Integrated Transformers with Laminated Magnetic Cores

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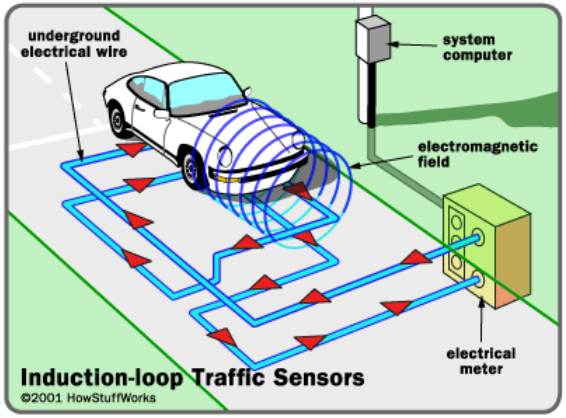
November 16, 2012

Outline

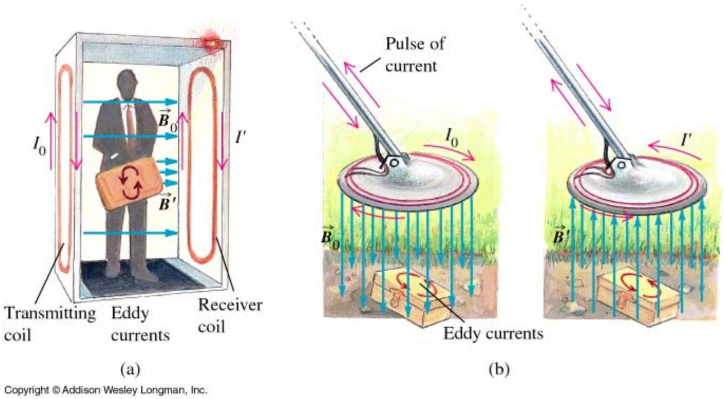
- Background
- Theory
- Materials
- Layout
- Measurement
- Results
- Conclusion

Use of Magnetics in our Everyday Lifes

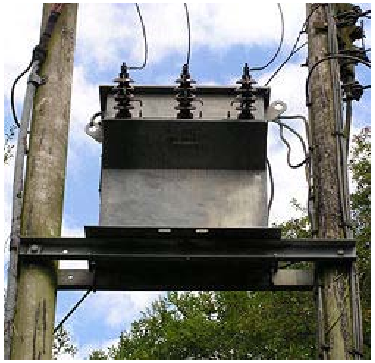
- Traffic lights
- Red-light cameras

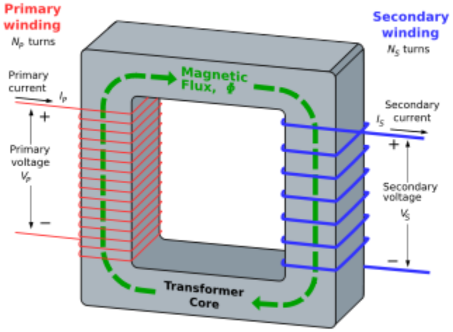


- Metal detectors

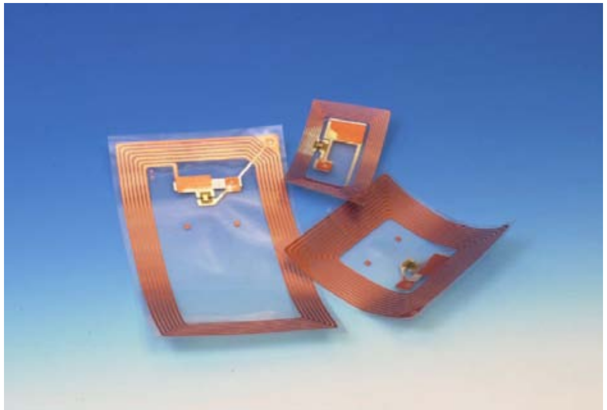


- Transformers



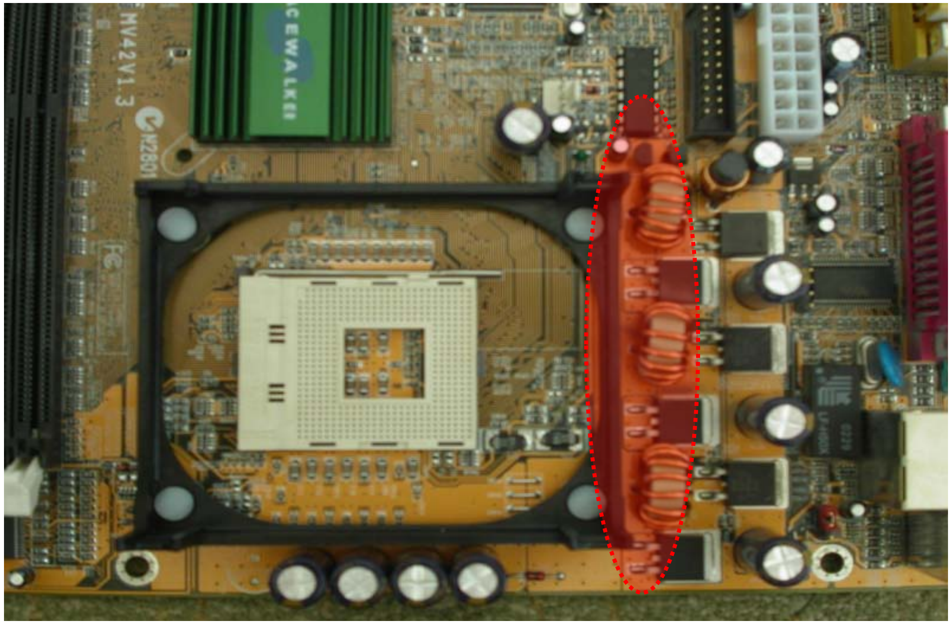


- RFID tags

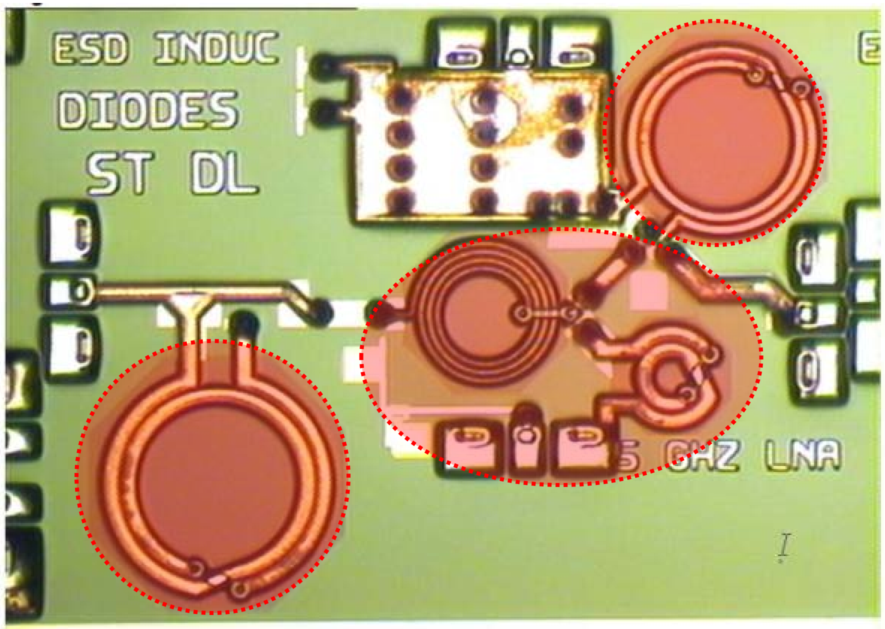


Texas Instruments Tag-it™

And in Electronics…



Voltage regulator module (VRM)

