Multiscale Nanolaminated Metallic Cores for High Frequency Magnetics

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Penn
Engineering

Properties of Some Magnetic Materials

	Fabrication Method	Material	Bs [T]	Hc [Oe]	ρ [mΩ·cm]
Ferrite	Sintering	NiZn	0.25	40	3E8
		NiZnCu	0.22	42.8	1E8
		4F1	0.32	2	1E6
Metallic films	Sputtering	CoZrO	1.3	1	600
		CoZrTa	1.52	0.015	100
	Electro deposition	NiFe	1.2	1.2	20
		CoFeCu	1.46	2.8	30
		NiFeMo	1.07	0.3	35
		CoNiFe	2.2	1	30

High resistivity
High sintering T
Low Bsat

High Bsat
Low Hc
CMOS-compatible
Low resistivity

Suppressing Eddy Currents Would Enable Use of High B_{sat} Materials

Multiscale Lamination Technology

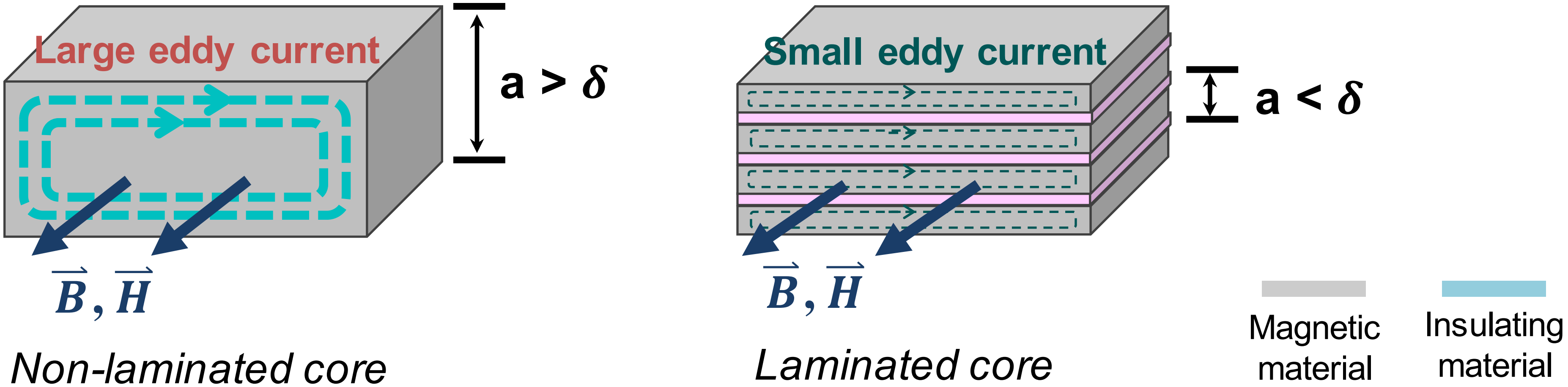
Skin depth: $\delta = \dfrac{1}{\sqrt{\pi\mu\sigma f}}$

μ : permeability [H/m]
σ : conductivity [1/Ωm]
f : frequency [Hz]

<u>Need to simultaneously achieve two size scales</u>

Large magnetic volume for high power (0.1-1 mm scale)

