Microfabrication technologies for highly-laminated thick metallic cores and 3-D integrated windings

Florian Herrault

Georgia Institute of Technology
Atlanta, GA

florian@gatech.edu
http://mems.gatech.edu/msma

PowerSoc 2012 Workshop

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Outline

- Metallic cores for high-frequency magnetics
- Highly-laminated magnetic metal cores
  - Concept
  - Fabrication and material selection
  - Core material characterization
  - Core loss measurements at High Fluxes and High Frequency
- Integrated Toroidal Inductors
  - Co-packaging of windings and cores
  - Microfabricated winding technology
  - Impedance measurements
- High-voltage Power Converter Experiments
- Conclusions

Metal Core Inductors

- **Advantages of electroplated metallic alloys**
  - High saturation (High operating flux density → inductor miniaturization)
  - Low coercivity (Low loss)
  - Ability to electroplate in magnetic field to define easy/hard axis
  - CMOS compatible
  - Ability to electroplate thick cores (for large power handling)
- **BUT**
  - Operation in the 1-20 MHz region requires a few μm thick film lamination for conventional ferromagnetic metals (permalloy, CoNiFe, CoFe,…)

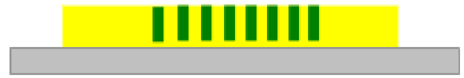
Our Approach and Goals – Magnetic Cores

- Technology-driven development of thick highly-laminated metallic alloys
- Demonstrate low eddy current losses in metallic alloys at MHz frequencies
- Operate these cores at very high fluxes and high frequencies
- Demonstrate high power handling
- Integrate cores and microfabricated windings

Previously-Reported Microfabricated Laminations

Electrodeposition of magnetic material

- Multiple deposition steps of seed layer
- Multiple photolithography for plating molds and insulators
- Overall core fabrication time is proportional to the number of layers



Electrodeposition of magnetic material

- One deposition of seed layer
- High-aspect-ratio plating mold is required for large cross-sectional core

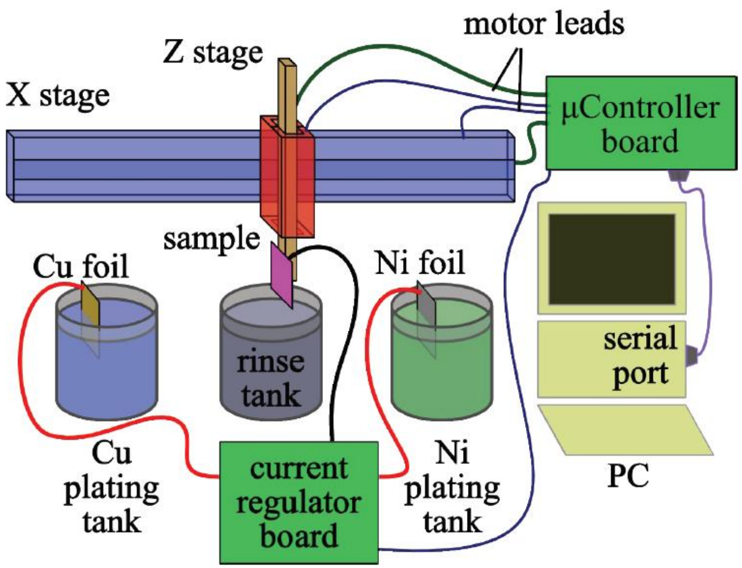
Sputter deposition of Magnetic material

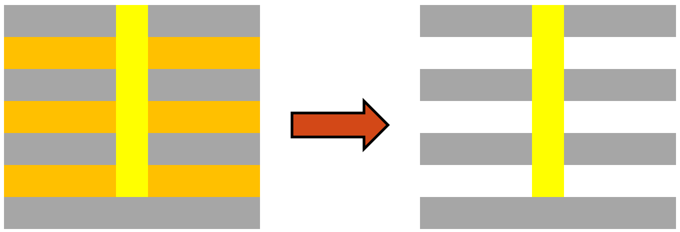
- Alternate sputtering of magnetic materials and insulation layers
- Single vacuum step
- Process time
- Some patterning complexity

Magnetic material

Insulation material

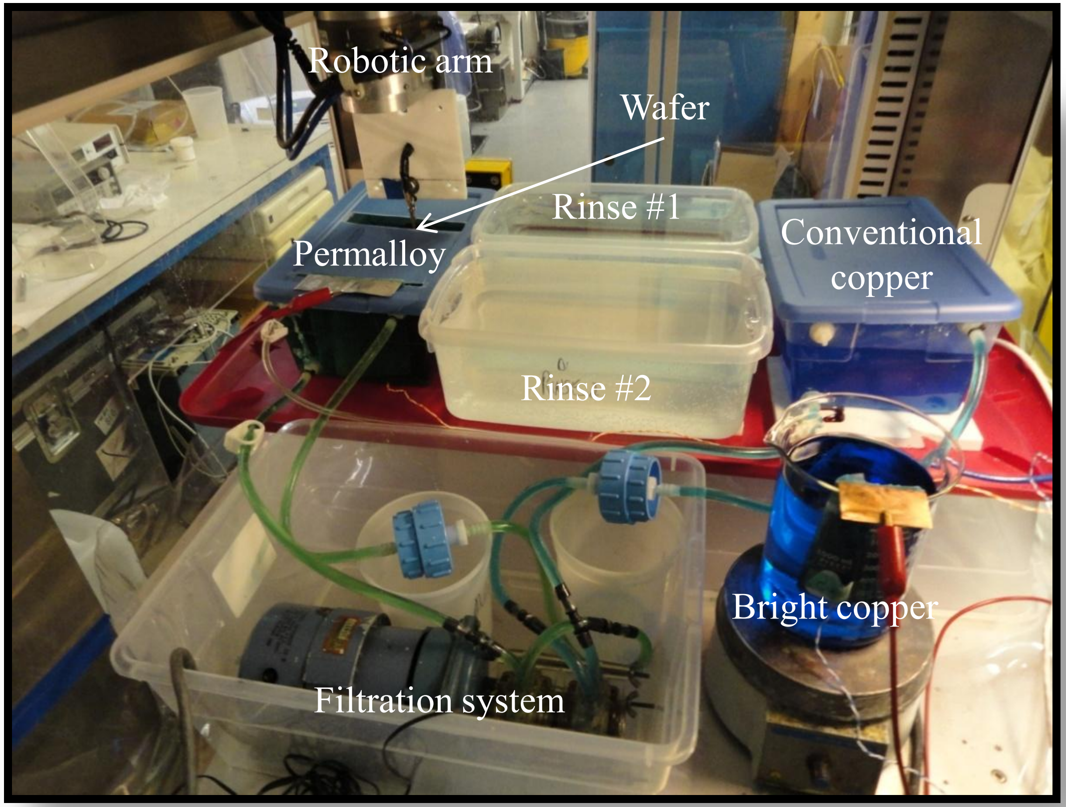
Micron-Scale Laminations via Robotically-Assisted Multilayer Plating





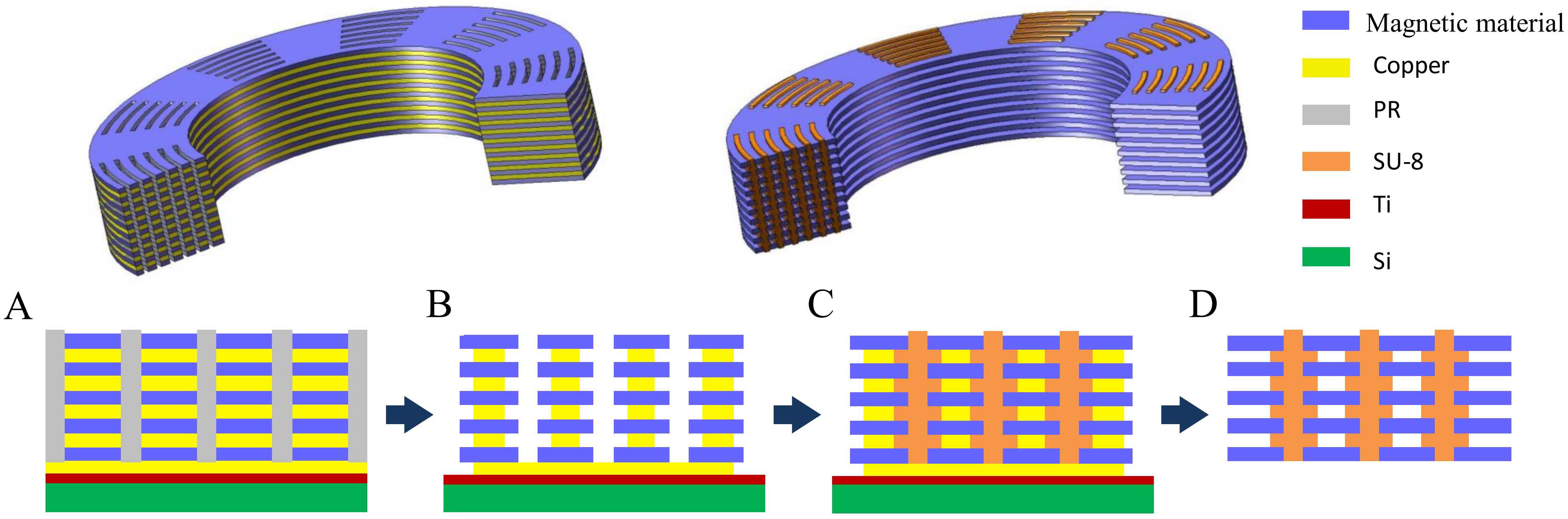
Multilayer plating through mold

Selective etching



"Electroplating-based approaches for volumetric nanomanufacturing," Tech. Dig. Technologies for Future Micro-Nano Manufacturing, Aug. 2011.

