Distributed Wireless Antenna Sensors for Mechanical and Biomedical Systems

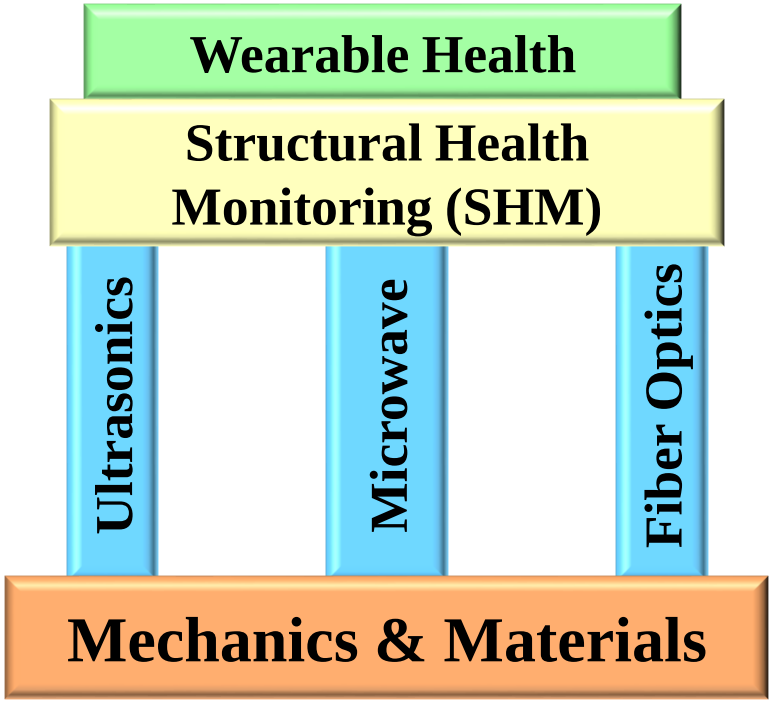
Haiying Huang, PhD

Professor

Mechanical and Aerospace Engineering

University of Texas at Arlington

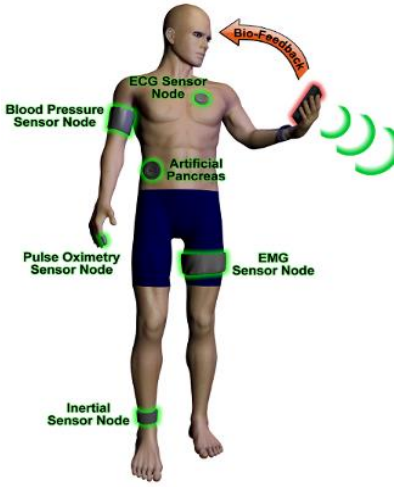
Advanced Sensor Technology Laboratory



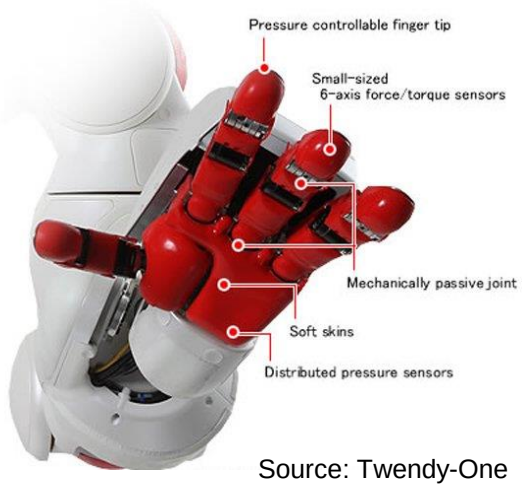
1. Distributed wireless antenna sensors for boiler condition monitoring
2. Smart sensing and dynamic fitting for enhanced comfort and performance of prosthetics
3. Remote generation and steering of ultrasound using microwave
4. Simultaneous strain and temperature measurement using a single Fiber Bragg Grating (FBG)
5. Integrated experimental-numerical framework for the study of early fatigue damage

Why Sensors?

Source: Airbus



Source: UVA Center for Wireless Health



Source: Twendy-One

Source: www.niwa.co.nz

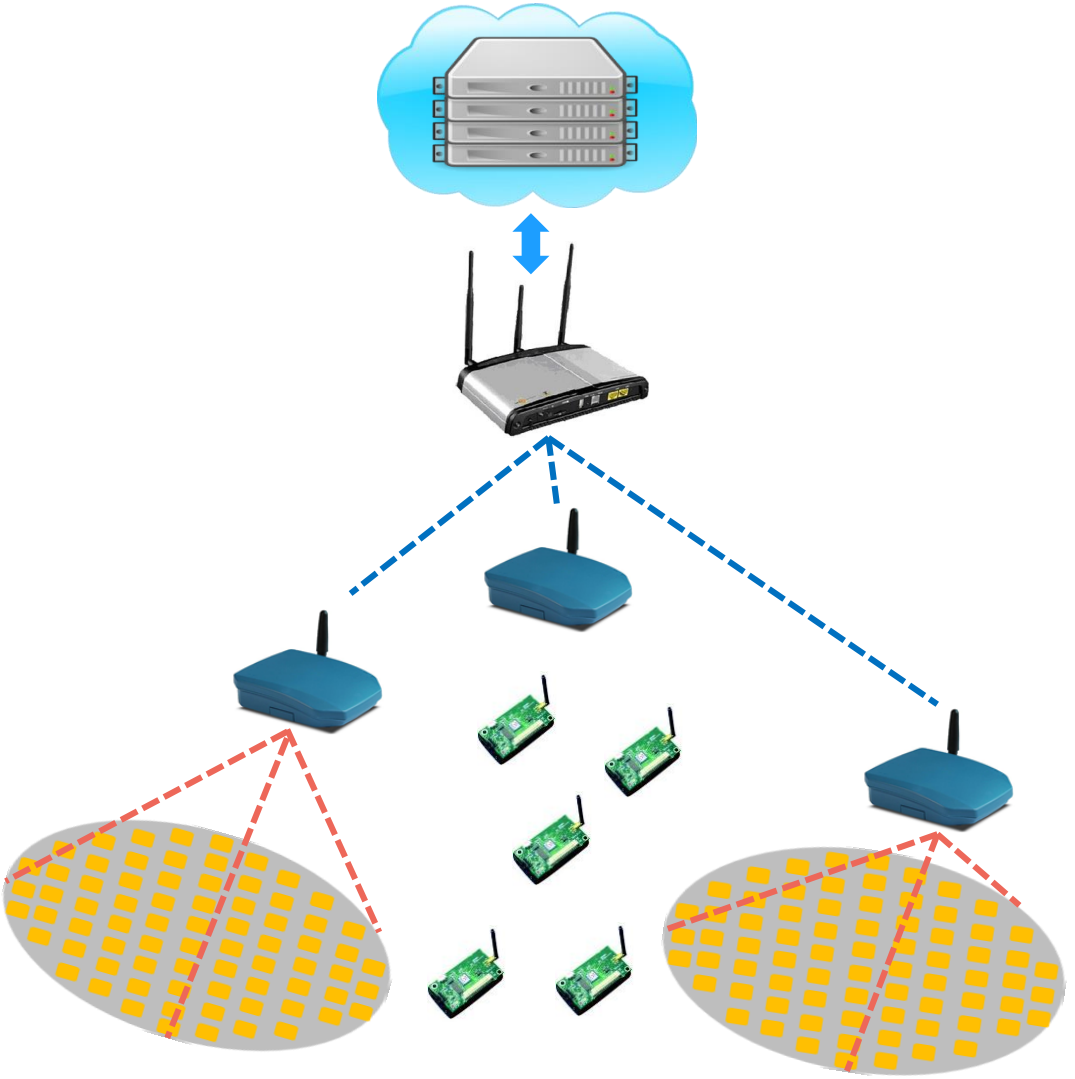
A Smart World Needs **Distributed** Sensors

