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

DE-FE0012272

Investigators:

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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

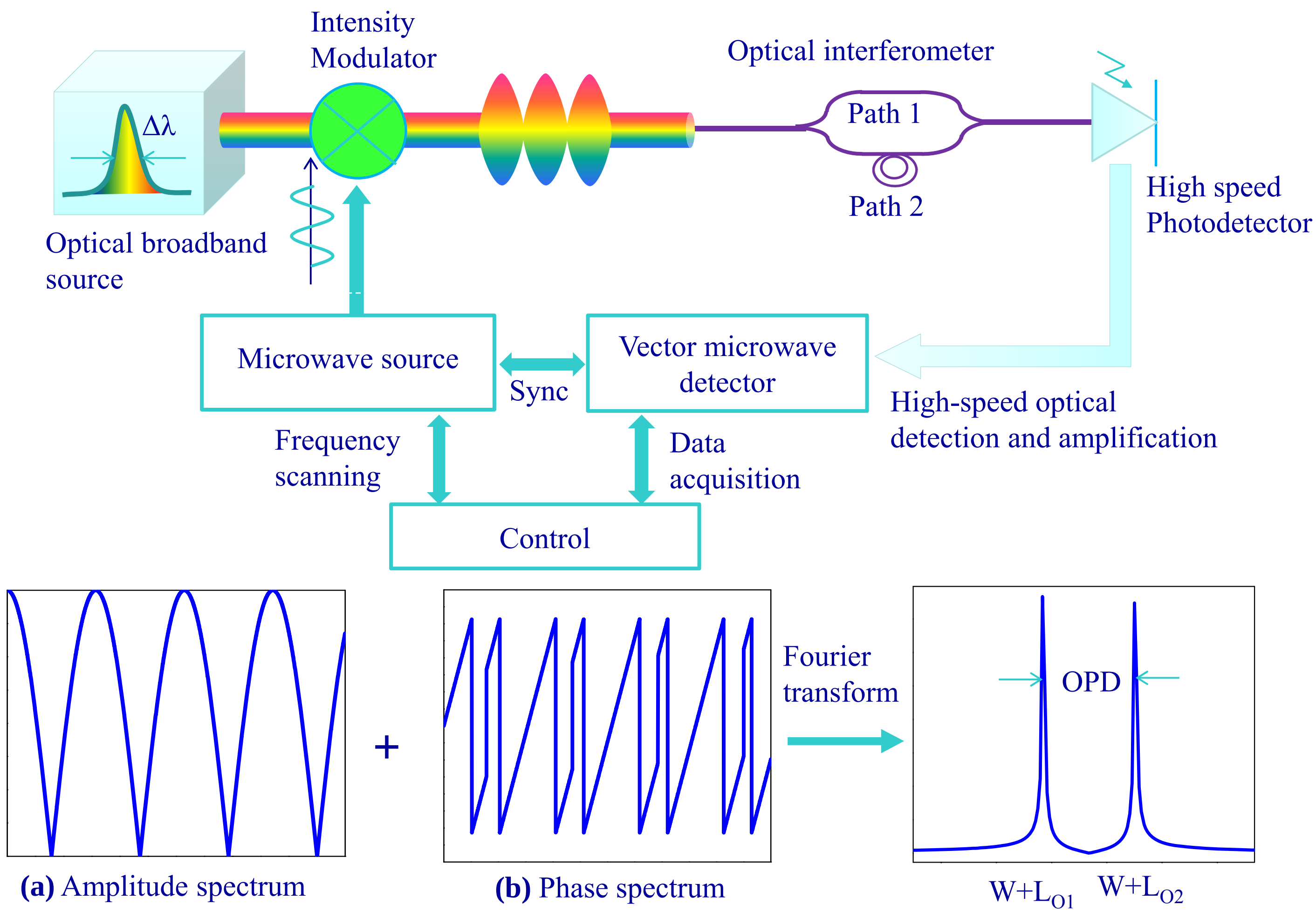
$$|E|^2 = |E_1 + E_2|^2 = 2A^2 + 2A^2 M \cos\left[\Omega \frac{L_{O1} - L_{O2}}{2c}\right] \cos\left[\Omega\left(t + \frac{2W + L_{O1} + L_{O2}}{2c}\right)\right]$$

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

Optical term

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

OCMI Concept



(a) Amplitude spectrum

(b) Phase spectrum

(c) Propagation delay

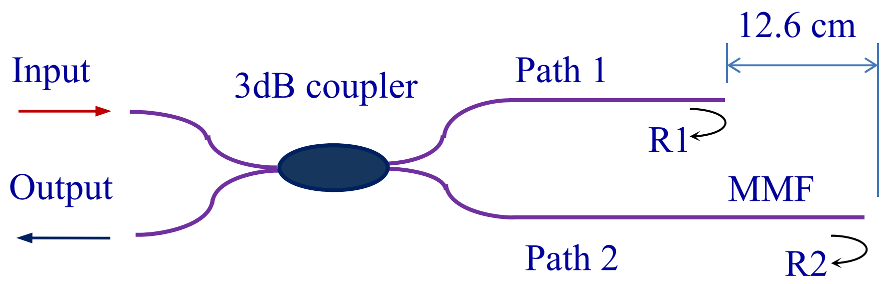
$$2A^2M\cos\left[\Omega\frac{L_{O1}-L_{O2}}{2c}\right]$$

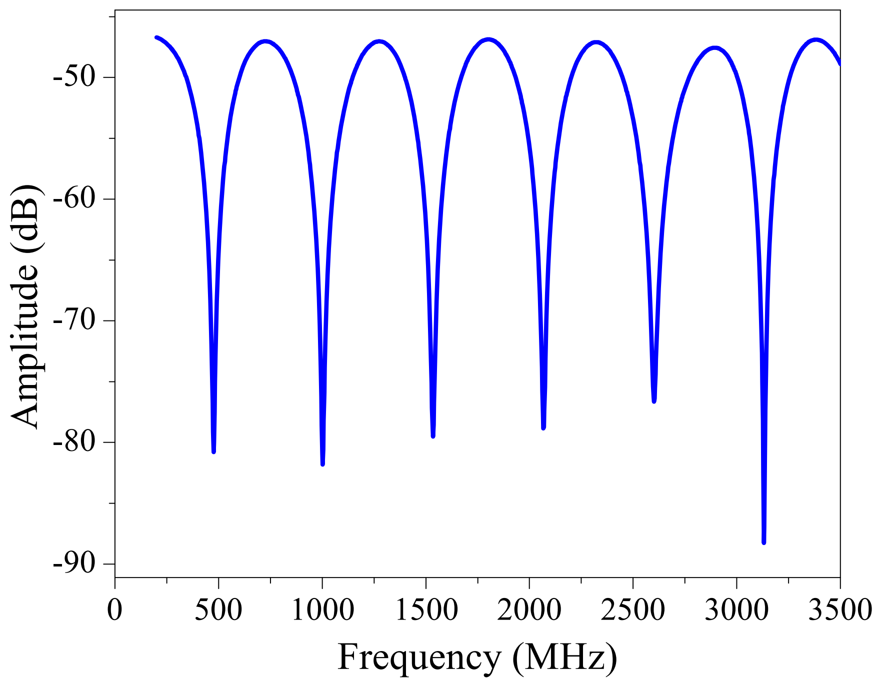
$$\Omega\left(\frac{2W+L_{O1}+L_{O2}}{2c}\right)$$

Measurement

Location

MMF: Low Multimodal Influences

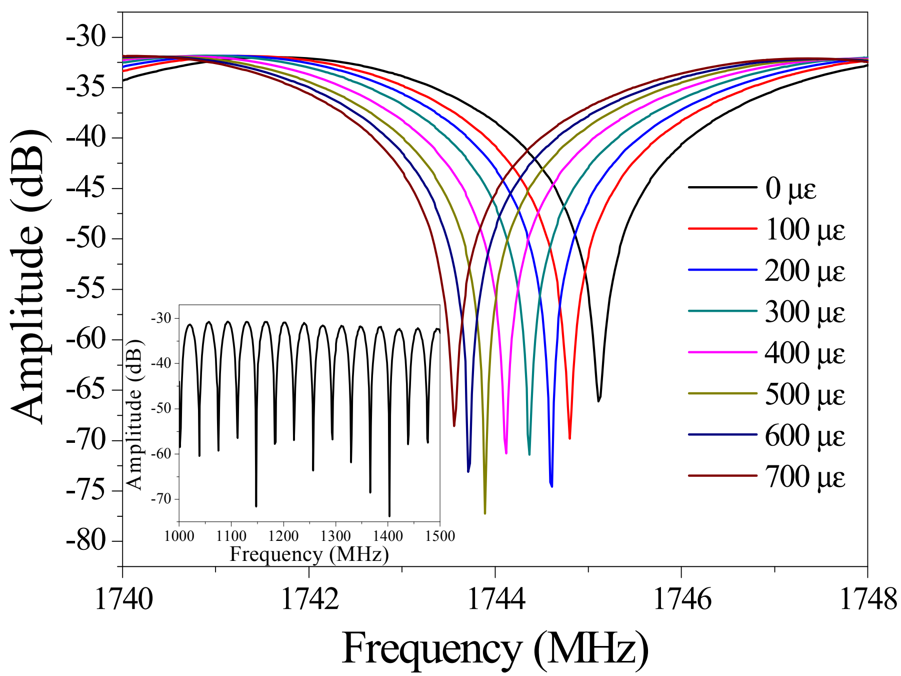


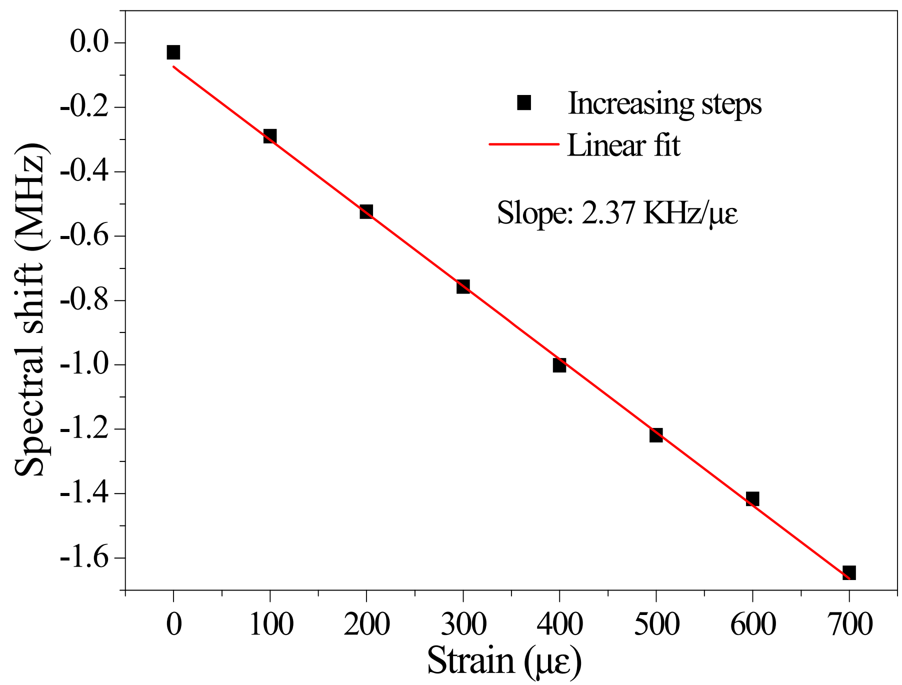


- **Michelson interferometer using multimode fibers (fused silica core of 200μm in diameter, 220μm cladding)**
- **Excellent fringe visibility**
- **No observable multimodal influences**

L. Hua., Applied Optics, 2015

Strain at 600ºC, 200μm Fiber

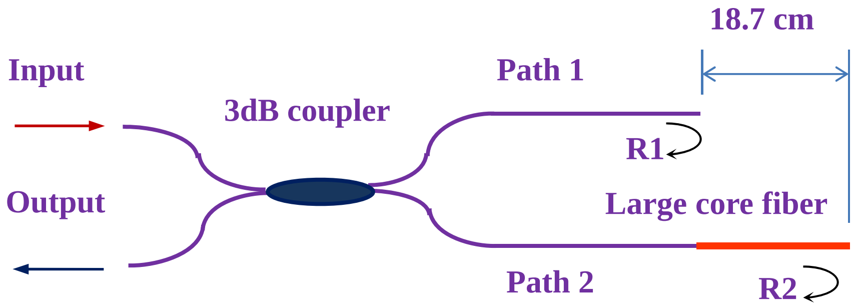




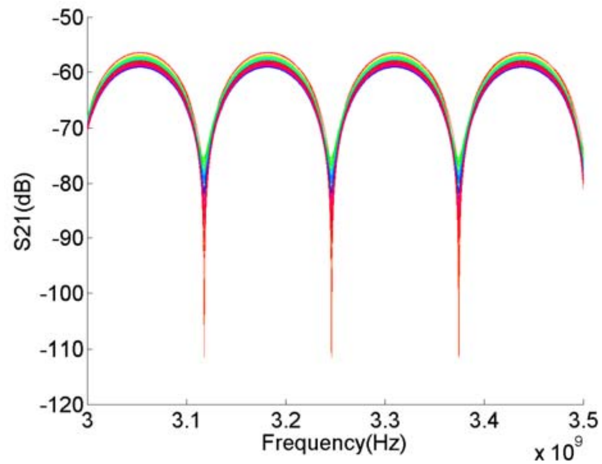
- **High sensitivity for strain sensing (~10με) at 600ºC**
- **Small temperature cross sensitivity**

L. Hua., Applied Optics, 2015

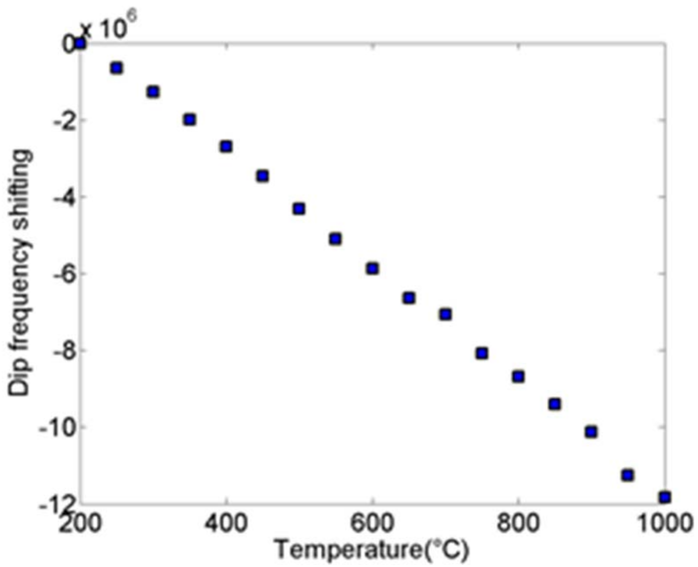
Quartz rod (800μm dia. Uncladded)



Fused silica rod 800μm dia.

