Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Haiying Huang, Franck Mbanya Tchafa, Jun Yao, Ankur Jain
Jiuyuan Nie, Jian Luo

Award #: DE-FE0023118
Duration: 1/1/2015-12/31/2017
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 °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

Radiation patch

Ground plane

\[ f = \frac{c}{2\sqrt{\varepsilon_r L}} \]

- Return Loss (dB)
- Frequency (GHz)

\[ f = \text{antenna resonant frequency} \]
\[ c = \text{speed of light} \]
\[ \varepsilon_r = \text{substrate dielectric constant} \]
\[ L = \text{patch dimension along current direction} \]
Patch Antenna Sensor

\[ f = \frac{c}{2\sqrt{\varepsilon_{\text{eff}} L}} \]

\[ \delta f = \frac{\partial f}{\partial \varepsilon_{\text{eff}}} \delta \varepsilon_{\text{eff}} + \frac{\partial f}{\partial L} \delta L \]

\[ \frac{\delta f}{f} = -\frac{1}{2} \frac{\delta \varepsilon_{\text{eff}}}{\varepsilon_{\text{eff}}} - \frac{\delta L}{L} \]

**Strain**: change dimensions of radiation patch \( \delta L/L \)

**Soot accumulation**: change effective dielectric constant \( \delta \varepsilon_{\text{eff}}/\varepsilon_{\text{eff}} \)

**Temperature**: changes both \( \delta \varepsilon_{\text{eff}}/\varepsilon_{\text{eff}} \) and \( \delta L/L \)
Achievement #1: Wireless Interrogation of Antenna Sensor Without Electronics
Wireless Interrogation of Antenna Sensor

- **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 Sensor Design

- Commercial high frequency circuit laminate (Rogers RO3210)
  - Temperature: up to 300 °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 mm²
  - 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
Wireless Interrogation of Antenna Sensor

- Interrogation power: 10 dBm
- Interrogation distance: 0.7 m
- Temperature range: 20-300°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

Structure mode

Antenna mode

$f_1$

$f_2$

$0$
Test Results - Wireless Interrogation

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

Instrument used is expensive, slow, & bulky
FMCW-based Wireless Interrogator

- Lower cost
- Compact
- Faster sampling rate
- Enable sensor multiplexing
FMCW-based Wireless Interrogation

The graphs show the relationship between the temperature change (°C) and the frequency change (Δfres / fres (ppm)). The equations for the data are:

- For 25 °C to 170 °C: 
  \[ y = 162.06x + 893.39 \] 
  \[ R^2 = 0.9961 \]

- For 25 °C to 170 °C: 
  \[ y = 169.69x - 533.37 \] 
  \[ R^2 = 0.9941 \]
Achievement #2: Sensor Fabrication for Temperature up to 1000°C
Material Selection

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

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

<table>
<thead>
<tr>
<th>Metals</th>
<th>Electrical Conductivity $10^6$ S/m</th>
<th>Melting point °C</th>
<th>High Temp. Stability in air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>58.5</td>
<td>1085</td>
<td>Poor</td>
</tr>
<tr>
<td>Gold</td>
<td>44.2</td>
<td>1064</td>
<td>Good</td>
</tr>
<tr>
<td>Aluminum</td>
<td>36.9</td>
<td>660</td>
<td>Poor</td>
</tr>
<tr>
<td>Zinc</td>
<td>16.6</td>
<td>420</td>
<td>Poor</td>
</tr>
<tr>
<td>Nickel</td>
<td>14.3</td>
<td>1455</td>
<td>Poor</td>
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<tr>
<td>Platinum</td>
<td>9.3</td>
<td>1768</td>
<td>Good</td>
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</tbody>
</table>

Materials illustrated:
- 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

<table>
<thead>
<tr>
<th>Sample</th>
<th>Front Patch mΩ/Square</th>
<th>Transmission Line mΩ/Square</th>
<th>Back Electrode mΩ/Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Sensor</td>
<td>8.2</td>
<td>31.0</td>
<td>23.1</td>
</tr>
<tr>
<td>Tx/Rx Antenna</td>
<td>3.5</td>
<td>8.6</td>
<td>6.4</td>
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</table>
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 sensor connected using SMA connector
- Tested at temperature up to 100 °C
- Interrogation distance of 0.7 m
- Sensitivity of -53.49 kHz/°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°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
Dimensions
Analytical Model
S-parameter

Measured S-parameter
Dimensions
Inverse Method
Dielectric parameters

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>6.17</td>
<td>6.15</td>
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<tr>
<td>Tangent loss</td>
<td>0.0022</td>
<td>0.002</td>
</tr>
</tbody>
</table>

UC San Diego
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 than 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
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