Realization of Sustainable Additively Printed Circuits using Aerosol-Jet Inkjet and Direct-Write Processes

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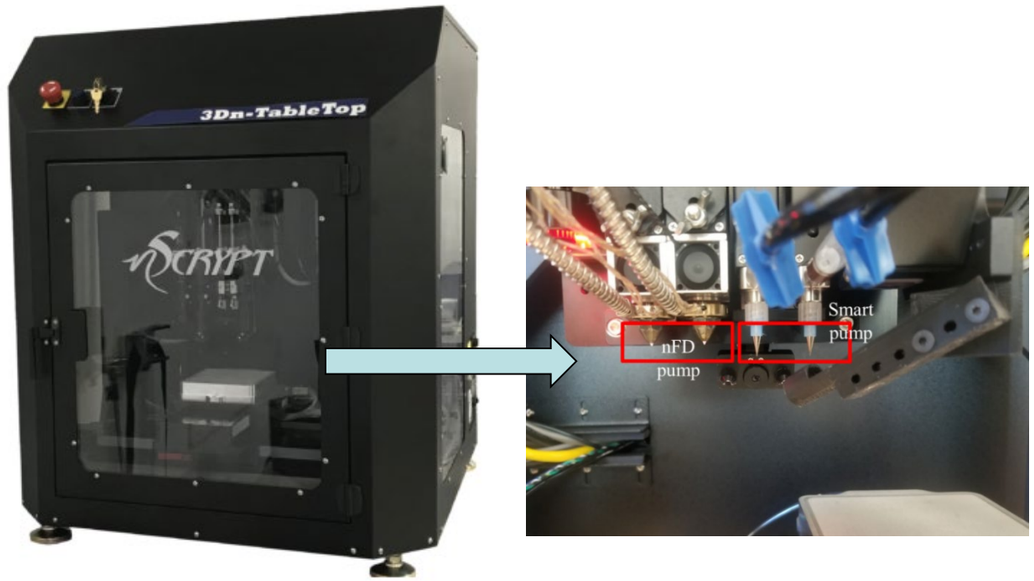
Motivation

- Additive methods for electronics fabrication eliminate the need for plating baths.
- Earlier inks used volatile solvents for achieving conductive traces.
- Interaction of water-based inks with substrates, including resistivity, shear strength, porosity, ink receptivity, and wettability, are not well understood.
- Water-based silver inks for additive printed circuits have the potential of eliminating harmful waste and enabling sustainable manufacturing processes.

Objectives

- Quantify the interconnection performance of aqueous-based inks with various interconnect materials such as ECA, and LTS
- Realization of additively printed circuits with water-based inks.
- Study of the intermetallic at the interface of conductive adhesive and additively printed circuits for reliable interconnection.
- Performance parity with laser-ablated copper-clad substrate for the various bonding materials employed.

Direct Write Inks



Electrically conductive adhesive(ECA)

Parameters	Value
Viscosity	110,000cP at 1 sec^{-1}
Specific gravity	3.2
Tg	-10˚C
Volume Resistivity	< 9 x 10^5 Ω*cm

Low Temperature Solder(LTS1)

Parameters	Value
Material Composition	57Bi/42Sn/1Ag
Metal Load	89-90%
Viscosity	160,000cPs
Melting Point	140˚C

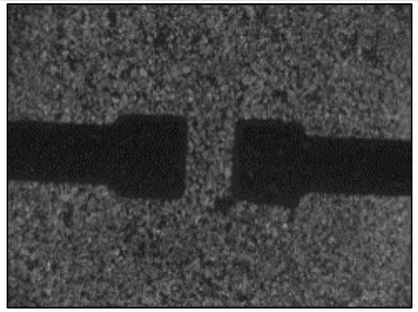
Sustainable Conductive(Silver) paste (Ink-A)

Parameters	Value
Viscosity	3500 - 6000 cP at 0.1 sec^{-1}
Ag Content	42 wt%
Volume resistivity	9 μΩ*cm

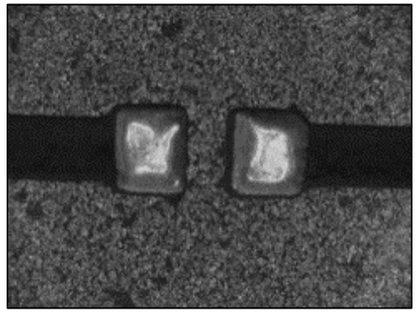
Low Temperature Solder(LTS2)

Parameters	Value
Material Composition	52In/48Sn
Metal Load	89%
Viscosity	950,000cPs
Melting Point	180˚C

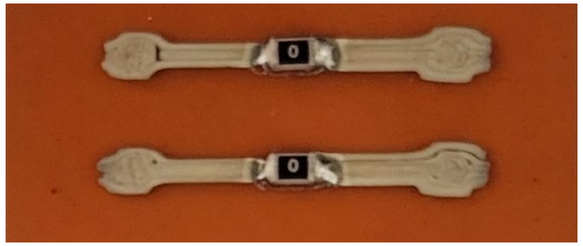
Test Vehicle-1 Process Parameters



Layer 1 - After conductive layer sintered



Layer 2 - After bonding material paste printing



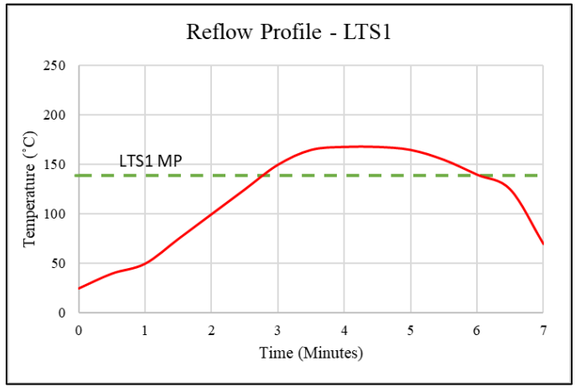
After Component attached and sintered

Print Process Parameters for various inks:

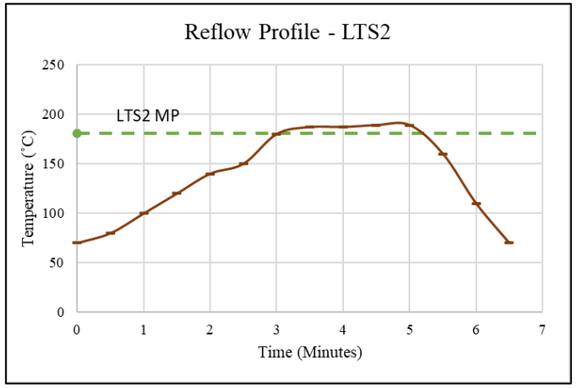
	Silver	ECA	LTS1	LTS2
Ink Pressure(psi)	12	15	25	25
Standoff Height (mm)	0.050	0.080	0.100	0.100
Print Speed (mm/s)	2	3	2	1
Infill Density (%)	100	100	100	100

Cure condition:
For sustainable silver: 100C for 2mins
For ECA: 150C for 30mins
Part Size: 0805 Discrete Parts

Components	Rated value
Resistor	0 Ohms
Resistor	1000 Ohms
Capacitor	1.8pF
Inductor	2.2µH



