Additive Manufacturing of Smart Parts with Embedded Sensors for In-Situ Monitoring in Advanced Energy Systems

DE-FE0012272

Investigators:

Hai-Lung Tsai (PI), Ming Leu, Missouri S&T
Hai Xiao, Clemson University
Junhang Dong, University of Cincinnati

Program Manager:

Richard Dunst, NETL

NETL Crosscutting Technology Research Review Meeting, Pittsburgh, PA, April 30, 2015

Outline

- Introduction
- Technical Progresses
- Summary of Research Accomplishments
- Future Work

Demands

- **Sensors and instrumentation are needed in advanced energy systems for**
  - Advanced process control/optimization
  - Health status monitoring of key components
  - System maintenance and lifecycle management

- **Sensors need to survive and operate in the high-T, high-P and corrosive/erosive harsh environments for a long time**

Status

- Traditionally, sensors are attached to or installed onto the component after the structure is fabricated
- Costly and complicated sensor packaging are required before installation
- Poor survivability and reliability of the sensors
- Discrepancy between the sensor reading and the actual status
- Potential performance compromise of the host materials/structures

Opportunities

- Smart parts – widely used and proven successful in civil engineering for structural health monitoring (SHM)
- Provide the real-time information of the component and system
- Reduce the complexity in sensor packaging and installation
- Increase the robustness and reliability of the system

Objectives

- **Main Objective:** Demonstrate the new concept of **sensor-integrated "smart part"** achieved by **additive manufacturing** and embedding **microwave-photonic sensors** into critical components used in advanced energy systems

- **Specific objectives**
  - Robust, distributed and embeddable microwave photonic sensors
  - Additive manufacturing techniques for rapid fabrication of "smart parts" and sensors embedment
  - Multifunctional transition layer between the embedded sensor and host material for sensor protection and performance enhancement
  - Models to correlate the sensor readings with the parameters of interest
  - Sensor instrumentation for *in situ* and distributed measurement
  - Feasibility tests and performance evaluation

Project Elements/Overview

- **Performers: Missouri S&T, Clemson, University of Cincinnati**
  - Three-year project started on Oct. 1, 2013
- **Interdisciplinary team**
  - Hai-Lung Tsai (PI), Professor of Mechanical Engineering, Missouri S&T, Modeling and AM of metal parts
  - Ming Leu, Professor of Mechanical Engineering, Missouri S&T, AM of ceramic parts
  - Hai Xiao, Professor of Electrical Engineering, Clemson University, Sensors and Instrumentation, test and evaluation
  - Junhang Dong, Professor of Chemical Engineering, University of Cincinnati, Sensor protections
- **Success criteria:**
  - Demonstrate concept and capability in simulated laboratory environments

Development of robust, distributed and embeddable sensors and instrumentation

Approach: Fully distributed microwave photonic fused silica and sapphire fiber sensors

Hai Xiao
Clemson University

- **Optical carrier based microwave interferometry (OCMI)**
  - Read optical interferometers using microwave
  - Optics as the carrier to perform measurement
  - Microwave as the signal to locate the sensors

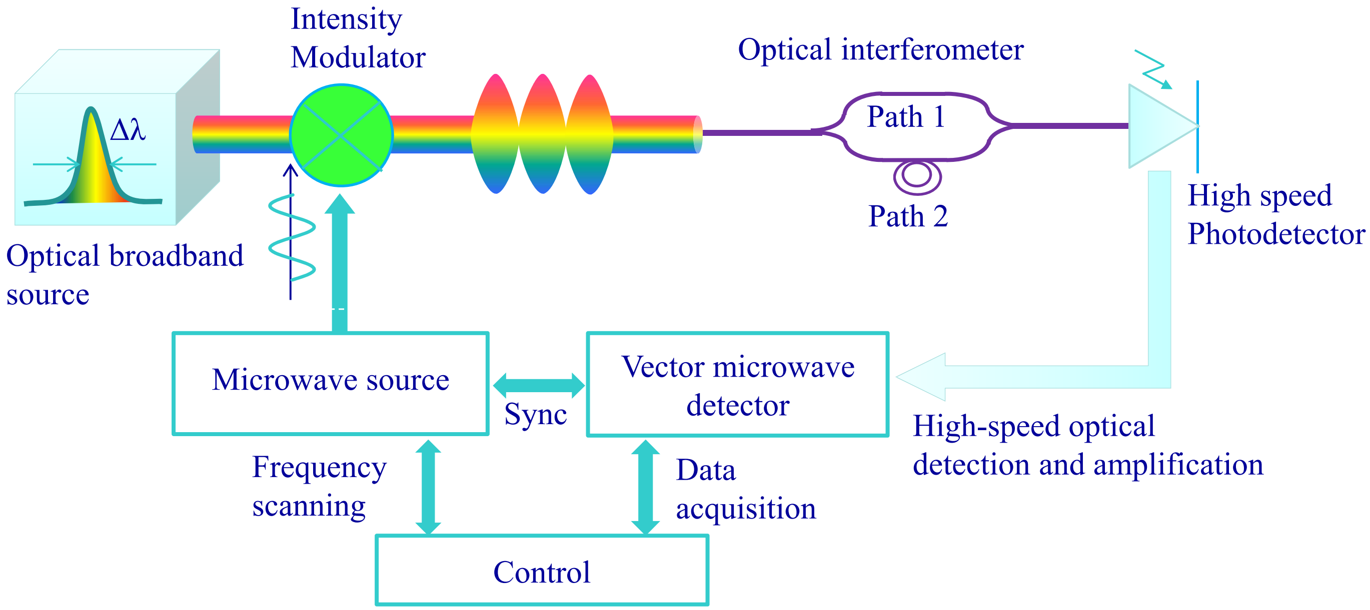
Microwave term

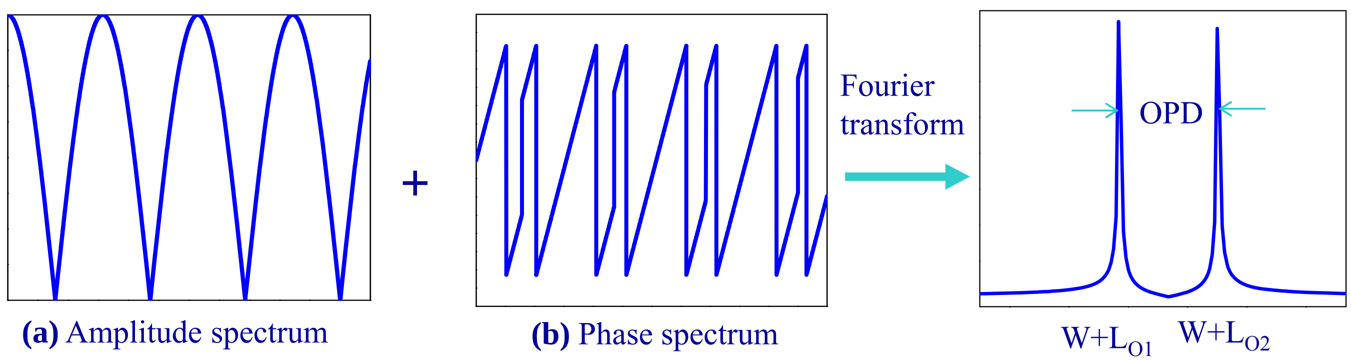
$$|E|^2 = |E_1 + E_2|^2 = 2A^2 + 2A^2 M \cos\left[\Omega \frac{L_{O1} - L_{O2}}{2c}\right] \cos\left[\Omega\left(t + \frac{2W + L_{O1} + L_{O2}}{2c}\right)\right]$$
$$+ 2A^2 \sqrt{\left\{1 + M\cos\left[\Omega\left(t + \frac{W + L_{O1}}{c}\right)\right]\right\}\left\{1 + M\cos\left[\Omega\left(t + \frac{W + L_{O2}}{c}\right)\right]\right\}} \cdot \int_{\omega_{min}}^{\omega_{max}} \cos\left(\omega \frac{L_{O1} - L_{O2}}{c}\right) d\omega$$

Optical term

J. Huang, et al., *Optics Express*, 2014.

OCMI Concept





(a) Amplitude spectrum

$$2A^2 M \cos\left[\Omega \frac{L_{O1}-L_{O2}}{2c}\right]$$

(b) Phase spectrum

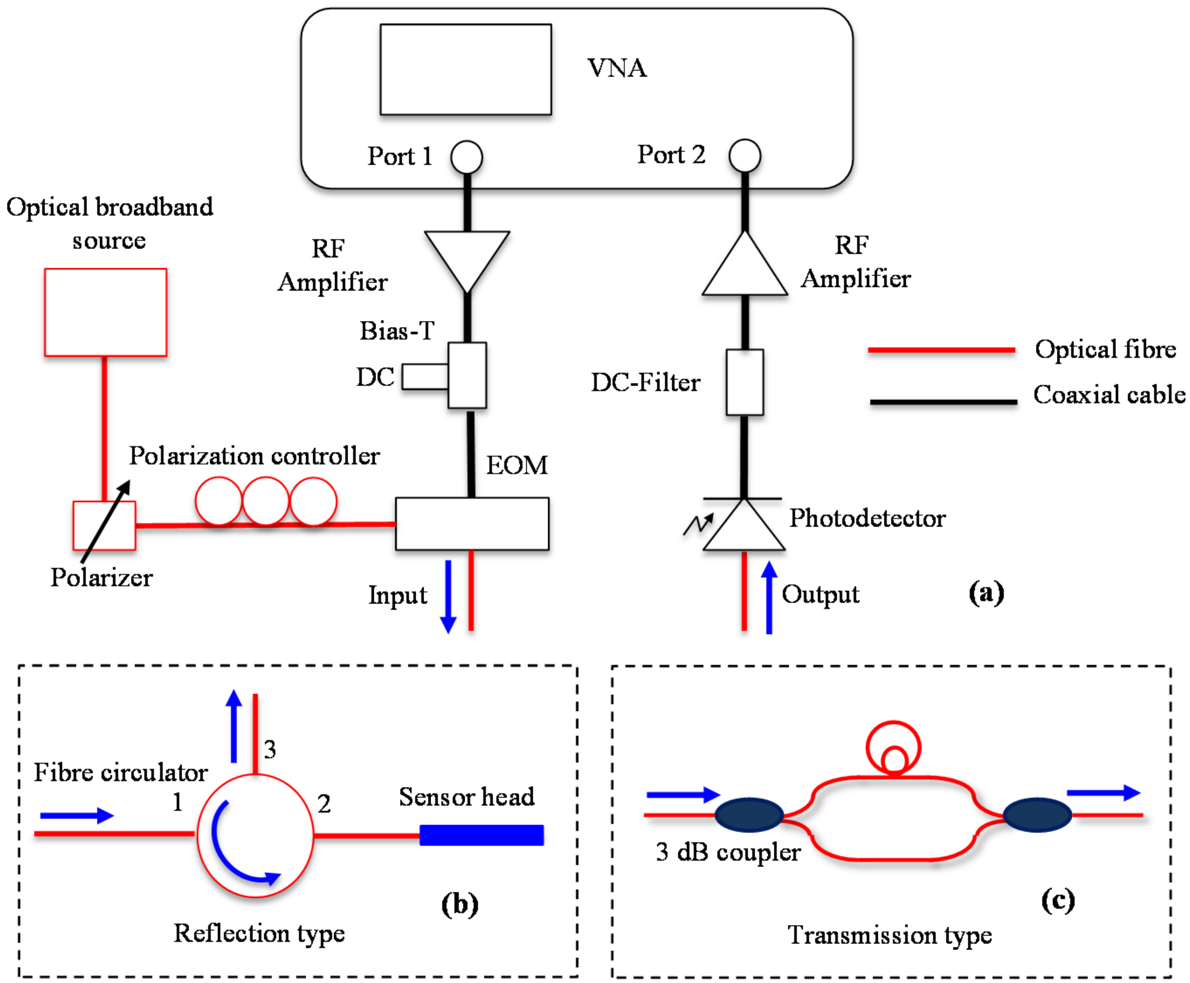
$$\Omega\left(\frac{2W+L_{O1}+L_{O2}}{2c}\right)$$

