Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

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Award #: DE-FE0023118

Duration: 1/1/2015-12/31/2017

Organization: University of Texas Arlington & UCSD

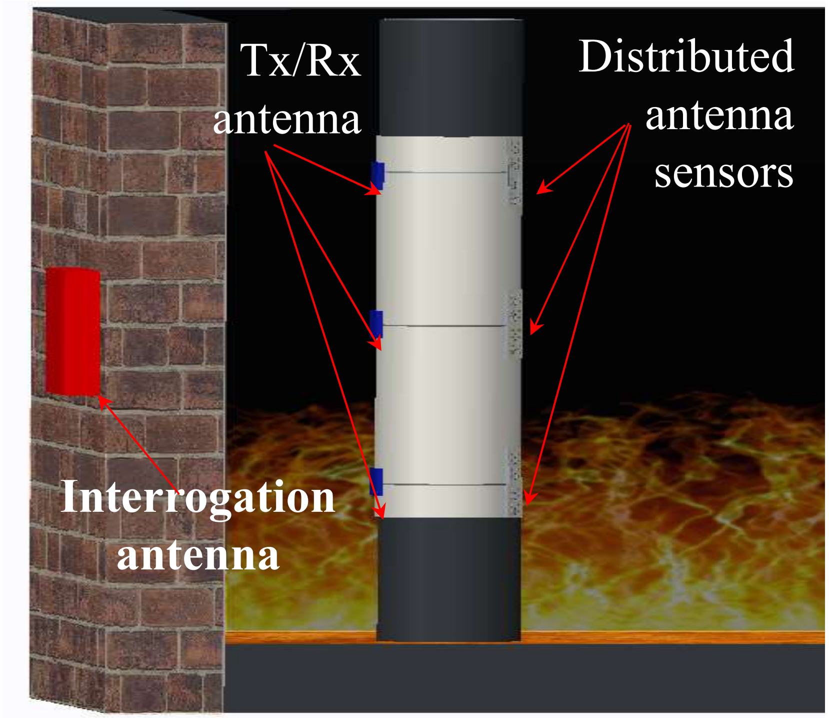
Outline

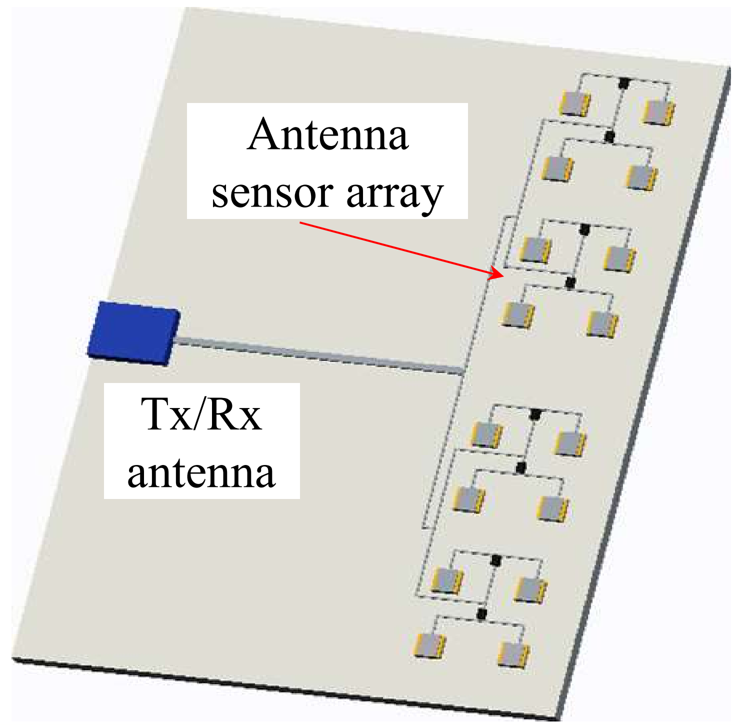
- Project overview
- Past achievements
- Current achievements
  - Simultaneous strain and temperature sensing using a single patch antenna
  - High temperature sensor fabrication using alumina and platinum paste
  - Wireless UWB Tx/Rx antenna design for high temperature material and validation on PCB
  - Thermo-mechanical fixture design and evaluation
- Summary & conclusions
- Future work
- Q&A

Project Overview

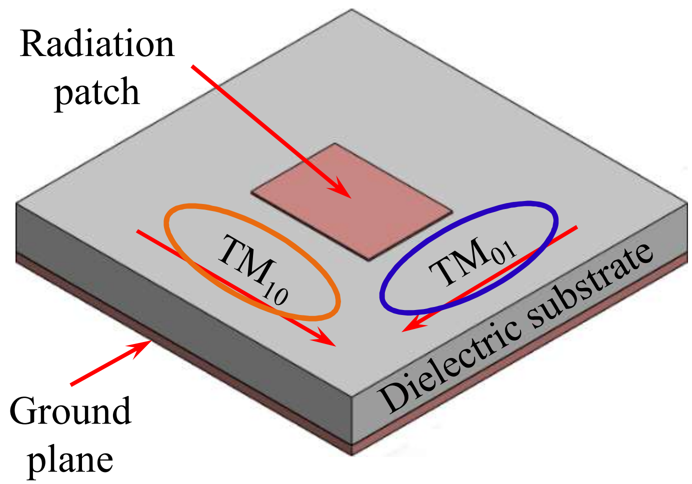
Realize distributed condition monitoring of steam pipes up to 1000^{o}C

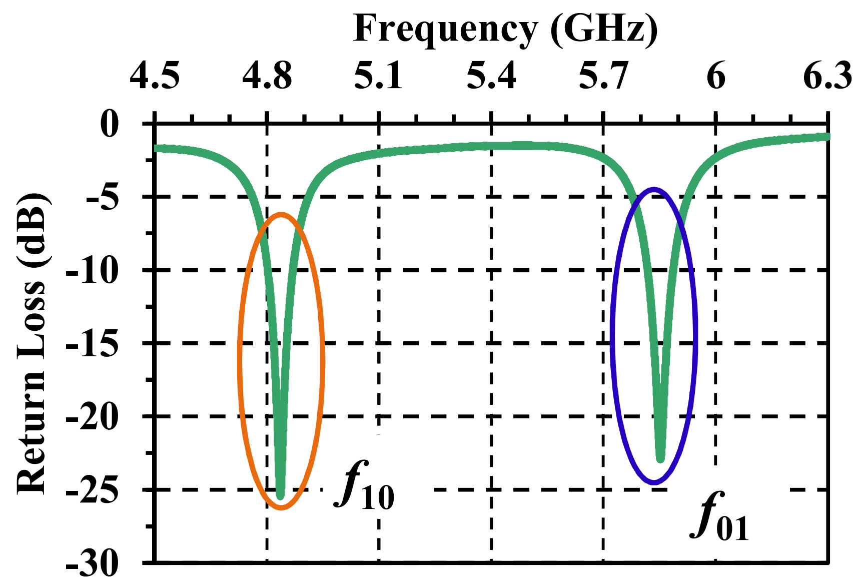
- ✓ Wirelessly interrogate antenna sensors without electronics
- ✓ Characterize antenna sensors for temperature, strain, and soot accumulation
- ✓ Fabricate antenna sensors using high-temperature materials





Dual-Frequency Patch Antenna





$$f_{mn} = \frac{C}{2\pi\sqrt{\varepsilon_{\mathrm{reff}}}}\sqrt{\left(\frac{m\pi}{L_e}\right)^2 + \left(\frac{n\pi}{W_e}\right)^2}$$

Temperature-strain Differentiation

$$f_{10} = \frac{c}{2\sqrt{\varepsilon_{reff}}L} \quad \Rightarrow \quad \frac{\delta f_{10}}{f_{10}} = -\frac{1}{2}\frac{\delta \varepsilon_{eff}}{\varepsilon_{eff}} - \frac{\delta L}{L}$$

$$\frac{\delta f_{10}}{f_{10}} = K_{TL}\Delta T + K_L \varepsilon_L$$

$$\frac{\delta f_{01}}{f_{01}} = K_{TW}\Delta T + K_W \varepsilon_L$$

$$\Rightarrow \quad \begin{Bmatrix} \Delta T \\ \varepsilon_L \end{Bmatrix} = \begin{bmatrix} K_{TL} & K_L \\ K_{TW} & K_W \end{bmatrix}^{-1} \begin{Bmatrix} \delta f_{10}/f_{10} \\ \delta f_{01}/f_{01} \end{Bmatrix}$$

