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

UCR Project Number: *DE-FE-0022993*
DOE Project Manager: *Jessica Mullen*
Project Duration: *07/01/2014 – 06/30/2017*

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National Energy Research Program/NETL, U.S. Department of Energy

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Outline

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  - Technical Challenges
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  - Multi-point (2~3) MCCC-FPI sensor
  - Long cable (2m) multi-point (10pts) sensor
  - MCCC-FPI for MW frequency ε_r measurement
- Conclusion

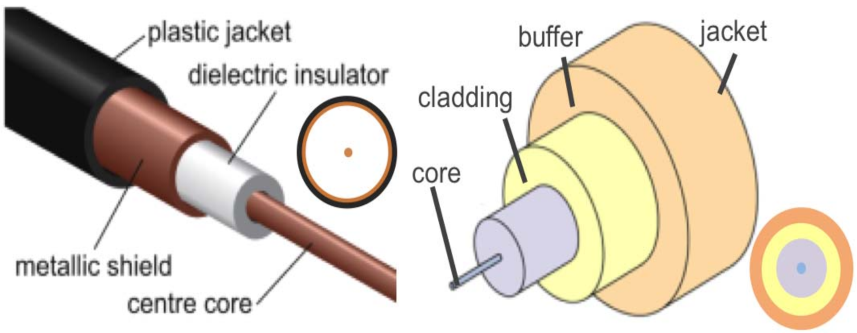
Introduction

- **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 technologies**
  1) Thermocouples, Pyrometer … （point measurement;)
  2) Fiber optic sensors (<800^{o}C …)

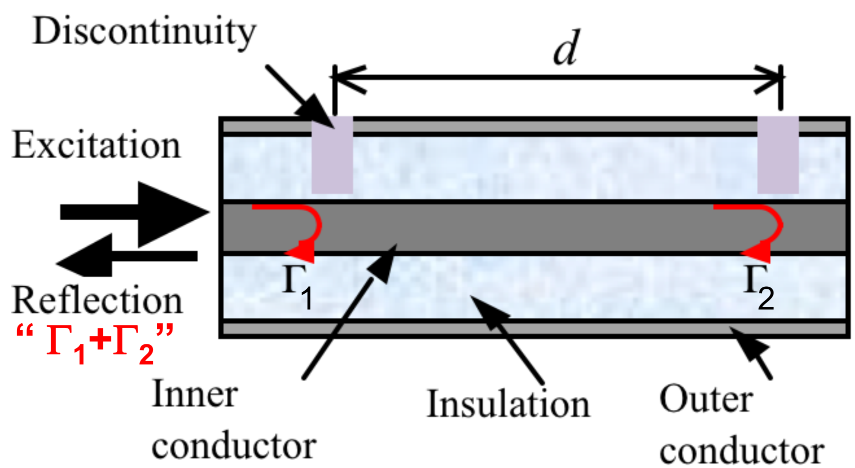
Research Objective

- **Project Goal:**
  - To develop materials for a new type of low cost, robust, (minimum packaging/protection) metal-ceramic coaxial cable (MCCC) Fabry-Pérot 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 develop sensor materials with desired electrical and dielectric properties as well as thermochemical and structural stability,
  2) to develop the instrumentation for signal processing and algorithm for operating the sensor and distributed sensing systems, and
  3) to fabricate 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.

Sensor Concept: Coaxial Cable Fabry-Pérot Interferometer (CC-FPI)



Coaxial Cable   Optical Fiber



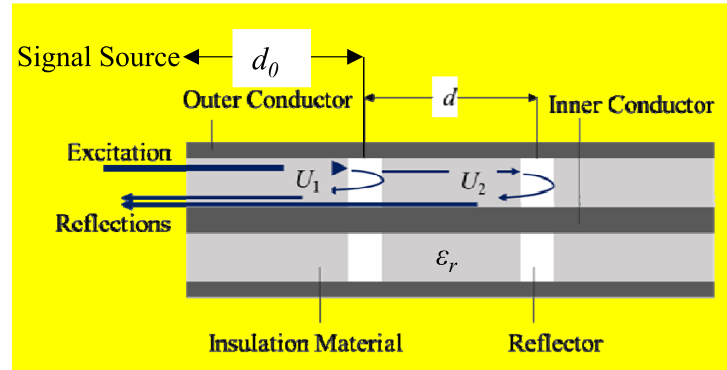
- **CC-FPI sensor operation principle**
  - **Device:** RF interferometer (analog to fiber optic interferometer)
  - **Signal:** interference of reflections from reflectors (ε disturbance)
  - **Operating mechanism:** Shift of interferogram by variation of "$d \times \varepsilon_r^{0.5}$"

CC-FPI Temperature Sensing Mechanism

- Two reflections (U_1 and U_2)

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

$$\textit{where} \quad \tau = 2d\sqrt{\varepsilon_r}/c \qquad t = 2d_0\sqrt{\varepsilon_r}/c$$

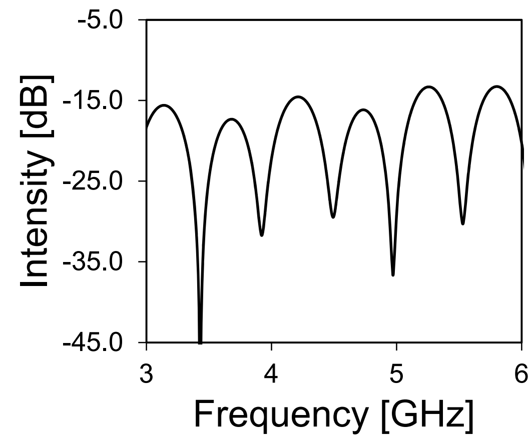


- Interference (U) – summation of U_1 and U_2

$$U = 2\cdot\Gamma(f)e^{-\alpha z}\cos\left(\pi f\frac{2d\sqrt{\varepsilon_r}}{c}\right)\cos\left[\pi f\left(\frac{4d_0\sqrt{\varepsilon_r}}{c}+\frac{2d\sqrt{\varepsilon_r}}{c}\right)\right]$$

- CC-FPI "d" and "ε_r" are temperature dependent

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



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

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

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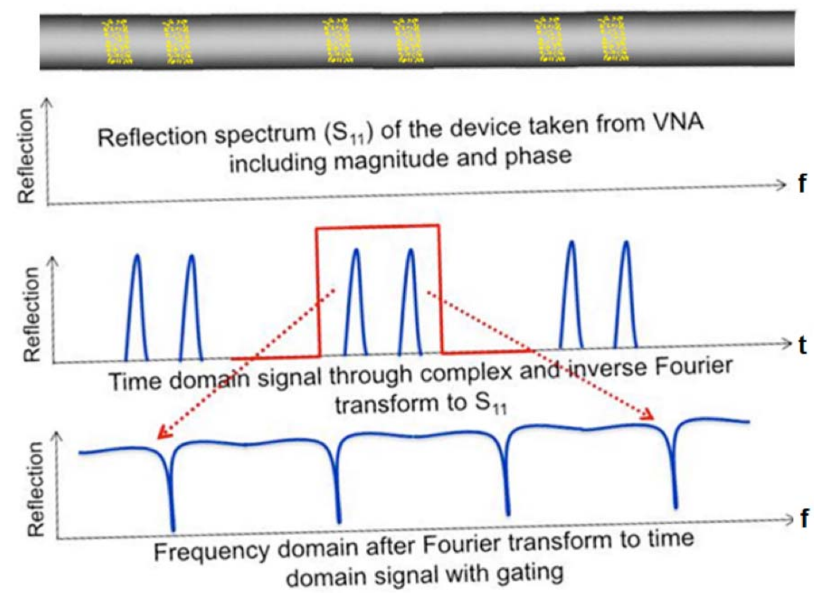
Concept: Multiple CC-FPI Sensors for Distributed Temperature Measurement

- 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)
- Position by extracting and analyzing the spectrum of a specific discrete FPI - *achieved by a novel joint time-frequency domain measurement technique*
- The reflected EM waves detected by a VNA for resolving amplitude and phase of each reflected signal
- *Goal:* accuracy $\pm$2^{o}C in a range of 350 – 1000^{o}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

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Technical Challenges

- Unavailability of MCCC
- Materials for the MCCC
  - *Conductors – stability and properties*
  - *Insulator and reflector – stability and properties*
- Understandings of parametric effects
  - *Dimensions of reflector*
  - *Inter-reflector length, d*
  - *Insulator and reflector* ε_r
  - *Operating frequency range …*

Proposed Research, Tasks, and Status

Task/ Sub-task#	Project milestone description	Project Duration – Start: 07/01/2014; End: 06/30/2017												Planned end date & status
		Project Year 1 (7/1/14-6/30/15)				Project Year 2 (7/1/15-6/30/16)				Project Year 3 (7/1/16-6/30/17)				
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
1.0	1. Management Plan and team building	•												7/31/14
2.1	1. Design the MCCC-FPI sensor. 2. Identified materials for MCCC-FPI to withstand up to 1000°C in relevant gases	•	•									Completed		12/31/14
2.2			•	•	•									6/30/15
3.1	1. Fabricated the single-point MCCC-FPI sensor and demonstrated single-point measurement up to 500°C with accuracy of ±2°C (GO/NO-GO) 2. Designed multi-point MCCC-FPI sensor and established instrument and software for distributed sensing (Task 4.1)				•	•	•							12/31/15
3.2				•	•							Completed		6/30/15
4.1	1. Design cascaded MCCC-FPI sensors and develop instrumentation and algorithms for distributed sensing 2. Fabrication of the multiple-point MCCC-FPI sensor (2 -3 FPI)					•	•	•				Completed		12/31/16
4.2								•	•	•				12/31/16
5.0	1. Fabricated Multipoint FPIs (16 Pts) in ~2m-long MCCC. 2. Demonstrated 16 FPIs in ~2m-long MCCC for distributed temperature measurement up to 1000°C with spatial resolution <10cm.									•	•	•	•	6/30/17
												On-Going •	•	6/30/17

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1. Materials selection and development for MCCC

Candidates of Materials for MCCC

Conductor	**Composition**	**CTE (10^{-6} m/m °C)**	**Tm (°C)**	**Elec. Resistivity**
S.S. (316L)	Fe w/ 16-18%Cr, 10-14%Ni, 2%Mo, 0.75%Si	19.9	1400	690 nΩ·m
Titanium	>99.2% Ti	8.55	1670	420 nΩ·m
Dielectric Material	**Composition**	**CTE (10^{-6} m/m °C)**	**Max Op. Temp (°C)**	**Dielectric Constant @ 1 MHz**
Al_2O_3	99.5% Al_2O_3	8.1-8.4	1750	9.8
Mullite	59% Al_2O_3 36%SiO_2 3%K_2O	5.9	1500	5.8
ZTA	Zr-Al_2O_3	8.1	1650	10.6
Sapphire	Al_2O_3	5.4	2000	9.3 – 11.5
Macor®	SiO_2-ceramic	9.4	1000	6.03
Fused Quartz	SiO_2	0.6	1000	3.8
Air	(N_2 + O_2)	Compressible	>2000	~1.0

MCCC Structural and Mechanical Stability

- Stainless steel (tube and wire) and dense α-alumina tubes have been selected as the basic materials for MCCC construction