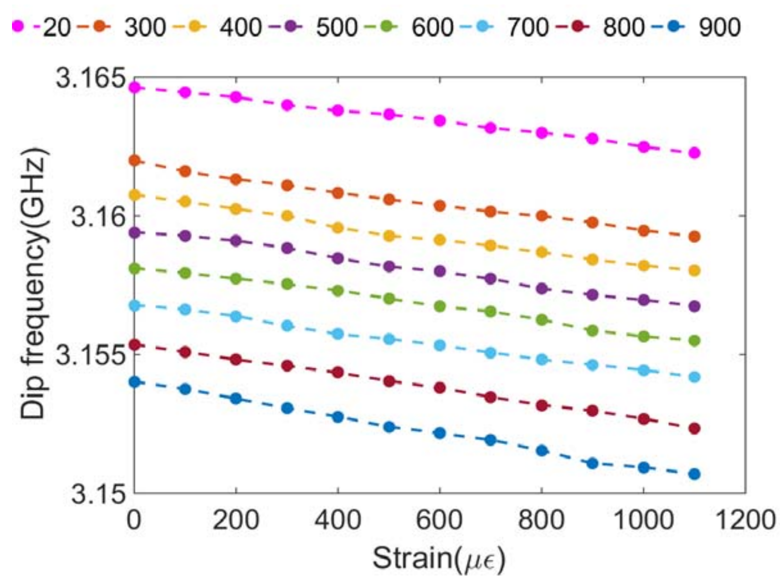


Interference fringes



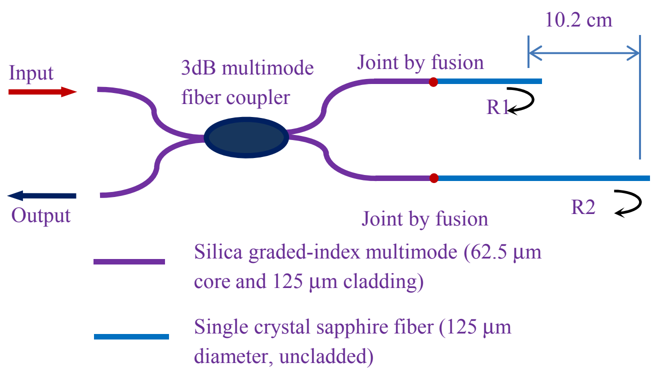
High temperature response

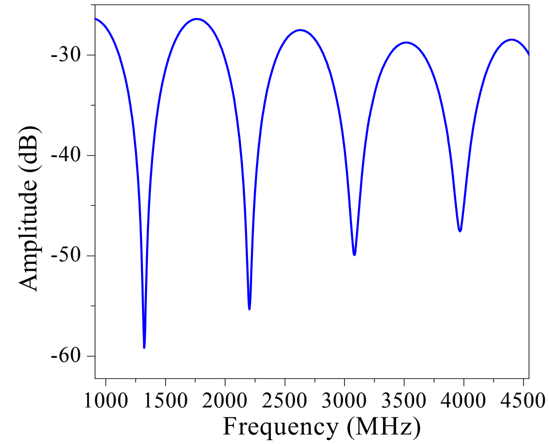
L. Hua., Applied Optics, 2015



Quartz rod can be used to measure strains at high temperatures

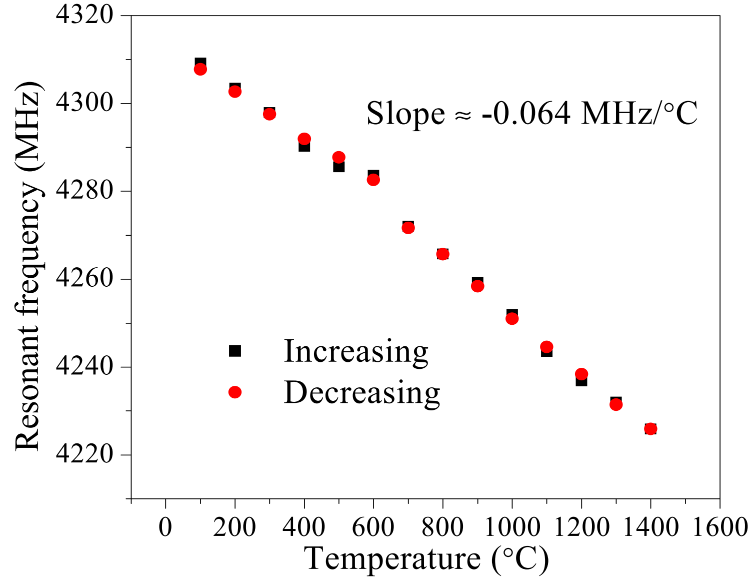
Sapphire Michelson Sensor (125 µm)





Sapphire fiber Michelson OCMI

Excellent fringe visibility > 30dB

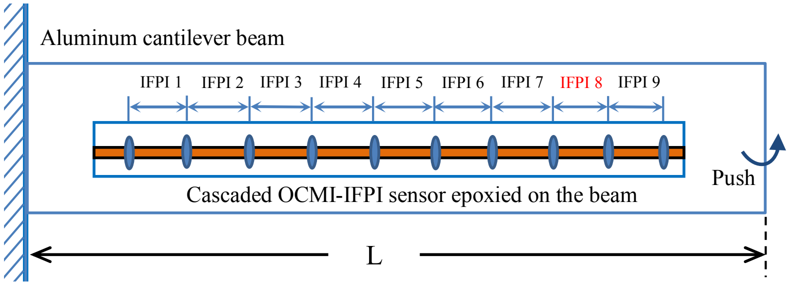


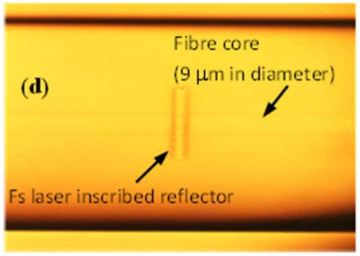
J. Huang, et al., *IEEE Photonics Technology Letters*, 2015.

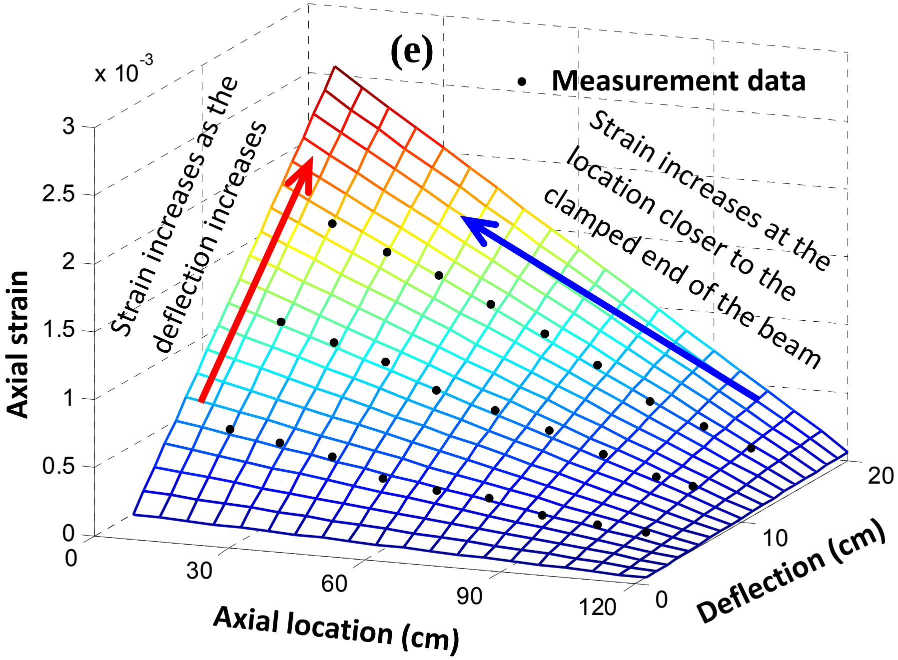
Fully distributed sensing

- 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.



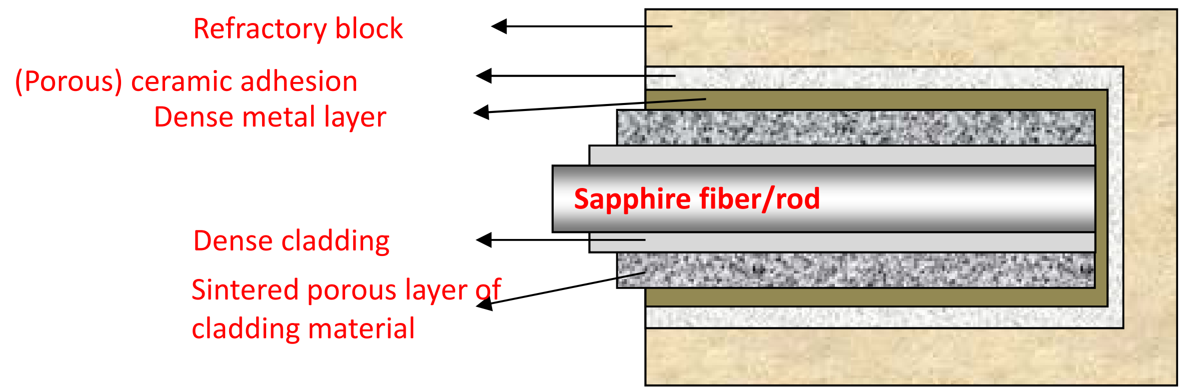




Develop a multifunctional transition layer between the embedded sensor and the host material for sensor protection

