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PHOENIX

Ultra-High Temperature Distributed Sensors

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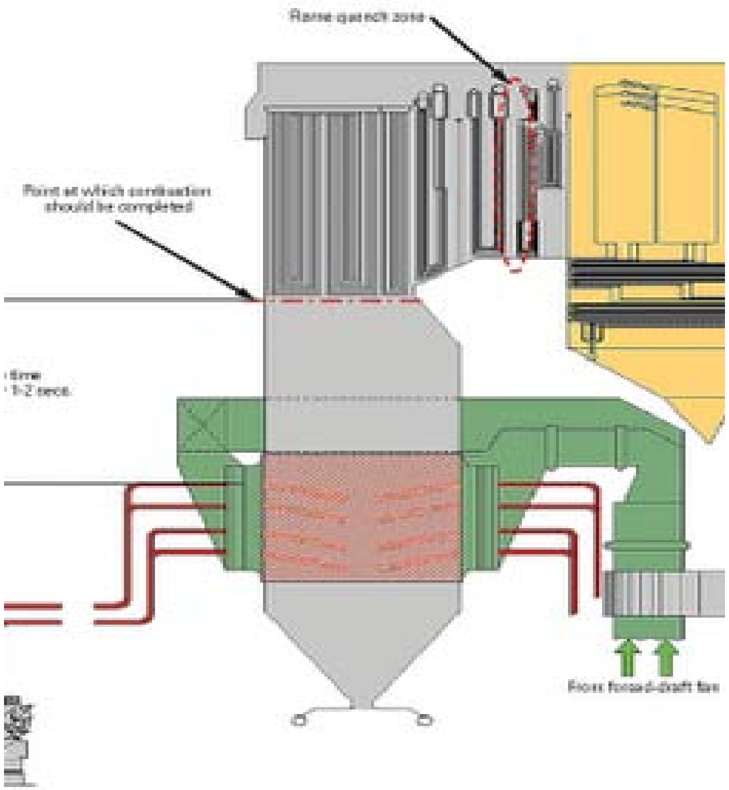
Agenda

- 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

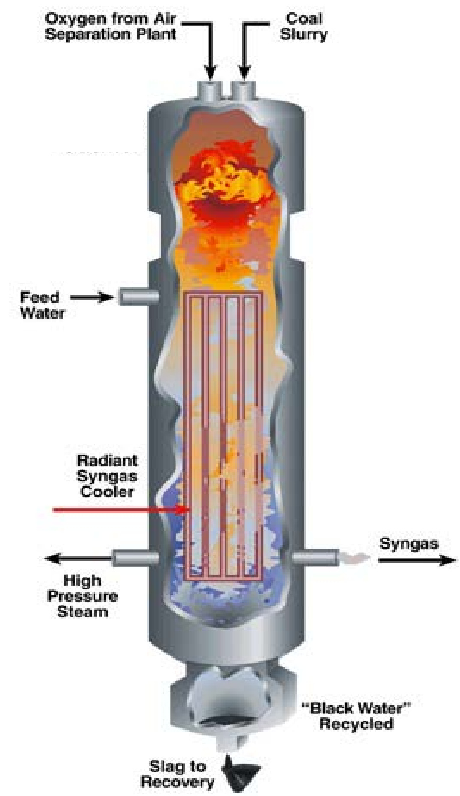
The Problem

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

Coal-Fired Boiler Plant

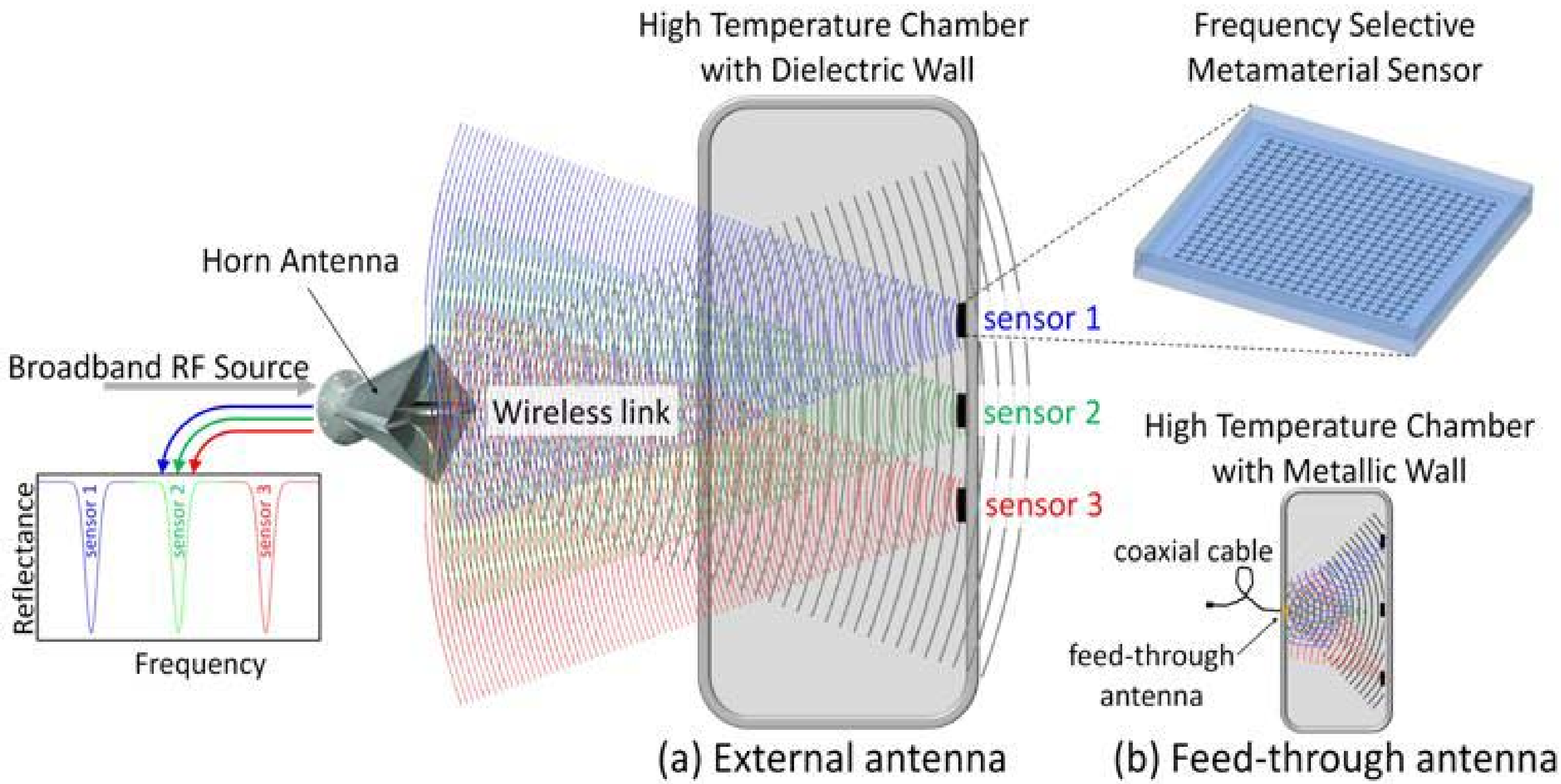


Coal-Gasification Plant

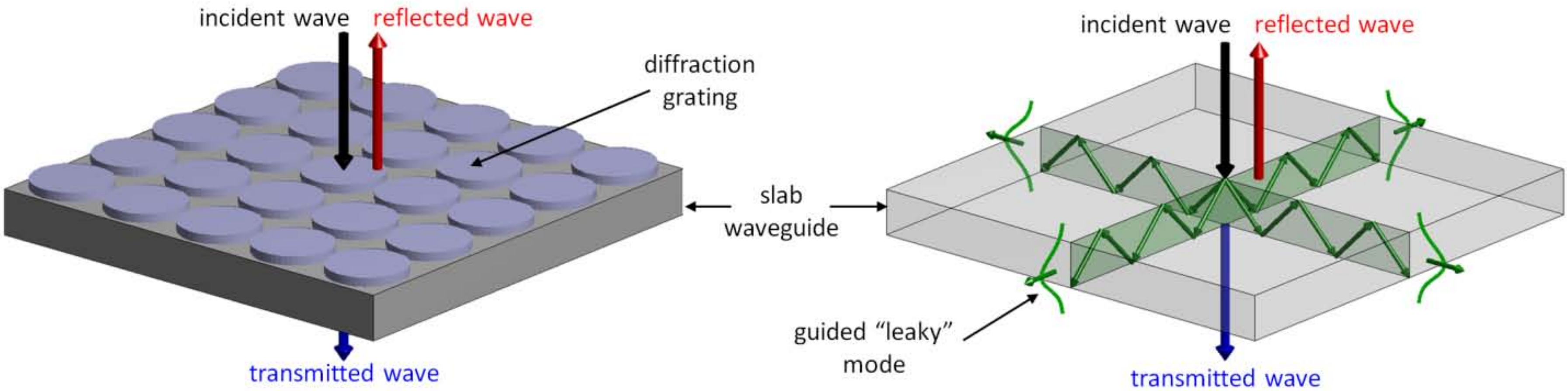


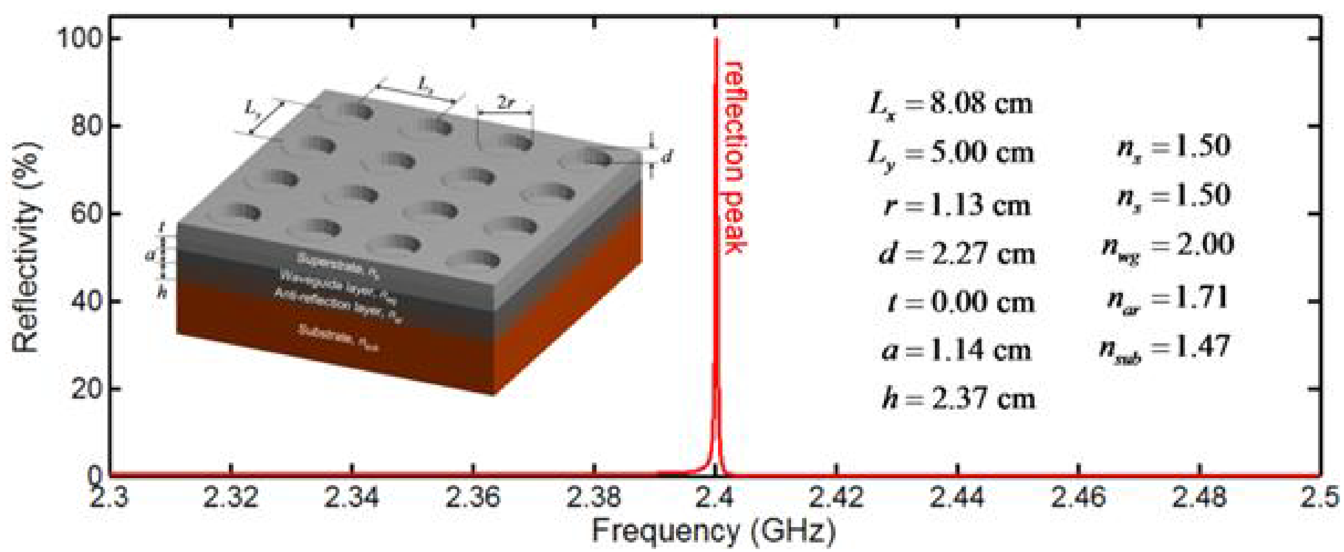
The Proposed Solution

Passive Wireless Sensors



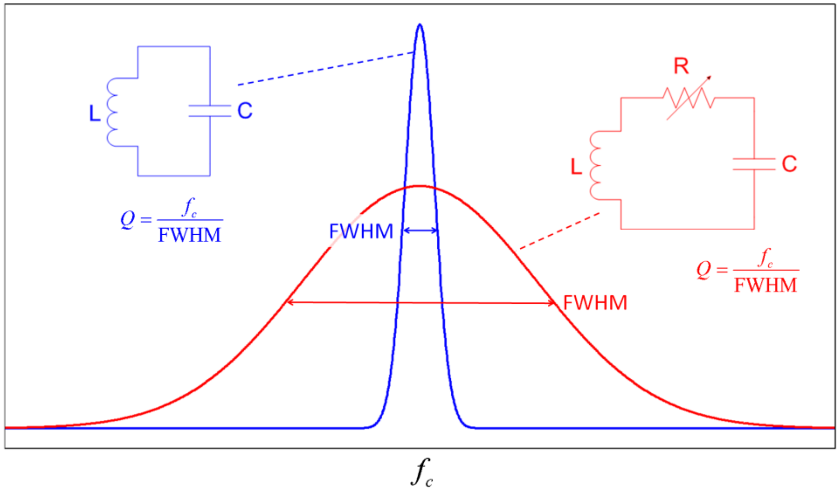
The Initial Approach
Guided Mode Resonance Filters (GMRFs)