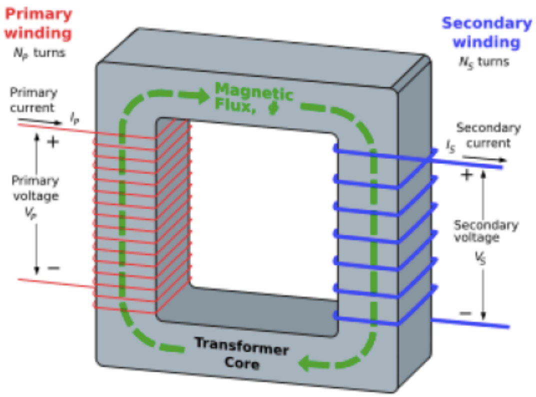


IMEC 5 GHz low noise amplifier

Transformers

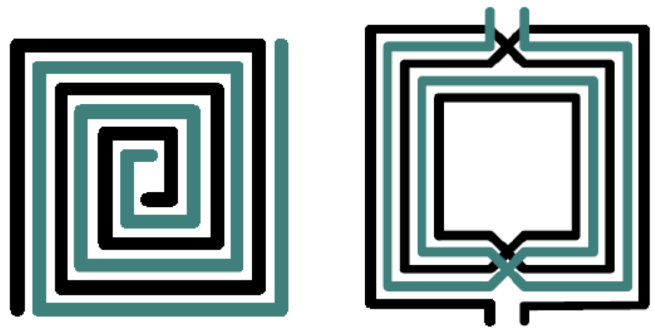
- Transformer: a device that transfers electrical energy from one circuit to another through inductively coupled electrical conductors.

Classical transformer

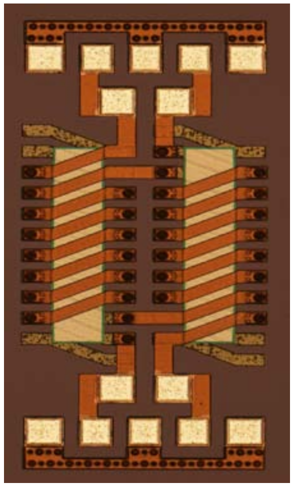


$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Planar spiral transformer



Integrated Solenoid



- A transformer is used for:
  - Voltage gain/reduction using turn ratios between the primary and secondary windings ($V_1/V_2 = N_1/N_2 = I_2/I_1$)
  - Impedance matching through turn ratios ($R_1/R_2 = (N_1/N_2)^2$)
  - Ground isolation, can be performed using a 1:1 transformer, or with various turn ratios for a voltage change.

Transformers vs. Inductors

- Mutual inductance is

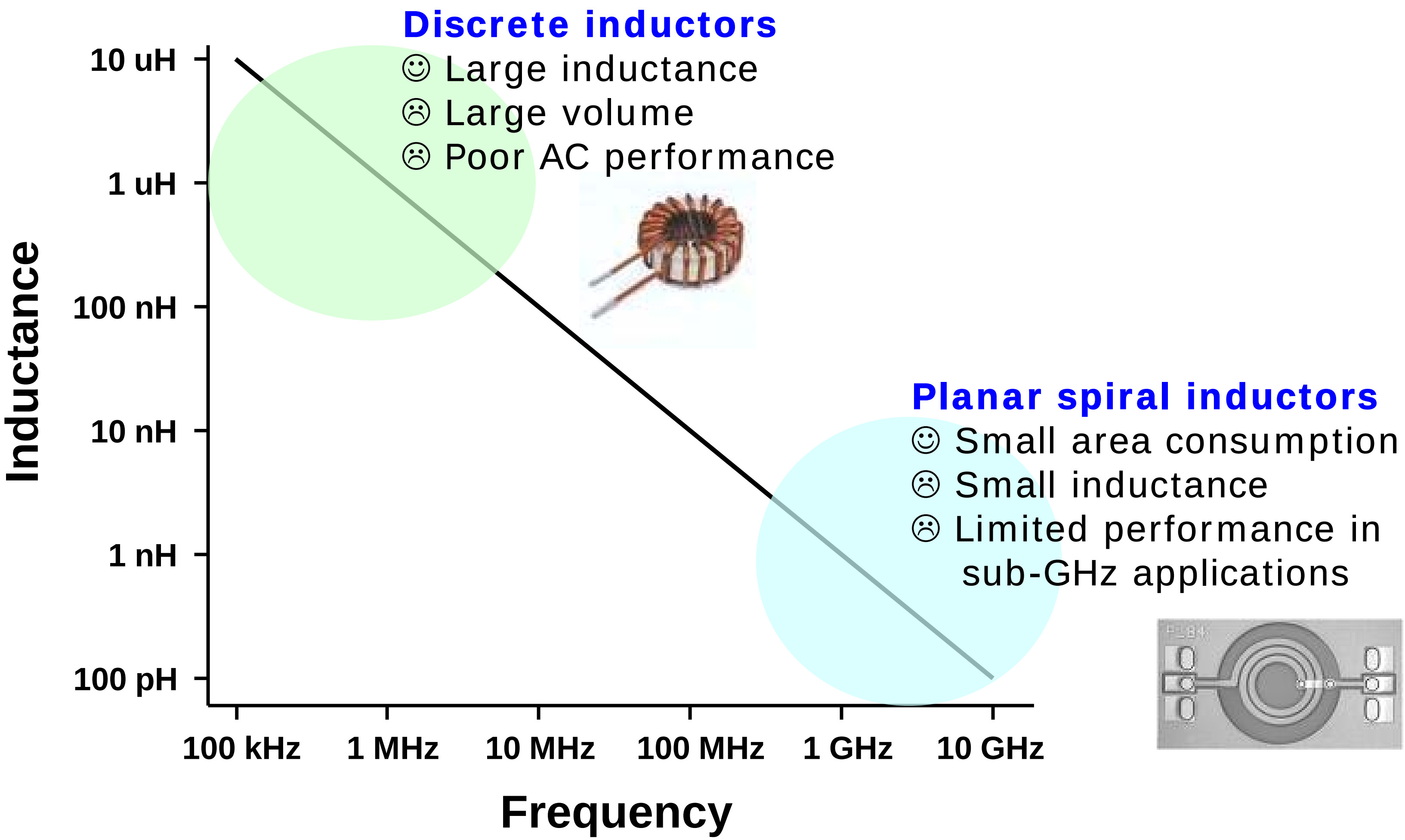
$$M = k\sqrt{L_1 L_2}$$

- For 1:1 turn ratio transformers

$$M = kL_1 \text{ if } L_1 = L_2$$

- Large primary and secondary inductances (per area) beget large mutual inductances (per area)!

Inductance & Frequency Tradeoff

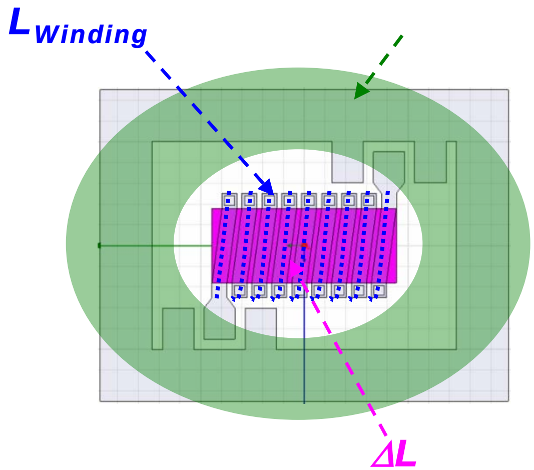


From A. Ghahary, "Fully integrated DC-DC converters," Power Electronics Technology, Aug. 2004

Solenoid Inductance

- Inductance of air core (AC) inductor:

$$L_{AC} = L_{Winding} + L_{Parasitic}$$



- Inductance of magnetic inductor: $L_{MC} = L_{AC} + \Delta L$

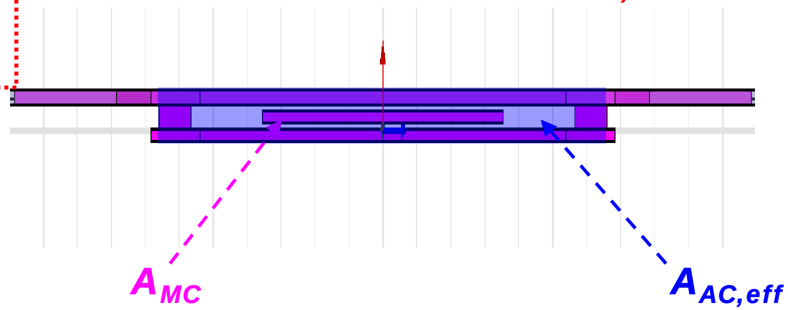
  - Solenoid inductor: $\Delta L = \frac{\mu_0 \mu_r N^2 w_M t_M}{l_M [1 + N_d(\mu_r - 1)]} = \frac{\mu_0 \mu_{eff} N^2 w_M t_M}{l_M}$

  where $\mu_{eff} \equiv \frac{\mu_r}{1 + N_d(\mu_r - 1)}$ **Due to the demagnetization effect**

