Ultra-High Temperature Distributed Sensors

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Antenna Design & RF Testing
Agenda

• Problem
• Metamaterial Solution
  – Design
  – Materials characterization
  – Prototype Testing
• Mechanically Modulated Antenna Solution
  – System Design
  – Prototype Testing
  – Antenna Design
  – Temperature Tests
• Characterization of RF Environment
• Next Steps
The Problem

To measure physical parameters (temperature, pressure, strain, etc.) in extreme temperature and highly corrosive environments.

Coal-Fired Boiler Plant

Coal-Gasification Plant
The Proposed Solution

Passive Wireless Sensors
The Initial Approach

Guided Mode Resonance Filters (GMRFs)
Initial Approach

Transduction concept

- Periodic arrays on the order of the RF wavelength generate a signature
- RF material properties change with temperature
- Signature changes can be calibrated to temperature
- Sensors can be designed to have distinct signatures enabling multiplexing

\[ Q = \frac{f_c}{\text{FWHM}} \]

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\[ f_c \]

\[ \sigma = 1.41 \text{ S/m} \]
\[ \sigma = 3.29 \text{ S/m} \]
\[ \sigma = 6.56 \text{ S/m} \]
\[ \sigma = 11.62 \text{ S/m} \]
\[ \sigma = 18.81 \text{ S/m} \]
\[ \sigma = 28.39 \text{ S/m} \]
\[ \sigma = 40.52 \text{ S/m} \]
\[ \sigma = 55.27 \text{ S/m} \]
\[ \sigma = 72.65 \text{ S/m} \]
\[ \sigma = 92.60 \text{ S/m} \]
\[ \sigma = 115.0 \text{ S/m} \]
Goal: Quantify temperature dependent RF material properties

- permittivity ($\varepsilon$) and permeability ($\mu$)
- measure transmission and reflection thru samples to back out the conductivity

$$\mu = \mu_0 (\mu_r' - j \mu_r'') = \mu_0 \mu_r' (1 - j \tan \delta_{\mu})$$

$$\varepsilon = \varepsilon_0 \varepsilon_r' - j \frac{\sigma_e}{\omega}$$
Materials Characterization

Experimental results - SiC

- Dielectric constant and Loss computed from raw data ($S_{11}$, $S_{21}$)
- Loss increases significantly with temperature

Dielectric Constant ($\varepsilon_r'$)

Loss ($\varepsilon_r''$)
Materials Characterization

Experimental results

Conductivity vs temperature for SiC at 22 GHz

![Graph showing conductivity vs temperature for SiC at 22 GHz]
Sensor Design

**GMR sensor concept**

**Guided Mode Resonance (GMR)**
- incident energy at a specific frequency is coupled into a transverse longitudinal mode, creating a notch in the reflected response
- simple construction
- sensitive to angle of incidence

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<thead>
<tr>
<th>Scattered Electric Field [dB]</th>
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At \((\theta = 0^\circ, \phi = 0^\circ)\)

- \(\tan \delta = 0.00\)
- \(\tan \delta = 0.25\)
- \(\tan \delta = 0.50\)
- \(\tan \delta = 0.75\)
- \(\tan \delta = 1.00\)
Sensor Design
Alternative sensor concepts

Element Resonance (SRR, dipole array etc.)
- less angle sensitive
- more complex geometry

Dipole array
Split ring resonator

<table>
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<tr>
<th>Electric Field Intensity (dB)</th>
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<tr>
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<td>-5</td>
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<th>Frequency (GHz)</th>
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Sensor Design

Sensor testing

- room temperature evaluation
- baseline measurements
- validation of test setup
Sensor Design

Sensor testing

- measurement of reflected energy vs frequency
- 16 – 24 GHz
- baseline data for “no target”
- dipole array shows good comparison to simulation

- GMR sensor has not shown simulated response
- edge diffraction effects possibly dominating response
- high loss of SiC results in weak coupling

Distance: 0.455 [m], 2" x 2" Size Targets

![Graph showing |s21| vs Frequency (dB) for different materials and environments.](image)
Sensor Design

Sensor testing

- Measurement of reflected energy vs frequency
- 16 – 24 GHz
- baseline data for “no target”
- Metamaterial sensor response compared to a metal plate
- Sensor response is not discernable, even at normal incidence

![Graphs showing |s21| (dB) vs Frequency for 2” x 2” and 4” x 4” targets](image)

- Distance: 0.45 [m], 2” x 2” Size Targets
- Distance: 0.45 [m], 4” x 4” Size Targets

Legend:
- Lab Env.
- Sensor - Lab Env.
- Metal Plate - Lab Env.
Sensor Design

Challenges with GMR (Metamaterial) Approach

1) The sensor response was weak and indistinguishable from background clutter.
   • Surface reflections swamped the GMR response
   • Material dielectric loss may prevent good coupling of the guided mode

2) A working metamaterial sensor would have to be very large to have a sufficient number of periods
   • Even a 4” x 4” sensor (approx 20 periods) had a response dominated by surface reflections and edge effects

3) The sensor was angle sensitive.
   • The sensor response changed or disappeared with any deviation from exact normal (90 degree) angle of incidence

Need a unique signature to discriminate sensor signal from background reflections (frequency shifting, harmonics, etc.)

