Ultra-High Efficiency Substrate-Embedded Inductors for Integrated Voltage Regulators

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Acknowledgements

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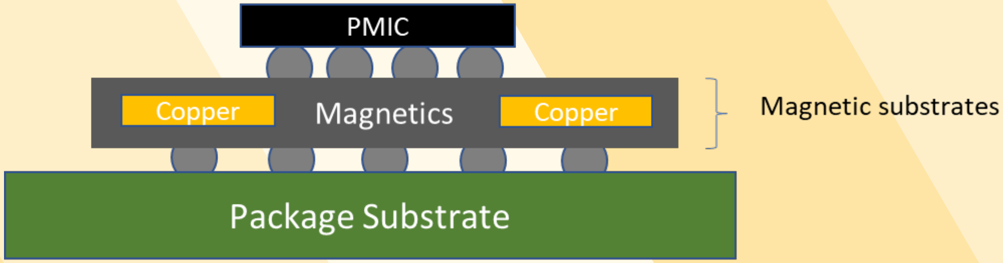
1. Goals and Objectives

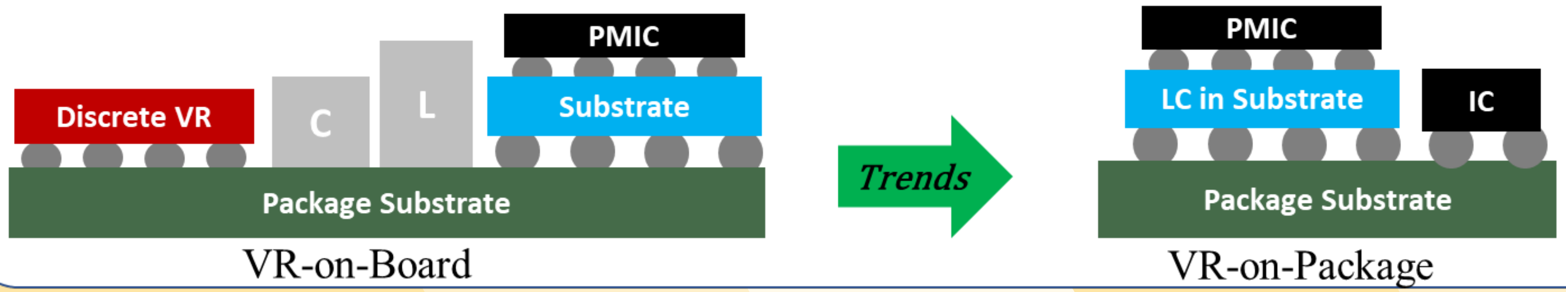
Demonstrate substrate-embedded, high current handling, magnetic core inductor for IVR



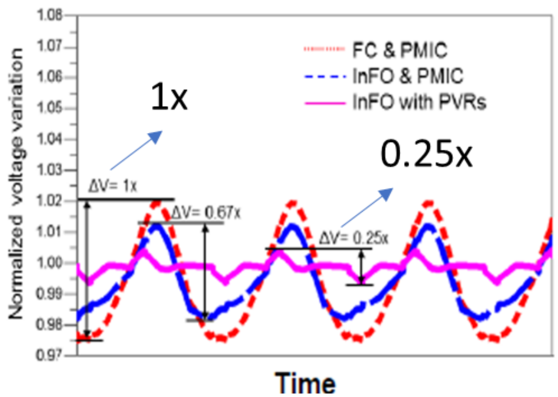
	Low-Frequency (1 – 10 MHz)		High Frequency (100 - 140 MHz)			
Metrics	Prior Art	Objectives	Prior Art	Objectives	Challenges	Tasks
Inductance (nH/mm²)	1.7	10-20	3.2	6	**Material Challenge** Trade-off between high permeability and frequency stability	Model and design magnetic-core inductors with target specifications
DC resistance (mΩ)	4.9	5	36	<10		
Current handling (A/mm²)	1	2	1	2	**Inductor Challenge** Inductor design for high inductance & current handling with low DC resistance	Develop new process to fabricate and characterize substrate-integrated inductors
Thickness (mm)	2	0.5	0.7	0.2 – 0.3		
Type	Discrete	Integrated	Discrete	Integrated	**Integration Challenge** Lack of embedding process to embed LC into substrate	Develop innovative process to embed LC into substrates

