AOI [2] Passive Wireless Sensors for Temperature and Corrosion Monitoring of Coal Boiler Components under Flexible Operation

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2022 Crosscutting Research and Advanced Energy Systems Project Review Meeting
SENSORS & CONTROLS PROGRAM
May 12, 2022 (9:30 am)

Award DE-FE0031912

Initial Acknowledgments:

Acknowledgment: "This material is based upon work supported by the Department of Energy Award Number DE-FE0031912"

Background:

- Operating profile of the existing coal-fired power plants has changed from high-capacity-factor (baseload) operation to *flexible operation*.
- Increased cycling operations with *increased thermal ramp rates, and rapid changes* in unit output have a major impact on reliability, efficiency and cost of the coal-fired power plants.
- Cycling causes increased wear-and-tear on high-temperature and high-pressure components, and shorter equipment lifespan due to thermal expansion/fatigue, increased corrosion and cracking.
- *Corrosion-related issues are emphasized as the major mechanism* for boiler tube failures under harsh-environments.

Background:

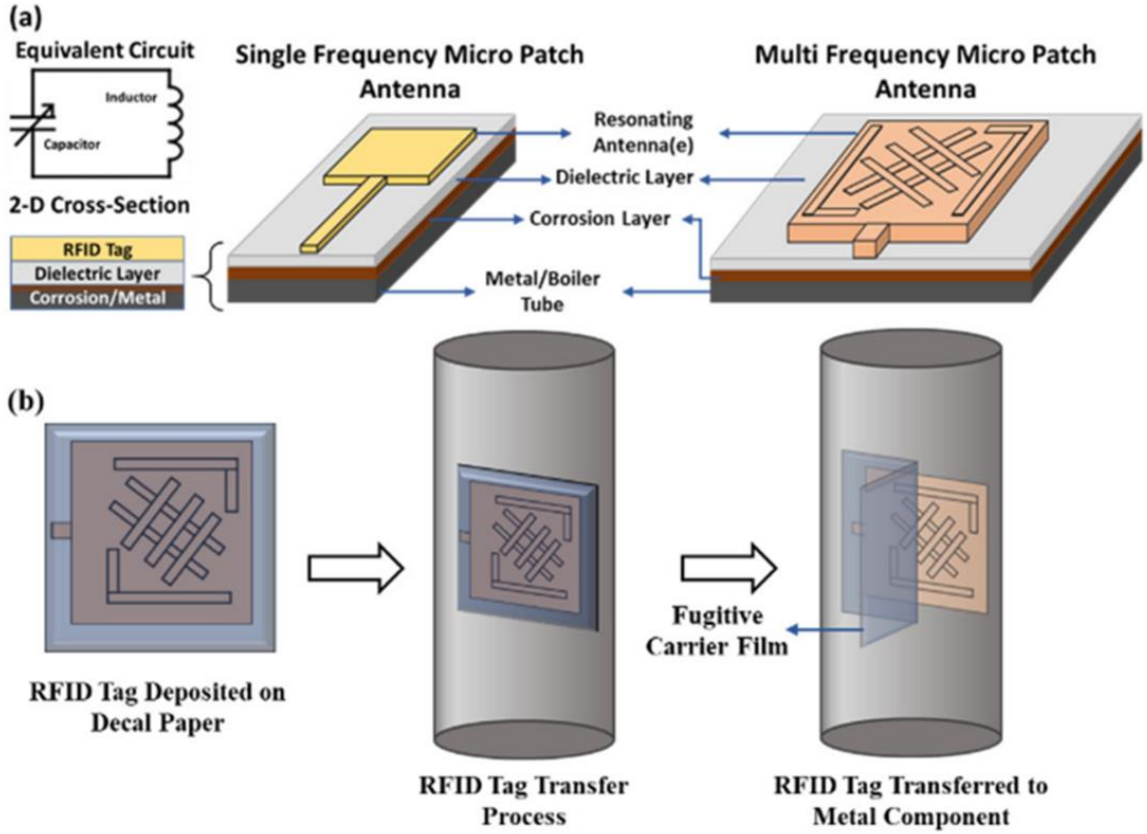
- Health and temperature monitoring of metal components and boiler tubes in the coal-fired power plants has technical challenges due to 500-1300°C and high steam- and/or flue gas-related harsh-environments.

- *Downtime inspection* and *metal loss coupons* are common techniques being utilized to assess the corrosion and related failures in power plants.

  Limitations:

  - Slow response rate
  - Increased personnel required
  - Limited testing/inspections possible
  - Operating capability at various temperatures

The Technology:



Item (a): Schematic of proposed sensor cross-section and equivalent circuit, which includes the single and mult-frequency micro-patch RFID tag printed onto ceramic barrier layer which will insulate and bond sensor to the metal specimen.

Item (b): Representation of peel-and-stick deposition approach to transfer the chipless RFID tag sensor to metal component.

The Technology:

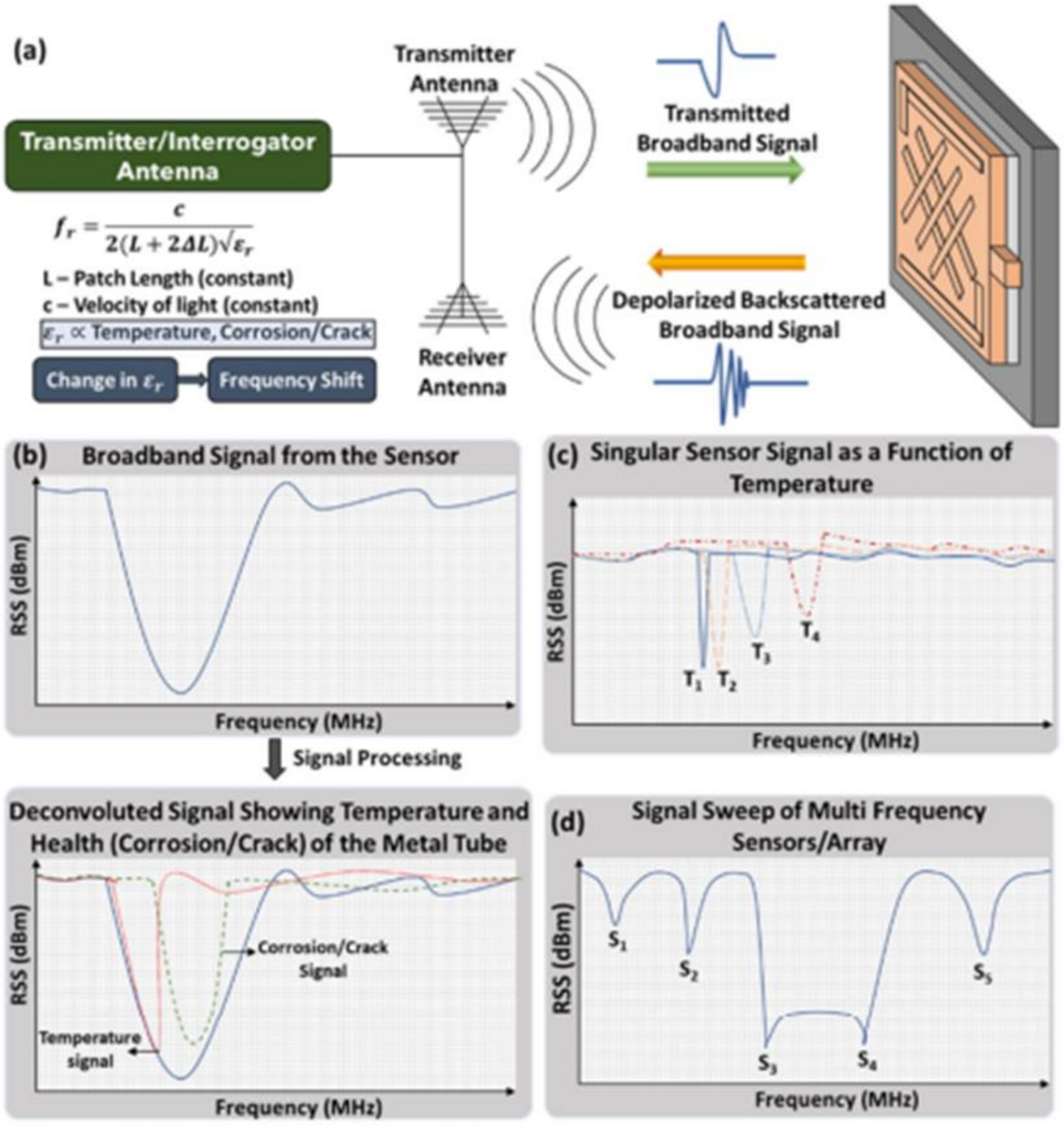
RSS= Received Signal Strength

Item (a)= *General Schematic*

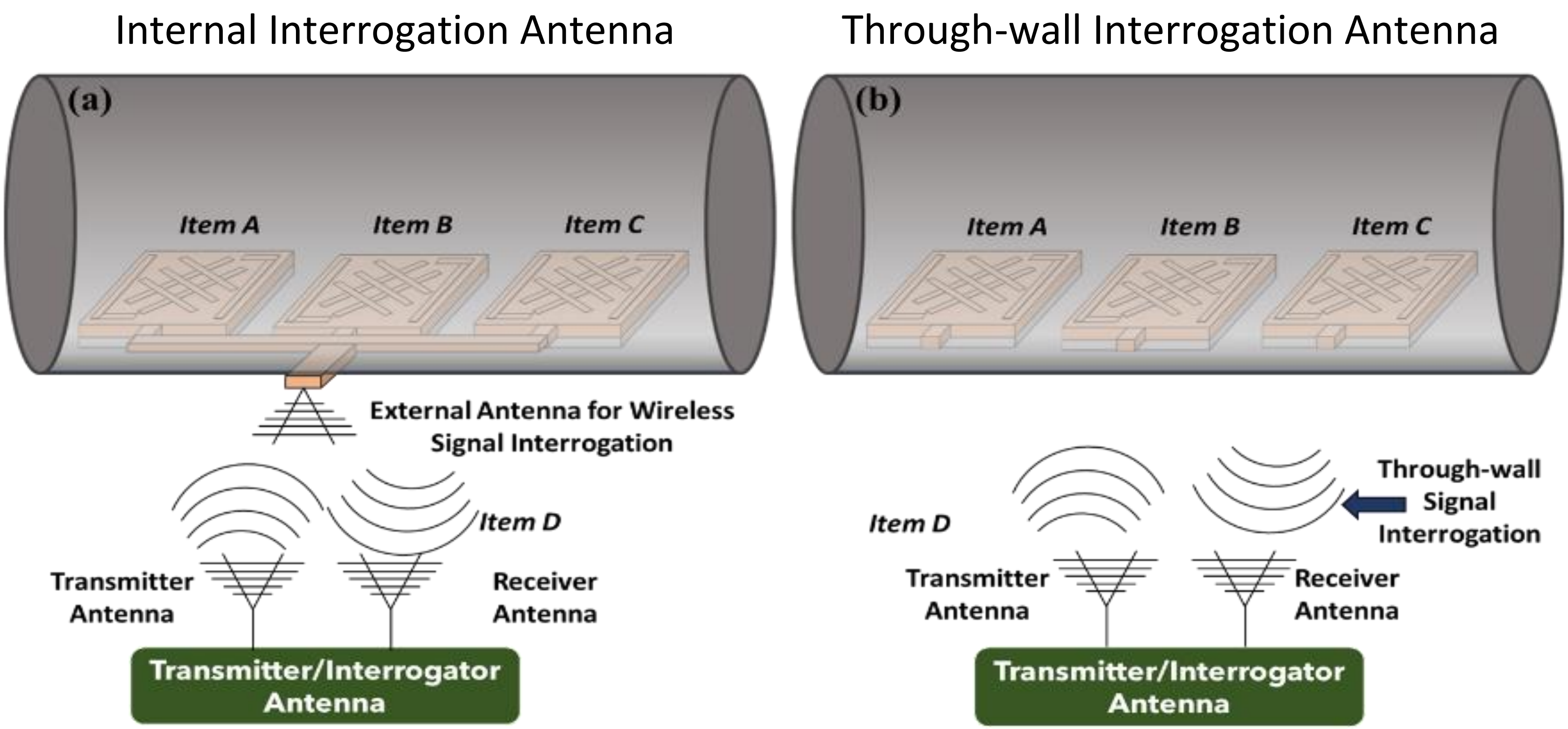
Item (b)= Received broadband signal and deconvoluting step to separate temperature and corrosion/crack information.

