Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

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Organization: University of Texas Arlington & UCSD

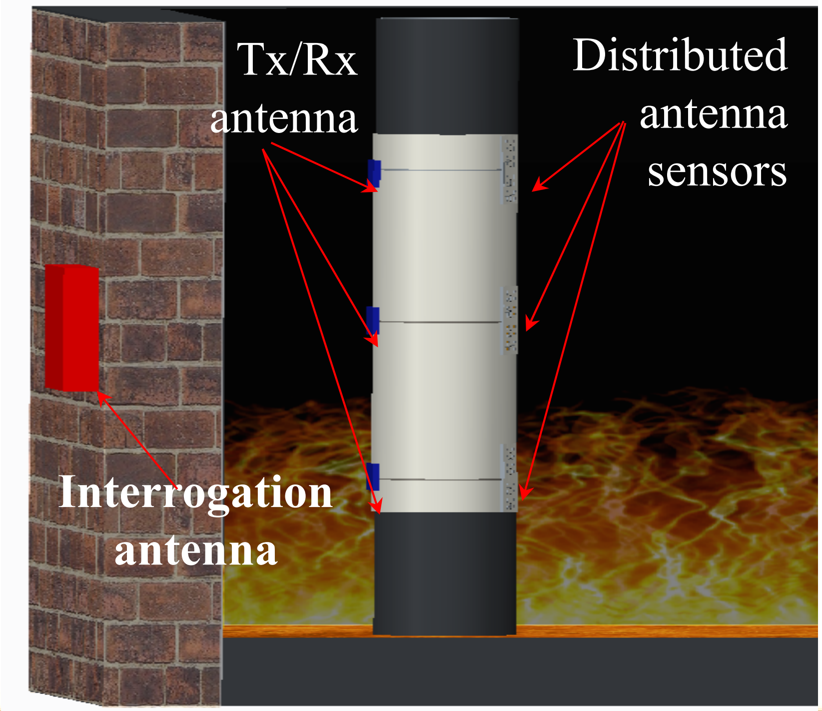
Outline

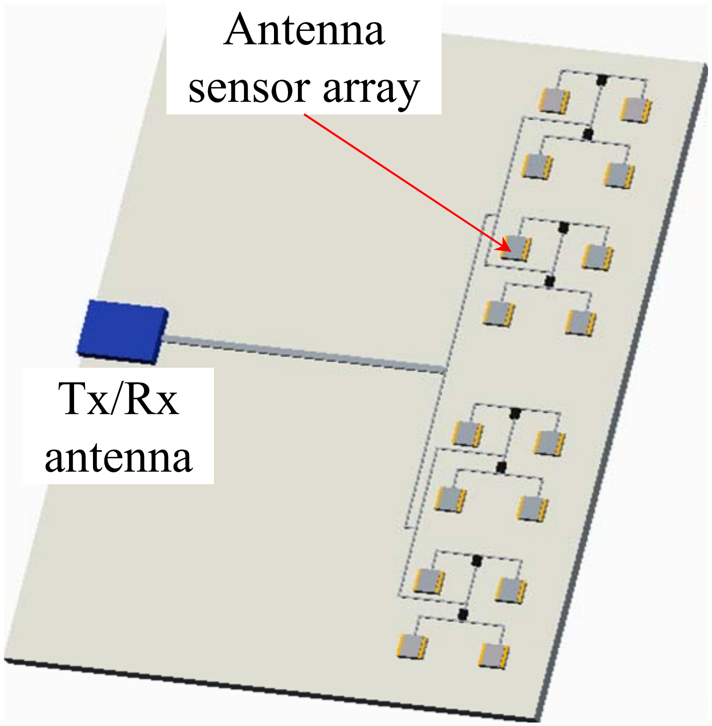
- Technical background/motivation
- Progresses
  - Wireless interrogation of antenna sensor without electronics
  - Sensor fabrication from high temperature materials
  - Dielectric property characterization
  - Efficient antenna simulation model
- Future work
- Q&A

Objectives & Overview

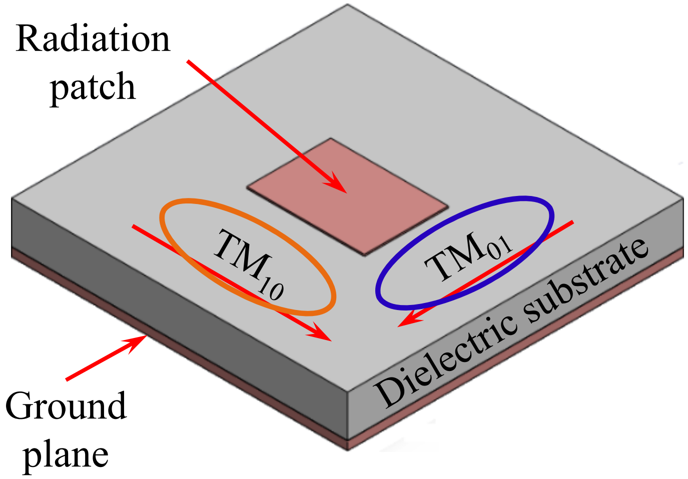
Realize distributed conditioning monitoring of steam pipes up to 1000 ^{o}C

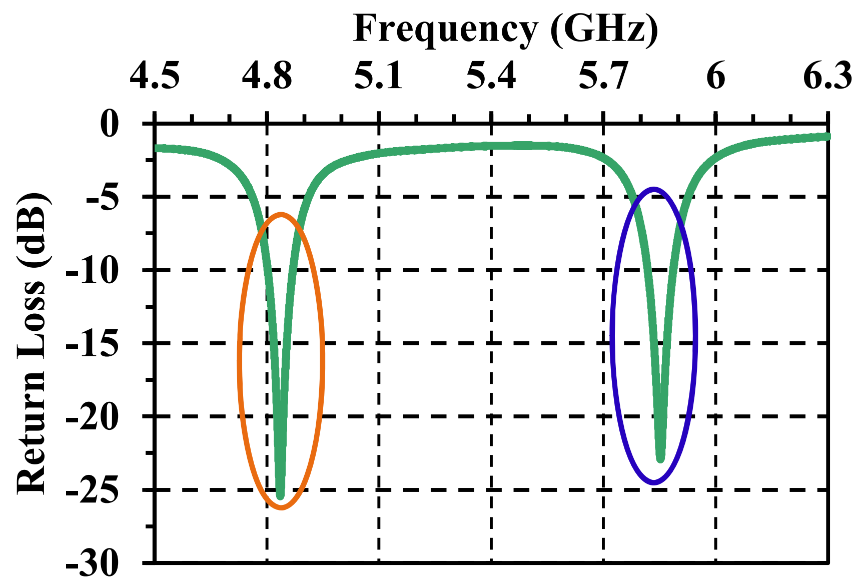
- *Wireless interrogation of flexible antenna sensor arrays*
- *Study material development, sensor design, and multivariant analysis*
- Monitor temperature and strain distribution of steam pipes
- Detect soot accumulation on steam pipes