Need a device that does not rely upon periodic structures of integral wavelength (single element devices)

Need a device that does not rely upon normal incidence of interrogating radio wave.
A New Wireless Sensor Design
Mechanically Modulated Antenna

• Each sensor is an antenna with a mechanical element which is interrogated wirelessly by Doppler radar.

• The mechanical element modulates the frequency response of the antenna.
  • The modulation frequency changes with temperature of the antenna.
  • Modulation shifts the reflected frequency away from the center frequency of the Doppler radar.

• Each antenna can be tuned to a unique frequency to multiplex several sensors with a single interrogator (radar).

• Each sensor has a unique signature outside spectral range of background reflections.
Initial Sensor Geometry

- Ground
- Folded Slot
- Post
- Vibration Beam
Slot Antenna Close-Up

FEA predicts beam natural frequency of 1980 Hz.
Interrogator Design
Doppler RADAR

- Acoustic excitation (1800 Hz)
- Doppler RF interrogation (10 GHz)
FEKO Simulation Results

Beam displacement changes antenna impedance and modulates antenna center frequency.

![Graph showing return loss vs frequency with center, (+) 558 µm, and (-) 558 µm beam displacement plots.](image-url)

- **Center**
- **(+) 558 µm beam displacement**
- **(-) 558 µm beam displacement**
Experimental Results
Mechanically Modulated Antenna

Initial experiments used laser excitation.
MMA Experimental Results
Acoustic Excitation

- RF Doppler placed 30 cm from target with 15 dBm power (30 mW)
- Acoustic source 1 m from target with 110 dBA at 1800 Hz
- Better acoustic capture efficiency when mounted on cardboard

Sensor in free space
Sensor on cardboard wall
Dipole Antenna Design

Objective: determine if amplitude or phase modulation dominates.

Height 1.12 cm
Stub tuner: 0.47 cm long
Resonates electrically around 16 GHz
Dipole antenna

- Assumes interrogator uses horn antenna with 15 dBi gain and 2W output.
- Dipole has low radar cross-section, and therefore low power reflection.
Dipole w/ rotated tuning arms
Temperature dependence

• Elastic modulus, density, and dimensions all depend on temperature and affect natural frequency.
• Modeling vibrating cantilever beam predicts 0.2 Hz/°C

• Experimentally measured peak resonant frequency with changing temperature.
• Data shows 0.3 Hz/°C temperature dependence.

Predicted resonant frequency vs temperature

![Graph showing predicted resonant frequency vs temperature](image)

Experimental results

![Graph showing experimental results](image)
Characterization of RF Environment

Overview

Goal: find regions of RF spectrum where attenuation is lowest
Characterization of RF Environment

Site Survey

• Babcock & Wilcox Small Boiler Simulator (SBS), Alliance Ohio
• Tim Fuller and Tom Flynn – B&W Power Generation Group
• B&W IRAD supports cost share
Characterization of RF Environment

Antenna installation

• antennas need to be broad band (2.5 – 40 GHz)
• must fit inside standard 3” viewport
• needs to withstand high temperatures

TEM horn antenna
Characterization of RF Environment

Antenna installation

- SMA Connector (3.5mm)
- Heat-Blocking Material
- Semi-Rigid Coaxial Cable with Teflon Material
- Feed Region
- Terminals of thermo-couples (Front & Back)
- Small Air Holes

Ant. A

Ant. B
Characterization of RF Environment

Antenna design

- Viewport installation does not affect gain performance significantly
Characterization of RF Environment

Field Tests

- 2 field tests
- Natural gas and biomass firing
- SBS convection pass
- Evaluated RF attenuation from 2.5 – 40 GHz
Characterization of RF Environment

Experimental results - biomass

Plots show difference in scattering parameter measurements made before and after biomass firing.
Characterization of RF Environment

Experimental results – coal firing

Conclusion: 10 GHz to 15 GHz should be a good window for operation of sensor.
Conclusions

• Testing at B&W SBS indicates RF link budget is satisfactory (natural gas, biomass, and coal firing)
• High temp RF materials characterization – strong response demonstrated (not important to new MMA design)
• Metamaterial sensor concept was not demonstrated – *indicates strong need for a sensor signal which is distinct from broadcast energy*
• Novel hybrid sensor concept developed – mechanically modulated antenna (MMA) with acoustic excitation
• MMA shows good signal discrimination against background- unique time based signature
• Remote excitation and interrogation experiments successful
• Demonstrated temperature dependent shift in modulation frequency
• MMA sensor shows broad field of view (+/- 70°)
• Modeled modulation mechanism and showed strong phase response
Next Steps

- Optimize antenna design: maximize change in impedance due to a unit displacement
- Investigate retroreflecting antenna array
- Optimize acoustic capture efficiency; enables lower acoustic power or larger beam deflections
- Evaluate dielectric antenna concept (smaller form factor, sapphire as antenna and package, not influenced by mounting specifics)
- Investigate sensor multiplexing (acoustic and RF multiplex)
- Develop Doppler interrogator (possibly COTS components)
- Develop high-temperature packaging
- Field test of MMA sensors in coal combustion and/or gasifier facilities
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