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

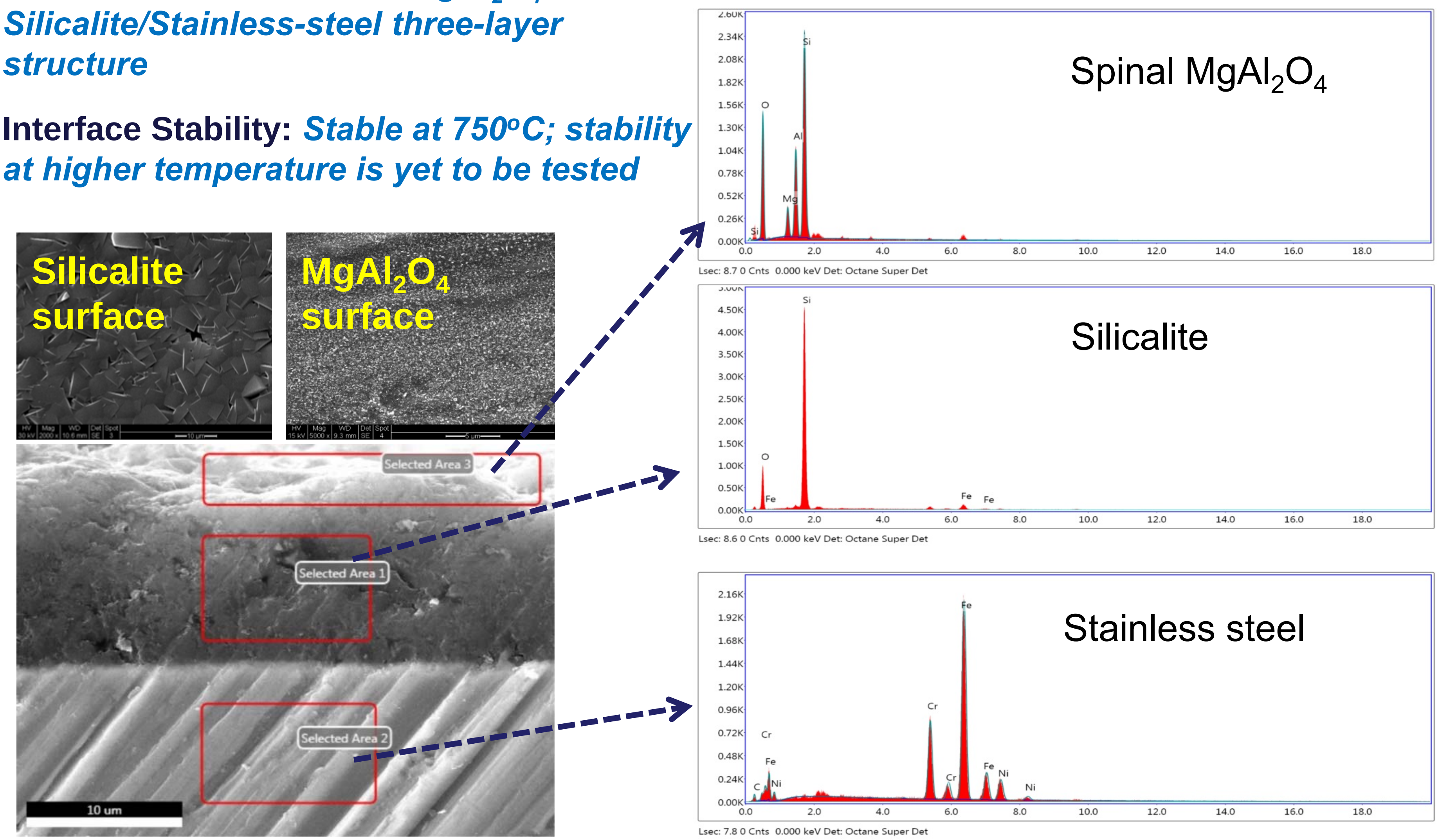
Junhang Dong,
University of Cincinnati



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

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***



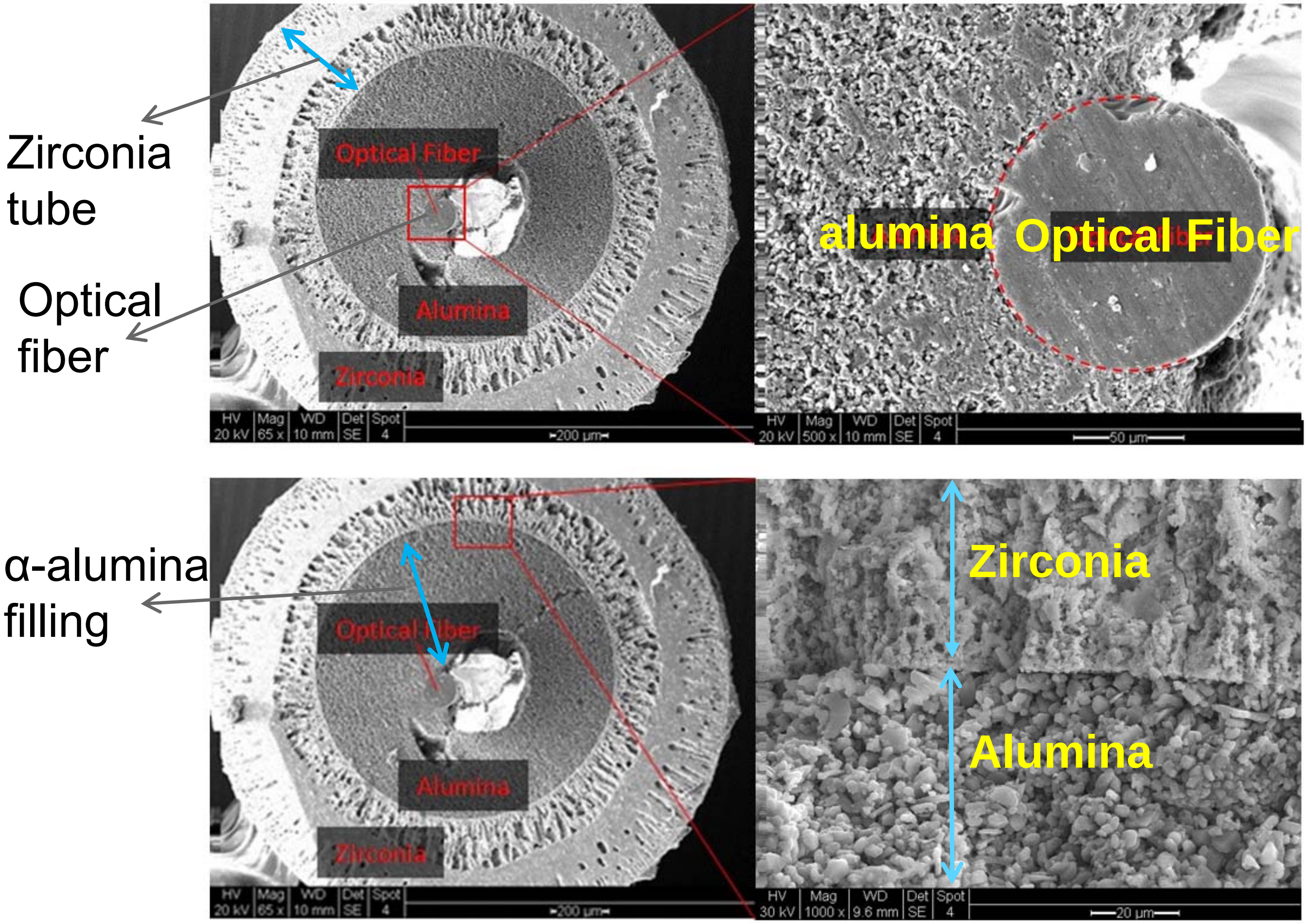
Multilayer-Protected FOS Fabrication

UNIVERSITY OF Cincinnati

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

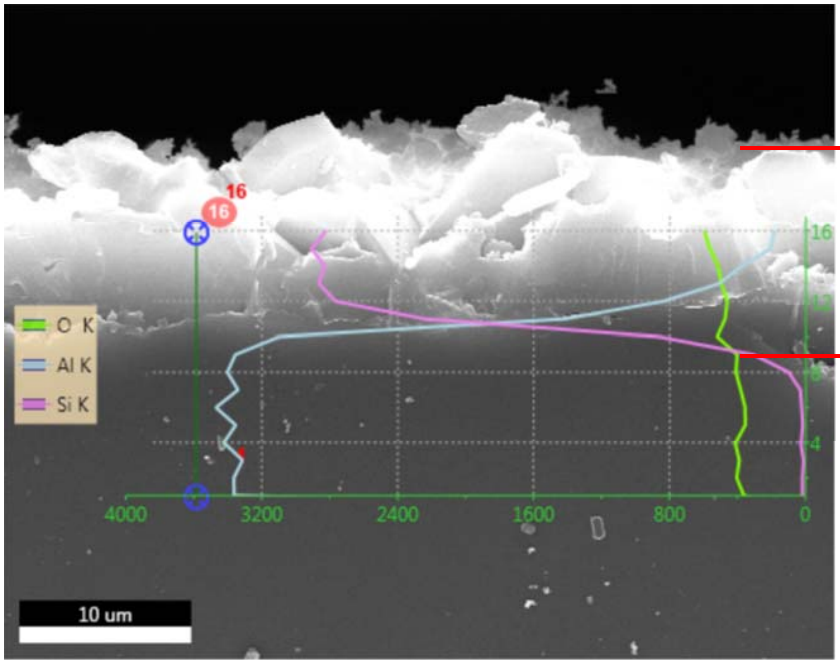
Fabrication: ***inserting optical fiber into zirconia small tube by alumina adhesives***

Stability: ***Fiber strongly attached to structure after thermal cycles; tested stability at 750°C***



Long-Term Stability of Sapphire Protection

- **The structures of silicalite-coated-sapphire is stable after firing at 1000°C for 200 h according to SEM and EDS examinations – No structural damage or elemental diffusion across the Silicalite/Sapphire interface was found.**



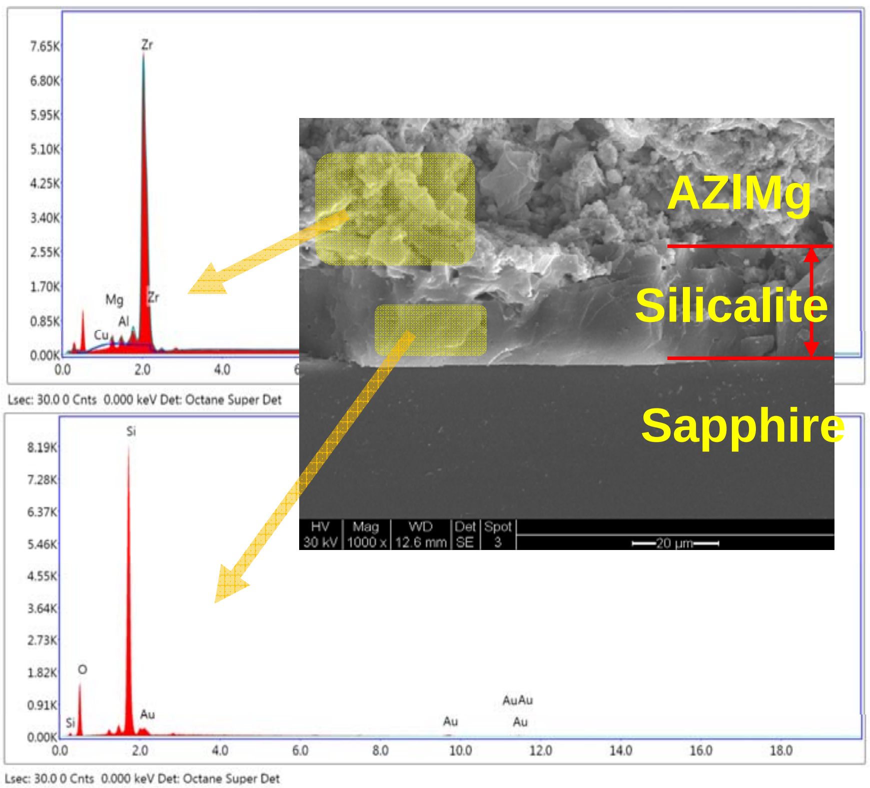
Polycrystalline silicalite

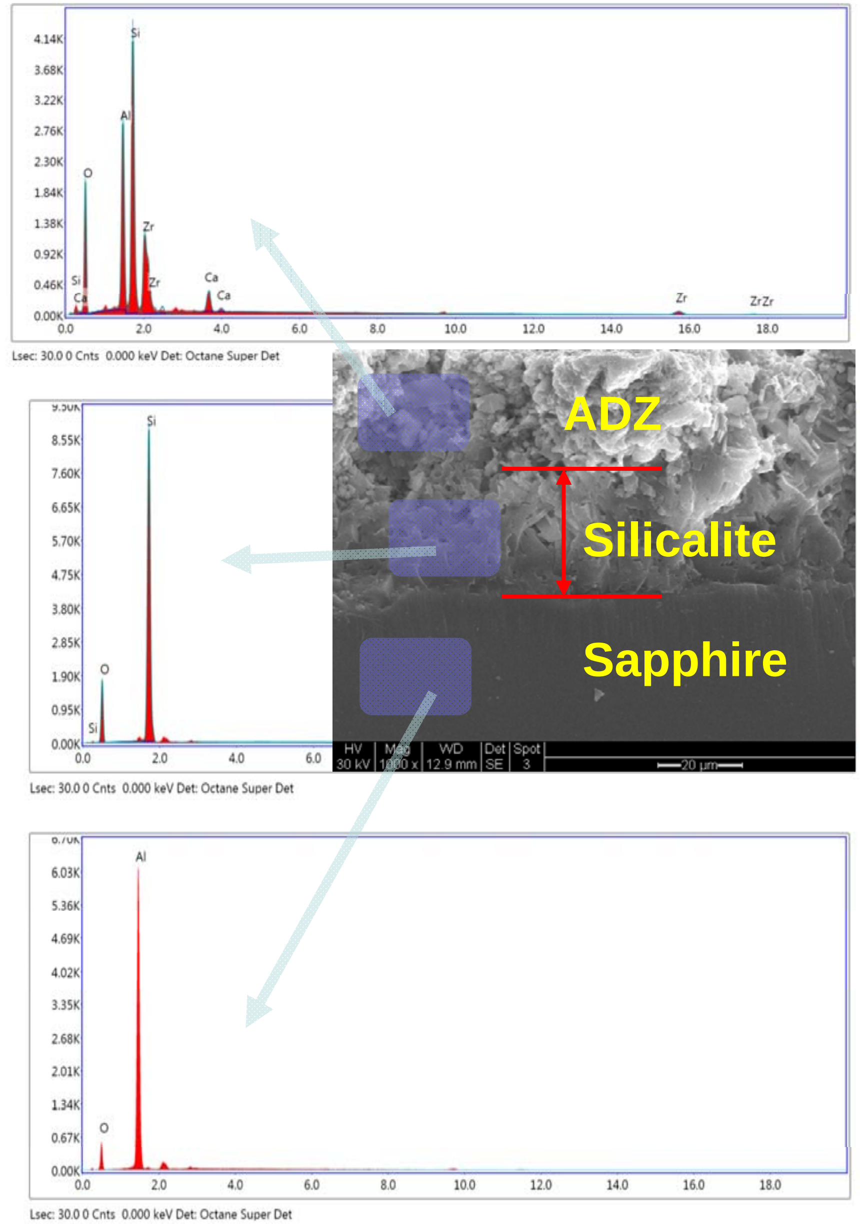
Sapphire chip

Long-Term Stability of Sapphire Multilayer Protection

UNIVERSITY OF Cincinnati

The structures of silicalite-coated-sapphire with an overcoats of ZAlMg (ZrO_2-Al_2O_3-MgO mixture) and ADZ ($Zr_{1-0.75x}Al_xSiO_4$) are both stable after firing at **1000°C for 200 h** according to SEM and EDS examinations – No structural damage or inter-layer element diffusion was found.





