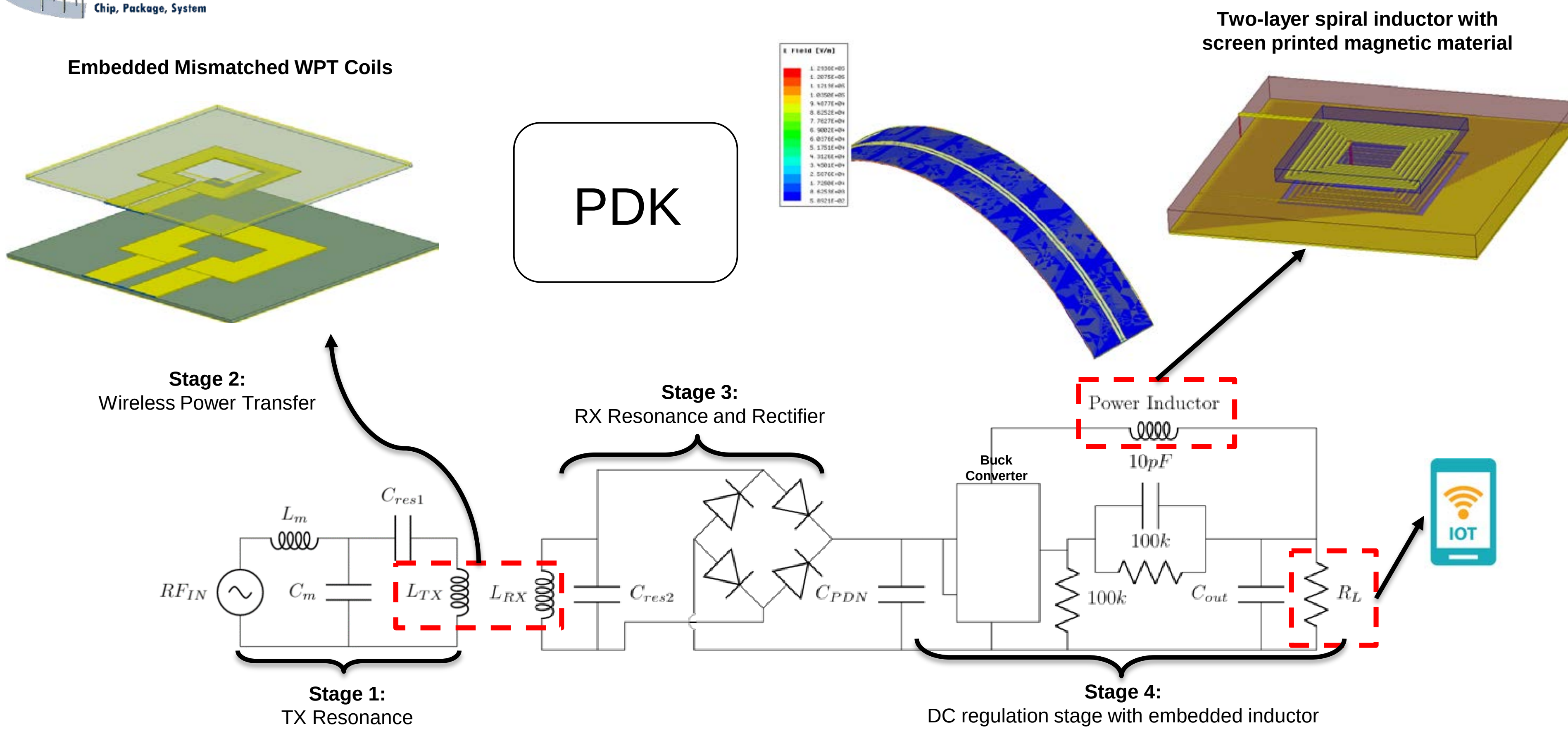






- ❑ PDK's contain parameterized models that:
  - Capture electrical – mechanical interactions, are well characterized & enable predictions
- ❑ Required for:
  - Automation
  - Miniaturization
  - High Volume Production

Machine Learning



Bayesian Optimization using ML

Courtesy: PDES & CAEML

- Eliminates hand tuning
- Can support tuning of 10 – 25 parameters simultaneously
- Can be used to reduce area and maximize efficiency
- Enables robust designs that work in the operating environment

