Ferric

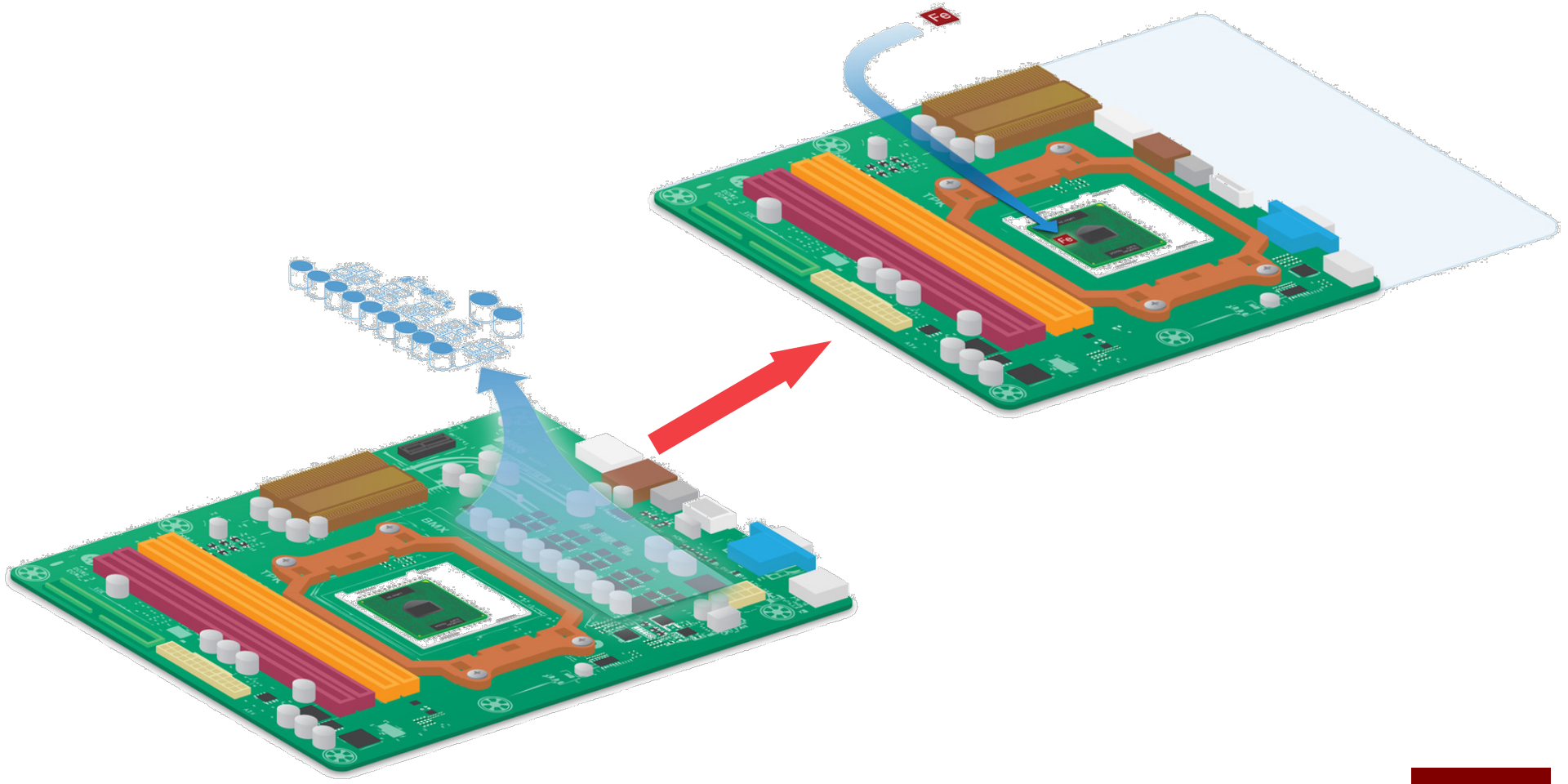
APEC

Thin Film Inductors for Integrated Power Conversion

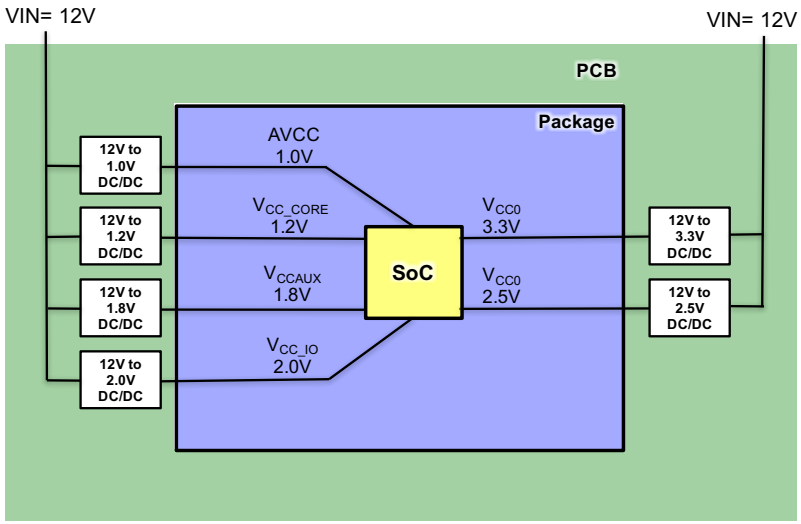
Ferric, Inc.
Noah Sturcken, PhD - CEO

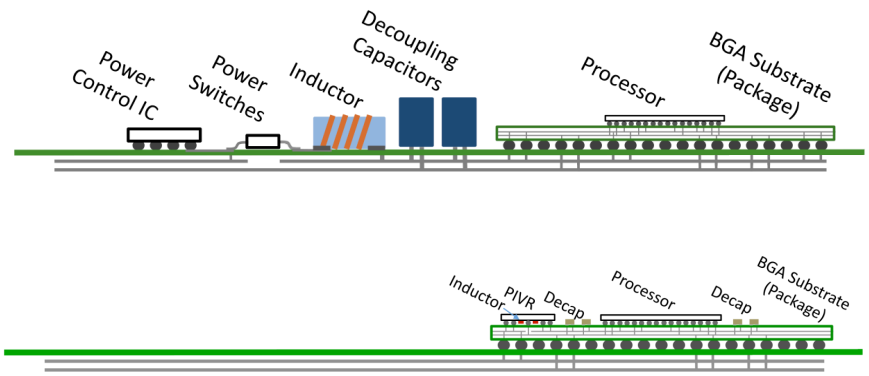
INTEGRATED VOLTAGE REGULATION (IVR)

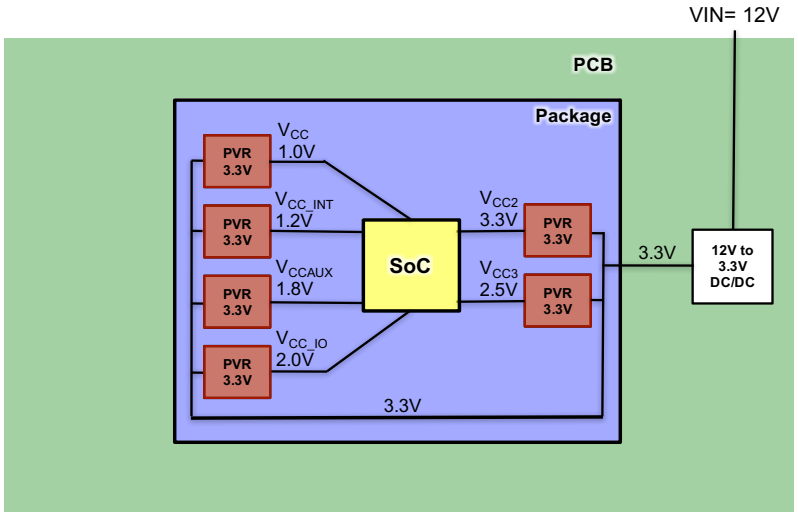
Switched inductor DC-DC power conversion with On-chip Magnetic Thin-Film Inductors Save Power, Space And Cost



FERRIC | Package Integrated Voltage Regulator (PIVR)



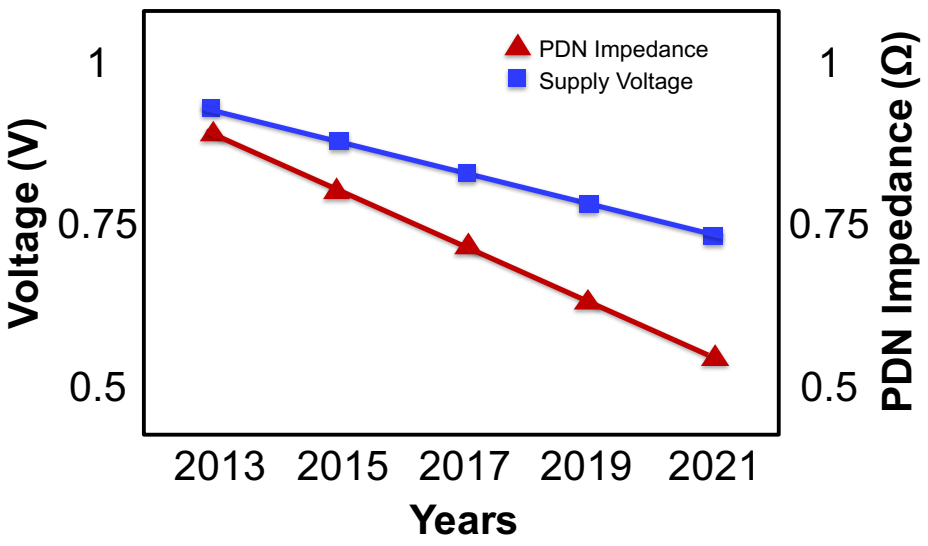


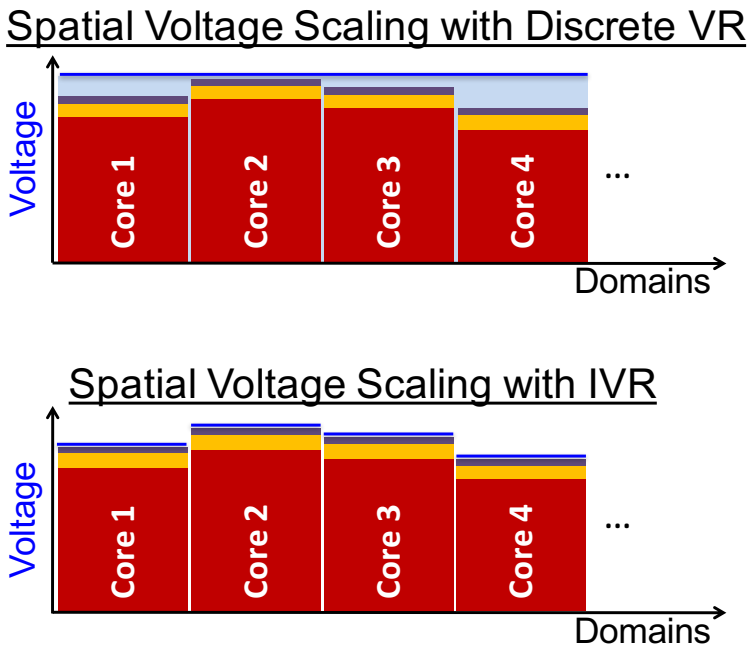


- Shrink power converters so they can be integrated with the IC
- Reduce I^2R losses associated with high current levels in board + socket + package
- Enable delivery of many independently scalable supplies

POWER SAVINGS: 20 – 50%

- **Lower Distribution Losses**: Ferric's Package Voltage Regulators (PVR) reduce losses in the power distribution network since they are placed at the true Point of Load
- **Improve Power Management**: Ferric's integrated solution improves spatial and temporal granularity for power management, significantly reducing power consumption