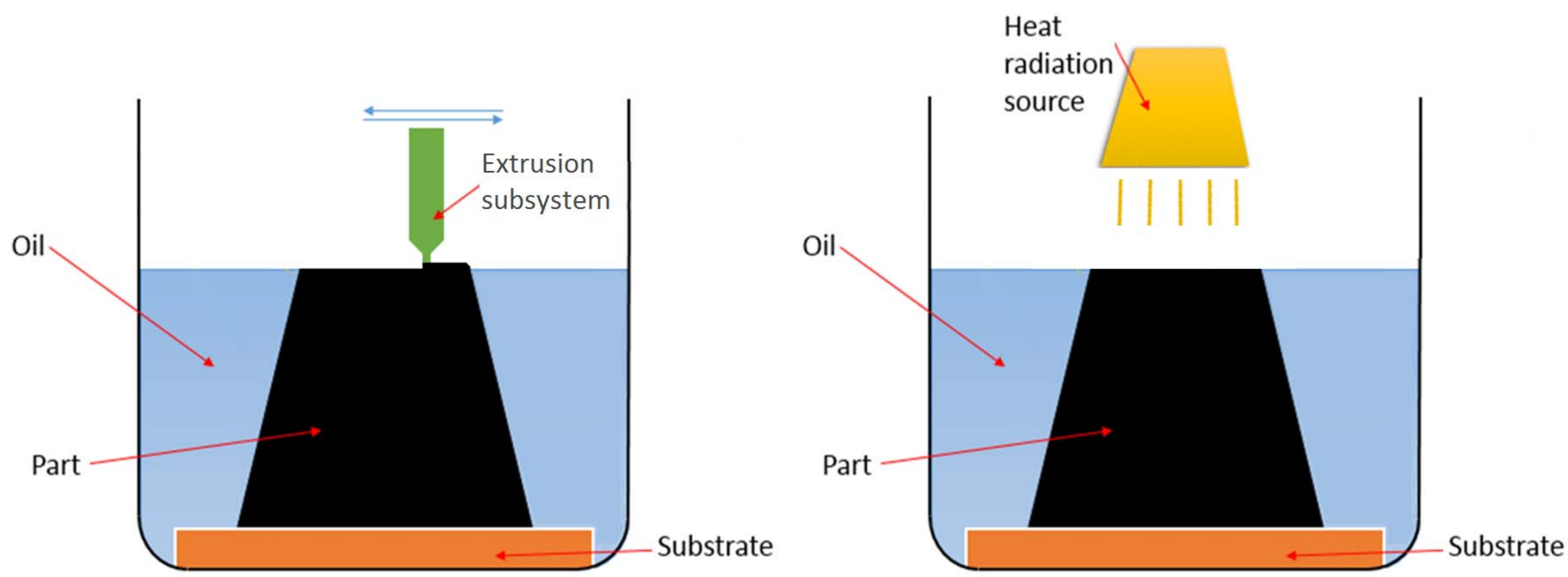
Additive Manufacturing of Liner Blocks (Ceramic) with Embedded Sensors

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

Ming Leu
Missouri University of Science and Technology

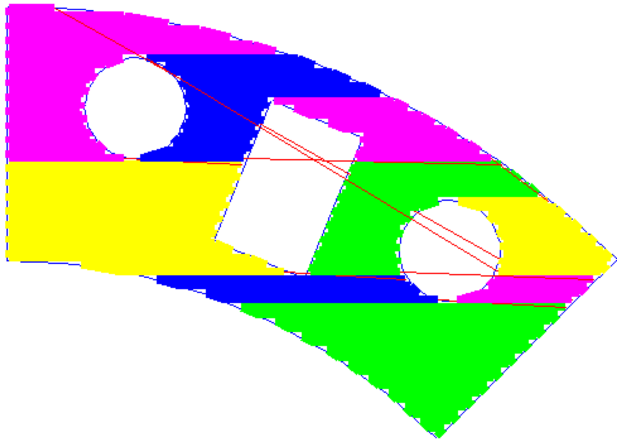
Novel AM Process

- A layer is deposited through a moving nozzle.
- Oil is pumped to surround the layer.
- Infrared lamp is used to partially dry the layer.
- Next layer is deposited.



Tool-path Planning Software

- An algorithm has been developed and coded into computer software to
  - Read the geometry of the part in STL format.
  - Slice the part.
  - Generate tool-path for each layer.
  - Generate a G&M code for output to a manufacturing machine for part fabrication by 3D printing.



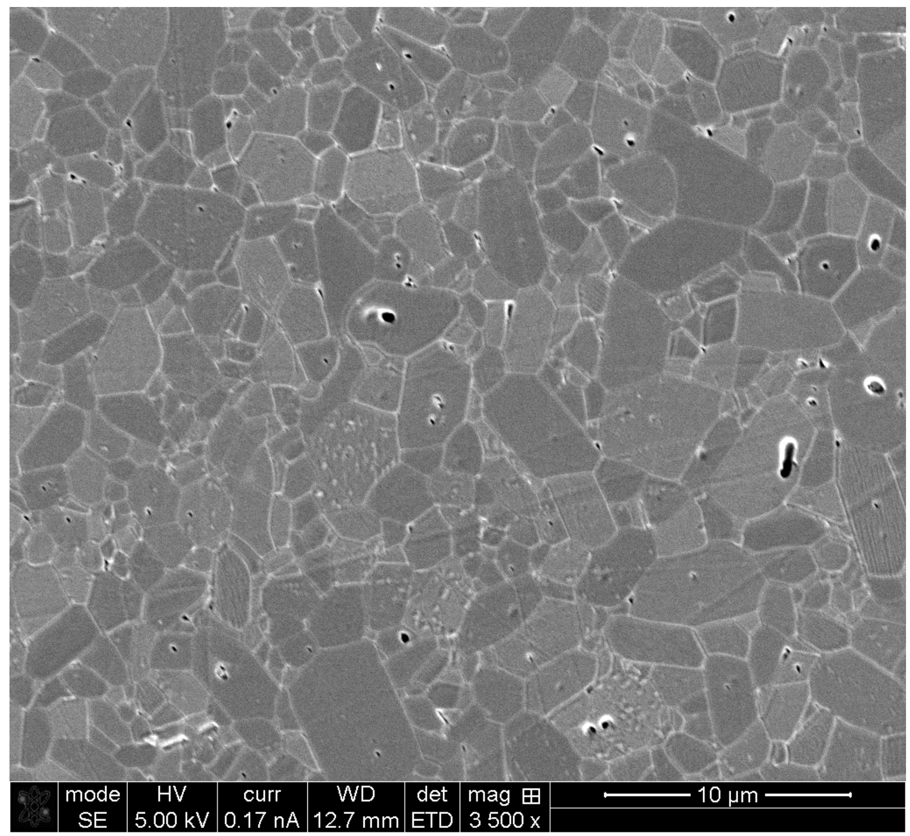
Example Printed Parts

Mechanical Properties Measured

- Relative density (Archimedes'): 98%
- Flexural strength (ASTM C1161 four-point bend): 364±50 MPa
- Young's modulus: 390±21 GPa
- Fracture toughness (ASTM C1412 chevron-notched beam, configuration A): 4.5±0.1 MPa.m0.5
- Hardness (ASTM C1327 Vickers indentation test): 19.8±0.6 GPa

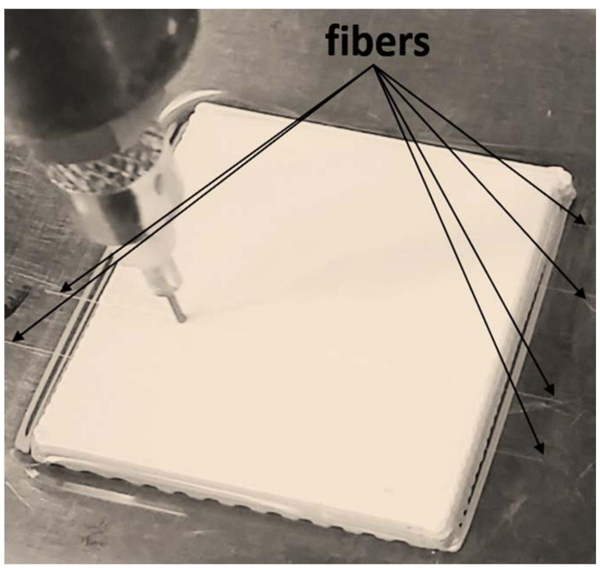
Microstructure Evaluation

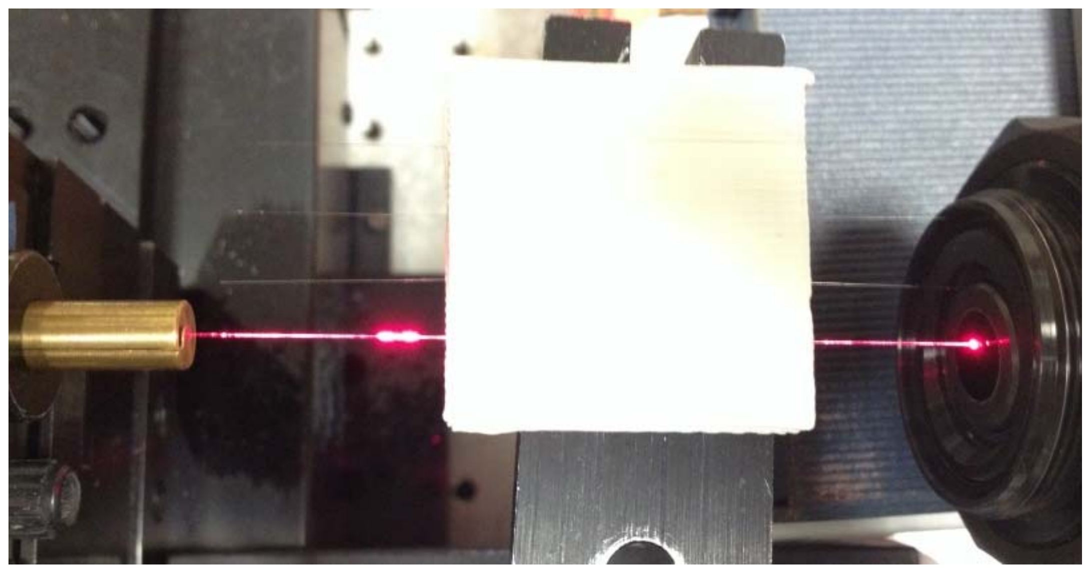
- Microstructure was observed under SEM
- Grains are highly packed
- Average grain size based on lineal intercept: 2.1 μm



Fiber Embedment

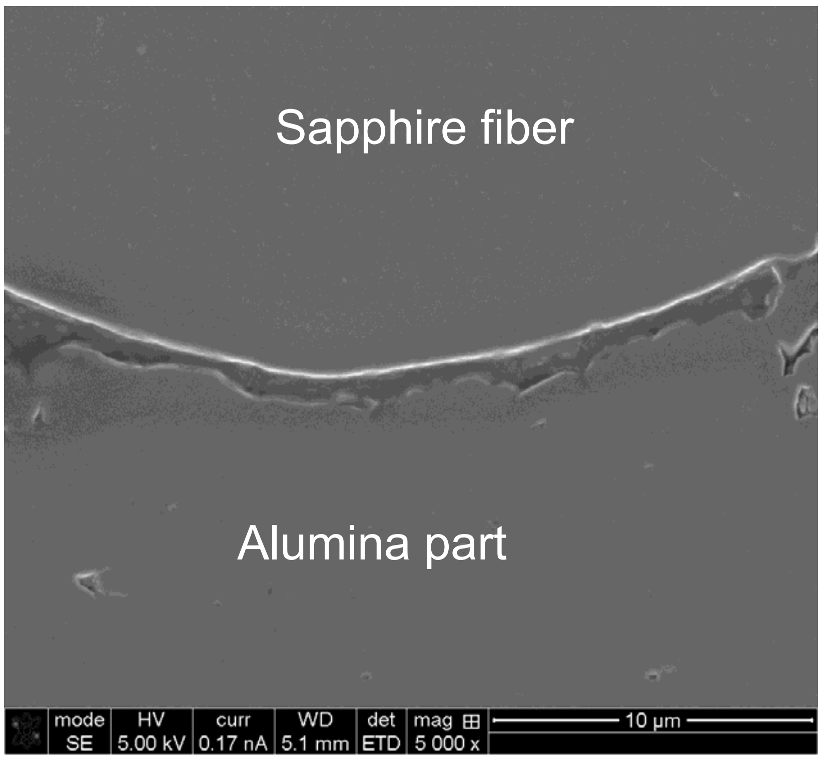
- Sapphire fibers of 75, 125 and 250 μm diameter were successfully embedded in the aluminum parts
- A signal was passed through the fibers to ensure that the embedded fibers are not damaged

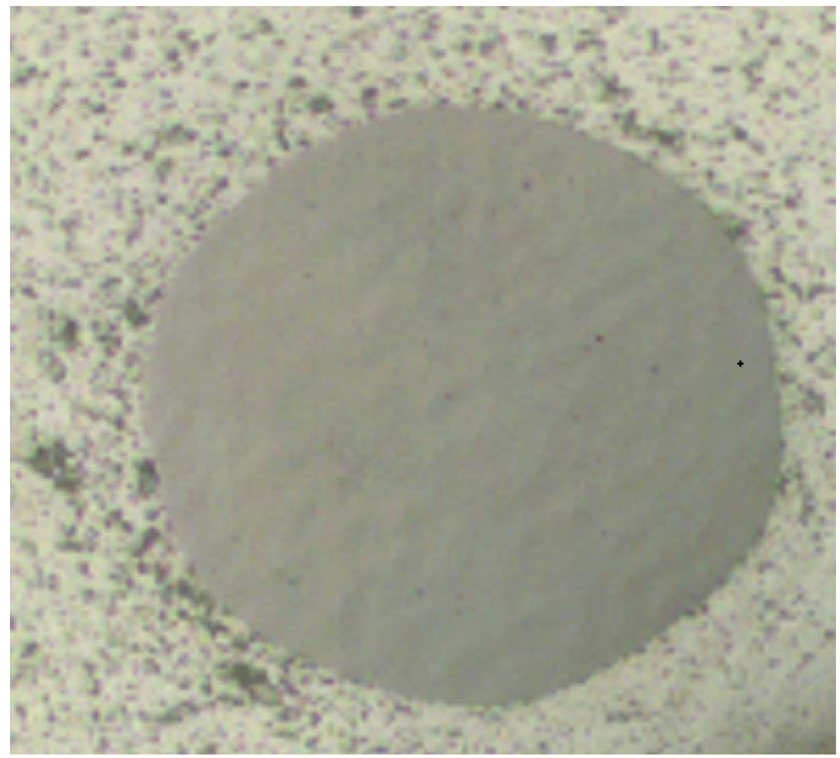




Fiber Embedment

- Micrographs of the embedded fibers show good mechanical bonding between fiber and part