Reflow Profile for LTS1

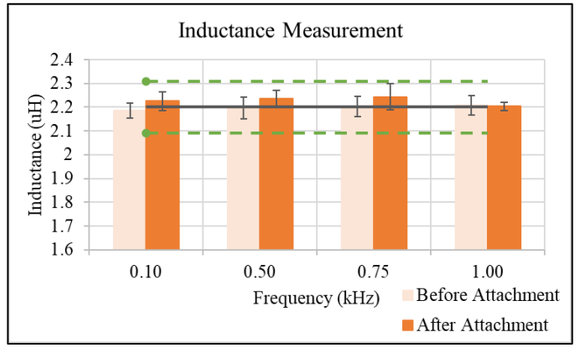


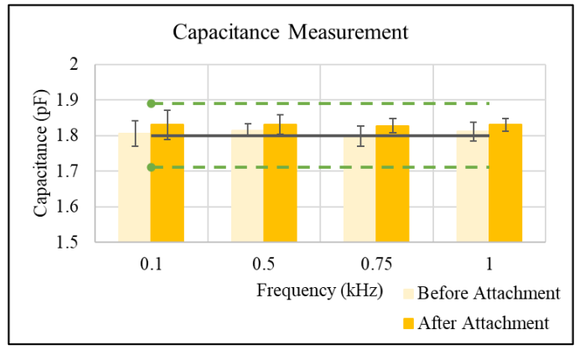
Reflow Profile for LTS2

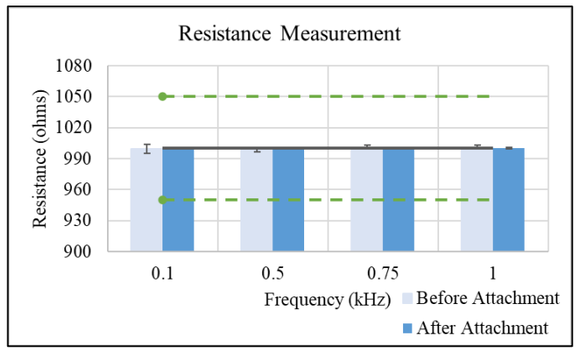
Ink-A, DW

Electrical Performance 0.1-1KHz

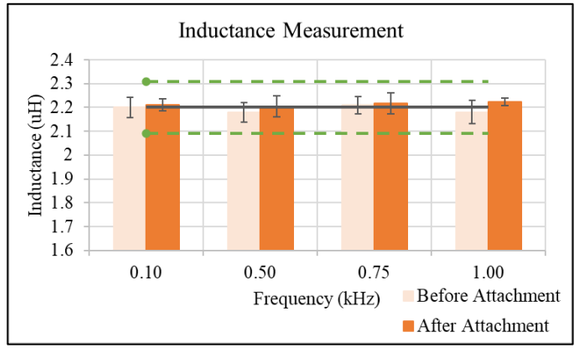
ECA

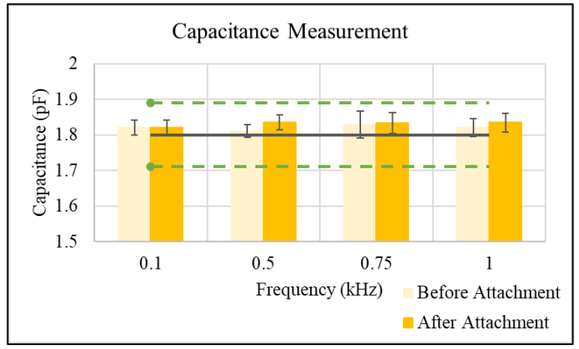


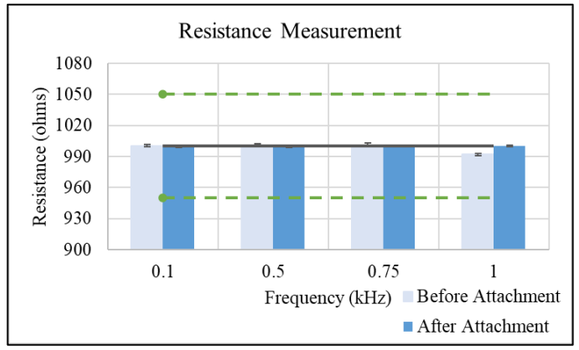




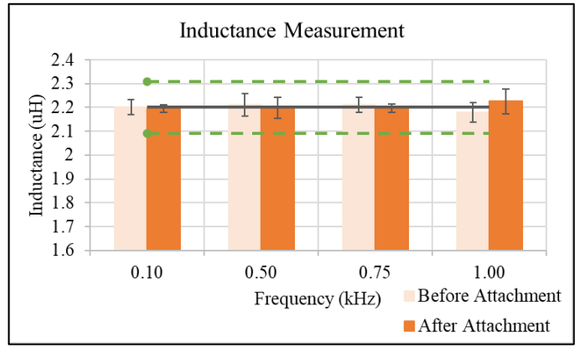
LTS1

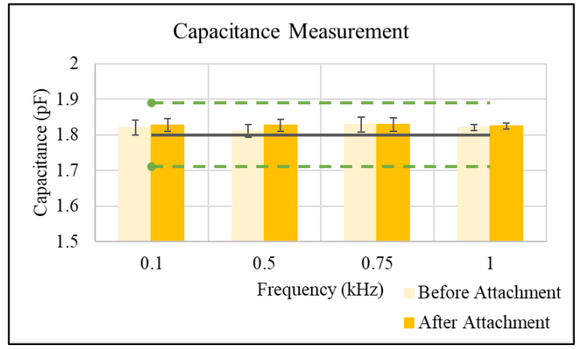


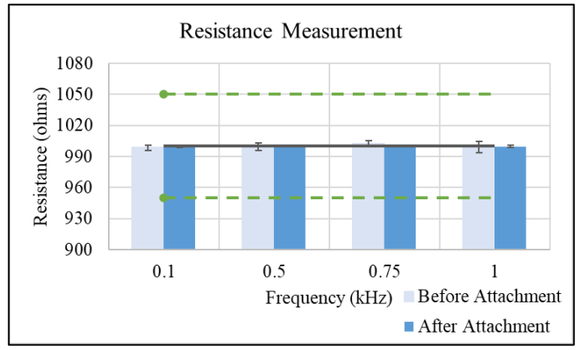




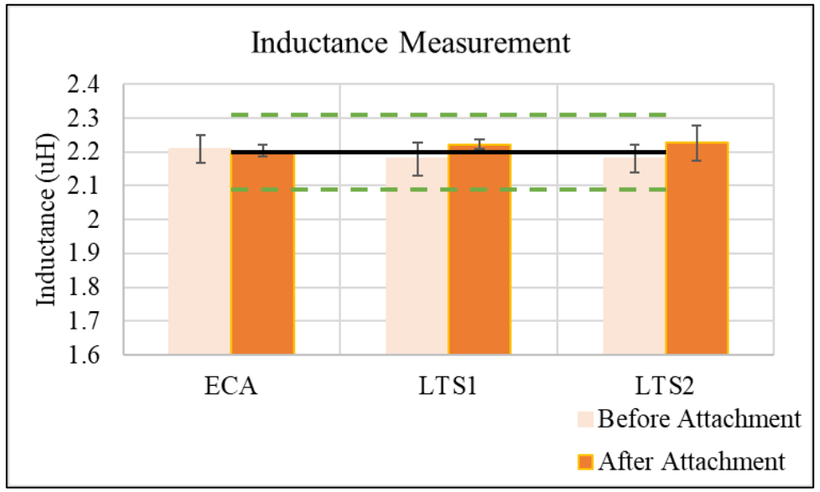
LTS2

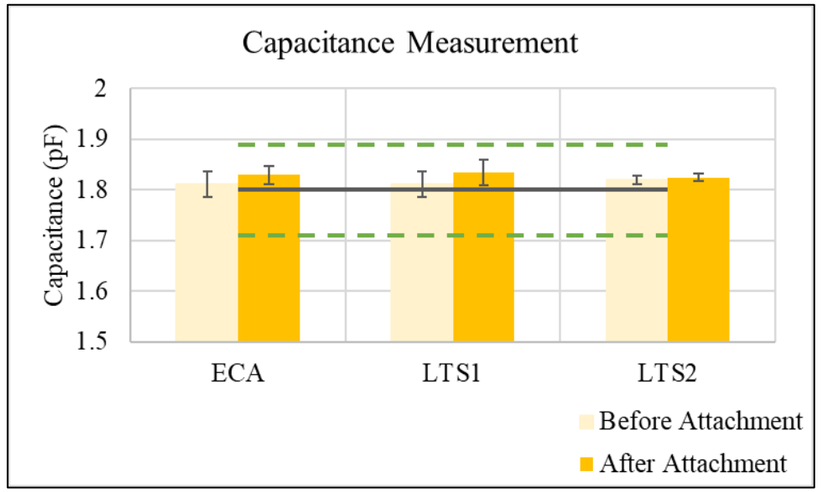


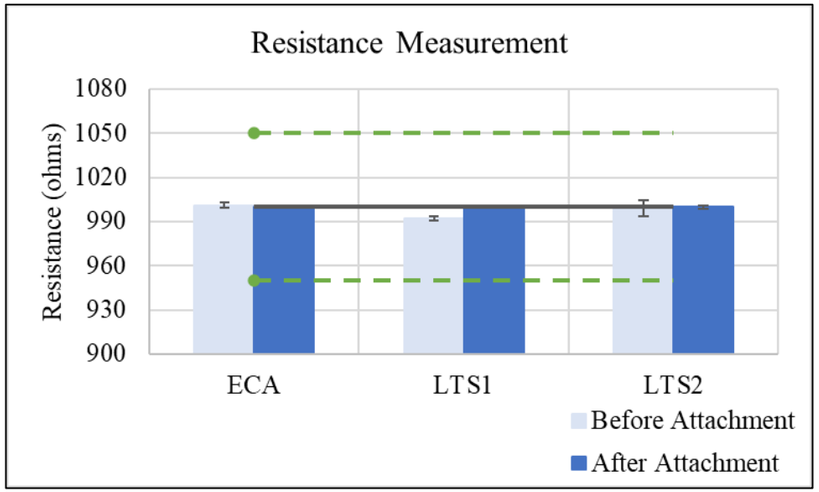




Electrical Performance Comparison @ 1 kHz



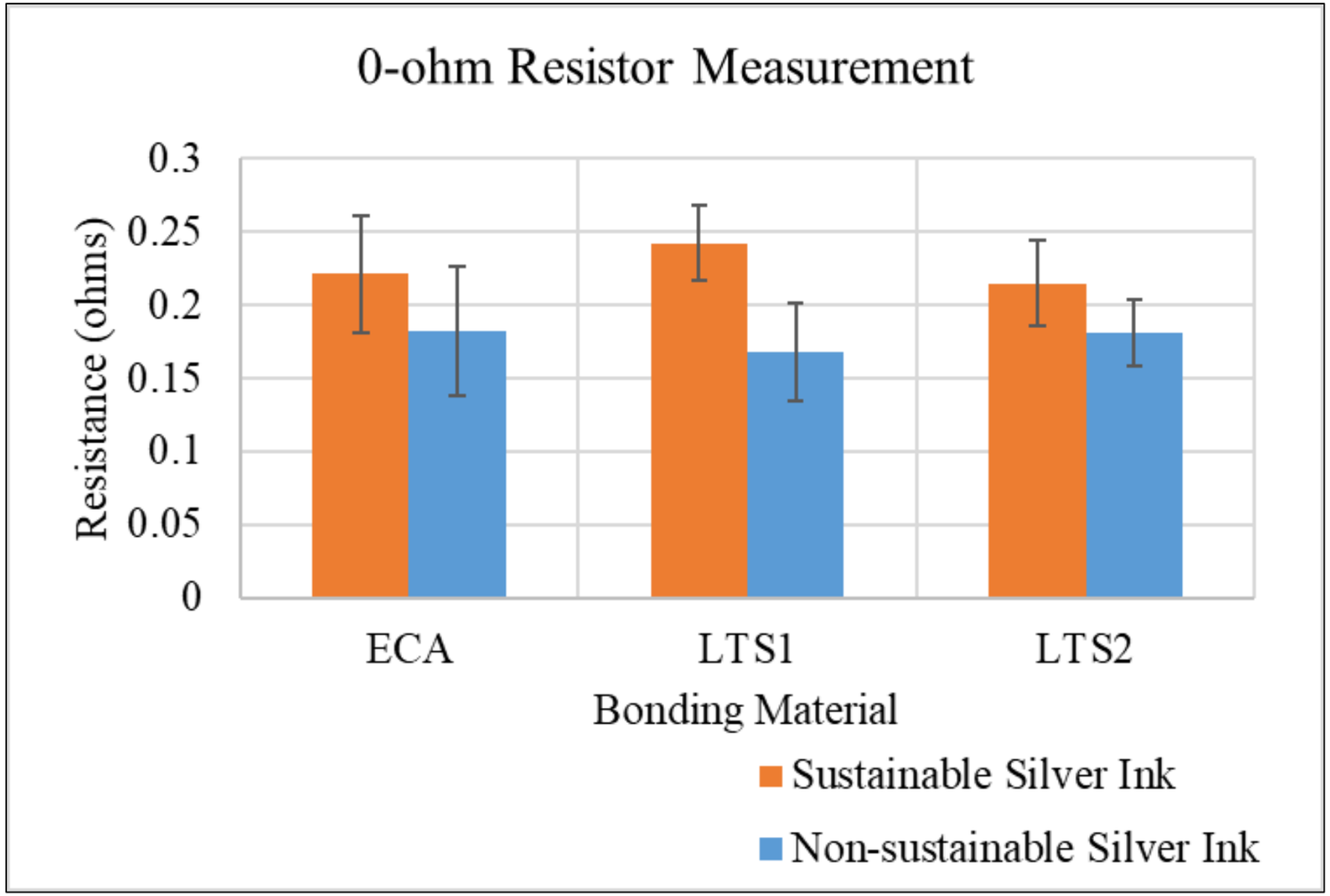




All measurements recorded at 1 kHz frequency for Capacitors and Inductors

Ink-A, DW

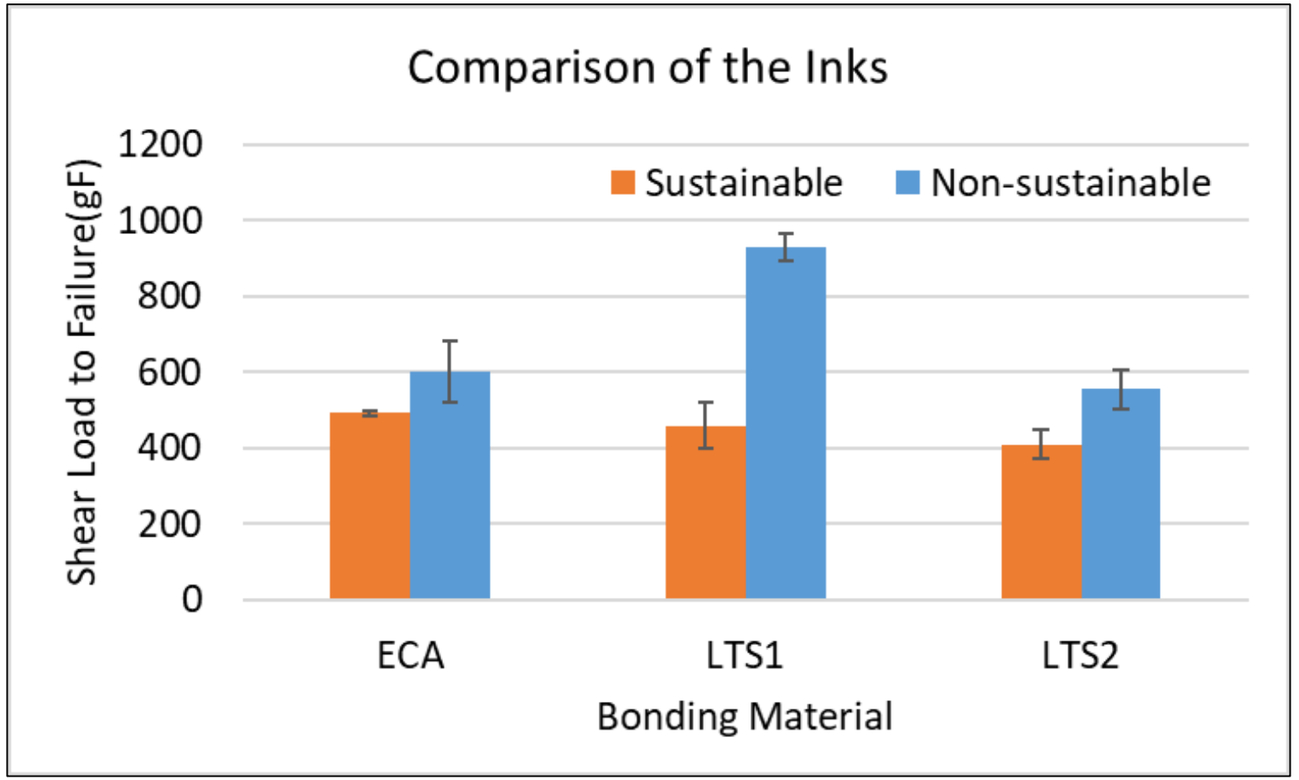
Sustainable vs Non-Sustainable Inks



Ink-A, DW

Mechanical Performance Comparison

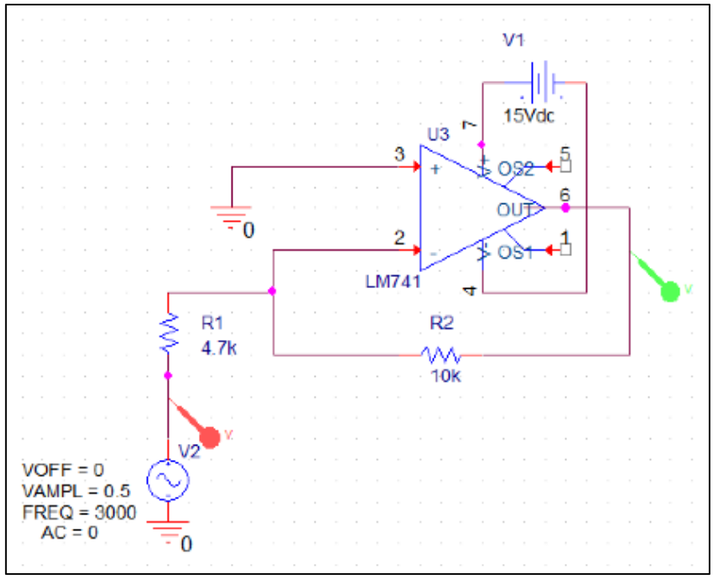
For the shear test,
Shear height = 20% of the component height from the surface
Shear tip size =0.60mm
