Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

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Organization: University of Texas Arlington & UCSD

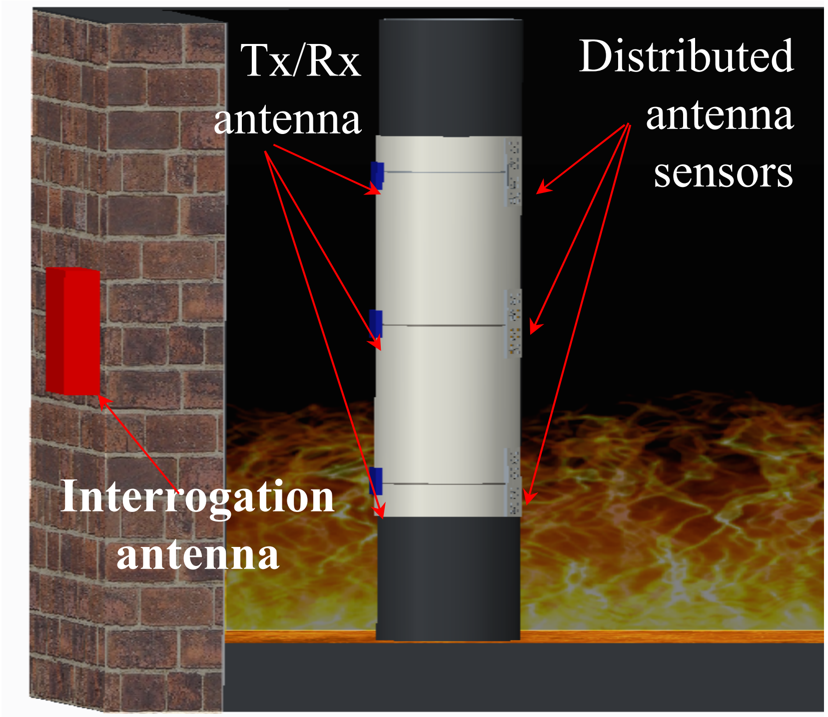
Outline

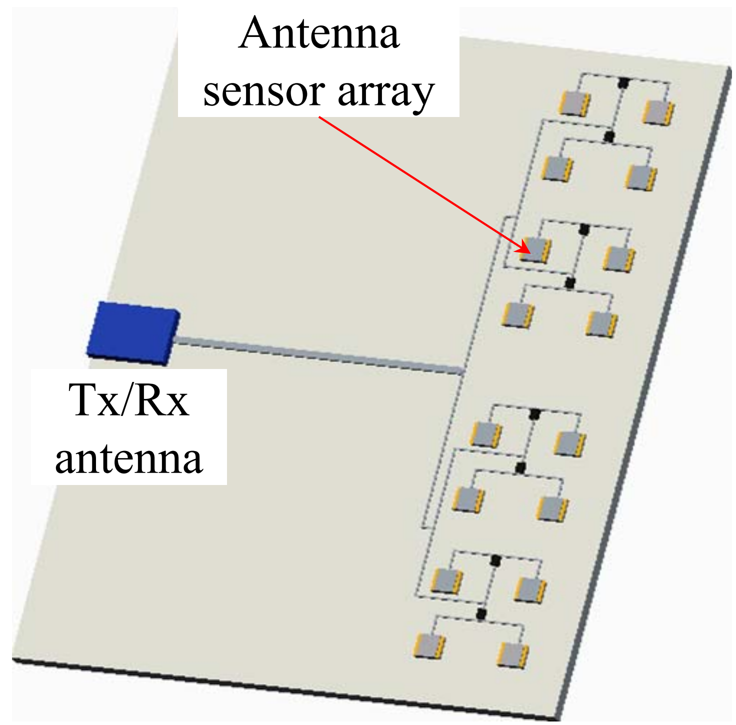
- Project overview
- Simultaneous strain and temperature sensing using a single antenna sensor
- Sensor fabrication using high-temp materials
- Summary & conlusions
- Future work
- Q&A

Project Overview

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

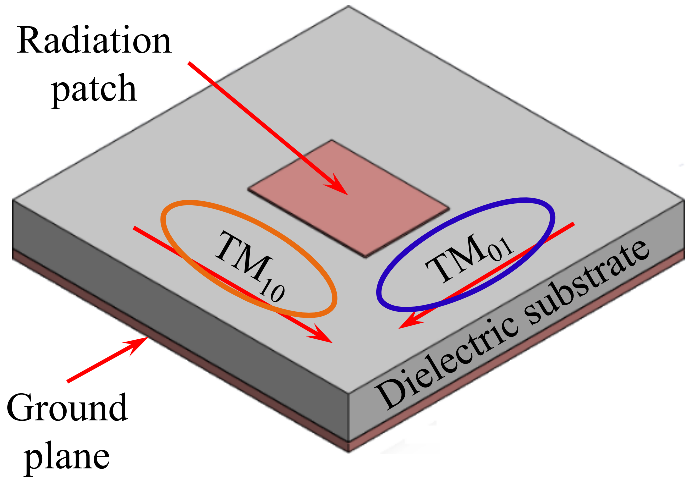
✓ *Wirelessly interrogate antenna sensor without electronics*
- Characterize antenna sensors for temperature, strain, and soot accumulation
- Fabricate antenna sensors using high-temperature materials

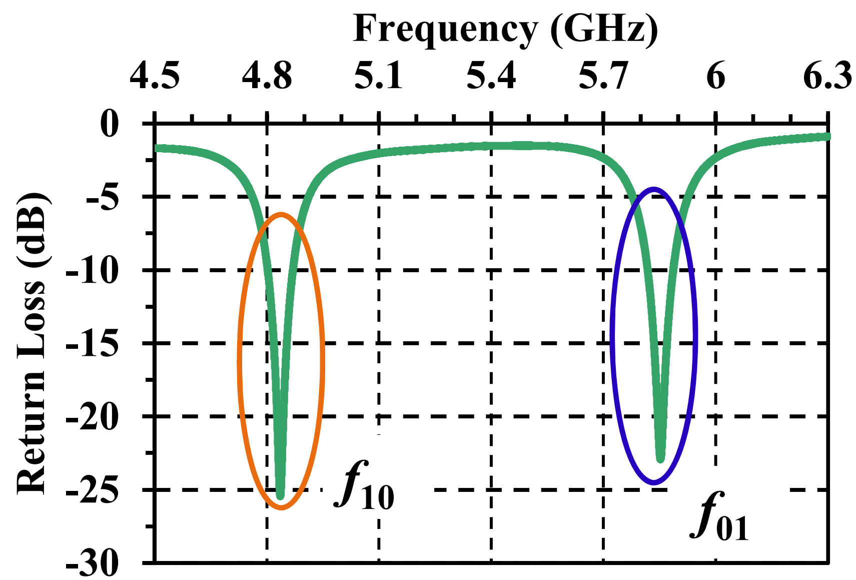




Simultaneous Strain and Temperature Sensing Using a Single Antenna Sensor

Dual-Frequency Patch Antenna





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

Temperature-strain Differentiation

$$f_{10} = \frac{c}{2\sqrt{\varepsilon_{reff}}\,L} \Rightarrow \delta f_{10} = \frac{\partial f_{10}}{\partial \varepsilon_{reff}}\delta\varepsilon_{reff} + \frac{\partial f_{10}}{\partial L}\delta L$$