Additive Manufacturing of Pipe (Metal) with Embedded Sensors

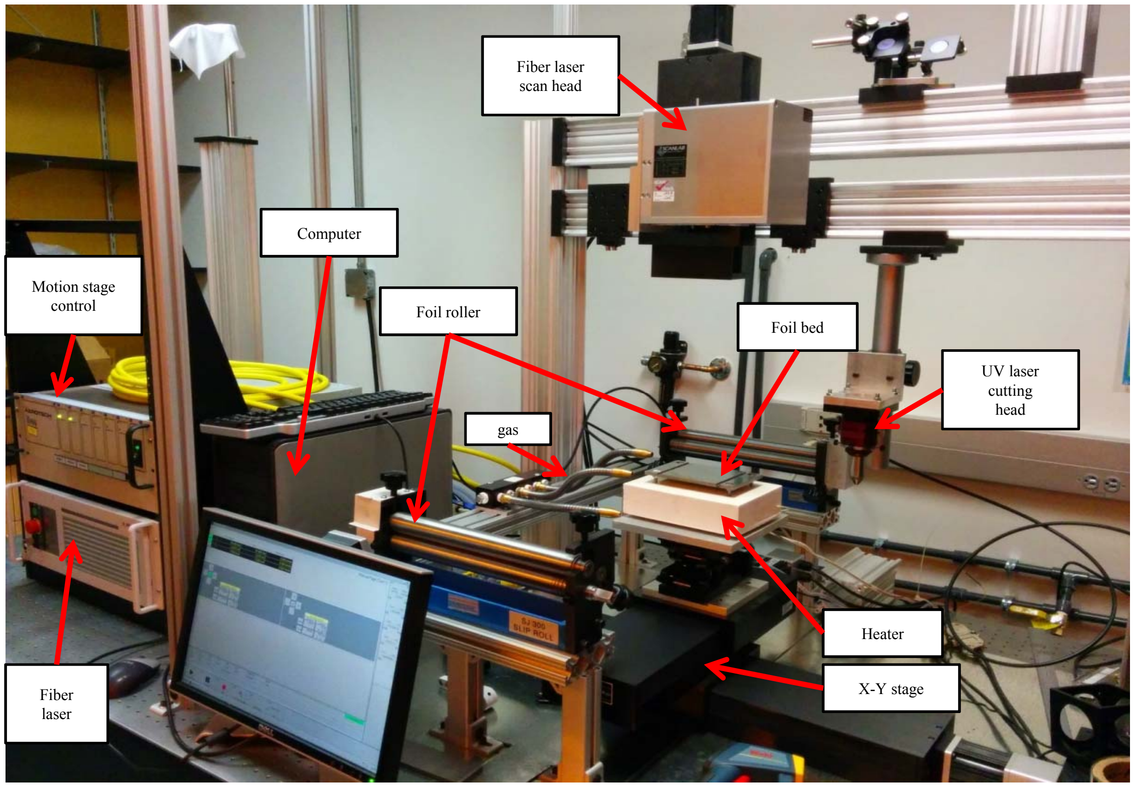
Approach: Foil-Based Dual-Laser Additive Manufacturing Technology

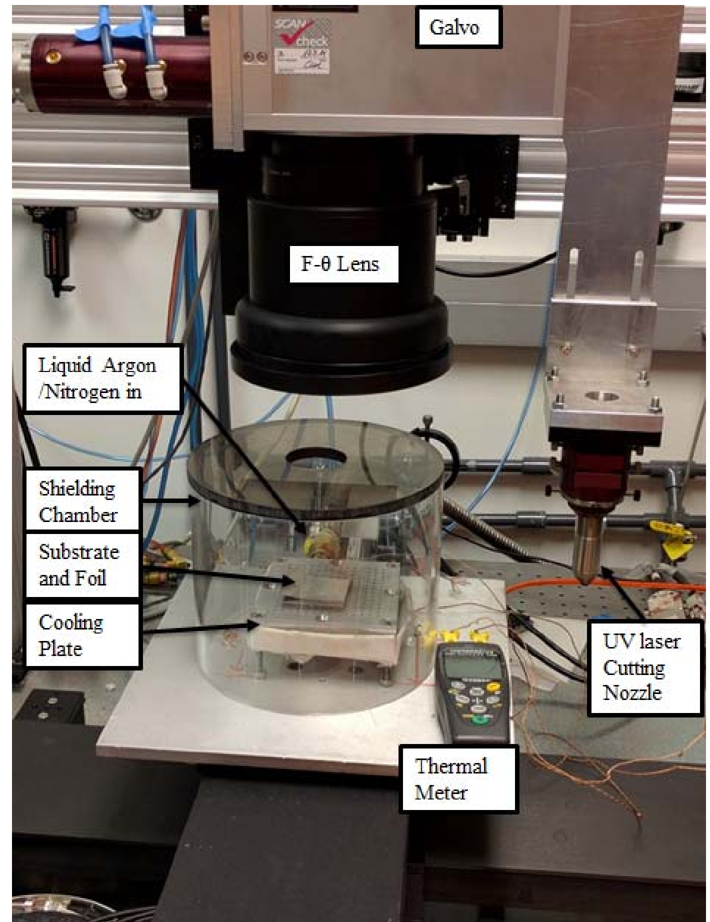
Hai-Lung Tsai

Missouri University of Science and Technology

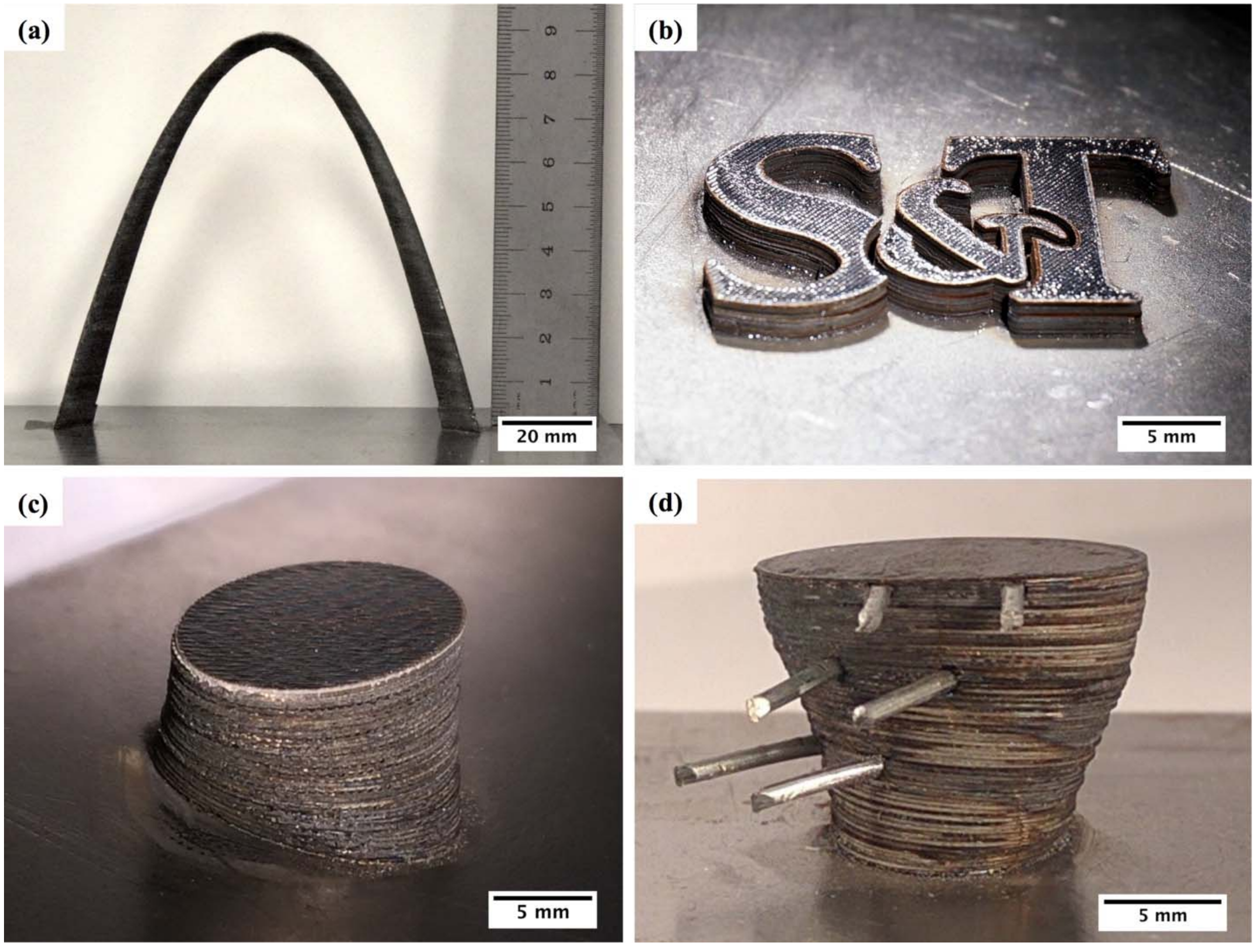
Foil-Based AM System Setup

- System Design, Hardware and Software Implementations, and Integration.

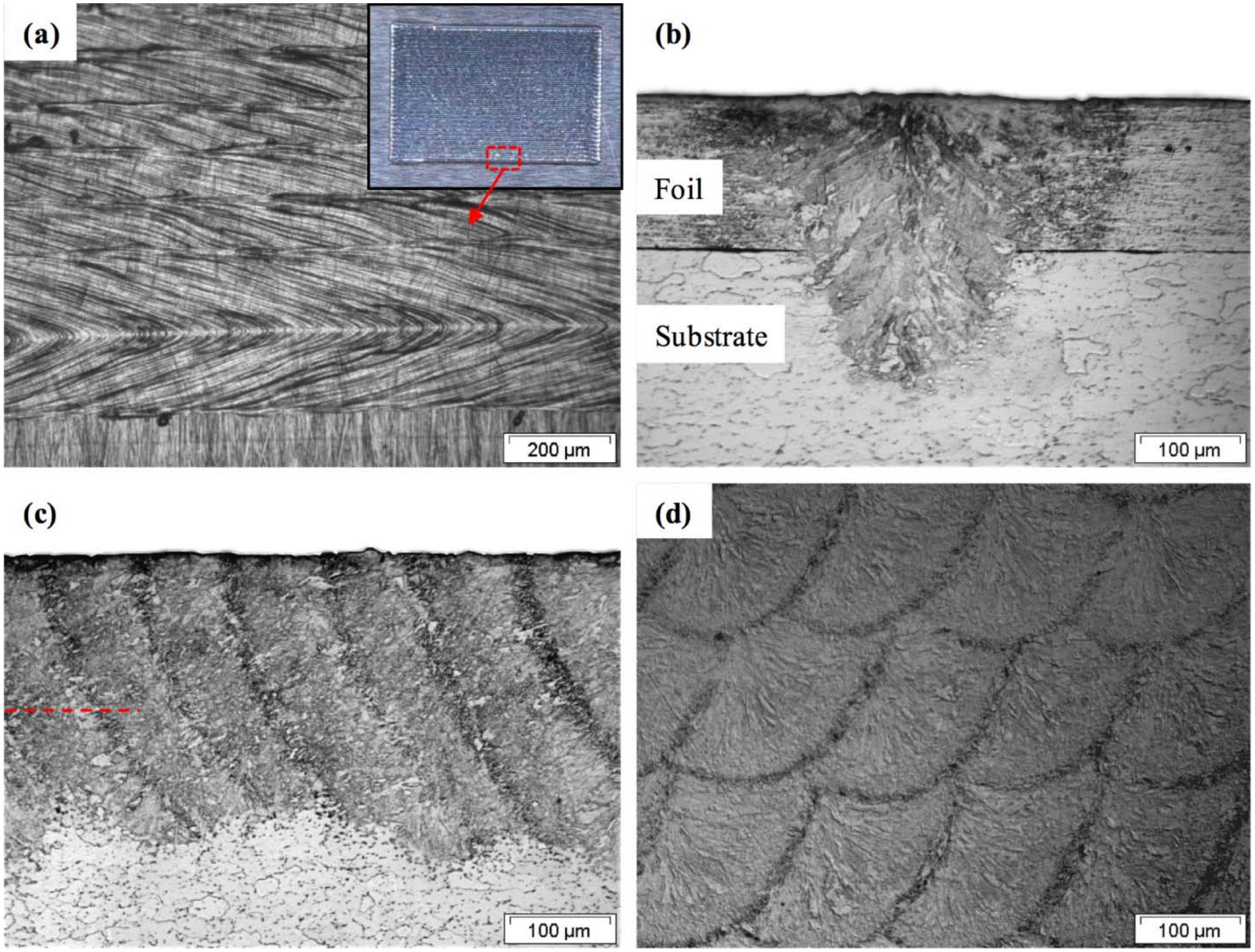




As-Fabricated Samples



Laser Welding



(a) Surface morphology of the raster-scan weld;

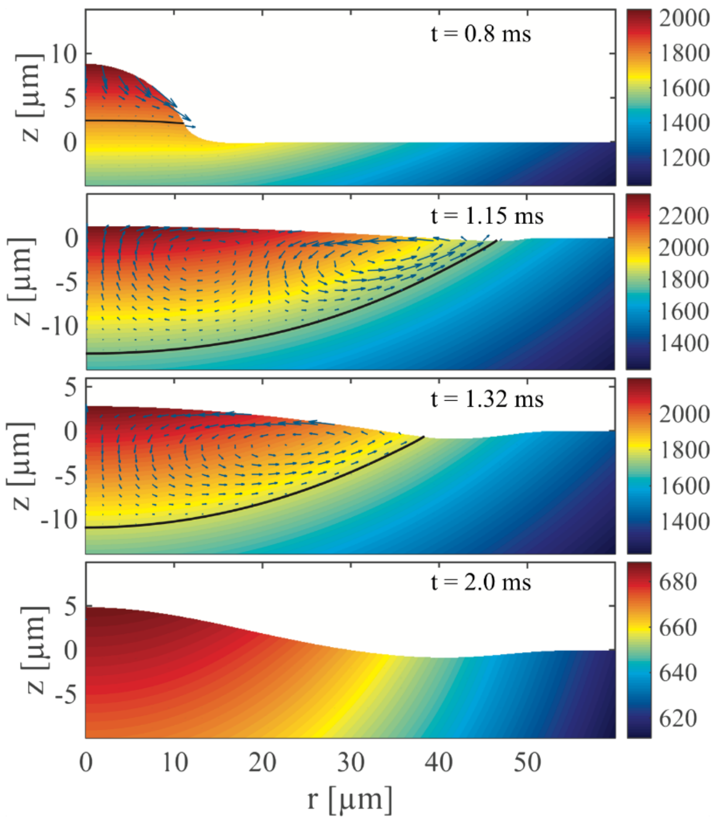
(b) Cross-section of a single-line laser foil-welding onto a substrate;

