Robust Metal-Ceramic Coaxial Cable Sensors for Distributed Temperature Monitoring in Fossil Energy Power Systems

Project #: DE-FE-0022993

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PRESENTATION OUTLINE

- **Introduction**
  - Challenge in in-situ, distributed HT measurement
- **Project Objective**
  - New MCCC-FPI sensor
- **MCCC-FPI Concept and Issues**
  - Proof of FPI concept (previous work)
  - Concept of this Work – MCCC
  - Hurdles to developing MCCC-FPI
- **Research Focus**
  - Material Development
  - Fabrication
  - Sensor test
- **Research Approach**
- **Tasks, Milestone, Timelines**
- **First Quarter Results**

INTRODUCTION

- **High temperature measurements in advanced fossil fuel power plants:**
  - Needs for real-time distributed temperature measurement for
    - Process control
    - Performance enhancement
    - Safety assurance (equipment, environment, and human)
  - Temperature sensors must
    - survive and function in corrosive gases (T ≥1000^{o}C and P >1000 Psi)
    - possess mechanical strength and small size for ease of installation with reliability,
    - have high sensitivity,
    - provide distributed sensing on single string covering large distance/area
    - be of low cost.
- **Current status**

1) Thermocouples（point measurement; intrusive to structure …)
2) Fiber optic sensors (can be distributed, e.g., Fiber Bragg gratings (FBGs) ; packaging difficulty, temperature limit <800^{o}C …)
3) Recently emerging coaxial cable Fabry-Perot Interferometric sensor (can be distributed; larger size and stronger to avoid bulky protection; problem is the unavailability of cable materials …)

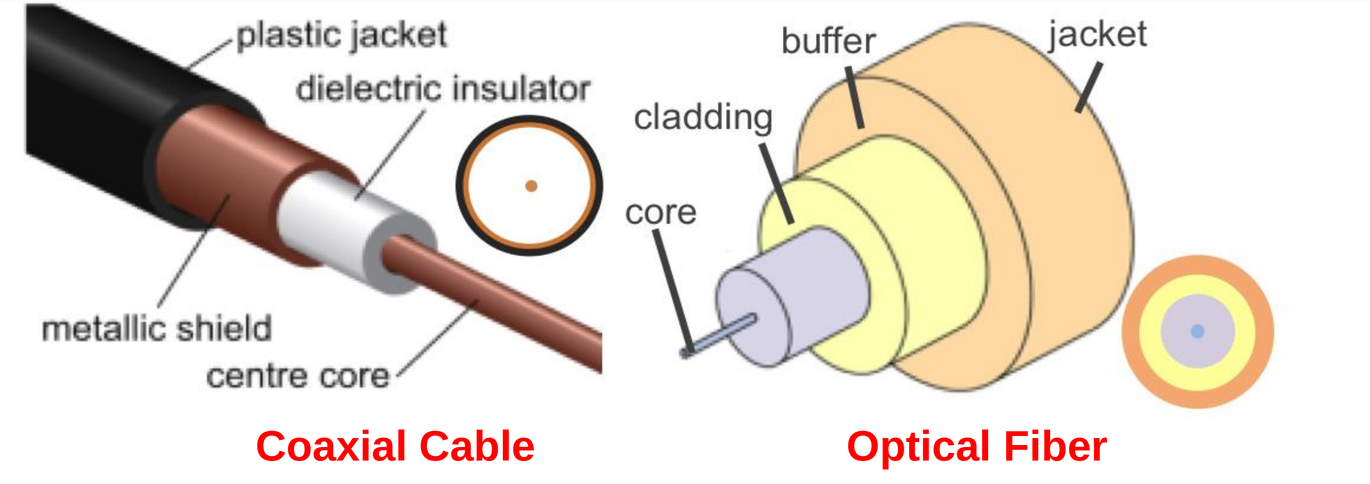
PROJECT OBJECTIVE

- **Project Goal:**
  - To *develop materials* for a new type of low cost, robust, (minimum packaging/ protection) metal-ceramic coaxial cable (MCCC) Fabry-Perot interferometer (FPI) sensor and demonstrate its capability of cascading a series of FPIs in a single MCCC for real-time distributed monitoring of temperature up to 1000^{o}C.
- **Technical Objectives:**
  1) to identify and optimize sensor materials with desired electrical and dielectric properties as well as thermochemical and structural stability,
  2) to construct the MCCC-FPI sensor and test the sensor stability in high temperature gases relevant to fossil energy power system,
  3) to develop the instrumentation for signal processing and algorithmic for operating the sensor and distributed sensing systems, and
  4) to demonstrate the MCCC-FPI sensor for real-time distributed temperature measurement and evaluate its performance in terms of sensitivity, spatial resolution, stability, and response speed that are important to practical applications.

CONCEPT AND CHALLENGE

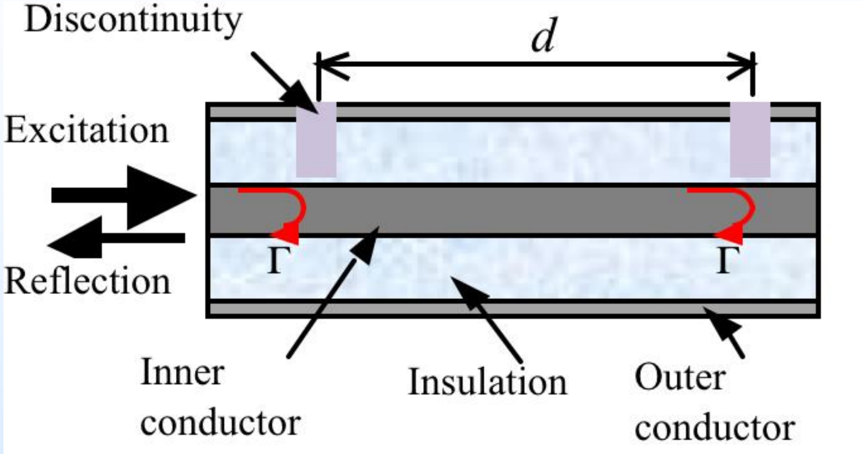
- **MCCC-FPI MW sensors**
- **Technical Issues – Material Unavailability**

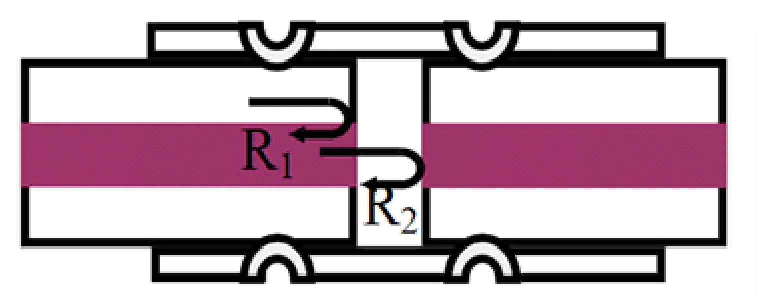
Optical Fiber vs. Coaxial Cable Communication – EM Wave Transmission



- **Both for EM transmission/communication**
- **Structural similarity**
- **Same governing theory (physics)**
- **Different frequency ranges of carried EM**
- **Both waveguides are useful for constructing sensors**
- **Readiness for instrumentation for sensor system**

Coaxial Cable Fabry-Perot Interferometric (CC-FPI) Sensor





Fiber Optical Interferometer

- **Principle of the CC-FPI sensor operation**
  - **Device:** RF interferometer analog to fiber optic interferometer
  - **Mechanism:** interference generated by reflectance from reflectors (ε disturbance)
  - **Detection:** Shift of interferogram

CC-FPI Temperature Sensing Mechanism

- Two reflected waves (*U1* and *U2*)

$$U_1 = \Gamma(f)e^{-\alpha z}\cos(2\pi ft) \quad \text{and} \qquad U_2 = \Gamma(f)e^{-\alpha z}\cos\left[2\pi f(t+\tau)\right]$$

$$\textit{where} \qquad \tau = 2d\sqrt{\varepsilon_r}/c$$

- Interference signal (*U*) – summation of the two reflected waves

$$U = 2\cdot\Gamma(f)e^{-\alpha z}\cos\left(2\pi f\,\frac{2d\sqrt{\varepsilon_r}}{c}\right)\cos\left[2\pi f\left(t+\frac{2d\sqrt{\varepsilon_r}}{c}\right)\right]$$

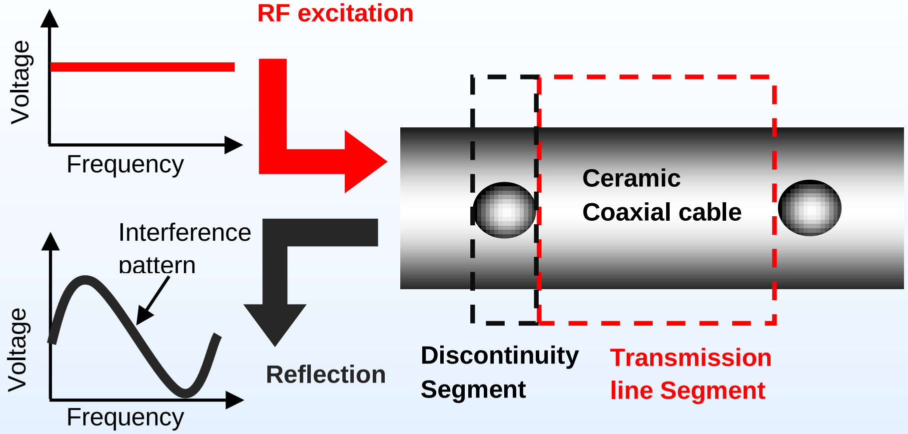
- CC-FPI Structural parameter (*d*) and (insulator) material property (ε_r) are temperature dependent

$$d_T = d_0 + b_T(T-T_0) \qquad \varepsilon_{r,T} = \sum_{i=0}^{n}(a_i \times T^i)$$

- U(T) is thus a function of temperature - *real-time temperature measurement by monitoring the interferometric spectrum shift, U(T)*

$$U(T) = K_1\cos(K_2\cdot\tau(T))\cdot\cos[K_2(t+\tau(T))] \qquad \tau(T) = 2d_T\cdot\varepsilon_{r,T}^{0.5}/c$$