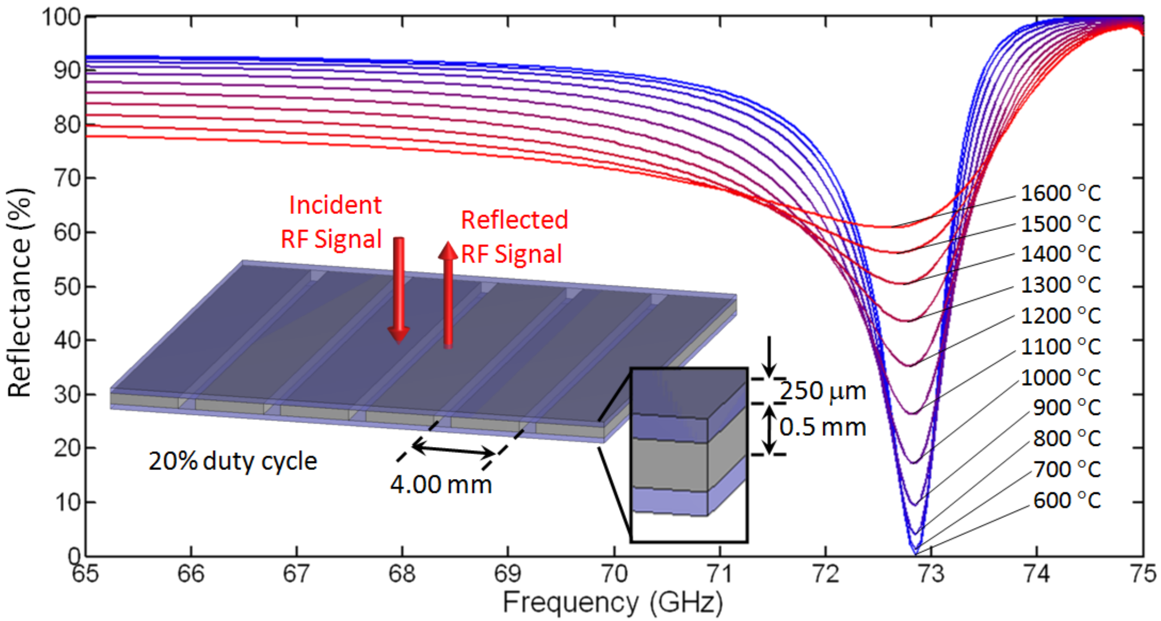


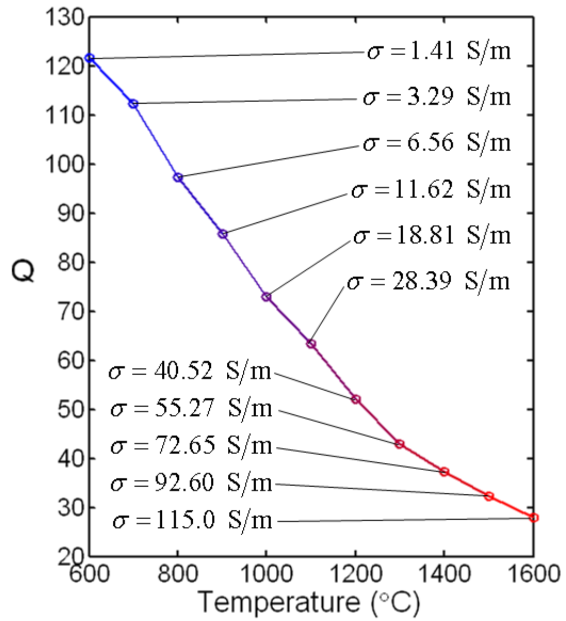


Initial Approach
Transduction concept

- 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 multiplex







Materials Characterization
Overview

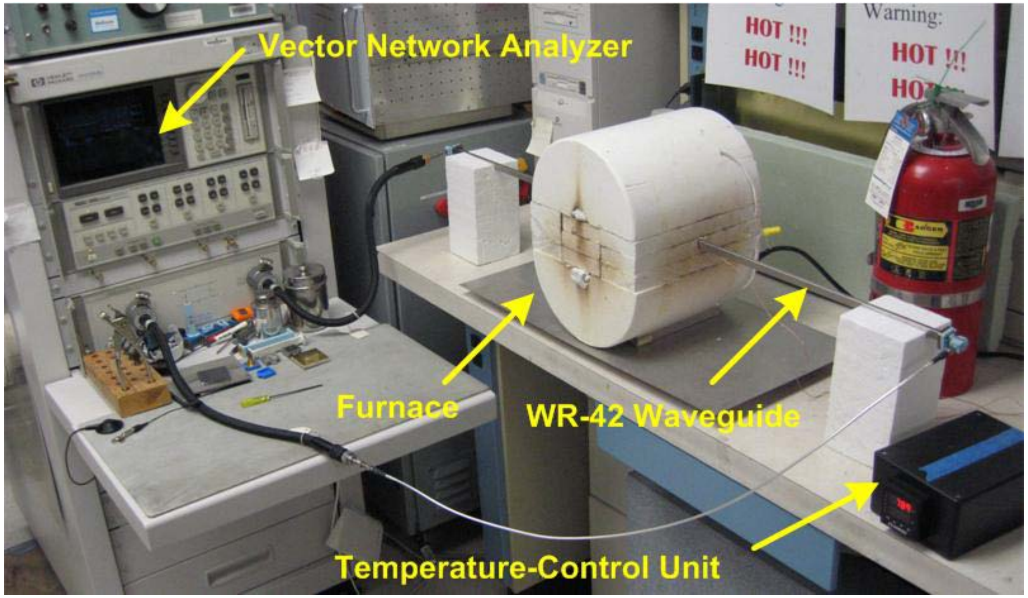
Goal: Quantify temperature dependent RF material properties

- permittivity (ε) and permeability (μ)
- measure transmission and reflection thru samples to back out the conductivity

- ε_r is the relative permittivity
- μ_r is the relative permeability
- $\tan\delta_\varepsilon$ and $\tan\delta_\mu$ are electric and magnetic loss tangents respectively
- σ_e is dielectric conductivity, and ω is angular frequency

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

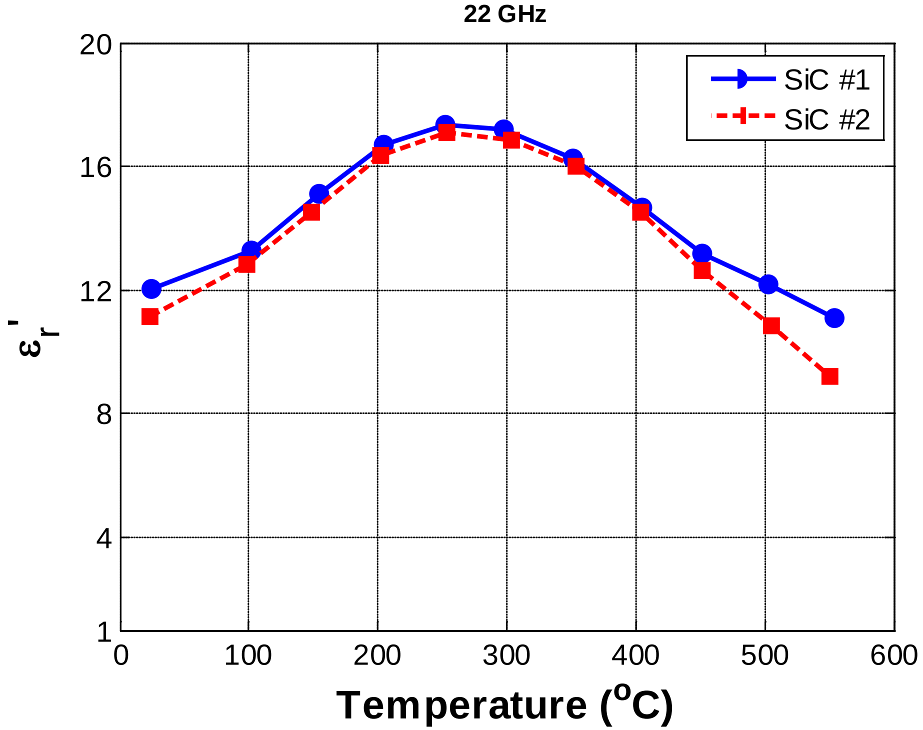
$$\varepsilon = \varepsilon_0\varepsilon_r' - j\frac{\sigma_e}{\omega}$$



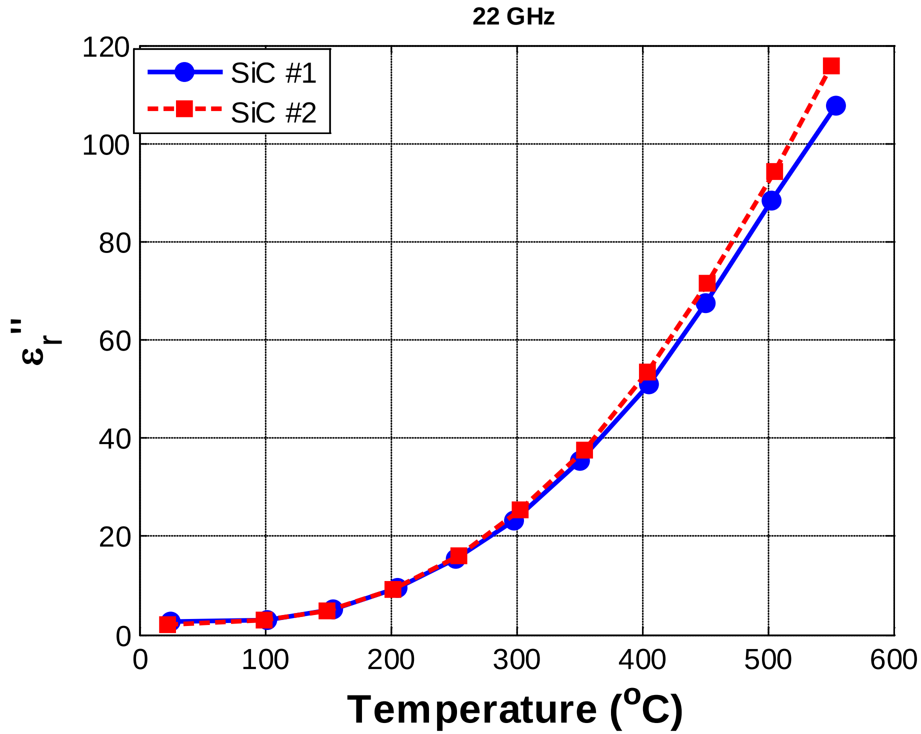
Materials Characterization
Experimental results - SiC

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

Dielectric Constant (**ε_r'**)

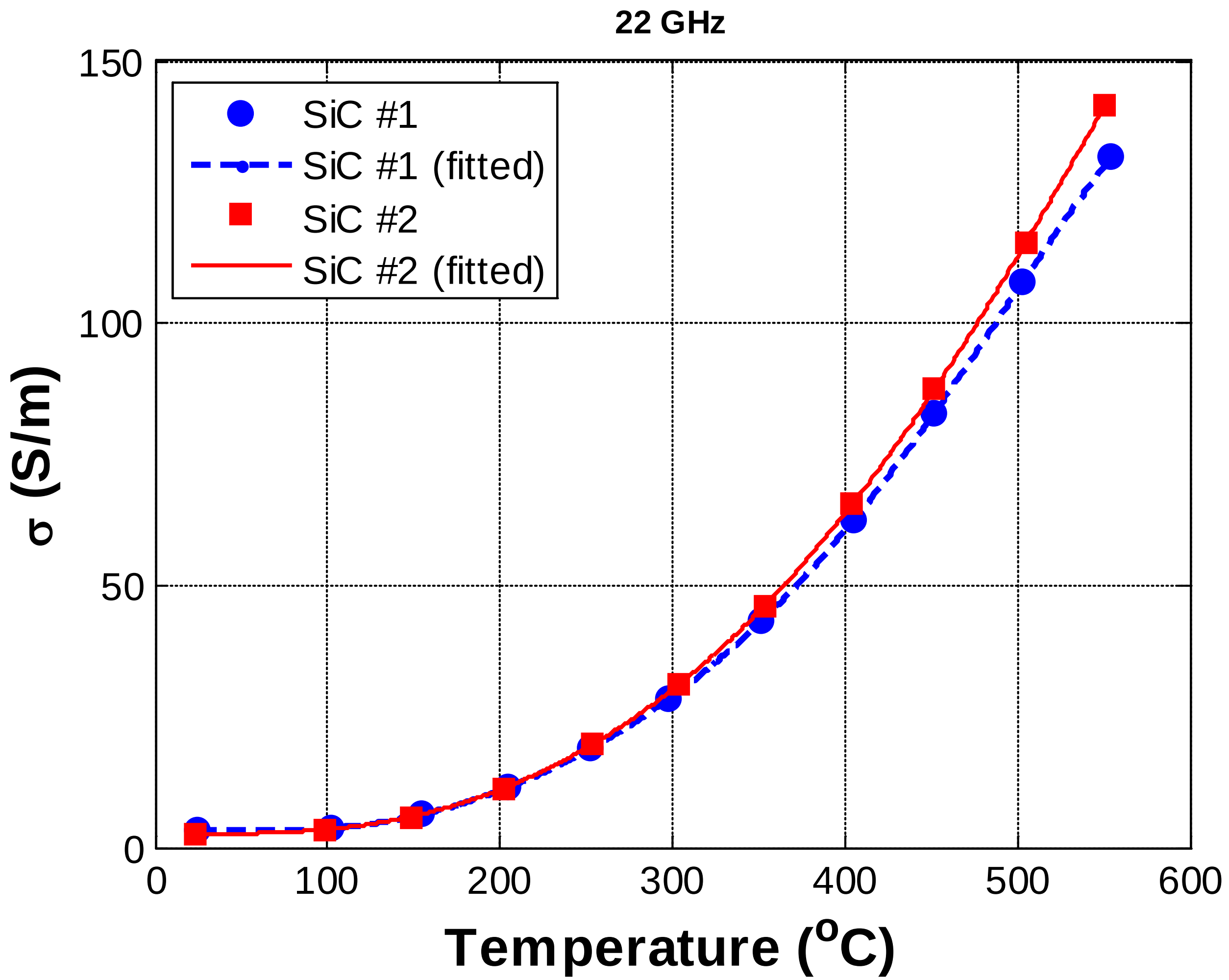


Loss (**ε_r''**)