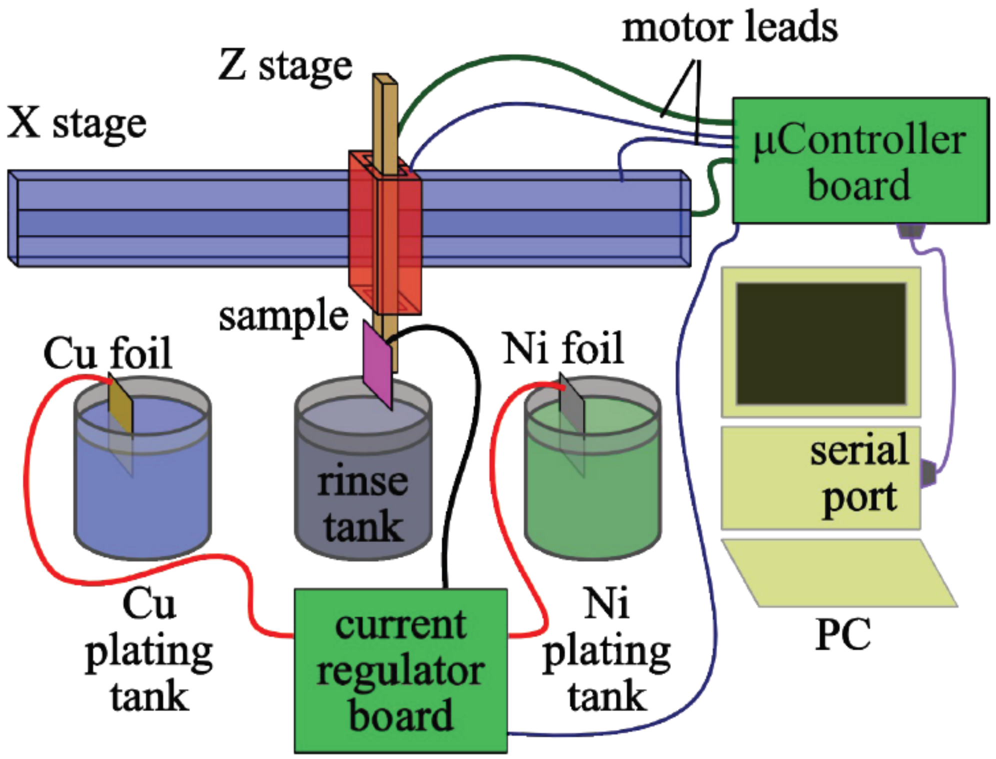
Suppressed eddy-currents at high frequency (micron scale at MHz f)