2. Strategic Need

System Miniaturization



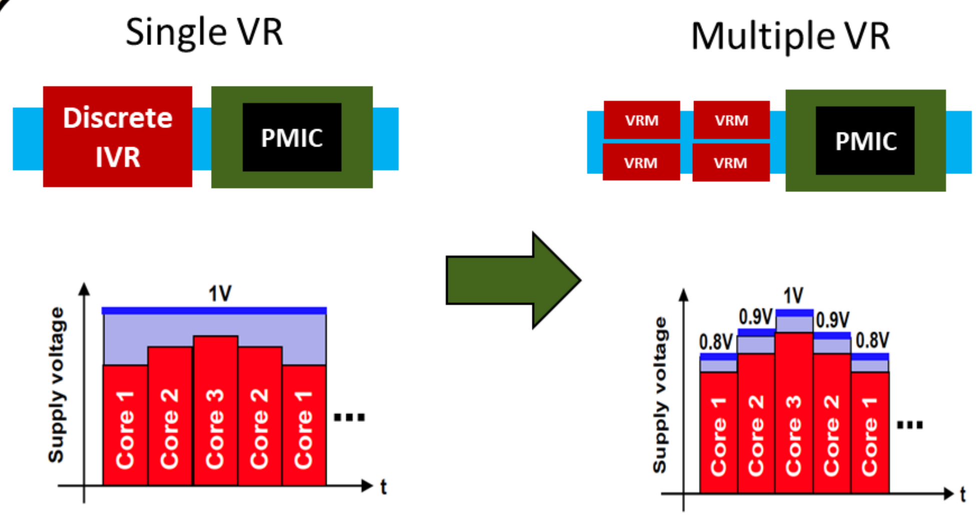
Reduced Voltage Variation



- 75% reduction in voltage variation

From [TSMC]

Granular Power Supply



- Per-core-voltage supply saves more energy

3. Unique Approach

Innovative Inductor Designs

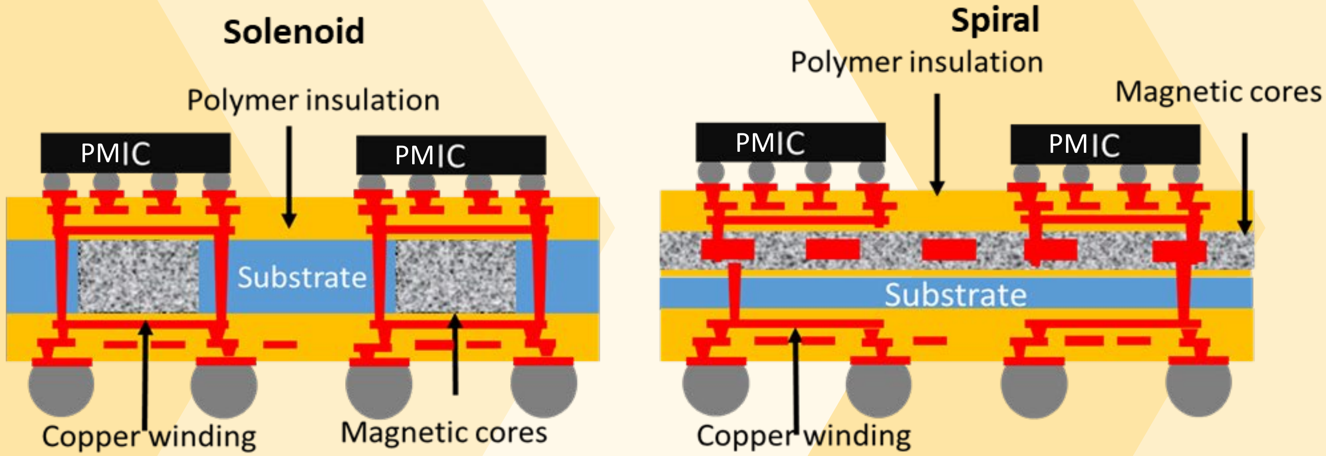
Unique inductor designs (2 geometrical options):

- Spiral inductors (2D)
- Solenoid inductors (3D)

Advanced Materials

Magnetic composites for high inductance density

- High permeability
- Trade-off high current handling and DC resistance



Advanced Integration Process

- Wafer-level substrate-compatible process to integrate inductor into substrates
- Reliability testing - Thermal cycling and warpage

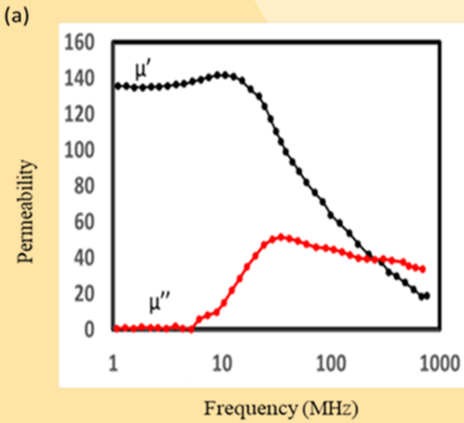
Characterization set-up

Electrical characterization

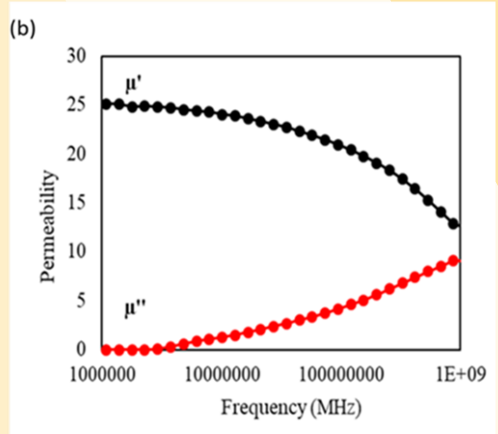
- L vs Frequency
- L vs Current
- DC resistance