CC-FPI Signal – Transmission or Reflection



RF excitation

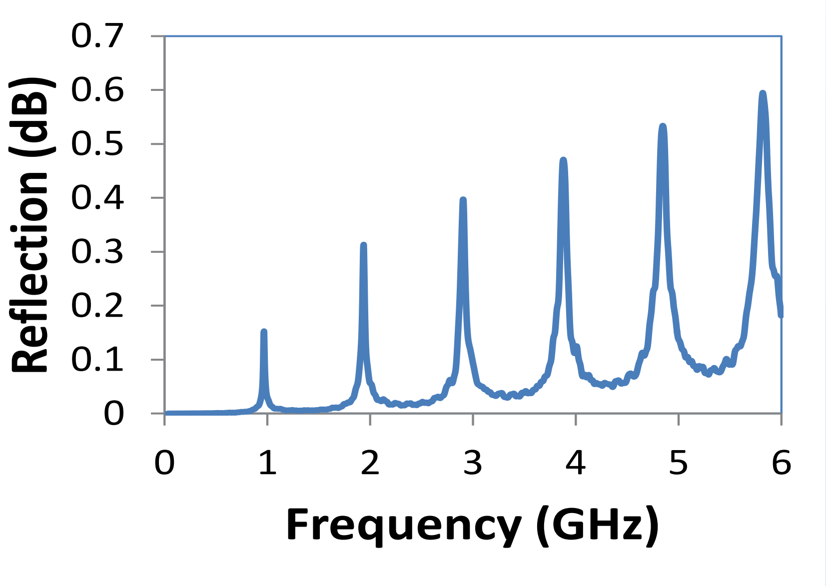
Interference pattern

Reflection

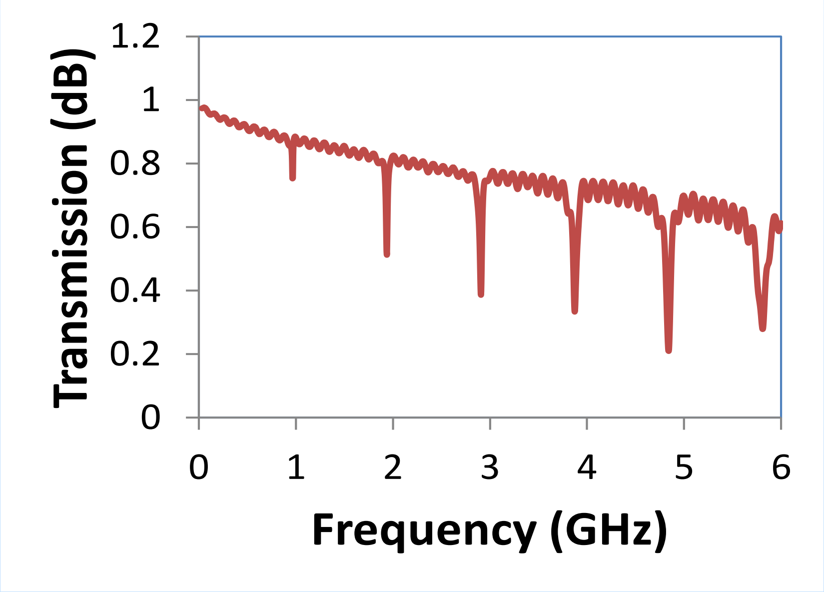
Ceramic Coaxial cable

Discontinuity Segment

Transmission line Segment



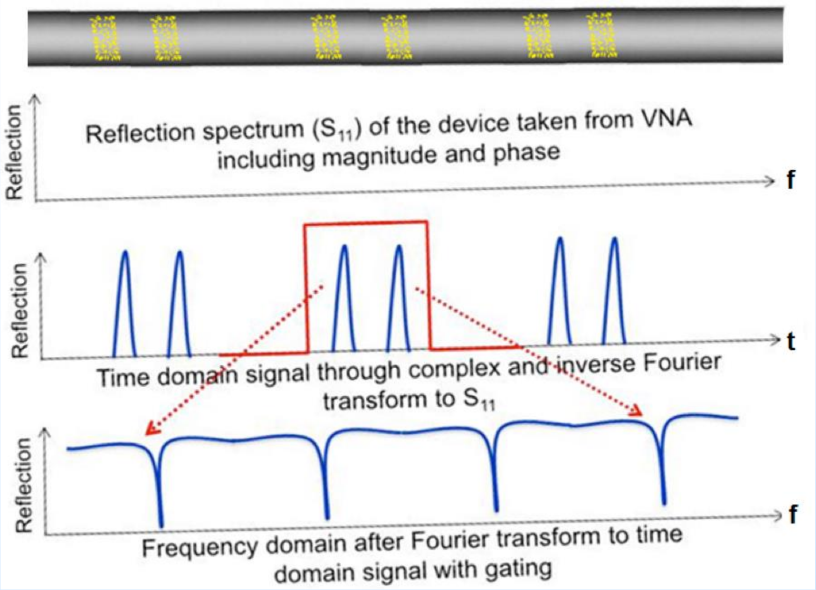
Reflection spectrum of CC-IFPI



Transmission spectrum of CC-IFPI

Multiple CC-FPI Sensors for Distributed Temperature Measurement

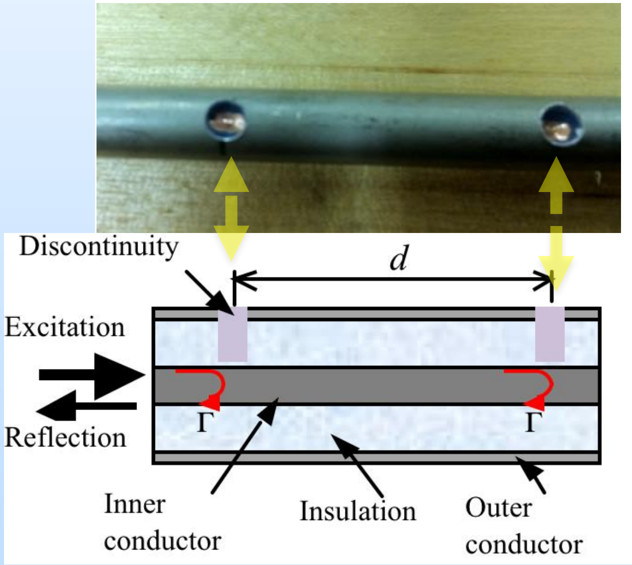
- Distributed CC-FPI sensor – multiple FPI along a single ceramic coaxial cable
- The reflectors of weak reflections and low insertion loss enable long distance coverage (2nd reflections are negligible)
- Individual sensor location by extracting and analyzing the spectrum of a specific discrete FPI - *achieved by a novel joint time-frequency domain measurement technique (Xiao et al., 2013/CU)*
- The reflected EM waves detected by a VNA for resolving amplitude and phase of each reflected signal
- Initial calculation showed that the total length of the distributed CC-FPI sensor can be over 80 meters
- *Goal:* accuracy ±2°C in a range of 350 – 1000°C and spatial resolution <10 cm

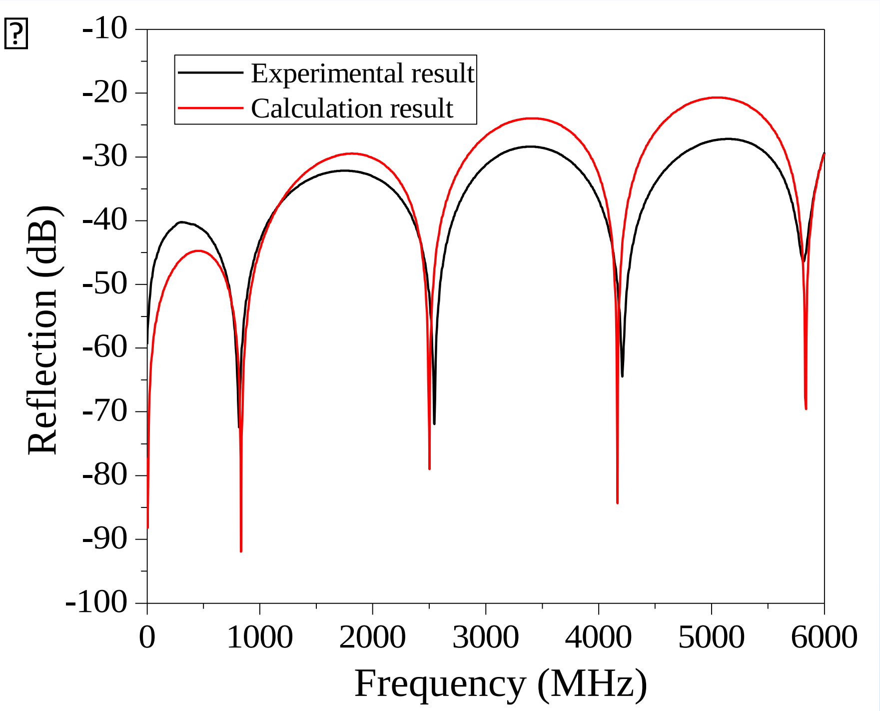


Joint-time-frequency domain interrogation of multi-point FPI in a single cable for distributed sensing with high spatial resolution