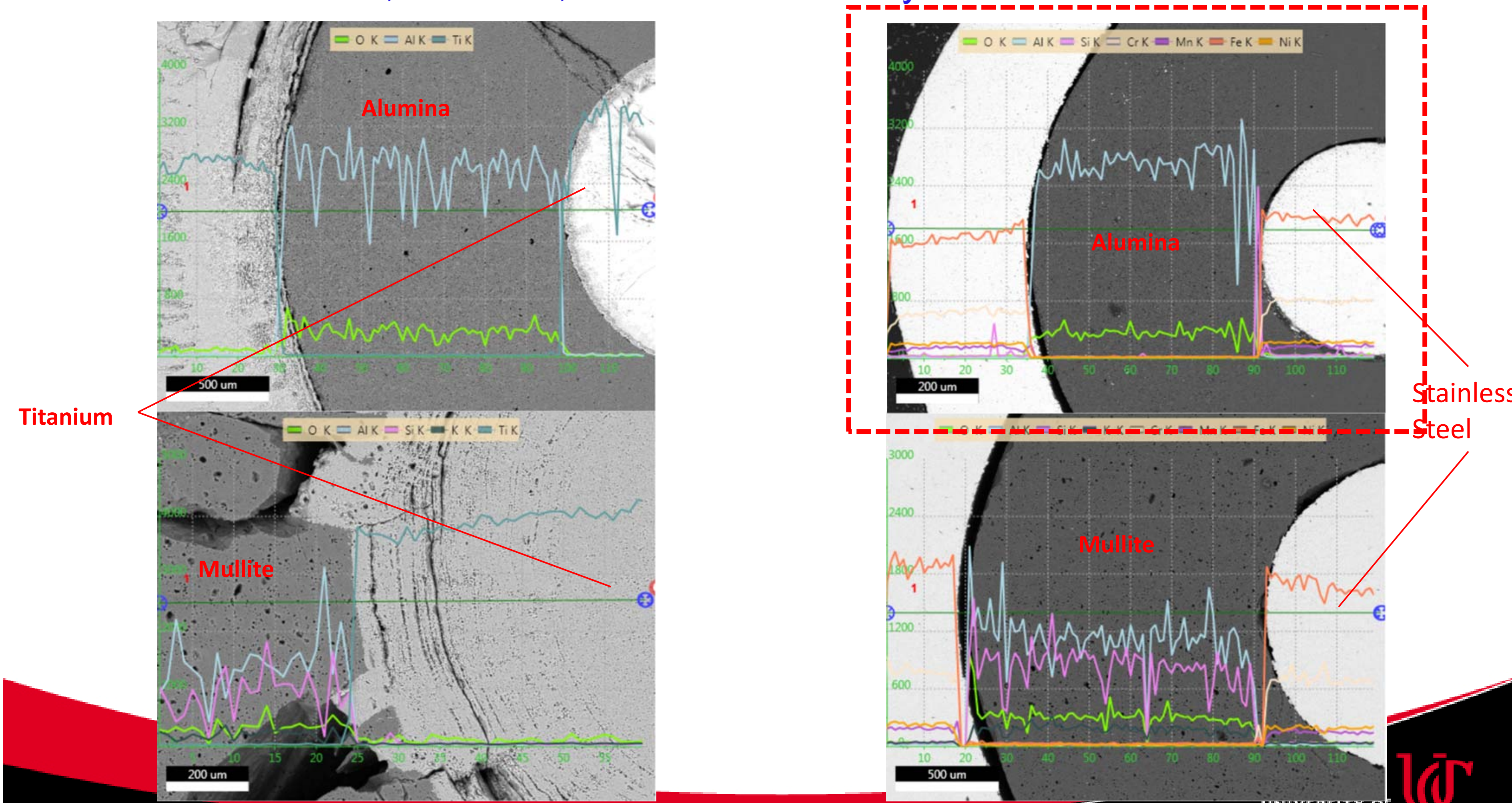
Titanium Samples

After 500 hours in direct contact with gas mixtures containing syngas and steam at 1000^{o}C

Stainless Steel Samples

MCCC Structural, Chemical, and Thermal Stability

- Stainless steel (tube and wire) and α-alumina tubes combination exhibited the best structural, chemical, and thermal stability



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2. Fabrication and evaluation of single-point MCCC-FPI

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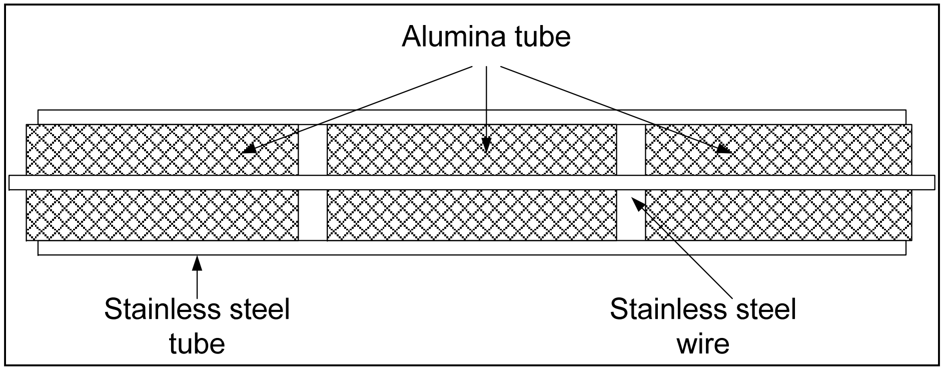
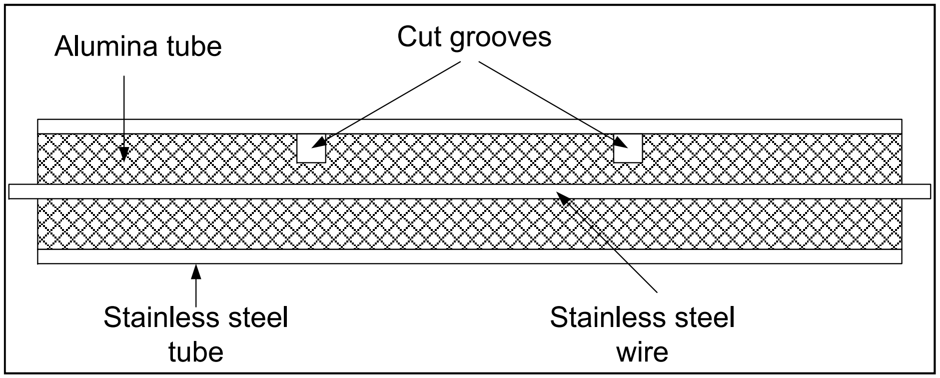
MCCC-FPI Sensor Design

Type *a*: Gap/Whole disc reflector with ceramic insulation



Type *b*: ceramic insulation with groove reflectors



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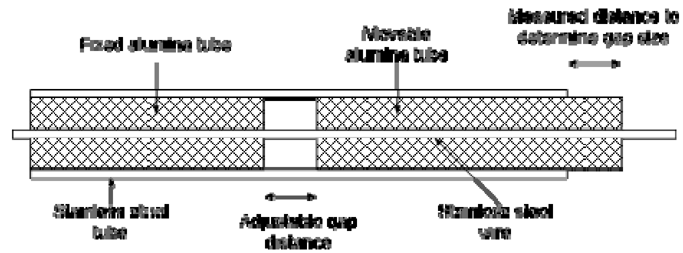
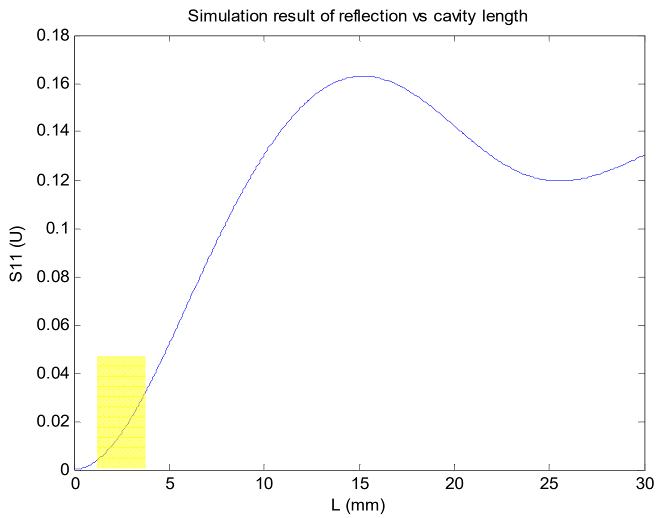
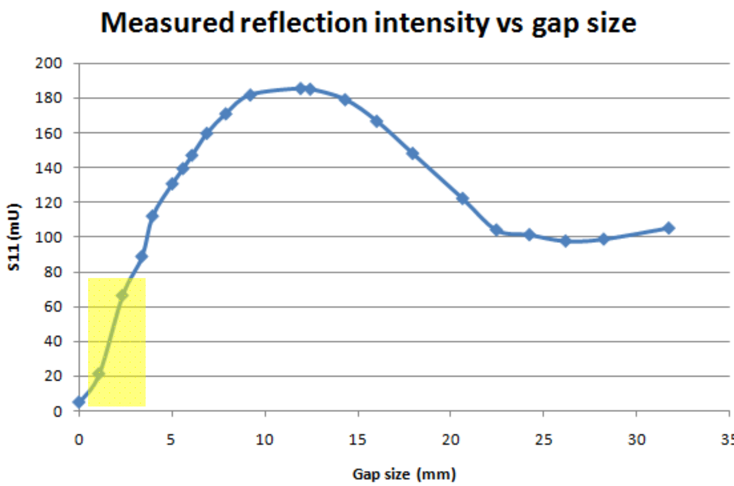
MCCC-FPI: Gap Size Determination

- A reflection of appropriate intensity is desired especially for development of single-cable multiplexed distributed sensors
- Air gap width of 1 – 4 mm appears to be suitable for sensor applications

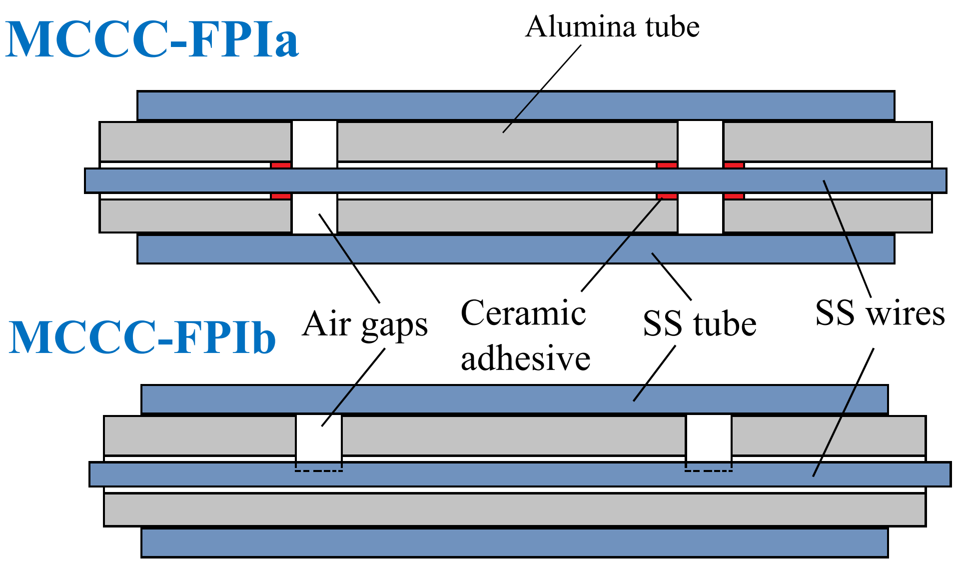


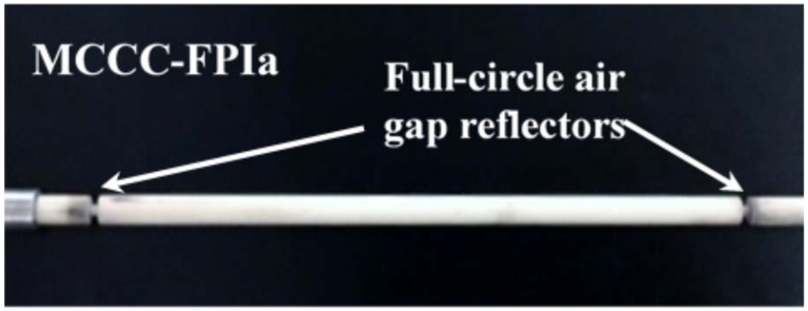


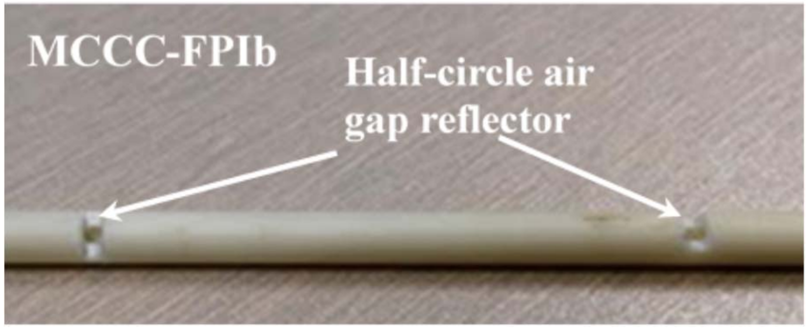


Model-predicted (left) and experimentally measured (right) reflection intensity as a function of reflectors' width.