Test speed = 12.7um/s



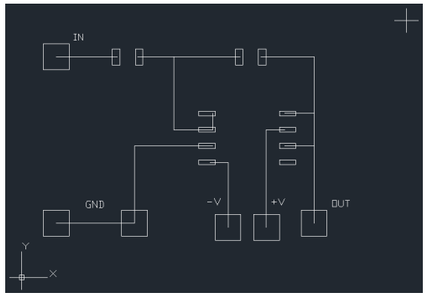
- ECA has the maximum shear strength, followed by LTS1 and LTS2 with sustainable silver.
- When compared to non-sustainable ink, sustainable inks have a similar tendency in terms of strength rating. However, they are lower than non-sustainable silver ink.
- The primary explanation for the observed test findings is that the metallization thickness of sustainable ink is roughly 7-8 microns as opposed to 20-30 microns for non-sustainable silver inks.

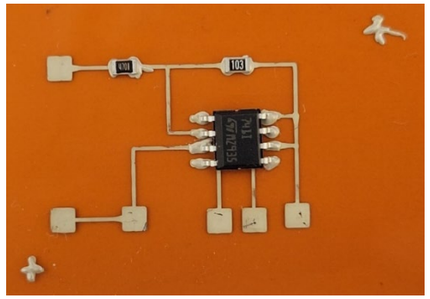
Ink-A, DW

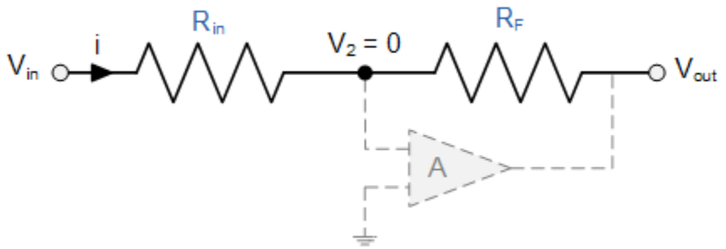
Test Vehicle 2 – Functional Circuit



Inverting Amplifier





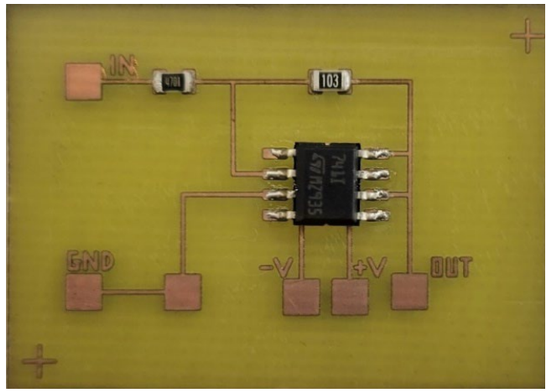


- The circuit was designed with a certain gain in consideration. Rf = 10kOhms and Rin = 4.7kOhms were utilized as resistors in the circuit shown in Figure. The gain calculation for it is as follows:

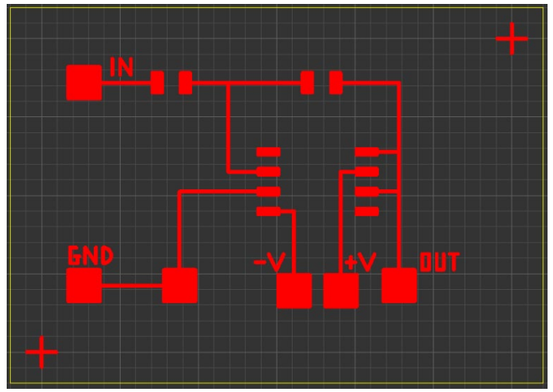
$$\text{Gain} = -\frac{Rf}{Rin}$$

- As a result, the gain of the circuit is 2.13 for the components utilized in it.