(c) Propagation delay

Measurement

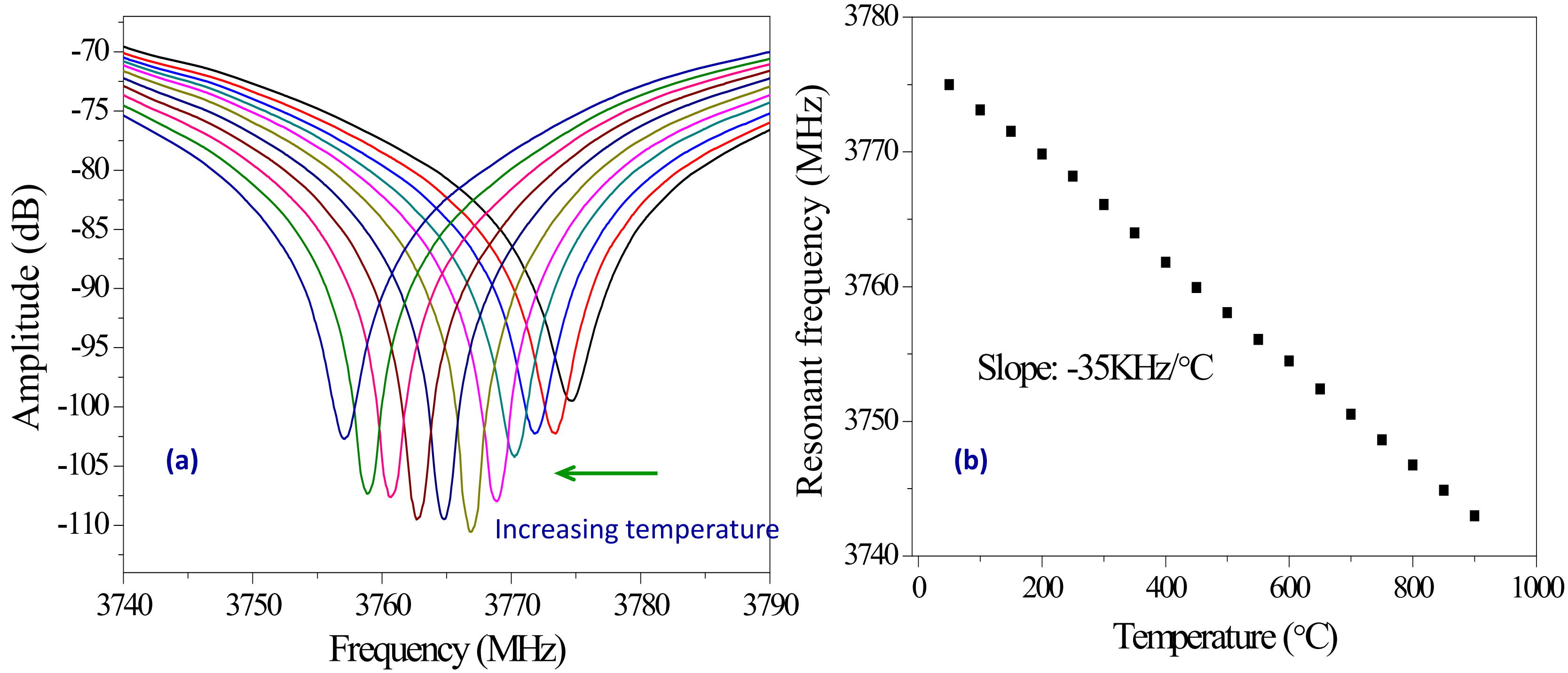
Location

Instrumentation



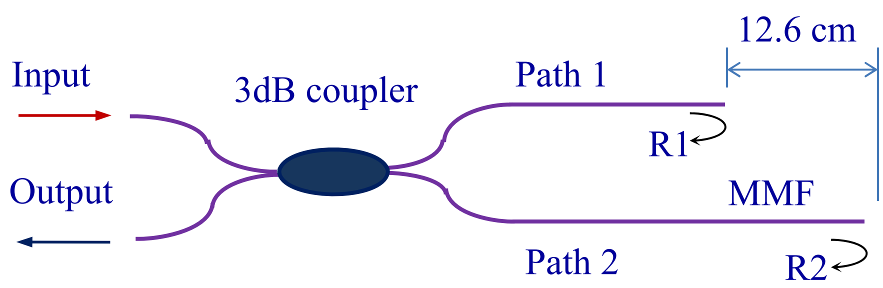
J. Huang, et al., *Optics Express*, 2014.

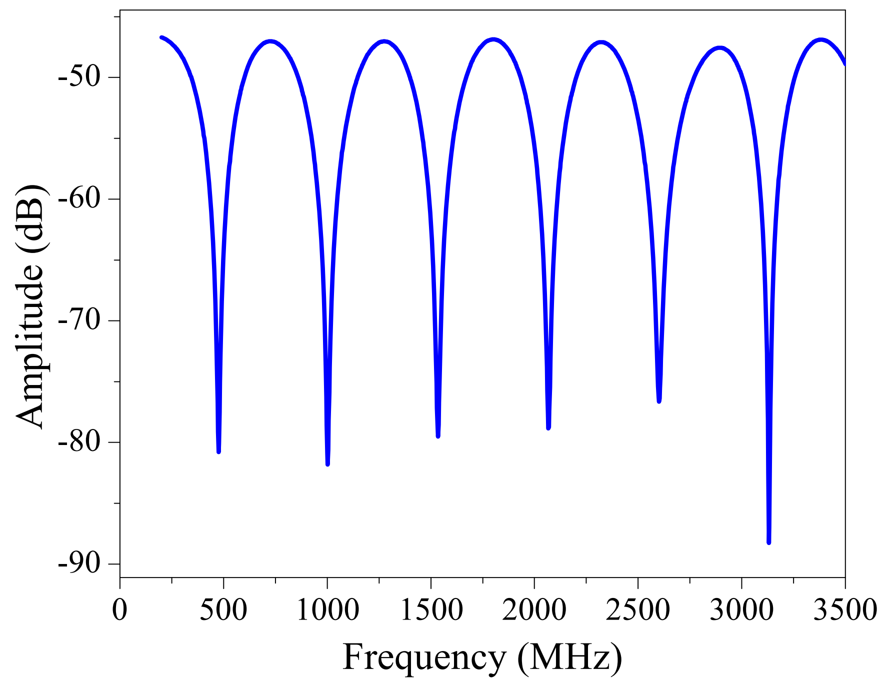
SMF OCMI Temperature Sensing



- Fabry-Perot OCMI using singlemode fiber
- Sensor length of 3cm
- Excellent signal quality
- Linear response to temperature up to 900□C

MMF: Low Multimodal Influences

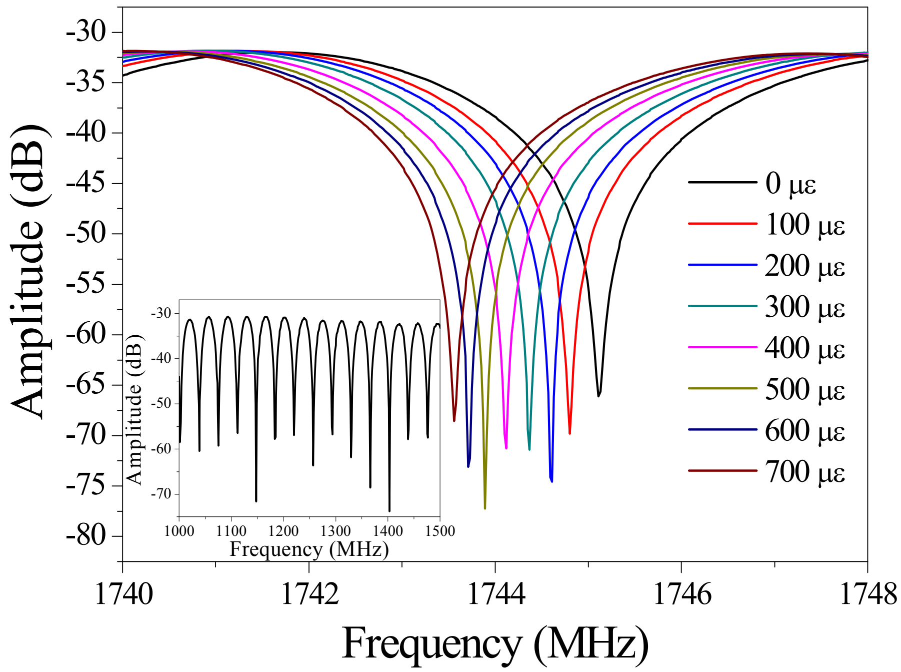


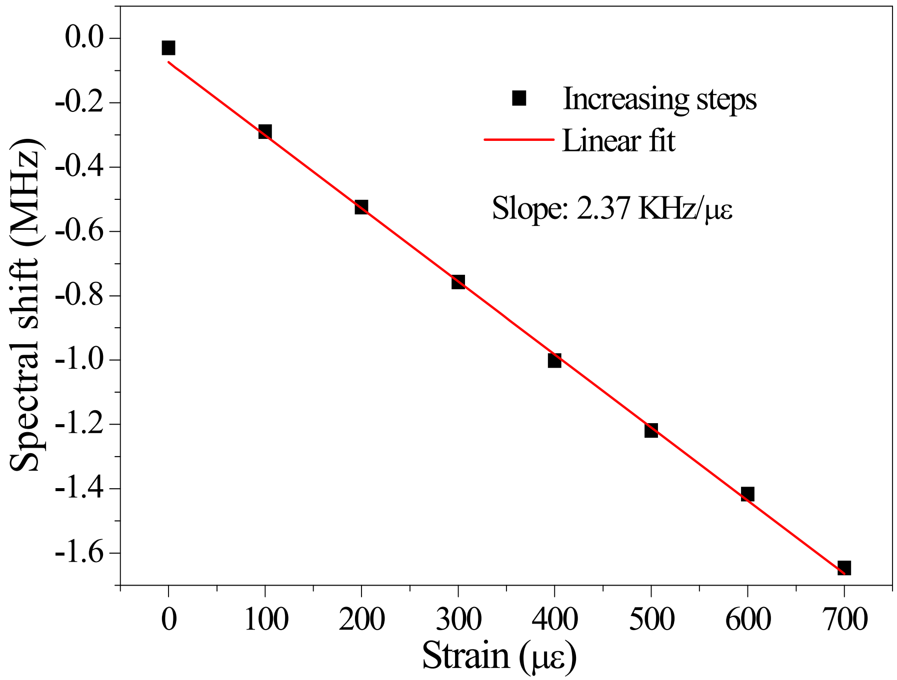


- **Michelson interferometer using multimode fibers (fused silica core of 200µm in diameter, 220µm cladding)**
- **Excellent fringe visibility**
- **No observable multimodal influences**

L. Hua., Manuscript submitted to *Applied Optics*

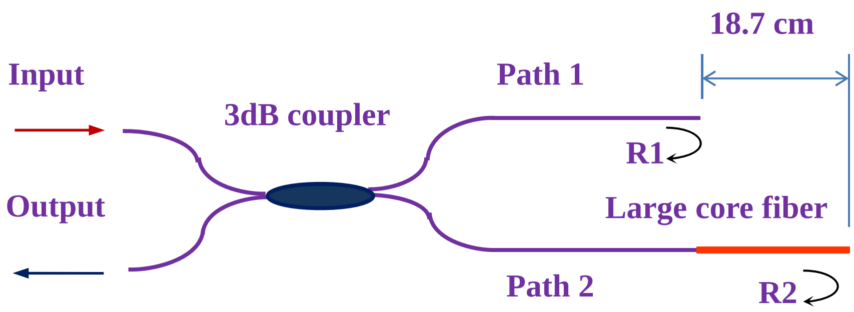
Strain at 600ºC, 200μm Fiber



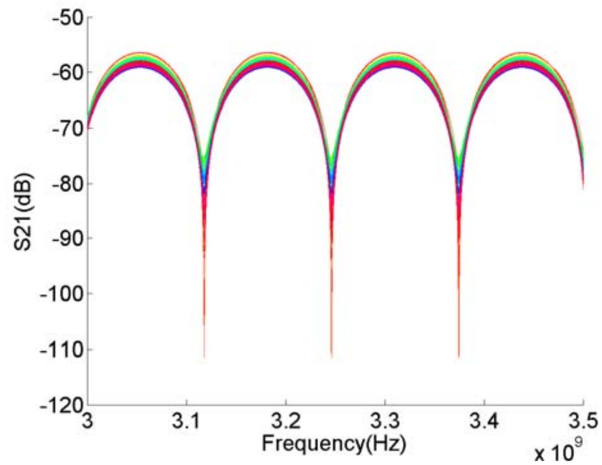


- **High sensitivity for strain sensing (~10με) at 600ºC**
- **Small temperature cross sensitivity**