Single-Point MCCC-FPI Structures







- **MCCC-FPIa**: ***d*** determined by expansion/contraction of metal wire
- **MCCC-FPIb**: ***d*** determined by expansion/contraction of Alumina tube

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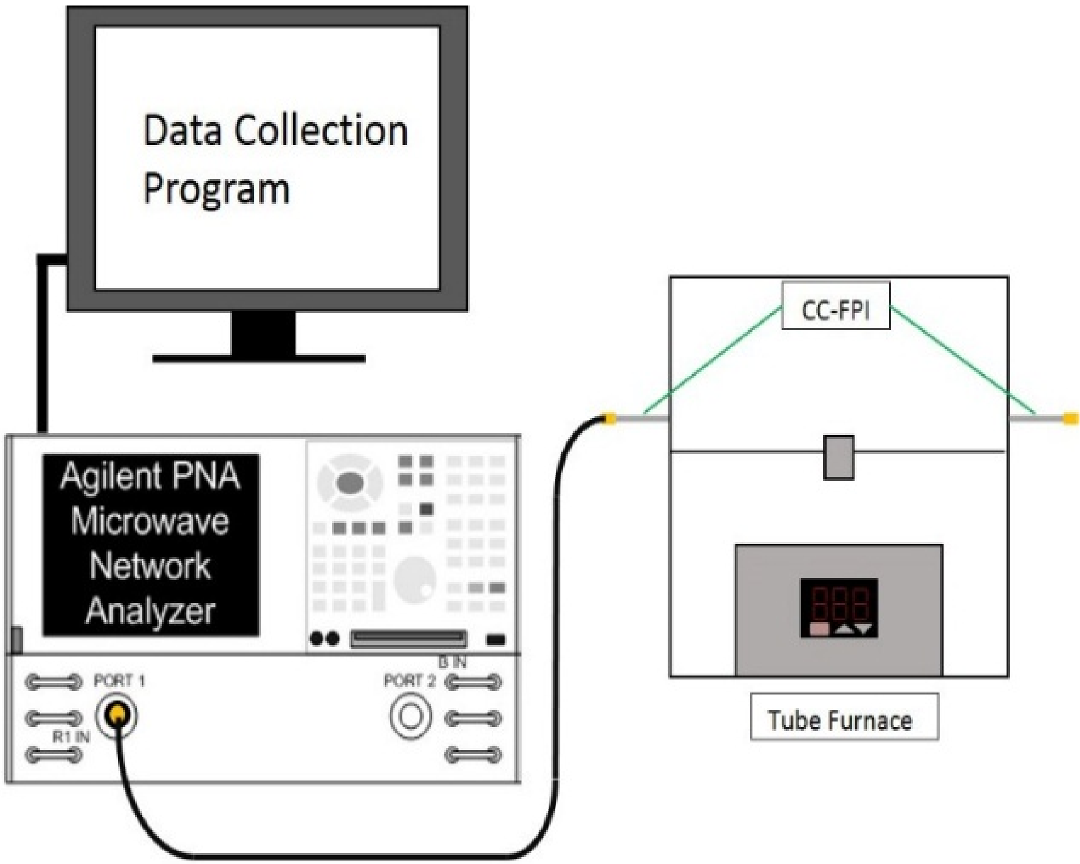
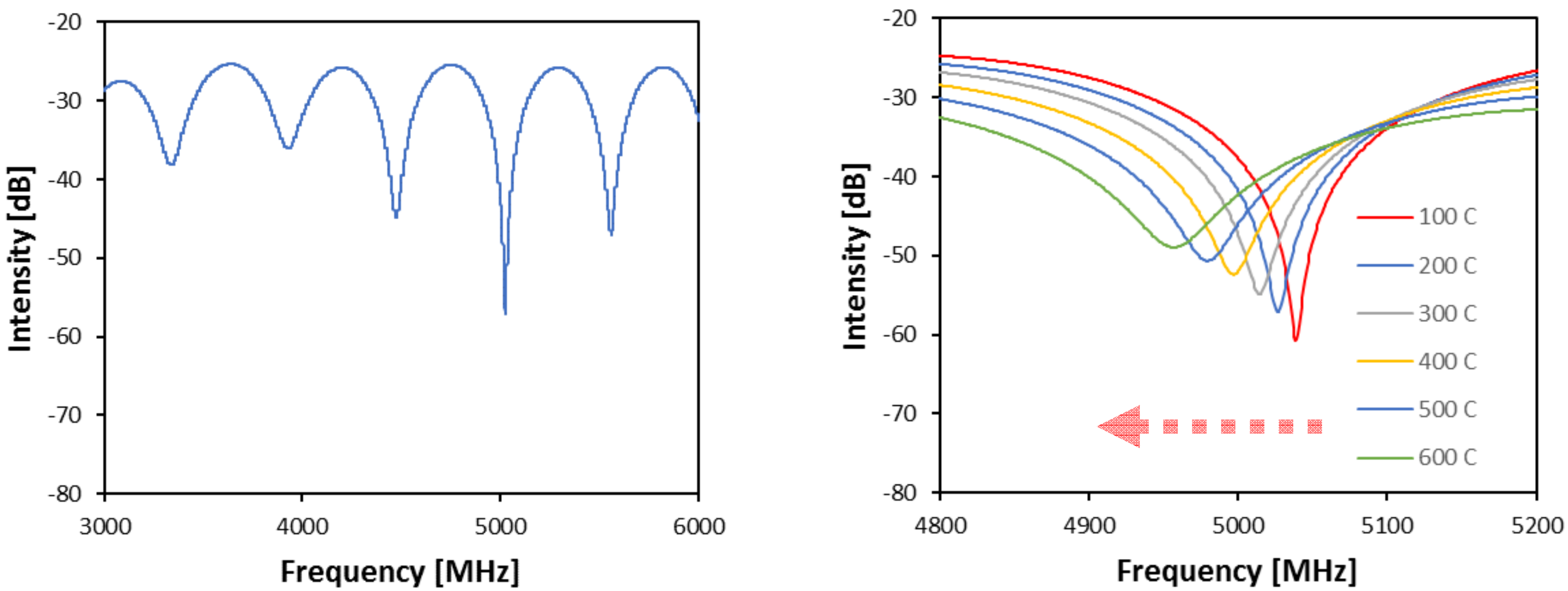
Sensor Operation Apparatus



Interferogram Evaluation as a Function of Temperature



Shift of resonant frequency as temperature increases (**MCCC-FPIa**)

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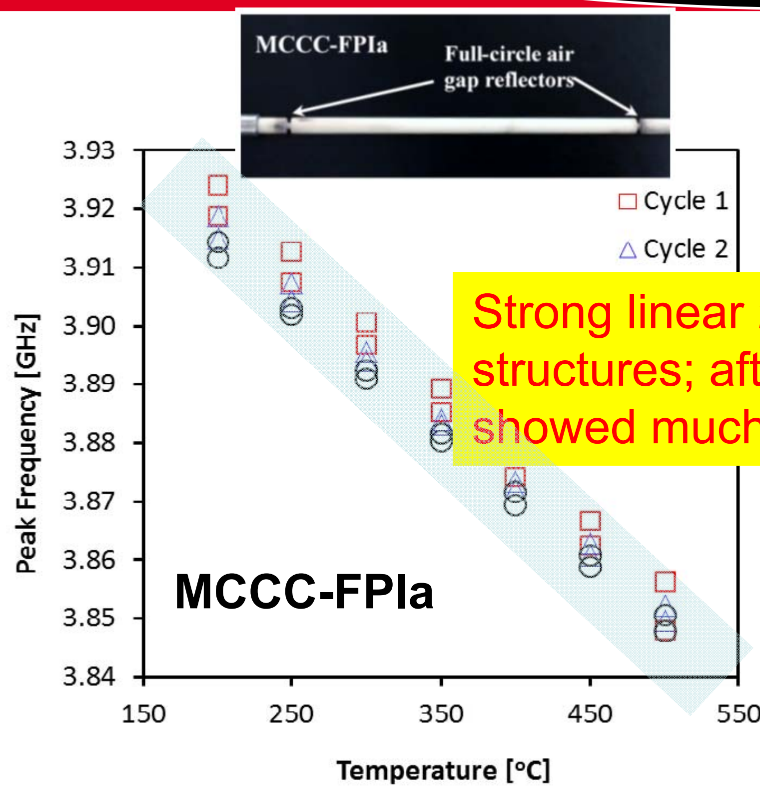
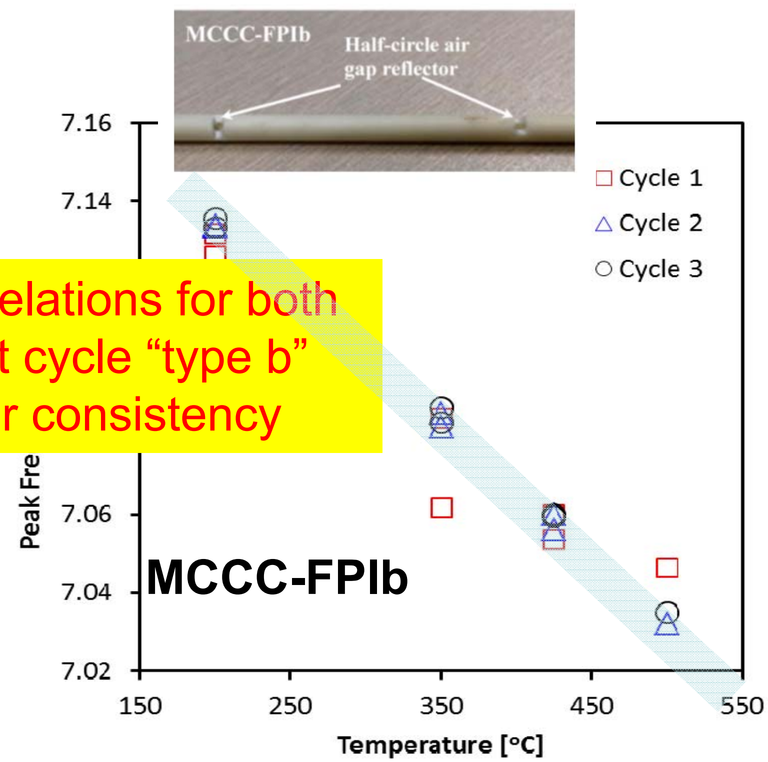
Correlation between Frequency and Temperature





Strong linear *f* ~ *T* relations for both structures; after first cycle "type b" showed much better consistency

Evolution of the relationship between resonant frequency and temperature during heating-cooling cycles

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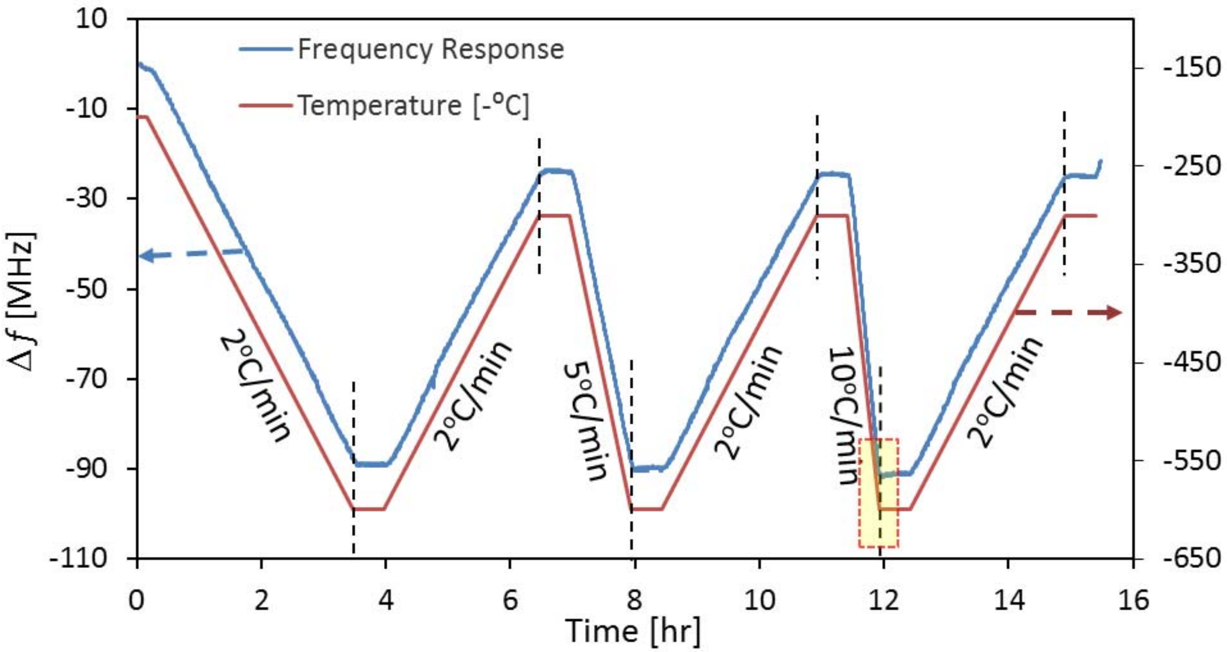
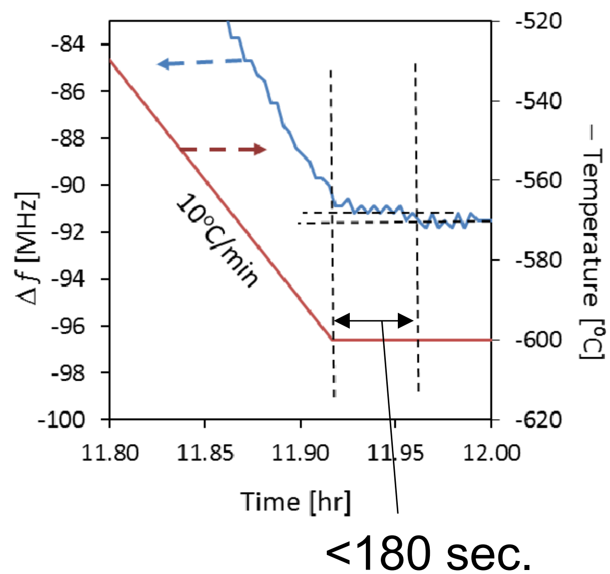
Sensor Response Speed

