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

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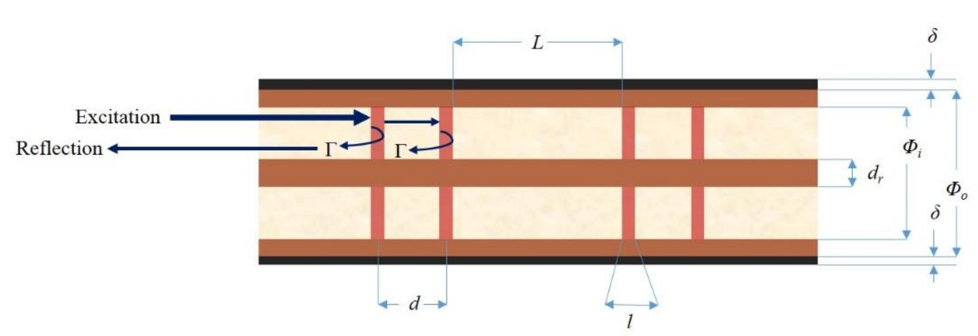
Introduction:

The development of cleaner coal-based power plants has necessitated real time monitoring of process conditions and equipment physical states. The realization of such monitoring capability will rely largely on the development of harsh environment sensors that are currently nonexistent. In recently years, various fiber optic sensors (FOS) have been under development and found many successful applications in harsh environments due to their unique advantages including compactness, high resolution, immunity to electromagnetic interference, remote operability, multiplexing capability, and thermal and chemical stabilities [1]. However, they are fragile, requiring very bulky, costly, and sophisticated packaging, and have a small dynamic range due to their limited reversible deformability. Coaxial cables may overcome the fragility issue and the signal generation and transmission mechanisms are governed by the same electromagnetic principles as in FOS.

Concept & Approach:

The approach to this project is to implement a well-known optical fiber interferometric sensor mechanism, the Fabry-Perot interferometer (FPI), in the coaxial cable (CC), referred as a CC-FPI sensor [3]. The CC-FPI sensors, as illustrated below, operate in radio frequency (RF) domain which allows choices of low-cost commercial components and instruments for sensor signal processing.



Assuming the amplitude reflection coefficients of the two reflectors are the same, the two reflected waves (*U1* and *U2*) are given as:

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

$$\text{where} \quad \tau = 2d\sqrt{\varepsilon_r}/c$$

where $\Gamma(f)$ is the amplitude reflection coefficient of the reflector; f is the frequency of the EM wave; α is the propagation loss coefficient; z denotes the cable axial direction; τ is the time delay between the two reflected wave; d is the distance between the two reflectors; ε_r is the relative permittivity of the inner dielectric material of the cable; and c is the speed of light in vacuum. The interference signal (U) is the summation of the two reflected waves, expressed as

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

The CC-FPI measures temperature by monitoring the interferogram shift from a reference defined at an arbitrary temperature (T_0) because d and ε_r are functions of temperature:

$$d_T = d_0 + \beta_T(T - T_0)$$

$$\varepsilon_{r,T} = \sum_{i=0}^{n}(a_i \times T^i)$$

The interference signal thus becomes a function of temperature and monitoring the interfeometric spectrum shift, $U(T)$, allows for real-time measurement of temperature by the CC-FPI.

$$U(T) = K_1\cos(K_2\cdot\tau(T))\cdot\cos[K_2(t+\tau(T))]$$

$$\tau(T) = 2d_T\cdot\varepsilon_{r,T}^{0.5}/c$$

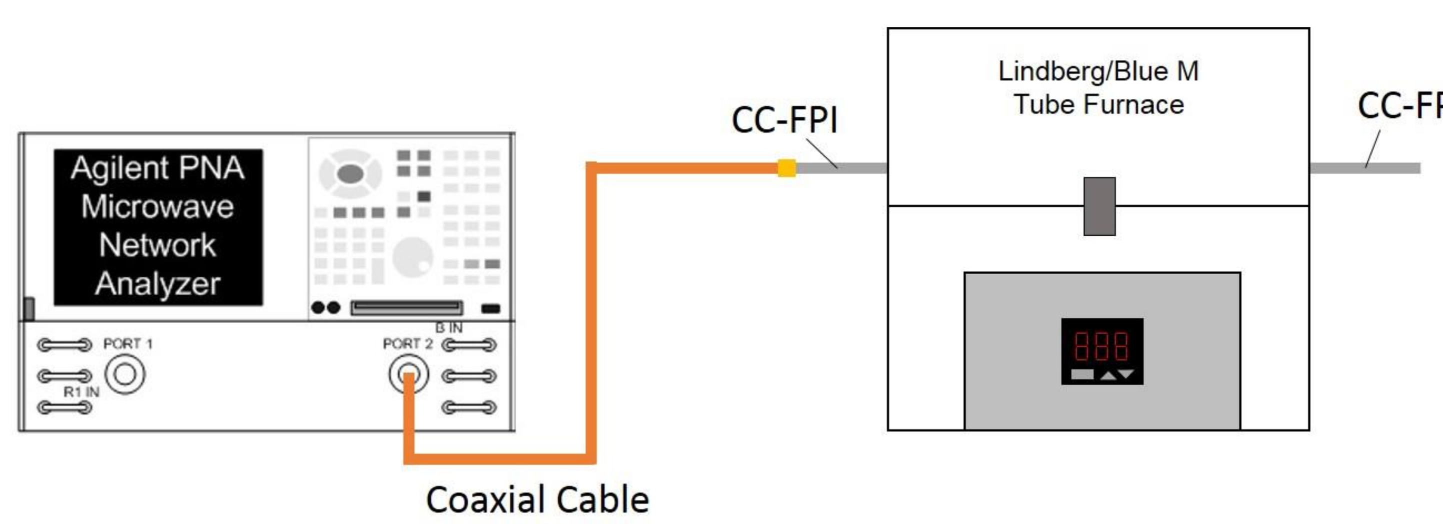
Objectives & Deliverables :