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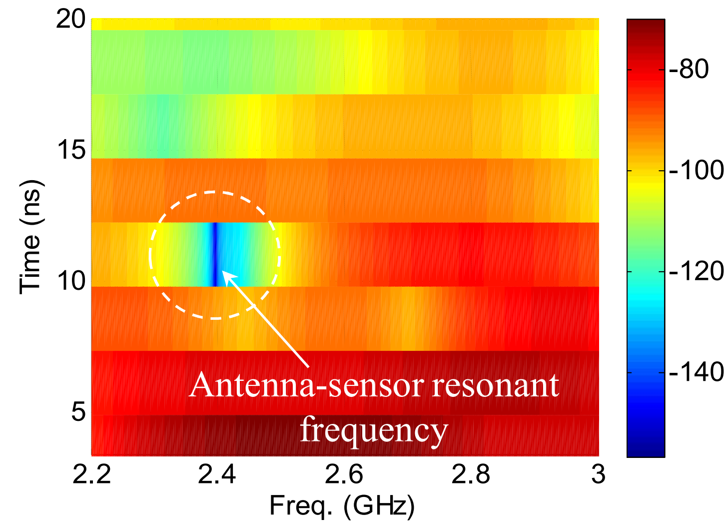
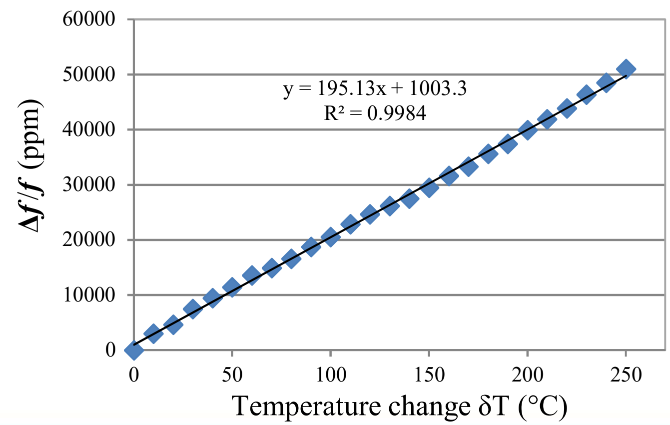
Past Achievements