Frequency shift (Δ*f*) for MCCC-FPIa as a function of time in response to the programmed temperature change





The response time is reasonably short and may be acceptable for the harsh environment measurements

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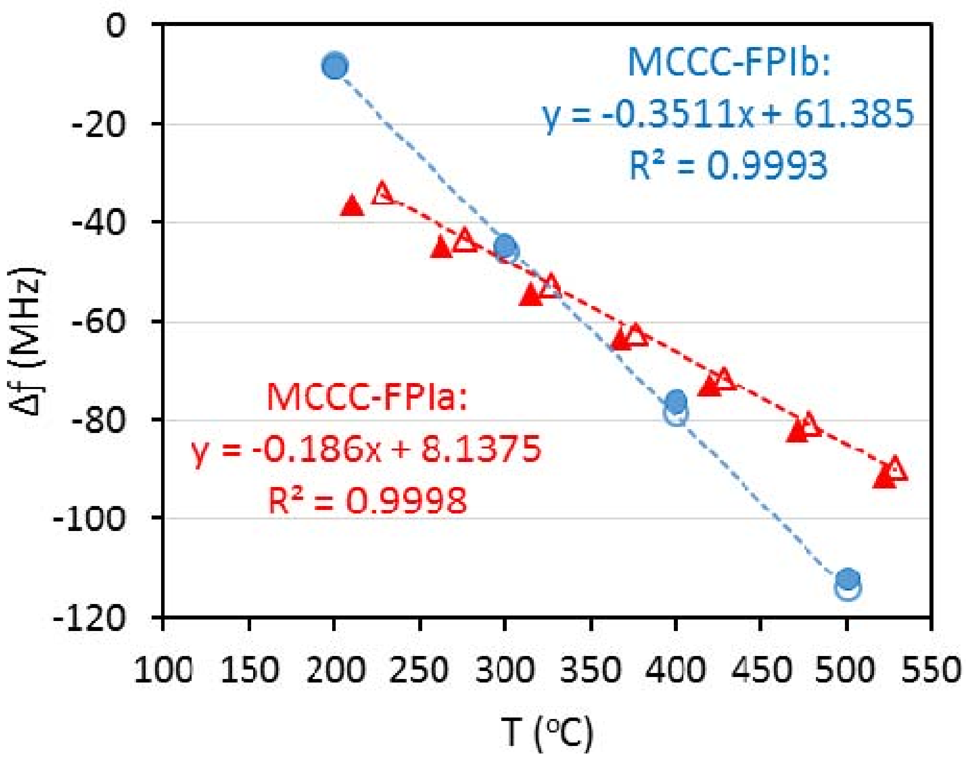
Temperature-Dependence of Δf and Sensitivity



Experimentally measured frequency shift Δf as a function of temperature for both MCCC-FPI with linear correlations

Resonant freq. used @ RT:
FPIa – 3.4 GHz; FPIb – 7.1 GHz

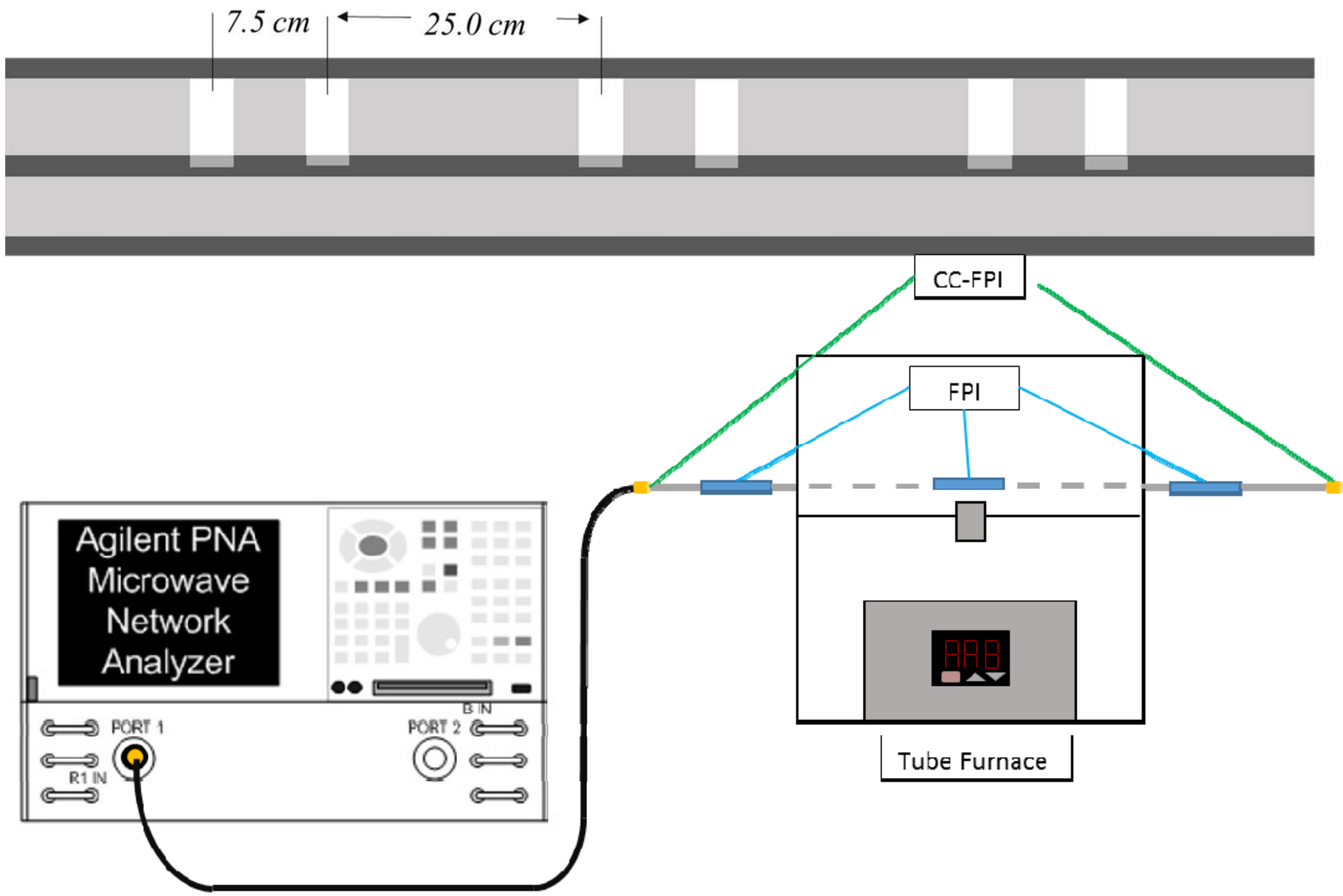
Temperature-dependences of Δf:
Excellent linear dependence –
FPIa (-0.186 MHz/°C)
FPIb (-0.351 MHz/°C)

Sensitivity:
FPIb higher than FPIa

Structure stability:
FPIb better than FPIa

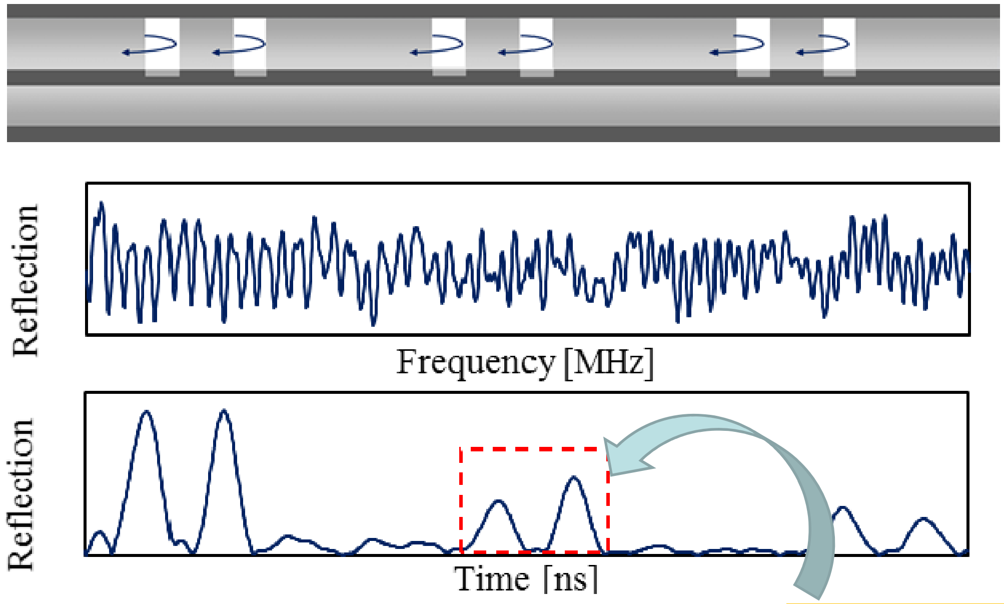
3. Design and fabrication of 2- or 3-point MCCC-FPI

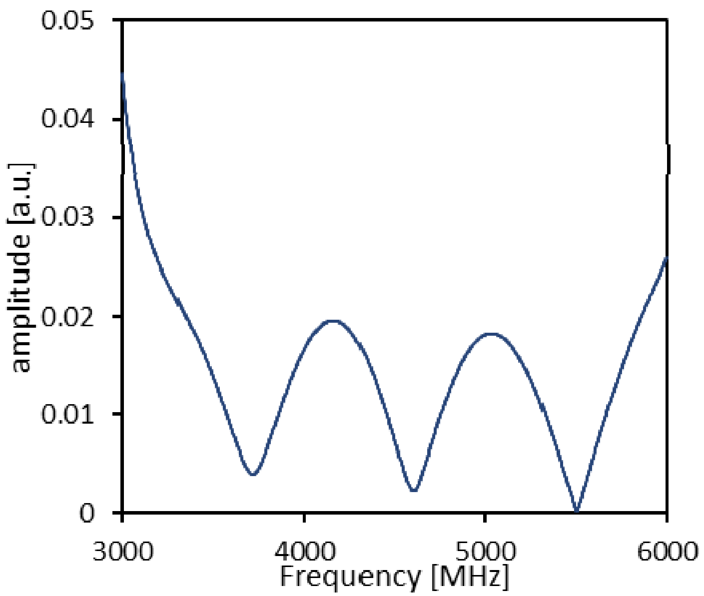
3-Point MCCC-FPI



3-Point MCCC-FPI

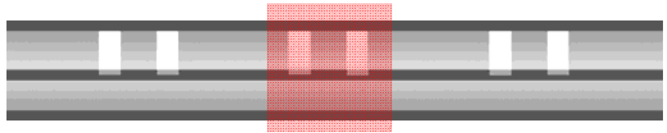
Joint-time-frequency domain operation.



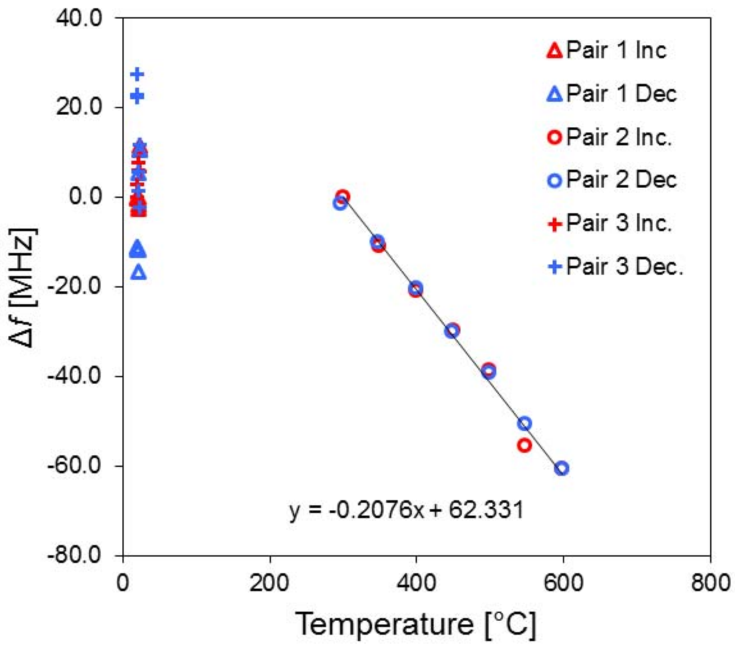


Red dashed box indicates gated FPI pair and its respective interferogram

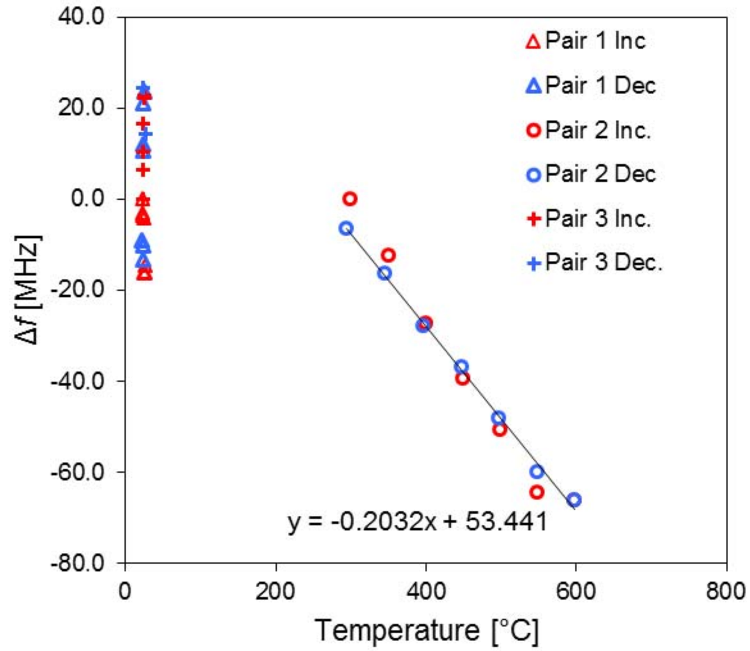
3-Point MCCC-FPI



Cycle 1



Cycle 2



Evolution of the relationship between resonant frequency and temperature during heating-cooling cycles. Pair 2 placed in center of tubular furnace.

