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Multimaterial Aerosol Jet Printing of Passive Circuit Elements

PRESENTED BY

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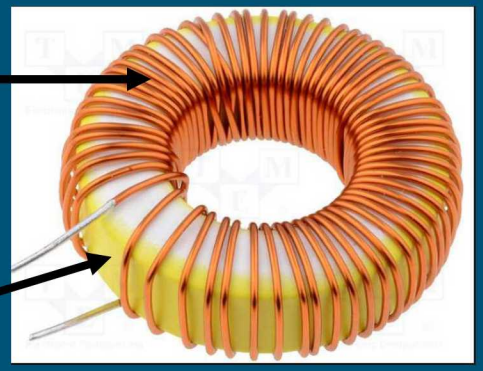
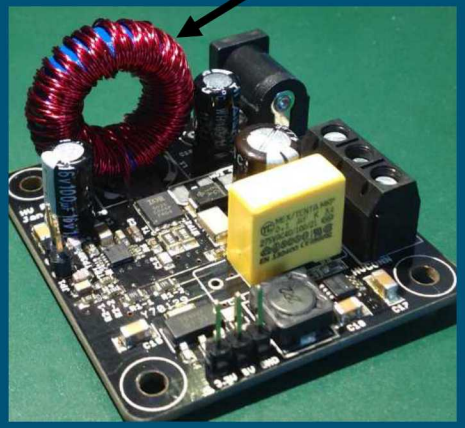
Inductance

- Inductors store energy in a magnetic field, just as capacitor stores energy in electric field
- Toroidal inductors are preferred over solenoidal designs due to reduced magnetic flux leakage, leading to higher inductance and less interference
- Inductance $=\mu(\frac{N^2 A}{l})$
  - μ is permeability of core with units of Henry/meter
  - N is number of turns in the coil
  - A is cross sectional area of the core
  - l is the circumference of the ring
- Bulky structure motivates printing microinductors



Toroidal

Solenoidal

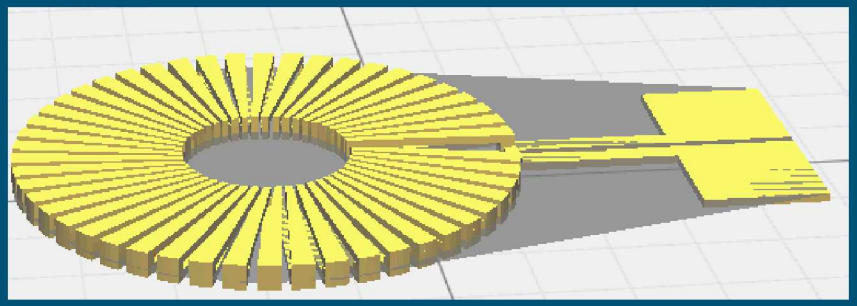


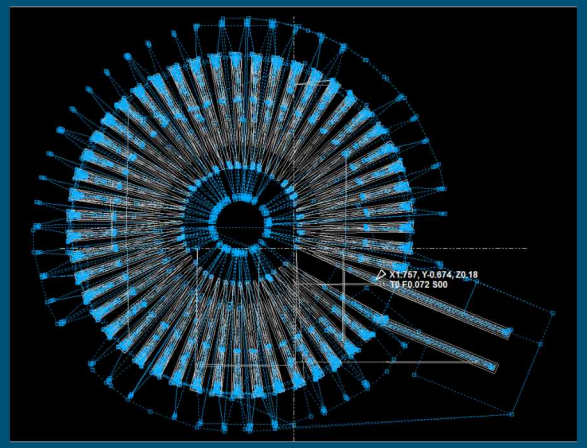
Aerosol Based Printing

- The aerosol jet printer deposits functional liquid inks following atomization and aerodynamic focusing to achieve high resolution patterns
- Aerosol jet printing allows integration of multiple materials
- For this research, silver nanoparticle and polyimide precursor inks were used to additively manufacture inductors
- Ink formulation and print parameters are designed for reliable printing, including aerosol and sheath gas flow rates, atomizer voltage, print speed, and temperature
- Pneumatic shutter requires a delay of ~0.5 s for well defined starting and stopping