$$\frac{\delta f_{10}}{f_{10}} = K_{TL}\Delta T - k_L \varepsilon_L$$

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

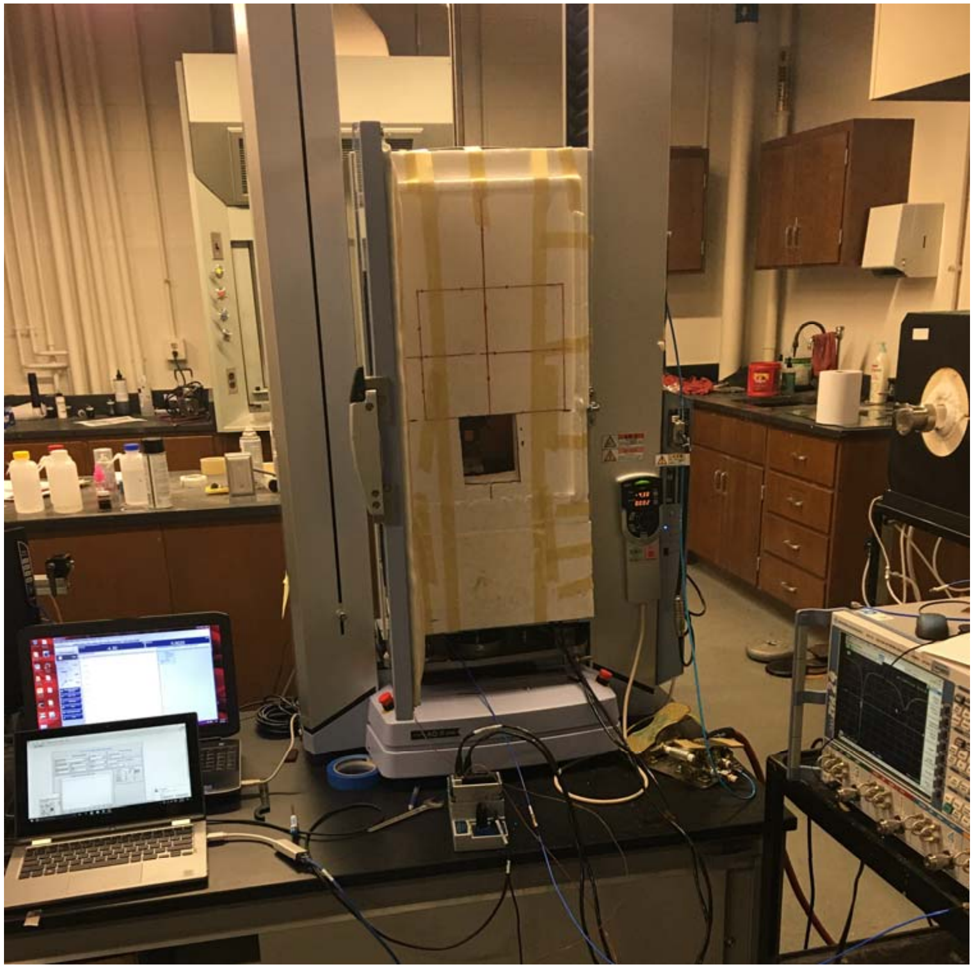
$$\Rightarrow \begin{Bmatrix} \Delta T \\ \varepsilon_L \end{Bmatrix} = \begin{bmatrix} K_{TL} & -k_L \\ K_{TW} & \upsilon k_T \end{bmatrix}^{-1} \begin{Bmatrix} \delta f_{10} / f_{10} \\ \delta f_{01} / f_{01} \end{Bmatrix}$$

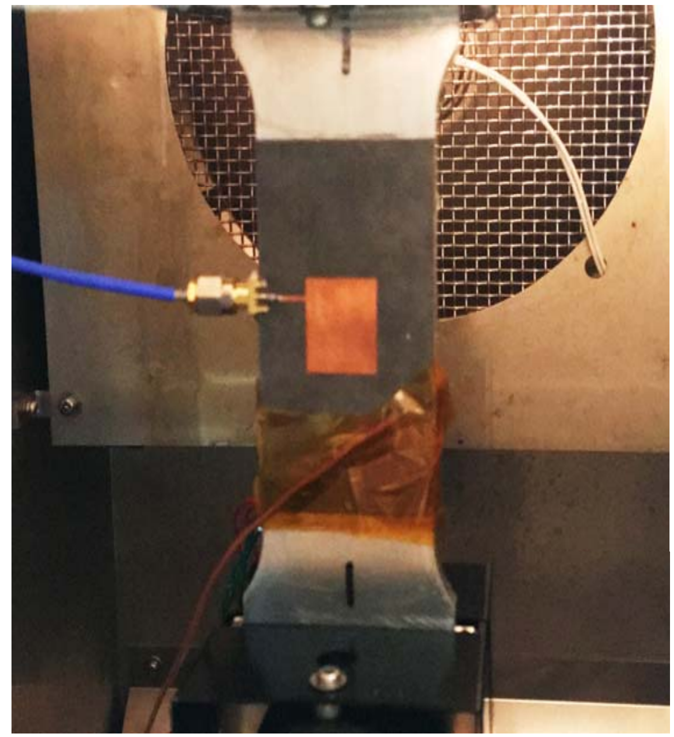
Instrumented Test Sample

- Commercial high frequency circuit laminate (Rogers RT/duroid 5880)
  - Temperature up to 350°C
  - Dielectric constant: 2.2
  - Thermal coefficient of dielectric constant (TCDk): -125 ppm/°C
  - Coefficient of thermal expansion: 31, 48, 237 ppm/°C in x-, y-, and z-direction

- Antenna sensor parameters
  - Operating frequency: 5.0 and 6.0 GHz
  - Size: ~ 20 mm x 16 mm