To develop a new metal-ceramic coaxial cable (MCCC) Fabry-Perot interferometer (FPI) sensor and demonstrate its ability for real-time, distributed monitoring of temperatures up to 1000ºC. The project has the following four specific technical objectives: (i) to identify and optimize metal and ceramic materials with desired electrical and dielectric properties as well as thermochemical stability, (ii) to construct the MCCC-FPI sensors and test the sensor stability in high temperature gas environments relevant to fossil energy power systems, (iii) to develop the instrumentation for signal processing and algorithmic integration for sensing systems, and (iv) 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.

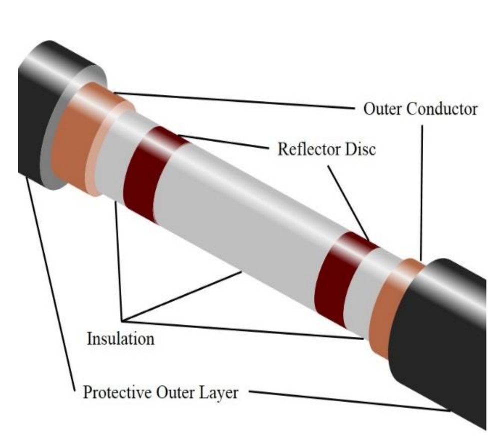
Year 1	Design sensor structure, identify/develop sensing materials, and fabricate single-point MCCC-FPI.	Annual report (6/30/2015)
Year 2	Examine single-point MCCC-FPI sensor performance and stability, and construct multi-point FPI sensors for distributed sensing.	Annual report (6/30/2016)
Year 3	Integrate sensor systems and perform distributed temperature measurement by the multi-point MCCC-FPI sensor.	Final report (6/30/2017)

Research Progress:

1. **Established facilities for metal-ceramic coaxial cable FPI (MCCC-FPI) sensor fabrication and test**



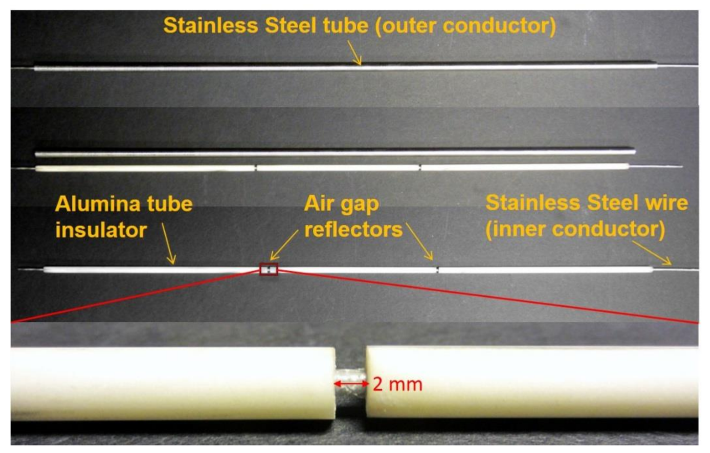
Sensor test apparatus

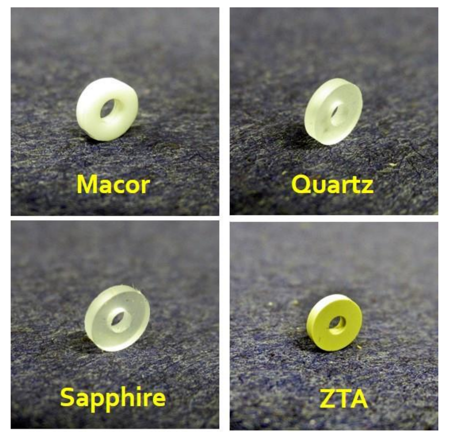


Structure of MCCC-FPI

2. **Fabricated single point MCCC-FPI sensors using ceramic materials and air as insulation and refractors and metal tubes and wires as conductors**

