Losses in laminated thin-film magnetic materials considering displacement current

Charles R. Sullivan and Di Yao
chrs@dartmouth.edu

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

http://power.engineering.dartmouth.edu

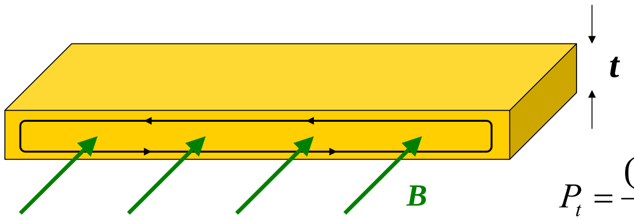
Introduction

Thin-film magnetic materials

- Magnetic materials are critical for integrated magnetics.
- Thin-film materials compared to ferrites:
  - Much higher saturation flux density (1~2 T).
  - Can have much lower hysteresis loss.
  - Much lower resistivity.
- Eddy current is an important loss mechanism.
- This is only one aspect of our work.

Introduction

Eddy-current loss in thin films

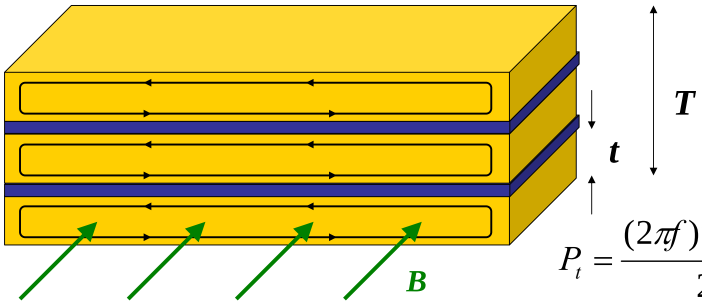


$$P_t = \frac{(2\pi f)^2 B_{peak}^2 V t^2}{24\rho}$$

- High resistivity ρ helps (e.g. nanogranular Co-Zr-O)
- Bigger thickness t :
  - Higher power handling
  - Higher loss (as t^3)

Introduction

Laminations

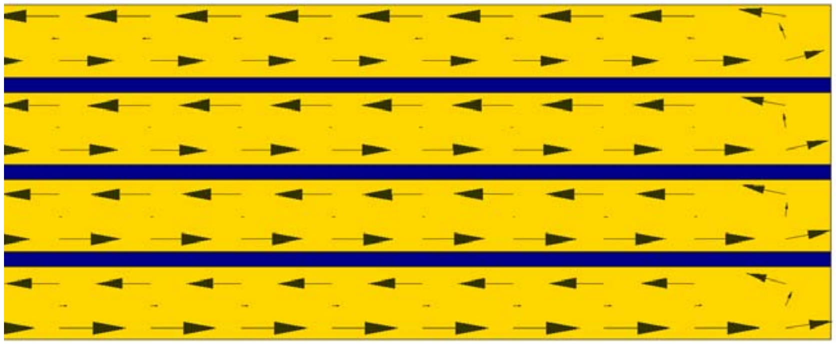


$$P_t = \frac{(2\pi f)^2 B_{peak}^2 V t^2}{24\rho}$$

- Higher power handling according to T
- Loss OK (as $T \cdot t^2$)

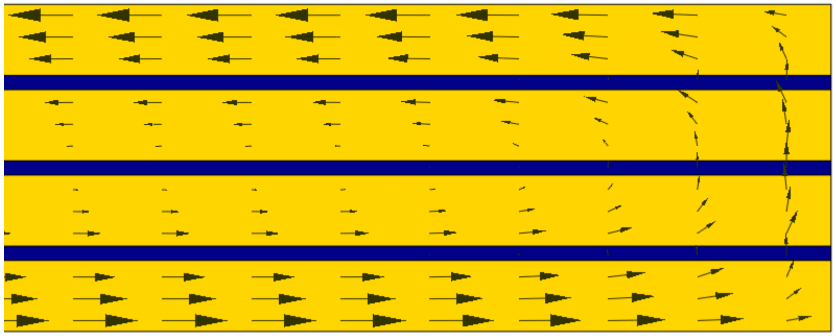
Introduction

Simulation



Introduction

Higher-frequency simulation



- Displacement current through dielectric
- Loss approaches single-slab loss

Introduction

Questions:

- When can we ignore displacement current?
- How can we predict loss with displacement current?
- What layer thicknesses give best performance?