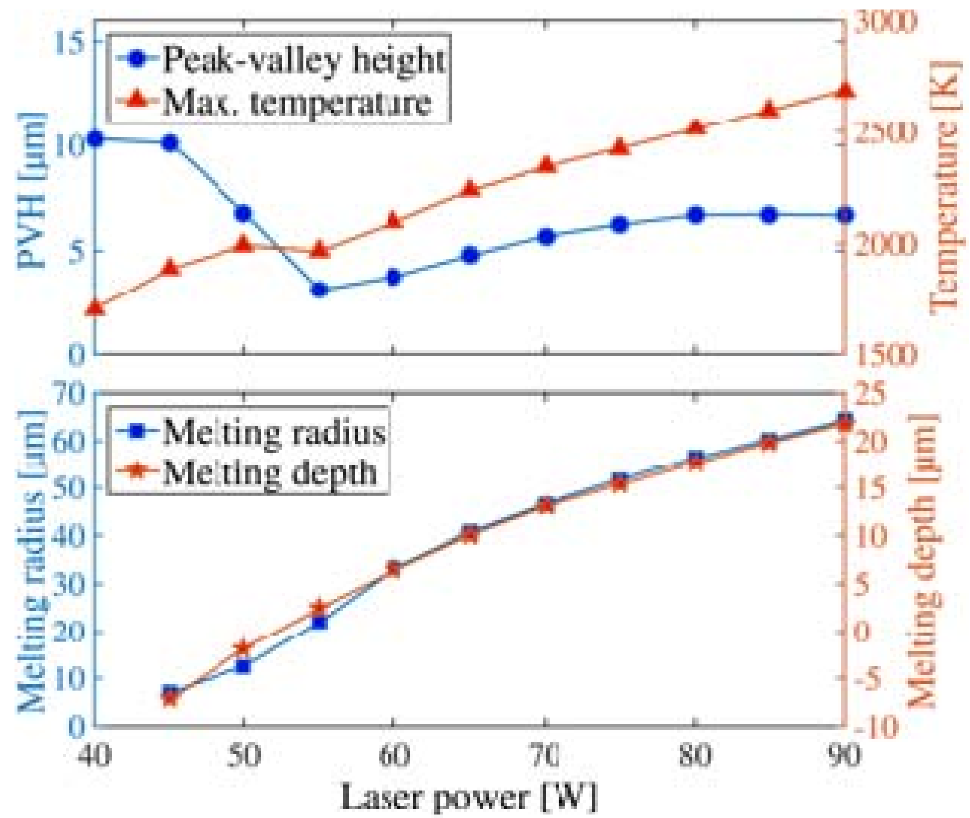
(c) Cross-section of the raster-scan weld of one-layer foil onto a substrate;

(d) Cross-section of a multi-layer raster-scan weld

Laser Surface Polishing - Modeling

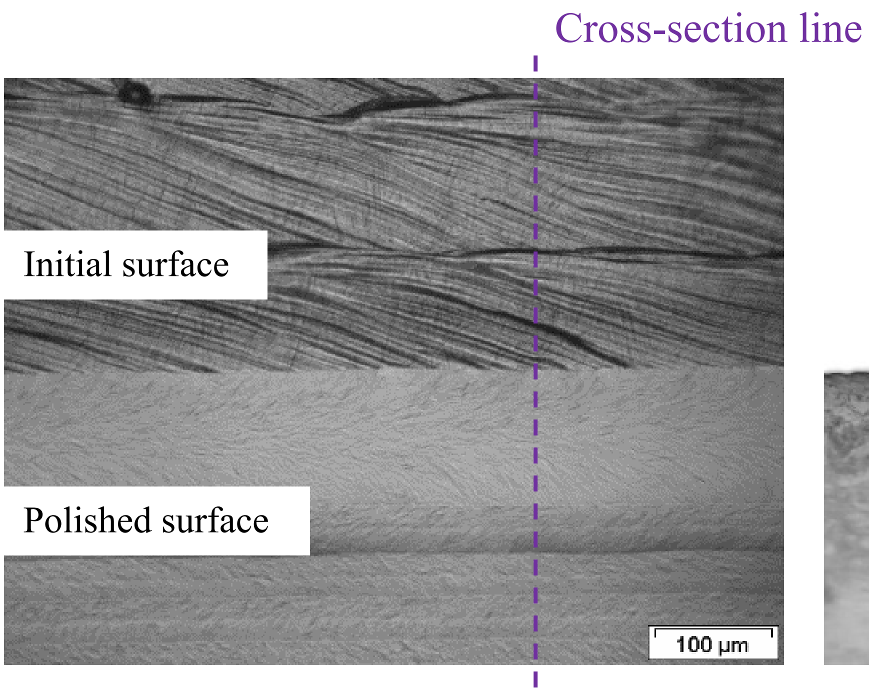
Simulation of the thermal and melt flow processes of laser polishing for a hemispherical bump on a flat substrate.



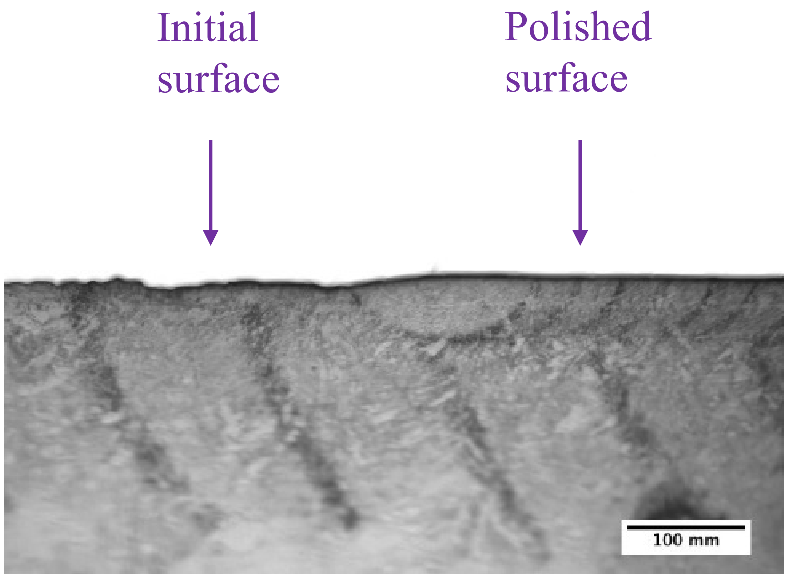


Laser Surface Polishing - Experiment

The surface roughness can be significantly reduced from about 20 μm to less than 3 μm

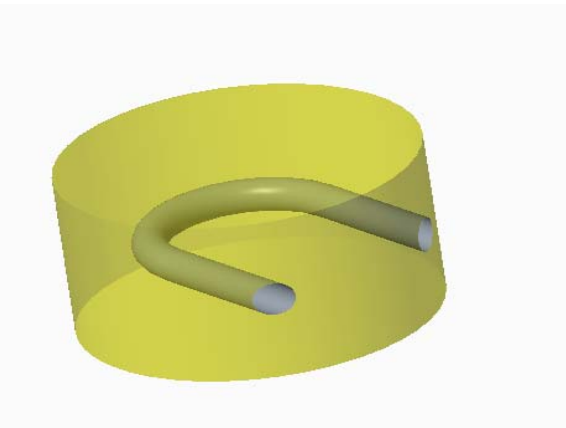


Top surface of laser polishing

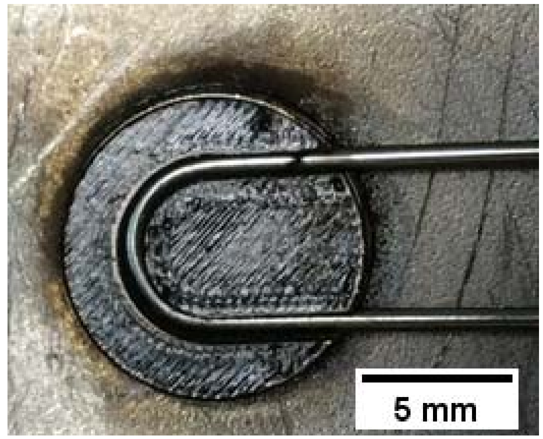


Cross-section of laser polishing

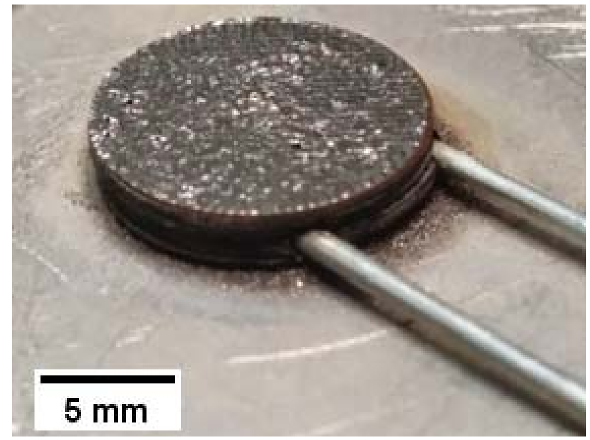
Sensor-Embedded Parts Fabrication



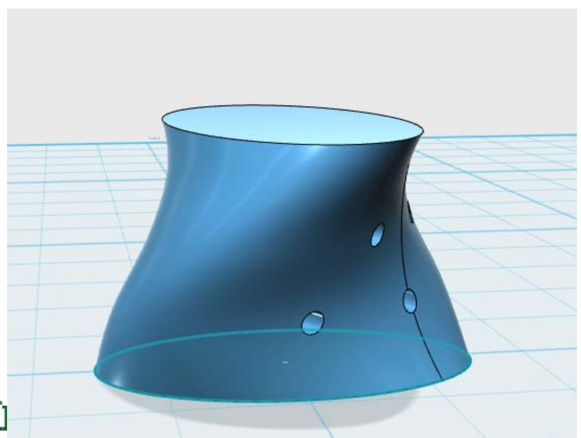
3D models for sensor embedding.

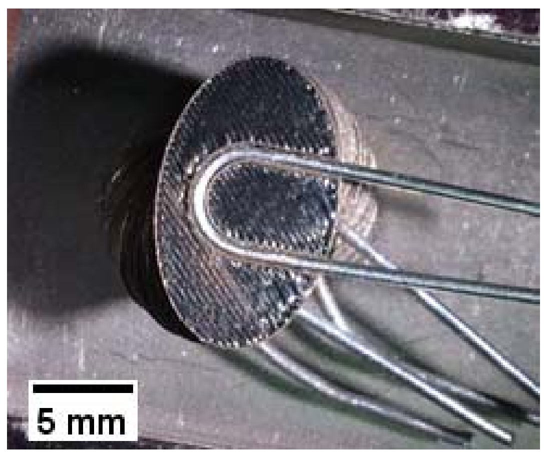


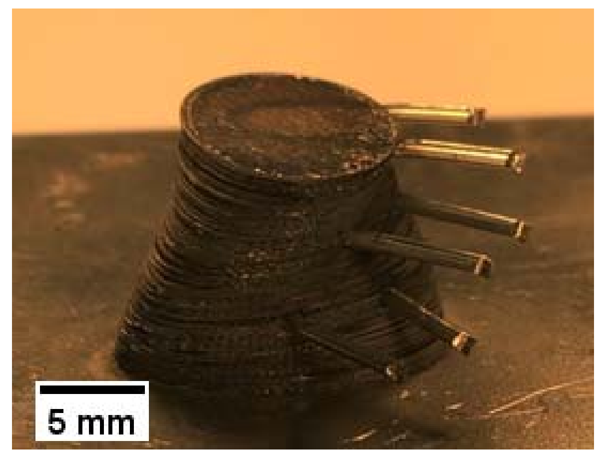
Curved sensors to be embedded in the printing process.



Sensors are embedded in the parts.



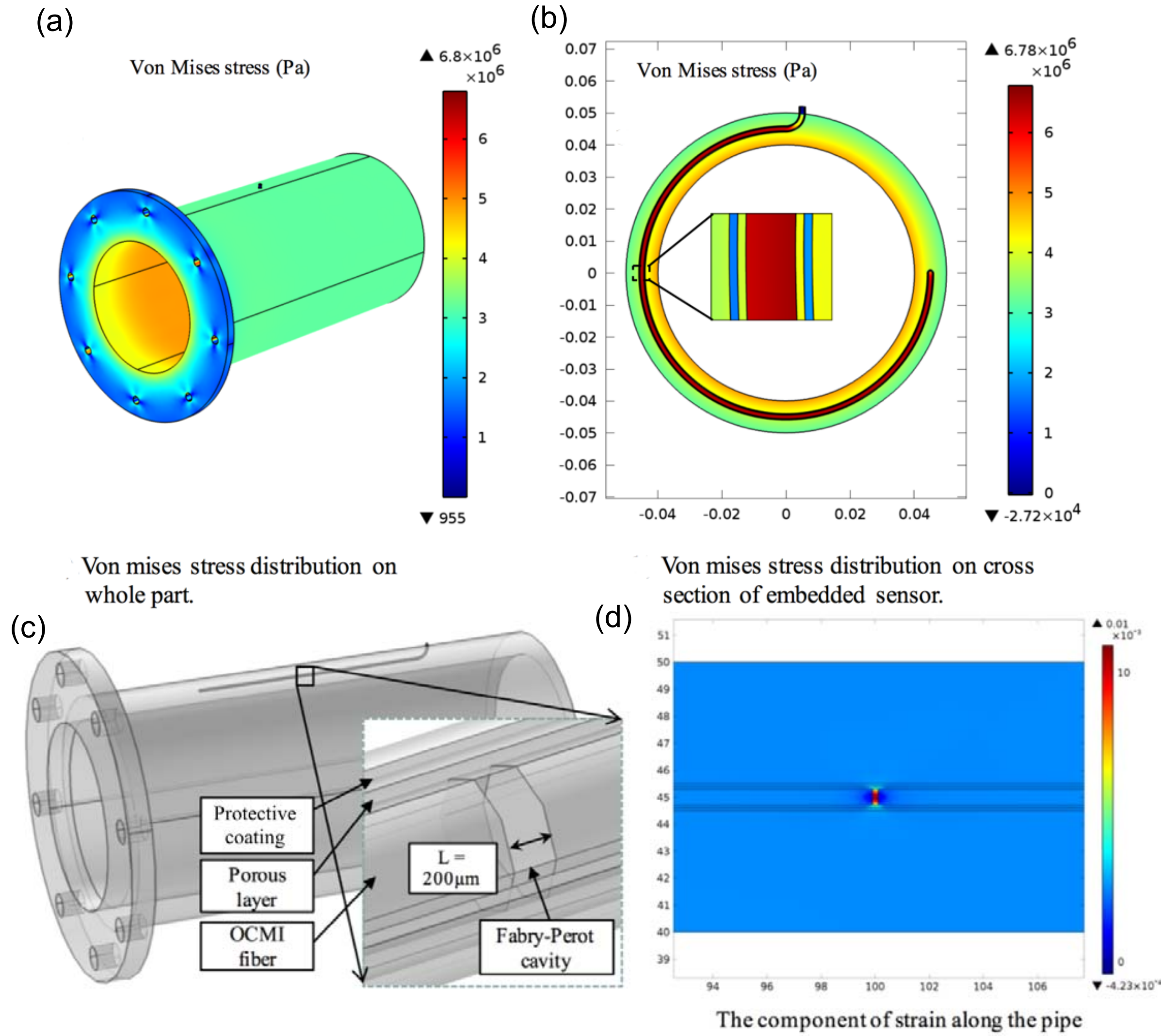




Thermal Stress-Strain Modeling of Embedded Sensors

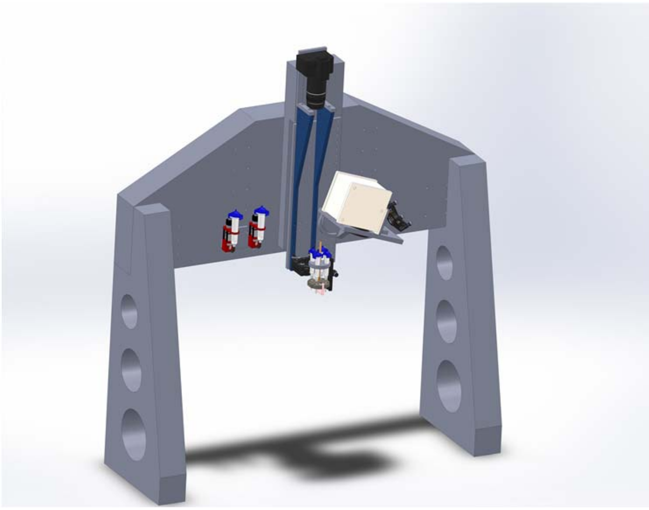
Pressure Caused Stress-Strain Distribution