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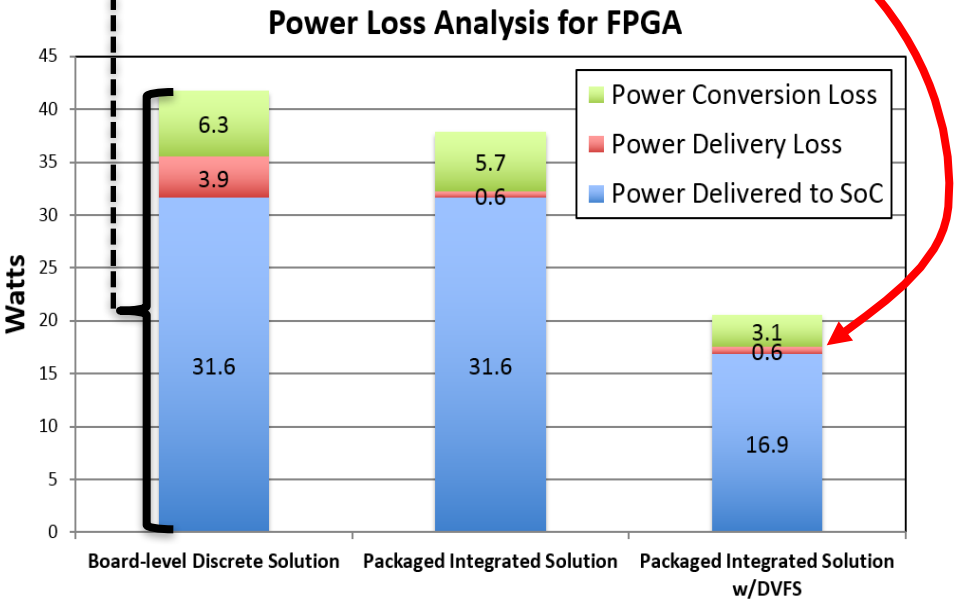
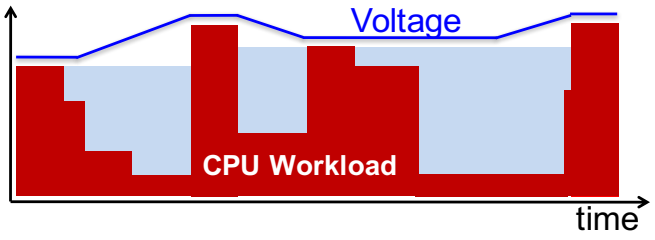
Total power delivered to DC-DC converter

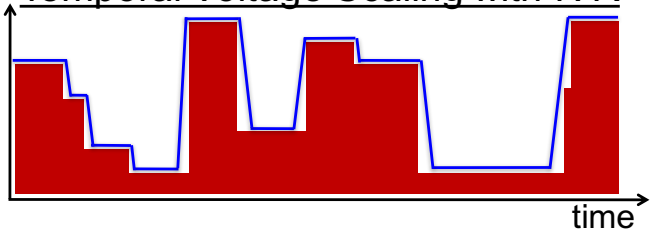
More than 50% reduction in overall power consumption from power management



Temporal Voltage Scaling with Discrete VR

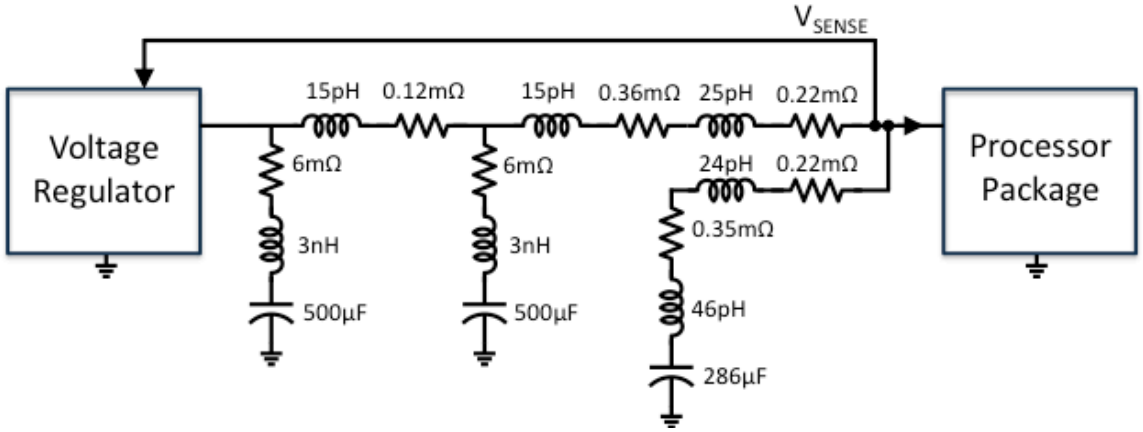


Temporal Voltage Scaling with IVR

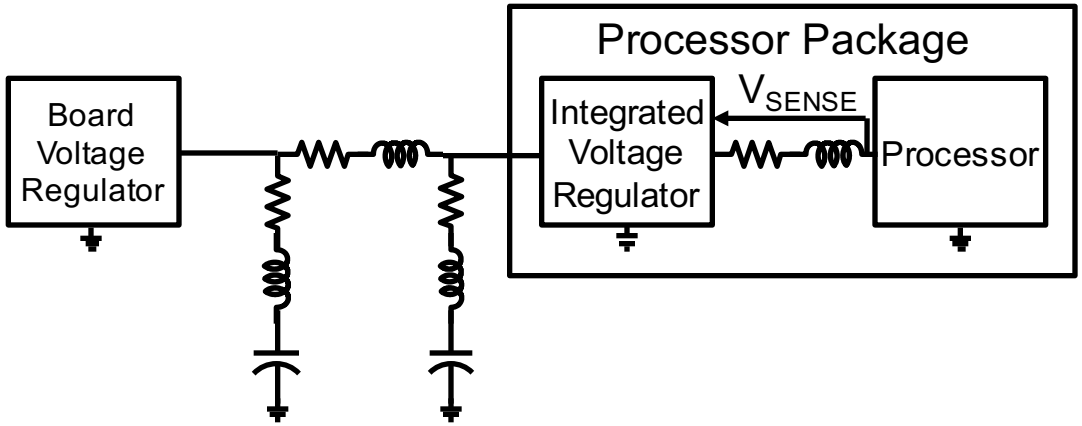


IMPROVED POWER INTEGRITY

Conventional Power Delivery Network (PDN)



Integrated Power Delivery Network (PDN)

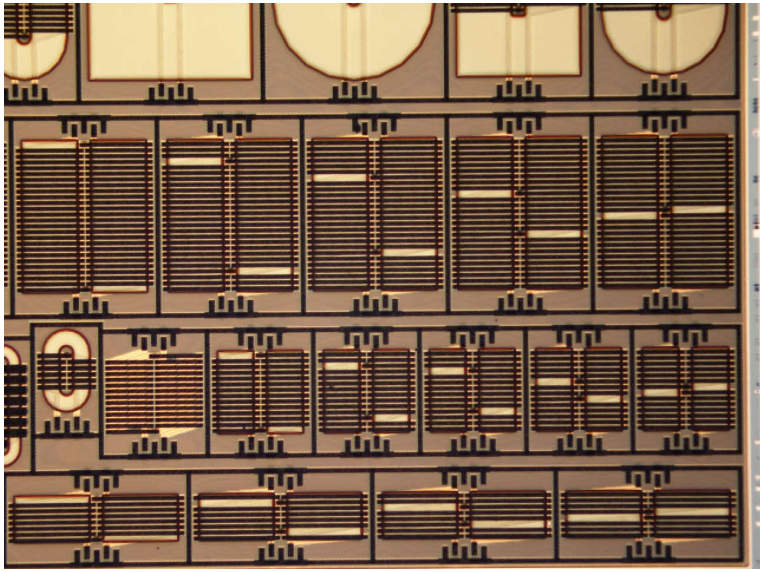


Ferric IVRs utilize high bandwidth (UGBW > 50MHz) feedback control and are placed in immediate proximity to the processor load:

- Regulate resonant impedance peaks from upstream PDN
- Reducing maximum broadband supply impedance to <1mΩ
- Reduce processor supply voltage margins for improved efficiency

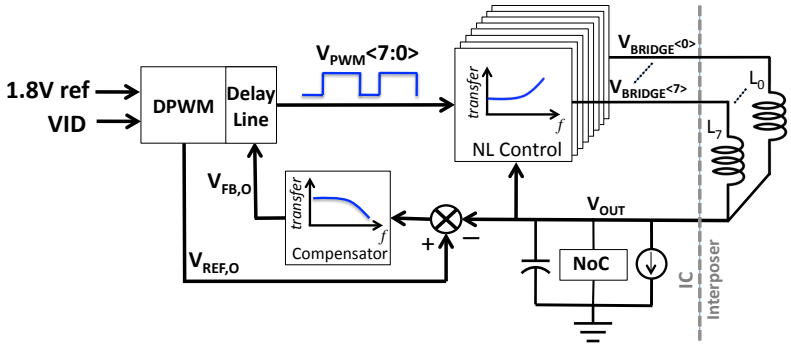
IVR TECHNOLOGY ELEMENTS

- **Integrated Inductors**
  - Inductance density
    - > 300nH/mm^2, > 8,500nH/mm^3
  - Current density > 12A/mm^2
  - DC Resistance < 40mΩ
  - Magnetic Coupling k > 0.9
  - Available monolithically at TSMC or on IPDs



Array of thin-film power inductors

- **Integrated Circuit Designs**
  - High switching frequency (>10MHz)
  - High bandwidth controller
  - Optimization for high efficiency
  - Optimization for high density



Example high-frequency buck converter architecture

OUTLINE

- **Ferric Thin-Film Power Inductors & Transformers**
- Ferric Device Libraries, Design and Models
- Ferric Power Converters

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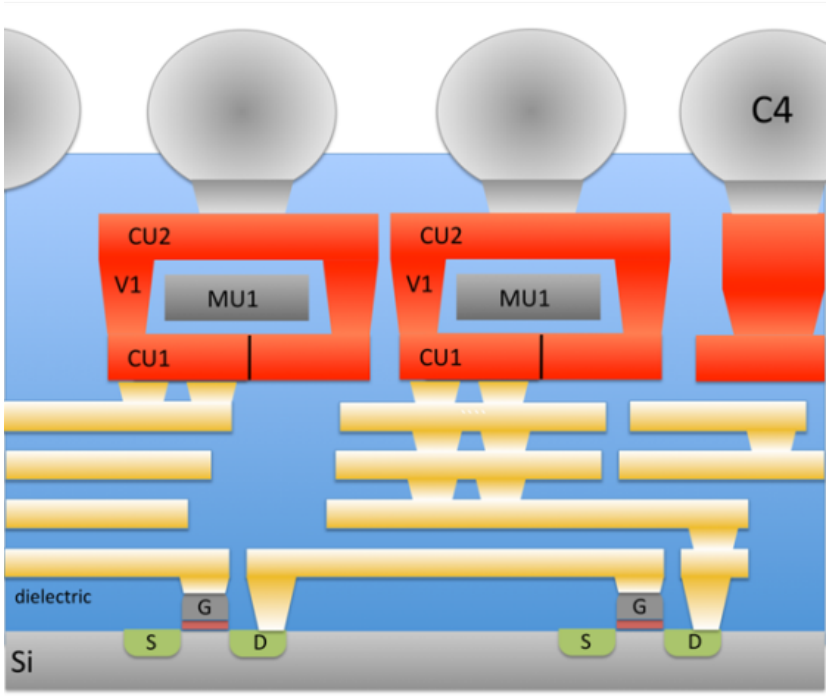
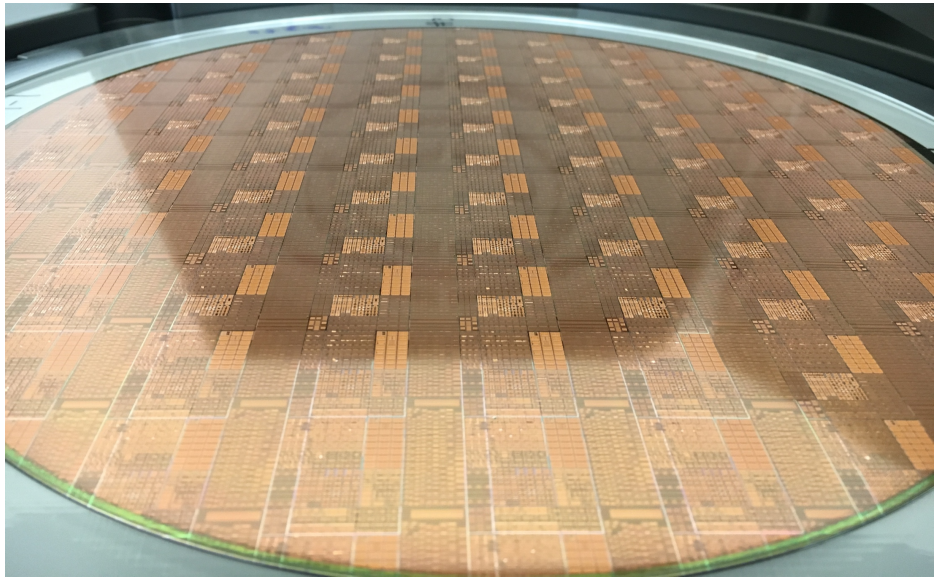
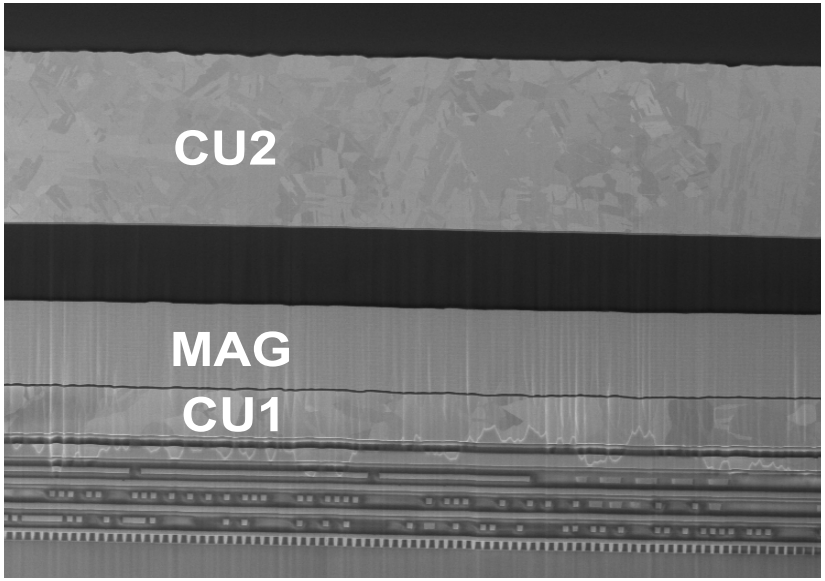
FERRIC INDUCTORS