Distributed Sensing - Challenges

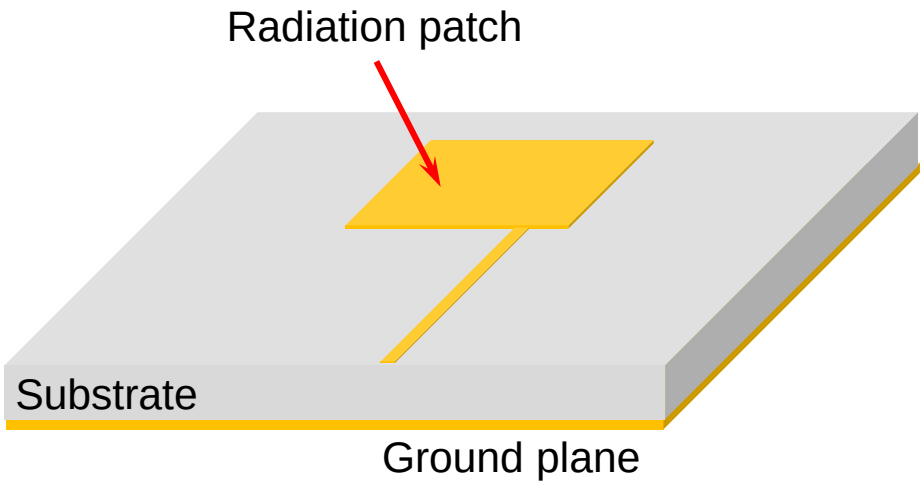
http://www.gereports.com/vital-signs-to-go-wireless-with-ges-body-sensors/

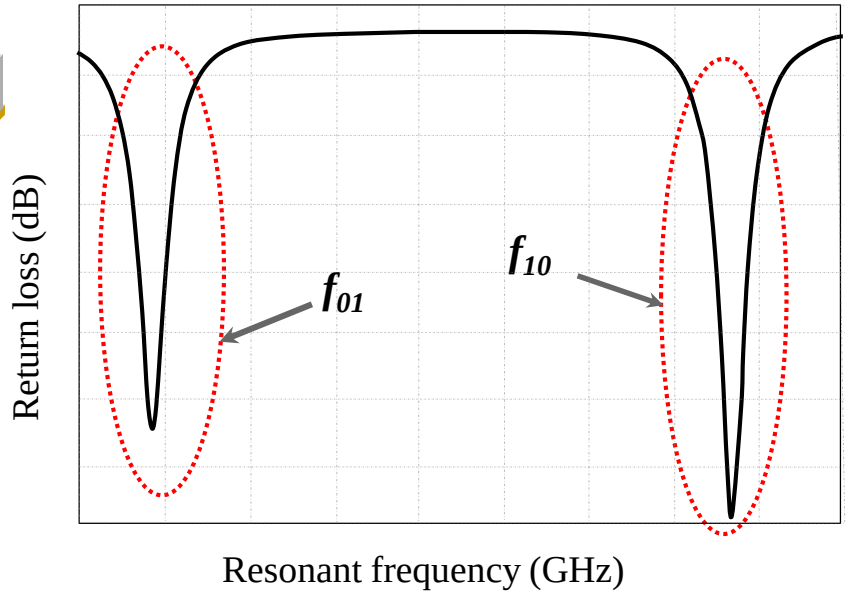
Most wireless sensors are point sensors

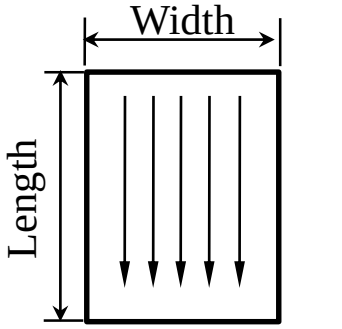
Cluster-based Wireless Sensor Network



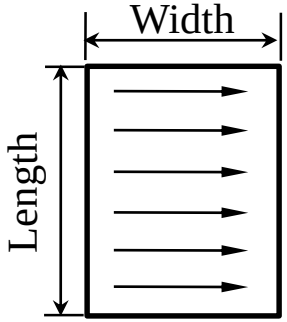
Introduction – Microstrip Patch Antenna







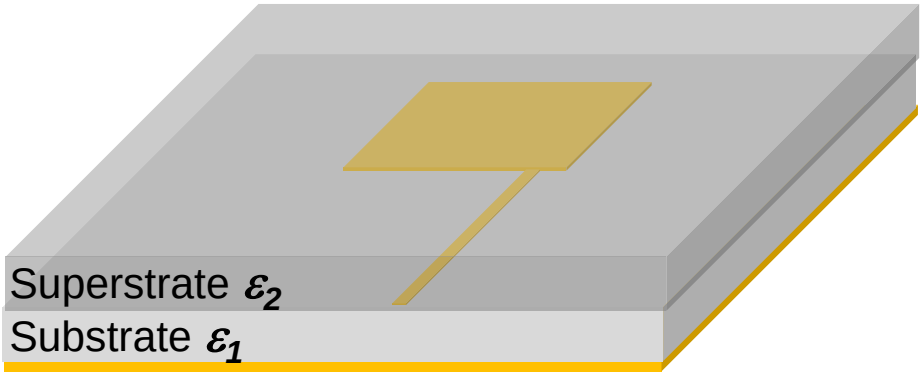
***TM*$_{01}$ mode**



***TM*$_{10}$ mode**

$$f = \frac{c}{2L_e\sqrt{\varepsilon_e}}$$

Microstrip Patch Antenna for Sensing



$$f = \frac{c}{2L\sqrt{\varepsilon_e}}$$

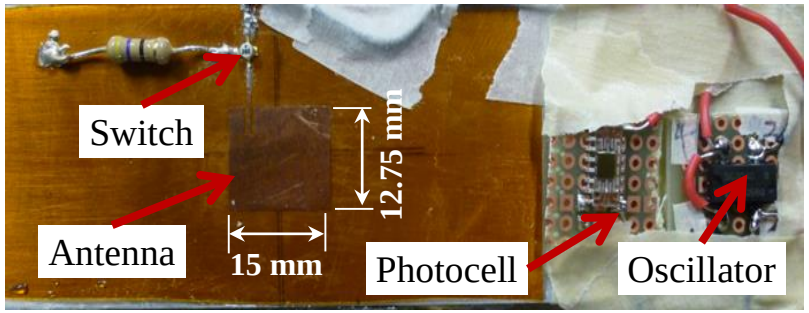
$$\delta f = \frac{\partial f}{\partial L}\delta L + \frac{\partial f}{\partial \varepsilon_e}\delta \varepsilon_e$$

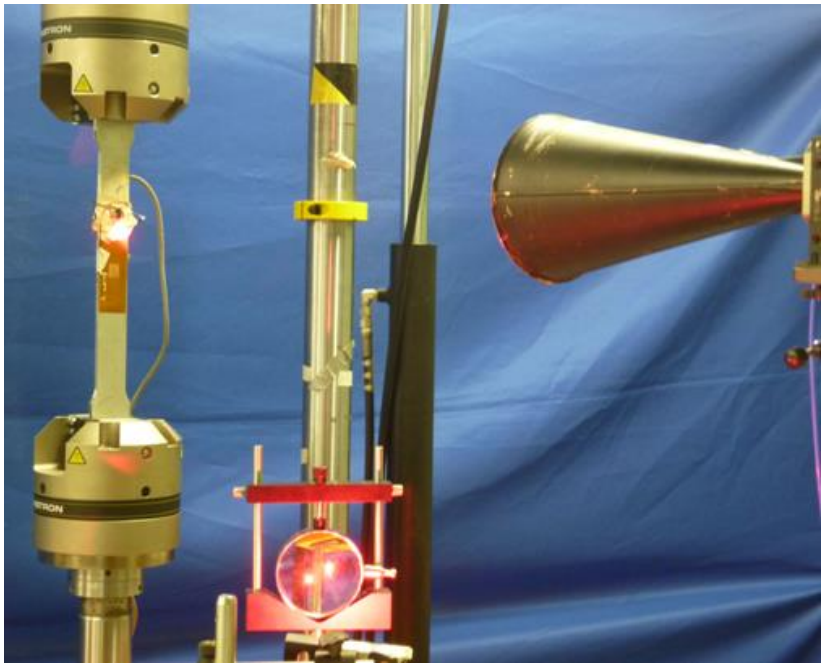
$$\varepsilon_e = q_1\varepsilon_1 + q_2\varepsilon_2 + (1 - q_1 - q_1)$$

$$\frac{\delta f}{f} = -\frac{\delta L}{L} - \frac{1}{2}\frac{\delta \varepsilon_e}{\varepsilon_e}$$