- Inductance enhancement:

$$\frac{\Delta L}{L_{AC}} = \frac{L_{MC} - L_{AC}}{L_{AC}} \approx \mu_{eff} \frac{A_{MC}}{A_{AC,eff}}$$

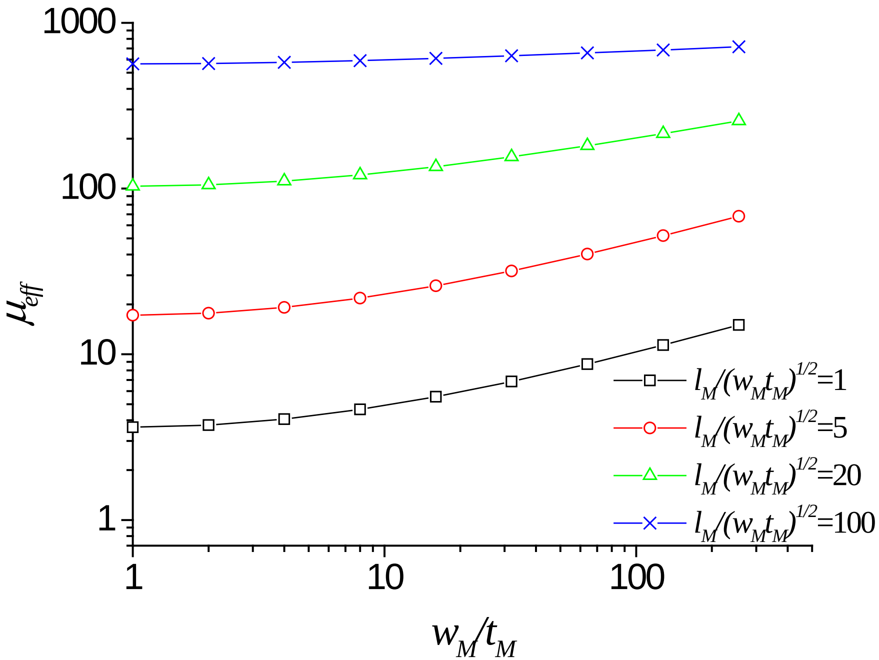
Gain much less than μ_r, but still significant.



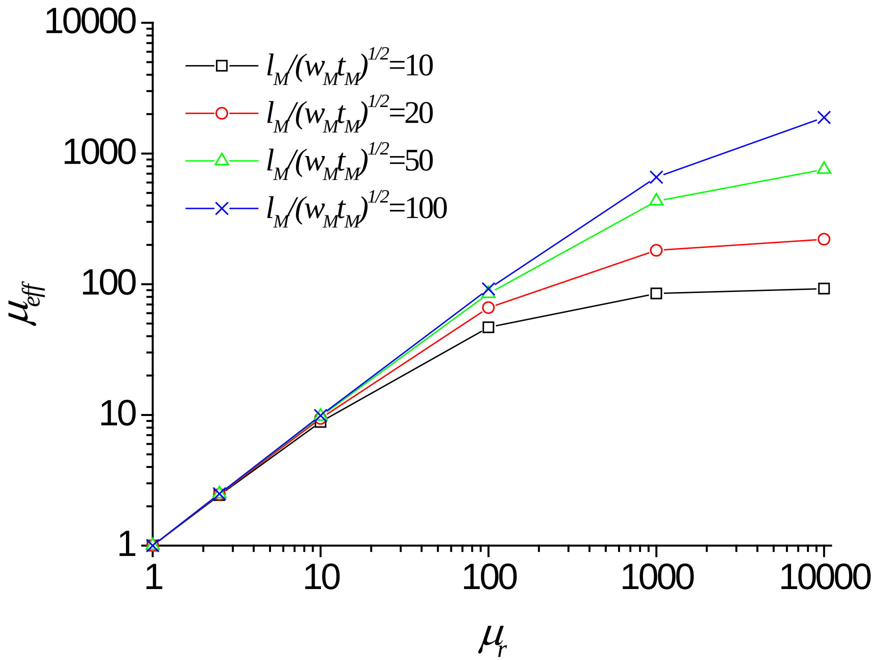
Ref.: D.W. Lee, K.-P. Hwang, S.X. Wang, IEEE Trans. Mag., 44, 4089-95, 2008.

Effective Permeability

μ_r = 1000



w_M/t_M = 64



- $l_M >> (w_M t_M)^{1/2}$ is preferred to maintain a high effective permeability, and greater inductance enhancement.
- The demagnetization effect is more severe for a higher μ_r.

Quality Factor Q & Fundamental Tradeoff

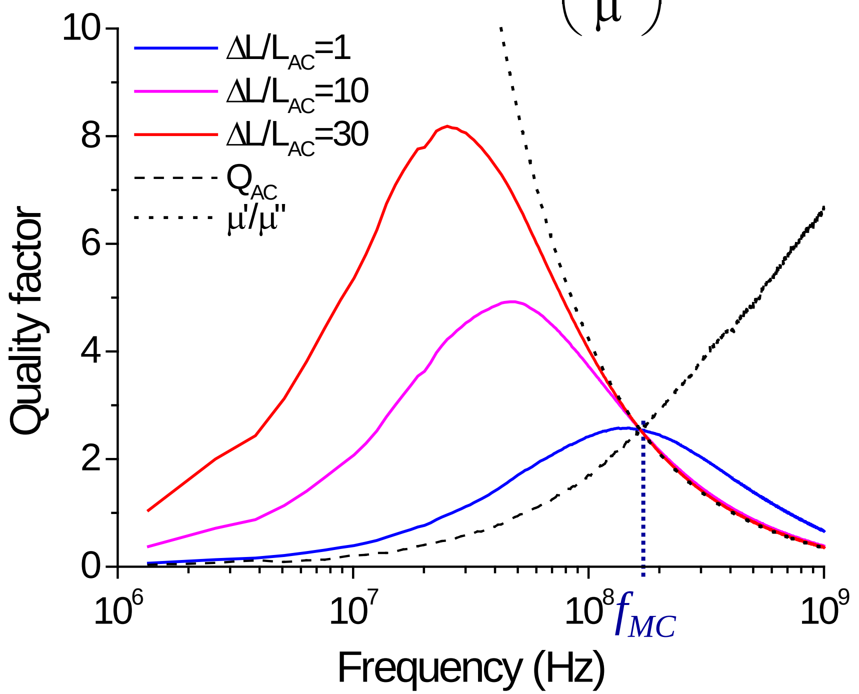
- Quality factor of air core inductor: $Q_{AC} = \omega \frac{L_{AC}}{R_{AC}}$

- Quality factor of magnetic inductor: $Q_{MC} = \omega \frac{L_{MC}}{R_{MC}} = \omega \frac{L_{AC} + \Delta L}{R_{AC} + \omega \left(\frac{\mu''}{\mu'} \right) \Delta L}$

→ If ΔL is very small, Q_{MC} becomes close to $Q_{AC} = \omega L_{AC}/R_{AC}$. If ΔL is very large compared to L_{AC}, Q_{MC} approaches the permeability ratio μ'/μ'' of the magnetic core.

