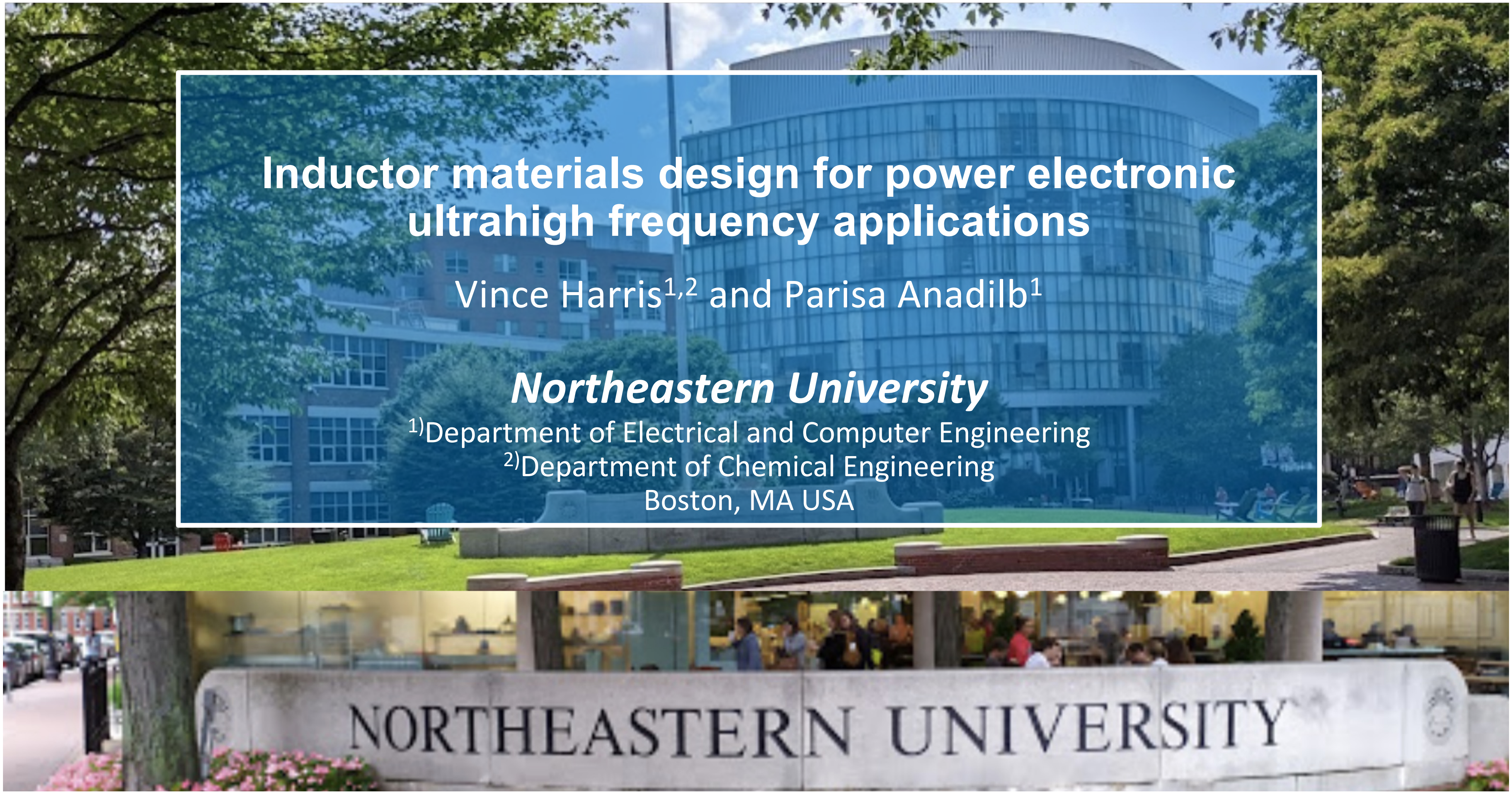

Inductor materials design for power electronic ultrahigh frequency applications

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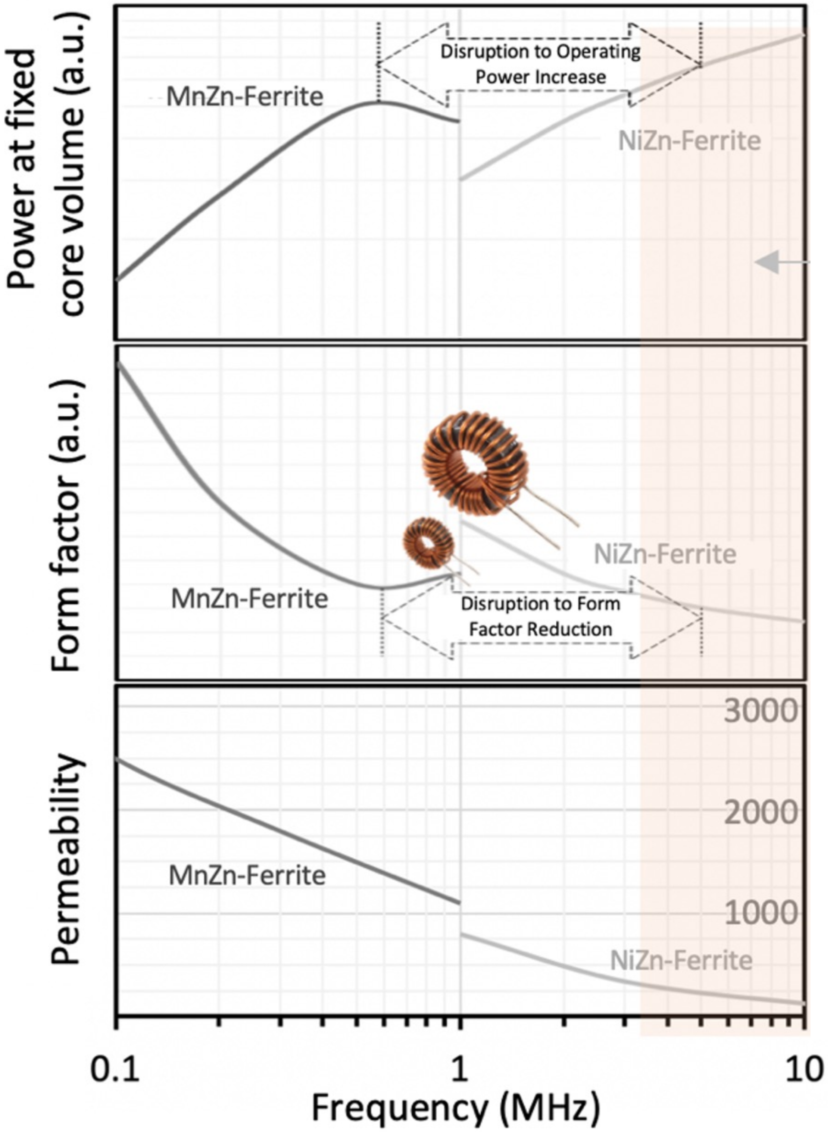
Boston, MA USA

Outline

- ➢ Motivation & Trends in Power Electronics
- ➢ Fundamental loss mechanisms
- ➢ Recent innovations
  - ❖ Grain boundary engineered all ferrite composites (*f* >1 MHz)
  - ❖ Interface engineered metal-ferrite composites (*f* > 100 kHz)
  - ❖ Ferrite-polymeric composites (*f* > 1 GHz)
- ➢ Summary & Outlook