Materials Characterization
Experimental results

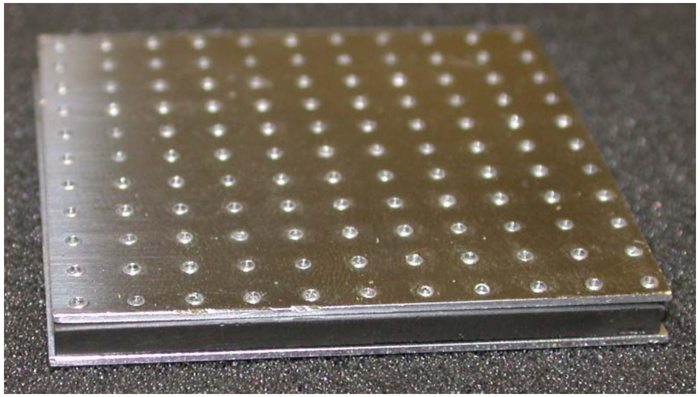
Conductivity vs temperature for SiC at 22 GHz



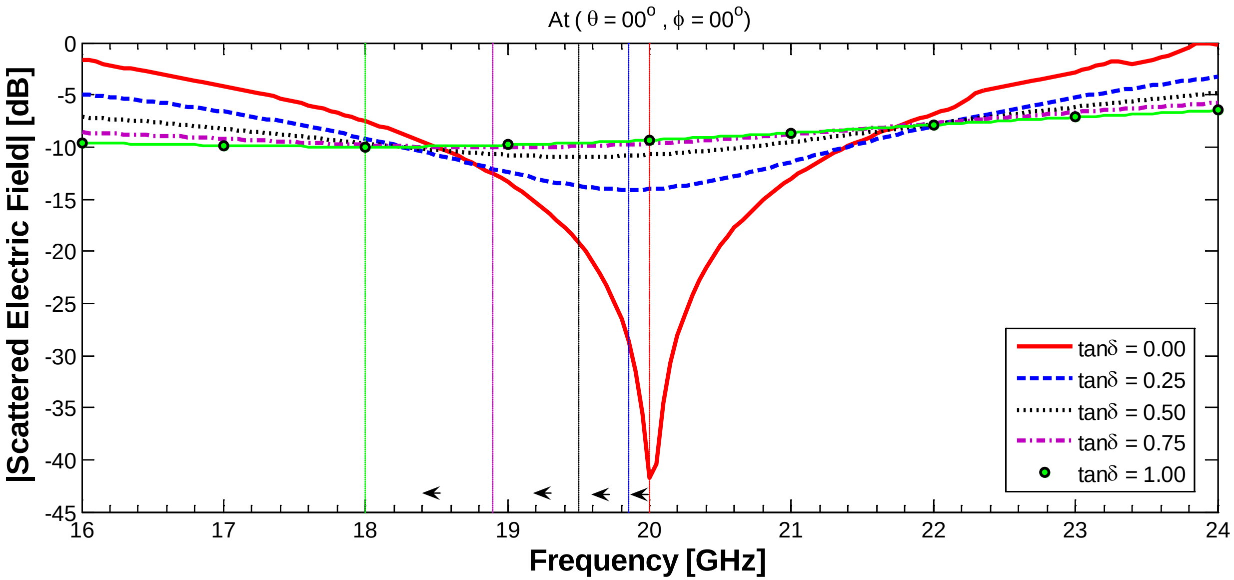
Sensor Design
GMR sensor concept

Guided Mode Resonance (GMR)

- incident energy at a specific frequency is couple into a transverse longitudinal mode, creating a notch in the reflected response
- simple construction
- sensitive to angle of incidence

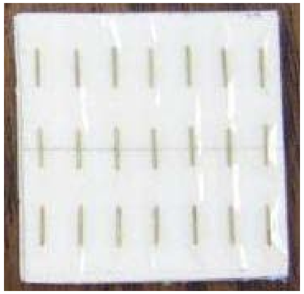


Guided mode sensor

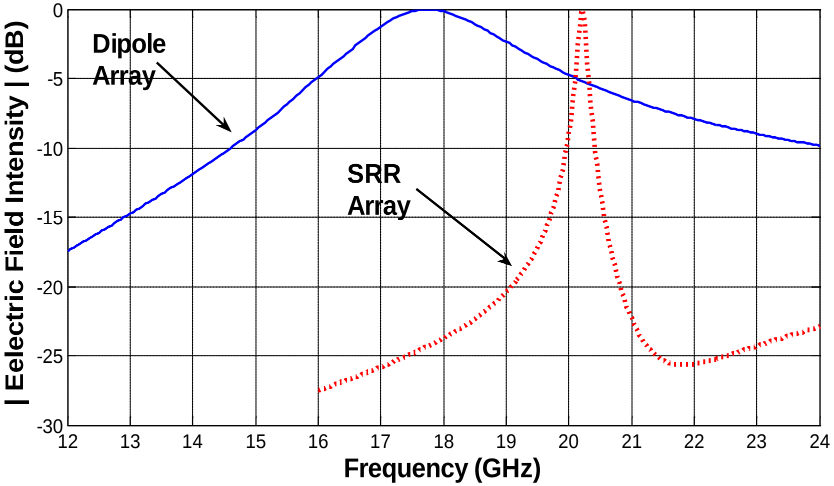


Sensor Design
Alternative sensor concepts

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

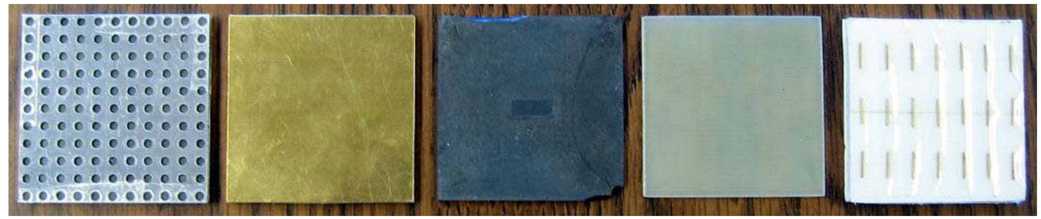

Dipole array

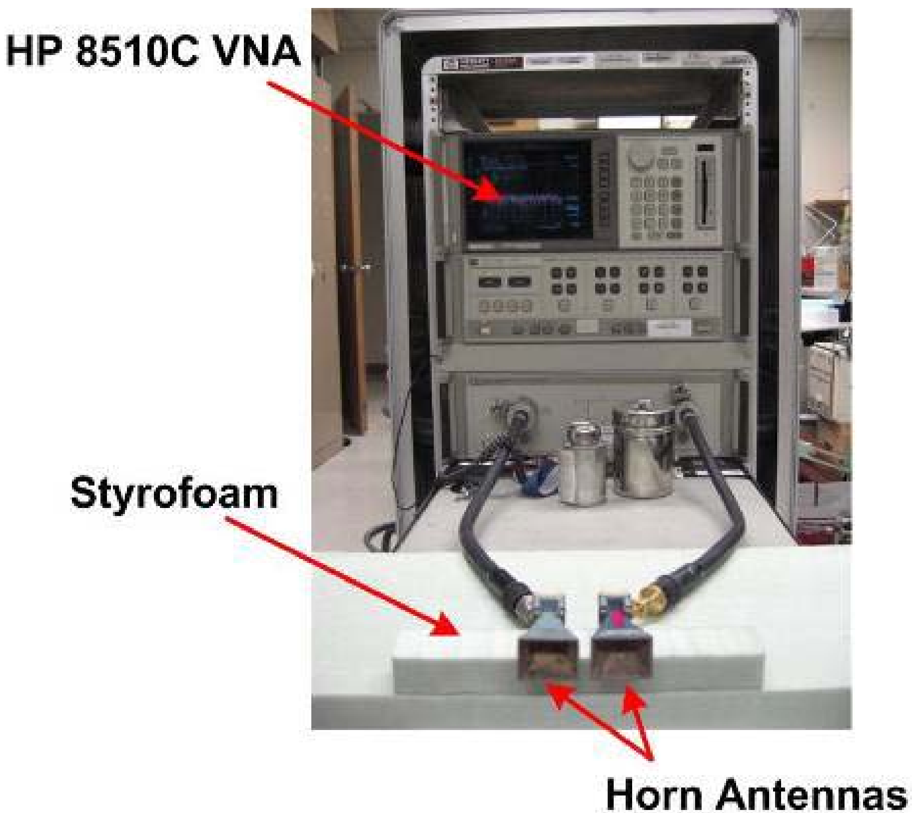

Split ring resonator

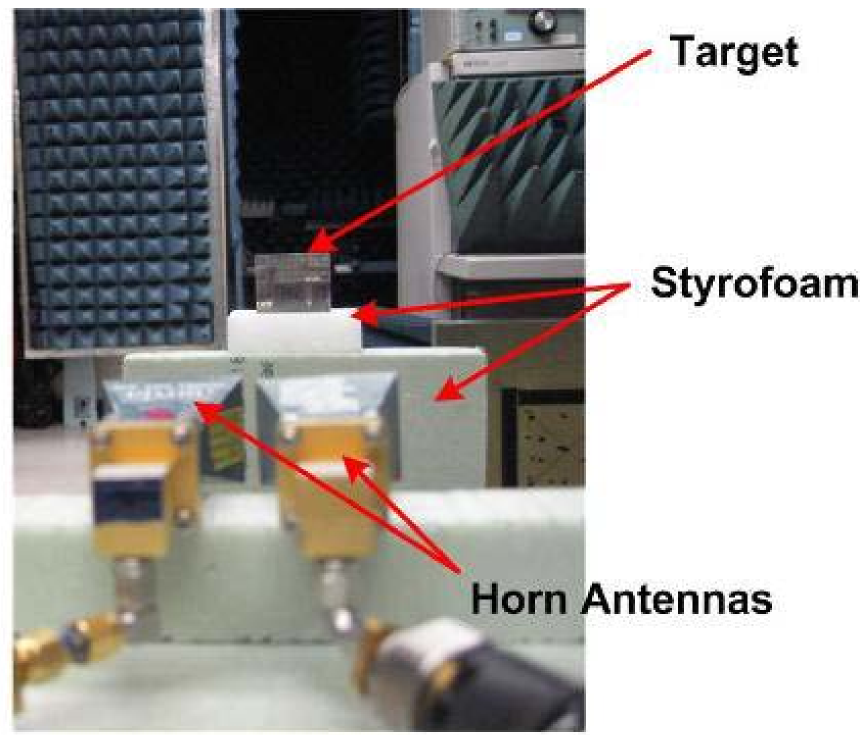


Sensor Design
Sensor testing

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

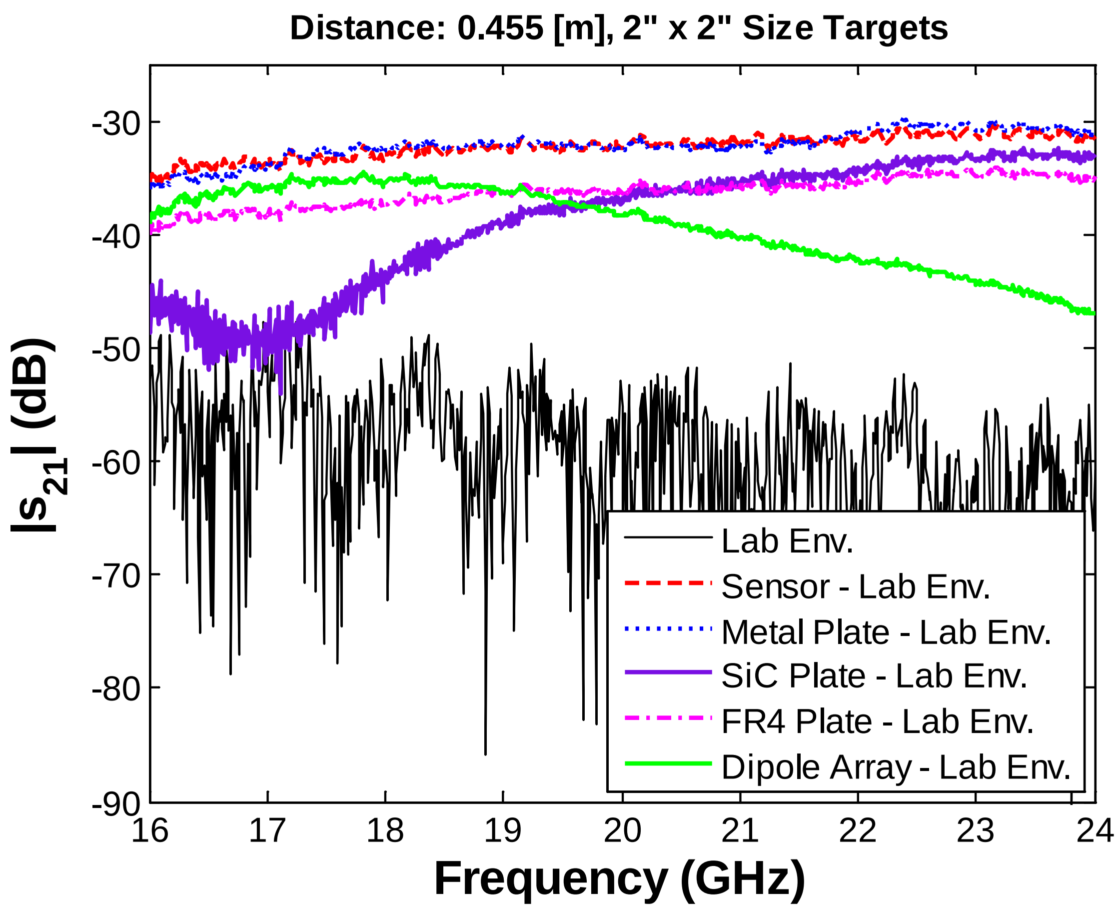






Sensor Design
Sensor testing

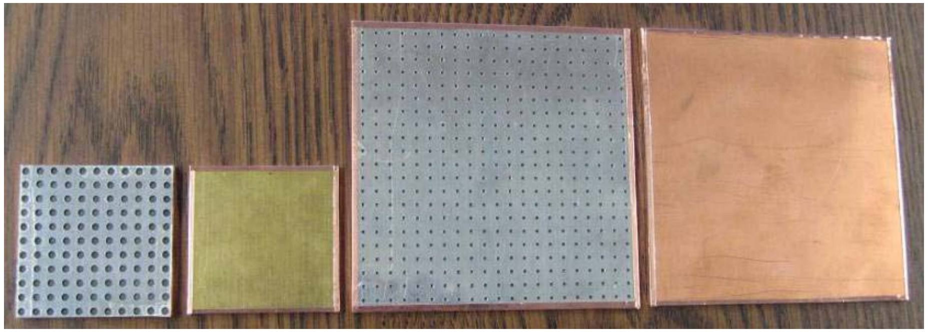
- measurement of reflected energy vs frequency
- 16 – 24 GHz
- baseline data for “no target”
- dipole array shows good comparison to simulation