Microstrip Patch Antenna





$$f = \frac{c}{2\sqrt{\varepsilon_r}\,L}$$

f = antenna resonant frequency
c = speed of light
ε_r = substrate dielectric constant
L = patch dimension along current direction

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Patch Antenna Sensor

$$\varepsilon_{reff} = q_1\varepsilon_1 + q_2\varepsilon_2 + \left(1 - q_1 - q_1\right)$$

$$f = \frac{c}{2\sqrt{\varepsilon_{eff}}\,L}$$

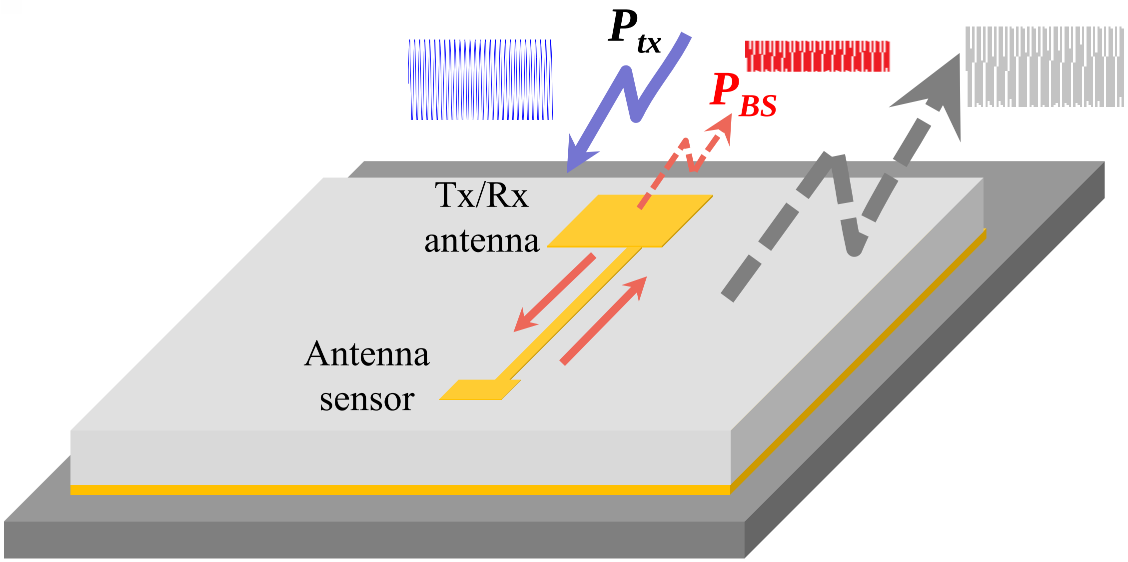
$$\delta f = \frac{\partial f}{\partial \varepsilon_{eff}}\delta\varepsilon_{eff} + \frac{\partial f}{\partial L}\delta L$$

$$\frac{\delta f}{f} = -\frac{1}{2}\frac{\delta\varepsilon_{eff}}{\varepsilon_{eff}} - \frac{\delta L}{L}$$

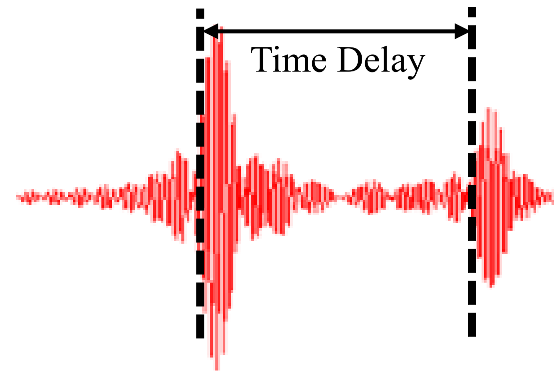
Strain: change dimensions of radiation patch $\delta L/L$
Soot accumulation: change effective dielectric constant $\delta\varepsilon_{eff}/\varepsilon_{eff}$
Temperature: changes both $\delta\varepsilon_{eff}/\varepsilon_{eff}$ and $\delta L/L$

Achievement #1: Wireless Interrogation of Antenna Sensor Without Electronics

Wireless Interrogation of Antenna Sensor

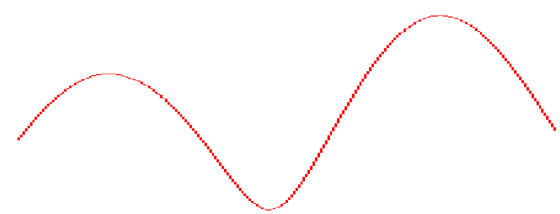


Backscattered Signal



- Tx/Rx antenna
  - Receive interrogation signal over broad bandwidth
  - Transmit antenna backscattering
- Transmission line
  - Delay antenna backscattering
- Antenna sensor
  - Encode temperature info in antenna backscattering

Antenna Backscattering Spectrum



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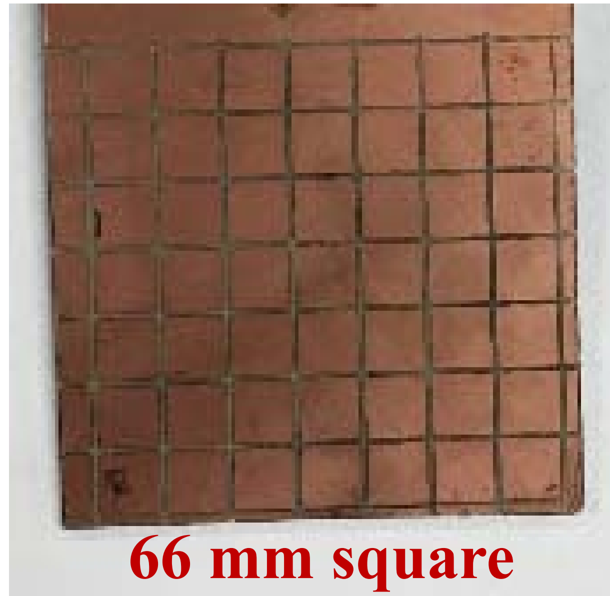
Antenna Sensor Design

