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 and Accomplishments
- Summary
- 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**

Traditional Approach

- 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 and 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**
- **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

Summary of accomplishments

- **Three types of fully distributed sensors for embedded applications**

1. **Microwave sensors** – uniquely harvest the robustness of high temperature coaxial cables
2. **Incoherent Optical carrier based microwave interferometry (OCMI) sensors** – can be used to interrogate previously difficult highly multimode fibers (e.g., quart rod and sapphire fiber)
3. **Coherent OMCI sensors** – can reach extremely high resolution

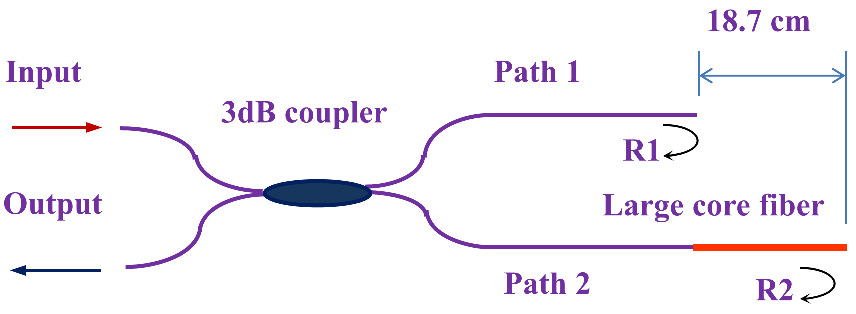
Microwave-Photonics Sensors

- **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**
  - **Can be implemented in either incoherent (make the optical term become zero) or coherence (keep the optical term)**

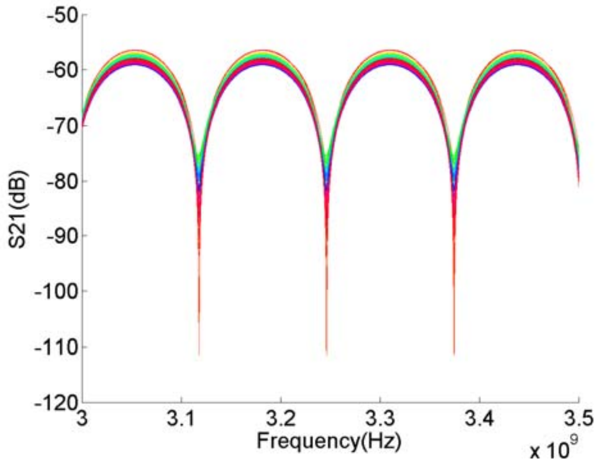
$$
\begin{aligned}
|E|^2 = |E_1 + E_2|^2 = 2A^2 + {} & \overbrace{2A^2 M\cos\left[\Omega\frac{L_{O1}-L_{O2}}{2c}\right]\cos\left[\Omega\left(t+\frac{2W+L_{O1}+L_{O2}}{2c}\right)\right]}^{\text{Microwave term}} \\
& \underbrace{+2A^2\sqrt{\left\{1+M\cos\left[\Omega\left(t+\frac{W+L_{O1}}{c}\right)\right]\right\}\left\{1+M\cos\left[\Omega\left(t+\frac{W+L_{O2}}{c}\right)\right]\right\}}\cdot\int_{\omega_{\min}}^{\omega_{\max}}\cos\left(\omega\frac{L_{O1}-L_{O2}}{c}\right)d\omega}_{\text{Optical term}}
\end{aligned}
$$

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

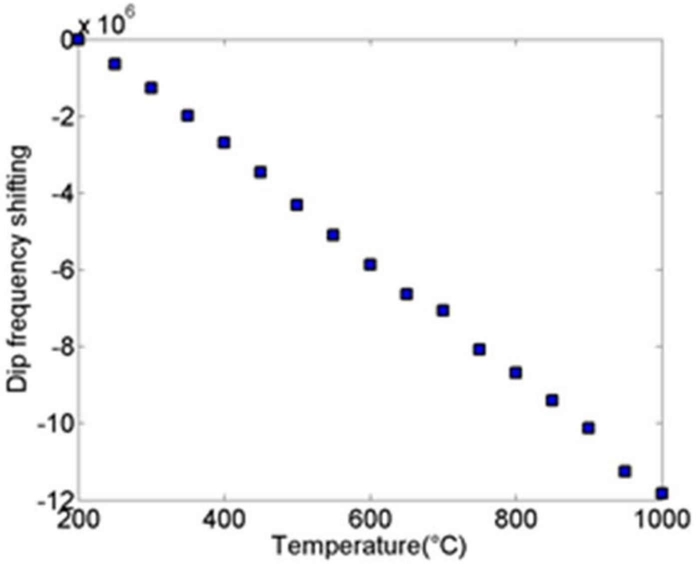
Quartz rod (800μm dia. Uncladded)



Fused silica rod 800μm dia.