Previous Work
Proof of CC-FPI Functionality

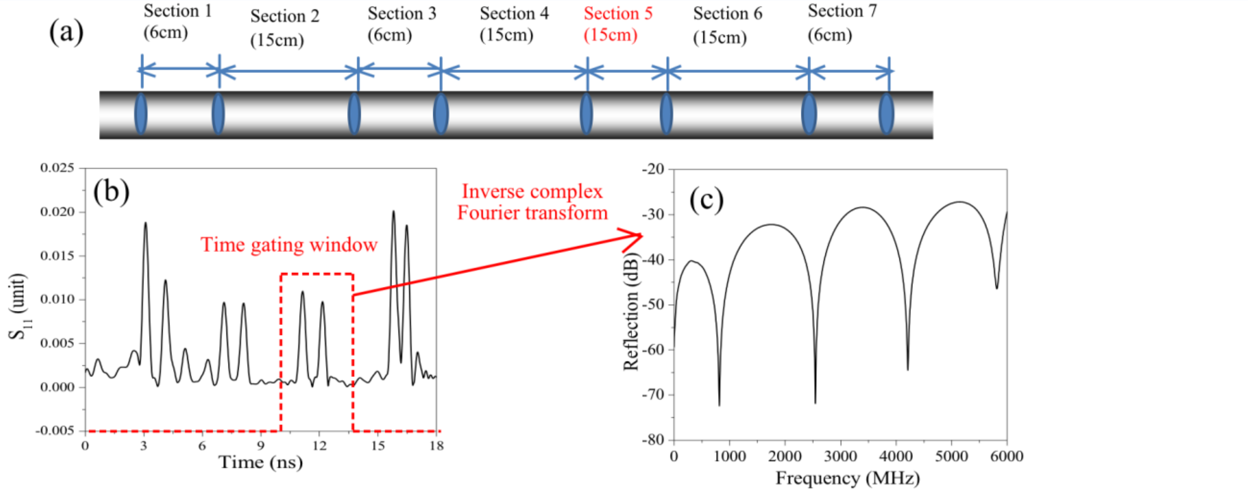
CC-FPI by hole drilling

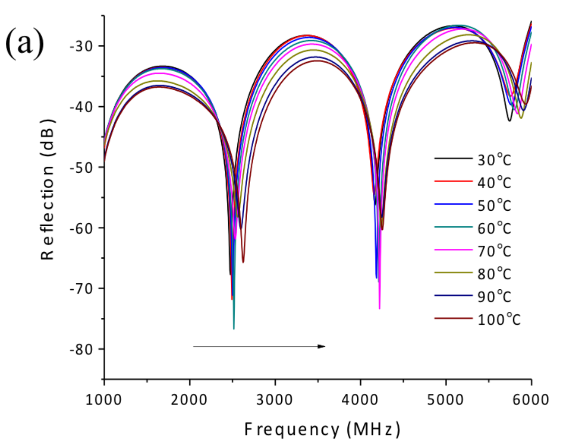


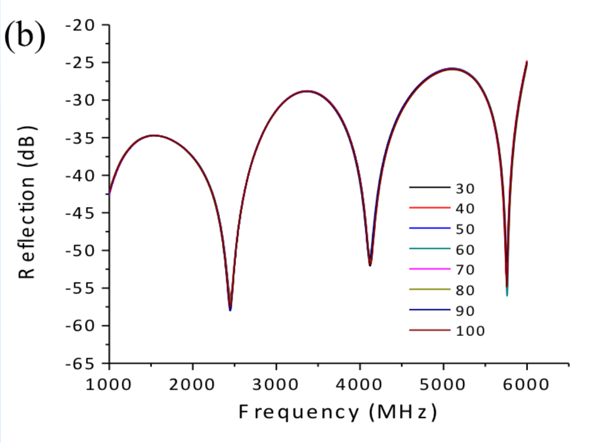


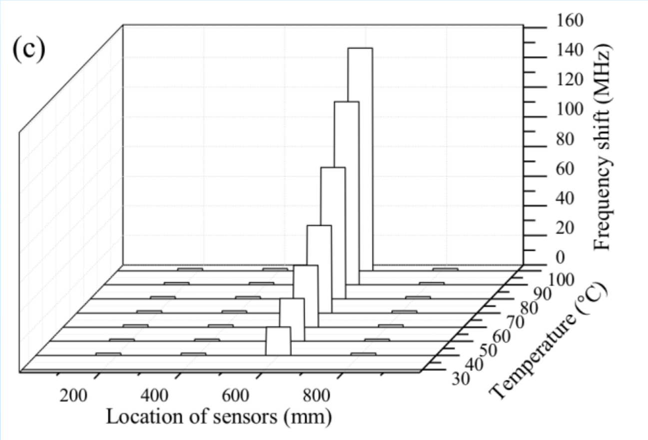
Previous Work – Multi-Point FPI

Multi-Point CC-FPI sensor for distributed measurement





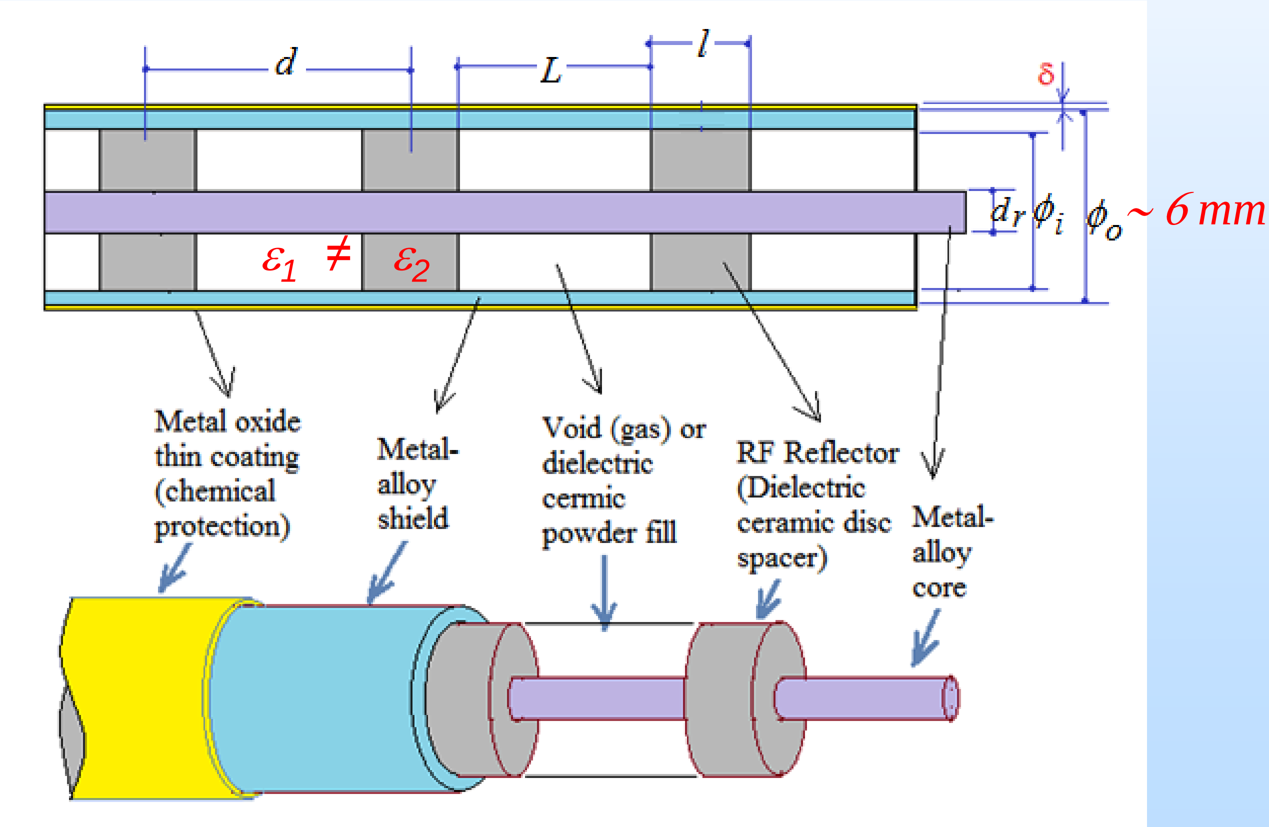




Concept of This Work – The Use of Metal-Ceramic Materials for CC-FPI (MCCC-FPI) Sensors

MCCC-FPI distributed sensors:

1. *Metal conductors (tube & wire) with ceramic (or air) insulation (or reflectors)*
2. *Eliminate bulky and expensive protective packaging*
3. *Withstand highly turbulent flows and particulate impact*
4. *Minimize destruction to the equipment for installation and maintenance*



Key Issues for Realization of the MCCC-FPI Sensors

MCCC materials for the proposed high-temperature FPI sensors are currently nonexistent.

1. *Commercial communication CC with metal (conductors) and polymer insulators are not for high temperature applications*
2. *Limited metal-ceramic CC are for high temperature RF communication and not suitable for MCCC-FPI construction*
3. *Fabrication method and FPI structure currently employed by the PIs (e.g. drilling holes through insulation) are not suitable for in-situ applications in fossil* energy system
4. Structural parameters (i.e. element dimensions) and insulator/reflector ε_r-contrast need to be optimized based on fundamental studies
5. Structural and material property stabilities in harsh conditions and impact on sensor performance (e.g. conductor surface oxidation and protection, microstructure evolution by thermal cycle and annealing, etc.)
6. Flexibility for installation and operation

Primary Research Focus

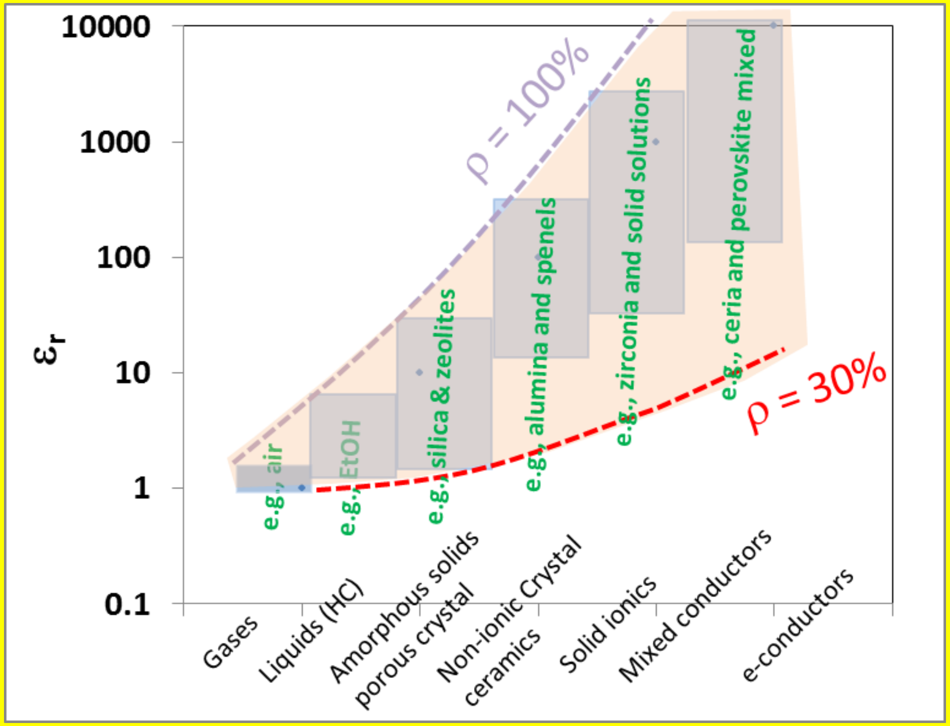
1. ***Developing MCCC Materials***
2. ***Fabricating MCCC-FPI Sensors***
3. ***Demonstrating Temperature Measurements up to 1000°C***

Ample Opportunity for MCCC Material Development

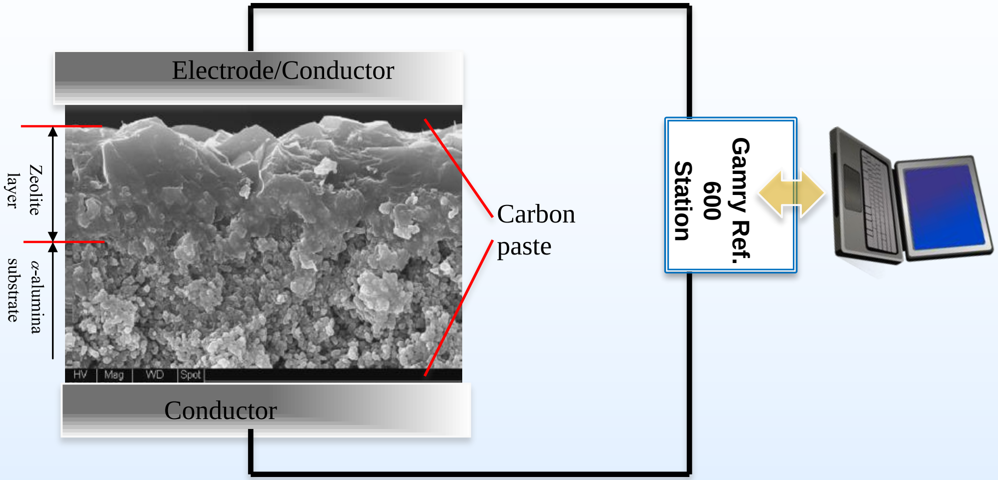
1. ***Metal and metal alloy conductors***
   - *Surface modification (tuning surface conductivity for HT applications)*
   - *Surface protection (e.g., N_2-filled for oxidation prevention)*
   - *Outer surface (contacting fossil gas) protection by ceramic thin films*
2. ***Ceramics for insulators and reflectors***
   - *The ε_r-contrast and signal strength*
   - *Thermal stability (structure & chemical)*
     - *Phase and microstructure*
   - *Compatibility*
     - *Conductor/insulator*
     - *Insulator/reflector*
3. ***Flexibility - insulator***
   - *Rigid tubes*
   - *Powdery pack*

Hetero-phase (or porous) materials with micron-level homogeneity (particles large enough to avoid sintering at < 1000°C – dp >2 μm), e.g., effective ε_r (porous):

$$\varepsilon_{r,eff} = \varepsilon_{air}\frac{\varepsilon^2+4\varepsilon+4+2x_f\varepsilon^2+2x_f\varepsilon-4x_f+9x_f^2\varepsilon(\varepsilon-1)}{\varepsilon^2+4\varepsilon+4-x_f\varepsilon^2-x_f\varepsilon+2x_f+9x_f^2(\varepsilon-1)}, \quad \varepsilon=\frac{\varepsilon_c}{\varepsilon_{air}}$$

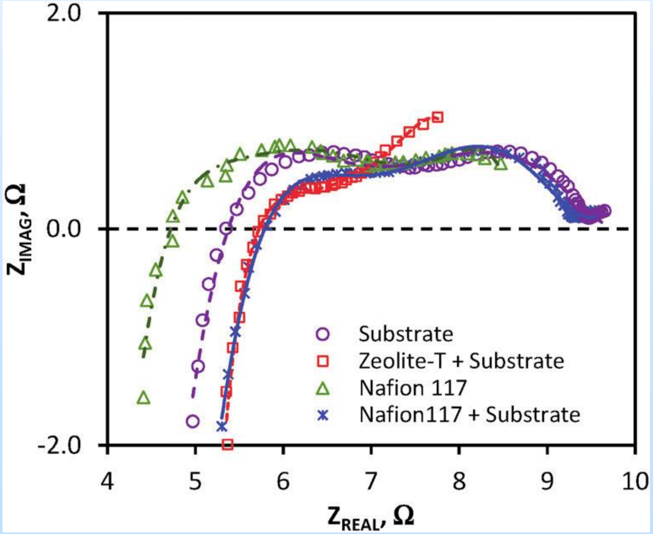


Dielectric Constant Measurement



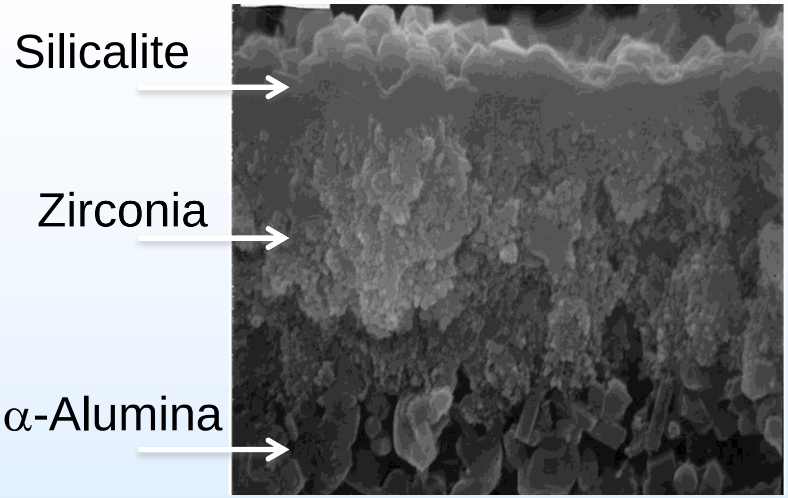
Using ceramic discs of selected materials

- *Impedance analysis*
- *Equivalent circuit modeling for dielectric constant determination*
- *Temperature dependence of ε_r*



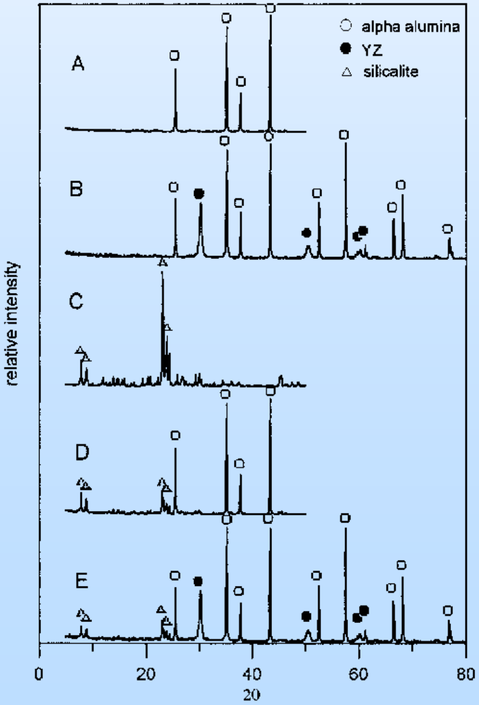
Dong & coworkers, Chem Commn. 50 (2014) 2416.

