PWR SOC 16
Integrated Power Conversion and Power Management
next generation technology for emerging business opportunities, October 3-5 2016, Madrid, Spain
new technologies new applications new markets

Design and Fabrication of Bond Wire Micro-Magnetics with LTCC core

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Outline

- More than Moore systems
- Bond wire magnetics and example of applications
- Ferromagnetic LTCC
- Miniaturized bond wire transformer and applications
- Optimization of the inductance value
- Conclusions

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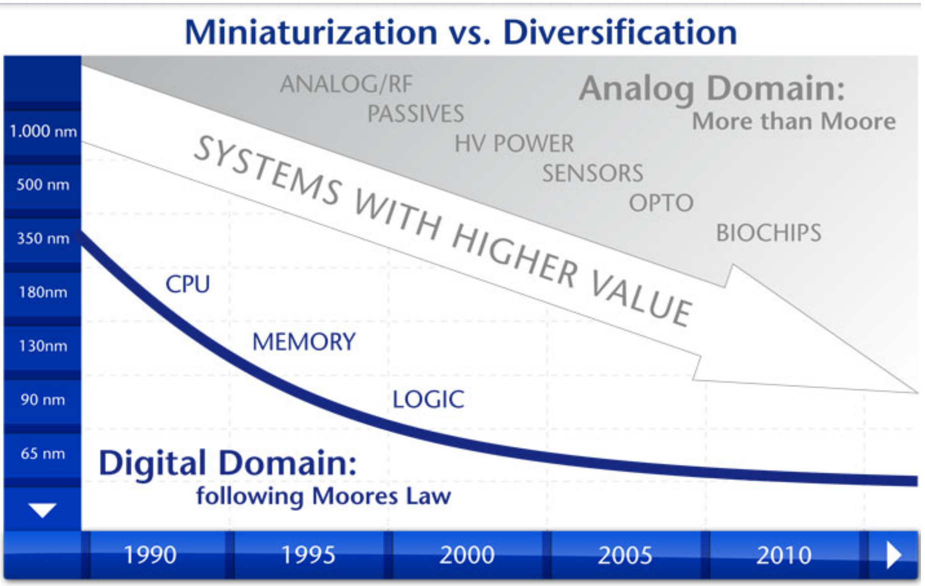
Introduction

- Technology improvements is leading towards miniaturization of circuits.
- Shrunk systems allow a **lower production cost** and **are less power demanding**
- The powered delivered by transducers/devices (inductors) depends on their volume
- Magnetic devices can be **integrated at package level** together with the dedicated IC through **MEMS technologies (IMEMS)**
- Nevertheless, devices embedded through MEMS techniques can be viewed as IC pre- or post-processing steps, or sometimes need a processing on a separate wafer
- In addition to MEMS processes**, bond wire technology** is able to give additional value to **More than Moore (MtM)** systems

More than Moore (MtM)

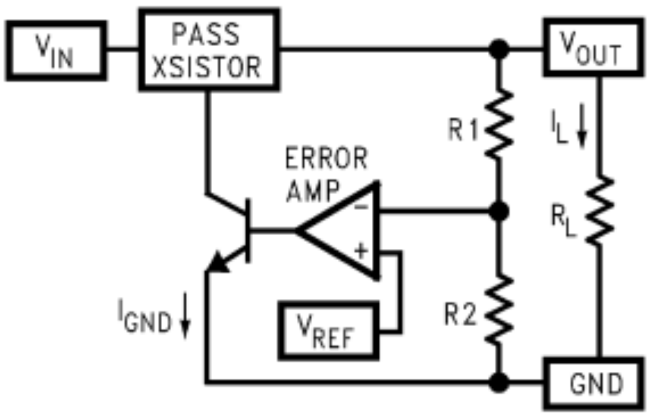


- Moore's law is valid only for **digital systems**
- A capacitor cannot be shrunk without new materials, as well as inductors.
- **High voltage devices** and power devices have **self-defining sizes**, dictated by the laws of physics and they scale poorly.
- The majority of **analog applications** fall in the technology node **of 0.13µm** and above.

- With **increasing miniaturization** of systems, analog ICs allow the possibility of **further embedded functionalities**.
- **MtM** systems provide additional value in different ways to migrate from the system board-level into the package (**SiP**) or onto the chip (**SoC**).

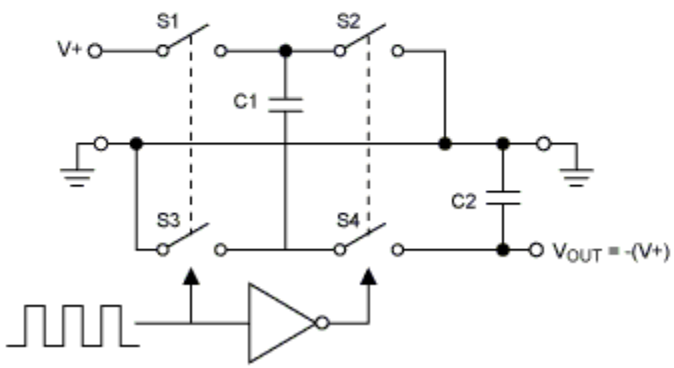
Typical Power Converters w/o Magnetic Components

Linear regulator



- **Pros**: no reactive devices. Easily integrable
- **Cons**: Very low efficiency if V_{OUT}/V_{IN}<<1. No boost voltage.

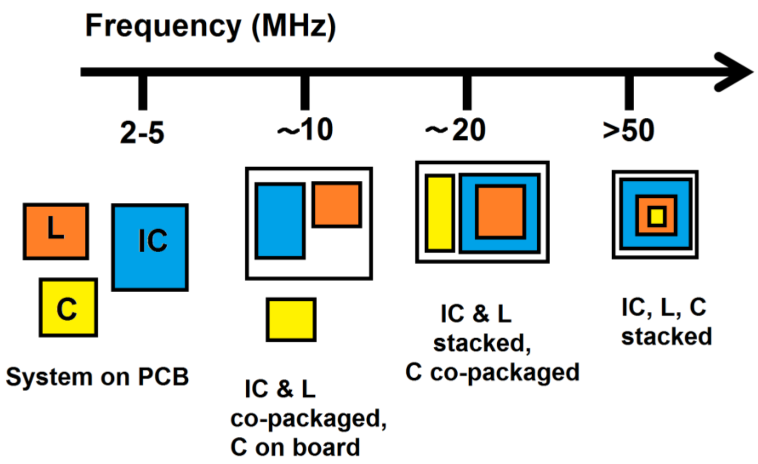
Switched capacitor circuit (charge pump)



- **Pros:** no reactive devices. Easily integrable. Higher efficiency compared to linear reg.
- **Cons:** Higher complexity. Losses proportional to frequency. $P_{lost}=\frac{1}{2}C(\Delta V)^2 f$

- Switched capacitor circuits offer more flexibility compared to linear ones, at the expenses of higher system complexity

Evolution of SMPS (Switched Mode Power Supply) Technology



- Increase of switching frequencies leads to smaller and smaller systems
- Passive components are potentially integrable at System on Chip (**SoC**) level
- At f>50MHz, air- core inductors, or magnetic core-based inductors?
  - **Efficient systems cannot exclude magnetic-core devices [1]**

[1] **C. O. Mathúna et al.** "Review of integrated magnetics for power supply on chip (PwrSoC)." *IEEE Tran. Power Electron.* 27.11 (2012): 4799-4816.