Core Fabrication Technology

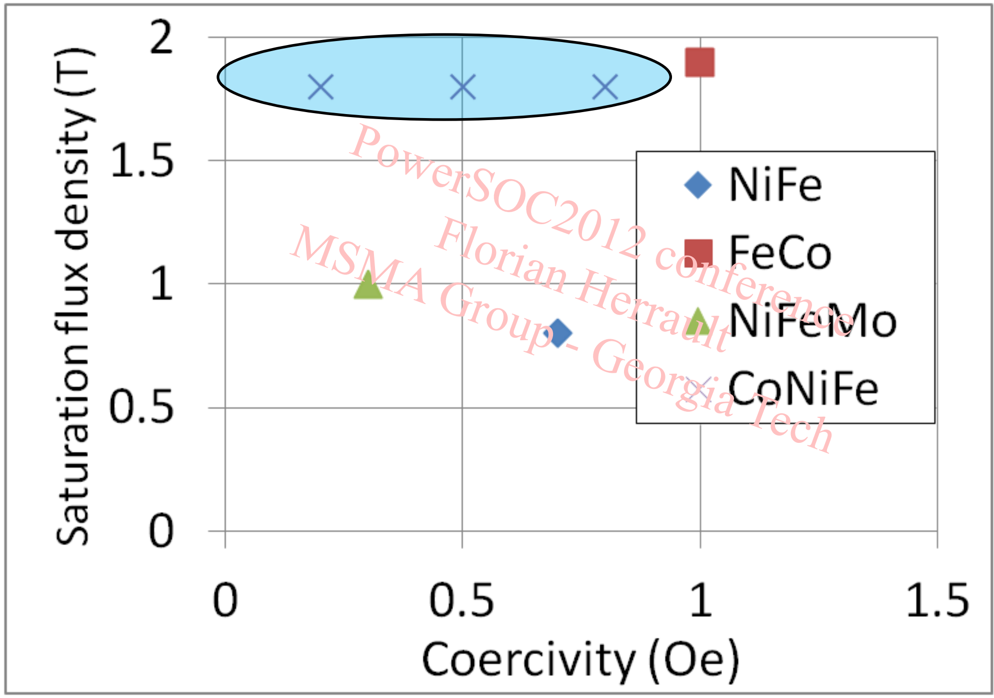


A. Through-mold sequential electroplating of magnetic/sacrificial layers
B. Mold removal, and partial etching of sacrificial material
C. Formation of polymer supports
D. Complete etching of sacrificial material
E. Polymer infiltration (not shown)

"Nanolaminated Permalloy Core for High-flux, High-frequency Ultracompact Power Conversion," TPES, in press.

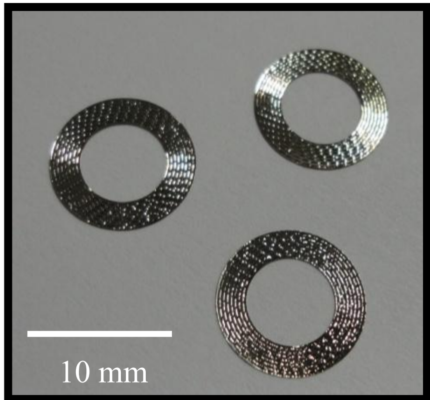
Magnetic Material Selection

- ***Baseline material ($Ni_{80}Fe_{20}$)***
  - » Bs ~ 0.8 T
  - » Hc ~ 0.7 Oe
- High saturation mat.($Fe_{10}Co_{90}$)
  - » Bs ~ 1.9 T
  - » Hc ~ 1 Oe
- Low coercivity mat. (NiFeMo)
  - » Bs ~ 1 T
  - » Hc ~ 0.3 Oe

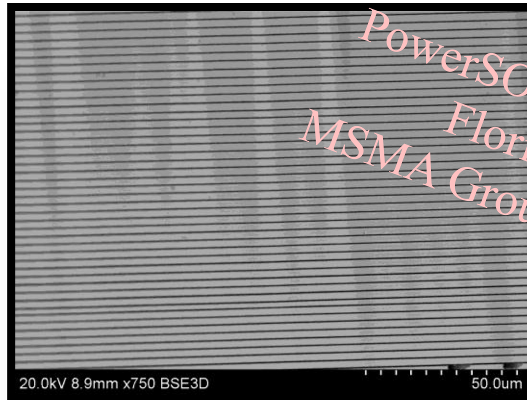


- ***Low coercivity and high saturation material (CoNiFe)***
  - » Bs ~1.8-2 T
  - » Hc ~ 0.2-1 Oe

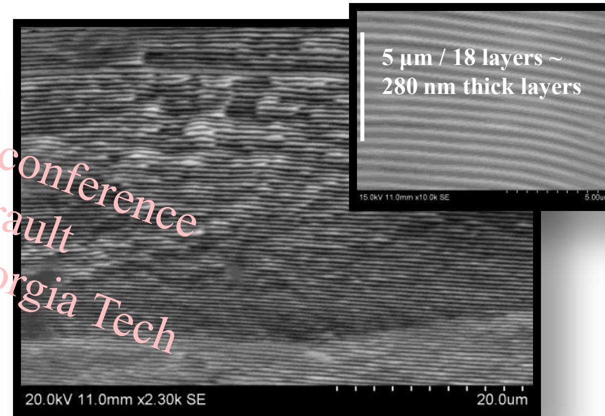
Highly-laminated Microfabricated Cores



*40-layer **permalloy cores** with 1-µm-thick laminations*

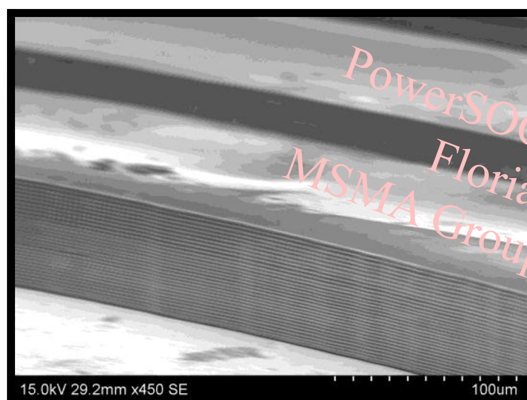


*Cross-sectional view: Thick (2 µm) **permalloy laminations** with thin (300nm) copper interlayers*



*Cross-sectional view: **300-nm-thick permalloy laminations** with 300-nm-tall interlayer gap **(300 layers)***

*40-layer **CoNiFe** core*



*40-layer **CoNiFe laminations** with lamination thickness ~ 1 µm*

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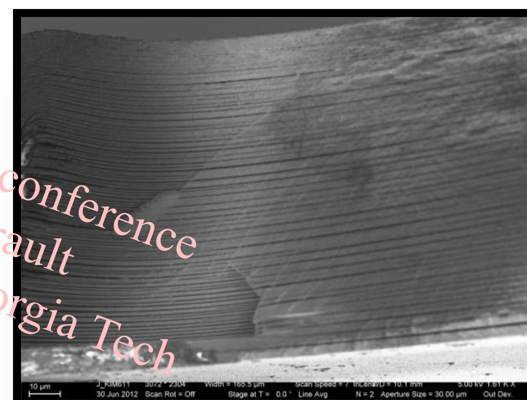


