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High Winding Ratio, High Frequency, Ultracompact Step-Up Transformers with Laminated Metallic Magnetic Cores

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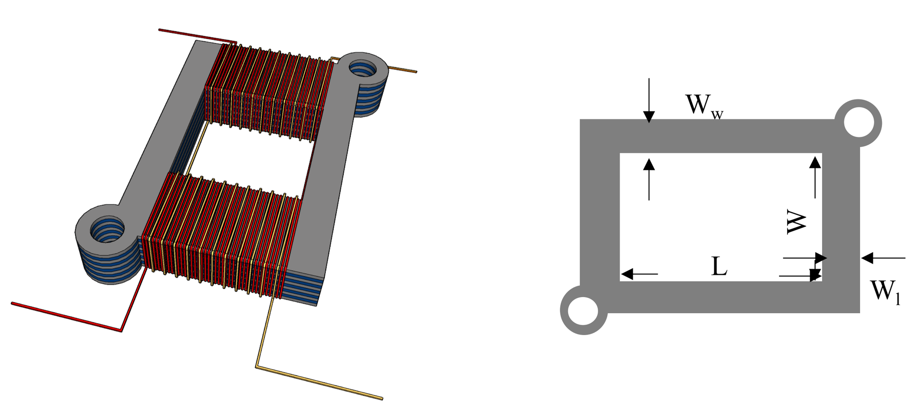
INTRODUCTION

- Miniaturization trends of electronic components require corresponding miniaturization of power supply modules
- Passive components such as transformers typically comprise the largest volume fractions of such modules
- Transformer size can be reduced by adopting advanced magnetic core materials
- Compared to ferrites, metallic alloys have high saturation flux density, enabling high energy density, but low electrical resistivity, causing eddy current loss at high frequency
- Laminated metallic alloy cores can suppress eddy currents while maintaining large magnetic volume

	Magnetic Materials	
Properties	Ferrite	Metallic Alloys
Flux density B_s (T)	< 0.5	1-2
Relative permeability μ_r	< 100	> 150
Resistivity ρ_m (Ω·m)	> 10^{-3}	< 10^{-7}
	Winding Materials	
	Copper	Aluminum
Mass density ρ (g/cm³)	8.96	2.7

- Transformer weight can be further reduced by replacing copper winding with aluminum