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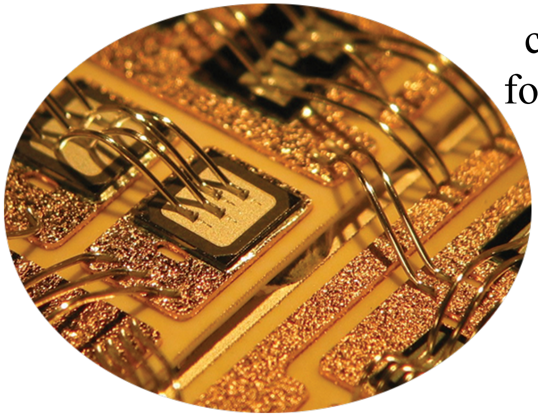
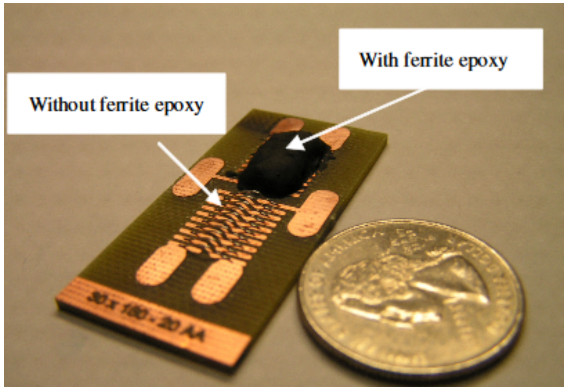
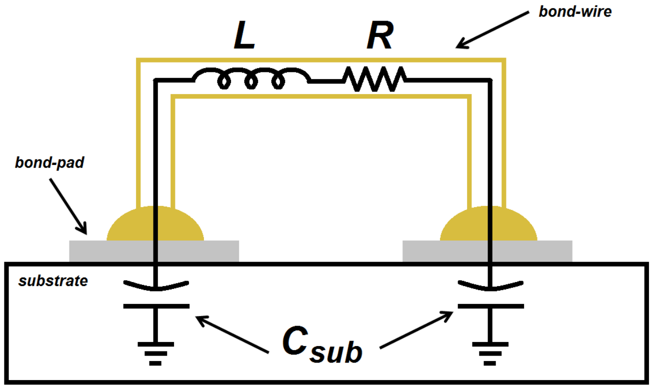
Bond Wires Applications



Generally used for chip interconnection for applications ~ GHz



...or as solenoids [2]



...can be used as standalone inductors (~1-2nH/mm), providing much less resistance than IC metal layers

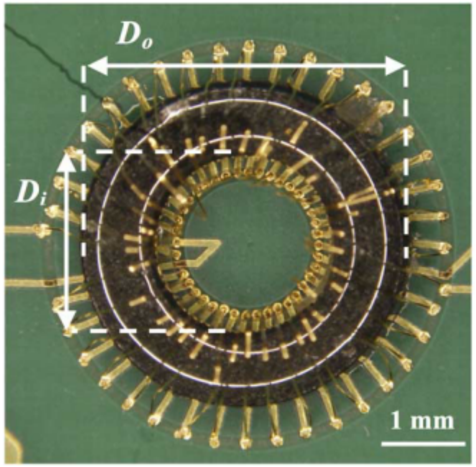
[2] J. Lu et al., "Modeling, design, and characterization of multiturn bondwire inductors with ferrite epoxy glob cores for power supply system-on-chip or system-in-package applications." *IEEE Trans. Power Electron.* 25.8 (2010).

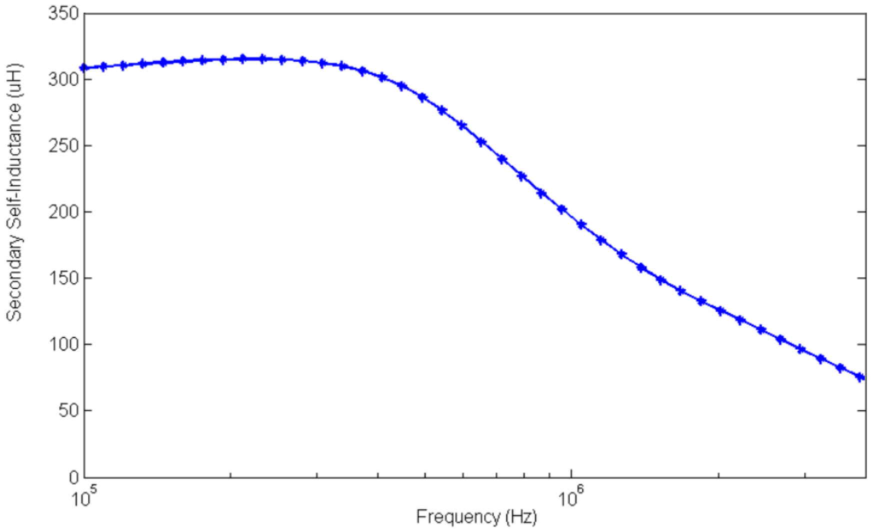
Bond Wire Magnetics Advantages

- Inductors/transformers can be embedded using standard IC bond wire technology.
- The upper metal layer is used for the bottom winding, bond wire for winding closure.
- Complementary technique compared to MEMS LIGA processes and simpler (no need of post processing steps or sacrificial layers):
  - Circuits can lay under the inductor and designed independently from the top magnetic, allowing **SoC** structure. With MEMS bulk/surface micromachining processes this is not possible (MEMS should be processed on a separate wafer).
- Allows for planar magnetic cores, the ***B*** field does not leak into the bottom circuit (with toroidal core no interferences, no latch-up, higher efficiency).
- Typical MEMS implementations are spiral inductors using very thick metallizations, and a top thin magnetic layer (inductance enhancement 10-20X → high demagnetization → *B* leaking outside the device)

Bond Wire Microtransformer with Ferrite Core (on pcb)

Top view (MnZn 75 ferrite core) [3]

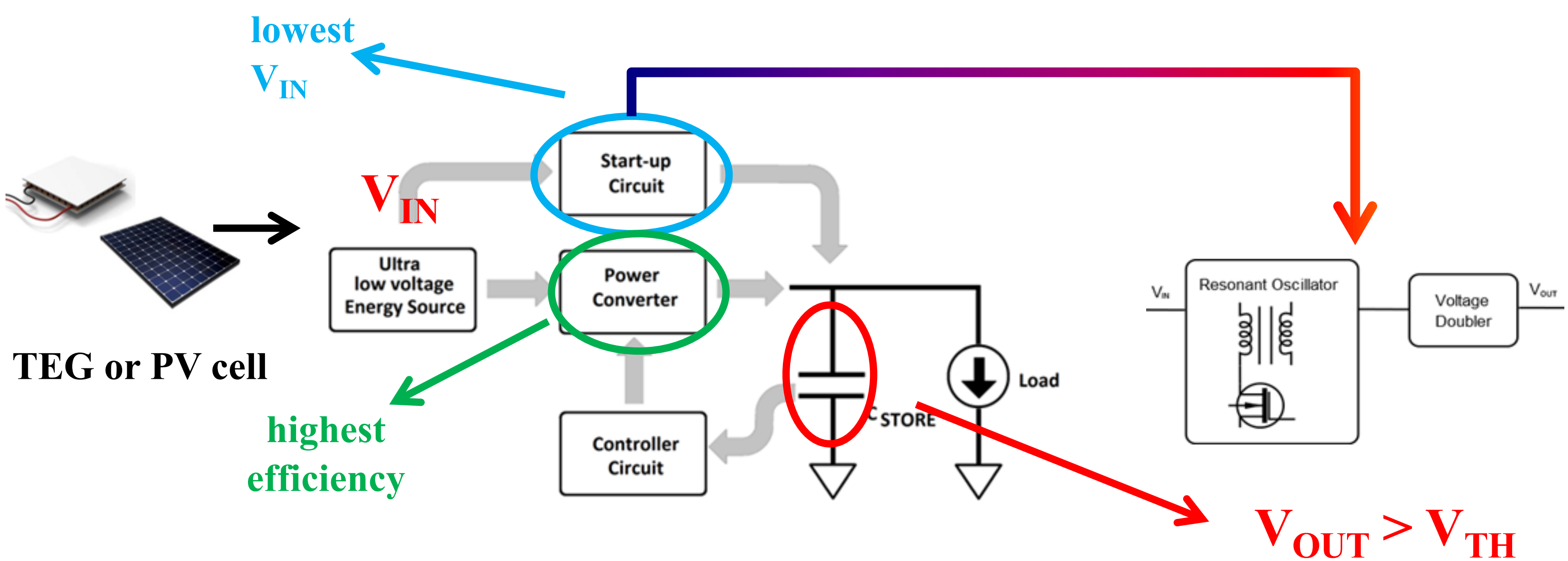




- Core thickness ≈ 500µm
- External (internal) diameter=3.95 (2.15) mm
- 1:N = 1:38
- L_{22} ≈ 315 µH @ f=100 kHz & V=100 mV
- Effective footprint area ≈ 25 mm²
- Rdc = 4.3 Ω
- Q @ f=100 kHz ≈ 6.2
- Very high Inductance density ≈ 12.8 µH/mm²
- Ferrite core μ_r=5000