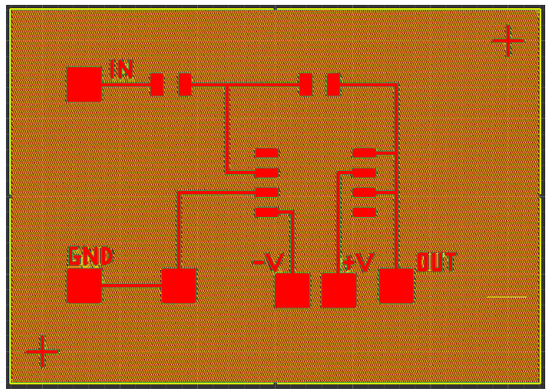
Test Vehicle 2 – Laser Trimmed FR4

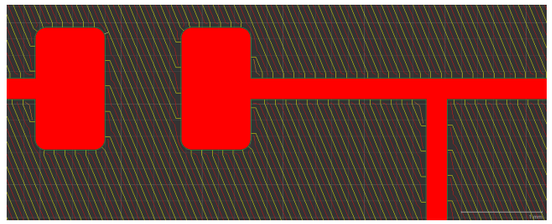


Laser Patterned with 1 oz. Cu-clad FR4 Op-Amp circuit



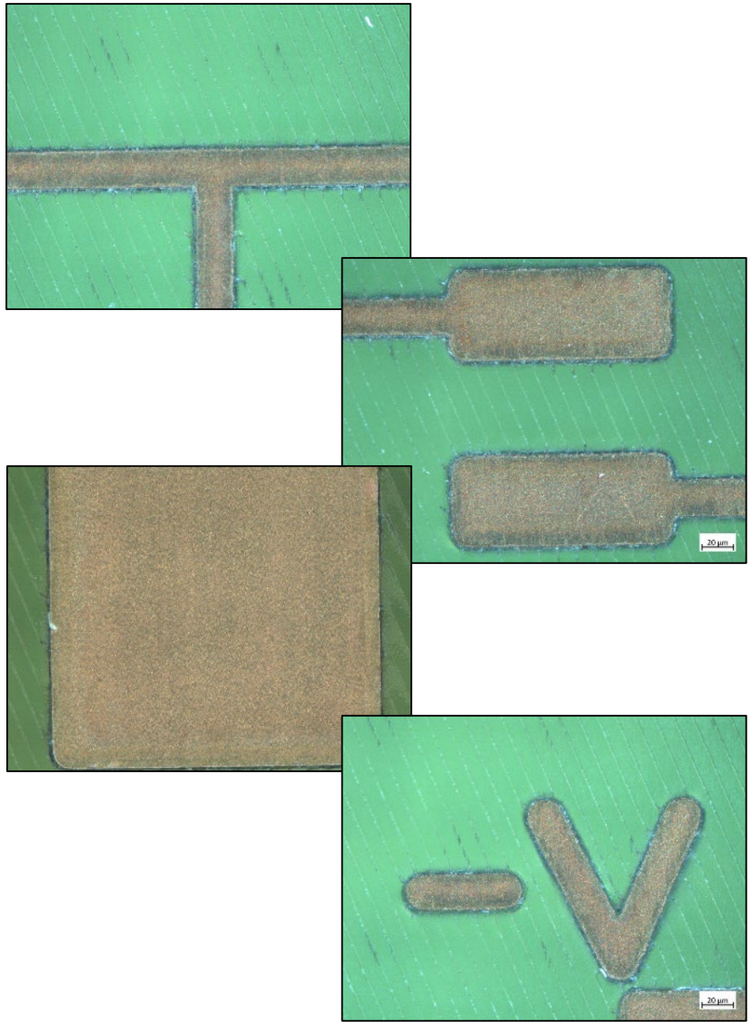
Laser Imaging pattern





Hatch and cut lines marked in yellow and heat lines marked in red

Scan Field image for the laser patterning after the tool setup

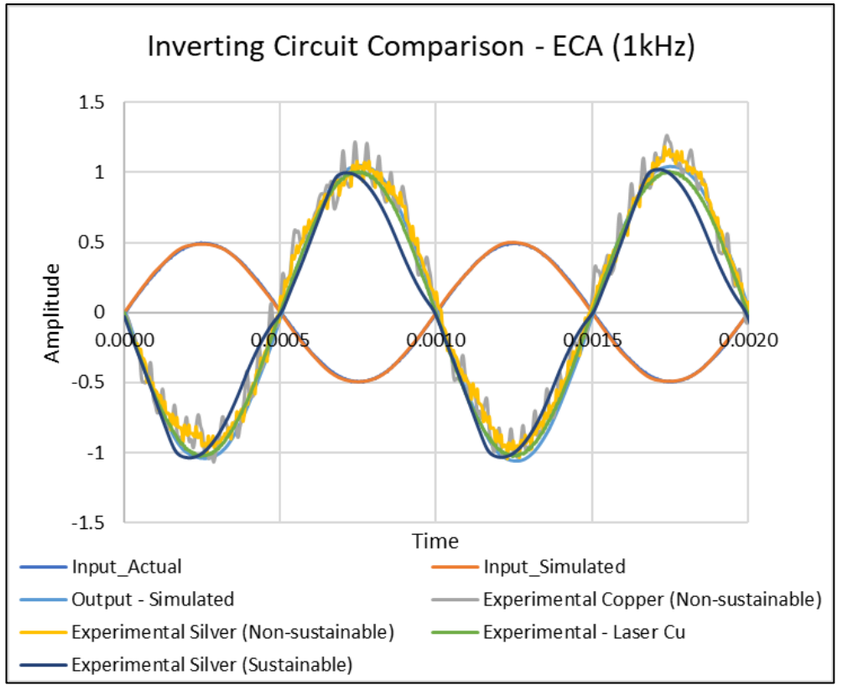


Optical Images

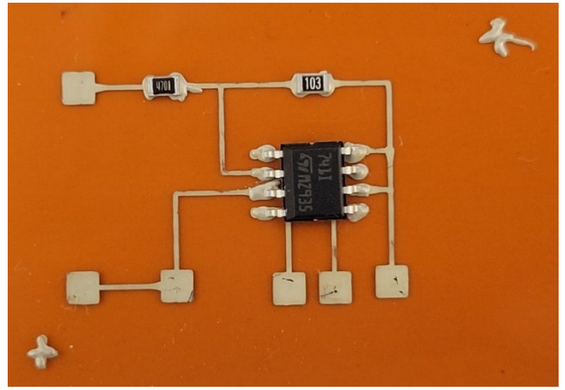
Ink-A, DW

Inverting Amplifier Circuit

ECA



	Laser	S-Ag	NS-Ag	NS-Cu
% Diff	±3.48	±2.59	±1.50	±14.45



BoM for the Inverting-Amplifier Circuit

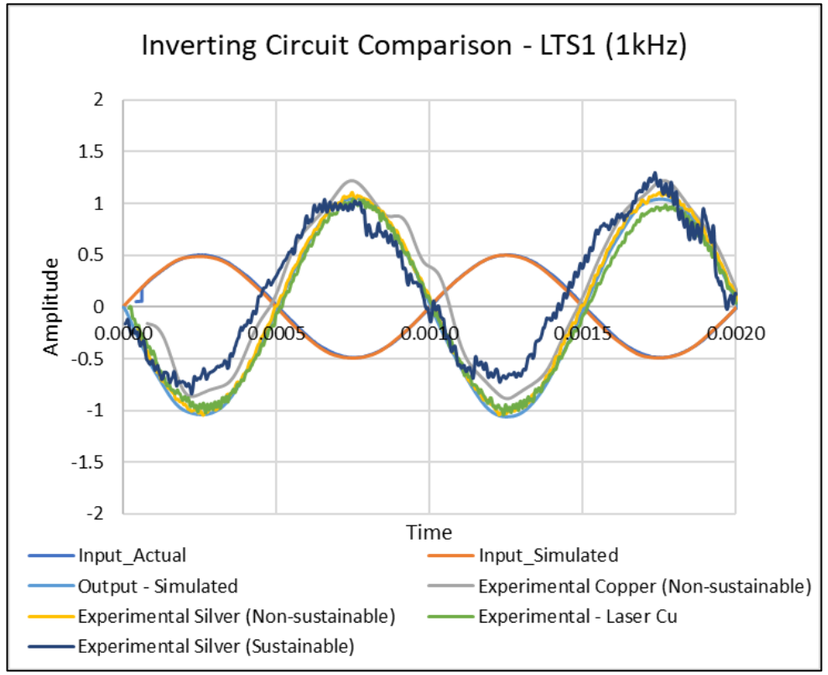
Components	Code	Rated value	Dimension (L X W X H)
Resistor	0805(2012 Metric)	10kOhms	2.00mm x 1.25mm x 0.50mm
Resistor	0805(2012 Metric)	4.7kOhms	2.00mm x 1.25mm x 0.65
IC 741	UA741ID	10V ~ 44V, ±5V ~ 22V	2.80mm x 2.50mm

$$\% \text{ Difference} = \frac{\text{Actual Gain} - \text{Designed Gain}}{\text{Designed Gain}} \text{ x } 100$$

Ink-A, DW

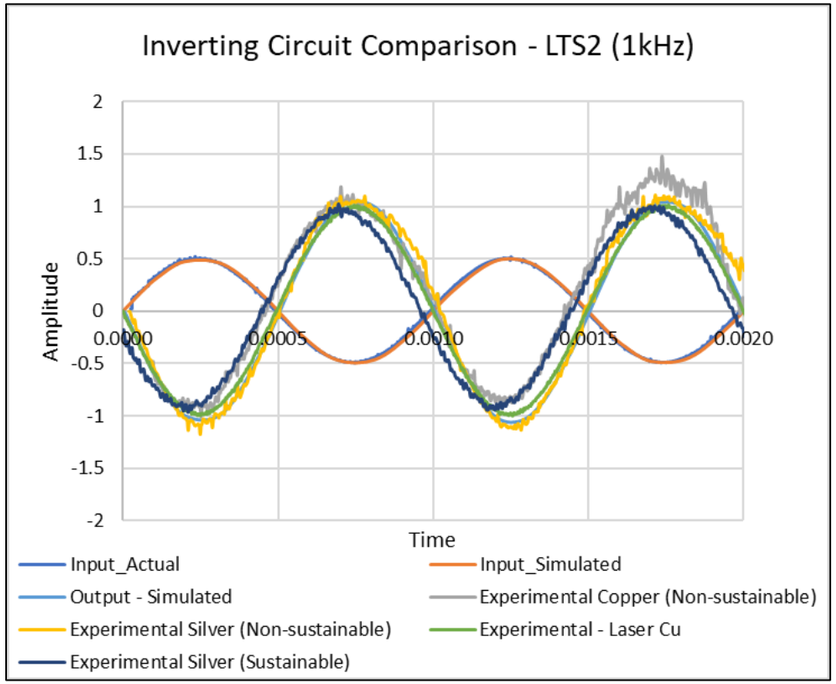
Test Vehicle 2 – With LTS2

LTS1



	Laser	S-Ag	NS-Ag	NS-Cu
% Diff	±2.88	±3.36	±2.95	±13.44

LTS2



	Laser	S-Ag	NS-Ag	NS-Cu
% Diff	±3.92	±7.96	±5.72	±6.81

$$\% \text{ Difference} = \frac{\text{Actual Gain} - \text{Designed Gain}}{\text{Designed Gain}} \text{ x } 100$$

