NESC Sensors & Instrumentation Webinar - July 20, 2021

Open Circuit Resonant (SansEC) Sensor Technology Applications

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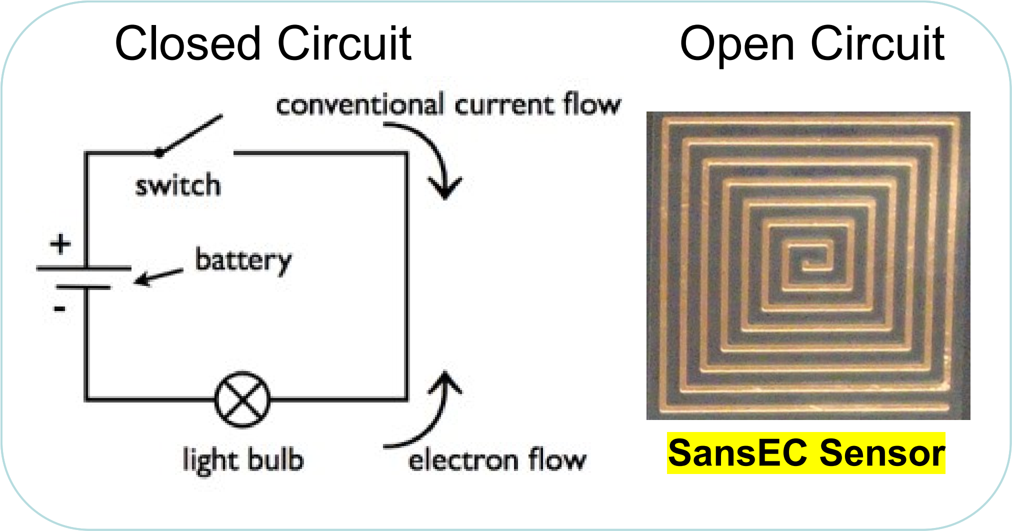
Outline

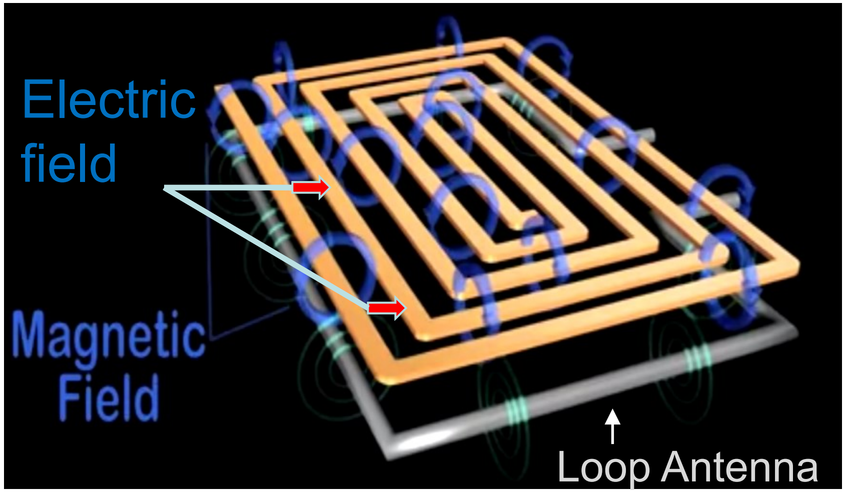
- **Introduction to SansEC Sensors**
  - Description & Theory
  - Computational Electromagnetic Modeling
  - Sensor Fabrication
  - Detectable Phenomena
- **Applications**
  - Composite Aircraft Smart Skin for Lightning Environments
  - Wearables
- **Detectable Phenomena**
- **Conclusions**
- **Reference Publications**

Introduction to SansEC Sensors

SansEC ⬄ Sans Electric Connection

- **Wireless** – No physical electrical connections
- **Passive** – No battery required;
- **Non-Contact** – EM Fields permeate out from sensor surface
- **Electromagnetic Resonator** – naturally oscillates with greater amplitude at some frequencies based on Inductance (L), Capacitance (C) & Resistance (R) of the total circuit





Introduction to SansEC Sensors

Components of the Measurement System

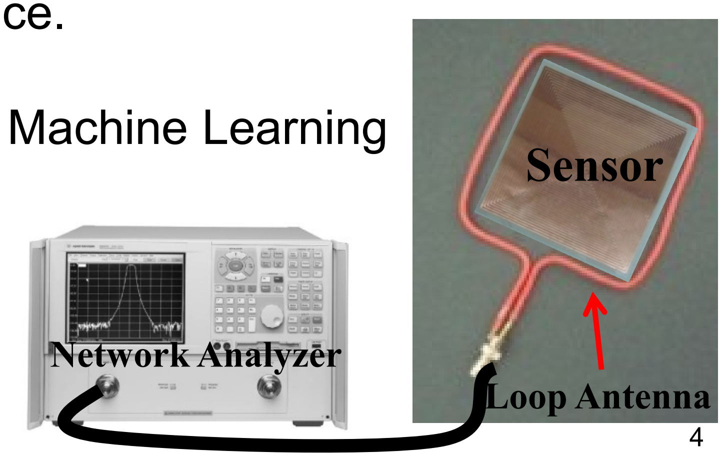
1. SansEC Sensor - Conductive coil designed to resonate at desired frequencies
   The trace length, trace width and gap width influence the resonate frequencies.

2. Interrogator RF Source -Typically a Network Analyzer is used, but excitation could come from any stable ambient RF source.

3. Interrogator Receiver - Typically a Network Analyzer is used to measure the reflection coefficient. This is the near field configuration. Data can be collected in the far field by using an electric field antenna connected to a loop antenna.

4. Loop Antenna – Induces magnetic excitation on sensor to generate a signal response
   Loop antenna is aligned parallel to sensor trace.

5. Signal Analysis – Deterministic Quantification using Machine Learning
   <u>Looks for relative change in resonant response to indicate change in device under test.</u>



Introduction to SansEC Sensors

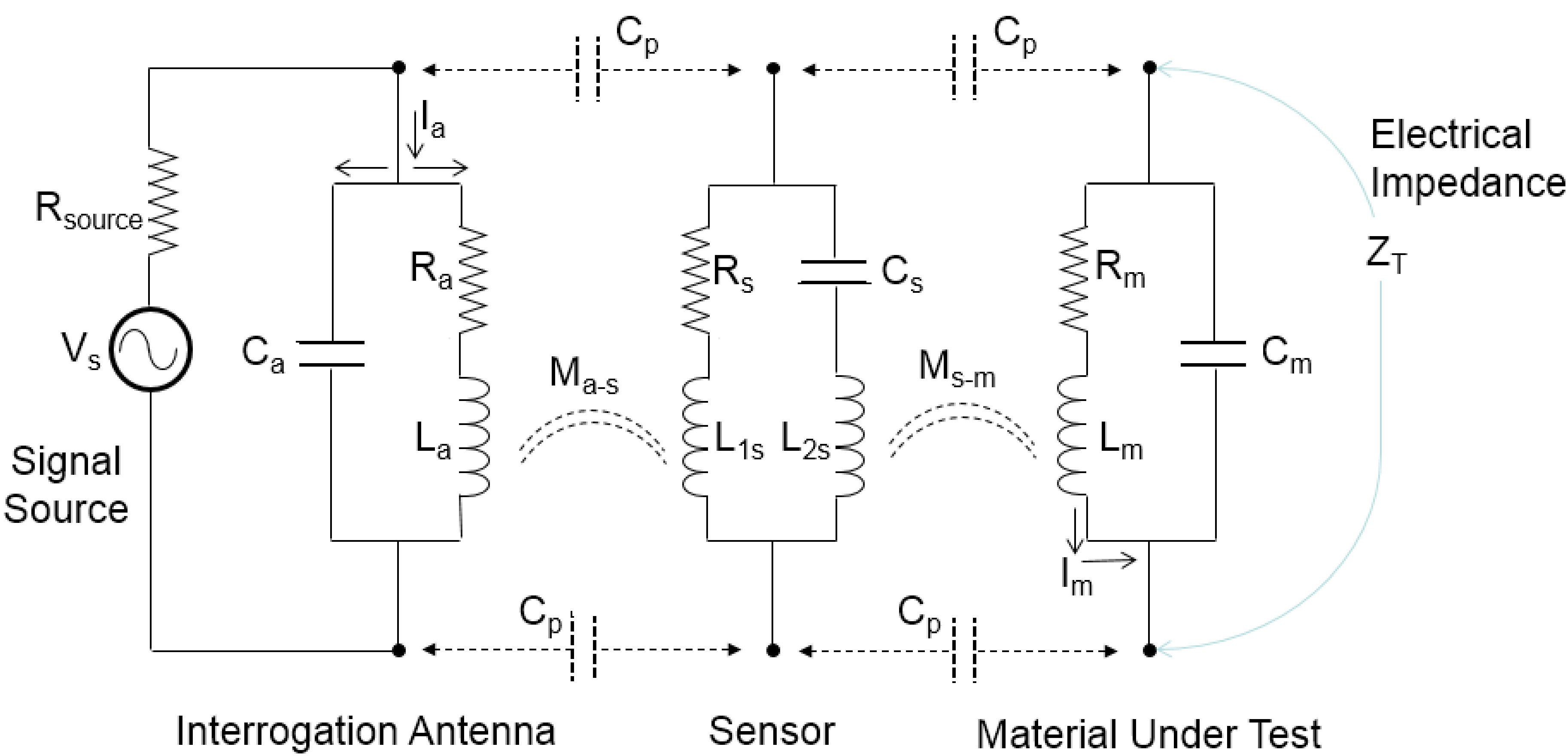
Signal Processing Data Features

For each Resonant Frequency, the following data features can be used in machine learning quantification from the reflection coefficient measurement.

- Frequency
- Amplitude
- Phase
- Q factor (3dB bandwidth)
- Electrical Impedance
- Derived Parameters (Inductance, Capacitance and Resistance)

SansEC Sensor Theory

Equivalent Circuit Model



Lumped components in Antenna circuit will change resonance

SansEC Sensor Theory

The SansEC sensor will have zero current at both ends of the resonant spiral. When excited by an oscillating electromagnetic field, the induced electromotive force (EMF) pushes the electrons carried by the conductor into the resonant state where the electrons move back and forth along the conductive trace.