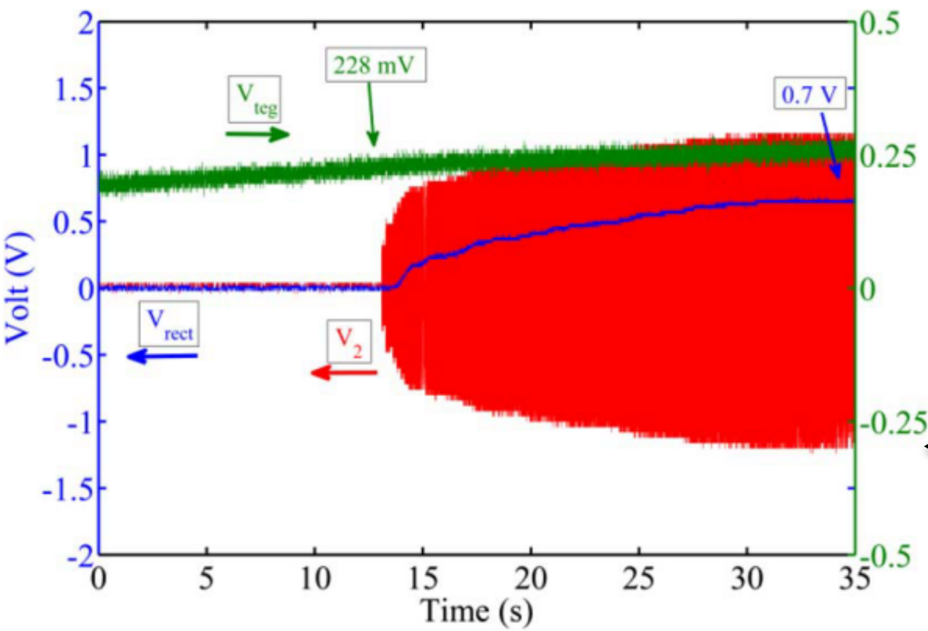
[3] E. Macrelli et al. "Modeling, Design, and Fabrication of High-Inductance Bond Wire Microtransformers With Toroidal Ferrite Core". *IEEE Trans. Power Electron.* 30.10, 2015, pp. 5724–5737.

Application of Bond Wire Transformers



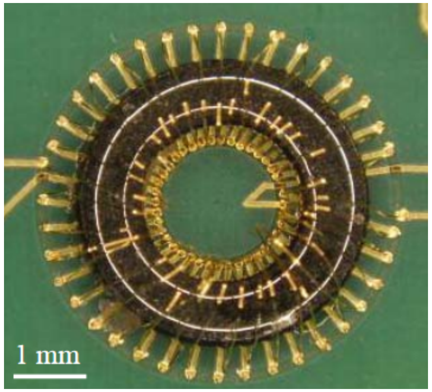
- Typical power converters cannot boost voltages lower than the V_{TH} of the power MOS.
- A **battery-less start-up circuit** is used to store energy in a capacitance
- The energy is used to drive the gate of the power devices (high voltage, low current)

Boost Oscillator with Bond Wire Microtransformer and Ferrite Core



Boost oscillator designed in a CMOS 0.35µm using DeplMOS [4]

(MnZn 75 ferrite core)



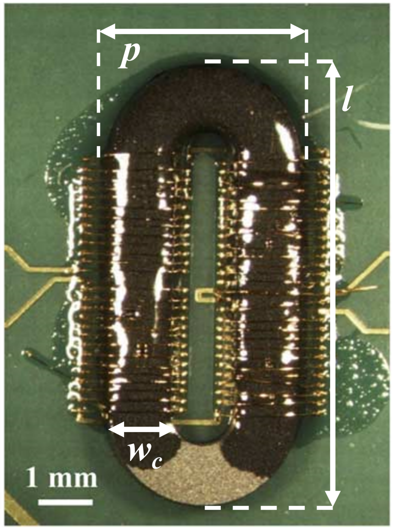
Converts **228 mV** into 0.7 V

dependent on the *Q*-factor of the transformer

[4] E. Macrelli et al. "Design of Low-Voltage Integrated Step-up Oscillators with Microtransformers for Energy Harvesting Applications". *IEEE Trans. Circuits Syst. I, Reg. Papers* 62.7, 2015, pp. 1–10.

Bond Wire Microtransformer with LTCC Core (on pcb)

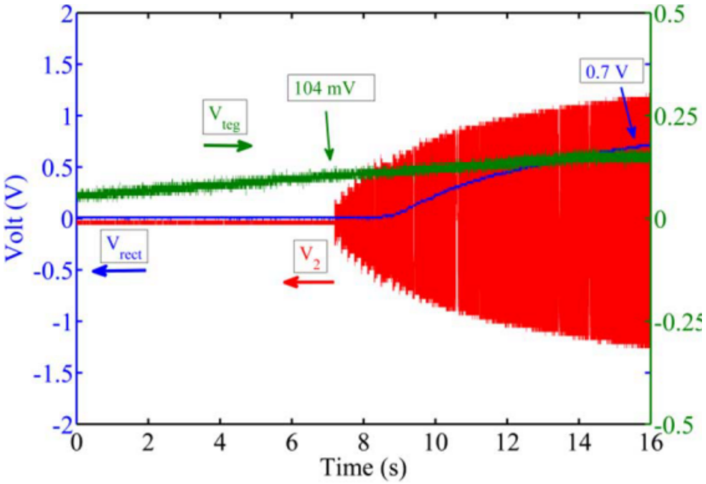
$l \times p \times w_c \times h$= 7.0 × 3.0 × 1.0 × 0.4 (mm)



ESL 40011 [4]
Ferrite core μ_r≈200

- Core thickness ≈ 400µm
- Major (minor) axis =7.0 (3.0) mm
- 1:N = 1:52
- L_{22} ≈ 30 µH @ f=100 kHz & V=100 mV
- Effective footprint area ≈ 28 mm²

Converts **104 mV** into 0.7 V



- The start-up voltage is inversely proportional to the turns ratio ***N*** and parasitic series ***Rdc*** resistance at the primary of the transformer.
- Incresing ***N, Rdc*** increases → no benefit.
- High μ_r (1000-5000) → ***Rdc*** increases in the MHz range

  → Need of **lower** μ_r material and high resistivity ρ_c like magnetic LTCC

[4] E. Macrelli et al. "Design of Low-Voltage Integrated Step-up Oscillators with Microtransformers for Energy Harvesting Applications". *IEEE Trans. Circuits Syst. I, Reg. Papers* 62.7, 2015, pp. 1–10.

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Example of Soft Magnetic Materials

Material	Resistivity ρ_c (Ω cm)
Co ferrite	10^7
Mg ferrite	10^7
NiZn ferrite	10^6
Cu ferrite	10^5
Mn ferrite	10^4
MnZn ferrite	$10^2 - 10^3$
Zn ferrite	10^2
Fe ferrite	$4 \cdot 10^{-3}$
Metallic glass	$125 \cdot 10^{-6}$
NiFe (permalloy)	$45 \cdot 10^{-6}$
SiFe (silicon steel, 2.5% Si)	$40 \cdot 10^{-6}$
Co alloy (50%)	$35 \cdot 10^{-6}$
SiFe (silicon iron, 1% Si)	$25 \cdot 10^{-6}$
SiFe (silicon iron, 0.25% Si)	$10 \cdot 10^{-6}$
Fe (iron)	$9.6 \cdot 10^{-6}$
Nanocrystalline	$1.2 \cdot 10^{-6}$

Material	Relative permeability μ_{rc}
Powder	10 – 60
NiZn ferrite	150
Cobalt	250
Nickel	600
50% Ni, 50% Fe (orthonol)	2000
MnZn ferrite	1000 – 4000
0.25% Si iron	2700
48% Ni alloy	4000
2.5% Si steel	5000
4% Si steel	7000
50% Co alloy	10 000
Metallic glass	10 000
Nanocrystalline	15 000 – 150 000
80% Ni, 4% Mo alloy	50 000
Mumetal 75% Ni, 5% Cu, 2% Cr	100 000
99.96 % pure iron	280 000
79% Ni, 17% Fe, 4% Mo (permalloy)	12 000 – 100 000
79% Ni, 5% Mo (supermalloy)	1 000 000

- Generally, as rule of thumb, the higher the permeability, the lower the resistivity
- Lower resistivity implies higher losses and lower frequencies application

Source: **[5] K. Kazimierczuk**, High-Frequency Magnetic Components. New York, NY, USA: Wiley, 2009.

