Tyndall National Institute
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Integrated Gate Drive Transformers using laminated amorphous Co Zr Ta B magnetic core

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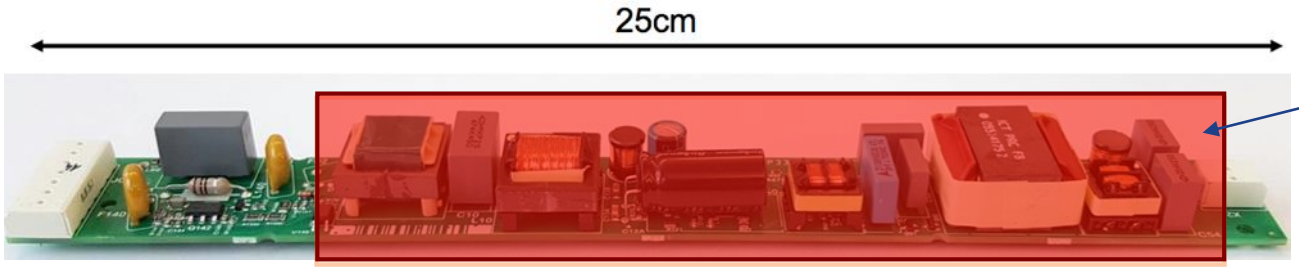
PWR SOC 18

Outline

- Background
- Construction of solenoid transformer
- Design
  - Specifications
  - Design parameters
  - Design space study using semi empirical equations
  - Finite Element modelling
- Fabrication of devices
- Electrical test
- Conclusions

Background

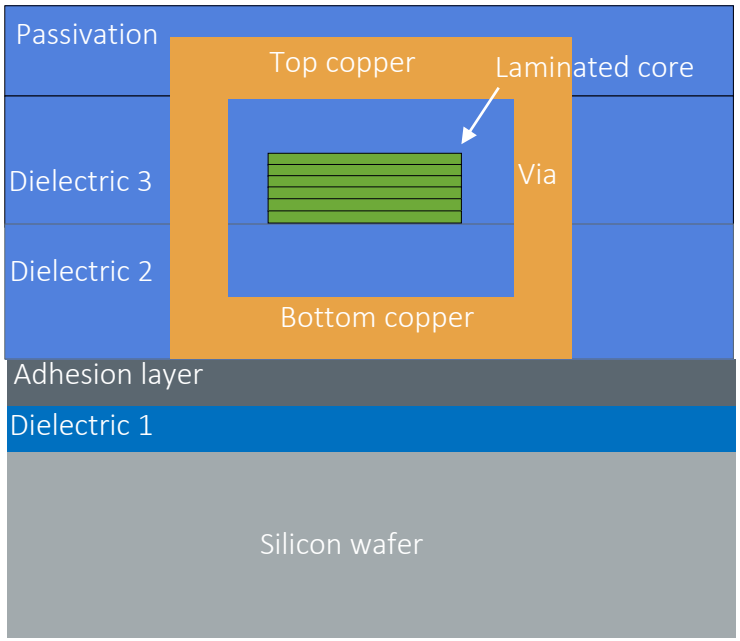
Electrical Driver (Light Engine) for LED Lighting

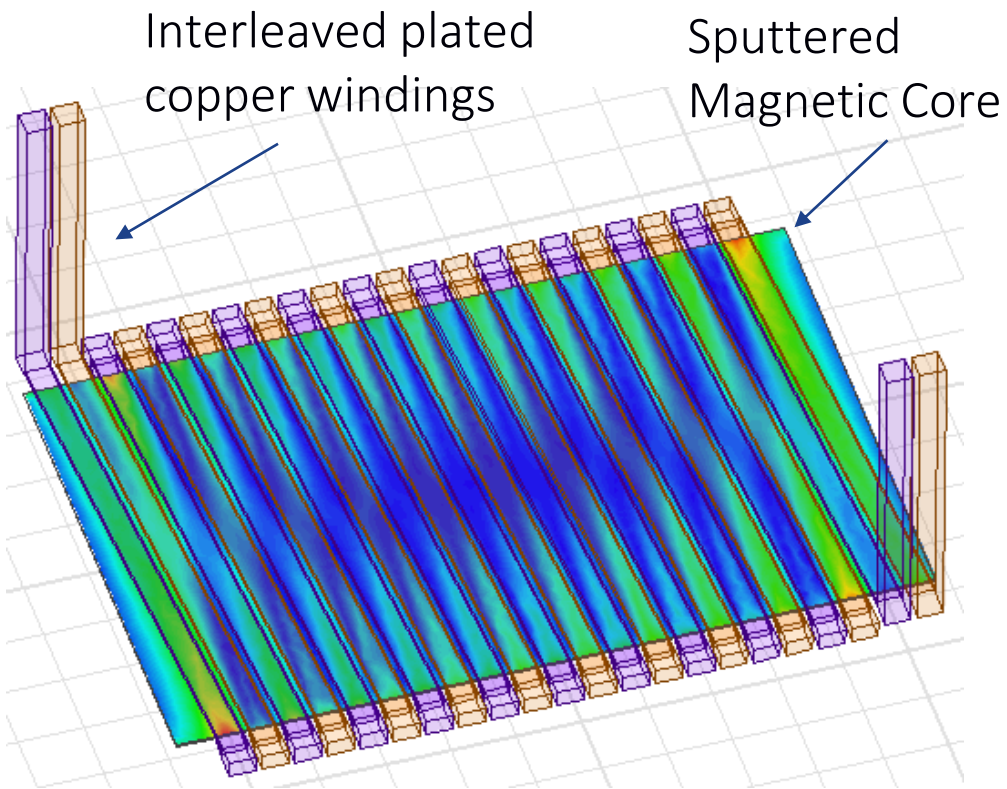


75 W LED driver with a volume of 25 cm x 2 cm x 3 cm (150 cm3)

- Electrical driver
  - The **biggest bottleneck** for size, weight and cost reduction as well as reliability and energy efficiency improvement. **LEDLUM, "Tiny Light Engine for Large Scale LED Lighting"**, aims to address this challenge (funded under European Union's Horizon 2020 programme)
- Strategy for improvement
  - High frequency power electronics
    - Reduction in passive component size => size and weight reduction
    - Elimination of electrolytic capacitors => life time improvement
  - Embedded active and passive components