Current Distribution

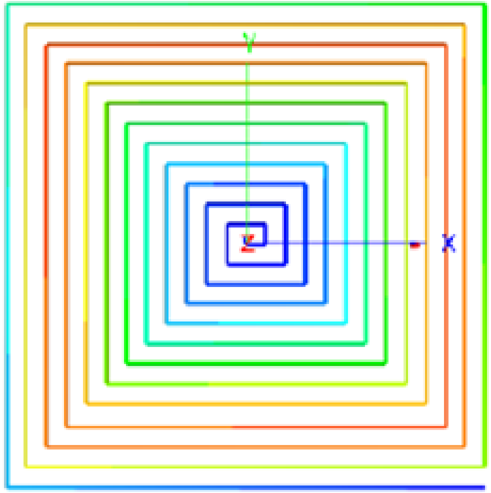
$$I = I_0 cos(\frac{\pi x}{l})e^{-i\omega t}$$

Charge Distribution

$$q = q_0 sin(\frac{\pi x}{l})e^{-i(\omega t+\frac{\pi}{2})}$$

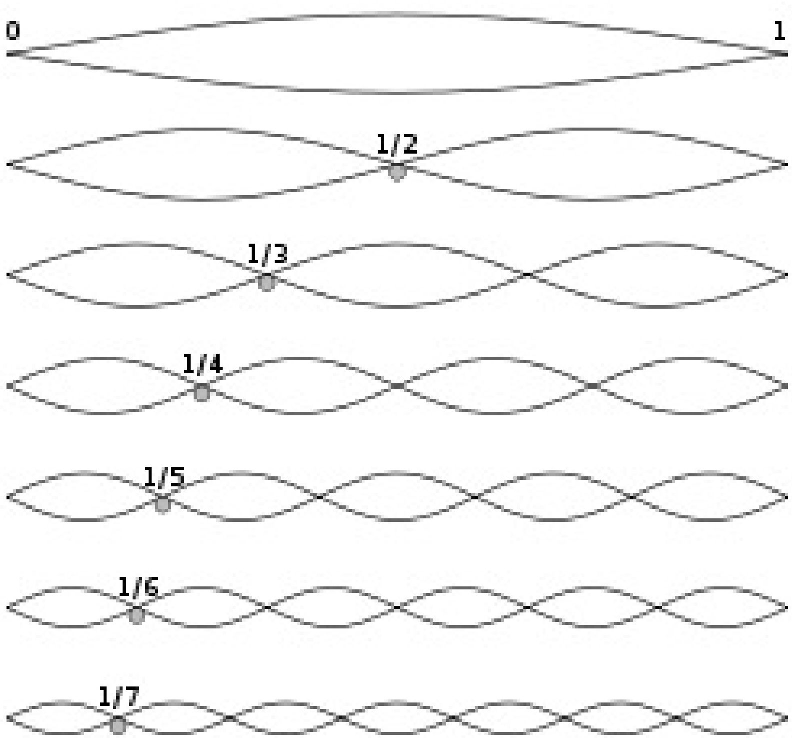
$$\omega = \frac{1}{\sqrt{LC}}$$

Current Distribution
(zero current at ends)

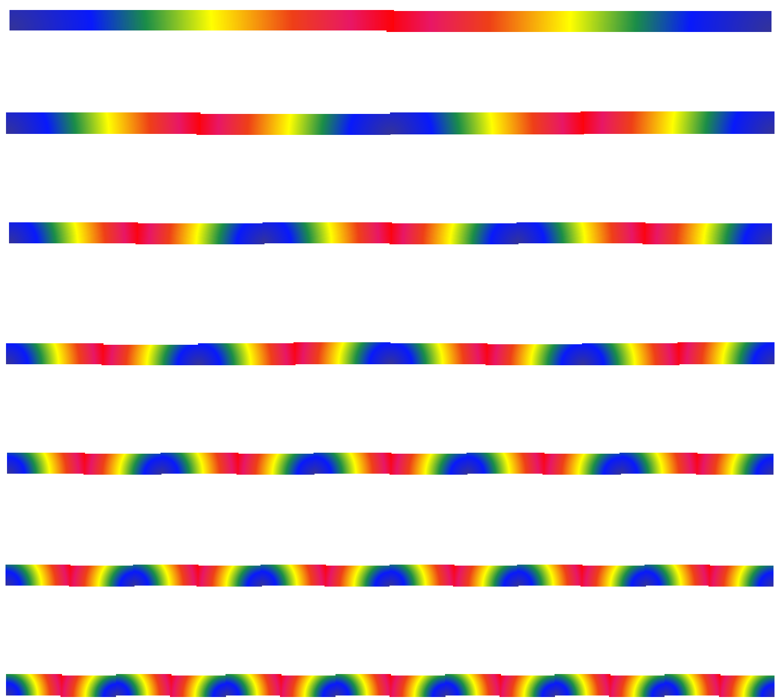


(blue: lowest currents to red: highest currents)

Resonant Modes



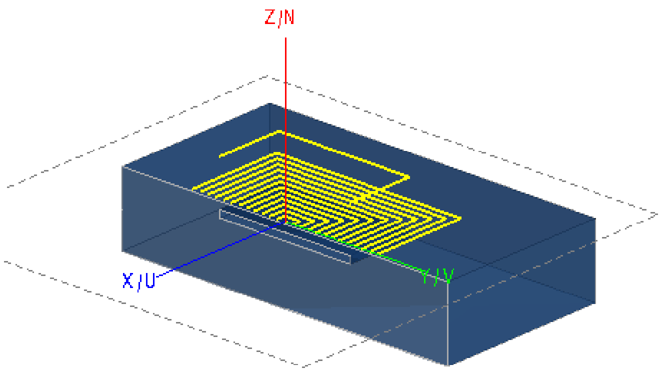
Current distribution along trace length



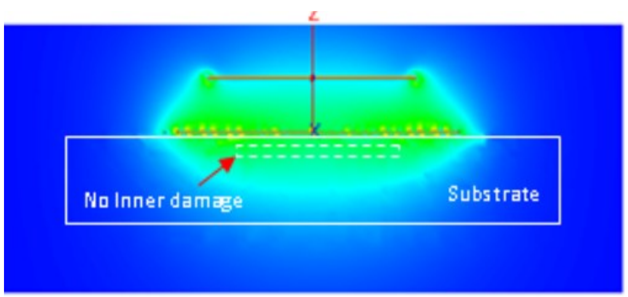
(blue: lowest currents to red: highest currents)

Computational Electromagnetic Modeling

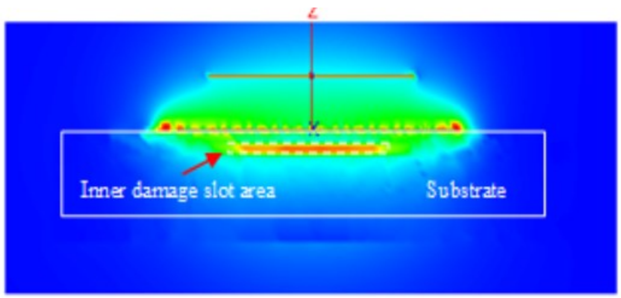
Response Characteristics from Delamination in Composite



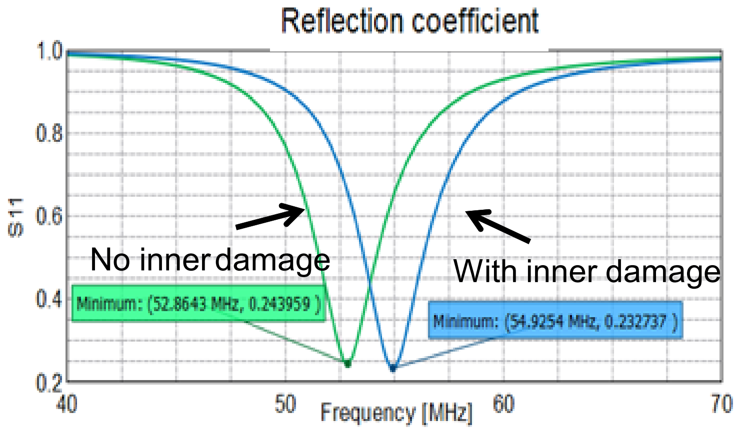
Fiberglass substrate model with inner damage



Electric field distribution No Damage (ε_r=3)



Electric field distribution With Damage (ε_r=1)