The Ferromagnetic LTCC Material Properties

L T C C = Low **T**emperature **C**o-fired **C**eramic
Commercial name **ESL 40012:** flexible cast film of magnetic powder dispersed in an organic matrix [6]

- Ceramic material with **relatively high** $\boldsymbol{\mu_r}$: <500-1000>
- High resistivity $\boldsymbol{\rho_c}$: <10^3-10^6 Ω·m>
- Sheet thickness $\boldsymbol{t_l}$ ~ 60 µm
- Fired shrinkage $\boldsymbol{S}$ ~ 17% (X, Y & Z)
- Suitable for high frequency magnetics (hundreds of MHz)

Two commercial samples of
ESL 40011 and ESL 40012

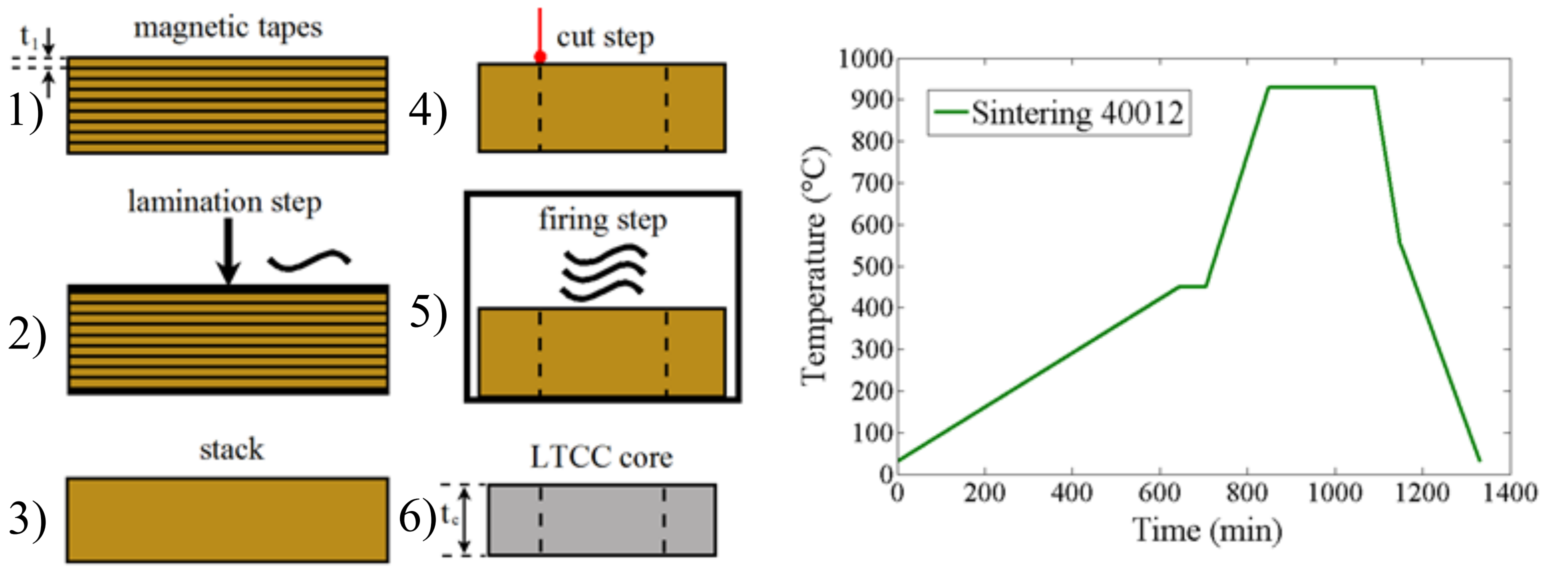
[6] **Y. M. Nguyen et al.** "Soft ferrite cores characterization for integrated micro-inductors." *J. Micromech. Microeng*. 24.10 (2014): 104003.

Permeability Change with Firing Temperature

- The magnetic properties of the ESL 40012 have been extensively investigated in literature [7]:
  - The real part of the permeability can range from 400 (Firing temperatures ~ 900°C) up to 1000 (Firing temperatures ~ 1300°C) , with a cut-off frequency f_c between 2 and 3 MHz, for toroids with n_l = 62 layers (~3.5 mm of thickness).
  - The peak of the imaginary part of the permeability (losses) can range from 250 (Firing temperatures ~ 800°C) up to 400 (Firing temperatures ~ 1300°C) at frequencies between 2 and 3 MHz, for toroids with n_l = 62 layers (~3.5mm of thickness).
  - For ferrites the cut-off frequency relative to the eddy currents losses of the of the real and imaginary part goes with the square of the thickness of the sample: thinner samples might provide better performances (at low frequencies hysteresis losses dominate)

[7] N. Blaz et al. "Complex permeability changes of ferritic LTCC samples with variation of sintering temperatures." *IEEE Trans. Magn.*, Vol. 48, n. 4 (2012), pp. 1563-1566.

The LTCC core Fabrication Procedure



1), 2), 3) n_l = 9 layers of green tapes of thickness t_l =60 μm are stacked with a warm isostatic press @ 14 MPa and T=70°C

4) In the cutting step the stack is cut in a toroidal race-track shaped pattern with a laser equipment (λ=355 nm and P=7 W)

5), 6) Firing phase and final sintered device.

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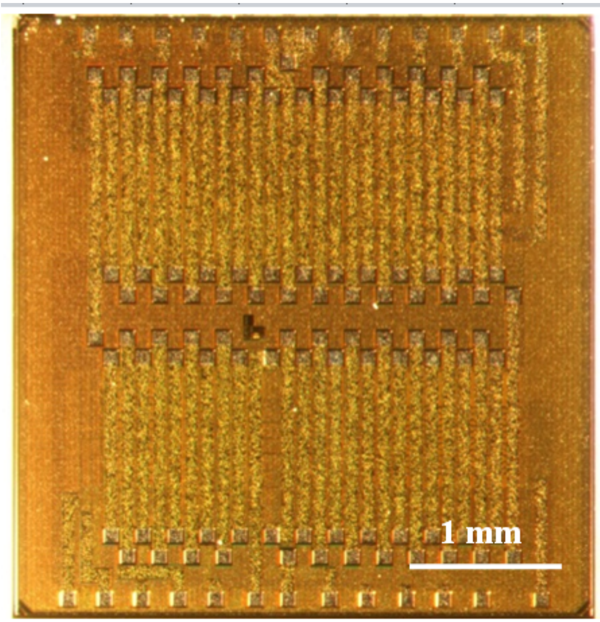
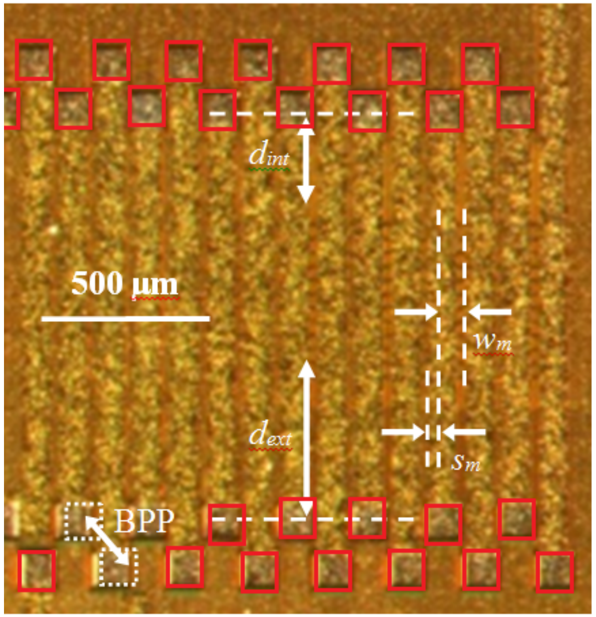
LTCC Microtransformer on-top-of-chip

Top view of the microtransformer bottom side

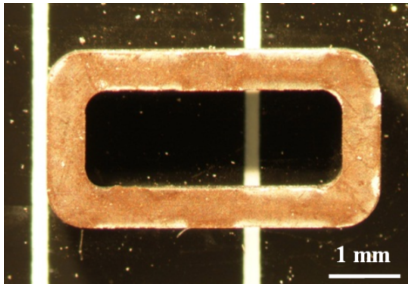


Zoomed view on the metal stripes, Pads are highlighted in red

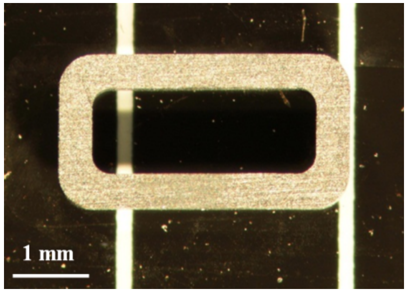


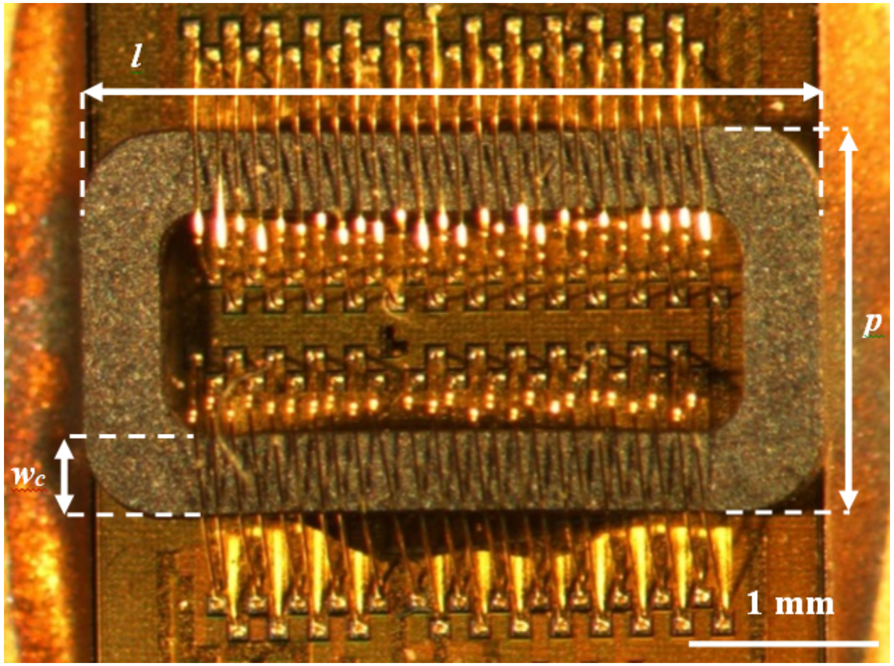
- Bottom winding realized in a 0.35µm CMOS process.
- Bottom winding realized with top metal level
- The minimum distance between the turns is coherent with the minimum distance allowed by the technology