Ferric CMOS integrated magnetic thin-films enable high-quality, high density, low-profile, on-chip/in-package inductive components

- **Integrated with TSMC CMOS**
  - Inductor layers available as Back-End-of-Line process option (similar to MIM Cap)
  - Circuit models, LVS, DRC
  - Inductor Cell Library



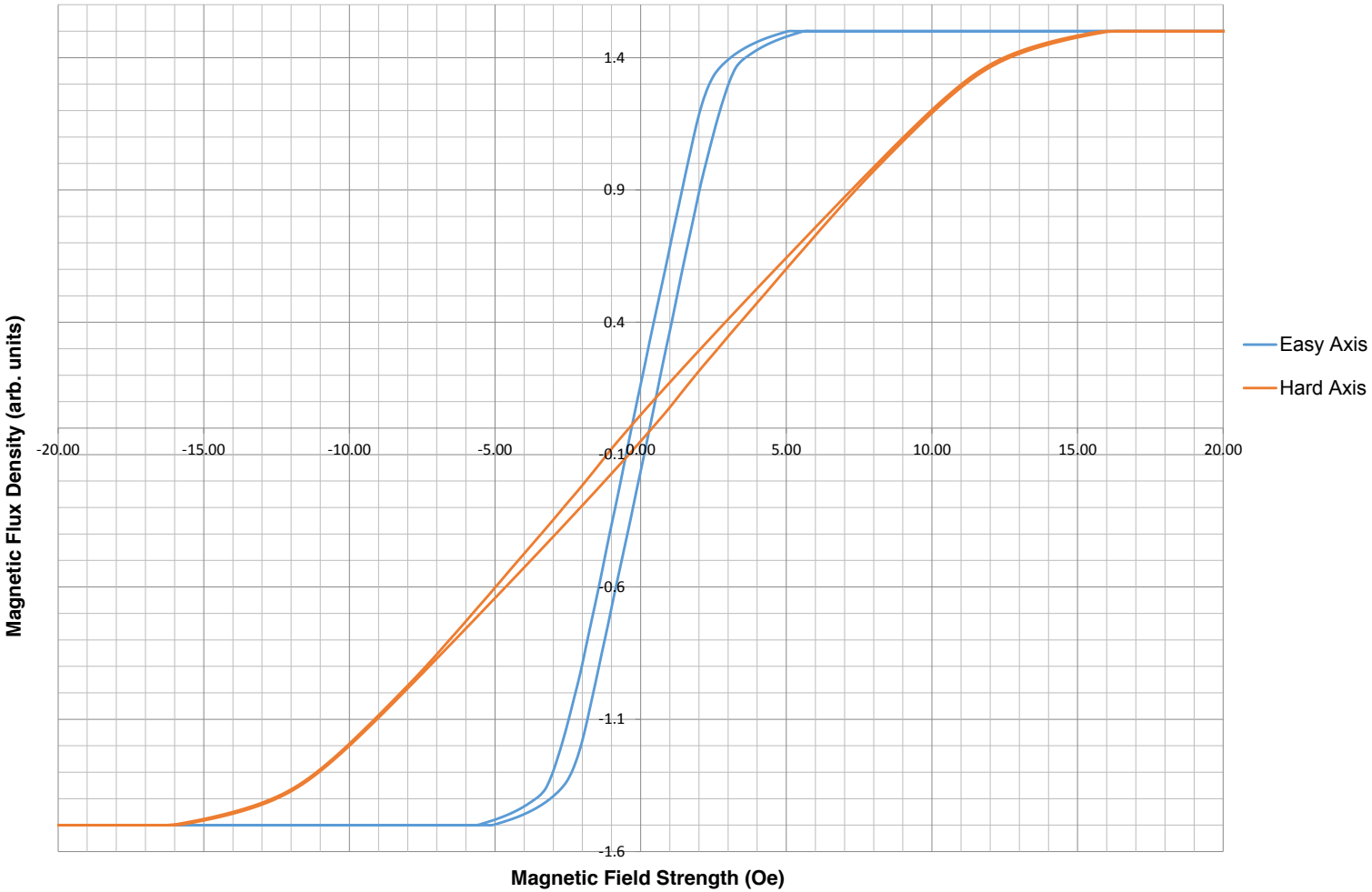




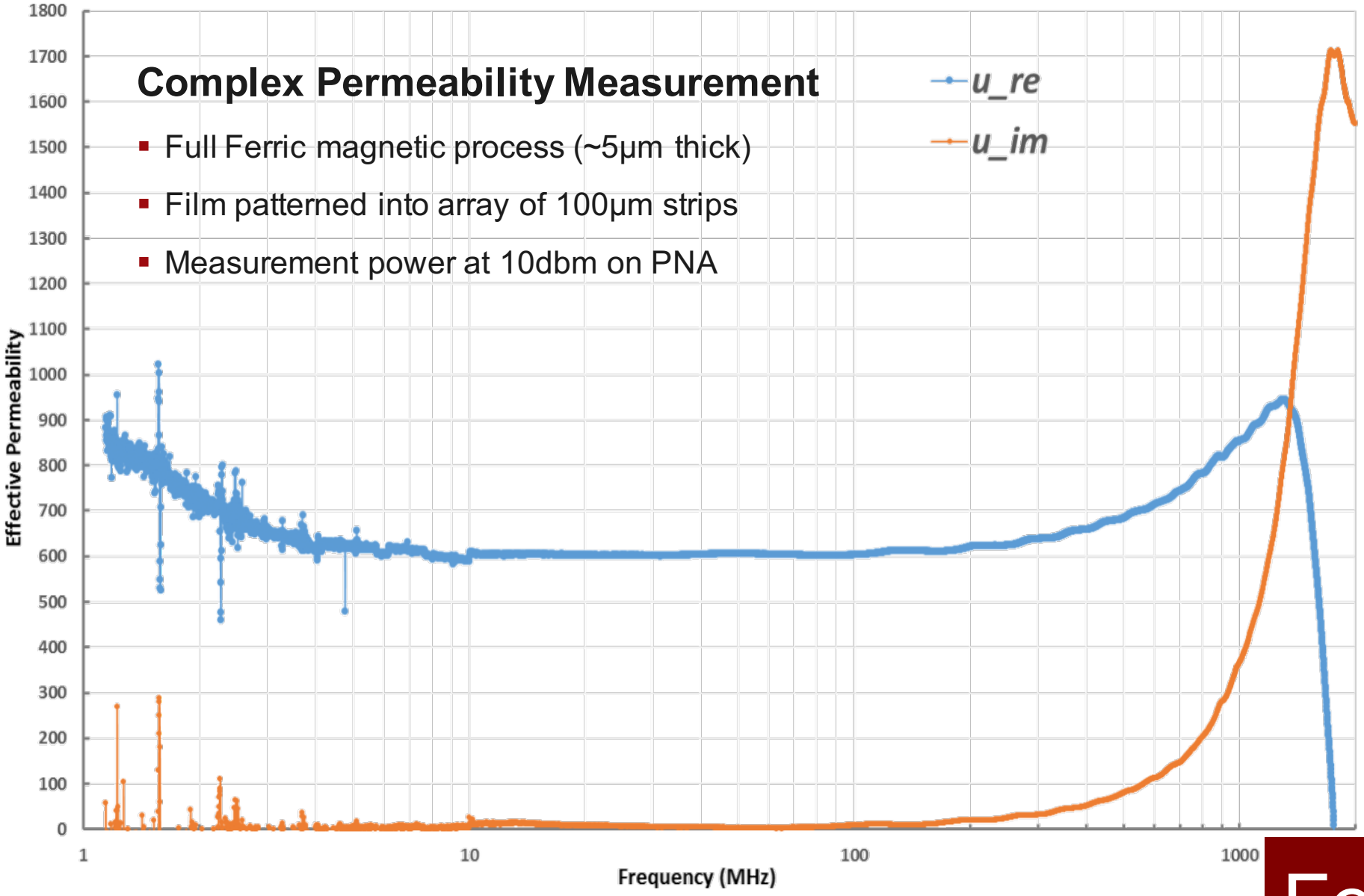
FERRIC INDUCTORS | Magnetic Cores

BH Loops

- Non-patterned film
- Full Ferric magnetic process
- Measured on BH-Looper at 16Hz
- Ms ~ 1.5T
- Hc ~ 0.39Oe



FERRIC INDUCTORS | Magnetic Cores



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FERRIC ***INDUCTORS*** | ***Highlights***

- Peak Q Factor > 20 @ ~100MHz
- Peak Inductance Density ~300nH/mm^2
- L/R_{DC} >200nH/Ω for L > 100nH
- L/R_{DC} of 120nH/Ω for L ~ 10nH
- Current Density exceeding 12A/mm^2 for coupled inductors (balanced current)
- Saturation Current exceeding 1.5A for single inductors
- Cross wafer inductance variability σ < 3%
- Other Devices in development:
  - Transformers, Baluns, transmission lines, antennas, improved inductor designs

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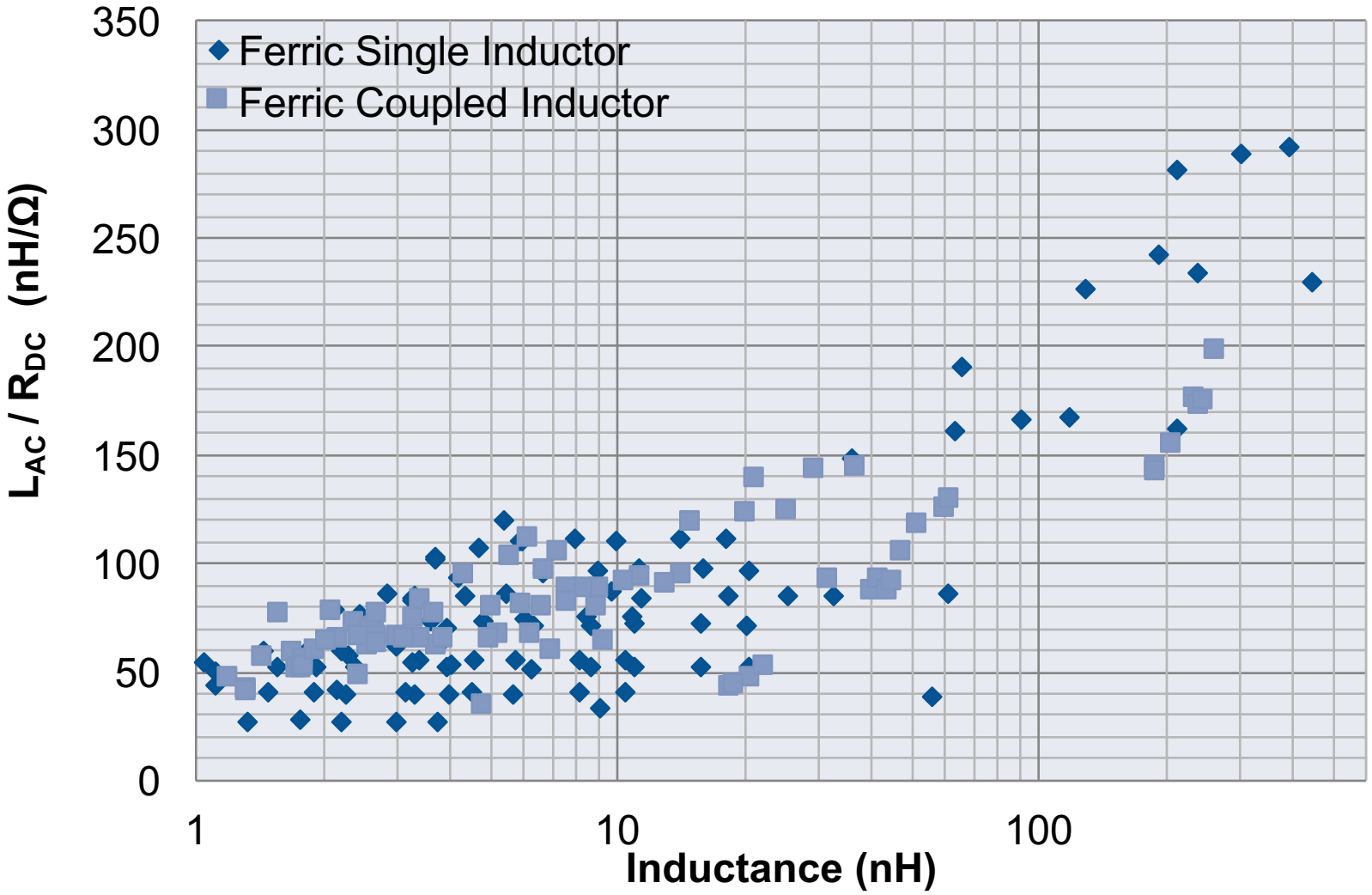
FERRIC *INDUCTORS* | *ELECTRICAL PERFORMANCE*