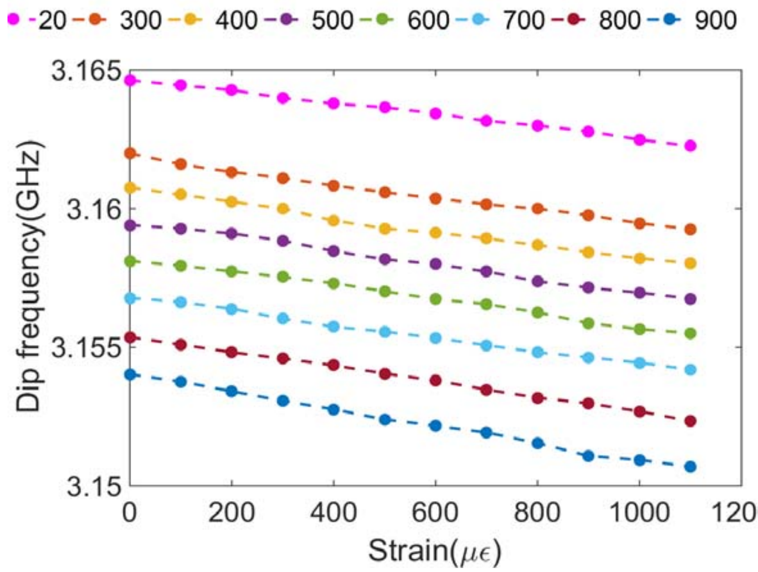


Interference fringes



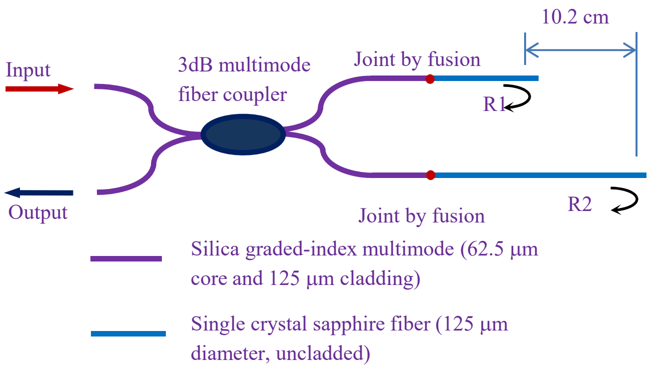
High temperature response

L. Hua., Applied Optics, 2015

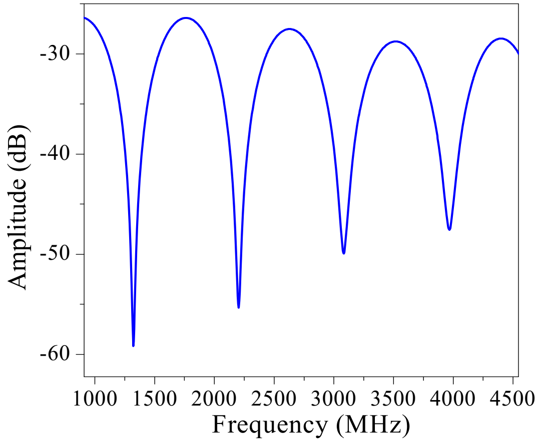


Quartz rod can be used to measure strains at high temperatures

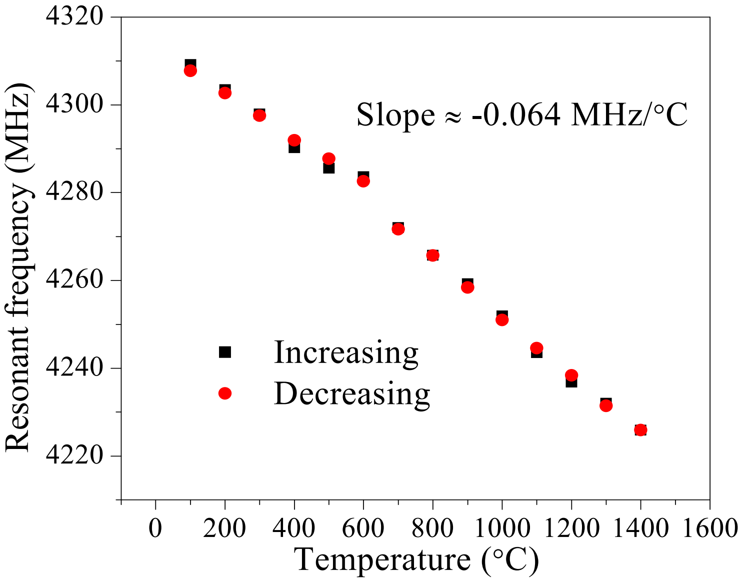
Sapphire Michelson Sensor (125 µm)