Motivation & Trends

- Driven and enabled by UWBG semiconductor materials, power electronic components and systems are shifting to higher frequencies, higher powers, and smaller form factors
  - What is high? Depends upon your stakeholder (DOE, DOD, commercial, EVs, etc.)
    - 100-250 kHz; 200-500 kHz; *f* > 1 MHz
    - High Power Pulse Generators (HPPGs) require >500 MHz of bandwidth
  - What are UWBGs? SiC, GaN, Ga_2O_3, AlN, BN, even diamond
- Passives must keep pace with these evolving needs!
  - Passives = Inductors & capacitors
  - **<u>Today, I will focus on Inductors</u>**
  - Energy storage, power conversion, and power conditioning (e.g., converters, inverters, transformers, filters)
  - Maintaining small form factors and high efficiency
  - Thermal management, low loss (SWAP+C+SSC)



Fundamental loss mechanisms in magnetic inductor materials

$$P_v = P_{hysteresis} + P_{classic\ eddy} + P_{excess\ eddy}$$

Measured value as
f (frequency)

$$\frac{P_{hysteresis}}{f} = k_h B^{\beta}$$

$$\frac{P_{eddy}^{classic}}{f} = \left(\pi^2 D^2 \middle/ 16\right) J_p^2 \ \frac{f}{\rho(f)}$$

$$P_{eddy}^{excess} = K_{eddy}^{excess} \sqrt{\frac{S}{\rho(f)}} B_p^{1.5} f^{1.5}$$

Sometimes referred to as “residual power loss, P_r”

Plotting of $\frac{P_v}{f}$ $vs.$ $\sqrt{f}$ allows for the deconvolution of individual components

Fundamental loss mechanisms in magnetic inductor materials

Circuit unit cell representing intrinsic magnetic properties of a **high-power inductor cores** with high power/frequency power dissipation mechanisms identified.

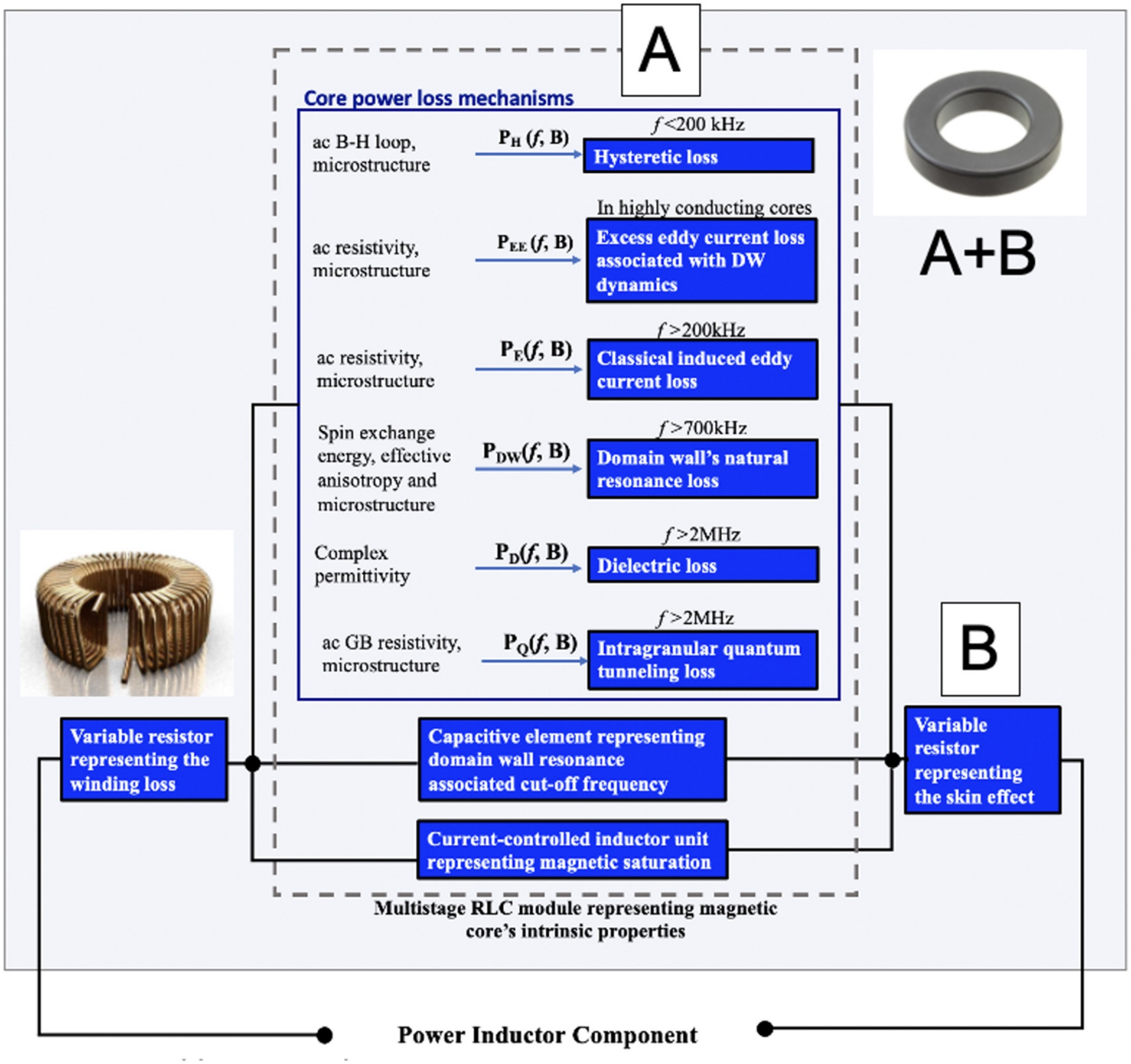
Inductor losses

Winding losses (i.e., copper losses resulting from Joule heating, or I^2R losses)

A: Core intrinsic losses

- ➢ Hysteretic
- ➢ Eddy current
- ➢ Domain wall resonance (residual)
- ➢ Dielectric loss
- ➢ Intergranular quantum tunneling

B: Core material skin effect



A

A+B

Core power loss mechanisms

ac B-H loop, microstructure — $P_H (f, B)$ — f<200 kHz — **Hysteretic loss**

ac resistivity, microstructure — $P_{EE} (f, B)$ — In highly conducting cores — **Excess eddy current loss associated with DW dynamics**

ac resistivity, microstructure — $P_E(f, B)$ — f>200kHz — **Classical induced eddy current loss**

Spin exchange energy, effective anisotropy and microstructure — $P_{DW}(f, B)$ — f>700kHz — **Domain wall's natural resonance loss**

Complex permittivity — $P_D(f, B)$ — f>2MHz — **Dielectric loss**

ac GB resistivity, microstructure — $P_Q(f, B)$ — f>2MHz — **Intragranular quantum tunneling loss**

B

Variable resistor representing the winding loss

Capacitive element representing domain wall resonance associated cut-off frequency

Current-controlled inductor unit representing magnetic saturation

Variable resistor representing the skin effect

Multistage RLC module representing magnetic core's intrinsic properties

Power Inductor Component

Are magnetics keeping pace with evolving power electronics needs?

- The short answer: No.
- Why? The short answer: There is not enough market interest validating new commercial R&D investment.
- Are there good ideas out there? Yes!
- Are they being generated by US scientists? Yes!
- How do we solve this problem? (Vince's model – may not be the only one)

Vince's Model	Scientists +	Small Biz +	Transition partners +	Stakeholder
	Fund + Academics & others	SBIR/STTR +	Primes (tiers 1 & 2) & commercial partners	+ Agencies & Sponsors End-users (est. market alliances)
	MRL/TRL 1-2	MRL/TRL 3-6	MRL/TRL 6- integration	Market insertion – both commercial & defense

Sponsors

- ONR Electric Ship Program (LJ Petersen)
- ONR Pulsed Power (R. Hoffman)
- DARPA DSO (STTR)
- STTR partner: Metamagnetics Inc.