Non-laminated core

Laminated core

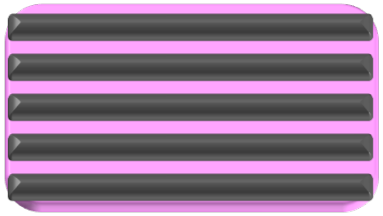
Sequential Multilayer Electrodeposition



Automated multilayer electroplating setup

Multilayer Copper/CoNiFe structure

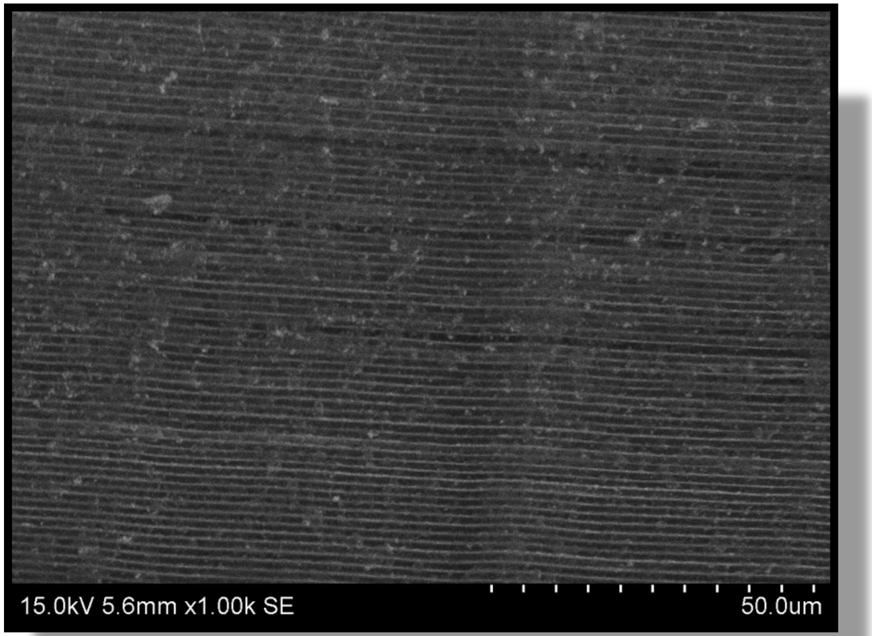
Copper selective etching



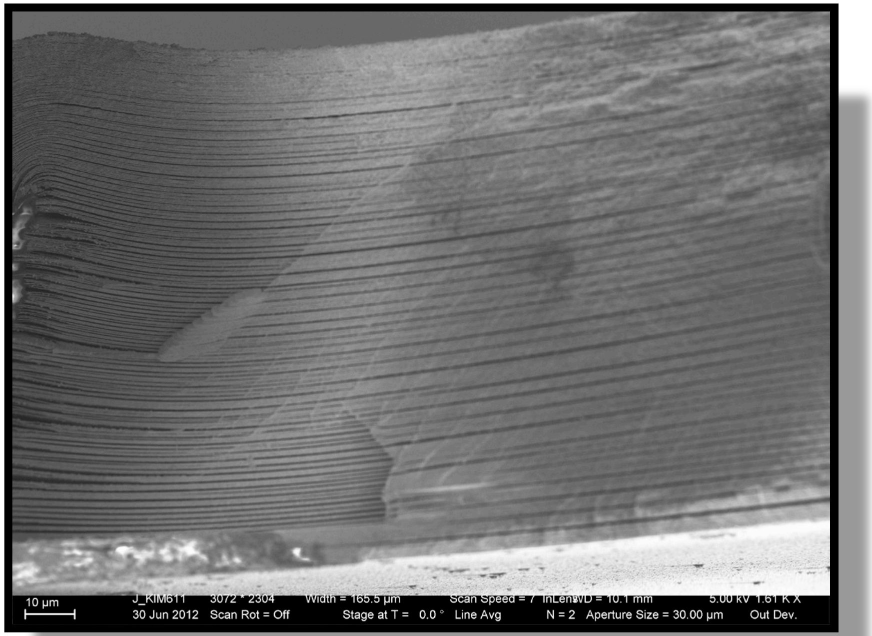
Electrically insulated CoNiFe multilayer

