Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Award #: DE-FE0023118

Duration: 1/1/2015-12/31/2017

Organizations: University of Texas Arlington
UC San Diego

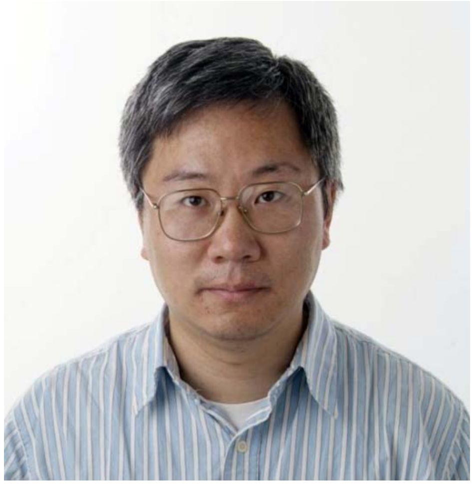
Outline

- Team members
- Technical background/motivation
- Potential significance
- Relevancy to fossil energy
- Planned tasks - SOPO
- Project milestones, budget, and schedule
- Project status
- Q&A

Team Members - PIs

Haiying Huang, PI
Professor of Mechanical & Aerospace Eng.

Research Interests:
Sensors (wireless, optical fiber, ultrasound, etc.)
Mechanics of Materials



Jian Luo, site-PI (UCSD)
Prof. of NanoEngineering and Materials Sci. & Eng.

Research Interests:
Materials processing & characterization
Interfacial engineering

Ankur Jain, Co-PI
Assistant Professor of Mechanical & Aerospace Eng.

Research Interests:
Heat Transfer, Thermal Measurements, Microscale Thermal Transport.

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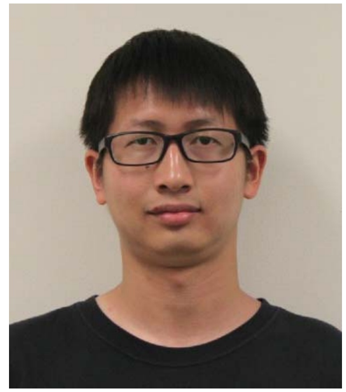
Team Members – Students & Post-doc

Franck Eric Tchafa
UTA PhD student (2014)

BS/MS: City Univ. of London 2010

Sensor design & characterization



Jun Yao
UTA PhD student (2012)

ME: Univ. of Shanghai for Sci. &Tech, 2012
BE: Southeast Univ., 2009

Wireless interrogation of patch antenna sensor

Vivek Vishwakarma
UTA PhD student (2012)

BS: Indian Institute of Technology 2012

Thermal measurement

Tao Hu
Post-doc, UCSD

PhD: City Univ. of Hong Kong, 2011
Post-doc: UC Davis

Material design and fabrication

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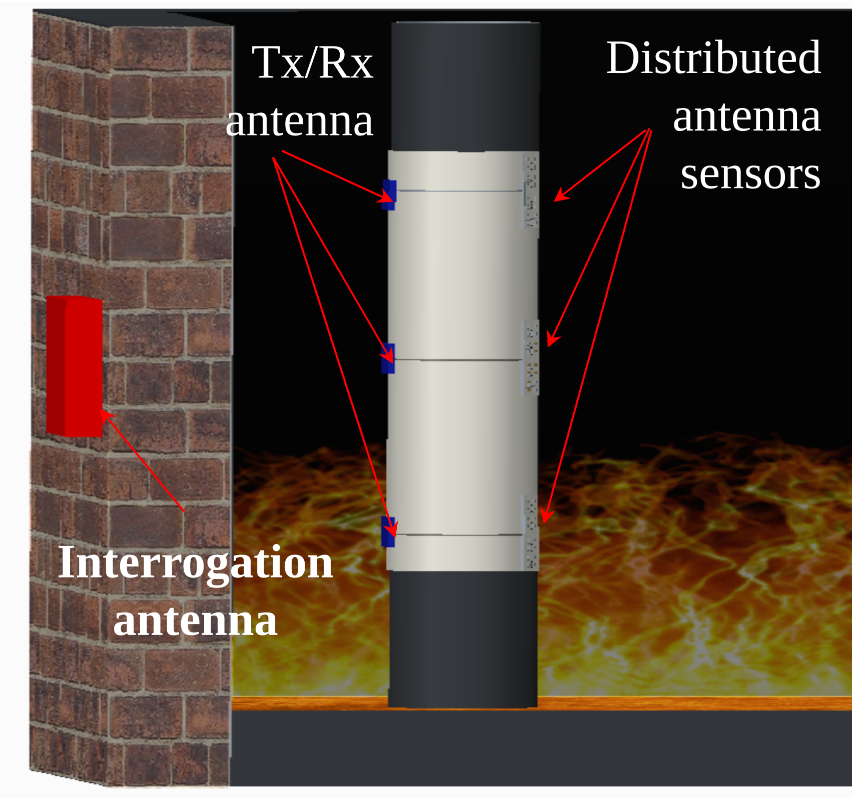
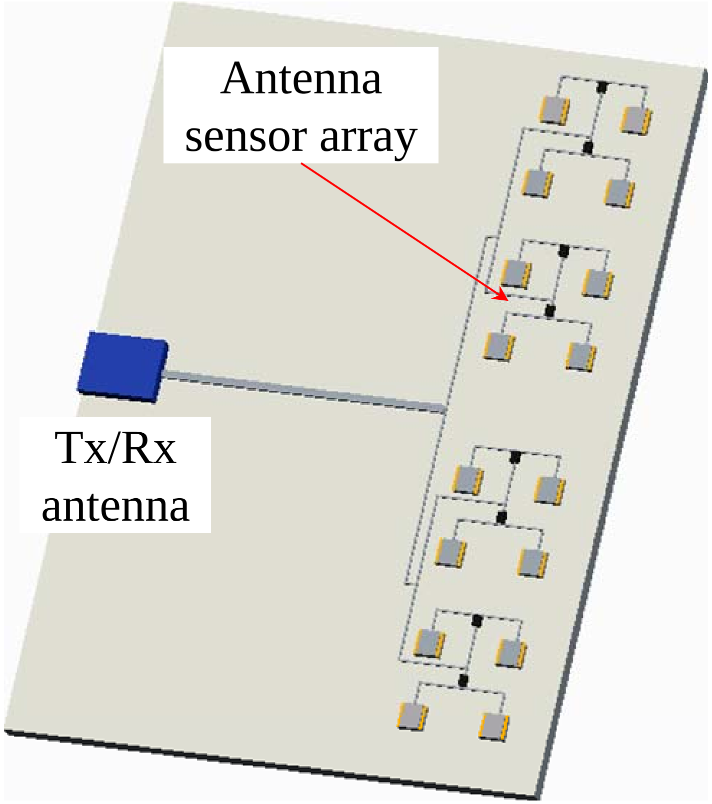
Objectives & Overview

Realize distributed conditioning monitoring of stream pipes up to 1000 °C

- Monitor temperature and strain distribution of steam pipes
- Detect soot accumulation on steam pipes





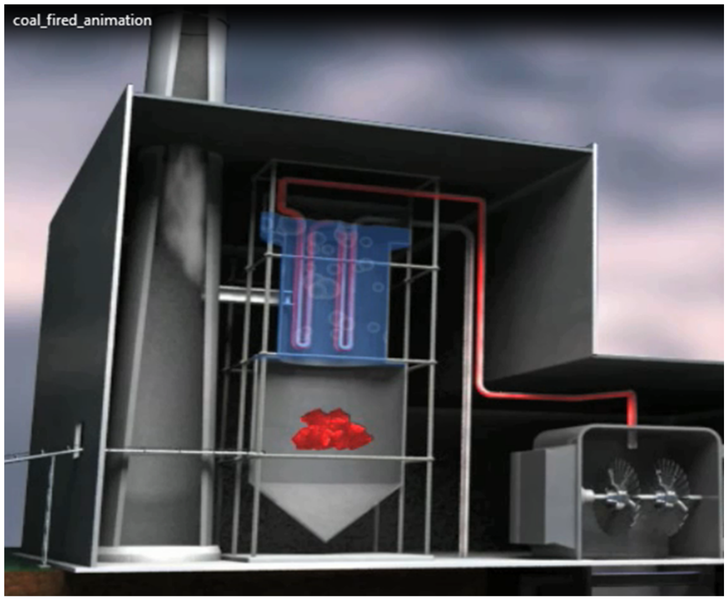
Potential Significances

- Introduce novel wireless sensor concept for high temperature applications
  - High temperature material development
  - Wireless interrogation without electronics
  - Multi-modality sensing (strain, temperature, soot accumulation)
  - Sensor multiplexing for distributed sensing

- Lay the foundation for producing a family of high temperature sensors that can monitor pressure, flow, gas, corrosion etc.