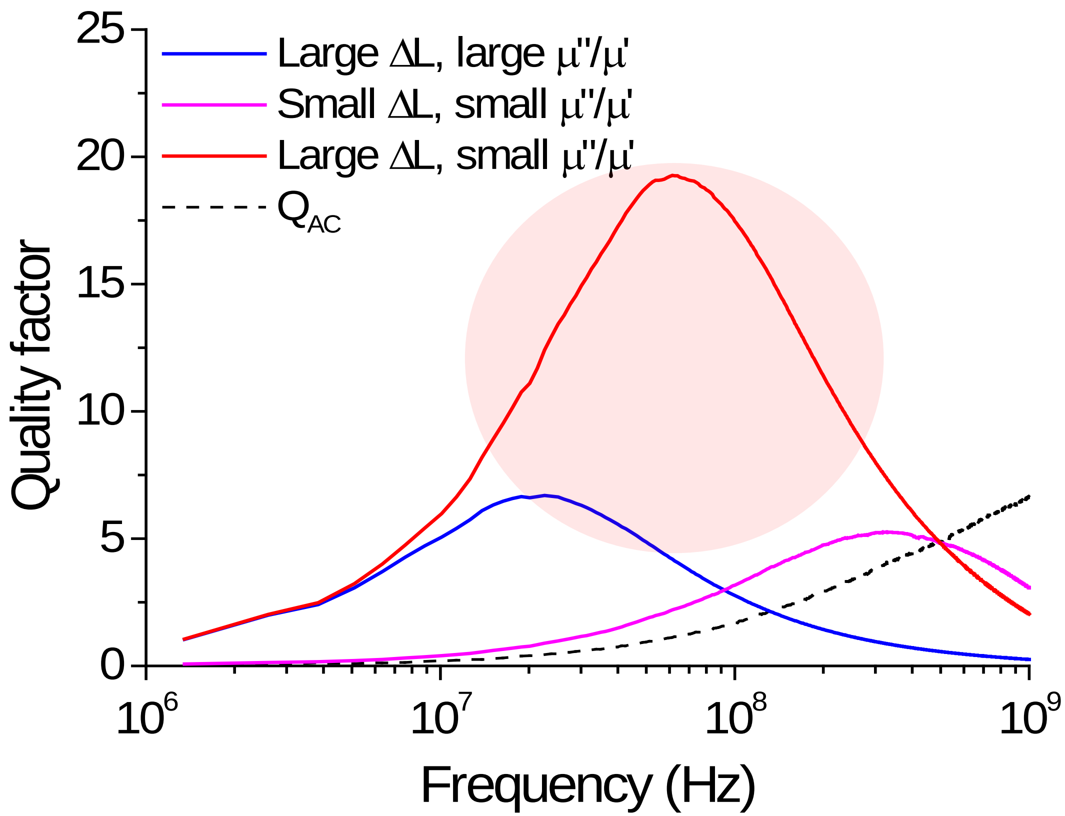
→ Q_{MC} is higher than Q_{AC} below the frequency f_{MC} at which Q_{AC} and μ'/μ'' cross each other, and Q_{MC} becomes less than Q_{AC} beyond this cross-over frequency. Hence f_{MC} can be considered as the useful bandwidth of the magnetic inductor.

→ **Larger Q values are obtained at lower frequencies for a given magnetic core.**



Ref.: D.W. Lee, K.-P. Hwang, S.X. Wang, IEEE Intl. Magnetics Conf., 2008

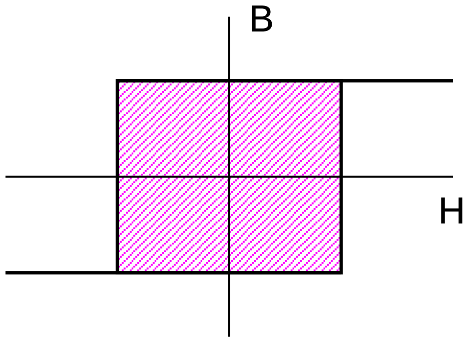
Directions for Magnetic Inductors/Transformers



- The reported device properties tend to have either large ΔL with large μ''/μ' or small ΔL with small μ''/μ'. The case of large ΔL with small μ''/μ' would be desirable to increase the quality factor and the useful bandwidth of the magnetic inductors and transformers.

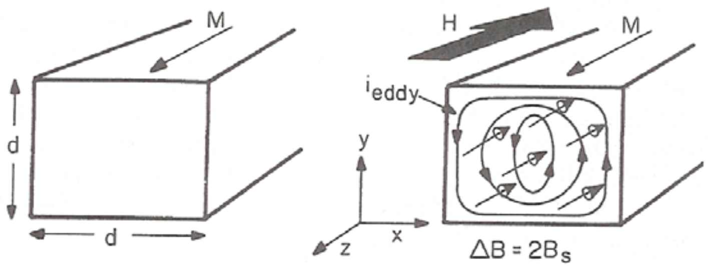
Materials- Loss Mechanisms

- Hysteresis loss:
  - The area inside the B-H loop is the energy lost per unit volume per cycle
  - Power loss = Frequency x Loop area



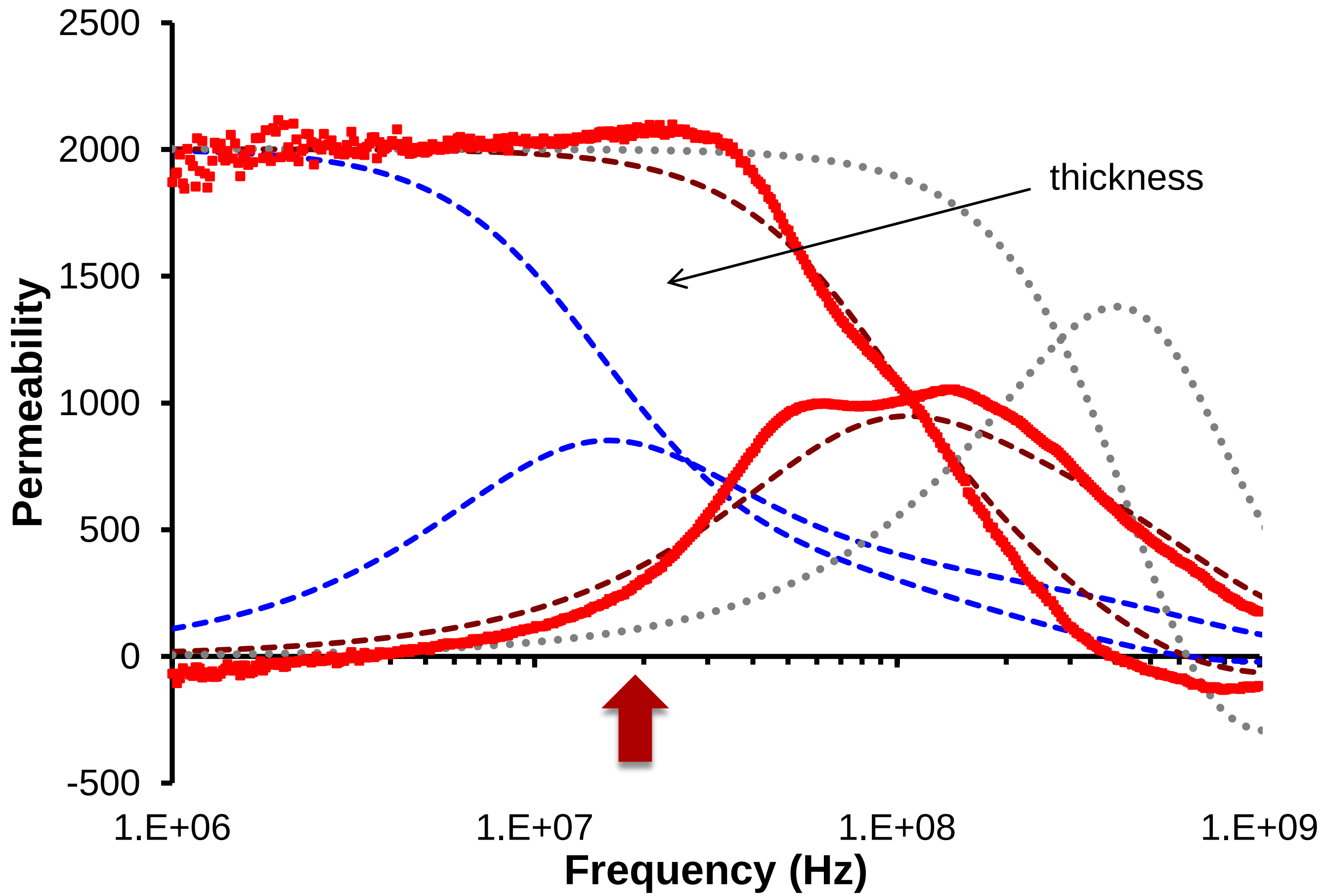
- Eddy current loss:
  - The change in the flux density causes the eddy current such that it opposes the initial flux changes
  - Classical eddy current loss:

$$\frac{P_{eddy\ current}}{vol} = \frac{\omega^2 B_m^2 d^2}{48\rho}$$



- Ferromagnetic resonance loss:
  - Imaginary permeability significantly increases as the operation frequency approaches the FMR frequency.