Ratio of AC Inductance (at 100MHz) to DC Resistance for a family of integrated power inductors

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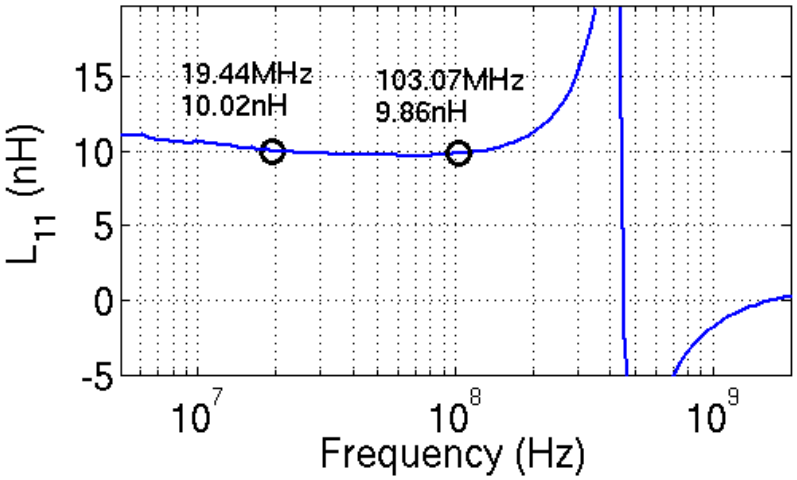
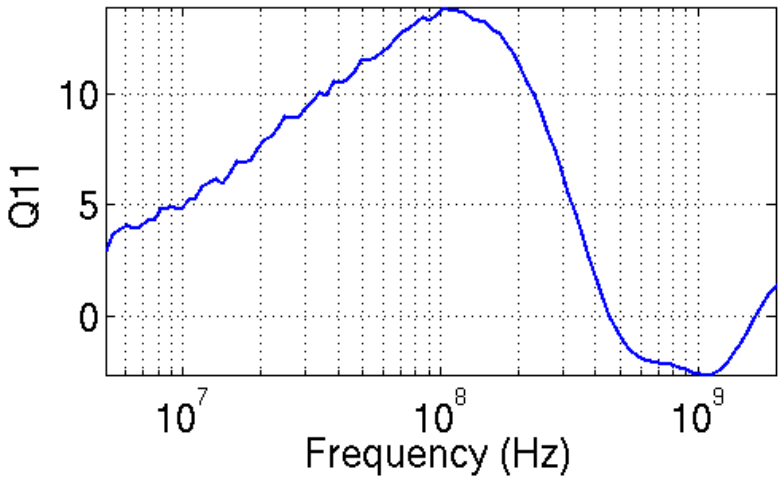
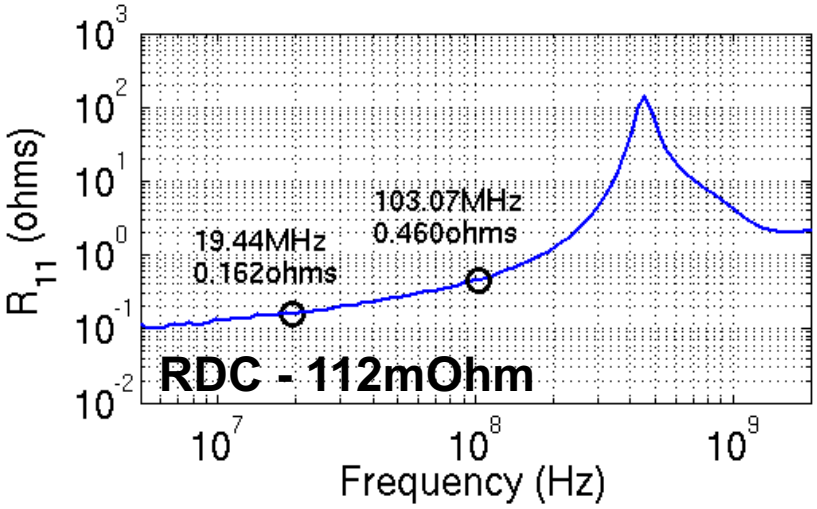
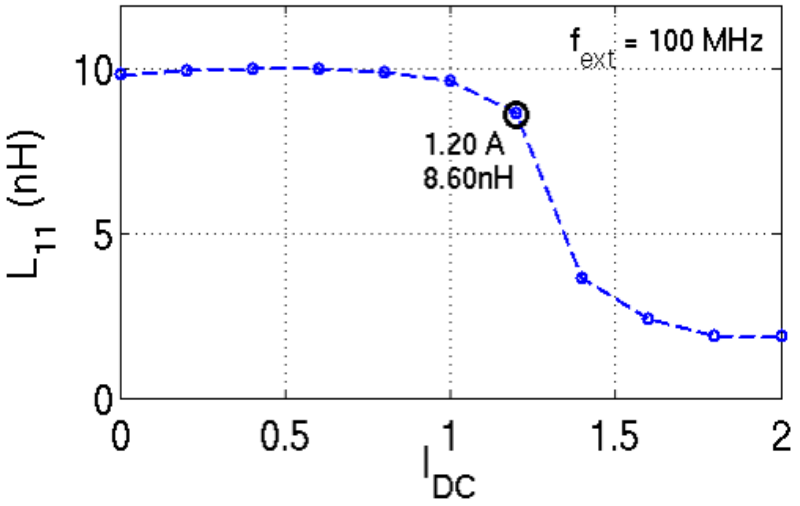
FERRIC INDUCTORS | SINGLE INDUCTOR EXAMPLE



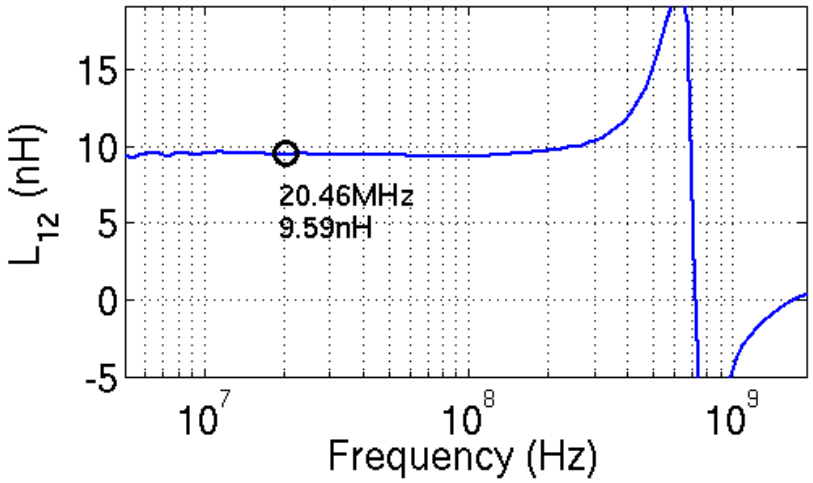


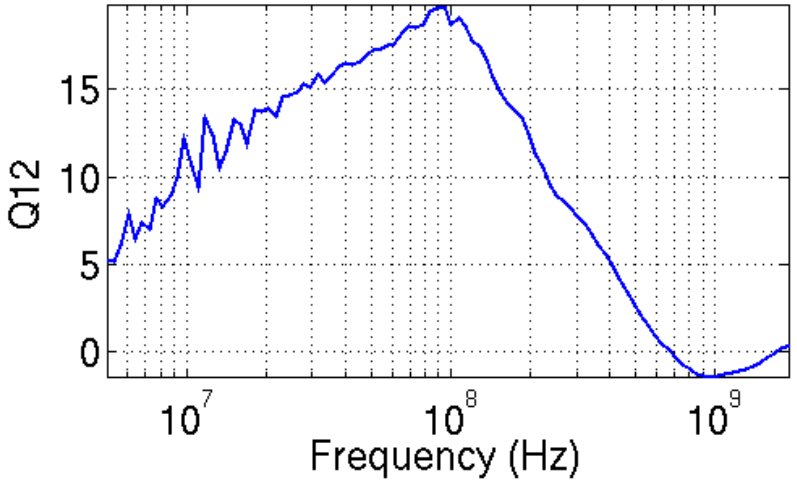


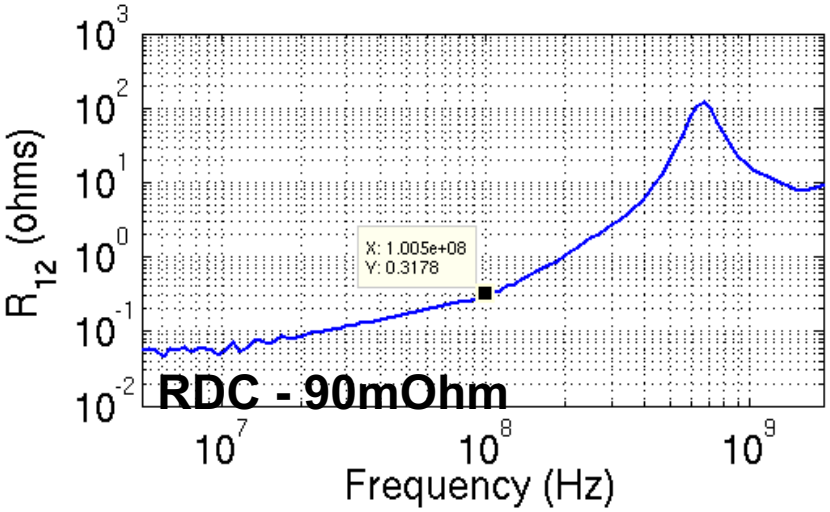


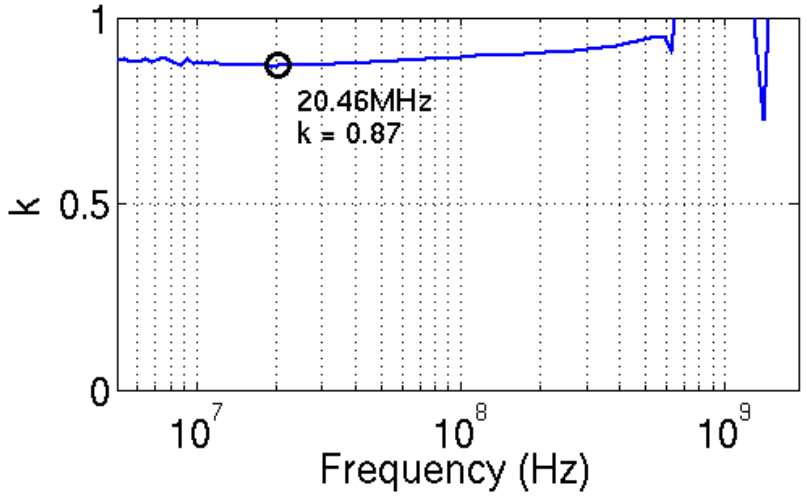
Inductor performance for a representative single power inductor