MCCC-FPI: alumina tube as insulator and air gaps as refractors



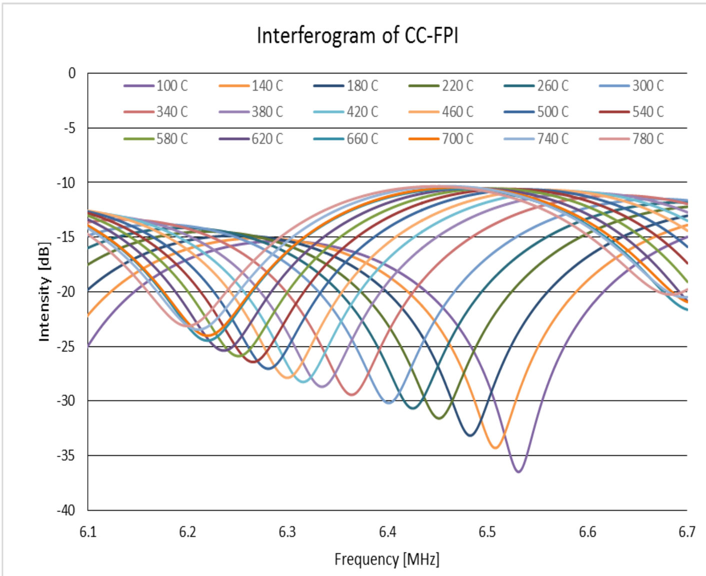


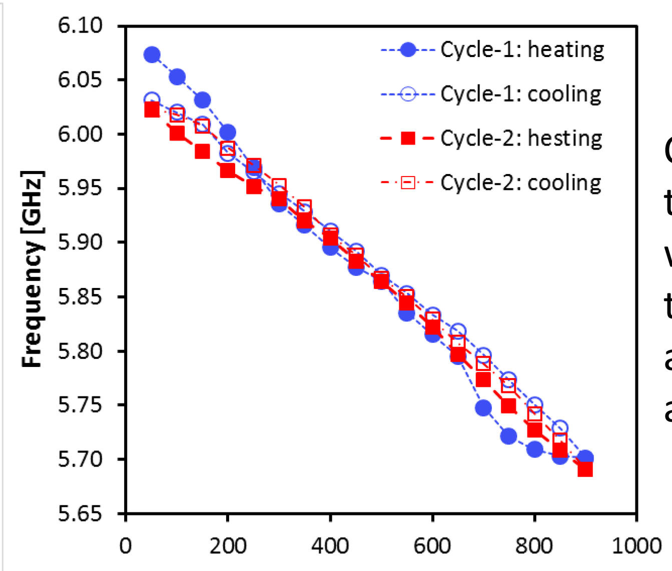
Examples of ceramic disc refractors

(Note: all MCCC-FPI sensors reported here used stainless steel tube and wire was outer and inner conductors, respectively.)

3. **Demonstrated temperature monitoring by single point MCCC-FPI sensors**

Spectrum shift as a function of temperature for the MCCC-FPI with alumina tube insulator and air gap refractors



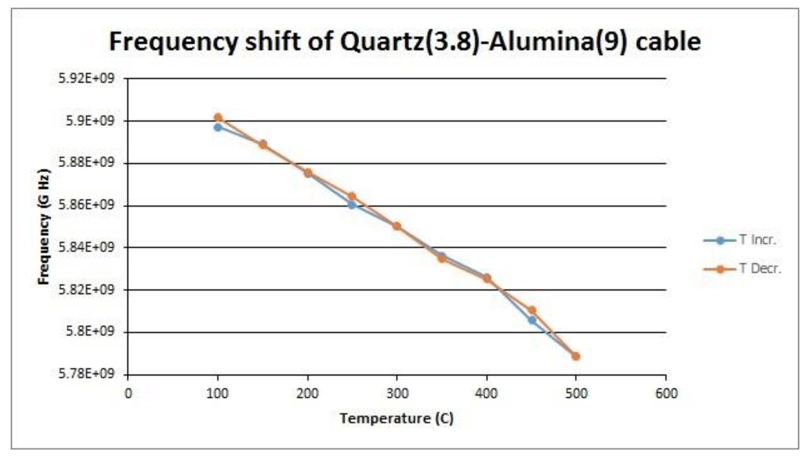


Correlation between temperature and wavelength shift for the MCCC-FPI with alumina insulator and air gap refractors

