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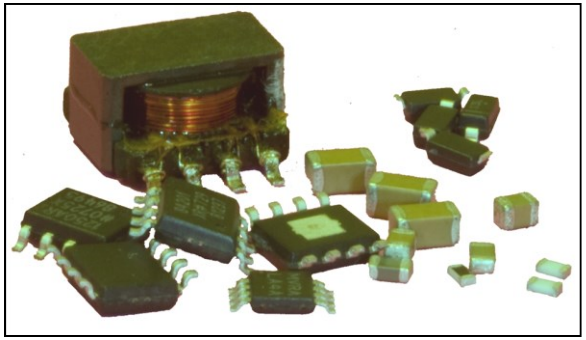
Air Core and Magnetic Core Transformers for Isolated Power Conversion

BAOXING CHEN

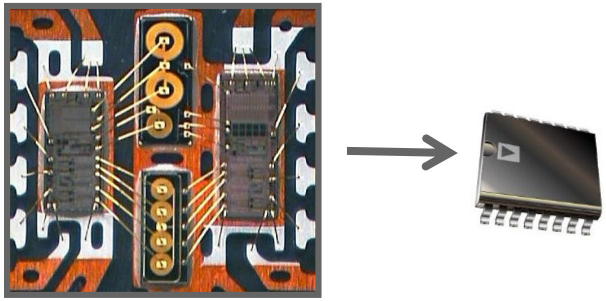
10/03/2016

PWRSOC Madrid 2016

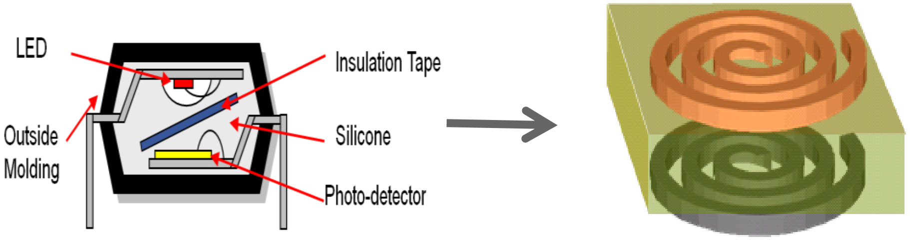
Micro-Transformers Replace Discrete Transformers, Diodes & Opto-couplers