FERRIC INDUCTORS | COUPLED INDUCTOR EXAMPLE









Inductor performance for a representative coupled power inductor

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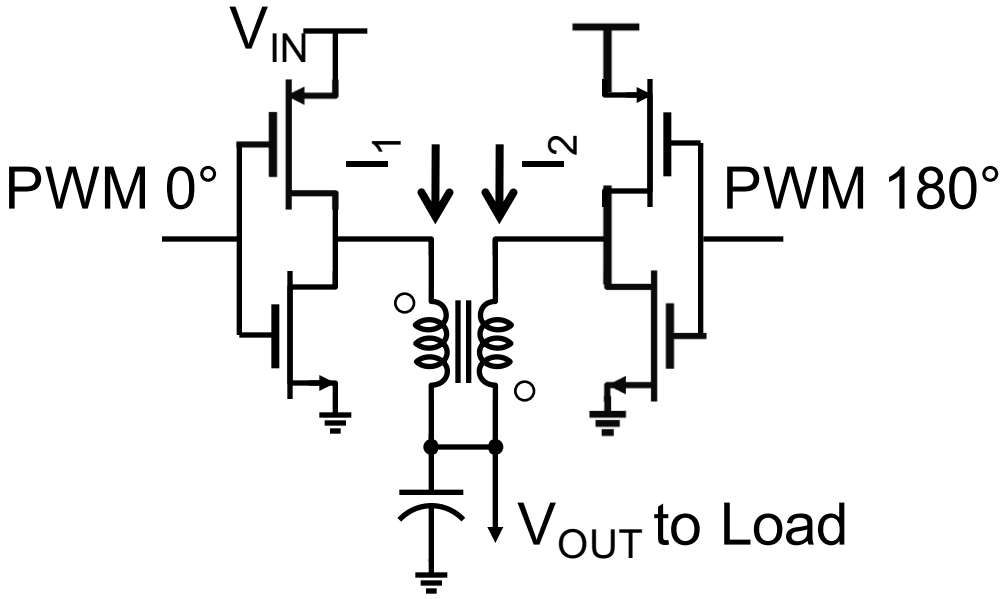
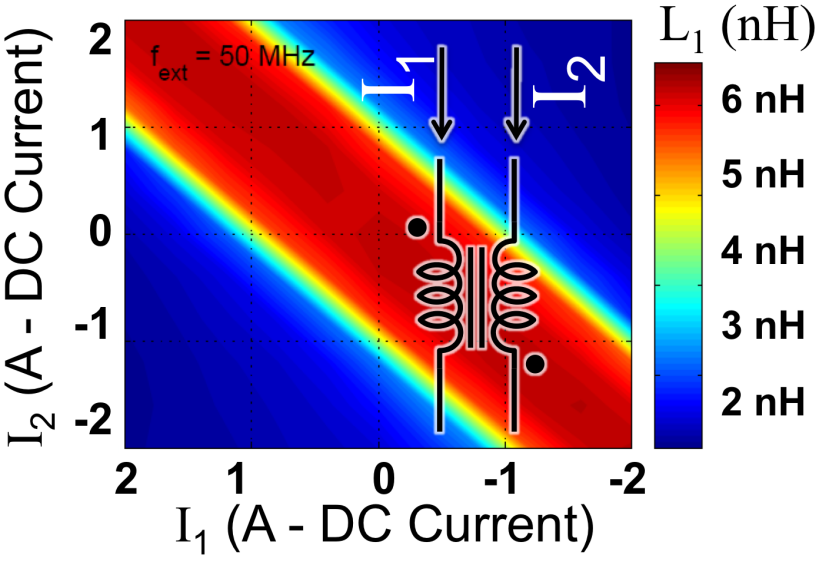
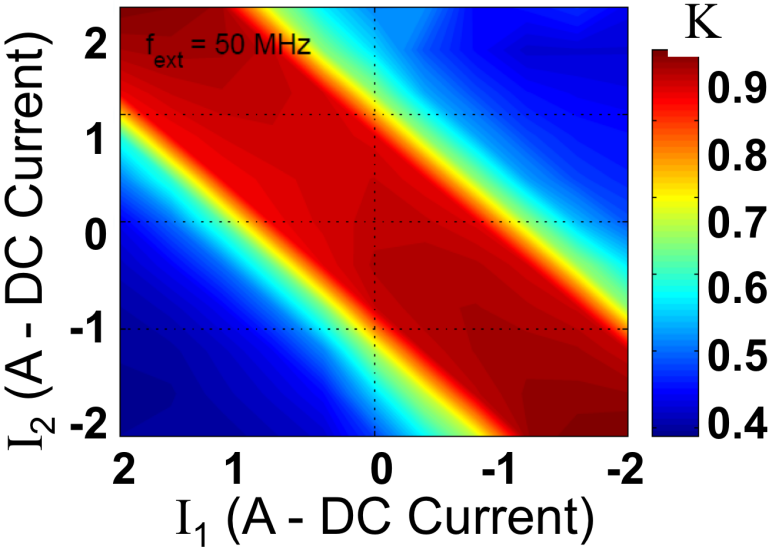
FERRIC INDUCTORS | COUPLED INDUCTOR SATURATION

Inductor coupling is used in two-phase buck converters to avoid magnetic saturation

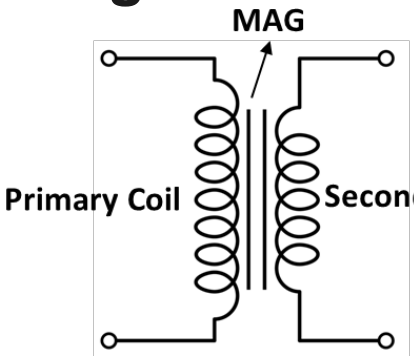


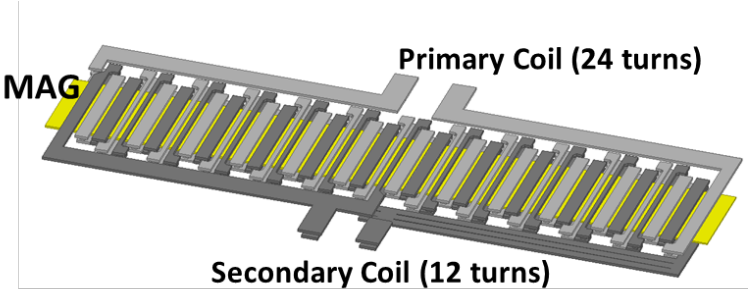




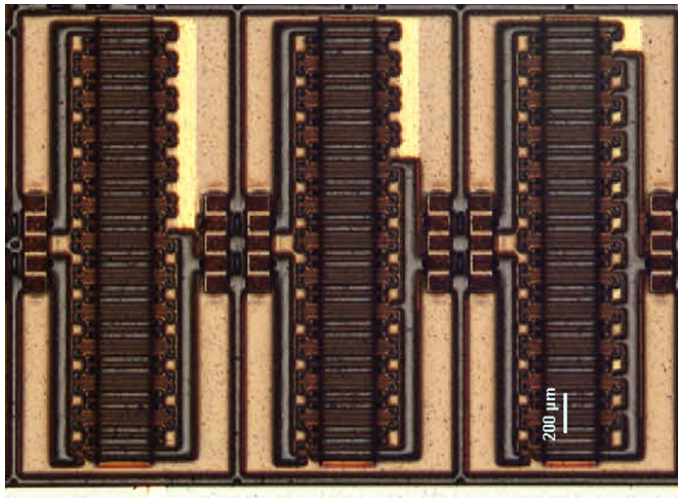
FERRIC DEVICES | Transformers Design

- Solenoid structure
  - Minimize capacitive/inductive coupling
- Elongated magnetic cores
  - Maximize permeability
- 24-turn primary coil
  - Number of secondary coil turns varies



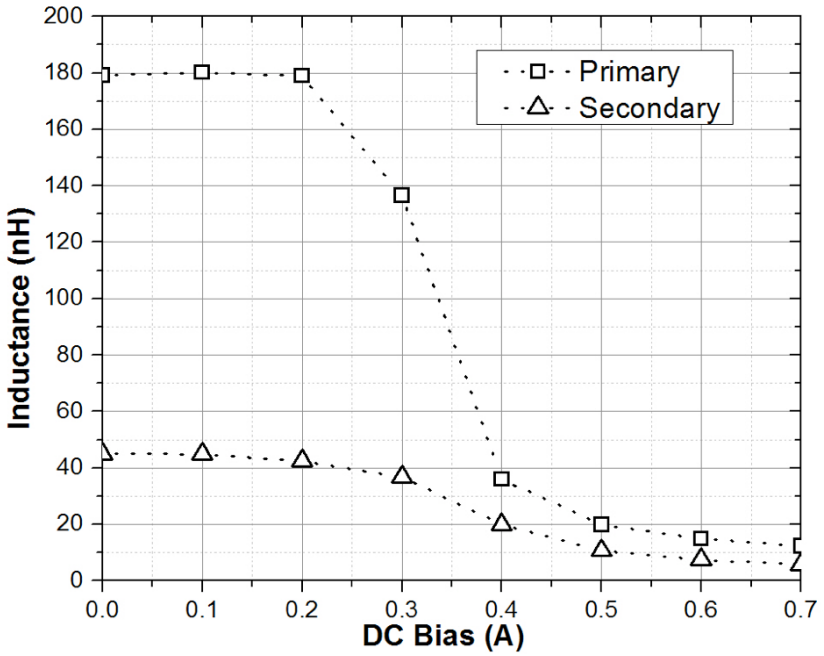


	Design (i)	Design (ii)	Design (iii)
Turns ratio	2:1	3:1	12:1
Primary Turns	24	24	24
Secondary Turns	12	8	2
Coil Width, µm	40	40	40
Core Width, µm	300	300	300
Core Length, µm	2200	2200	2200
Device Width, µm	712	721	712
Device Length, µm	2286	2286	2286

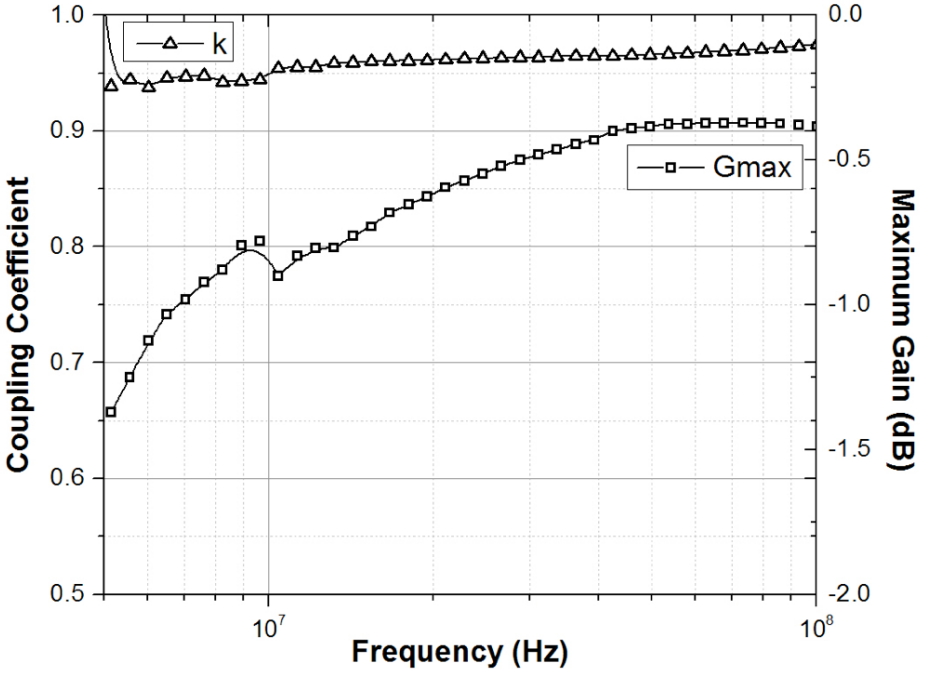


FERRIC DEVICES | Transformer Electrical Performance

	Design (i)	Design (ii)	Design (iii)
Turns ratio	2:1	3:1	12:1
DC resistance, Ω (primary, secondary)	1.35, 0.34	1.36, 0.17	1.39, 0.02
Inductance, nH (primary, secondary)	175, 44	166, 19	151, 2
Peak Q	16	14	11
Frequency, MHz	up to 80	up to 80	up to 100
Coupling coefficient	0.96	0.95	0.74
Saturation current, mA	300	300	300



Inductance versus applied DC bias of transformer design (i). The saturation current is defined as current when L drops by 20%, which is around 300 mA in this plot.



Coupling coefficient and maximum available gain of transformer design (i).