Ink-A, DW

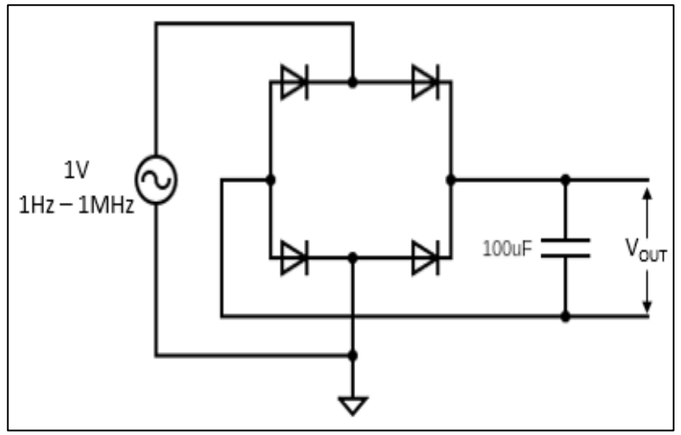
Aerosol Jet Sustainability Study

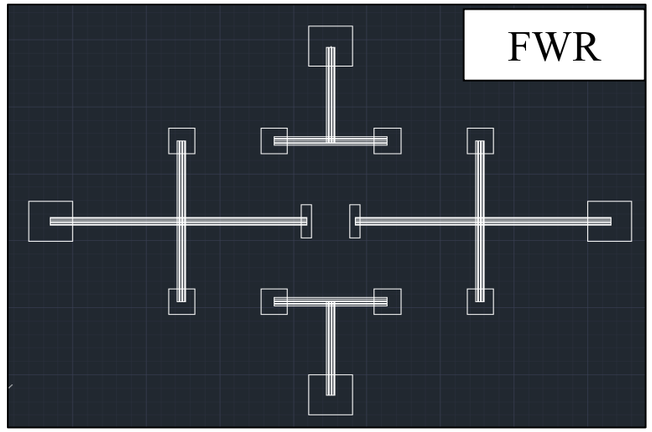
Aerosol Jet	Sustainable Ink A1	Non-sustainable Ink A2
Ag concentration	60 wt%	55 wt%
Viscosity	150 cP	30 - 45 cP
Particle Size	400 – 700 nm	10 – 20 nm
Bulk Resistivity	14 μΩ-cm	3 μΩ-cm

Aerosol Jet Printing Parameters		
Parameters	Sustainable Ink A1	Non-sustainable Ink A2
Atomizer used	Pneumatic (PA)	
PA MFC	1200 sccm	700 sccm
Exhaust MFC	50 – 100 sccm	30 – 50 sccm
Carrier gas MFC	70 sccm	90 sccm
Stage Speed	4 mm/s	5 mm/s
Platen Temperature	30 °C	50 °C
Ink Temperature	Ambient	Ambient
Nozzle Diameter	300 μm	300 μm
Standoff Height	2 mm	
No. of Passes	4 (lines), 1 (pads)	
Cure Conditions	250 °C for 20 min.	250 °C for 10 min.

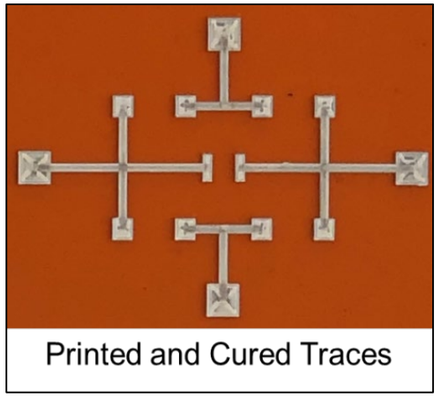
Full Wave Rectifier

- Full wave rectifier converts the AC input signal to a DC output signal with a smoothing capacitor used to smooth the output ripples

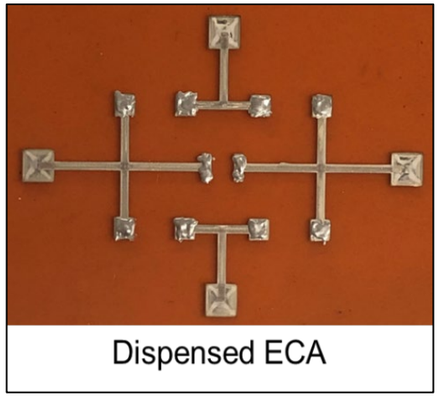




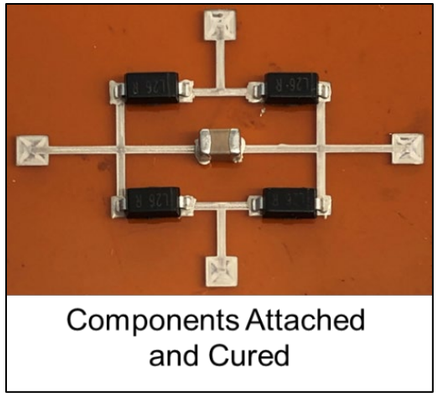
FWR Circuit Schematic



Printed and Cured Traces



Dispensed ECA



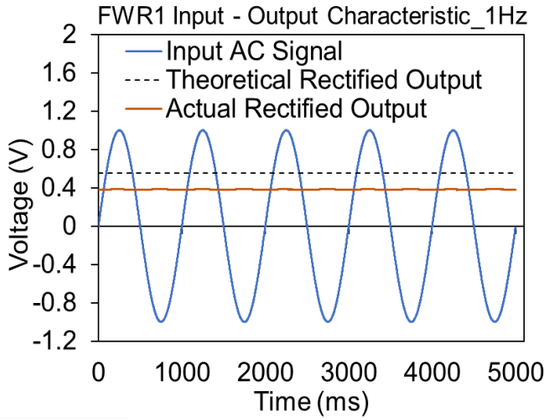
Components Attached and Cured

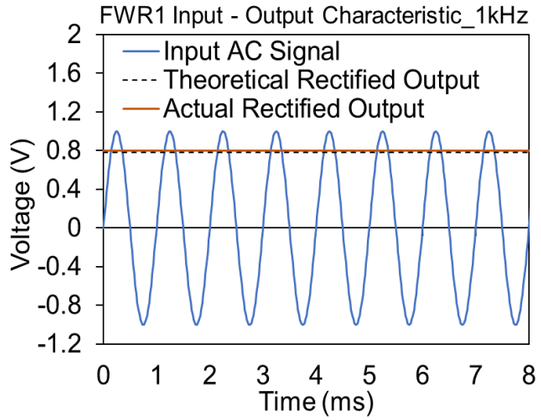
Fabrication Process

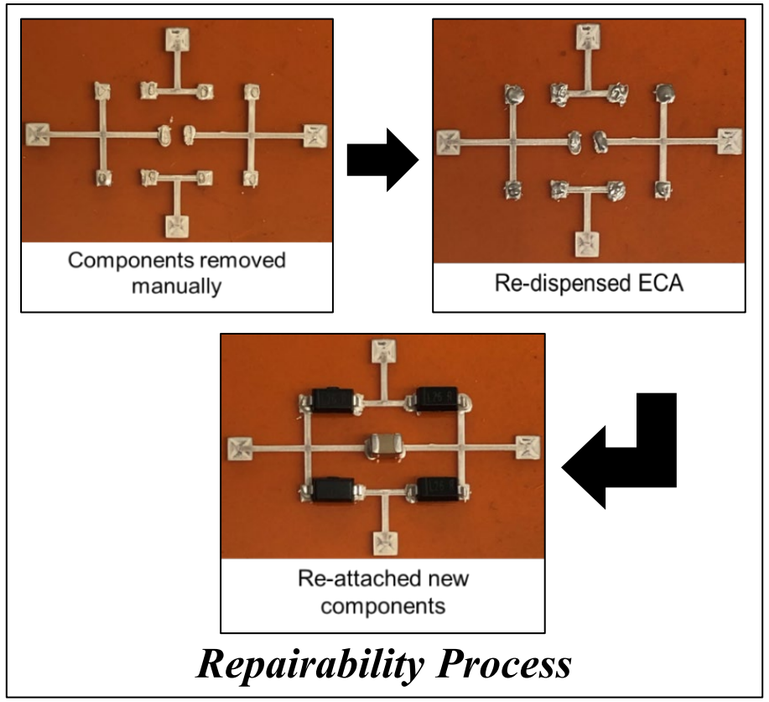
Ink-B, AJ

FWR: Performance and Repairability

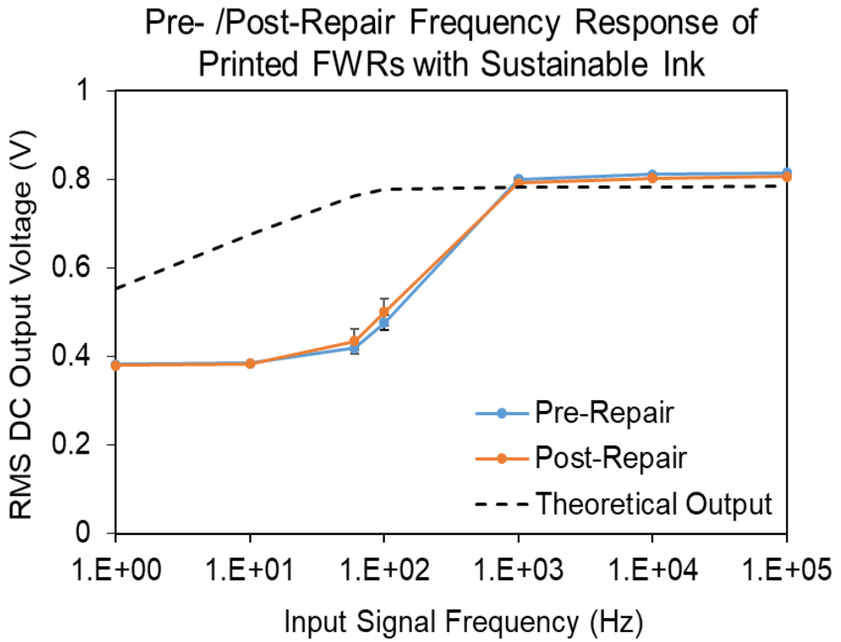
- As the input signal frequency increases, the realized output of the rectifier matches the theoretical one







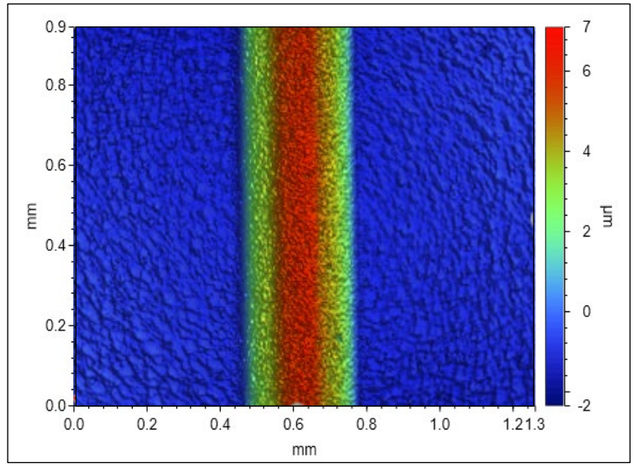
Repairability Process

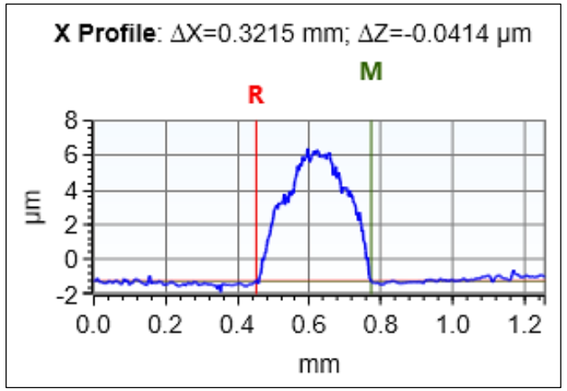


Ink-B, AJ

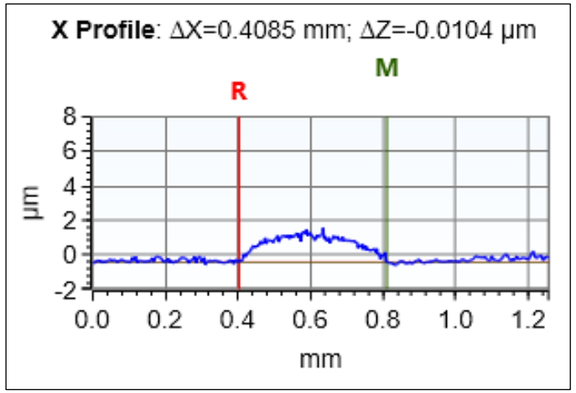
Aerosol Jet: Ink Characterization

- Even though the non-sustainable ink has half the resistivity of the sustainable ink (owing to smaller particle size, the sustainable ink trace has four times the C.S.A. (with same print passes), owing to it having half the resistance of the non-sustainable ink