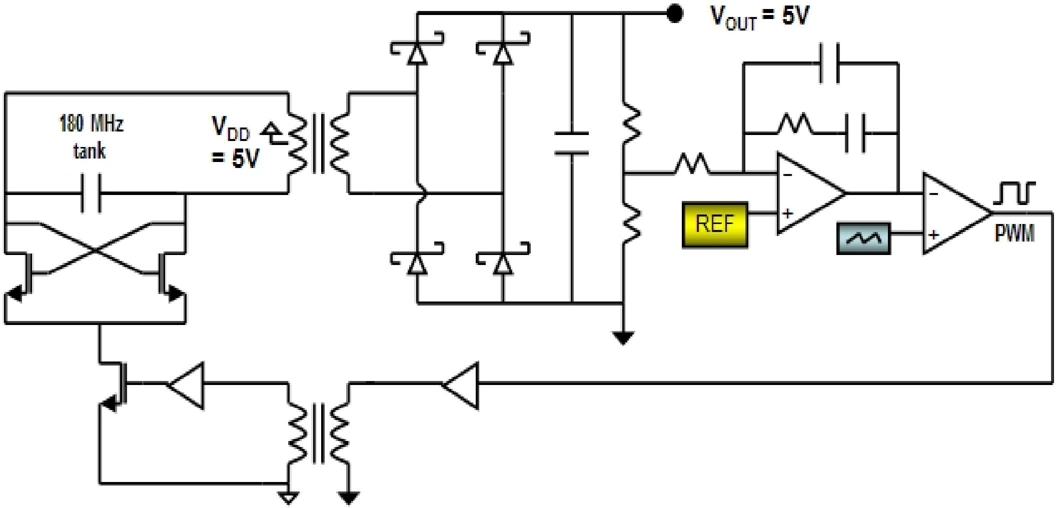
Conventional, Discrete Solution



½ W Isolated Power & 4 High Speed Data Channels



High speed, low power and integration



- High-freq energy conversion
- low-freq energy regulation

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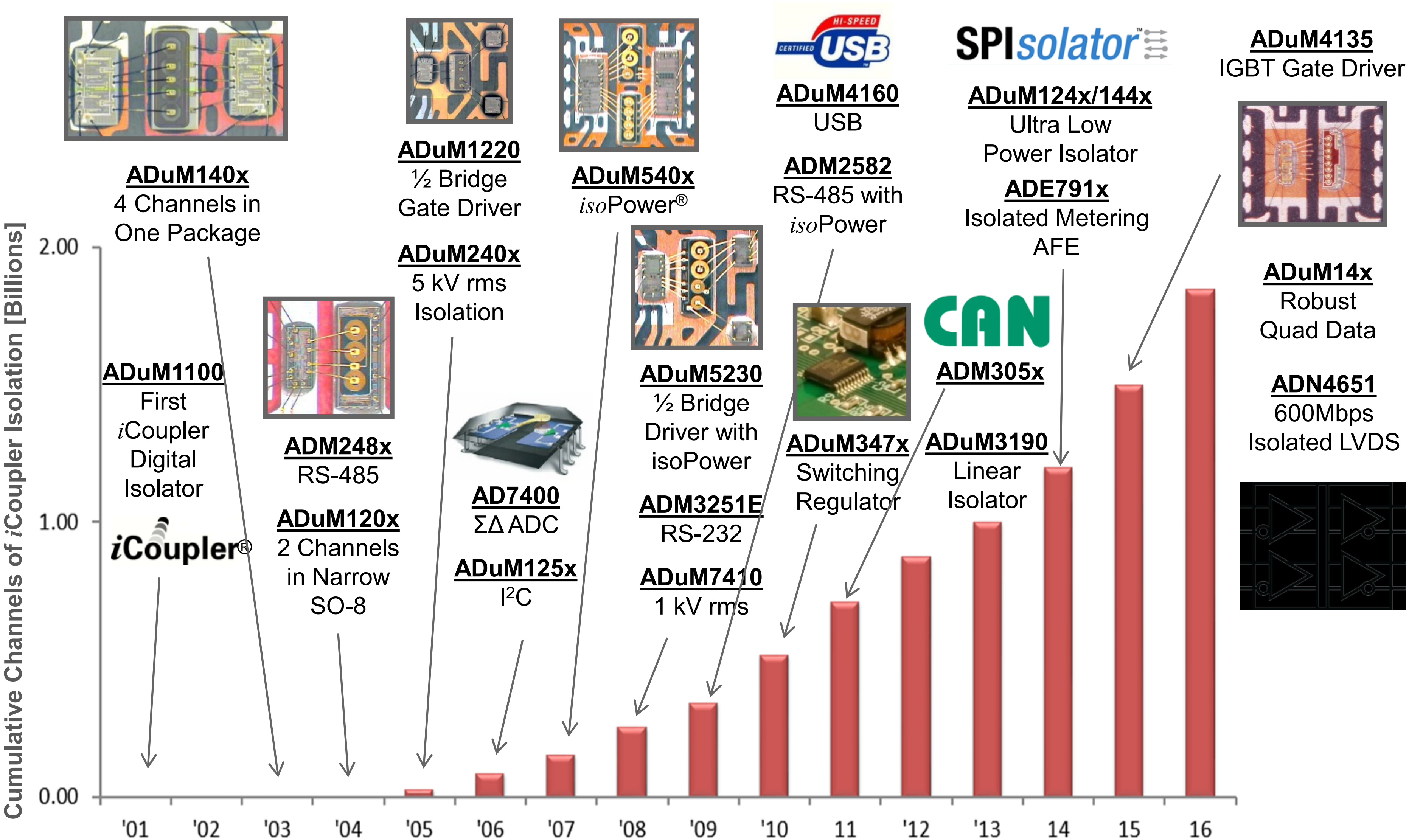
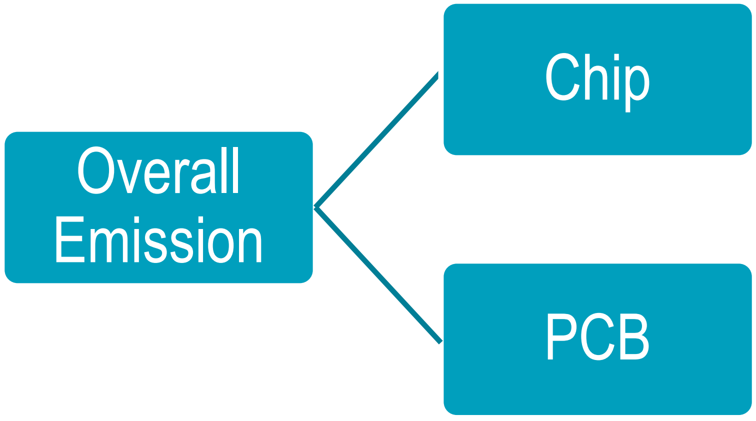
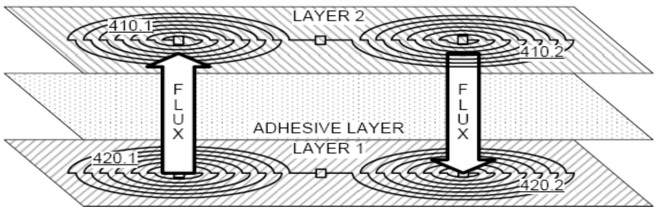
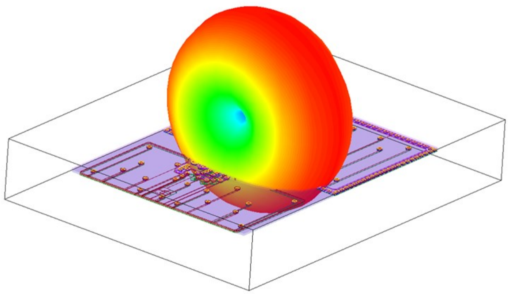
Micro-Transformers Enable Signal and Power Isolation: >1.8 Billion Micro-Transformers Have Been Shipped

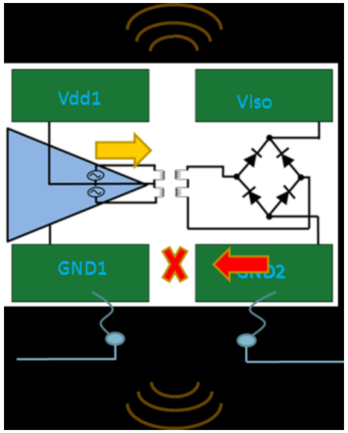


Power Transformer Radiation Minimized Through Anti-Phase Center Tape But PCB Radiation Needs Mitigation