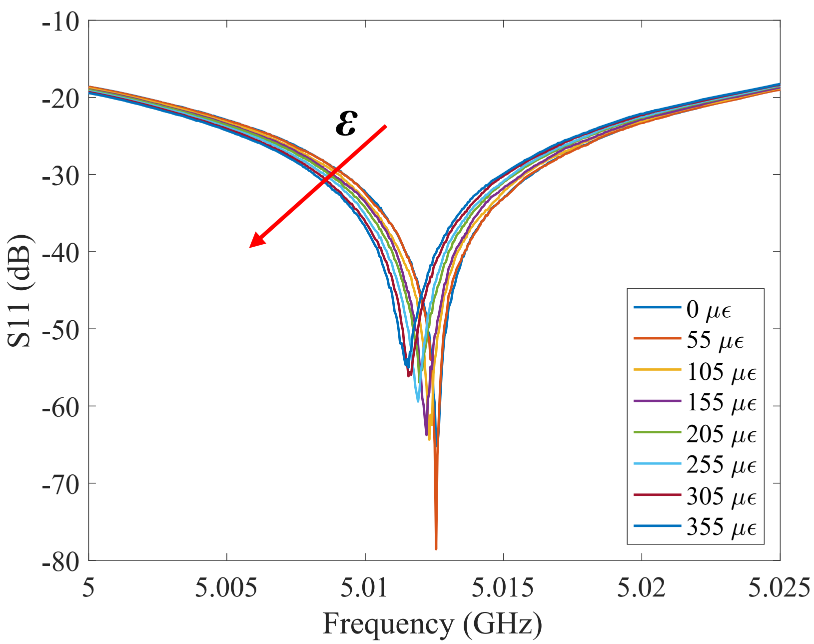
Thermal-mechanical Experiment

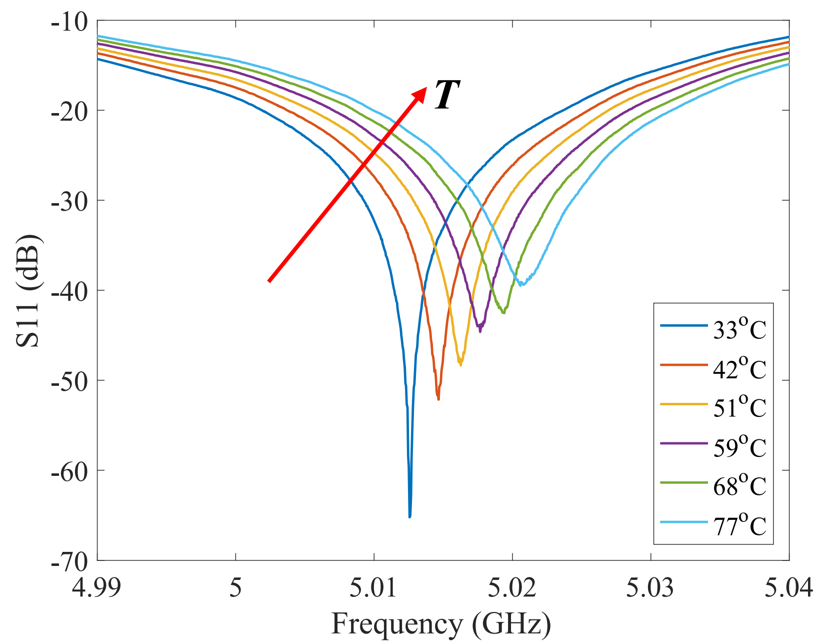




Furnace operation range: 280^{o}C
Maximum load: 10 kN

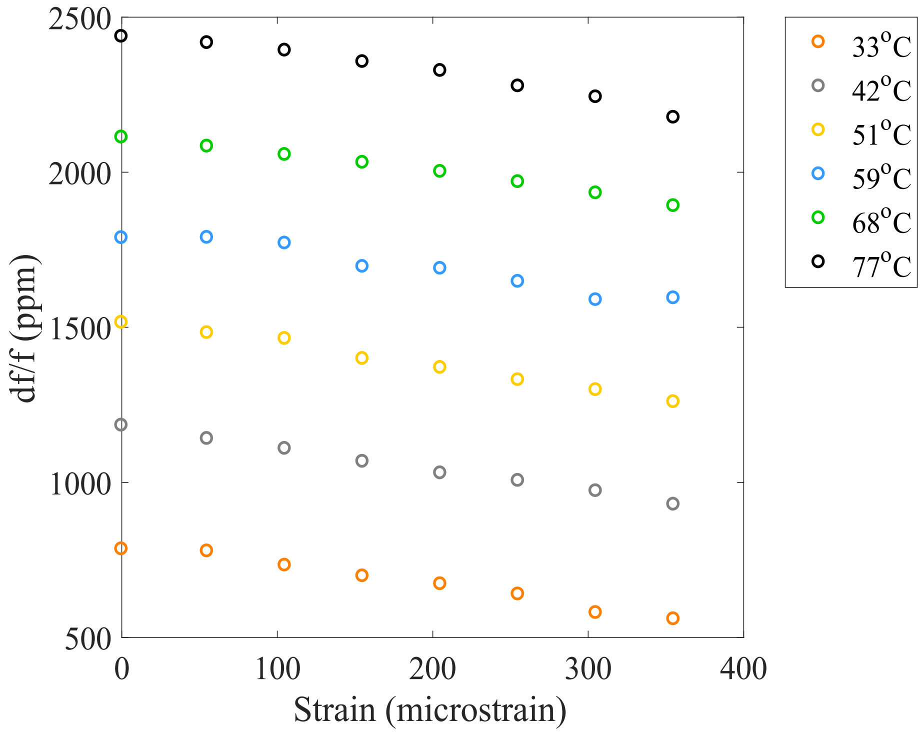
Measurement Results



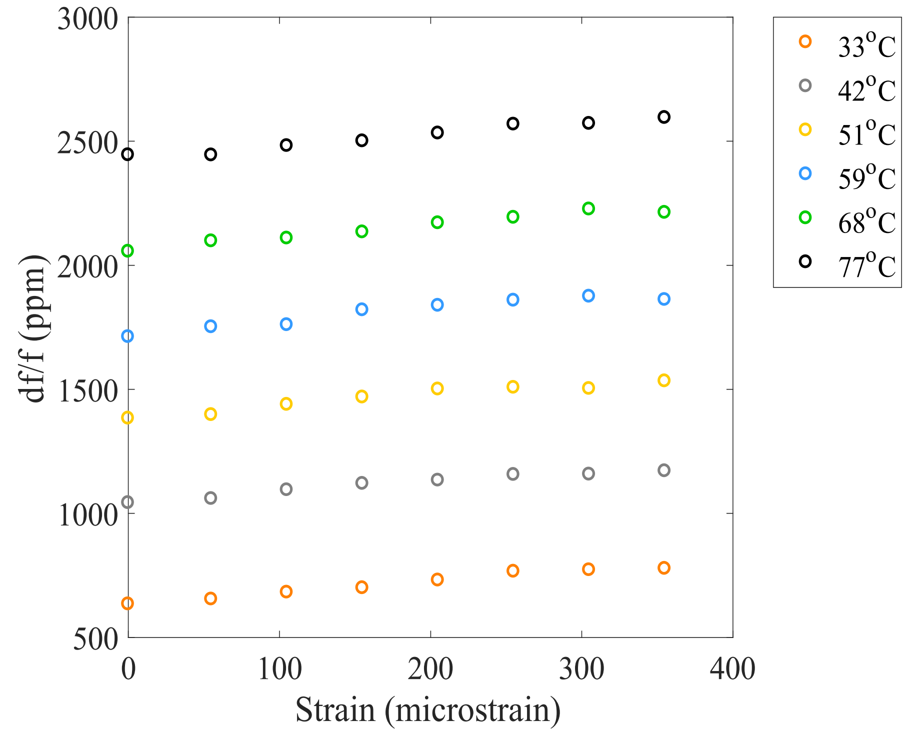


Simultaneous Strain & Temp. Sensing

Loading direction



Transverse direction



Excellent linearity: R^2 = 0.9986 and 0.9992 respectively

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Simultaneous Strain & Temperature Sensing

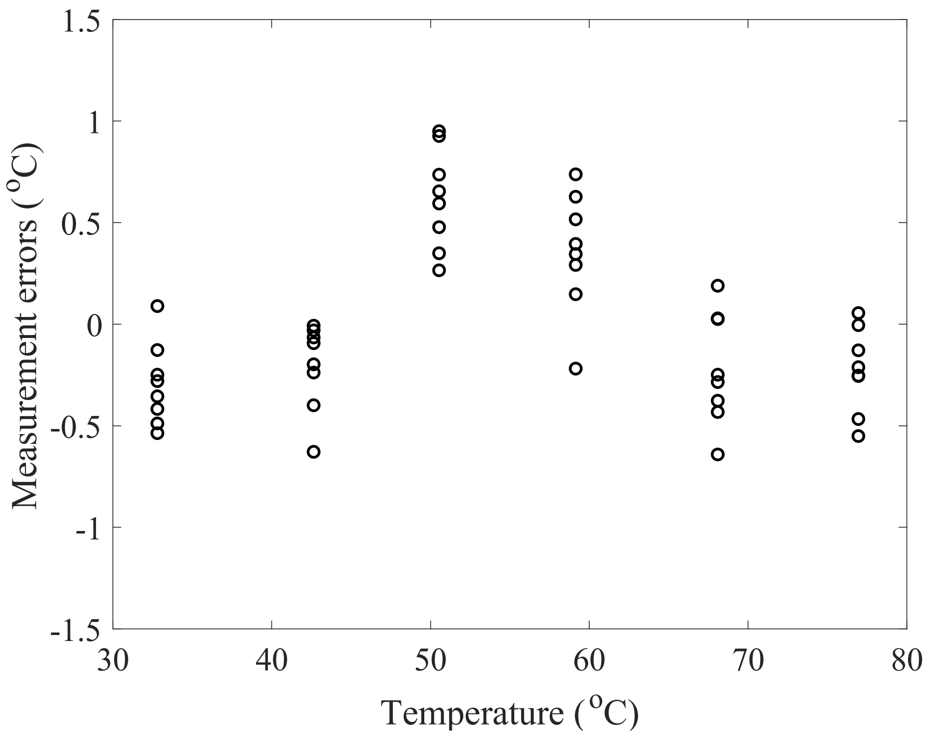
- **Fitting frequency shift as a linear function of strain & temp.**

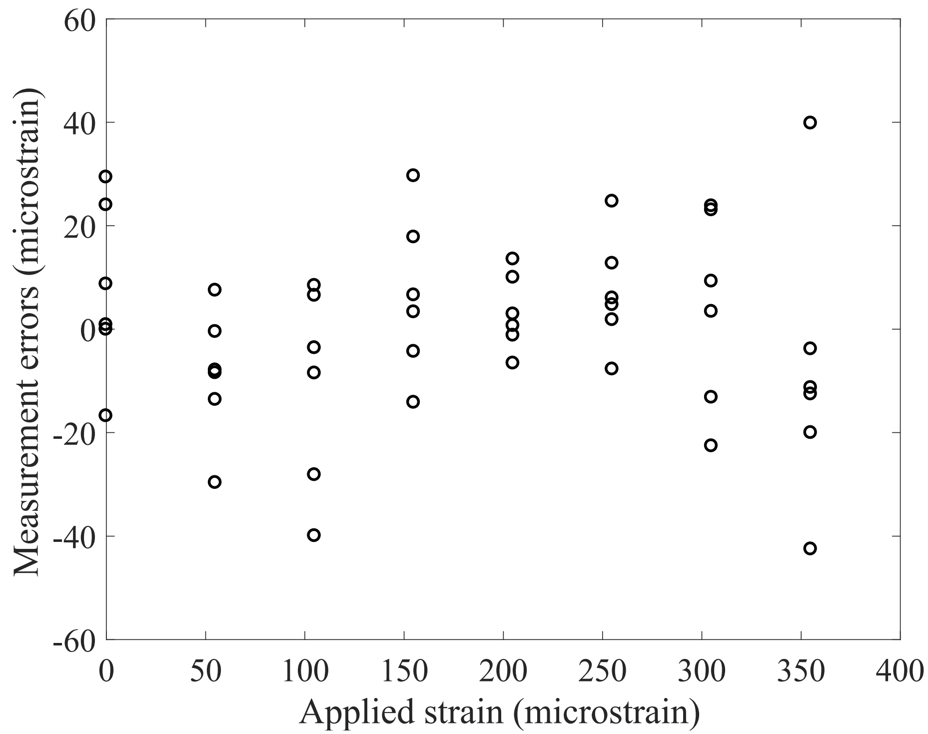
$$\begin{Bmatrix} \delta f_{ld} / f_{ld} \\ \delta f_{td} / f_{td} \end{Bmatrix} = \begin{bmatrix} -0.6839 & 37.32 \\ 0.4432 & 40.74 \end{bmatrix} \begin{Bmatrix} \varepsilon \\ T \end{Bmatrix} - \begin{Bmatrix} 328.4 \\ 746.1 \end{Bmatrix}$$