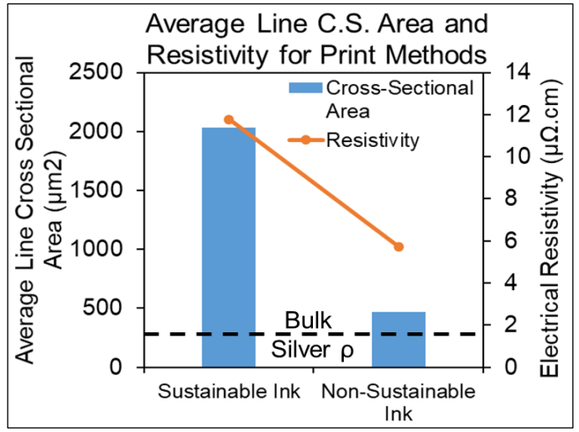


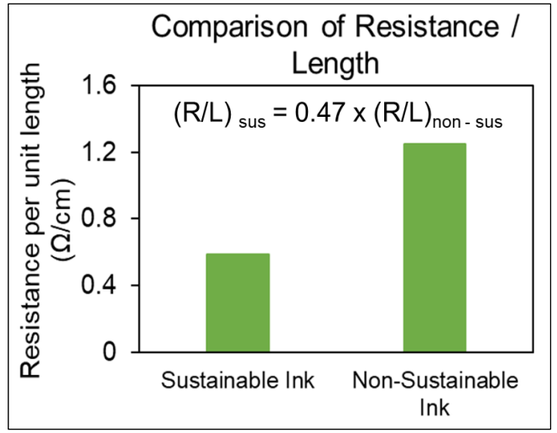


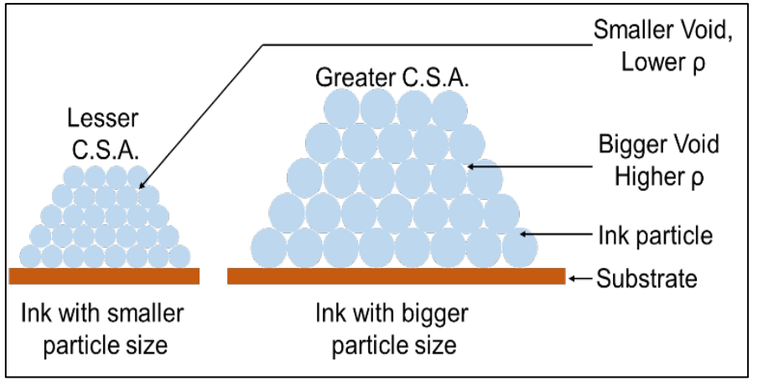
Non-sustainable Ink



Sustainable Ink



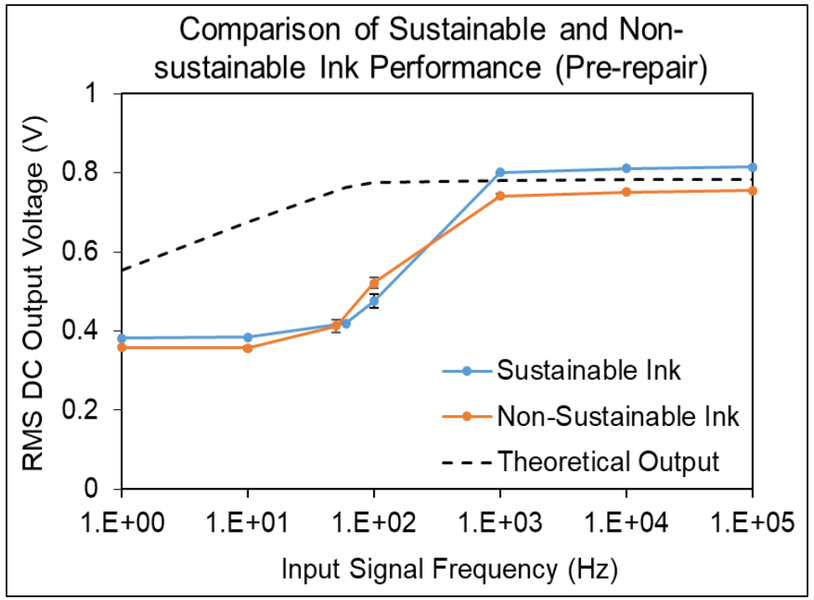


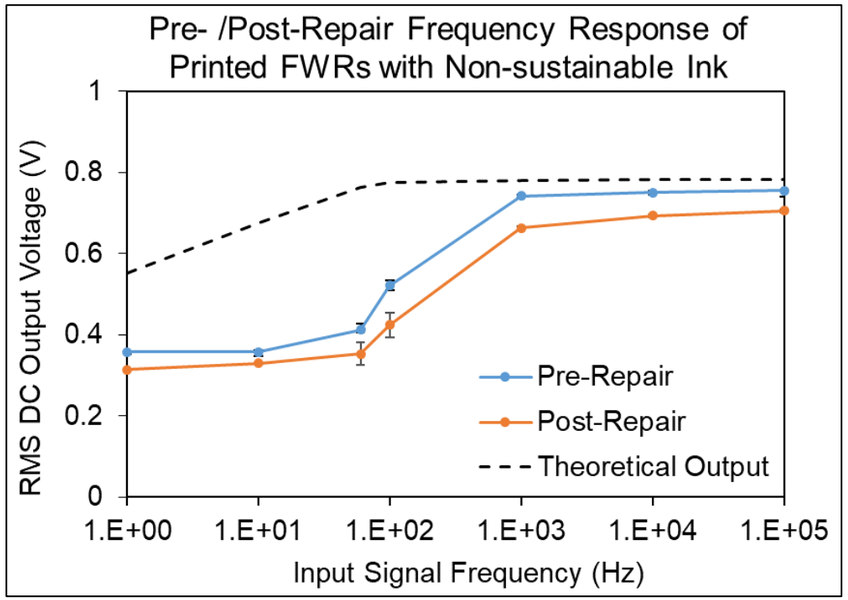


Ink-B, AJ

Sustainable v/s Non-sustainable Ink

- Owing to higher R/L, the non-sustainable ink frequency response is slightly lower than that of the sustainable ink
- Also, post-repair, the frequency response of the FWR printed by the non-sustainable ink is marginally lower than pre-repair performance

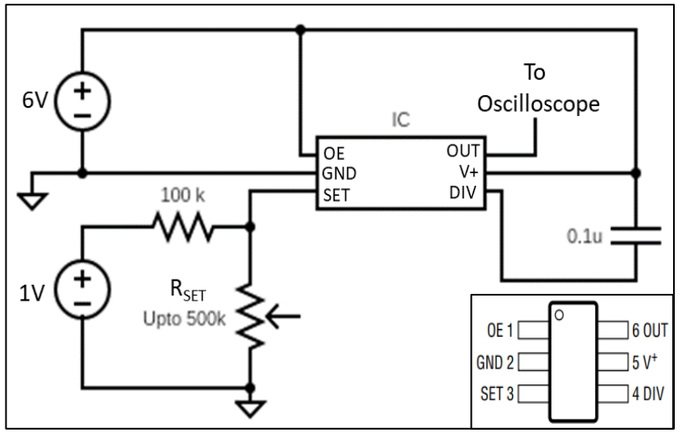


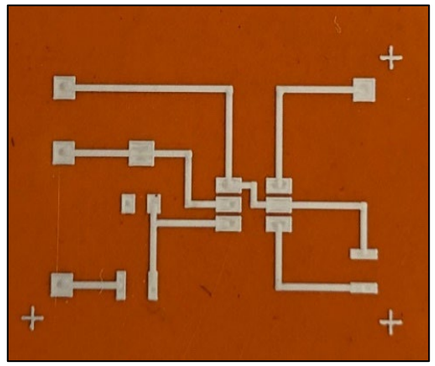


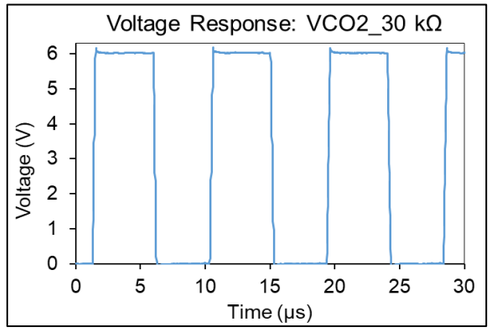
Ink-B, AJ

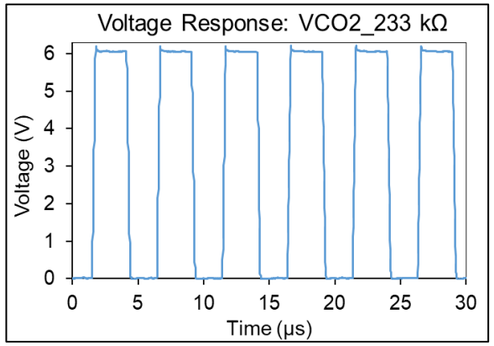
Voltage Controlled Oscillator

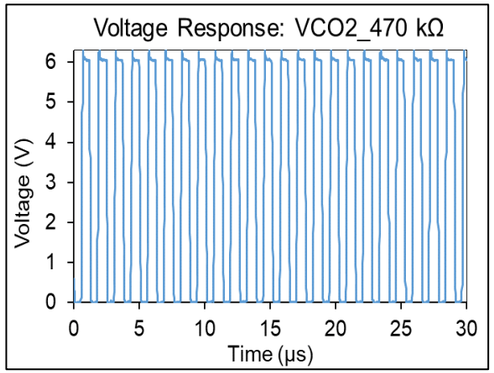
- As the R_{SET} value is increased with the potentiometer, the frequency of the AC signal generated using the VCO increases