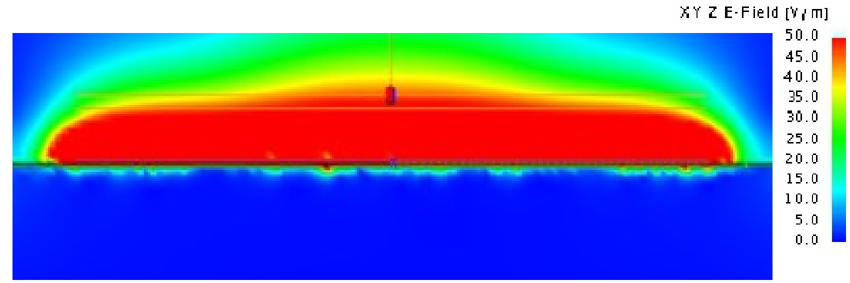


Computed SansEC resonant response

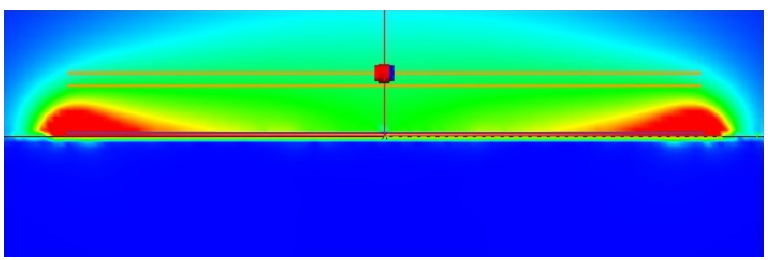
Computational Electromagnetic Modeling

Response Characteristics of CFRP Damage

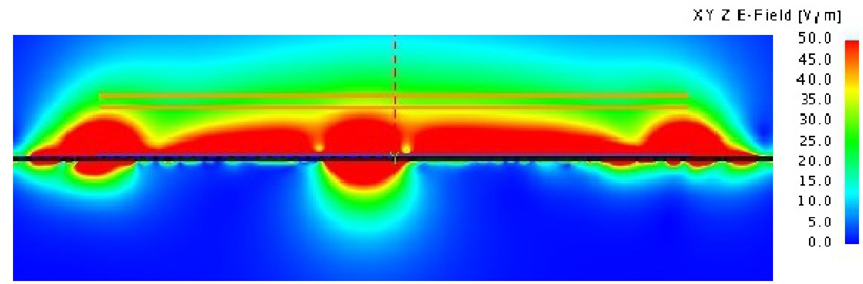
Electric Field Visualizations



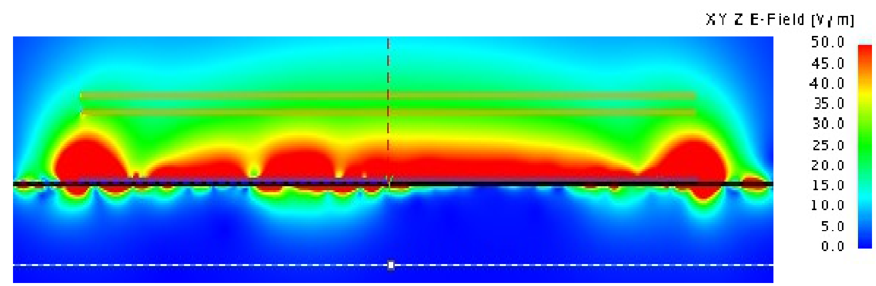
Delamination



No Damage

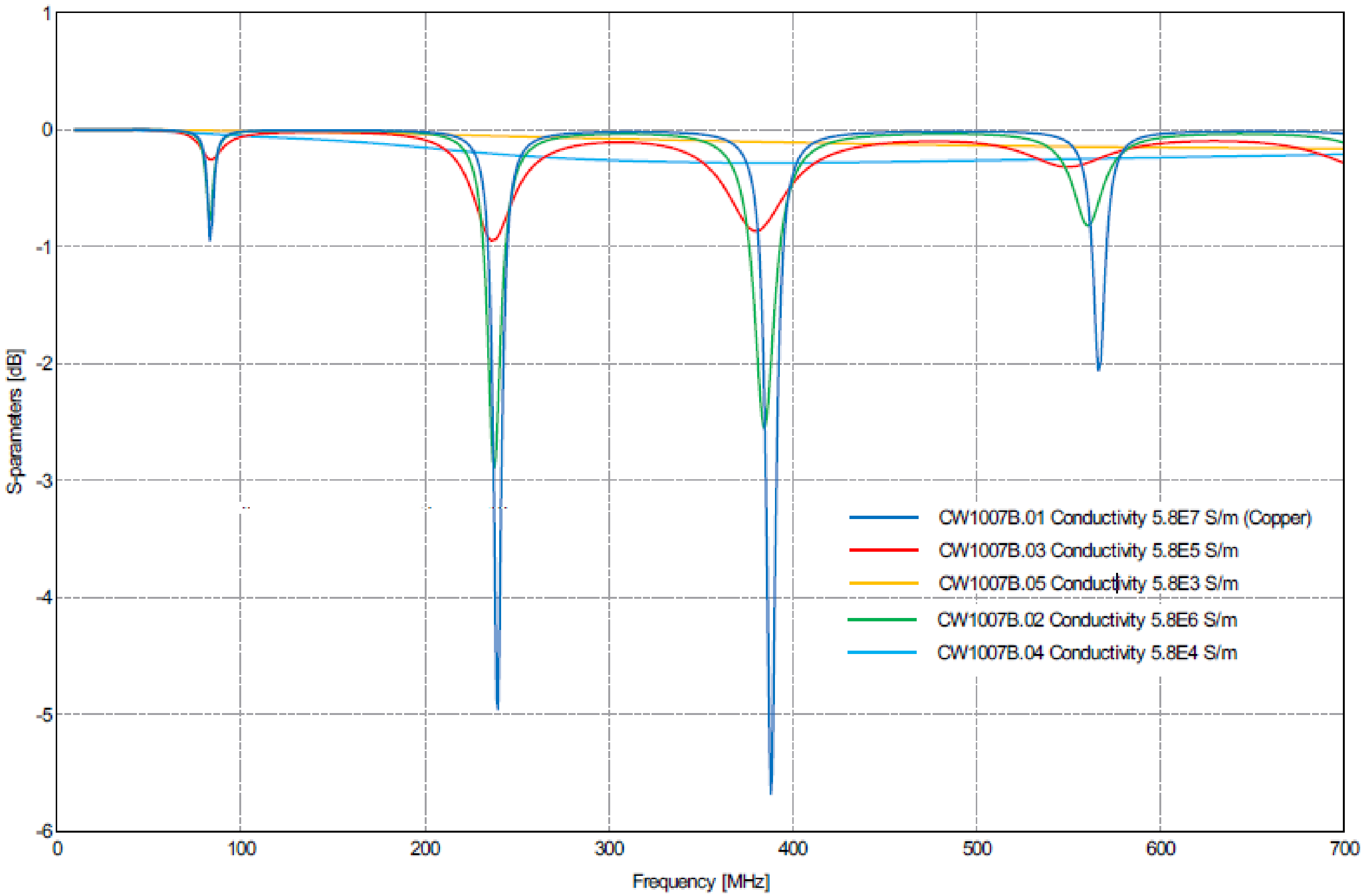


Puncture



Void

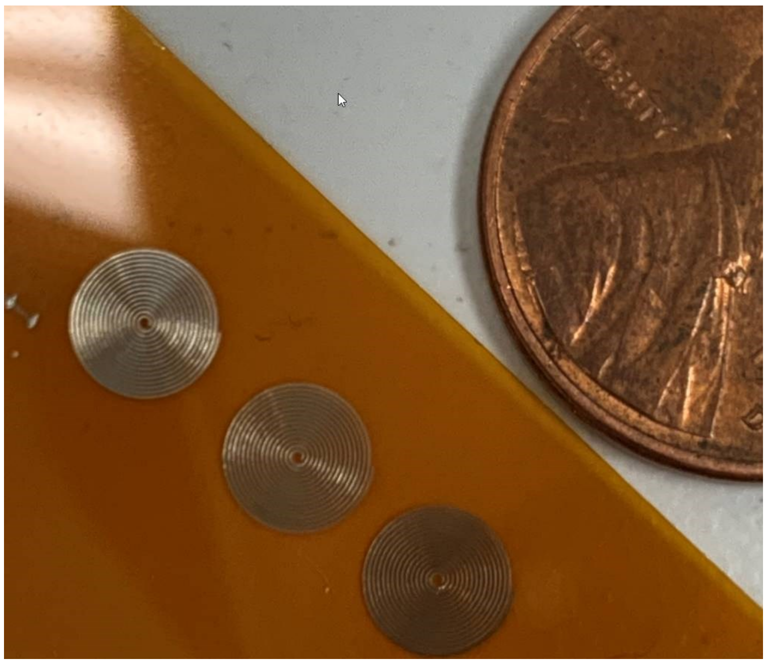
Response Characteristics with changing Trace conductivities



SansEC Sensor Fabrication

Sensors can be various shapes or sizes

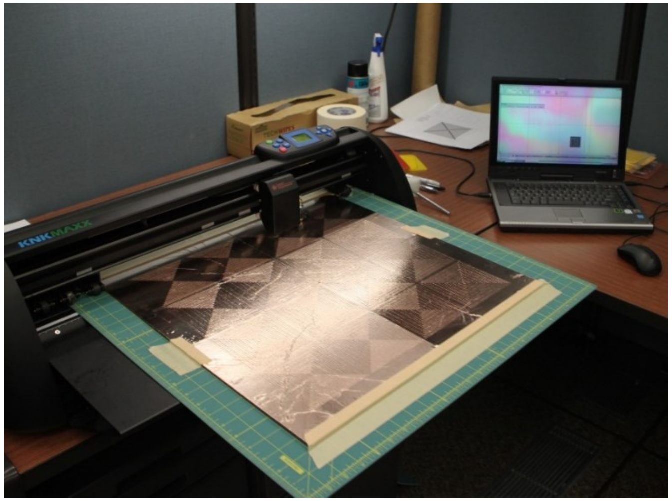
The sensors free space resonate frequencies are determined by the overall length of the conductive trace along with the trace width and gap width.



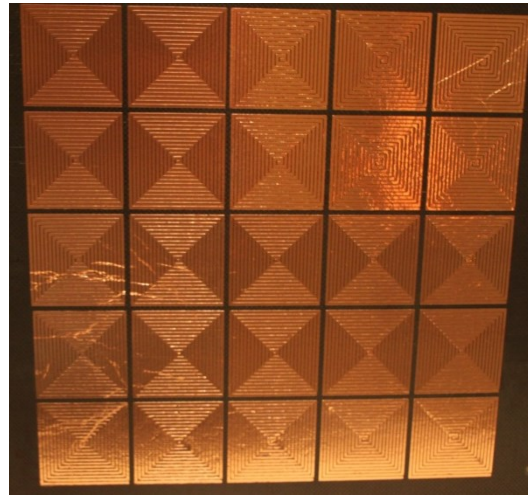
.04 mm trace width from NanoJet printer
(second generation Aerosol 3D printing technology)

.15 mm trace width using conventional etching
printed circuit board manufacturing techniques