Materials- Theory of Laminations



Fitting Equations:

$$\delta = \frac{1}{\sqrt{\pi \sigma \mu_i \mu_0 f}}$$

$$\mu_r = \mu_i \frac{(1-i)}{d/\delta} \frac{e^{(1+i)d/\delta} - 1}{e^{(1+i)d/\delta} + 1}$$

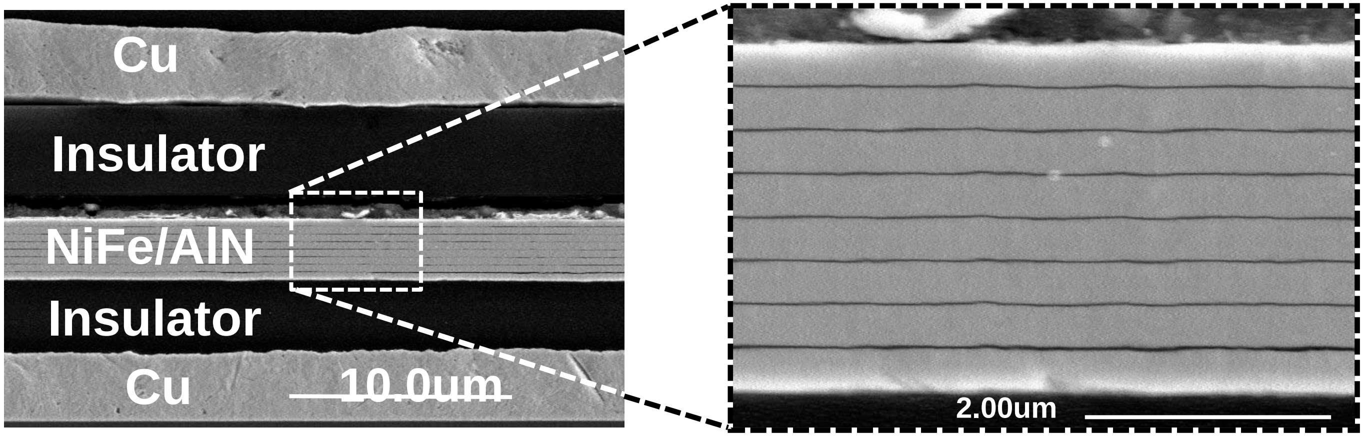
$$\mu_i = \mu' - i\mu''$$

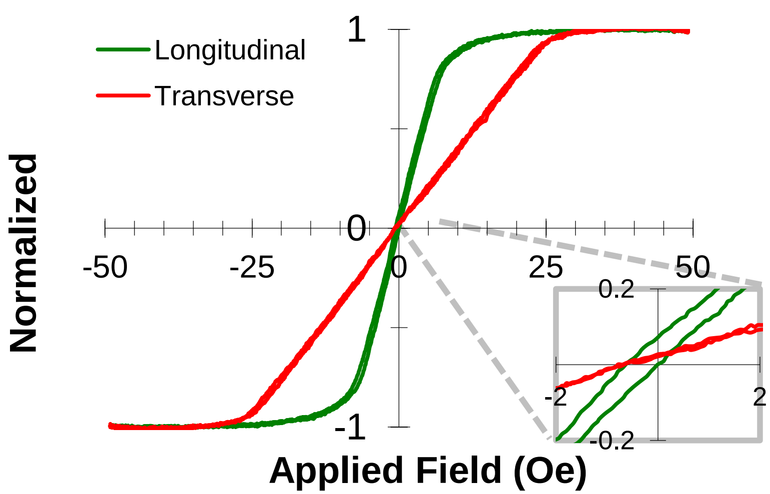
$$= \frac{\omega_m(\omega_k + \omega_m + i\omega\alpha)}{(\omega_k + i\omega\alpha)(\omega_k + \omega_m + i\omega\alpha) - \omega^2} + 1$$

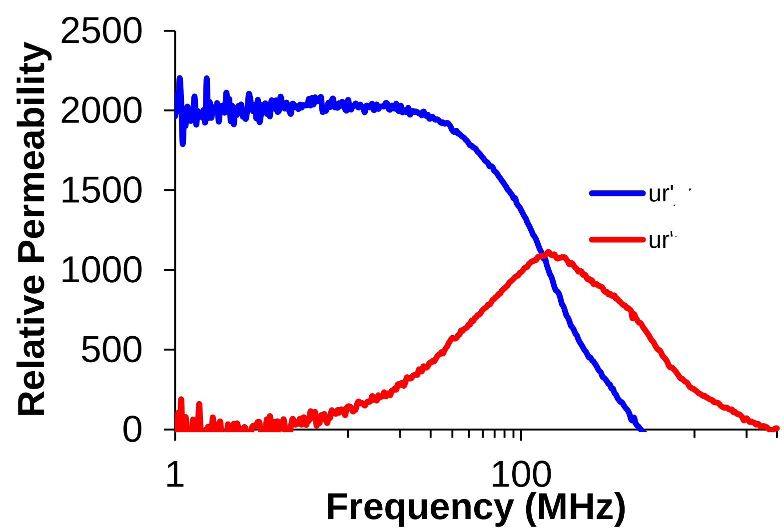
Ref: E. V. D. Riet and F. Roozeboom J. Appl. Phys., vol. 81, Jan. 1997.

Fabricated Laminated Film

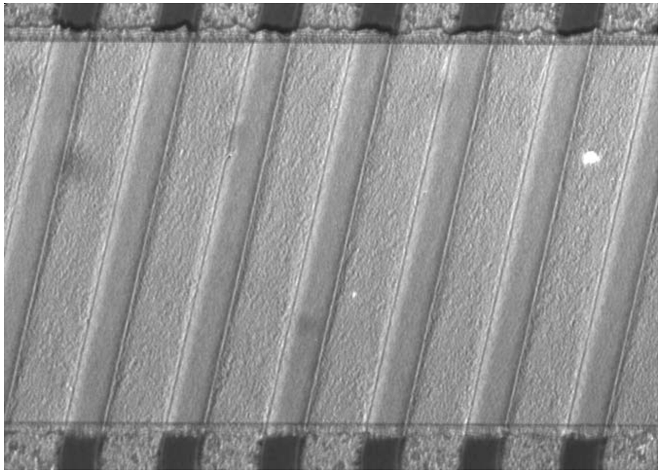
- Properties measured on sample fabricated on the wafer