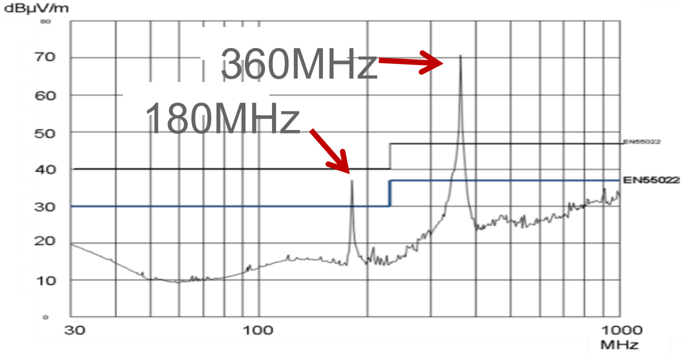


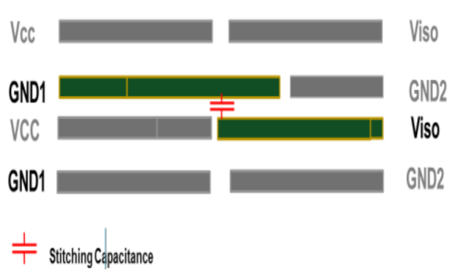




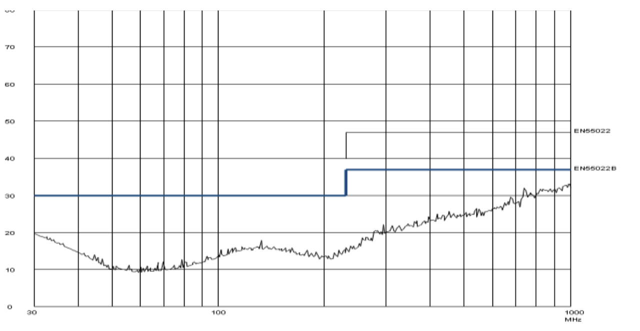


No PCB Suppression techniques

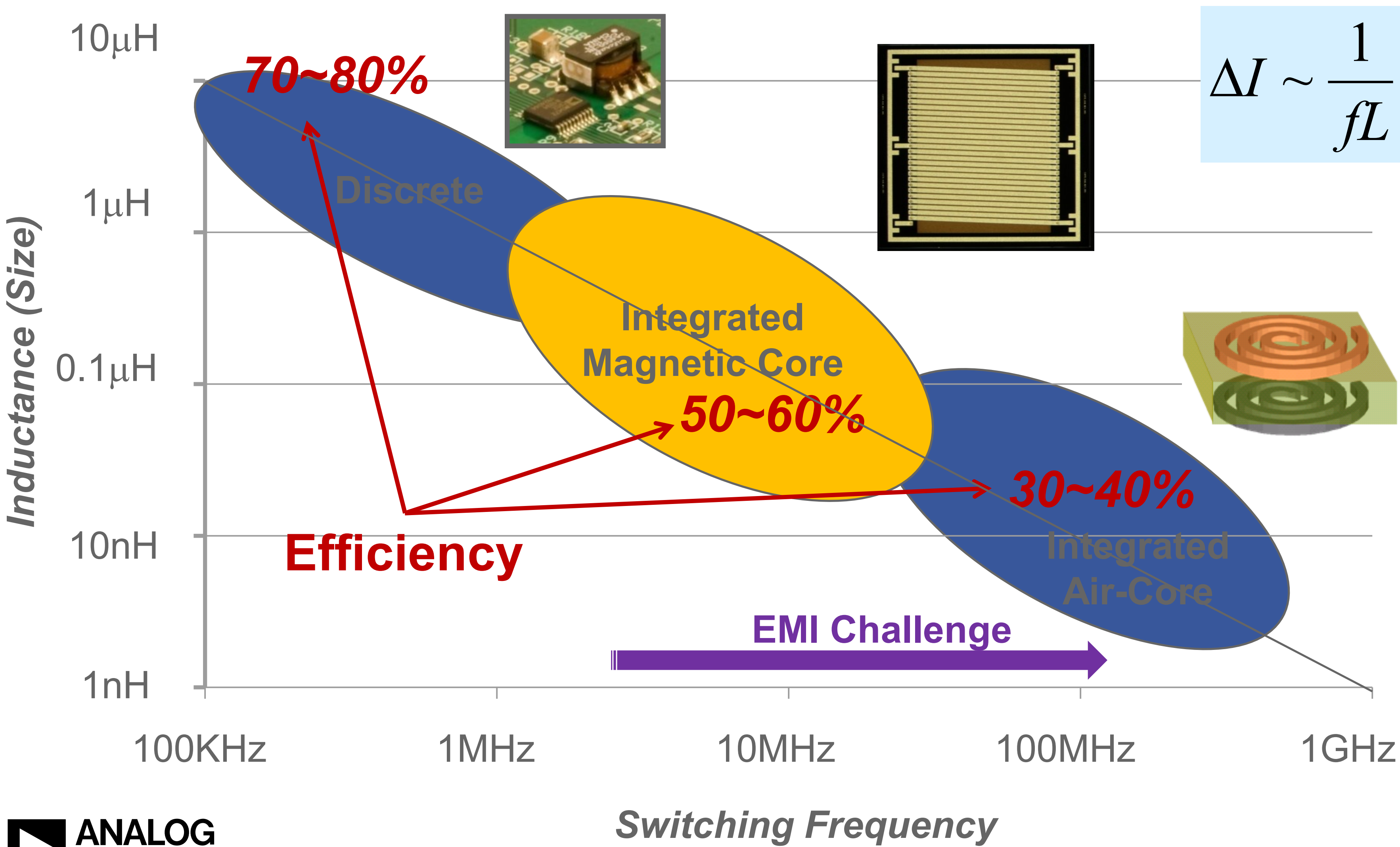




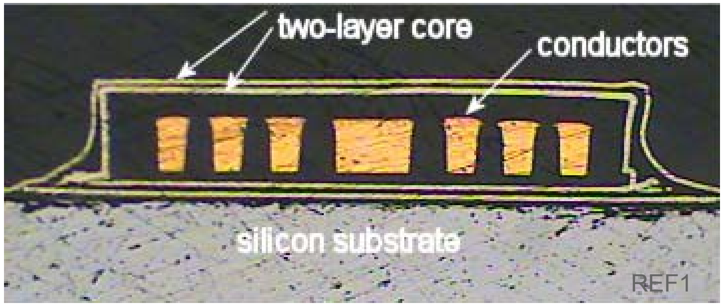
PCB Suppression techniques

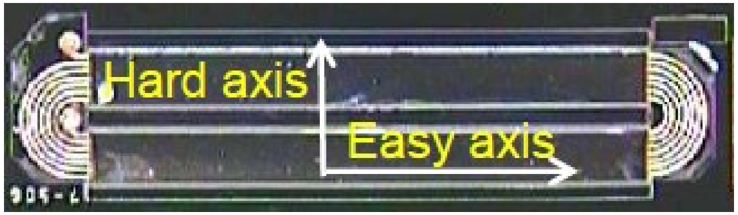


Integrated Magnetics Bridge The Gap Between Air-Core and Discrete Transformers

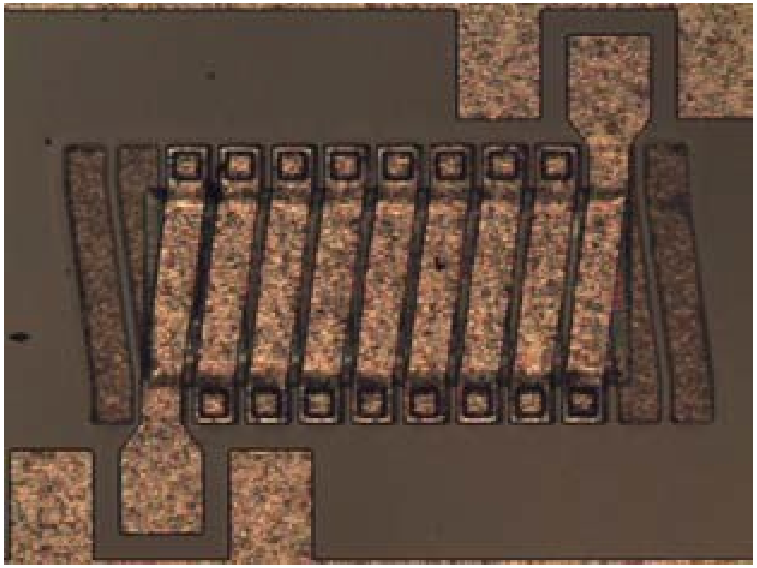


Inductor Configurations: Pot-Core vs Solenoid





*Tyndall Cian O'Mathuna Group



*Stanford S Wang Group

- Magnetic layers enclosing spirals
  - Minimum flex leakage (radiation)
- Complex core structure
  - Difficulty in domain alignment control
  - Significant core loss

- Windings enclosing magnetic core
  - Via complexity
  - Flux leakage (radiation concern)
- Simple core structure
  - Higher permeability
  - Easy domain alignment
  - Flux parallel to surface

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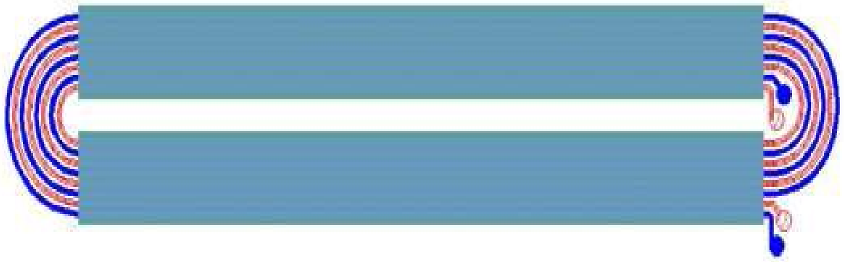
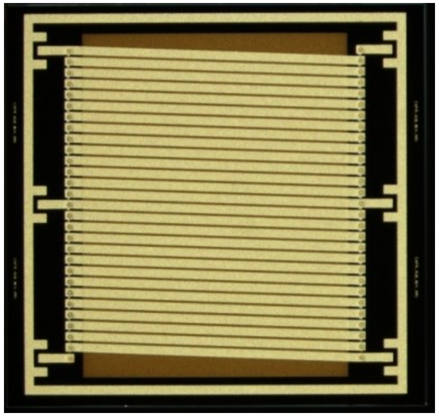
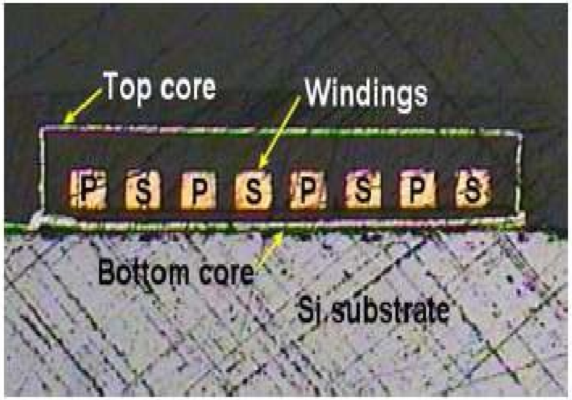
Transformer Configurations For Achieving Isolation