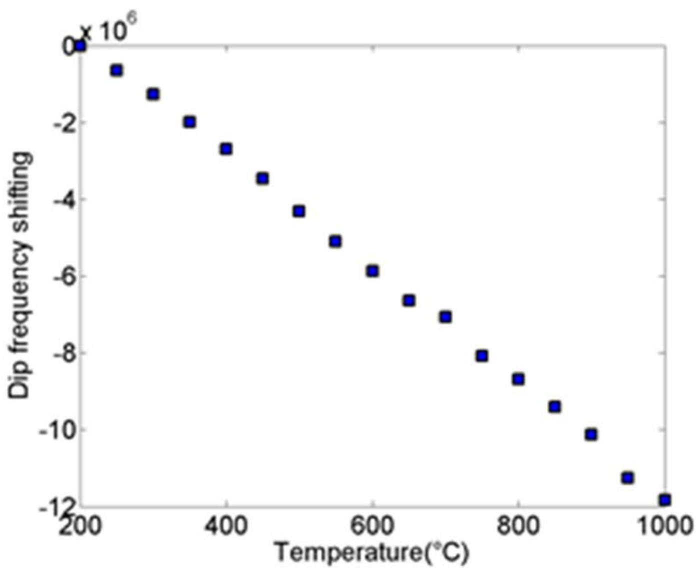
Quartz rod (800μm dia. Uncladded)



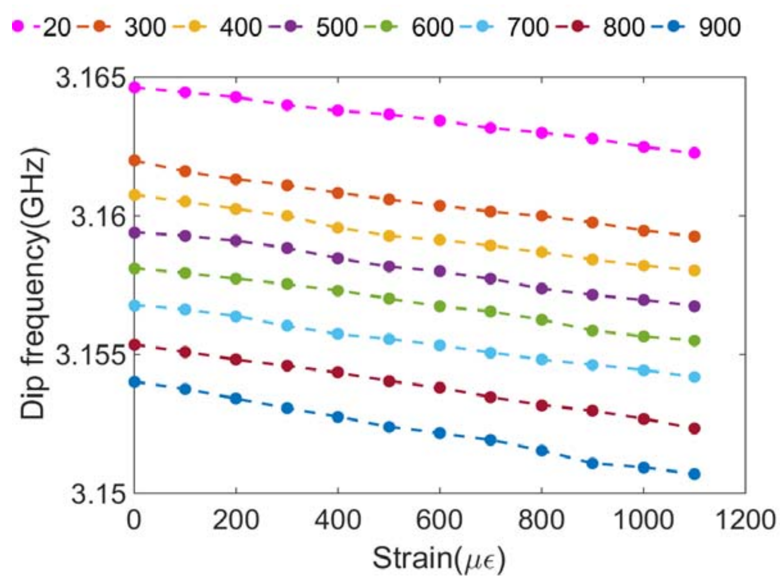
Fused silica rod 800μm dia.



Interference fringes

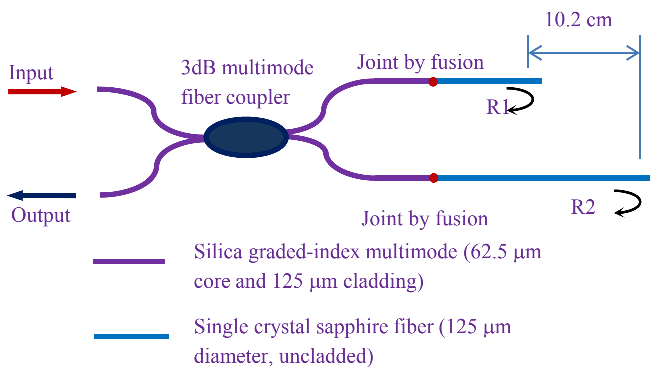


High temperature response

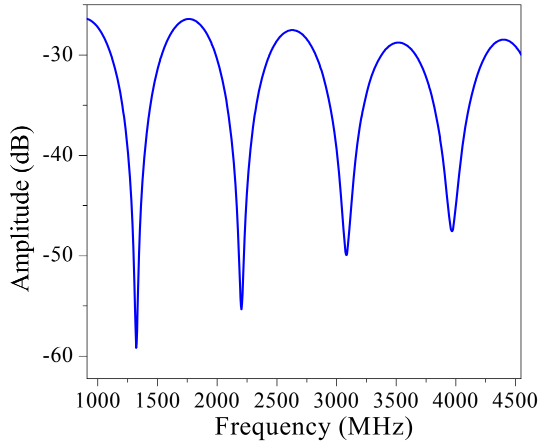


Quartz rod can be used to measure strains at high temperatures

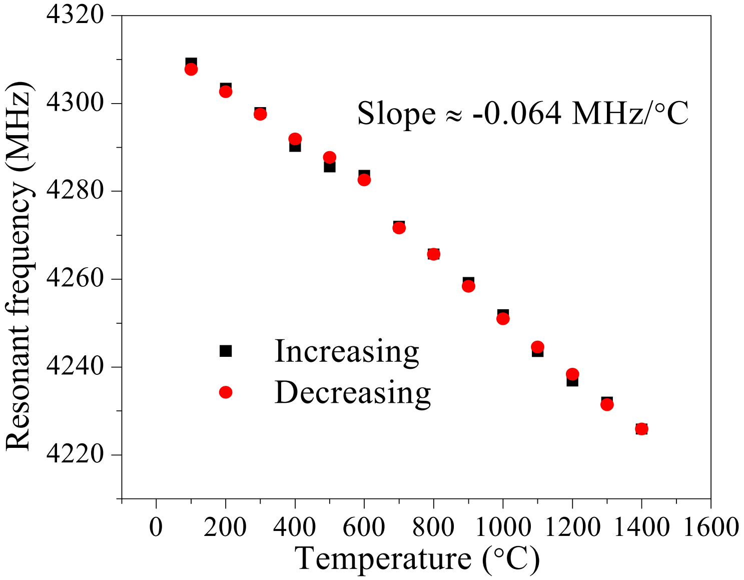
Sapphire Michelson Sensor (125 µm)



Sapphire fiber Michelson OCMI



Excellent fringe visibility > 30dB

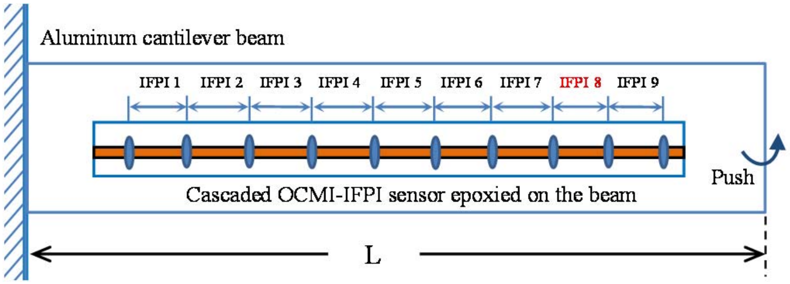


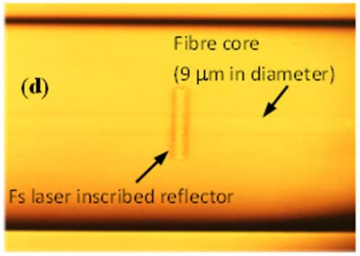
J. Huang, et al., *IEEE Photonics Technology Letters*, 2015.

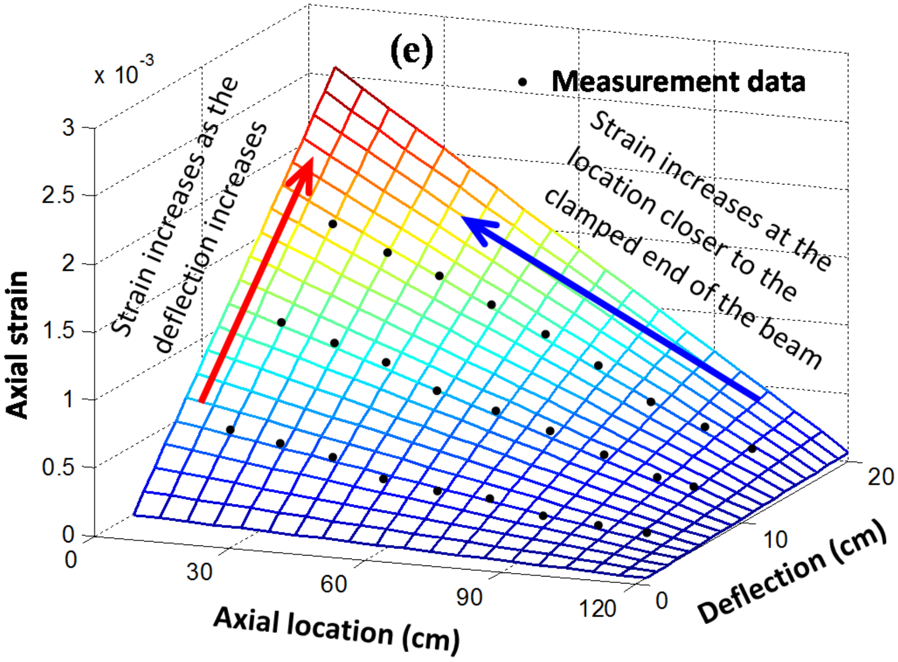
Fully distributed sensing

- Spatially continuous (no dark zone), fully distributed sensing.
- High spatial resolution (<1cm)
- High sensitivity (~με)
- Flexible gauge length (1cm – 100m)
- Long reaching distance (~km)
- Can be implemented using various fibers including sapphire and quartz rods