- Commercial high frequency circuit laminate (Rogers RO3210)
  - Temperature: up to 300 ^{o}C
  - Dielectric constant: 10.2
  - Thermal coefficient of dielectric constant (TCDk): -459 ppm/°C
  - Coefficient of Thermal Expansion: 13 ppm/°C

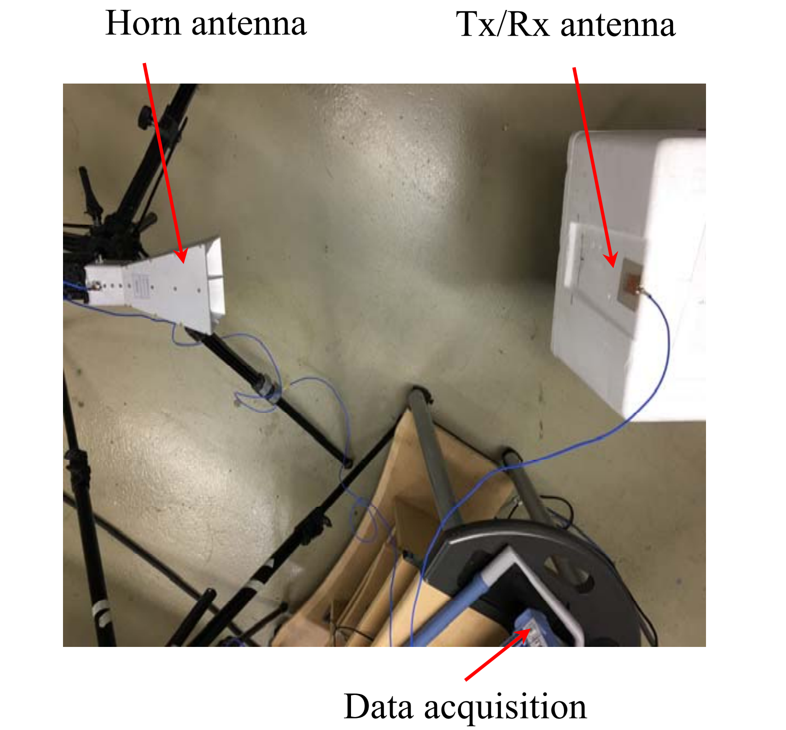
- Antenna sensor parameters
  - Operating frequency: 2.4 GHz
  - Size: 23.8 X17.4 mm^2
  - Transmission line: 200 mm long

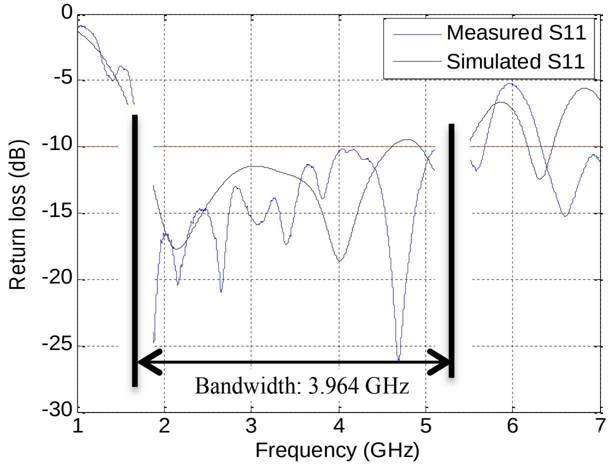
Broadband Tx/Rx Antenna

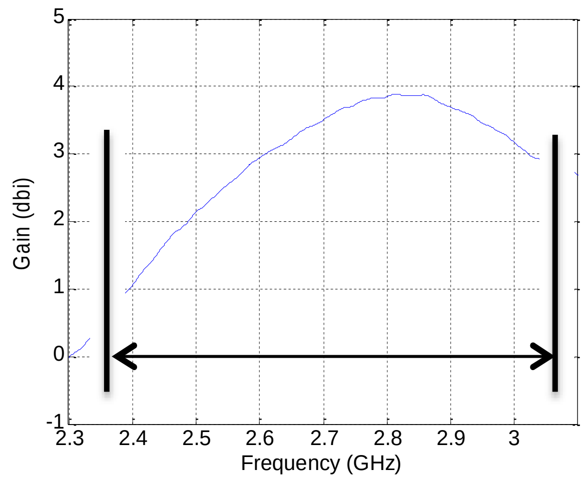


- Radiation patch: conventional design
- Ground plane: Reactive impedance surface (RIS) metamaterial
  - Increase bandwidth
  - Enhance radiation gain