Item (c)= Frequency shift for reflected power for singular sensor to change in sensing parameters (temperature).

Item (d)= Multi-frequency signature read for multi-sensor array measured by interrogator antennae.



The Technology:



Item A-C: Each sensor pattern will have a different dimensions/geometry which permits the sensors to couple at a different frequency band.

Item D: Represents the interrogator antenna that will be used to broadcast and read the reflected power from the RFID sensors.

Program Objectives:

The specific project objectives are as follows:

1) **Design passive (chipless) wireless RFID patch** and interrogator antennas which will be implemented in a wide frequency band for high-temperature sensing of corrosion and crack propagation at temperatures up to 1300°C;
2) **Develop materials and methods to fabricate a microstrip patch antenna sensor** composed of a robust conductive material pattern and interlayer ceramic coating (incorporate this sensor into a "peel-and-stick" preforms that will efficiently transfer and bond to the metal specimens of interest);
3) **Investigate the wireless RFID sensor response in accelerated high-temperature and high steam environments**, and correlate corrosion and cracking mechanisms (and kinetics) with response of the sensors;
4) **Investigate the wireless signal acquisition and processing of data** transferred in various configurations by multiple sensors within the same environment and through-wall transmission of the signal by a singular RFID sensor;
5) **Demonstrate monitoring the health of metal components in service within a coal-fired power plant**.

Task Assignments:

Task 1.0 Project Management and Planning.

Task 2.0 Passive RFID Sensor Design and Initial Benchtop Testing.

Task 3.0 Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process

Task 4.0 Cyclic Passive Wireless Sensor Testing.

Task 5.0 Through-Wall Signal Transmission for RFID Wireless Sensor Testing.

Task 6.0 Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration.

= Tasks initiated (but slightly behind schedule)

= Tasks not started

SUMMARY of TECHNICAL TASKS and MILESTONES

Task 2.0 – RFID Sensor Design and Initial Benchtop Testing.

Task 2.0 – RFID Sensor Design/Initial Benchtop Testing:

- ***Subtask 2.1: Passive Wireless Design (Q1-6)***
  - Design appropriate RFID sensor using ANYSIS Maxwell modelling package.
  - Chipless RFID microstrip patch antenna design, where the geometry of the conductive pattern on the specimen and the dielectric properties (and thickness) of insulating layer will alter the frequency behavior (which is proportional to temperature variation, corrosion, and corrosion induced cracking).
- ***Subtask 2.2: Wireless Sensor Fabrication on Polymer/Ceramic Substrates and Benchtop Testing (Q3-5)***
  - Screen/ink-jet printing techniques will be used to fabricate the sensors using metallic (Ag, Pt, etc.) inks on polymer or non-conductive substrates. Both the sensors and interrogator designs will be tested at low temperature (<100°C) both outside and inside the proposed metal tubes.
  - Sensors/antenna pairs will be tested parallel to each other at various lengths, offset distances, and related orientations.
- ***Subtask 2.3: Advanced Signal Processing Methods for Deconvoluting the Wireless Response (Q4-11)***
  - Define signal processing method (such as Non-Parametric (NP) Methods and Parametric Modelling (PM) Methods) to define the measurement parameters (T, c, s) separately, and modeling their interactions to build a model for defining corrosion and crack events during testing.

Task 3.0 – Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process.

Task 3.0 – Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process:

- ***Subtask 3.1- Investigation of Various Material Systems for the Wireless Sensor Fabrication***
  - *Refractory metals and electroceramic oxides* will be for operation at 500°-1300°C, varying humidity levels, and pressure developed in the system.
  - *Electrical/Physical properties:* Electrical conductivity, corrosion resistance, chemical/thermal stability, susceptibility to temperature, electric and magnetic field.

- ***Subtask 3.2 Fabrication of RFID and Patch Antenna Sensors Directly onto Planar Metal/Ceramic Substrates***
  - Sensor designed in Task 2 will be *fabricated onto a planar metal/ceramic substrate* with the materials system.
  - Several patterning and deposition techniques (direct ink writing, micro-casting, screen-printing) will be investigated based on the geometrical form factor of the sensor/arrays.

Task 3.0 – Direct-Writing (2D/3D Patterning) of Refractory and Sensor System:

- ***Subtask 3.3- Development of Inexpensive Transfer Process and Baseline Testing***
  - *Methods to transfer the sensor to the active energy system component* (*flat substrates*).
  - The work will investigate (but not be limited to): the effect of ink/paste characteristics on wetting and transfer of the patterns, organic overlay effect on “sticking” to metal surfaces, pyrolysis of fugitive under- and over-lay coatings, bonding of print after carrier pyrolysis.

- ***Subtask 3.4- Direct Transfer of Sensor to Metal Tubing and Thermal Processing Development***
  - *Three (3) initial sensor configurations* (without passive communication circuit) will be designed, with focus on temperature, corrosion, and corrosion induced crack tests.
  - Electrical performance testing of the sensors *directly transferred on metal tubing or curved substrates via transfer process* will be completed at 500^{o}-1300°C in varying atmospheres in WVU’s existing automated sensor test stands. Baseline electrical performance will be assessed.

Design and Testing of 4 Near-Field Sensors:

Design 1: PCB with Cu electroding

- **Objective:** To evaluate modelling and testing methodology before high-temperature expeirments.
- Inductor patterned on a PCB board with full backside with Cu electrode
- Parallel LC pattern formed with the full back electrode.

Design 2: Alumina with Ag electroding

- **Objective:** To evaluate modelling and testing methodology before high-temperature expeirments.
- Inductor patterned on a dense alumina substrate with 2” x 2” of Ag ground plane and Ag electrode
- Parallel LC pattern formed with the full back electrode.

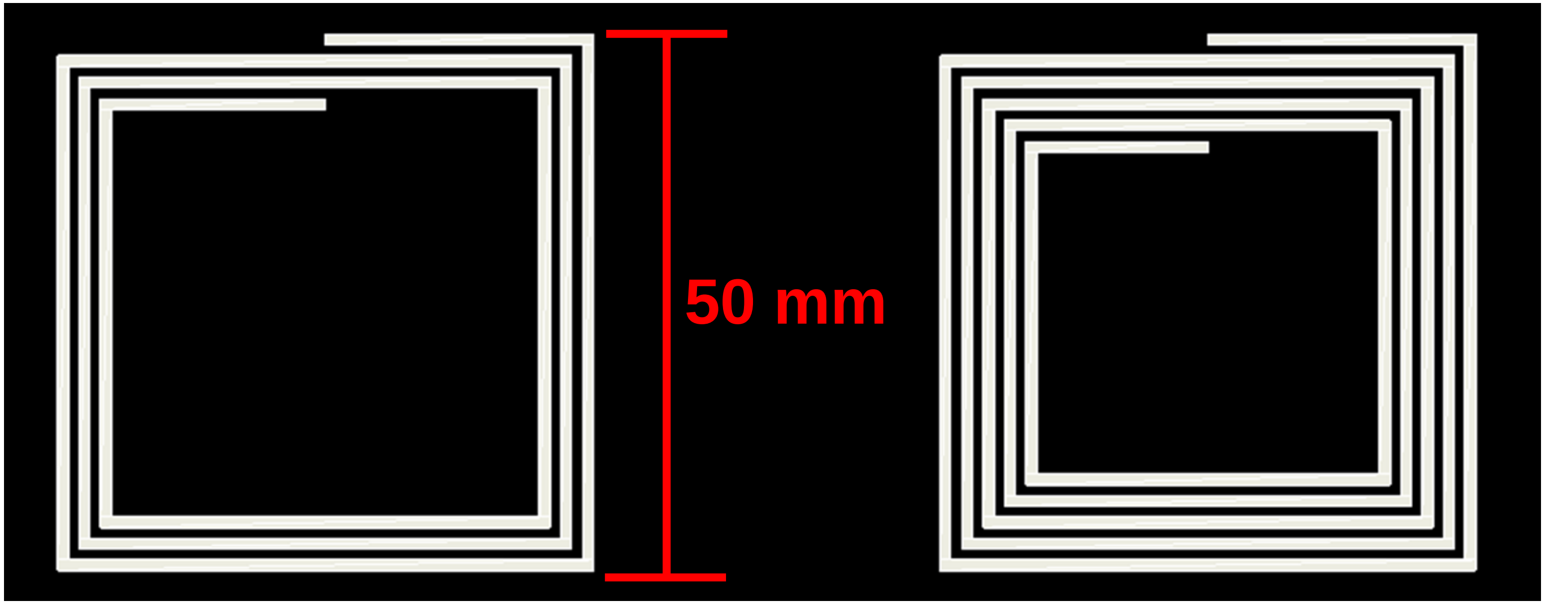
Design 3: Alumina with Ag electroding and stainless-steel ground plane

- **Objective:** To evaluate modelling and testing methodology before high-temperature expeirments.
- Inductor patterned on a dense alumina substrate with ¼” thick stainless steel ground plane with Ag electrode
- Parallel LC pattern formed with the full back electrode.

Design 4: Alumina with ITO electroding

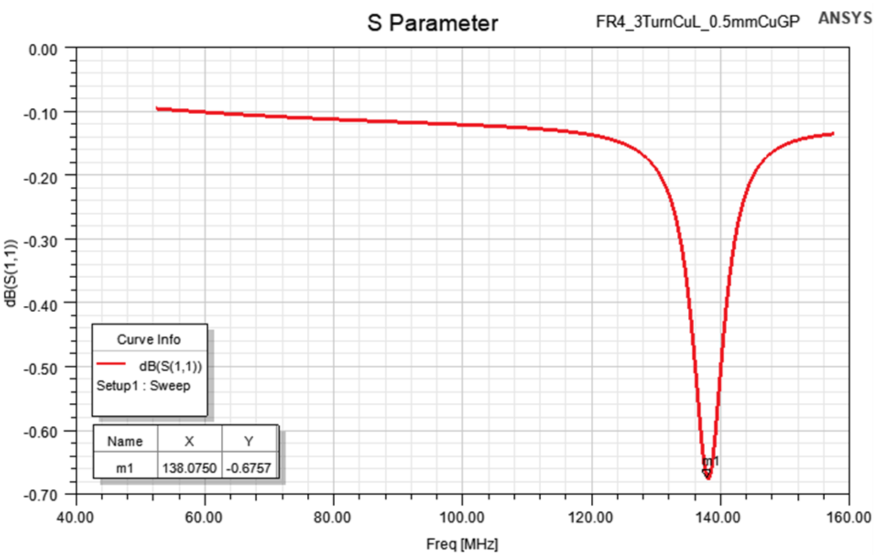
- **Objective:** To evaluate modelling and testing methodology before high-temperature expeirments.
- Inductor patterned on a dense alumina substrate with alumina capacitor printed between ITO
- Parallel LC pattern formed with alumina electrode separator.

Design 1- LC Sensor Using PCB and Cu Electroding:

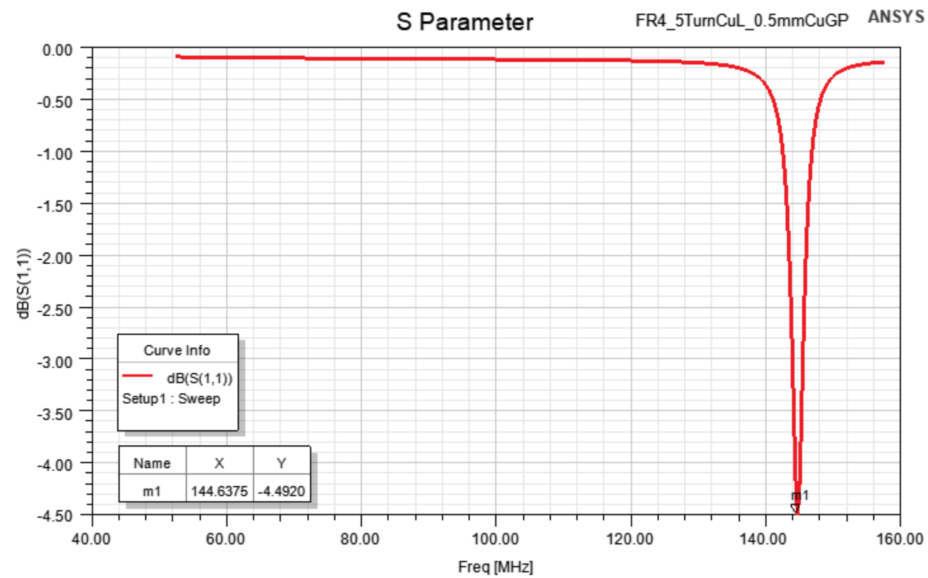


- Initial sensor will be fabricated from off-shelf PCB with Cu electroding.
- Width of lines are 1 mm.
- Single resonance peaks are achieved with both designs (40 MHz-200 MHz).
- 2" x 2" ground plane is fabricated on the back, which forms a parallel compactor with inductor (as inductor electrode acting as one side of the parallel capacitor).