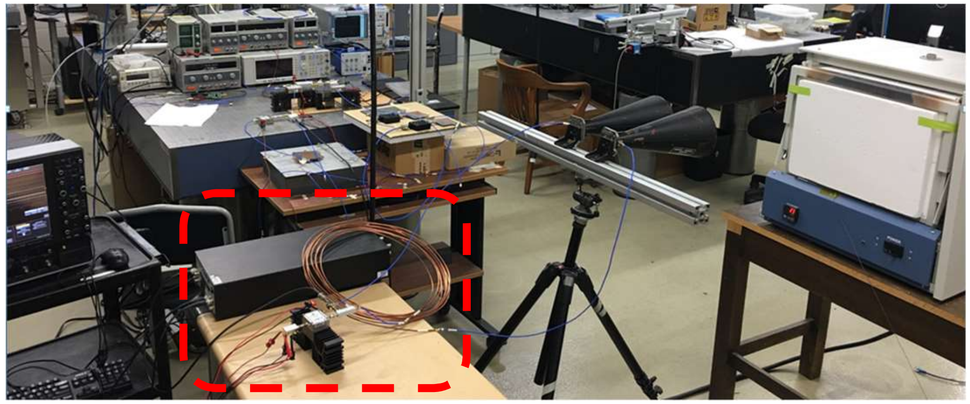
Wireless Interrogation - VNA

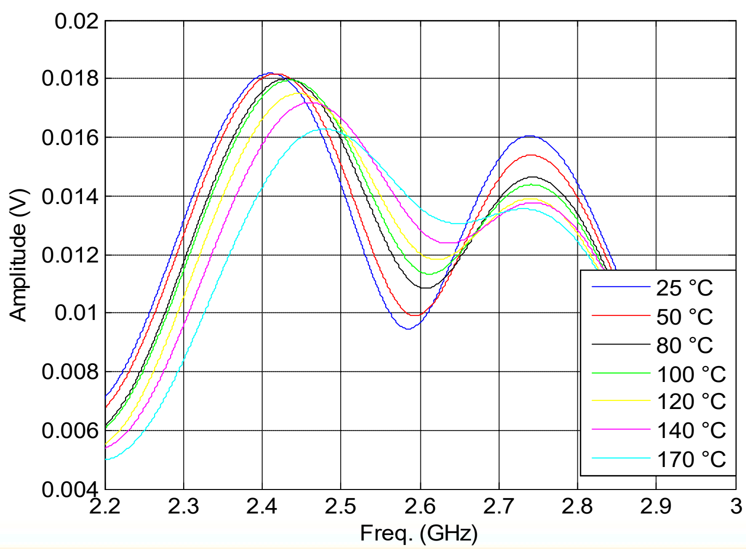


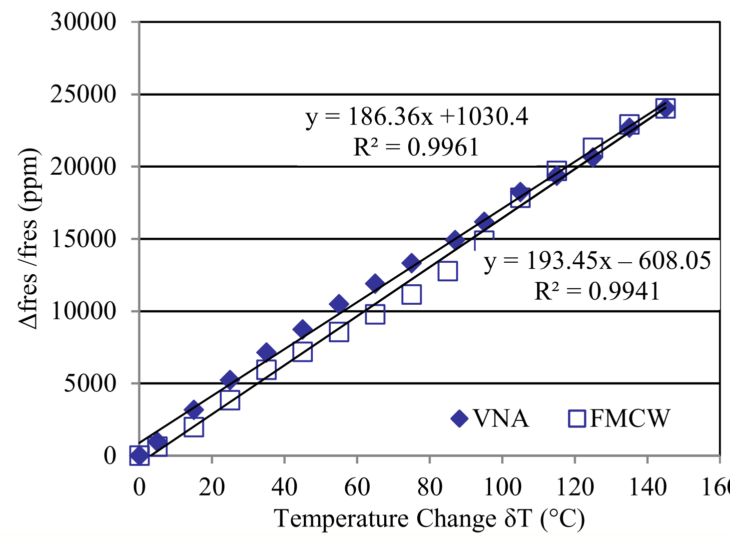


Yao, J., *et al.* 2016, *IEEE Sensors Journal, 16(19),* p7053 - 7060

Wireless Interrogation – FMCW Radar







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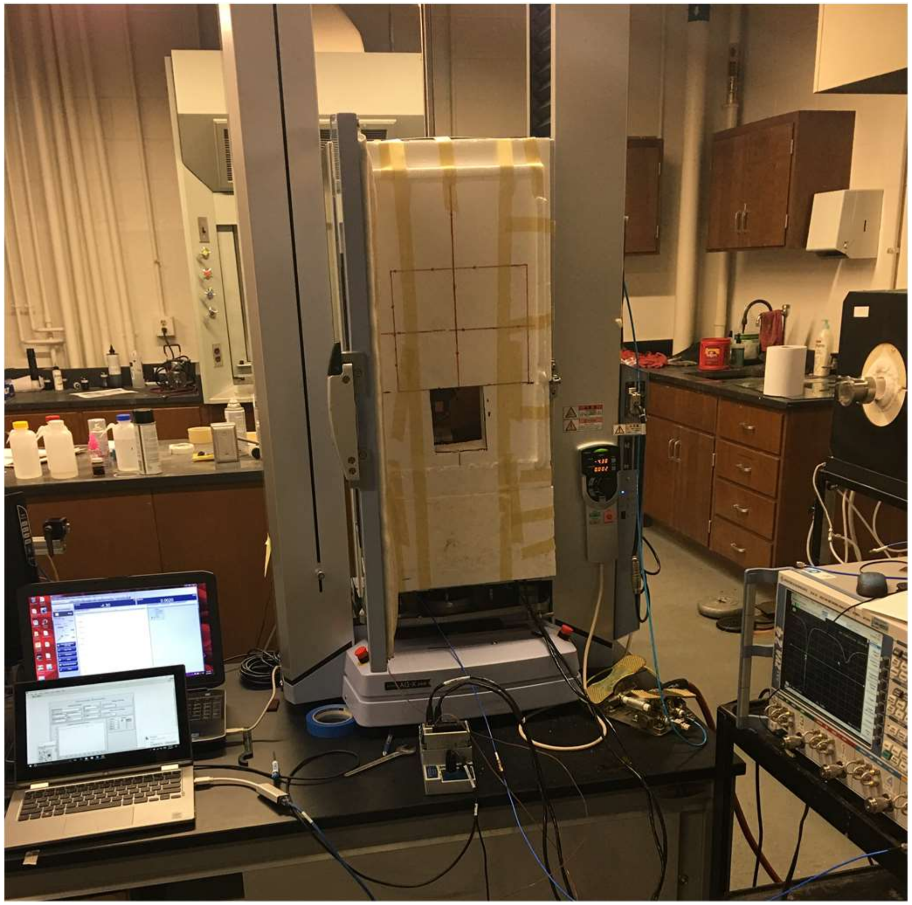
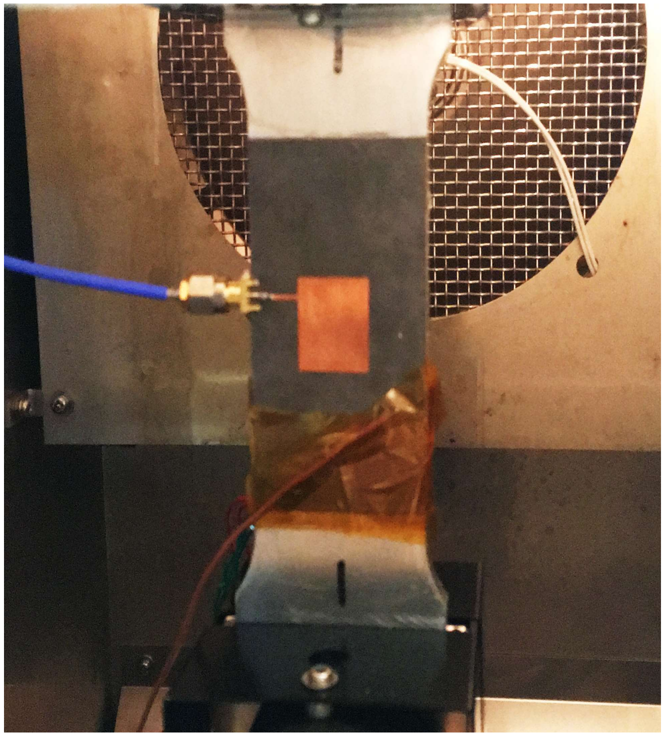
Single Antenna for Strain & Temp. Sensing

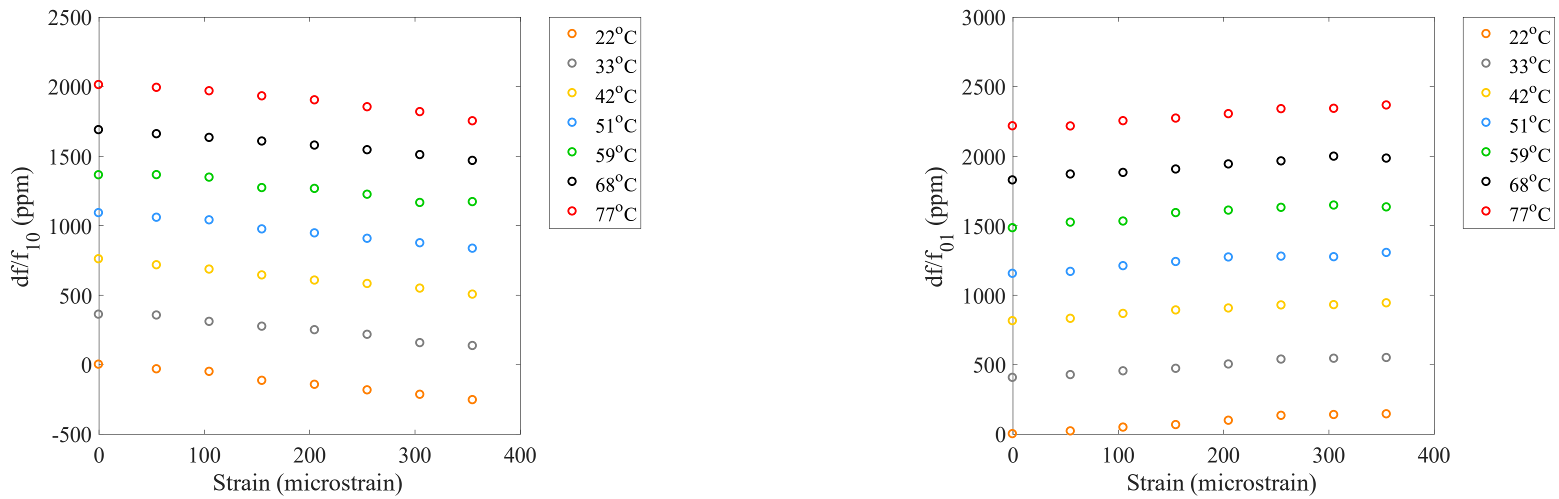




Furnace operation range: 280^{o}C
Maximum load: 10 kN

Simultaneous Strain & Temp. Sensing

Loading direction (TM10) **Transverse direction (TM01)**



Excellent linearity: R^2 = 0.9991 for TM10 and 0.9995 for TM01

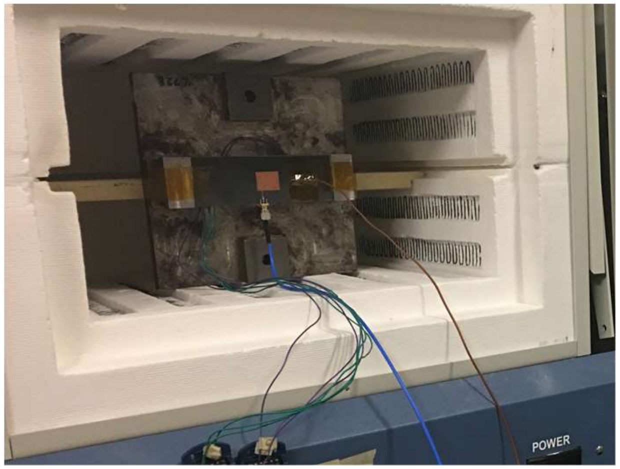
$$\begin{Bmatrix} \delta f_{10}/f_{10} \\ \delta f_{01}/f_{01} \end{Bmatrix} = \begin{bmatrix} 37.43 & -0.6861 \\ 40.49 & 0.4302 \end{bmatrix} \begin{Bmatrix} \Delta T \\ \varepsilon_L \end{Bmatrix}$$

- **Temperature error**: $\pm$ 0.4^{O}C
- **Strain error:** $\pm$17.22 µe

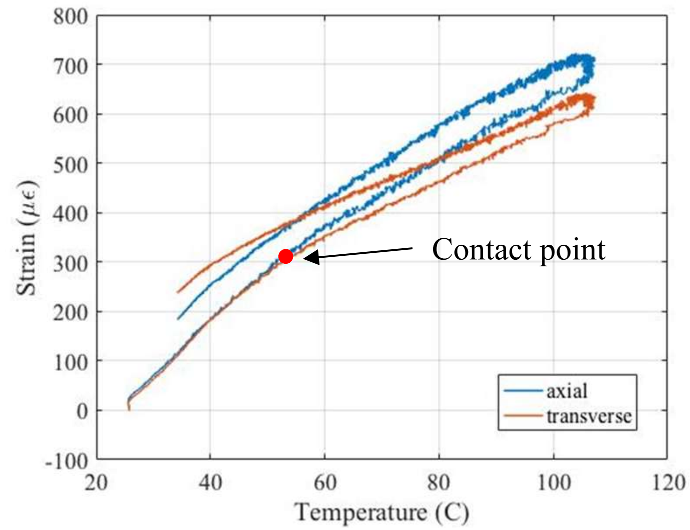
Tchafa F. and Huang H., *IOP Smart Mater. & Struct.*, accepted 04/2018

Progress #1: Characterize Text Fixture for Strain and Temperature Loading Inside an Oven