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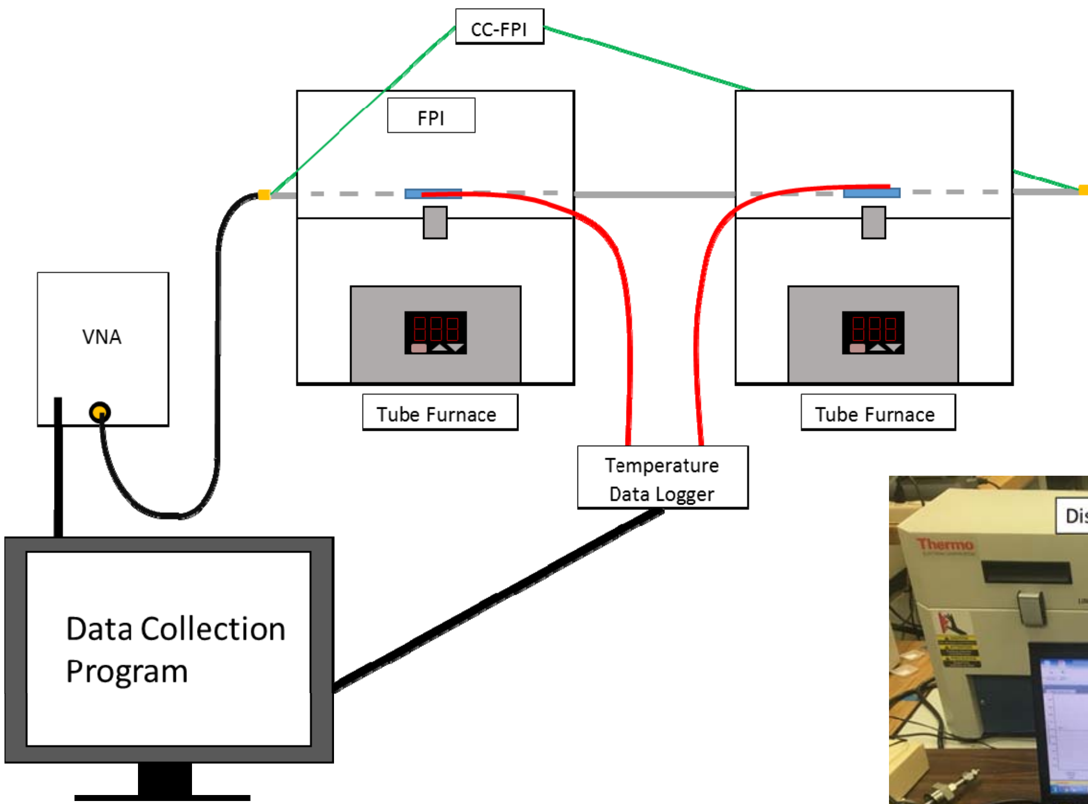
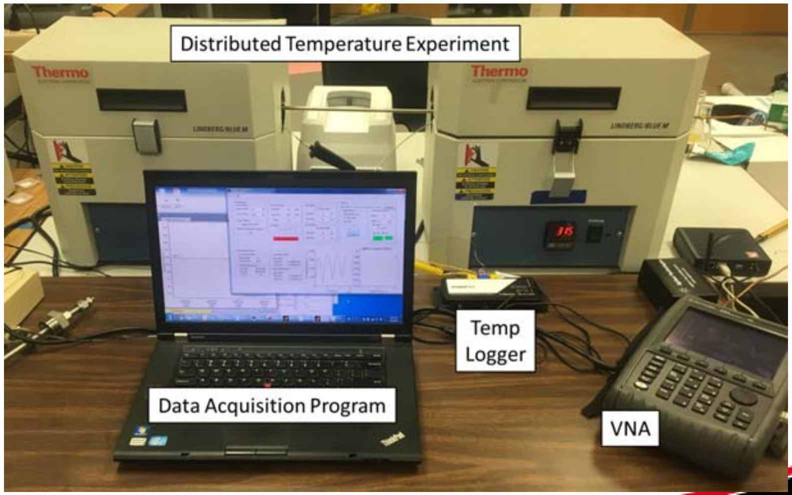
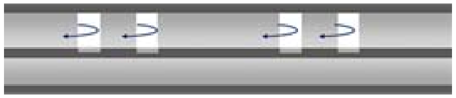
Multi-Point MCCC-FPI

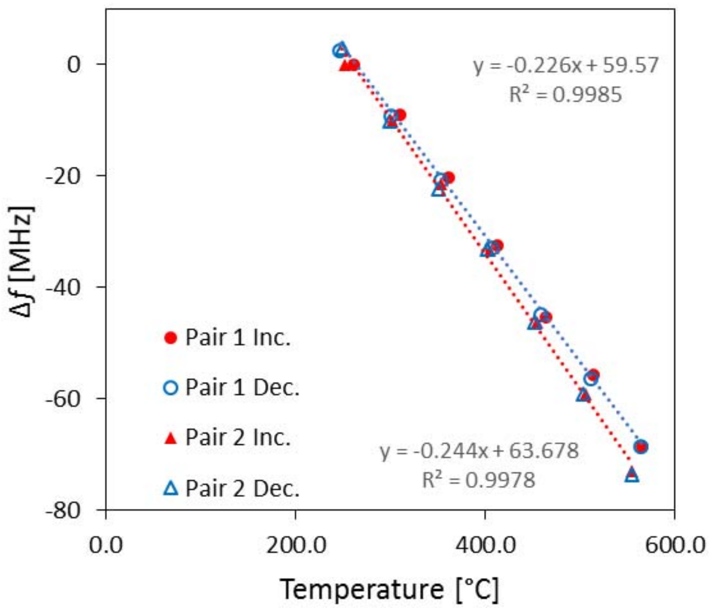




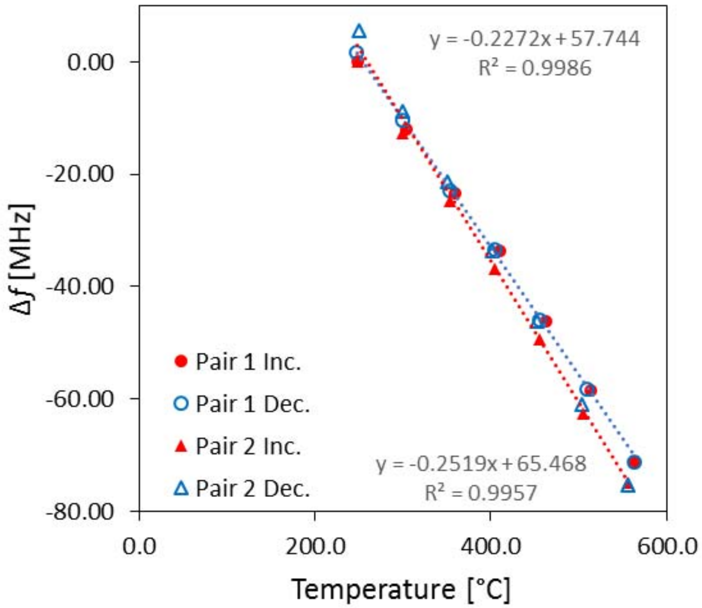
2-Point MCCC-FPI



Cycle 1



Cycle 2



Evolution of the relationship between resonant frequency and temperature during heating-cooling cycles.

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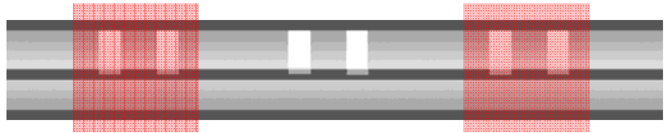
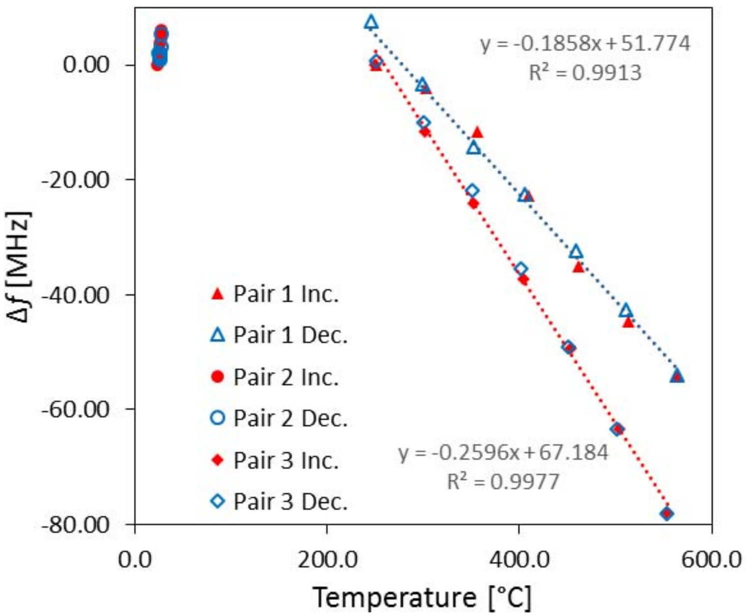
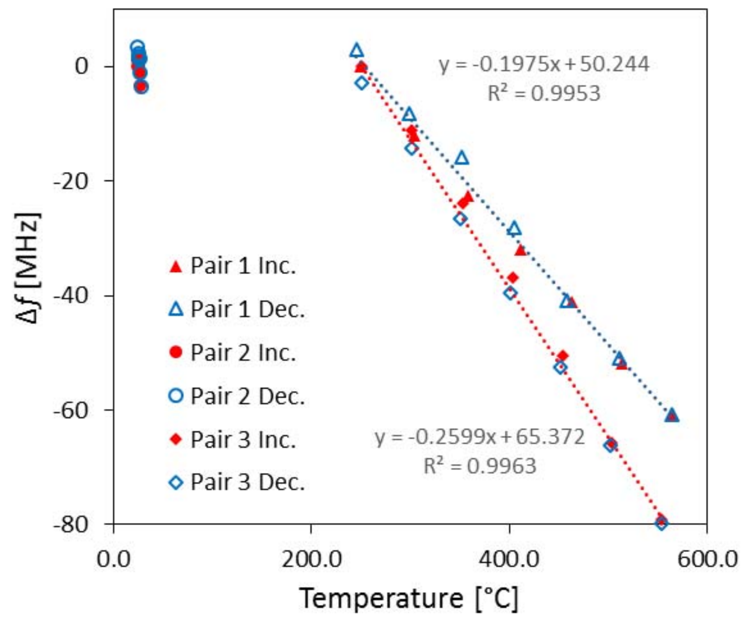
3-Point MCCC-FPI