Design 1- LC Using PCB and Cu- ANSYS Model:



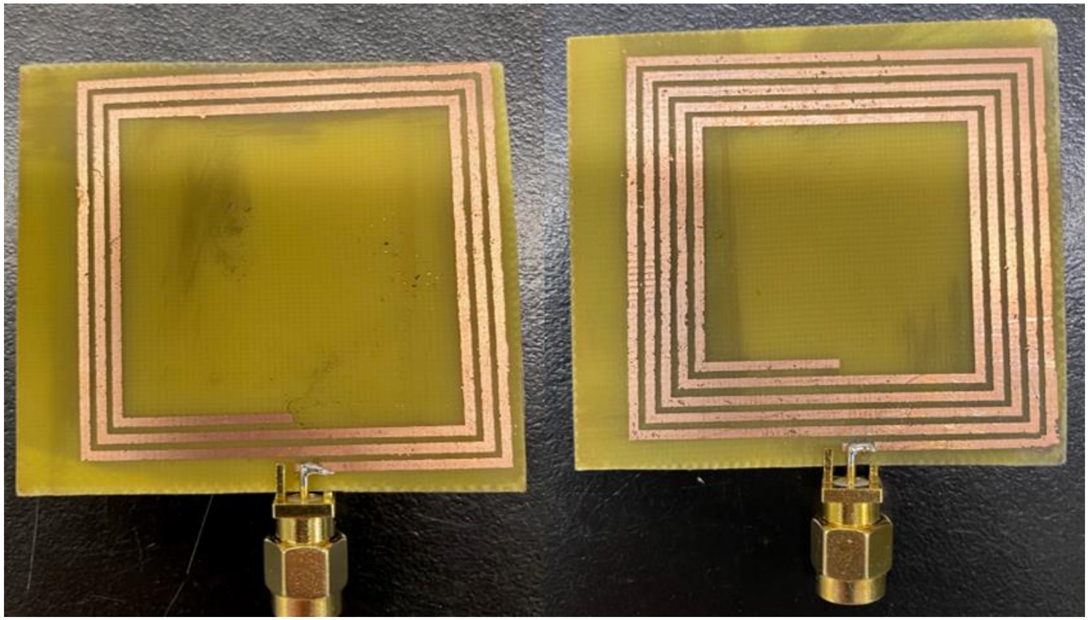
Three-turn S11



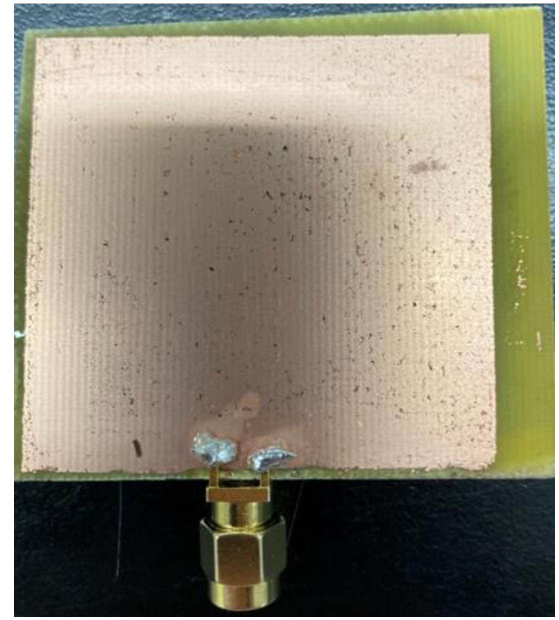
Five-turn S11

- Resonant frequency from three-turn was calculated at 138 MHz.
- Resonant frequency from five-turn was calculated at 145 MHz.

Design 1- LC Sensor Using PCB and Cu Electroding:



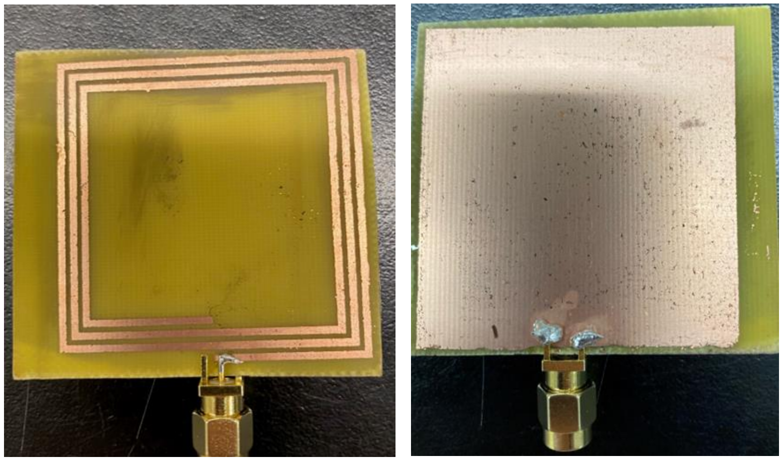
(Three turn and five turn LC on PCB)



(Copper ground plane)

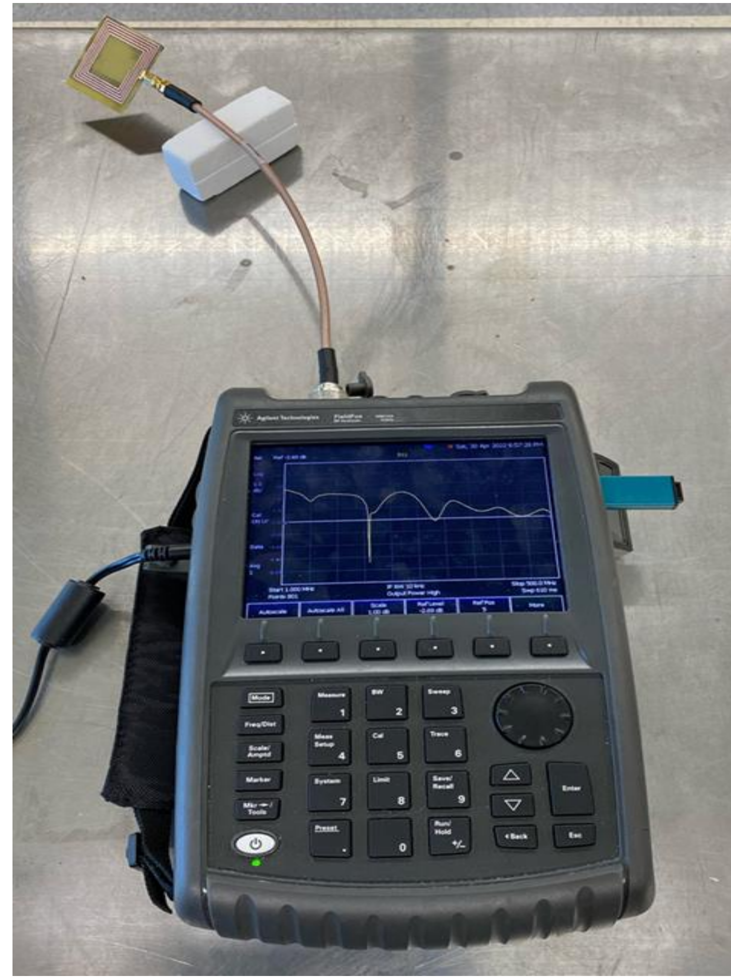
- Both a 3-turn and 5-turn inductor was fabricated on PCB with Cu electroding.
- A negative resist was printed on wax paper and thermally transferred.
- Ferric chloride was used to etch copper followed by acetone removal of the resist.

Design 1- LC Wired Testing Method:



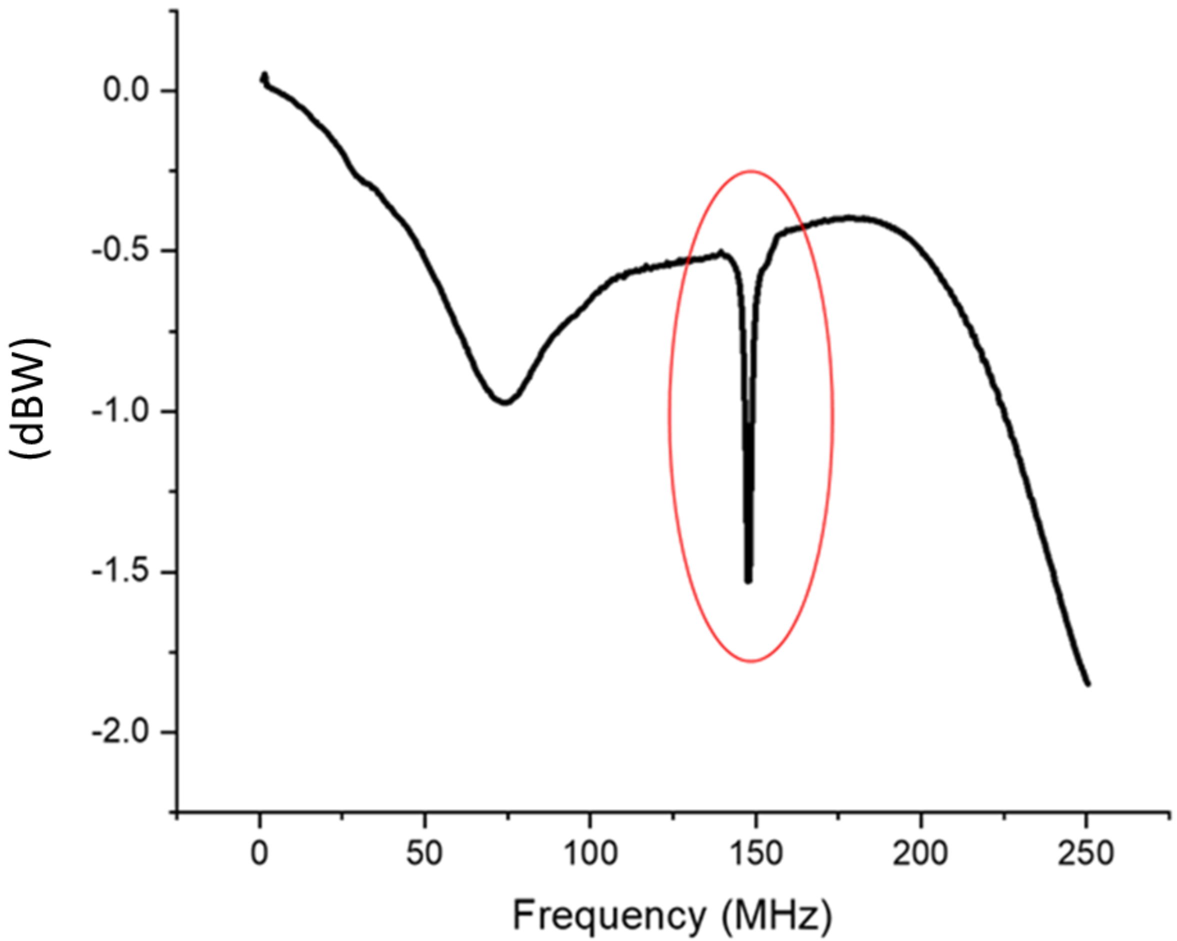
(3-turn PCB based sensor with SMA connection)

- VNA is used for our signal generation with the sensor connected via a coaxial cable and a soldered SMA connection.
- Test completed in air at ambient temperature (not within isolation chamber).
- S11 parameter recorded over a period of 4 h.