- **Determining strain & temp. from the normalized frequency shifts**

$$\begin{Bmatrix} \varepsilon \\ T \end{Bmatrix} = \begin{bmatrix} -0.6839 & 37.32 \\ 0.4432 & 40.74 \end{bmatrix}^{-1} \begin{Bmatrix} \delta f_{ld} / f_{ld} + 328.4 \\ \delta f_{td} / f_{td} + 746.1 \end{Bmatrix}$$

Measurement Errors





- **Temperature error**: 0.42°C
- **Strain error:** 17.45 με

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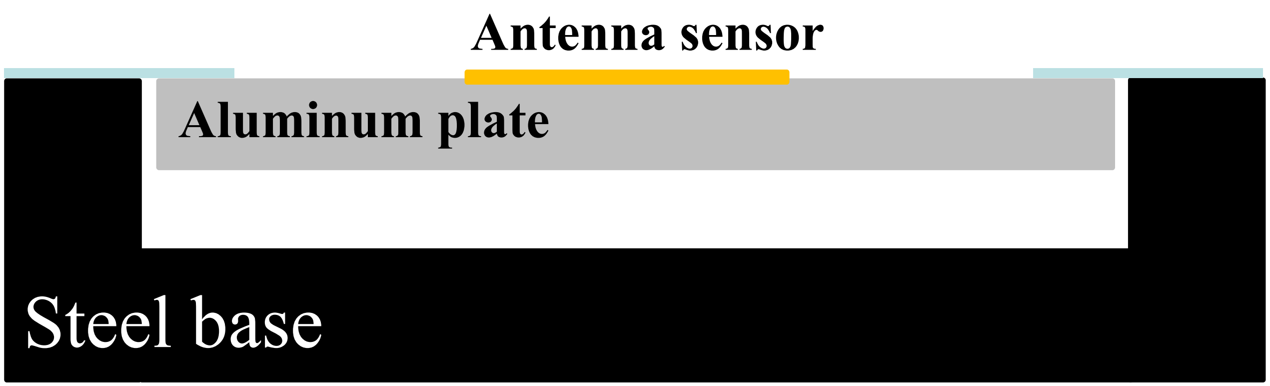
High-Temp Thermal-Mechanical Fixture



$$F_{Al} = F_{St} \quad \Rightarrow \sigma_{Al} A_{Al} = \sigma_{St} A_{St}$$

$$\delta L_{Al} - d = \delta L_{St} \Rightarrow \alpha_{Al} \delta T - \sigma_{Al} / E_{Al} - d = \alpha_{St} \delta T + \sigma_{St} / E_{St}$$

$$\Rightarrow \quad \varepsilon_{Al} = \left[(\alpha_{Al} - \alpha_{St}) \delta T - d \right] \times \left(1 + \frac{A_{Al} E_{Al}}{A_{St} E_{St}} \right)^{-1}$$

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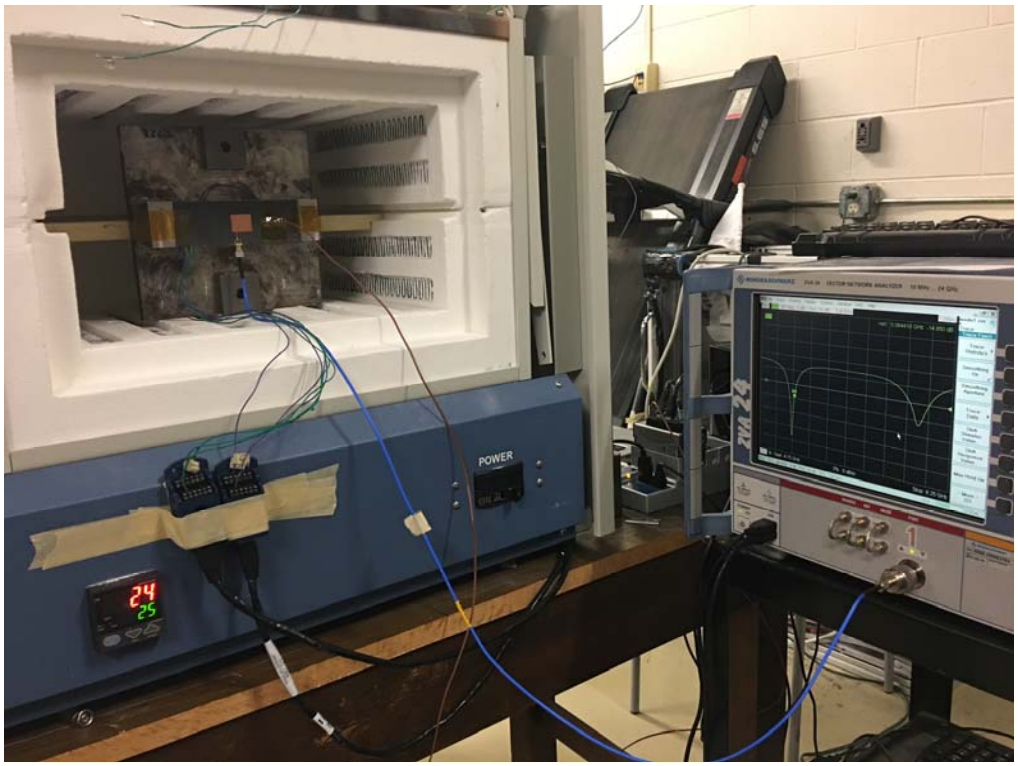
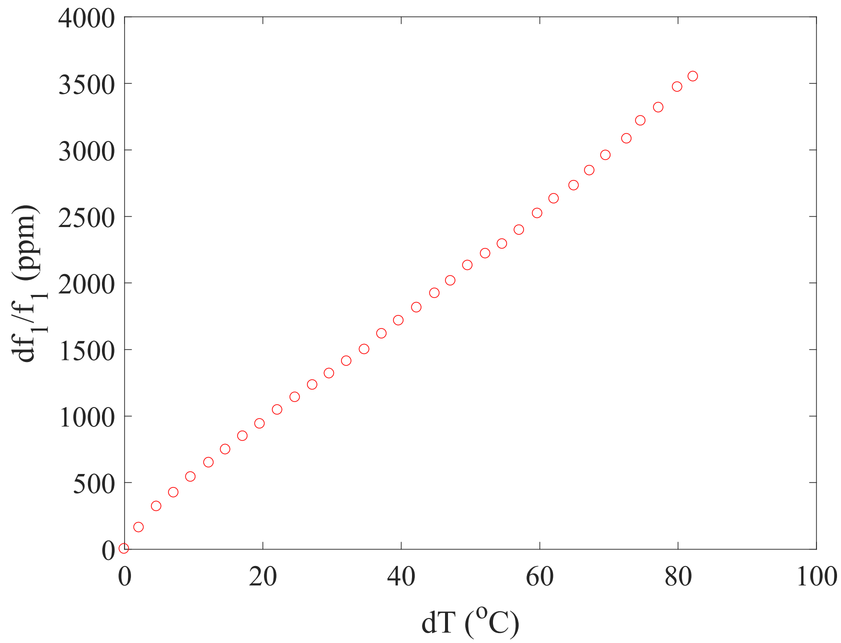
High-Temp Thermal - Mechanical Test