The Fabricated Device



laminated single stack of the ferromagnetic LTCC core before (top) and after (bottom) the firing step.



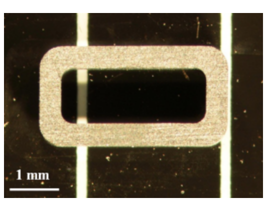


The final device after the bonding phase
$l \times p \times w_c \times h = 3.8 \times 2.0 \times 0.5 \times 0.39$ (mm)

[8] E. Macrelli et al. "Design and Fabrication of a 29 uH Bondwire Micro-Transformer with LTCC Magnetic Core on Silicon for Energy Harvesting Applications". *Procedia Engineering* 87, 2014, pp. 1557–1560.

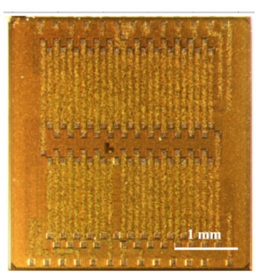
PwrSoC integration: hybrid solution

- LTCC ferrite core requires high-temperature firing
- CMOS compatibility can be tackled by using hybrid integration
  - Fully sintered ferrite core with higher inductance density is fabricated off-chip
  - Core is assembled on-top of the SoC with upper windings made of bonding wires
  - Cost-effective solution with high throughput wire bonding machines
- Control circuitry and switches devices can be fabricated with standard silicon technology → **PwrSoC integration**



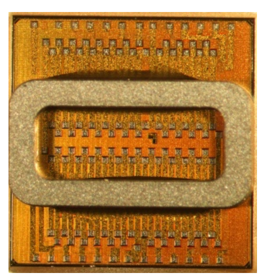
Sintered core

+

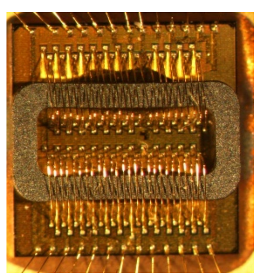


SoC

=

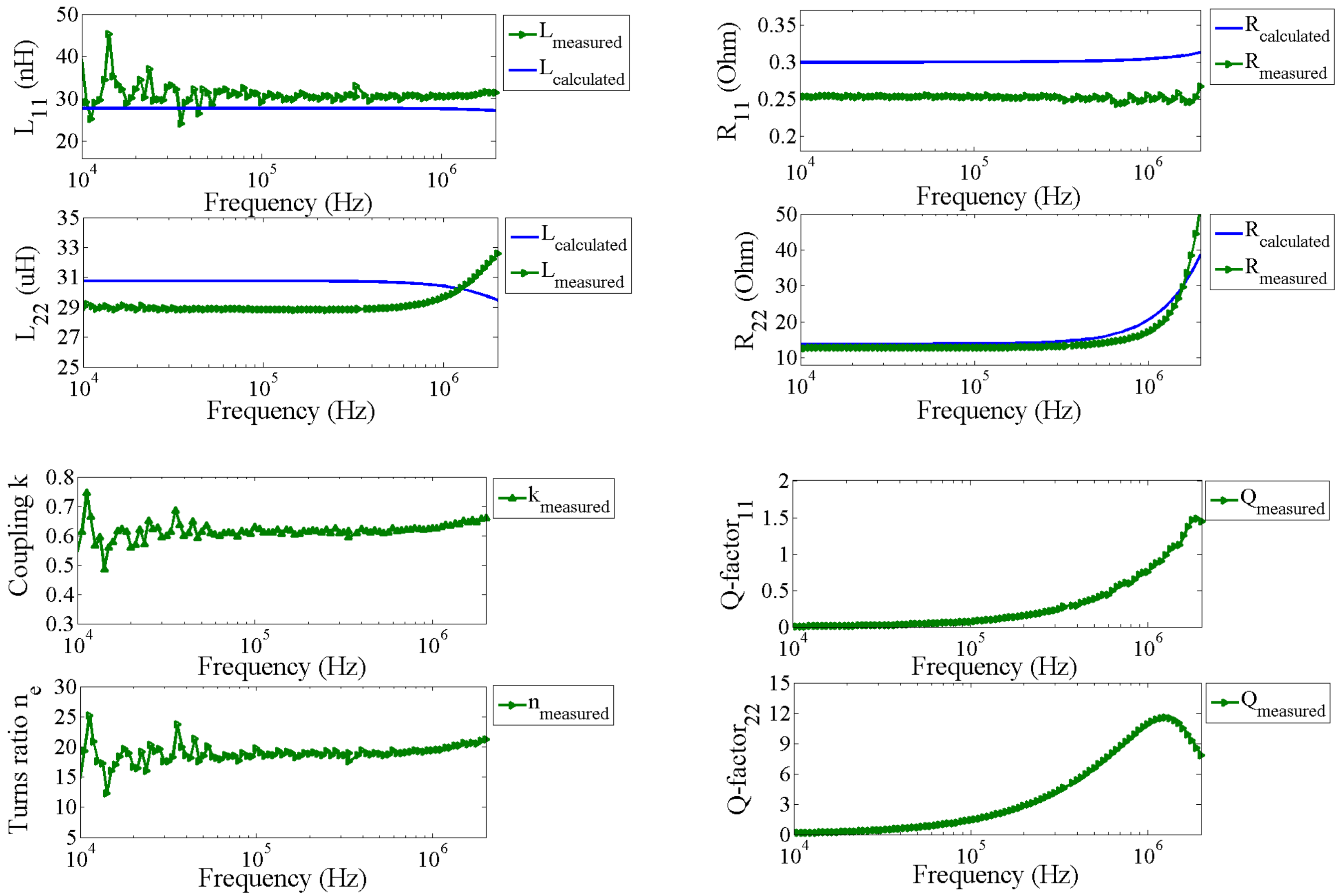

On-top

→


PwrSoC

[6] Y. M. Nguyen et al. "Soft ferrite cores characterization for integrated micro-inductors." *J. Micromech. Microeng*. 24.10 (2014): 104003.

Experimental Measurements



- Obtained @ 100 mV
- Q_{max} = 11.6 @ 1.3 MHz
- L_{22} = 31 µH @ 1.3 MHz
- Density = 2.23 µH/mm²
- L/R_{DC} ~ 2.6 µH/Ω

Summary

Core	**LTCC**
L_{11}^{LF} (nH)	**12.8**
L_{22}^{LF} (µH)	**30.8**
R_{w1}^{LF} (Ω)	**0.30**
R_{w2}^{LF} (Ω)	**14.8**
I_{max} (A)	**4.9**
f_{min} (kHz) @ 0.1 V RMS	**246**
Q_{max} @ 1.3MHz	**11.6**