*300-layer **CoNiFe laminations** with lamination thickness < 0.3 µm*

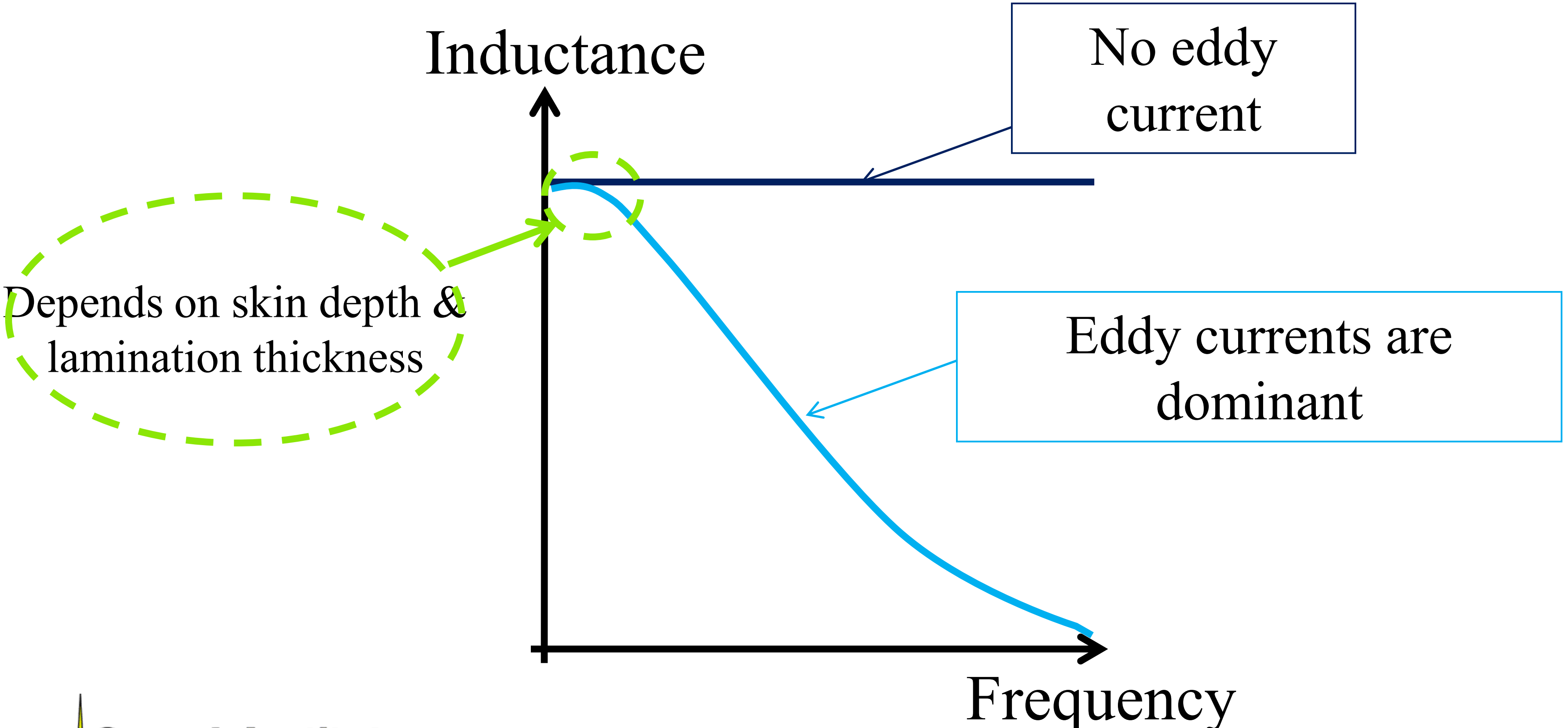
Wound Test Inductors

- Test Core Geometry
  - » OD:10mm, ID:6~8mm
- Packaged with test bobbins
  - » Characterization with high-power core loss measurement setup
- CoNiFe (1.8 T, < 1 Oe) vs. NiFe (0.8 T, 2 Oe)

Wound inductors with inductances > 1 μH using 7-strand litz wire

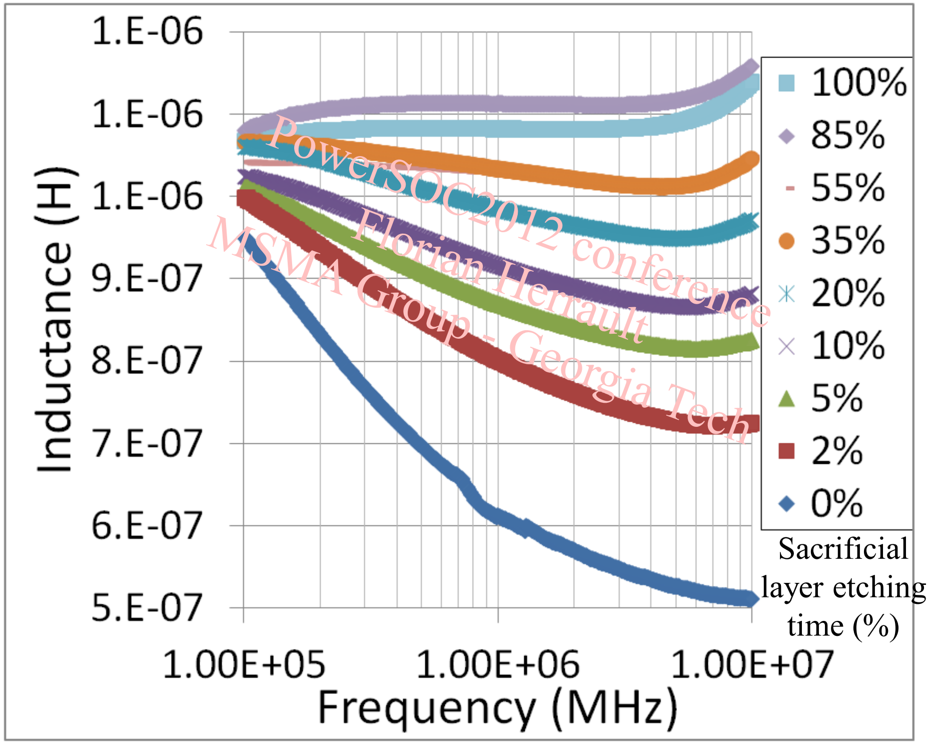
Manifestation of Eddy Currents in Inductors

Suppressed eddy currents in metal cores manifested by constant inductance as a function of frequency

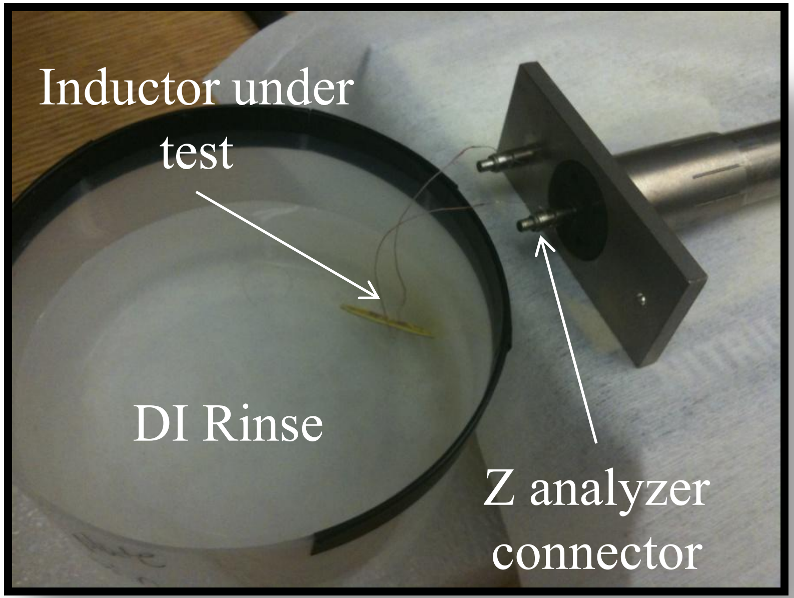


In-Situ Measurements of Sacrificial Metal Etching

- Inductors packaged and wound before copper core etch
- Constant-voltage measurements performed in DI water



Inductor inductance as a function of frequency parameterized by sacrificial layer etching time



In-situ core loss suppression experiment

"Nanolaminated Permalloy Core for High-flux, High-frequency Ultracompact Power Conversion," TPES, in press.