Laminated core fabrication

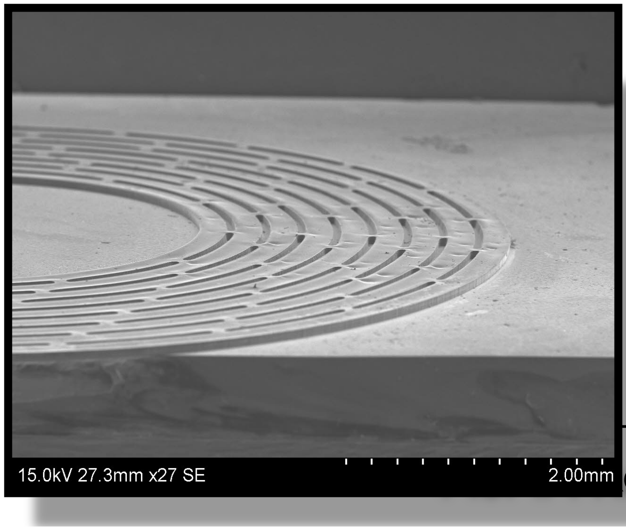
Highly-laminated CoNiFe

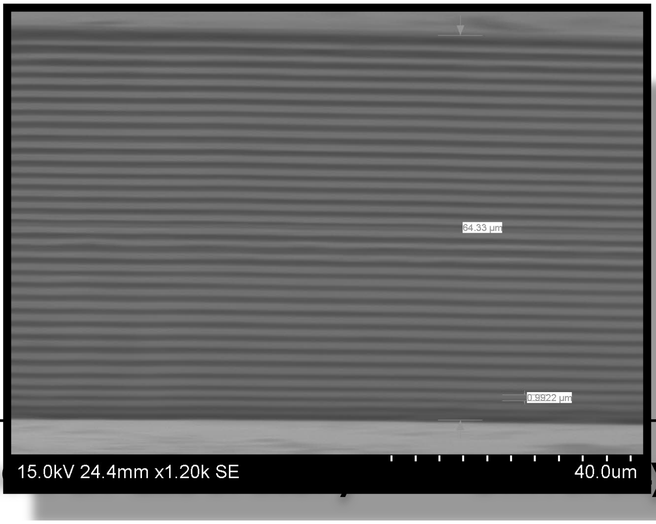


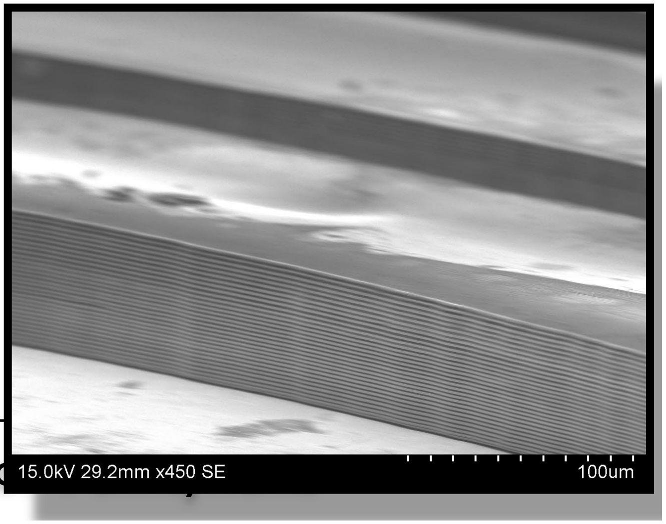
100-layer CoNiFe laminations with lamination thickness < 1 μm