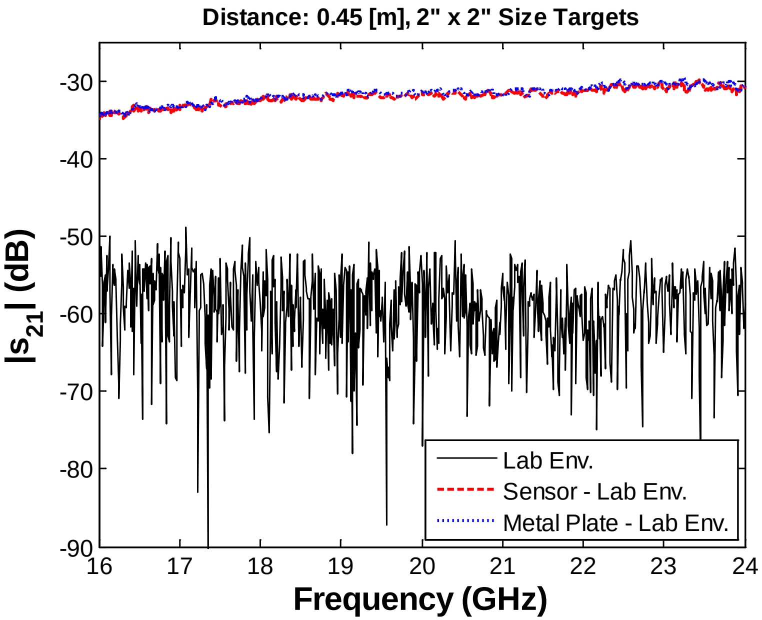
- GMR sensor has not shown simulated response
- edge diffraction effects possibly dominating response
- high loss of SiC results in weak coupling

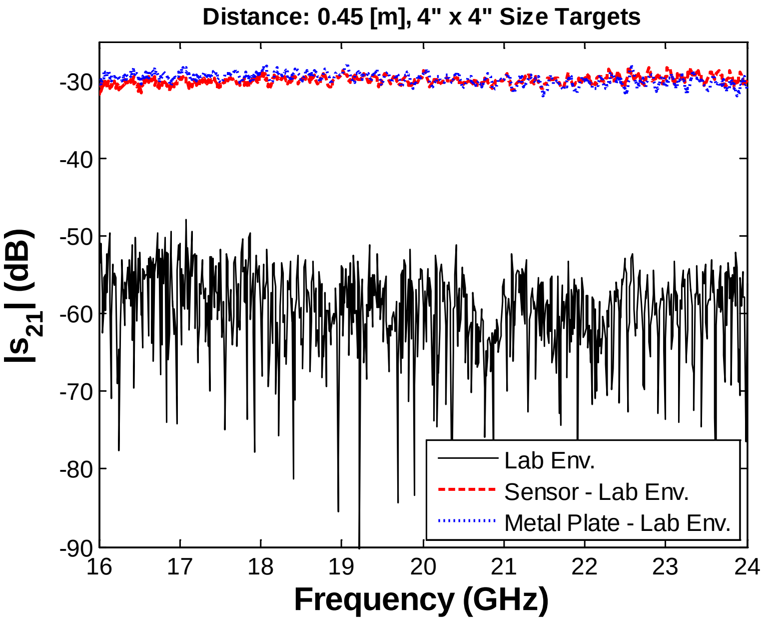
Sensor Design
Sensor testing

- 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



2" x 2"   4" x 4"





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

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

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

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

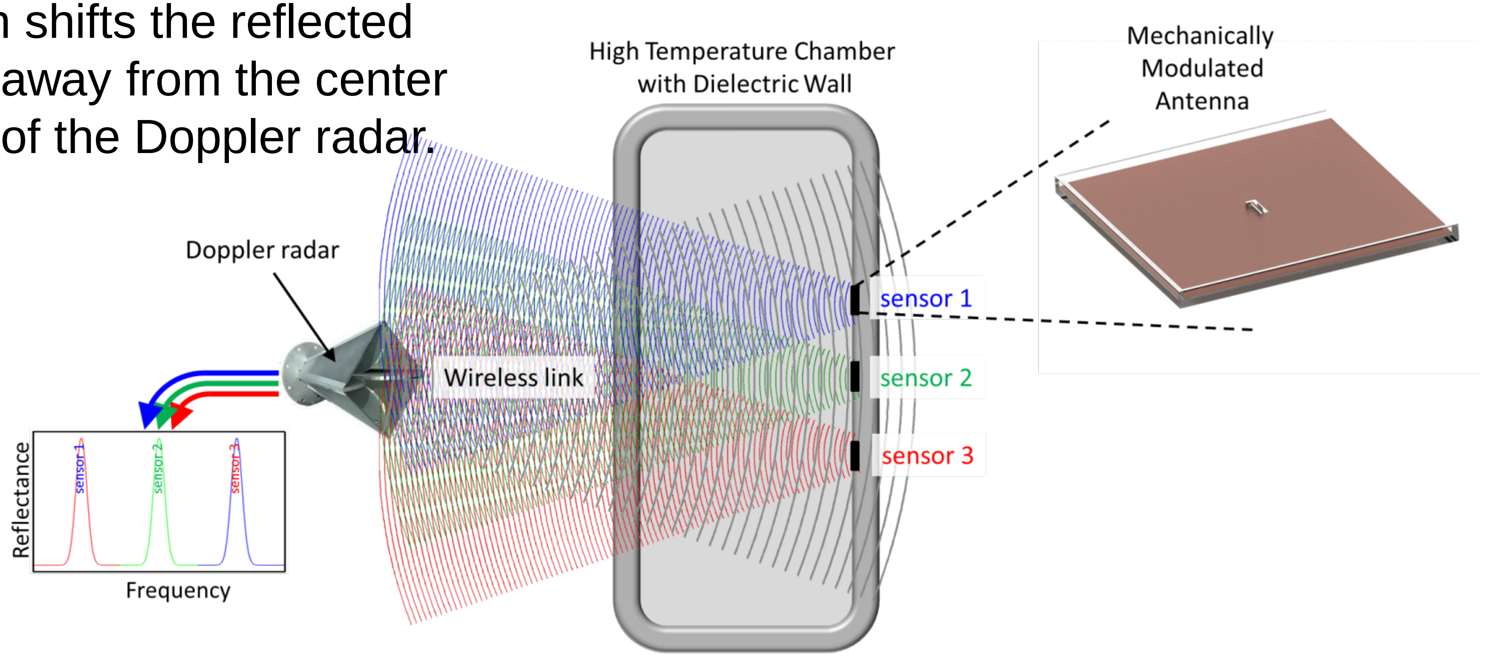
3) *The sensor was angle sensitive.*
   - The sensor response changed or disappeared with any deviation from exact normal (90 degree) angle of incidence

⇨Need a device that does not rely upon normal incidence of interrogating radio wave.