Sapphire fiber Michelson OCMI



Excellent fringe visibility > 30dB

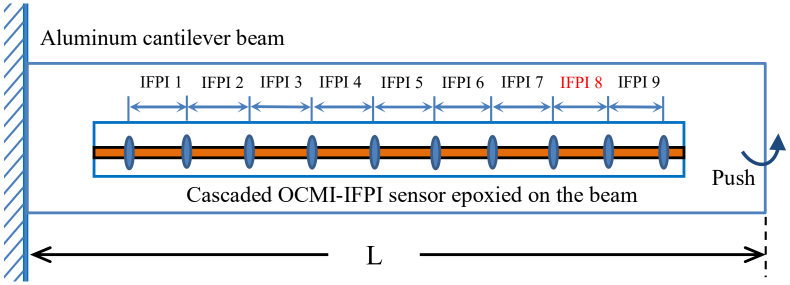


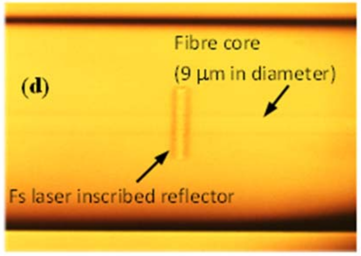
J. Huang, et al., *IEEE Photonics Technology Letters*, 2015.

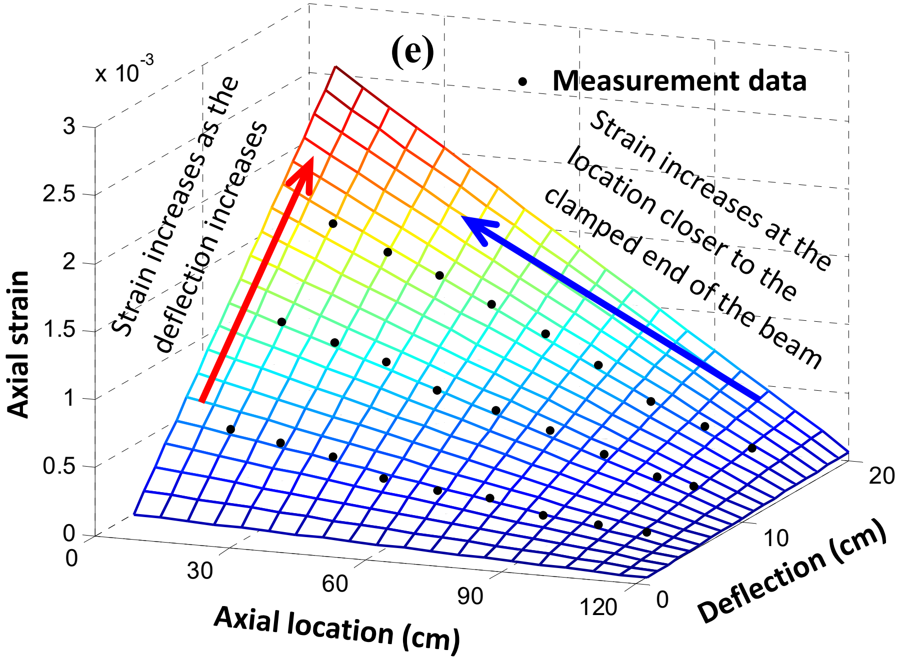
Distributed sensing

- 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.