High-Temp. Thermo-Mechanical Fixture



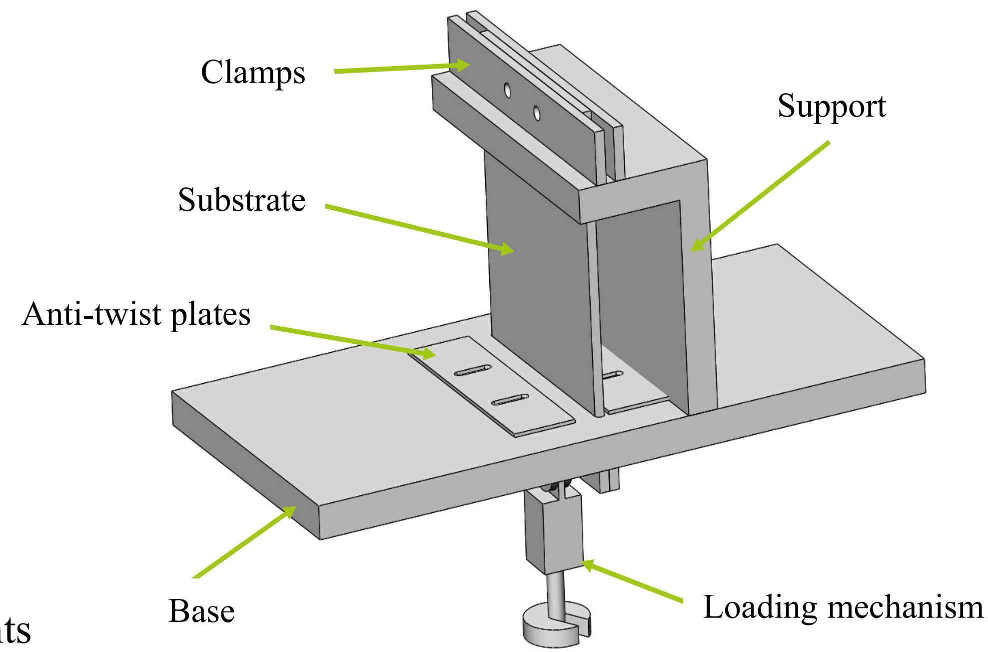
Design #1



- Previous approach: generate mechanical strain with temperature change due to CTE mismatch between base plate and fixture
- What we figured out
  - Strain gages posses a thermal output – reference needed to extract mechanical strain
  - Mfg. correction curve not suitable as it is affected by bonding as well base material

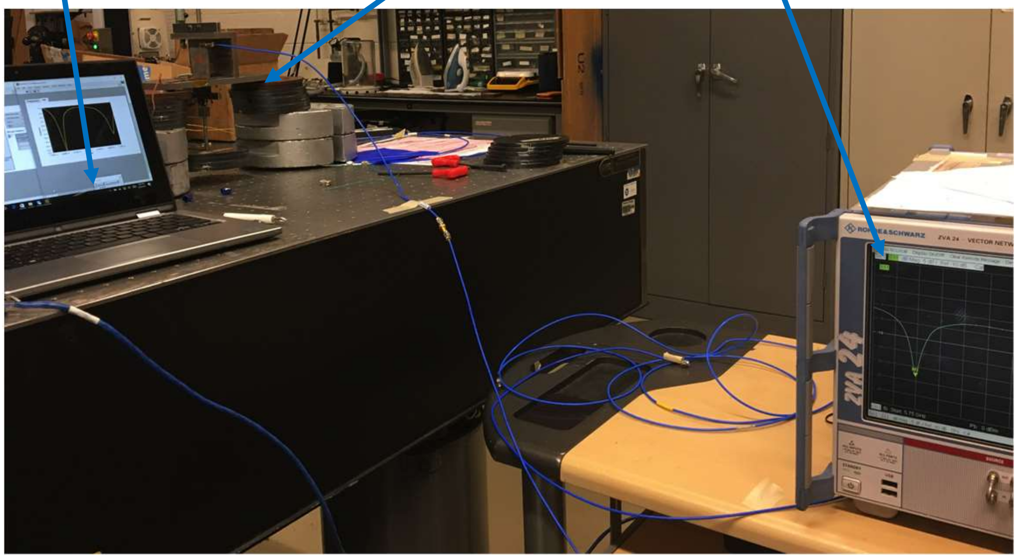
High-Temp Thermo-Mechanical Fixture

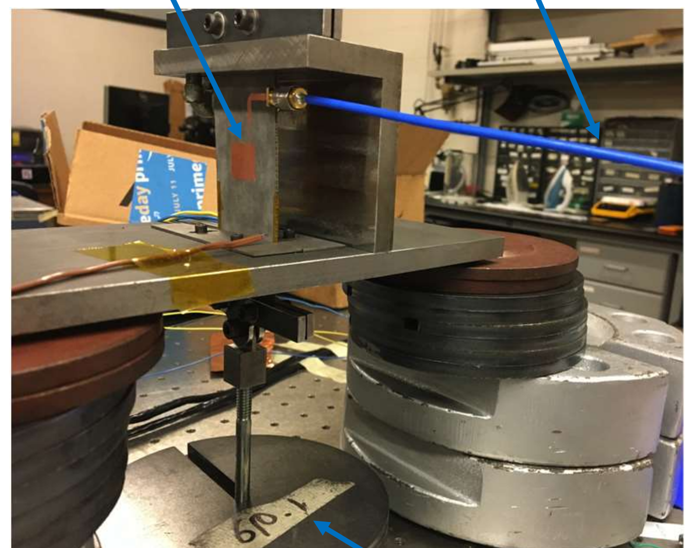
- Decouple strain and temperature
  - Strain is generated by weight
  - Temperature controlled by furnace
- Design constraints
  - Furnace dimensions
  - Substrate tensile properties
  - Strain resolution
  - Uniaxial loading
- Limitations
  - Limited strain generation based on substrate properties and size of weights
  - Need substrate with equal CTE along x- and y-directions to avoid bending of specimen



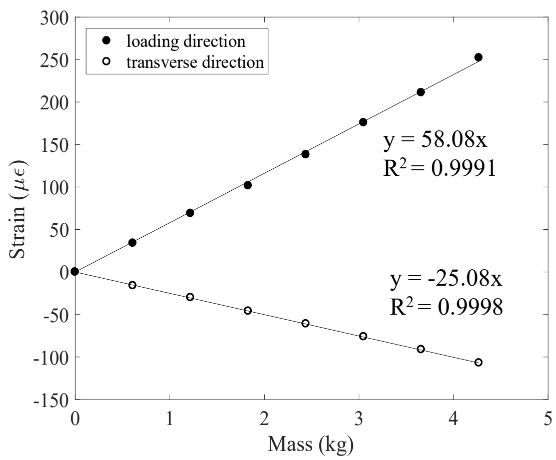
Design #2

Fixture Characterization Outside of Oven

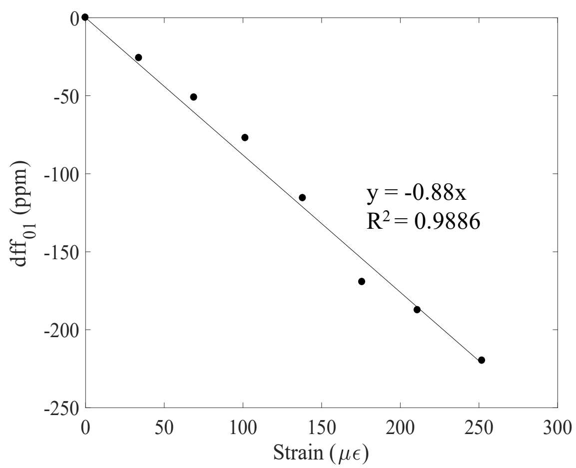




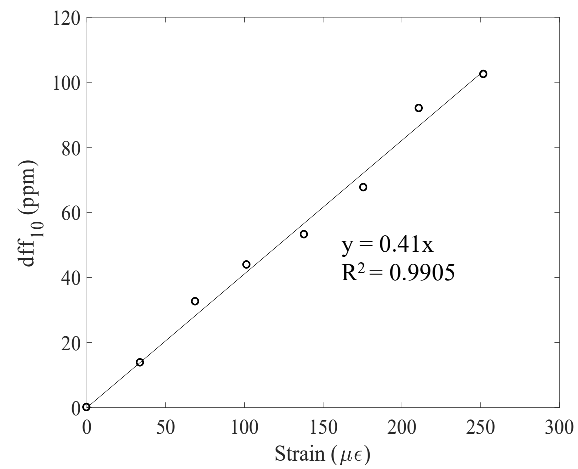
Fixture Characterization – Strain Measurement



Loading direction



Transverse direction



- **Measured Poisson's ratio: 0.43 – good agreement with literature (0.4)**
- **Excellent linearity: R^2 = 0.9886 and 0.9905 for the loading and transverse direction respectively**
- **Measurement error: ± 9 microstrain**

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Progress #2: Fabricate Antenna Sensor Using High-Temperature Materials

Sensor Fabrication Using Alumina + Pt Paste

Substrate ultrasonic bath (cleaning process)