Recent innovations (it’s not all bad news!)

- Grain boundary engineering (nano-composites f >1 MHz), 2021
- Interface engineering (f ~ 100 kHz), 2023
- Composites (micro-composites f >1 GHz), 2022

Solution for
f > 1 MHz
applications

METAMAGNETICS

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles

Sponsored by ONR and ONR SBIR/STTR
Innovation originated from Northeastern CM^{3}IC

Key publications:

- Parisa Andalib, Vincent G Harris, “Grain boundary engineering of power inductor cores for MHz applications,” Journal of Alloys and Compound, 832, 153131 (2020).
- Y. Chen, P. Andalib, V. Harris, “Magnetic Materials with Ultrahigh Resistivity Intergrain Nanoparticles,” 2021, 11,211,187, patent allowed.

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles (***<u>GOALS: 1-3</u>***)

Note: The principal loss mechanism for these materials operating at *f* > 1 MHz and high-power density conditions are ***classic eddy currents*** (P_e)

$$\boxed{\frac{P_{eddy}^{classic}}{f} = \left(\pi^2 D^2 \Big/ 16\right) J_p^2 \; \frac{f}{\rho(f)}}$$

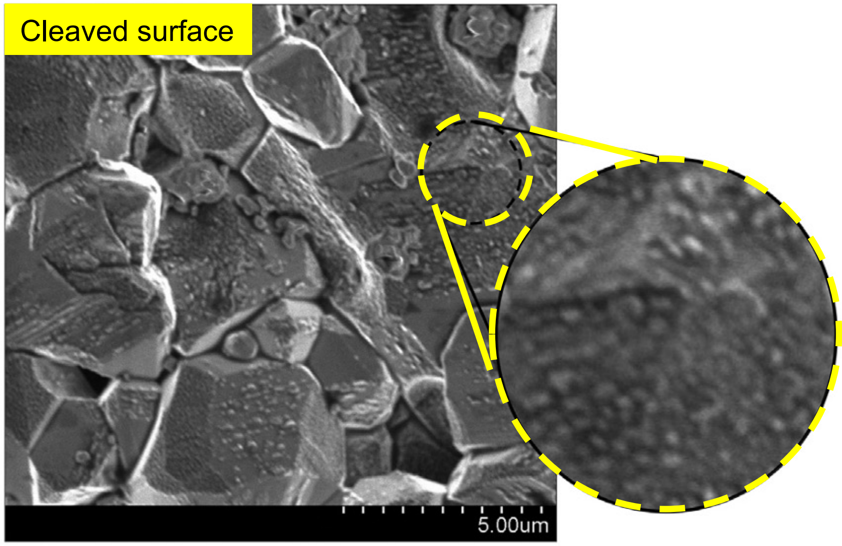
D: circular cross-section (geometric diameter)
J_p: maximum current density

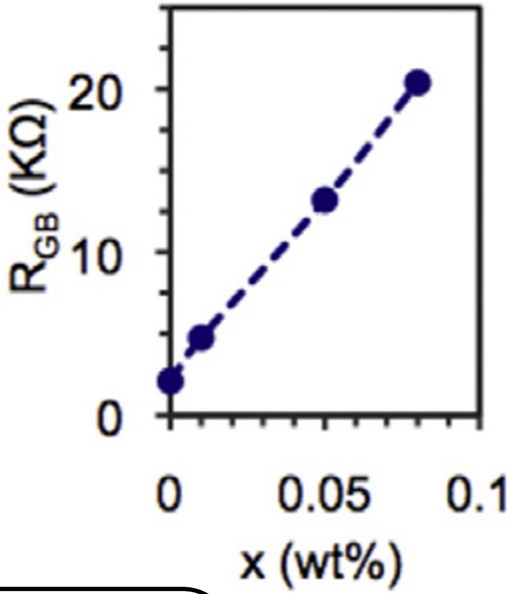
1. Introduce highly resistive particles to the grain boundary region to suppress *intergrain eddy currents* without disruption to intergrain magnetic continuity.

2. Reduce total power loss (P_v) without degradation to permeability et al.

3. Maintain SWAP+C+SSC

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles

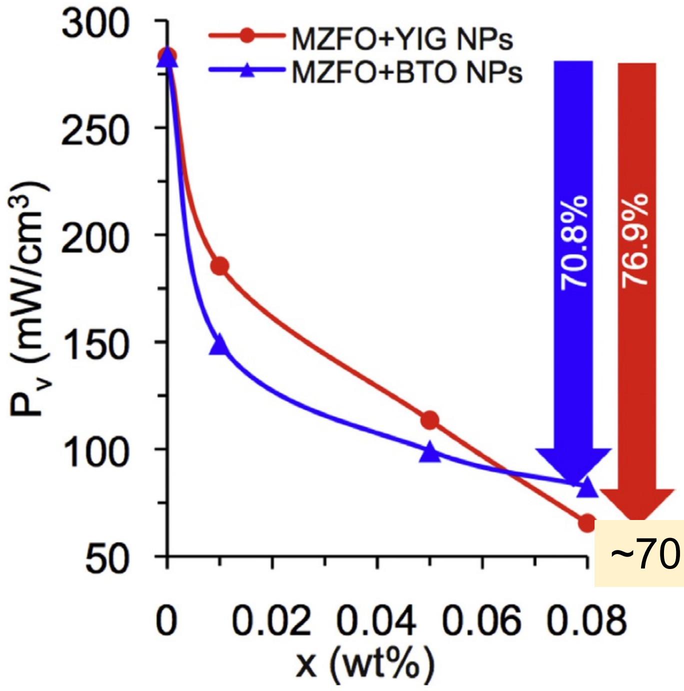




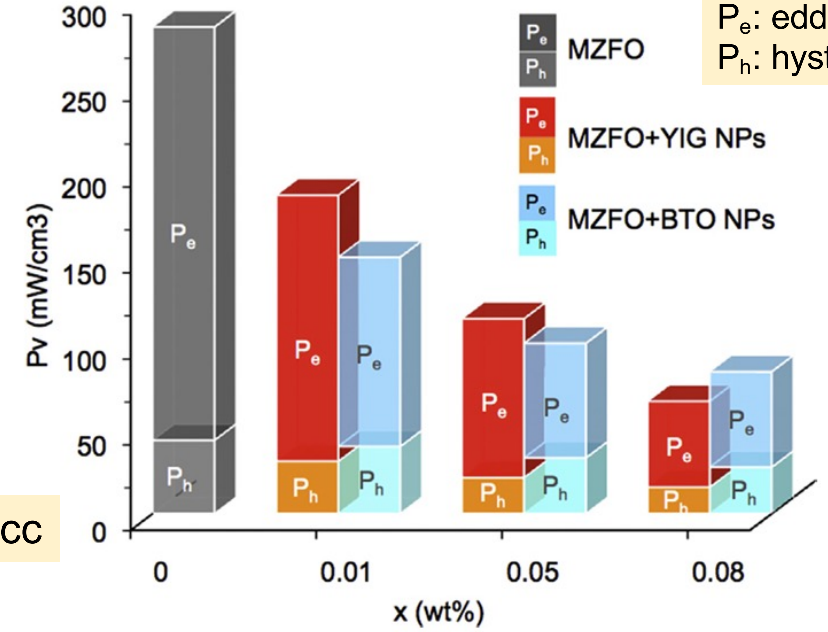
- **GB engineering is not new**: SiO_2, Nb_2O_5, Ta_2O_5, HfO_2, ZrO_2, V_2O_5, etc.
- GB engineering using magnetic resistive particles is *NEW!*
- Key: Collocation of particles to GB must overcome diffusion into the principal lattice.