(VNA test set-up)

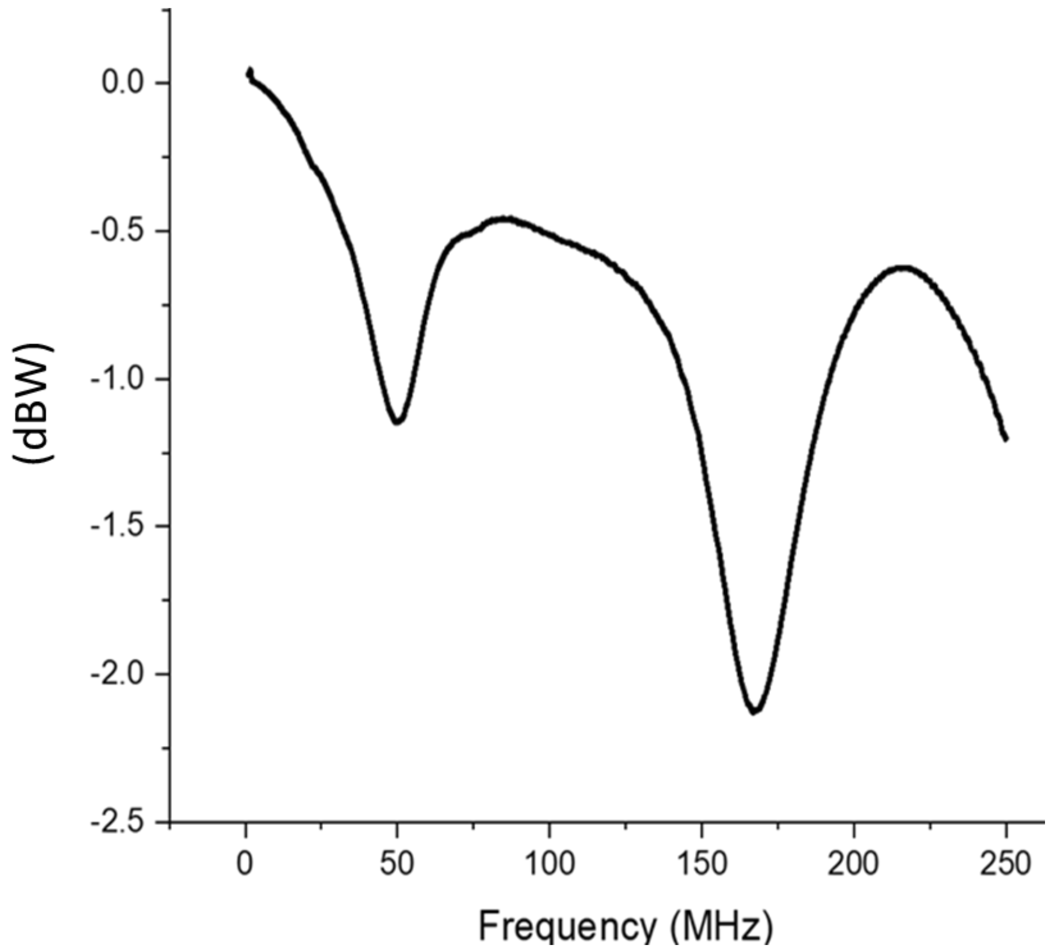
Design 1- LC Wired Testing Results:



3-Turn LC Sensor

- Resonance peak identified at 148 MHz while the model predicted 138 MHz.
- Low reflected power recorded for sensor, showing importance of connection.

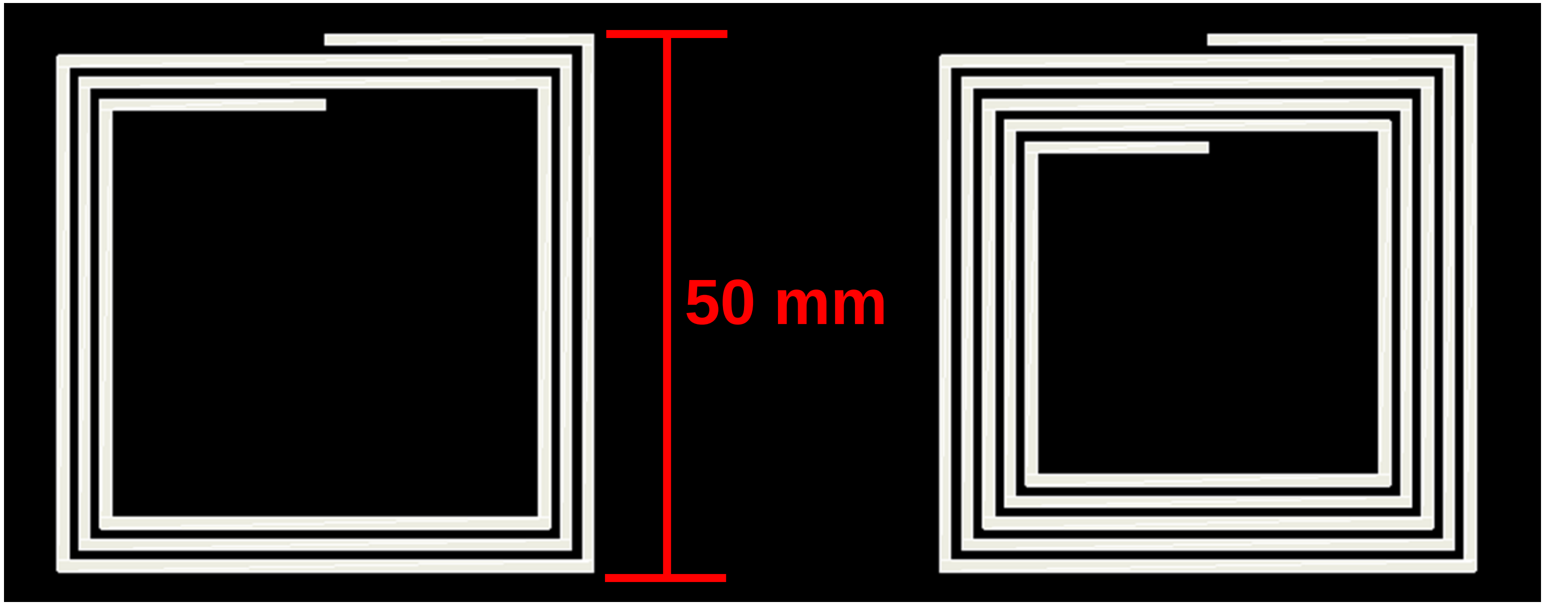
Design 1- LC Wired Testing Results:



5-Turn LC Sensor

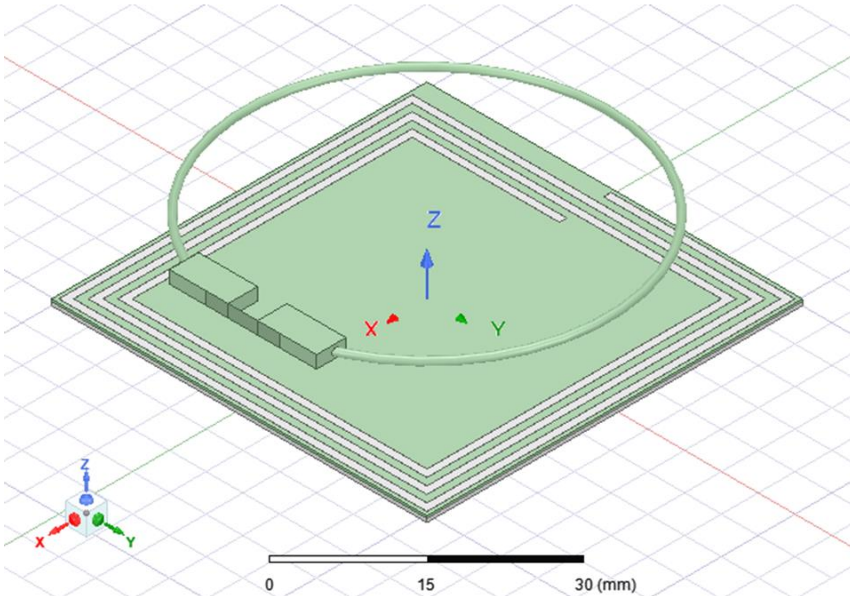
- Resonance peak identified not identified while the model predicted 150 MHz.
- Low reflected power recorded for sensor, showing importance of connection.

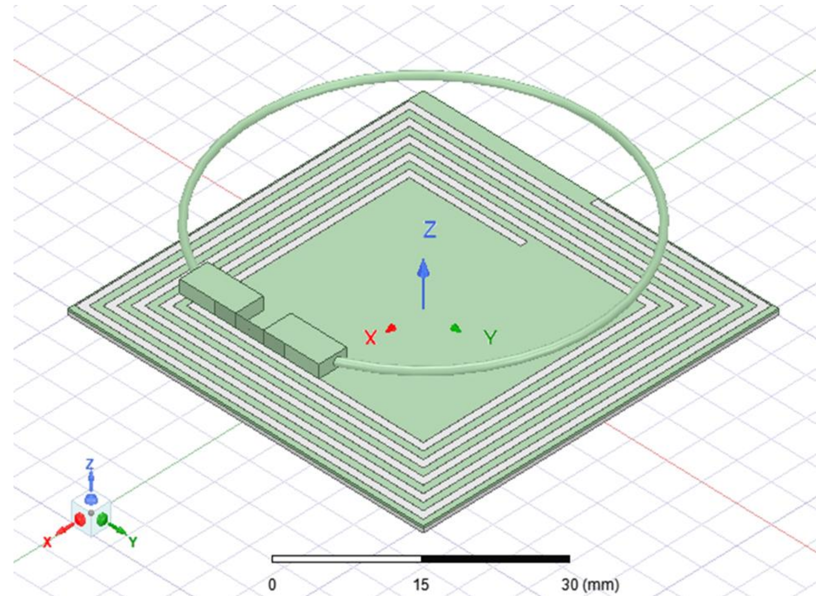
Design 2- LC Using Alumina Substrate and Ag Patterns:



- LC sensor based on the PCB original model and wired results.
- Single resonance peaks are achieved with both designs (40 MHz-200 MHz).
- 2” x 2” ground plane is fabricated on the back which acts as a capacitor.