Micro-Transformer Construction



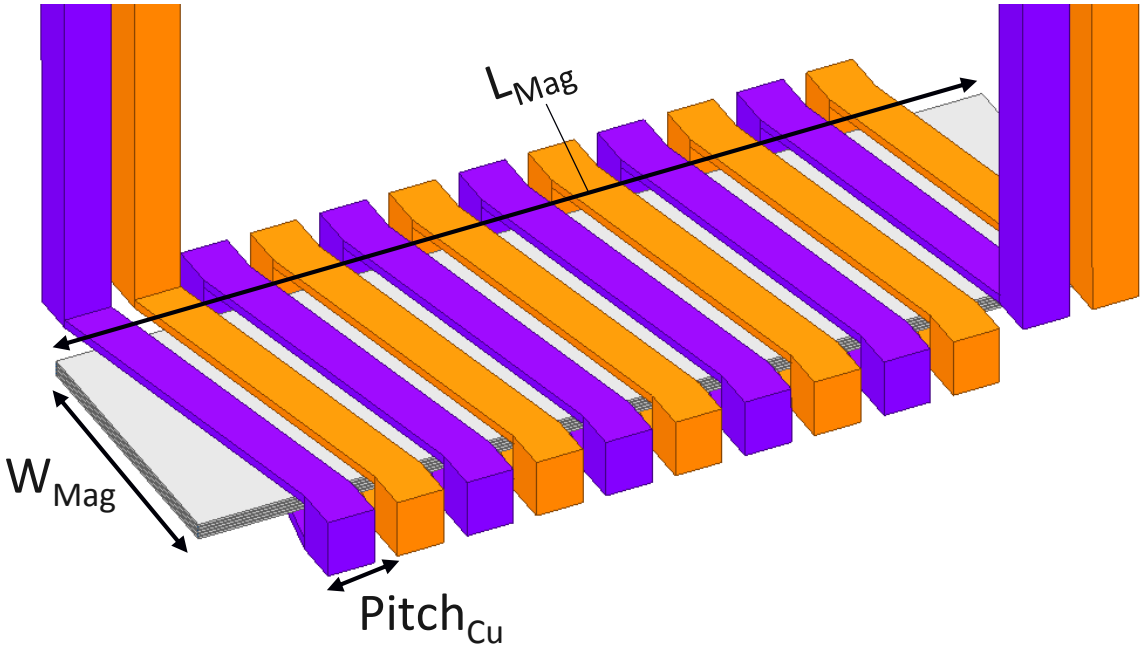


Transformer specifications

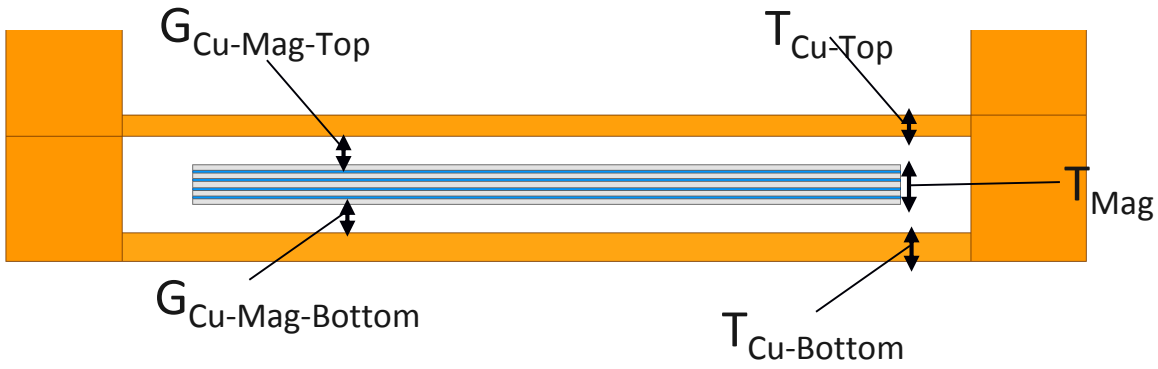
Integrated gate drive transformer

Parameter	Symbol	Value	Unit
Inductance per phase	L	300	nH
Peak to Peak current	I_{PP}	0.1	A
DC current	I_{DC}	0	A
Switching frequency	f_{SW}	15 - 20	MHz
Coupling factor		80% - 90%	

Solenoid transformer design Parameters



Parameter	Symbol
Magnetic Core Length	L_{Mag}
Magnetic Core Width	W_{Mag}
Magnetic Core Thickness	T_{Mag}
Cu track pitch	$Pitch_{Cu}$
Cu track thickness	T_{Cu}
Vertical gap between Cu track and magnetic core	$G_{Cu\text{-}Mag}$



Study of design space

- Study of design space is performed using modified analytical expressions of inductance and DCR.

$$L \approx \mu_0 \mu_{eff} N^2 \left(\frac{W_{Mag} T_{Mag}}{L_{Mag}} \right)$$

Where, $\mu_{eff} = \frac{\mu_r}{1 + F_{Demag}(\mu_r - 1)}$ = Effective permeability

$$R_{DC} \approx 2N\rho_{Cu} \left[\frac{L_{Cu}}{W_{Cu} T_{Cu}} + \frac{(T_{Cu} + H_{Via})}{W_{Via}^2} \right]$$

ρ_{Cu} = Resistivity of Cu

N = Number of turns

F_{demag} = Demagnetization factor

- The parameters listed in the CONSTANT, INPUT VARIABLES and OUTPUT VARIABLES tables define the design space.