➔Need loss model.

Introduction

Modeling approaches

- Lumped-circuit models
  - Can estimate where the effect is important.
  - Accurate loss model?
- Analytical modeling
  - No closed-form solution
  - Accurate loss model?
- Numerical methods (e.g. finite-element)
  - Can accurately model losses
  - Hard to use in design optimization

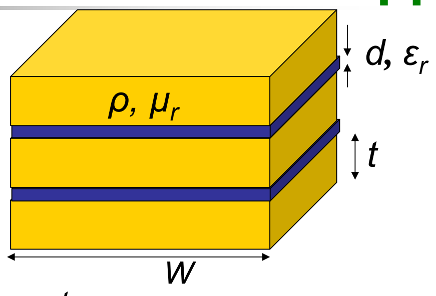
Our approach

- Curve-fit to finite-element results.
- Not “just a curve fit”
  - Match analytical results for limits:
    - Low displacement current (high-impedance dielectric layers) $P_t = \frac{(2\pi f)^2 B_{peak}^2 V t^2}{24\rho}$
    - High displacement current (low-impedance dielectric layers) $P_T = \frac{(2\pi f)^2 B_{peak}^2 V T^2}{24\rho}$
  - Simplify parameter space

Outline

- Introduction
- Collapsing the parameter space
- Curve fit
- Experimental verification
- Conclusions

Parameter space



- Eight parameters:
  - Frequency, *f*
  - Width, *W*
  - Number of layers, *n*
  - Thickness of magnetic layers, *t*
  - Thickness of dielectric layers, *d*
  - Relative permittivity of the dielectric, ε_r
  - Resistivity of the magnetic material, *ρ*
  - Relative permeability of the magnetic material, μ_r

Hypothesis

In the range of interest, two parameters:

- Number of layers *n*,
- Frequency ratio $f/f_c = \hat{f}$ where $f_c = \frac{TD}{\varepsilon_r \varepsilon_0 \rho W^2}$

are adequate to determine a power ratio

$$F_p = \frac{P_e}{P_T}$$

Actual loss

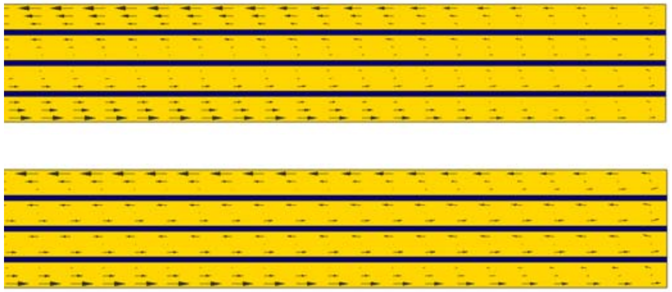
Loss based on total thickness

i.e,

$$F_p = F_p\left(n, \frac{f}{f_c}\right) = F_p\left(n, \hat{f}\right)$$

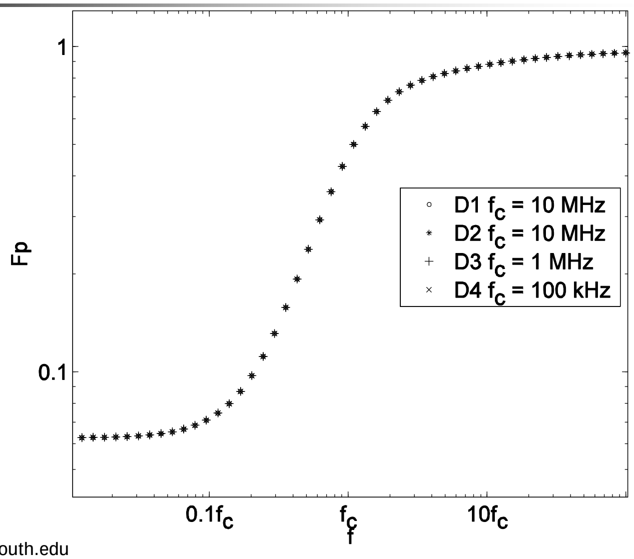
Testing the hypothesis

- COMSOL finite-element simulations.
- 2460 simulations with systematically varied parameter values.