Strain: change dimensions of radiation patch $\delta L/L$
Bio/chemical: change effective dielectric constant $\delta\varepsilon_e/\varepsilon_e$
Temperature: changes both $\delta L/L$ and $\delta\varepsilon_e/\varepsilon_e$

Wireless Antenna Strain/Vibration Sensor





Antenna configuration

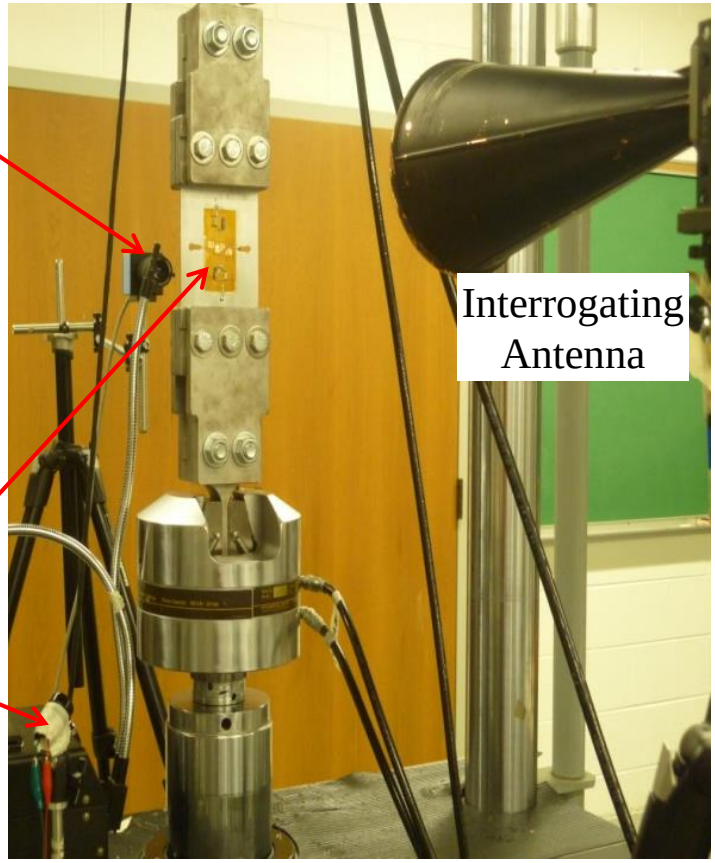
- **Radiation patch**: laser machined from copper film
- **Substrate**: Kapton polyimide film
- **Ground plane**: aluminum specimen

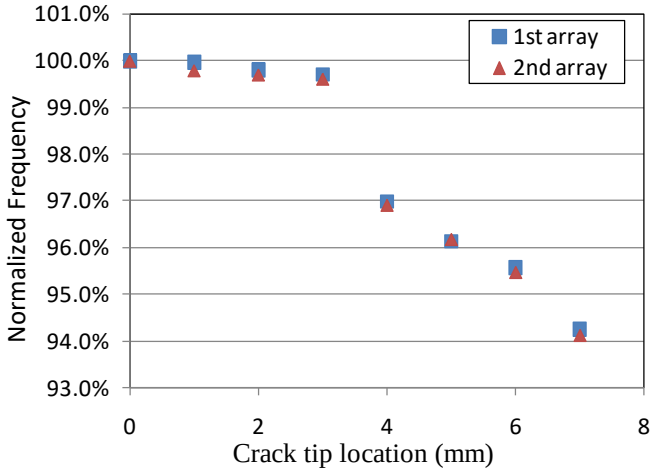
Amplitude modulation circuit

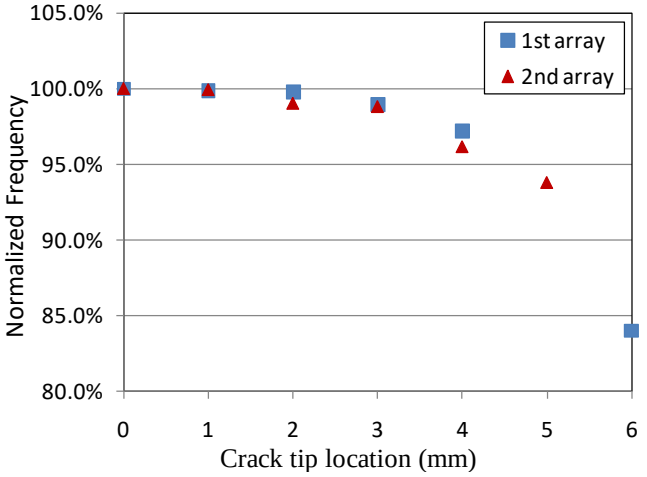
- **Switch**: pHEMT transistor
- **Oscillator**: 0.63 mW @ 32.8 kHz
- **Solar cell**: 3.2X2.5 mm^2

- ✓ **Interrogation distance: ~ 1 m**
- ✓ **Strain sensitivity: 5 kHz/με**
- ✓ **Strain resolution: 20 με**
- ✓ **Sampling rate: 320 Hz**