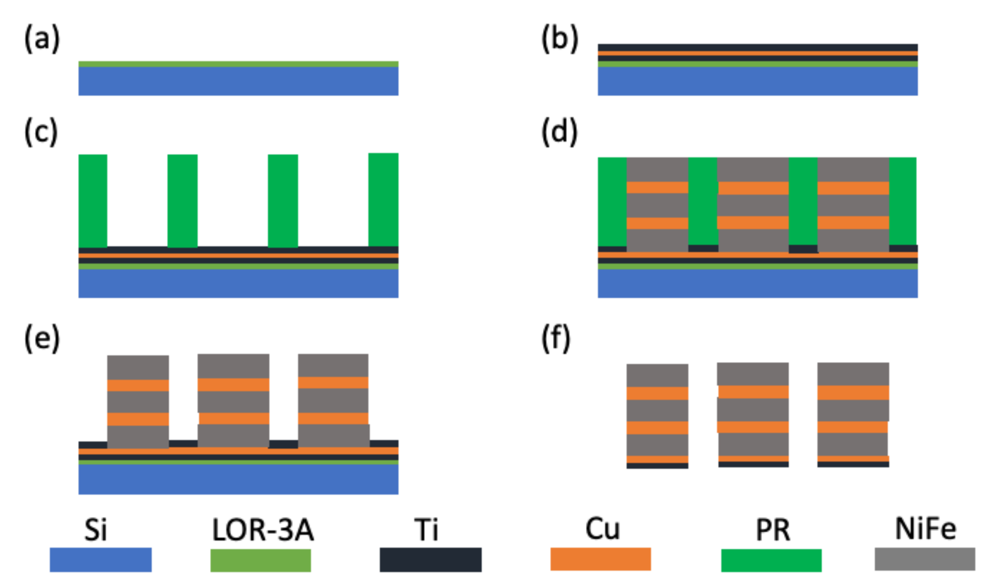
TRANSFORMER DESIGN & FABRICATION

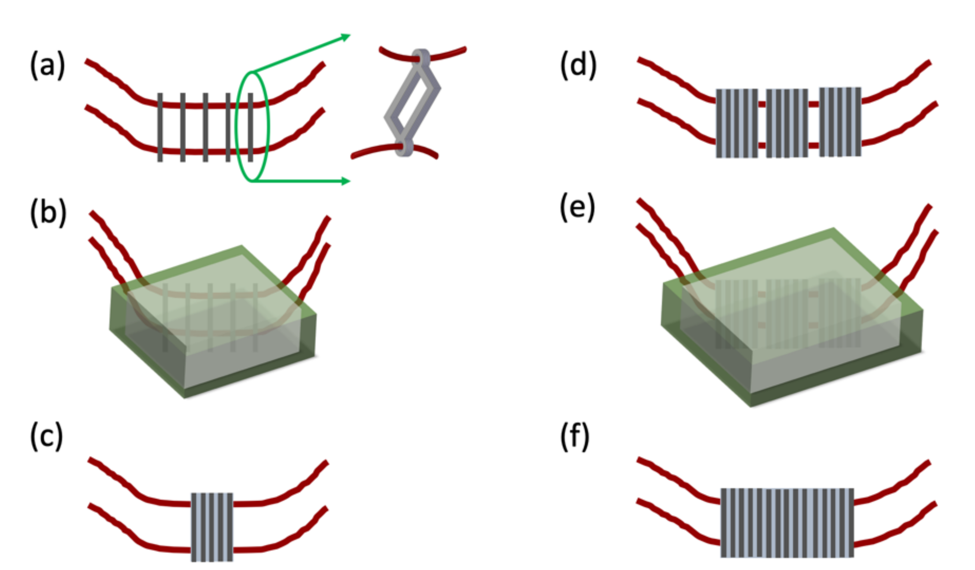


	Magnetic Core Dimensions							
Sample No.	W (mm)	L (mm)	t_m (mm)	t_{m0} (μm)	W_w (mm)	W_l (mm)	N_p (turns)	N_s (turns)
S1	0.8	1.2	0.27	1	0.39	0.3	8	80
S2	1.2	1.2	0.24	2	0.73	0.3	12	120
S3	1.2	1.2	0.24	3	0.73	0.3	12	130
S4	1.2	1.2	0.18	3	0.73	0.3	12	130
S5	1.2	1.2	0.18	6	0.73	0.3	12	130

t_m: effective core thickness, t_{m0}: individual magnetic layer thickness, N_p: primary coil turn number, N_s: secondary coil turn number.

- Transformer core comprises a rectangular, multilayer laminated structure, with alternating permalloy (NiFe) and electrical insulation layers
- Two ring-like features at diagonal ends of the core assist in lamination self-assembly
- Individual magnetic lamination thicknesses (t_{m0}) are designed up to the NiFe skin depth at 2 MHz (6.3 μm)
- Except for S1, the targeted primary and secondary inductance for these transformers are above 2 μH and 200 μH





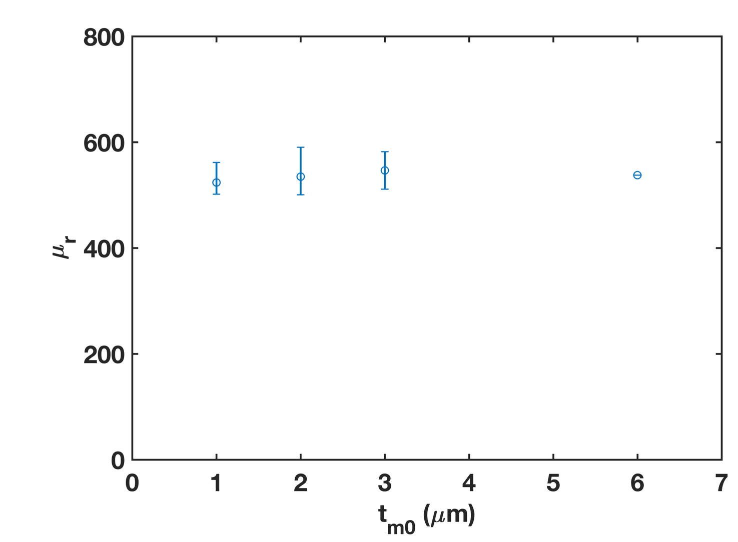
- Laminated magnetic core fabrication is facilitated using a hierarchical approach
- Sequential electrodeposition is used to create NiFe/Cu multilayer constructs
- Self-assembly is exploited to transform the multilayer constructs into core segments
- Multiple core segments could be further assembled into thicker cores by repeating the previous procedure