Toolpath Generation

- Toolpath used as machine commands for movement and operations during manufacturing
- Intricacy and size of the part presents a challenge for toolpath generation (slicing) from model
- Minimize movement and shuttering to simplify and shorten prints
- Successful toolpath created using Simplify3D software has fewest unnecessary moment and shuttering steps



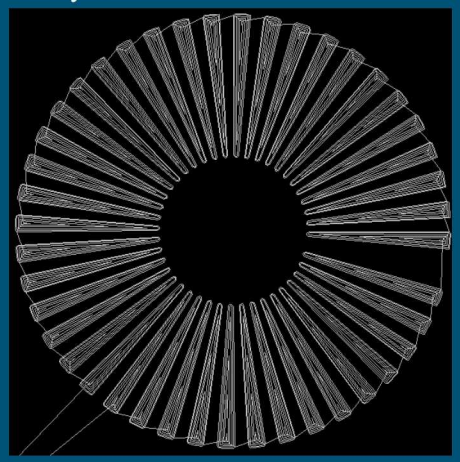


Unnecessary moment and shuttering steps lead to poor printing with low yield

Model and Design of Toroid

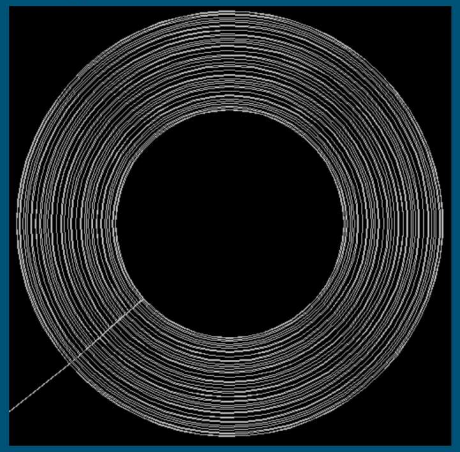
- Layers 1 and 3 together create the coil of the inductor
- Layer 2 generates the dielectric core of the inductor separating layers 1 and layer 3
- Final toolpath with multi layer/material for toroidal inductor is made possible through aerosol jet additive manufacturing