Top View



Interleaved Primary and Secondary for Best Mutual Coupling



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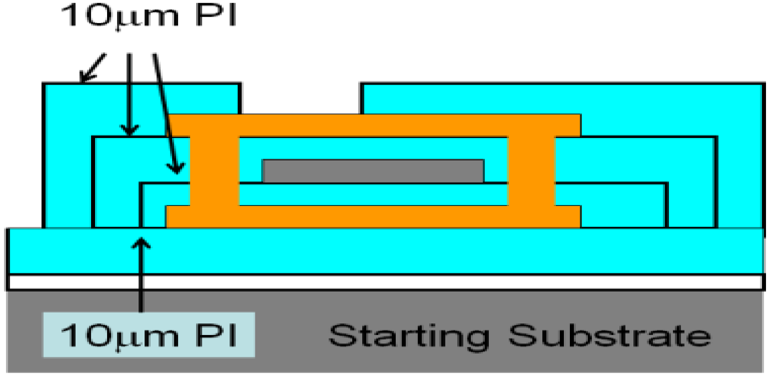
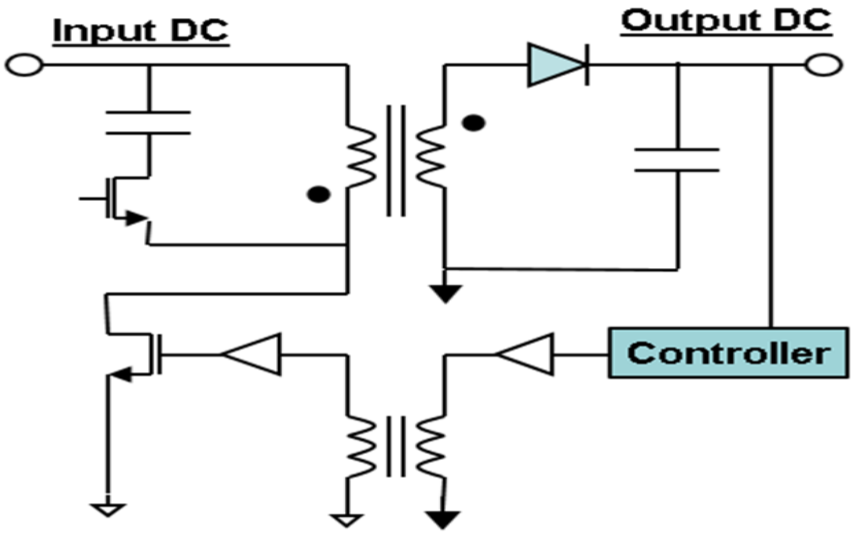
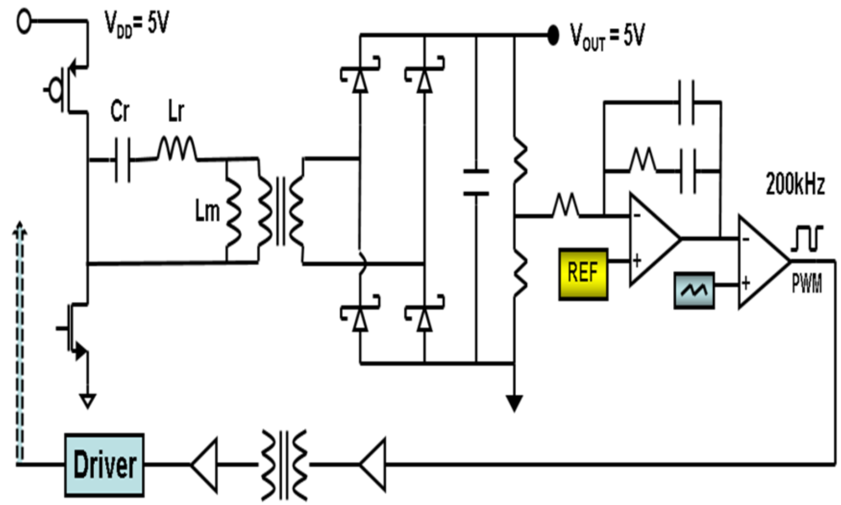
Side by Side or Stacked



Analog Approach >5kVrms Isolation

Converter Architectures Suitable For Integration





Flyback

- ➢Simple with fewest components
- ➢No output filtering inductor
- ➢ Load dependent saturation current
- ➢Limited power density

LLC converter

- ➢High efficiency (ZVS)
- ➢Load current provided by resonant current
- ➢High power density
- ➢Need Lr or use leakage inductance

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Equations for Magnetic Solenoid Inductors

$$L = \frac{\mu_0 \mu_r N^2 w t_m}{l}$$

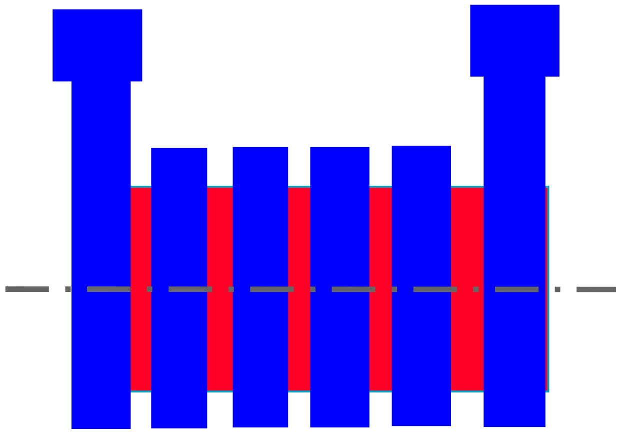
$$R_{dc} = \frac{2Nw\rho}{w_c t_c}$$

$$C \approx 2N\varepsilon_0 \varepsilon_r \frac{w_c w}{t_i}$$

$$Q = \frac{\omega L}{R} = \frac{\omega \mu_0 \mu_r N t_m w_c t_c}{2l\rho}$$

$$I_{sat} = \frac{B_{sat} l}{\mu N}$$

$$E = \frac{1}{2}\frac{Li^2}{wl} = \frac{1}{2}\frac{t_m B_{sat}^{\;2}}{\mu}$$



High Q

- Large w_c Coil Width
- Large t_c Coil Thickness
- Short Length $l \geq w_c$!
- Higher Permeability μ_r
- Large t_m