Thermal Structural & Chemical Stability Study

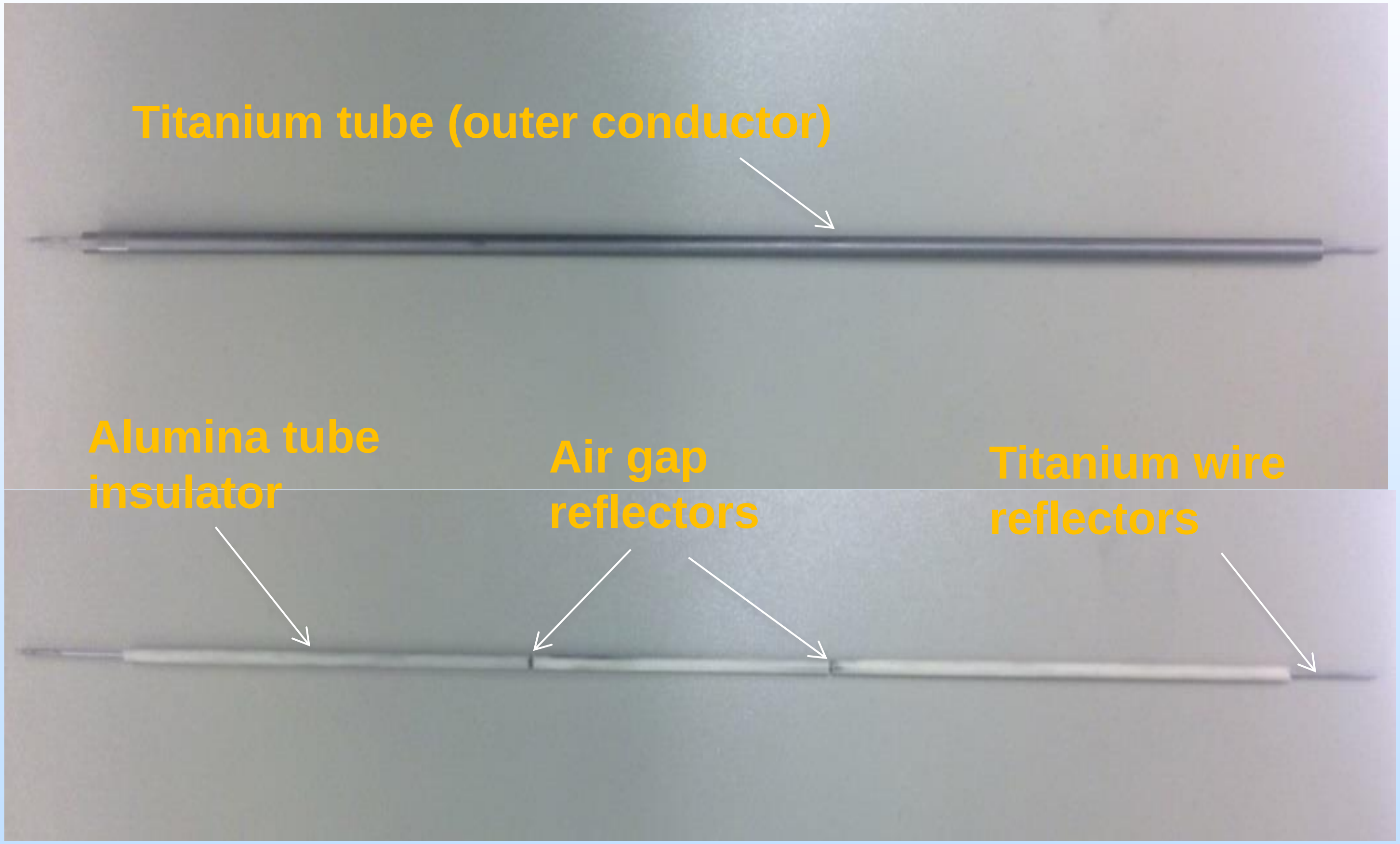


1. ***Multilayer coatings***
   - *Microstructure stability*
   - *Grain growth/sintering temperature*

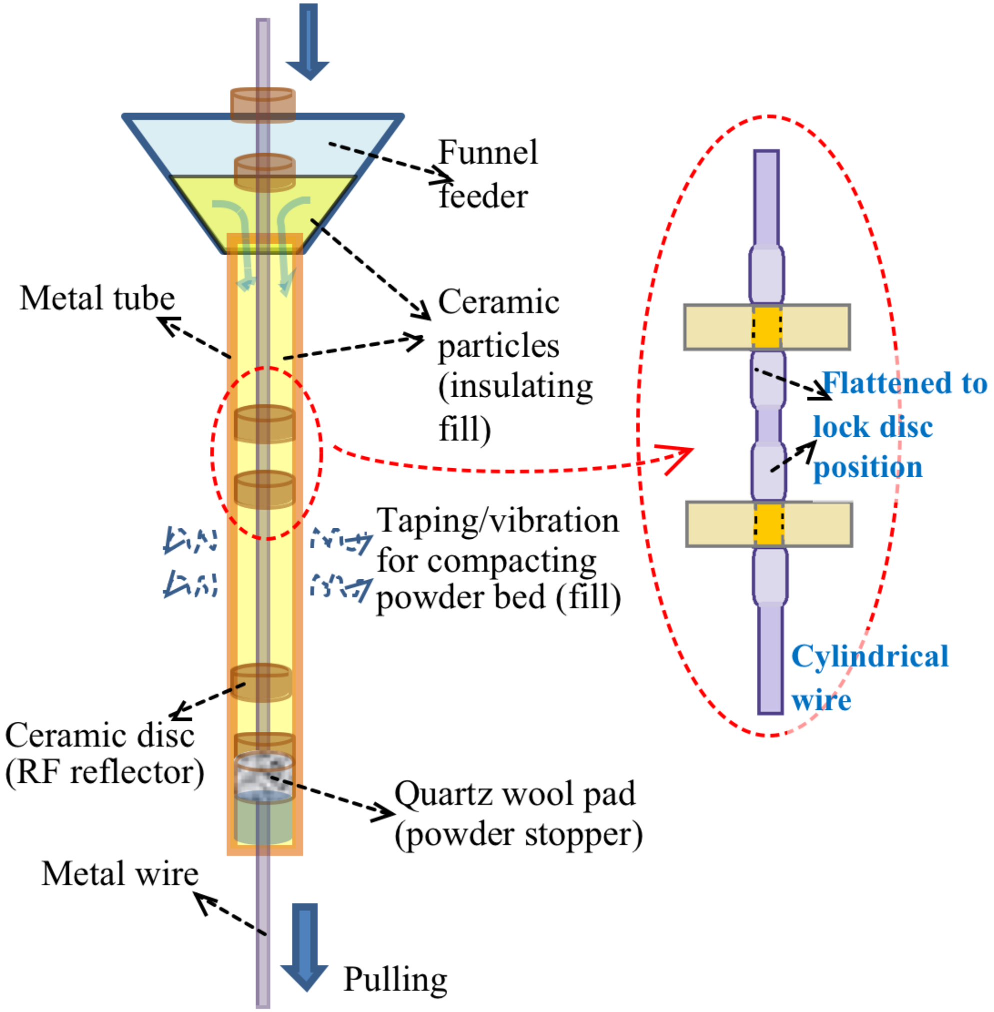
2. ***High Temperature phase & chemical Stability***
   - *New phase formation (XRD)*
   - *Solid state ion diffusion (EDS)*



Tubular Insulator (Rigid)



Packed Powder Insulators (Flexible)

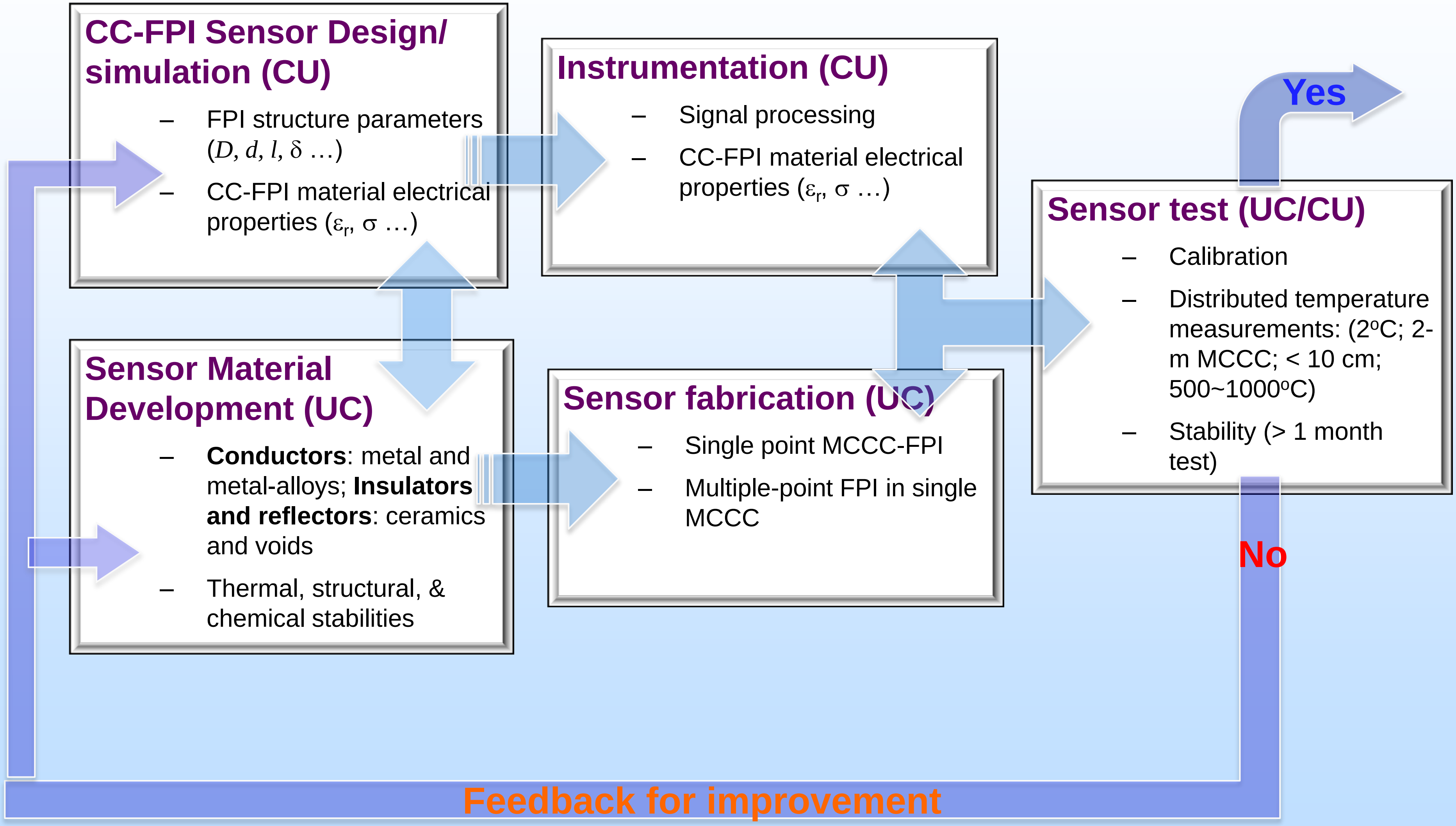


1) *The inner conductor (metal wire core) with ceramic discs (RF reflectors)*

2) *Vacuum-vibration filling of insulation*

3) *Stabilization of MCCC structure and properties by thermal shock (e.g., ~ 1250^{o}C) followed by annealing (max. appl. T ~ 1000^{o}C)*