Layer 1



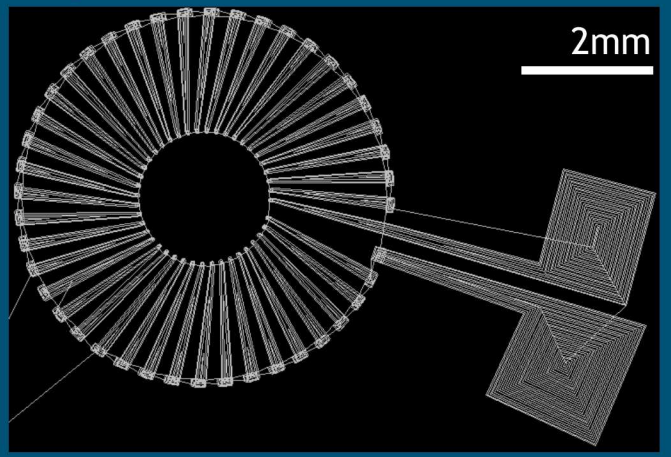
Silver NP ink

Layer 2



Polyimide precursor ink

Layer 3



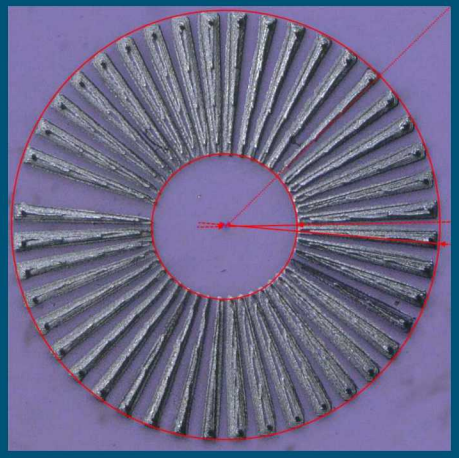
Silver NP ink

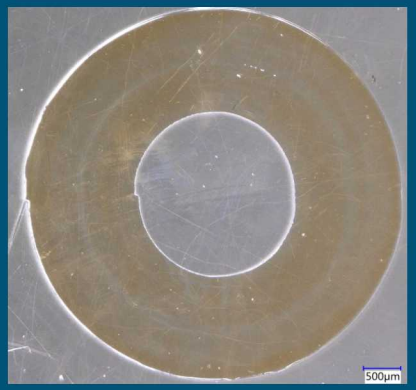
Printing Parameters of Toroid

Printing parameters varied due to machine being used and adjusted for other experiments

	Silver NP ink	Polyimide precursor ink
Tip diameter	233 µm	233 µm
Aerosol flow rate	8-12 sccm	10-15 sccm
Sheath flow rate	30-40 sccm	40-50 sccm
Atomizer voltage	30-35 volts	32-35 volts
Substrate Speed	8 mm/s	5 mm/s

2mm

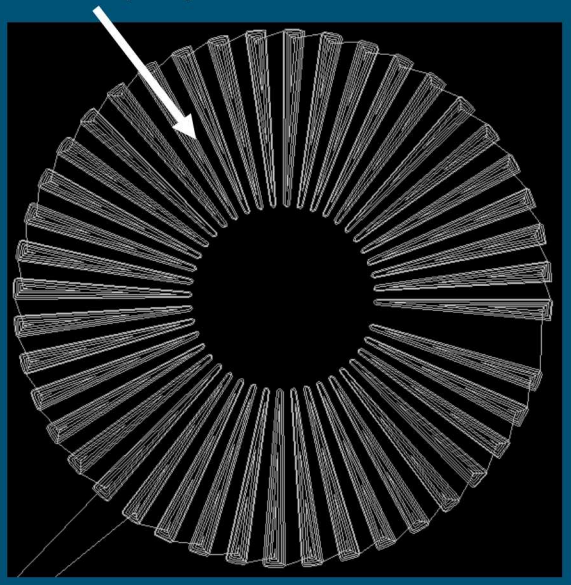




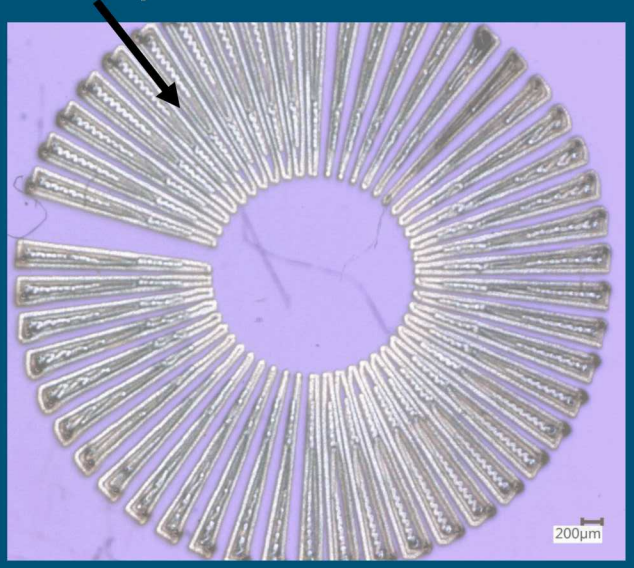
Sizing Issue

- The individual coil sections exhibit overlap and under-filling in the top left and bottom right during printing (section size varies around ring)
- This can result in electrical shorting and poor conductivity
- Possible causes include control box connections, software, and precision of motors