Thicker t_m => Higher Energy Density

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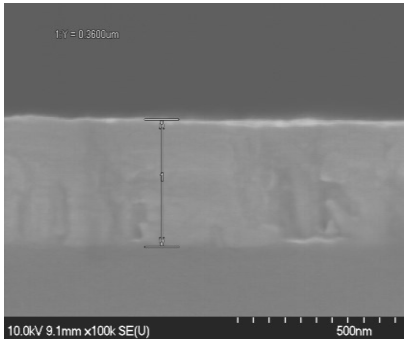
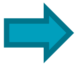
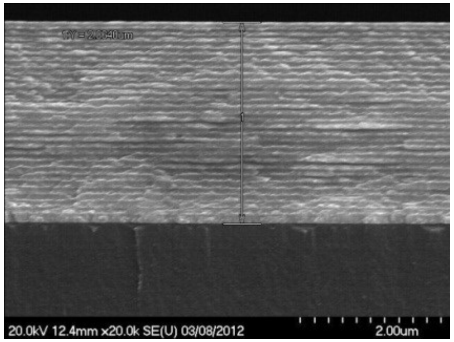
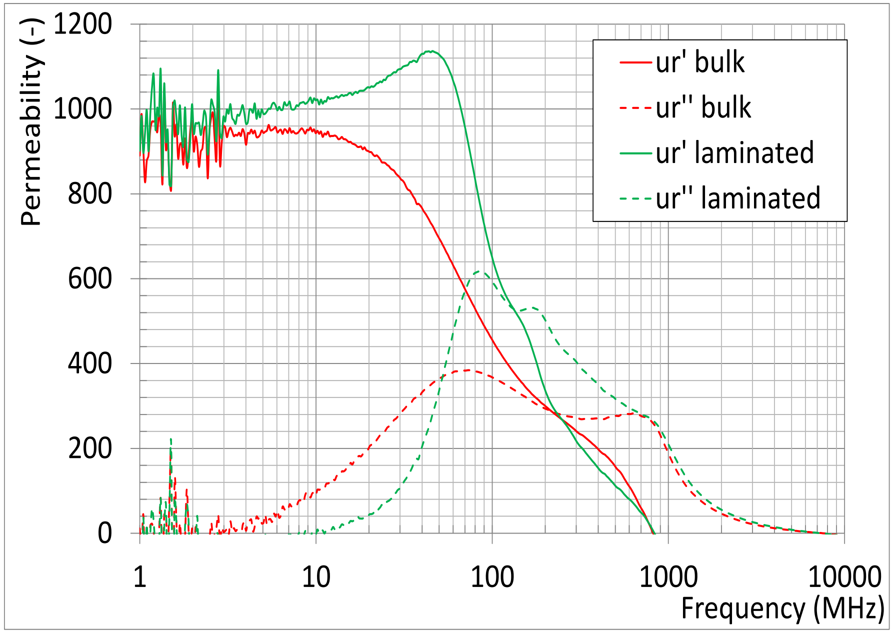
Core Lamination Reduces Loss Tangent

- Bulk Permalloy (NiFe)
  - Stable soft magnetic material
  - 2 um NiFe
- Laminated Permalloy (NiFe)
  - High quality core with multiple layers of NiFe
  - 20x (NiFe /AIN)
- Dedicated magnetic material deposition system (Oerlikon EVOII)









Parameter	Measured Result
Thickness	~microns
Saturation	1.1T
Relative Permeability	~1000
Coercivity	Low < 0.1 Oe
Curie Temp	570ºC

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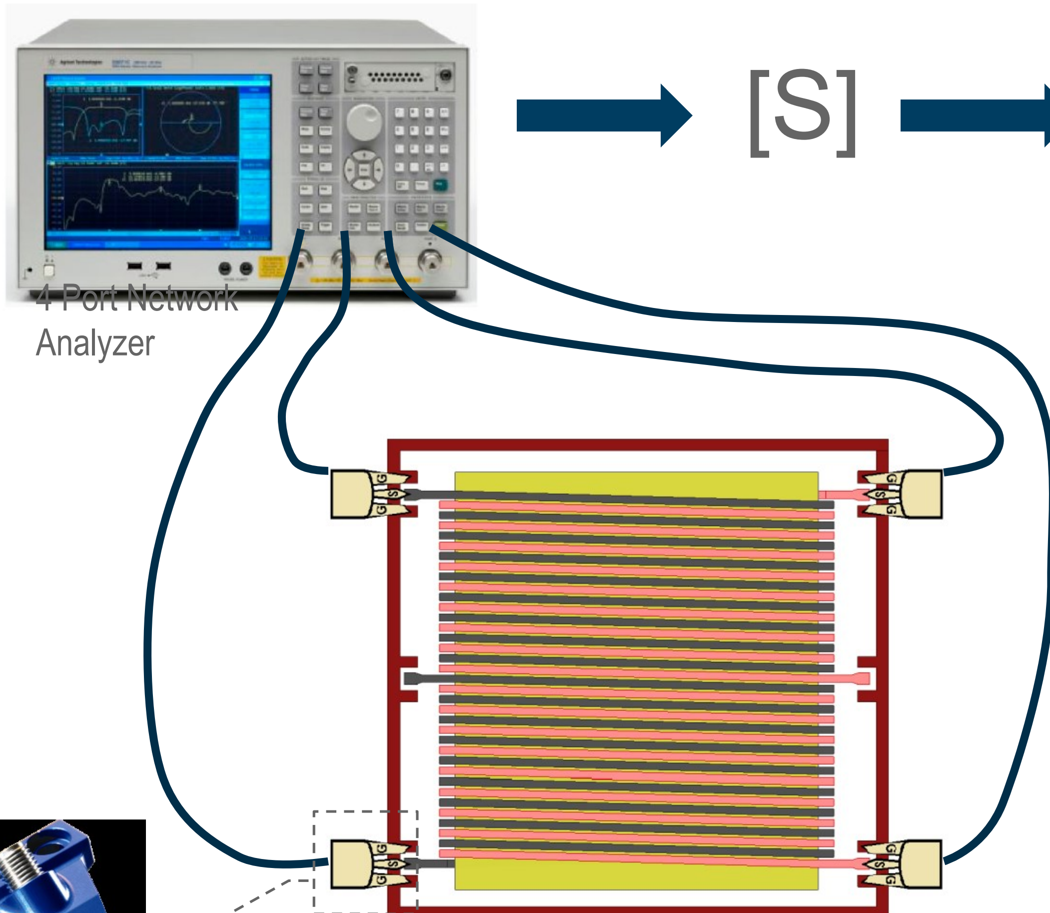
Transformer On-Wafer Characterization