Cycle 1



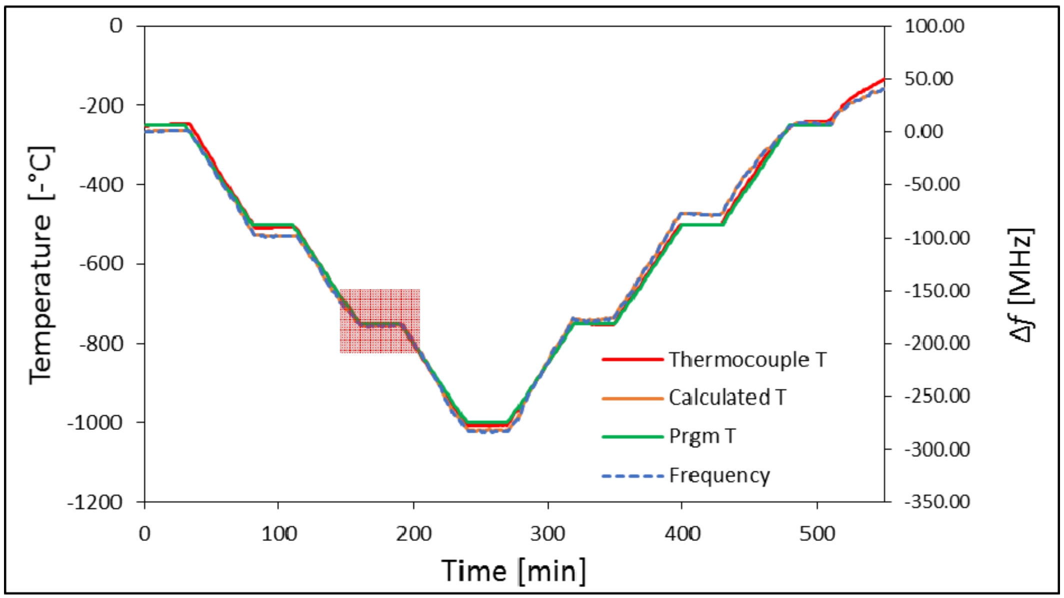
Cycle 2

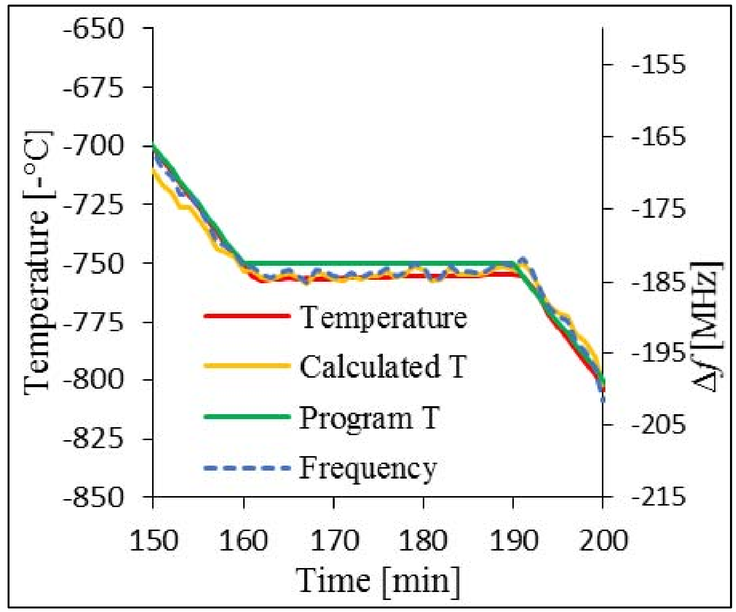




Evolution of the relationship between resonant frequency and temperature during heating-cooling cycles.

Response of MCCC-FPI





Evolution of the relationship between resonant frequency and temperature during heating-cooling cycles.

4. Evaluation of multi-point MCCC-FPI (10-16 pts in ~2m-long MCCC)

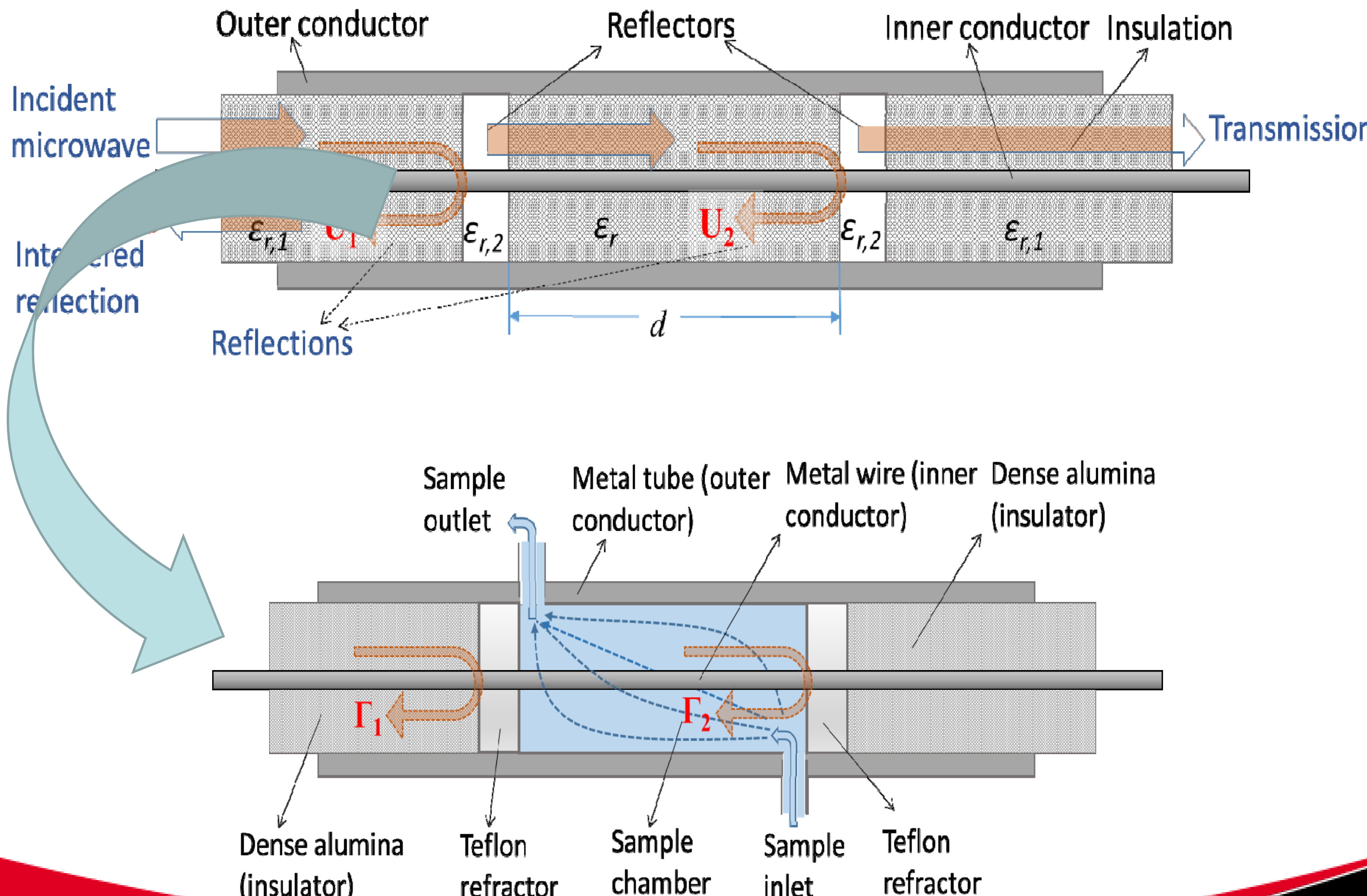
Research still ongoing

Summary

- Research progress of this project is on schedule
- Research accomplishments
  - Identified and developed metal ceramic materials for construction of MCCC-FPI sensors with good stability in harsh environments
  - Fabricated and demonstrate single point MCCC-FPI sensor for temperature measurement up to 1000^{o}C
  - Fabricated and demonstrated MCCC-FPI sensor with 2 – 3 FPIs (2 – 3 sensing points)
  - Long cable (2m) multi-point (10pts) sensor under development

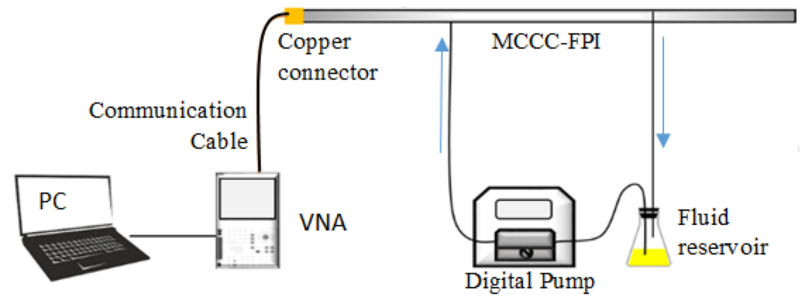
5. MCCC-FPI for dielectric constant measurements for sensor material development

Sensor Concept



Sensing Mechanism

$$f_N = \frac{Nc}{2d\sqrt{\varepsilon_r}}$$

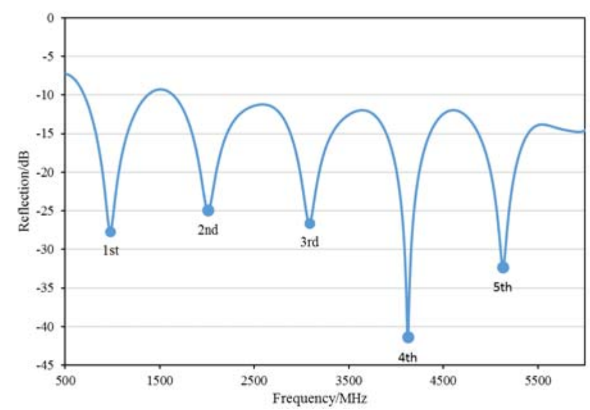


$$U1 = \Gamma(f)e^{-\alpha z}e^{-j2\pi f\frac{2d_0\sqrt{\varepsilon_{r,1}}}{c}}$$

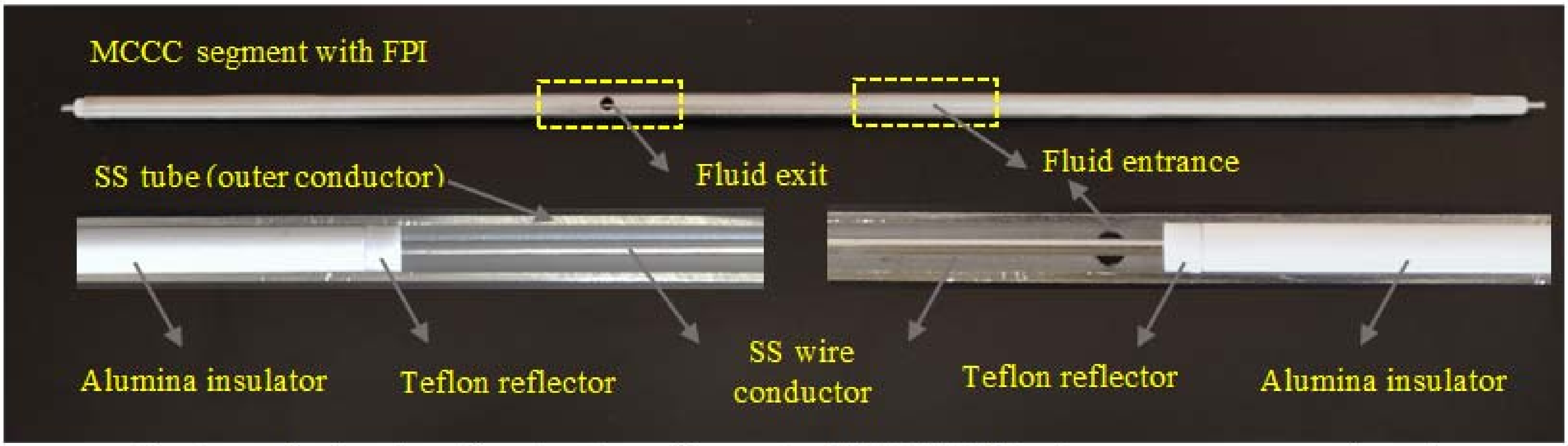
$$U2 = -\Gamma(f)e^{-\alpha z}e^{-j2\pi f\frac{2d_0\sqrt{\varepsilon_{r,1}}+2d\sqrt{\varepsilon_r}}{c}}$$

$$U = 2j\cdot\Gamma(f)e^{-\alpha z}e^{-j2\pi f\frac{2d_0\sqrt{\varepsilon_{r,1}}+d\sqrt{\varepsilon_r}}{c}}\sin(2\pi f\,\frac{d\sqrt{\varepsilon_r}}{c})$$

$$f_N = \frac{Nc}{2d\sqrt{\varepsilon_r}}$$



Sensor Construction



Photograph showing the structure of an actual MCCC-FPI microwave sensor and section

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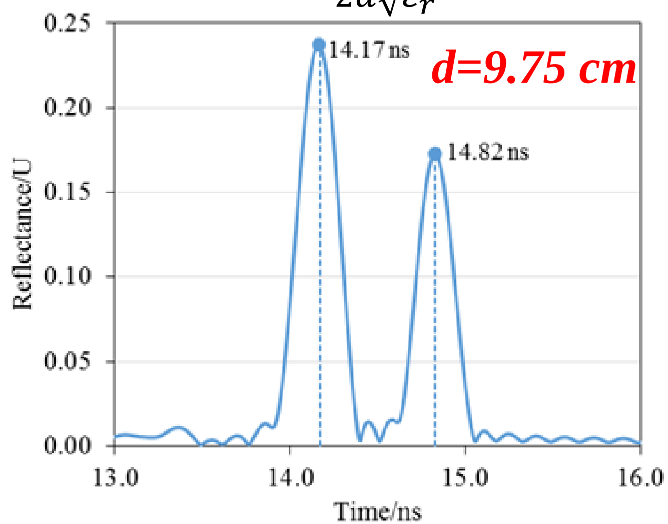
Determination of "*d*" Value

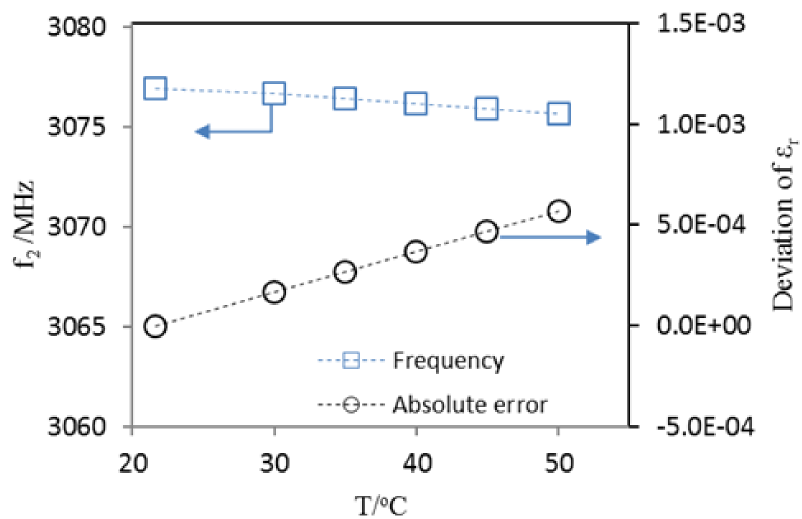
- The inter-reflector distance "d" is precisely determined from interferogram with dry air or vacuum (ε_r ~1.0)
- Temperature effect on Δf at 20 – 50 C is negligible compared to effect of ε_r changes

$$f_N = \frac{Nc}{2d\sqrt{\varepsilon_r}}$$



The time domain spectrum of the air-filled MCCC-FPI.