4. Characterization of Composite Material

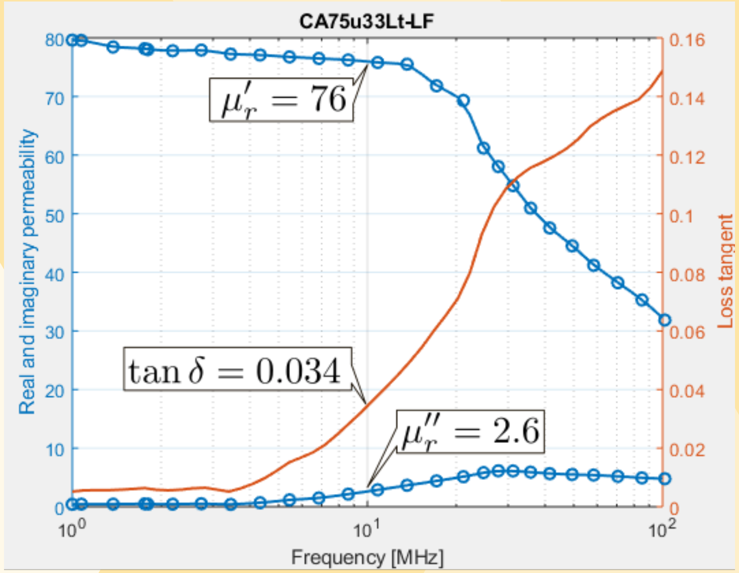
4.1 Electrical Properties



Low Frequency



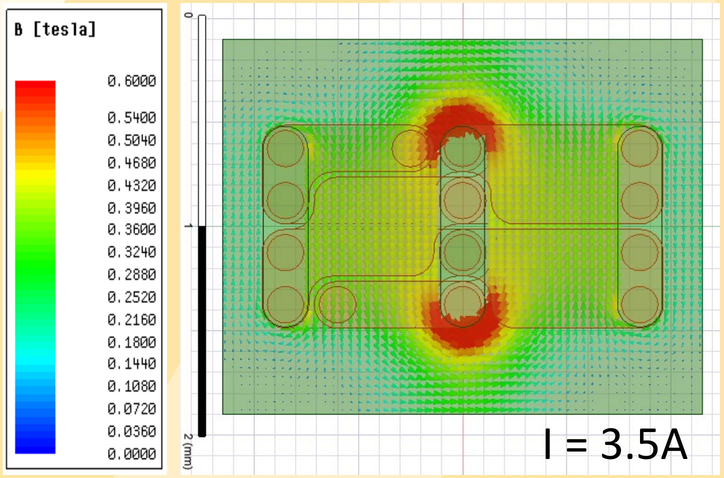
High Frequency



Parameter	Low frequency	High frequency
Permeability (H/m)	150 at 10 MHz	25 at 140 MHz
Loss tangent	0.146	0.230

Required material properties for 96% efficiency:

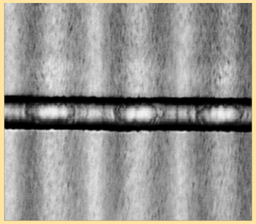
- The permeability is somewhere in between 50 and 150
- Loss tangent must be less than 0.033
- Magnetic saturation field must be greater than 0.6 Tesla