4 Port Network Analyzer

Transformer Open Die

[S] → [Z]

$$L_{pri} = im(Z_{11,diff\ mode})/\omega$$

$$R_{pri} = re(Z_{11,diff\ mode})$$

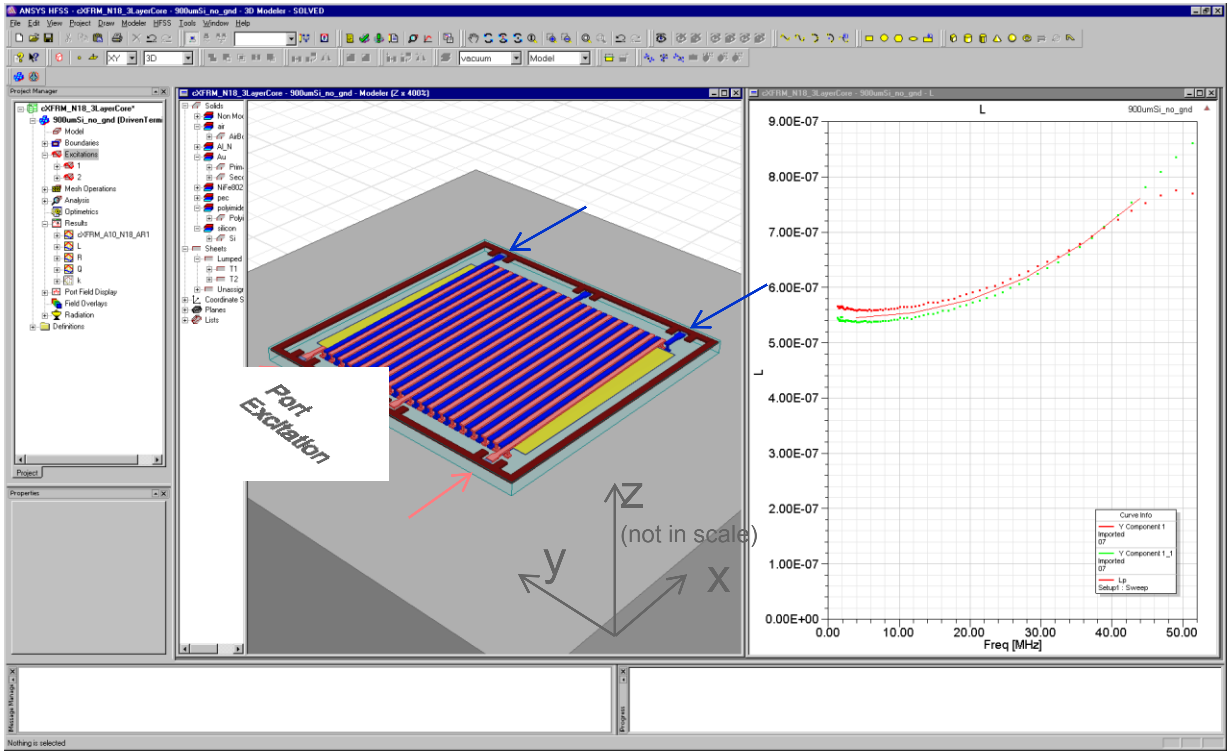
$$Q_{pri} = \frac{im(Z_{11,diff\ mode})}{re(Z_{11,diff\ mode})}$$