300-layer CoNiFe laminations with lamination thickness < 0.3 μm

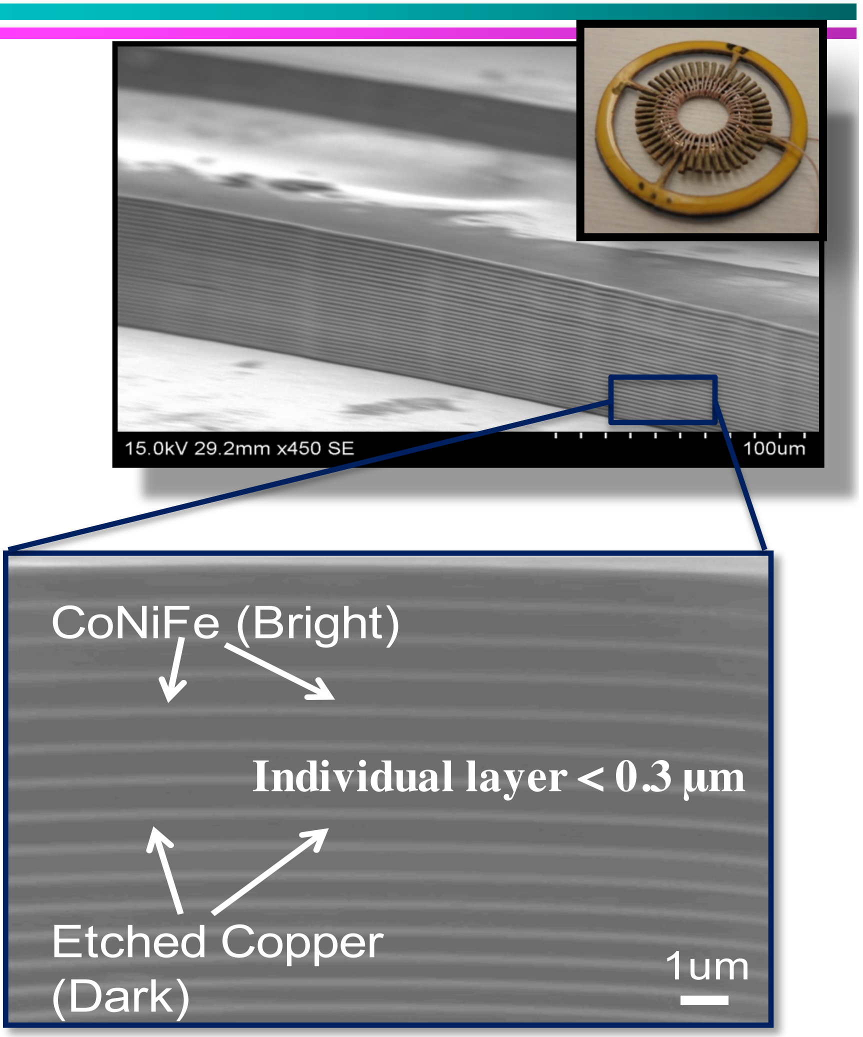






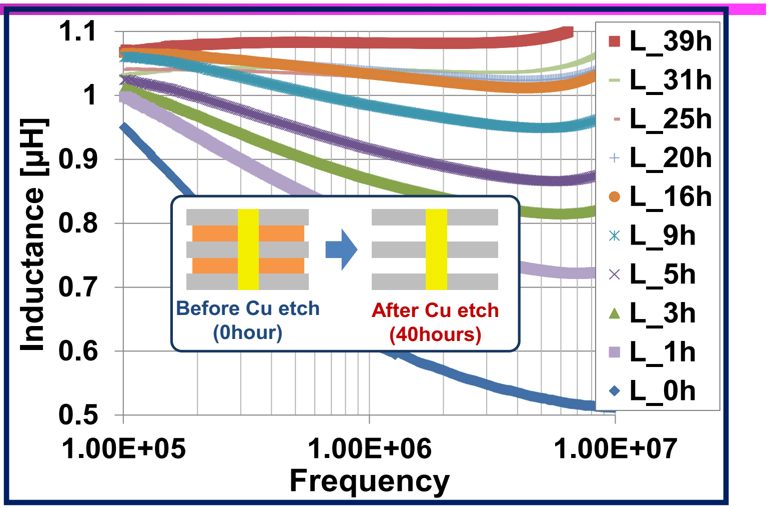
Fabricated Cores and Inductors

Batch fabricated multilayer cores

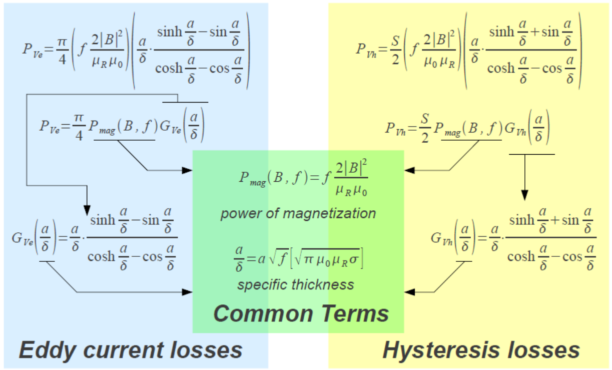


300nm CoNiFe laminations (Bs: 1.8T, Hc: 0.5Oe)

Laminated Core Performance



In-situ measurement of eddy-current suppression



$$P_{Ve}=\frac{\pi}{4}\left(f\frac{2|B|^2}{\mu_R\mu_0}\right)\left(\frac{a}{\delta}\cdot\frac{\sinh\frac{a}{\delta}-\sin\frac{a}{\delta}}{\cosh\frac{a}{\delta}-\cos\frac{a}{\delta}}\right)$$

$$P_{Ve}=\frac{\pi}{4}P_{mag}(B,f)G_{Ve}\left(\frac{a}{\delta}\right)$$

$$G_{Ve}\left(\frac{a}{\delta}\right)=\frac{a}{\delta}\cdot\frac{\sinh\frac{a}{\delta}-\sin\frac{a}{\delta}}{\cosh\frac{a}{\delta}-\cos\frac{a}{\delta}}$$