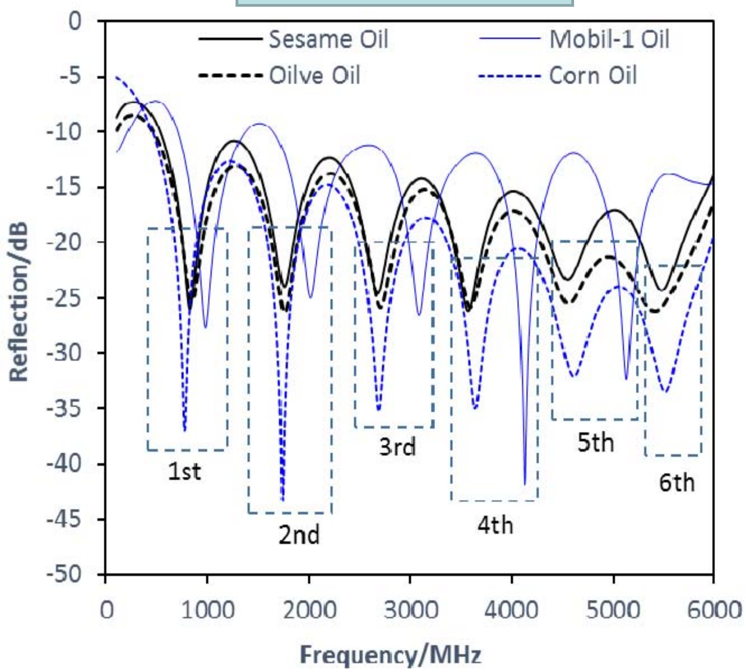
$$\Delta\varepsilon_r = \left(\frac{Nc}{2df_N}\right)^2 - \left(\frac{Nc}{2d_T f_N}\right)^2$$



The 2[nd] resonant peak frequency (f_2) of dry air filled MCCC-FPI and the $\Delta\varepsilon_r$ as functions of temperature.

Fluid Dielectric Constant Measurement

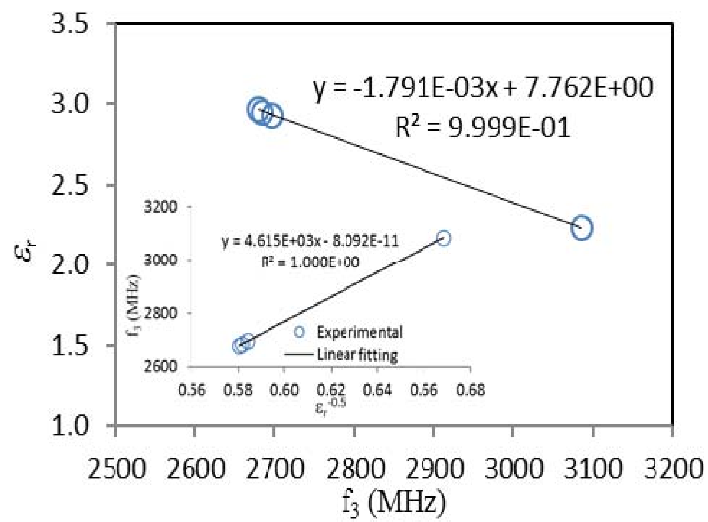
$$f_N = \frac{Nc}{2d\sqrt{\varepsilon_r}}$$



The frequency domain interferometric reflection spectra of the MCCC-FPI when filled with sesame oil, olive oil, corn oil, and Mobil-1 oil, respectively.

Dielectric constants of the oils measured at room temperature (24°C) by the MCCC-FPI in comparison with literature values

Oil	This work								Reference [11-16]	
	f_2/GHz	ε_r	f_3/GHz	ε_r	f_4/GHz	ε_r	f_5/GHz	ε_r	f/GHz	ε_r
Sesame	1.75	3.09	2.68	2.97	3.57	2.97	4.55	2.86	0.001~9	3.11~2.42
Olive	1.75	3.09	2.70	2.93	3.59	2.94	4.56	2.87	0.31~0.91	3.11~2.46
Corn	1.74	3.12	2.68	2.96	3.65	2.85	4.61	2.78	2.8~3.0	2.66~2.61
Mobil-1	2.02	2.33	3.08	2.24	4.12	2.23	NA	NA	NA	2.1~2.8



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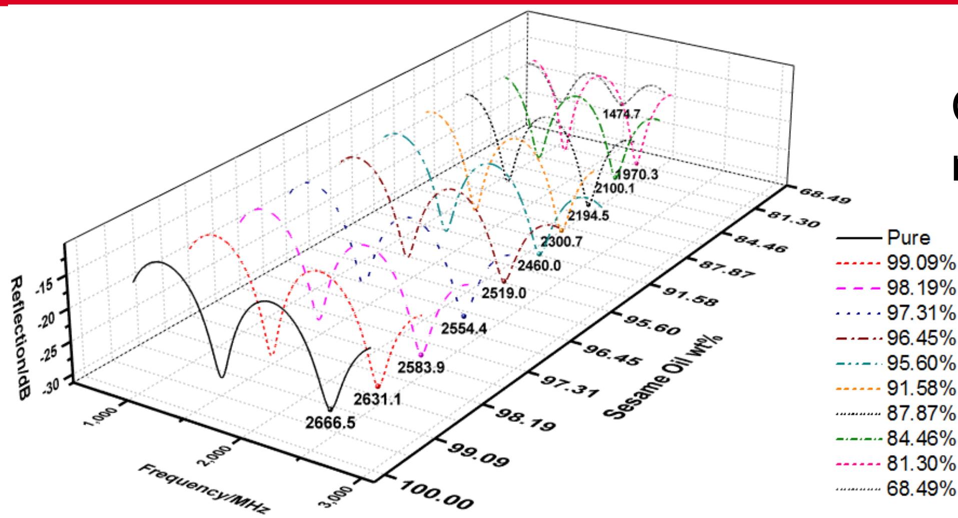
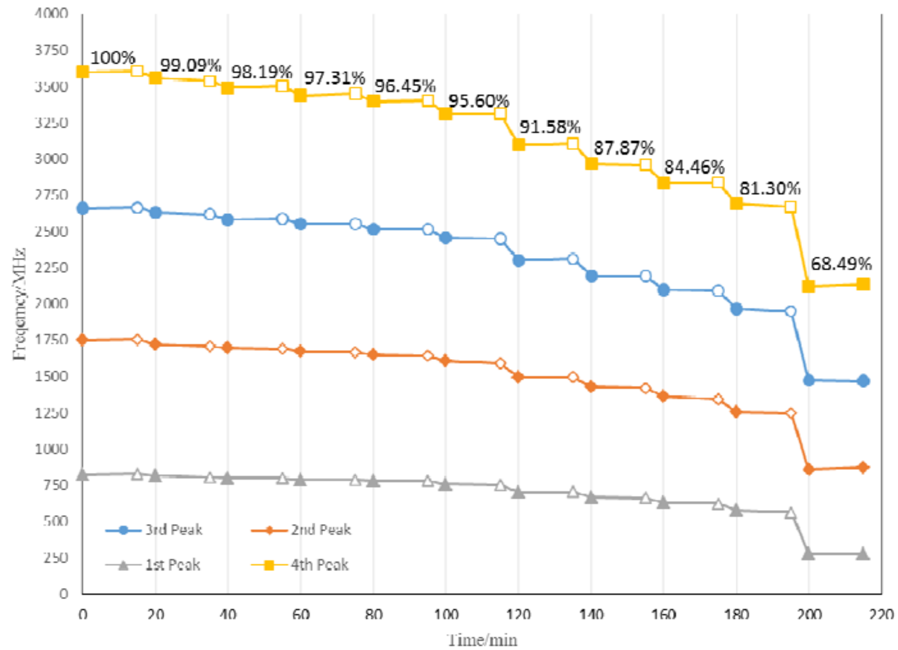
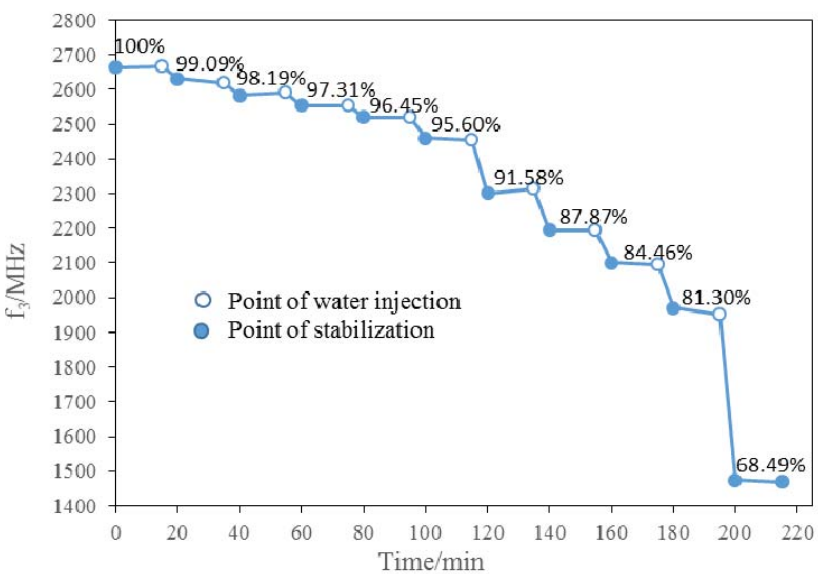
Online Monitoring of Fluid Dielectric Constant



Continuous monitoring of sesame oil/water mixture with varying water contents





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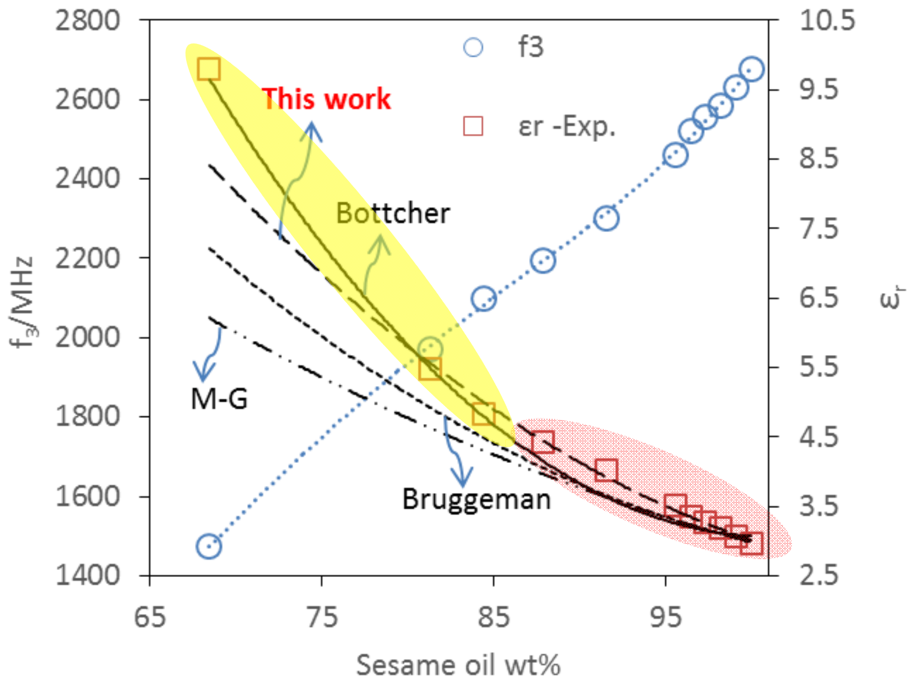
Mixing Rule for ε_r of Mixtures

Comparison between experimental values and model predictions of $\varepsilon_{r,mix}$ for sesame-water binary mixture



Maxwell-Garnett: $$\frac{\varepsilon_{r,mix}-\varepsilon_{r,s}}{\varepsilon_{r,mix}+2\varepsilon_{r,s}} = \frac{\varepsilon_{r,d}-\varepsilon_{r,s}}{\varepsilon_{r,d}+2\varepsilon_{r,s}}\varphi_d$$

Bruggeman: $$\frac{\varepsilon_{r,mix}-\varepsilon_{r,d}}{\varepsilon_{r,s}-\varepsilon_{r,d}}\left(\frac{\varepsilon_{r,s}}{\varepsilon_{r,mix}}\right)^{1/3} = 1-\varphi_d$$

Bottcher: $$\frac{\varepsilon_{r,mix}-\varepsilon_{r,s}}{3\varepsilon_{r,mix}} = \frac{\varepsilon_{r,d}-\varepsilon_{r,s}}{\varepsilon_{r,d}+2\varepsilon_{r,mix}}\varphi_d$$

Proposed mixing rule based on thermodynamic theory

$$\ln \varepsilon_{r,mix} = \sum_i x_i \ln \varepsilon_{r,i}$$

- The new mixing rule dramatically improved prediction at relatively low water content;
- The Bottcher's model performs well for high water content.