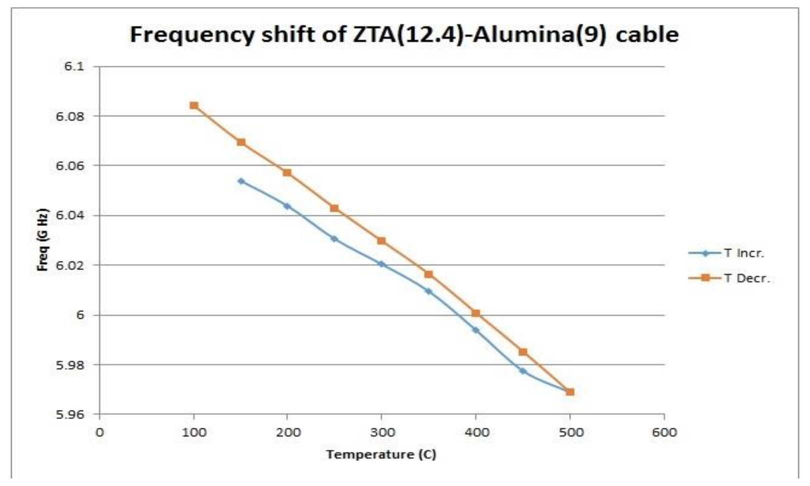
Basic properties of the ceramic materials used

Material	Composition	T_{max}, ºC	ε_r, @ 1MHz	CTE, 10^{-6} m/m·ºC
α-alumina	99.8% Al_2O_3	1750	9.5	8.4
Zirconia Toughened Alumina (ZTA)*	ZrO_2-Al_2O_3	1650	10.6	8.1
Sapphire (SAP)*	Al_2O_3	2000	9.3-11.5	5.4
Fussed quartz (QTZ)*	SiO_2	1000	3.8	0.6
Macor® (MAC)*	SiO_2-ceramic	1000	6.03	9.4
Air	Gas (mainly N_2+O_2)	>2000	~1.0	compressible

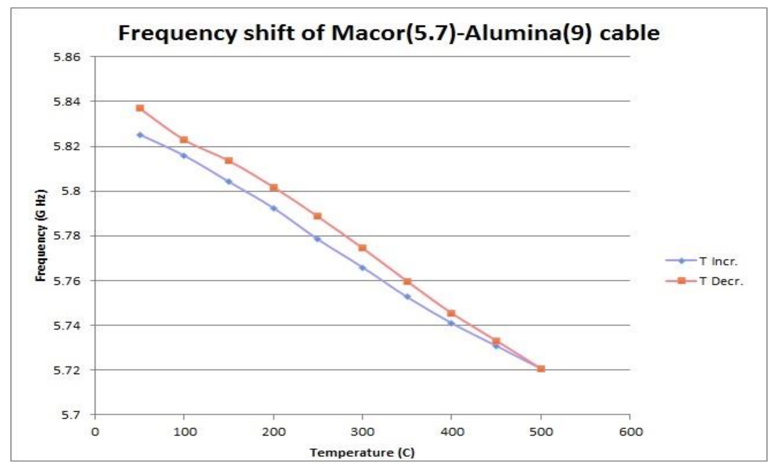
Correlation between temperature and wavelength shift for the MCCC-FPI with alumina insulator and Quartz disc refractors



Correlation between temperature and wavelength shift for the MCCC-FPI with alumina insulator and ZTA disc refractors



Correlation between temperature and wavelength shift for the MCCC-FPI with alumina insulator and Macor disc refractors



Results/Observations: **For all MCCC-FPI sensors, the wavelength shift exhibited generally linear dependence on temperature up to 900ºC (current test limit); consistency of temperature measurement improved by thermal cycles.**

Conclusions:

(1) Single point MCCC-FPI sensors have been successfully fabricated with various materials for insulation and refractors;
(2) For all MCCC-FPI sensors, the wavelength shift exhibited generally linear dependence on temperature indicating the capability for in-situ temperature monitoring;
(3) The sensors passed test up to 900ºC;
(4) The positioning of the refractors and insulation must be stabilized and secured for required accuracy and consistency.

Literature:

1. H. Jiang, R. Yang, X. Tang, A. Burnett, X. Lan, H. Xiao, J. Dong, *Sensors & Actuators B-Chem.* 177 (2013) 205-212; K. Remmel, H. Jiang, X. Tang, J. Dong, X. Lan, H. Xiao, *Sens. Actuators B-Chem.* 160 (2011) 533– 541; X. Tang, K. Remmel, X. Lan, J. Deng, H. Xiao, J. Dong, *Anal. Chem.* 81 (2009) 7844-7848
2. J. Huang, T. Wang, L. Hua, L. Fan, H. Xiao, M. Luo, *Sensors* 13 (2013) 15252-1526.