Testing the hypothesis

- 4 sample data sets shown, all four layers
- Not all match this well, but
- We can define a region in which they match within 2%



Region of validity

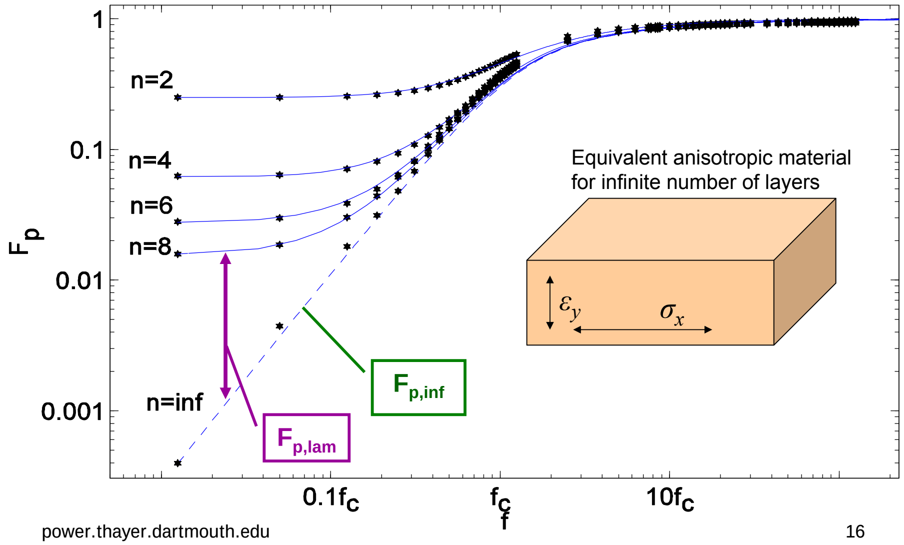
We can describe the loss by

$$F_p = \frac{P_e}{P_T} = F_p\left(n, \frac{f}{f_c}\right) = F_p\left(n, \hat{f}\right)$$

with under 2% error when

- Most flux is in magnetic material $\mu_r t/d \geq 100$
- Much wider than thickness $W/(T+D) > 20$
- Thinner than half a skin depth $T+D < \delta/2$

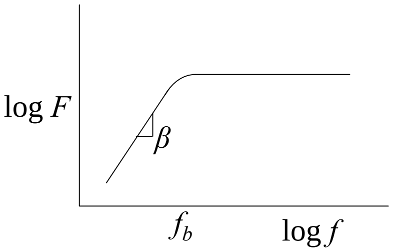
Curve fit



Curve fit

Curve fit functions

- “Dual Slope”



$$F(f) = k\left[\frac{f}{\left(f_b^a + f^a\right)^{1/a}}\right]^{\beta} \approx \begin{cases} k\left[\dfrac{f}{f_b}\right]^{\beta} & \text{for } f \ll f_b \\ k & \text{for } f \gg f_b \end{cases}$$

Curve fit

Final curve fit

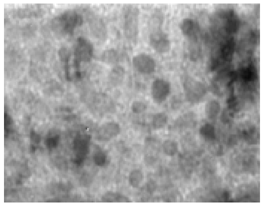
$$F_p\left(\hat{f}, n\right) = \underbrace{\left[\frac{\hat{f}}{\left(1+\hat{f}^a\right)^{1/a}}\right]^b \cdot \frac{\hat{f}}{\left(1+\hat{f}^d\right)^{1/d}}}_{\boxed{F_{p,inf}}} + \underbrace{\frac{1}{n^2} \cdot \frac{1}{\left(1+\hat{f}^e\right)^{1/e}}}_{\boxed{F_{p,lam}}}$$