High-Frequency Inductance Measurements

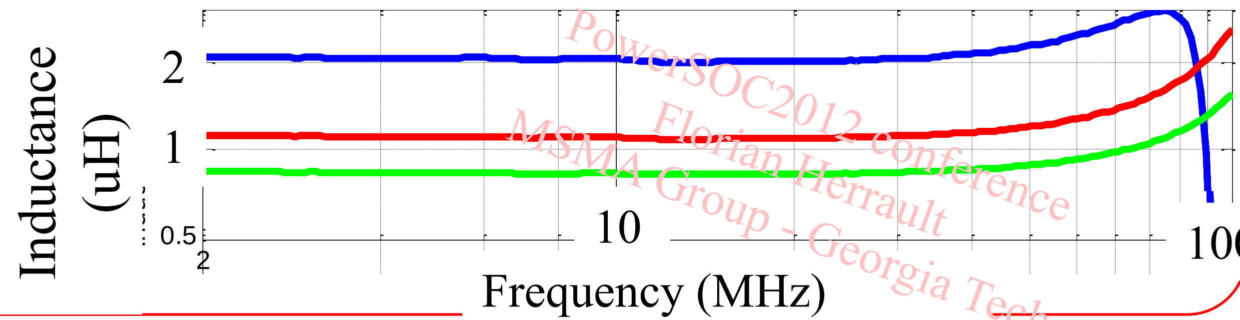
Inductors with ***permalloy*** cores

36-turn inductors

Blue: 0 bias current

Red: 0.5 A bias curent

Green: 0.95 A bias current



Inductors with ***CoNiFe*** cores

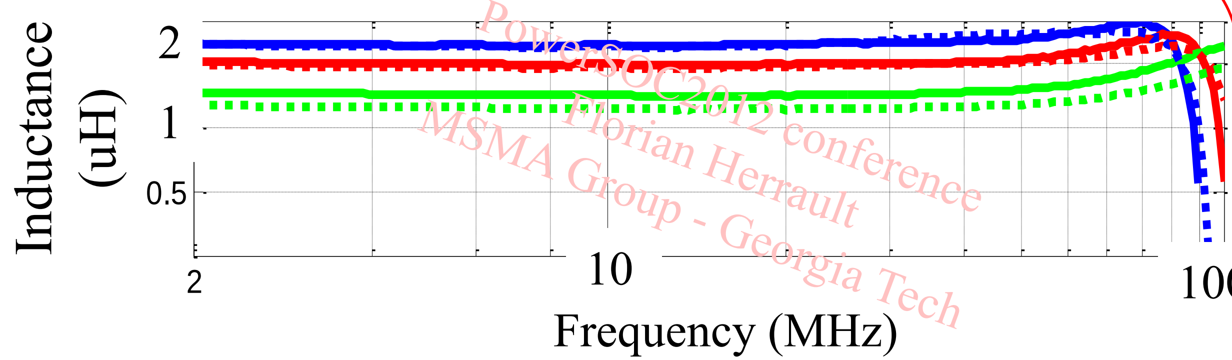
18-turn inductors

Solid lines: Inductor #1

Dotted lines: Inductor #2

300 core layers

0.3-0.5 nm thick layers



Blue: 0 bias current

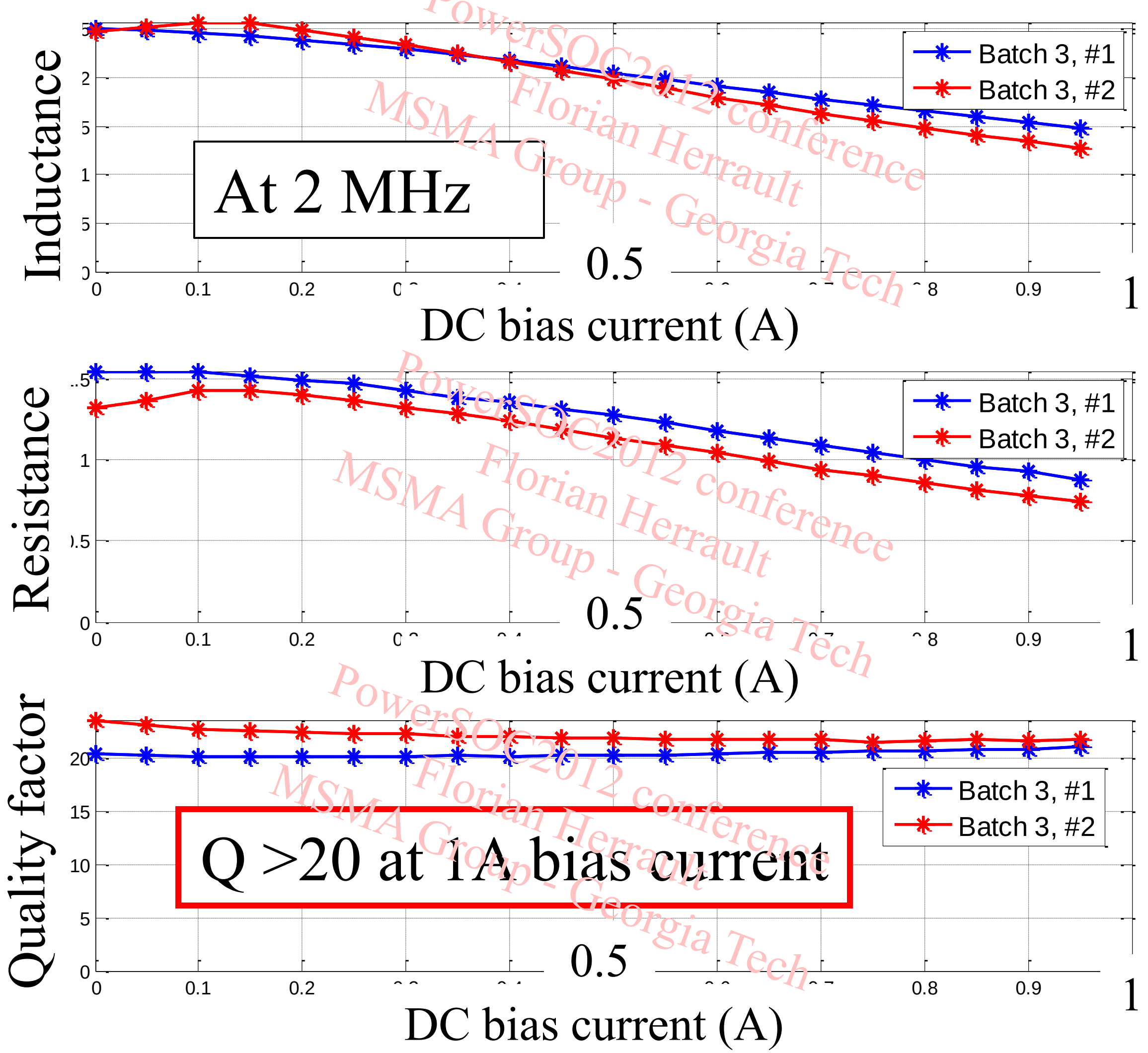
Red: 0.5 A bias curent

Green: 0.95 A bias current

CoNiFe Cores – Bias Current Measurements

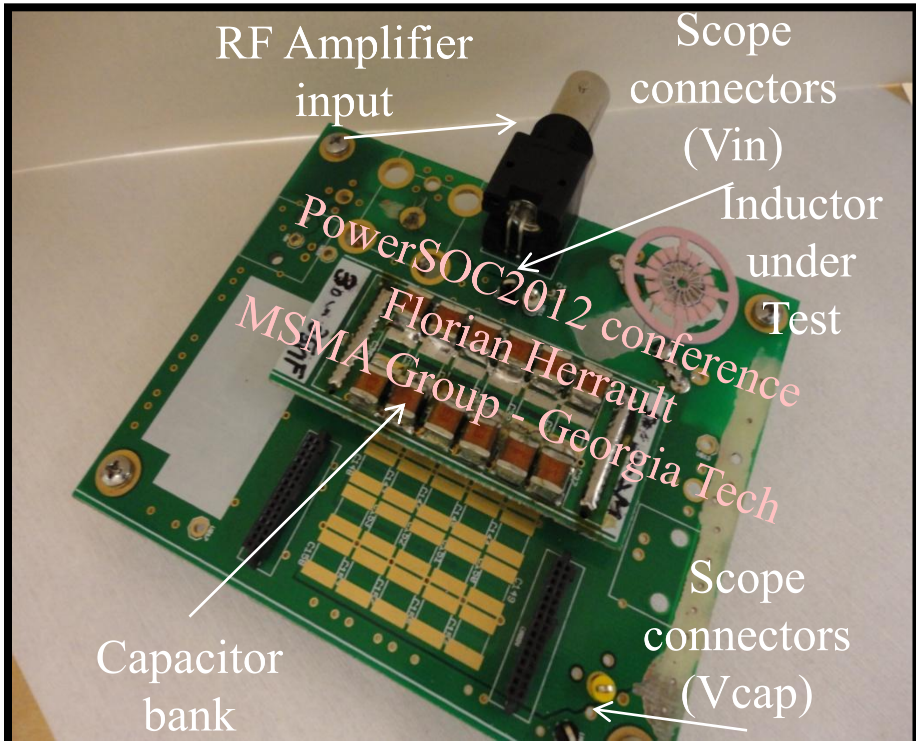
- 18 turn CoNiFe inductor
- 300 core layers
- 0.3-0.5 μm thick layers

	I_{sat} (A)		
	10% L drop	20% L drop	30% L drop
#1	0.35	0.55	0.75
#2	0.35	0.5	0.65