- Advance understanding and control of high temperature dielectric properties at gigahertz frequencies

Relevance to Fossil Energy



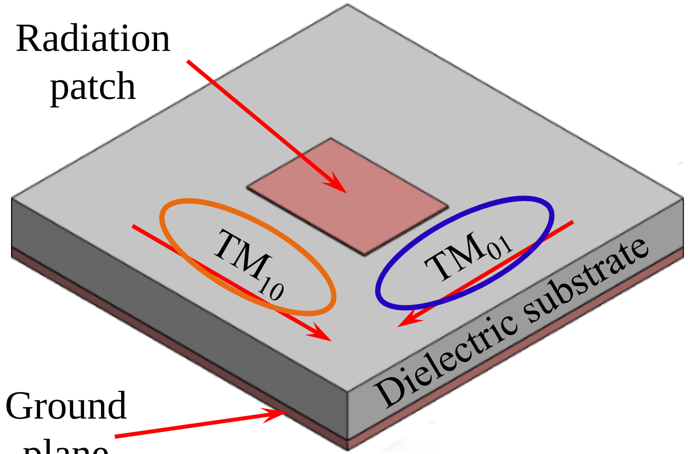
Condition Monitoring of Steam Pipes

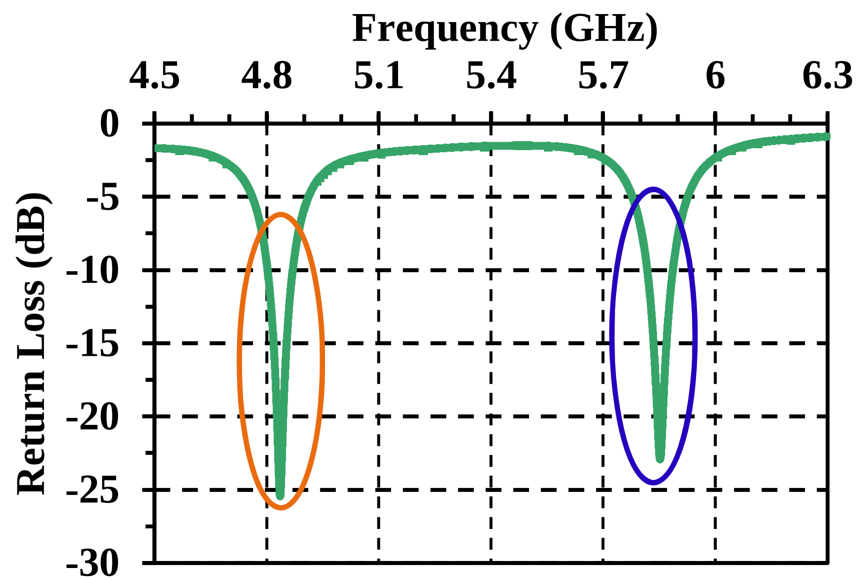
- Enhance safety (high temperature, high pressure, corrosive environment)
- Improve heat transfer efficiency by optimizing soot cleaning

Distributed Multi-variant Sensing

- Enable detailed condition monitoring of boilers
- Gain fundamental understanding of combustion and heat exchange processes
- Help develop and refine simulation models
- Achieve better design and more efficient operation of boilers

Microstrip Patch Antenna





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

f = antenna resonant frequency
c = speed of light
ε_r = substrate dielectric constant
L = patch dimension along current direction

Patch Antenna for Sensing

$$\varepsilon_{reff} = q_1\varepsilon_1 + q_2\varepsilon_2 + (1 - q_1 - q_1)$$

$$f = \frac{c}{2\sqrt{\varepsilon_{eff}}\,L}$$

$$\delta f = \frac{\partial f}{\partial \varepsilon_{eff}}\delta\varepsilon_{eff} + \frac{\partial f}{\partial L}\delta L$$

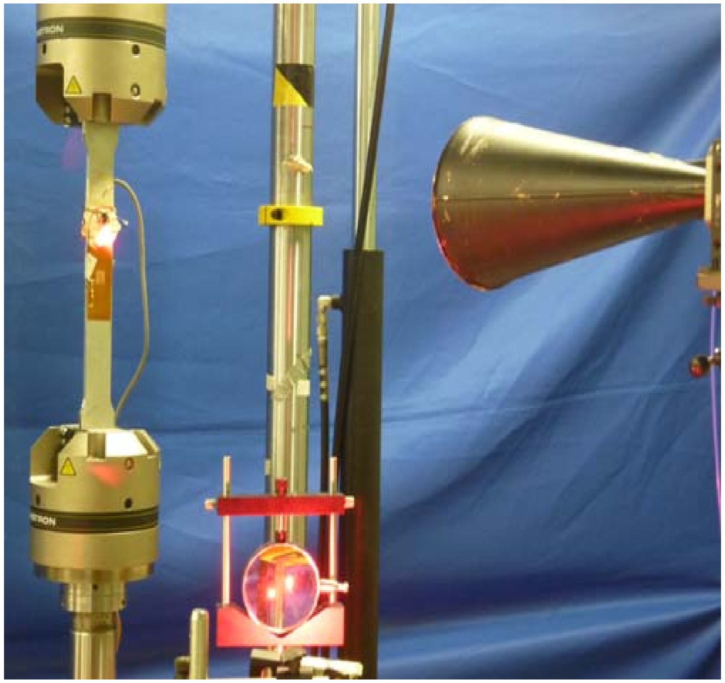
$$\frac{\delta f}{f} = -\frac{1}{2}\frac{\delta\varepsilon_{eff}}{\varepsilon_{eff}} - \frac{\delta L}{L}$$

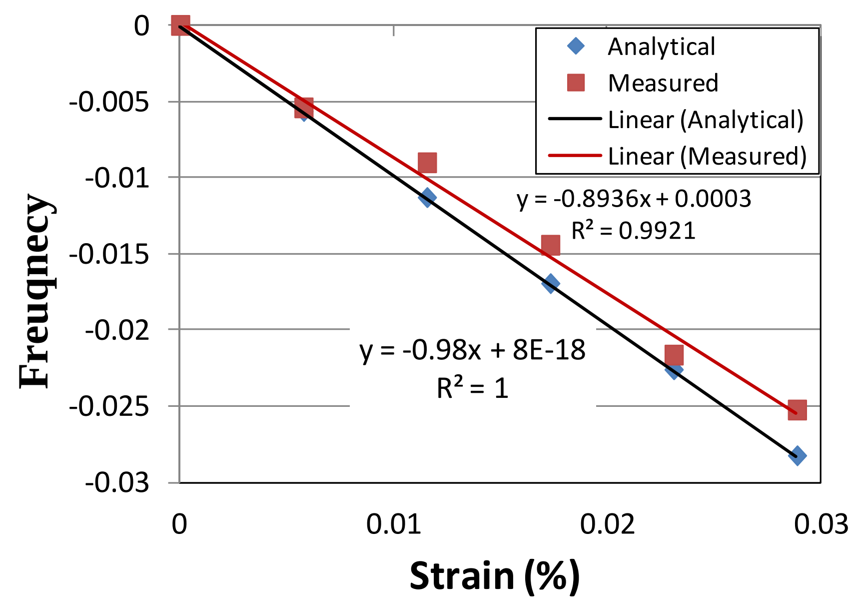
Strain: change dimensions of radiation patch $\delta L/L$

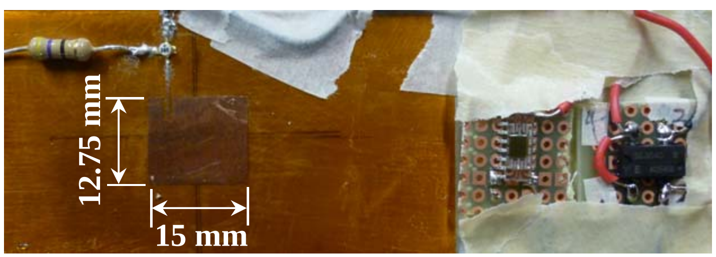
Soot accumulation: change effective dielectric constant $\delta\varepsilon_{eff}/\varepsilon_{eff}$