↑

Tape cast Pt paste on surface

↑

Curing process for 4 hours

↗

Remove mask if necessary

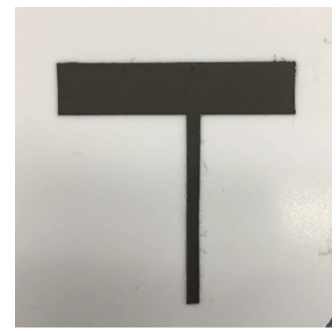
↘

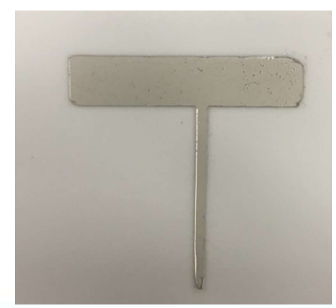
Overnight drying of paste in oven

↓

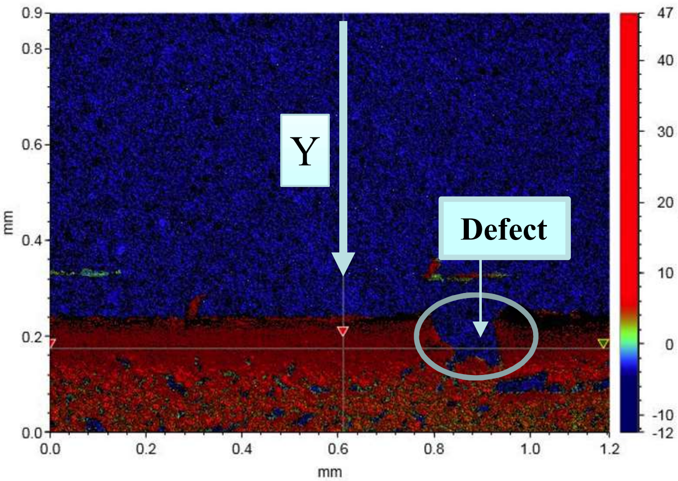
Dry the paste and sinter Pt

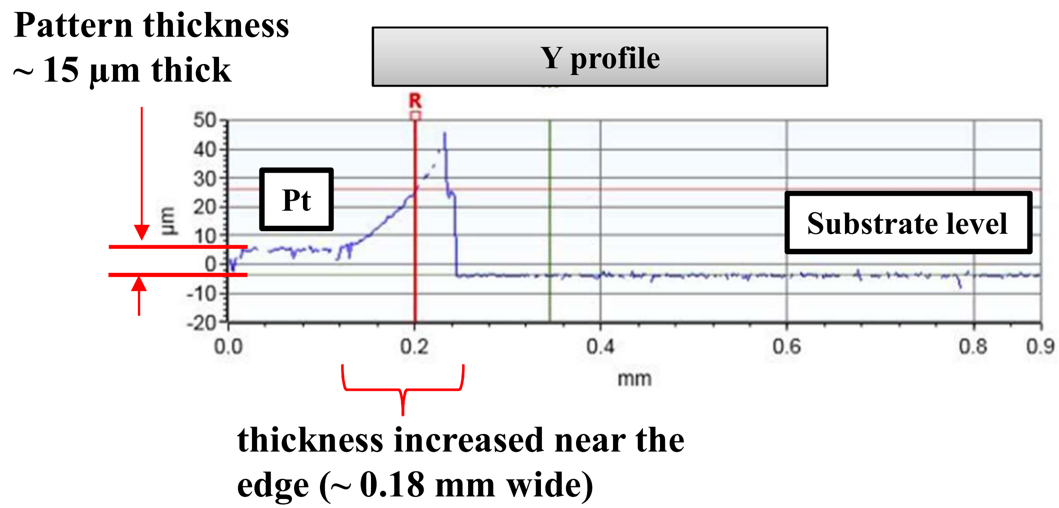
8 °C/min to 100 °C, 10 min hold, then 8 °C/min to 1000 °C, 10 min hold





Surface Characterization



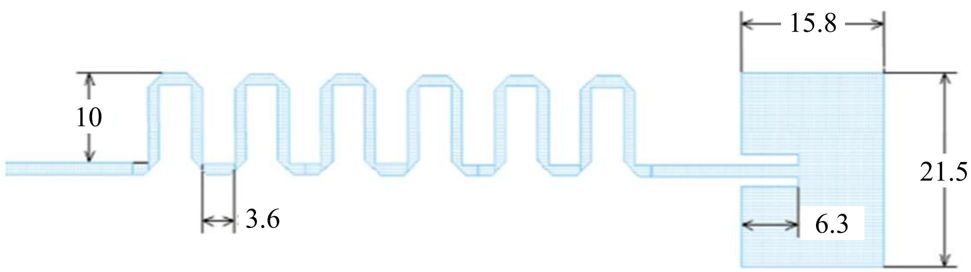


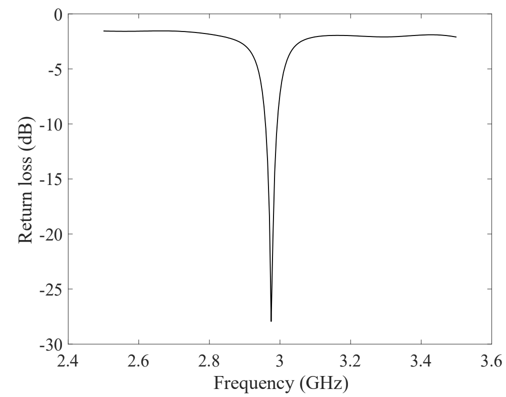
- Challenges
  - Uncontrollable platinum voids
  - Other defects (no straight line edges)
  - Difficult to achieve desired antenna shape
  - Low gain

- Proposed solutions
  - Sensor fabrication with large offset
  - Laser machining for razor-sharp edges
  - Sensor redesign for performance improvement

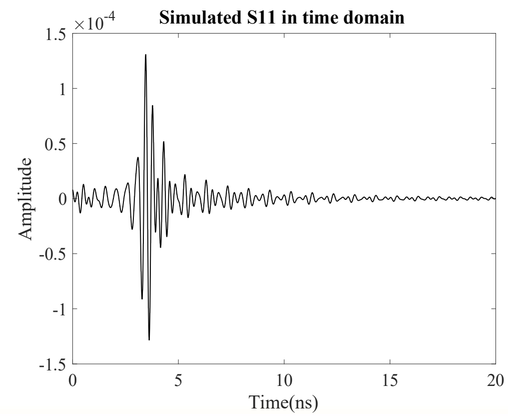
High Temperature Antenna Sensor Design

Design of the antenna sensor using alumina and platinum

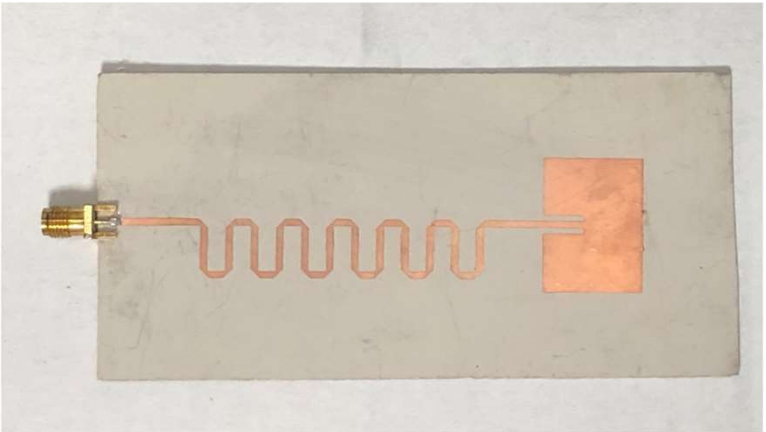


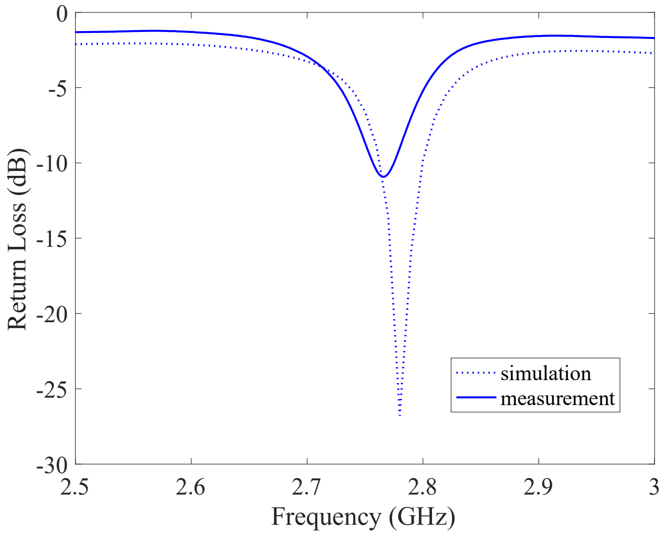


- Dimensions in (mm)
- Design dielectric: 9.8
- Substrate thickness:1.2 mm
- Resonant frequency: ~3 GHz
- Time delay: 3.5 ns