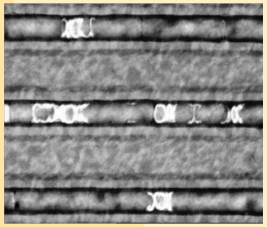


4. Characterization of Composite Material

4.2 Mechanical Properties

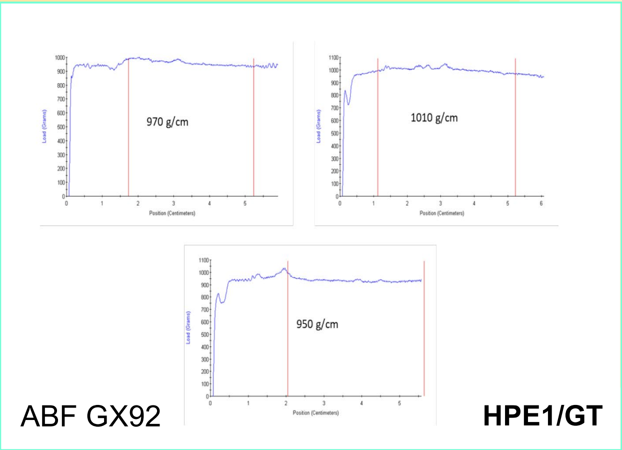
1. E-less Copper adhesion to composites


Magnetic surface


Local Roughness

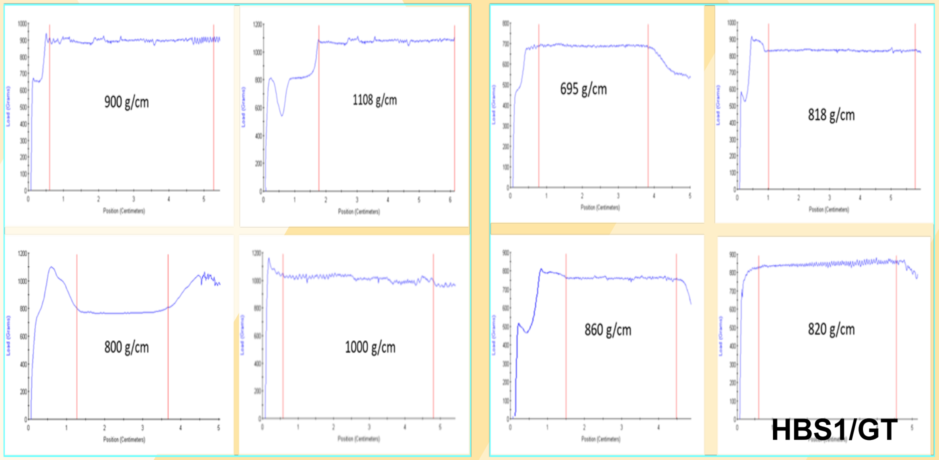
- E-less copper cannot be directly deposited on composite.
- E-less depends on Palladium catalysts being anchored in rough surfaces.
- Magnetic composites get roughened during and magnetic particles fall off the sheet.
- A dielectric layer is needed between magnetic and copper seed layer.

2. Polymer adhesion to composites



Film	Adhesion strength (g/cm)
ABF GX 92	976 (avg of all values)

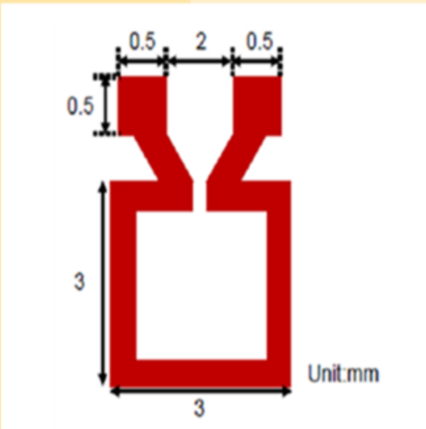
ABF GX92 XV2130F



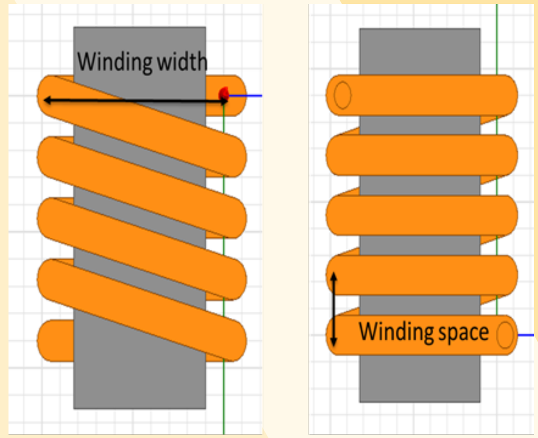
Film	Adhesion strength (g/cm)
ABF GX 92	952 (avg of all values)
XV2130F with sputtered Ti-Cu seed	799 (avg of all values)

5. Modeling of Inductor Topologies

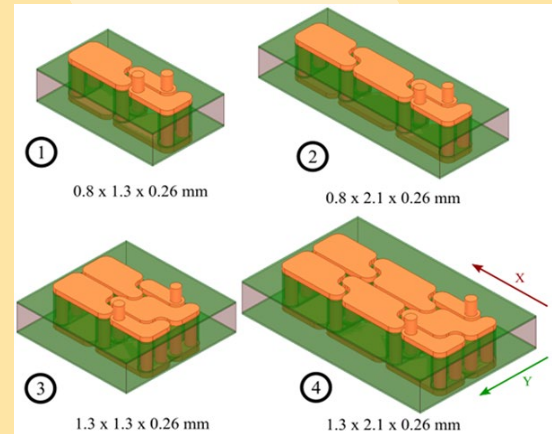
5.1 Low-Frequency Composite



Planar Inductors



Solenoid Inductors



Toroid Inductors

Metrics	Objectives	Designed performance		
		Spiral Inductor	Solenoid Inductor	Toroid Inductor
Inductance Density	10-20 nH/mm^2	10.05 nH/mm^2	11 nH/mm^2	50 nH/mm^3
DC Resistance	5 mΩ	10 mΩ	11 mΩ	10 mΩ
Thickness	500 µm	505 µm	600 µm	500 µm

- 3D inductor architectures show lower L/R ratio but have a higher current handling
- Such topologies have more design complexity compared to planar inductors

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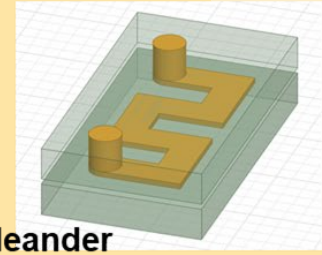
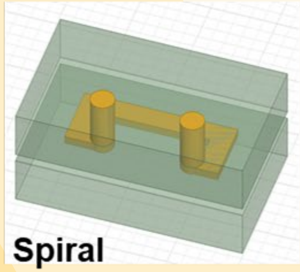
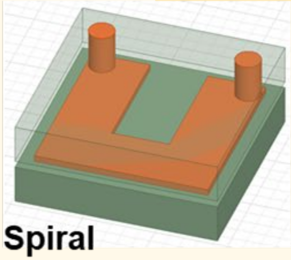
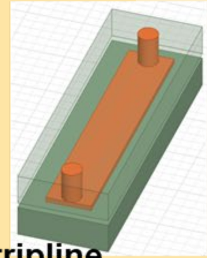
5. Modeling of Inductor Topologies