Temperature: changes both $\delta\varepsilon_{eff}/\varepsilon_{eff}$ and $\delta L/L$

Prior Work – Strain Sensing



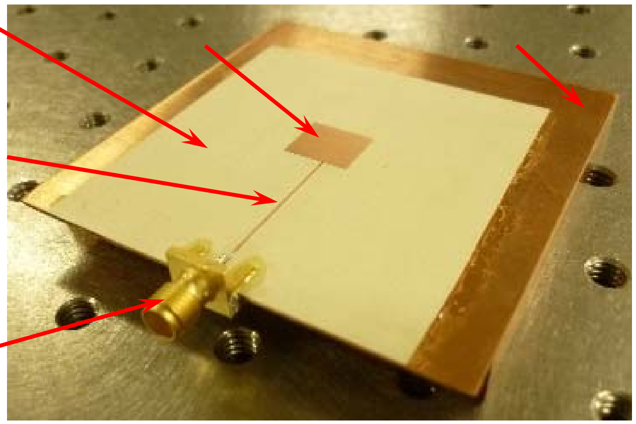


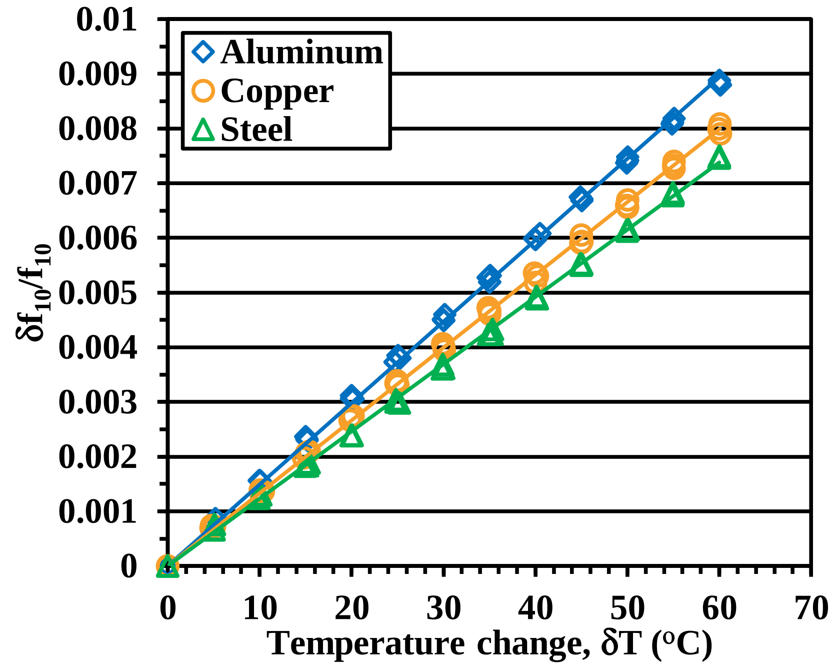


Strain sensitivity: ~ 1 ppm/με

Strain resolution: 20 με

Prior Work – Temperature Sensing





- Commercial high freq. dielectric substrate
- CTE: 17 ppm/°C
- $\delta\varepsilon_r/\delta T$: -160 ppm/°C

Estimated errors: ±2.2°C

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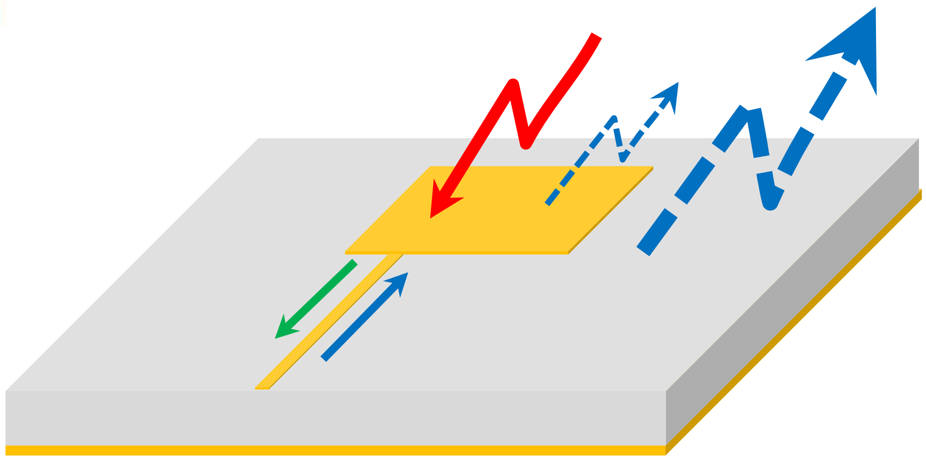
Challenge #1 & Potential Solutions

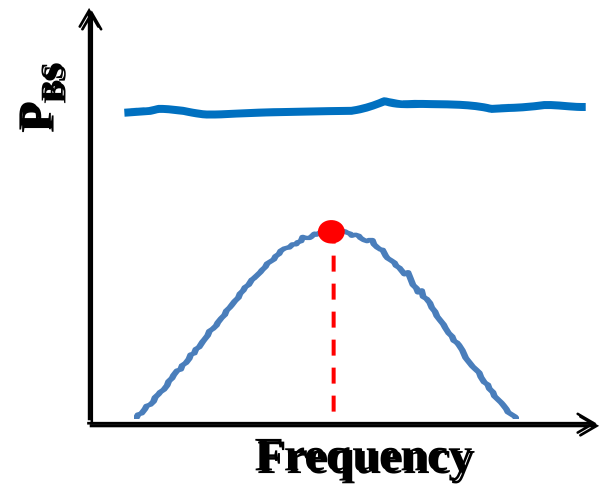
Challenge #1: coupled effects of strain, temperature, soot on antenna radiation characteristics

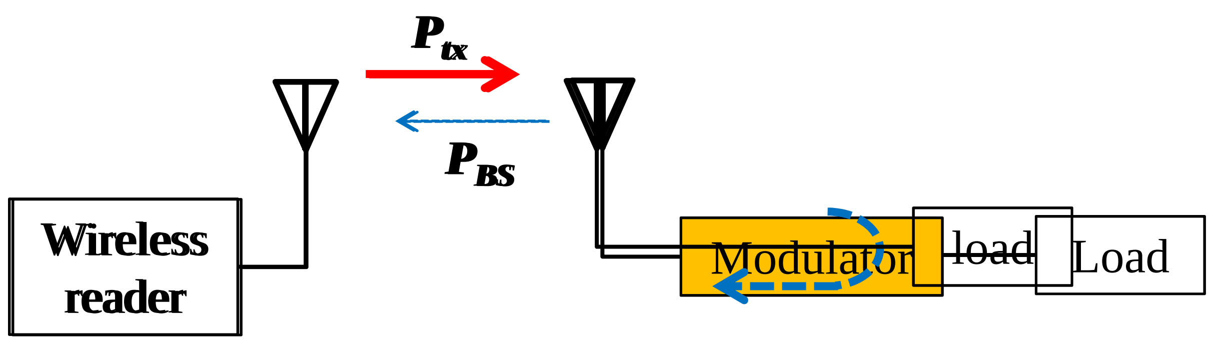
Potential Solutions:

- Tailor material properties to isolate the effects
- Extract two parameters simultaneously from two resonant frequencies of a single antenna sensor
- Extract all three parameters simultaneously using parameter identification