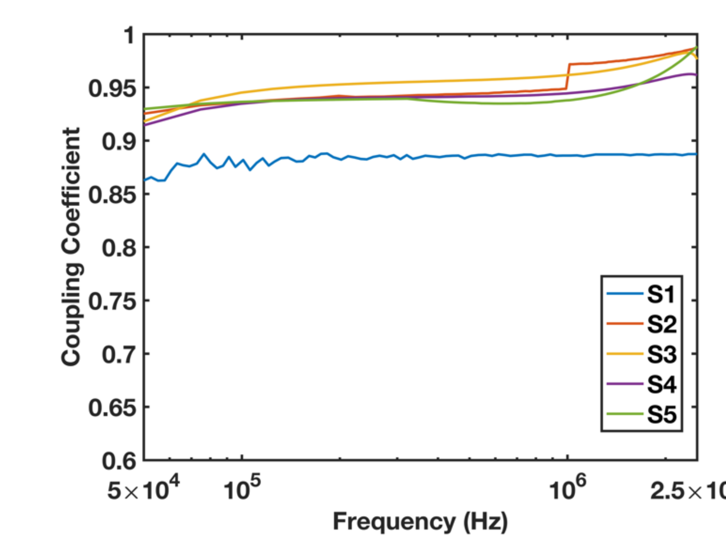
TRANSFORMER CHARACTERIZATION

- Transformers exhibit high primary and secondary inductance values, which are maintained up to their resonance frequencies in the MHz range
- Inductance ratio between primary and secondary is smaller than the square of the turns ratio, attributable to magnetic coupling of less than unity in these devices
- Calculated effective relative permeability of the laminated magnetic cores is close to 600, and does not change significantly with increasing individual magnetic layer thickness
- Except for S1, all transformers show coupling coefficients of 0.9-0.95 in frequency ranges of interest

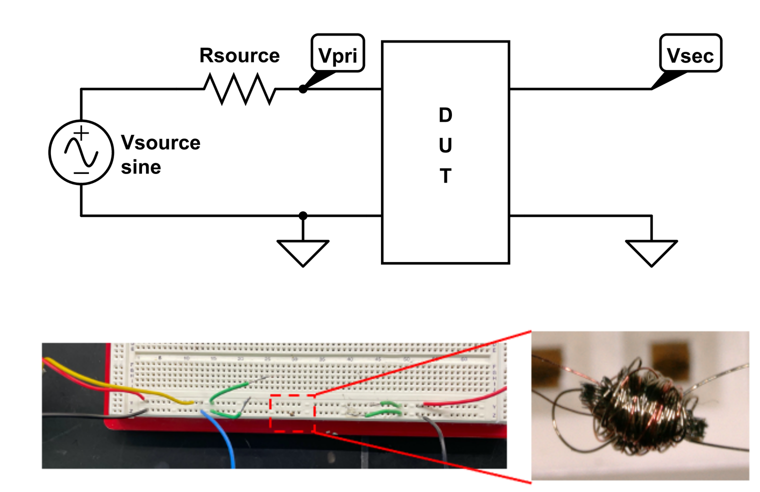
Sample No.	L_p at 50 kHz (μH)	L_s at 50 kHz (μH)	L_p at 1 MHz (μH)	L_s at 1 MHz (μH)	R_p at 50 kHz (Ω)	R_s at 50 kHz (Ω)	R_p at 1 MHz (Ω)	R_s at 1 MHz (Ω)	f_{0p} (MHz)	f_{0s} (MHz)
S1	0.66	67	0.66	60	1.2	4.7	1.4	21	4.6	5.6
S2	2	175	2.02	180	9	10	12	137	3.1	4.4
S3	2.96	312	3.34	273	4.3	33	6.5	179	2.6	3.9
S4	1.95	198	1.97	200	3.6	32	4.9	144	2.9	3.7
S5	2.75	253	2.2	234	1.6	13	5.4	369	2.6	3.5

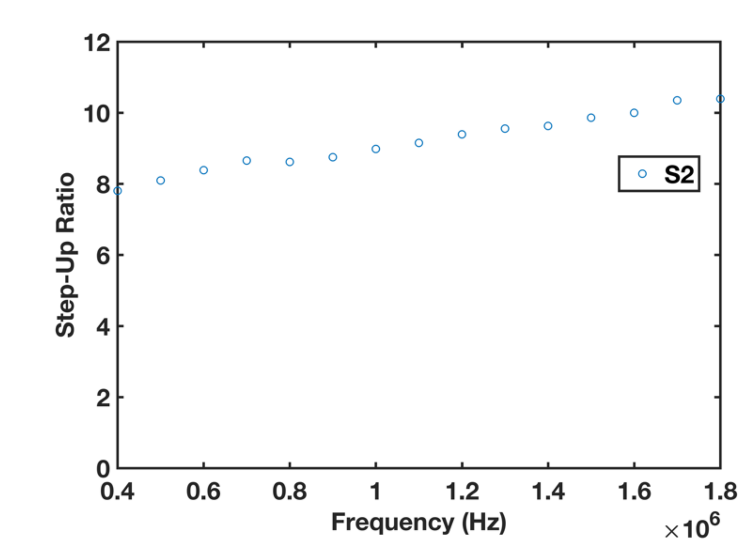
L_p: primary inductance, L_s: secondary inductance, R_p: primary resistance, R_s: secondary resistance, f_{0p}: primary self-resonance frequency, f_{0s}: secondary self-resonance frequency.