- LHS: SEM image that supports the collocation of particle *clusters* to GBs
- RHS: GB resistance is measured and plotted vs. the amount of introduced nanoparticles
- The linear increase also supports the collocation of particle clusters to GBs

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles



~70 mw/cc

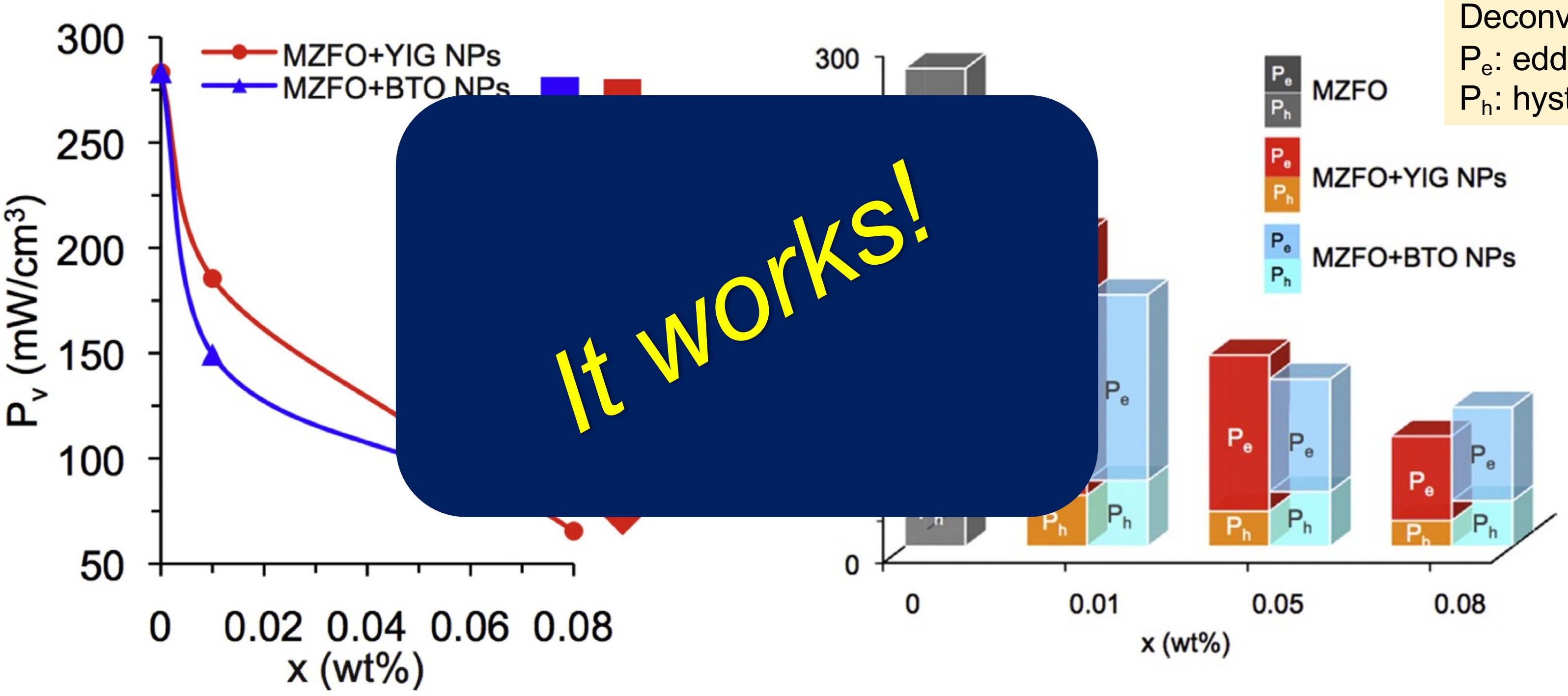


Deconvolution
P_e: eddy losses
P_h: hysteretic losses

YIG vs BTO (control) comparison in total losses (Pv) and permeability.
Same size particles; similar electrical resistance, one magnetic (YIG) & one not (BTO)

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles

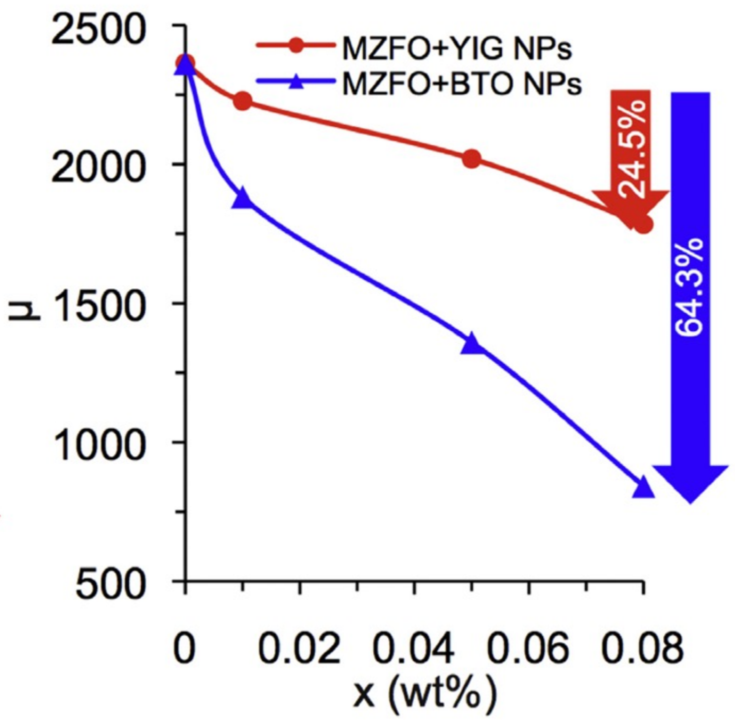
Deconvolution
P_e: eddy losses
P_h: hysteretic losses

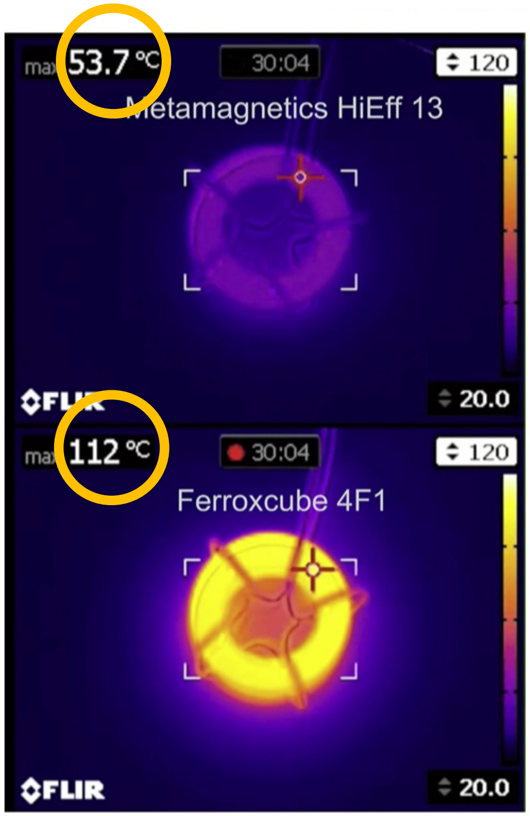


It works!