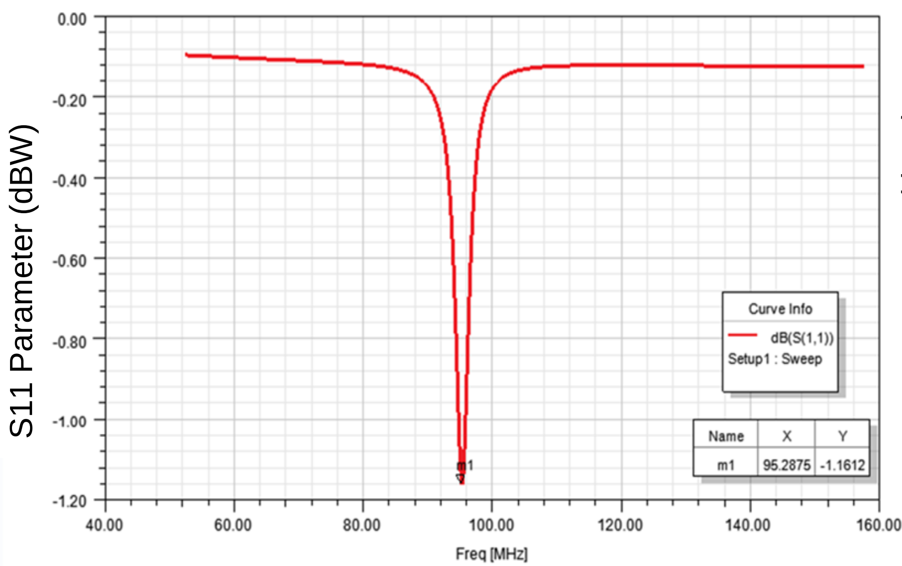
Design 2- Sensor Using Alumina and Ag- ANSYS Model:



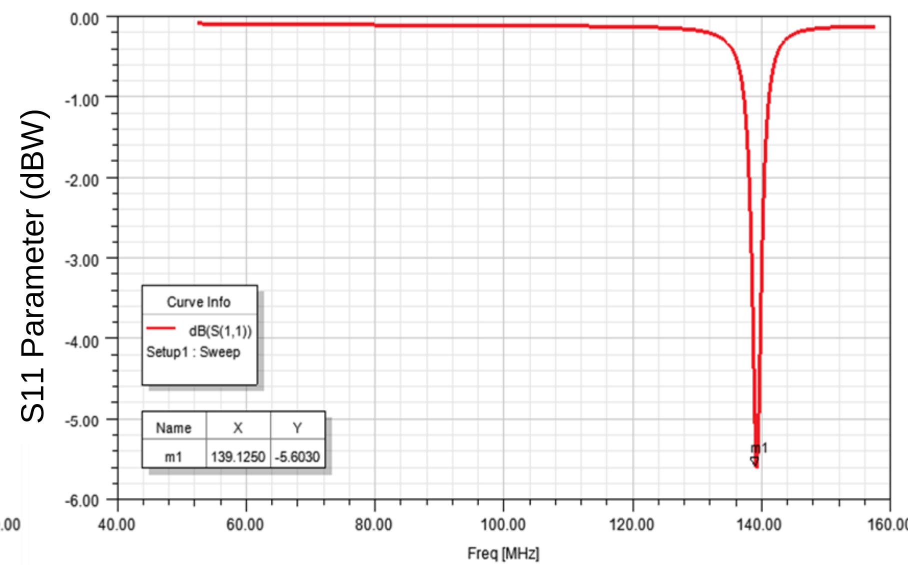


- There is a radiation boundary imposed on an airbox surrounding the entirety of the sensor and excitation components with side length of 75 mm.
- All models were interrogated via lumped port excitation to replicate accurately the antenna interrogation in the experimental work.

Design 2- Sensor Using Alumina and Ag- ANSYS Model Results:



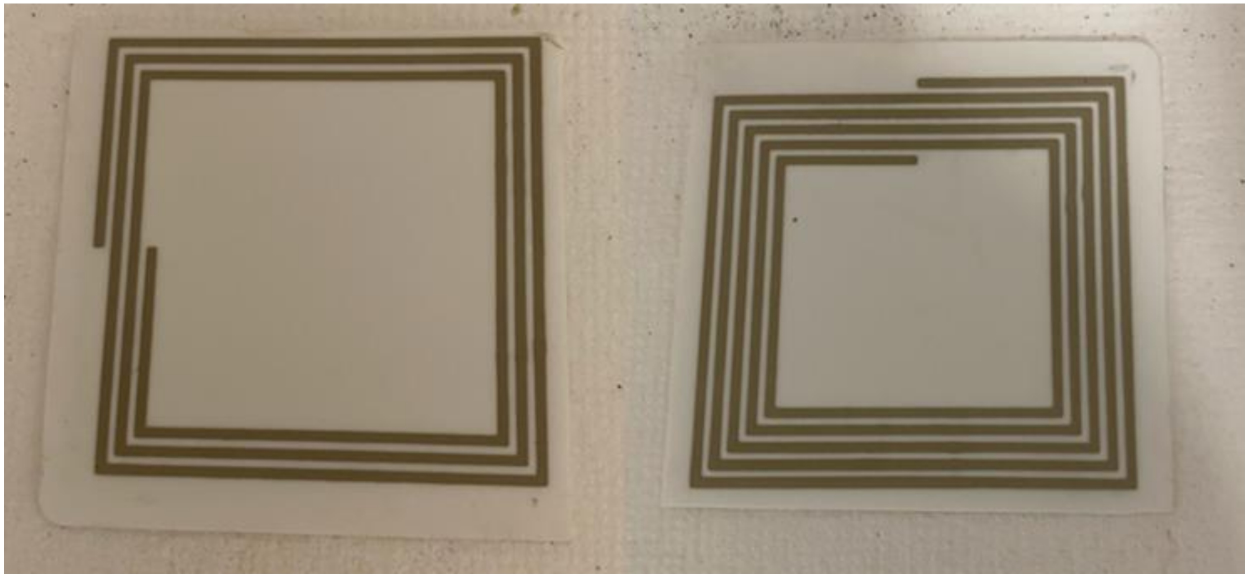
3-turn S11



5-turn S11

- Targeted frequencies of 20 MHz to 200 MHz for all models
- Resonant frequency from 3-turn was calculated at 95 MHz.
- Resonant frequency from f5-turn was calculated at 139 MHz.

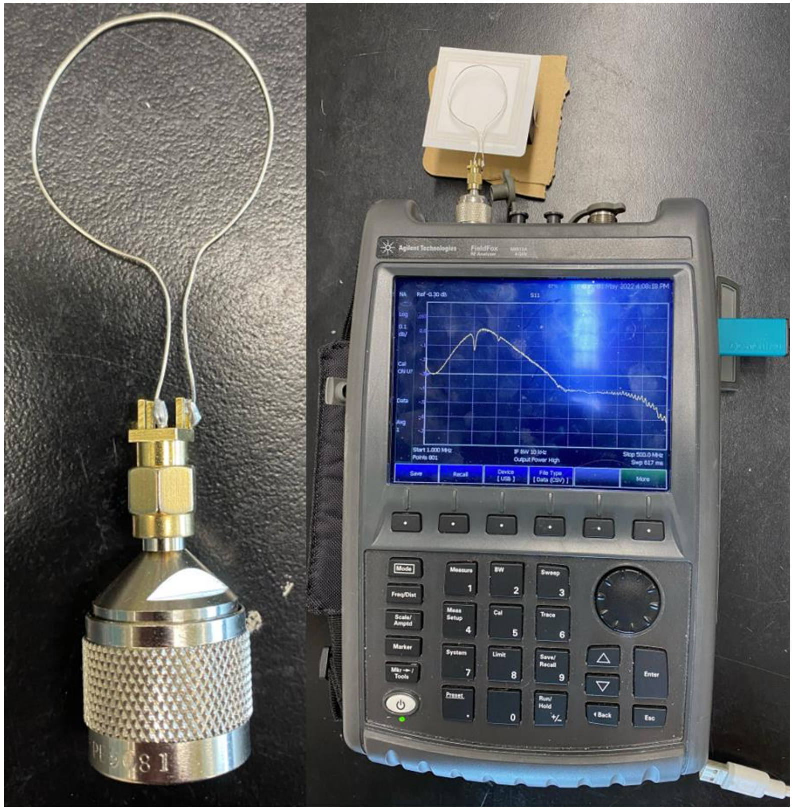
Design 2- LC Using Alumina Substrate and Ag Patterns- Fabrication Technique:

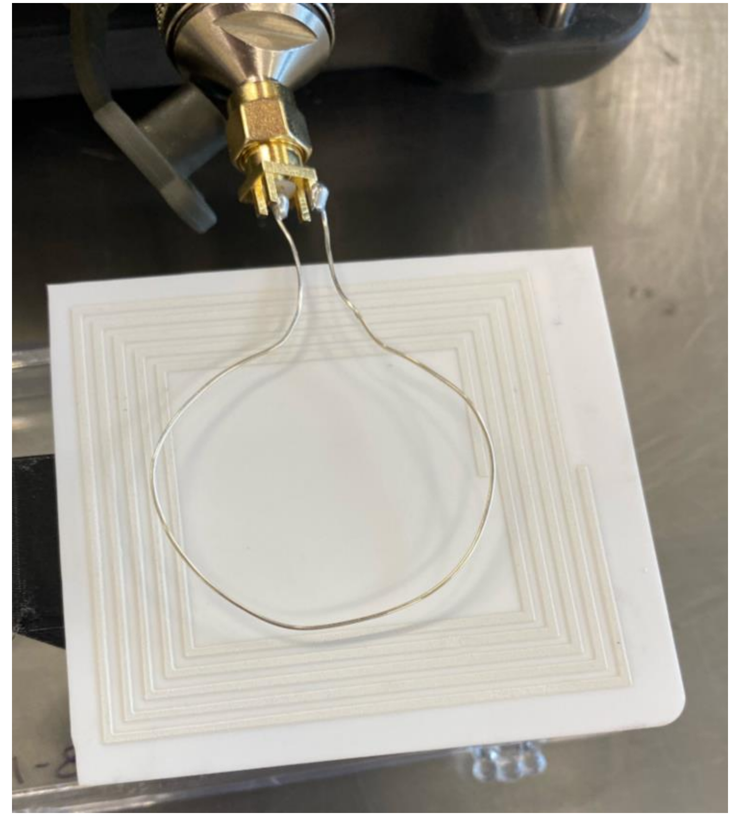


(3-turn and 5-turn alumina based LC with silver ink inductors)

- Alumina substrate was used as the dielectric and the Ag inductor patterns were screen printed.
- Ink synthesized using micron-size Ag particles mixed within a organic vehicle to create a printable ink.
- Sensors were fired at 550 °C to remove the binder and bond the Ag to the alumina substrate.

Design 2- LC Using Alumina Substrate and Ag Patterns- Near-Field Testing:

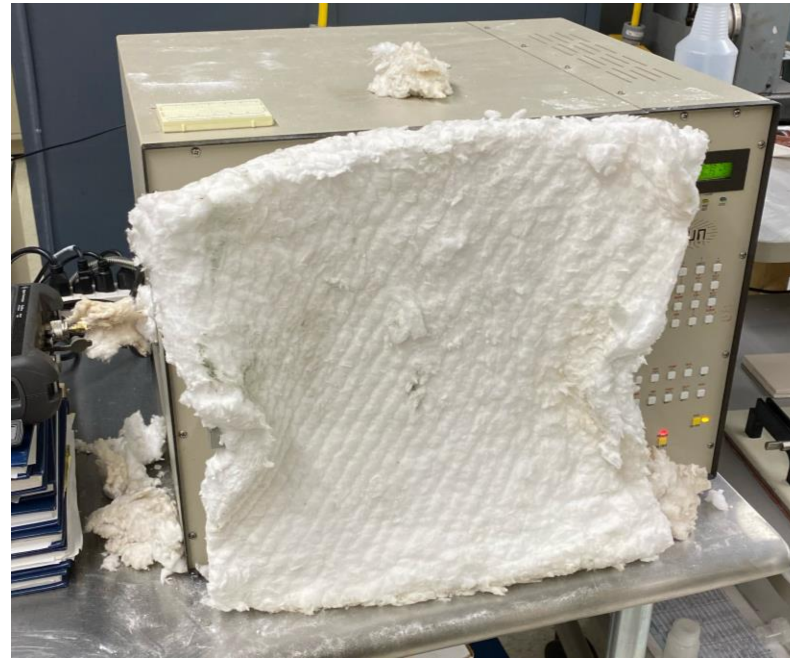




- Silver loop (monopole) antenna was used to test the sample at room temperature.
- VNA set-up to measure S11 parameter wirelessly.
- The sensor where then interrogated 3 cm from the antenna.