OUTLINE

- Ferric Thin-Film Power Inductors
- **Ferric Device Libraries, Design and Models**
- Ferric Power Converters

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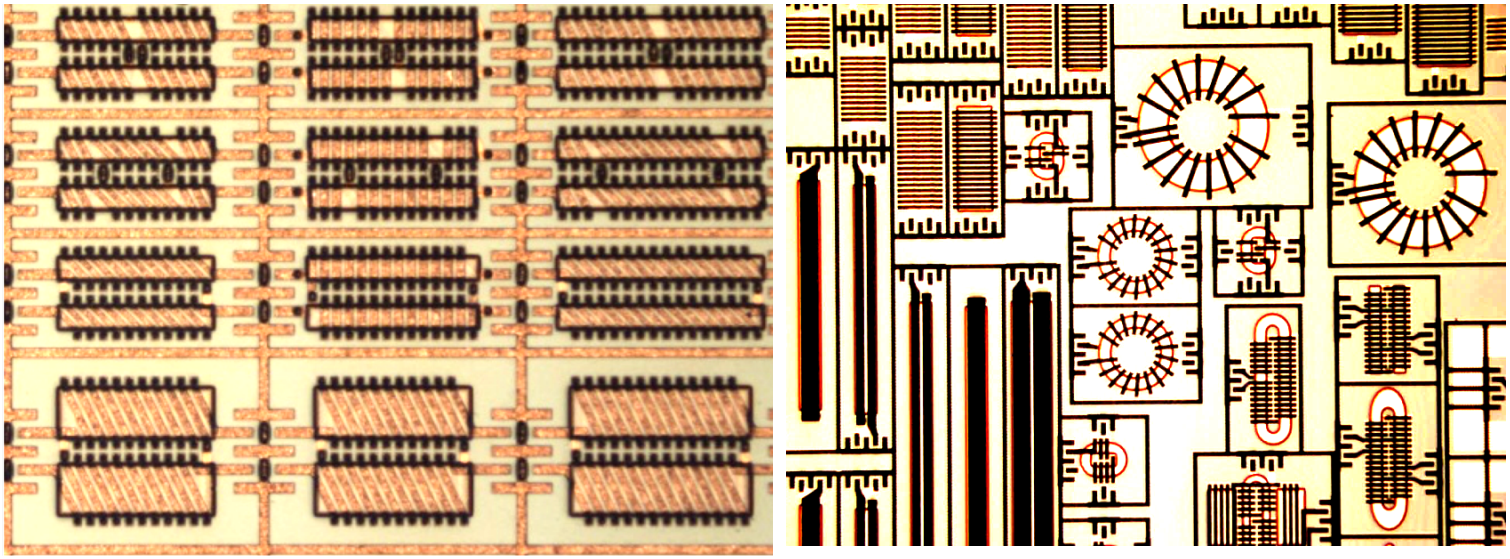
FERRIC INDUCTOR LIBRARY

- Many electrical parameters controlled by design with single fabrication process
  - Inductance, Resistance and saturation current
  - Coupling coefficient and turns ratio for transformers



Microscope image for a subset of Ferric Inductor Cell library devices

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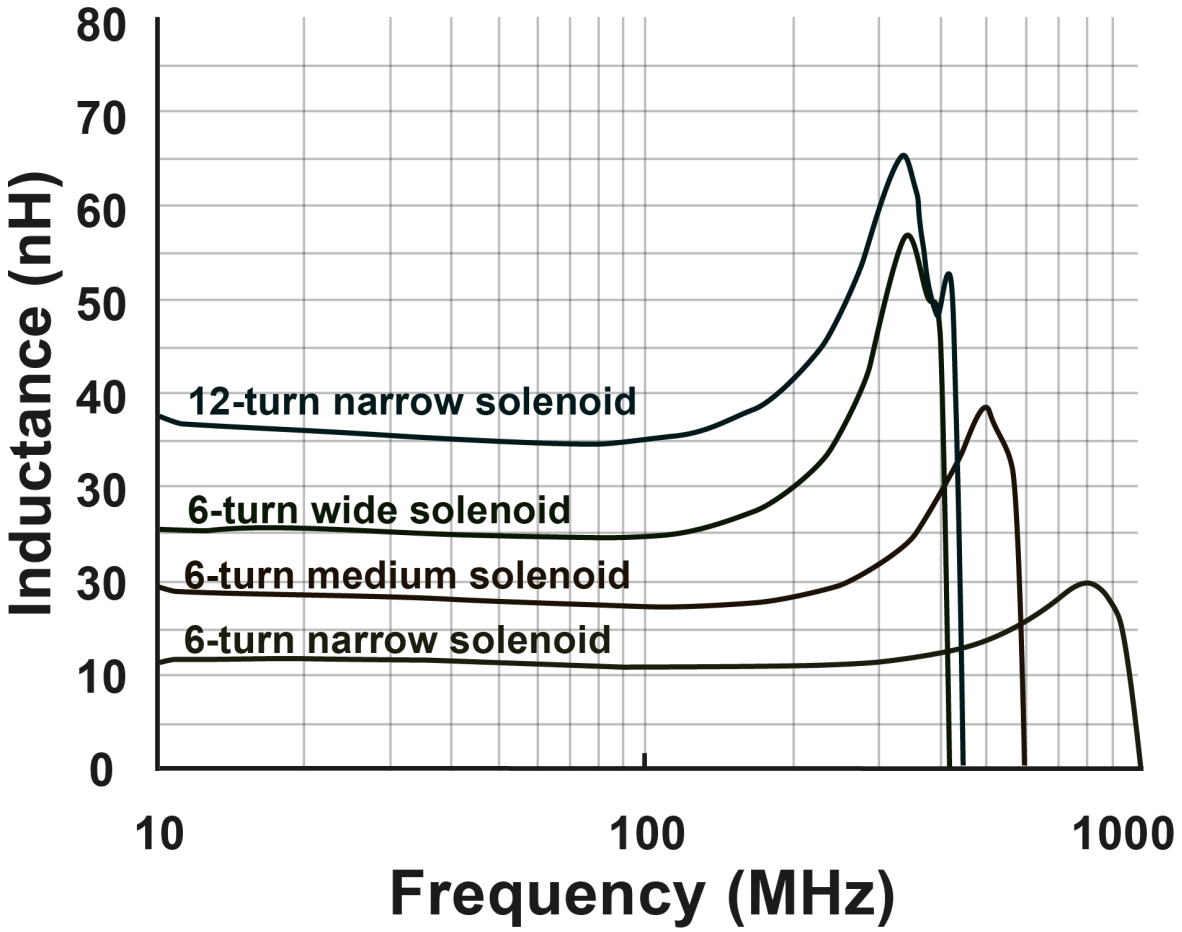
FERRIC INDUCTOR LIBRARY

Wide inductor design space is covered with a single manufacturing process



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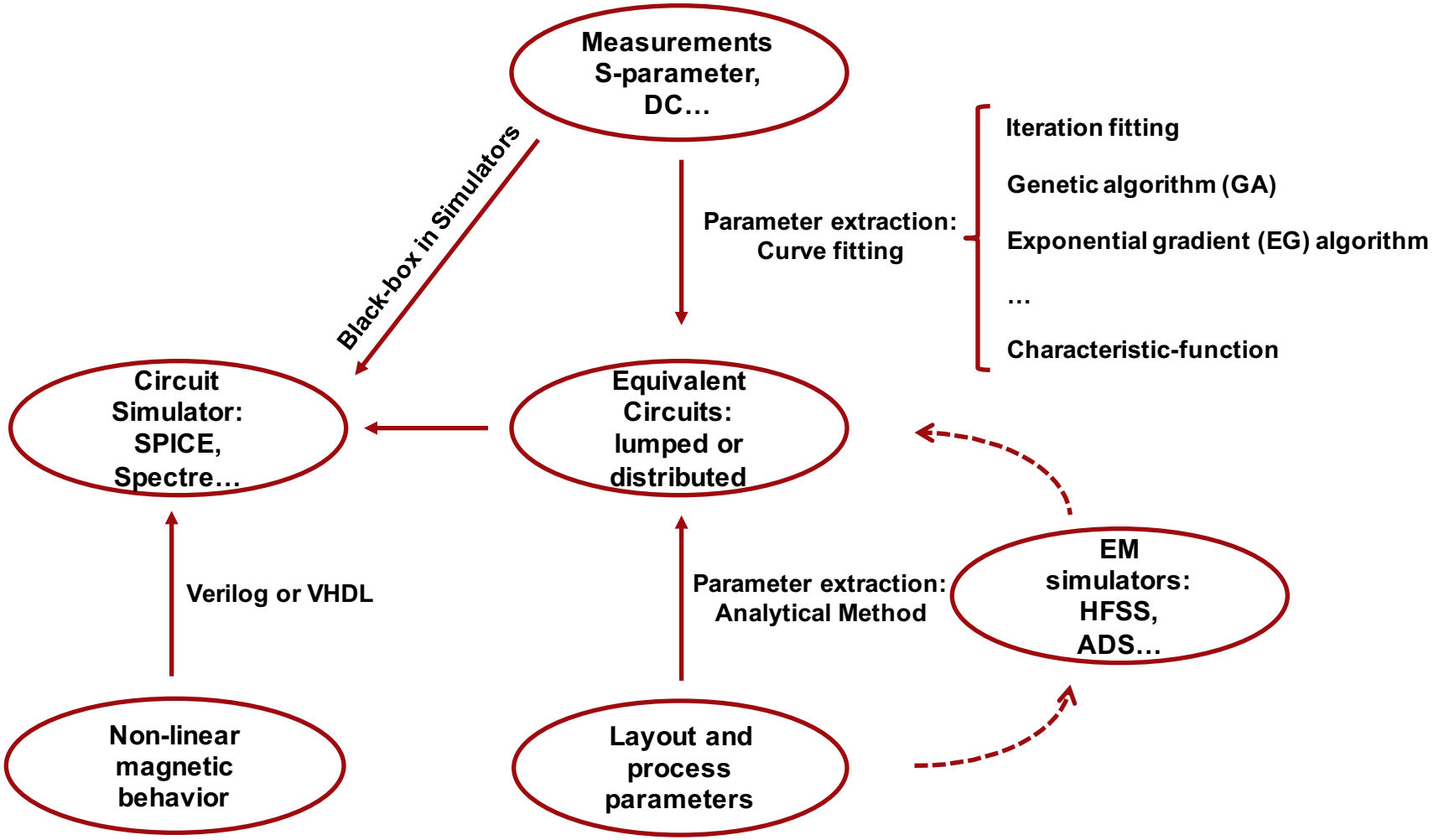
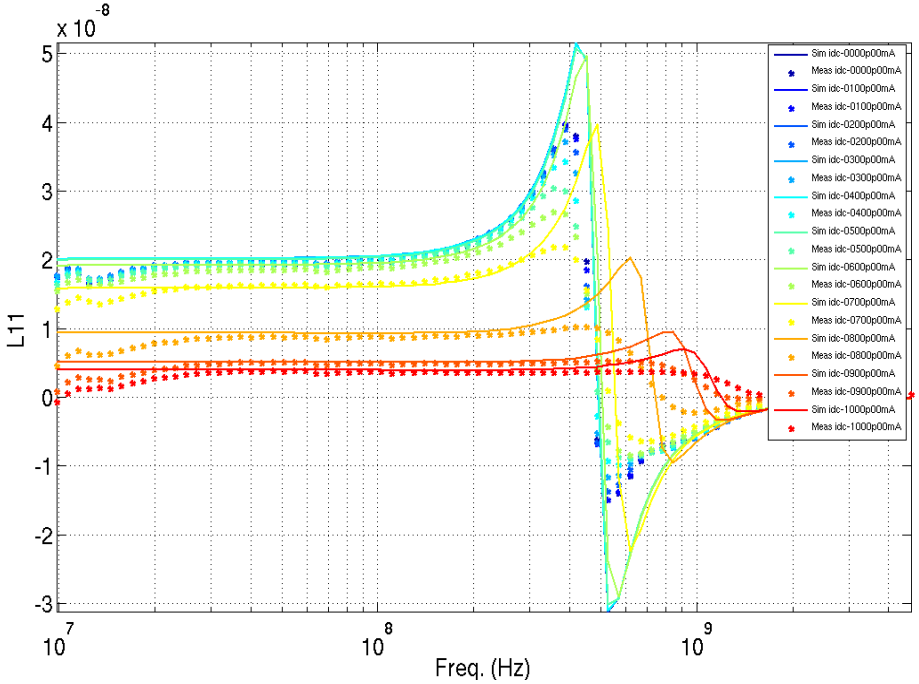
FERRIC INDUCTOR MODELS