Research Approach



CC-FPI Sensor Design/ simulation (CU)

- FPI structure parameters (D, d, l, δ …)
- CC-FPI material electrical properties (ε_r, σ …)

Instrumentation (CU)

- Signal processing
- CC-FPI material electrical properties (ε_r, σ …)

Sensor Material Development (UC)

- **Conductors**: metal and metal-alloys; **Insulators and reflectors**: ceramics and voids
- Thermal, structural, & chemical stabilities

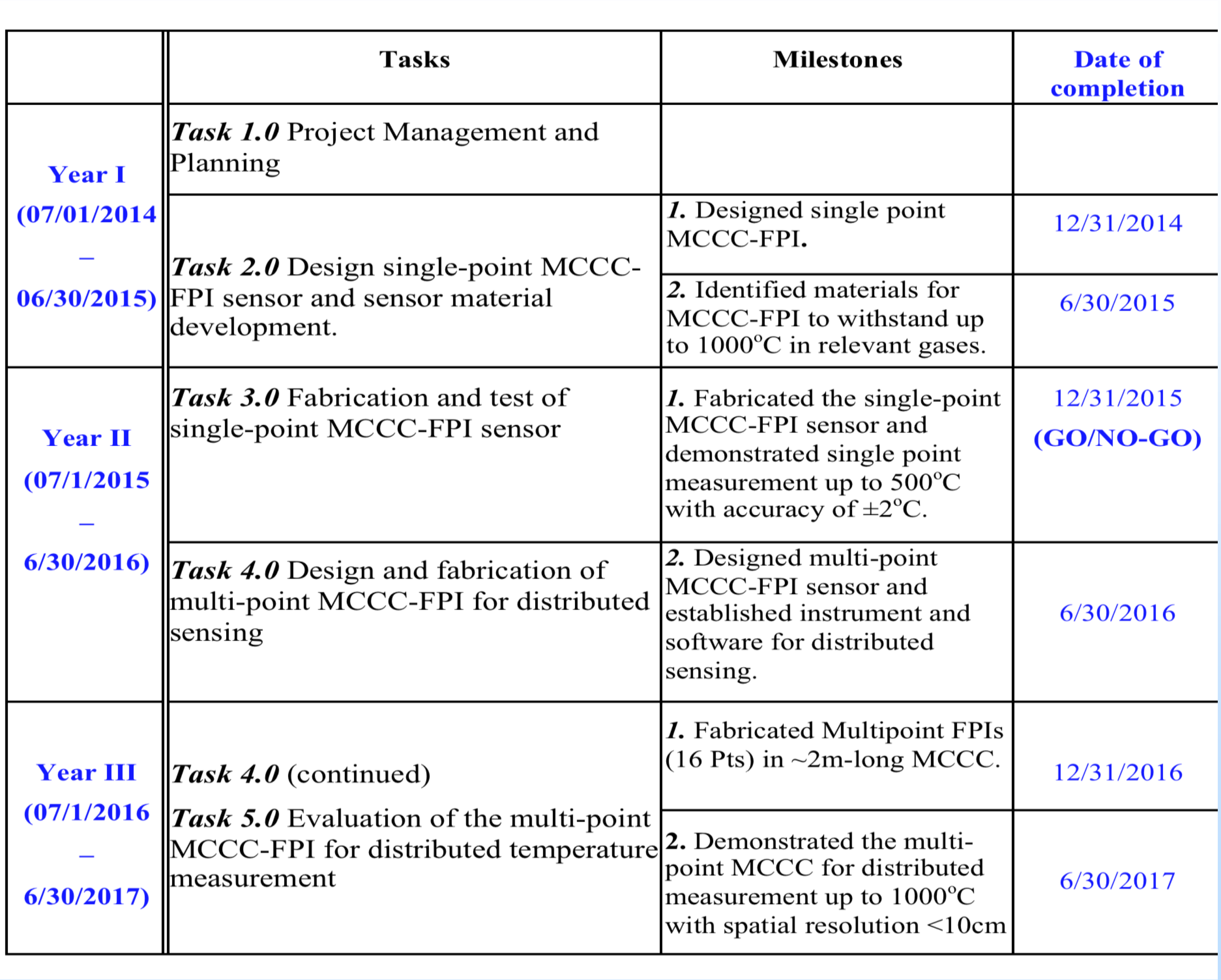
Sensor fabrication (UC)

- Single point MCCC-FPI
- Multiple-point FPI in single MCCC

Sensor test (UC/CU)

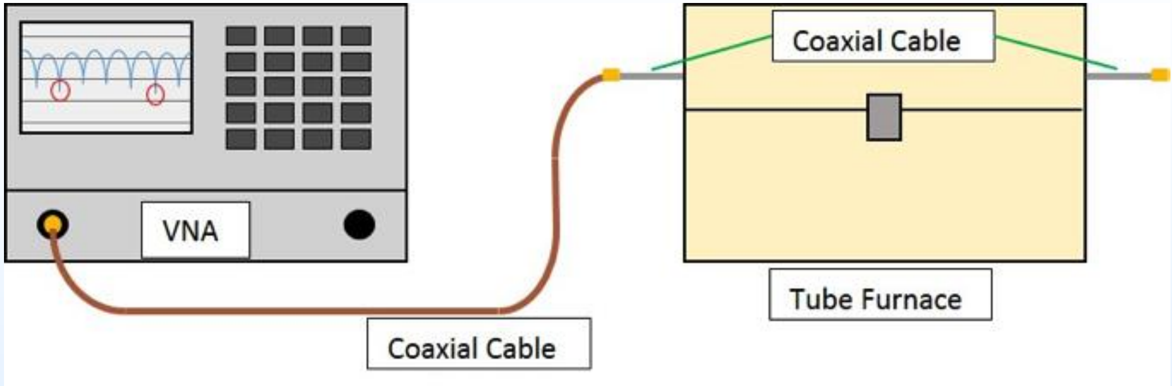
- Calibration
- Distributed temperature measurements: (2°C; 2-m MCCC; < 10 cm; 500~1000°C)
- Stability (> 1 month test)

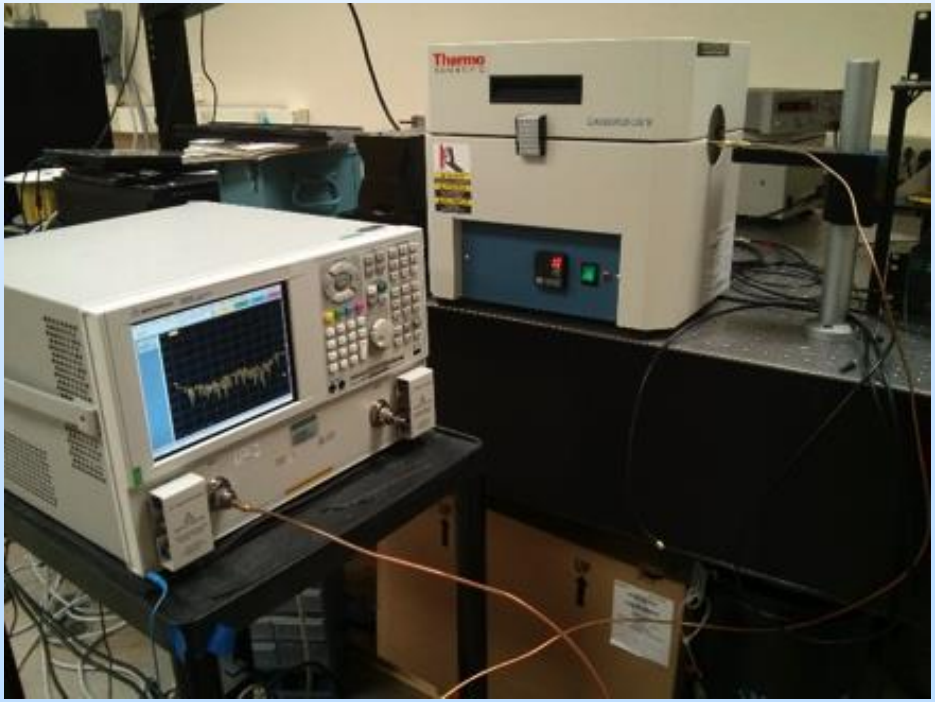
Task, Milestone, and Timeline



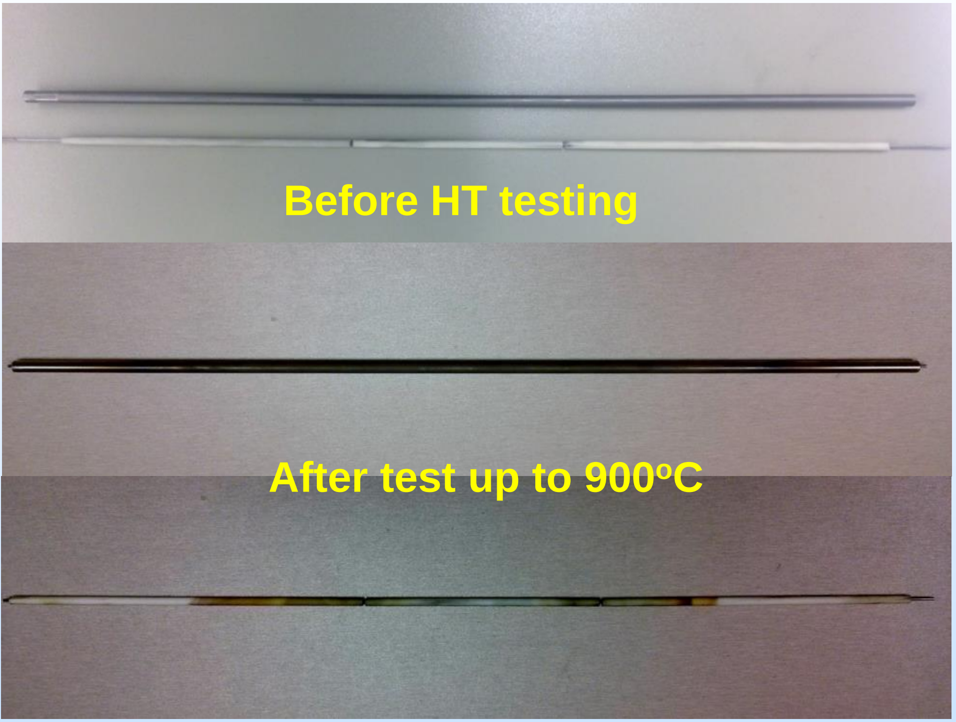
	Tasks	Milestones	Date of completion
Year I (07/01/2014 – 06/30/2015)	***Task 1.0*** Project Management and Planning		
	Task 2.0 Design single-point MCCC-FPI sensor and sensor material development.	***1.*** Designed single point MCCC-FPI.	12/31/2014
		2. Identified materials for MCCC-FPI to withstand up to 1000°C in relevant gases.	6/30/2015
Year II (07/1/2015 – 6/30/2016)	***Task 3.0*** Fabrication and test of single-point MCCC-FPI sensor	***1.*** Fabricated the single-point MCCC-FPI sensor and demonstrated single point measurement up to 500°C with accuracy of ±2°C.	12/31/2015 **(GO/NO-GO)**
	Task 4.0 Design and fabrication of multi-point MCCC-FPI for distributed sensing	***2.*** Designed multi-point MCCC-FPI sensor and established instrument and software for distributed sensing.	6/30/2016
Year III (07/1/2016 – 6/30/2017)	***Task 4.0*** (continued) ***Task 5.0*** Evaluation of the multi-point MCCC-FPI for distributed temperature measurement	***1.*** Fabricated Multipoint FPIs (16 Pts) in ~2m-long MCCC.	12/31/2016
		2. Demonstrated the multi-point MCCC for distributed measurement up to 1000°C with spatial resolution <10cm	6/30/2017