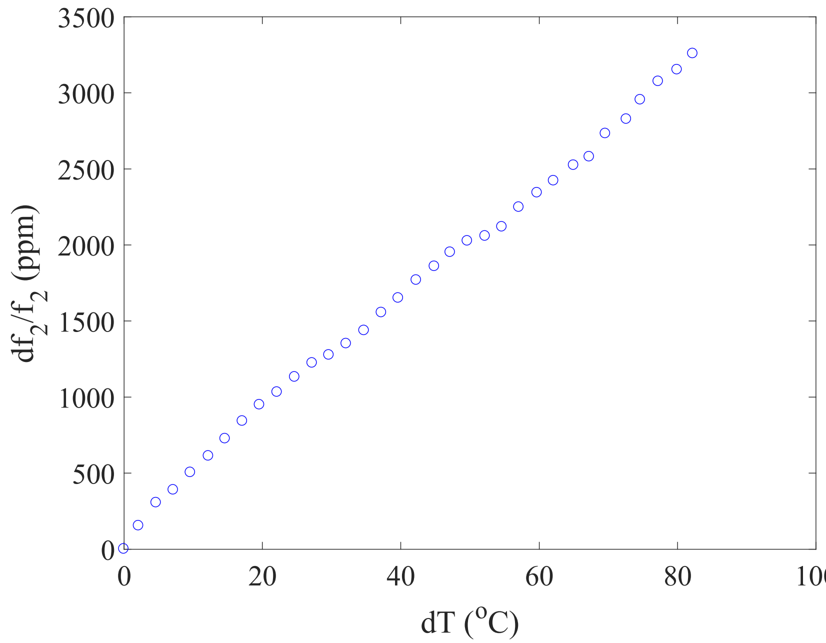


High Temperature Thermal-Mechanical Test

Measured sensitivities - temperature only

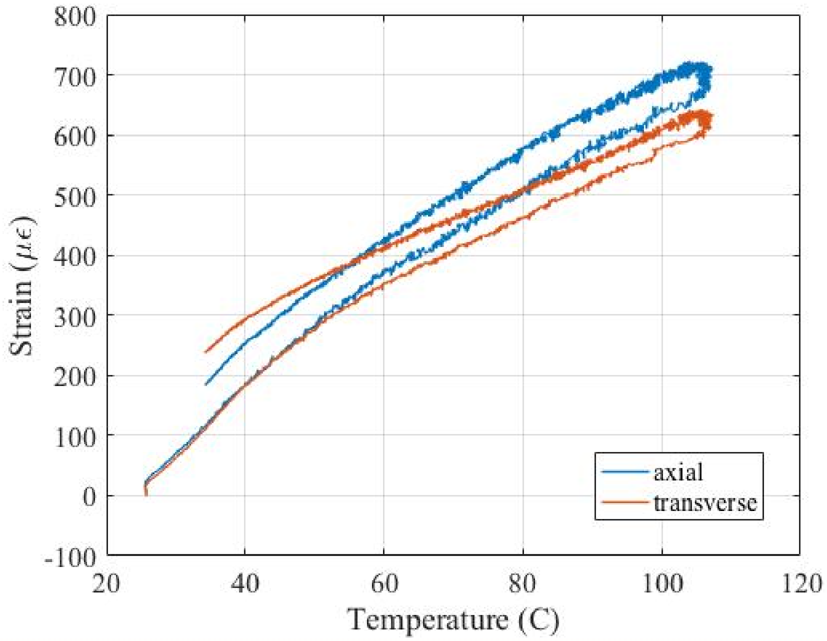
- TM10 mode (df_1/f_1) : 42.92 ppm/^{o}C
- TM01 mode (df_2/f_2) : 39.97 ppm/^{o}C

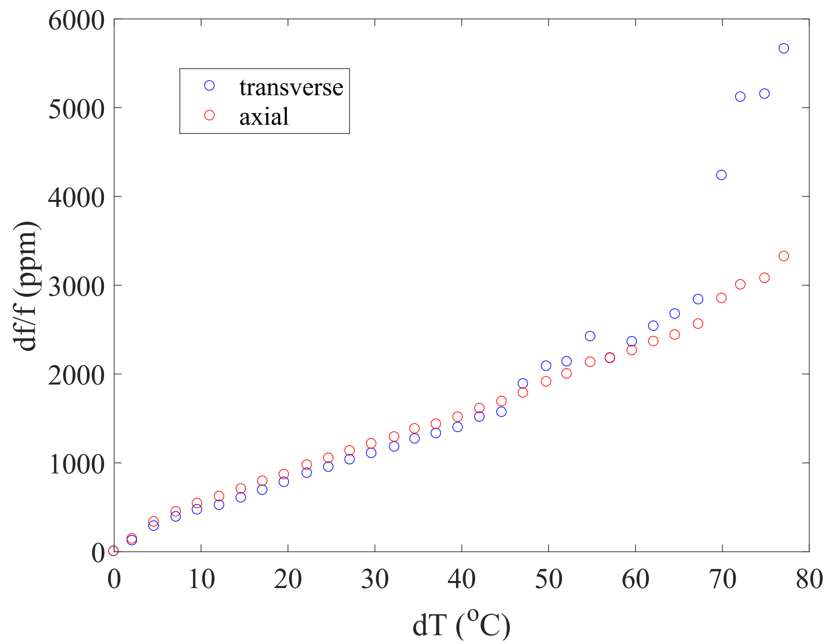




High-Temp Thermal-Mechanical Test

- Contact happens at ~ 52°C
- Up to 700 με is achieved using test fixture
- Strain measurements are different during heating and cooling
    - Al sample and steel base cool at a different rate

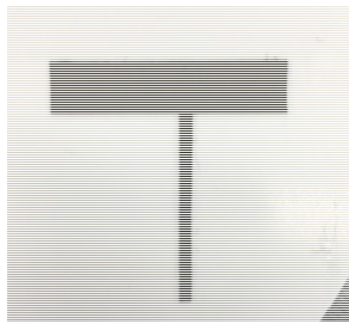




Fabricate Antenna Sensor Using High-Temp Materials

Alumina Substrate + Platinum Paste

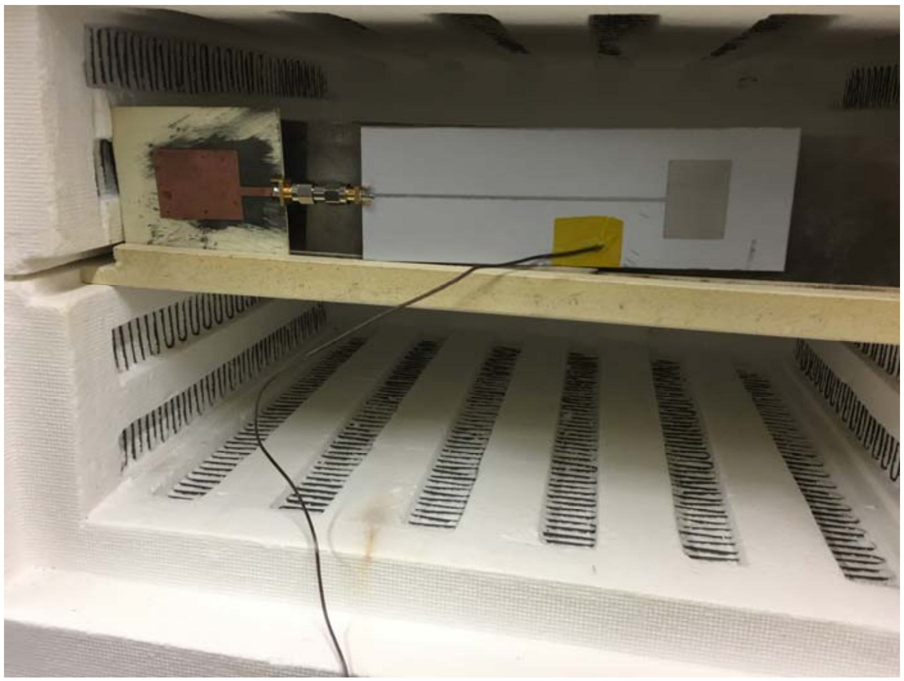
Dry Pt paste with mask on alumina substrate