$$L_m = im(Z_{12,diff\ mode})/\omega$$

$$k = \frac{L_m}{L_{pri}L_{sec}}$$

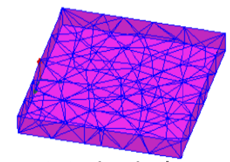
GSG RF probe

Transformer Modeling with HFSS



ANSYS

3D; Full wave EM simulator; Finite element method



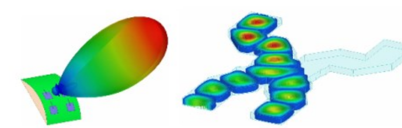
tetrahedral

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \cdot D = \rho$$

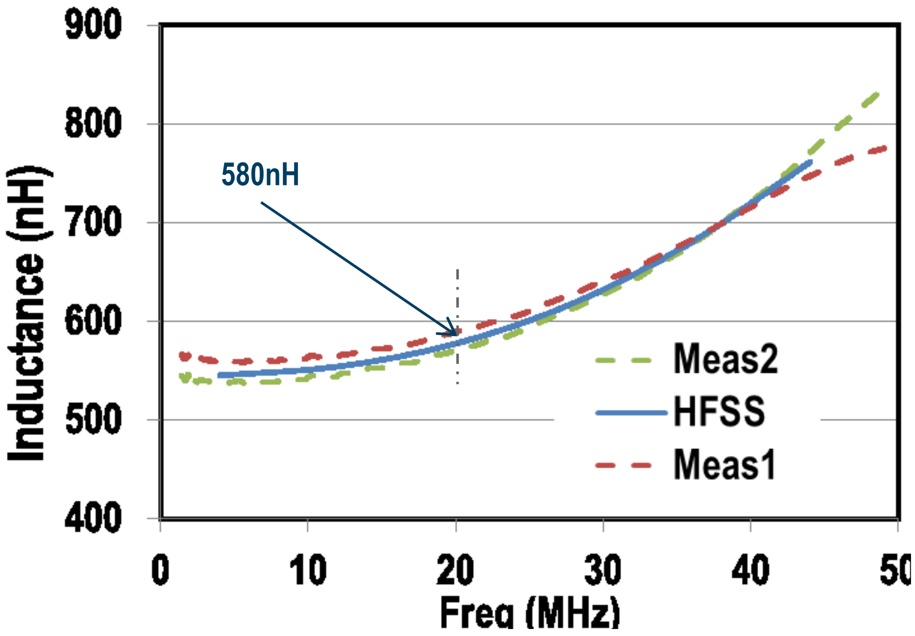
$$\nabla \cdot B = 0$$

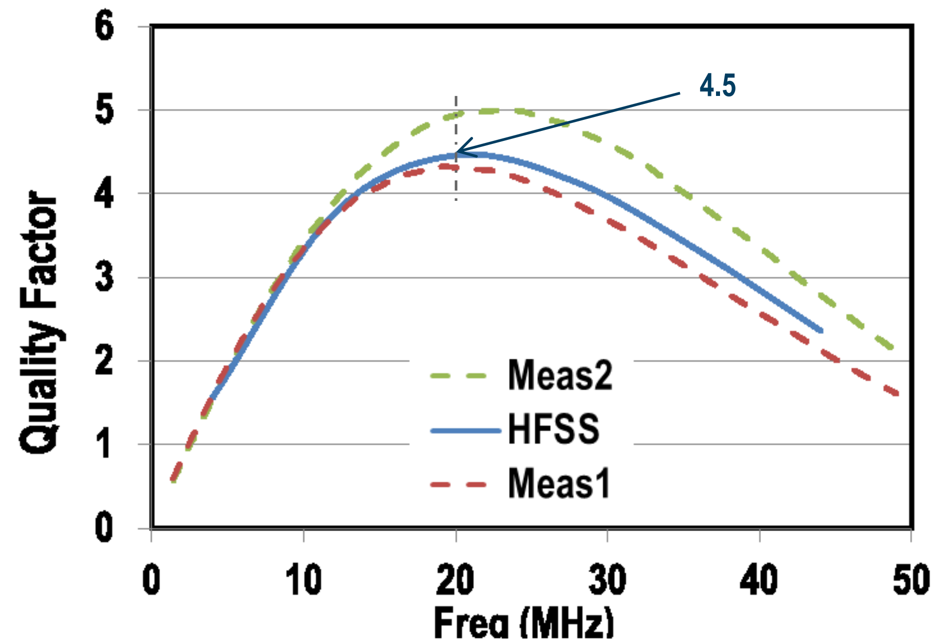


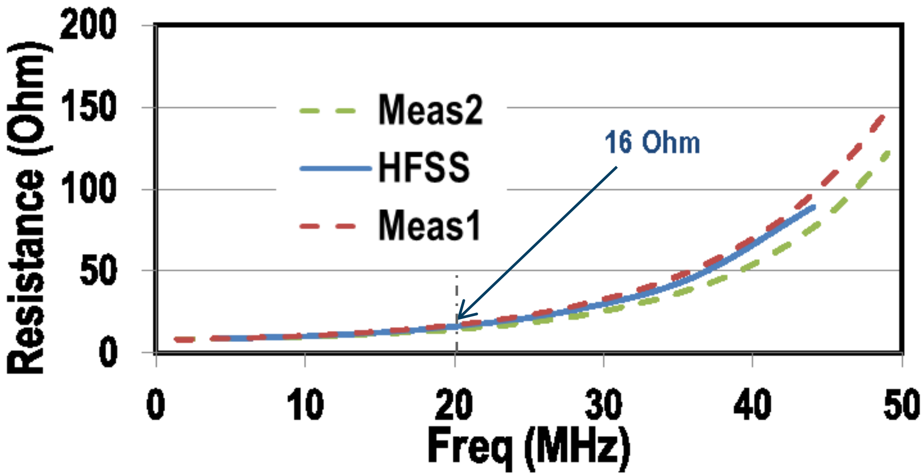
HFSS

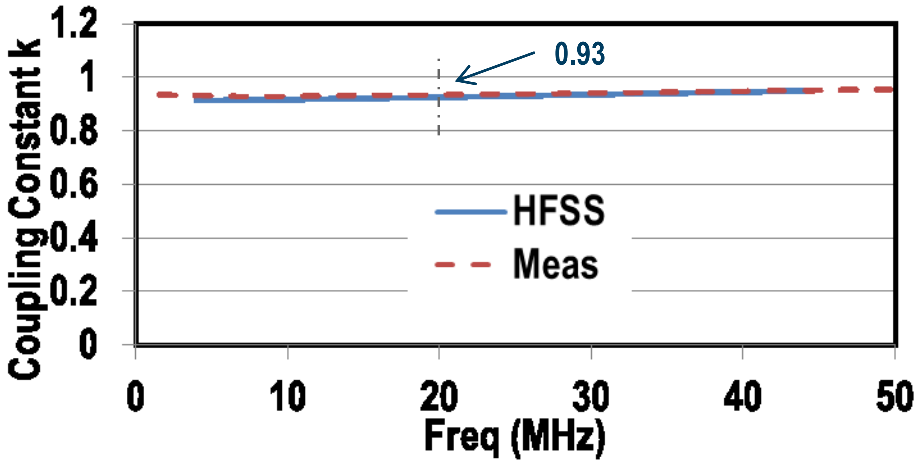
	Thickness (µm)	Material	Conductivity (S/m)
Winding	4	Gold	3.5875e7
Core	2	NiFe	NiFe: 1.4e7

2µm Core Transformer Characteristics – Simulation & Measurement

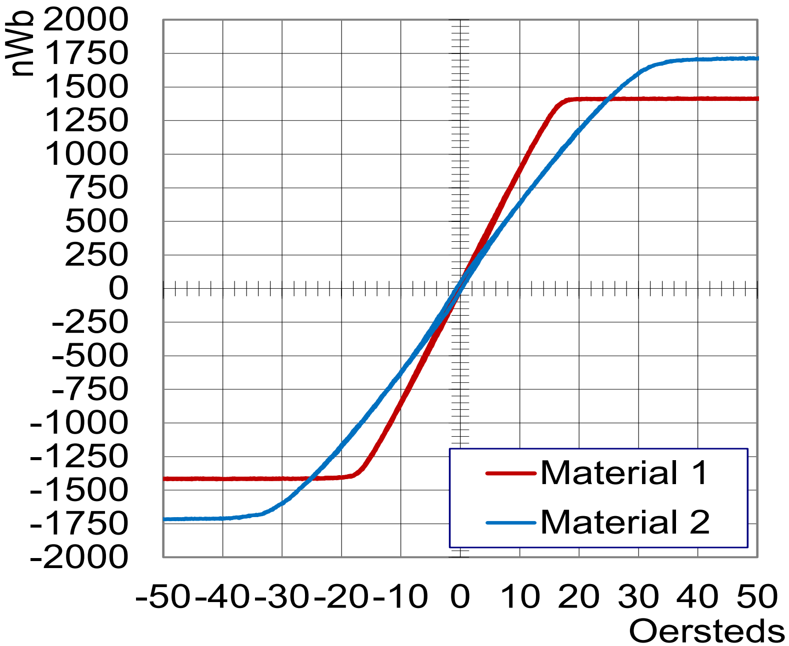


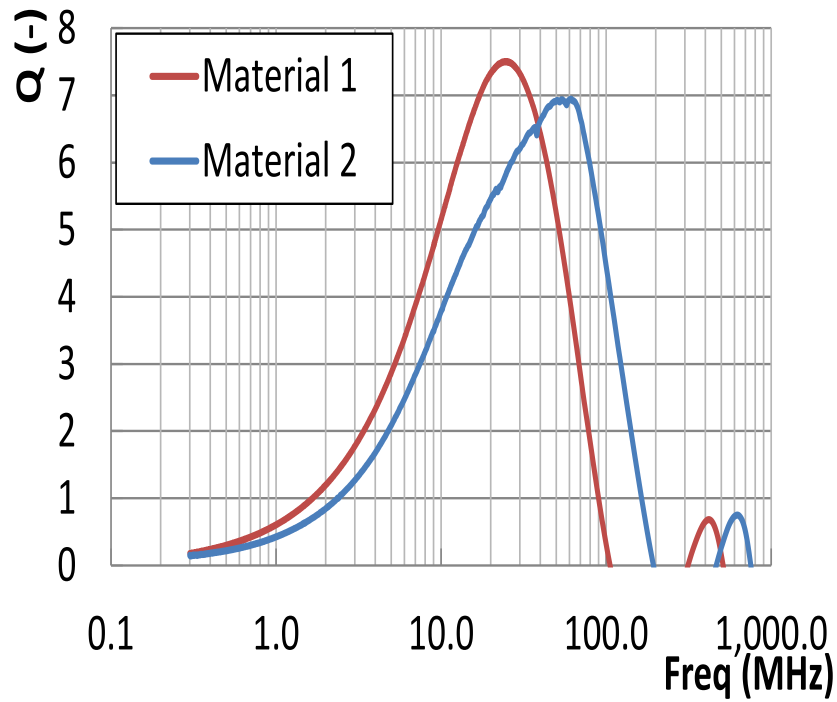






Improved Quality Factor for 4μm Thick Core





- 4um amorphous magnetic core
  - **Qmax~7.5 – close to target Q=8,**
  - **Major core stability improvement.**