First Quarter Results:
MCCC-FPI Test Apparatus



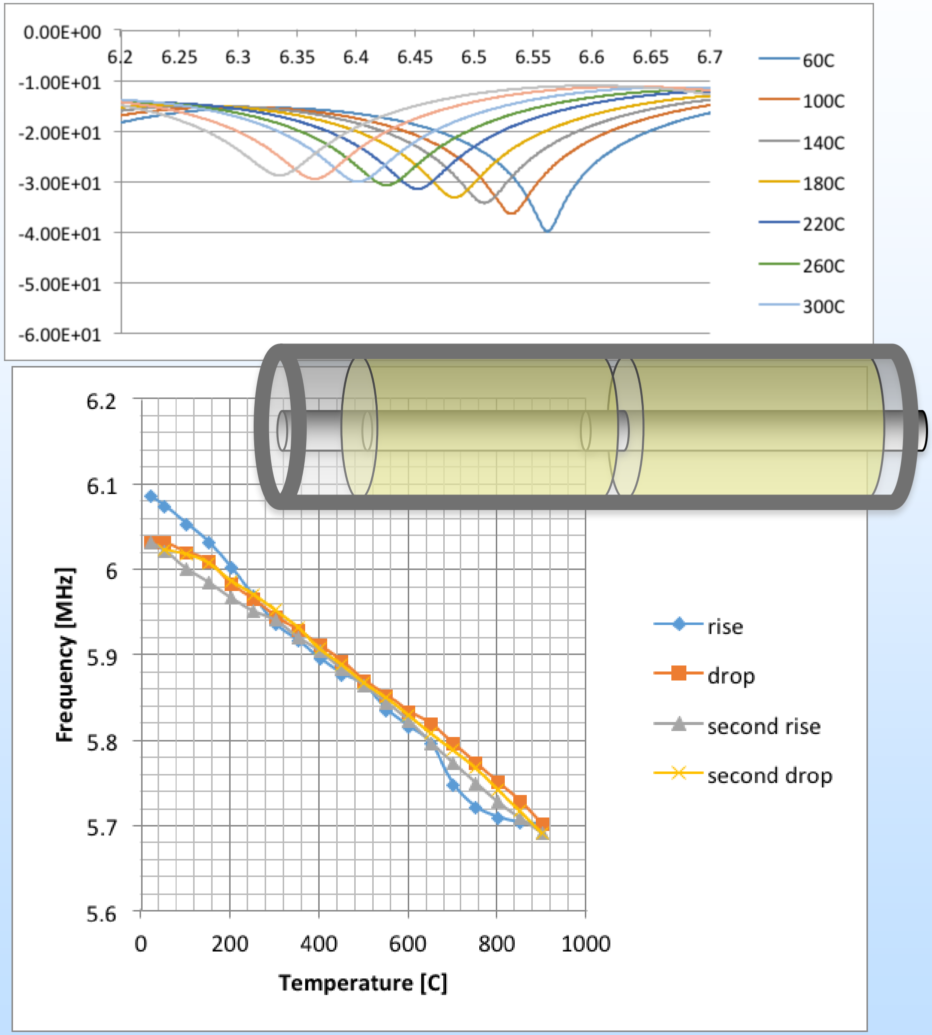


First Quarter Results:
Single Point MCCC-FPI



Before HT testing

After test up to 900°C

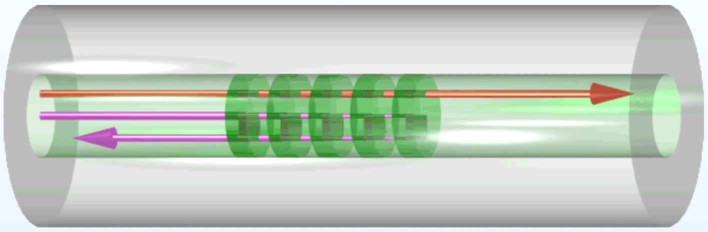


Single point CC-FPI: stainless steel conductors (tube and wire), alumina insulator, and air gap (~1 mm) reflectors.

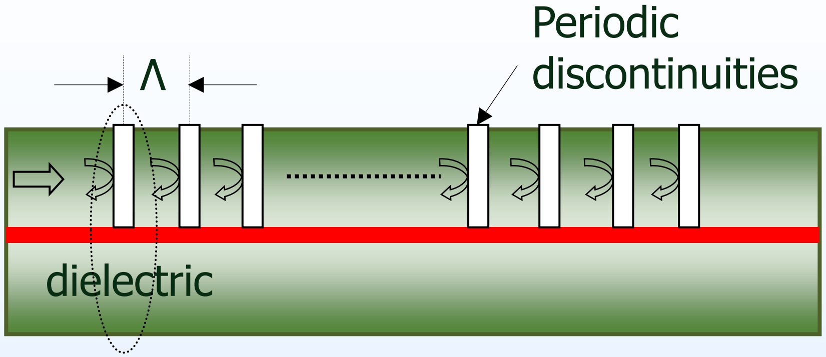
Q & A

THANK YOU

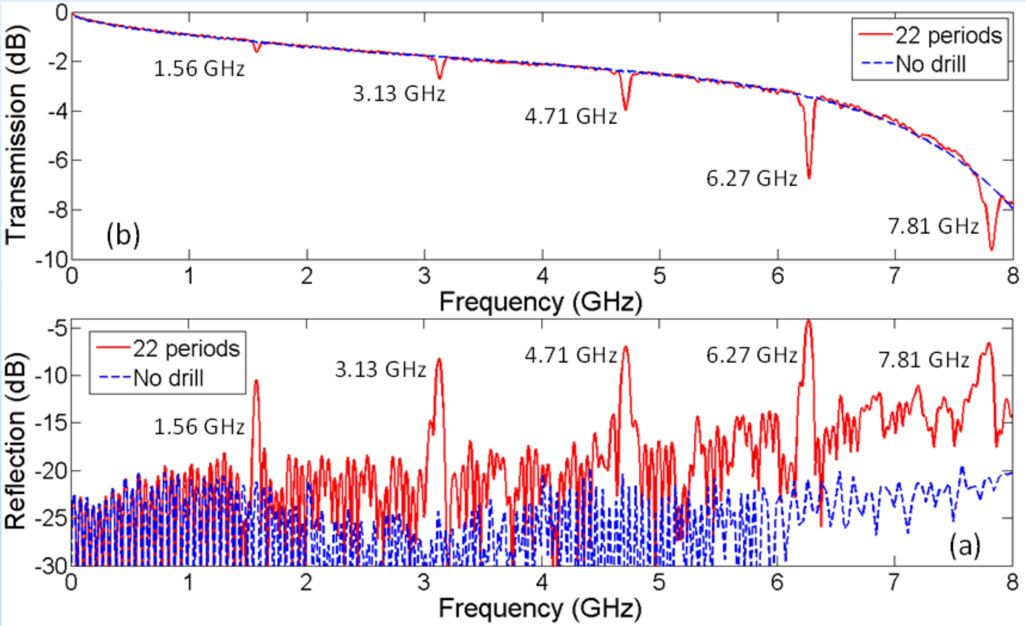
Coaxial Cable Bragg Grating

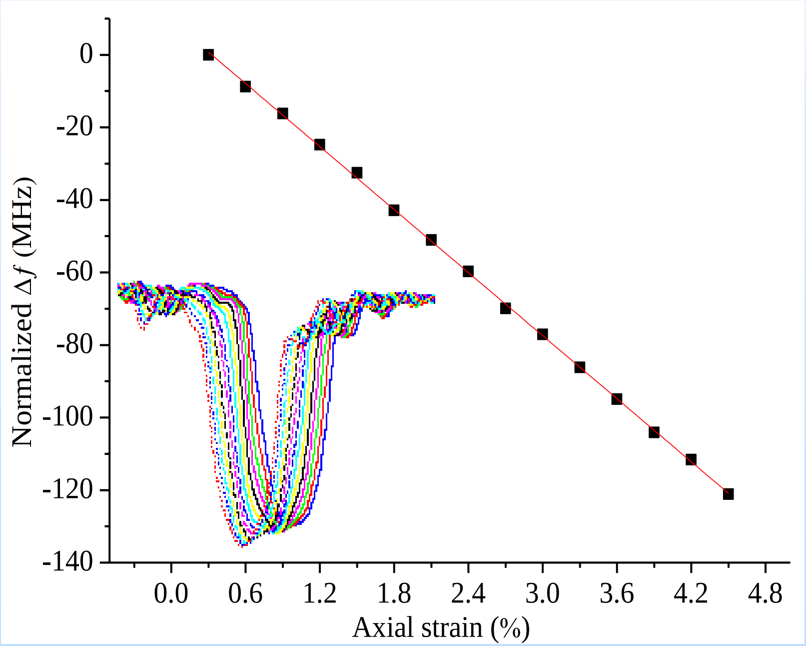


Fiber Bragg grating (FBG)