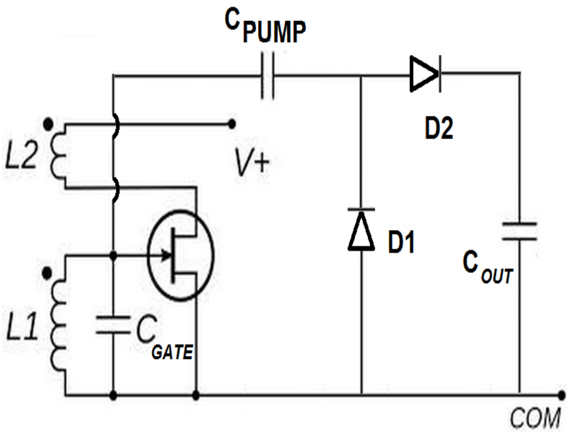
Comparison with Commercial Transformers

Parameter	This device	LPR4012	LPR6235
Core type	LTCC Ferrite	Ferrite	Ferrite
n_{12}	50	10	10
k*	0.65	0.95	0.95
A_r (mm^2) x h (mm)	15 x 0.5[a]	16 x 1.1	36 x 3.5
L_{22} (μH)@Q_{max}	31	190	2500
L_{22} / R_{DC} (μH/Ω)	2.4[e]	16.4	213.7
L_{22} / A_r (μH/mm^2)	2.1	11.9	69.4
L_{22} / A_r x h (μH/mm^3)	4.1	10.8	19.8
Q_{22}[b](max)	11.6@1.3MHz	57@850kHz	88@158kHz
I_{max} (A)	≈ 1.0[c]	1.7[d]	1.3[d]
Integration	**on-chip**	discrete	discrete

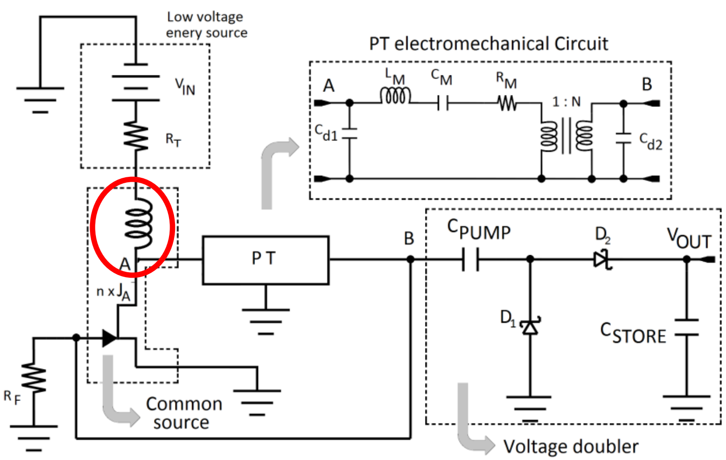
[a]: without substrate.
[b]: at 0.1 V RMS.
[c]: recommended to avoid wires damage.
[d]: due to core saturation.
[e]: can be increased by increasing the diameter of bonding wires
*: can be enhanced by a higher tightening of the winding

Applications of the Device

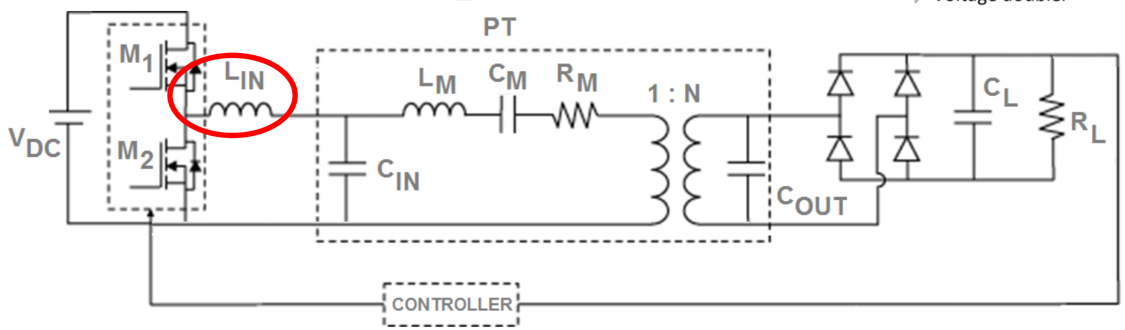
Step-up oscillators based on Armstrong topology



PT (Piezoelectric Transformer) based step-up oscillators



Compact PT based, resonant DC/DC converters



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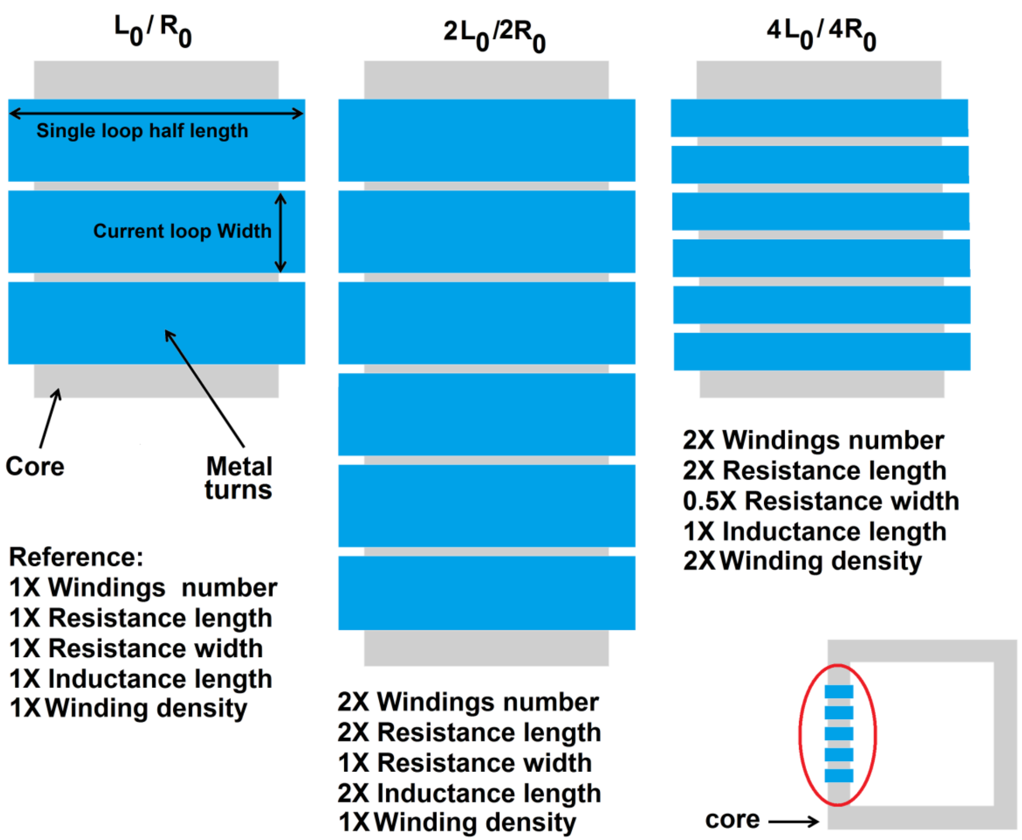
Optimization Based on the Winding

Top views of fractions of a square toroid (racetrack core) inductor

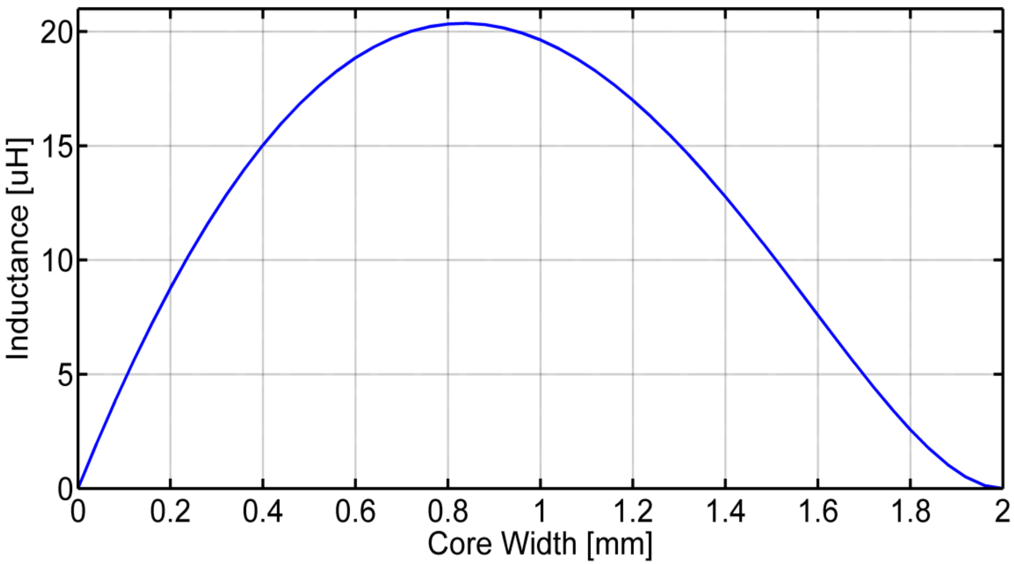


- Higher turn number and width constant →L/R ratio unchanged, but higher footprint area [9]
- Higher turn number and width constant →L/R ratio unchanged

- Optimization cannot be based on the winding

[9] **A. Camarda et al.** "Design Optimization of Integrated Planar Magnetic Core Inductors". *IEEE Trans. Magn.* 51.7, 2015, pp. 1–10.