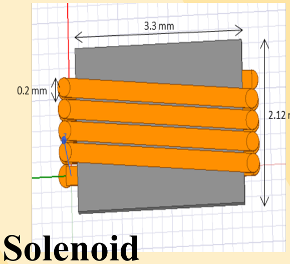
5.2 High-Frequency Composite


Meander


Spiral


Spiral


Stripline



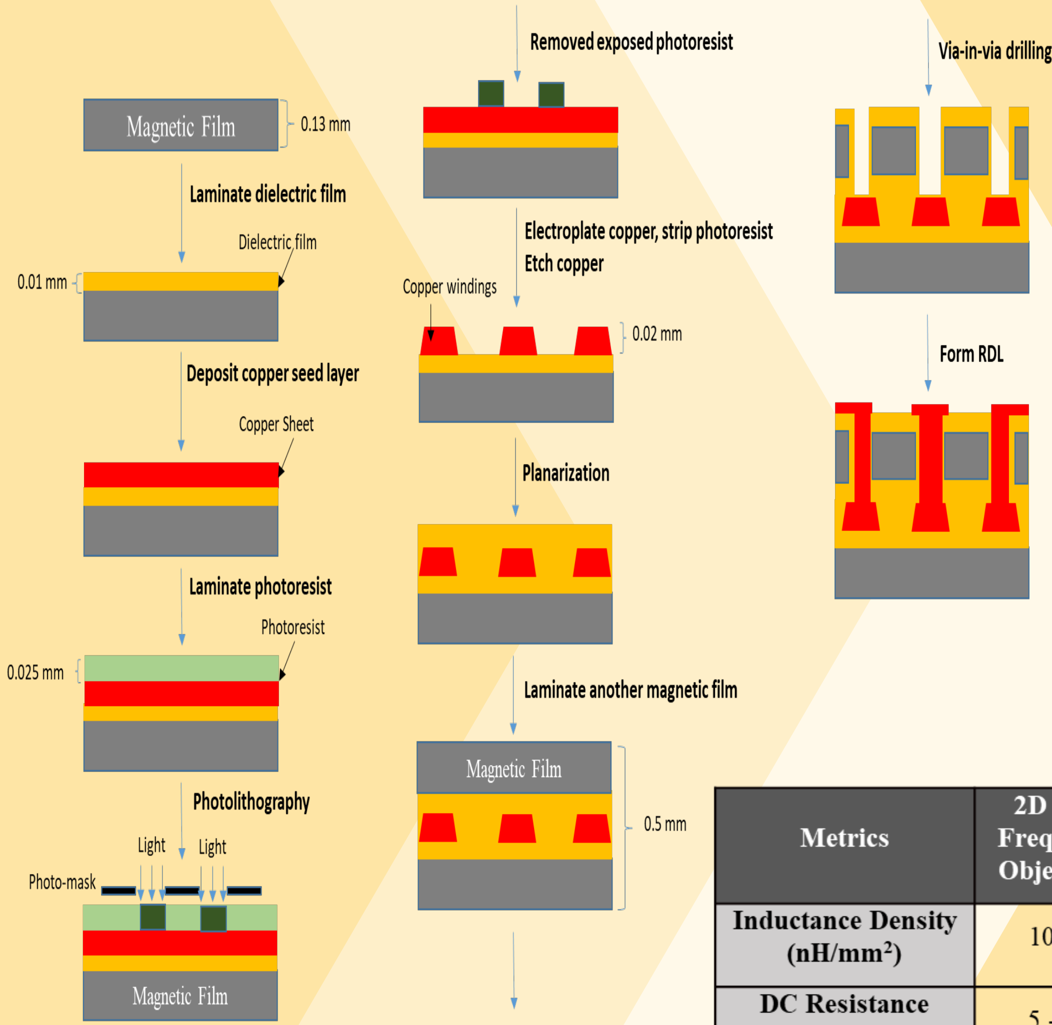
Solenoid

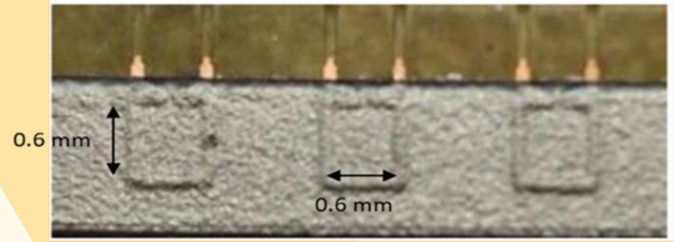
Metrics	Objectives	Designed performance					
		Meander	Spiral	Spiral	Strip line	Solenoid	Toroid
Inductance Density (nH/mm^2)	6	7.04	6.89	7.75	7.27	7.92	13.6 nH/mm^3
DC Resistance (mΩ)	<10	9.79	8.91	5.34	4.74	6.14	5.5
Thickness (µm)	220-300	260	260	260	260	280	300