Evenly spaced sections



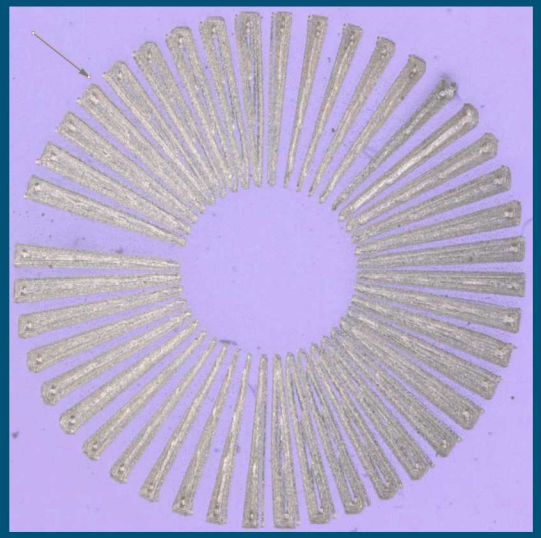
Overlap and under-filled section



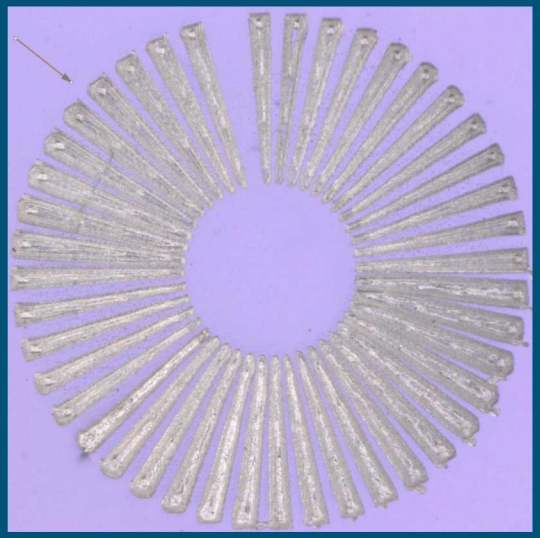
Size Testing

- Testing prints for possible causes with no change (1), swapping X and Y axes on control box(2), and rotating toolpath 90° counter clockwise (3)
- No difference with changed in control box or toolpath
- Testing motor precision was done using normal toolpath at double the size with no section sizing issue

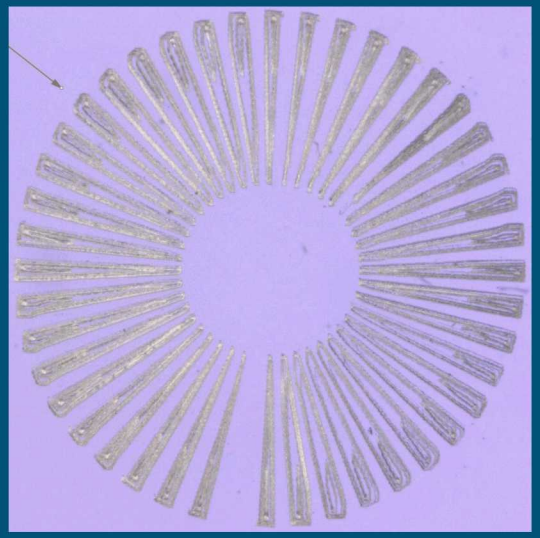
No change (1)



Control Box Swap (2)



Toolpath Rotation (3)