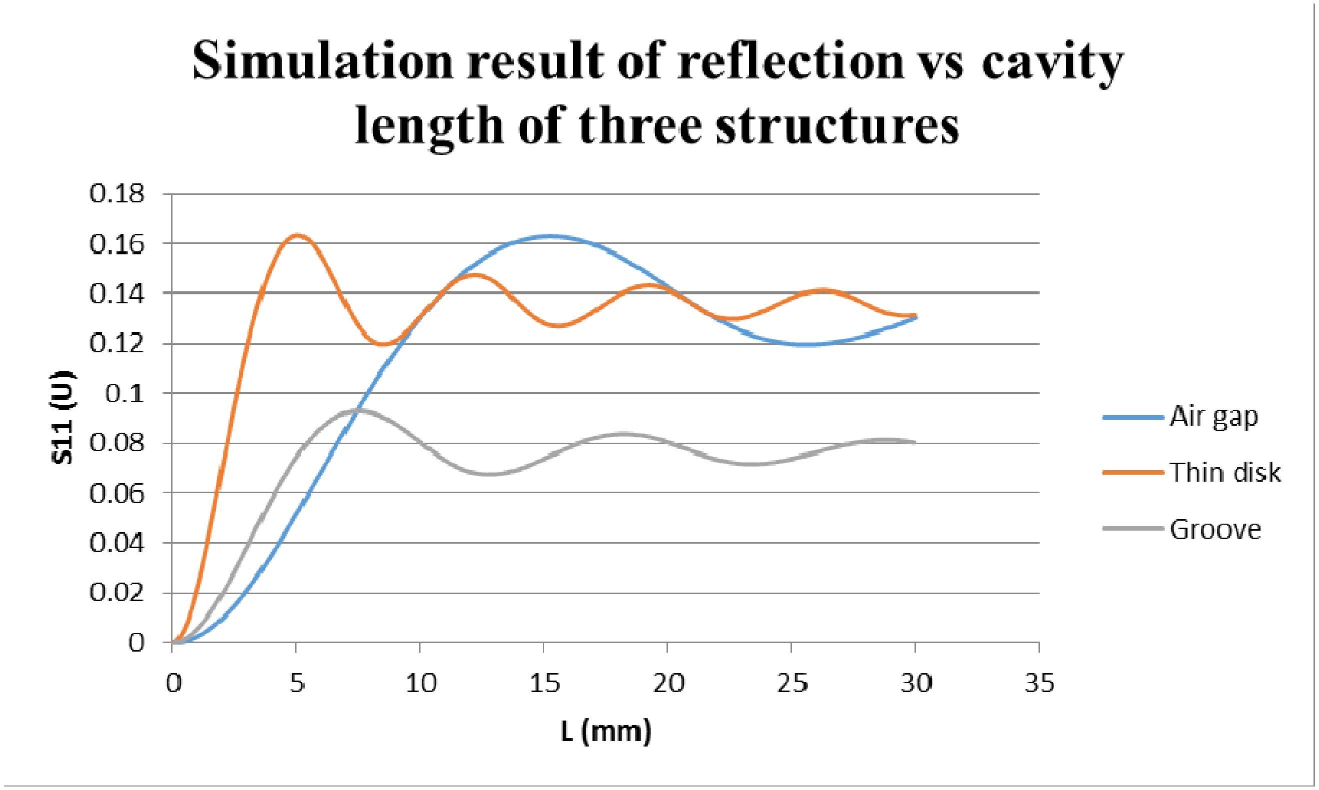
Conclusions

- Developed the MCCC-FPI sensor and establish its operating protocol and data processing models for measuring fluid dielectric constant in microwave frequency range;
- Developed new theoretical mixing rule for improved correlation and prediction of fluid mixture dielectric constant based on the knowledge of pure fluid dielectric properties; and
- The application of this sensor for measuring ε_r for packed ceramic powders is to be tested.

Q&A

Thank You

MCCC-FPI: Reflector width as a function of intensity



*Courtesy of Clemson

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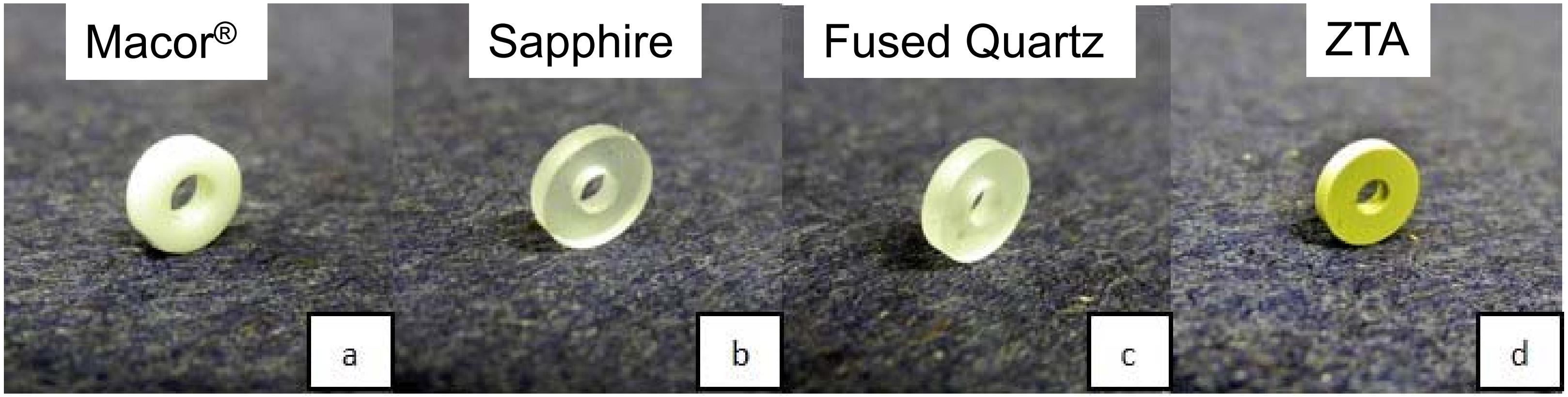
MCCC-FPI Materials: Reflectors



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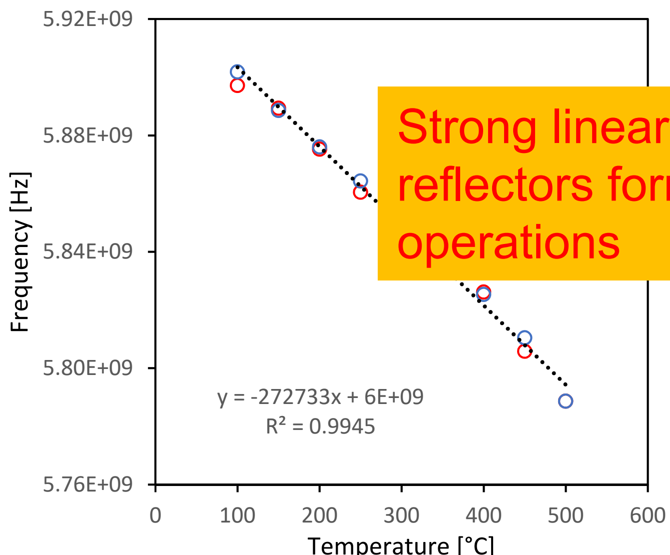
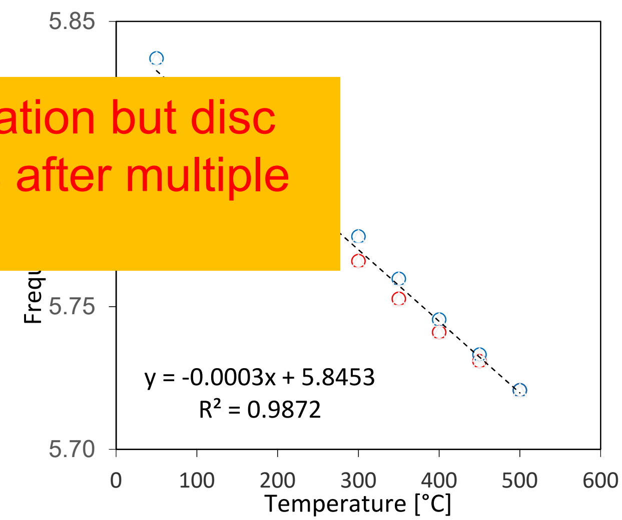
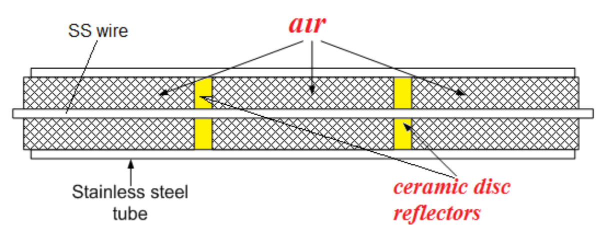
Single-Point MCCC FPI
- Ceramic Disc-Alumina Dielectric



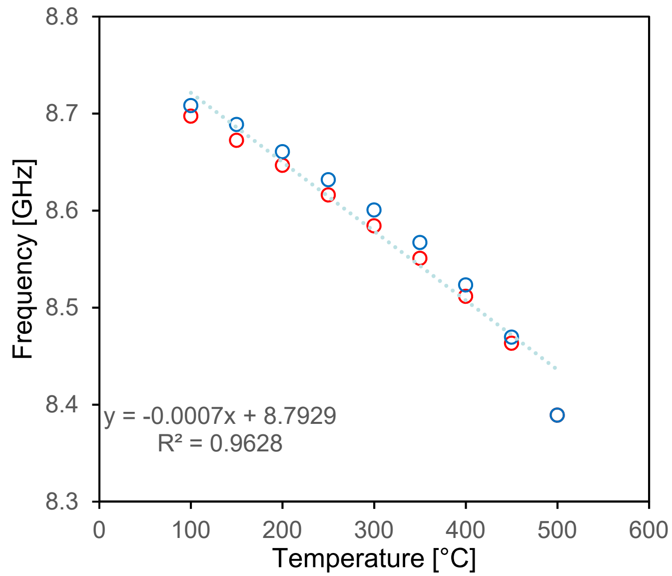


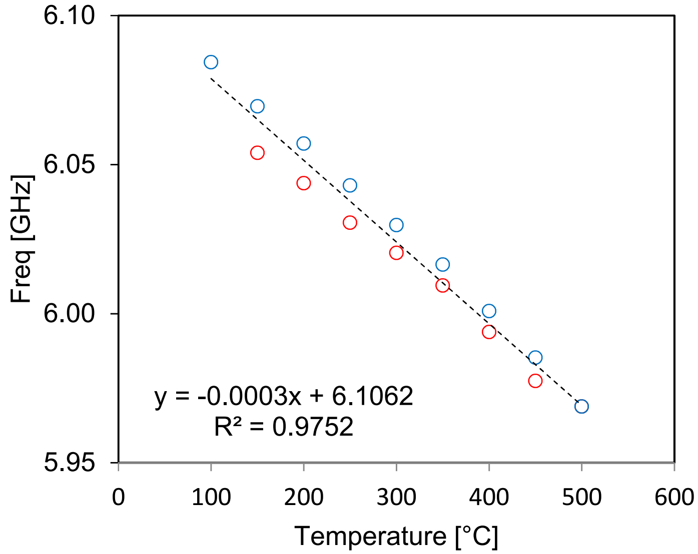
Strong linear *f* ~ *T* relation but disc reflectors form cracks after multiple operations



Shift of resonant frequency as temperature increases

Single-Point MCCC FPI -Ceramic Disc-Alumina Dielectric





Shift of resonant frequency as temperature increases