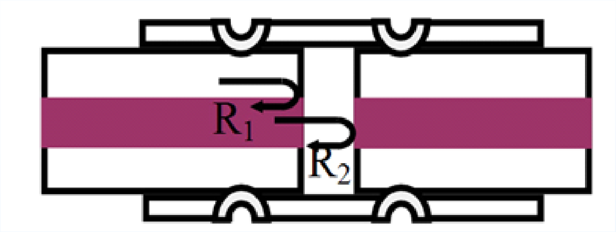
Coaxial cable Bragg grating



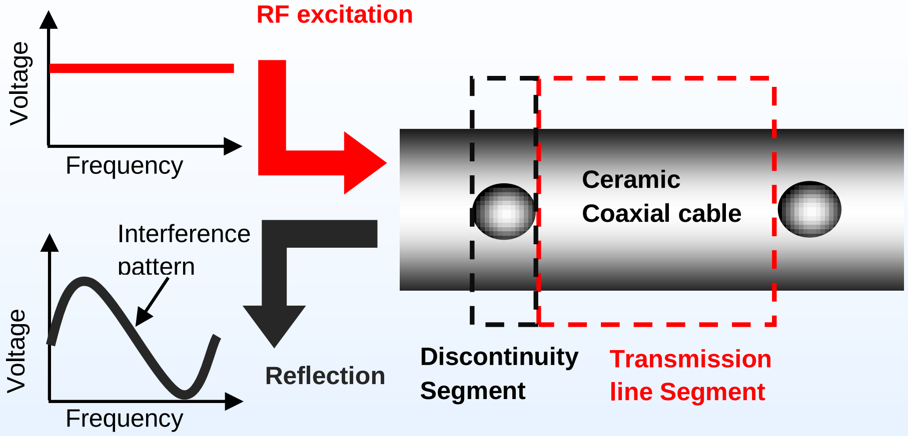


T. Wei et al., *Applied Physics Letters*, 2011

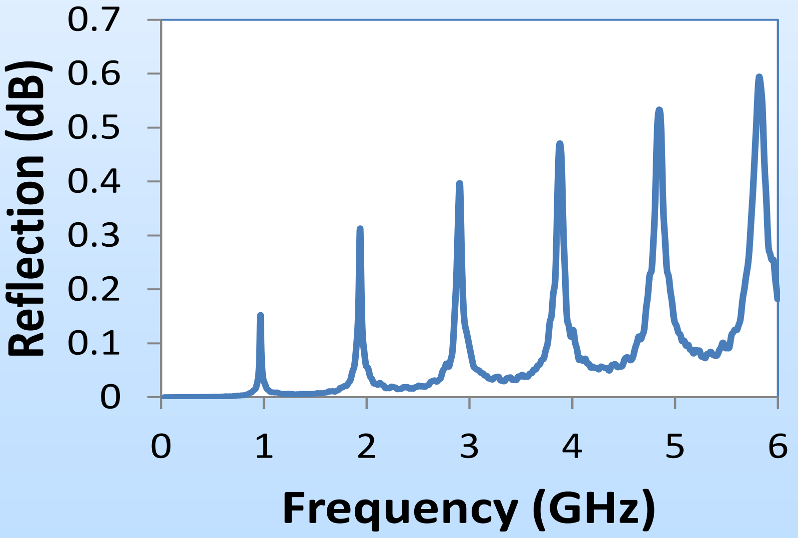
Coaxial Cable F-P Interferometer



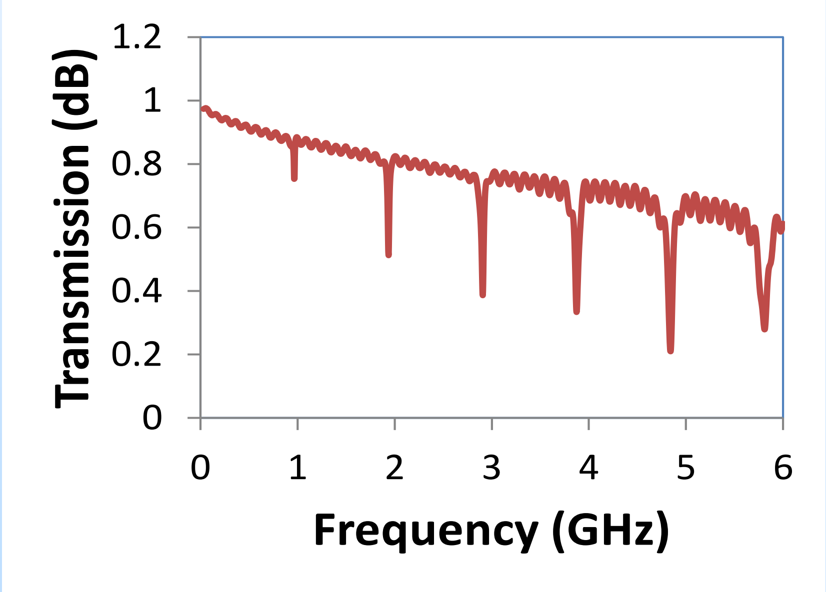
Fiber optic Fabry-Perot Interferometer



Coaxial cable Fabry-Perot Interferometer

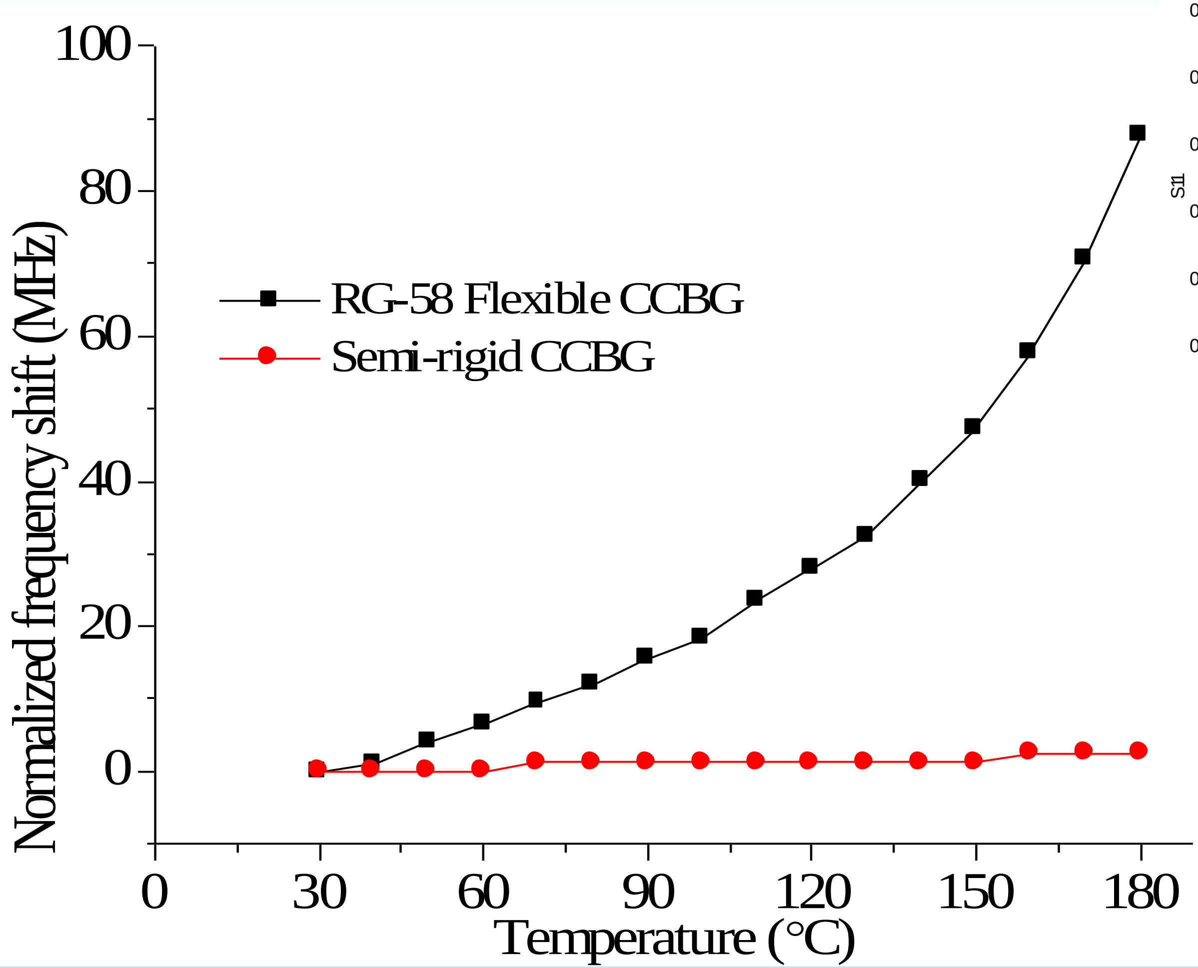


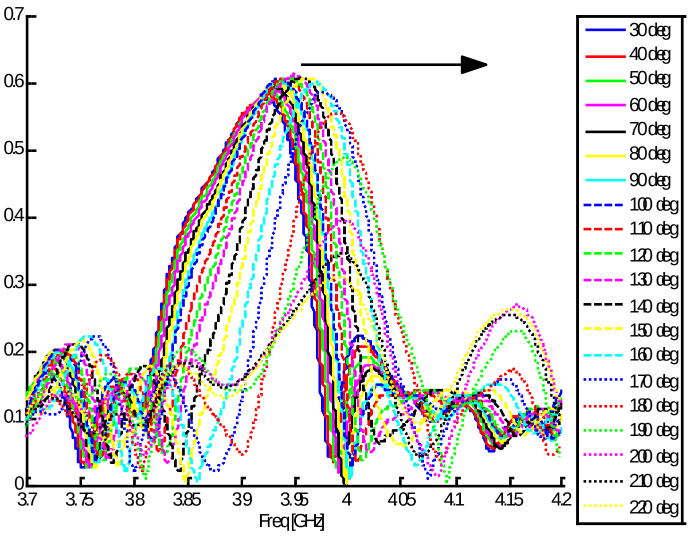
Reflection spectrum of CC-IFPI



Transmission spectrum of CC-IFPI

Temperature Measurement

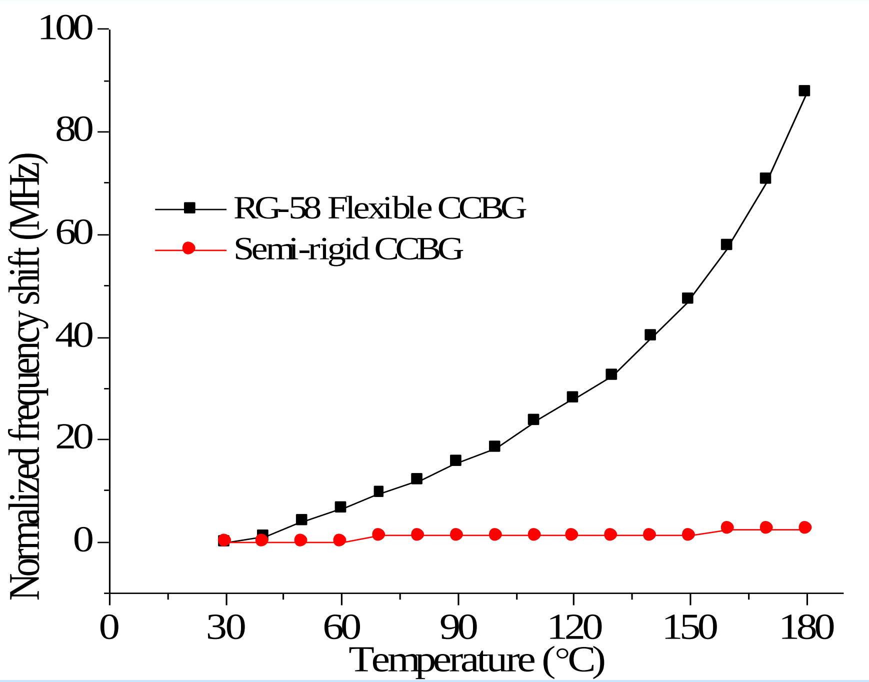




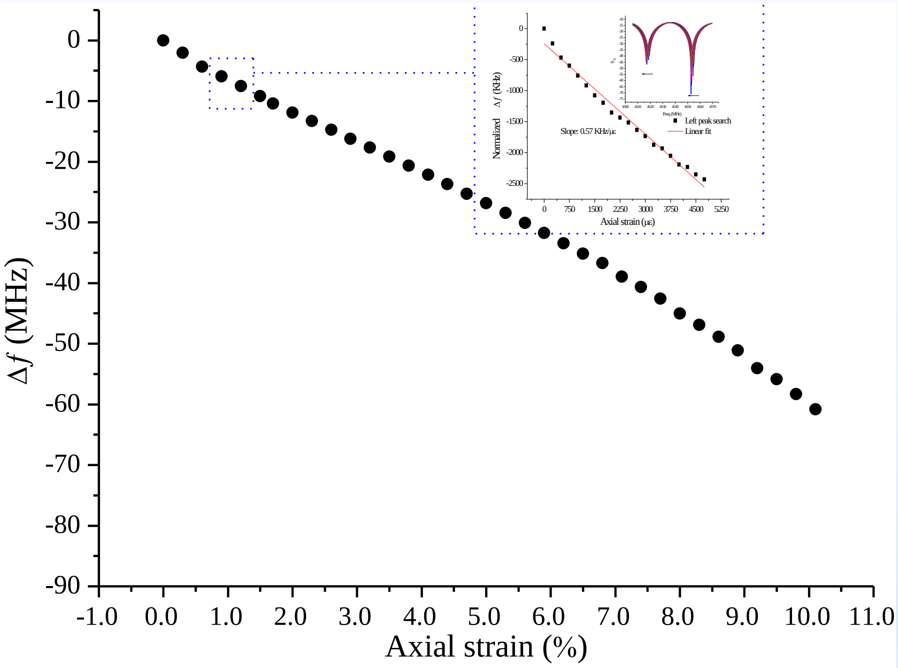
- ✓ CCBGs made of different cables have dramatically different temperature sensitivity.
- ✓ Cables with different temperature sensitivities can be used for temperature compensation.