Tx/Rx Antenna Characterization







- Bandwidth: ~ 4 GHz
- Gain: 1-4 dBi @ 2.4-3.6 GHz

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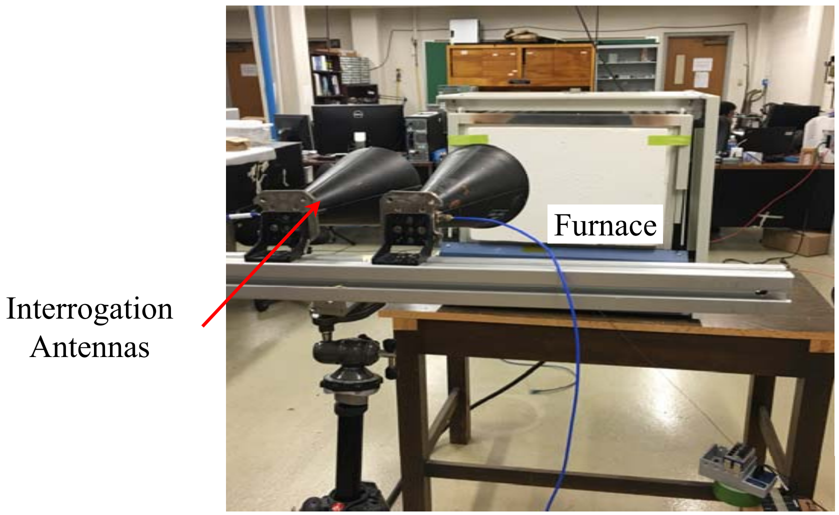
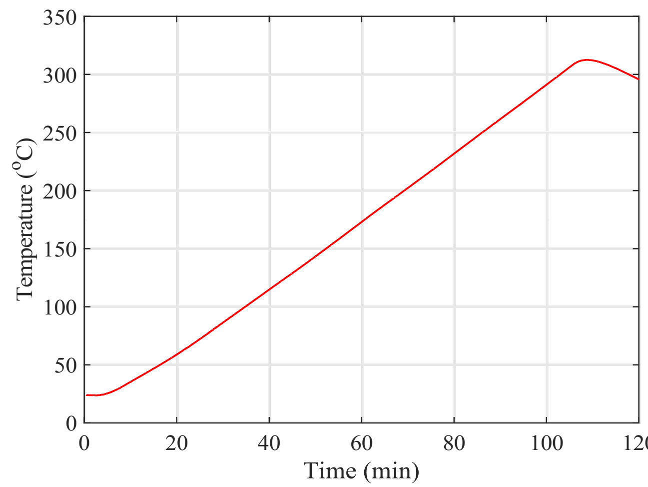
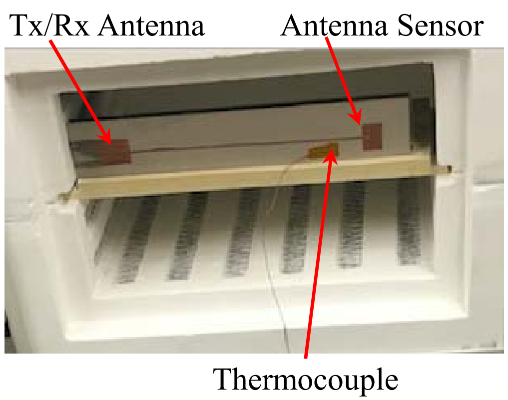
Wireless Interrogation of Antenna Sensor







- Interrogation power: 10 dBm
- Interrogation distance: 0.7 m
- Temperature range: 20-300^{o}C