INPUT VARIABLES

Parameters	Range
I_{sat} [A]	0.5 – 0.7
N_{turn}	1 – 30
W_{cu} [µm]	80 – 200
W_{mag} [mm]	0.2 – 3.0

OUTPUT VARIABLES

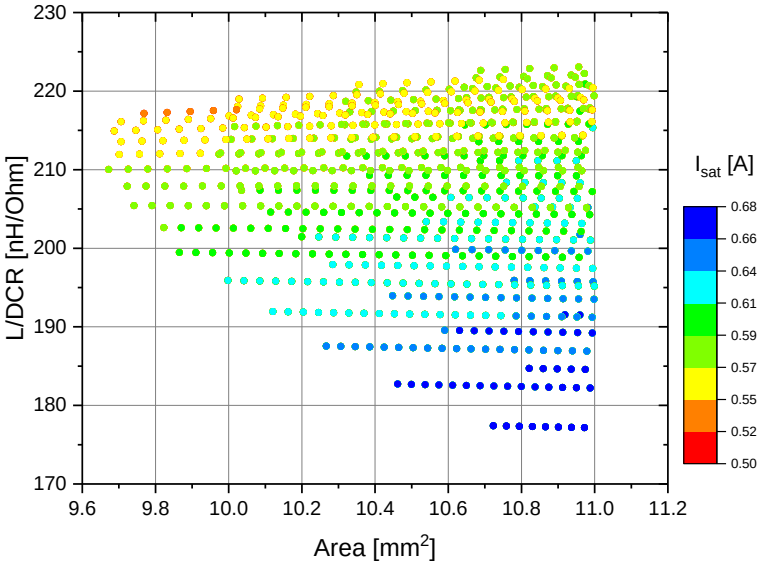
Parameters	Value ± tolerance
L_{self} [nH]	300 ± 10%
Area [mm^2]	10 ± 20%
DCR [Ohm]	3 ± 50%
L/A [nH/mm^2]	50 ± 20%
B_{max} [T]	< 1.1

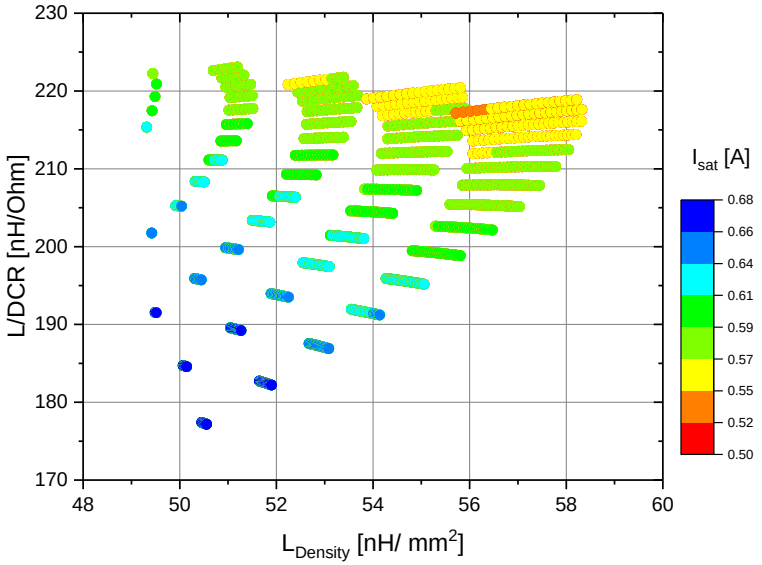
CONSTANTS

Parameters	Value
Frequency [MHz]	15 – 20
μ_r	350
tan(δ)	0.1
T_{mag} [µm]	4.7
T_{cu} [µm]	15
$Pitch_{cu}$ [µm]	100
B_{sat} [T]	1.2