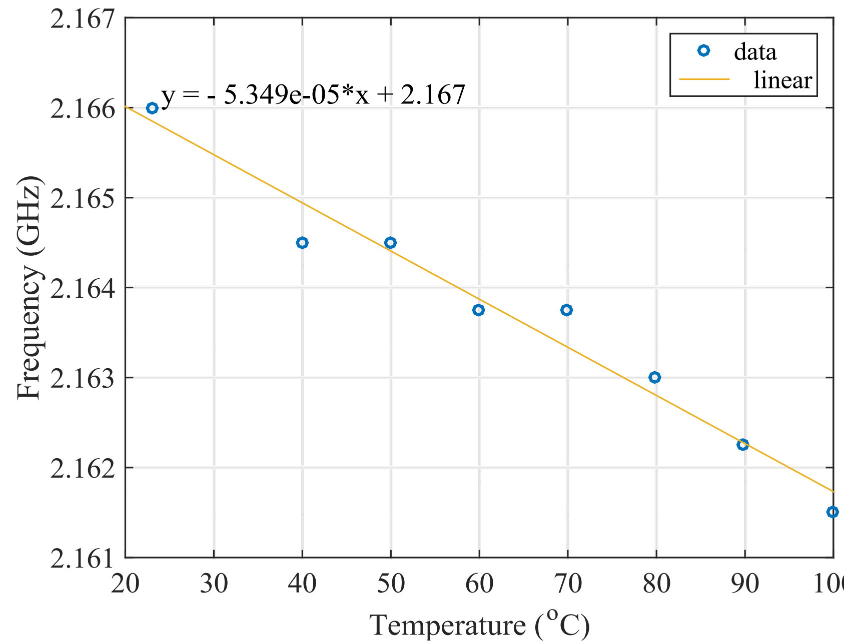


Remove mask

Fire Pt paste at 1000°C for 10 min

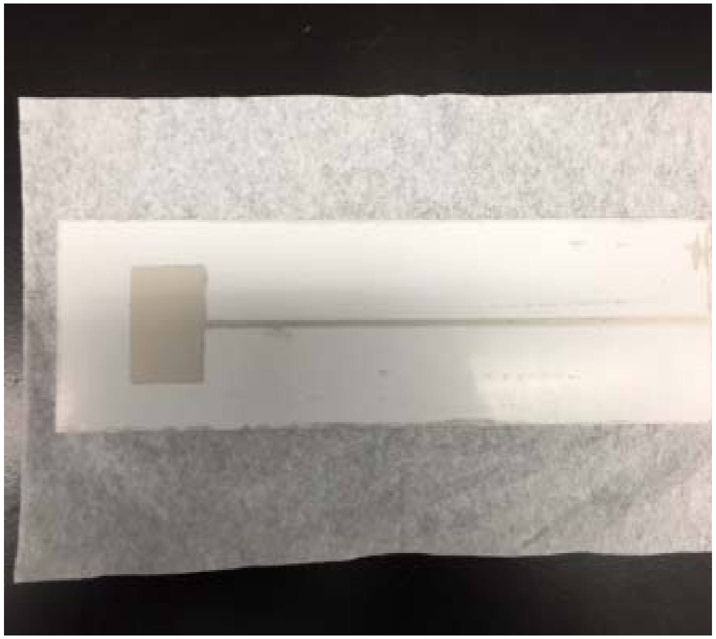
High-Temp Antenna Sensor

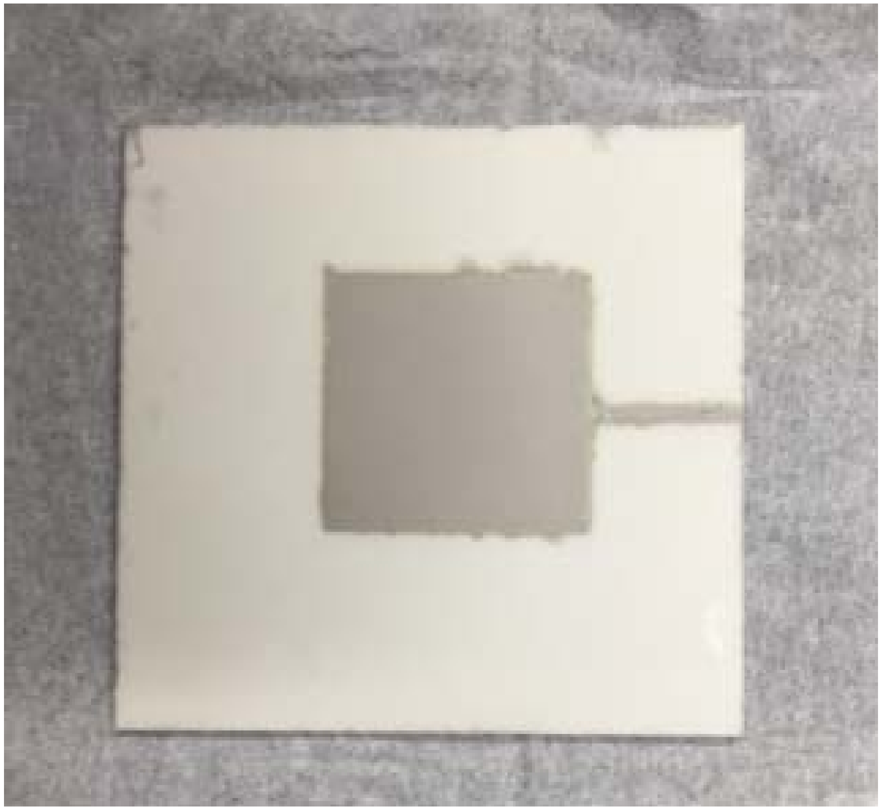




Limitation: low antenna gain (-10 dBi vs. 6 dBi)

Irregular Edges





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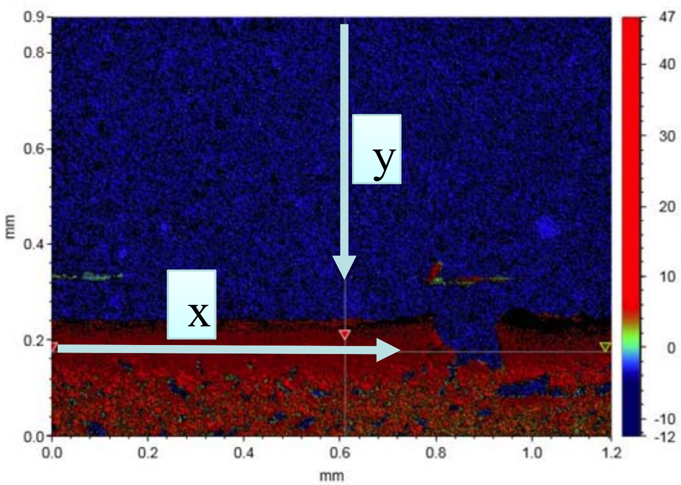
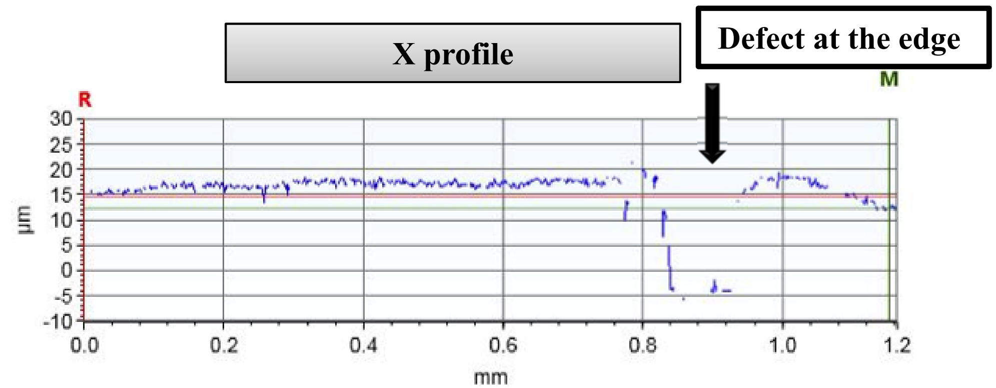
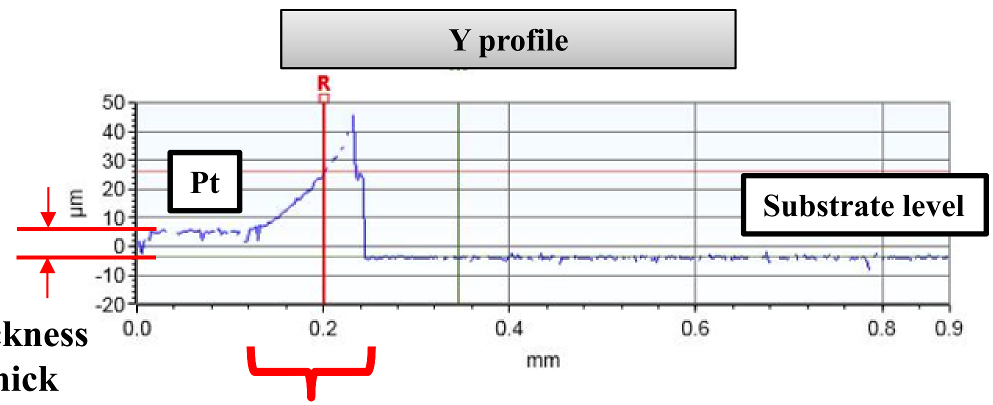
Surface Characterization