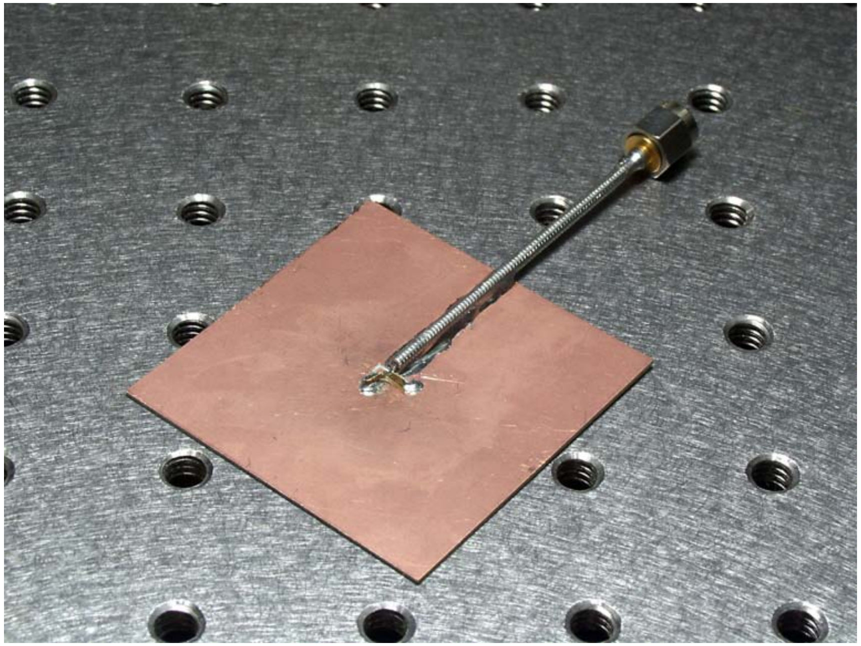
A New Wireless Sensor Design

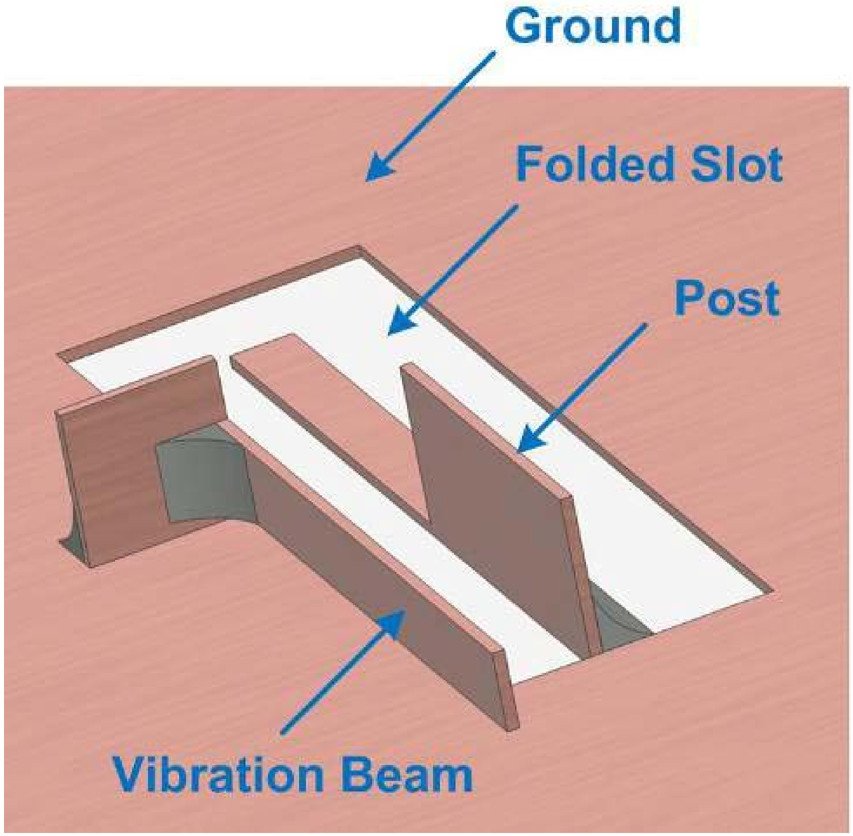
Mechanically Modulated Antenna

- 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

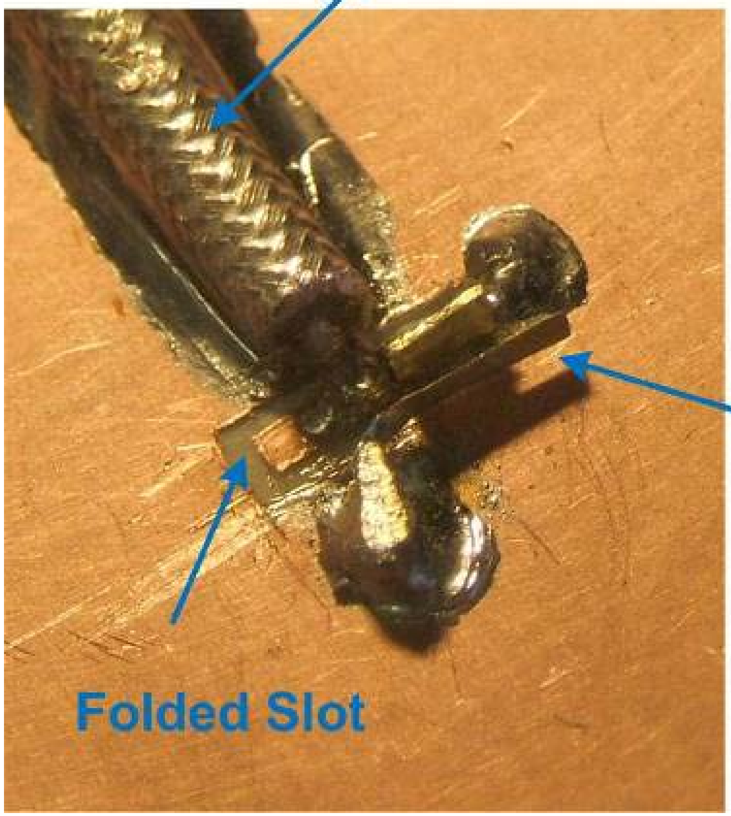


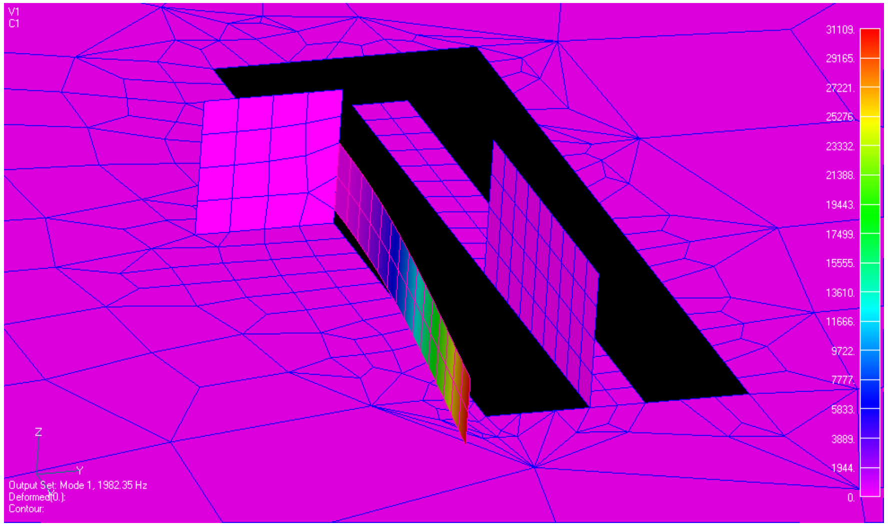
Initial Sensor Geometry





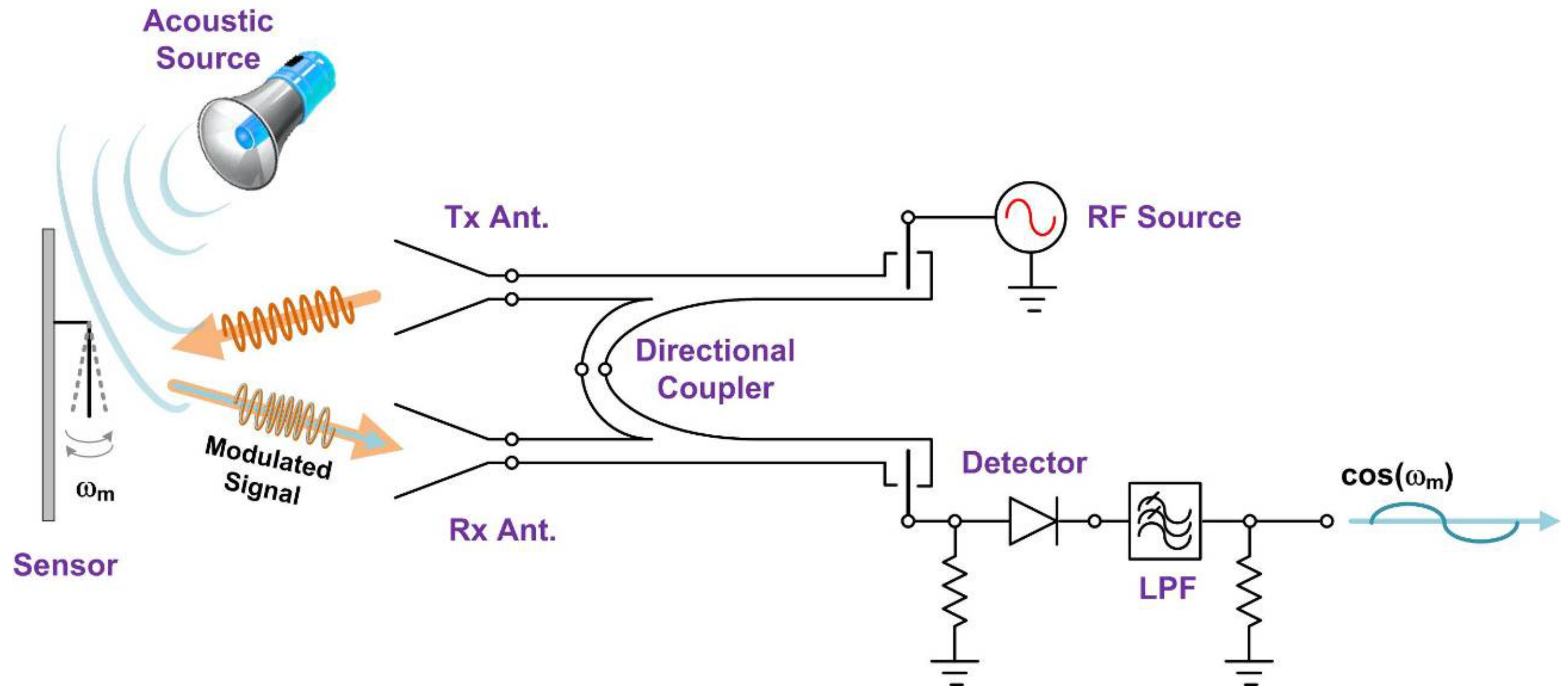
Slot Antenna Close-Up





FEA predicts beam natural frequency of 1980 Hz.

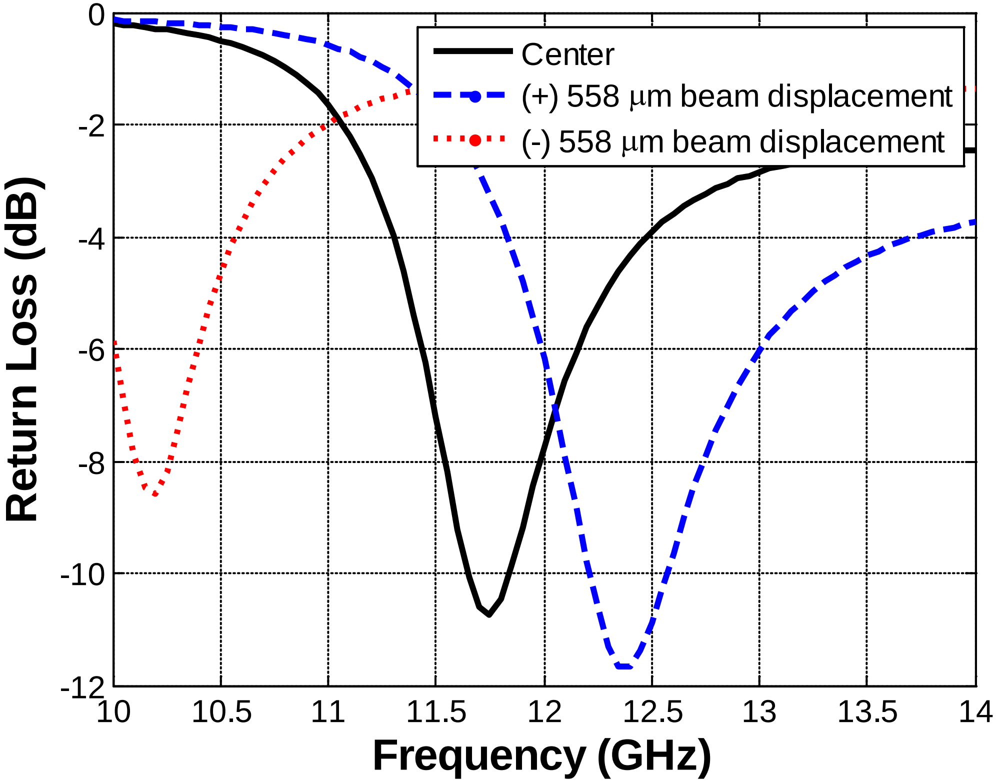
Interrogator Design
Doppler RADAR

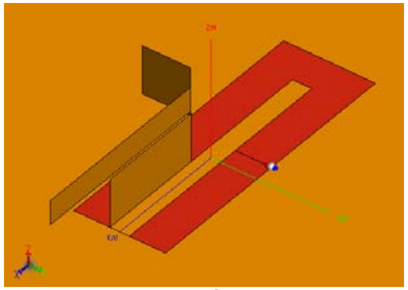


- Acoustic excitation (1800 Hz)
- Doppler RF interrogation (10 GHz)

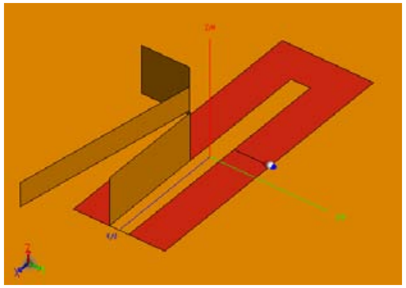
FEKO Simulation Results

Beam displacement changes antenna impedance and modulates antenna center frequency.