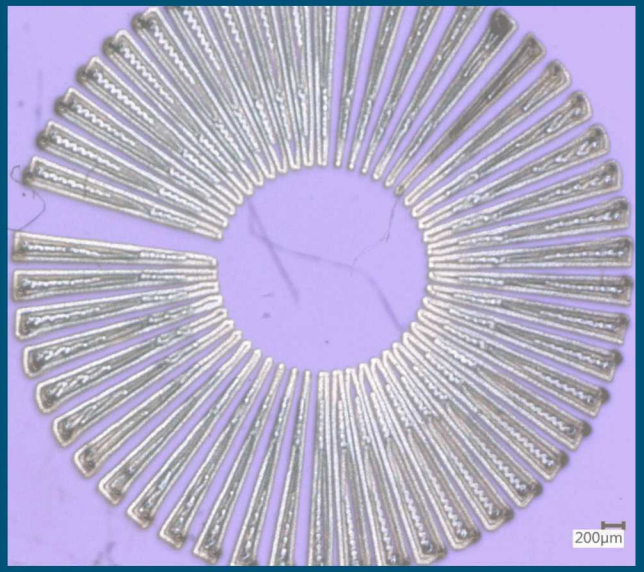


2mm

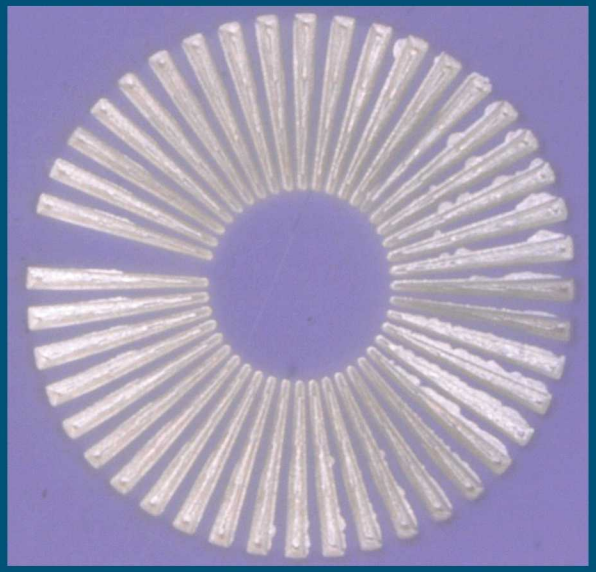
Sizing Solution

- Issue attributed to motor precision because there was no issue at 2x size
- Added gear reducer with a 7:1 turning ratio to both the X and Y axes motors, increasing accuracy by 7x

Before



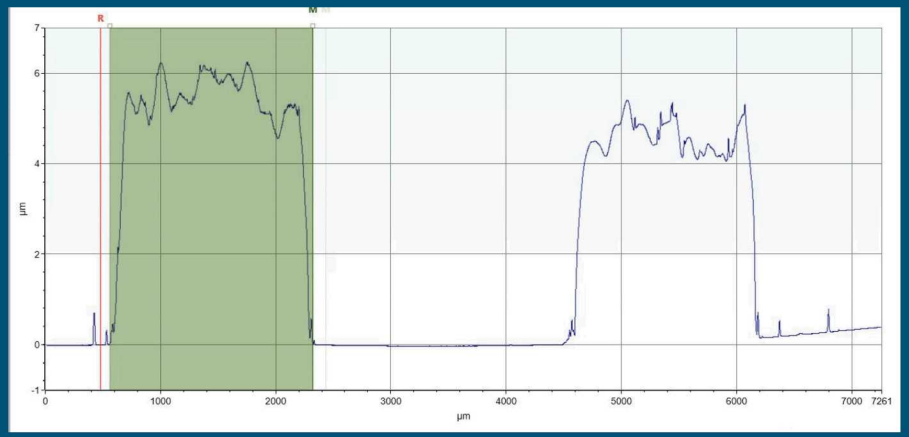
After



Printed Inductor Parameters

- Parameters used for inductor are the number of turns in the coil (N), cross sectional area of core (A), toroid circumference (l) and the permeability of the core (μ)
- N = 43
- A = 11,200μm² with an average height of 6μm
- $\mu = 4\pi \cdot 10^{-7}$ assuming permeability of the dielectric is the same as free space
- l = 18.85mm