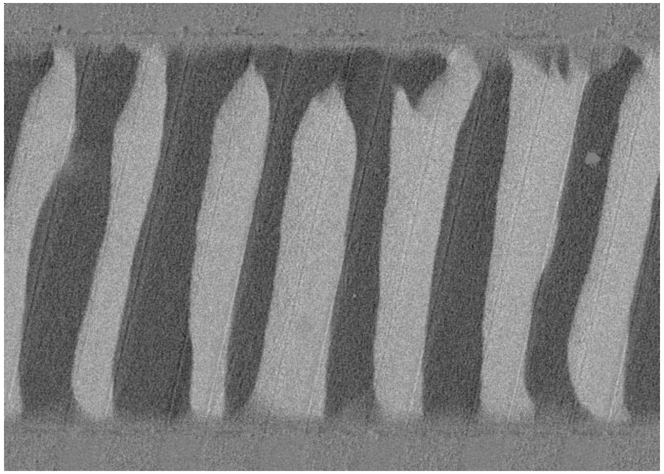




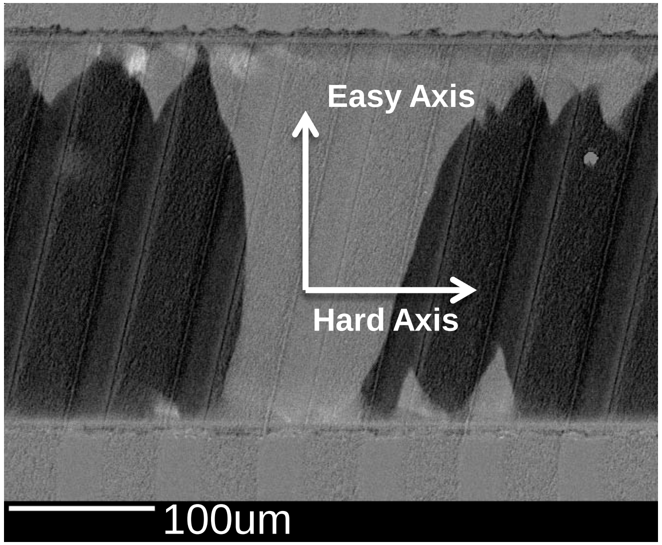
Kerr Domain Images



Background Image



Kerr Image – Hard Axis Excitation

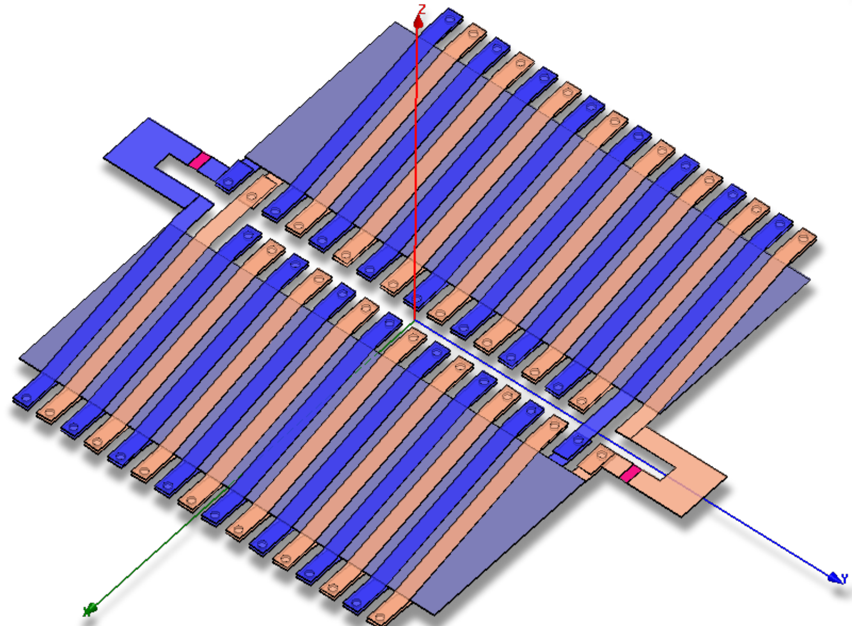


Kerr Image – Easy Axis Excitation

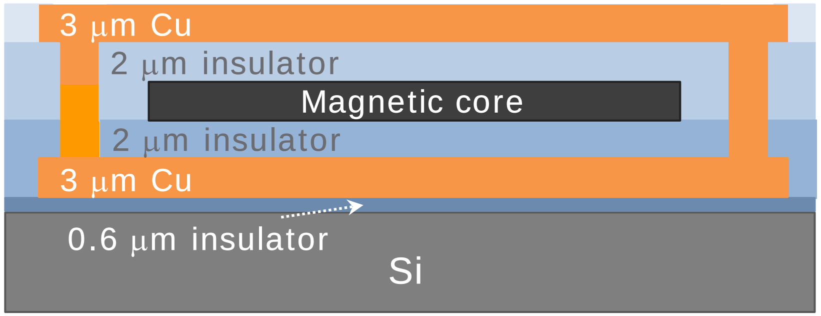
- For operation, field is applied along the hard axis
- Domain patterns are not affected by the underlying coil patterning

Device Design

- Solenoid-style transformer
  - Interleaved coils, 2 series
  - 4/8/16 turns per series
- Cu coils
  - 40 um wide, 3 um thick
- $Ni_{81}Fe_{19}$ Core
  - $[NiFe_{(350nm)}/AlN_{(7nm)}]_8$
  - 2.8/5.6 um thick
  - 150/300/500 um wide
- Vias
  - 7 um total thickness
  - 2 um below core, 2 um above
  - 30 um diameter



16 Turn Transformer
500 um wide core

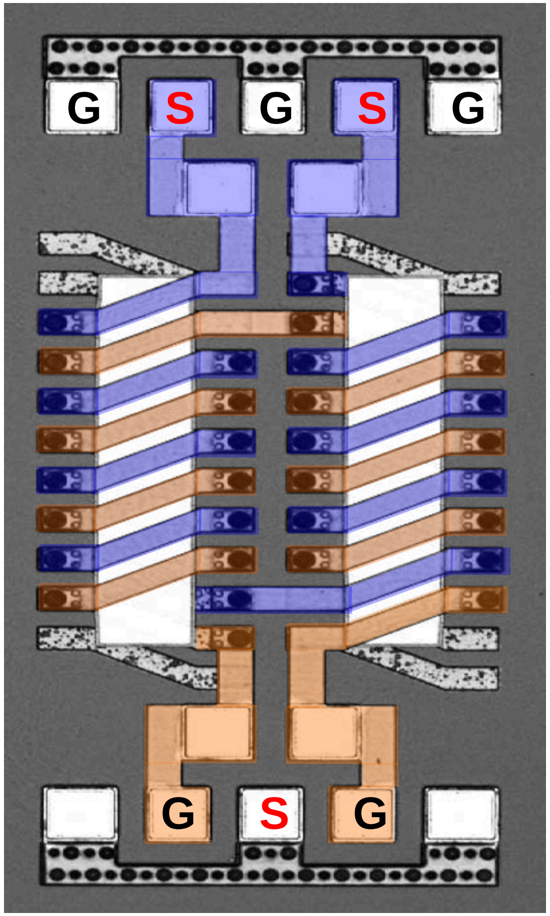


Measurement Methods

- 2-Port Measurement
  - Measure primary with secondary open
  - Measure primary with secondary short
  - Remove pad parasitics using open-short de-embedding structures

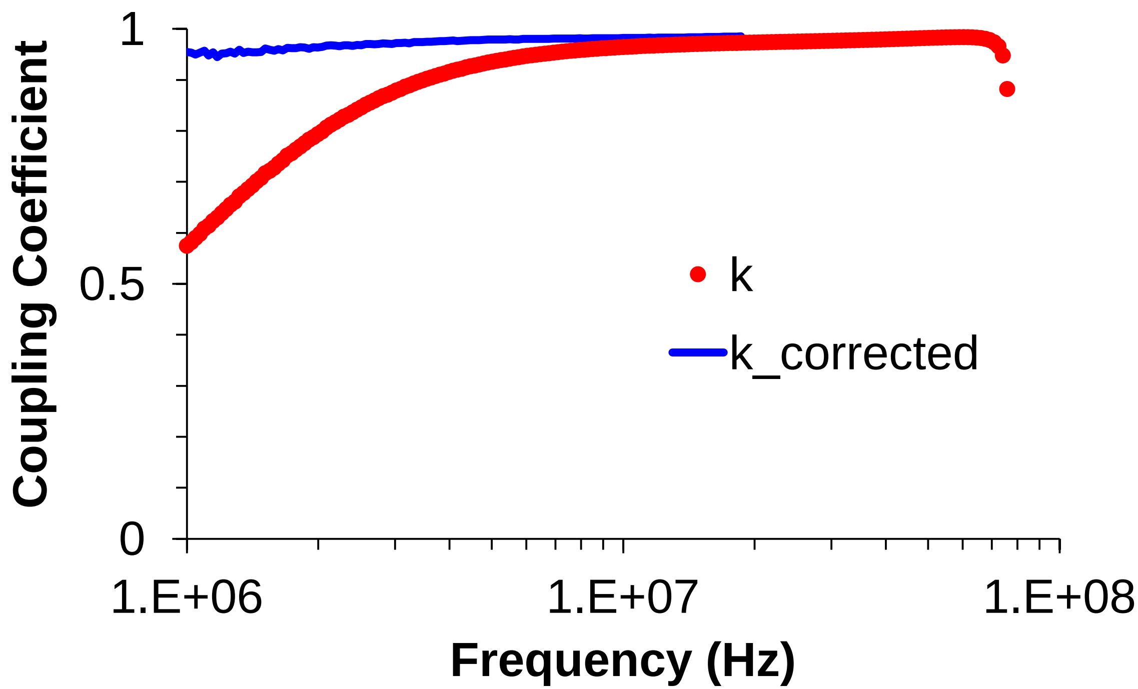
For $L_1=L_2$, and Q >> 1:

$$k \approx \sqrt{1-\frac{L_{open}}{L_{short}}}$$



Coupling Coefficient- Correction

- Measured device has 300 um wide x 5.6 um thick core, with 32 turns (16 turns per solenoid)
- k = 0.97 at 20 MHz (peak Q without the correction)

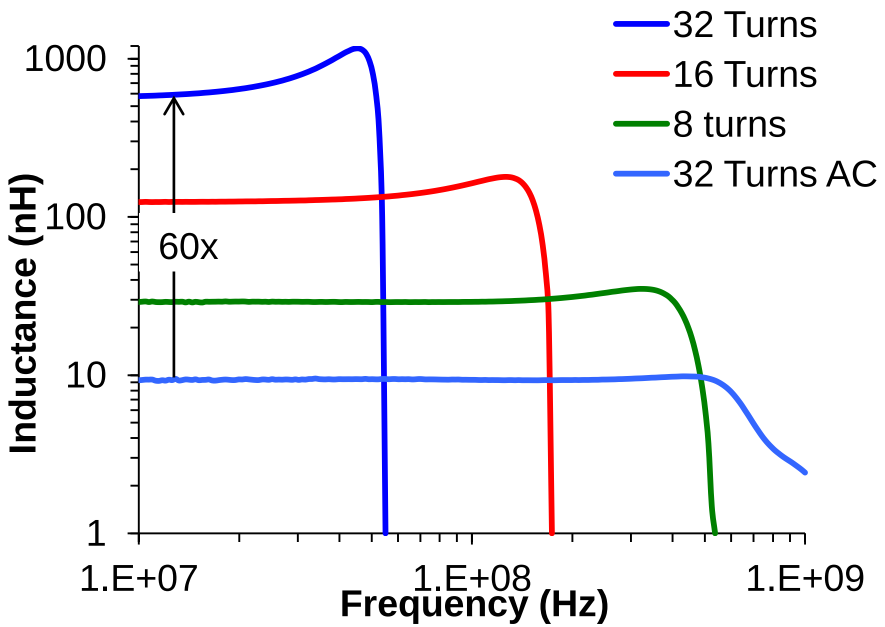


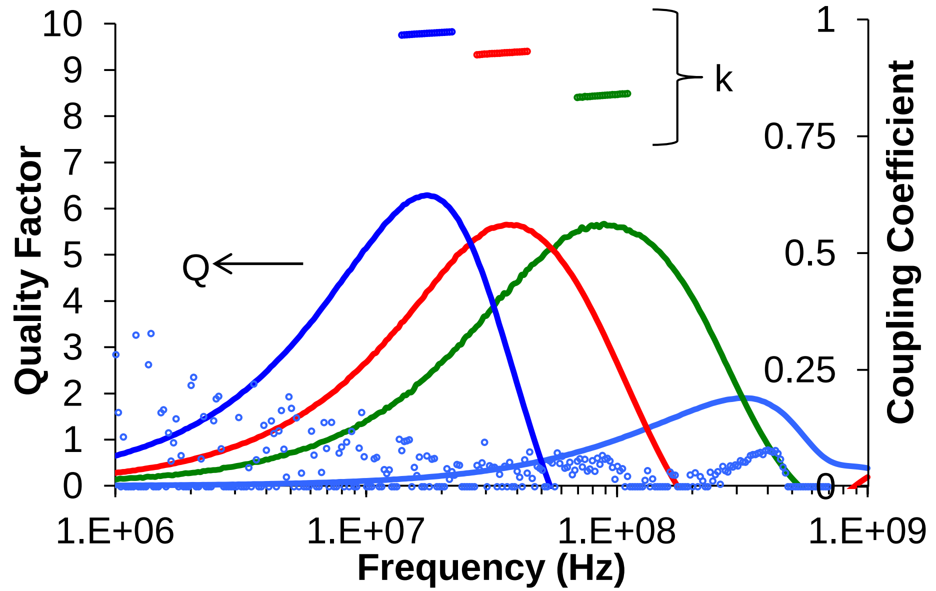
$$For\,Finite\,Q:$$

$$k_{corrected} = \sqrt{\left(1-\frac{L_{short}}{L_{open}}\right)\left(\frac{1+Q^2}{Q^2}\right)}$$