Eddy current losses

$$P_{mag}(B,f)=f\frac{2|B|^2}{\mu_R\mu_0}$$

power of magnetization

$$\frac{a}{\delta}=a\sqrt{f}\left[\sqrt{\pi\mu_0\mu_R\sigma}\right]$$

specific thickness

Common Terms

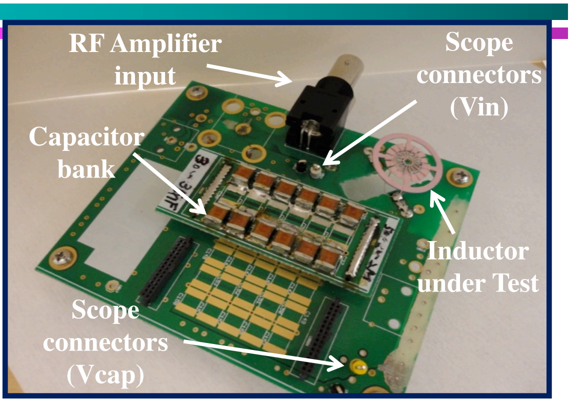
$$P_{Vh}=\frac{S}{2}\left(f\frac{2|B|^2}{\mu_0\mu_R}\right)\left(\frac{a}{\delta}\cdot\frac{\sinh\frac{a}{\delta}+\sin\frac{a}{\delta}}{\cosh\frac{a}{\delta}-\cos\frac{a}{\delta}}\right)$$

$$P_{Vh}=\frac{S}{2}P_{mag}(B,f)G_{Vh}\left(\frac{a}{\delta}\right)$$

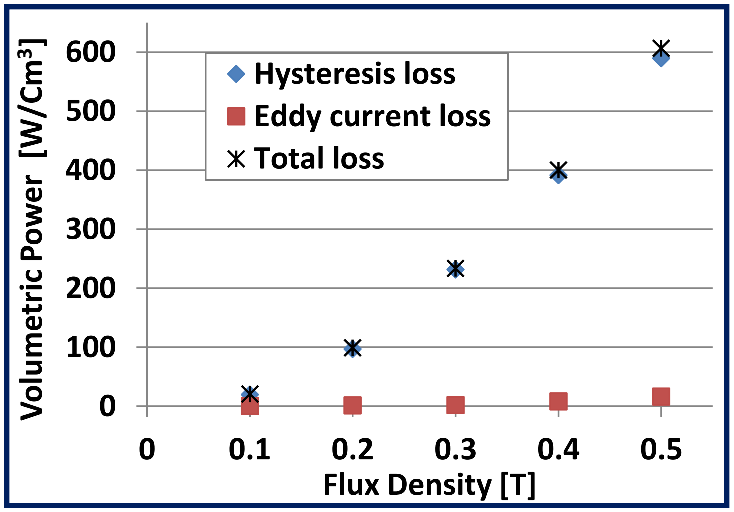
$$G_{Vh}\left(\frac{a}{\delta}\right)=\frac{a}{\delta}\cdot\frac{\sinh\frac{a}{\delta}+\sin\frac{a}{\delta}}{\cosh\frac{a}{\delta}-\cos\frac{a}{\delta}}$$