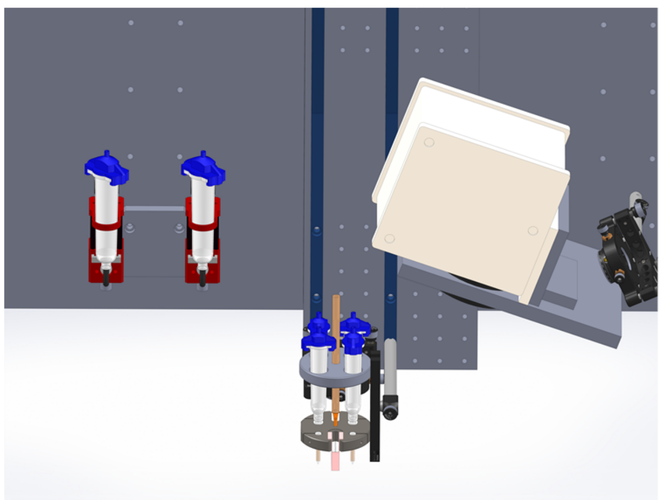
Temperature Caused Stress-Strain Distribution

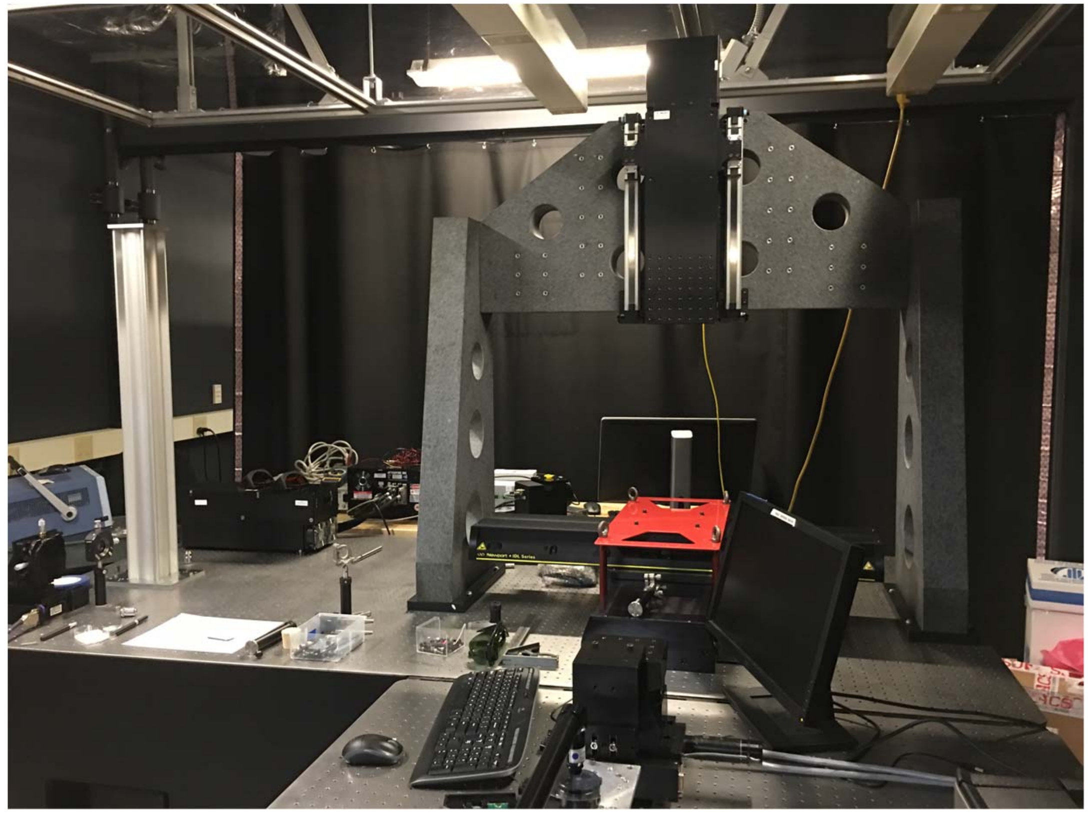


CLEMSON UNIVERSITY

IIM system under construction

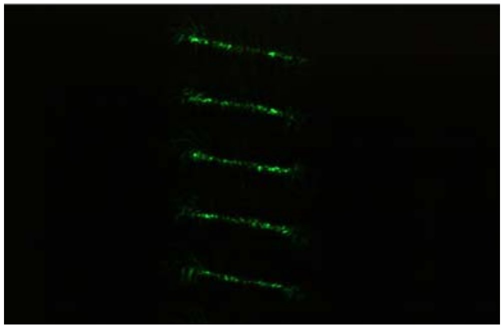


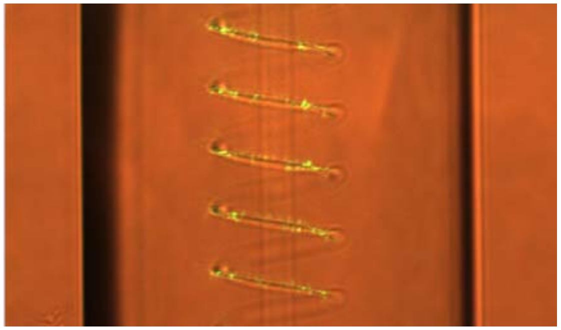


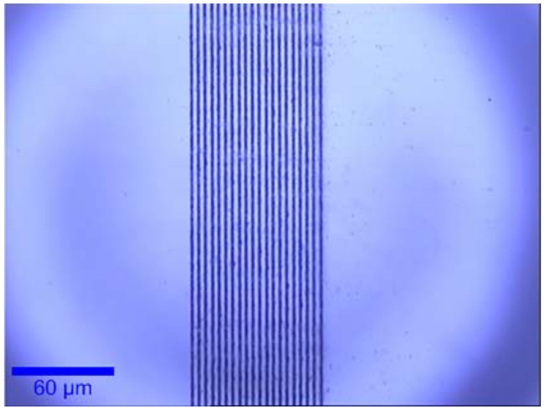


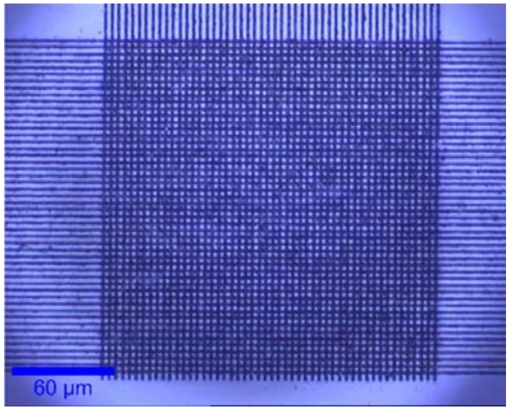
Helical structure inside fiber

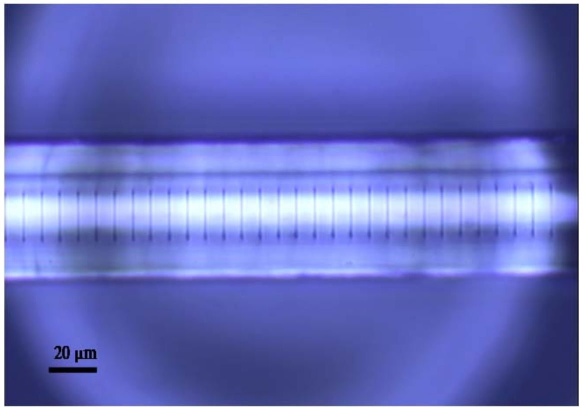
Fs laser micromachined structures



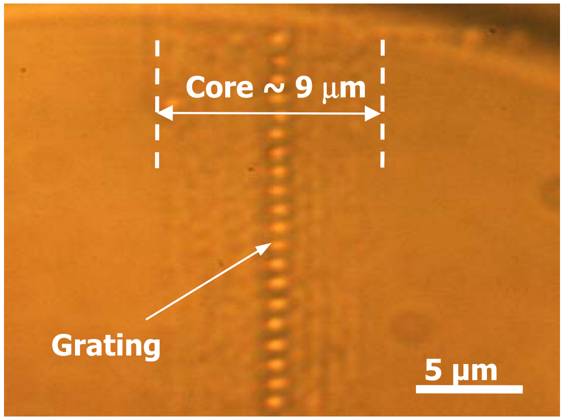


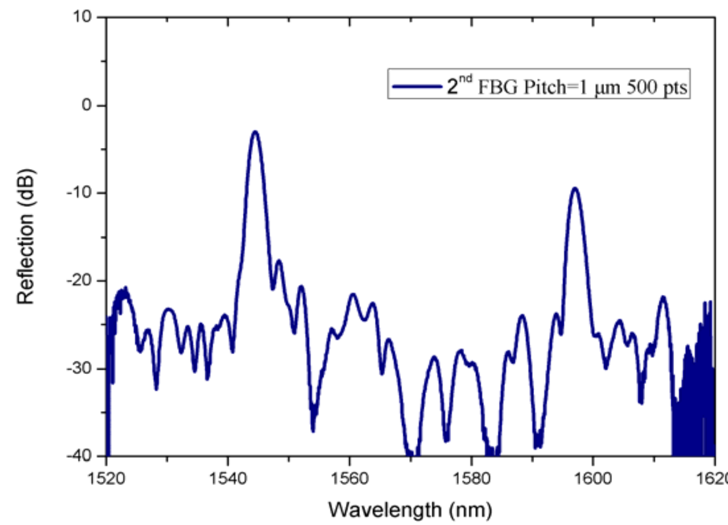


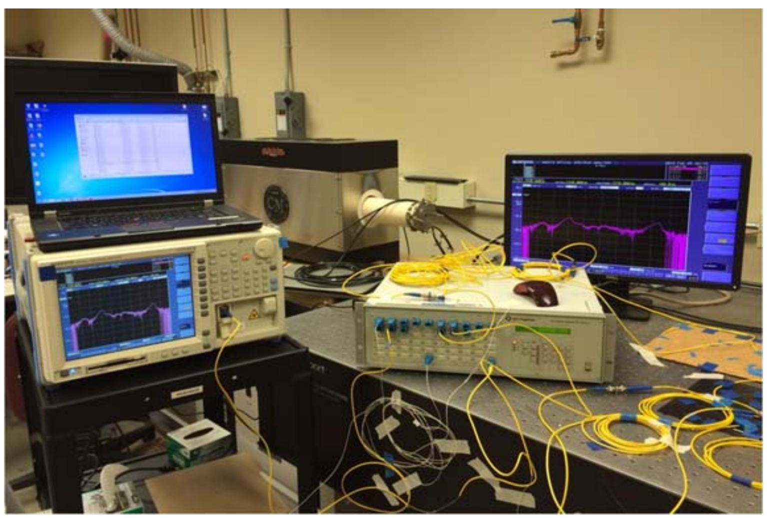


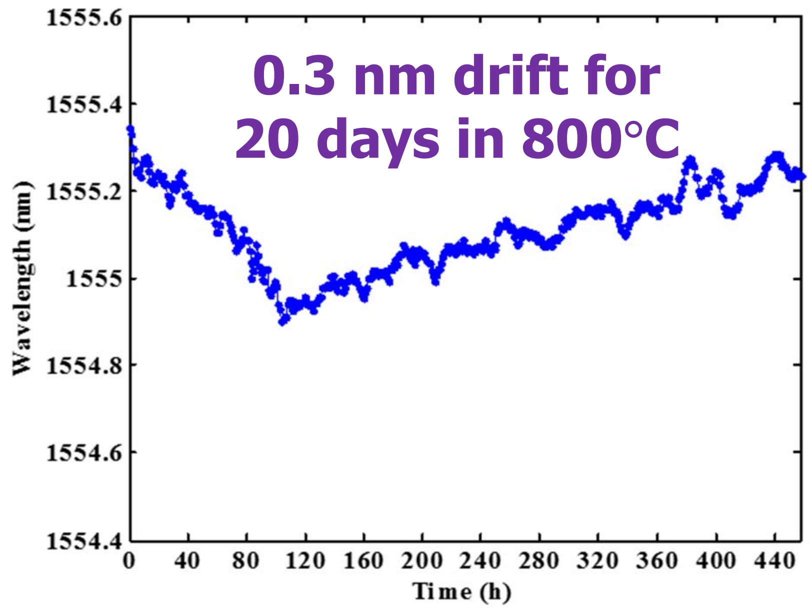


Fs laser inscribed FBGs

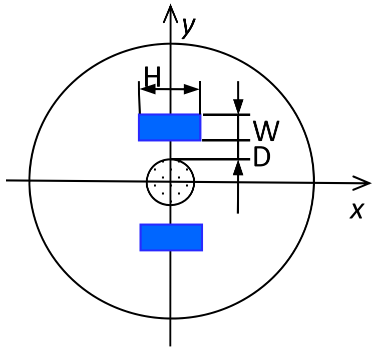


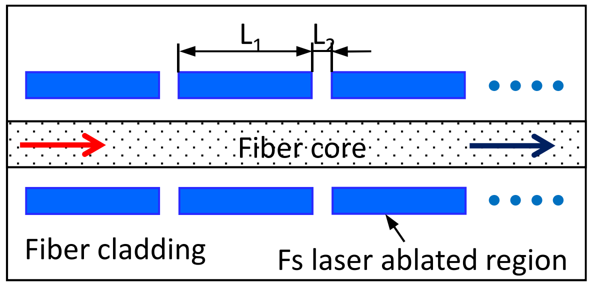


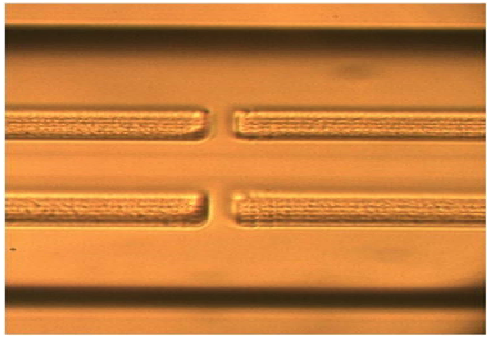


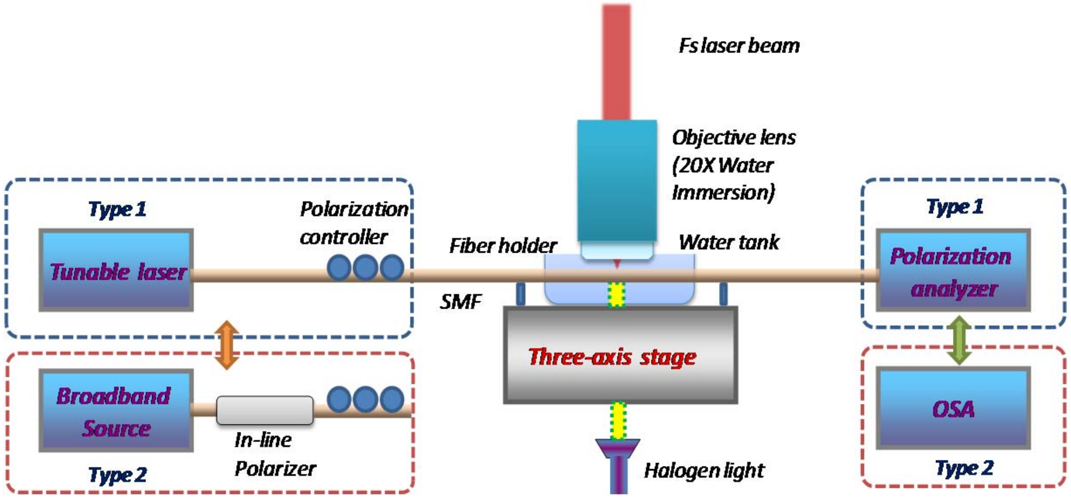


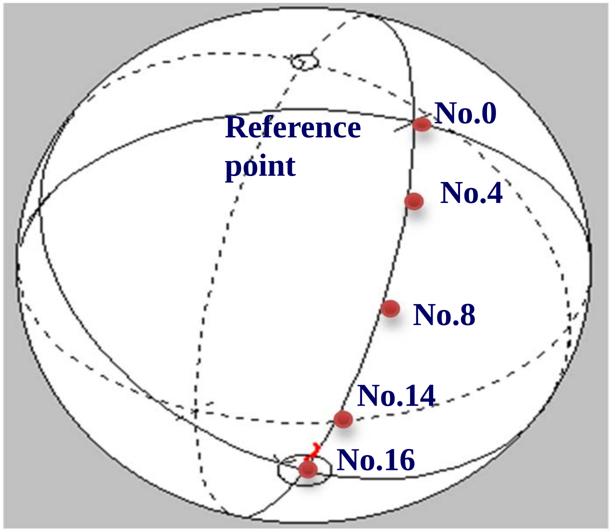
Fiber inline waveplate







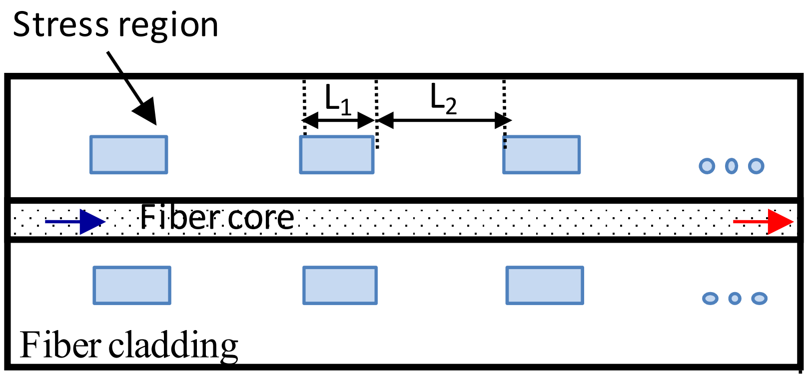


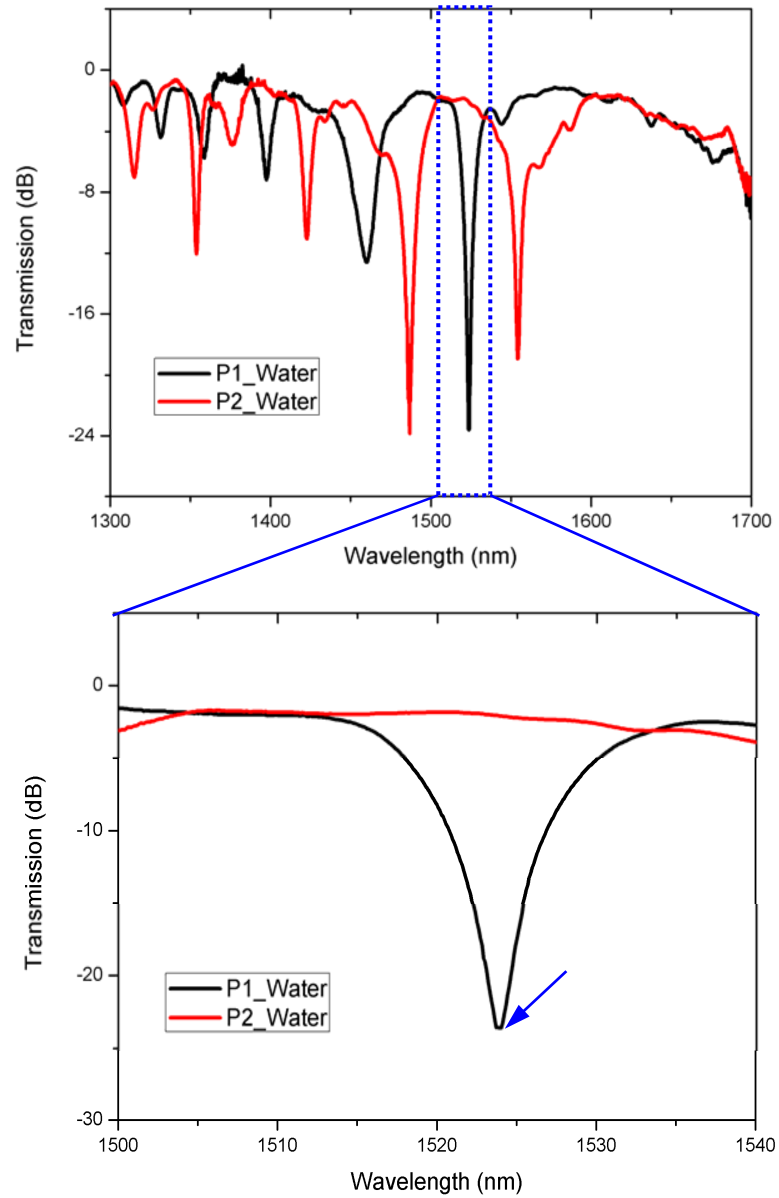


- The polarization status can be flexibly changed by fs laser induced stress patterns inside the fiber
- Waveplates of any desired phase retardance can be fabricated in a SMF