1. Lee, D. W., et al. (2008). IEEE Transactions on Magnetics **44**(11): 4089-4095

Design space study

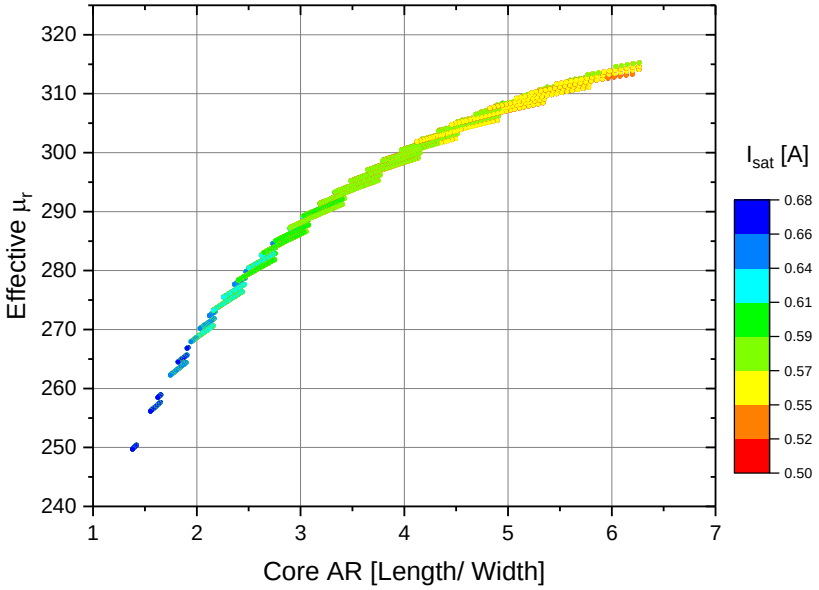


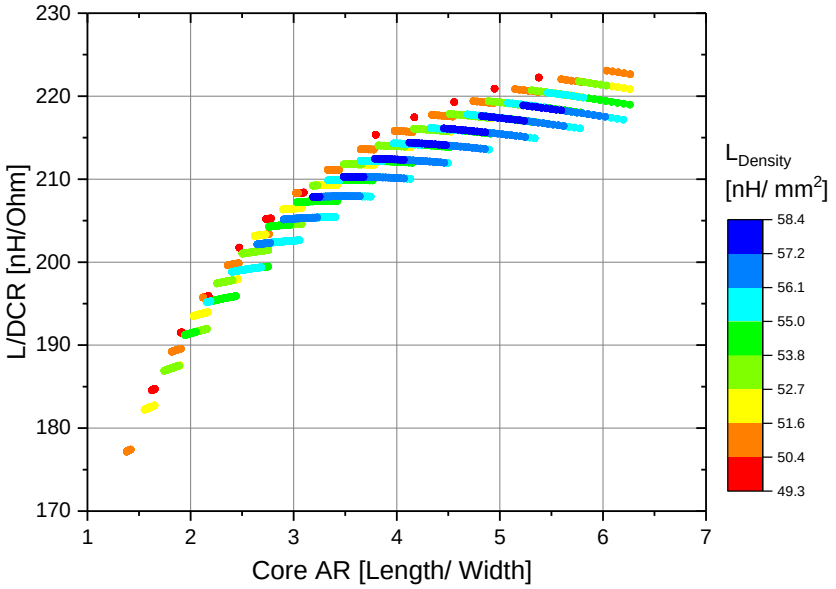


- Within a specified area, higher Isat requirement leads to lower L/DCR.

- Higher Isat requirement leads to lower L/DCR, as well as lower inductance density.

Design space study



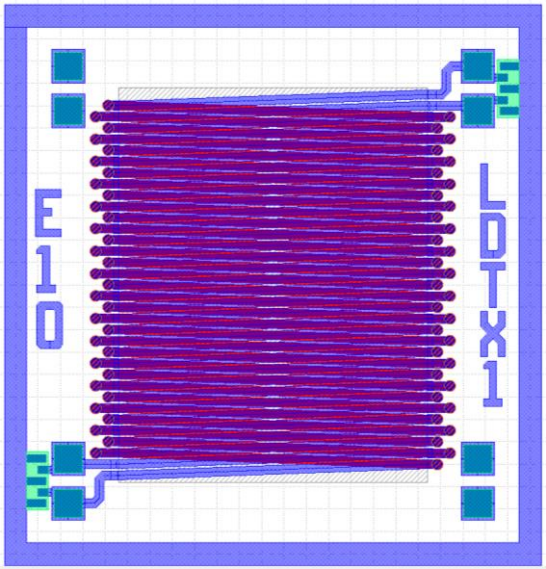


- Higher Isat requirement leads to lower aspect ratio and lower effective permeability of the magnetic core.

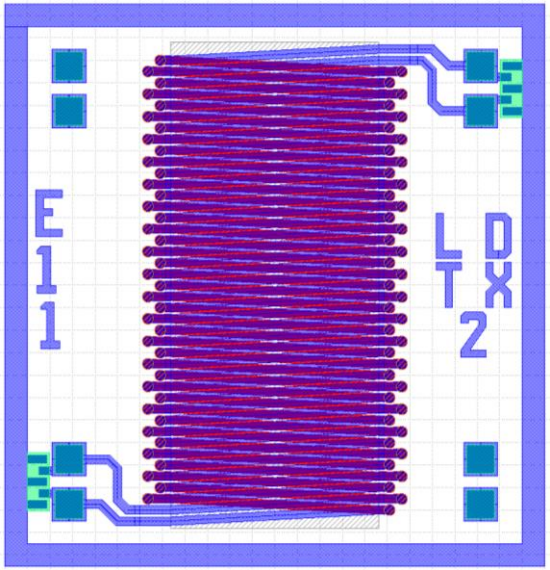
- Higher inductance density and L/DCR can be achieved by using a higher core aspect ratio.

Transformer designs

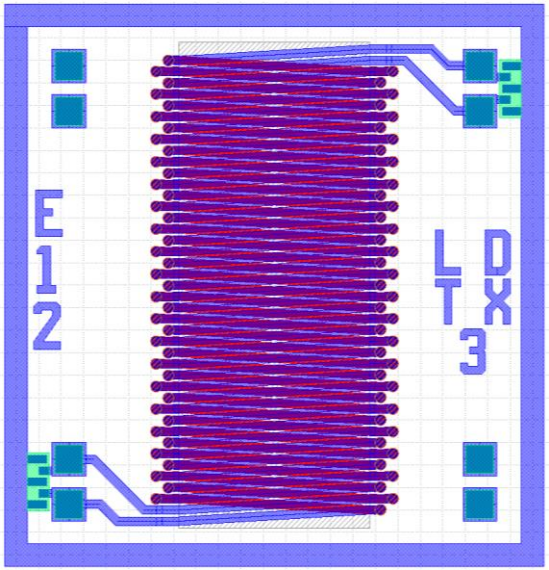
Design #1



Design #2



Design #3



Design #	Core Length	Core Width	Core Aspect Ratio (L_{Mag}/ W_{Mag})	Number of turns per winding
1	3520 µm	2760 µm	1.2	16.5
2	4325 µm	1850 µm	2.3	20.5
3	4325 µm	1700 µm	2.6	20.5