Design 2- LC Using Alumina Substrate and Ag Patterns- Near-Field Temperature Testing:

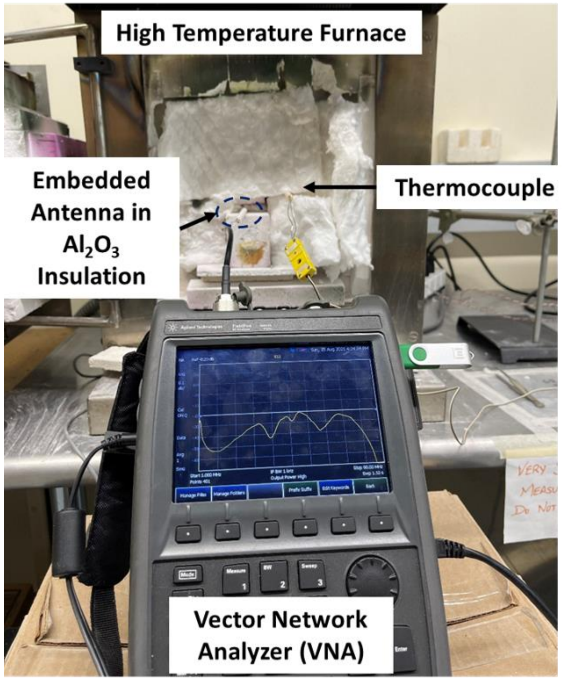
(VNA and antenna attached to environmental chamber)



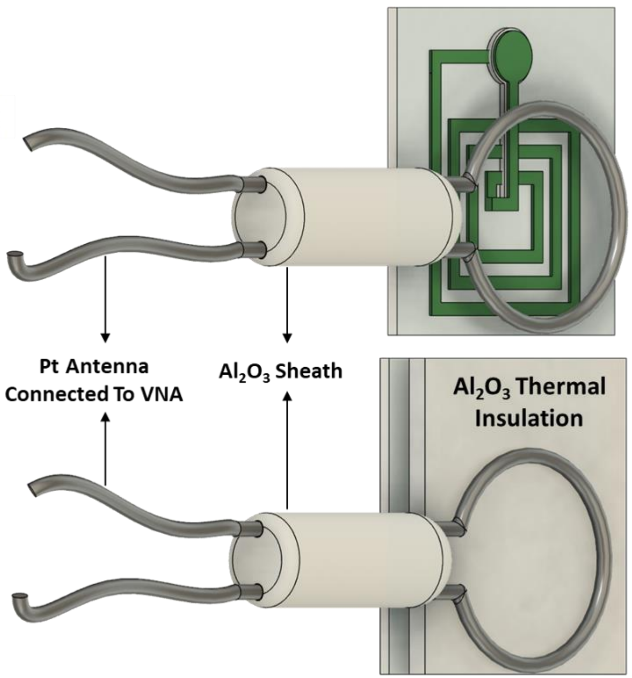
(environmental chamber)

- Connected our VNA testing to an environmental chamber which operates from temperatures 0-300 °C.
- 8 inch silver loop antennae fabricated and inserted within the environmental chamber.
- Wireless interrogation of alumina sensor from 40°C to 280°C

Design 2- LC Using Alumina Substrate and Ag Patterns- Near-Field Temperature Testing:

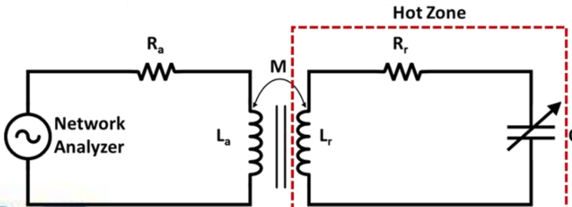


Schematic of Pt Antenna and LC Resonator

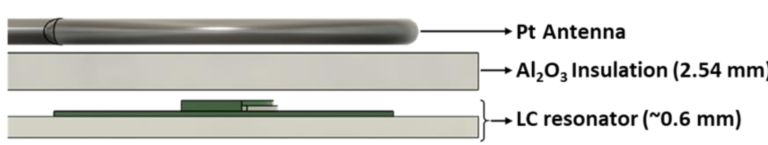


- **Wireless interrogation** is performed by a **single port vector network analyzer (VNA)**.
- S_{11} **– reflection loss** is measured as a **fn. of temperature**.

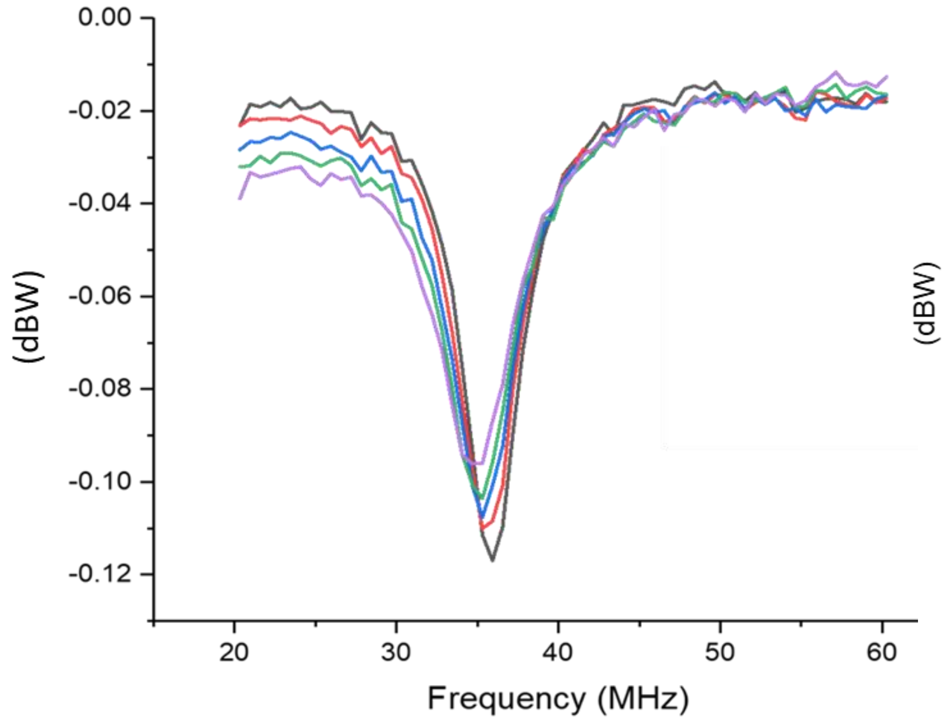
Equivalent Circuit



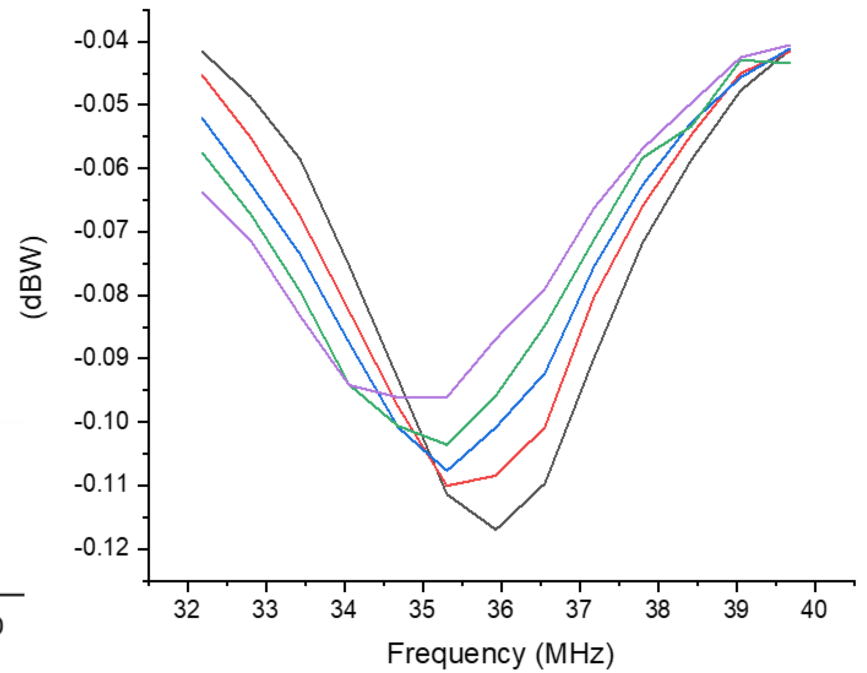
Cross-Section View



Design 2- LC Using Alumina Substrate and Ag Patterns- Near-Field Temperature Testing:



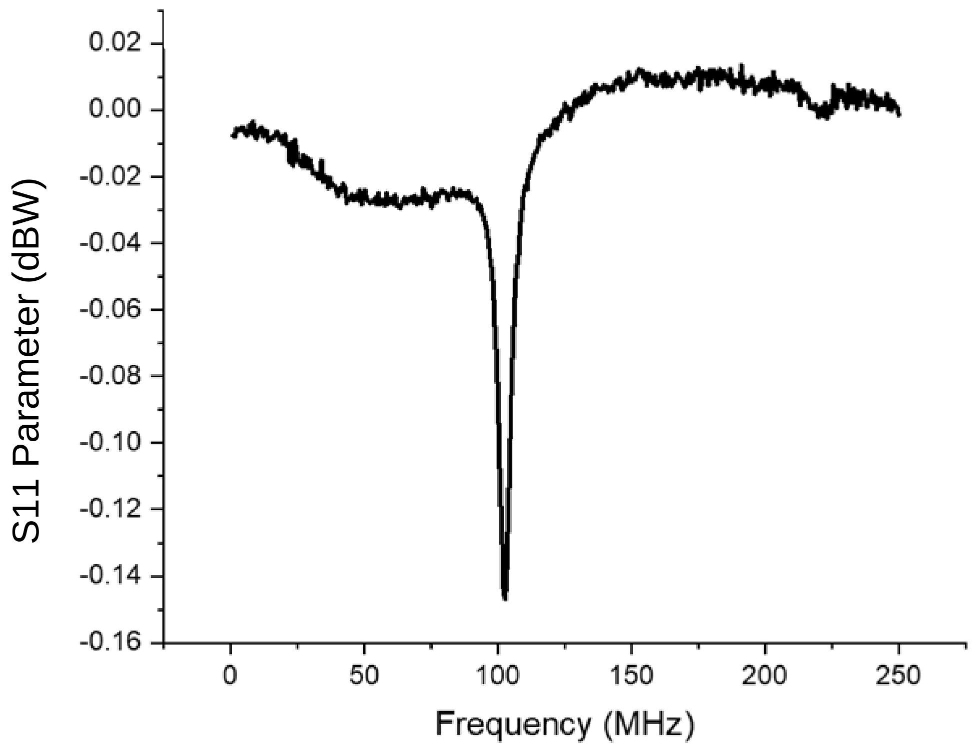
(Resonant frequency peaks at 36 MHz)



(Magnification of peak shift)

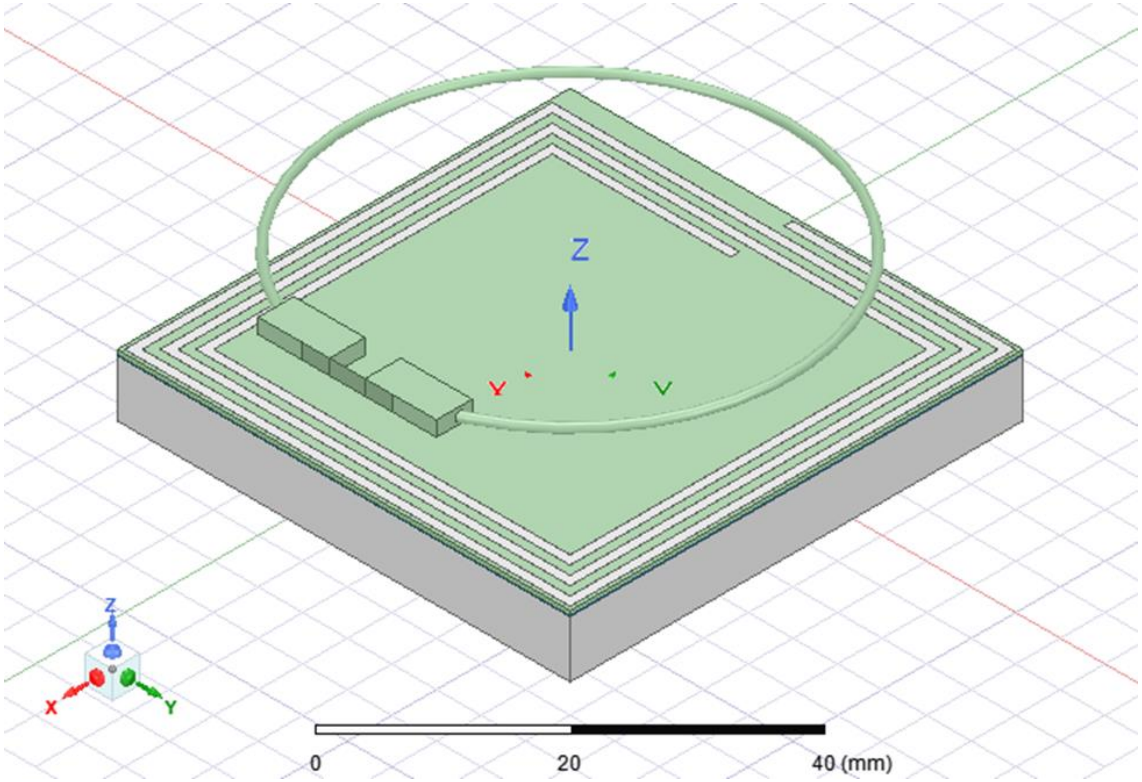
- Downshift in frequency can be seen as temperature increases and a widening of the peaks.
- Frequency shift of 0.0125 MHz per °C was measured from the results.