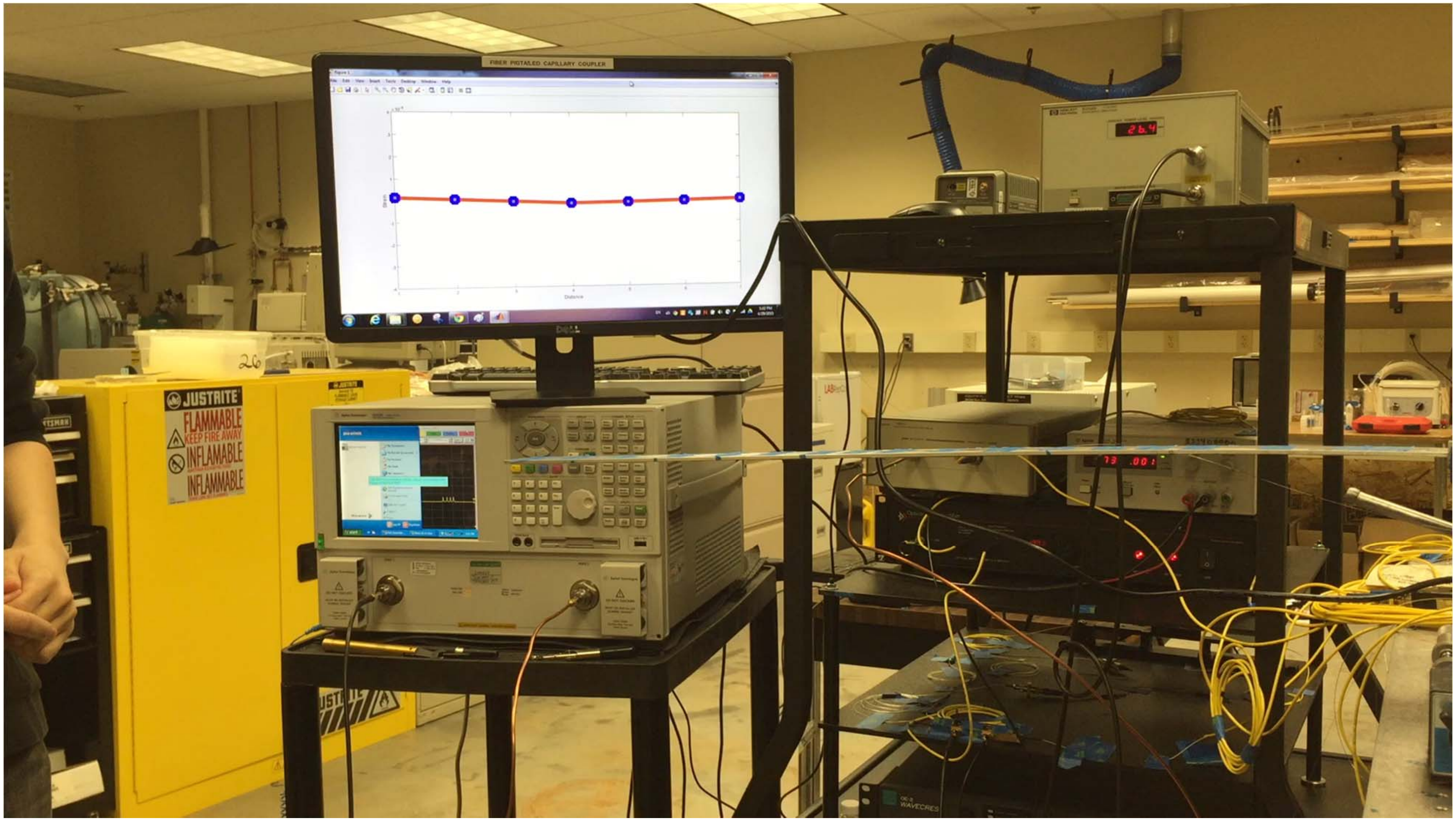
J. Huang, et al., *Optics Express*, 2014.







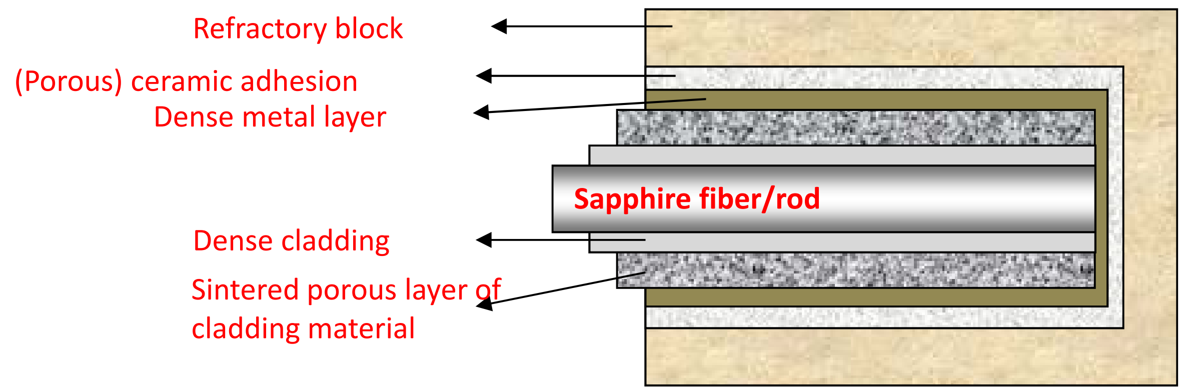
Distributed Strain Sensing



Develop a multifunctional transition layer between the embedded sensor and the host material for sensor protection

Approach: Design and select ceramic and metal materials based on structural and chemical potteries

Junhang Dong,
University of Cincinnati

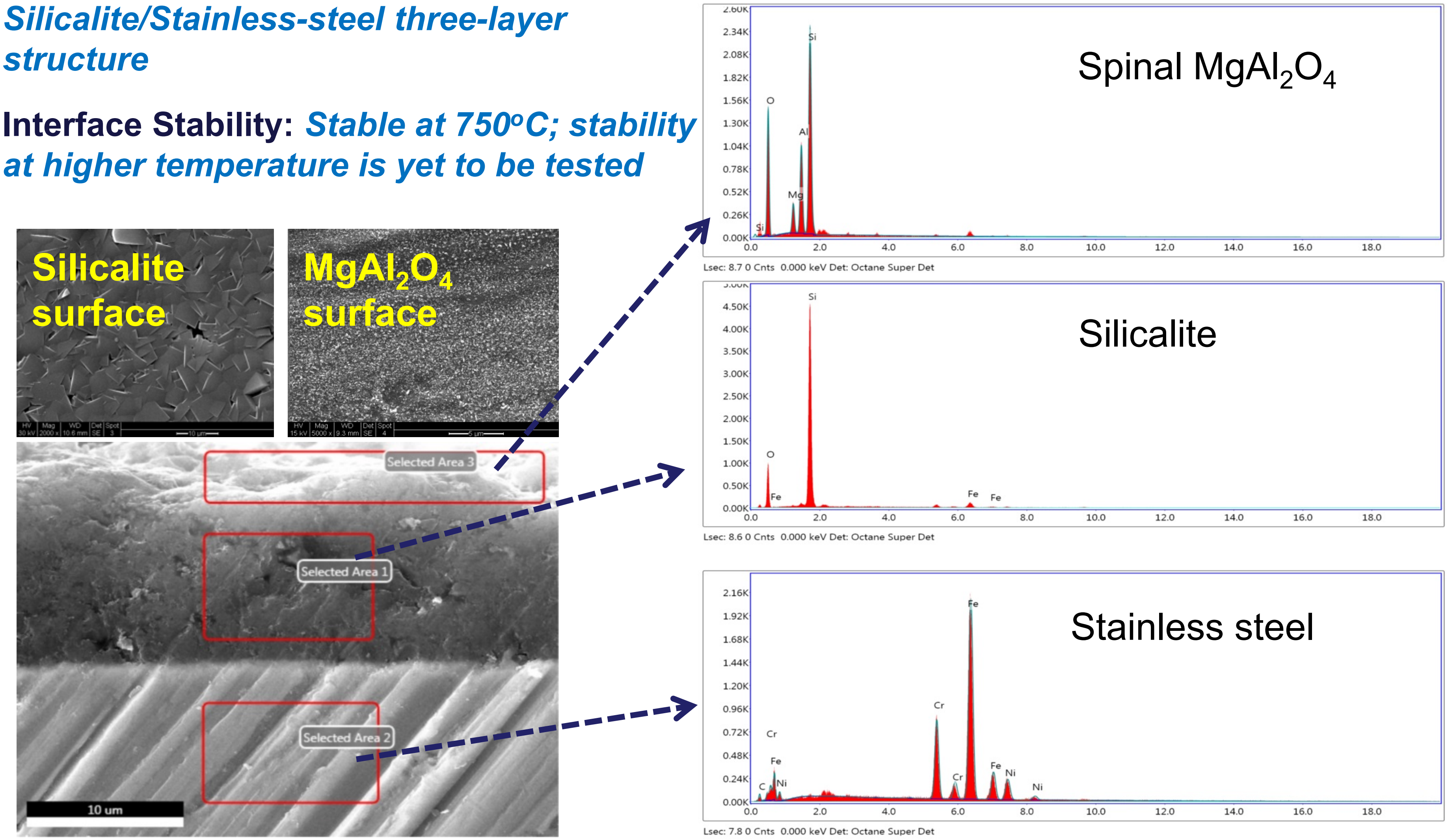


Interface Thermochemical Stability in the Layered Structure for Sensor Protection/Installation

University of Cincinnati

Solid-Solid Connections: ***$MgAl_2O_4$ / Silicalite/Stainless-steel three-layer structure***

Interface Stability: ***Stable at 750°C; stability at higher temperature is yet to be tested***

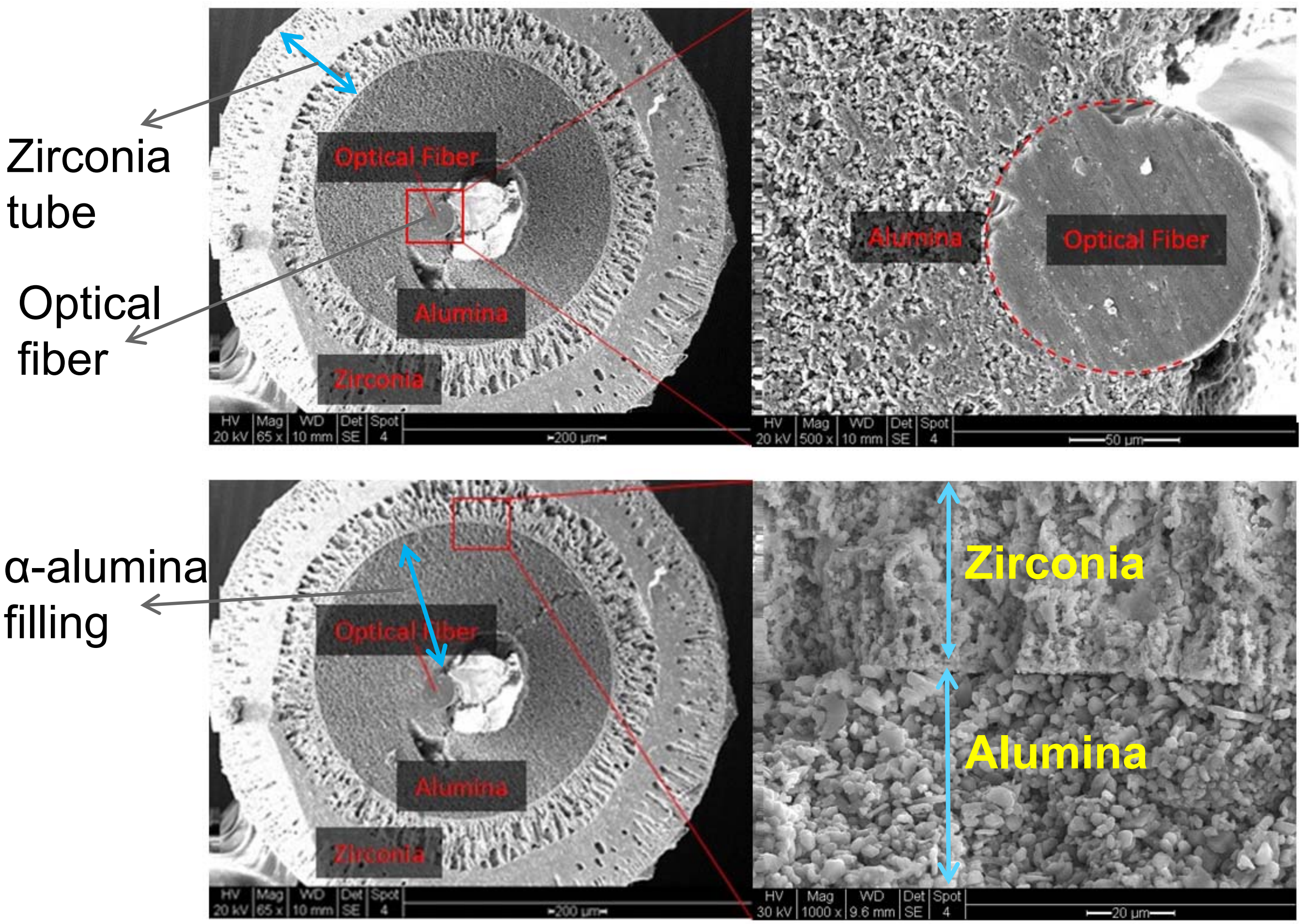


Multilayer-Protected FOS Fabrication

Structure: *(Zirconia)/(α-alumina)/(silica optical fiber)*

Fabrication: *inserting optical fiber into zirconia small tube by alumina adhesives*

Stability: *Fiber strongly attached to structure after thermal cycles; tested stability at 750^{o}C*