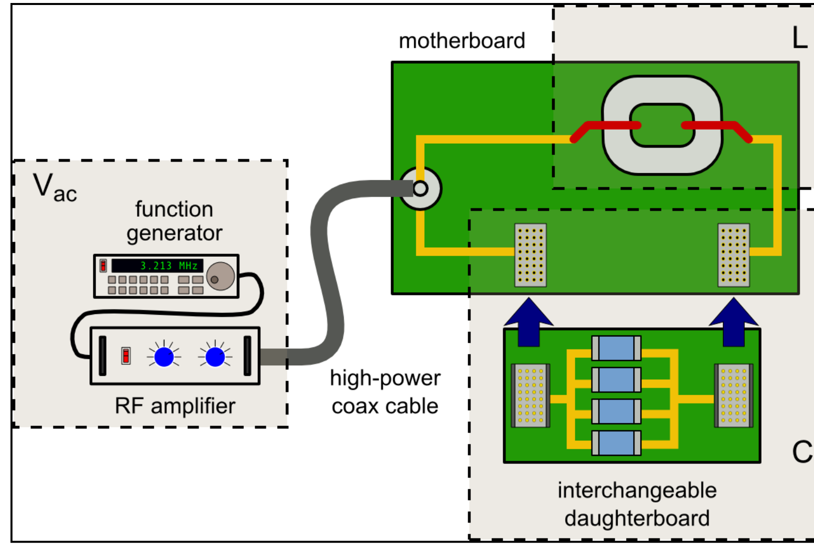


Impedance measurements under DC bias at 2 MHz

HFHF Characterization Setup

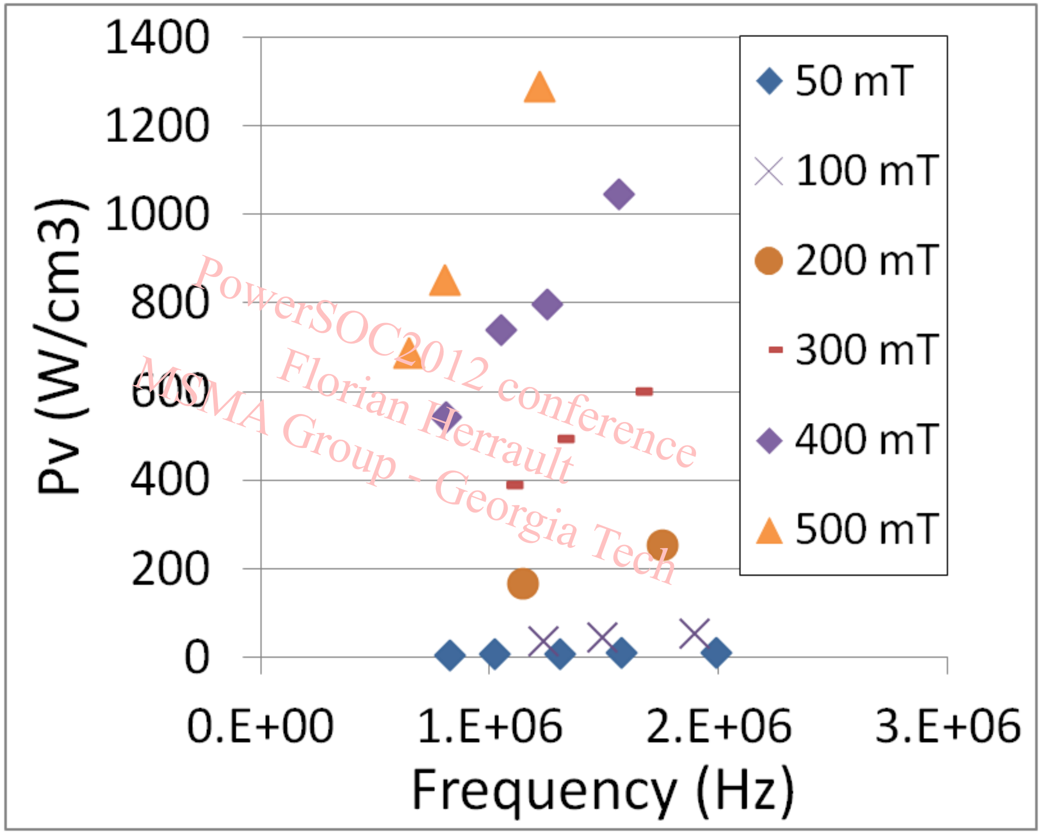


Inductor Core Loss Test Board with 35nF capacitor boards



Capacitor boards for frequency-dependent measurements

HFHF Core Loss Measurements



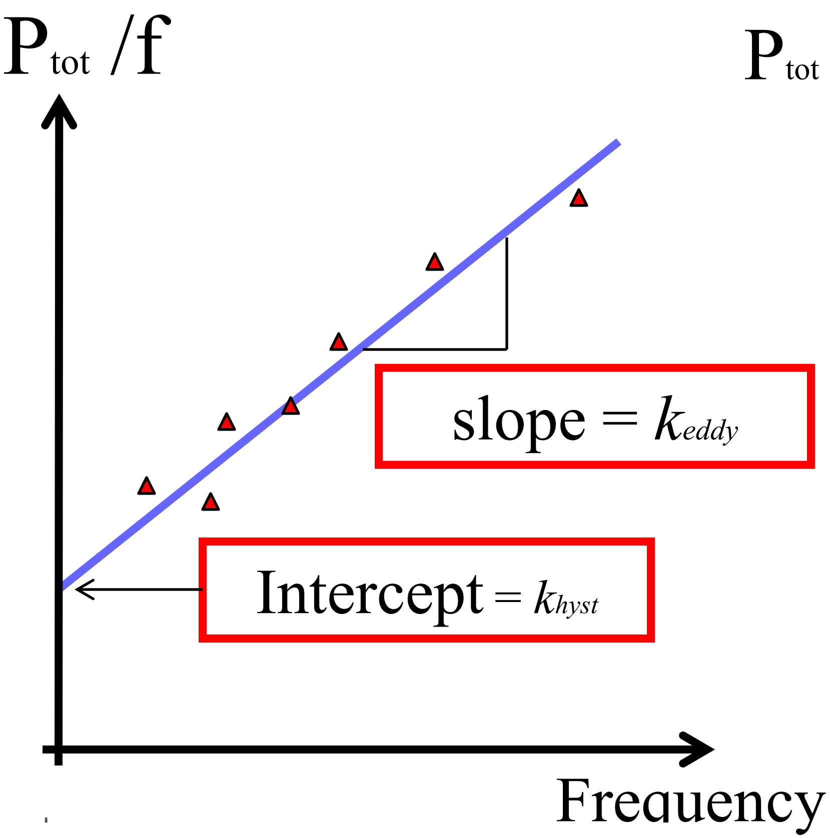
Dissipated power in the inductor as a function of frequency and parameterized by AC peak flux density

"Nanolaminated Permalloy Core for High-flux, High-frequency Ultracompact Power Conversion," TPES, in press.

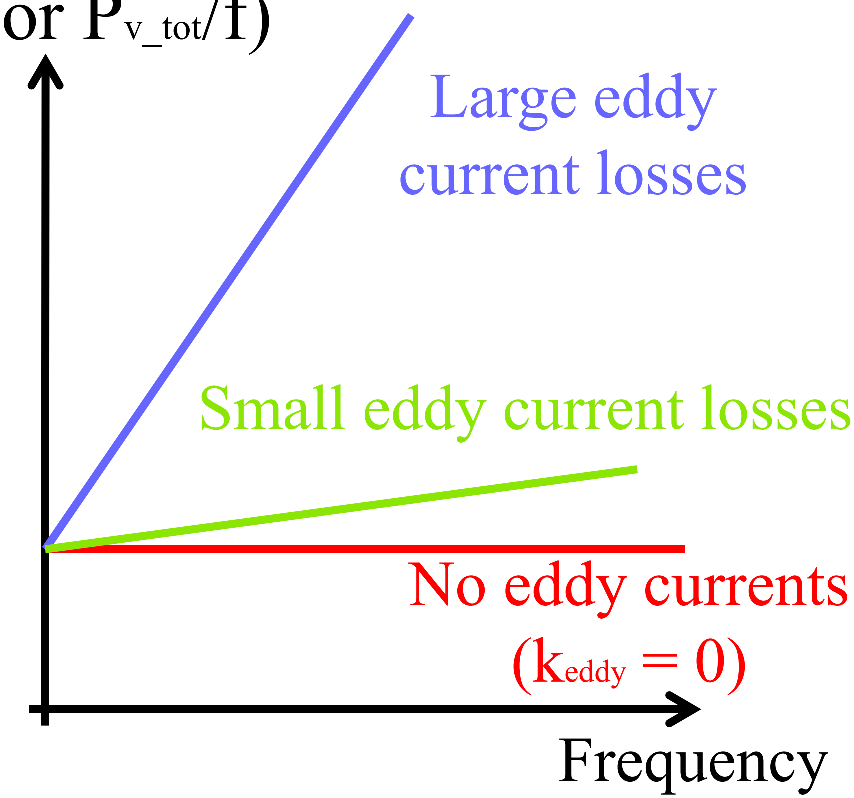
Analytical Separation of Eddy Current Losses

- Eddy current losses exhibit f^2 dependency
- Hysteresis losses exhibit f dependency

$$P_{tot} = P_{eddy} + P_{hyst} \quad \begin{cases} P_{tot} = k_{eddy} * f\,^\wedge 2 + k_{hyst} * f \\ \boxed{P_{tot} / f = k_{eddy} * f + k_{hyst}} \end{cases}$$