Multi-site Crack Growth Monitoring

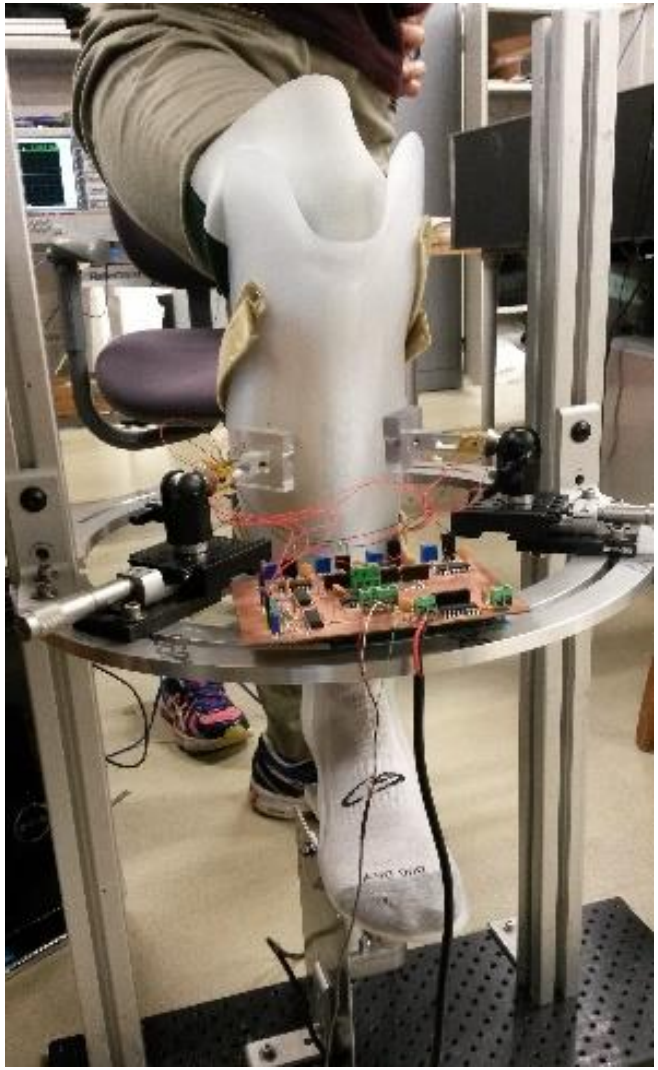






Sensitive to sub-millimeter crack growth

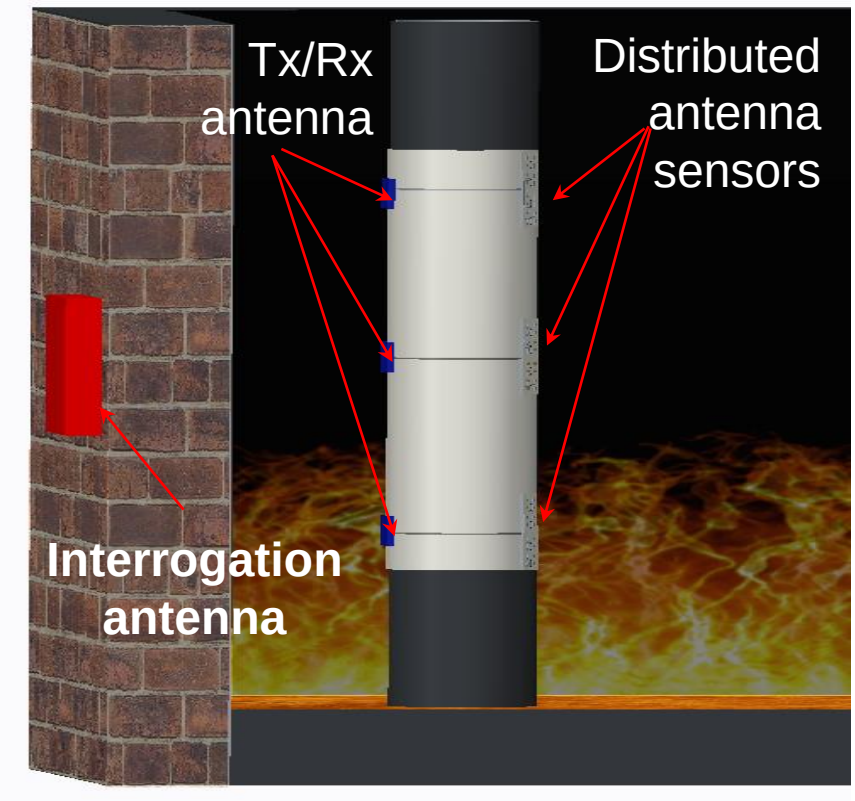
Wireless Antenna Sensor for Smart Prosthetics

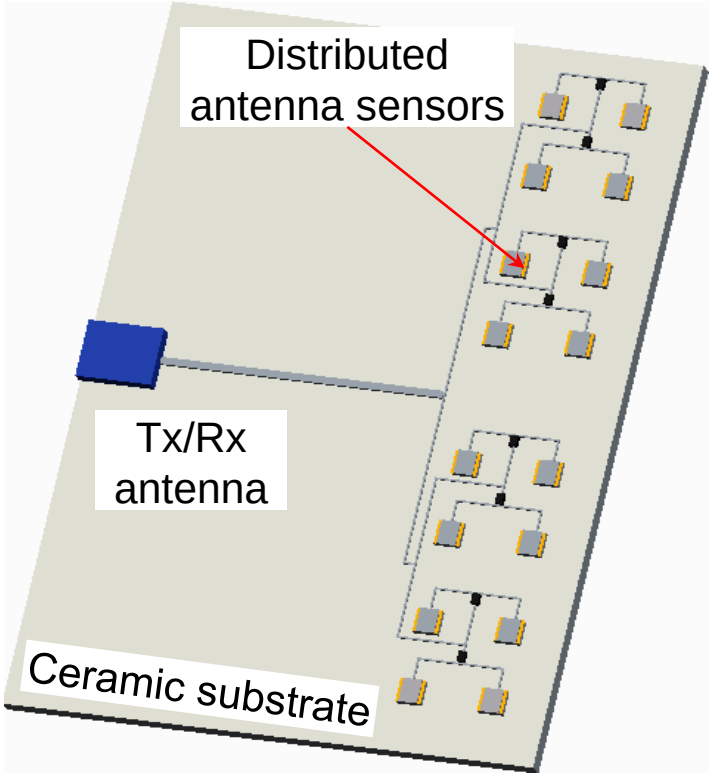


- Measurands: shear/pressure, bio-impedance, limb circumference
- Rapid prototyping on large-area flexible substrate
- Wearable wireless interrogation

Funded by CDMRP Orthopedic Research Program

Antenna Sensors for Boiler Monitoring



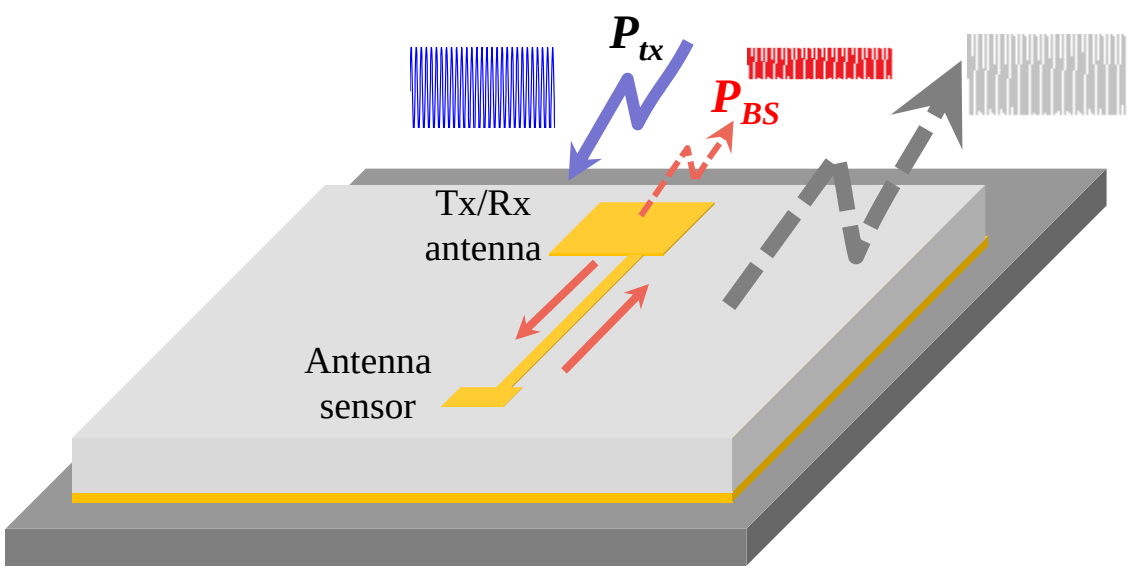


Funded by DOE University Coal Research Program

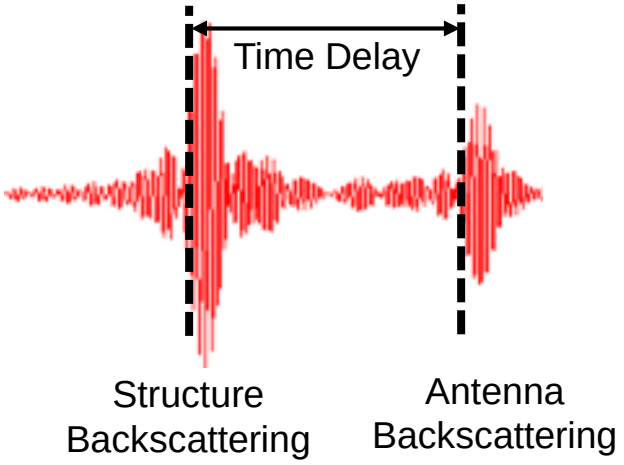
- Wireless interrogation without electronics
- Simultaneous ash and temperature sensing