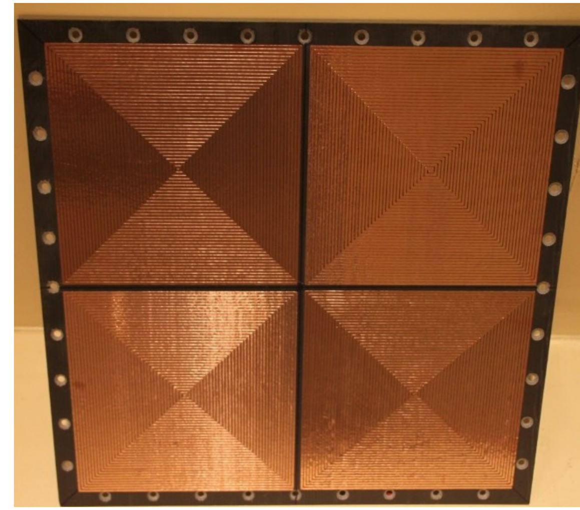
SansEC Sensor Fabrication



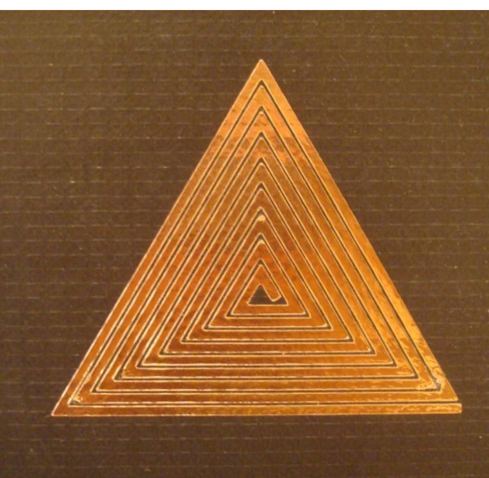
Klick-n-Kut Cutter



5x5 Square Array

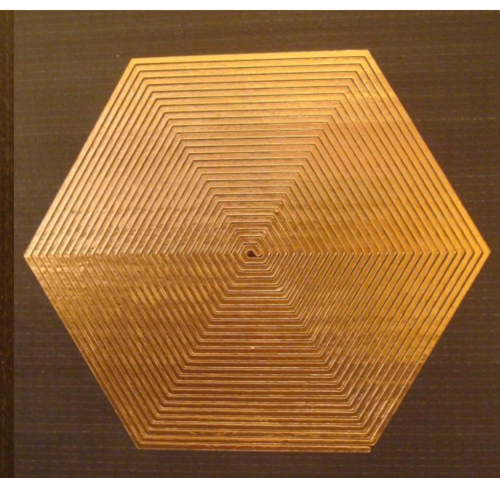


2x2 Square Array



Triangular

Square

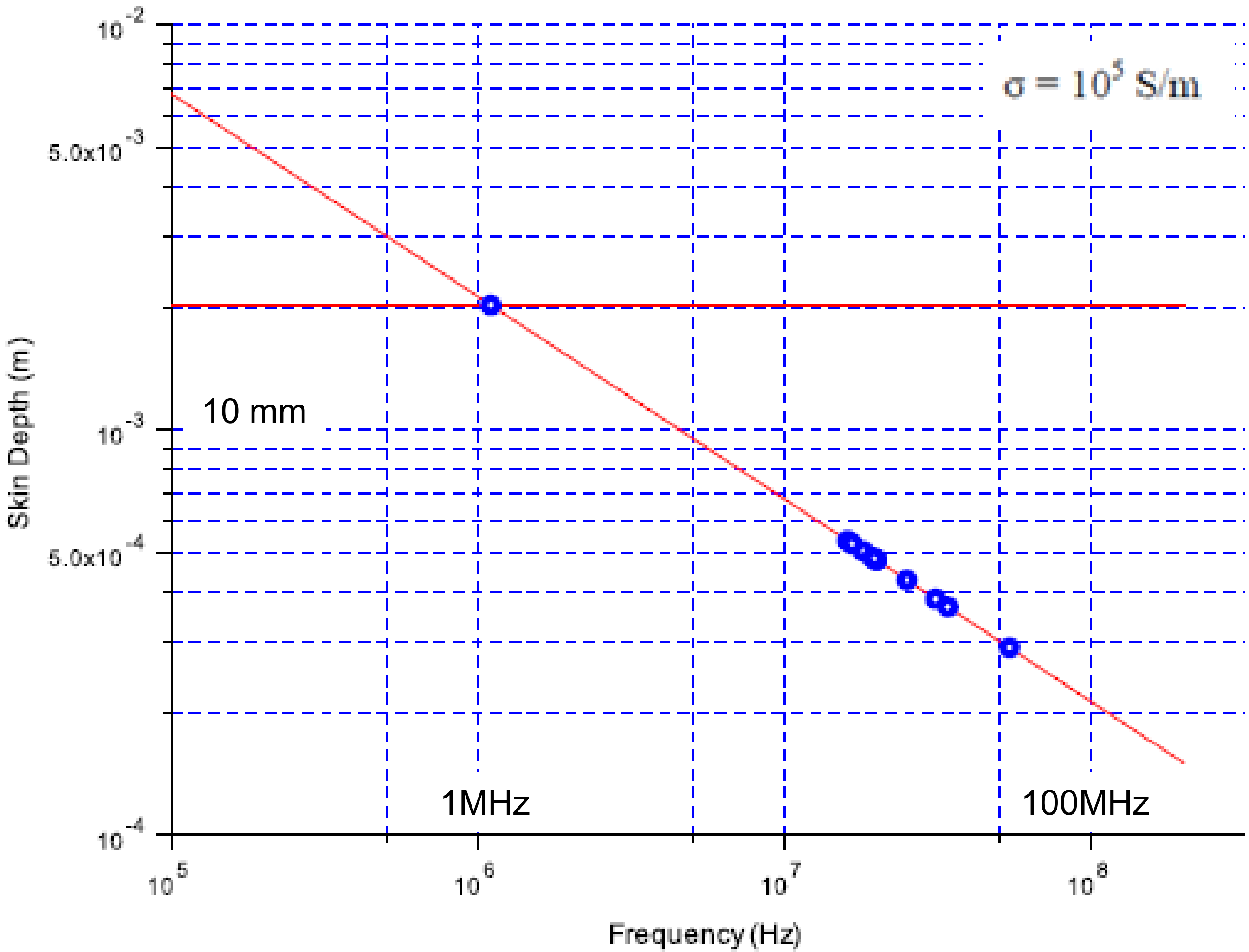


Hexagonal

Circular

SansEC Sensor Fabrication

Skin Depth relative to Frequency



The sensor trace thickness must be greater than the skin depth

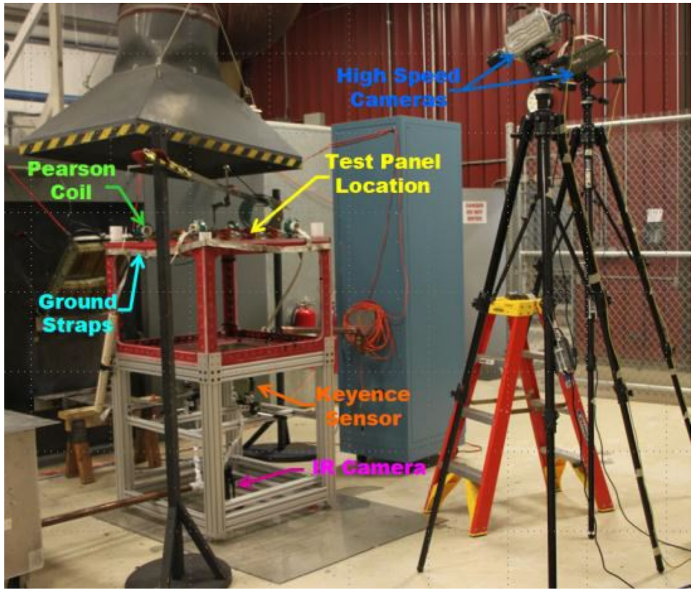
Applications – Composite Smart Skin

Program research focused on using SansEC Sensors on Carbon Composites

- Composite aircraft require a thin layer of metal in the outer skin to protect avionics and airframe from lightning damage.
- Post-flight ground inspection is conducted after a suspected lightning strike to identify continued air worthiness. (Visual inspections/Tap Test)

- Demonstrated Lightning Strike Protection conductive layer can be replaced with resonant sensors to provide comparable lightning mitigation characteristics and damage detection.

Lightning Testbed



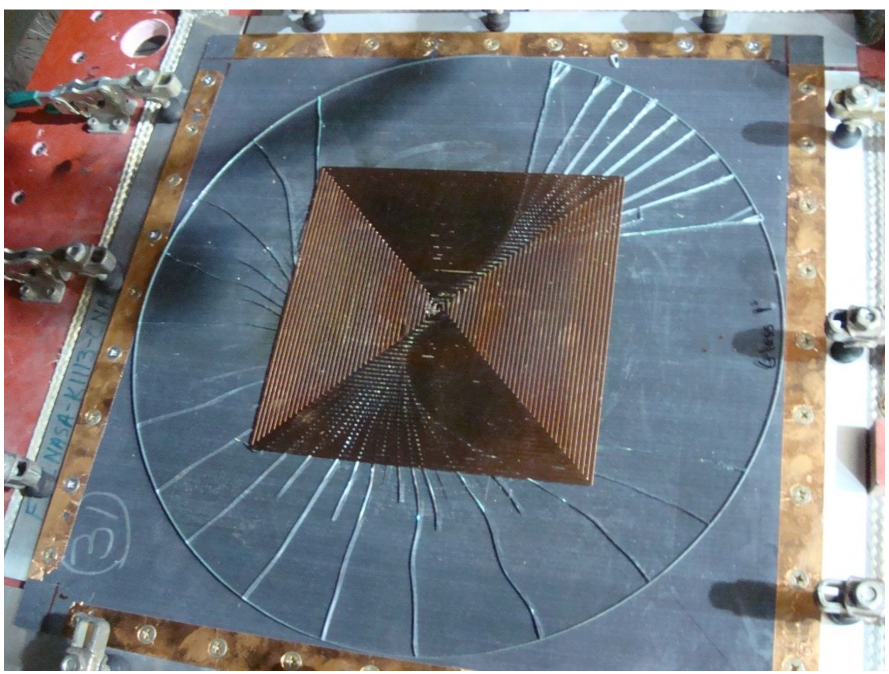
Lightning Strike Video

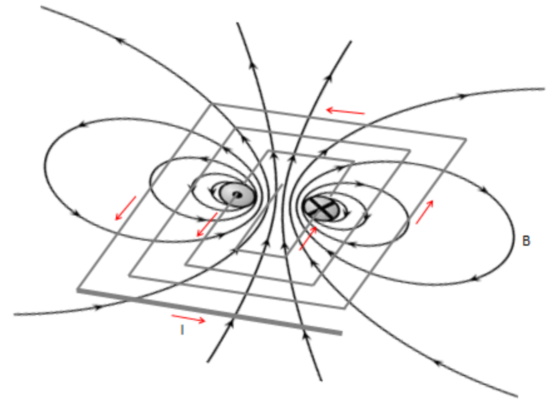
Applications – Composite Smart Skin

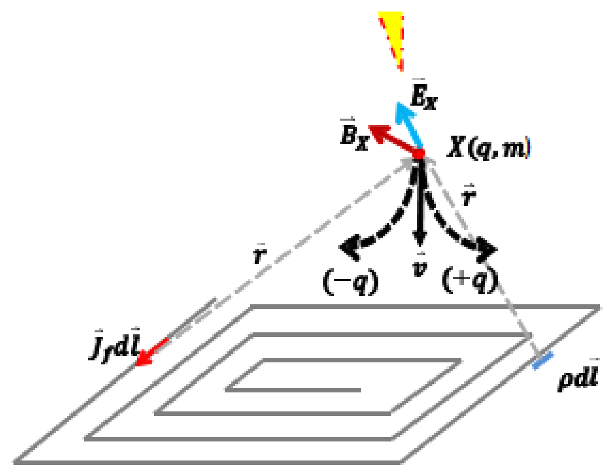
Lorentz Force

Sensor will generate a Lorentz Force on incoming charged particle

$$\vec{F} = q(\vec{v} \times \vec{B}_X + \vec{E}_X)$$

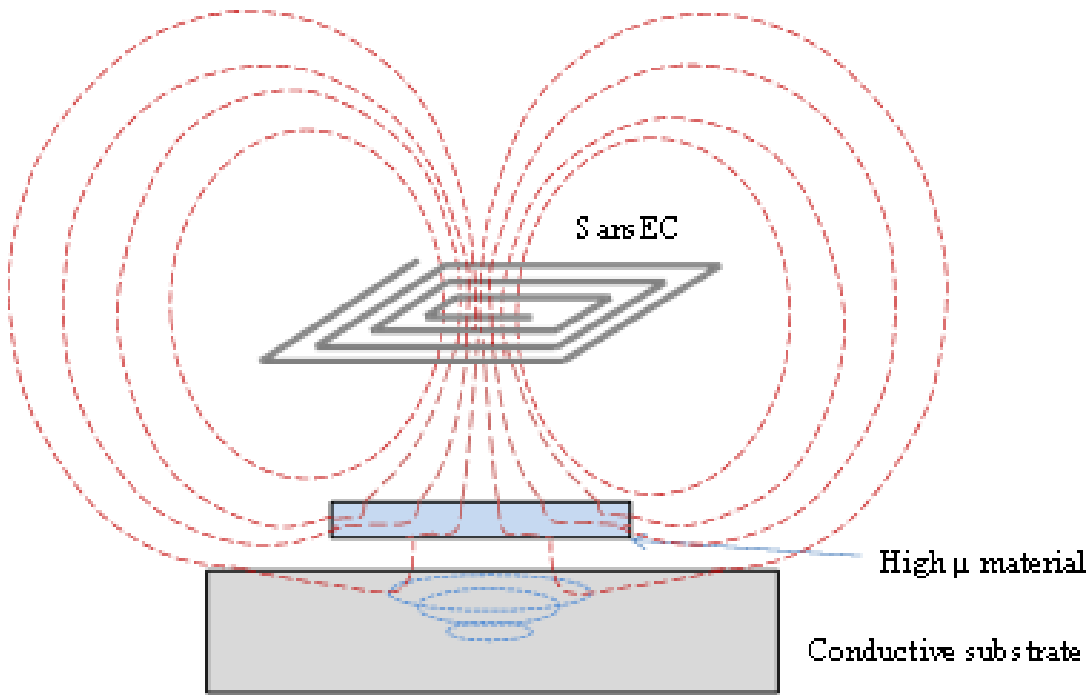






Applications – Composite Smart Skin

Operation on Carbon Fiber Composites requires a thin sheet of high permeability material to sustain the resonance.