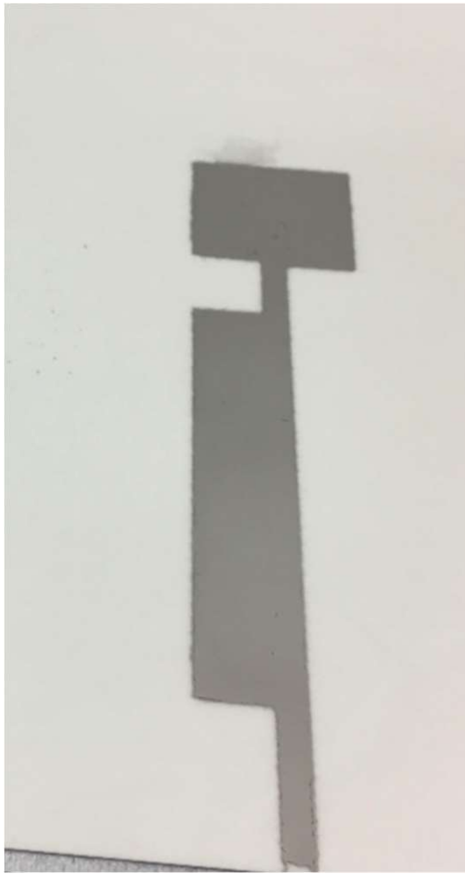
Validating High-T Antenna Sensor Using PCB