Top Copper

Bottom Copper

Passivation window

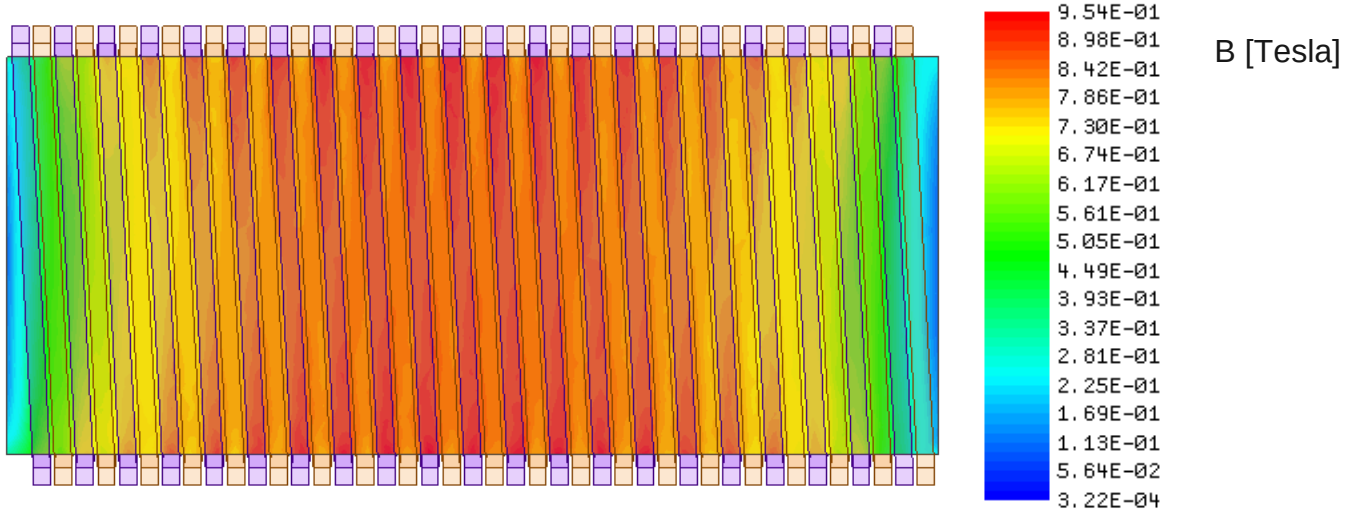
Finite Element Simulation results for transformer designs

Parameters	Unit	Design #1	Design #2	Design #3
Core Aspect Ratio (L_{Mag}/ W_{Mag})	-	1.2	2.3	2.6
Inductance per phase @ f_{SW}	nH	350.2	303.2	281.4
DC Resistance per phase	Ohm	2.96	2.53	2.34
Equivalent Series Resistance (ESR) @ f_{SW}	Ohm	5.6	5.1	4.8
Coupling factor	%	86.2	90.1	90.2
B_{Max} @ I_{PP} = 0.1 A	Tesla	0.22	0.25	0.28

Current applied

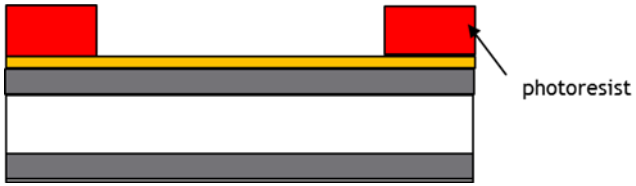
in one winding.

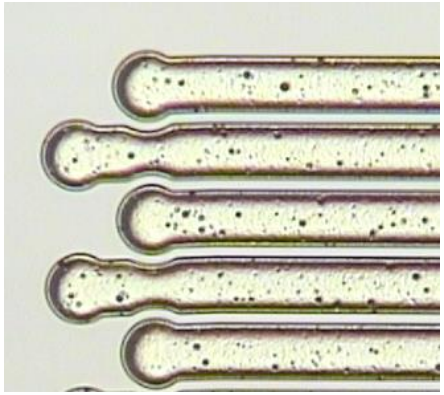
I_1 = 0.5 A



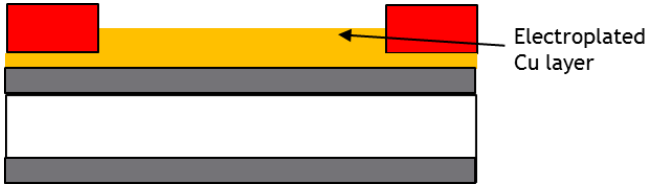
Fabrication process

Spin-coating of photoresist and lithography for bottom Cu layer

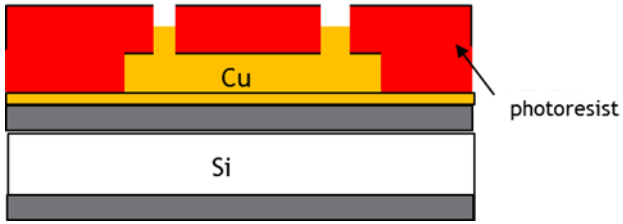


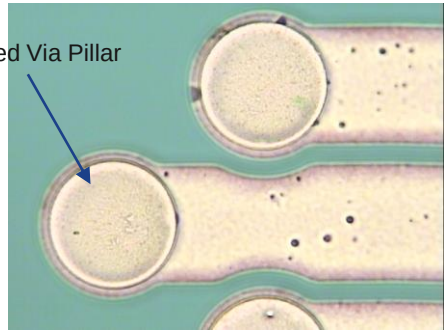


Electroplate bottom coil layer.



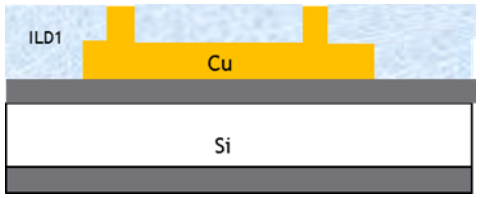
Via1 patterned and electroplated.