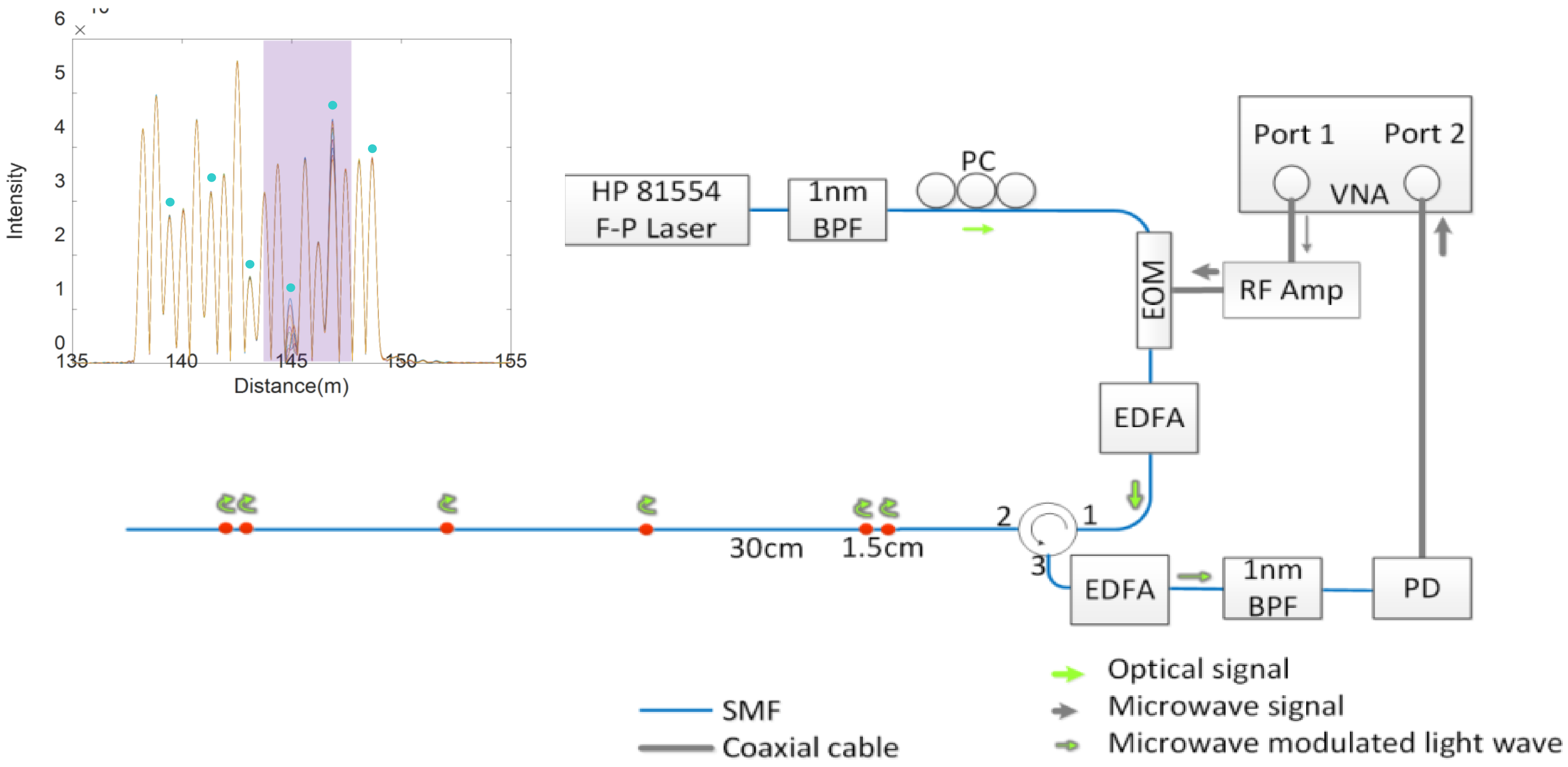






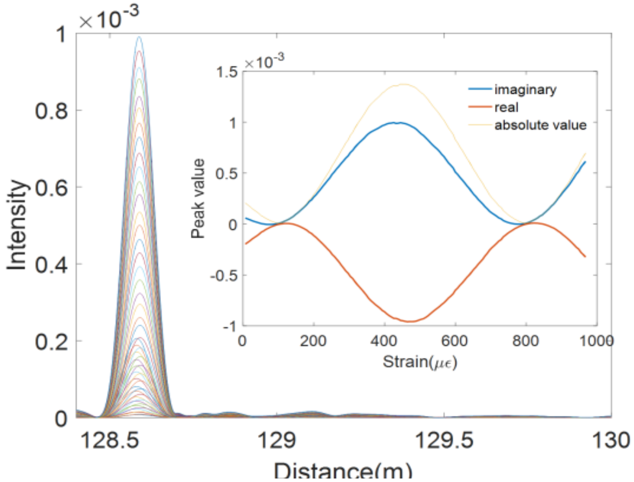
Coherent OCMI System

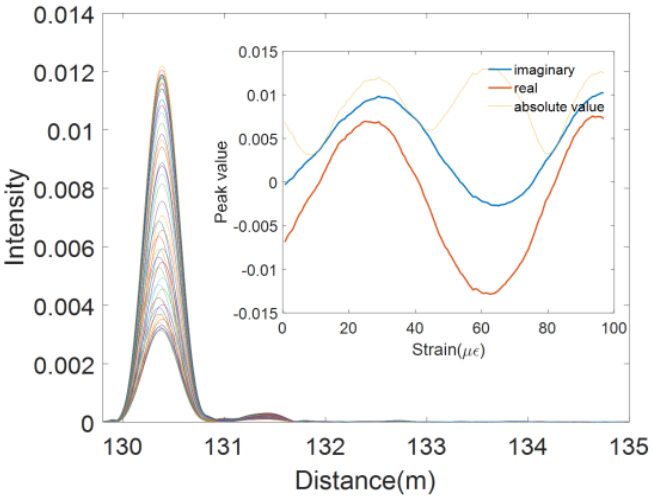
- Use a coherent light source
- Arrange the interferometers within the coherent length of the source