Design 2- LC Using Alumina Substrate and Ag Patterns- Near-Field Testing:



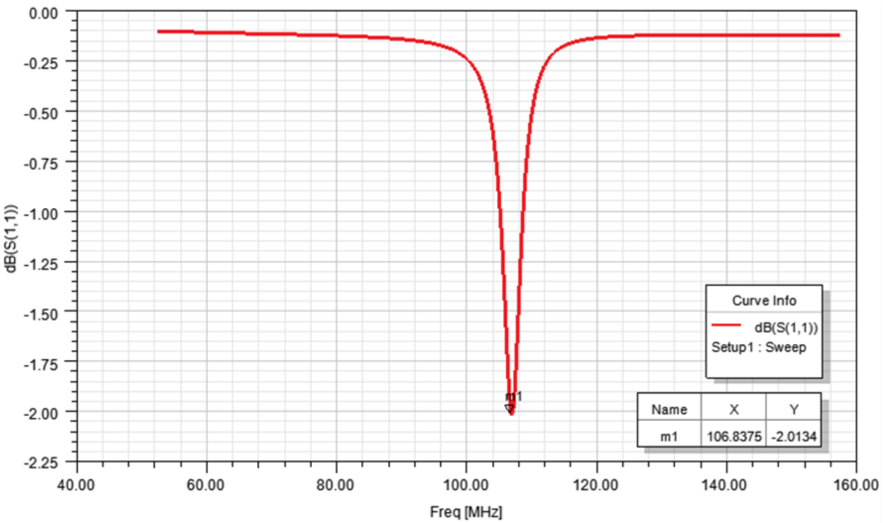
- To maximise signal to noise ratio a reading of the background was recorded and removed from the collected S11.
- Resonant frequency peak can be see at 101 MHz which is in agreement with the ANSYS model at 95 MHz.

Design 3- LC Using Alumina Substrate on Stainless Steel with Ag Patterns- ANSYS Modelling:

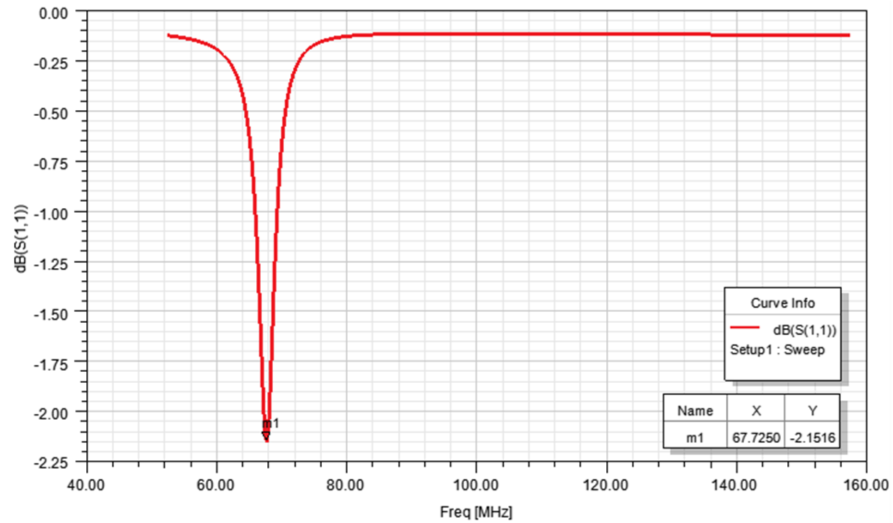


- Three-turn model of alumina based LC sensor bonded to boiler grade stainless steel.
- Model shows ¼" thick ground plane of SS 304H bonded via 50 µm of glass sealing/bonding material.

Design 3- LC Using Alumina Substrate on Stainless Steel with Ag Patterns- ANSYS Modelling:



3-turn S11



5-turn S11

- Resonant frequency from three-turn was calculated at 107 MHz.
- Resonant frequency from five-turn was calculated at 68 MHz.
- Note the stainless steel ground plane greatly downshifts the resonant frequency peak of the five-turn.

Design 4- LC Using Alumina Substrate with ITO Patterns:

- Conventional LC resonator based on mutual inductive coupling method was designed, fabricated and characterized.

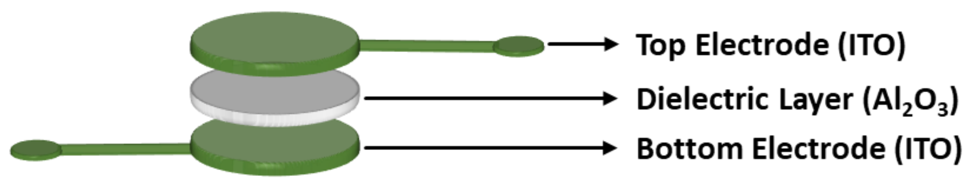
- IDE capacitor replaced with parallel capacitor architecture to increase the capacitance and decrease the geometry (45 × 30 mm).

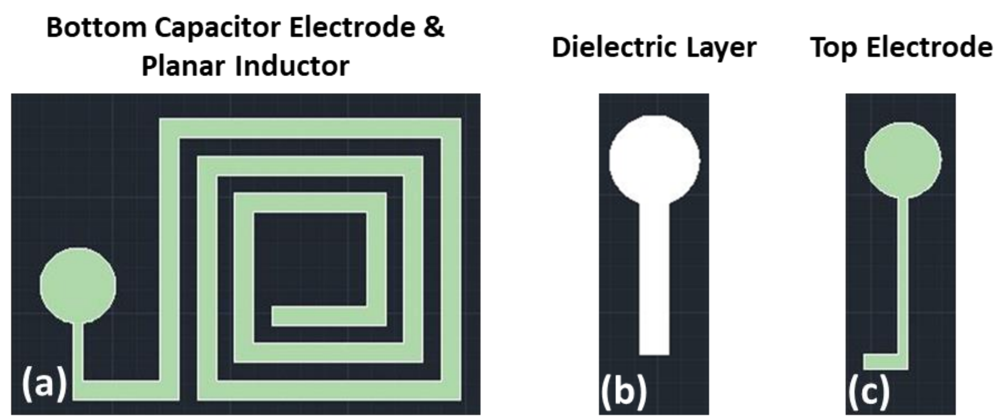
- First layer: Bottom ITO electrode + planar inductor (~40 μm)

- Dielectric Layer: Al_2O_3 (~40 μm)

- Bottom Layer: Top ITO electrode (~40 μm)

Parallel Capacitor Architecture





Design 4- LC Using Alumina Substrate with ITO Patterns- ANSYS Modelling:

Ink Formulation:

- ❖ Organic Vehicle: **Johnson Matthey 62-5 (Ethyl cellulose/terpineol)**
- ❖ Dispersant: **1 drop fish oil**
- ❖ Functional ceramic particles (**ITO**): **35 vol.%** in organic vehicle
- ❖ Dielectric layer for parallel plate capacitor (**Al_2O_3**): **40 vol.%** in organic vehicle

Conventional Screen-Printing:

❖Screen printed directly on the substrate with a **230-mesh screen yielding ~20 µm wet film thickness per layer.**

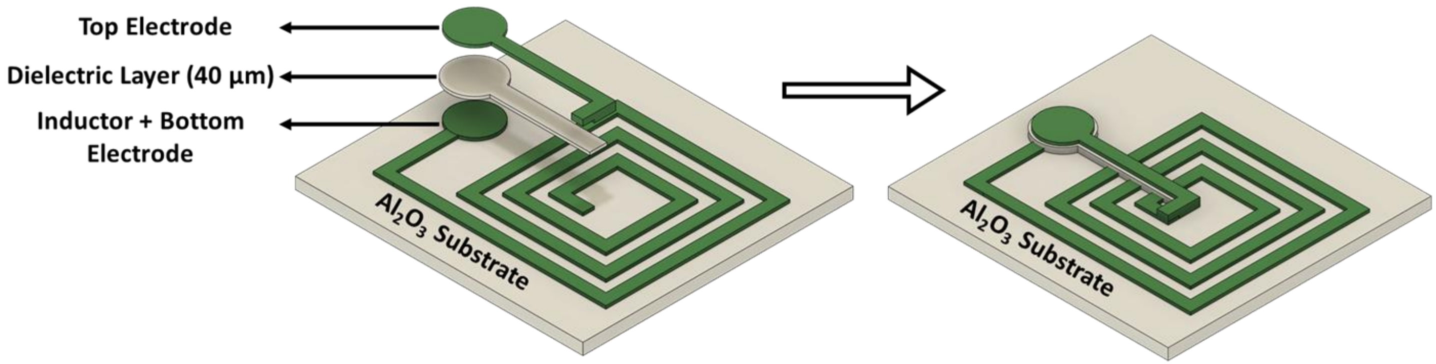
❖**2-layers** of the **ITO electrodes** and the **Al_2O_3 dielectric** was printed on **a 0.5 mm thick Al_2O_3 substrate.**

❖**Co-sintered** at **1250^{o}C for 4 h** in ambient atmosphere conditions.

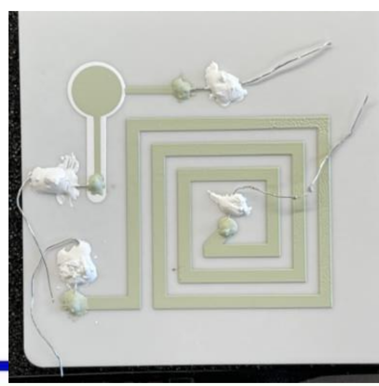
Design 4- LC Using Alumina Substrate with ITO Patterns- ANSYS Modelling:

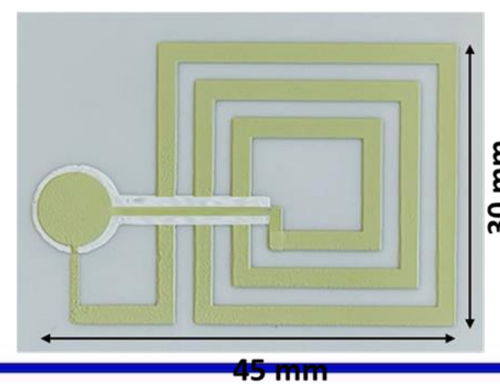
❖Two designs were fabricated:

- ❖**With L and C separated to test the individual parameters of the LC resonator.**
- ❖**Coupled LC circuit.**



L & C separated | **Coupled LC Resonator**





Design 4- ANSYS Electrical Simulation:

Simulated f_r using ANSYS HFSS:

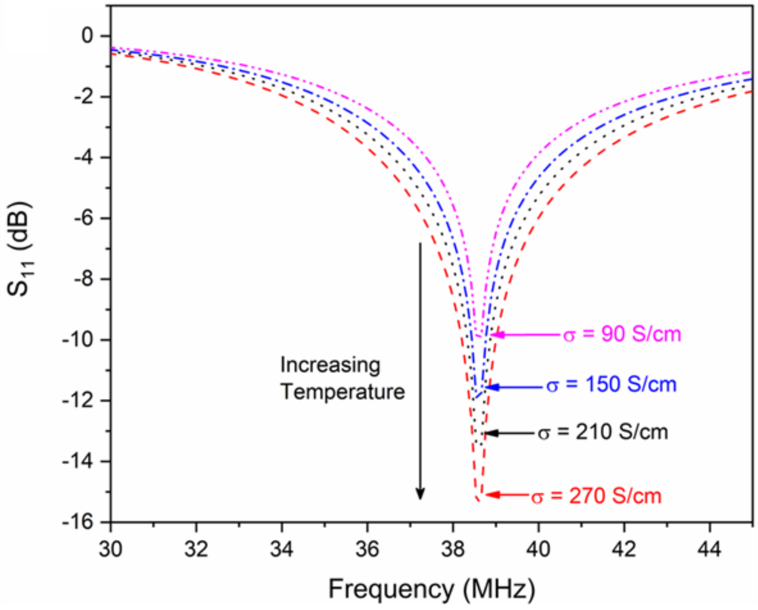
- Electrode conductivity**: 90 S/cm.**
- ε_r-Al_2O_3: **9.6 at room temperature**.
- Dielectric thickness (d): **42 µm**.