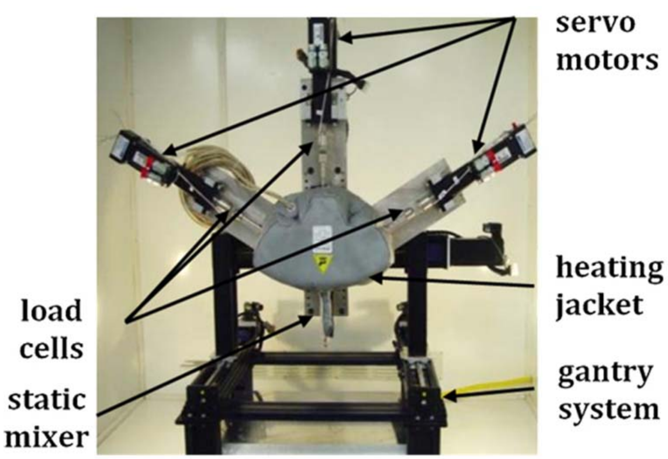
Additive Manufacturing of Liner Blocks (Ceramic) with Embedded Sensors

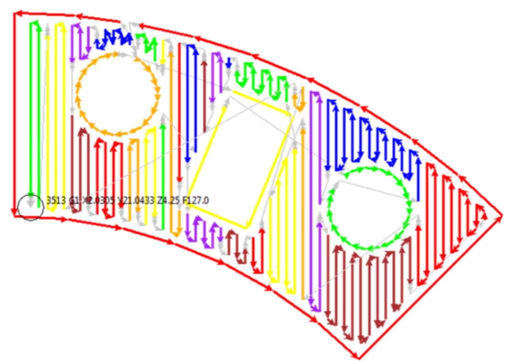
Approach: Multi-extruder freeze-form extrusion based additive manufacturing

Ming Leu
Missouri University of Science and Technology

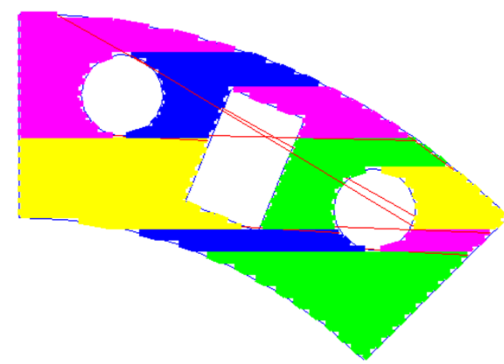
Tool Paths Planning and Optimization

- **Main Advantages of Our Software**
  - Capability of embedding sensors
  - Avoid unnecessary starts and stops
  - Reduce fabrication time





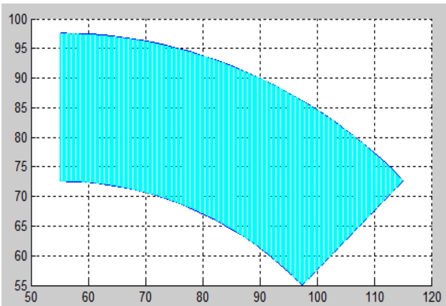
Tool path generated by Skeinforge (many stops)



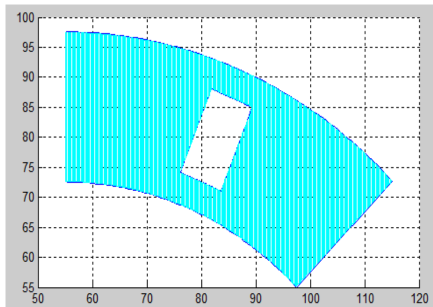
Tool path generated by our software (few stops)

Adaptive Rastering

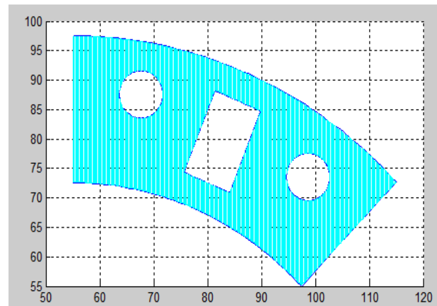
- This technique can reduce geometrical errors and fabrication time simultaneously.



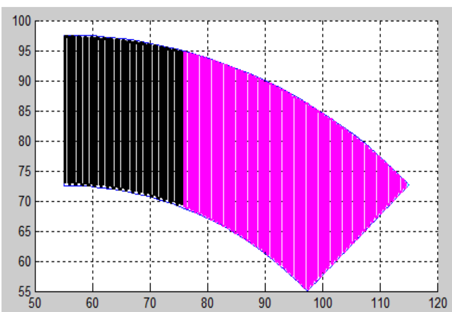
Travel= 7055 mm



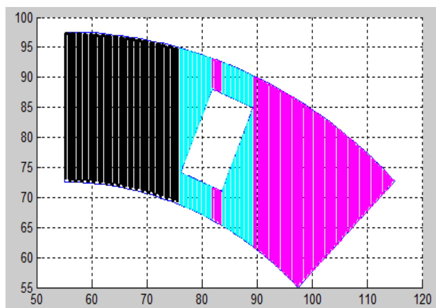
Travel= 6441 mm



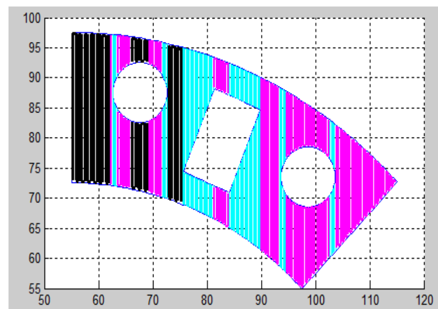
Travel= 5835 mm



Travel= 3455 mm



Travel= 3590 mm

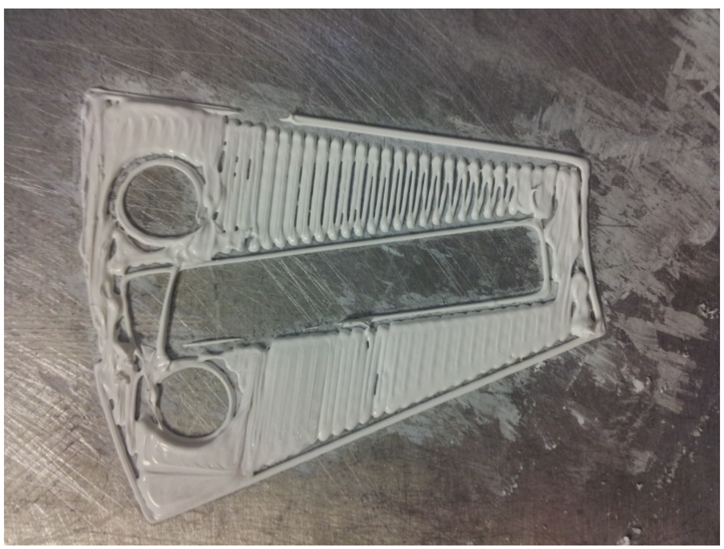


Travel= 3508 mm

* Cyan: 0.2 mm width; Magenta: 0.35 mm; Black: 0.55 mm

Tuning the Process Parameters

- Process parameters tuned include nozzle speed, ram speed, raster spacing, layer thickness, temperature of chamber, temperature of paste, start dwell time, stop distance, start and stop forces.

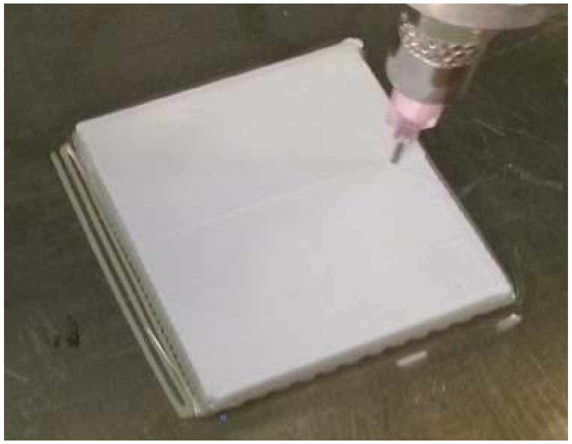


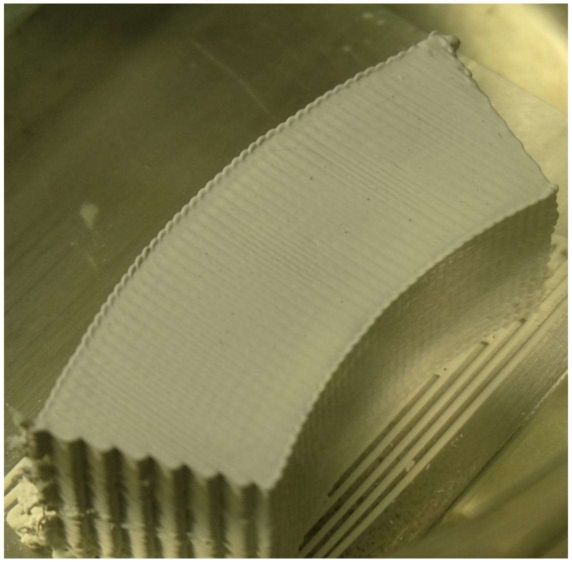
Before tuning the parameters

After tuning the parameters

Fabricating the Designed Parts

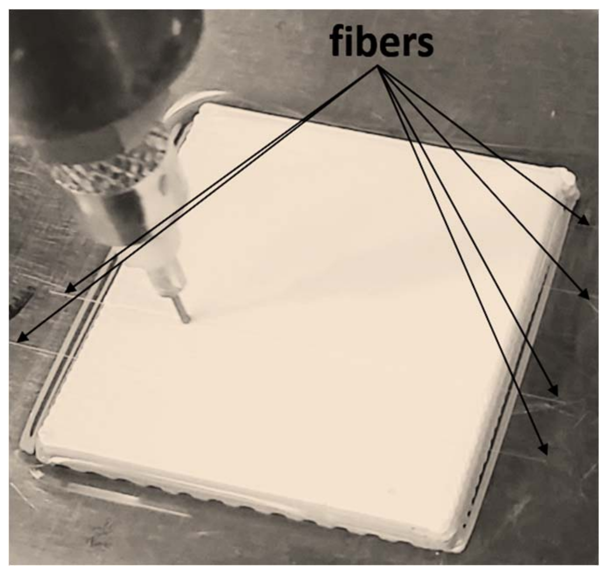
- More sample parts fabricated using the developed process.





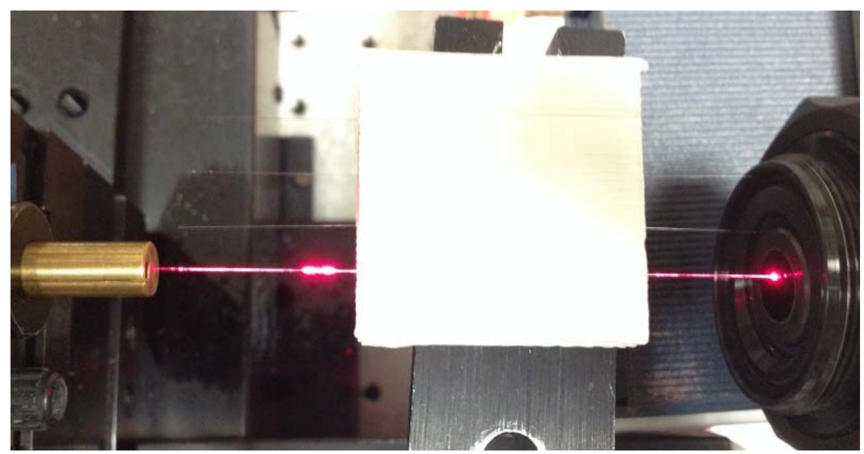
Embedding Fibers in Parts

- Silica and sapphire fibers were embedded in the parts during the fabrication process.
- The objective was to examine the effects of fabrication process, sintering process, material interaction, and part shrinkage on the fibers.



Testing of Parts with Embedded Sesors

- Attenuation tests performed at Clemson University showed that the **sapphire fibers were not damaged**.
- Measurements of 4 sapphire fibers showed the total optical loss of 5dB.
- The causes of attenuation is currently under investigation.