L. Yuan, et al., *Optics Express*, 2016.

Fiber inline polarizer



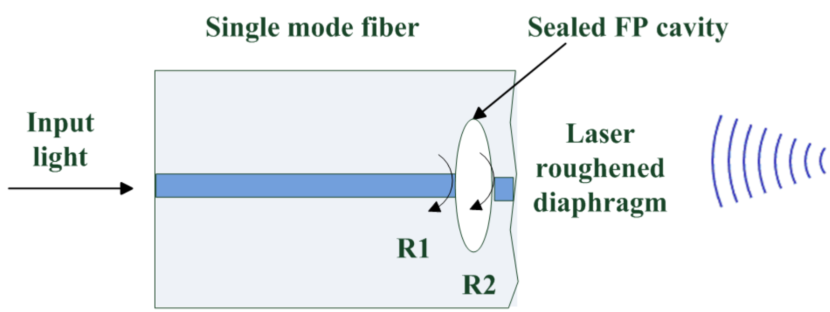


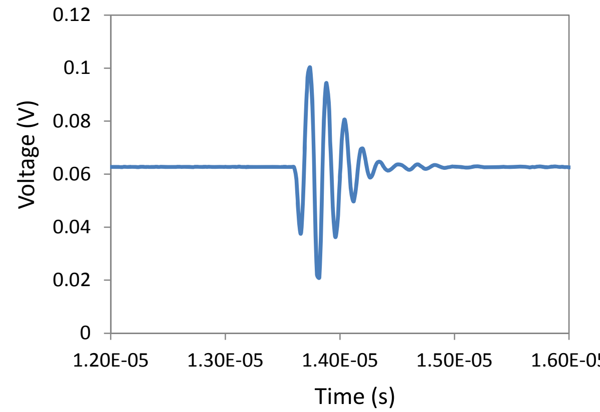
- **Fs laser inscribed periodic stress patterns near the core of a single mode fiber**
- **Polarization dependent core-cladding mode coupling result in an inline polarizer**
- **Fiber polarizers can be fabricated anywhere we want**

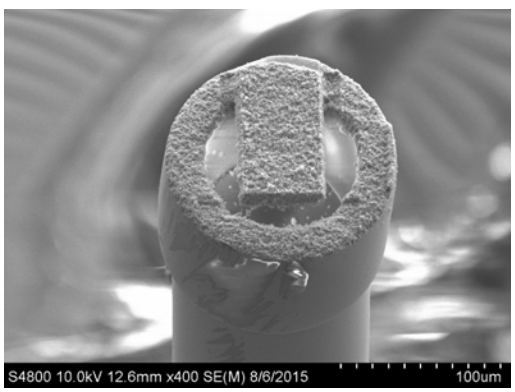
J. Huang, et al., *Optics Express*, 2014.

Diaphragm based ultrasonic sensor

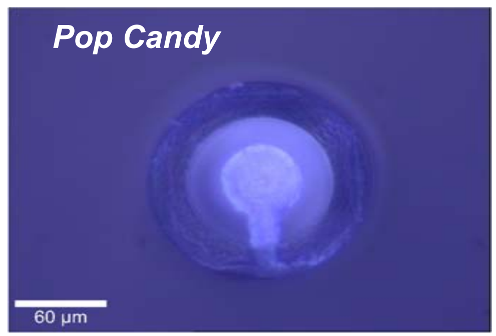
- **Endface diaphragm based acoustic sensor**

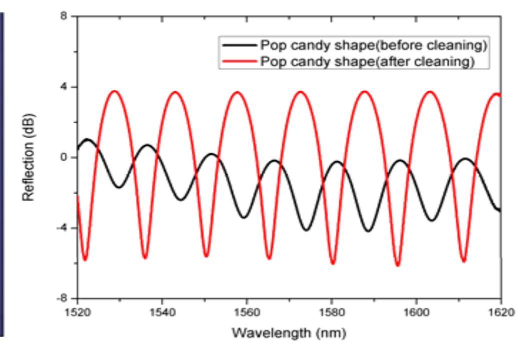


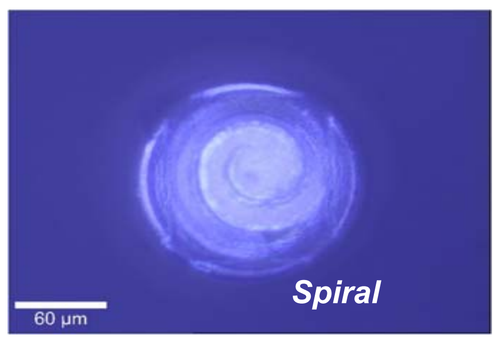


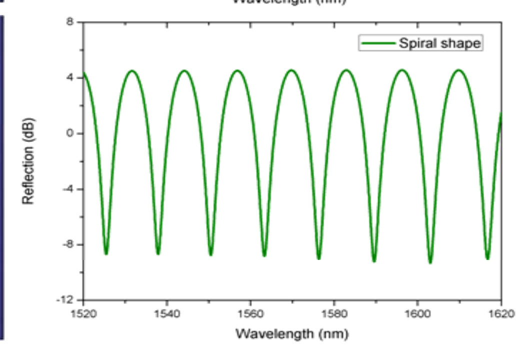


Cantilevers









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
- 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
  - Information integrative smart manufacturing system
- 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
- **Test embedded sensors in smart parts**
- **Making sensors while making the parts**
- **Initial tests of sensors embedded in the smart parts**