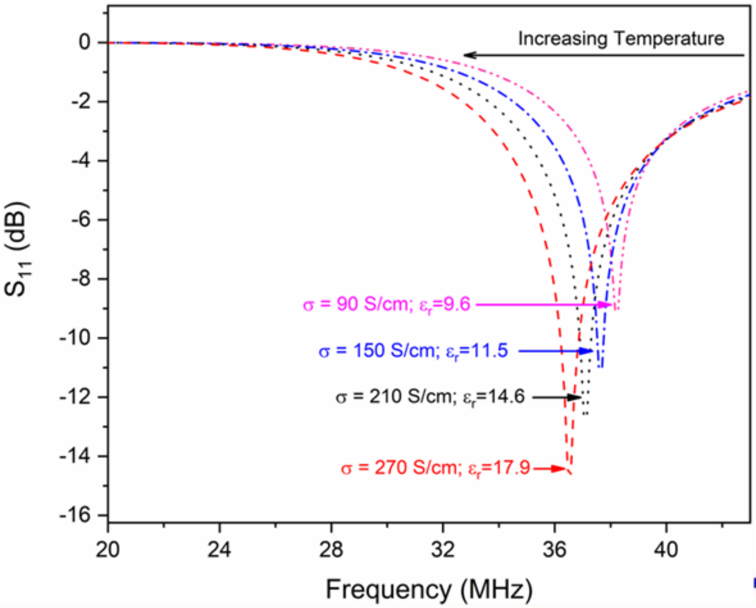
Simulation – 1 (Top):

- Constant $\boldsymbol{\varepsilon_r}$.
- σ increased from 90 – 270 S/cm.
- T↑, Q_f ↑.

Simulation – 2 (Bottom):

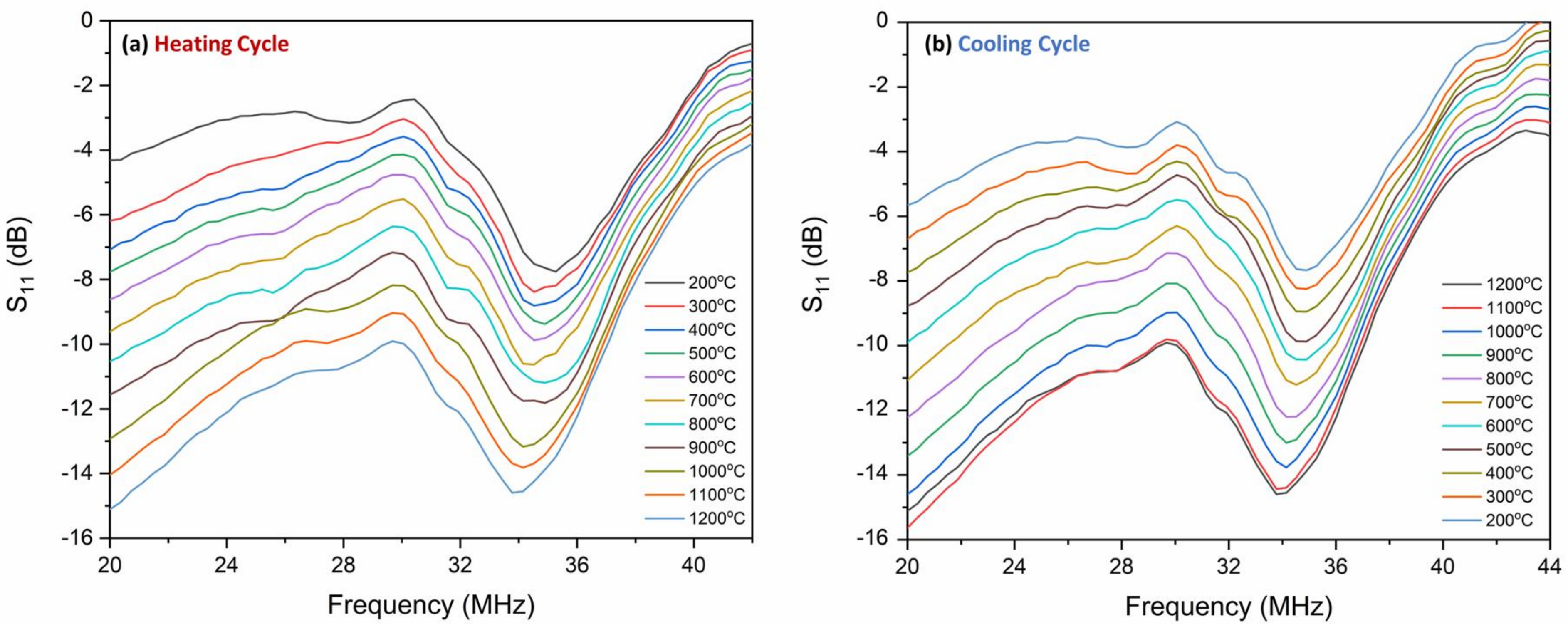
- $\boldsymbol{\varepsilon_r}$ from **room temperature to 1200ºC**.
- **σ increased** from **90 – 270 S/cm**.
- $\boldsymbol{f_r}$ shifts towards **lower MHz**.





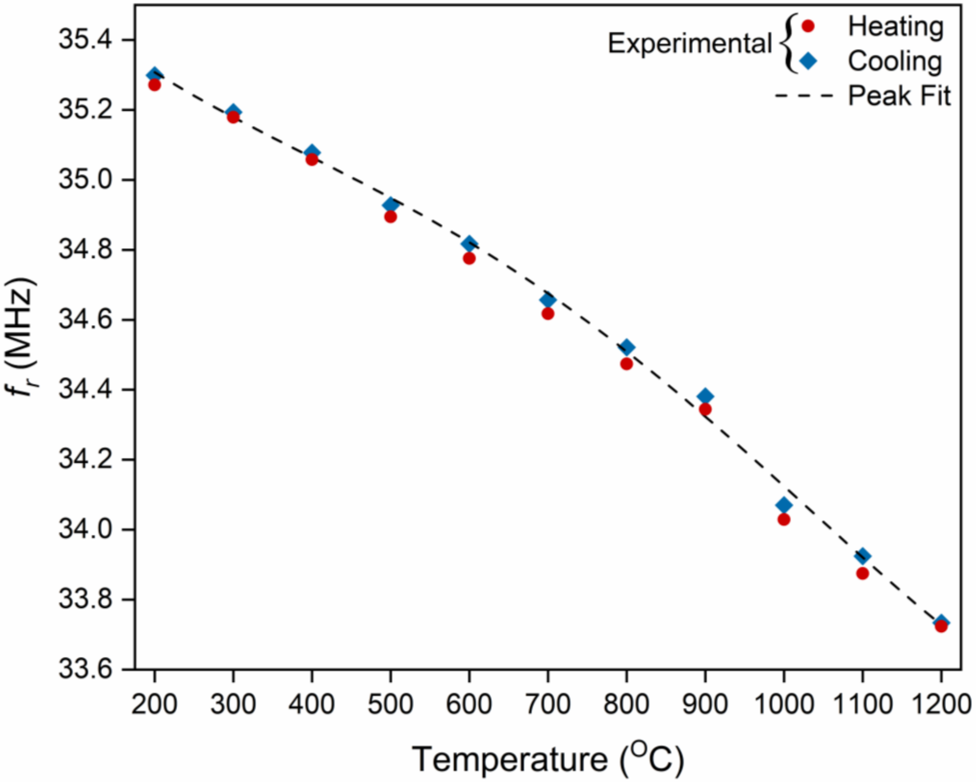
Design 4- Wireless Characterization – Response:

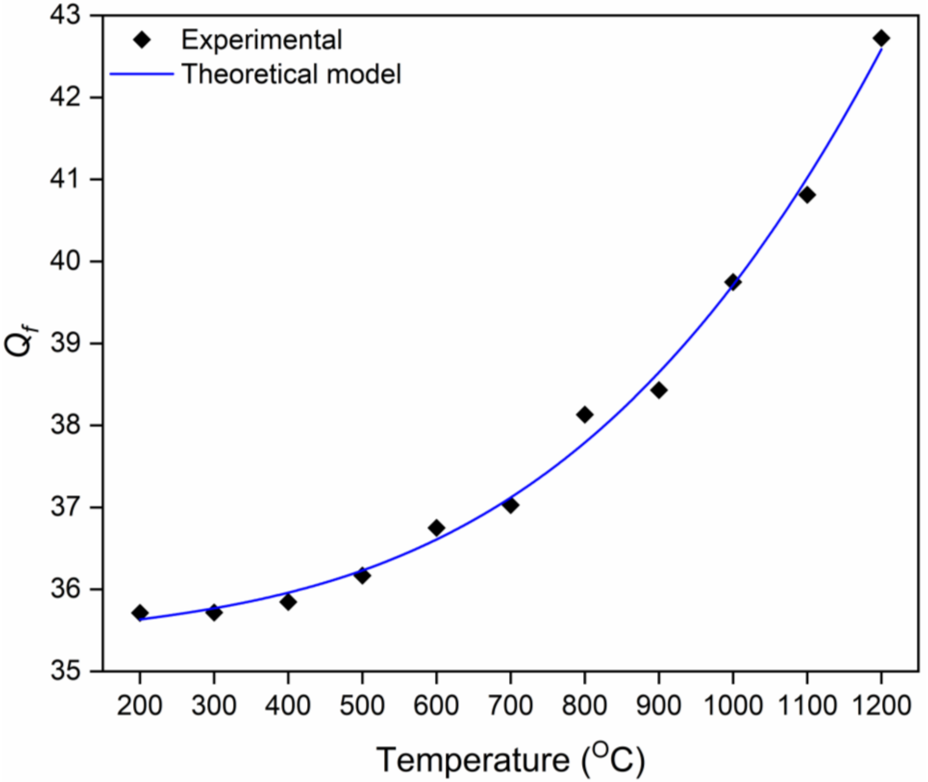
- The wireless characterization was performed from **200 – 1200ºC** to measure the ***f_r* vs T** during the **(a) heating cycle and (b) cooling cycle.**
- **Δ*f_r*** observed **between 32 – 37 MHz.**



Design 4- Wireless Characterization – f_r vs T & Q_f vs T

- The f_r from the **heating** and **cooling** cycle was plotted against T to represent the **frequency response** has a **3rd order polynomial fit**.
- Q_f **increases** as a function of **T** due **semiconducting nature** of the **ITO**.





Brief Task Descriptions Not Initiated as Schedule in SOPO:

Task 4.0 – Development of Embedded Interconnection Design and Smart Anchor Testing

Task 5.0 – Through-Wall Signal Transmission for RFID Wireless Sensor Testing

Task 6.0- Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration (WVU/Longview)

* Tasks will be initiated in next quarter of the program

Near-Term Future Work:

In the coming quarter we plan to:

- Initiate work on method to bond dielectric substrate and/or dielectric/conductor pattern to SS base/corrosion material.
- Investigate the corrosion mechanisms of three boiler grade steels, SS304H SS347H and SS347HFG, before baseline sensor testing.
- Corrode steels at high temperatures and humidity with various coatings and barrier layers over 100 h.
- Continue evaluation of LC sensors at high temperature, especially bonded to SS substrates in both air and humid/air (400-800 °C).
- Correlate corrosion of SS with sensor shift at high temperature in air and humid/air.

Acknowledgments:

- We would like to thank **U.S. Department of Energy (DOE)** for sanctioning this project **DE-FE0031912**.

- **Heather Hunt**, project manager at U. S. Department of Energy, is greatly appreciated for his insight and valuable guidance.

- We also would like to acknowledge Mr. Harley Hart, Dr. Qiang Wang, and Dr. Marcela Redigolo for their cooperation and valuable assistance in the WVU Shared Facilities.

- Kindly acknowledge faculty and staff of West Virginia University for their support.

Thank you!

Questions

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