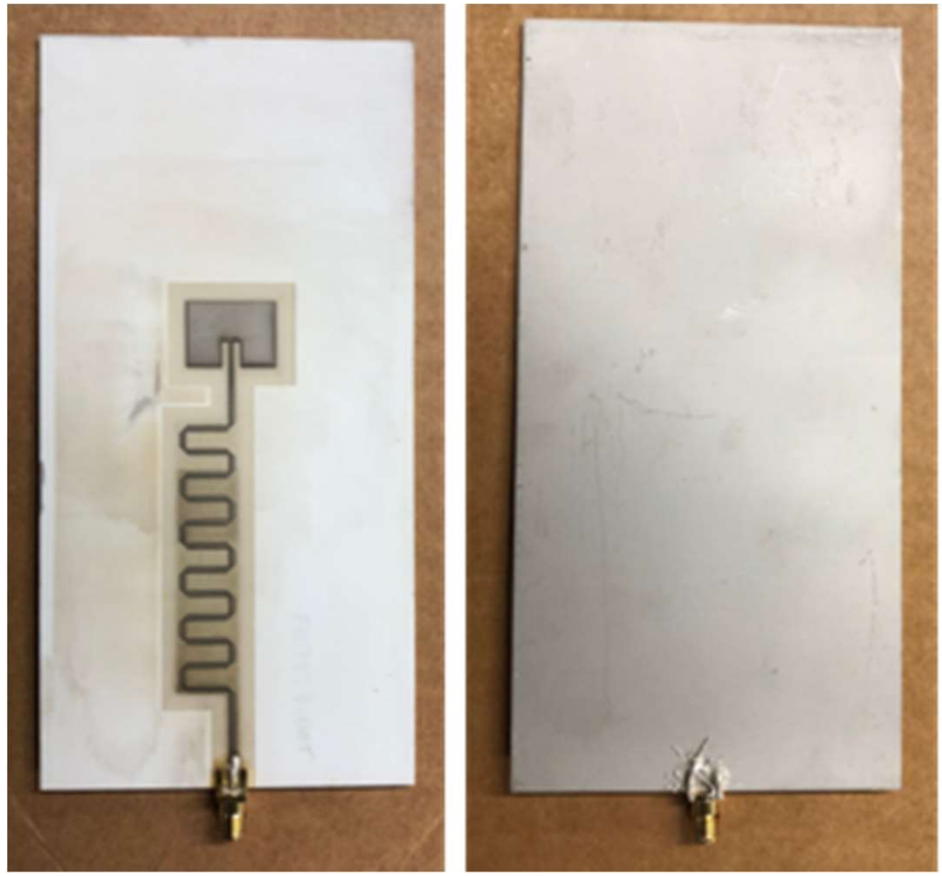


- Substrate: Rogers 3010
- Thickness:1.27 mm

Fabricate High Temperature Antenna Sensor

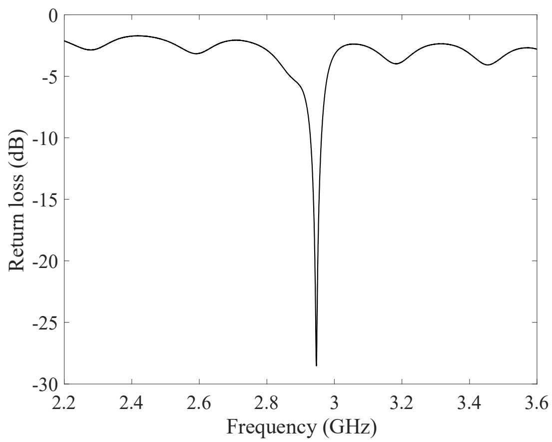


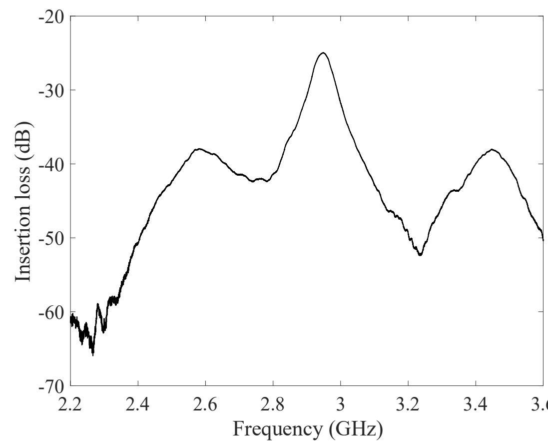
Before laser machining

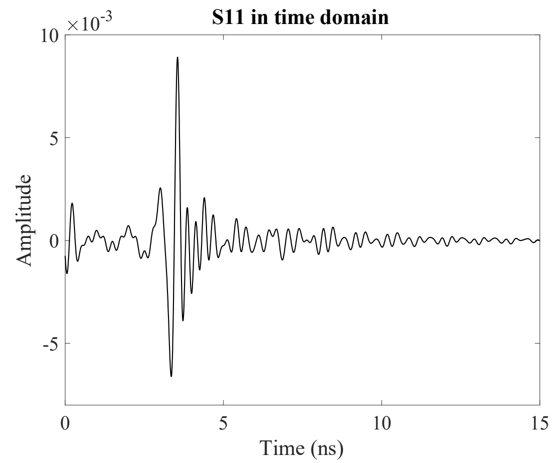


After laser machining to obtain sharp edges

High-T Antenna Sensor Characterization

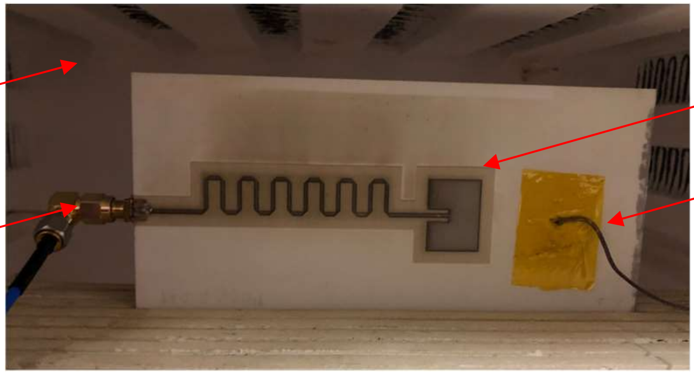


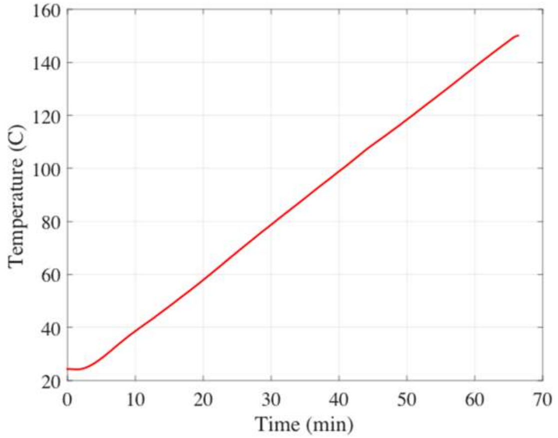


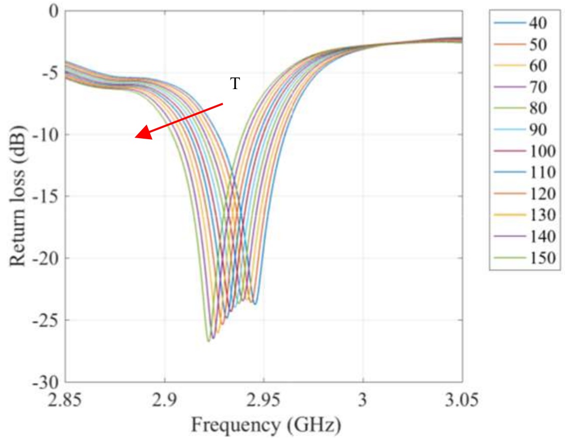


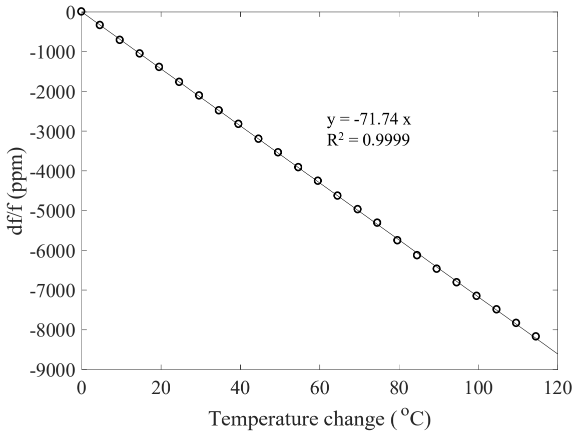
- Resonant frequency: 2.95 GHz (good agreement with design frequency of 3 GHz)
- Measured gain: 3.3 dBi (major improvement from previous sensor gain of -9 dBi)
- Meandering line provides 3.5 ns delay
- **Significant improvements in performance compared to previous design**

Temp. Sensitivity of High-T Antenna Sensor



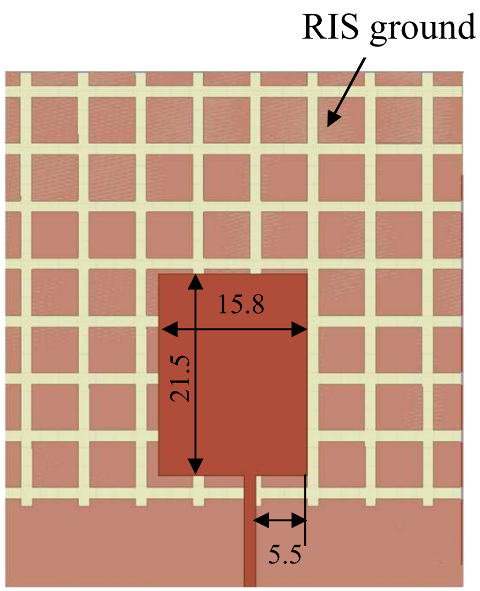




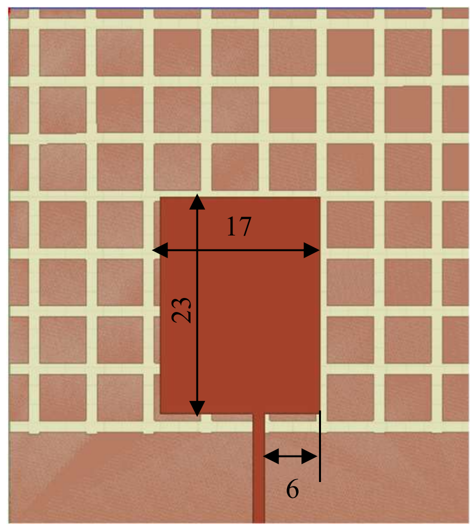


- **Measurement error: ± 0.38°C**
- **Extracted TCDk: 127.5 ppm/°C**

High-T UWB Antenna - Design

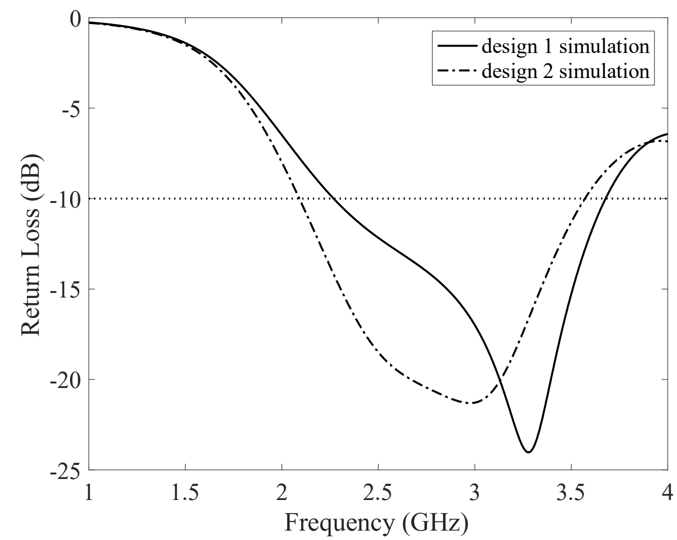


design 1



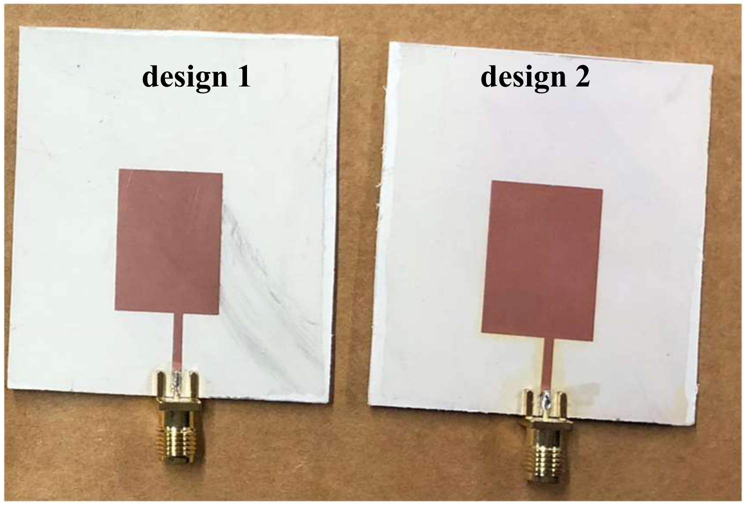
design 2

Simulated S11 parameters

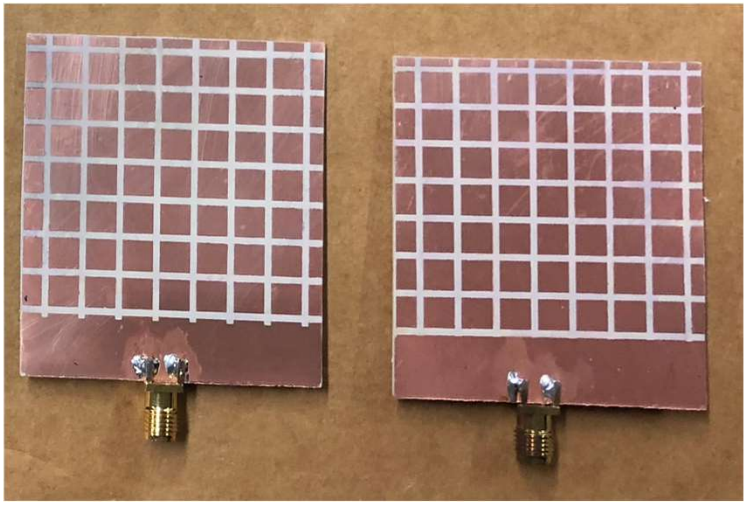


- Dimensions in (mm)
- RIS ground: 4.9 x 4.9 mm^2 with 1.2 mm spacing
- Substrate size: 49 mm x 55 mm
- 1.5 GHz bandwidth for both design using alumina and Pt