Optimization of the Core Width



Inductance of a toroidal inductor:

$$L < \frac{4n_0^2\left(L_B - 2\cdot W_C\right)^2\cdot t_C\cdot W_C\cdot \mu_0\cdot \mu_r}{\left(L_B - 1.44\cdot W_C\right)}$$

- $L_B{}^2 = 16\text{mm}^2$ → L_A (L_B) → internal (external) side
- t_C □ $\mu_r = 10^{-1}$m → t_C → core thickness, $t_C << W_C$
- $n_0 = 5\cdot 10^3$ m^{-1} → n_0 = linear turn density

Maximum achievable inductance L_{max}

$$L_{\max} / L_B^2 < 0.509\cdot n_0^2\cdot t_C\cdot \mu_r$$

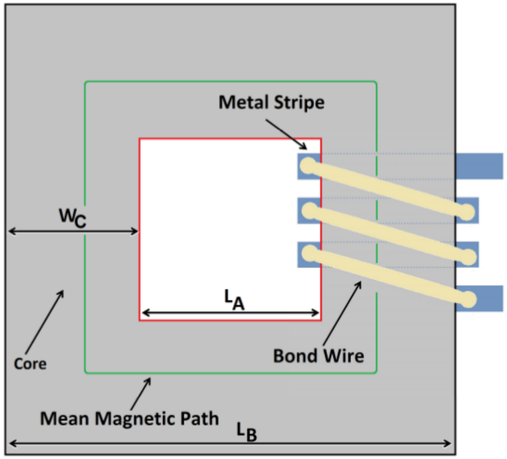
↔

Optimum Core Width W_{opt}

$$W_{opt} = \frac{5}{24}L_B \cong 0.208\cdot L_B$$

[9] **A. Camarda et al.** “Design Optimization of Integrated Planar Magnetic Core Inductors”. *IEEE Trans. Magn.* 51.7, 2015, pp. 1–10.

Correct estimation of the inductance

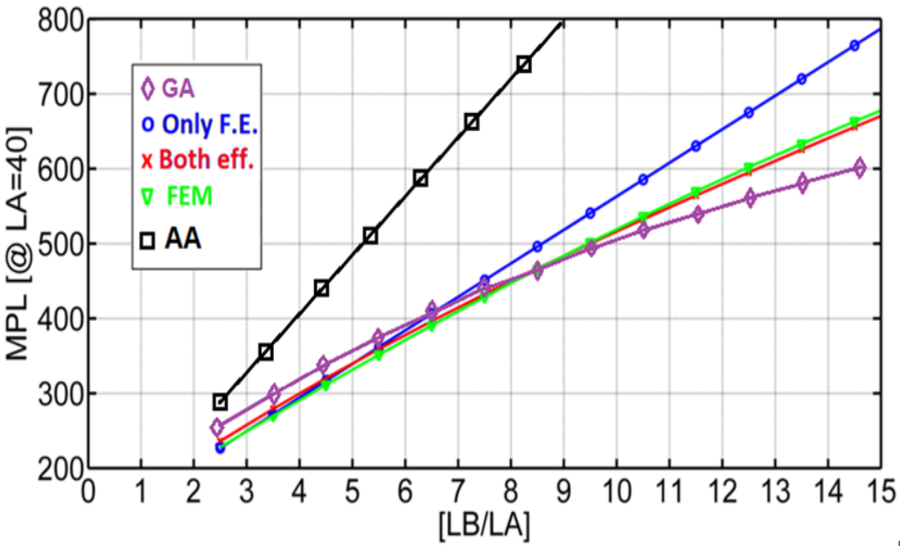


Developed formula for MPL taking into account → Magnetic non-uniformity in the core; Folding Effect (not a round toroid) F.E. → $MPL_{eff} \cong \dfrac{5.78W_C}{\ln \dfrac{4L_A + 5.78W_C}{4L_A}}$ [9]

Inductance formula:

$$L = \frac{N^2}{\Re} \qquad MPL \neq \frac{4L_A + 4L_B}{2} \quad \text{(A.A.)}$$

$$\Re = \frac{MPL}{\mu_0 \mu_r A_C} \qquad MPL \neq \sqrt{4L_A \cdot 4L_B} \quad \text{(G.A.)}$$

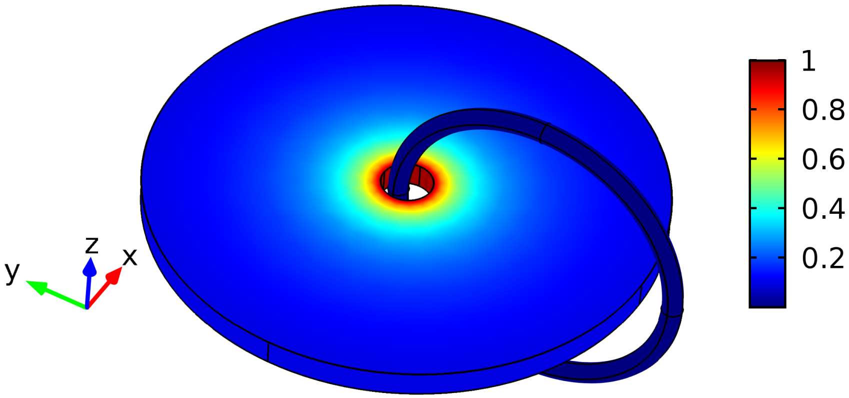


[9] **A. Camarda et al.** “Design Optimization of Integrated Planar Magnetic Core Inductors”. *IEEE Trans. Magn.* 51.7, 2015, pp. 1–10.

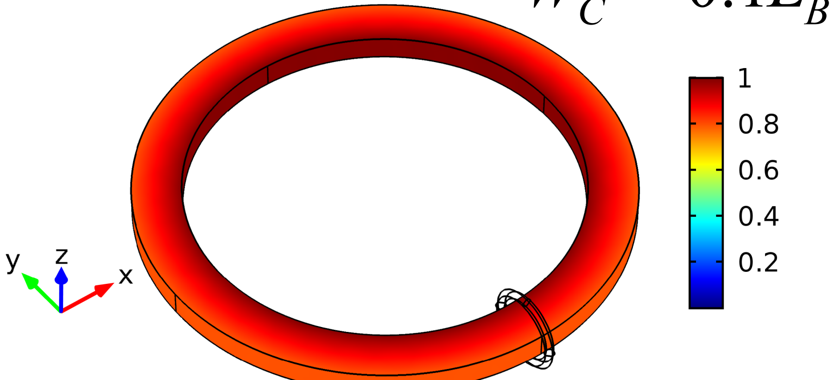
A Further Optimization

- Some considerations
  - **The magnetic flux density is not uniform not even in the optimized structure: this is a waste of area**
  - **The External borders of the core, give little contribution to the whole magnetic path**
  - **Narrower cores provide more uniform magnetic fields.**

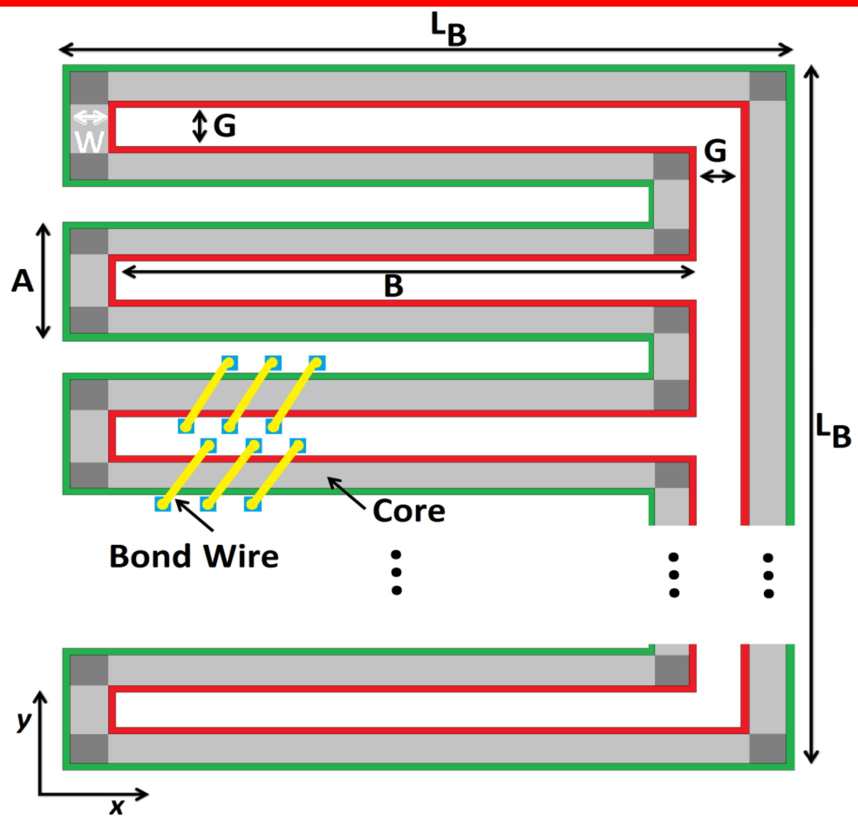
$W_C = 0.45L_B$



$W_C = 0.1L_B$



Serpentine Toroid



K number of parallel arms along y

Advantages:

- Thinner core → B is more uniform → less waste of used area
- Higher area used → less waste of unused area
- Intuitively can present higher performances

$$L < \frac{\left(\int_0^{P_{IT}} n(x)dx\right)^2}{\Re} = \frac{\left\{n_0 \cdot \left[P_{IT} - 4 \cdot \left(K/2-1\right) \cdot W\right]\right\}^2}{\Re}$$

$$A = \frac{L_B - \left(K/2-1\right) \cdot G}{\left(K/2\right)}$$

$$B = L_B - G - 2 \cdot W$$

$$W = \left(A - G\right)/2$$

One DoF G=200µm
With LB=4mm

Parameters for DC resistance evaluation

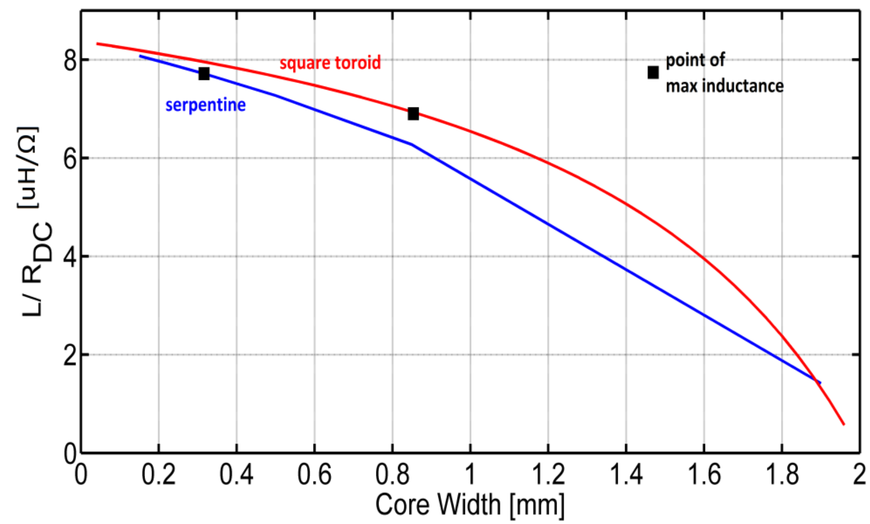
VALUES FOR R_{dc} EVALUATION

Parameter	Value
Core Width W_C	W_{opt} (at $L_B = 4$ mm)
Metal conductivity σ_M	$3.25 \cdot 10^7$ S/m
Metal thickness t_M	3.2 µm
Metal Width W_M	180 µm
Metal stripe Length l_M	W_C
Metal spacing s	20 µm
Bonding wire diameter	32 µm
Bonding wire conductivity σ_G	$4.5 \cdot 10^7$ S/m
Bonding wire length l_{BW}	$\pi W_C / 2$
Two bond wires in parallel for each metal stripe	

Optimum Square Toroid vs Optimum Serpentine

Parameter	Geometry		
	SSTC	Serpentine	
L_{MAX}	18.16 µH	26.6 µH	19.7 µH
I_m	20.3 mA	17.4 mA	20.3 mA
f_{min} @ 1 V	436 kHz	348 kHz	401 kHz
L_{MAX} / R_{DC}	6.9 µH/Ω	7.8 µH/Ω	6.9 µH/Ω
e_M	236 pJ/mm^2	251 pJ/mm^2	251 pJ/mm^2
W_c	0.83 mm	0.325 mm	0.325 mm
N	48	142	122

- L_B^2= 16mm^2
- t_C □ μ_r=10^{-1}m
- n_0 = 5·10^3 m^{-1}
- B_S= 1T
- μ_r=10^5
- t_C = 1µm



- Serpentine: lower saturation current.
- Lowering the turn number in the serpentine in order to obtain the same I_m of the SSTC, allows in any case to have better performances of the SSTC

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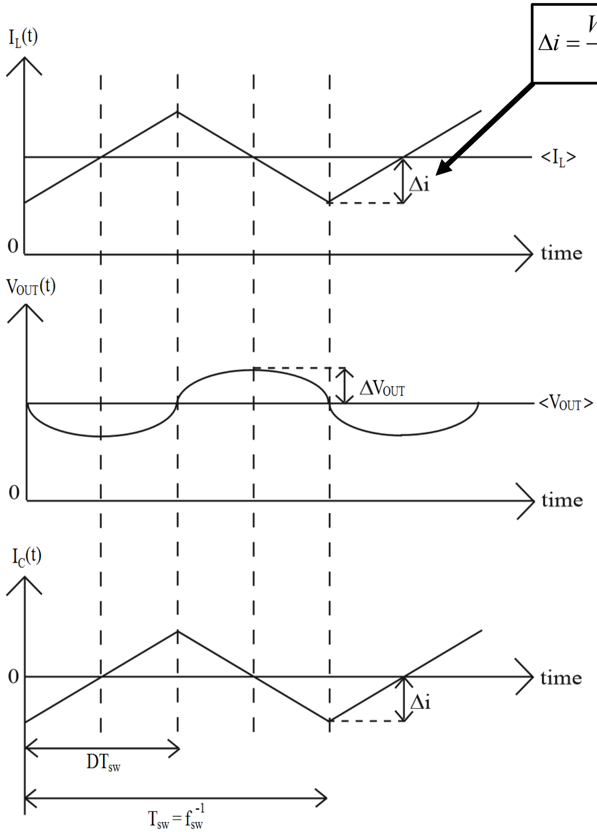
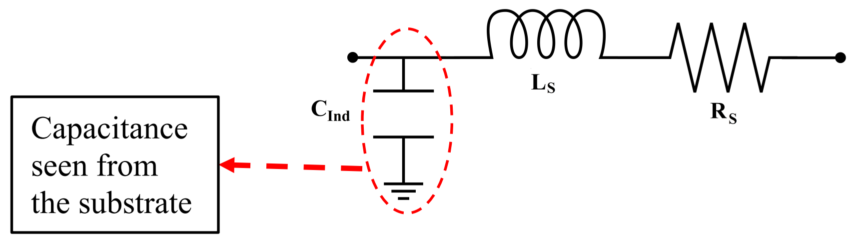
Evaluation of Inductor losses in a power converter

- Buck converter case:

$$\Delta i = \frac{V_{OUT}(1-D)}{2 f_{sw} L_S}$$





$$P_{Ind} \cong \frac{R_S}{L_S} \frac{V_{OUT}[1-D]}{2} \left(\frac{\langle I_L \rangle^2}{\Delta i \cdot f_{sw}} + \frac{\Delta i}{3 f_{sw}} + \cancel{\frac{C_{Ind} L_S V_{OUT}^2}{D^2 R_s \Delta i}} \right)^*$$

$R_S = R_S(f_{sw})$ but if $f_{sw} \leq f_{QMAX}$ then $R_S(f) \cong R_{DC}$

- Given the same footprint area and same Δi, Serpentine toroid can achieve a higher inductor performance wrt Optimized Toroid, up to:

$$\boxed{1 - \frac{7.8\mu H/\Omega}{6.9\mu H/\Omega} = +13\%}^{**}$$

- Assuming the inductor losses a ~10-15% of the total losses, the power converter can experience an increased efficiency of 1.5%-2%

*valid if $R_S = R_{DC}$
**assuming a laminated core, $R_s \approx R_{dc}$

Outline

- ➢ More than Moore systems
- ➢ Bond wire magnetics and example of applications
- ➢ Ferromagnetic LTCC
- ➢ Miniaturized bond wire transformer and applications
- ➢ Optimization of the inductance value
- ➢ Conclusions

Conclusions

- Bond wire magnetics give additional value to MtM systems
- PwrSoC are thus possible using standard bondwire technology
- No additional post-processing steps are required
- LTCC cores can be easily patterned and embedded (100% compatible with bonding wire technology)
- LTCC material is good for the MHz range (good $\boldsymbol{\mu_r}$ and high $\boldsymbol{\rho_c}$)
- Through high resolution patterning techniques the inductance value can be augmented and optimized.

Thank you for your attention!!

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