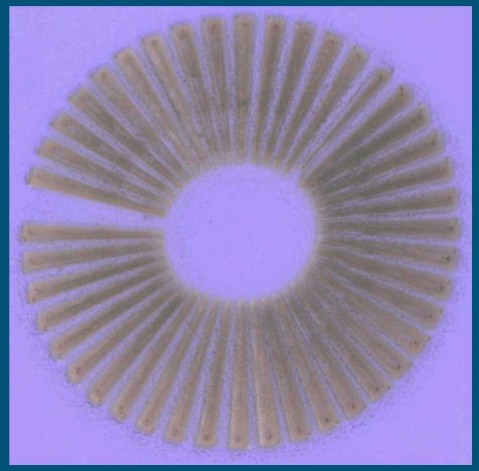
Cross Section of Core



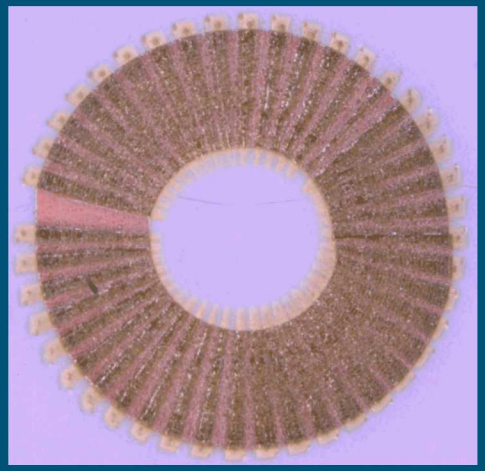
Printing of Final Part

- Silver ink cures for 30 minutes at 170° C
- Polyimide precursor ink bakes for an hour at 80° C then hard bakes for 45 minutes at 200° C
- Slow curing of polyimide precursor necessary to prevent bubbling and crack formation