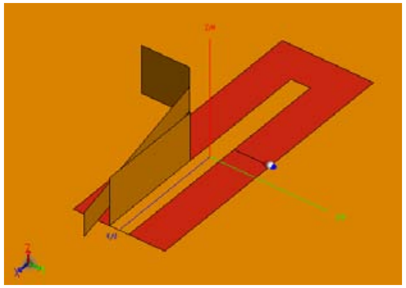




center



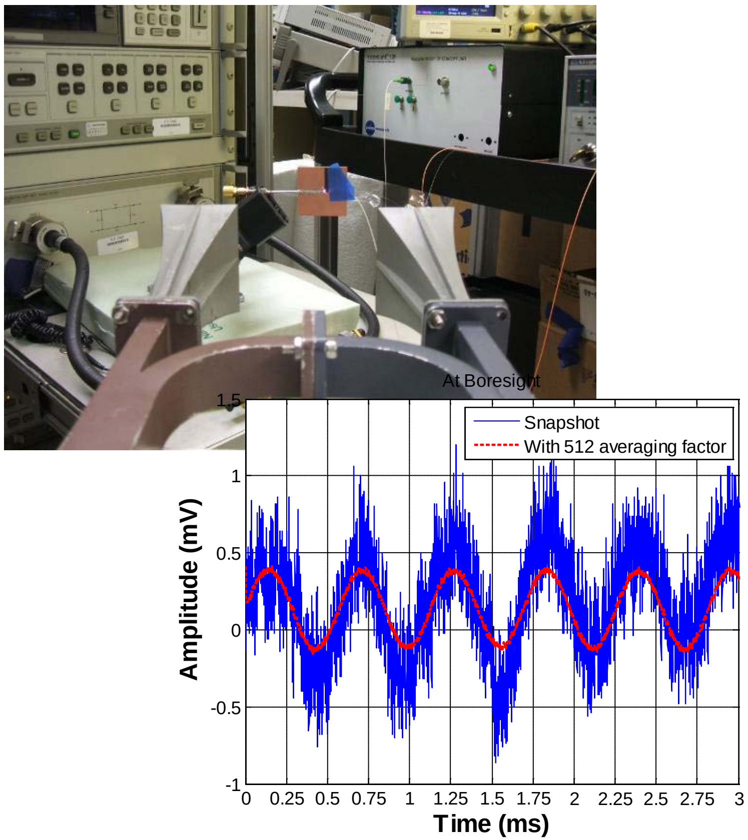
+ 558 µm



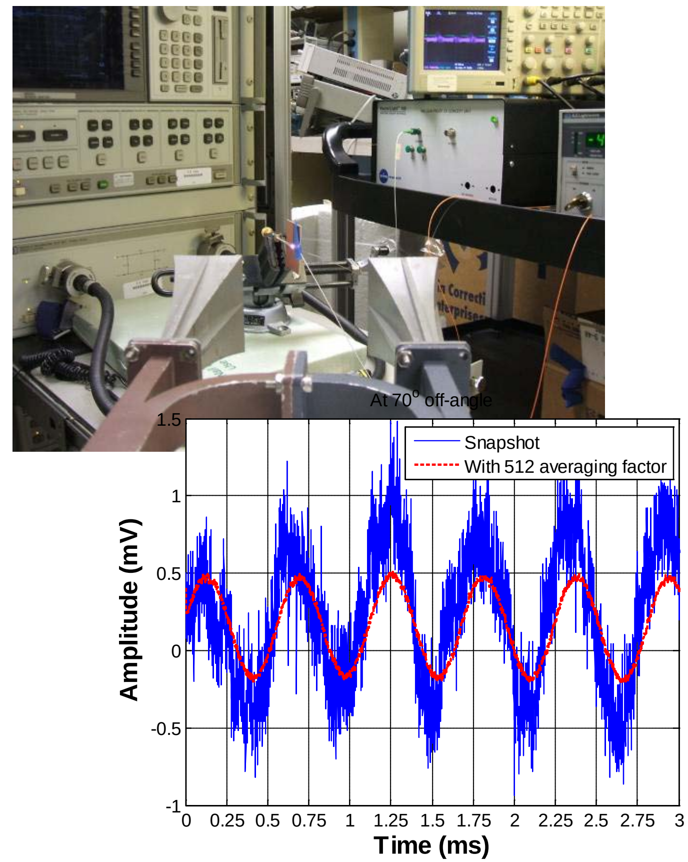
- 558 µm

Experimental Results
Mechanically Modulated Antenna

Normal incidence



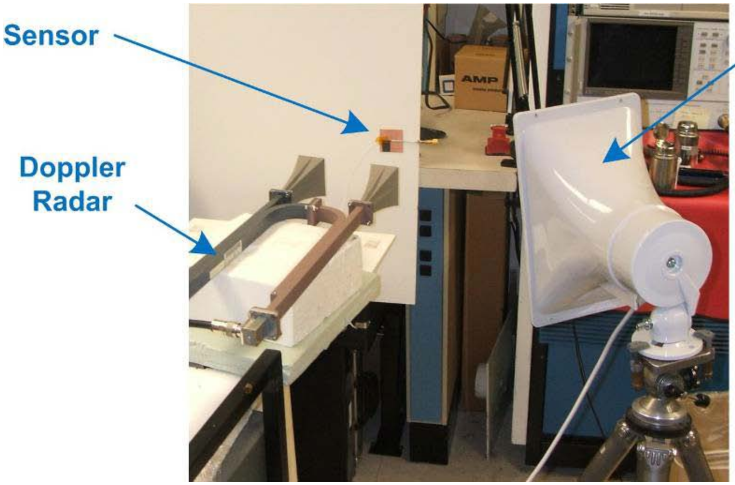
70° incidence

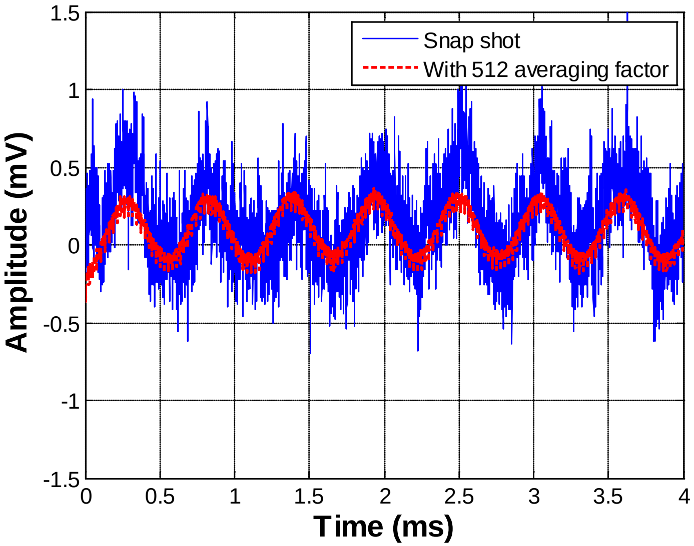


Initial experiments used laser excitation

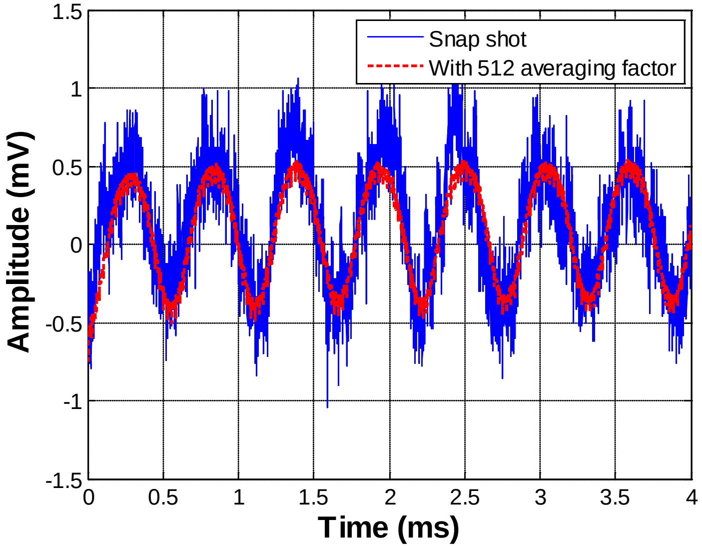
MMA Experimental Results
Acoustic Excitation

- 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





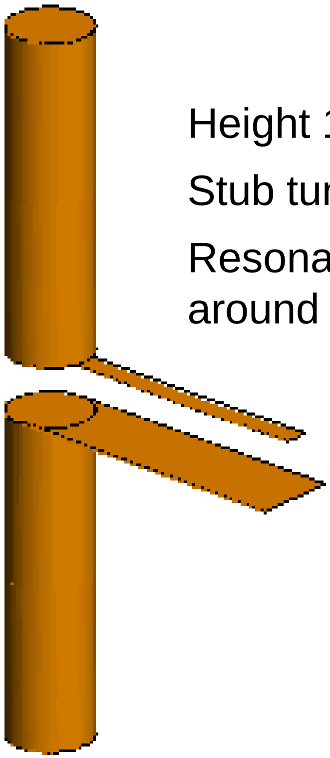
Sensor in free space



Sensor on cardboard wall

Dipole Antenna Design

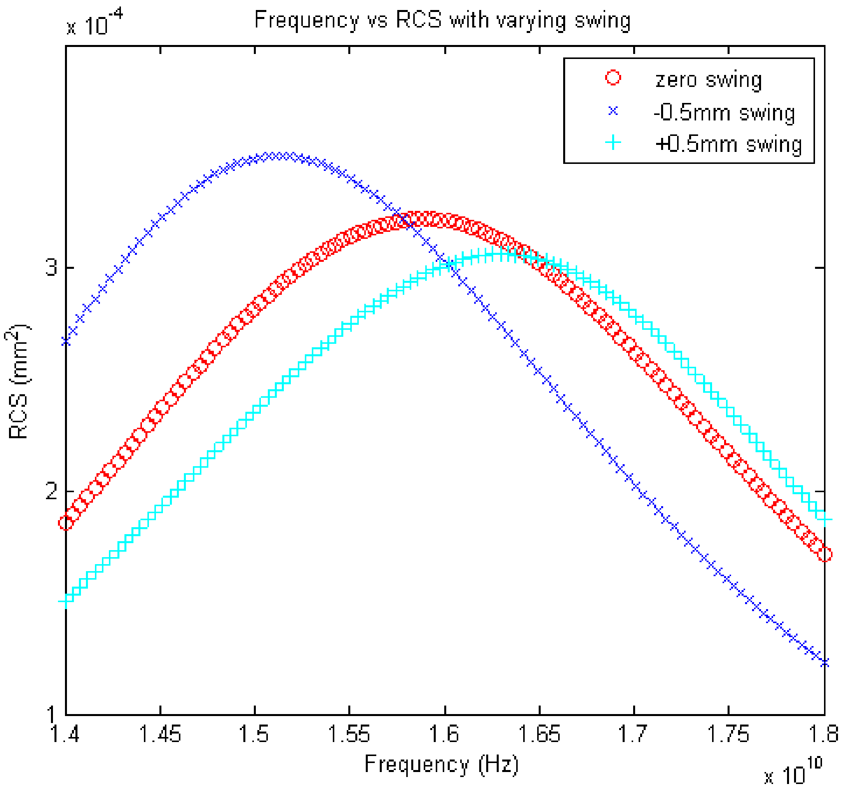
Objective: determine if amplitude or phase modulation dominates.



Height 1.12 cm

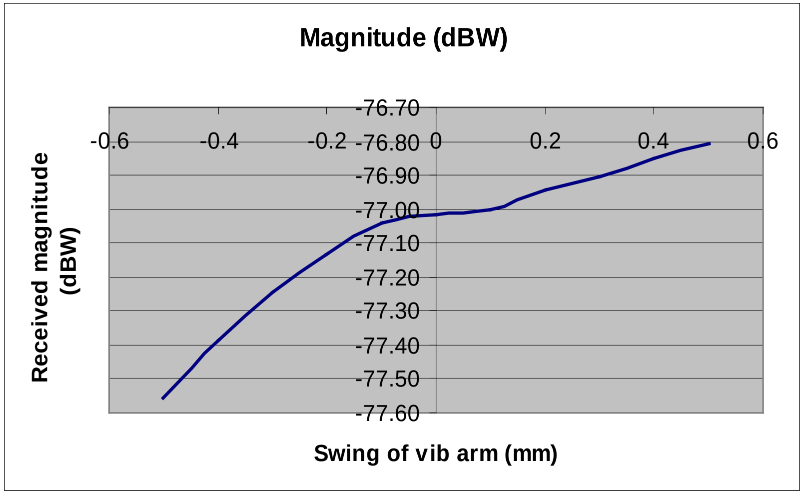
Stub tuner: 0.47 cm long

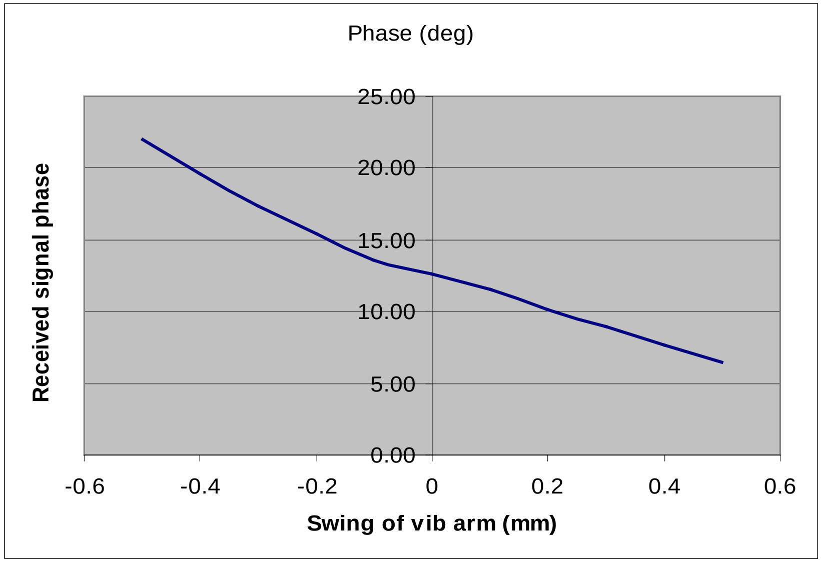
Resonates electrically around 16 GHz



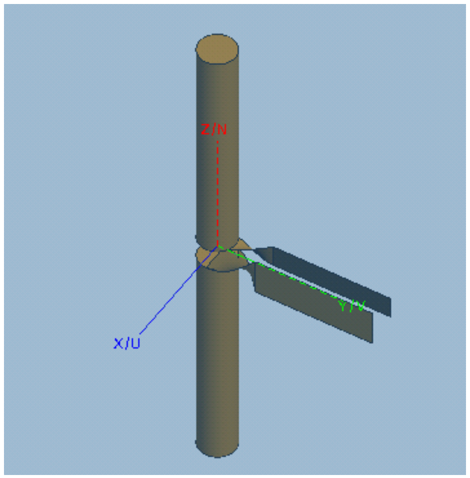
Dipole antenna

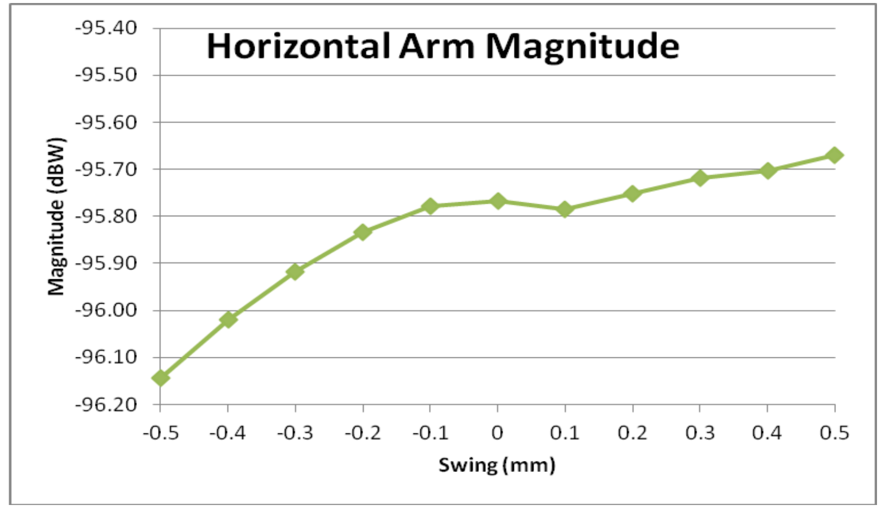
- Assumes interrogator uses horn antenna with 15 dBi gain and 2W output.
- Dipole has low radar cross-section, and therefore low power reflection.