Digital Signal Processing

Measured S-parameter in frequency domain

↓

Pad the S-parameter with zeros from DC to sweeping start frequency

↓

IFFT

↓

Backscattered signal in time domain

↓

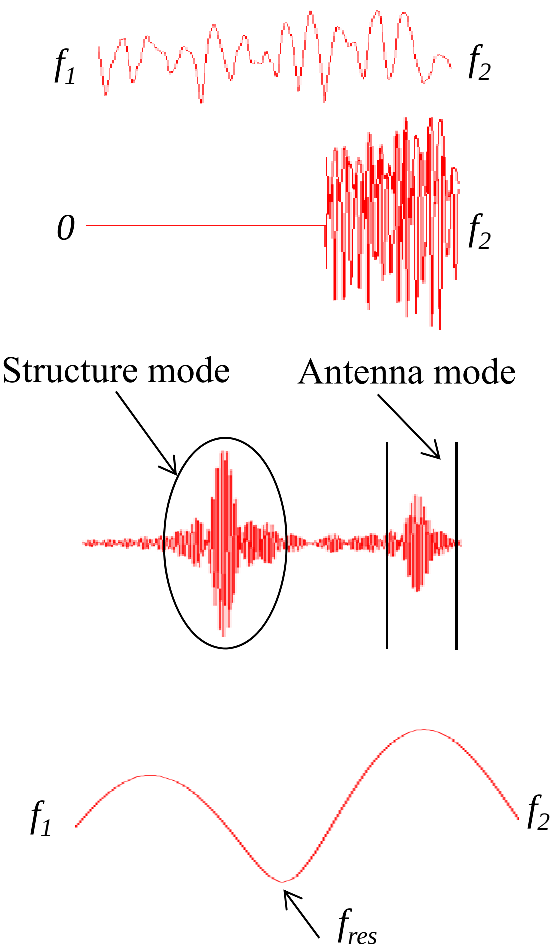
Time Gating

↓

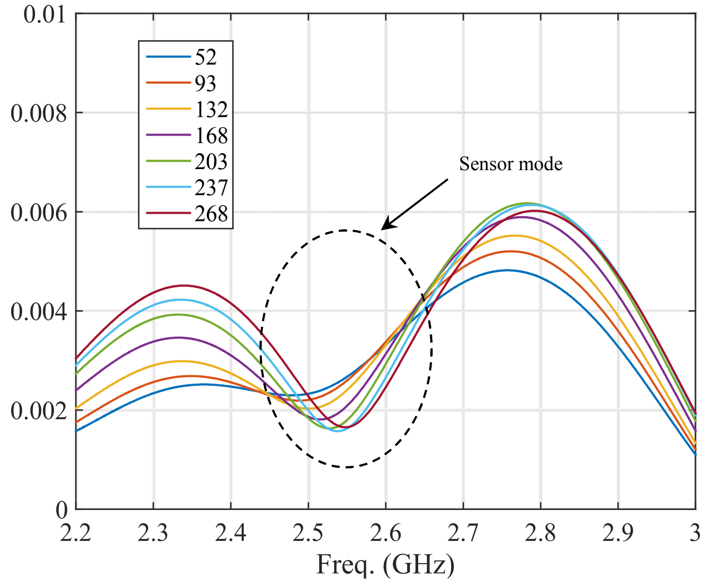
FFT

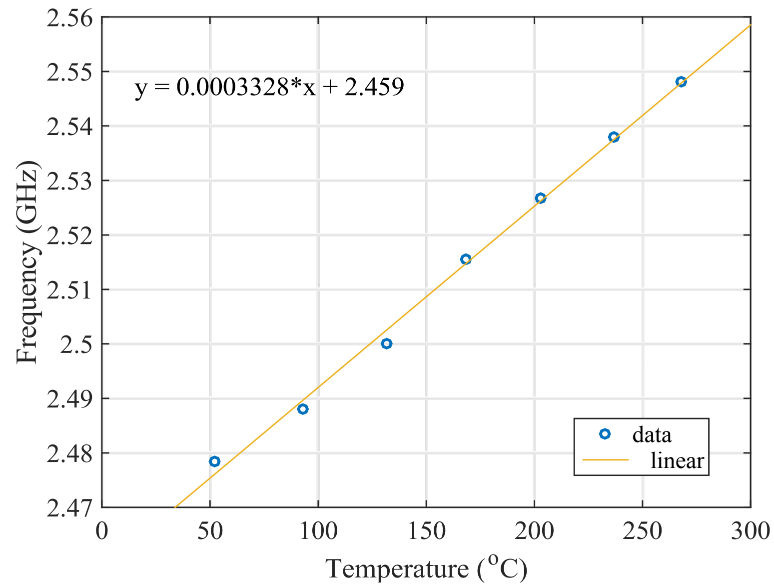
↓

Reflection coefficient of antenna-sensor



Test Results - Wireless Interrogation





- Excellent linearity: $R^2 = 0.996$
- Temperature sensitivity: 332.8 kHz/°C

Instrument used is expensive, slow, & bulky

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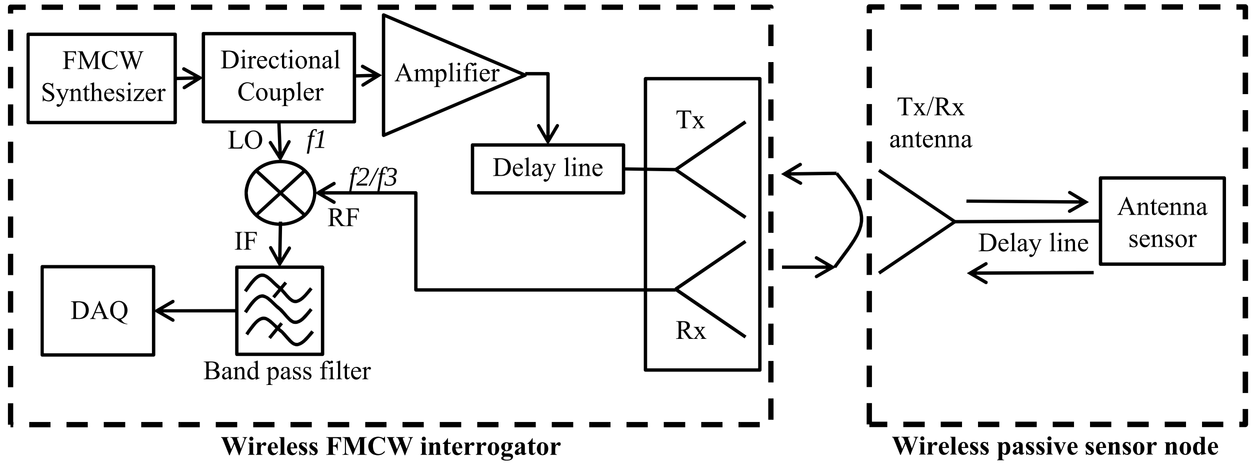
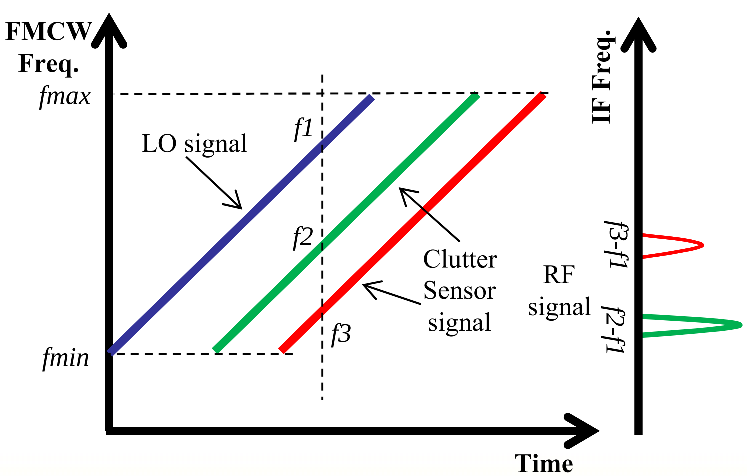
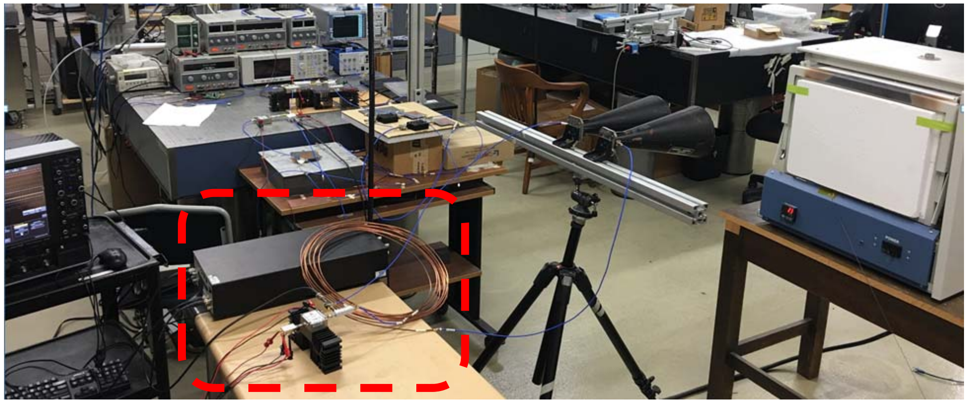
FMCW-based Wireless Interrogator