UWB Antenna – PCB Implementation

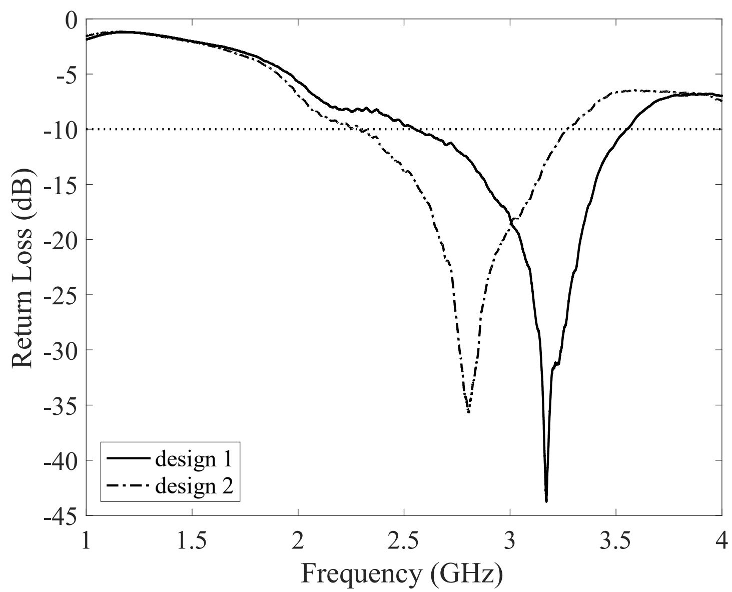


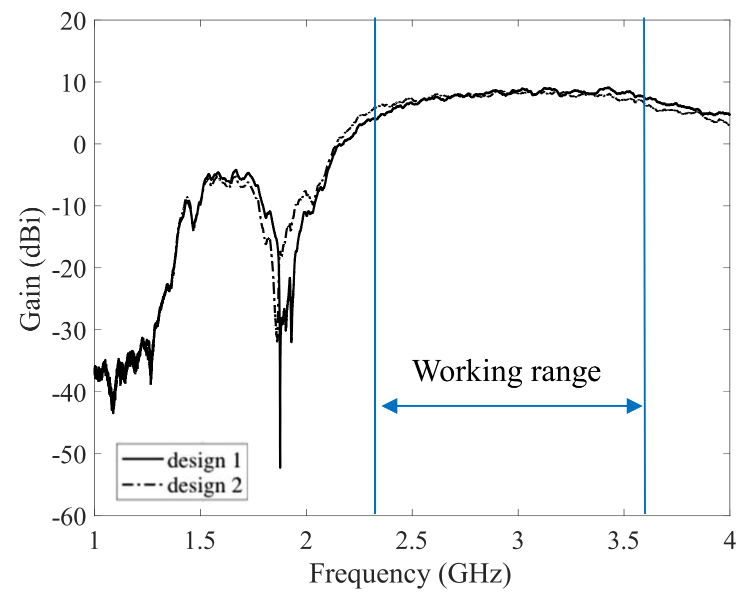
Front



Back

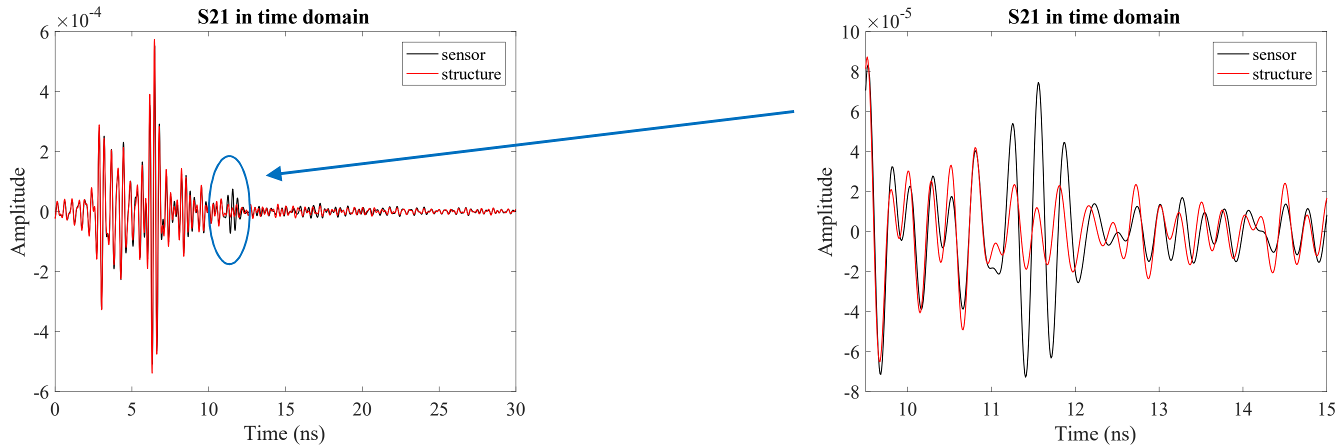
PCB UWB Antenna - Characterization

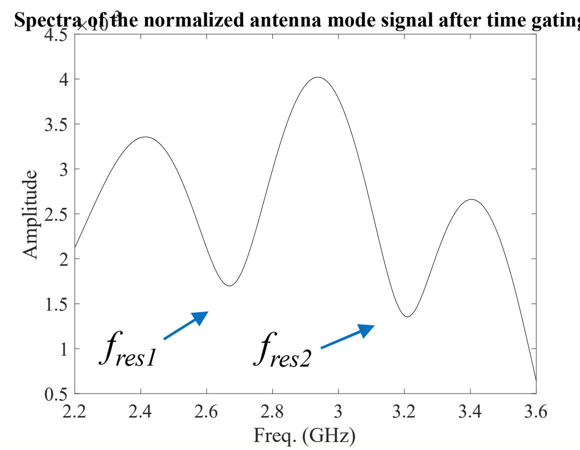




- Broad bandwidth achieved for both designs
- Measured bandwidth: ~1 GHz
- Relatively flat gain in desired working range with mean gain of ~ 8dBi

PCB UWB Antenna – Wireless Interrogation





- Wireless interrogation distance: 0.6 m
- Interrogation power: 10 dBm
- Interrogating horn antenna gain: 12 dBi

Summary of Achievements

- Improved sensor fabrication process
  - Use laser machining to achieve precise dimensions and razor-sharp edges
  - Identified thickness variation issue through surface profiling
- High temperature sensor fabrication using high-temperature materials
  - Temperature sensitivity of 71.74 ppm/^{o}C with measurement error of $\pm$0.38^{o}C
  - Extracted thermal coefficient of dielectric constant of 127.5 ppm/^{o}C
  - Gain improvement through substrate thickness increase
- Thermo-mechanical fixture design and evaluation
  - Strain generated from applied weight and no longer from CTE mismatch
  - Limited to substrate with same CTE in both x- and y-direction to avoid bending
- Wireless UWB Tx/Rx antenna design on high temperature material
  - Design using alumina and Pt
  - Performance evaluation using commercial PCB

Publications

- Yao, J., Tchafa, F. , Jain, A., Tjuatja, S. and Huang, H., 2016, "Far-field Interrogation of Microstrip Patch Antenna for Temperature Sensing without Electronics", v16, n19, *IEEE Sensors Journal,* p 7053 - 7060.
- Jun Yao, PhD thesis, "Dynamic wireless interrogation of antenna-sensor in harsh environment", Dec. 2016
- Tchafa, F., Yao, J., and Huang, H., "Wireless Interrogation of a High Temperature Antenna Sensor Without Electronics", ASME International Mechanical Engineering Congress & Exposition (IMECE2016), Phoenix, Arizona, Nov. 2016
- Tchafa, F., and Huang, H., "Simultaneous strain and temperature sensing using a microstrip patch antenna", International Workshop on Structural Health Monitoring (IWSHM 2017), Stanford, California, Sept. 2017
- Tchafa, F., and Huang, H., "Microstrip Patch Antenna for Simultaneous Strain and Temperature Sensing", IOP Smart Mater. & Struct., accepted 04/2018

Future Work

- Demonstrate high-temperature wireless interrogation up to 1000^{o}C
- Demonstrate high-temperature thermo-mechanical testing in fixture
- Implement antenna sensor array
- Investigate antenna sensor for soot detection
- Explore flexible & inexpensive high temperature materials

Question & Answers