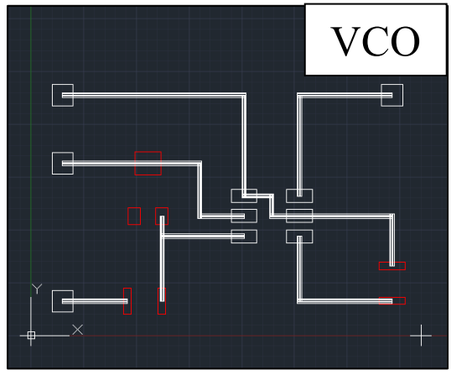


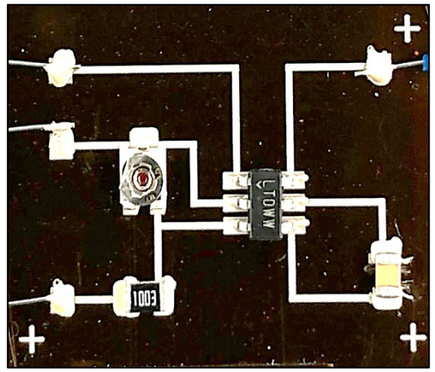








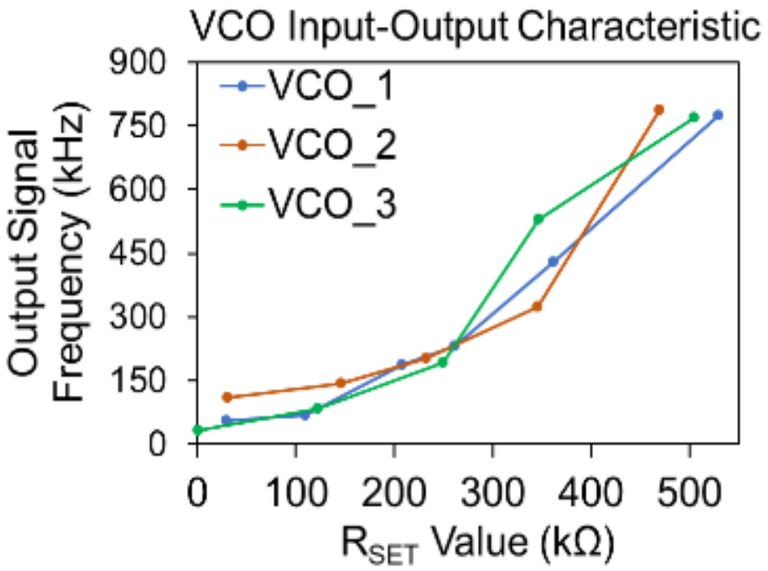


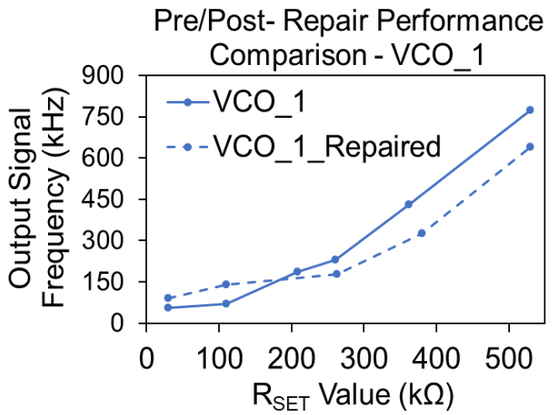


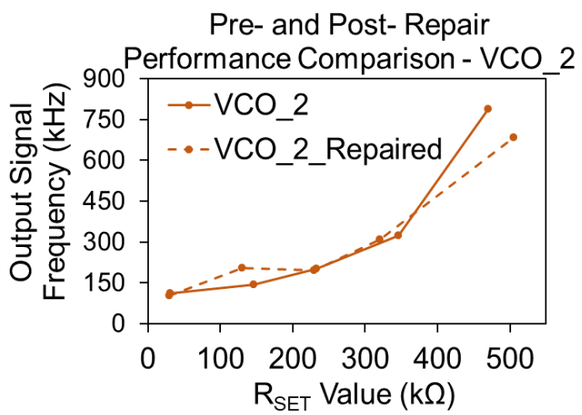
Ink-B, AJ

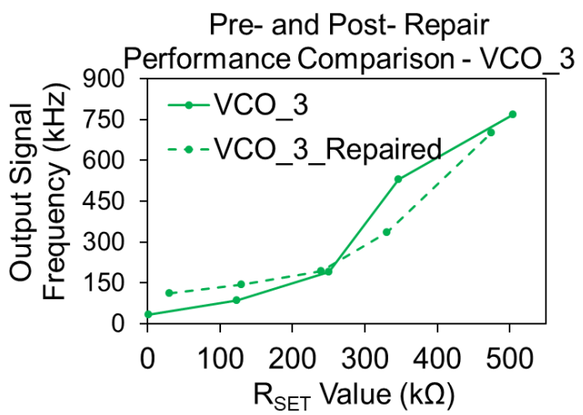
VCO: Performance & Repairability

- The performance of all 3 VCO samples is nearly the same, demonstrating the print consistency of the sustainable ink
- A repairability study was also conducted on the VCOs, wherein, the pre- and post-repair performance was found to be similar



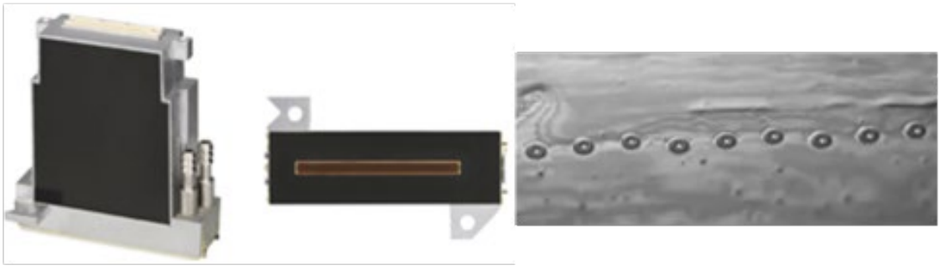






Ink-B, AJ

Inkjet: Printer and Material Specs



Printer Specifications	
Substrate table, mm	227 x 327
Print speed, mm/s	Up to 500
CAD formats	Bitmap, PDF
Viscosity, cP	2-20
Other features	➢ Vacuum table ➢ Material reservoir ➢ Base heating up to 90°C

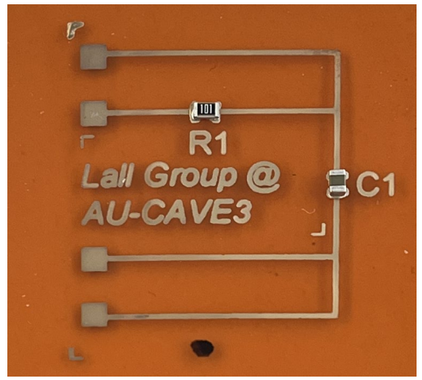
Printhead Specifications	
Name	Konica Minolta KM512
Technology	Piezo DOD Shared wall 3 cycle
Resolution, dpi	360 dpi
Number of nozzles	256 x 2 lines = 512 nozzles
Droplet volume, pL	42
Printing width, mm	36.1
Max frequency, kHz	7.6

Ink Characteristics	
Ink	Ink-C
Nature	Silver Nanoparticle Ink
Color	Silver
Viscosity	8 cP to 12 cP
Solubility	Water
Sintering Temperature	150°C for 10 mins.

Properties of ECA	
Material	Silver
Viscosity, cP	30,000
Curing Conditions	150 (°C) for 30 mins
Color	Silver
Physical State	Paste