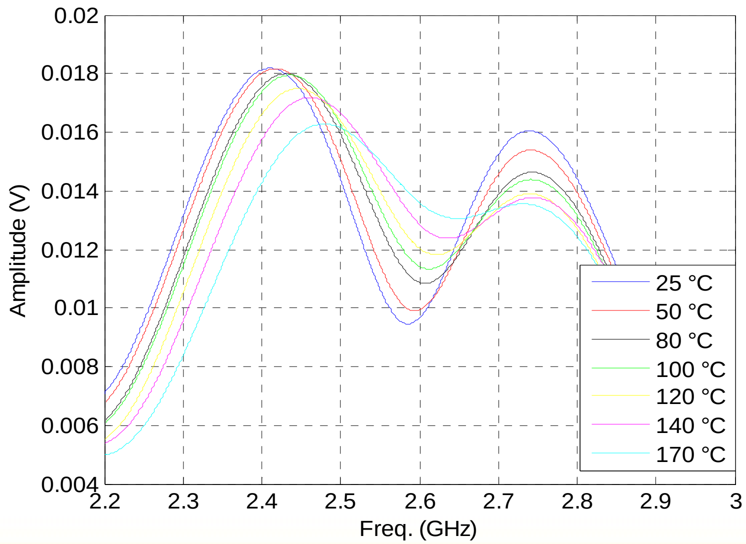


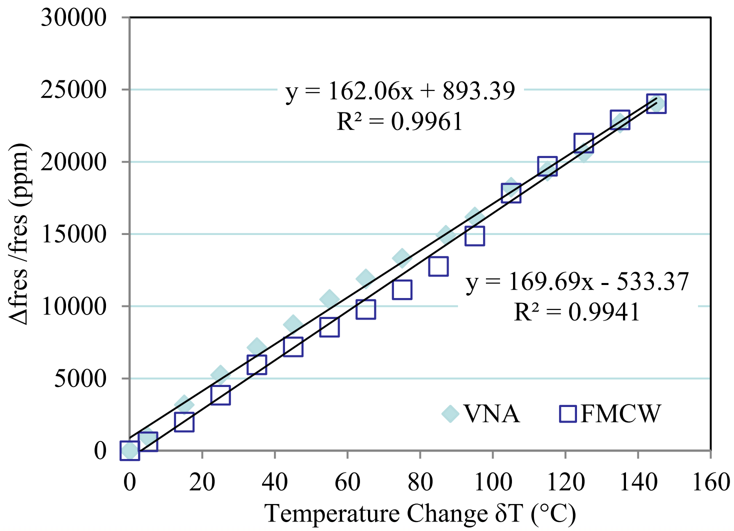


- Lower cost
- Compact
- Faster sampling rate
- Enable sensor multiplexing

FMCW-based Wireless Interrogation







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Achievement #2: Sensor Fabrication for Temperature up to 1000^{o}C

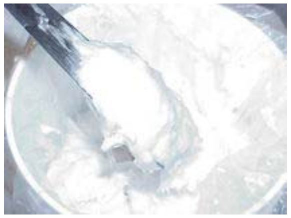
Material Selection

- **Electrode materials**
  - Stable up to 1000°C
  - High electrical conductivity

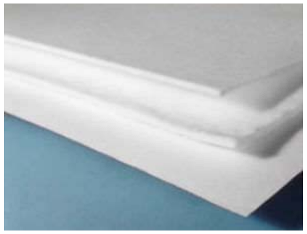
Metals	Electrical Conductivity 10^6 S/m	Melting point °C	High Temp. Stability in air
Copper	58.5	1085	Poor
Gold	44.2	1064	Good
Aluminum	36.9	660	Poor
Zinc	16.6	420	Poor
Nickel	**14.3**	**1455**	**Poor**
Platinum	**9.3**	**1768**	**Good**

- **Substrate material**
  - Stable up to 1000°C
  - Temperature-depend dielectric constant
  - Low tangent loss

Alumina Wafer

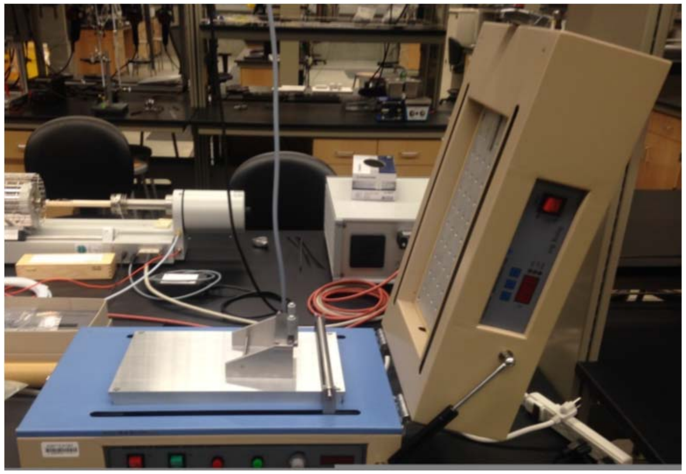


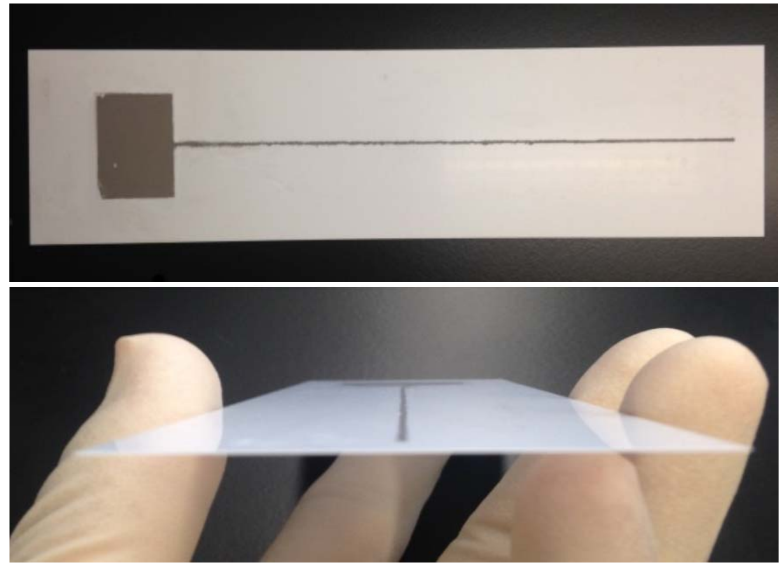
Alumina Paste



Alumina Paper

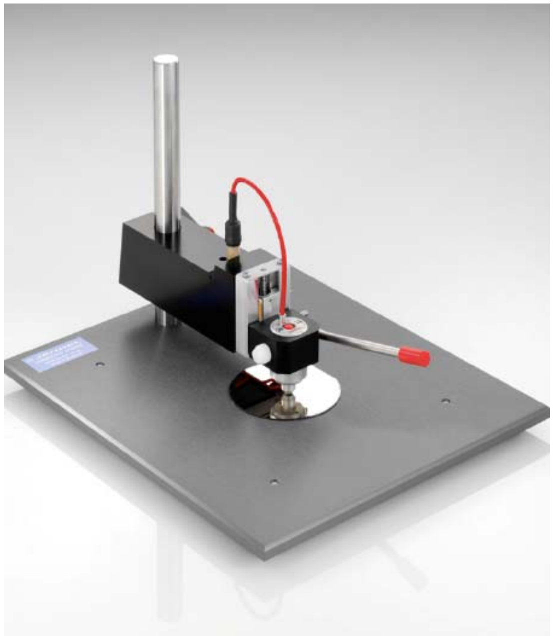
Sensor Fabrication





- Tape casting using platinum paste
  - Well established for fabricating layered structures
- Adhesive masks for precise control of radiation patch pattern
- Improve conductivity
  - Vacuum-assisted drying for reducing pores
  - Multilayer pasting to achieve thicker electrodes