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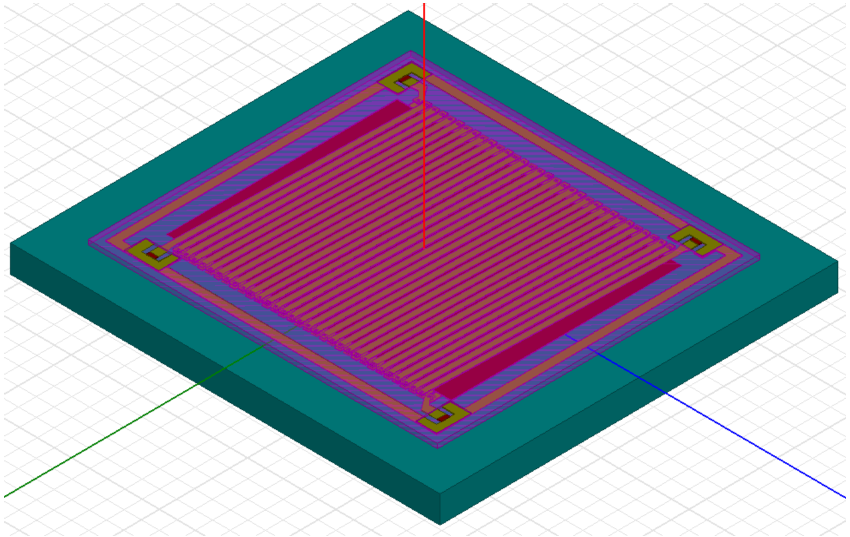
Winding Thickness Improvement

- Device FEM models



- **DCR reduction effect:**

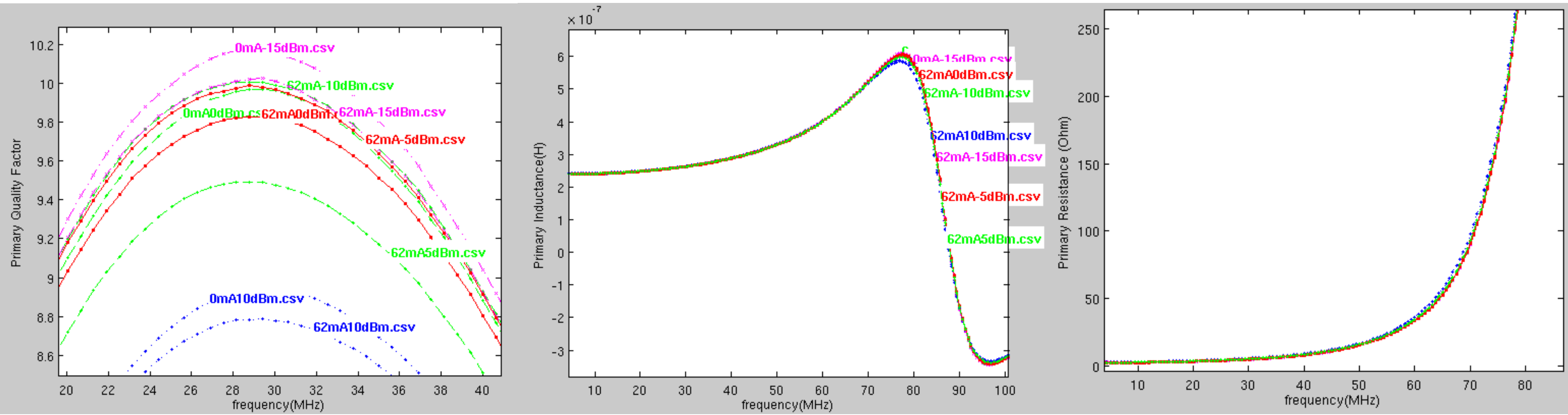
Model option	Q max (-)
2x6 um Au (default)	7.70
2x8 um Au	8.85
2x10 um Au	9.71

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}}$$

Skin depth for Au @ 20 MHz:
17.5 um

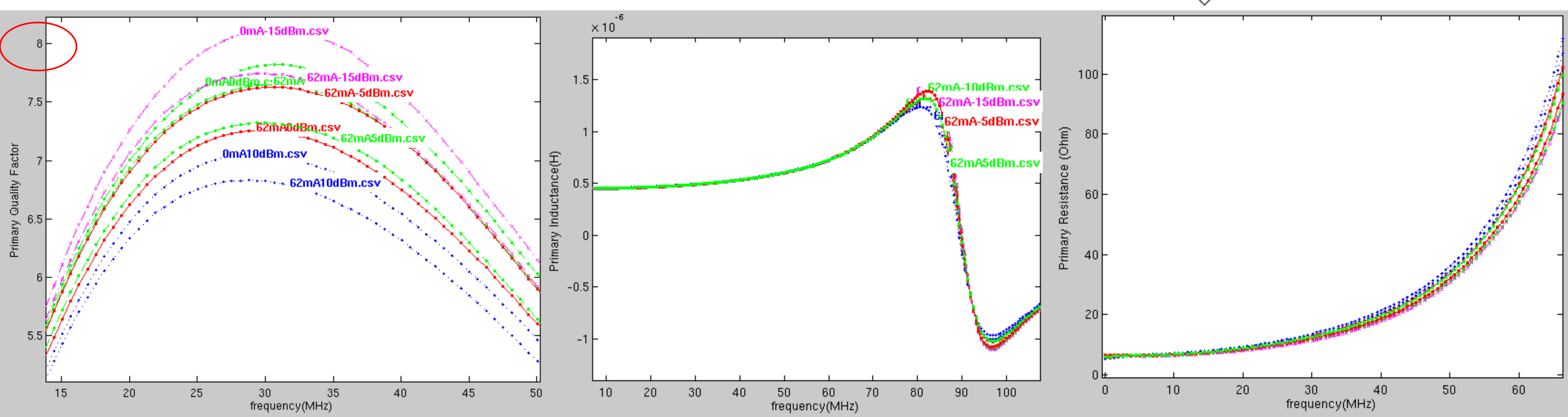
- **Model: Increased thickness of Au metallization by 2 um will deliver Q>8**

Effect of DC Bias and Large AC Signal on RF Performance



Material 1

NiFe



Summary

- Magnetic Core Has the Potential to Improve Converter Efficiency and Reduce EMI for Integrated DC/DC Converters
- Intertwined Solenoid Transformers Have Been Modeled & Characterized and Have Excellent Magnetic Coupling
- 2μm Multilayer Core Lead to a Q of 5 at 20MHz For the Intertwined Transformers
- 4μm Multilayer Core With 8μm Thick Winding Achieved Q > 10
- Effect of DC Bias and Large Signal on Transformer Performance Have Been Characterized
- DC/DC Converter Passed Class B EMI and Achieved 46% Efficiency at 200mW

Acknowledgements: Contributions from iCoupler group & ADLK FAB ipassive team in ADI

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