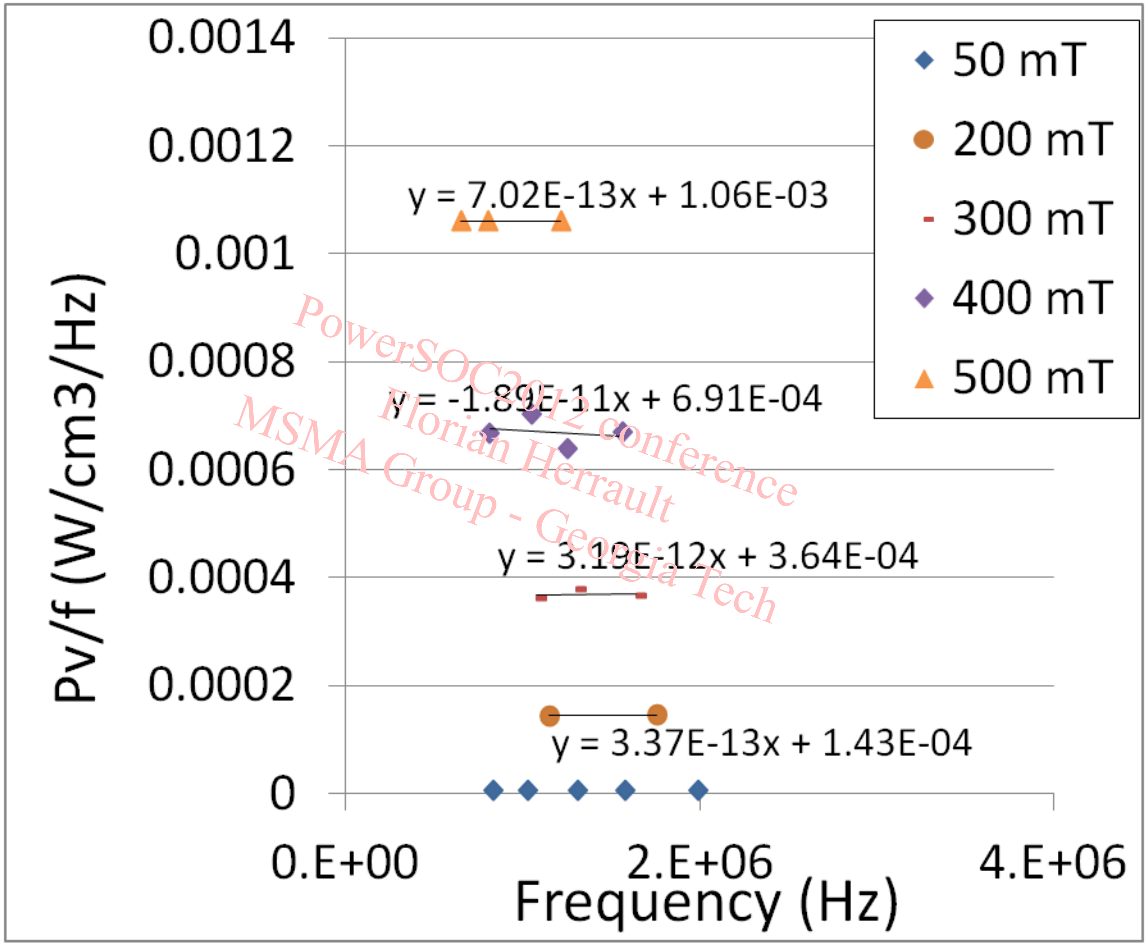


Analytical Extraction of Core Losses



Interpretation

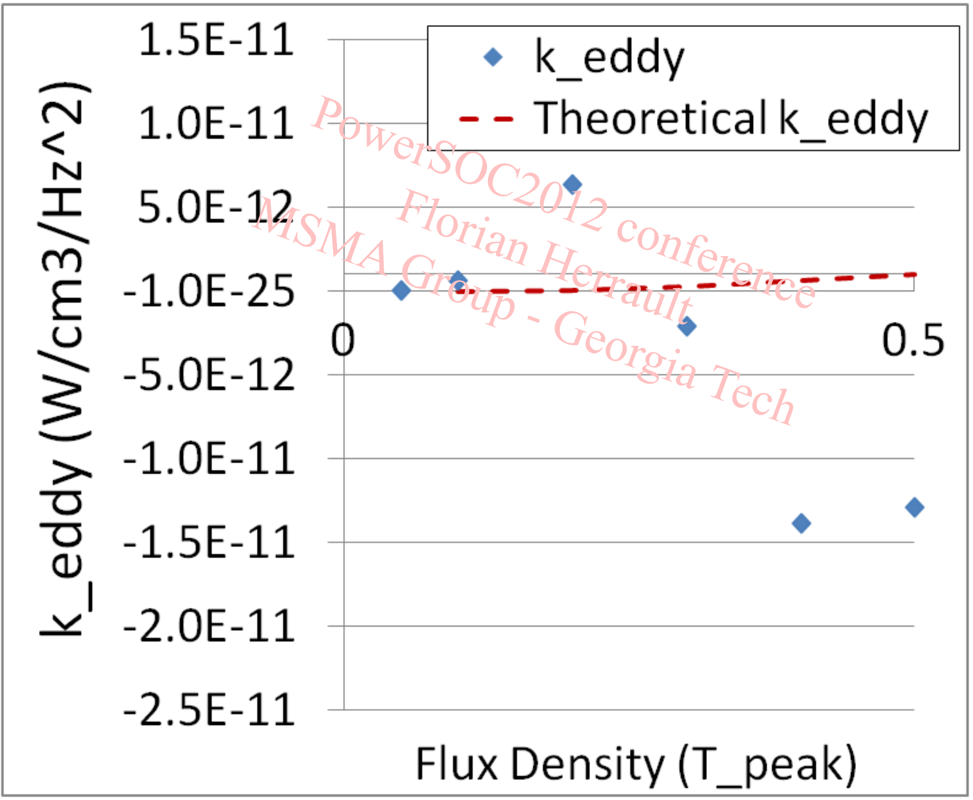
Post-Processed HFHF Core Loss Data

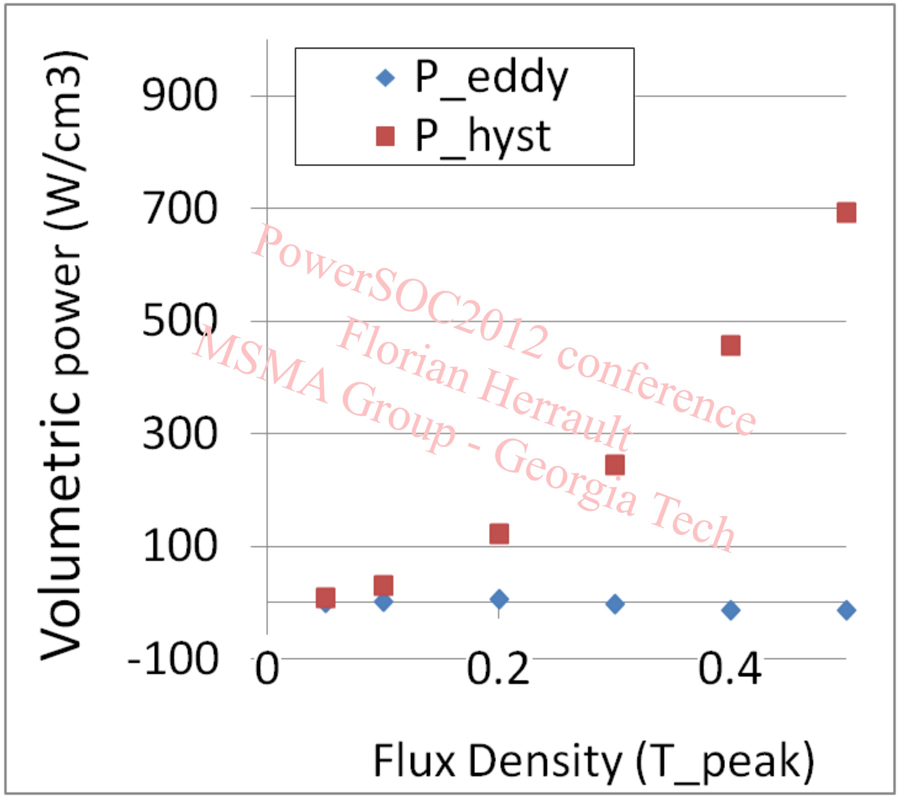


"Nanolaminated Permalloy Core for High-flux, High-frequency Ultracompact Power Conversion," TPES, in press.

High Flux NiFe Core Loss Distribution

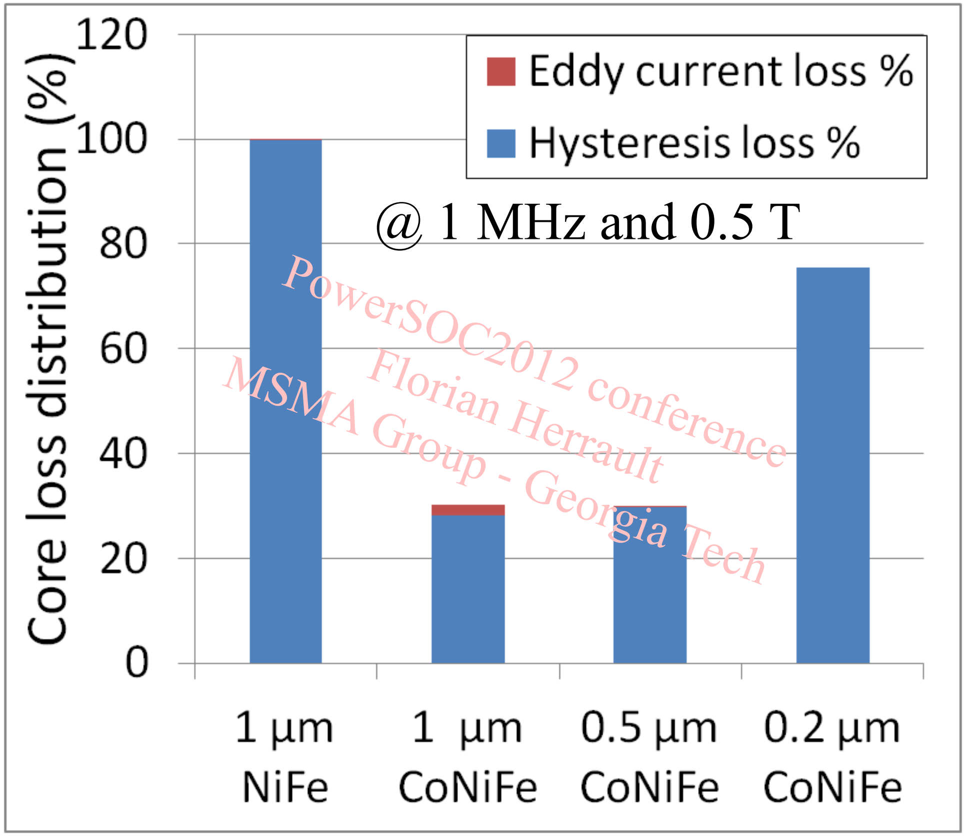
- Eddy and hysteresis losses extracted at 1 MHz as a function of flux
- At high fluxes, eddy losses have been suppressed and are negligible compared to hysteresis losses at 1 MHz





"Nanolaminated Permalloy Core for High-flux, High-frequency Ultracompact Power Conversion," TPES, in press.