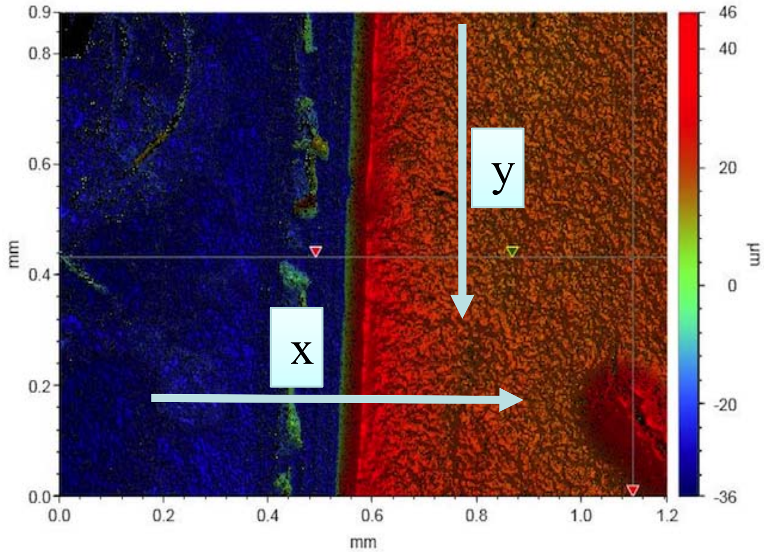


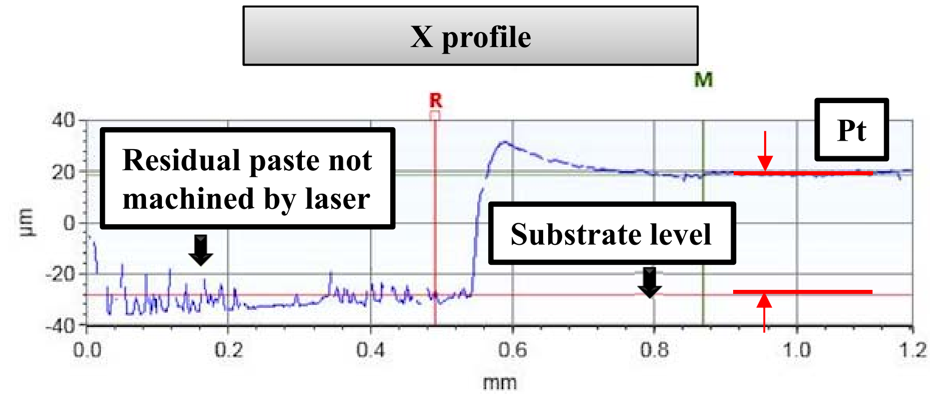


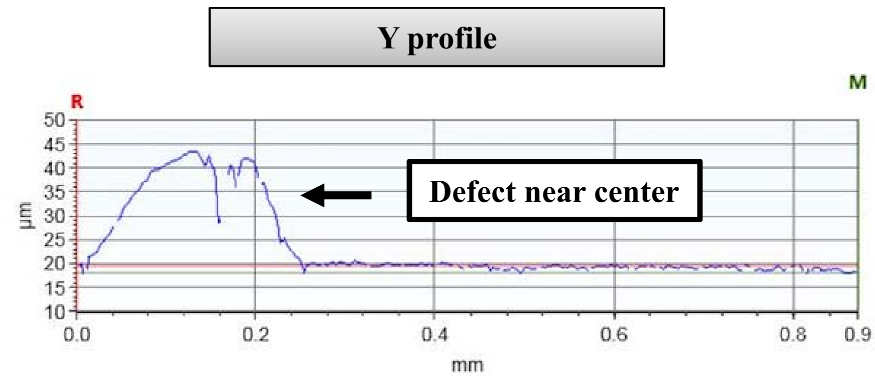
Pattern thickness 8 ~ 10 µm thick

thickness increased near the edge (~ 0.15 mm wide)