Sheet Resistance Characterization

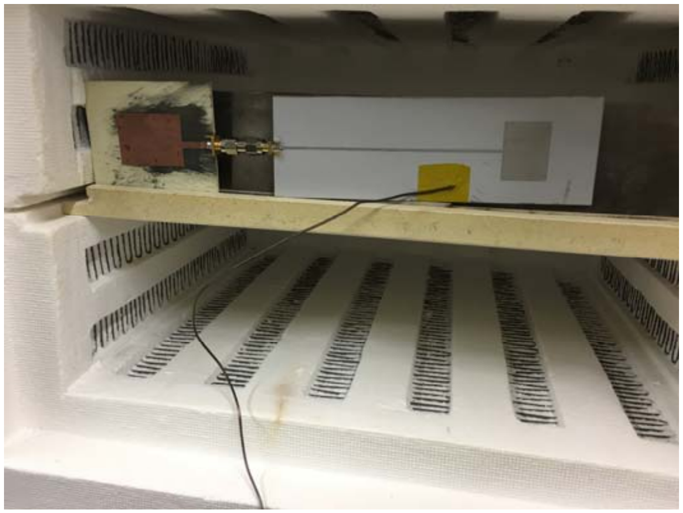


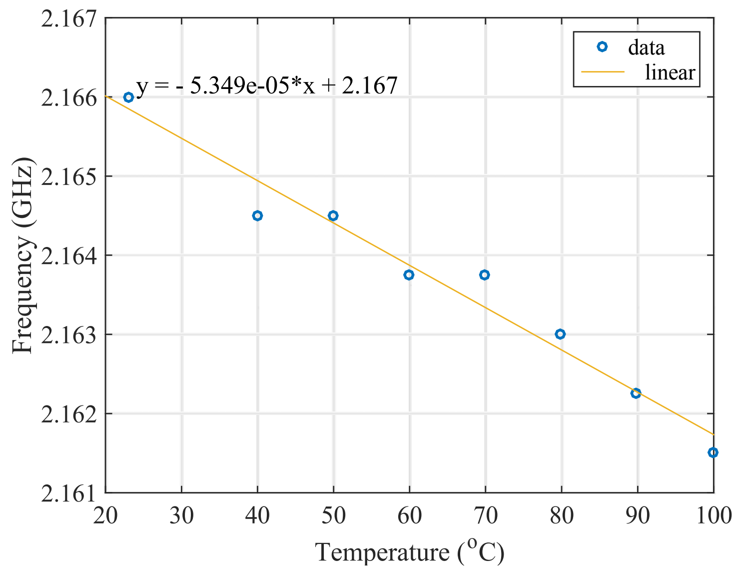
Jandel Four point probe with RM3000 Test Unit

Average Sheet Resistance of Pasted Electrode at Various Location

Sample	Front Patch mΩ/Square	Transmission Line mΩ/Square	Back Electrode mΩ/Square
Antenna Sensor	8.2	31.0	23.1
Tx/Rx Antenna	3.5	8.6	6.4

Test of Antenna Sensor on Alumina Wafer

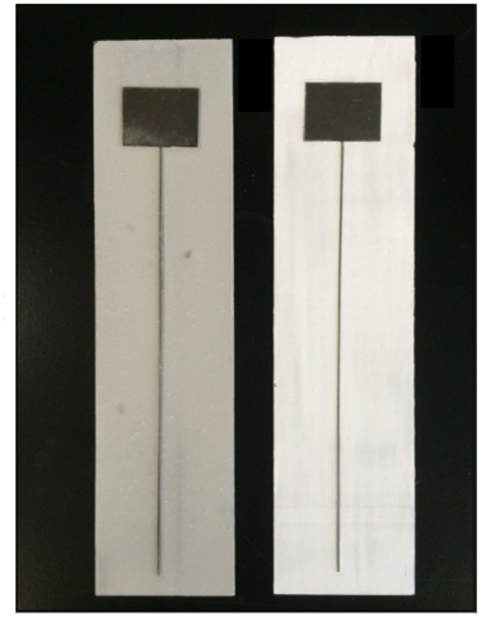


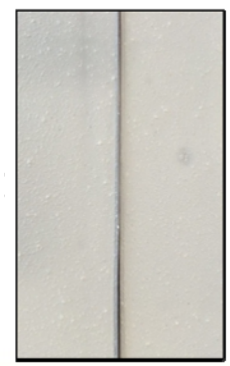


- Tx/Rx antenna fabricated on Rogers substrate
- Antenna sensor fabricated from platinum paste and alumina wafer
- TxRx and antenna ensor connected using SMA connector
- Tested at temperature up to 100 ^{o}C
- Interrogation distance of 0.7 m
- Sensitivity of -53.49 kHz/^{o}C

Flexible Dielectric Substrates

- Investigated alternative sensor materials
  - Reduce cost
  - Achieve flexible substrates
- Materials considered
  - Nickel-copper alloy as electrodes
  - Ceramic paper and adhesives as substrates
    - Ceramabond 571
    - Ceramabond 671
- Preliminary results
  - Oxidation of electrodes during annealing at 100^{o}C
  - Poor performance due to inhomogeneity of paste
  - Difficulties in controlling paste viscosity
  - Substrate thickness is very thin after drying
  - Substrate is brittle and easily peals off