Core Lamination Performance Summary



Comparison of core loss at 1 MHz and high operating AC peak flux density

Microfabricated Inductors with highly-laminated metallic cores

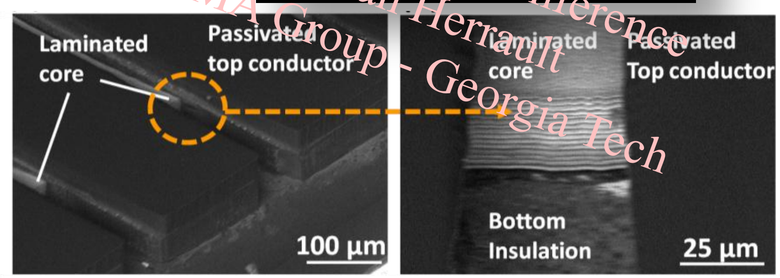
Hybrid integration process

Independently-fabricated magnetic cores are integrated halfway through the winding fabrication process

"Integrated Toroidal Inductors with Nanolaminated Metallic Magnetic Cores," Tech. Dig. PowerMEMS 2012 workshop.

Monolithic process

Co-fabrication of the windings and the cores through sequential micro-fabrication steps of electroplating and polymer insulation



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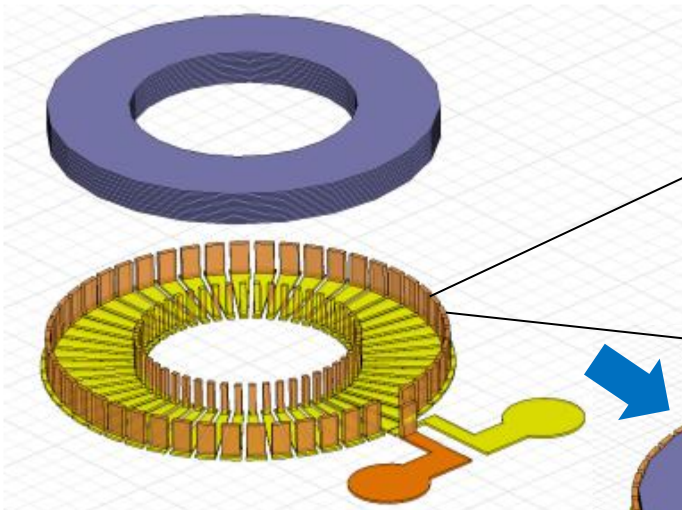
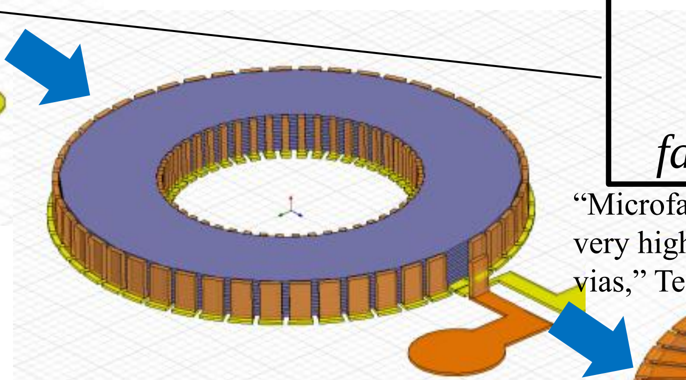
"Monolithically-fabricated laminated inductors with electrodeposited silver windings," Tech. Dig. MEMS 2013.

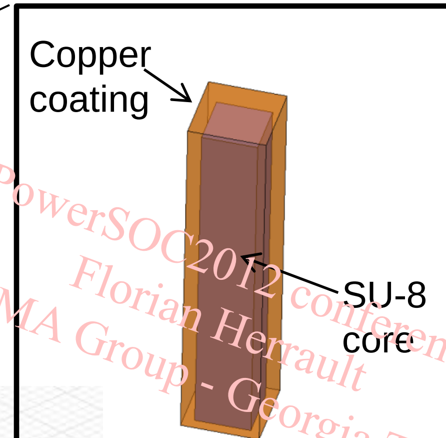
Hybrid Integration Concept Overview



Independent fabrication of cores and windings

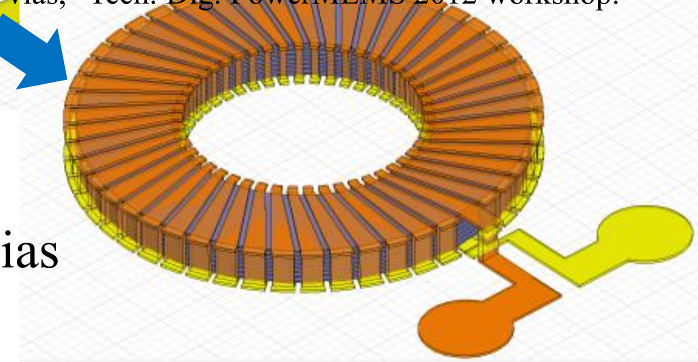


Drop-in pre-insulated core



Key winding fabrication concept

"Microfabrication of air-core toroidal inductor with very high aspect ratio metal-encapsulated polymer vias," Tech. Dig. PowerMEMS 2012 workshop.



Microfabrication of top copper windings

- High-aspect-ratio copper-coated polymer vertical vias
- Insulated cores dropped into the winding frame
- Top winding fabricated core integration

Microfabricated Inductors

- 50-turn microfabricated inductors (non-optimized geometry)
- New generation of integrated cores with CoNiFe layers
- Microfabricated conductor heights ~ 0.5 mm