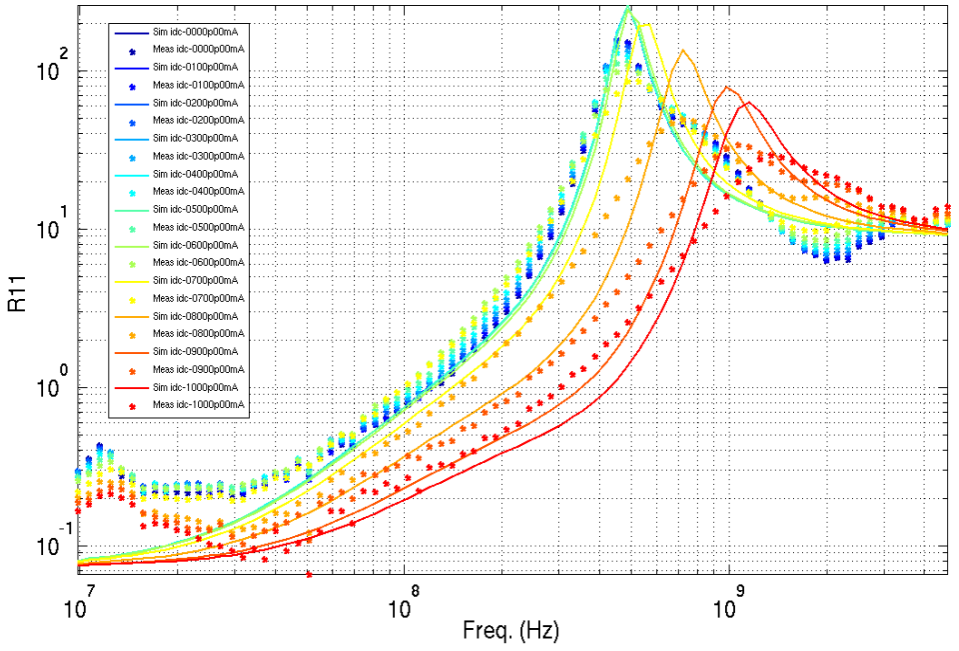
FERRIC INDUCTOR MODELS

L & R VS. FREQUENCY WITH I_{AVG} SWEEP: MEASUREMENT & SIMULATION

Broadband compact circuit models are available for Ferric Library devices including magnetic saturation



Measured inductor inductance data (dots) compared with SPECTRE model (lines)



Measured inductor resistance data (dots) compared with SPECTRE model (lines)

OUTLINE

- Ferric Thin-Film Power Inductors
- Ferric Device Libraries, Design Support and Models
- **Ferric Power Converters**

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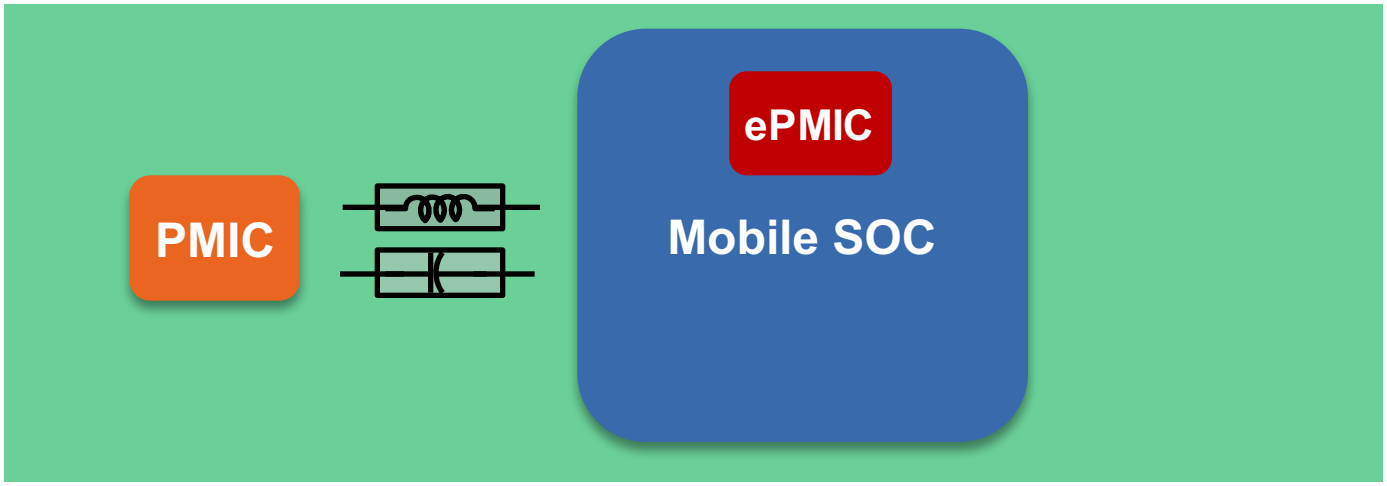
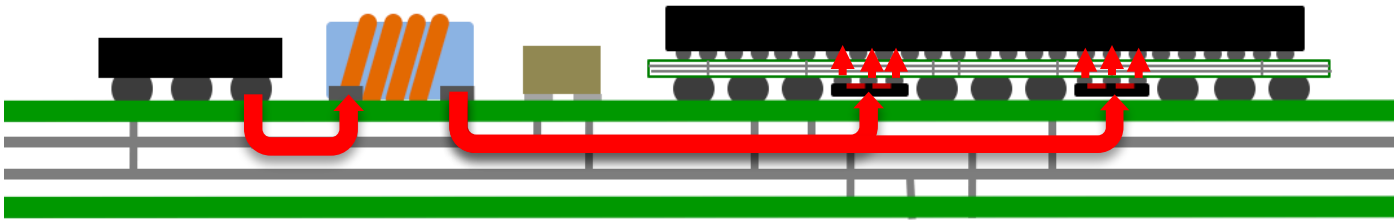
FERRIC | Embedded Power Management IC (ePMIC)

Top View



Cross-Section View



- >10 IVR Bucks with thin-film inductors on embedded PMIC (ePMIC)
  - – Buck count increase to provide per-core DVFS
  - – 1 Buck from master PMIC
  - + *Reduction in BOM, board area, power delivery losses*
  - +*Improved power management → improved performance-per-watt*

FERRIC | Package VR | FE1038D

Fe01038D Power Converter

3A Chip Scale DC-DC Step-Down Power Converter with Integrated Inductor

Description

The Fe01034D is an 8-phase Buck converter with fully integrated powertrain, including thin-film power inductors. The Fe01034D integrates interface, power management, voltage control and power train circuitry (including power FETs, inductor and capacitor) all in one die, 2.0mm x 3.2mm.

The Fe01034D is designed to meet the precise voltage and fast transient requirements of high-performance processor, DSP, FPGA, and memory in distributed power architecture. The power converter's high-bandwidth regulation, coupled with high switching frequency powertrain driving magnetic composite integrated inductor technology deliver high-quality, small footprint power management for high performance loads.

High switching-frequency DC-DC power conversion with integrated power inductors greatly reduces board area, layout complexity, and BOM. The Fe01034D provides improved energy efficiency for true point of load (POL) applications and significantly reduced design cycle and overall system cost.

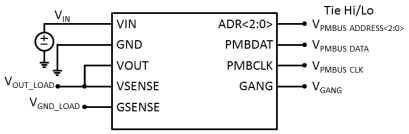


Figure 1: Application Schematic
Total Area 6.4 mm^2

Features

- Integrated Thin-Film Magnetic Inductors
- Efficiency > 85%
- Multi-Phase Operation
- Single Input Supply Operation
  - 1.8V-2.5V
- Programmable Output Voltage
  - 0.6V-1.5V
- Output Current
  0mA – 3A
- Small footprint
  - 2.0mm × 3.2mm
  - 180µm IO Pitch
- Low Profile
  - 400µm
- Digital Power Management Interface
- High switching frequency
  - 100MHz
- Programmable soft start
- Load Regulation
- Line Regulation
- Fast Input Step
- Programmable Ramp Rates
- Auto Phase Shedding
- Output LDO
- Gang operation
- On-chip power monitor
- On-chip temperature monitor
- Under Voltage Lockout, Over Current, Over Voltage and Thermal Protection.

Application

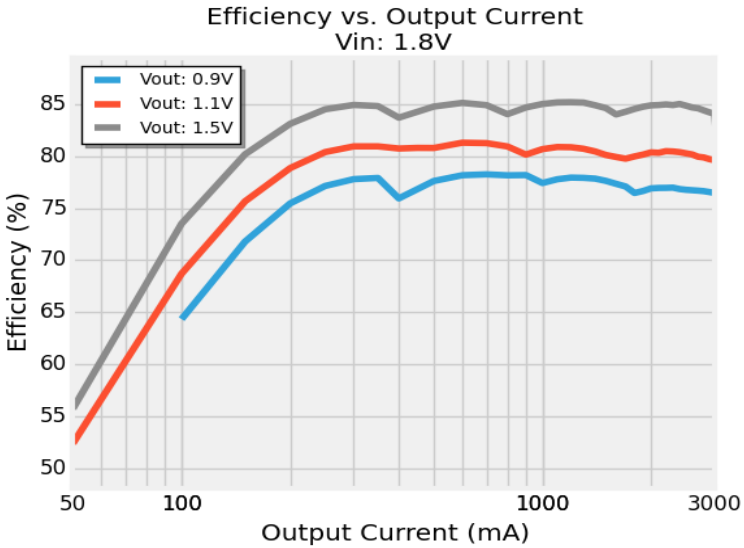
Point of load regulation for processors, DSPs, FPGAs, and ASICs

Noise sensitive applications such as A/V, RF and Gbit I/O

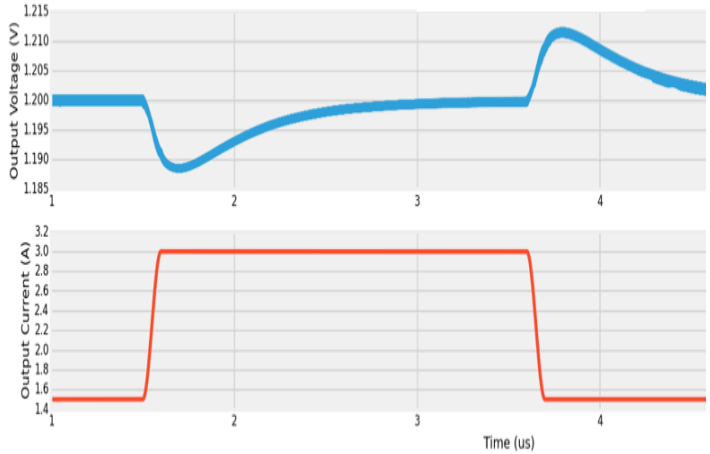
Blade servers, RAID storage systems, LAN/SAN adapter cards, wireless base stations, industrial automation.

Ordering Information

Part Number	Temp Rating (°C)	Package
Fe01034D	-40 to +85	FC Bare Die - 59 Cu Bump
TDB	Evaluation Board	

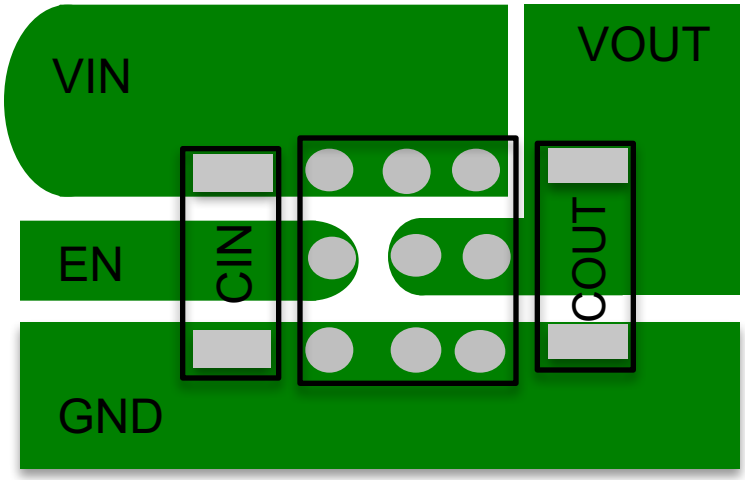


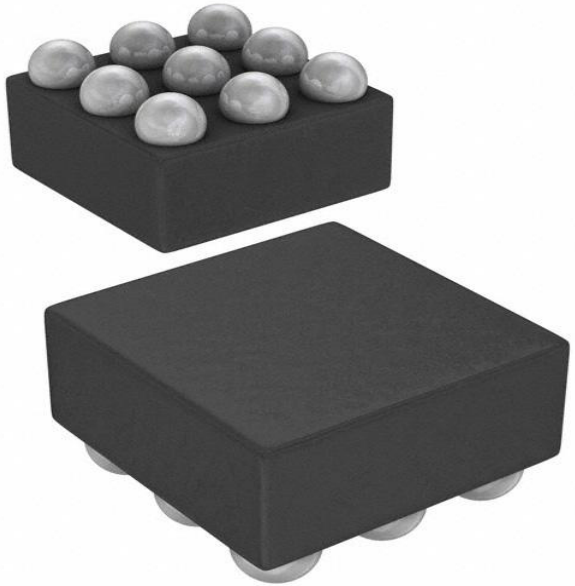
Efficiency VIN = 1.8V, VOUT = 0.9V, 1.2V, 1.5V



Load Transient: VIN = 1.8V, VOUT = 1.2V, IOUT = 1.5A - 3A

FERRIC | µVR | BOOST CONVERTER





Inductors embedded in Wafer Level Package
Reduce board footprint by 400%!