Wireless Sensing Without Electronics

Principle of Operation

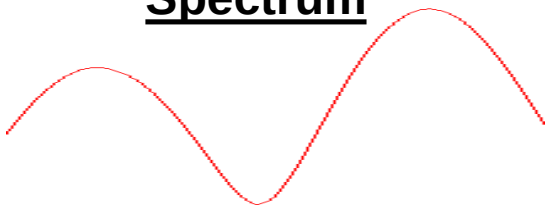


Backscattered Signal



- 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

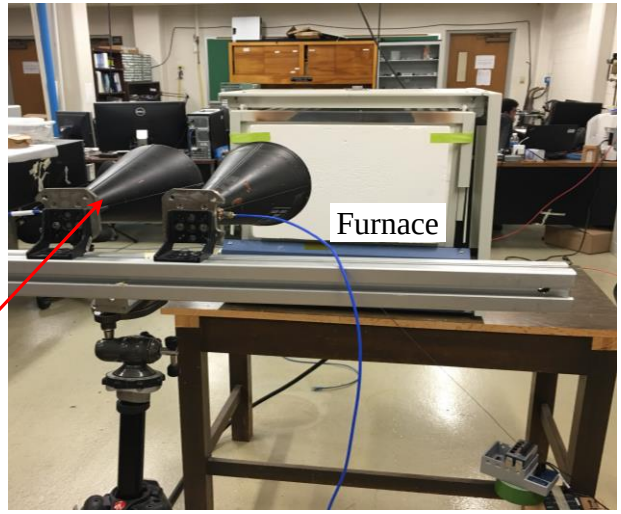
Antenna Backscattering Spectrum

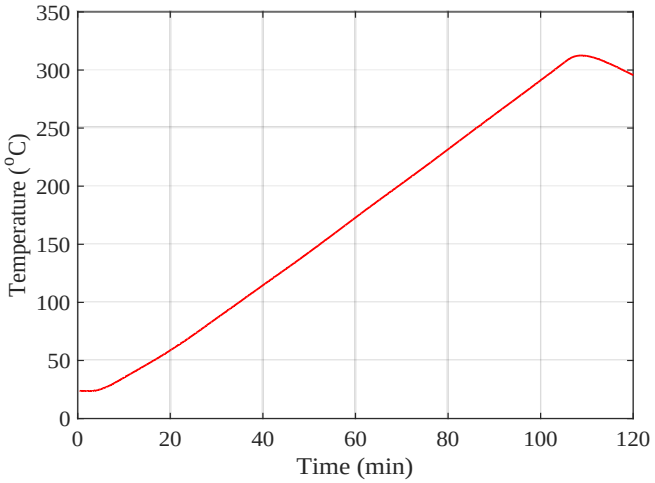


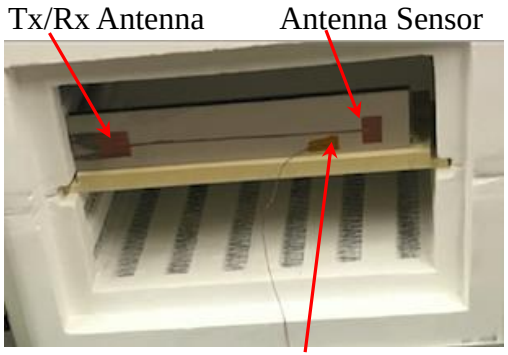
13

Experimental Setup

Interrogation Antennas

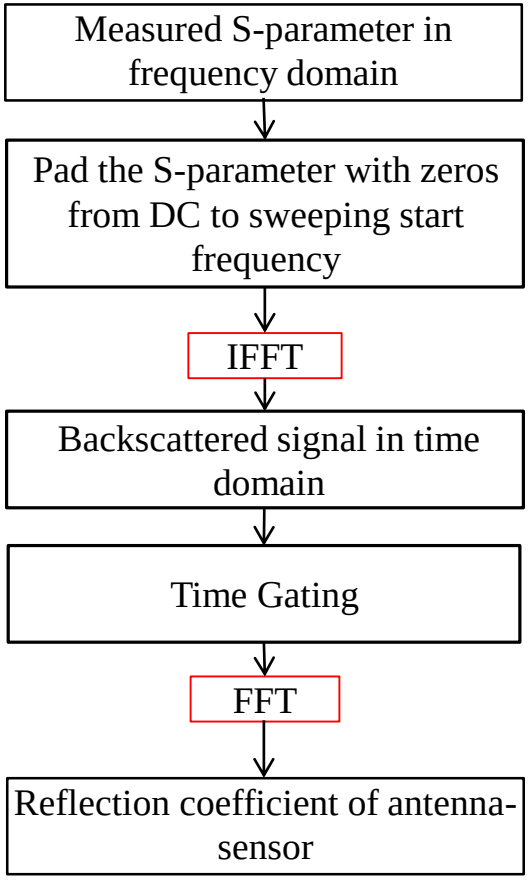


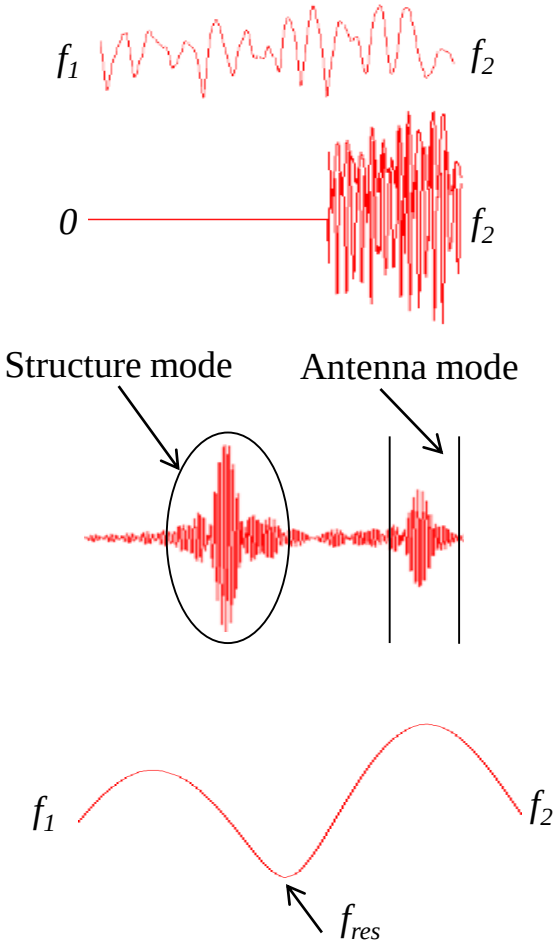




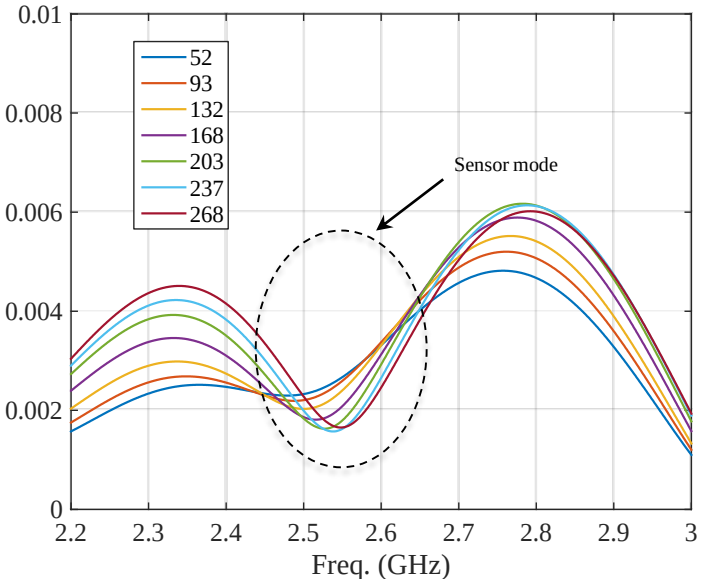
- Interrogation power: 10 dBm
- Interrogation distance: 0.7 m
- Temperature range: 20-300°C