Additive Manufacturing of Pipe (Metal) with Embedded Sensors

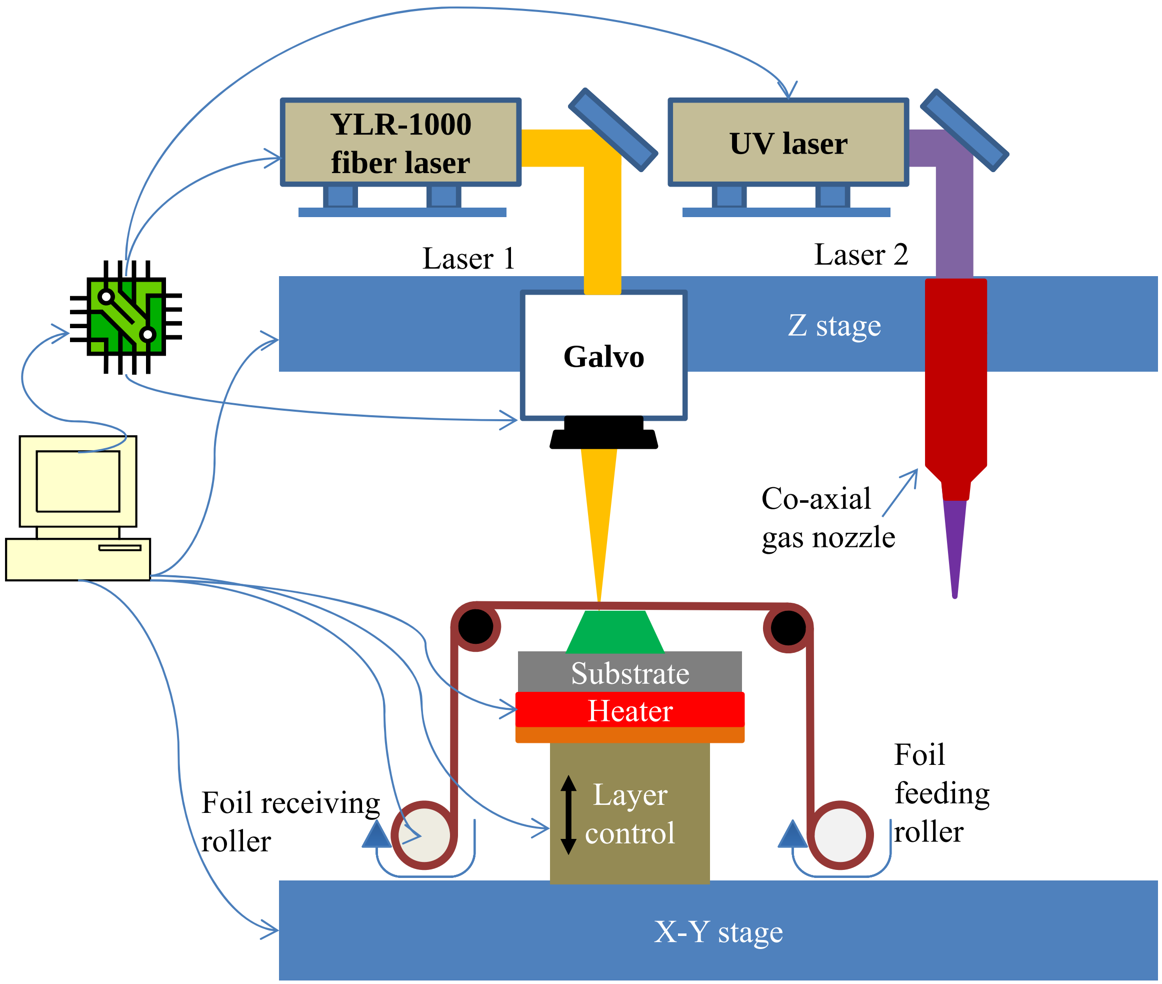
Approach: Foil-Based Dual-Laser Additive Manufacturing Technology

Hai-Lung Tsai

Missouri University of Science and Technology

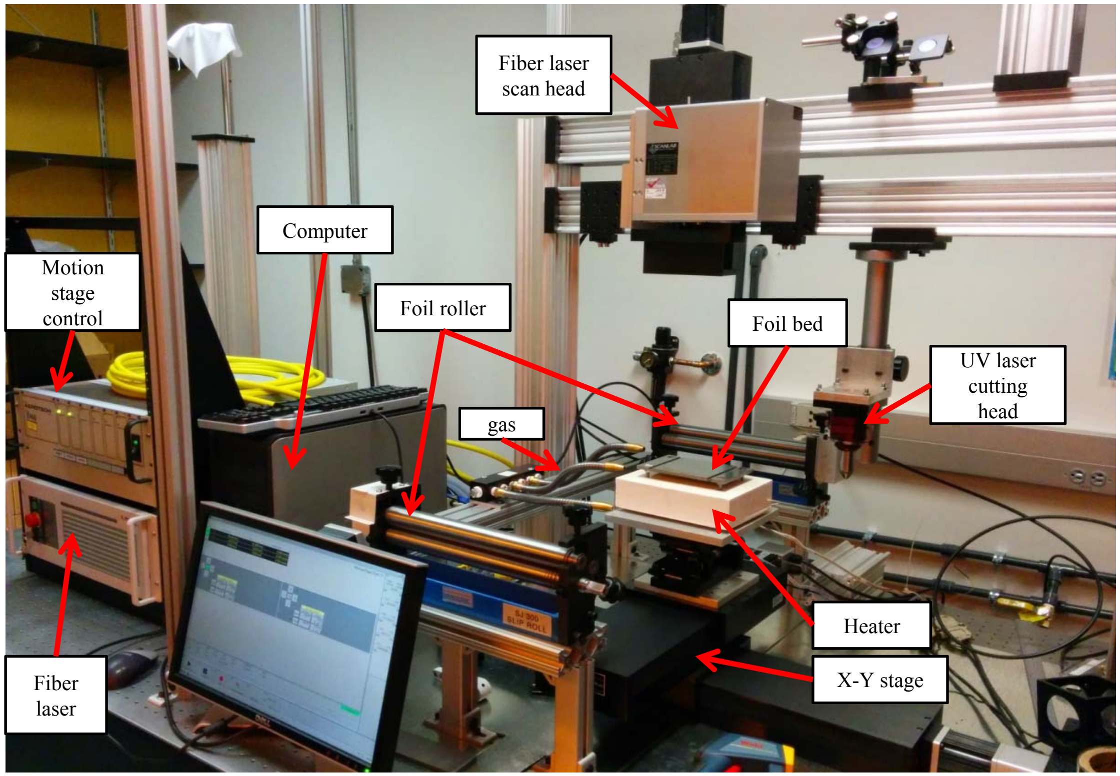
Foil-Based Dual-Laser AM Technology

❑ **System Schematic Overview**

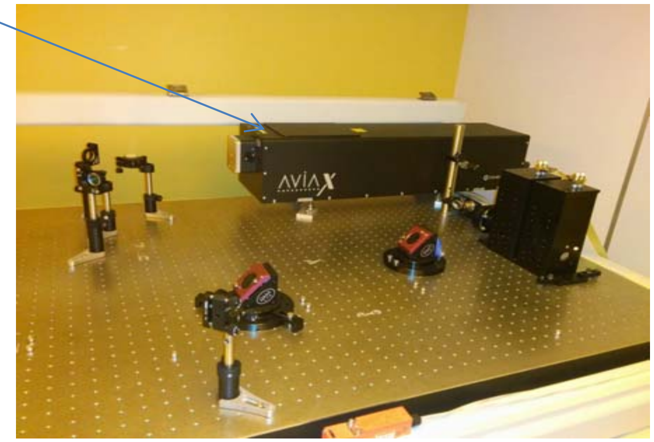


Foil-Based Dual-Laser AM Technology

- Hardware implementation



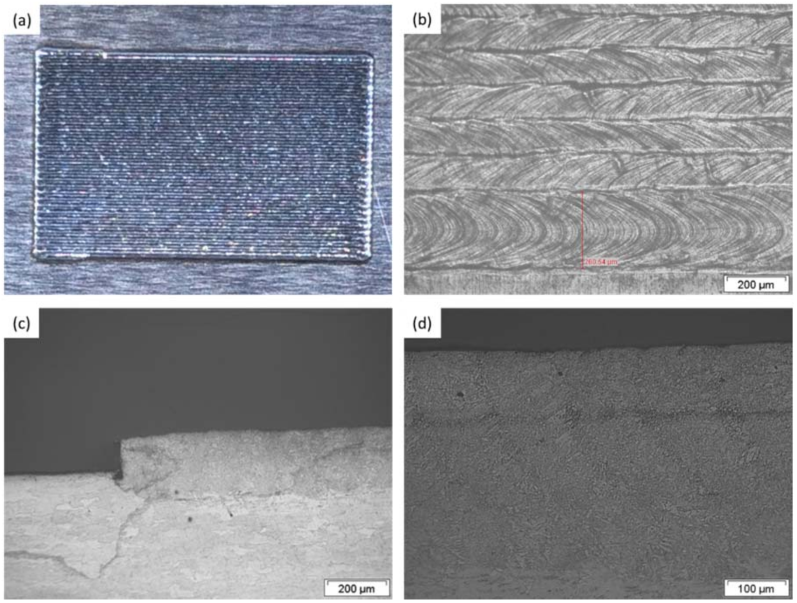
UV laser



- Software development and integration

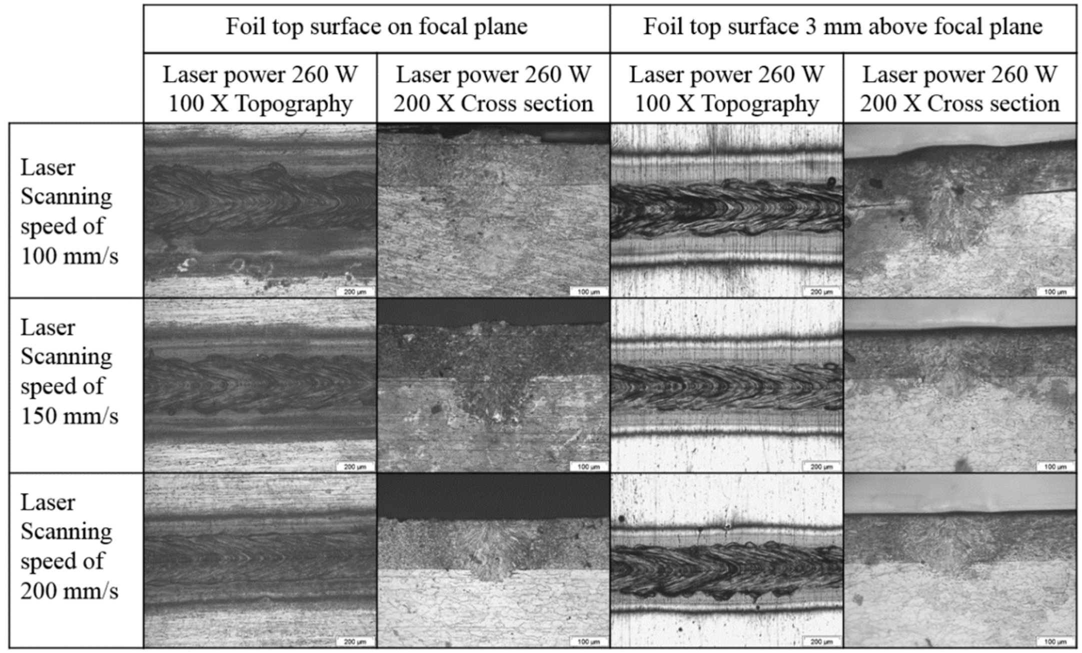
The home designed and made chiller

Results: High power laser welding of foils



(a) The photo of welding surface, (b) a detailed surface morphology of melting pool, (c) the cross section of single-layer surface welding, (d) the cross section of two-layers surface welding.

- Surface finish can be improved by laser re-melting process.