Applications – Composite Smart Skin

Previous Program Research

Universal Common Practice Guide for Lightning Damage Testing of Composites Panel Design

<u>Layup</u>: 16 ply tape with 2 ply fabric

[(SURF)(ECF)(0/90F)/45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45/(0/90F)]

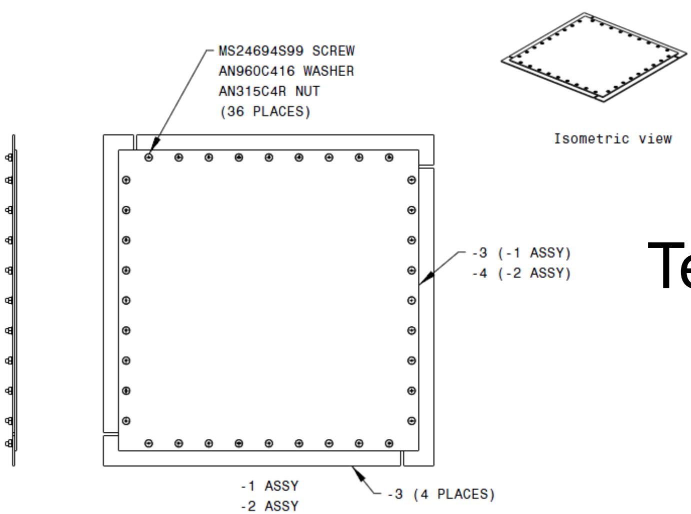
<u>Tape</u>: Hexcel 8552/AS4 (HexPly 8552/AS4),

<u>Fabric</u>: Hexcel 8552/AS4 (HexPly 8552 / A193-PW, 3K-70-PW)

<u>Lightning Protection</u>: Dexmet 3CU7-100FA (3mil copper mesh)/ SansEC Smart Skin

<u>Primer:</u> 0.5-1.5 mils thickness

<u>Top coat</u>: 4 to 6 mils per Mil-F-18264 or equivalent.



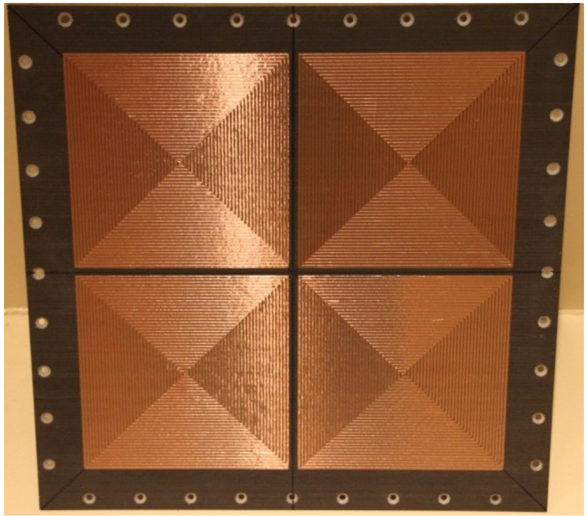
Test Panel

Applications – Composite Smart Skin

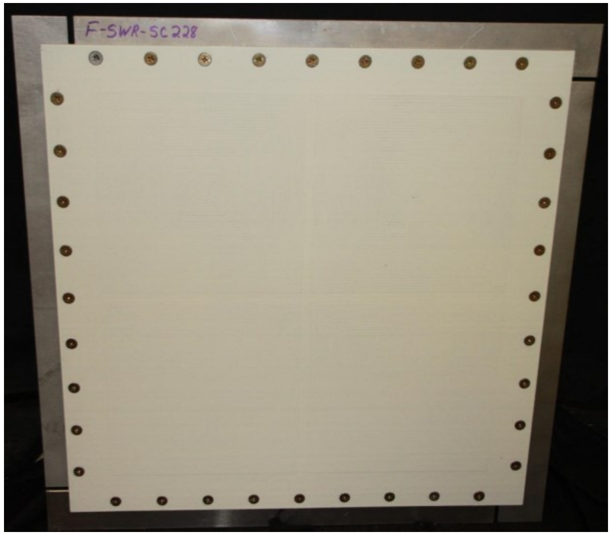
Previous Program Research

SansEC Fiberglass Reinforced Plastic LSP Test Panels

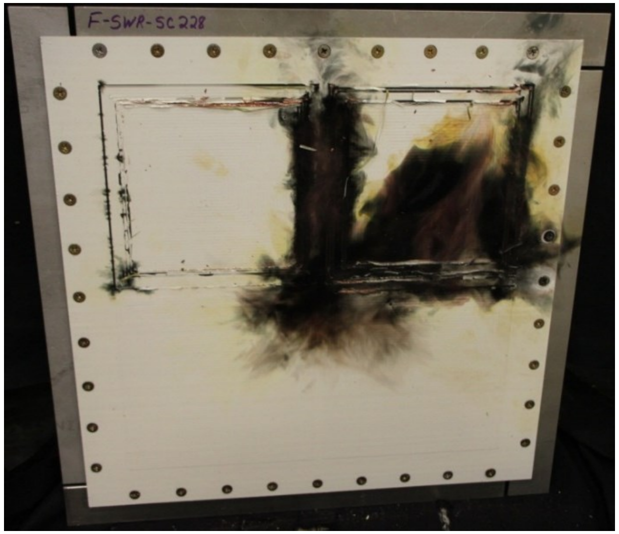
Pre-Paint Test Panel



Pre-Strike Test Panel



Post-Strike Test Panel



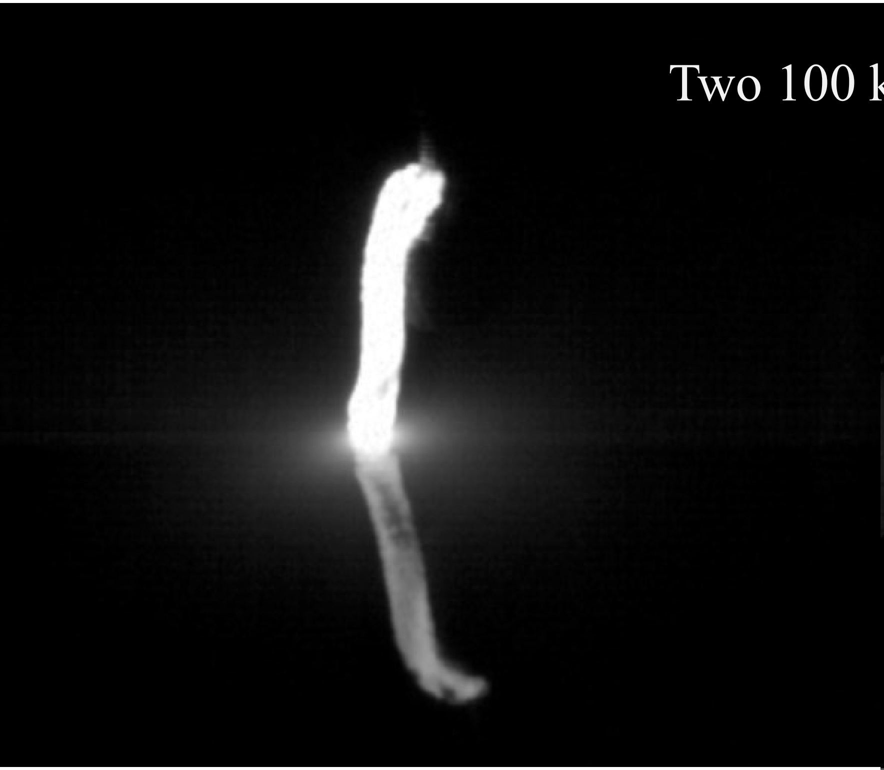
8 inch SansEC Array

Applications – Composite Smart Skin

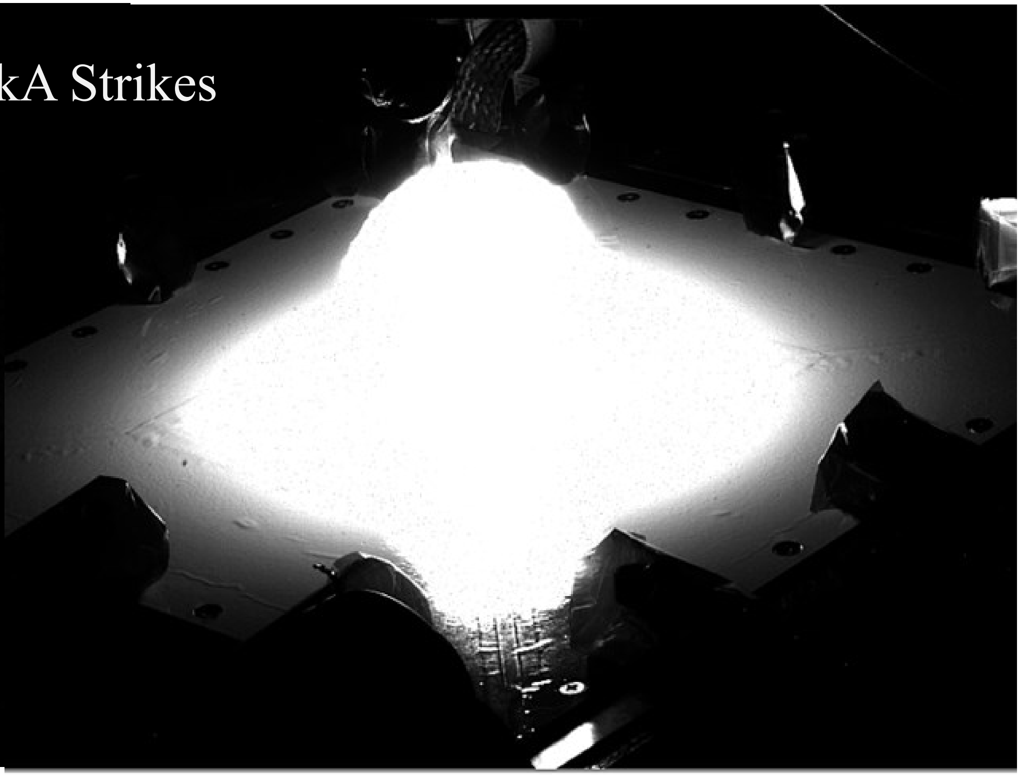
Previous Program Research

Carbon Fiber Panel Lightning Direct Effects Testing

Two 100 kA Strikes



High Speed Video First Frame showing Lightning Strike Initial Attachment on Mesh Protected Carbon Panel