Hysteresis losses

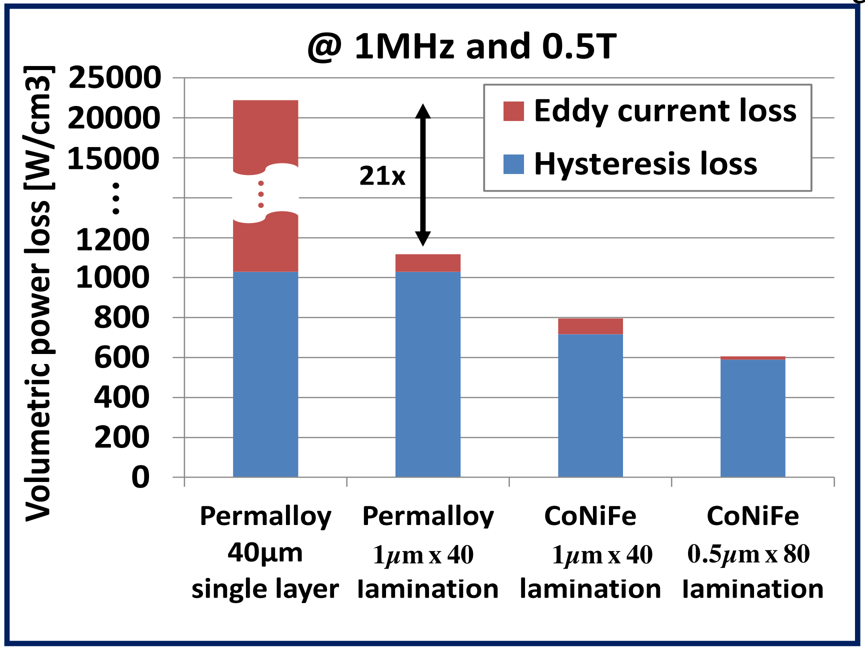
Analytical decomposition of core losses



HFHF core loss testing board



Suppressed eddy-currents at 1MHz up to 0.5T
70 layers of 500nm CoNiFe lamination

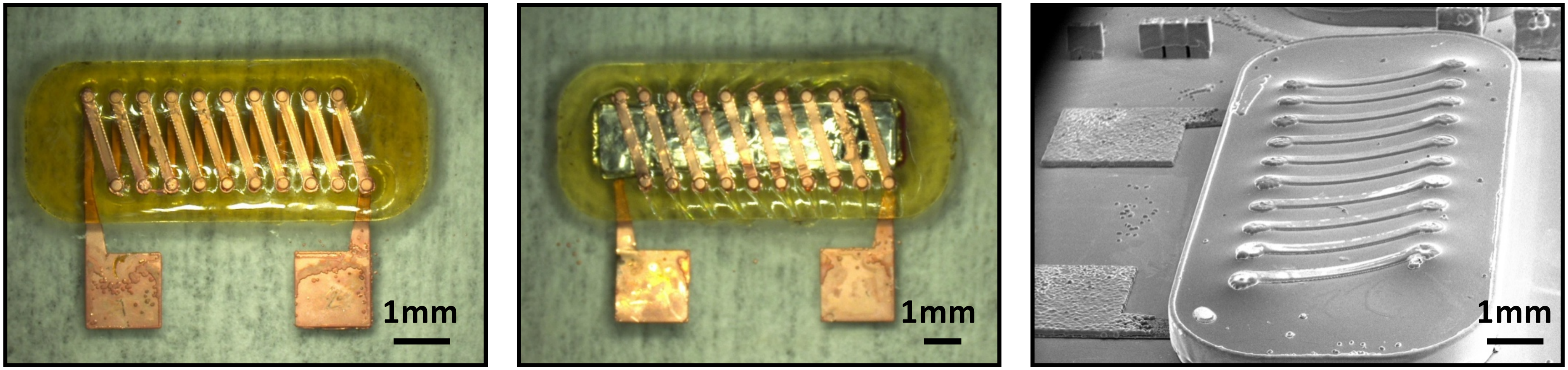


Core loss comparison

Loss at 500 mT peak = 600 W/cm^3
Loss at 40 mT peak = 4 W/cm^3

Solenoid Microfabricated Inductors

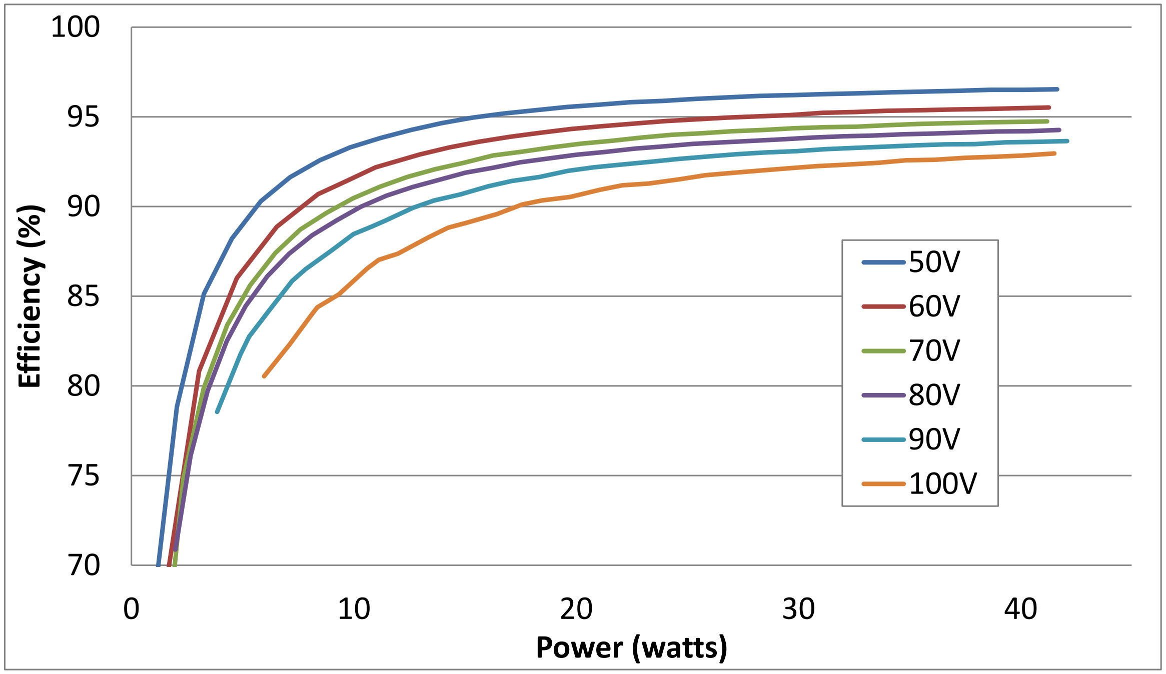
- Fabricated 10-turn microfabricated inductor (1mm tall)
  - Winding thickness ~70 µm
  - Air-core and Magnetic-core inductor
- Solenoid CoNiFe core
  - 300 layers with 1-µm-thick lamination



(left) microfabricated 10-turn solenoid air-core inductor.
(middle) microfabricated 10-turn solenoid inductor with CoNiFe multilayer core.
(right) SEM image of microfabricated 10-turn solenoid inductor.

Microfabricated Solenoid Inductors: Converter Test

- Tested in a power converter at MIT
- Power converter operating condition
  - 50 - 100V input operation, 3-8 MHz switching frequency, 10-45 W output power
- Efficiency of 97% at 50V input, and 93% at 100V input



Converter efficiency as a function of output power at various input voltages. Experimental measurements of a solenoid microfabricated inductor (9 turns, 2000 layers of 1µm-thick-CoNiFe core) tested in MIT's PowerChip power converter

Biographies and Reference

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Mark G. Allen received the B.A. degree in chemistry, the B.S.E. degree in chemical engineering, and the B.S.E. degree in electrical engineering from the University of Pennsylvania, Philadelphia, and the S.M. and Ph.D. degrees from Massachusetts Institute of Technology, Cambridge. In 1989 he joined the faculty of the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, ultimately holding the rank of Regents' Professor and the J.M. Pettit Professorship in Microelectronics, as well as a joint appointment in the School of Chemical and Biomolecular Engineering. In 2013 he left Georgia Tech to become the Alfred Fitler Moore Professor of Electrical and Systems Engineering and Scientific Director of the Singh Nanotechnology Center at the University of Pennsylvania. His research interests are in the development and the application of new micro- and nanofabrication technologies, as well as MEMS. A Fellow of the IEEE, Professor Allen received the IEEE 2016 Daniel P. Noble Award for contributions to research and development, clinical translation, and commercialization of biomedical microsystems.

Ref: Kim, Kim, Allen, et al., *IEEE Trans. Power Elec.*, vol. 30, no. 9, p. 5078-87, 2015