- The strip line inductor shows higher inductance with a low DC resistance. The designs account for tolerance due to fabrication
- At fs > 10 MHz only low voltage converters can be modeled. Then this material cannot be used for 48V to 1V, only for application 3.3V to 1V and 1.7V to 1V. With the high-frequency material (due to lower permeability) the saturation current is greater than 3.0 A

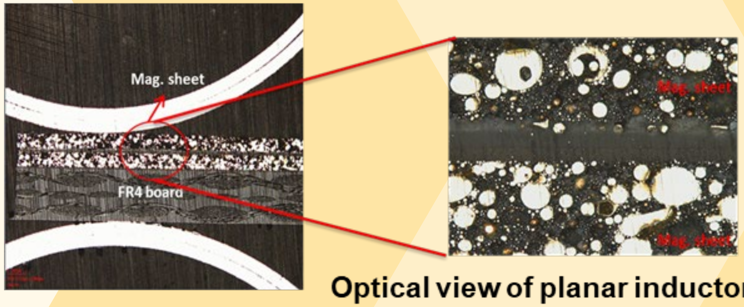
6. Inductor Fabrication

6.1 Spiral (2D) Inductors





The top view of spiral inductors

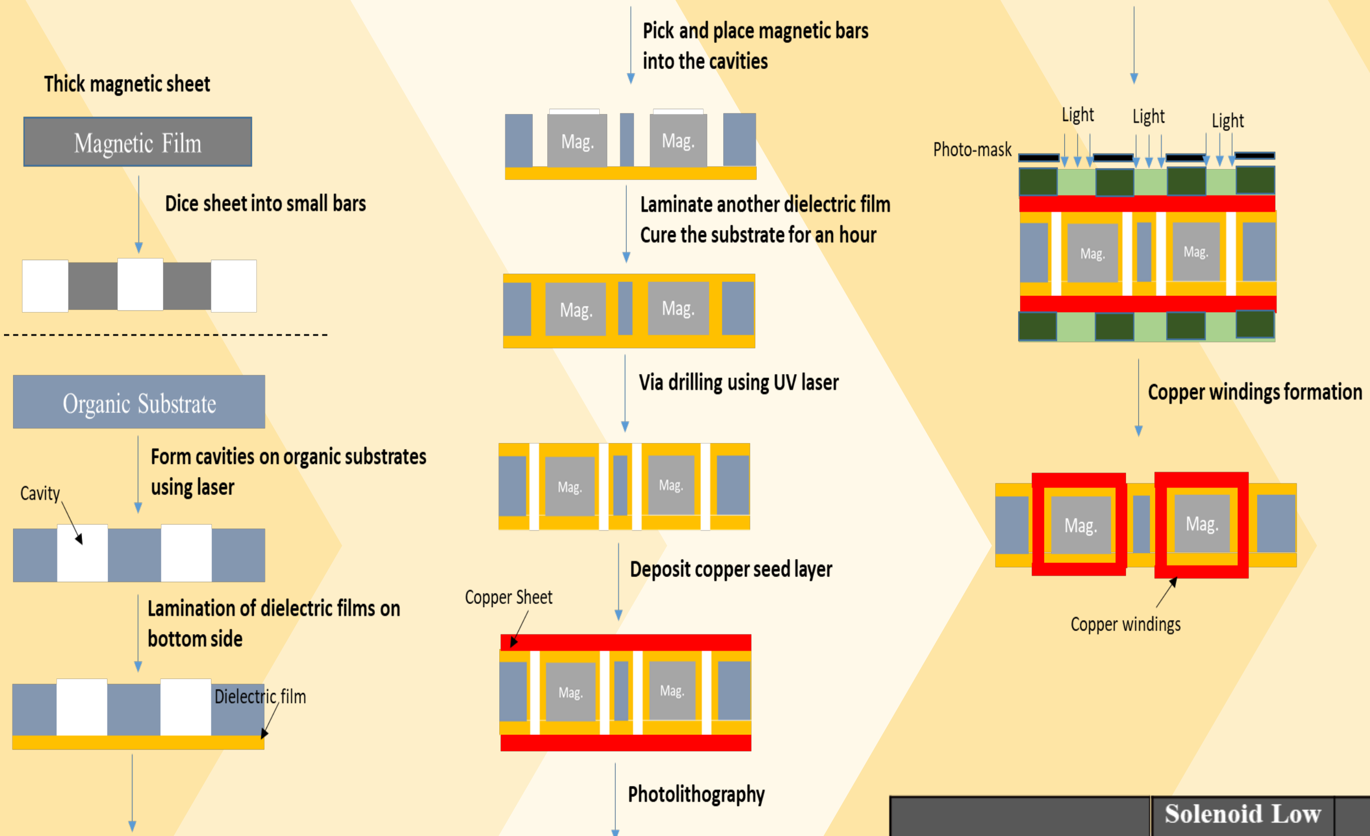


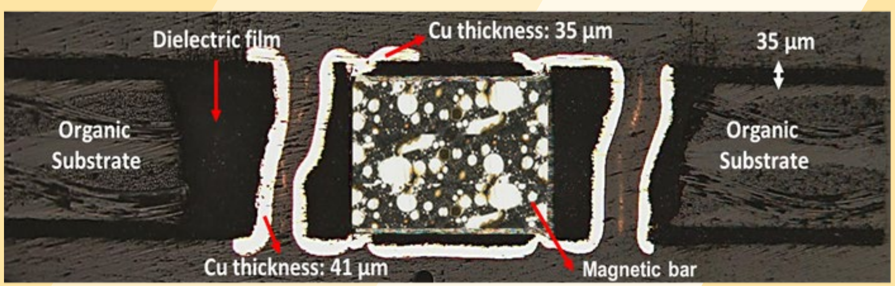