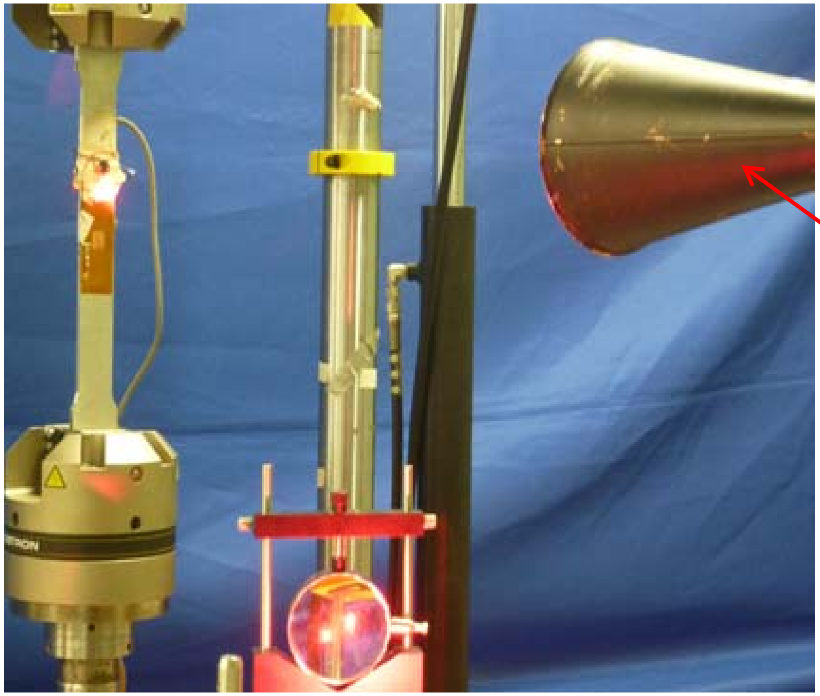
Wireless Interrogation





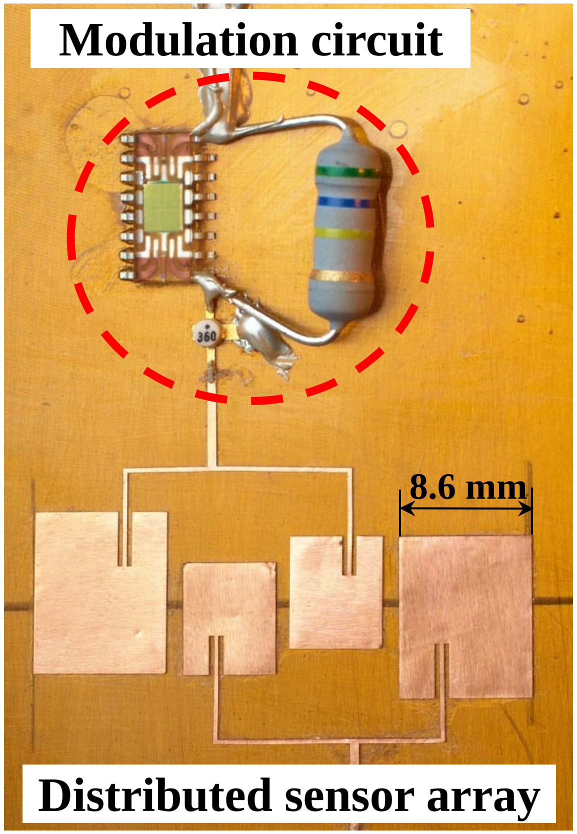


Prior Work – Wireless & Sensor Multiplexing



Interrogation antenna

Interrogation distance: > 1 m

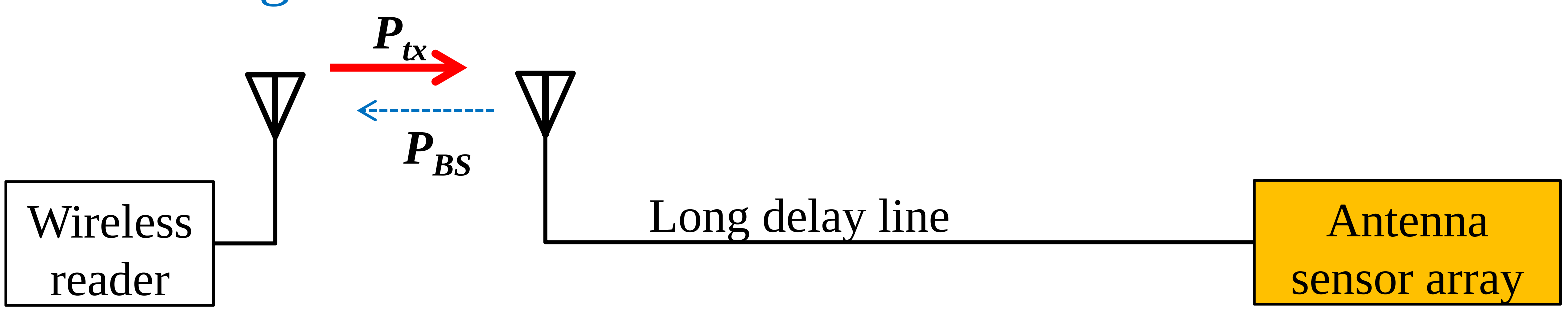


Challenge #2 & Potential Solutions

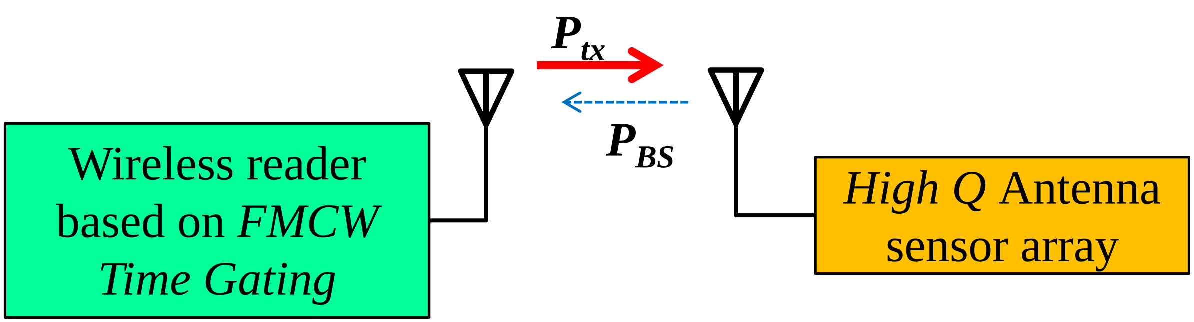
Challenge #2: wireless interrogation without electronics

Solutions:

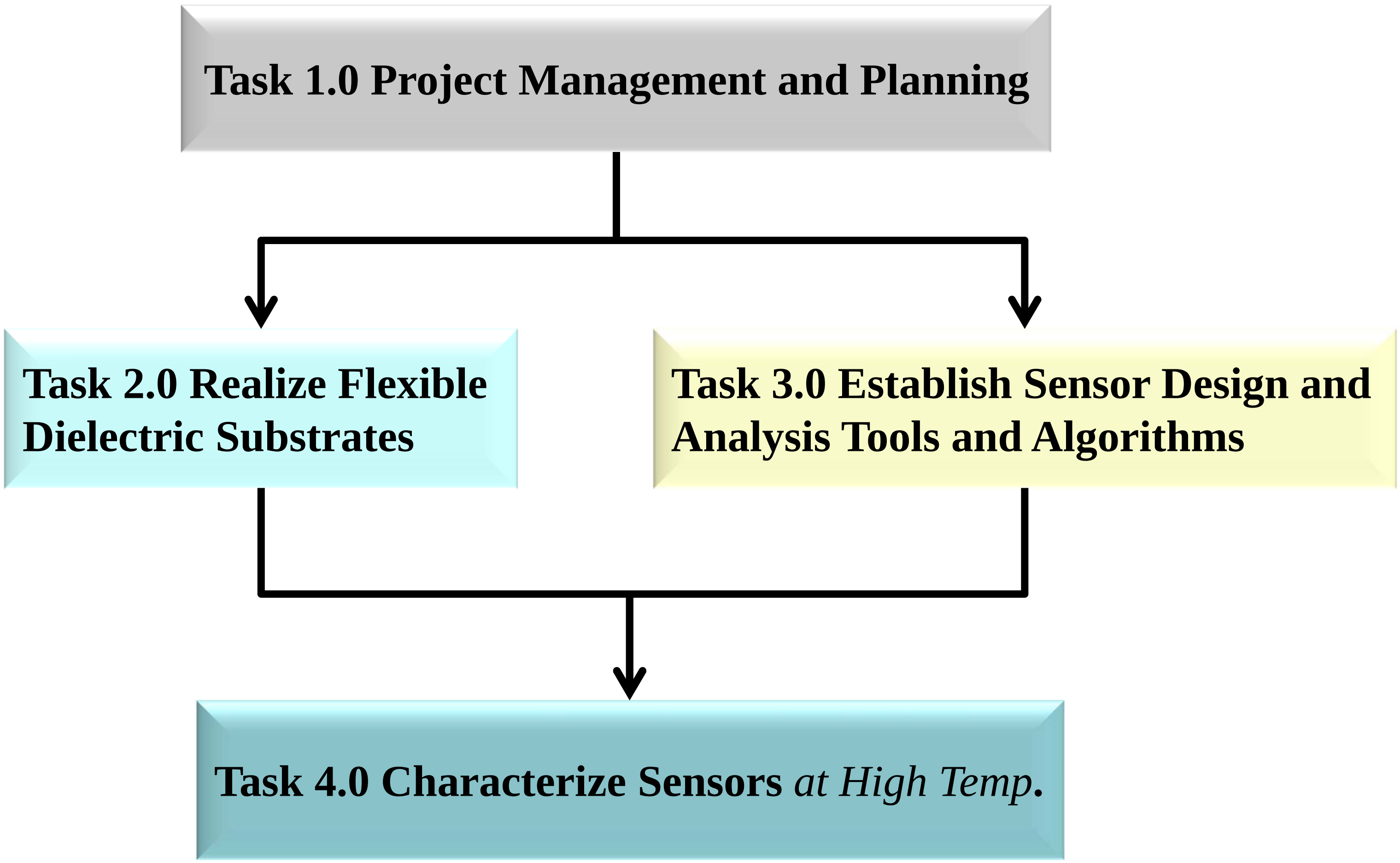
- Use a long transmission line



- Implement FMCW-based time gating technique



Planned Research Tasks



Task 1.0 Project Management and Planning

- Hold kick-off meeting
  - Modifications to the Project Management Plan
  - Reporting schedule
  - Plan for regular project meetings
- Revise & submit Project Management Plan
- Prepare & submit required NEPA documentation

Task 2.0 Realize Flexible Dielectric Substrates

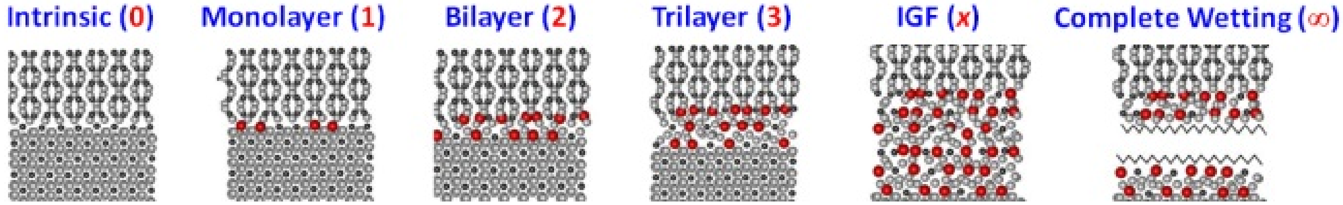
- Subtask 2.1 – Design dielectric properties of high temperature materials
- Subtask 2.2 – Synthesize flexible dielectric substrates
- Subtask 2.3 – Characterize properties of substrate materials
  - *Microstructure*
  - *Dielectric Property*
  - *Mechanical Property*

Deliverables:

- Materials and sintering recipes
- Flexible dielectric substrates with desired material properties
- Validated material dielectric property measurement method

Subtask 2.1 – High Temp. Material Design

- Preliminary design
  - Silica (SiO_2) as starting point: well established processing route;
  - Binary SiO_2-TiO_2 ceramics: good sinterability and tunable dielectric constant;
  - More exotic oxides, *e.g.* $CaTiO_3$ and $BaZrO_3$, ZrO_2 and YSZ (Y_2O_3-stabilized ZrO_2): further improve the dielectric properties
- Further development (a high-risk and high-return effort)
  - Doping and interfacial engineering to improve the processability, microstructure, and dielectric property via controlling grain boundaries



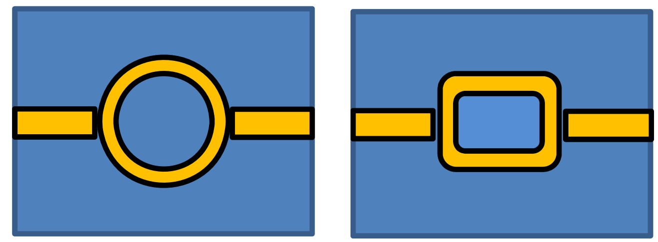
Various grain boundary structures that may control sintering, microstructural development and dielectric properties [Figure courtesy of Dillon & Harmer, see an Overview article by Cantwell, Tang, Dillon, Luo, Rohrer, and Harmer, *Acta Materialia*, 62: 1-48 (2014) for details]

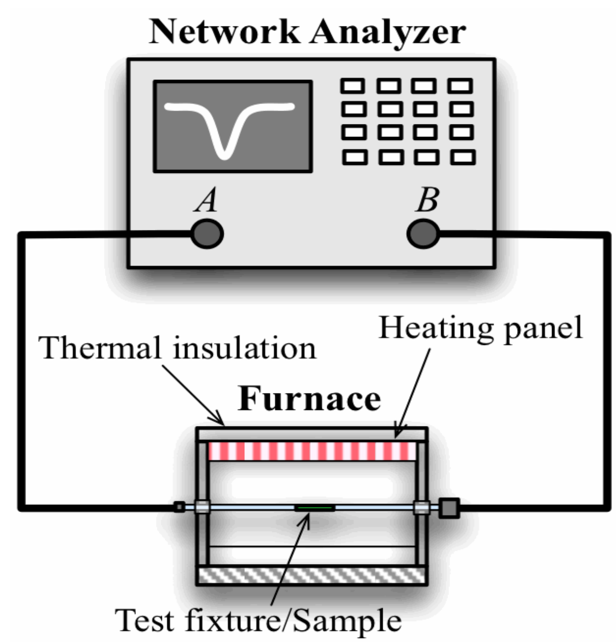
Subtask 2.2 – Synthesize Flexible Substrates

- Sol-gel method and tape casting
  - Uniformly layer of ~10-200 μm thick
  - Select sintering aids/dopants to control both processing & properties
- Selection of electrode materials
  - Ni as primary electrode material: high-temperature stability, good oxidation, corrosion resistance
  - Ultra-thin Au film: sufficiently stable at high temperatures (but more expensive than Ni; "ultra-thin" to reduce the cost)
- "Flashing sintering" (a high-risk and high-return effort)
  - Reduction of sintering temperatures
  - Low-temp. co-sintering of the metallic electrodes and dielectric oxides

Subtask 2.3 – Characterize Material Properties

- Microstructure characterization
  - Microstructure and compositions
  - Grain boundary structures at atomic scale
- Dielectric property characterization
  - Resonant frequency and fractional bandwidth (*Q* factor) of the ring resonator
  - Repeatability at elevated temperature
- Mechanical property characterization
  - Detect cracking, spalling, etc.
  - Conformability





Task 3.0 Sensor Design and Analysis

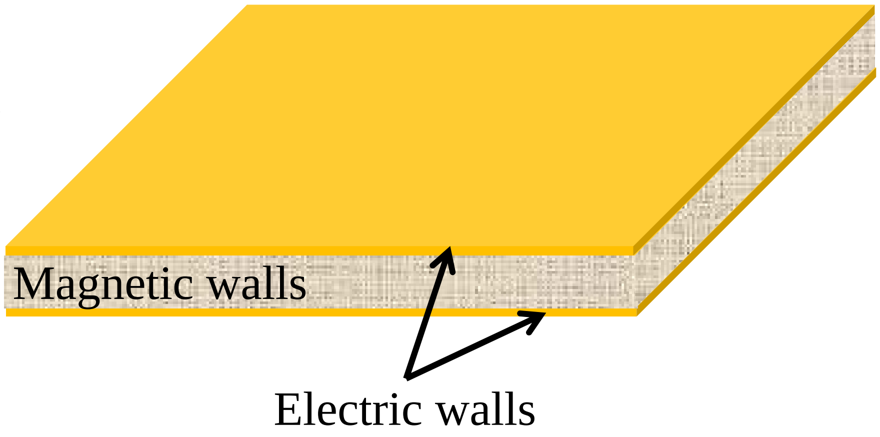
- Subtask 3.1: establish efficient antenna simulation model
- Subtask 3.2: develop multi-variant regression algorithms
- Subtask 3.3: perform parameter studies to optimize dielectric property
- Subtask 3.4: design distributed antenna sensor array

Deliverables:

- Cavity model of antenna sensor
- Nonlinear regression algorithm for multi-variant analysis
- Optimal design of antenna sensor array

Subtask 3.1: Establish Efficient Antenna Model

- Simulation model is needed for
  - Parametric studies
  - Multi-variant analysis
- Cavity model
  - Cavity bounded by top & bottom electric walls
  - Magnetic wall all along the periphery.