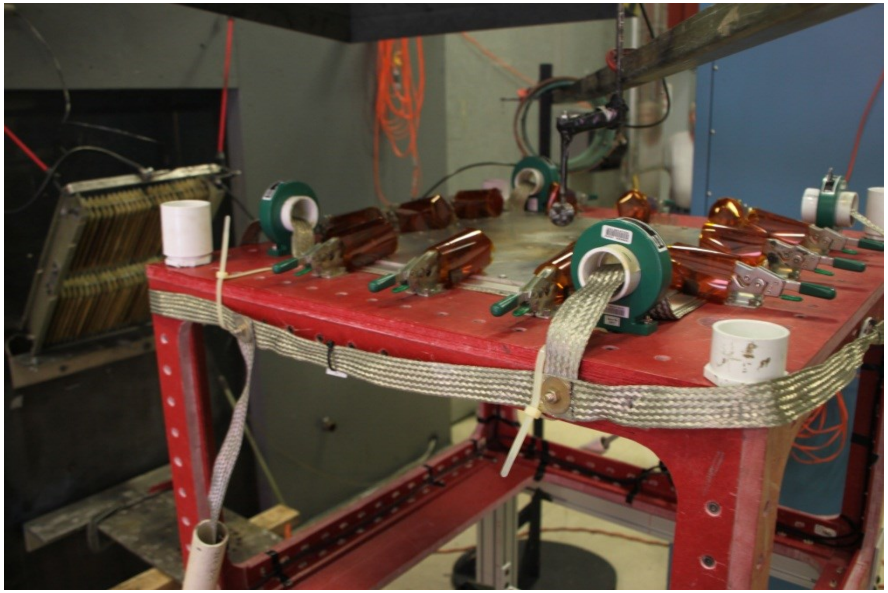


High Speed Video First Frame showing Lightning Strike Initial Attachment on SansEC Protected Carbon Panel

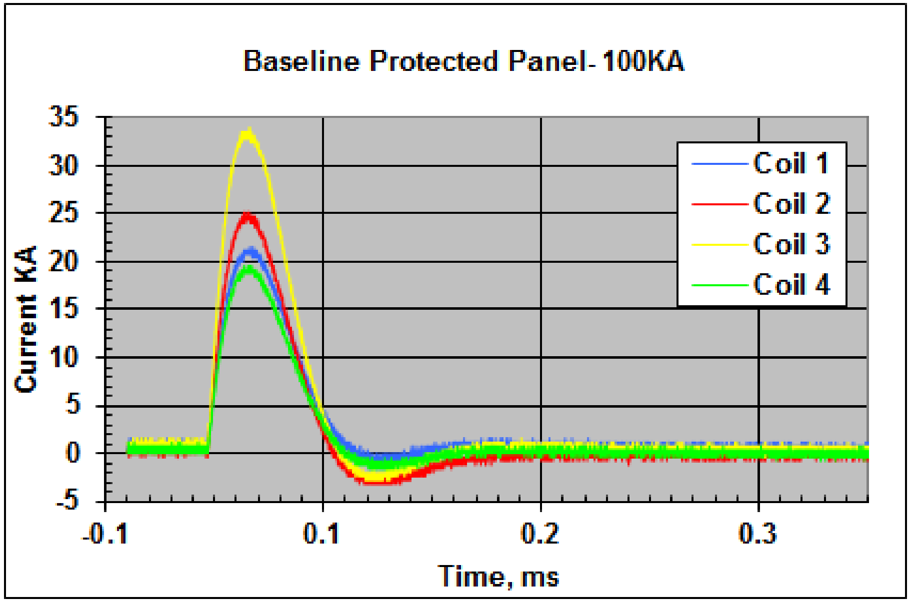
Applications – Composite Smart Skin

Previous Program Research

Electrical Current on the 4 Edges of the Test Panel were Independently Monitored during Lightning Test



Pearson Probes mounted on Test Bed



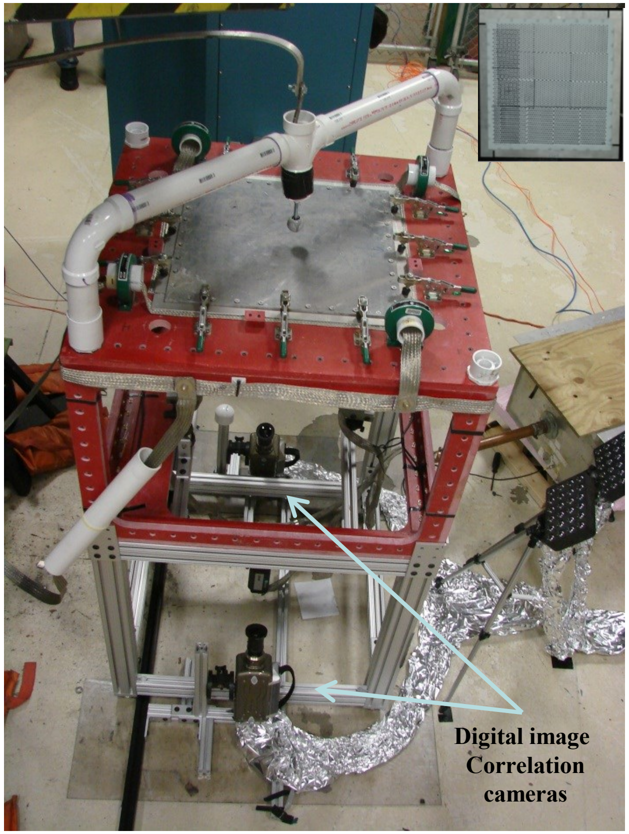
Current Data collected during 100KA Strike

- 4 independent current monitors enable measurements on the 4 edges
- Inductive effects from ground strap installation should be minimized

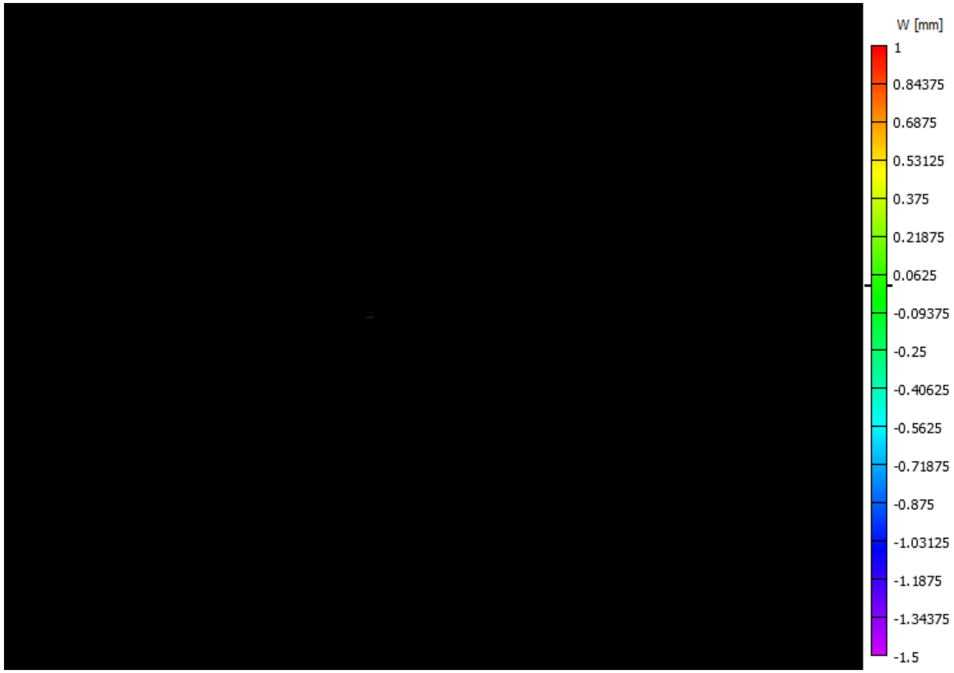
Applications – Composite Smart Skin

Previous Program Research

Mechanical deflection is measured using optical sensors or digital image correlation cameras