- **Total Board Solution Size:** ~3.0mm^2
  - 1x WLCSP Boost Converter Chip (1x 1.44mm^2)
  - 2x 0402 Discrete Capacitors(2x 0.5mm^2)

Fe

FERRIC | μVR BOOST | FE1004U

FE01004U Power Converter

0.1A Chip Scale DC-DC Step-Up Power Converter with Integrated Inductors

Description

The FE01004U is a synchronous step-up DCDC converter with integrated power FETs, inductor and capacitor. The nominal input voltage range is 1.8V to 6.0V. The output fixed voltages is 2.5V-5V in increments of 0.1V with ±2% accuracy. Up to 100mA of continuous output current can be drawn from this converter. Fast switching frequency allows for the use of small size input / output capacitors and enables wide loop bandwidth within a small footprint and low profile. The FE01004U solution offers greatly reduced board area, layout complexity and BOM. With a WLCSP package size of 1.2mm x 1.2mm, a total board solution of 2.5mm² can be achieved.

Features

- Integrated Magnetic Thin-Film Inductors
- Up to 90% Efficiency
- Internal Synchronous Rectification
- Input Voltage Range: 1.8V-5.5V
- Fixed Output Voltage: 2.5V-5V with ±2% accuracy (0.1V increment)
- Output Current: Up to 100mA OR 500mA
- Operating Quiescent Current: 0.5 μA
- Small Footprint: 1.2mm x 1.2mm
- Low Profile: 400μm
- Total Board Solution Size: 2.5 mm²
- Pulse Frequency Modulation
- Soft Start
- Under Voltage Lockout
- Over Current Protection
- Over Voltage Protection
- Load Disconnect
- Output LDO for VIN > VOUT

Typical Schematic

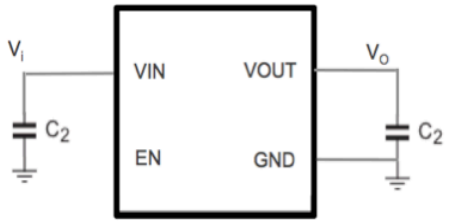


Figure 1: FE01004U Application Schematic

Applications

Low-Voltage Li-Ion Batteries

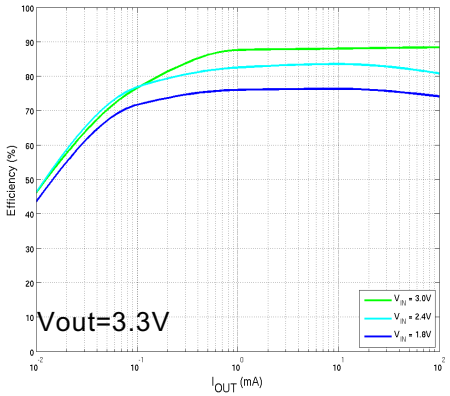
Smart Phones, Tablets, Portable Devices

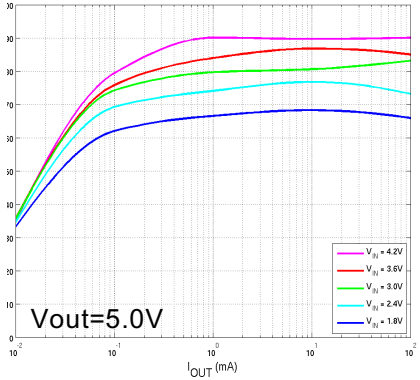
Wearable devices

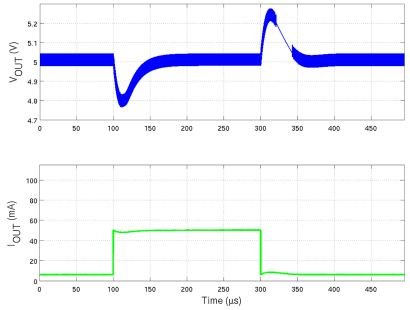
PC Peripherals

Ordering Information

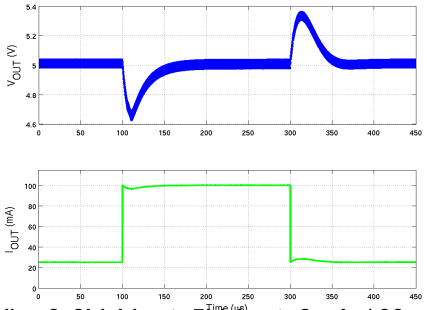
Part Number	Temp Rating (°C)	Package
FE01004U	-40 to +105	9-pin WLCSP
TBD	Evaluation Board	



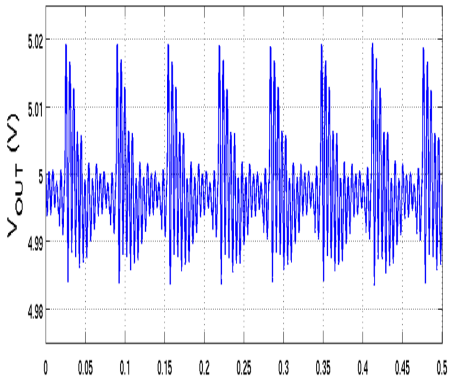




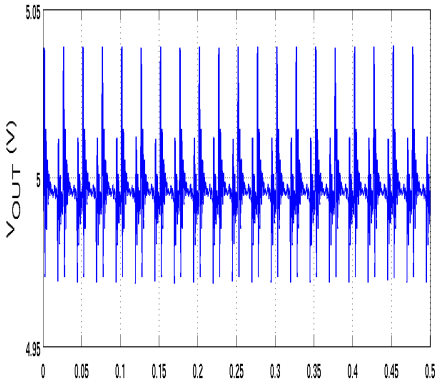
Vin=3.6V,Vout=5V, Iout=6mA-50mA



Vin=3.6V, Vout=5V, Iout=6mA-100mA



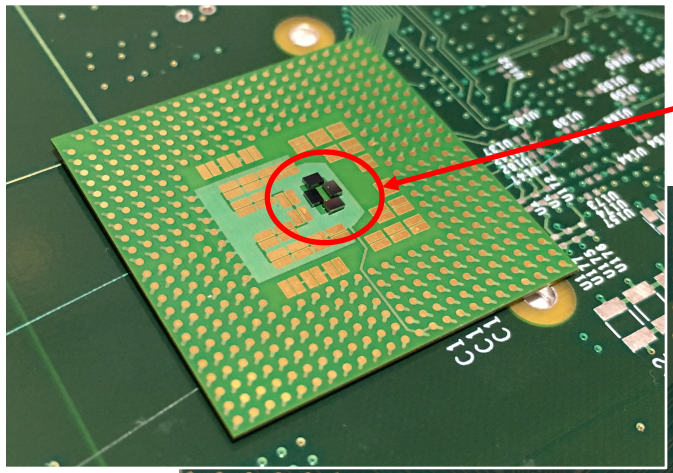
Vin=3.6V,Vout=5V, Iout=50mA



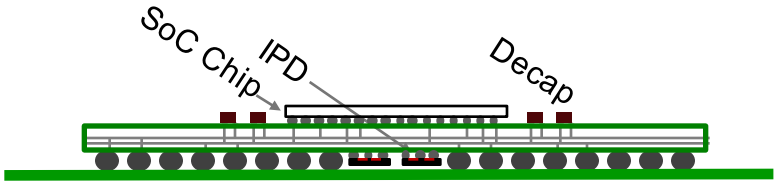
Vin=3.6V,Vout=5V, Iout=100mA

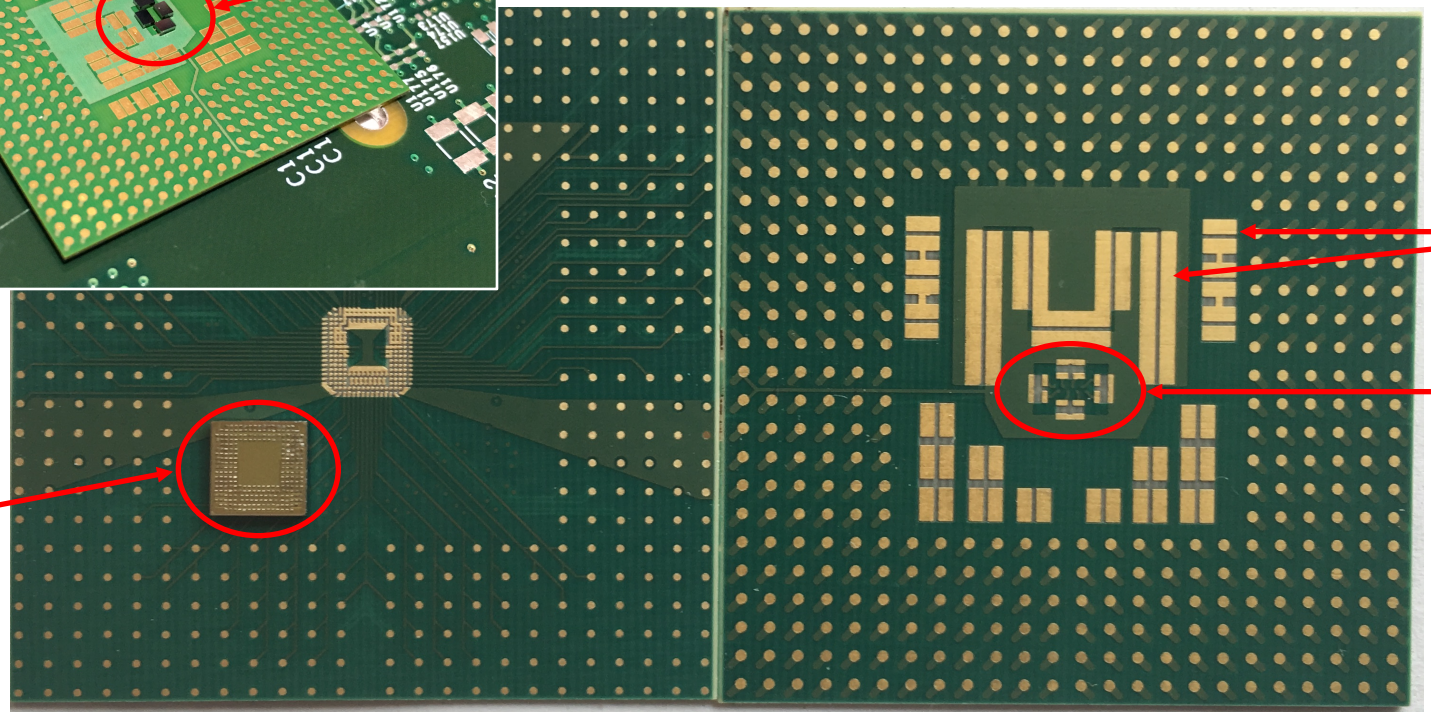
FERRIC IPDs | SOC embedded Voltage Regulator (eVR)

- Ferric Power Inductor IPD integrated on SoC package 'landside'
- Ferric SoC-IVR Die: IVR controller, half-bridge and cap – SoC and 'slammer' loads
- >85% efficiency for 1.5V to 0.85V conversion, 2A/mm^2 current density



Assembled IPDs





Cap sites

IPD Land sites

SoC-IVR Die

Substrate Die Side **Substrate Land Side**

Fe

FERRIC
THE COMPANY

- Fabless semiconductor technology company, founded in 2011
  - Located in New York
- Integrated magnetic component and power conversion technology
- Ferric integrated power inductors are **available at TSMC now**
- Company Focus:
  - semiconductor device manufacturing
  - magnetic thin-films
  - RF device design, characterization and modeling
  - CMOS IC design for power conversion applications
- Chip Sales, Design, IP and Process Licensing

Fe

QUESTIONS?

Fe