Ink-C, IJ

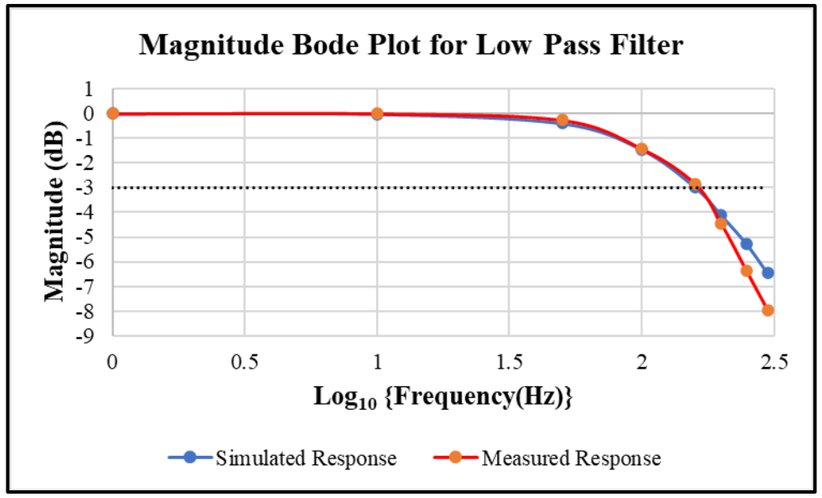
Low Pass Filter – Frequency Response

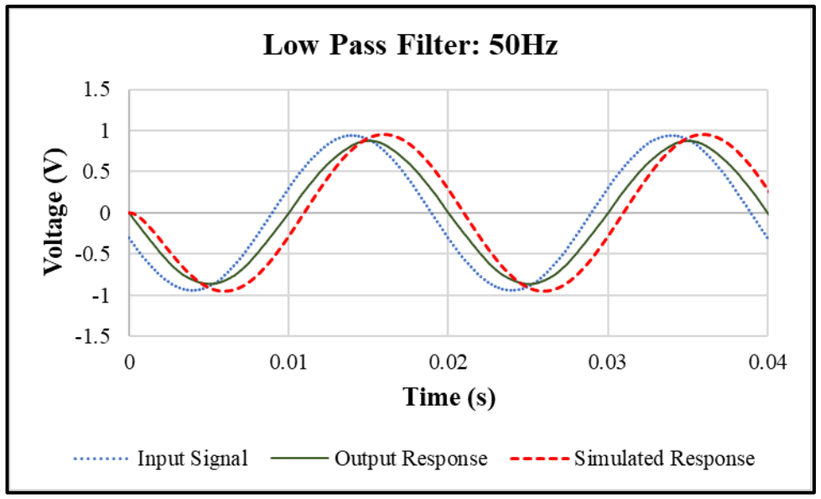


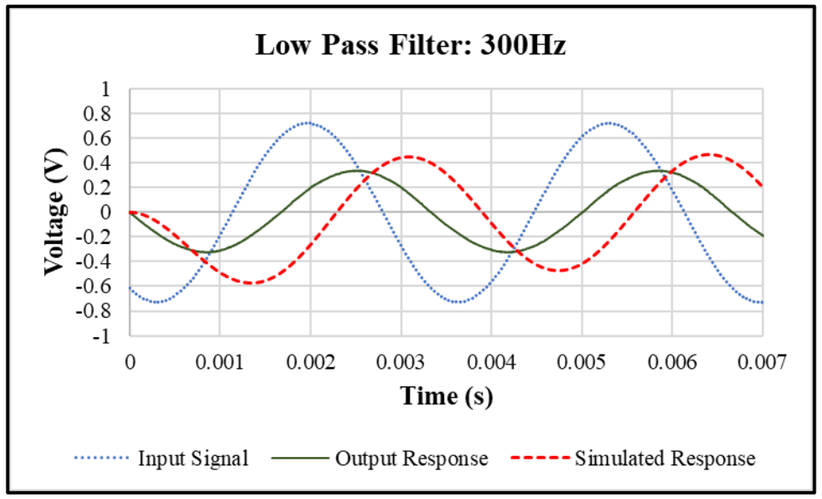
$$R = 100\Omega$$

$$C = 10uF$$

$$f_c = \frac{1}{(2\pi RC)} = 160Hz$$

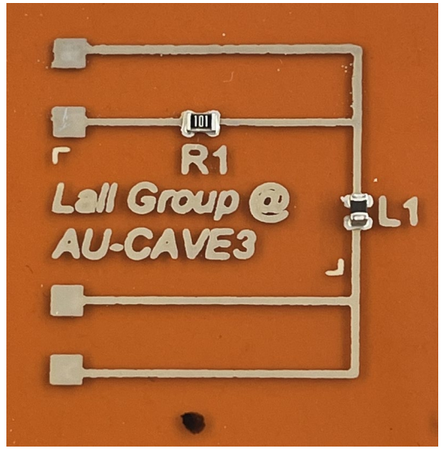






Ink-C, IJ

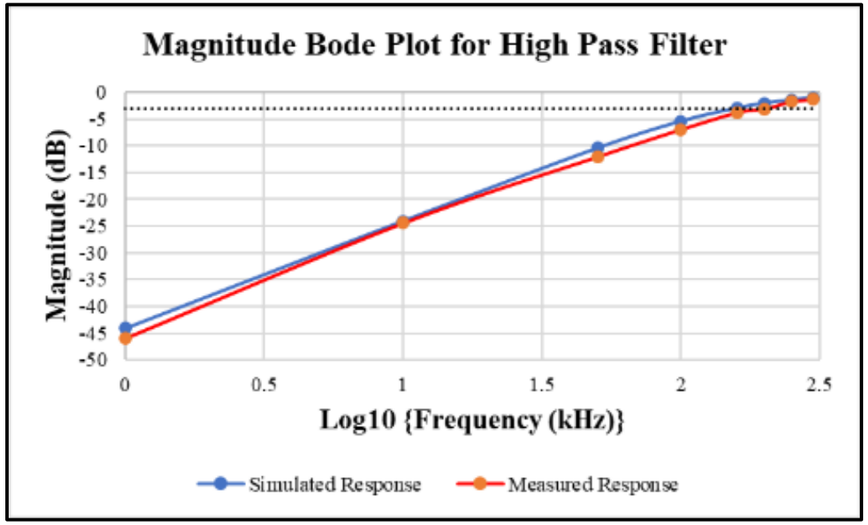
High Pass Filter – Frequency Response

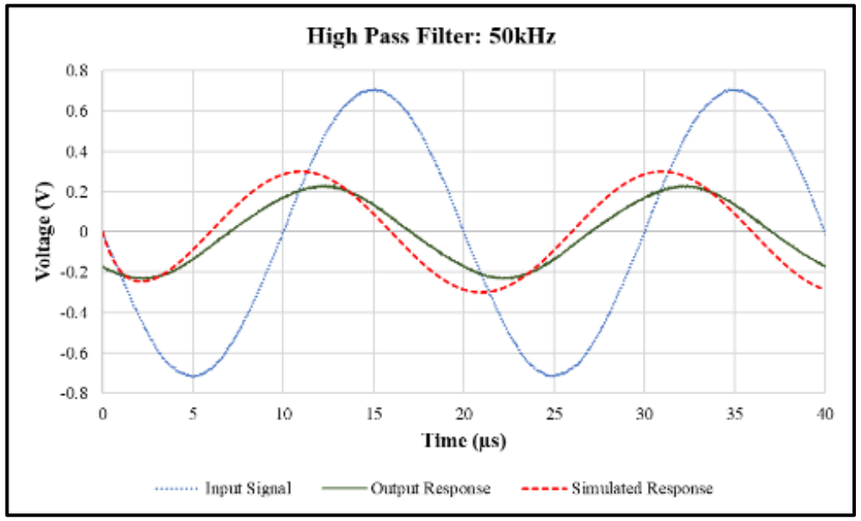


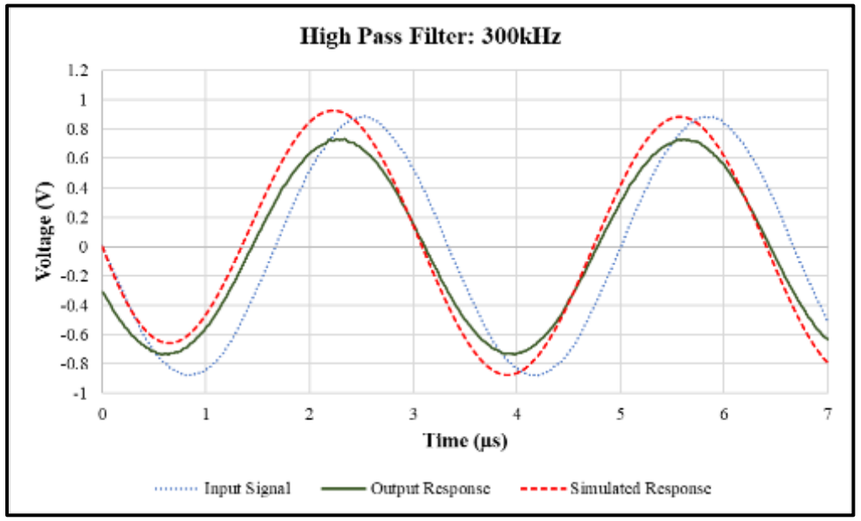
$$R = 100\Omega$$

$$L = 100uH$$

$$f_c = \frac{R}{(2\pi L)} = 160kHz$$

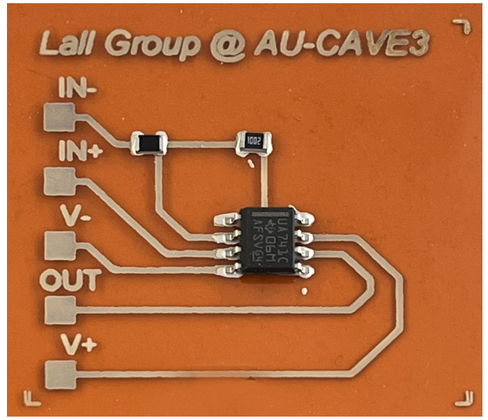






Ink-C, IJ

Non-Inverting Amplifier: Frequency Response

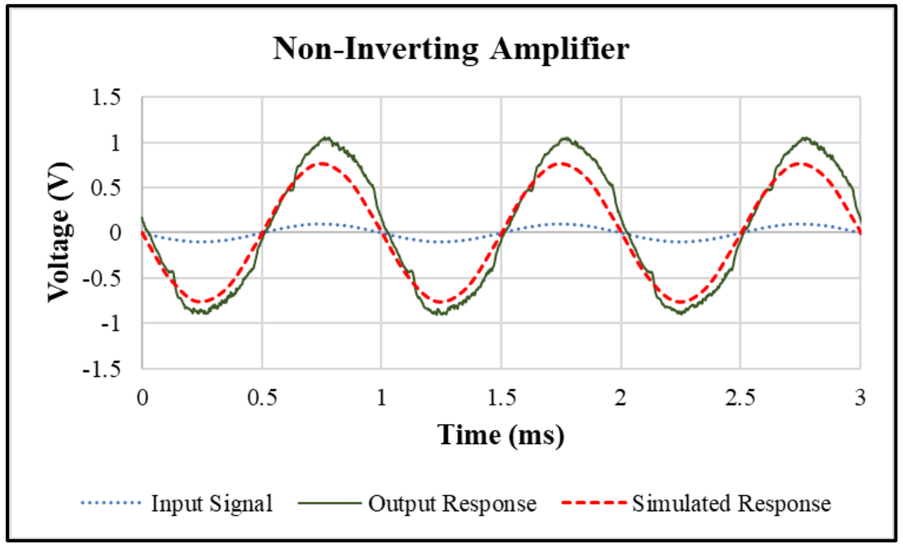


$$R_1 = 1.5k\Omega;\ R_2 = 10k\Omega$$

$$V_{in} = \frac{R_1}{R_1 + R_2} \times V_{out}$$

$$\textbf{Gain} = \frac{V_{out}}{V_{in}}$$

$$= 1 + \frac{10k}{1.5k} = 7.6$$



Filter/op-amp	Ink A
Low Pass Filter (Hz)	156.64 (2.1% Error)
High Pass Filter (kHz)	173.07 (8.2% Error)
Op-amp Gain	7.3 (3.9% Error)

Summary and Conclusions

- In this study, the use of sustainable water-based inks has been assessed for the fabrication of additively printed circuits on three platforms, including – direct write, aerosol-jet and ink-jet.
- Surface mount devices have been attached using a number of materials, including electrically conductive adhesives and low temperatures solders – SnBiAg and SnIn.
- Electrical performance indicates that component attachment on sustainable inks allowed for component operation within the rated resistance, inductance, and capacitance values.
- Mechanical performance for ECA has the highest mechanical strength, followed by LTS1 and LTS2.
- A number of circuits have been studied for volatile and non-volatile inks, including - inverting amplifiers, full-wave rectifiers, voltage-controlled oscillators, low-pass filters, and high-pass filters
- Performance has been compared to non-sustainable inks, and theoretical targets with computation of deviations in both cases.
- Repairability of the circuits has been explored to show the ability to achieve comparable performance pre-and-post repair.