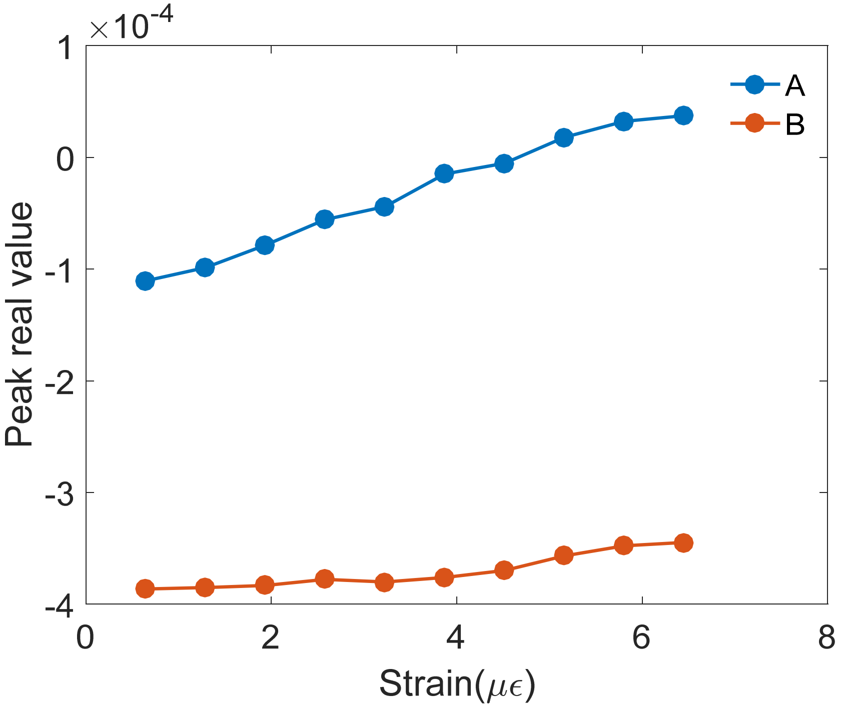


Very high resolution

- Use both real and imaginary part of the signal (quadrature)
- Resolution reaches 10nε using an interferometer with a length of 10cm.