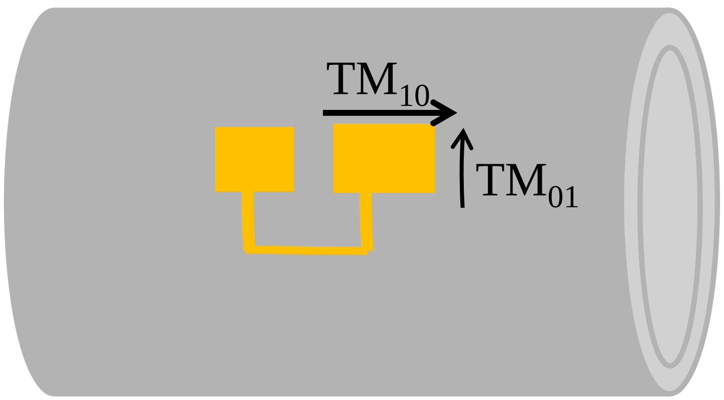


- Governing Equations

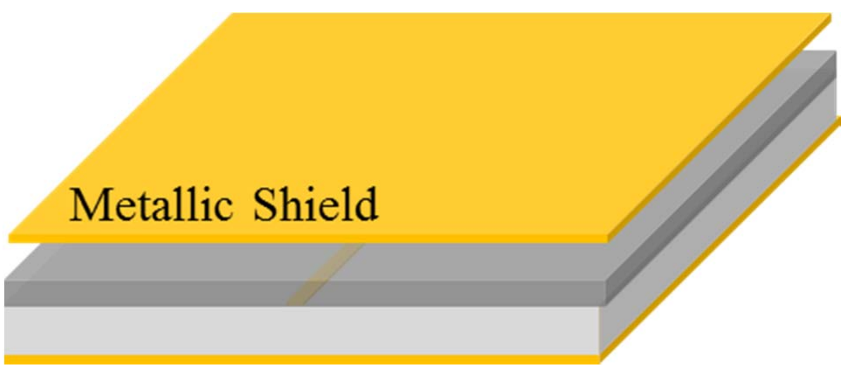
$$E_z(x,y) = \sum_m \sum_n A_{mn} \psi_{mn}(x,y).$$

$$Z_{in} = -j\omega\mu_0 I_0 \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\psi_{mn}^2(x_0, y_0)}{k^2 - k_{mn}^2} G_{mn}$$

Subtask 3.2: Develop Multi-variant Analysis



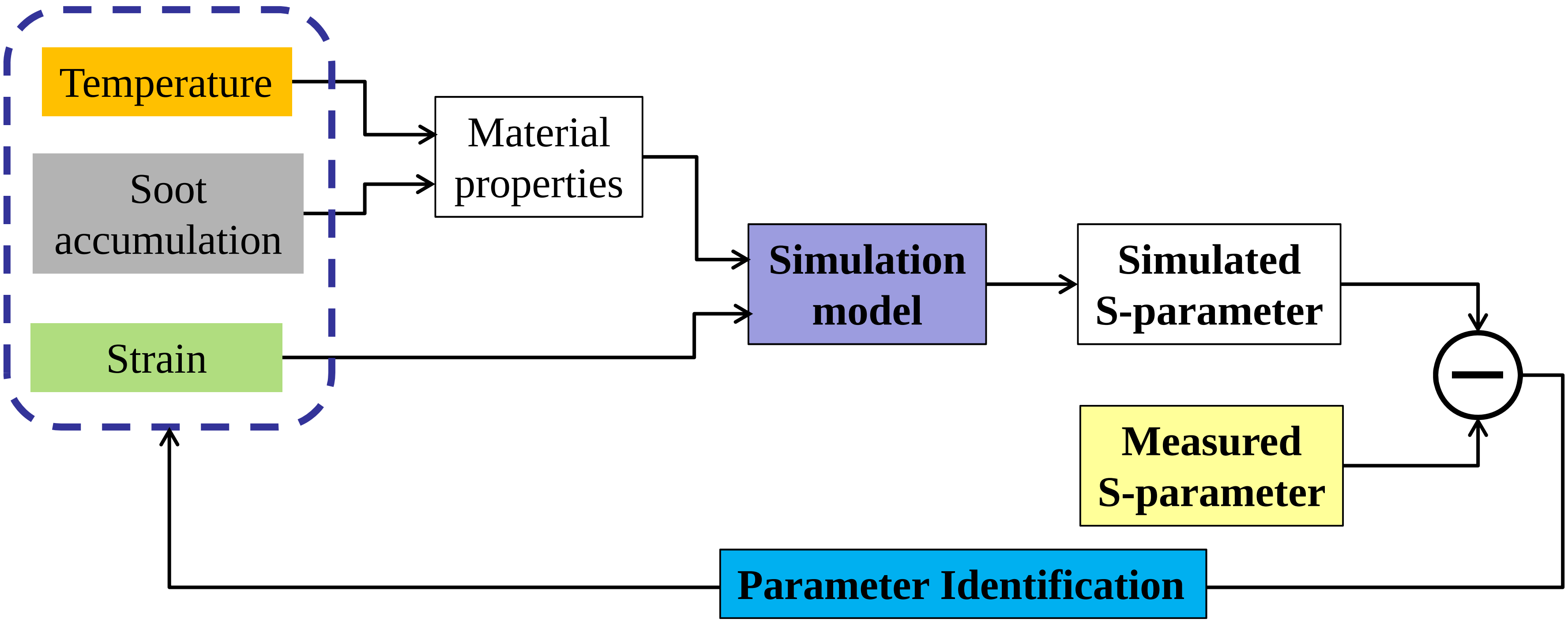
- Circumferential strain only
- *TM_{10}* resonance: thermal expansion & soot
- TM_{10} resonance: strain, thermal expansion & soot



Temperature/strain sensor

$$\begin{cases} \dfrac{\delta f_{10}}{f_{10}} = k_T \Delta T - \varepsilon_L \\ \dfrac{\delta f_{01}}{f_{01}} = k_T \Delta T - \upsilon \varepsilon_L \end{cases} \Rightarrow \begin{cases} \varepsilon_L = \dfrac{1}{\upsilon - 1}\left(\dfrac{\delta f_{10}}{f_{10}} - \dfrac{\delta f_{01}}{f_{01}}\right) \\ \Delta T = \dfrac{1}{k_T}\left(\dfrac{\delta f_{10}}{f_{10}} + \varepsilon_L\right) \end{cases}$$

Subtask 3.2 – Parameter Identification

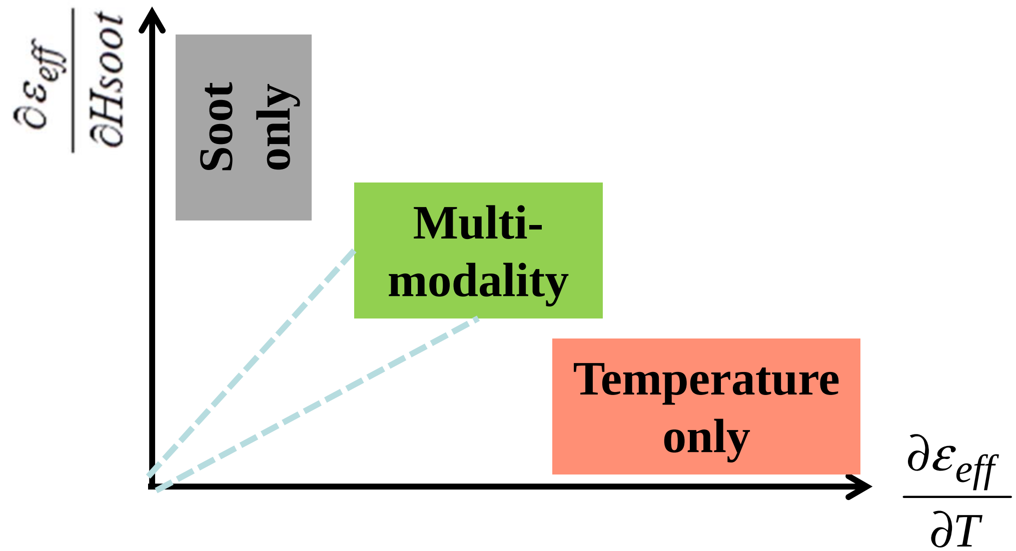


- Extract all three parameters from one single S-parameter measurement
- Adjust input parameters to match simulated & measured S-parameters