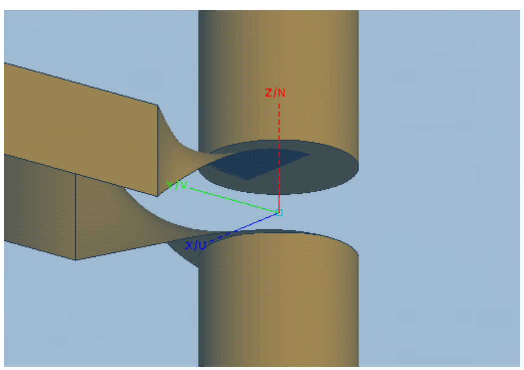


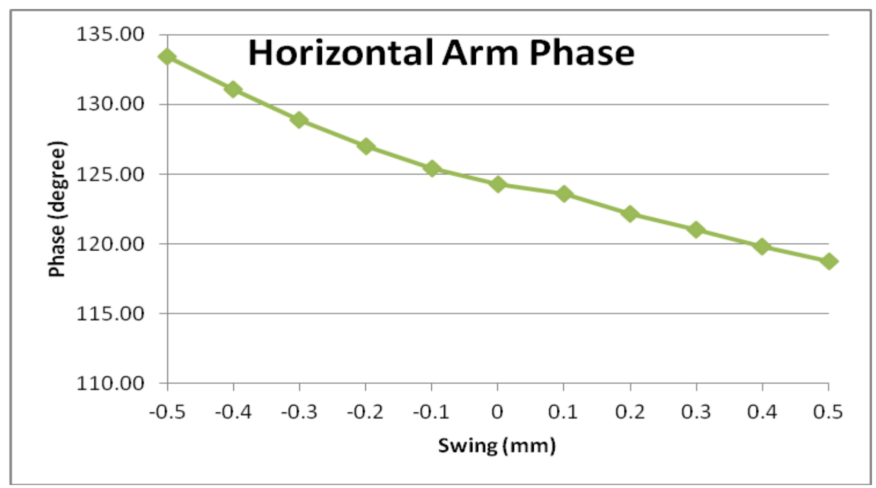


Dipole w/ rotated tuning arms



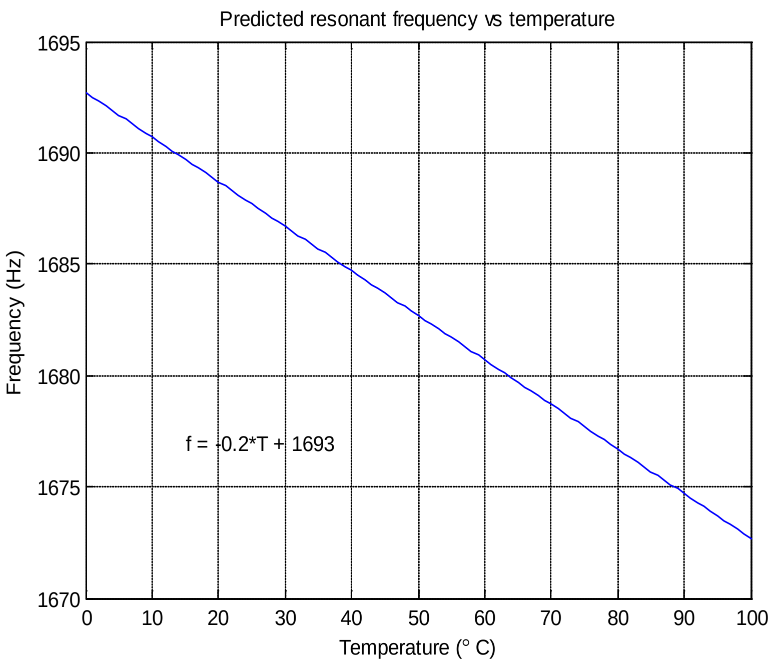


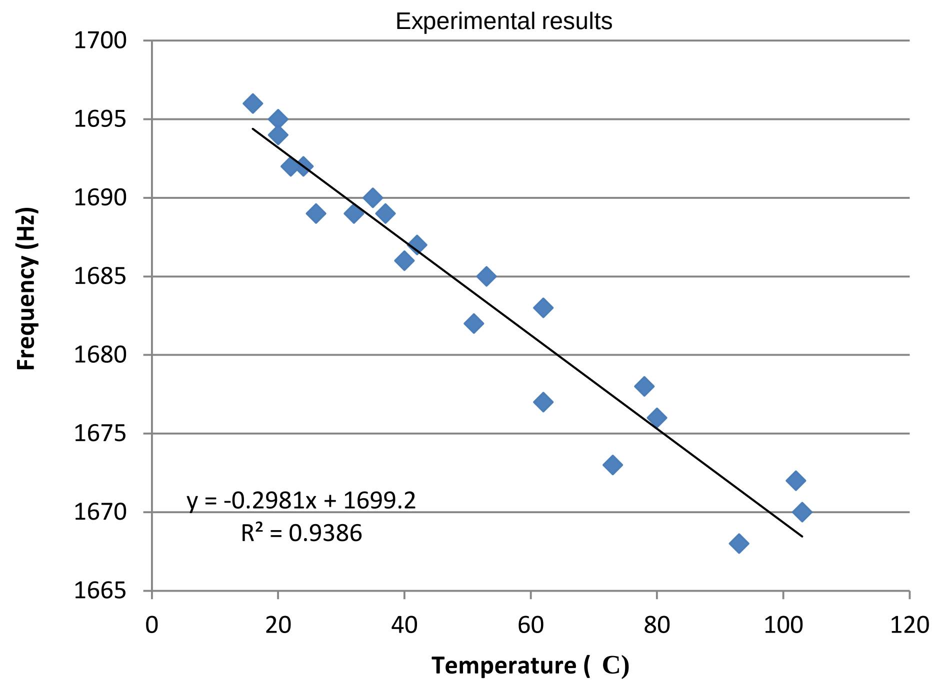




Temperature dependence

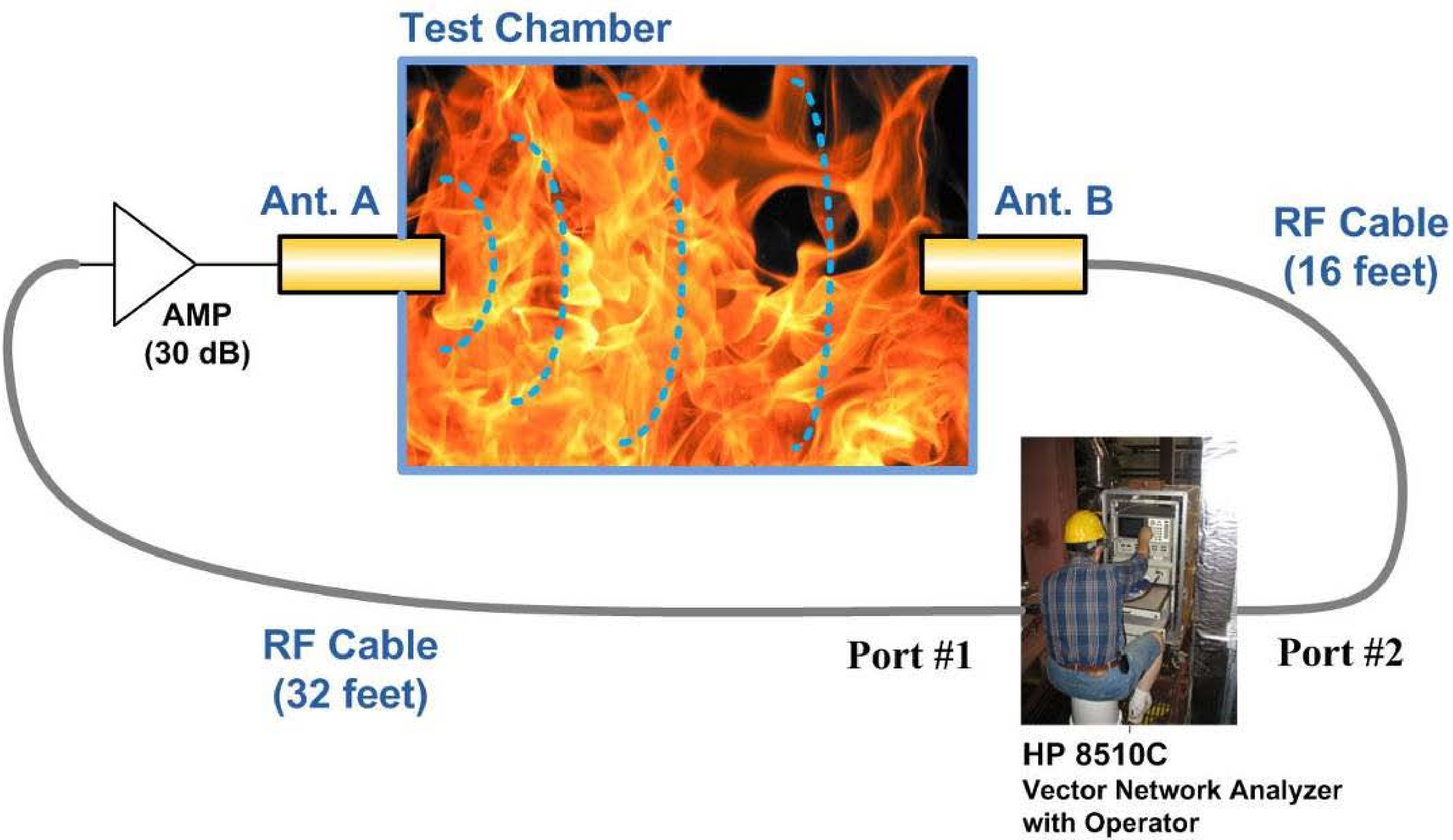
- Elastic modulus, density, and dimensions all depend on temperature and affect natural frequency.
- Modeling vibrating cantilever beam predicts 0.2 Hz/ C
- Experimentally measured peak resonant frequency with changing temperature.
- Data shows 0.3 Hz/ C temperature dependence.





Characterization of RF Environment
Overview

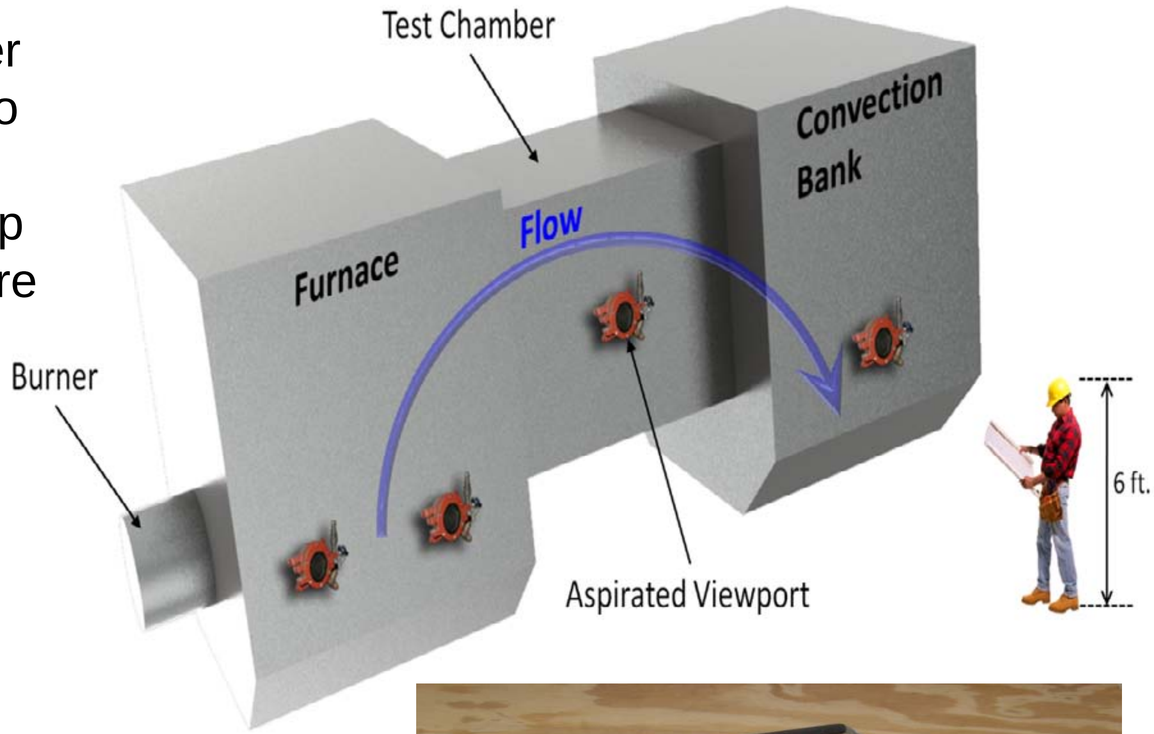
Goal: find regions of RF spectrum where attenuation is lowest