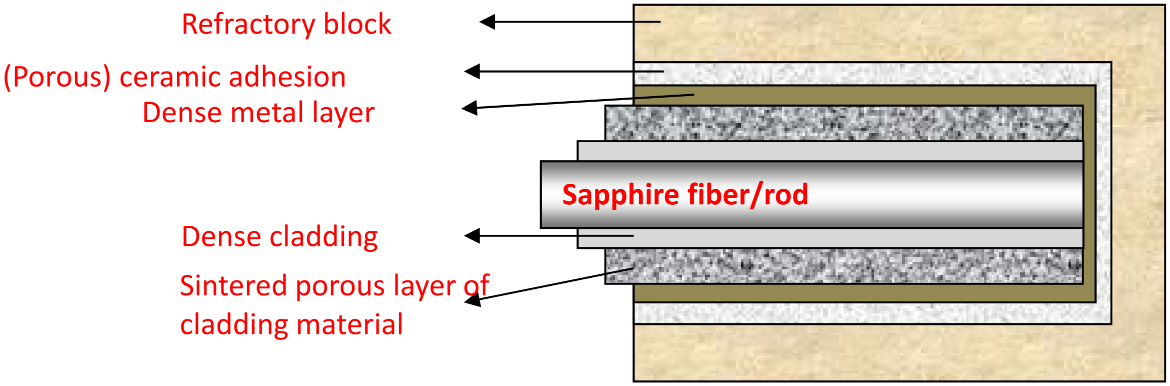
Incoherent and Coherent OCMI

- **Incoherent OCMI – use incoherent (i.e., broadband) optical source**
  - Large dynamic range
  - Resolution is limited, about 10^{-5} - 10^{-6}
- **Coherent OCMI – use coherent (i.e., narrow bandwidth) optical source**
  - Limited dynamic range
  - Resolution can be extremely high, about 10^{-8} - 10^{-9}
- **The two can be combined into a single system with two optical sources to achieve a high resolution in a large dynamic range.**
  - Sensing Range (Spatial resolution): 100 km(1m), 2km(2cm)

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



Summary of Accomplishments

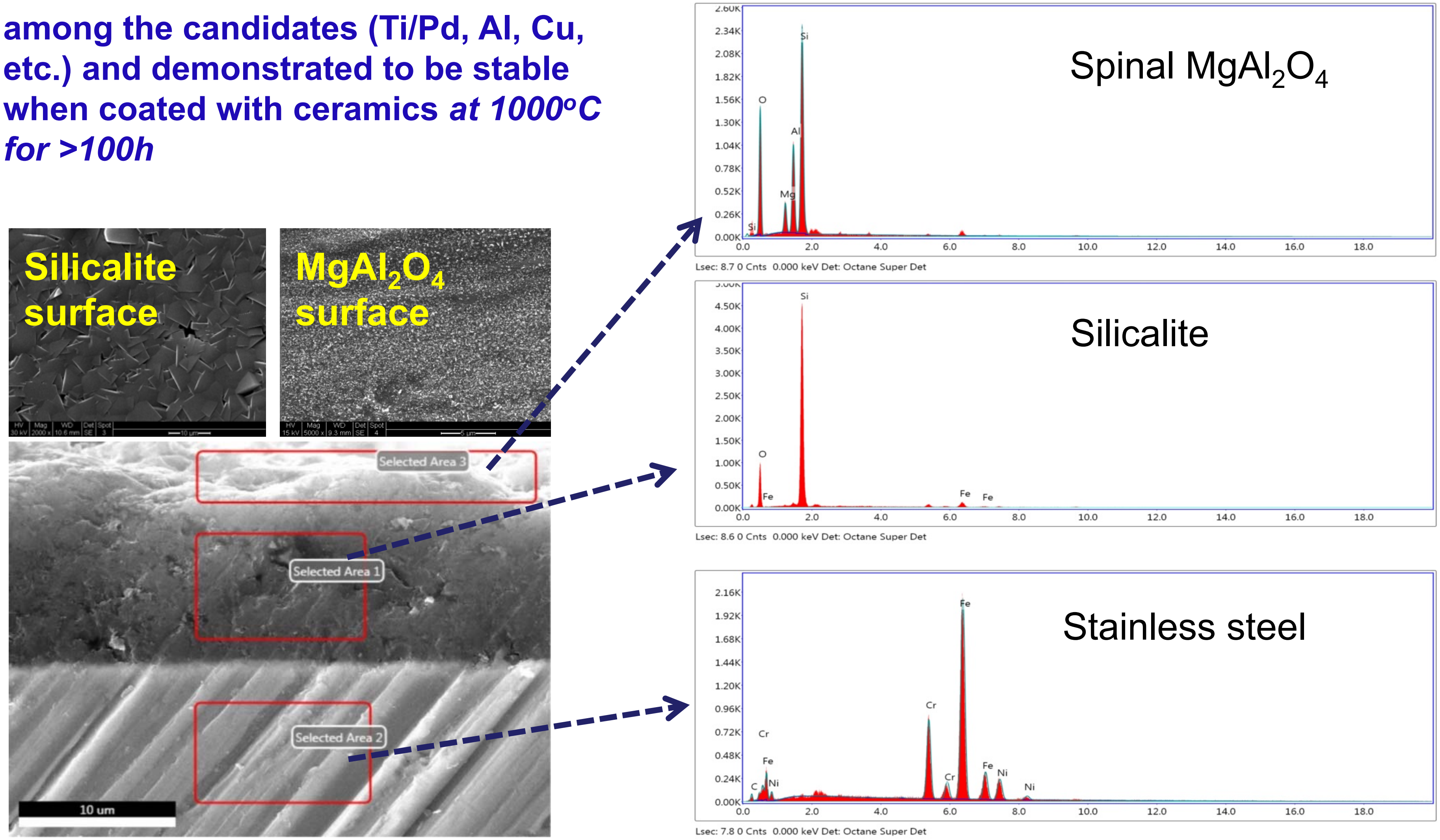
- **Silica fiber optic sensors packaged in the ceramic host capillary tubes are fully functional at high temperature (tested up to 1000^{o}C) with good stability**