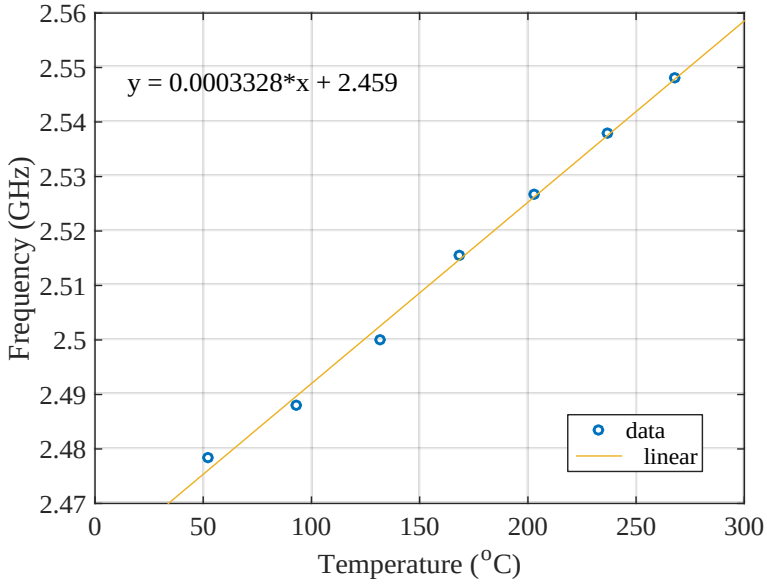
Digital Signal Processing





Wireless Temperature Sensing

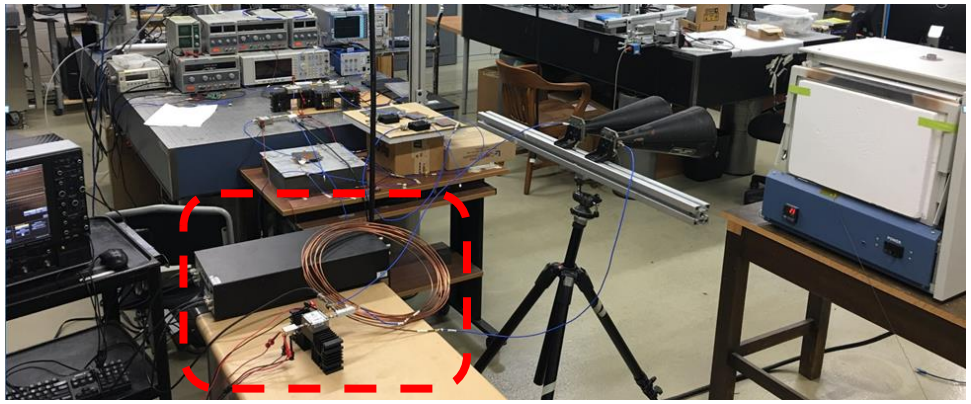


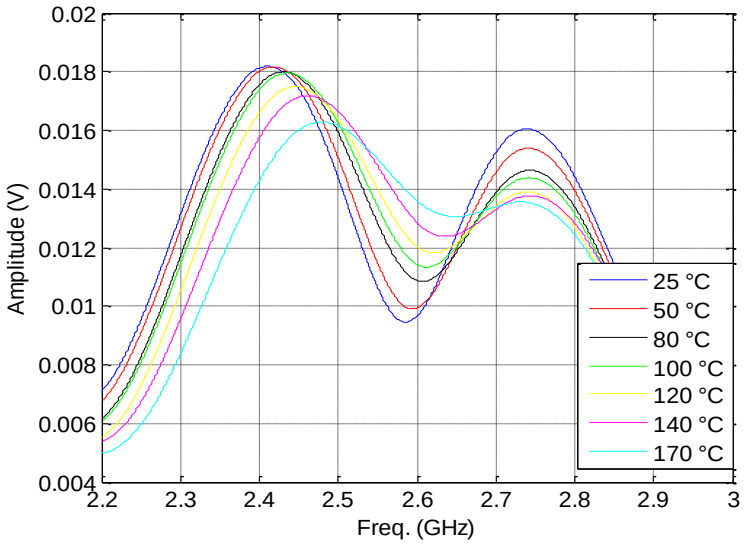


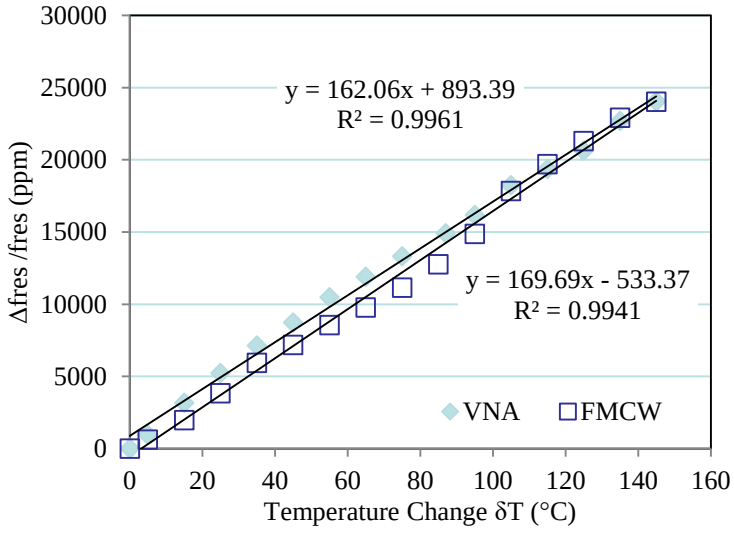
- Excellent linearity: $R^2 = 0.996$
- Temperature sensitivity: 332.8 kHz/°C

Instrument used is expensive, slow, & bulky

FMCW-based Wireless Interrogation

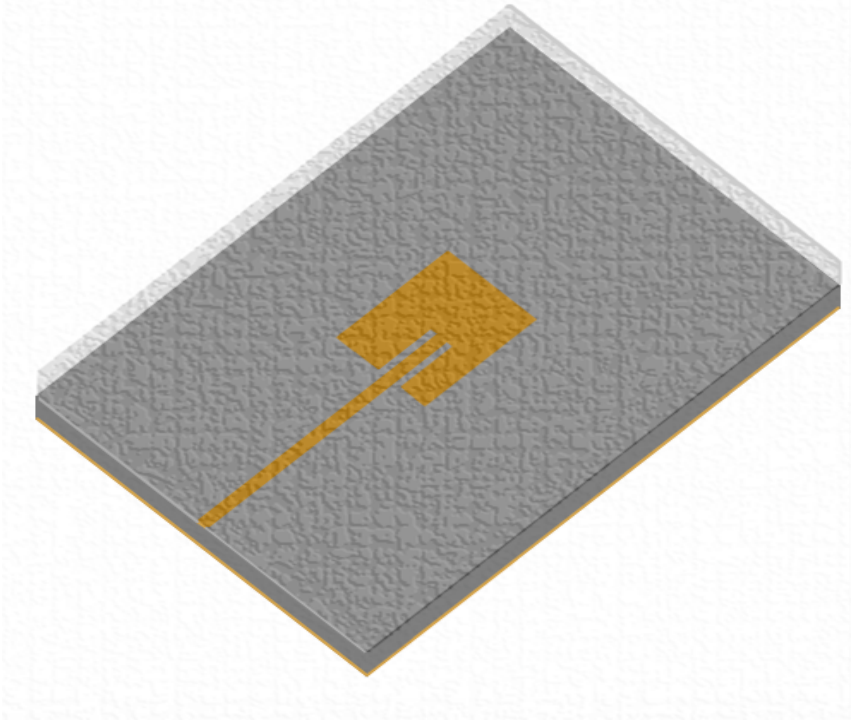






Simultaneous Ash and Temperature Sensing

Effect of Ash Accumulation on Antenna Freq.



- Unloaded condition

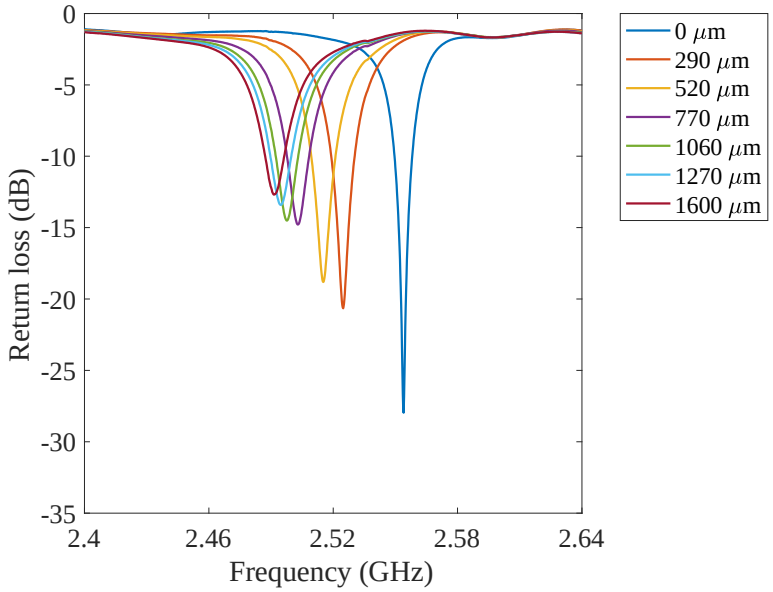
$$\varepsilon_{re} \cong \varepsilon_{r1}$$