Subtask 3.3: Optimize Dielectric Property

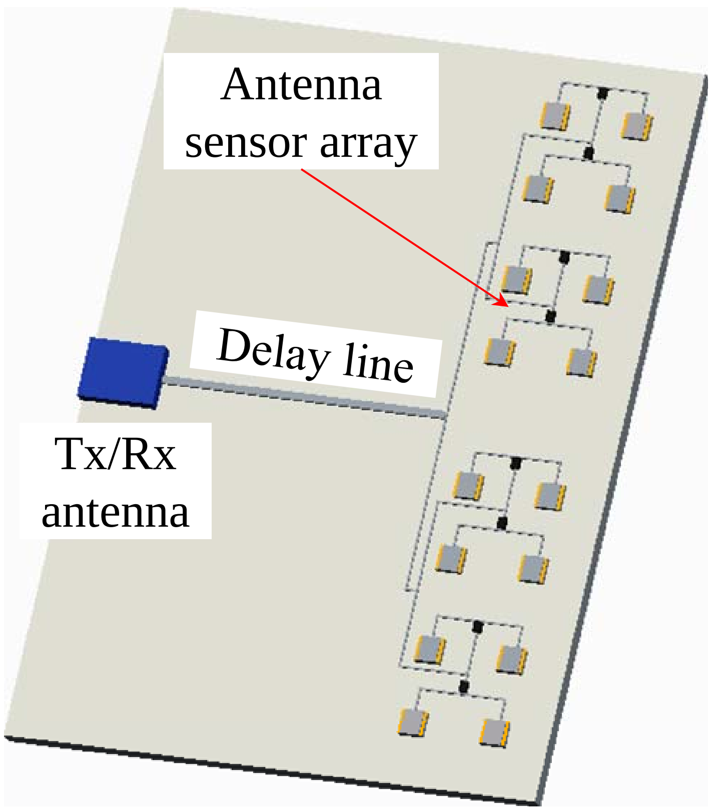
$$\frac{\delta f}{f} = -\frac{1}{2}\frac{\delta \varepsilon_{eff}}{\varepsilon_{eff}} - \frac{\delta L}{L}$$

$$\delta \varepsilon_{eff} = \frac{\partial \varepsilon_{eff}}{\partial T}\delta T + \frac{\partial \varepsilon_{eff}}{\partial H_{soot}}\delta H_{soot}$$

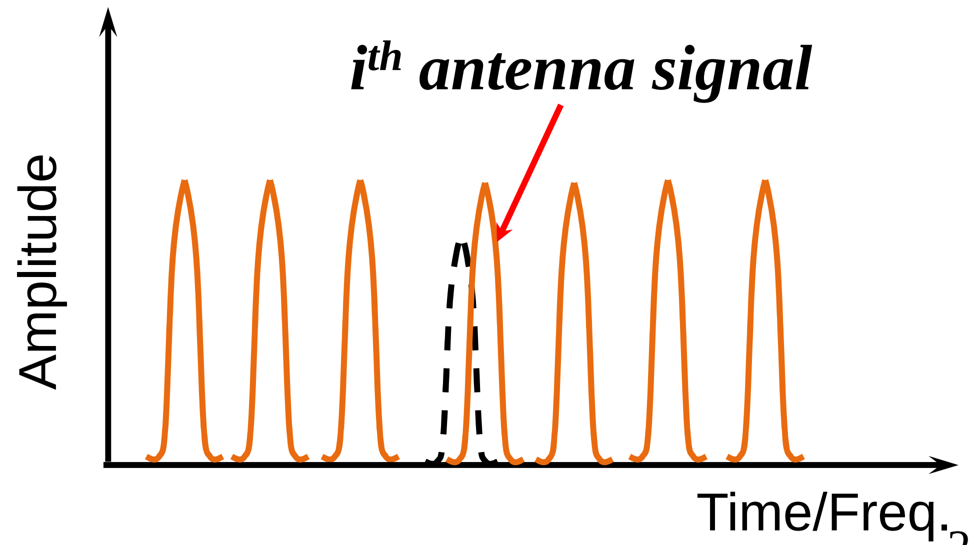


- **Single-modality**: enhance sensitivity to temperature or soot
- **Multi-modality**: balance sensitivity to temperature, strain, soot

Subtask 3.4: Achieve Distributed Sensing



- Tx/Rx antenna: broadband
- Antenna sensors: narrowband
- Varying delay line length
- Frequency division and/or time division multiplexing



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Task 4.0 Characterize Sensor at High Temp.

- Subtask 4.1: design and implement temperature chamber
- Subtask 4.2: realize wireless interrogation of antenna sensors without electronics
- Subtask 4.3: evaluate distributed wireless sensing at high temperatures

Deliverables

- Demonstrate wireless interrogation of passive antenna sensors
- Validate sensing capability of antenna sensors at high temp.

Subtask 4.1: Implement Temperature Chamber

- Model: Lindberg/Blue M BF51732PC
- Temperature range: 100-1200^{o}C
- Chamber dimension: 11 x 12 x 11 inches
- Vertical lift door
- A refractory brick wall will be constructed & placed in front of the lift door
- Metal casing may be removed