- **Silicalite layers directly grown on the sapphire fibers may be used both as fiber cladding and sensor protection (up to ~900^{o}C)**

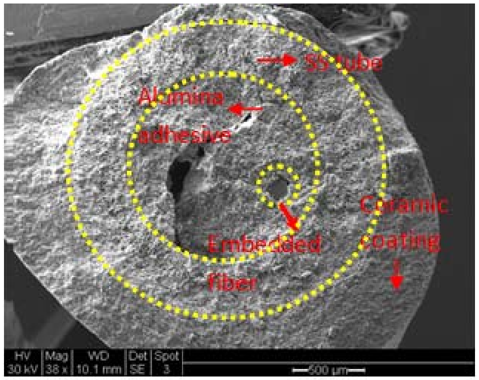
- **MgAl2O4 layers can be used as sapphire cladding for operation up to 1250^{o}C.**

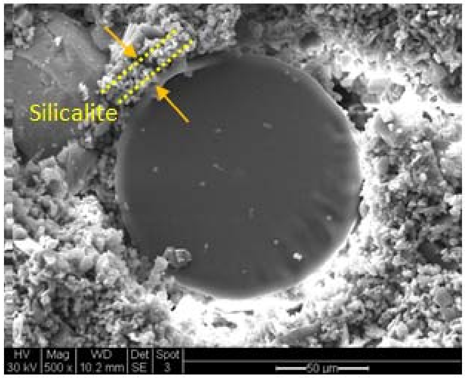
Interface Stability in Layered Structure for Sensor Protection

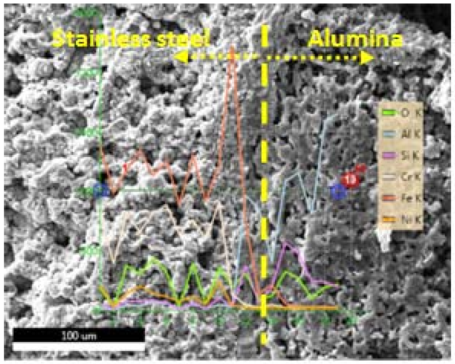
Results: Stainless steel has been identified as the most stable metal among the candidates (Ti/Pd, Al, Cu, etc.) and demonstrated to be stable when coated with ceramics *at 1000°C for >100h*

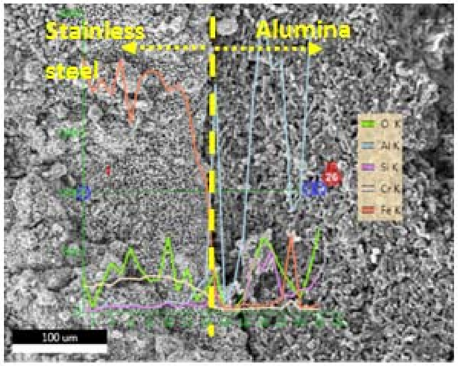


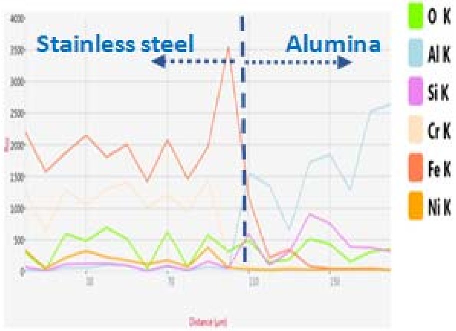
Sensor Protection by ceramic adhesive in sintered SS capillary tube

