Losses in laminated thin-film magnetic materials considering displacement current

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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

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

$Laminations$

- 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
Introduction

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)
    - High displacement current (low-impedance dielectric layers)
  - Simplify parameter space

Introduction

Collapsing the parameter space

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, \( \varepsilon_r \)
  - Resistivity of the magnetic material, \( \rho \)
  - Relative permeability of the magnetic material, \( \mu_r \)

Outline

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

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

\[
F_P = \frac{P_e}{P_T}
\]

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.

**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**

Equivalent anisotropic material for infinite number of layers
Curve fit functions

- "Dual Slope"

\[ F(f) = k \left( \frac{f}{f^a_b \cdot (f^a_b + f^a)} \right)^\beta \]

\[
\begin{align*}
F(f) & = k \left( \frac{f}{f^a_b} \right)^\beta & \text{for } f \ll f^\beta_b \\
& \approx k \left( \frac{f}{f^a_b} \right)^\beta & \text{for } f \gg f^\beta_b
\end{align*}
\]

Final curve fit

\[
F_p(\hat{f}, n) = \left( \frac{\hat{f}}{1 + \hat{f}^a_b} \right)^{1/a} \cdot \left( \frac{\hat{f}}{1 + \hat{f}^d_a} \right)^{1/d} + \frac{1}{n^2} \cdot \left( 1 + \hat{f}^c_e \right)^{1/e}
\]

- Maximum error: 10%

Material tested: Co-Zr-O

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

Tested thicknesses (not shown):
- $t = 100$ nm
- $d = 20$ nm
- Total 50 layers; 6 $\mu$m

Measurement Results

- Ryowa PMF-3000 permeameter
- New model
- Hysteresis loss?
- Layer shorts?
- 3D flux?
- 1000X
- No displacement current

Experimental verification
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.