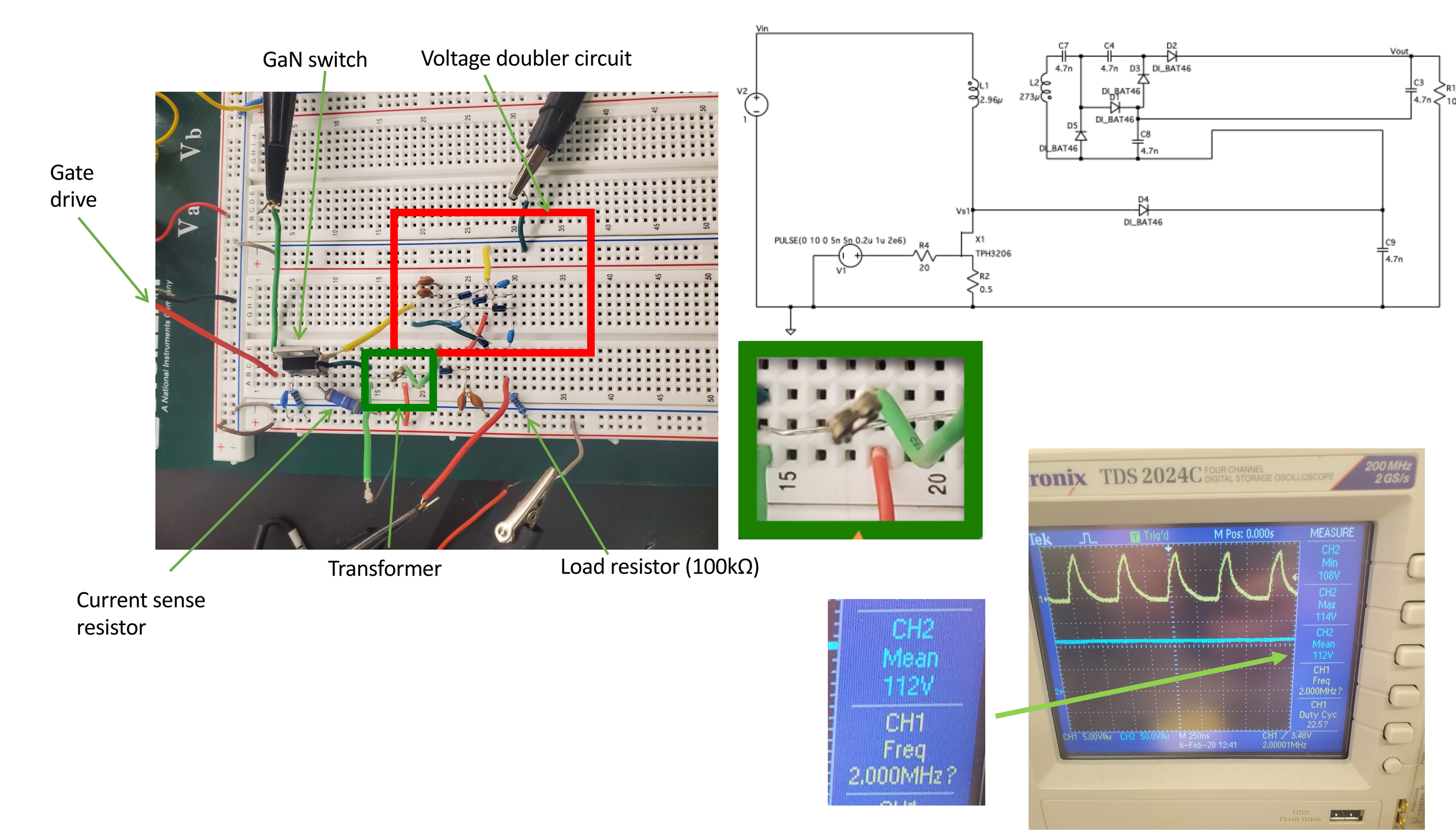
- The measured step-up ratio of S2 is 7.8 at 0.4 MHz and increases to 10 at 1.6 MHz. With a primary voltage of 3.8 V peak to peak, a secondary voltage of 34.6 V peak to peak is observed





- Fabricated transformer is tested in a customized flyback converter circuit
- With a 5 V input voltage and a 100 kΩ load resistor, an output voltage of 112 V is observed, and calculated power delivered to the load resistor is 125 mW

- The fabricated transformers show 7 times higher inductance per volume and 5 times higher inductance per weight compared to commercial coupled inductors



KEY CONTRIBUTIONS

- High winding ratio, ultracompact step-up transformers for DC-DC converters
- Primary and secondary inductances in microhenry and hundreds of microhenry ranges, capable for high power handling
- Volume and weight less than commercial devices with similar inductances, showing promise for use in space-constrained electronic systems

ACKNOWLEDGEMENTS

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