Optical view of planar inductor

Metrics	2D Low Frequency Objectives	2D Low Frequency Fabricated Values	2D High Frequency Objectives	2D High Frequency Fabricated Values
Inductance Density (nH/mm²)	10-20	12.38	6	8.21
DC Resistance (mΩ)	5 - 10	9.83	< 10	7.72
Thickness (µm)	500	435	200 - 300	315

6. Inductor Fabrication

6.2 Solenoid (3D) Inductors

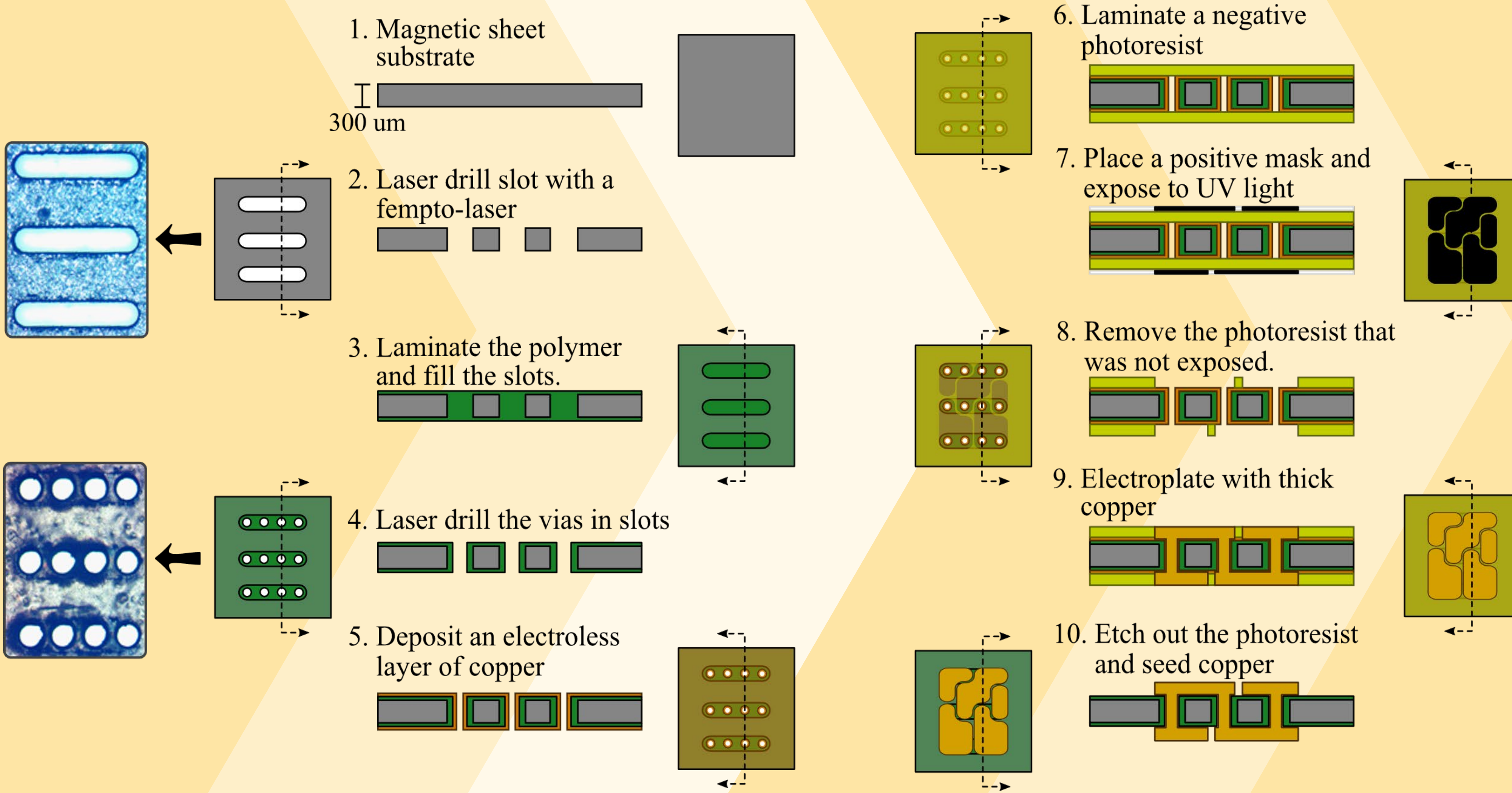




Metrics	Solenoid Low Frequency Objectives	Solenoid Low Frequency Fabricated Values
Inductance Density (nH/mm²)	10-20	To be Measured
DC Resistance (mΩ)	5 - 10	
Thickness (µm)	200 - 300	