YIG vs BTO (control) comparison in total losses (Pv) and permeability.
Same size particles; similar electrical resistance, one magnetic (YIG) & one not (BTO)

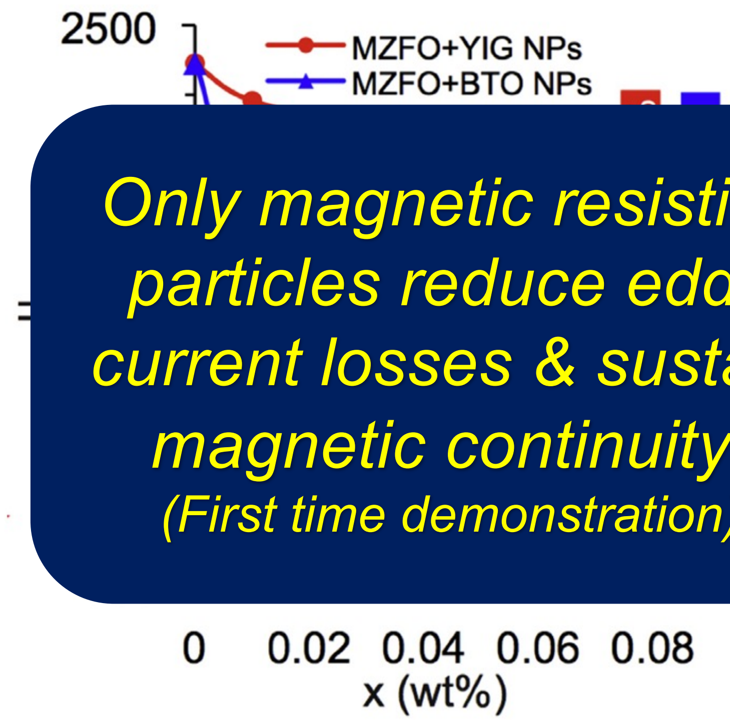
Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles





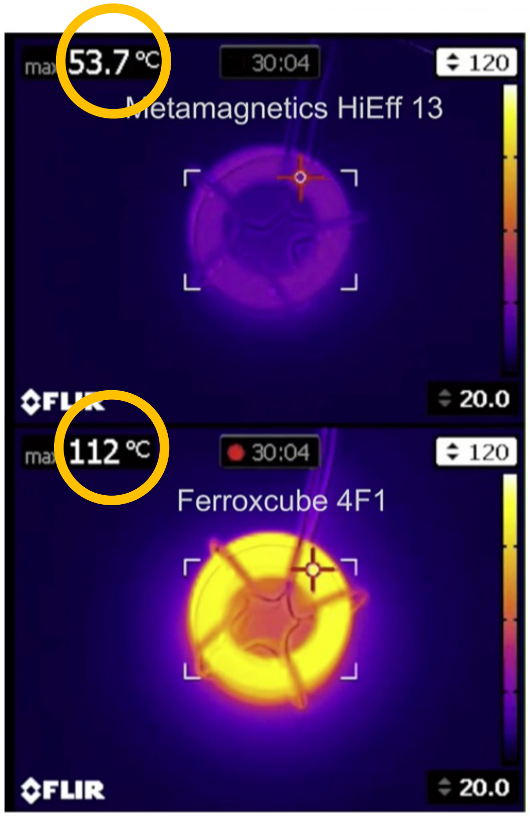
- Both cores are driven by identical excitation signals (at 3 MHz, 10 mT)
- The image represents a 120 seconds elapsed duration
- The core temperature is posted - upper left
- The upper core is ferroxcube reformed with 0.08 wt-% NZFO.
- The bottom panel is the same ferroxcube product.

Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles



Only magnetic resistive particles reduce eddy current losses & sustain magnetic continuity!

(First time demonstration)



- Both cores are driven by identical excitation signals (at 3 MHz, 10 mT)
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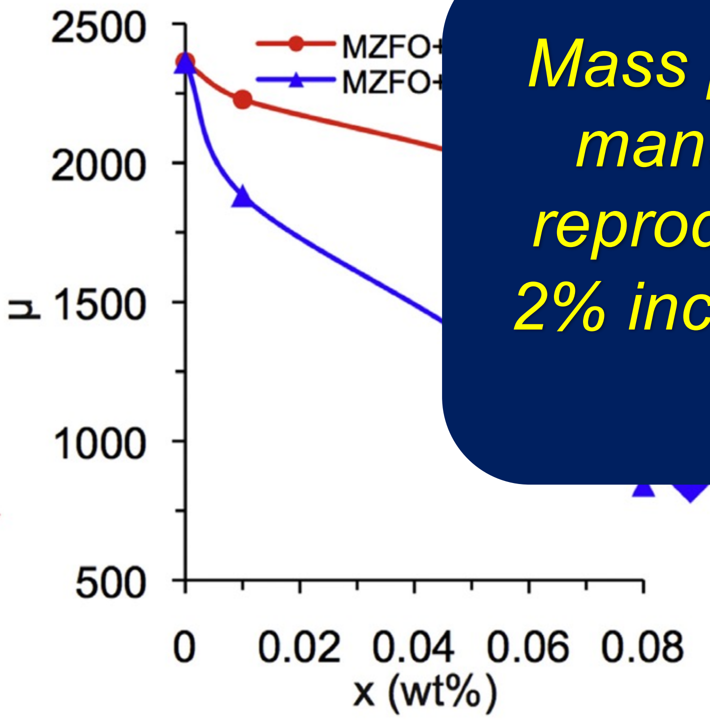
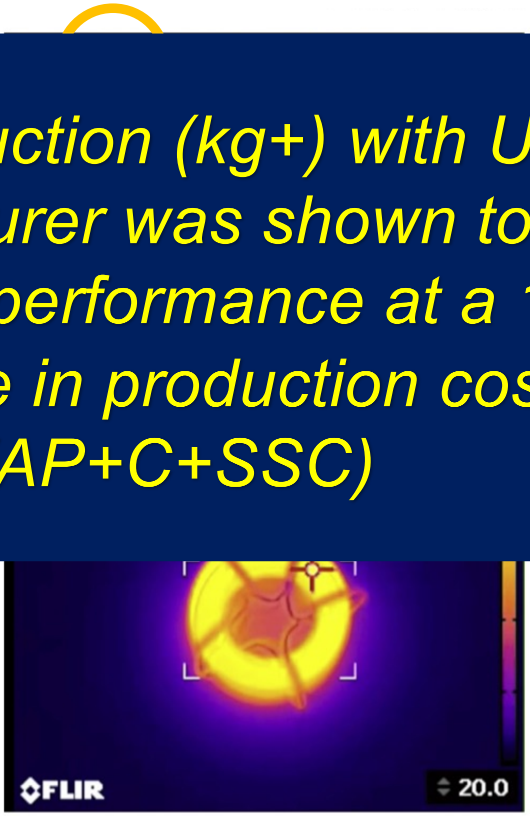
Grain boundary engineering: Magnetic vs. nonmagnetic resistive nanoparticles



Mass production (kg+) with US manufacturer was shown to reproduce performance at a 1-2% increase in production costs (SWAP+C+SSC)



oth cores are driven by entical excitation signals t 3 MHz, 10 mT)

he image represents a 20 seconds elapsed uration

he core temperature is osted - upper left

he upper core is ferroxcube reformed with 0.08 wt-% NZFO.

- The bottom panel is the same ferroxcube product.

Solution for
10s < f <100s kHz
applications

Interface engineering of composites: Ferrite particulate coating of ferromagnetic metallic fibers (nanocrystalline)

Sponsored by DARPA STTR (Metamagnetics)
Innovation originated from Northeastern CM^{3}IC

Key publications:

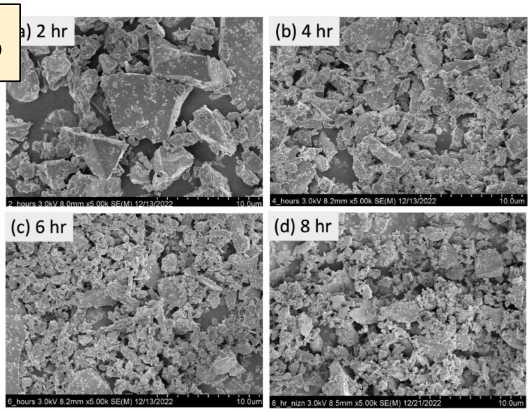
- P. Andalib and V. Harris, "“Ferromagnetic metal - ferrite composites for high frequency inductor applications,”, 2020, patent submitted.