Characterization of RF Environment

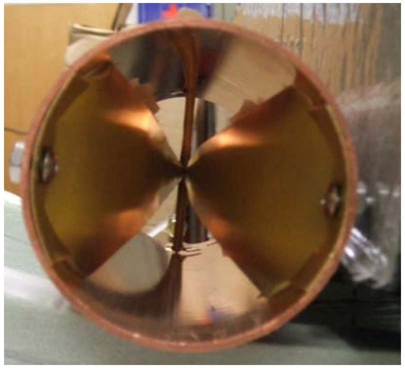
Site Survey

- 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

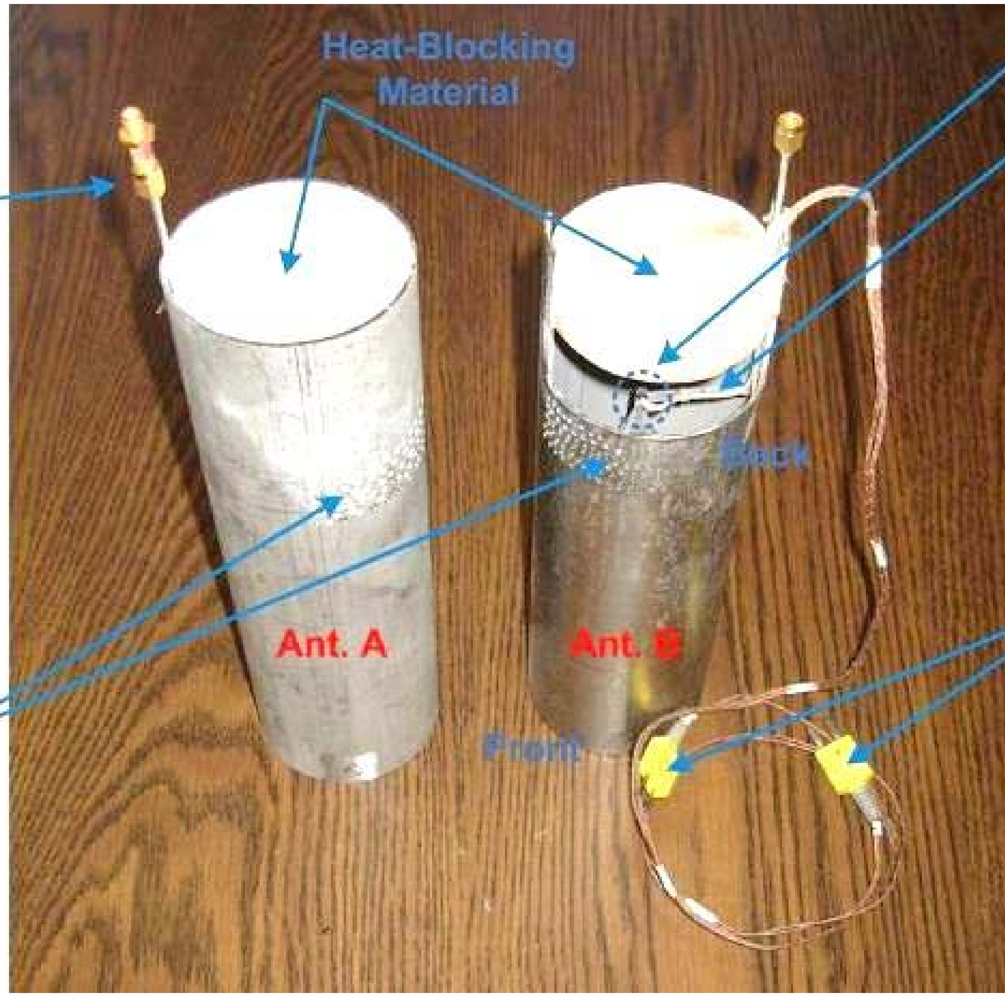


Viewport installations

TEM horn antenna

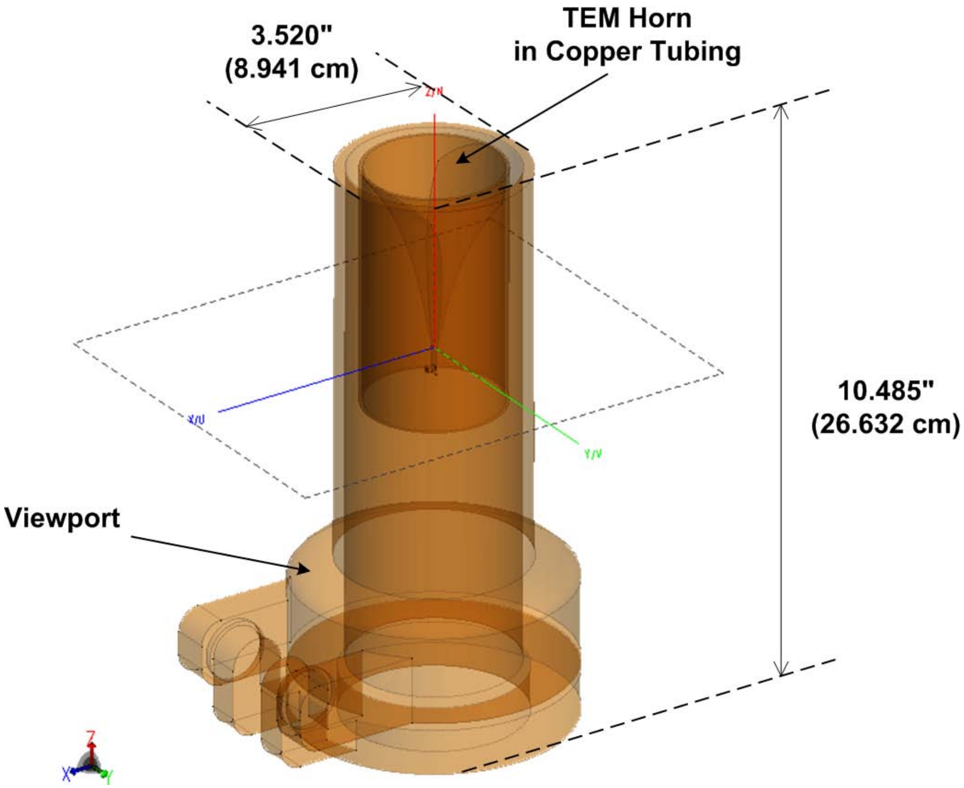
Characterization of RF Environment

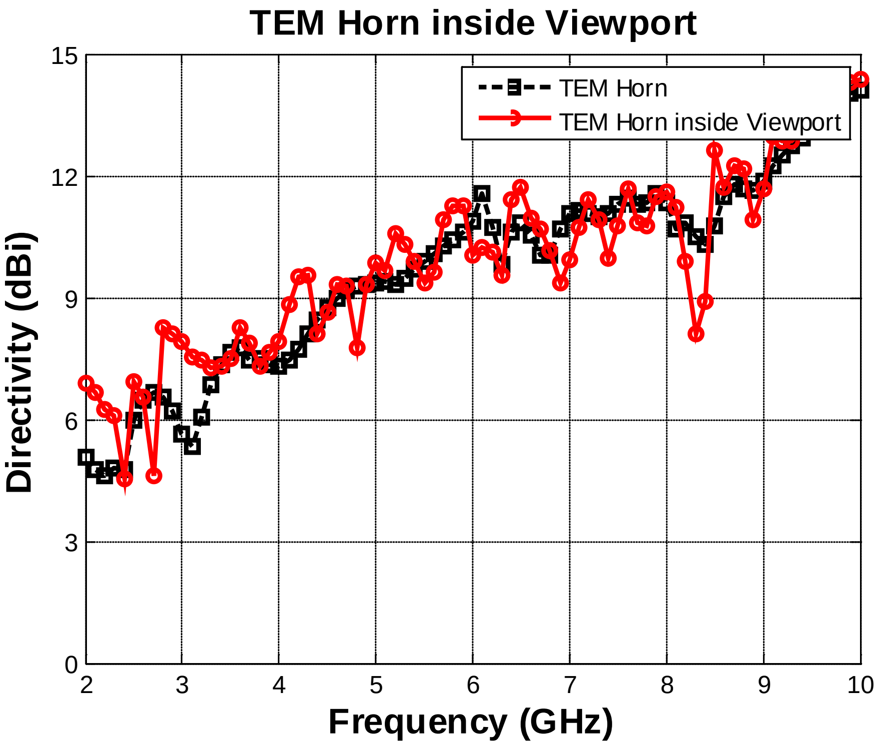
Antenna installation



Characterization of RF Environment
Antenna design

- Viewport installation does not affect gain performance significantly



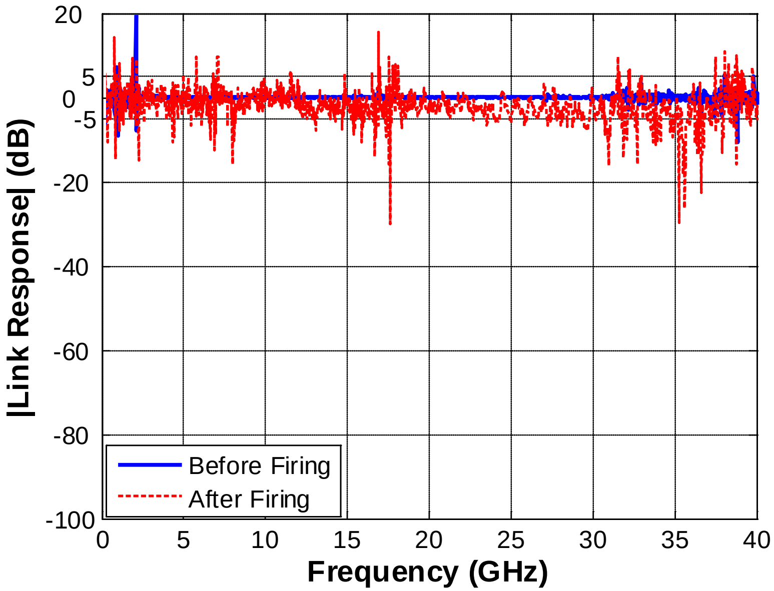


Characterization of RF Environment
Field Tests

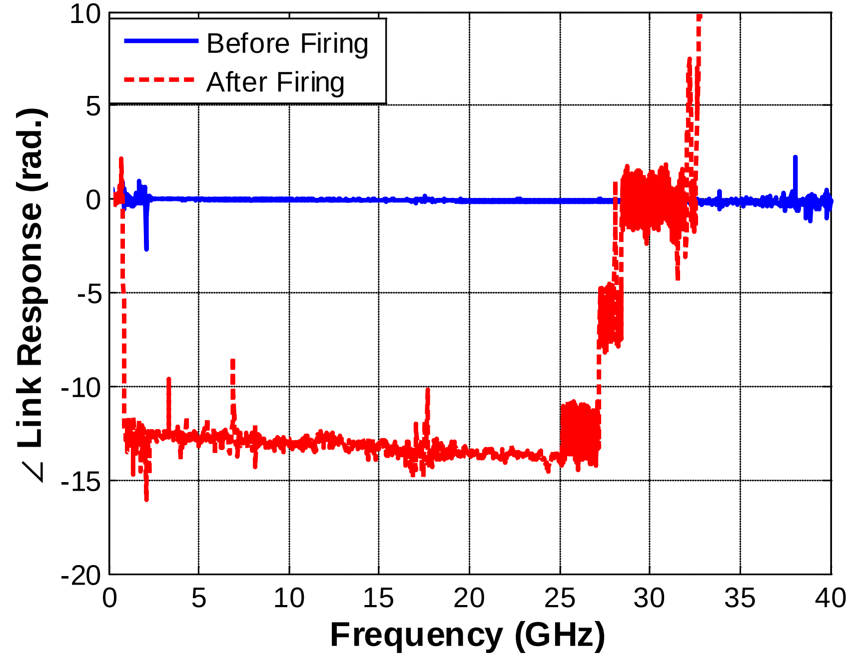
- 2 field tests
- Natural gas and biomass firing
- SBS convection pass
- Evaluated RF attenuation from 2.5 – 40 GHz

Characterization of RF Environment
Experimental results - biomass

Magnitude



Phase

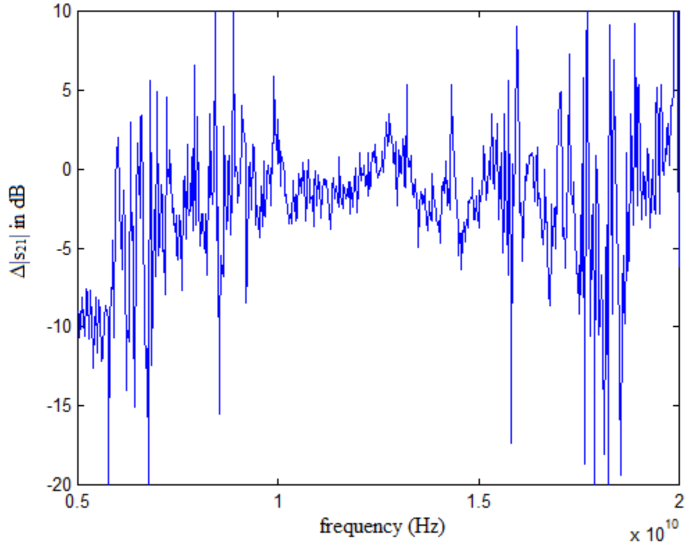


Plots show difference in scattering parameter measurements made before and after biomass firing.

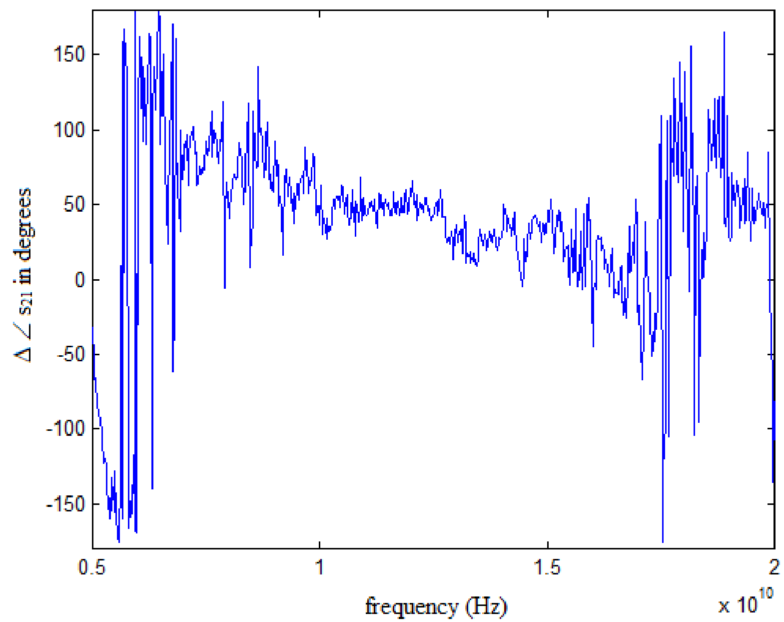
Characterization of RF Environment

Experimental results – coal firing

Magnitude



Phase



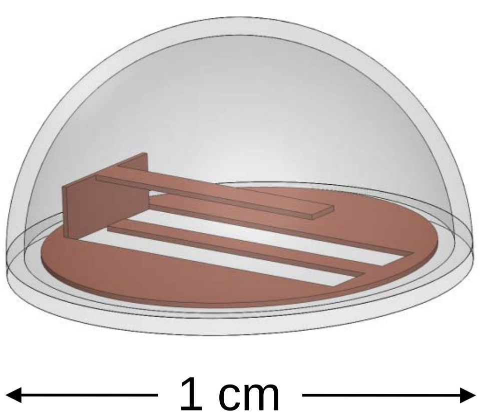
Conclusion: 10 GHz to 15 GHz should be a good window for operation of sensor.

Conclusions

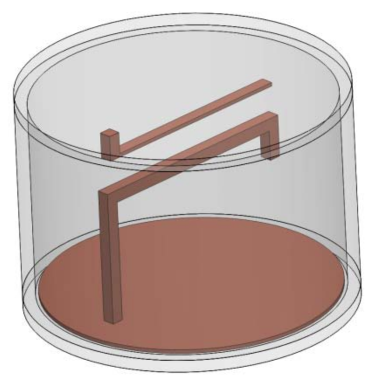
- Testing at B&W SBS indicates RF link budget is satisfactory (natural gas, biomass, and coal firing)
- High temp RF materials characterization –strong response demonstrated (not important to new MMA design)
- Metamaterial sensor concept was not demonstrated – ***indicates strong need for a sensor signal 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 ofMMA sensors in coal combustion and/or gasifier facilities



Mechanically
Modulated
Dielectric
Antennas



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