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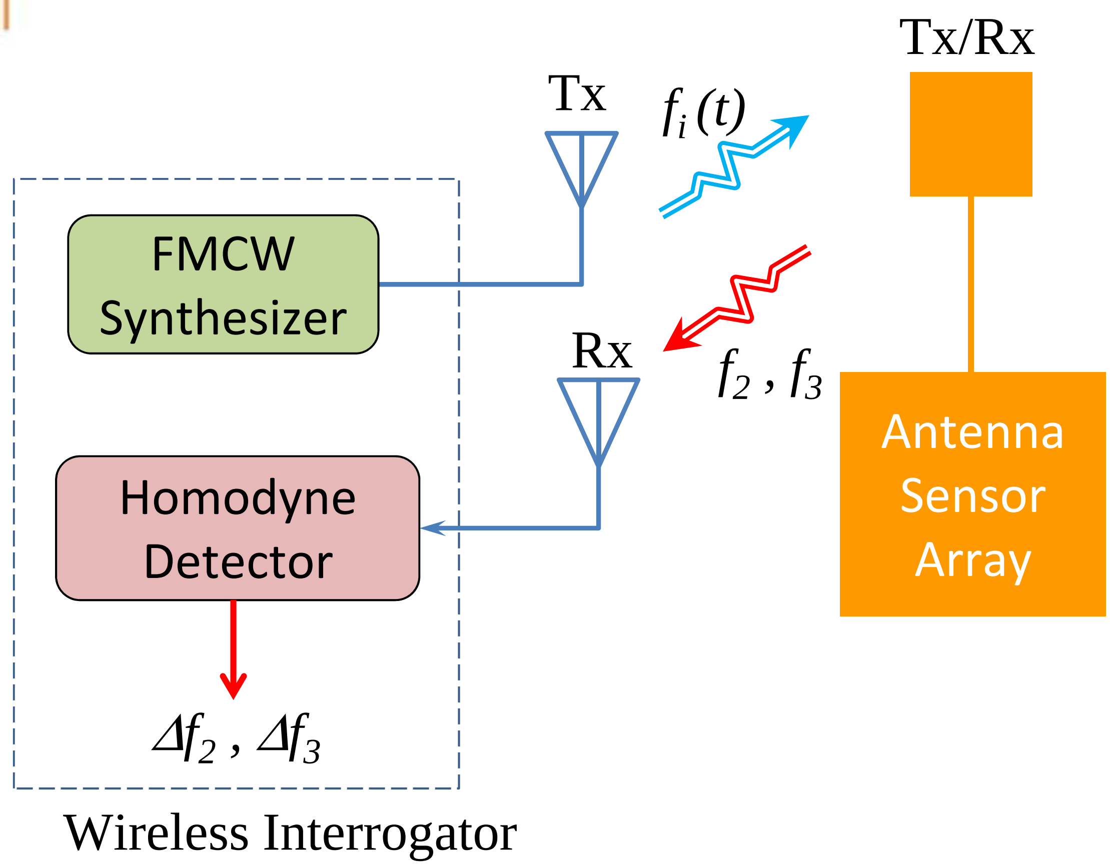
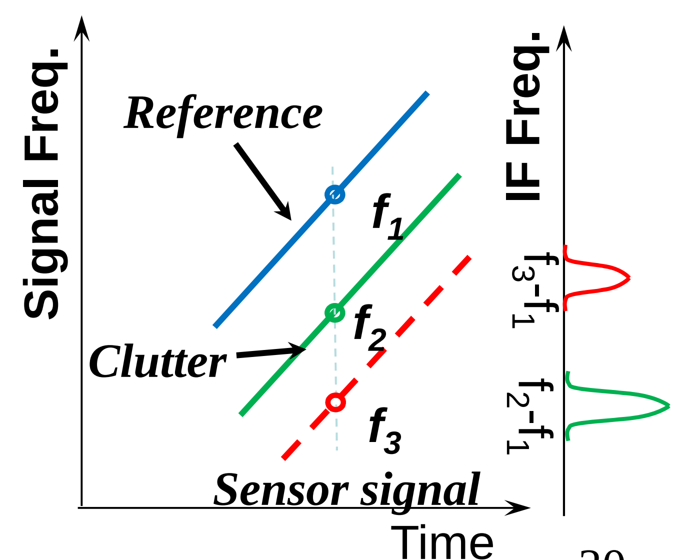
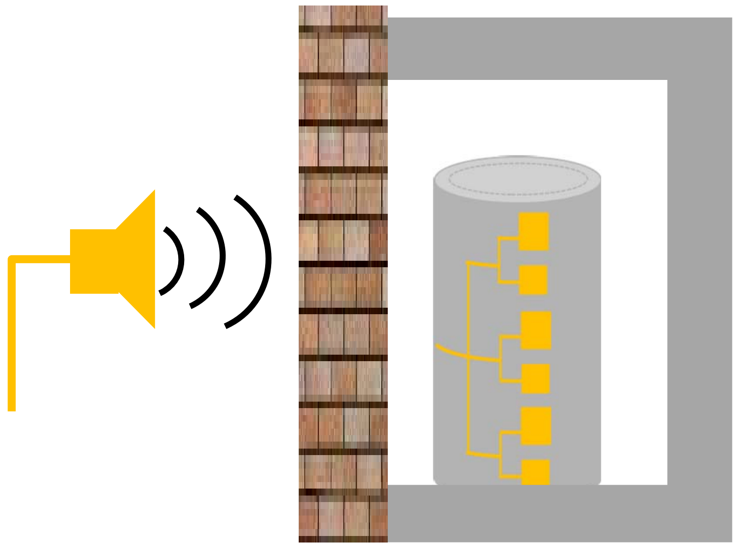
Subtask 4.2: Realize Wireless Interrogation



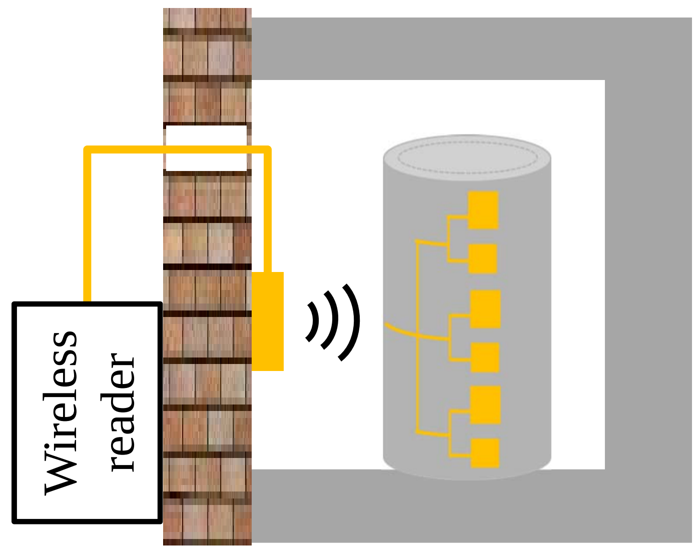
Δf_i are separated based on travel distance



Subtask 4.3: Evaluate Distributed Sensing



Temperature chamber



Temperature chamber

- Close pipes pressurized at different pressure level
- Local thinning of pipe wall to imitate corrosion
- Effects of soot & moisture on antenna sensor radiation
- Wireless interrogation outside & inside of refractive brick wall

Project Outcomes

- Methodology to realize low-cost antenna sensor arrays
  - Sustain high temperature and harsh environments
  - Cover a large area and conform to curved surfaces
  - Measure multiple physical parameters at multiple locations
- Wireless interrogation techniques without electronics
  - Capable of interrogating distributed antenna sensors
  - Reasonable interrogation distance, resolution, and speed
- Material and fabrication recipes and fabrication techniques
  - Robust against high temperature and harsh environment
  - Controllable dielectric properties
  - Flexible substrate

SOPO – Schedule

Tasks , subtasks & milestones	Start	End
T1 Project planning	1/1/15	2/16/15
• ST1.1 Kick-off meeting	1/1/15	1/15/15
• ST1.1 Revise PMP	1/15/15	2/15/15
✓MS-1 Revise PMP approved by DOE	2/17/15	2/17/15
T2 Realize flexible substrates	1/1/15	12/30/15
• ST2.1 Design high temp. materials	1/1/15	4/30/15
✓MS2 Document material recipe	4/30/15	4/30/15
• ST2.2 Synthesize flexible substrates	5/1/15	11/30/15
✓MS3 Demonstrate flexible substrates	11/30/15	11/30/15
• ST2.3 Characterize material prop.	11/1/15	8/31/16
✓MS4 Finalize material recipe	8/31/16	8/31/16
T3 Establish sensor design tools	1/1/15	12/31/16
• ST3.1 Establish simulation model	1/1/15	7/31/15
• ST3.2 Develop nonlinear regression	8/1/15	6/30/16
✓MS 5 Demonstrate algorithm for multi-modality sensing	6/30/16	6/30/16
• ST3.3 Perform parametric studies	4/1/16	6/30/16
• ST3.4 Design distributed sensors	7/1/16	12/30/16
✓MS6 Demonstrate distributed antenna sensor array	12/30/16	12/30/16
T4 Validate sensor performance	4/1/16	12/30/17
• ST4.1 Implement temp. chamber	4/1/16	9/30/16
✓MS7 Demonstrate temp. chamber	9/30/16	9/30/16
• ST4.2 Realize wireless interrogation of passive wireless antenna sensors	10/1/16	3/31/17
✓MS8 Demonstrate wireless interrogation of passive sensors	3/31/17	3/31/17
• ST4.3 Evaluate distributed wireless sensing at high temperatures	4/1/17	12/31/17
✓MS9 Validate sensor performance at high temperatures	12/31/17	12/31/17

SOPO – Milestones

2/17/2015: revised Project Management Plan approved by the DOE-NETL technical contact

4/30/2015: document material selection and synthesis recipe

11/30/2015: demonstrate fabrication of flexible dielectric substrates

8/31/2016: finalize material recipe

6/30/2016: demonstrate nonlinear regression algorithms

12/31/2016: demonstrate distributed antenna sensor array

9/30/2016: demonstrate temperature chamber

3/31/2017: demonstrate wireless interrogation of passive antenna sensors

12/31/17: validate sensor performance at high temperatures

SOPO – Budget

- **Total budget**: $399,311 ($314,371 UTA + $84,940 UCSD)
- Salary & F.B.: $149,254 (PIs, Post-doc, PhD & undergrad. student)
- Equipment: $5,611 for a furnace up to 1200^{o}C
- Travel: $14,988
- M&S: $14,988
- Subaward: $84,940
- Tuition: $21, 305
- Conference registration fee: $2,745
- Overhead: $106,214

Project Member	Year 1 (2015)	Year 2 (2016)	Year 3 (20177)
Haiying Huang	$98,031	$80,060	$82,642
Ankur Jain	$16,615	$19,040	$17,983
Jian Luo (UCSD)	$34,697	$28,117	$22,126

Project Status

- **Official starting date: 1/1/2015**

- Funding in place
- Students & post-doc recruited

- Kick-off meeting in progress

Question & Answers

Thanks for your attention!