Interface engineering: Ferrite coating of ferromagnetic metal fiber-based composites

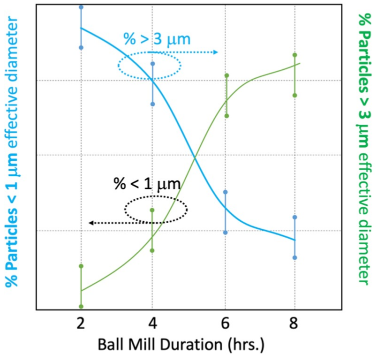
A

Dia. 50 um

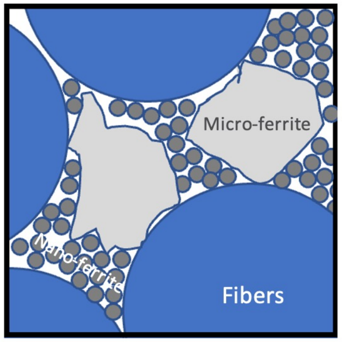
B



Bimodal size distribution



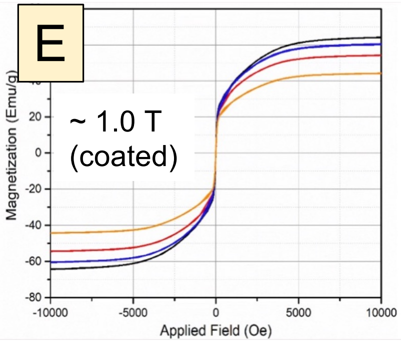
C



D

Figure 5. Winding machine to supplement the large-scale fabrication setup.

E



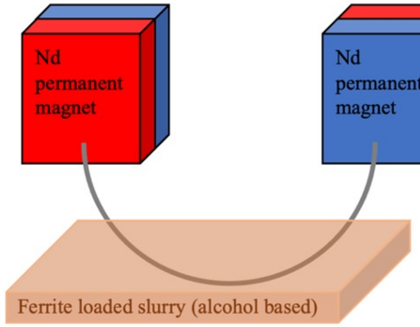
Sample	Description	Magnetization
Black	Core of untreated wires	1.1 T
Blue	45% ISOBAM, ALL NZFO, 2cm microwires	1.05 T
Red	35% ISOBAM, NZFO+YIG, 2cm microwires	0.91 T
Orange	45% ISOBAM, ALL YIG, 2cm microwires	0.78 T

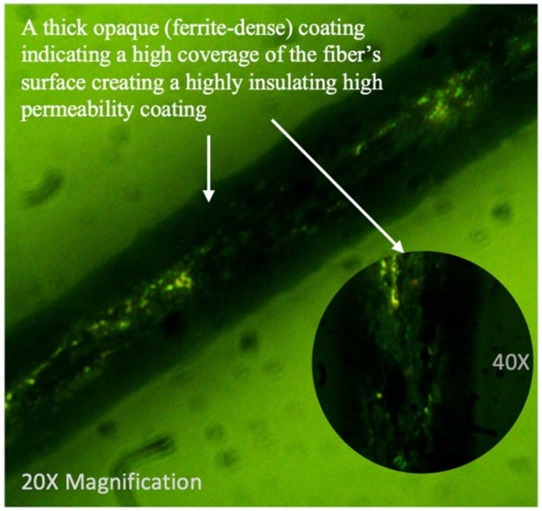
Interface engineering

Magnetic-Field-Enhanced Dip-Coating process improved by adjusting the surface tension of the slurry and the surface wetting affinity evaluated by optical microscopy (40X magnification).

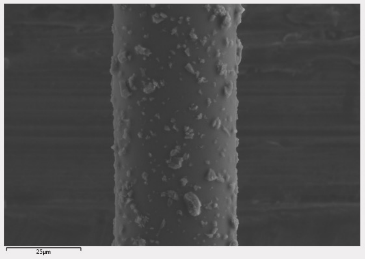
Enabling further core loss reduction and an effective scale-up manufacturing:
A thick uniform ferrite-dense coating enabled by "Magnetic-Field-Enhanced Dip-Coating"*

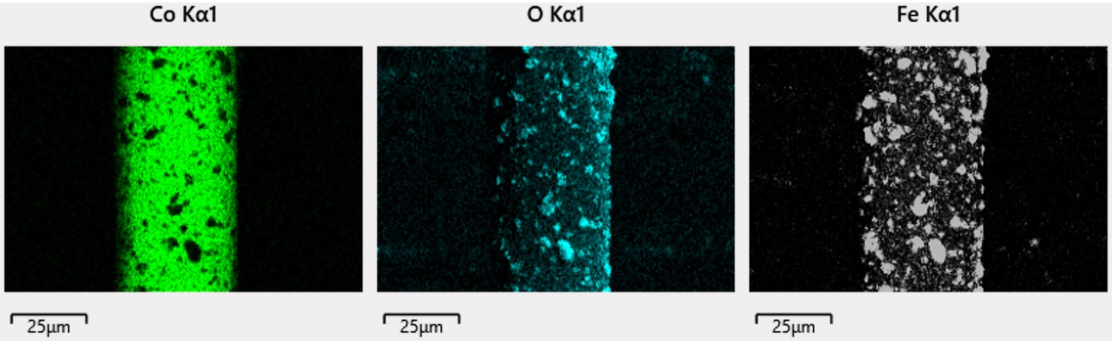
An improved magnetic field pattern using two permanent magnets of opposite polarity placed side by side attached the ends of the fiber:




A thick opaque (ferrite-dense) coating indicating a high coverage of the fiber's surface creating a highly insulating high permeability coating

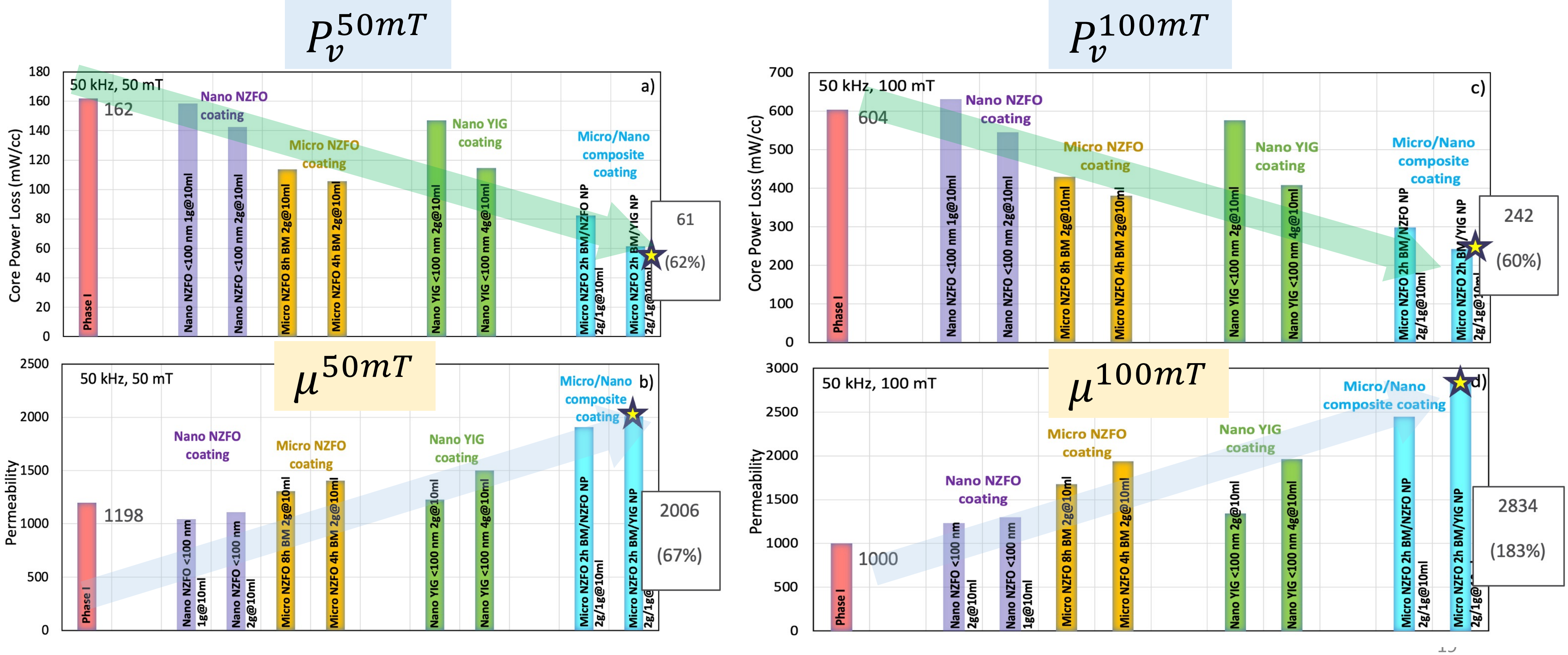
** Patent to be submitted, Vincent G Harris and Parisa Andalib.*