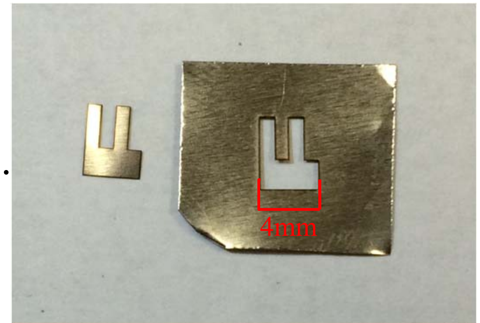


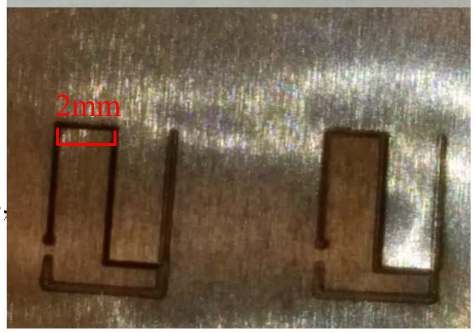
Comparison between welding performed on and off the focal plane.

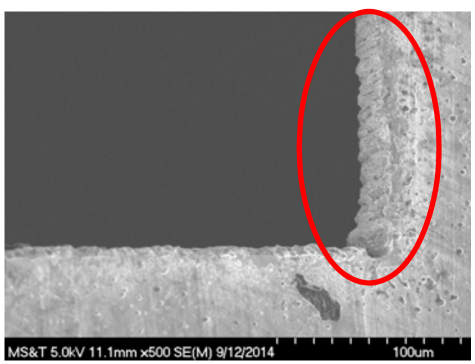
Surface ripple (roughness) and welding depth limit the processing parameter window. A slow scanning speed offers deep welding, but leads to greater ripples on the top surface. Increase the scanning speed at the same laser power decreases penetration depth.

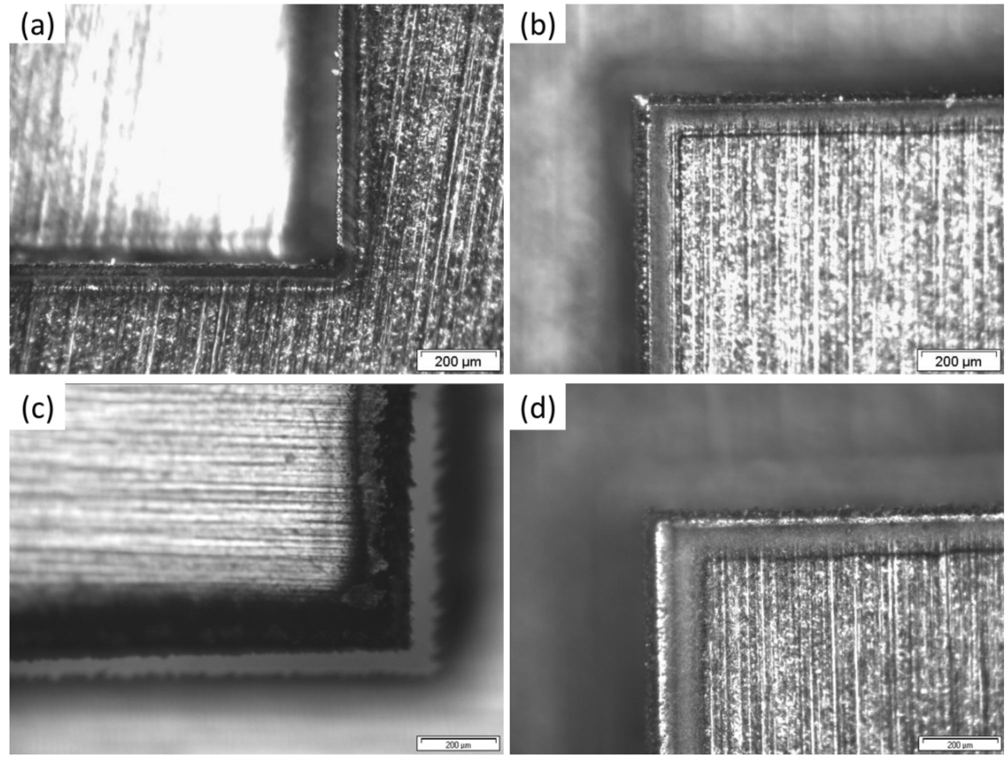
Results: UV laser precision cutting of foils

- Clean cutting edge.
- Minimum metal deformation.
- Limited heat-affected zone.
- Optimized the process parameters, including laser power, laser repetition rate, cutting speed, and assisting gas.





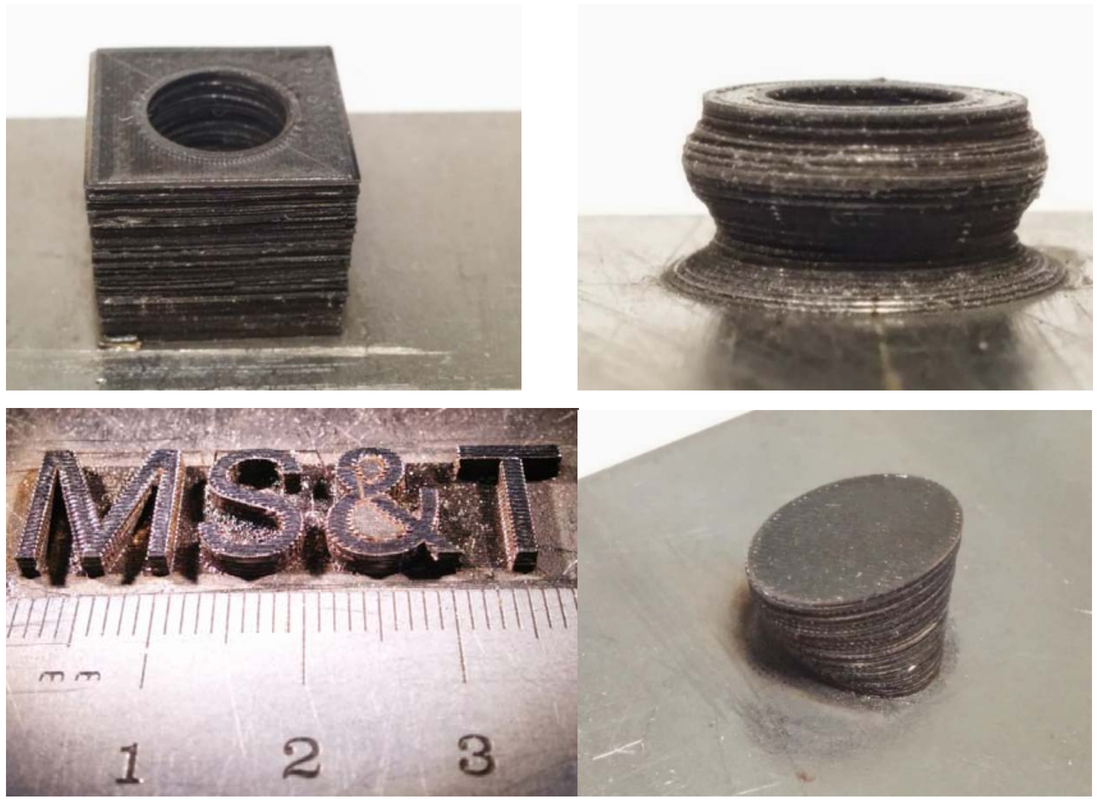




Effect of assisting gas: (a) ambient air, (b) ambient nitrogen, (c) coaxial pressing air, and (d) coaxial pressing nitrogen.

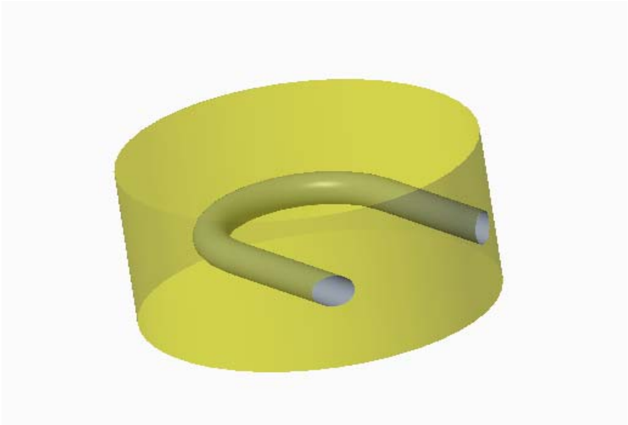
- High quality clean-cut with minimum heat-affected zone can be achieved.

Preliminary Results: Parts built by Foil-Based Dual-Laser AM

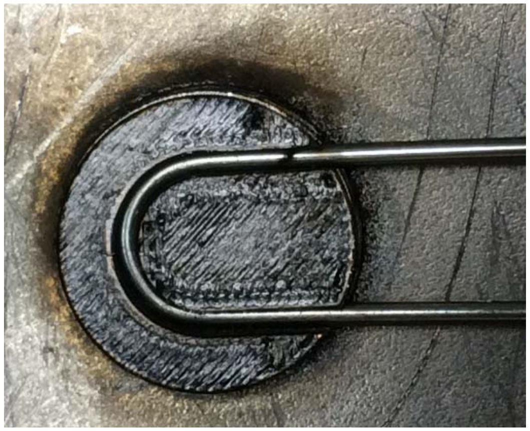


- Some samples printed by the newly developed AM method. Top left is a cubic with a void cylinder in the center; top right is a pot designed to test the ability of building curve edges; bottom left is the Missouri University of Science and Technology logo; and bottom right is a deformed ellipse sample.

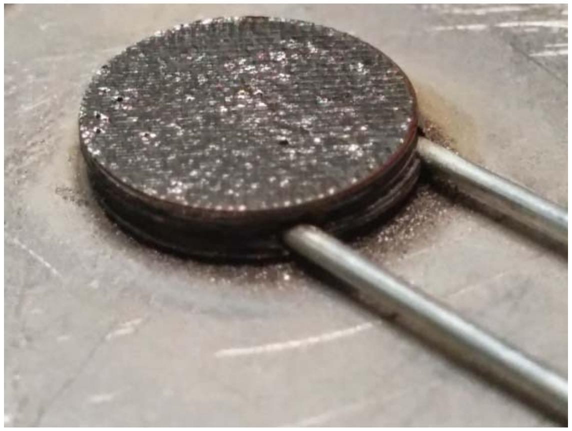
Preliminary Results: Sensor embedding for high-temp environment



3D model for sensor embedding.



A curved sensor to be embedded in the printing process.



Sensor is embedded in the part.

- One important advantage of additive manufacturing is it allows a perfect embedding of sensors in the part during the printing process. The embedded sensors can be used to measure in real-time the temperature, pressure, and strain in high energy environment.

- An example of sensor embedded part, printed with our AM method. A curved channel is created and then a sensor is embedded during the printing process.