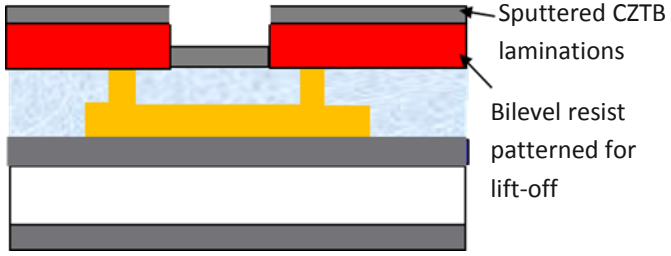


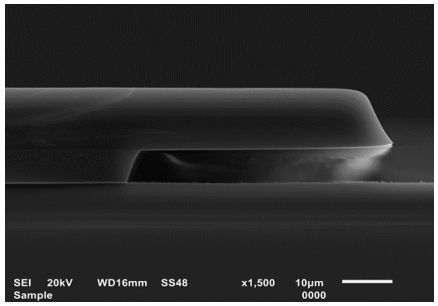
Fabrication process

Strip photoresist, etch seed layer, and spin-on inter-layer dielectric (ILD)

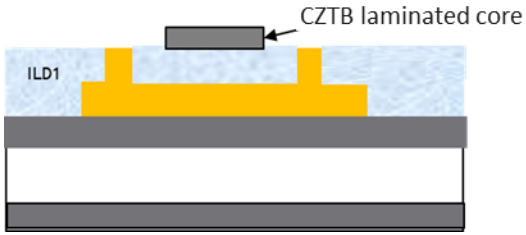


CZTB core patterning by lift-off, and sputter deposition of CZTB laminated core.

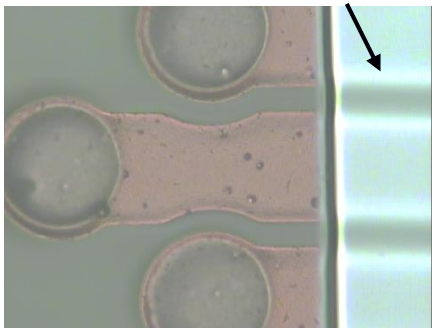




CZTB laminated core patterned by lift-off, photoresist stripped.

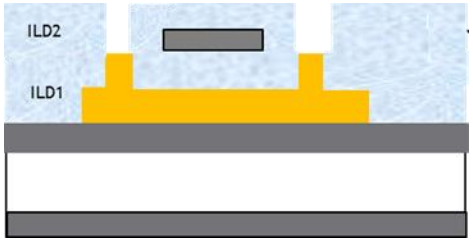


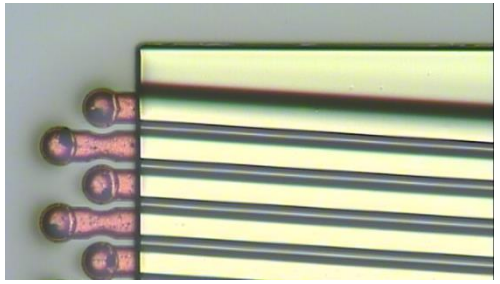
CZTB Laminate



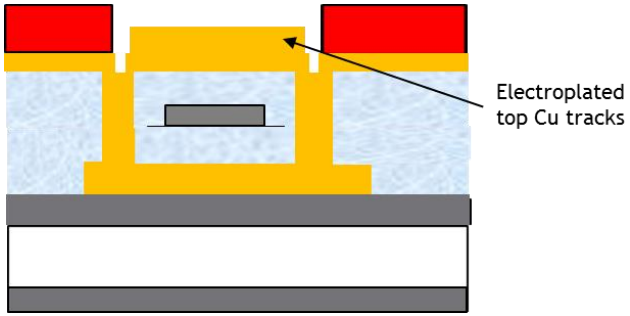
Fabrication process

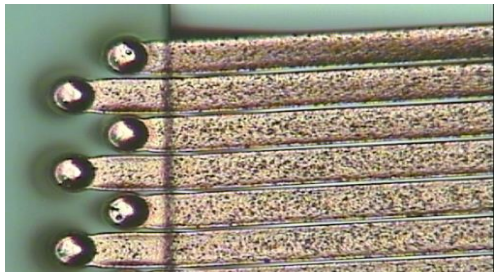
Spin-on inter-layer dielectric (ILD2) . Pattern to expose via tops.



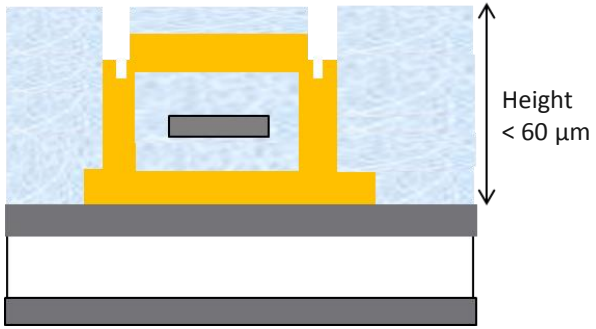


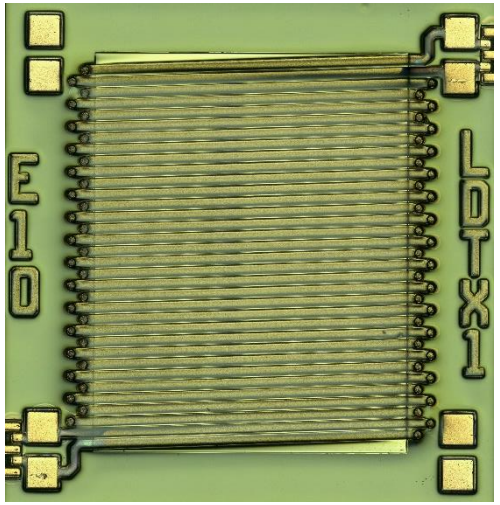
Sputter top Cu seed layer, pattern vias and top Cu tracks, electroplate vias and top Cu tracks.