SEM

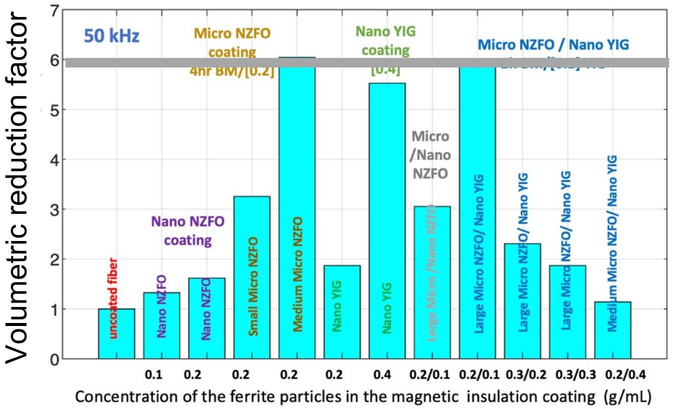


Energy dispersive spectroscopy
(Note: Incomplete coverage used for illustrative purposes)

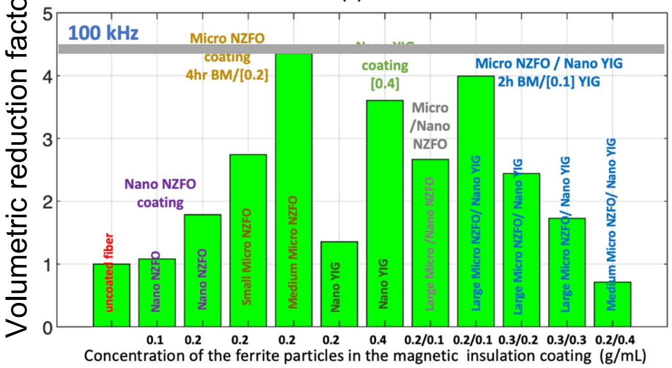
Interface engineering: Ferrite coating of ferromagnetic metal fiber-based composites



Interface engineering: Ferrite coating of ferromagnetic metal fiber-based composites



(a)



$$L = \frac{\mu_o \mu_d N^2 a}{2\pi} \ln\left(\frac{r_2}{r_1}\right)$$

Comparisons to metallic core

6.0 X reduction in volume relative to host at 50 kHz

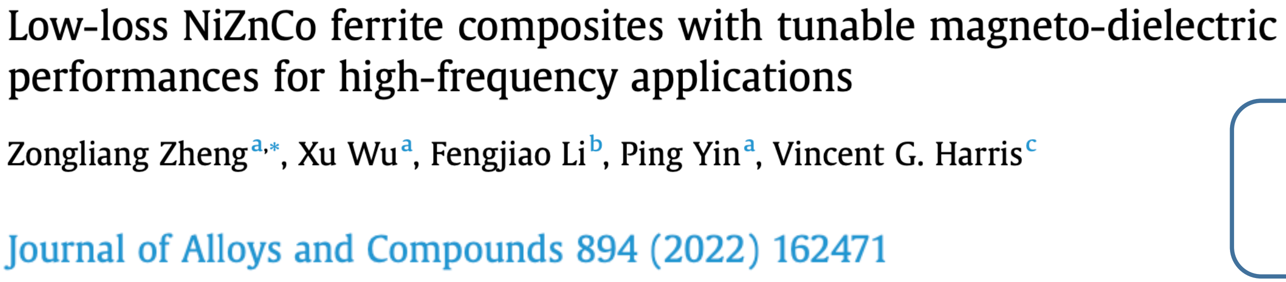
4.4 X reduction in volume relative to host at 100 kHz

SWAP+C+SSC

- The innovation is the magnetic insulating coating
- This approach can be applied to any host metal incl. Metglas or nanocrystalline products (e.g., Finemet) or others. **See Paul Ohodnicki (U Pitt, 11:00 AM this morning)**

Solution for
100s MHz < *f* < 1 GHz
applications

Innovation: New inductor composite materials to address HPPG systems and other HF power needs



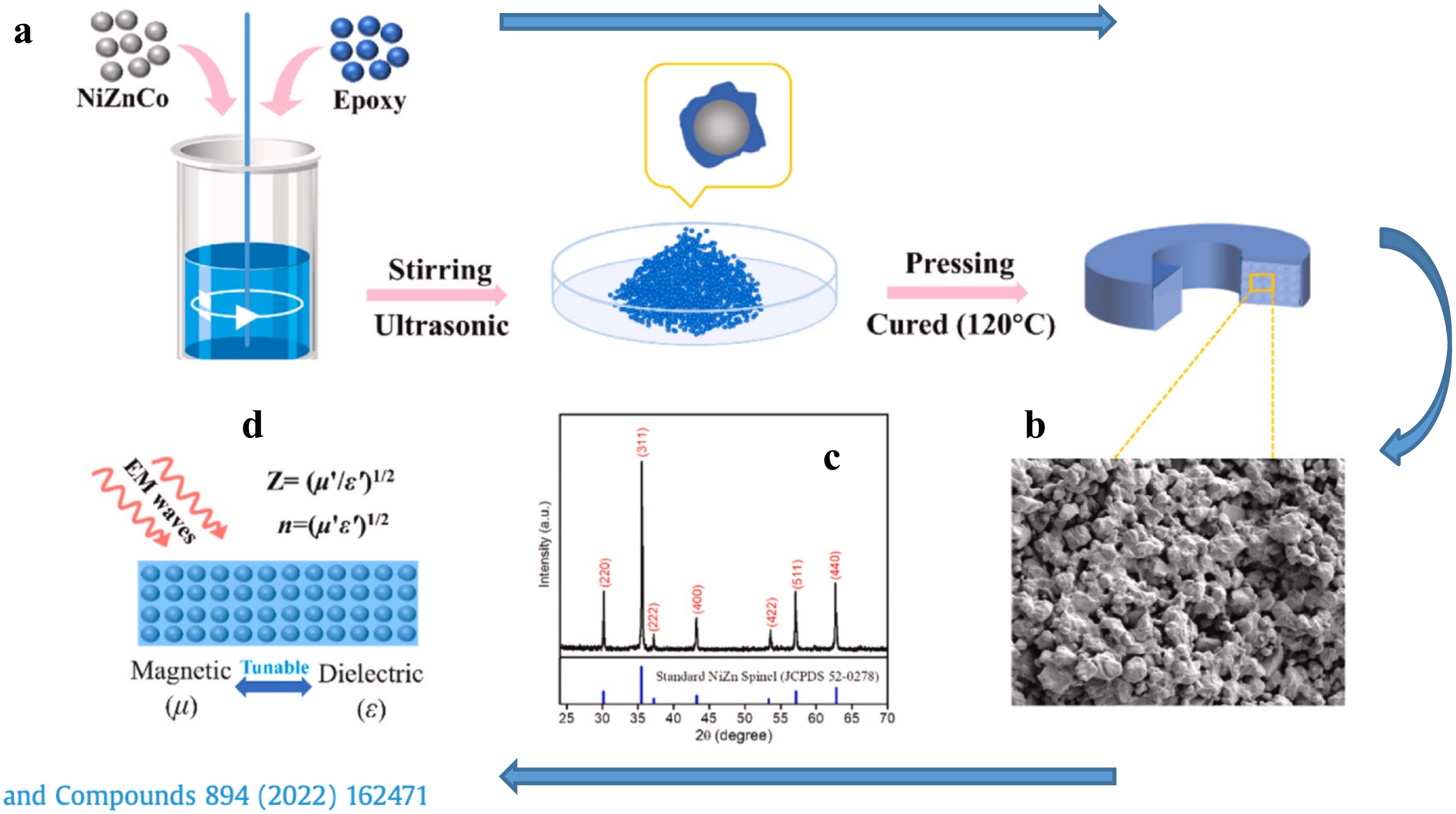
Low-loss NiZnCo ferrite composites with tunable magneto-dielectric performances for high-frequency applications