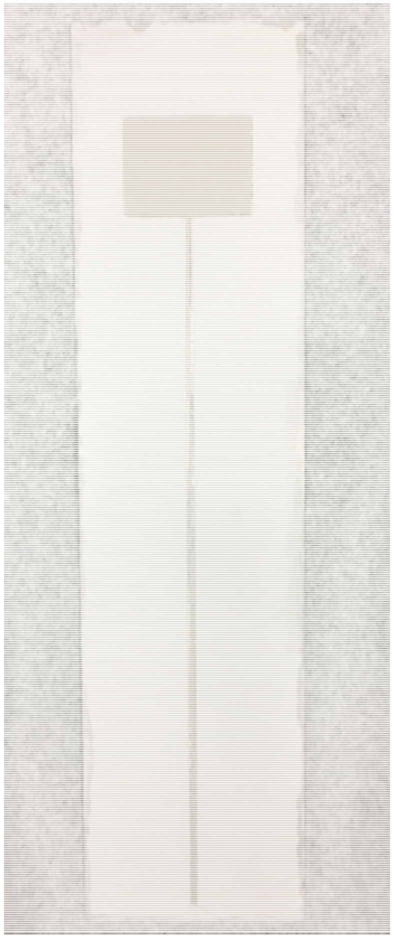
Laser Trimming





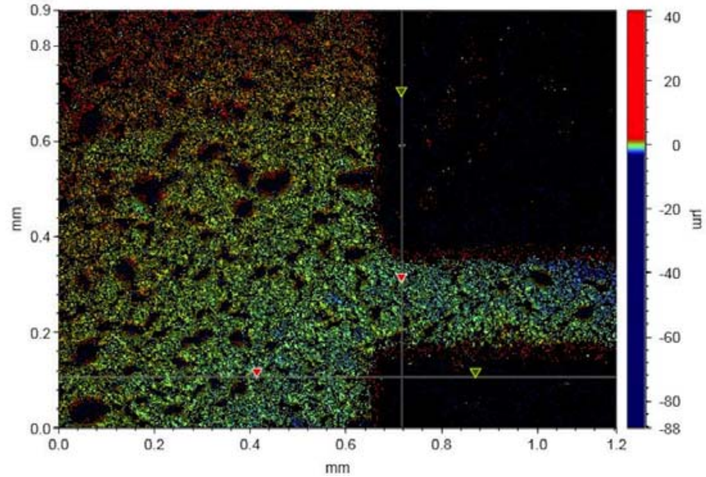


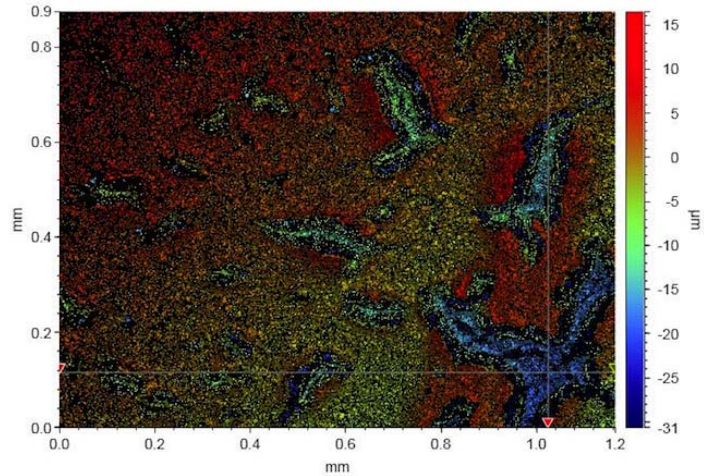
Laser Machined Antenna Sensor



thickness ~ 20 µm

Thickness ~ 50 µm





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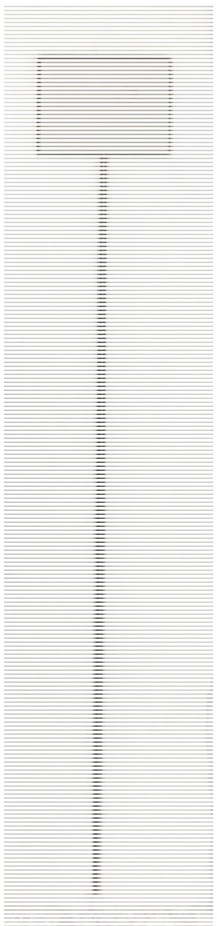
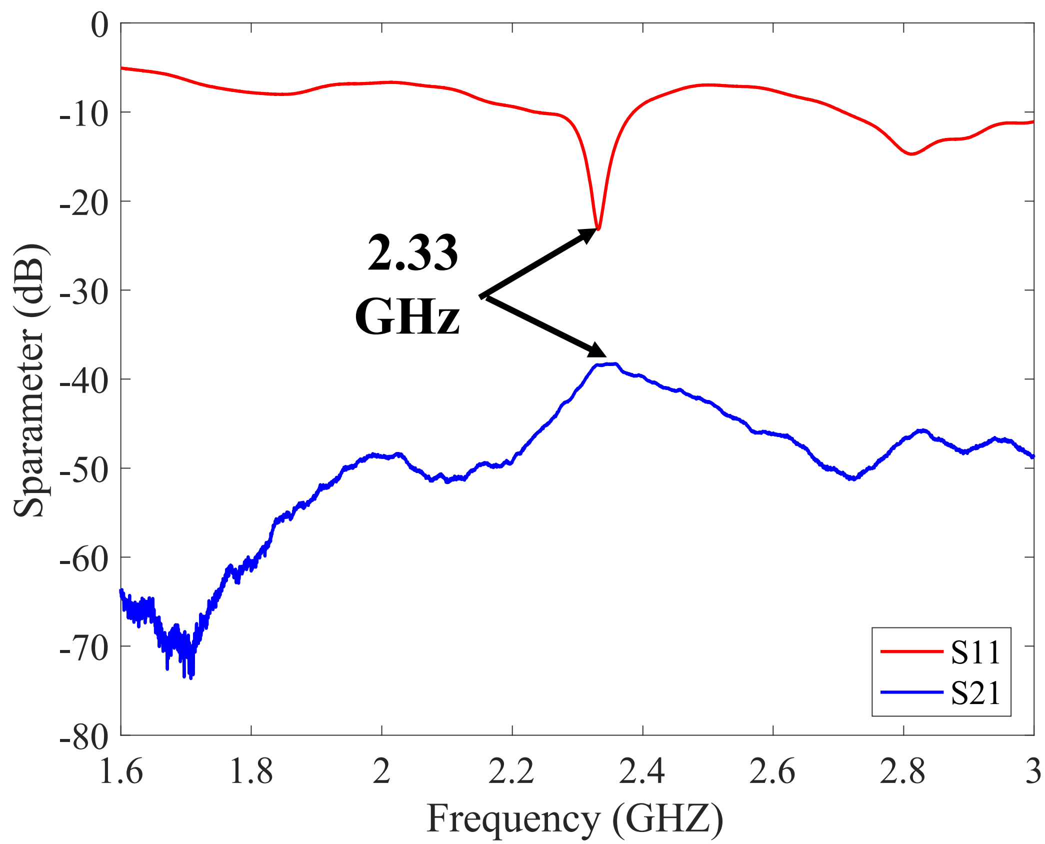
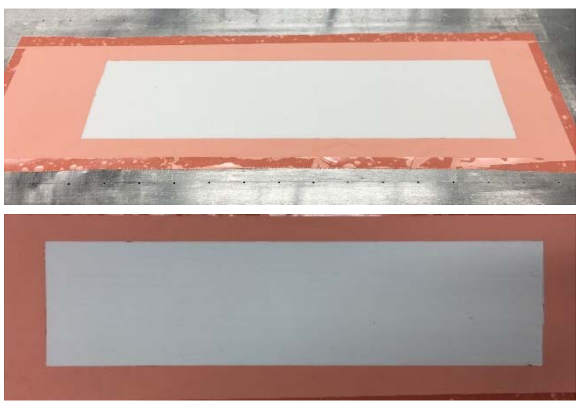
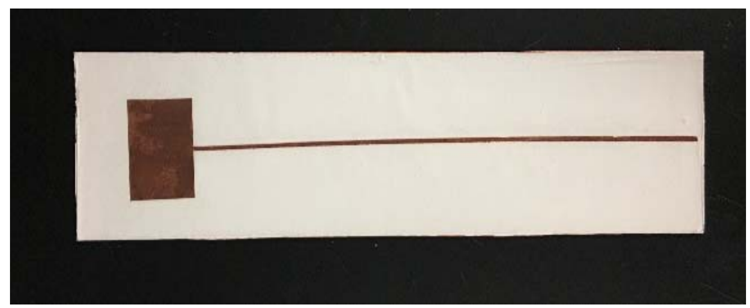
Scattering Parameter Measurements





Copper Film + Ceramic Paste





Achievement Summary

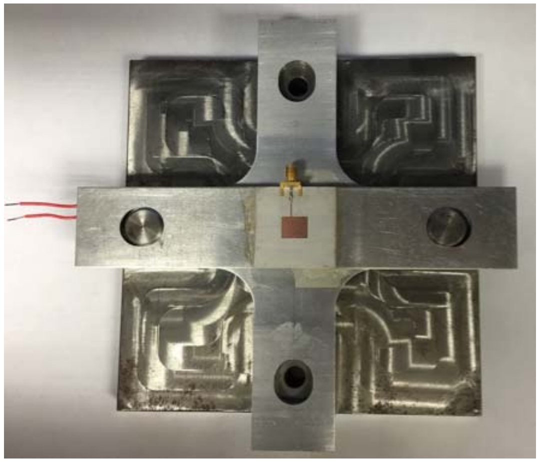
- Validated simultaneous strain and temperature measurement using one signal antenna sensor
  - Measurement errors: 0.42°C for temperature and 17.45 με for strain
- Obtained preliminary results from high-temperature test fixture
  - Strain applied up to 700 με
  - Strain level can be controlled by initial gap between sample and base
- Improved sensor fabrication process
  - Use laser trimming to achieve precise dimensions and smooth edges
  - Identified thickness variation issue through surface profiling
- Explored inexpensive materials for sensor fabrication

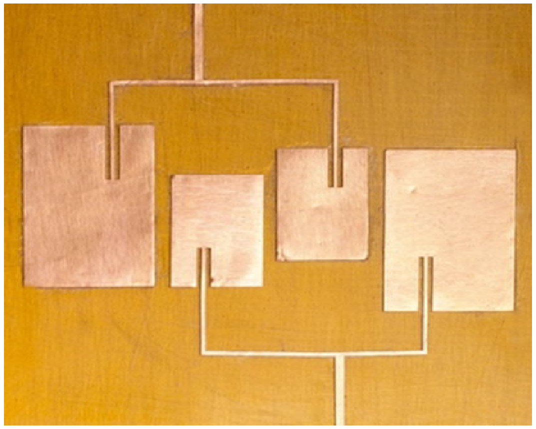
Publications

- Yao, J., Tchafa, F. E., 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. (top 25 downloaded in Sept. 2016)
- Jun Yao, PhD thesis, "Dynamic wireless interrogation of antenna-sensor in harsh environment", Dec. 2016
- Yao, J., Tchafa, F.E., 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.E., and Huang, H., "Simultaneous strain and temperature sensing using a microstrip patch antenna", abstract submitted to IWSHM 2017

Future Work

- Finalize experimental fixture for high-temp thermal-mechanical testing
- Simultaneous measurement of strain and temperature using a signal patch antenna sensor up to 1000°C
- Finalize fabrication of sensors using alumina wafer /platinum paste
- Explore flexible & inexpensive high temperature materials
- Implement antenna sensor array
- Investigate antenna sensor for soot detection





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Question & Answers

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