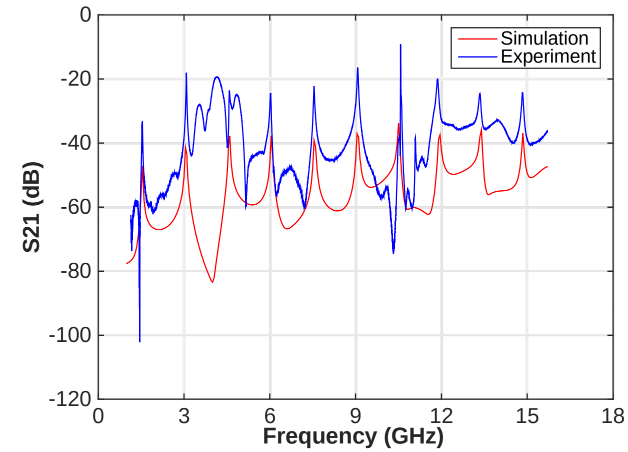


Achievement #3: Established Procedures for Material Property Characterization

Dielectric Property Characterization

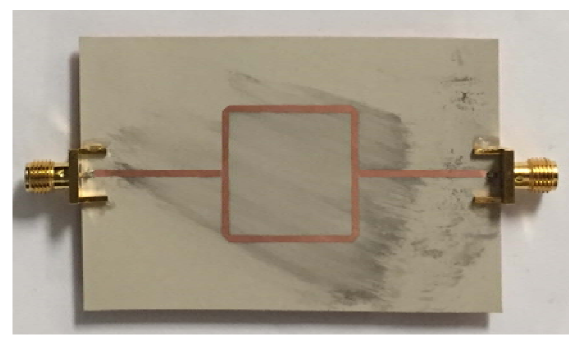
Dielectric parameters → **Analytical Model** → S-parameter

Dimensions →



Measured S-parameter → **Inverse Method** → Dielectric parameters

Dimensions →

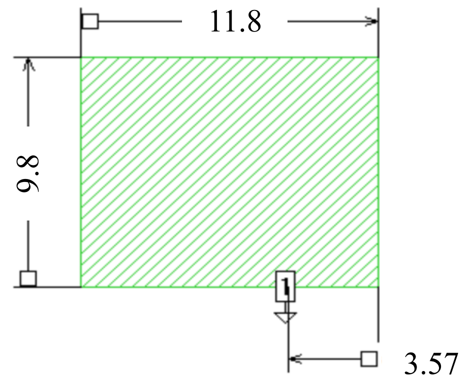


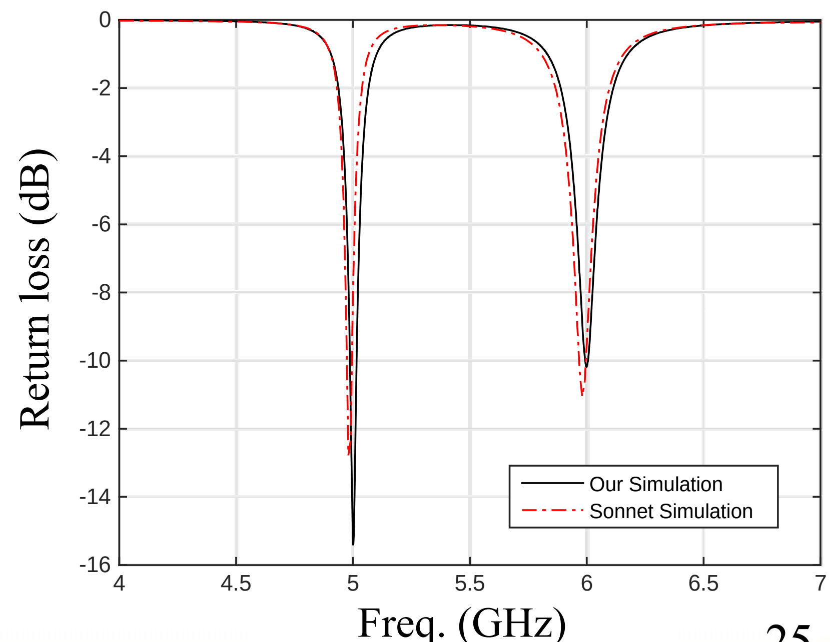
	Measured	Specification
Dielectric constant	***6.17***	6.15
Tangent loss	***0.0022***	0.002

Achievement #4: Established Efficient Simulation Model for Simultaneous Temperature/Strain Sensing

Efficient Antenna Simulation Model

- Simulation model is needed for
  - Parametric studies
  - Multi-variant analysis
- Cavity model (CM)
  - Efficient model for analysis of the patch antenna
  - More accurate that the transmission line model
  - Good physical insight but complex in nature
- Comparison of CM simulation to commercial electromagnetic simulation tool (Sonnet) gives 0.2 % difference at resonant peaks





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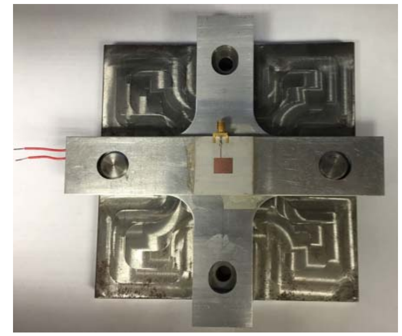
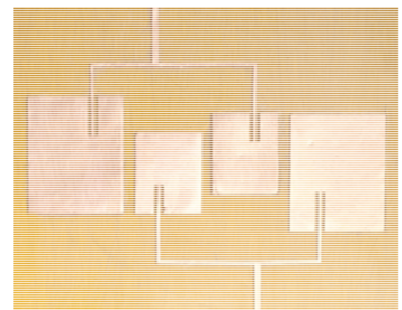
Summary

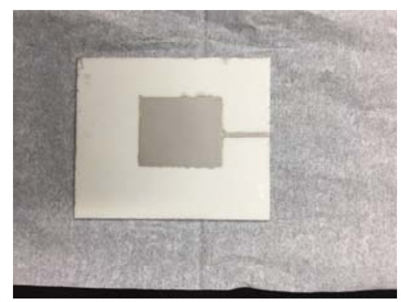
- Demonstrated two wireless interrogation techniques for antenna sensors without electronics
- Explore techniques to fabricate antenna sensor from high temperature materials
- Established theoretical foundation for
  - Dielectric property characterization
  - Multivariate analysis of antenna sensors
- Publications
  - One journal manuscript under preparation (90%)
  - One conference accepted (SMASIS 2016)

Future Work

- Simultaneous measurement of strain and temperature using a patch antenna sensor
- Wireless interrogation of antenna array
- Finalize fabrication of sensors using Alumina wafer/Platinum
- Explore flexible & inexpensive high temperature materials







Question & Answers