Zongliang Zheng[a,*], Xu Wu[a], Fengjiao Li[b], Ping Yin[a], Vincent G. Harris[c]

Journal of Alloys and Compounds 894 (2022) 162471

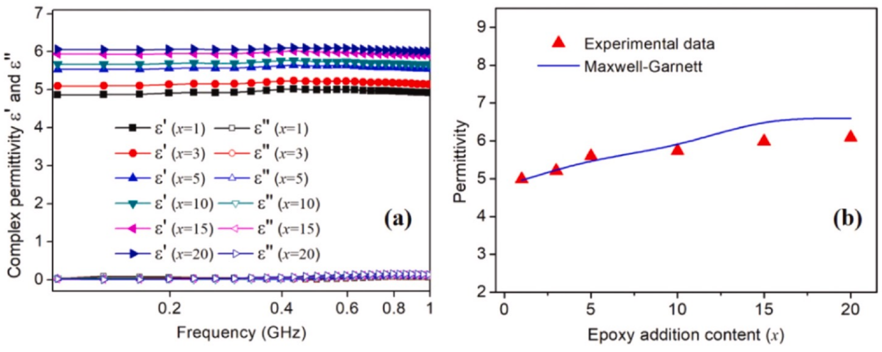
Ferrite-based polymer
composites

New inductor materials to address HPPG system needs



Journal of Alloys and Compounds 894 (2022) 162471

Complex permittivity



SEM image of microstructure

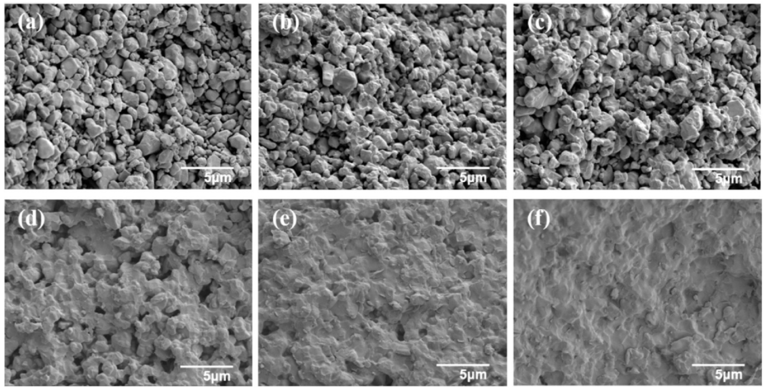
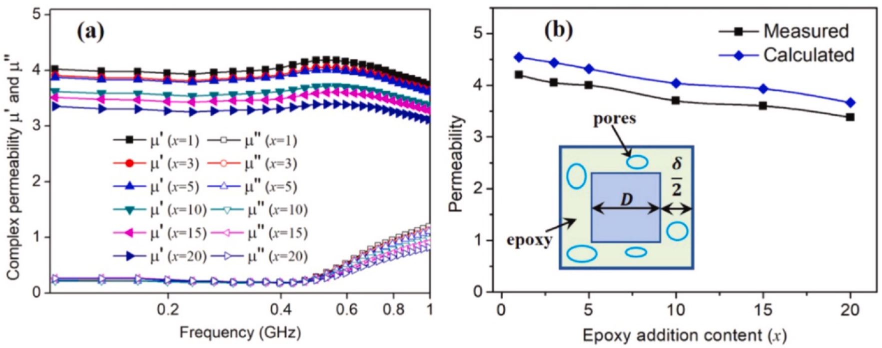


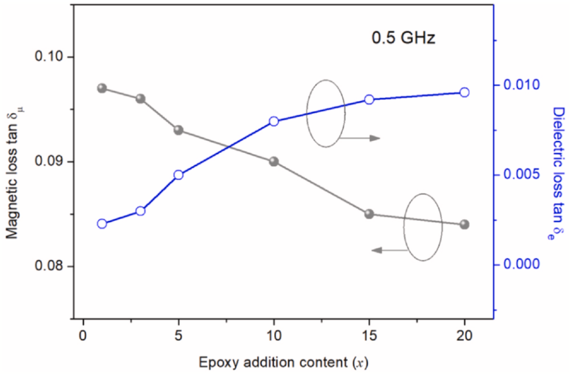
Fig. 2. SEM micrographs of as-prepared composites with epoxy addition amount x = (a) 1, (b) 3, (c) 5, (d) 10, (e) 15, and (f) 20 wt%.

Complex permeability



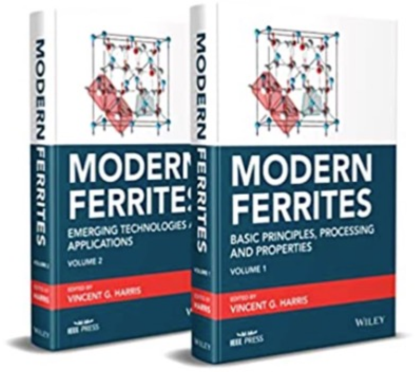
Journal of Alloys and Compounds 894 (2022) 162471

Loss behavior



Summary & Outlook

- COTS inductor materials are ill-suited to address the needs of the ***evolving*** power electronics community in both performance and SWAP+C.
- Academic and small businesses have in recent years developed materials and processing innovations resulting in new magnetic materials that represent potentially disruptive advances to meet these needs.
- These advanced materials reflect SWAP+C+SSC stratagems.
- These materials remain at MRL/TRL of 1-2 and require further investment to advance MRL/TRL and enhance the likelihood of successful market transition.
- Long-time experts in these areas of great importance are dropping out of the ecosystem (by retirement) without being replaced and this is an increasingly urgent matter.
- Replacements on the global stage are in largely the Asia-Pacific regio et al. threatening a repeat of the RE supply chain and geopolitical problem.



Amazon

The perfect Christmas, Hanukkah, Birthday, Graduation, or just “make-up” gift!

See my “Just-fund-me link” and support my legal defense fund….