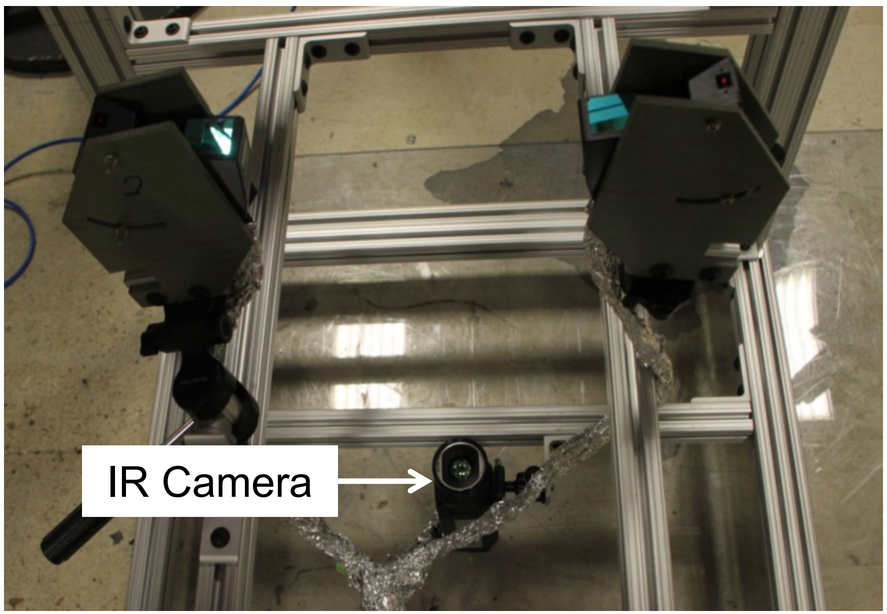
Digital Image Correlation Video



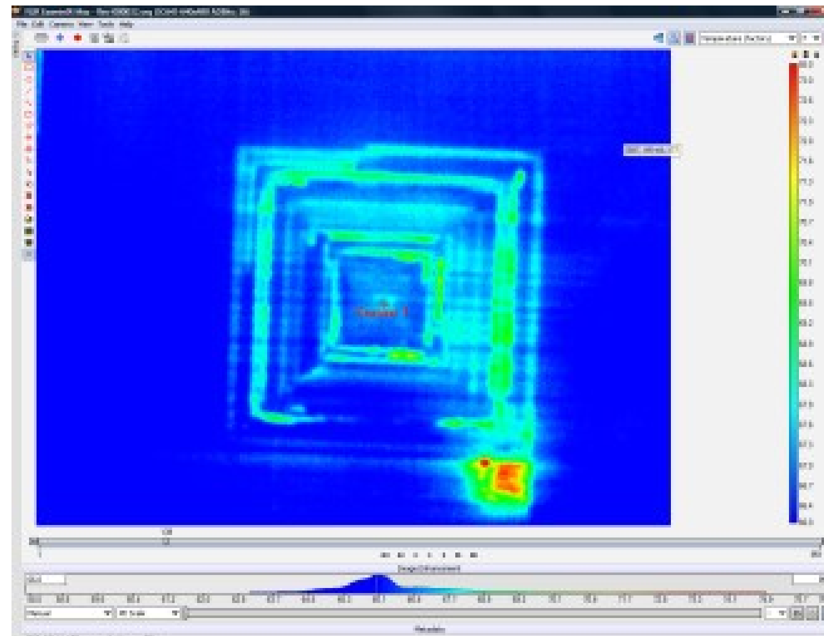
Applications – Composite Smart Skin

Previous Program Research

Backside Thermal Data was Acquired using FLIR Systems SC645 IR Camera



Infrared (IR) Camera Setup

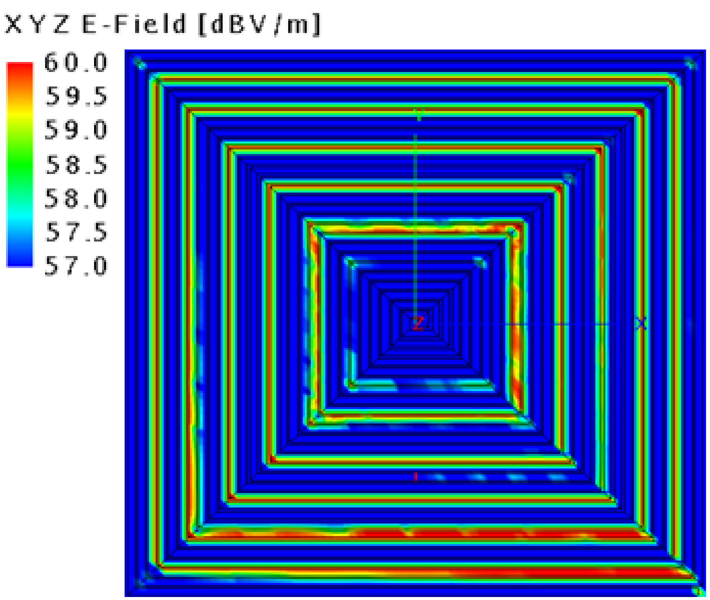


Backside IR image of 8” SansEC LSP on Fiberglass Substrate

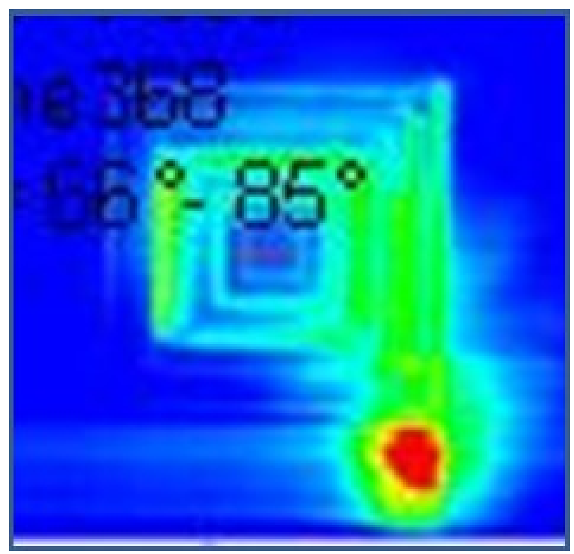
Applications – Composite Smart Skin

Previous Program Research

- Hotter temperatures in the IR image represent the location of lightning attachment or current propagation.
- Lightning Attachment was observed to occur at high electric field locations.



Computed E Field



Backside IR Temperature

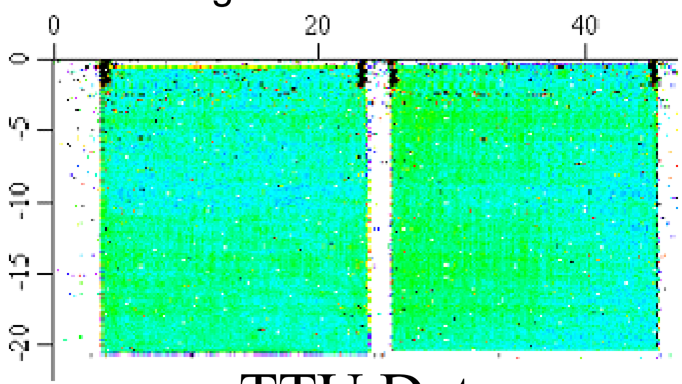
Post Strike Damage

Applications – Composite Smart Skin

Previous Program Research

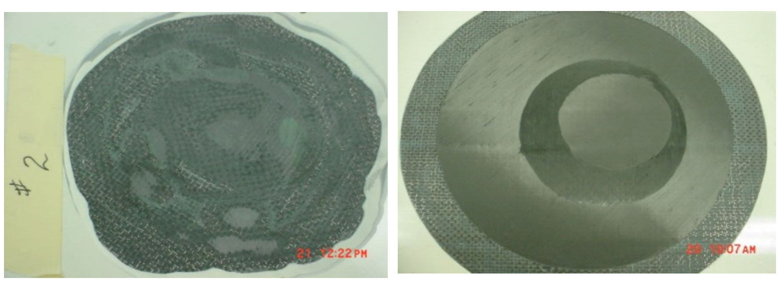
Lightning Experiments – Damage Assessment

- **<u>Pre-Test NDI:</u> Inspect the cured panel with a <u>through transmission ultrasonic</u> (TTU)'C' scan inspection at 5 MHz. A defect is defined as an area with ultrasonic attenuation that is at least 6db larger than the attenuation of the adjacent areas without flaws greater than 0.50 inch in diameter. Multiple defects are allowed, up to three (3) per panel as long as they are at least 1.00 inch apart.**
- **<u>Post-Test NDI:</u> Pulse-Echo Ultrasonic Assessment, X-ray Assessment (Optional)**
  - Areas with ultrasonic attenuation >6dB larger than adjacent areas without flaws or defects.
- **<u>Destructive Damage Assessments</u>**
  - Taper sand to remove damaged material, use P-E Ultrasonics to verify. Then count plies remaining.



TTU Data

Photos from NASA Document Number: DOC-128697



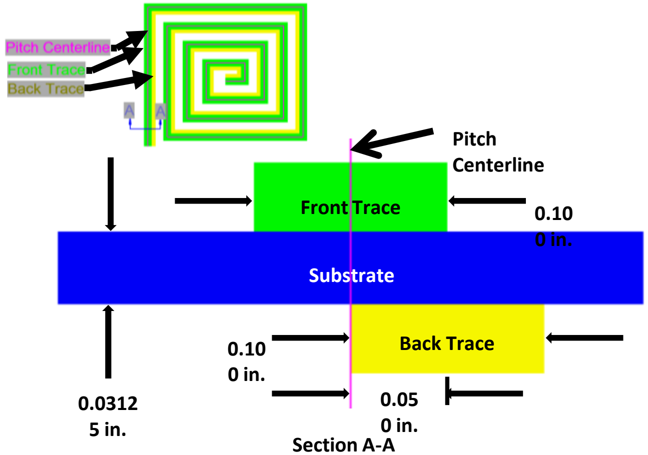
Damage Assessment

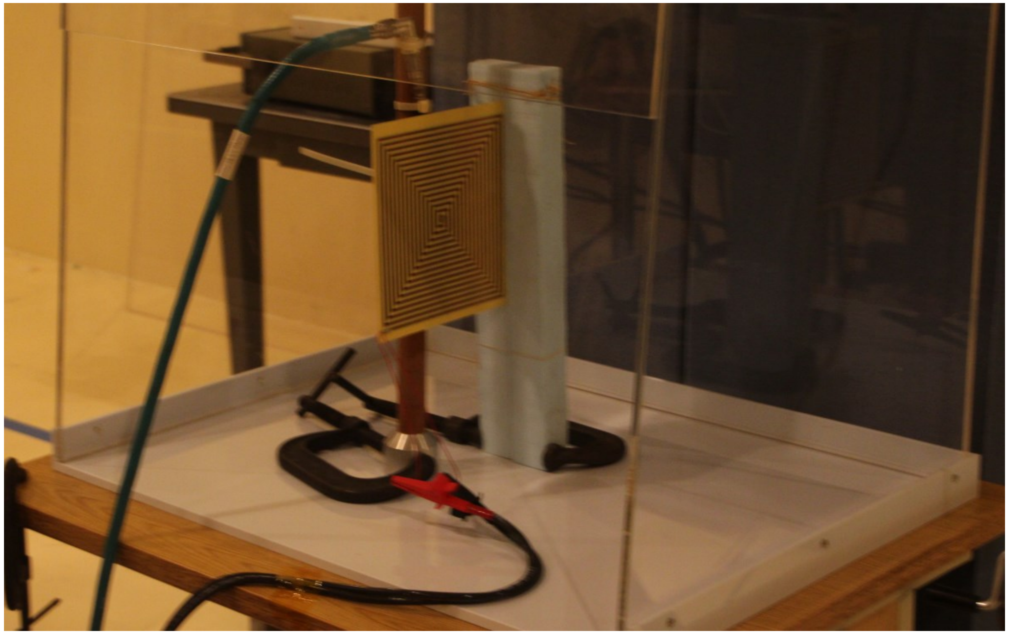
Applications – High Efficiency Plasma Generator

Previous IRAD Research

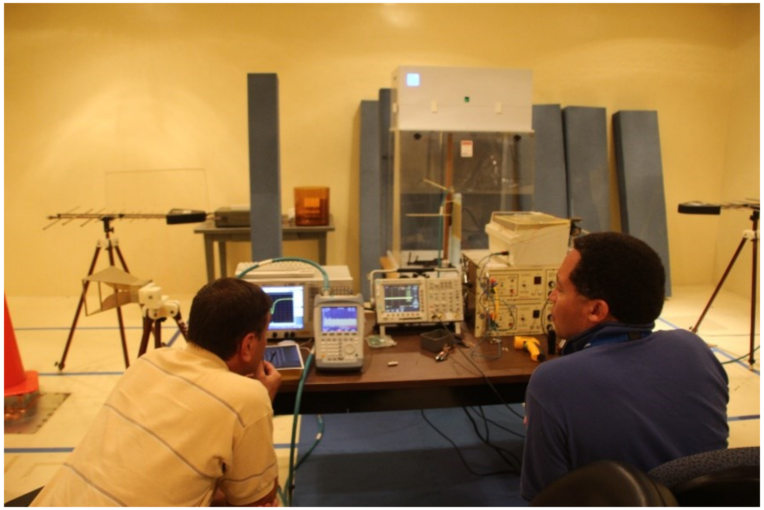
Dielectric Barrier Discharge (DBD) SansEC Sensor