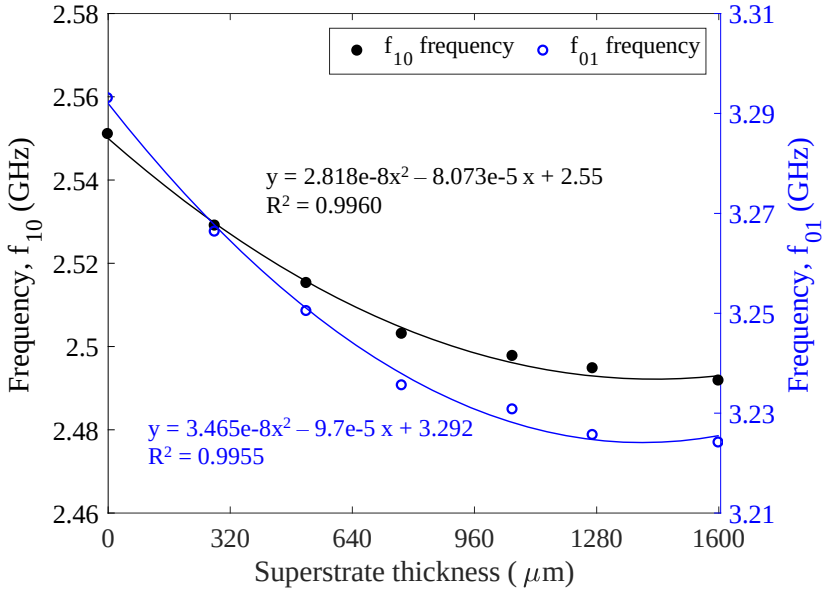
- Loaded condition

$$\varepsilon_{re} = f(\varepsilon_{r1}, \varepsilon_{r2}, h_2)$$

$$f_{10} = \frac{c}{2L\sqrt{\varepsilon_{re}}}$$

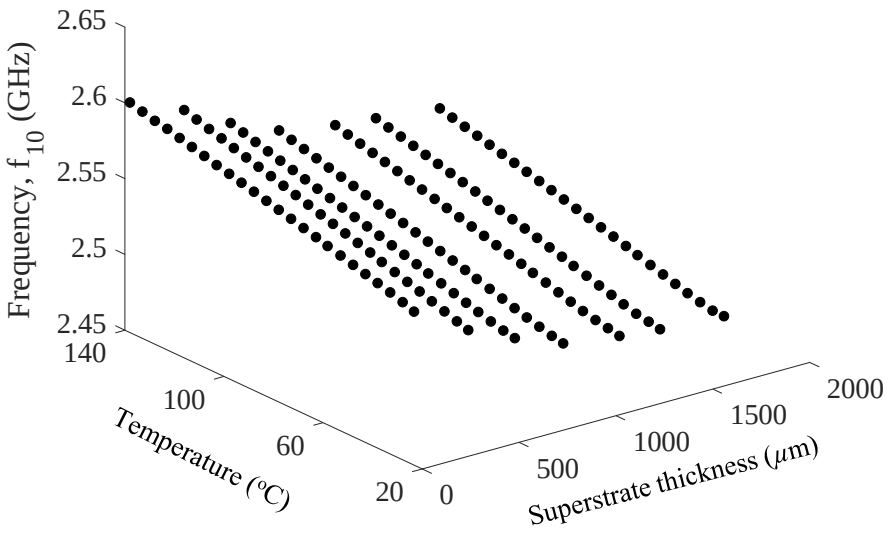
Effect of Ash Thickness - Measurement

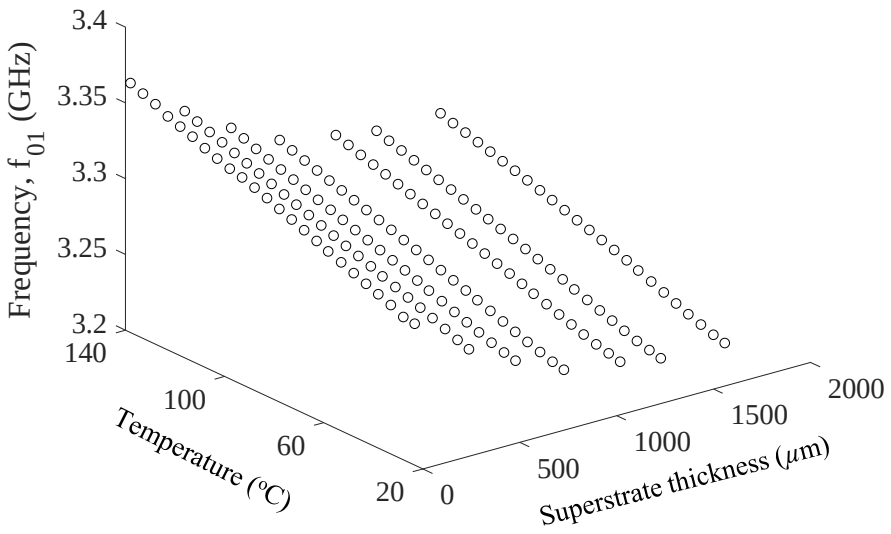




- Ash extracted dielectric constant: 1.66 @ room temp
- R^2 values of 0.9960 and 0.9955 for f_{10} and f_{01} freq.

Effects of Ash Thickness & Temp. - Meas.

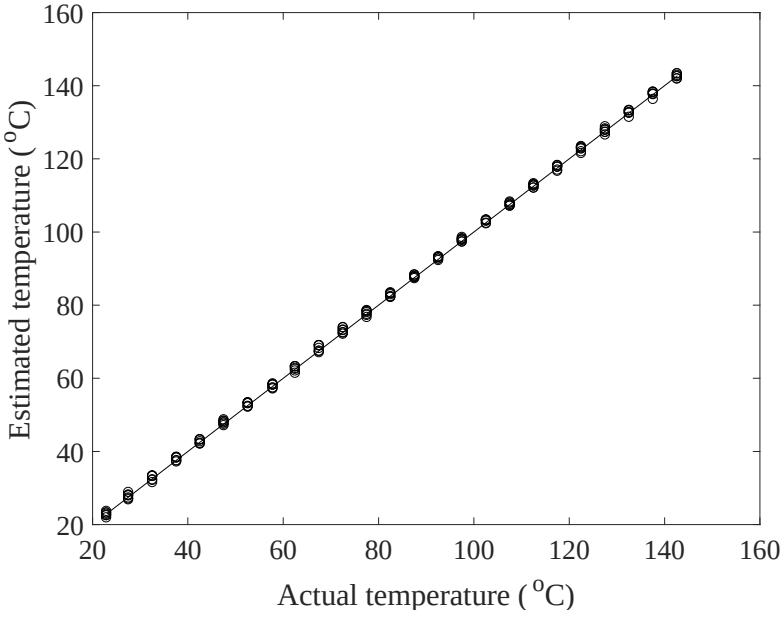


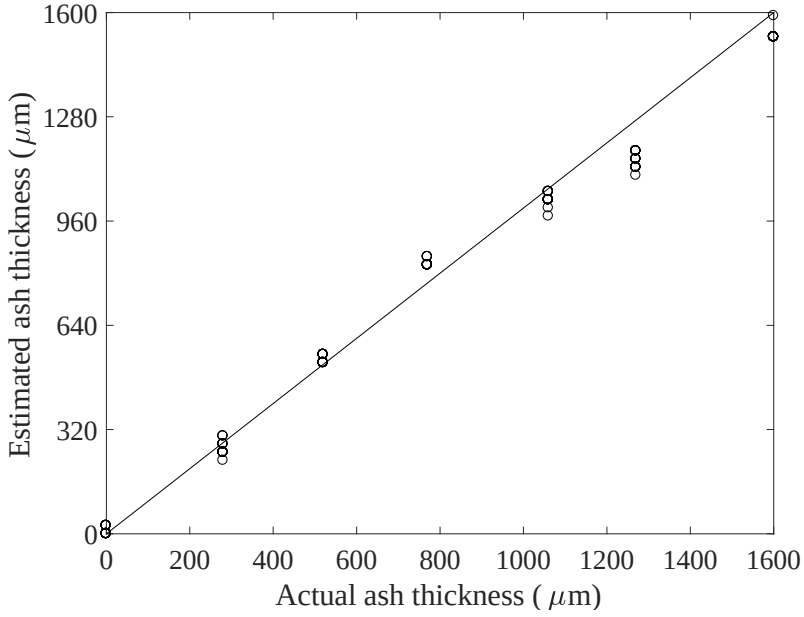


	P_{00}	P_{10}	P_{01}	P_{20}	P_{11}	R^2
f_{10}	2.539e+09	-7.896e+04	4.711e+05	26.08	-6.654	0.9965
f_{01}	3.279e+09	-1.025e+05	6.099e+05	38.91	-40.51	0.9982

$f_{ij} = P_{00} + P_{10}\cdot d + P_{01}\cdot T + P_{20}\cdot d^2 + P_{11}\cdot d\cdot T$ where d is the superstrate thickness and T the temperature