$$= \sqrt{k\left(\frac{1+Q^2}{Q^2}\right)}$$

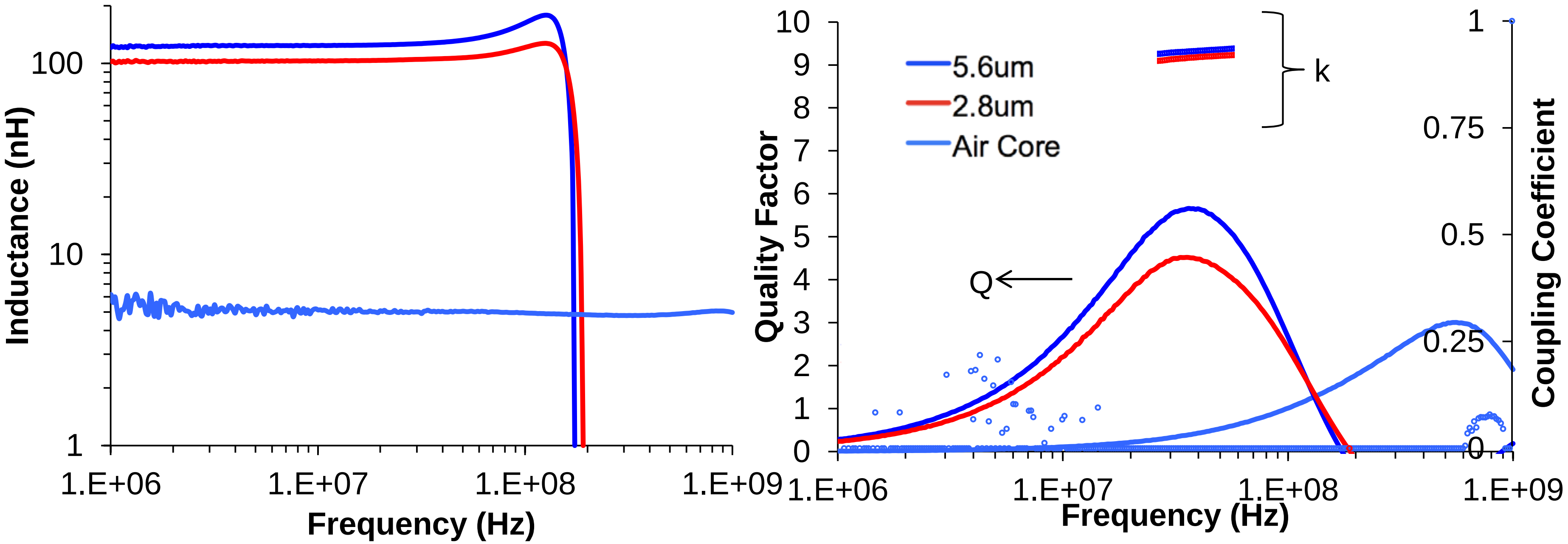
Device Properties vs. N





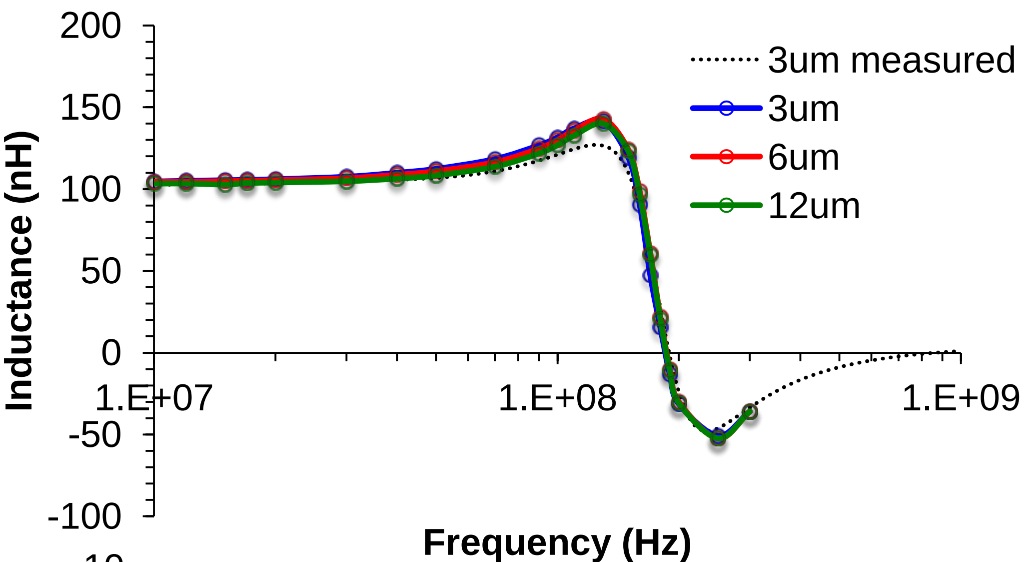
- All devices have: 500 um wide x 5.6 um thick core, two coils in series
- Coupling coefficient is measured at Q_{peak} without correction
- **32-turn transformer has inductance enhancement by 60x over air-core, and a nearly perfect coupling coefficient at 0.97**
- Air core device had negligible coupling across frequency

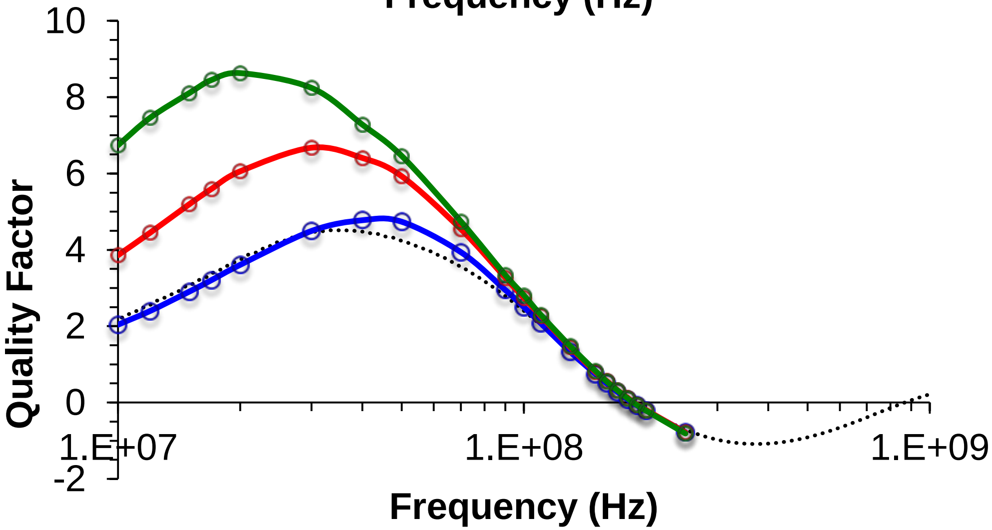
Device Properties vs. Film Thickness



- All devices have: 500 um wide core with 16 turns, two coils in series (8 turns per solenoid)
- **Thicker core leads to more enhancement in inductance. Inductance enhancement in 16-turn transformer (>~20x) is more limited by the demagnetization field than that in 32-turn transformer (>~60x).**

Device Properties vs. Coil Thickness





- **Thicker coils do not change inductances, but can increases the quality factor for slightly lower frequencies**
- High frequency quality factor is determined by magnetic core losses and the AC losses in Cu coils**:**

$$Q_{MC} = \omega \frac{L_{MC}}{R_{MC}} = \omega \frac{L_{AC} + \Delta L}{R_{AC} + \omega \left(\frac{\mu''}{\mu'} \right) \Delta L}$$

- **Quality factor is also limited by the LC resonance.**

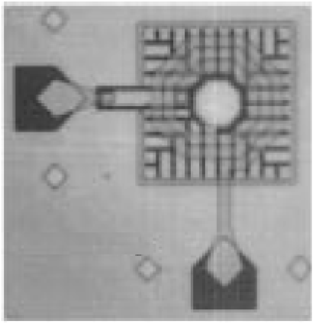
Conclusion

- **High-performance integrated magnetic transformers were successfully designed and fabricated:**
  - Inductance enhancement of 60× over the air core equivalent, the inductance density reached 178 nH/mm^2, and a peak quality factor of 6.3.
  - Compact thin film transformers with coupling efficiency >0.97

- **Analytical and numerical models can accurately describe the actual device properties**:
  - The fundamental trade-offs (ΔL vs ΔR) of the integrated magnetic inductors and transformers can be well understood and utilized for optimal design.
  - Magnetic materials selection and characterization by permeameter and Kerr microscope are important for device design and experimental trouble shooting.

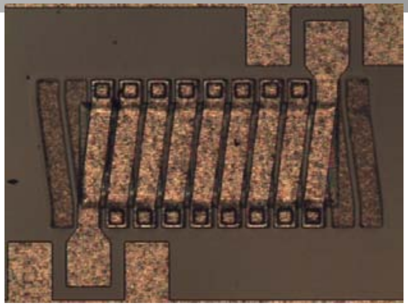
Backup Slides

Magnetic Inductors/Transformers for Power Conversion Fabricated by Stanford Collaboration



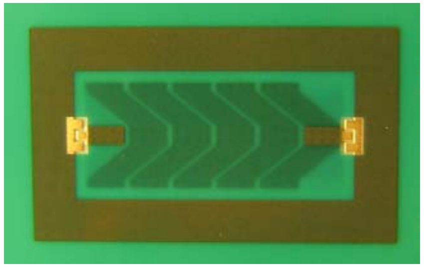
A.M. Crawford, et al.
IEEE Trans. Magn.
2002, p.3168-70

Planar spiral inductor with CoTaZr core, CMOS compatibility, Q ~ 2.7 @ 1 GHz



D. W. Lee, et al.
IEEE Trans. Mag., 44, 4089-95, 2008

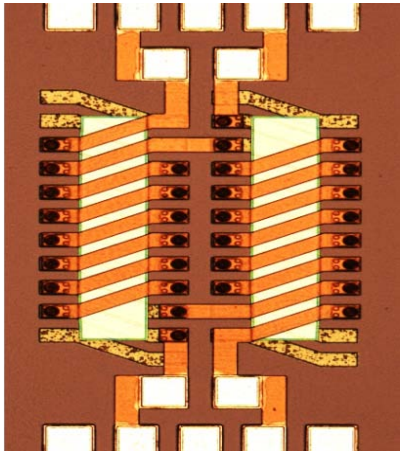
Planar solenoid inductor with CoTaZr core,
Inductance enhancement over air core = 34x
Q>6 @ 26 MHz



L. Li, D. W. Lee, et al.

IEEE Trans. Advanced Packaging, 32(4), 780-787, 2009

On-package solenoid inductor with CoFeHfO core, Q = 22 @ 200~300 MHz, R_{dc} ~ 10 mΩ



Magnetic transformers with laminated NiFe/AlN cores