Develop Thermal Mechanical Models of the Smart Part

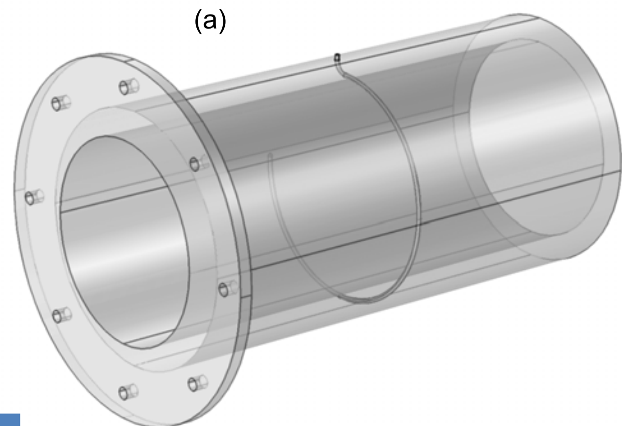
Approach: Finite element models to derive the pressure-temperature-strain coupling relationships

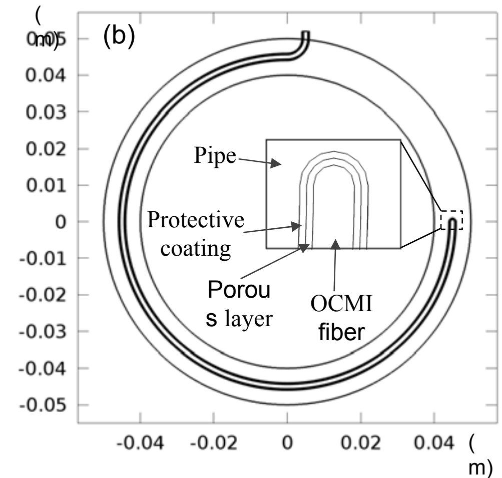
Hai-Lung Tsai

Missouri University of Science and Technology

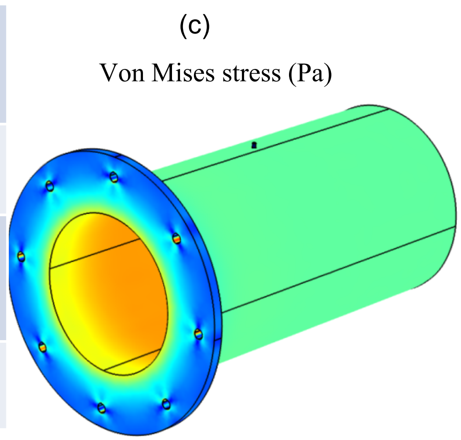
Preliminary Results: Stress and strain on the smart pipes

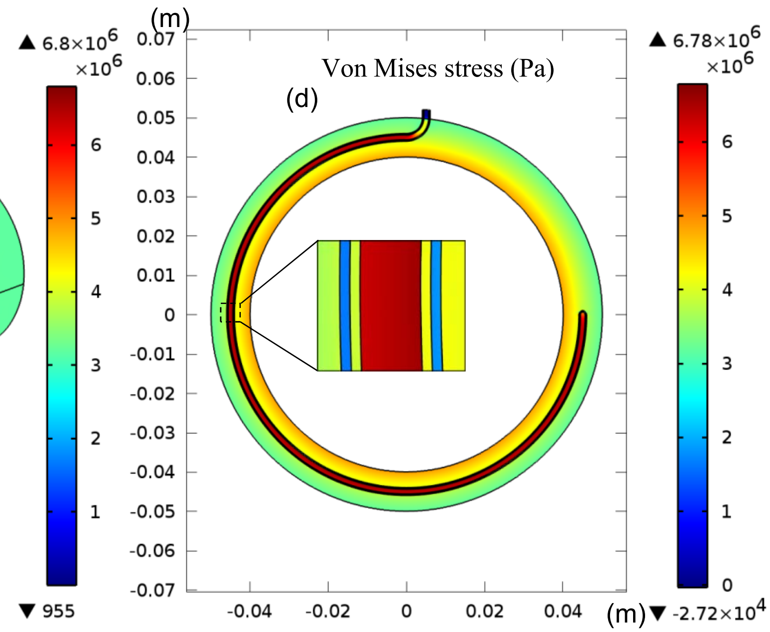
- Coating layer thickness and properties.
- Length of sensor.
- Porous layer thickness and properties.
- Significant difference of material properties.





Materials	Young's modulus [Pa]	Yielding strength [Pa]	CTE [1/K]
Steel AISI 4340	2.05×10^{11}	470×10^{6}	1.23×10^{-5}
Ti-Ni Alloy	7.90×10^{10}	445×10^{6}	1.1×10^{-5}
Porous Alumina (20%)	2.09×10^{11}	--	6.4×10^{-6}
Sapphire	3.45×10^{11}	63.0×10^{6}	4.5×10^{-6}





- There are stress concentrations between the steel, Ti-Ni coating, porous alumina, and sapphire fiber.

Preliminary Results: Stress and strain on the smart pipes

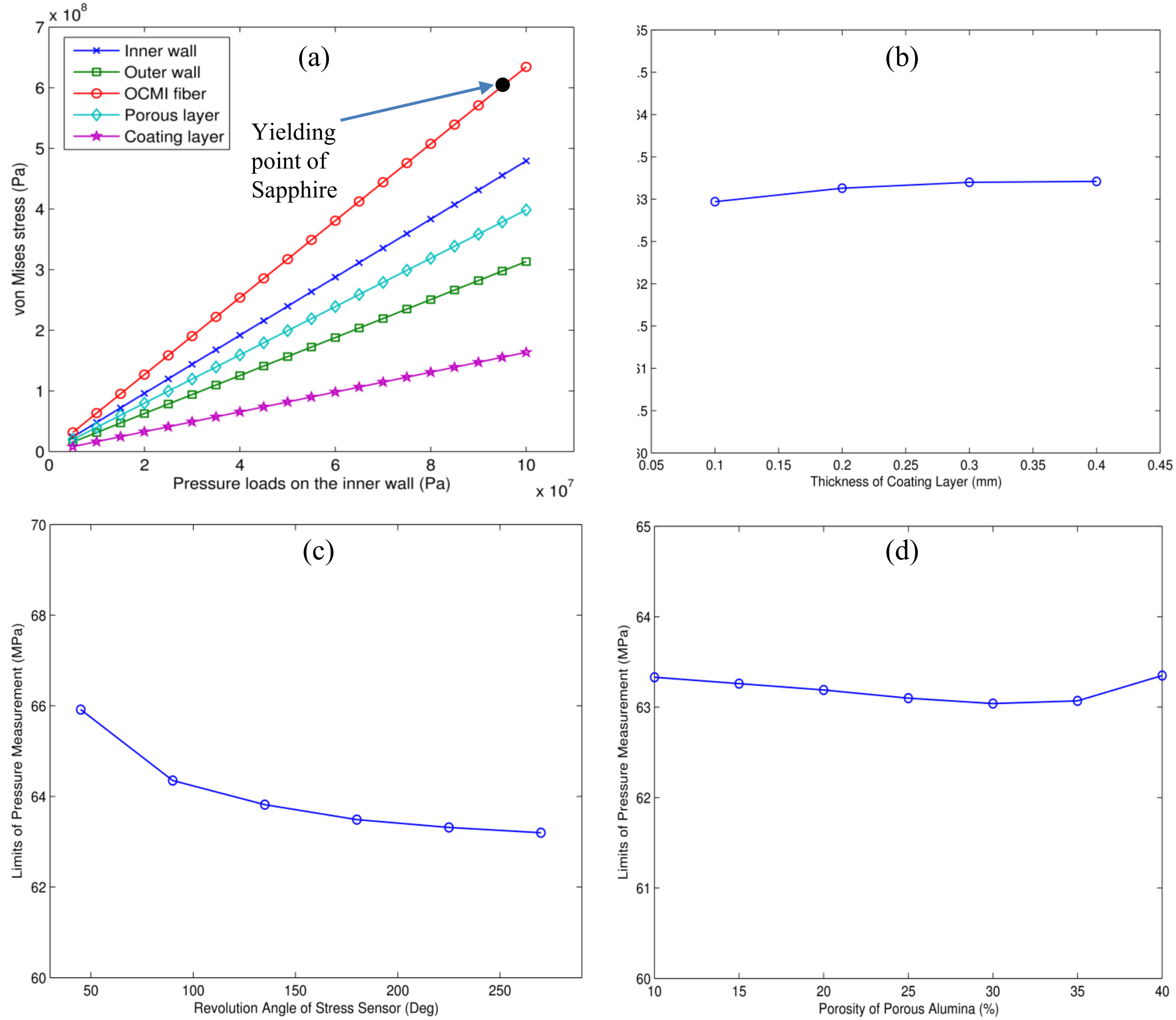
(a) Sapphire sensor will firstly reach its yield strength as the pressure load increases.

(b) Thickness of protective coating layer vs. measurement limit.

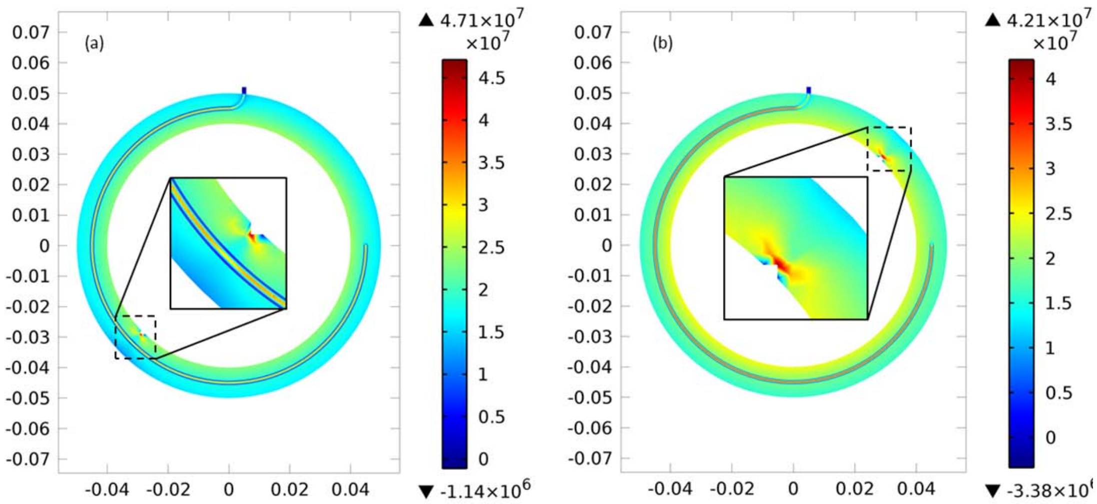
(c) Sensor length (revolution angle) vs. measurement limit.

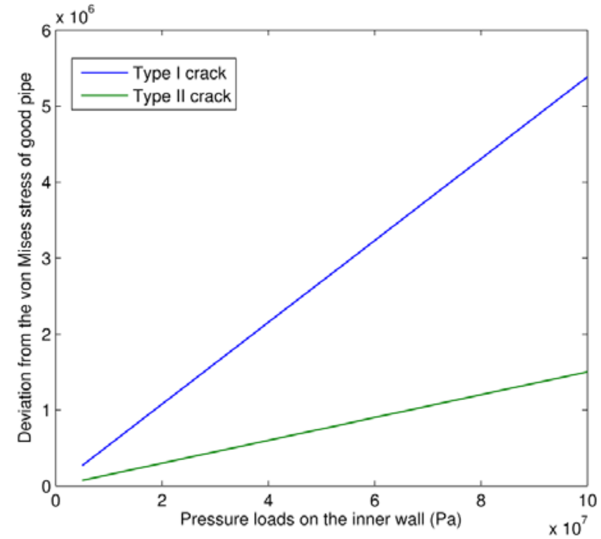
(d) Porosity vs. measurement limit.

- The measuring range is limited mainly by the OCMI sapphire fiber.



Preliminary Results: Stress and strain on the smart pipes





- Two types of cracks: (a) next to the sensor and (b) away from the sensor.
- The depth of crack is 1 mm; the thickness of pipe is 10 mm.
- The cracks can only influence the local stress distribution next to the crack.

- Additional stresses detected by the sensor over the free-crack case.

- **The technique can be used to detect possible initial cracks on the smart pipe.**

Summary of Progresses

- Microwave photonic sensors and instrumentation have been developed and proven effective
- Protective coating materials have been identified and successfully coated on silica and sapphire substrates
- Additive Manufacturing techniques have been developed for fabrication of smart parts
  - Multi-extruder freeze-form extrusion for ceramic parts
  - Foil-Based Dual-Laser Additive Manufacturing for metals
- Models have been developed to study the induced stress/strain on the sensor caused by external high pressures or high temperatures

Future Work

- **Continue optimization and improvement on**
  - Sensors: stability, loss sensitivity, temperature cross sensitivity, protection, embedment
  - Additive manufacturing techniques and processes
    - Ceramic: sintering, new materials, functionally gradient, mechanical tests
    - Metal: surface improvement, 3D metal parts
  - Modeling: temperature and pressure coupled models
  - Protective coating: multilayer structure and coating on real sensors
- **Embed sensors during additive manufacturing to make smart parts**
- **Initial tests of sensors embedded in the smart parts**