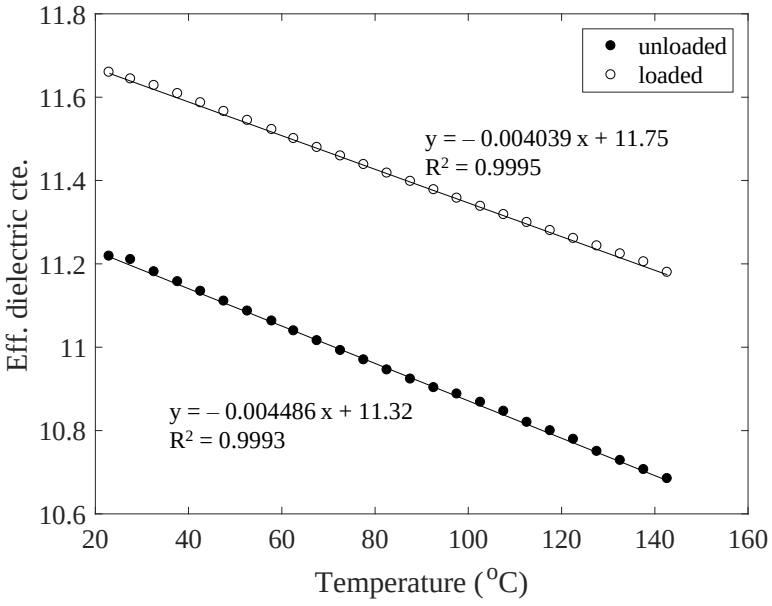
Measurement Uncertainty

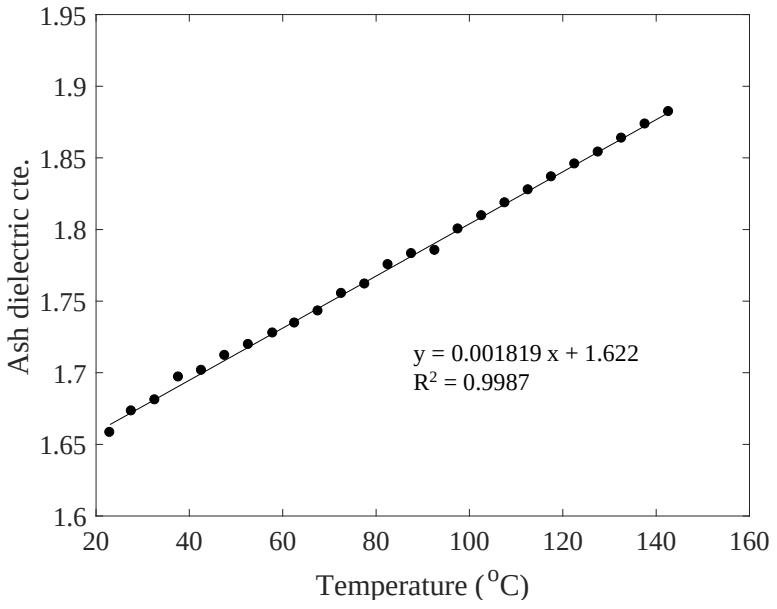




- **Temperature**: ±0.58^{O}C
- **Thickness:** ±58.05 µm

Dielectric Properties of Ash





- **Dielectric constant**: 1.66
- **TCDk**: 1121 ppm/°C

Summary – Distributed Antenna Sensors

- **Demonstrated:**
  - ✓ **Sensing principles**: strain, crack, temperature, strain&temperature, pressure, shear/pressure
  - ✓ **Fabrication**: flexible substrate (up to 4 sensors)
  - ✓ **Wireless interrogation**: dynamic interrogation without electronics, low-cost interrogation unit
  - ✓ **Sensor multiplexing**: frequency and spatial division (up to 4 sensors)

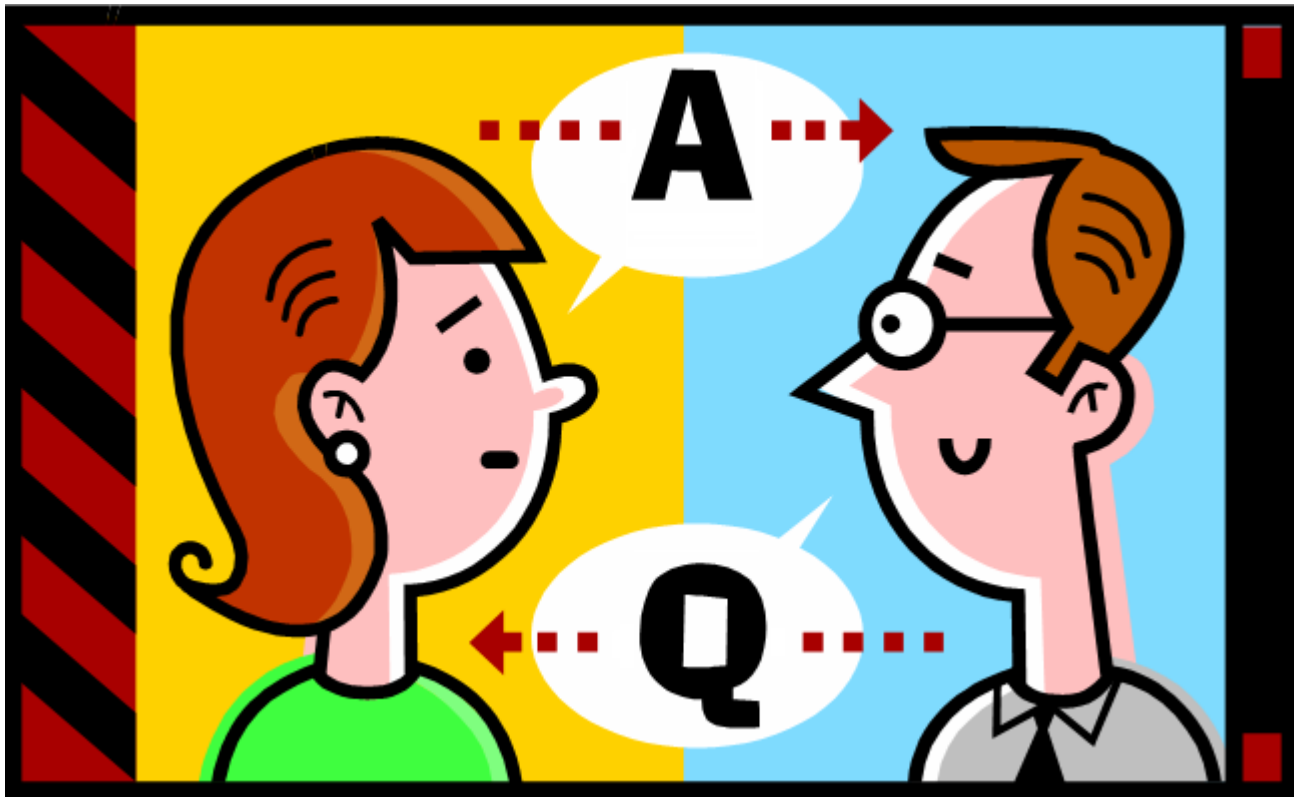
- **On-going and future work**
  - ➢ **Sensing modalities**: bio-impedance, soot, moisture, circumference, …
  - ➢ **Fabrication**: large-area flexible substrate + dense distribution
  - ➢ **Wireless interrogation**: increase sensor count
  - ➢ **Data processing**: multi-variant parameter identification

Publications

- "Antenna sensors in passive wireless sensing systems" in *Handbook of Antenna Technologies* edited by Zhi Ning Chen, published by Springer.
- **Huang, H.**, 2013, "Flexible wireless antenna sensor: a review", *IEEE Sensors Journal*, Special Issue on Flexible Sensors and Sensing Systems, v13, n10, p3865-3872

- Mbanya Tchafa, F. and **Huang, H.**, 2018, "Microstrip patch antenna for simultaneous strain and temperature sensing", *Smart Materials and Structures*, v27, 065019.
- **Huang, H.**, F. Farahanipad, and A. K. Singh, 2017, A stacked dual-frequency microstrip patch antenna for simultaneous shear and pressure displacement sensing, *IEEE Sensors Journa*l, v17, n24, 8314-8323
- 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", *IEEE Sensors Journal*, v16, n19, p 7053 - 7060.
- Sanders, J., Yao, J. and **Huang, H.**, 2015, "Microstrip patch antenna temperature sensor", *IEEE Sensors Journal*, v15, n9, p5312-5319

Questions & Answers



Thanks for your attention!