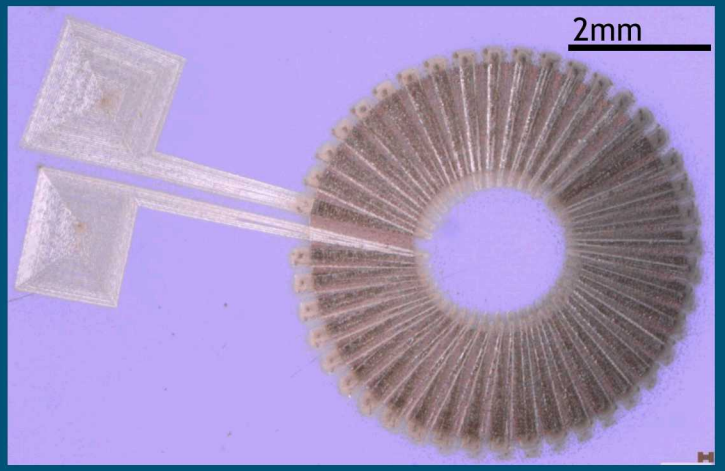
Layer 1



Layer 2



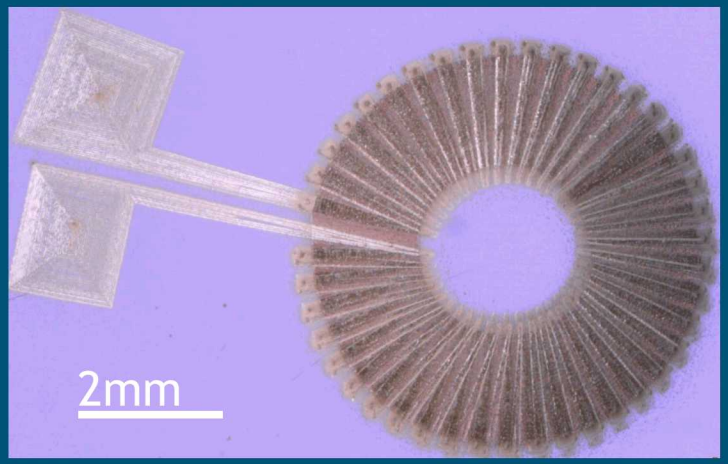
Layer 3



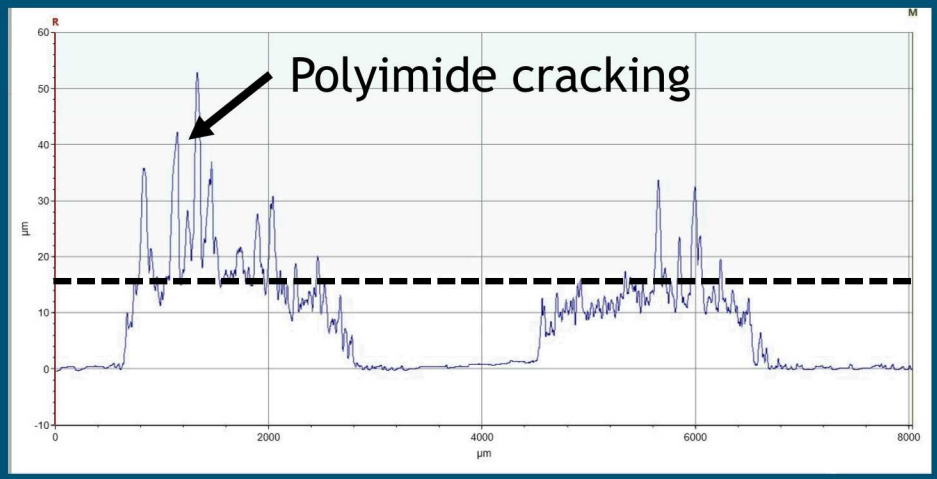
Inductance and Size

- Measured six successful inductors at 1kHz with a value of about 1.2µH (hoping to simulate)
- Poor contacts made reliable measurements challenging
- Max height of inductor was about 55µm due to cracking from the polyimide (height without polyamide cracking is about 15µm)
- Outer diameter is just under 6mm and inner diameter is just under 2mm

Microscope image of Inductor



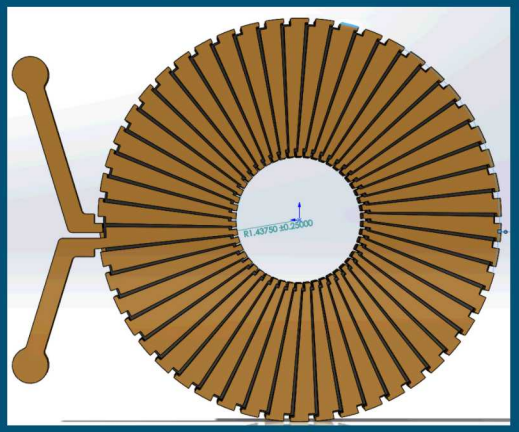
Cross section of Inductor



New Design for 2μH Inductor

- Target core height of 50μm increasing the cross sectional area over 12x
- Incorporating nickel ink into the core making a five layer manufacturing process to wrap the nickel with a polyamide dielectric
- Increasing the number of turns in the coil from 43 to 50
- Outer diameter of 9.125mm and inner diameter of 2.875mm results in an increased cross sectional area and circumference of ring
- Overall height of inductor to be about 80μm

New Design



3mm

Future

- Looking at other possible materials for the coil
- Hope to use a material with high permeability for the core, ideally iron
- Hybrid manufacturing to fabricate iron core separately
- Increase height of core using trapezoidal cross section instead of rectangular cross section to prevent breaks in coil connections

Summary and Future

- Aerosol jet technology used to manufacture printed inductor and possible manufacturing of other electronics
- High precision motors needed for printed electronics
- Possible area for printed electronic toolpath generation software
- Successfully additively manufactured inductor looking to improve overall inductance for future research
- This research is just a small part in the bigger picture of printed and embedded electronics manufacturing

Thank you