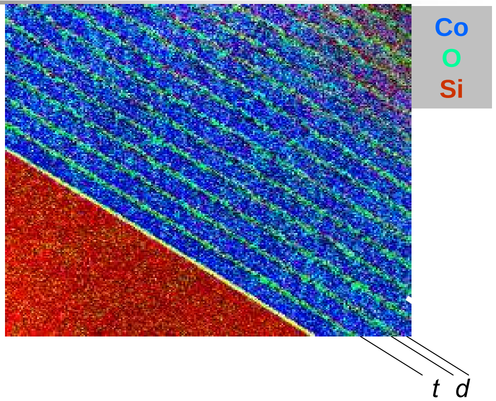
- Maximum error: 10%

Experimental verification

Material tested: Co-Zr-O

- Nano-granular composite:
- Co particles in Zr-O matrix
- High resistivity compared to metallic films (~300 μΩ cm)





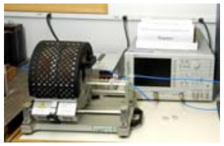
Tested thicknesses (not shown):

t = 100 nm d = 20 nm

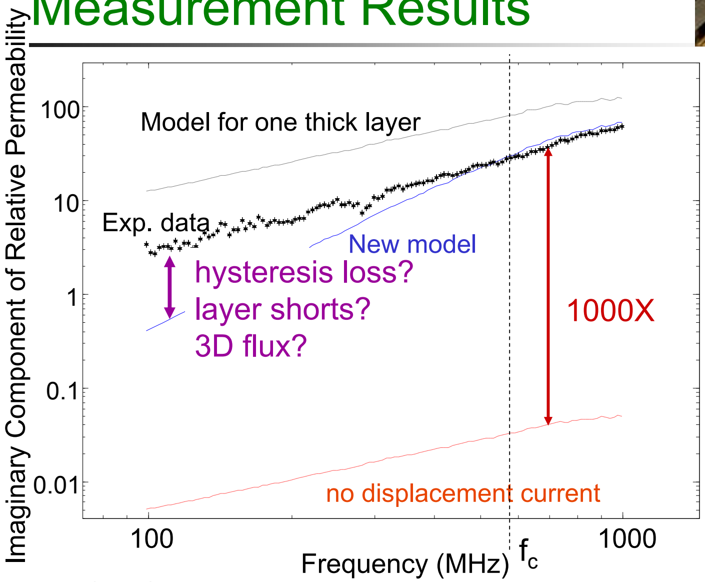
Total 50 layers; 6 μm

Experimental verification

Measurement Results

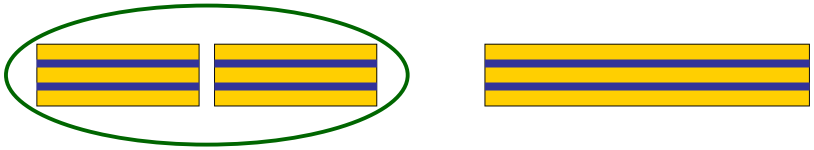


Ryowa PMF-3000 permeameter

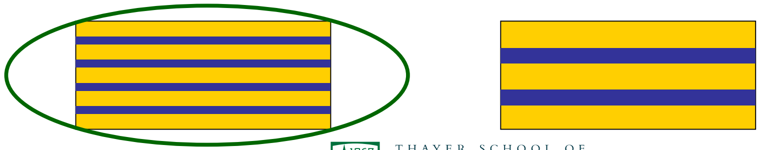


Design implications

- Smaller width helps:

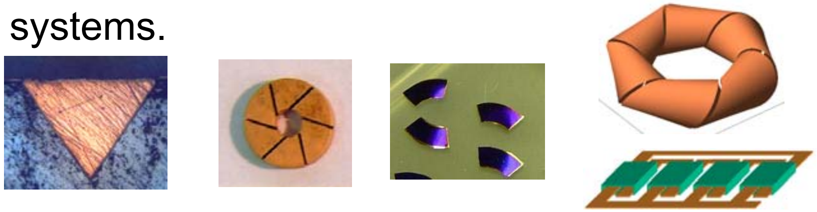


- For same total thickness of insulation (*D*) and magnetic material (*T*), finer divisions are better:



Main result

- Simple formula accurately calculates loss in multilayer films including effect of displacement current.
- Can use in design and optimization of processes, devices, circuits and systems.



Not addressed (future work)

- Loss estimation for out-of-plane flux.