Double sided SanEC Design for DBD Test

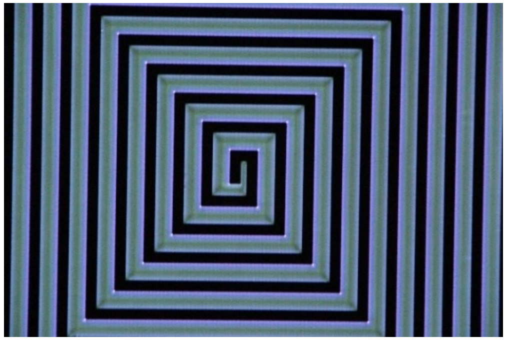




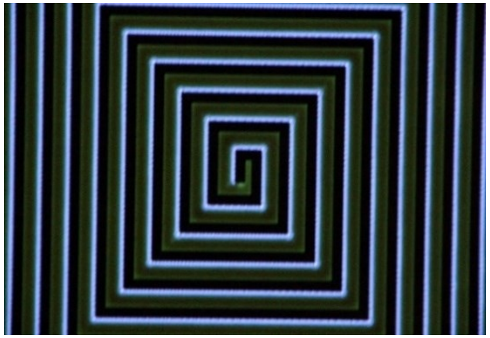
DBD Sensor Mounted inside Ventilation Hood



Experimental Setup



Response at 2KHz



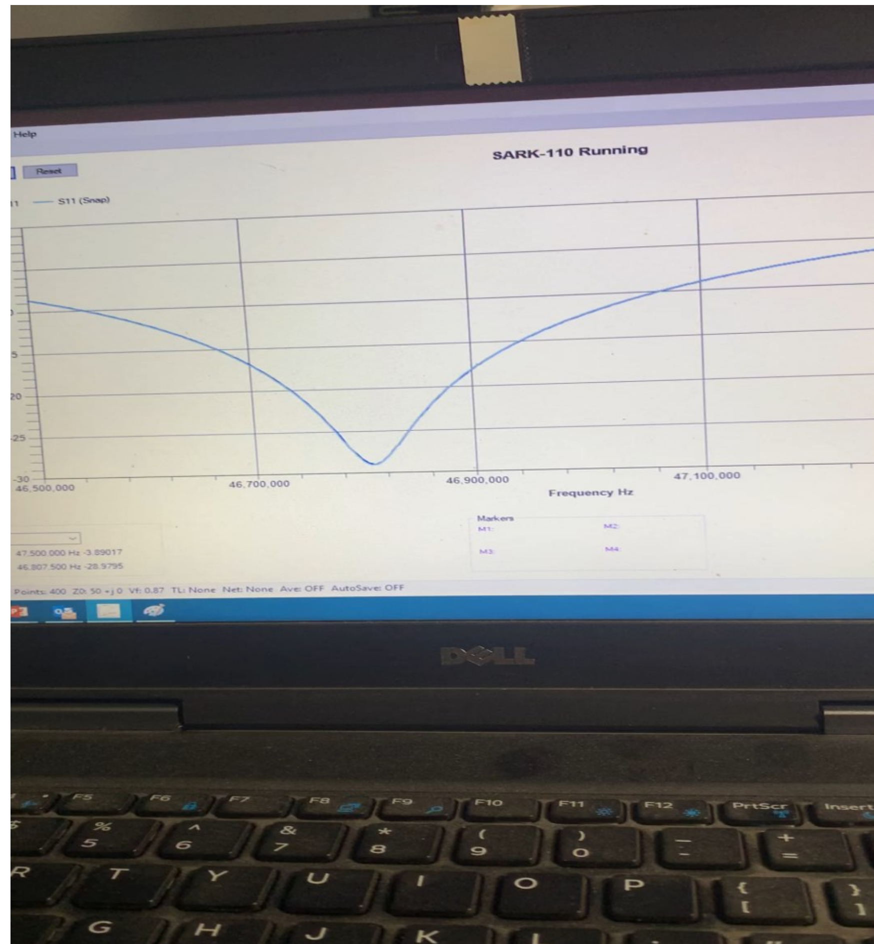
Response at 10KHz

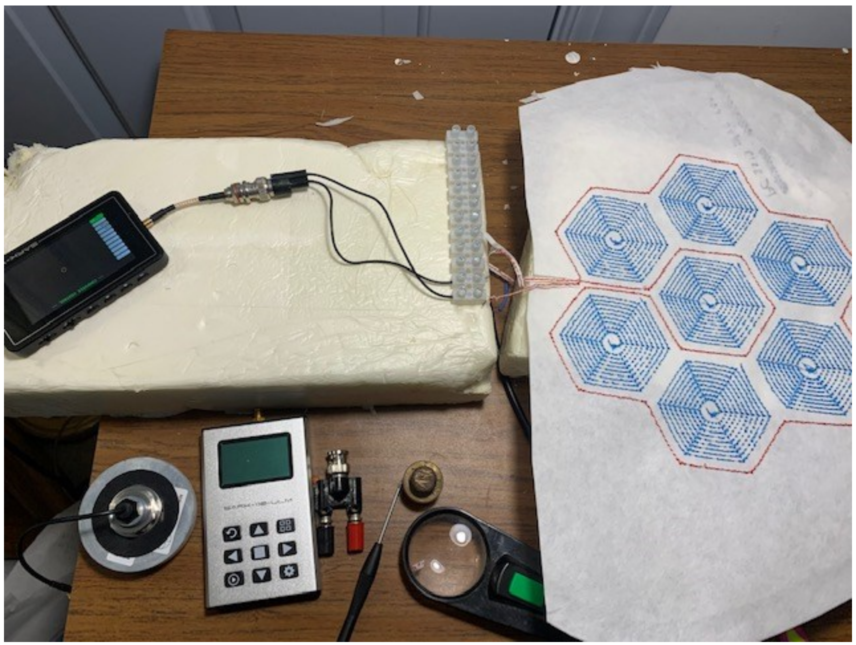
Langley Research Center

Applications - Wearables

Conductive Yarn Sensors Embedded in Textiles

Video showing instantaneous temperature change





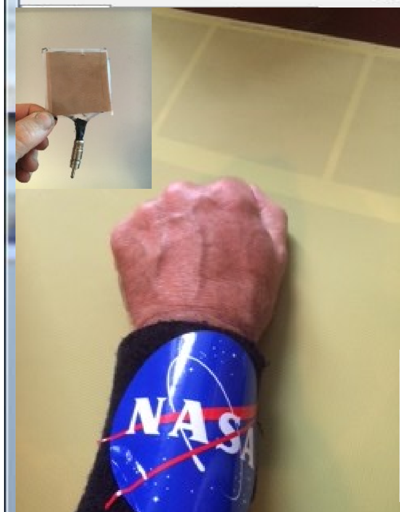
Experimental Setup

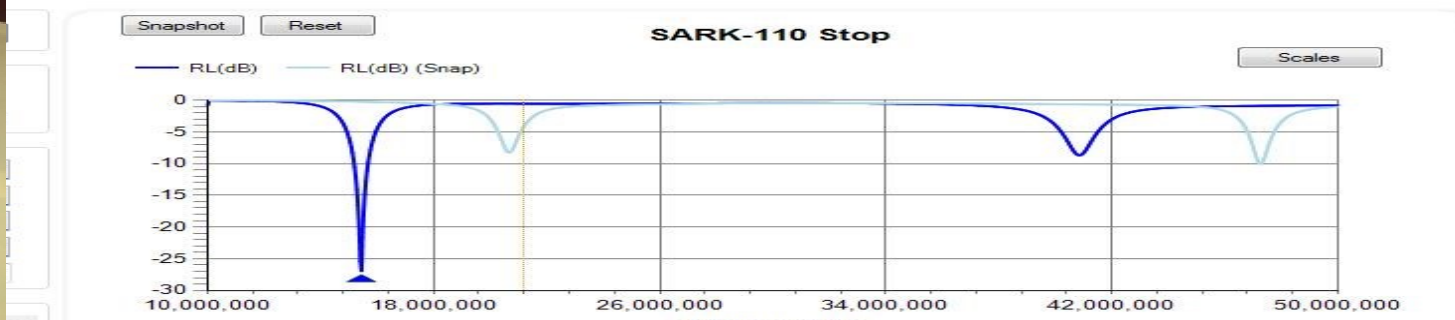
Applications - Wearables

Hand Gesture Measurements

SARK Plots

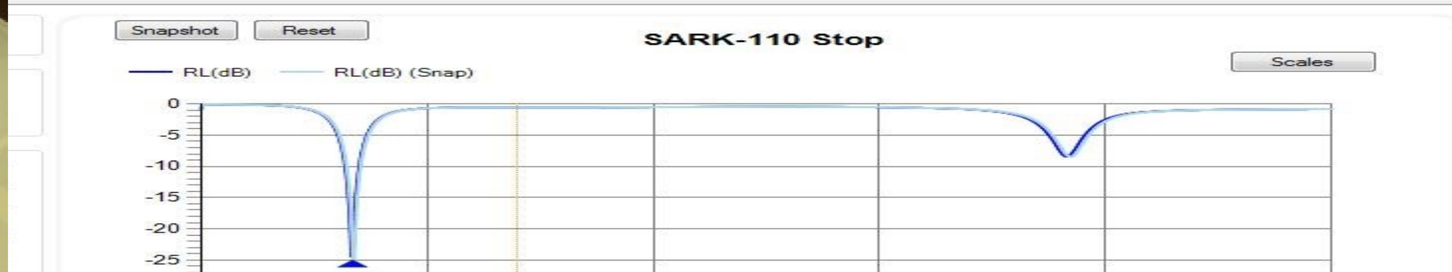
File View Marker Settings Tools Export Help





	Null Amplitude (dB)	Null Frequency (Hz)	Δ Amplitude (dB)	Δ Frequency (Hz)	Q Factor
1:	-26.955615	15.440000			10.122481
2:	-8.693877	40.840000	18.261738	25.400000	17.968892

Tools Export Help



	Null Amplitude (dB)	Null Frequency (Hz)	Δ Amplitude (dB)	Δ Frequency (Hz)	Q Factor
1:	-24.432011	15.360000			9.971637
2:	-8.410655	40.640000	16.021356	25.280000	18.008625

Points: 1000 Z0: 50 +j 0 Vf: 0.87 TL: None Net: None Ave: OFF

Detectable Phenomena

If the monitored phenomena undergoes a change in its electrical impedance, SansEC sensing can possibly detect it.

- Structures & Materials
  - Composite Damage
  - Stress & Strains
  - Flutter/Morphing
- Physiological Measurements
  - Vital Signs
  - Body Mechanics
  - Intercranial Fluids
- Chemistry
  - PH Level
  - Contaminations
  - Water/Ice Detection
  - Mineral Exploration
- Habitat Environmental Conditions
  - Temperature
  - Humidity
  - Pressure
- Rocket/Jet Engines
  - Fuel Cavitation
  - Performance Monitoring
  - Turbine Blade Monitoring
- Autonomous Assembly
  - Proximity
  - Angular Rotation
  - Fastener Torque
  - Integrity Monitoring

Conclusions

SansEC Sensors

- Wireless
- Passive
- Non-Contact
- Electromagnetic Resonators

- Used to detect change in a physical phenomena by measuring/monitoring electrical impedance
- Measurement components include the sensor, interrogator, loop antenna and signal processing
- The physics-based data features work well in machine learning algorithms for quantification

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