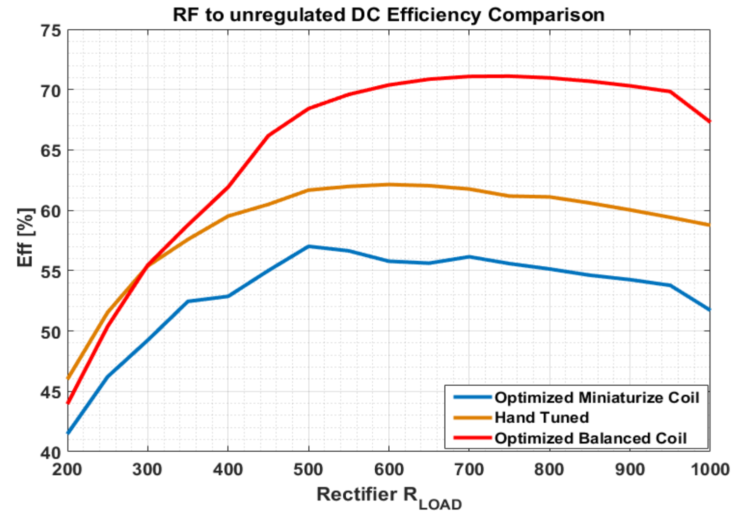
Machine Learning - Rigid

Tuning Parameters

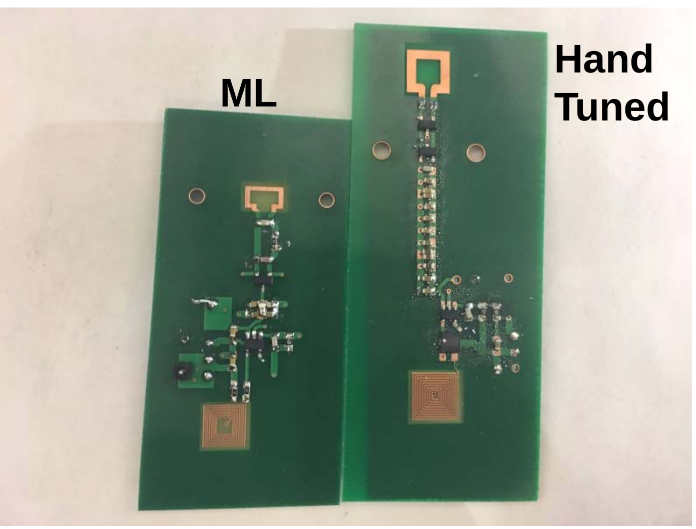
Stage 2: Wireless Power Transfer (12 Parameters)
TX & RX Horizontal Side Length
TX & RX Vertical Side Length
TX & RX Line Width
TX & RX Horizontal GND Cut-Out
TX & RX Vertical GND Cut-Out
TX & RX Feeding Gap

Stage 1 & 3: Rectifier Circuit (4 Parameters)
Matching Network
Resonance Capacitors

Stage 4: DC regulation with Two-Layer Embedded Spiral Inductor (5 Parameters)
Line Width
Side Length
Magnetic Material Thickness
Number of Turns
Spacing Between Turns



Courtesy: PDES Consortium



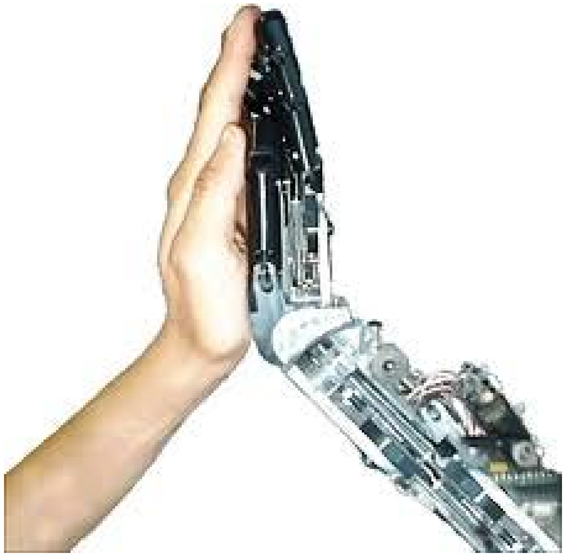
	Hand Tuned	Machine Learning
RF Coil Area	56.25 mm^2	20.1 mm^2
Inductor Area	56.25 mm^2	40.48 mm^2
System Efficiency	50.89%	58.14 %

Summary

- Power Delivery using FHE requires:
  - Embedded Coils
  - Flexible Batteries
  - Embedded Inductors
  - Embedded Capacitors
  - Thinned Chips
- Designs require models that capture electrical – mechanical interactions
  - Bending, Stretching, Twisting …
  - Predictive models
- Such interactions are difficult to capture in the available tools and often times the results are difficult to believe
- Calibrated models using measurements therefore required
- Parameterized models in Process Design Kits (PDK) can be very powerful since they support predictive capability
- Machine Learning can be a useful technique to populate PDKs and to enable reliable designs (works under operating conditions)

Thank you

Questions?



Discussions?

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