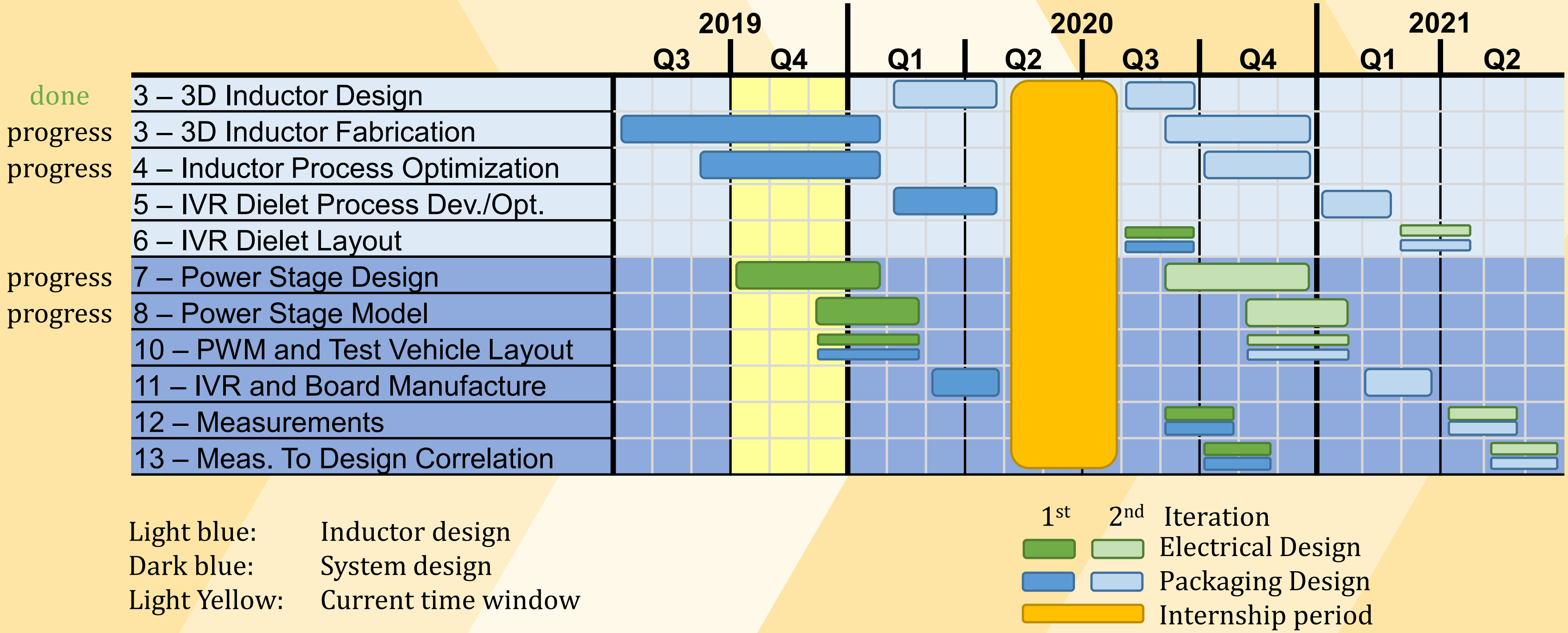
6. Inductor Fabrication

6.3 Toroid (3D) Inductors



7. Schedule

- Toroidal single inductor is already designed
- Optimization of fabrication process ongoing
- A single inductor based 4-phase buck converter is in design step
- A Journal paper will be prepared with the analysis results to date
- Next step will be preparing a measurement setup to measure the inductor under DC current bias and with triangular current waveform
- Next iteration will be the design of a tapped inductor-based converter



8. Summary

- Modeled and designed spiral inductors for target specifications as below.
  - Low Frequency: L - 10 nH/mm^2 , R – 5 mΩ, thickness – 0.5 mm
  - High Frequency: L – 6 nH/mm^2 , R – < 10 mΩ, thickness – 0.3 mm
- Developed and optimized process flow for fabricating substrate integrated inductors.
- Fabricated and characterized planar inductors for low and high frequency applications:
  - Low-Frequency: L – 12.38 nH/mm^2 , R – 9.83 mΩ
  - High-Frequency: L – 8.21 nH/mm^2 , R – 7.72 mΩ
- Fabricated solenoid inductors for low and high-frequency applications
- Modeled novel toroid inductors and currently optimizing the fabrication process

Next Milestones:

- Fabricate toroid inductors and measure the inductance
- Establish effect of undercut on the inductance density
- Lower losses with high L/R_{dc} with filled vias
- Model and fabricate inductors for 48V-1V applications using very low loss materials