Temp. and Strain Measurement

Temperature Responses

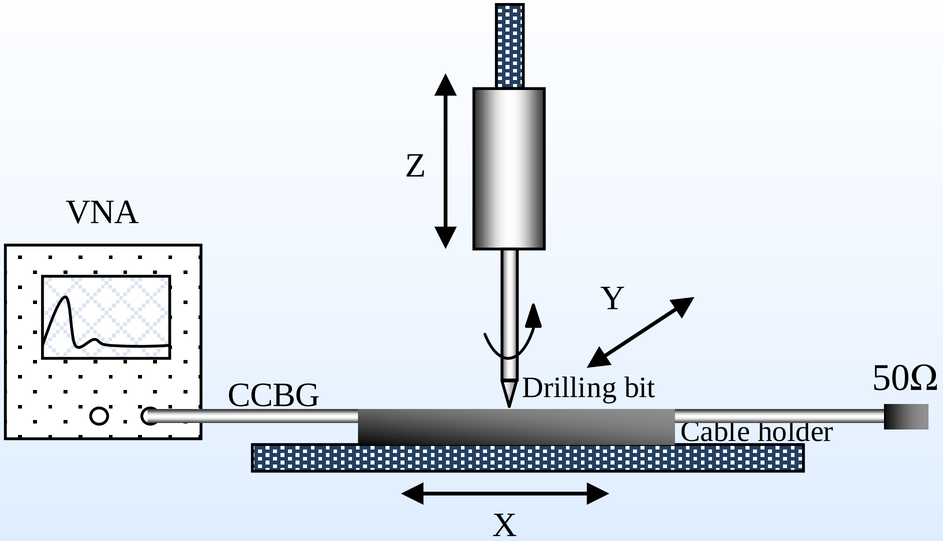


Large Strain Measurement

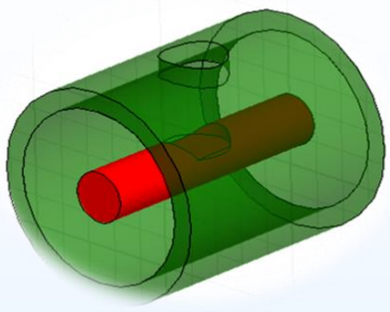


- **Different cable has different temperature responses**
- **Large strain measurement (>10%) with high sensitivity (~με)**

Fabrication by drilling holes

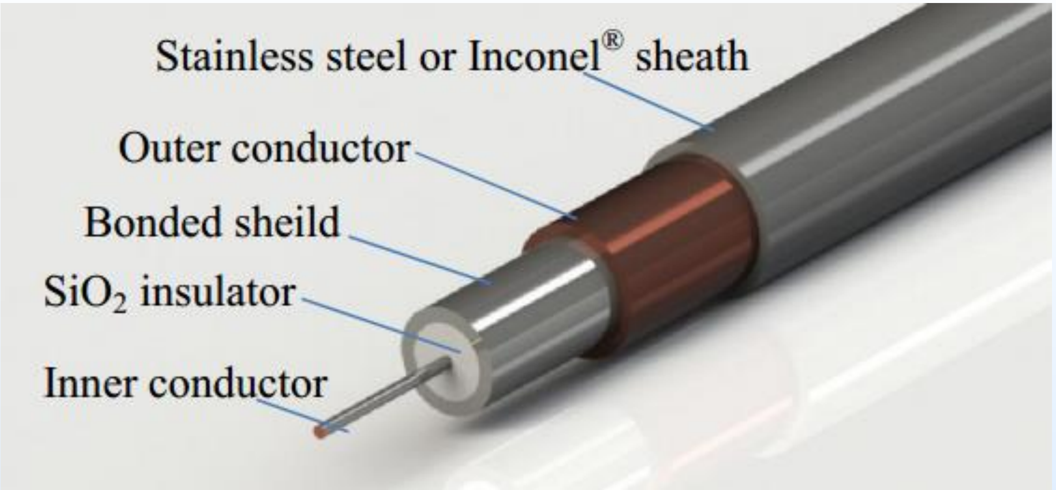


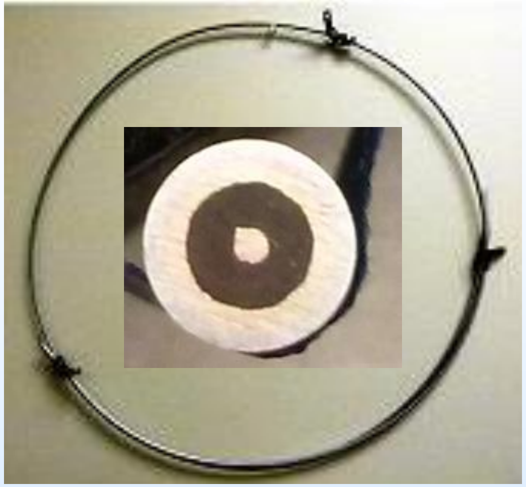
Schematic setup of fabrication system



- Using a computer numerical control (CNC) machine to drill holes into the cable.
- Replacing the dielectric material with air to create the impedance discontinuity
- Problem: poor repeatability, contaminations, poor robustness

Ceramic Coaxial Cable

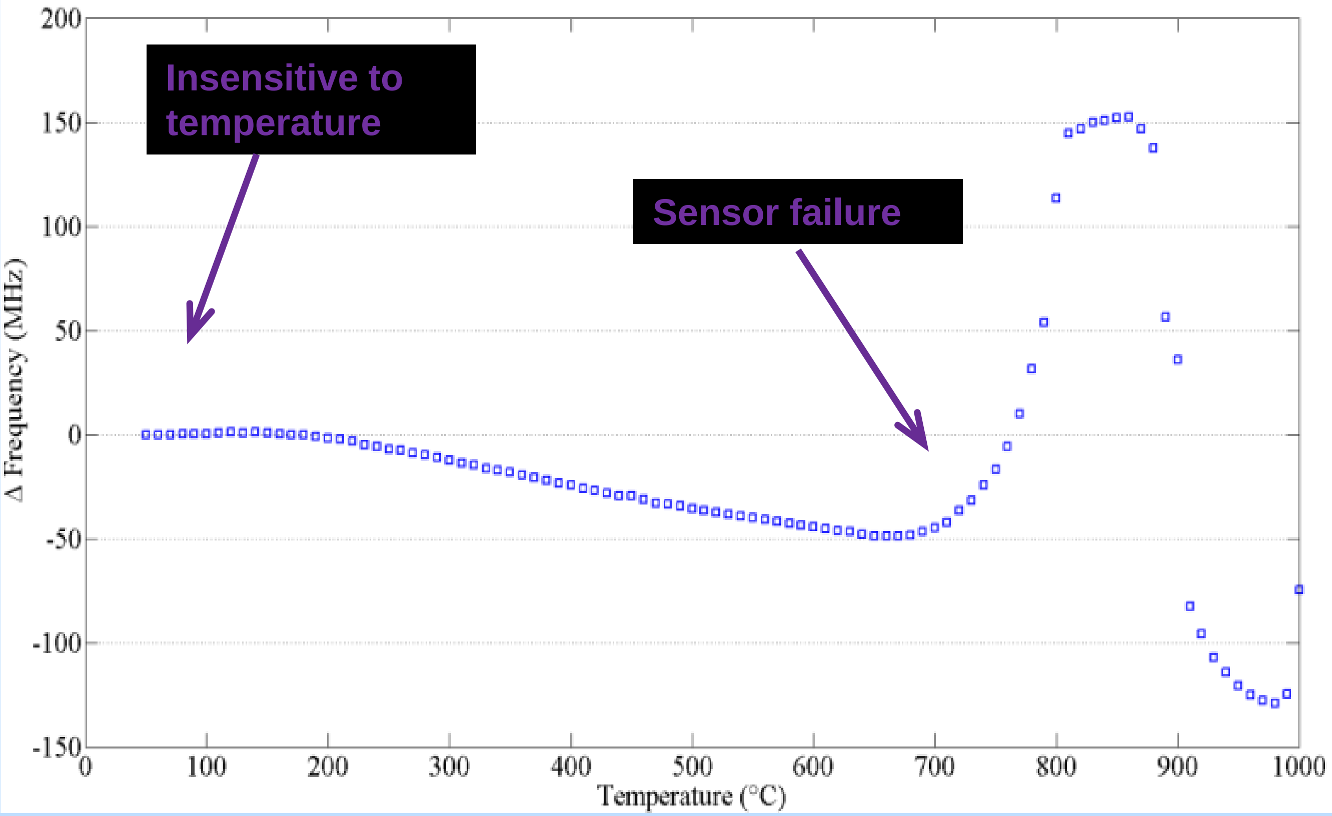




- Made by using sintered SiO2 as the insulation layer
- Can operate at high temperatures up to 1000°C and high pressures up to 10,000 psi
- Operate in the frequency range up to 20 GHz
- Have a very small attenuation of 0.08 dB/m that allows the signal to be transmitted over a long distance
- Have the necessary flexibility for deployment

Problems

- Insensitive at temperature less than 170C
- Signal transmission okay
- Sensor failed after 650C

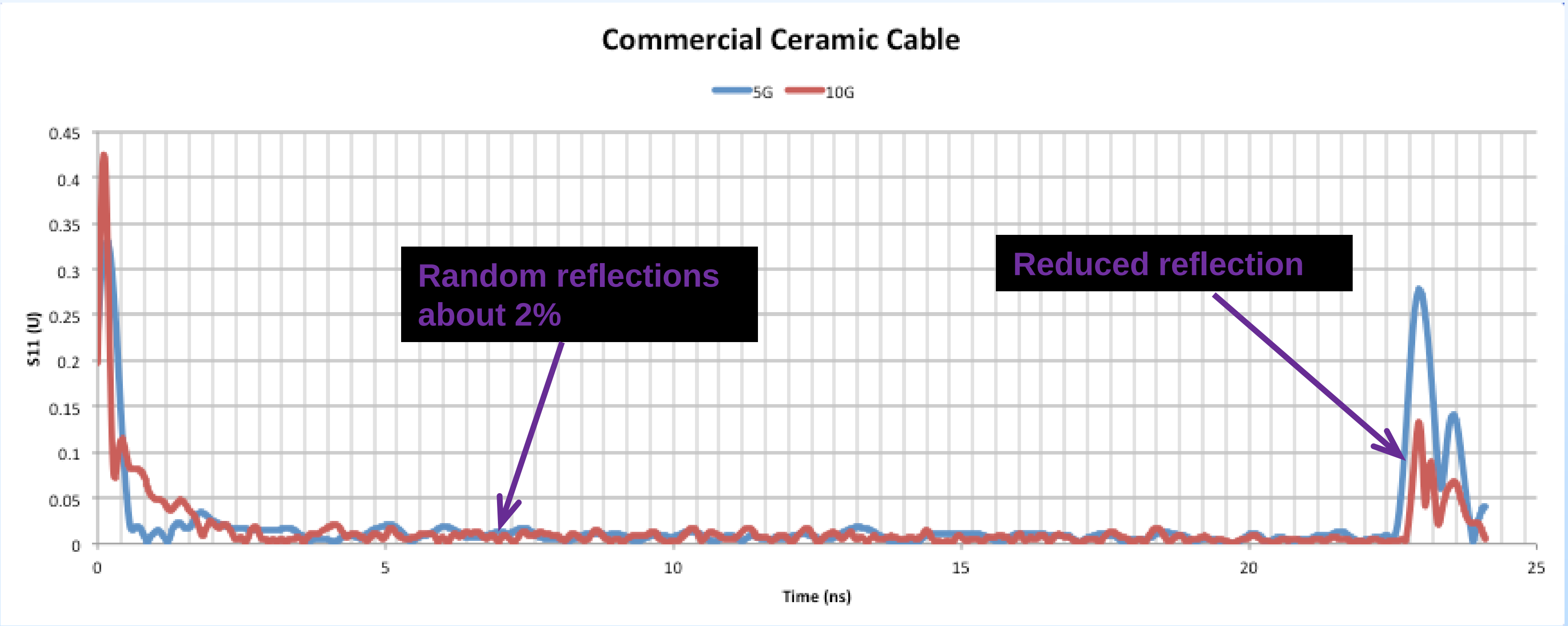


Insensitive to temperature

Sensor failure

Large unstable residual reflections

- Random noise as big as 2% reflection
- These reflections are unstable at high temperatures
- The drilled holes degraded (reduced reflections) at high temperatures



Random reflections about 2%

Reduced reflection