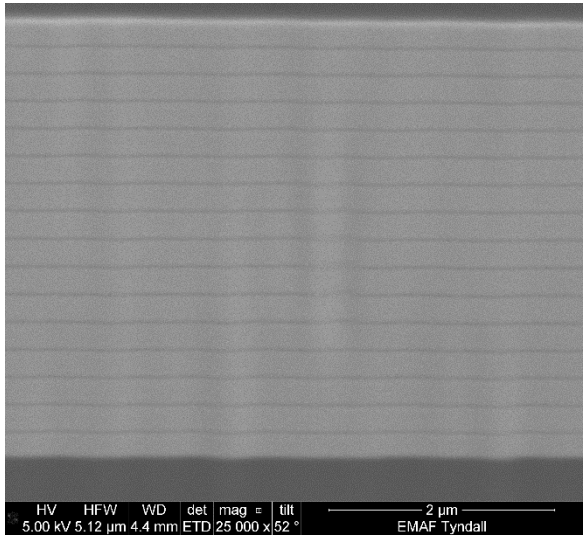


Strip resist, etch top Cu seed layer. Spin on passivation and open contact pads.

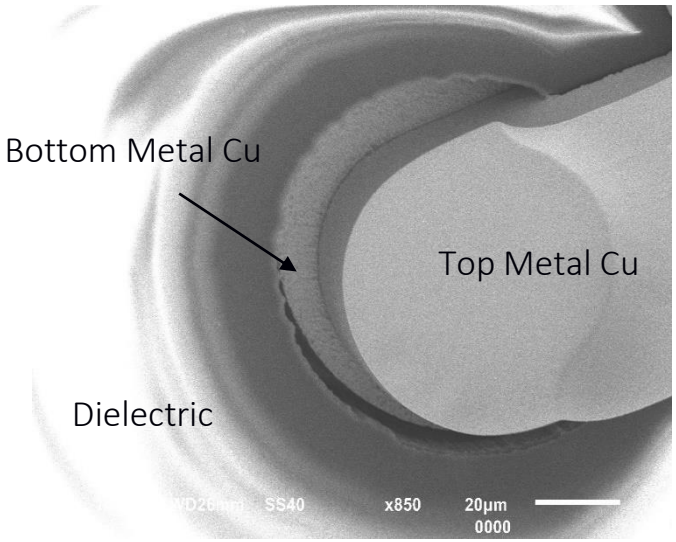




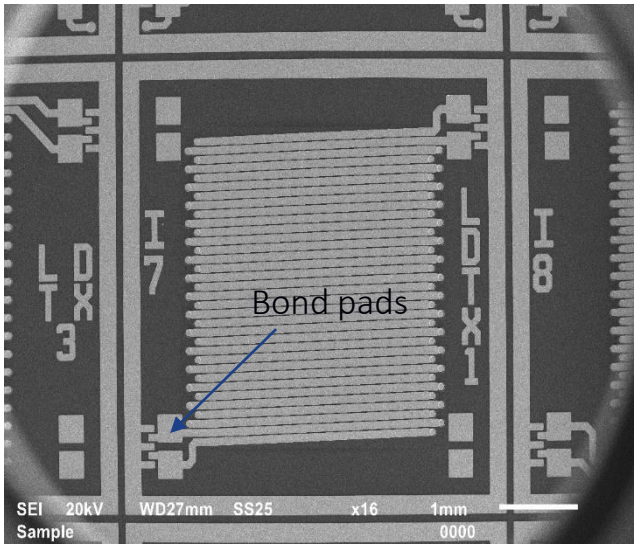
Fabrication of devices



Laminated magnetic core

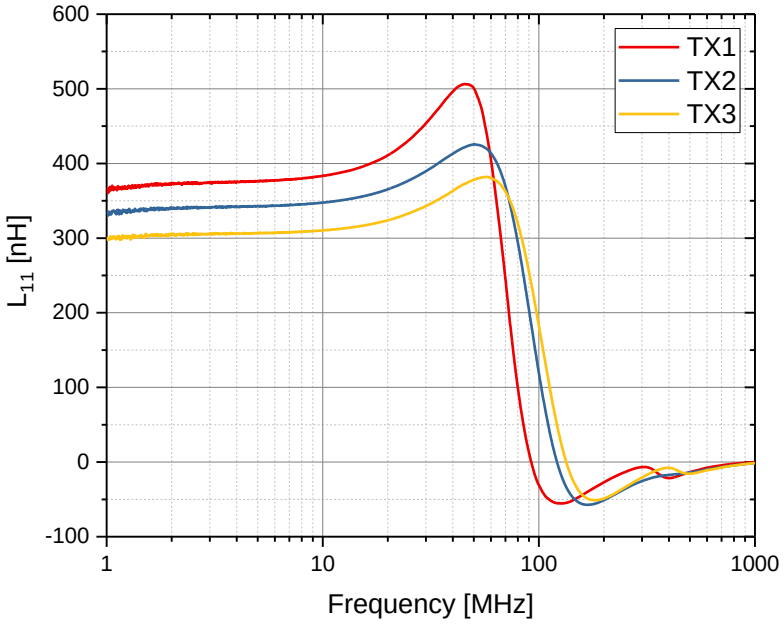


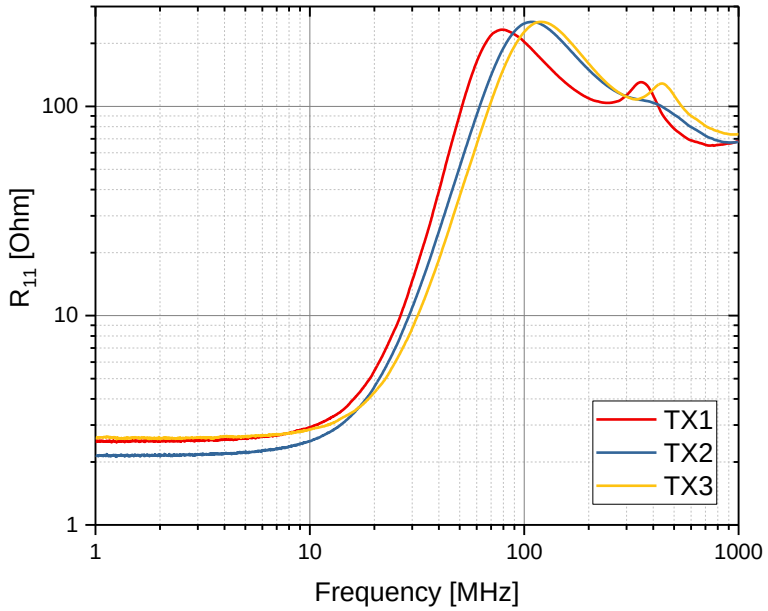
Top copper to bottom copper connection



Devices prior to final passivation

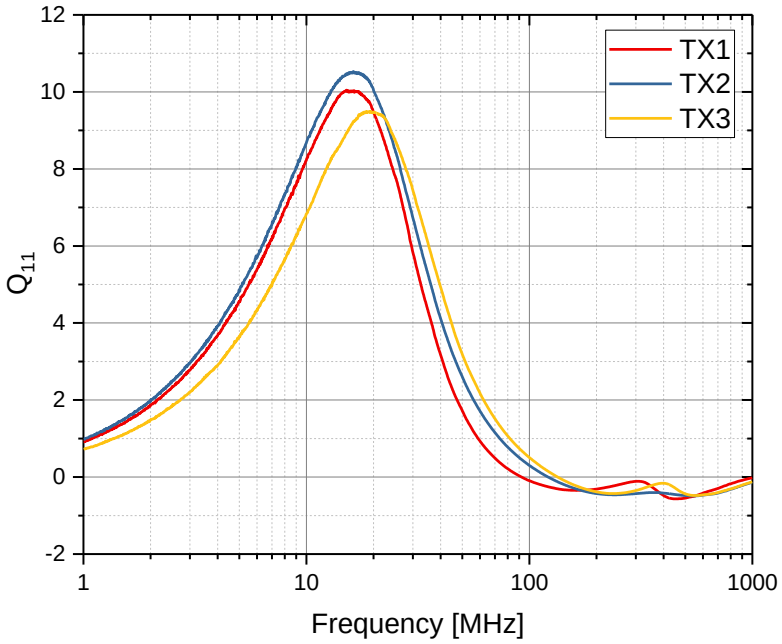
Small signal S-parameter measurement

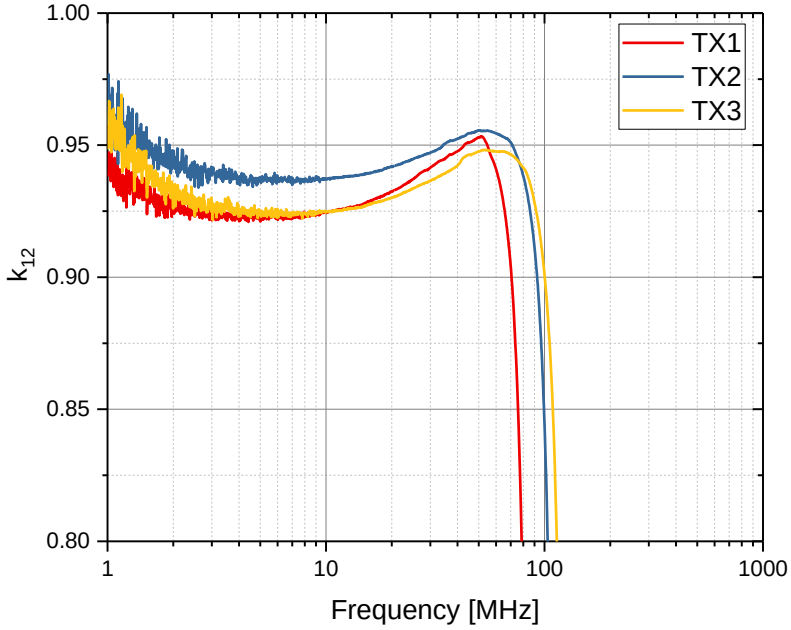




- Resonance due to parasitic capacitance occurring at >85 MHz
- TX1 has lowest aspect ratio and highest core width => highest L11
- TX1 has largest core volume and highest loss

Small signal S-parameter measurement

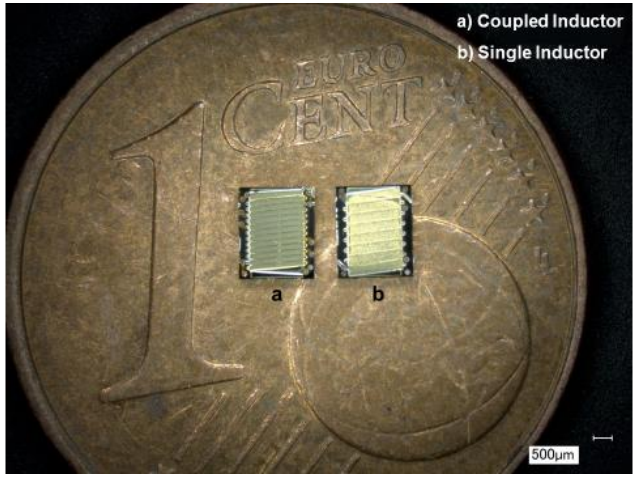




- Maximum Q occurring between 15 to 20 MHz
- Coupling factor > 0.925

Other application areas

- This fabrication process has also been used to magnetic dervices for use in Point-of-Load (POL) converter applications
- Pranay Podder et al, “Electrical Characterisation of Thin Film CZTB Solenoid Inductors for PwrSiP” poster at PwrSoc 18
  - Targeting ~ 30 MHz operation
  - Single and coupled inductors
  - Designed for high Q
  - Measured device Q ~24 at ~30MHz.



Conclusions

- Thin film laminated CZTB gate drive transformer fabricated and characterised
- Electrical properties suitable for application with frequencies 15-20 MHz
- BEOL compatible planar solenoid transformer with thickness < 60 µm

Acknowledgements

- Work carried out in LEDLUM, “Tiny Light Engine for Large Scale LED Lighting”

- This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 731466.

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