Partially-fabricated windings on a glass substrate

Batch of dropped-in cores

Fully-fabricated inductor

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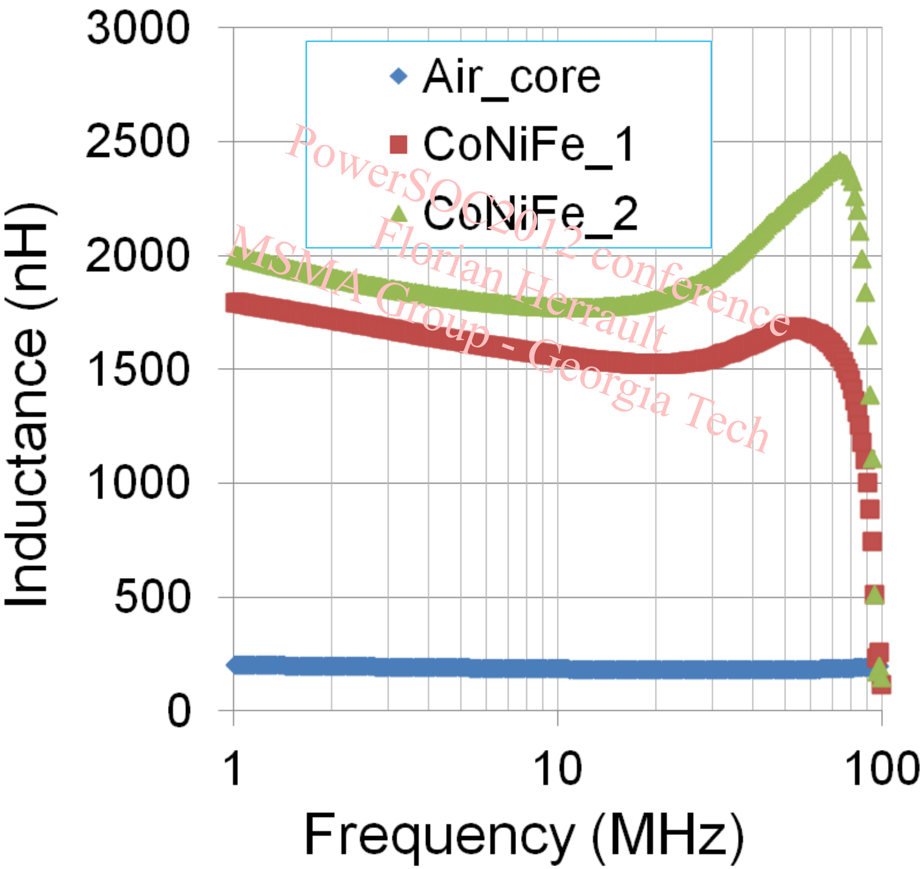
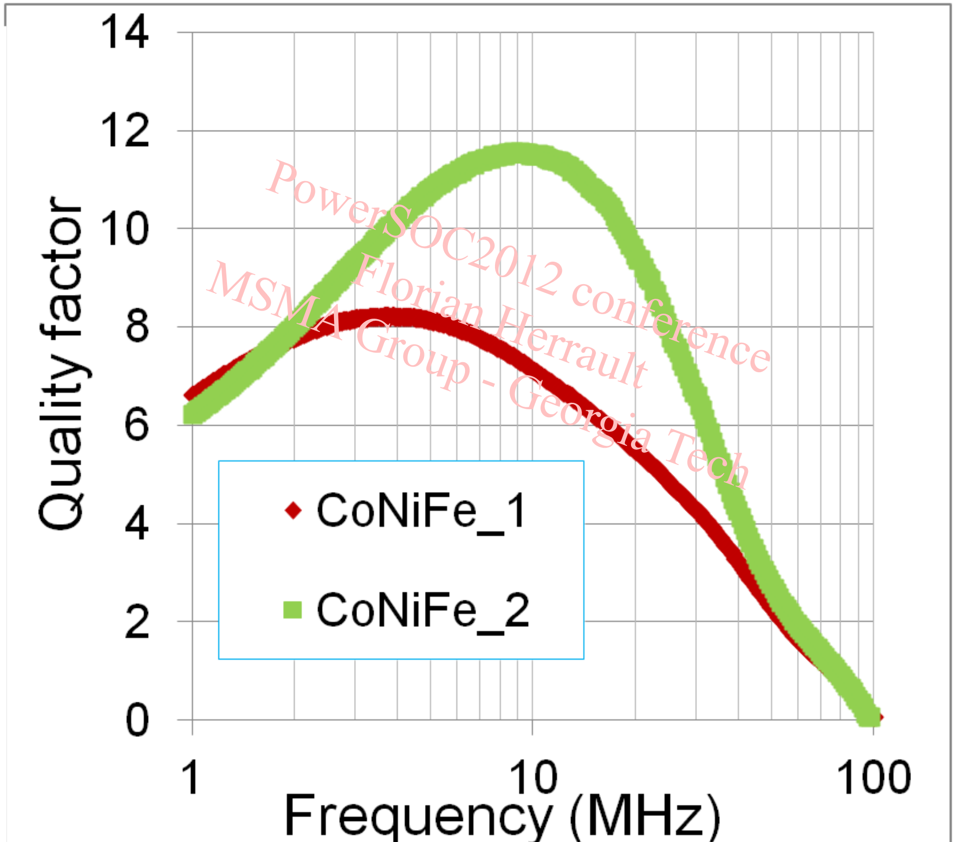
"Integrated Toroidal Inductors with Nanolaminated Metallic Magnetic Cores," Tech. Dig. PowerMEMS 2012 workshop.

Impedance Measurements of Microfabricated Inductors

- 50-turn microfabricated inductors with CoNiFe cores
- 100 layers – 300 nm thick layers



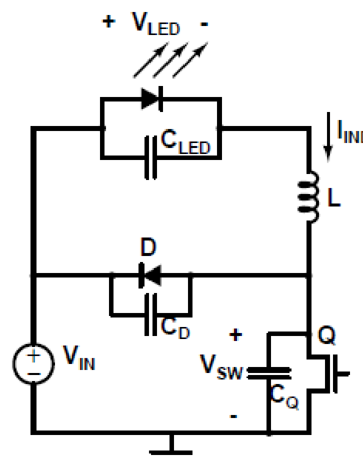


"Integrated Toroidal Inductors with Nanolaminated Metallic Magnetic Cores," Tech. Dig. PowerMEMS 2012 workshop.

Power Converter Measurements

Power converter circuit board and integrated inductor

Testing board with wirebonded inductor



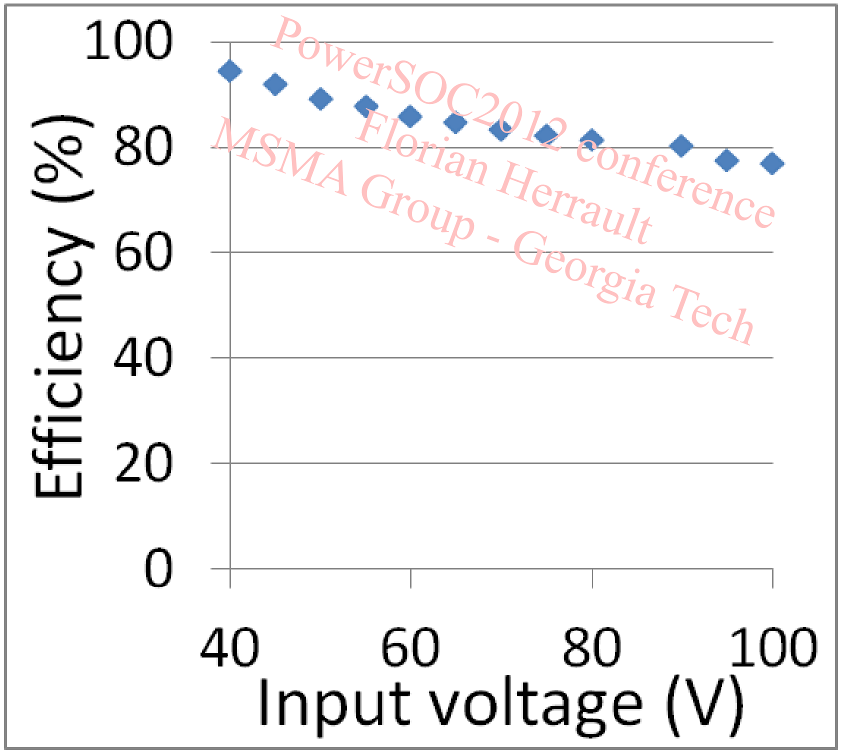
ZVS buck converter

"A technology overview of the PowerChip development program," TPES, in press.

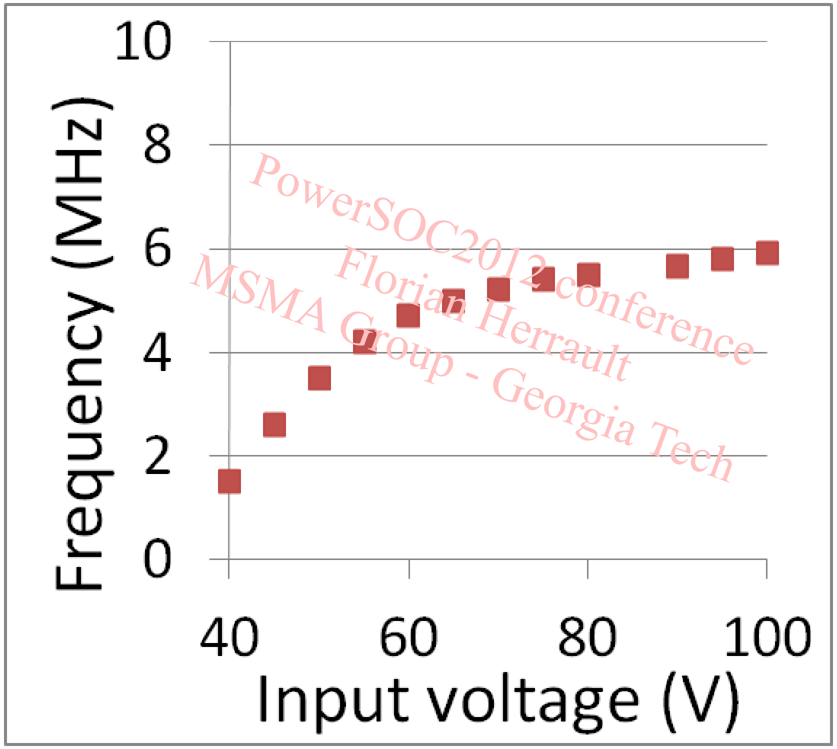
100 V Power Converter Measurements

- 1.5 µH inductor with CoNiFe cores
- P_out ~ 25-35 W
- V_out = 35 V

Massachusetts Institute of Technology



Power converter efficiency as a function of input voltage



Power converter switching as a function of input voltage

Summary

- Highly Laminated Metallic Cores: Technology-driven approach
  - Negligible eddy current losses
  - High Saturation flux densities
  - Low hysteresis losses
  - Electroplating-based technology compatible with thick magnetic core fabrication and CMOS manufacturing
- Microfabricated Inductors
  - Cores and windings are co-packaged
  - Demonstrated for large inductance inductors and small multi-phase topologies
- Demonstration in 100 V power converter
  - Operation at 2-6 MHz and 35W output power
- Ongoing work on material reliability (corrosion, stress, packaging) and in-field material electroplating