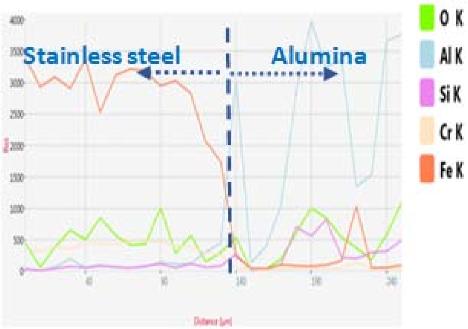












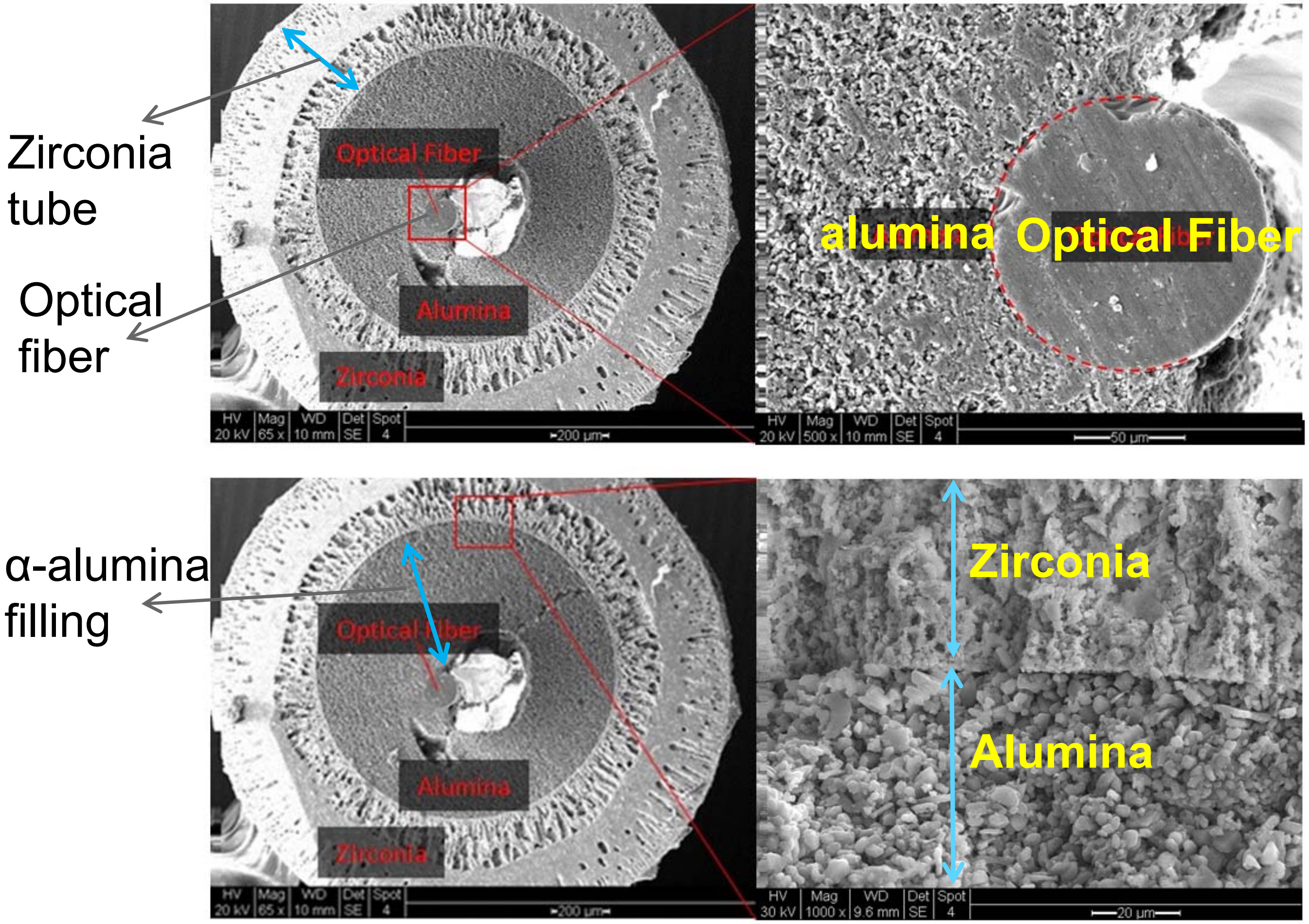
Stainless steel hosted fiber unit:

Fused silica optical fibers as a packaged sensor unit for direct installation in “smart bricks”. Porous ceramic adhesion layers (e.g. alumina and zirconia based materials) used to fix the fiber with the host capillary tube.

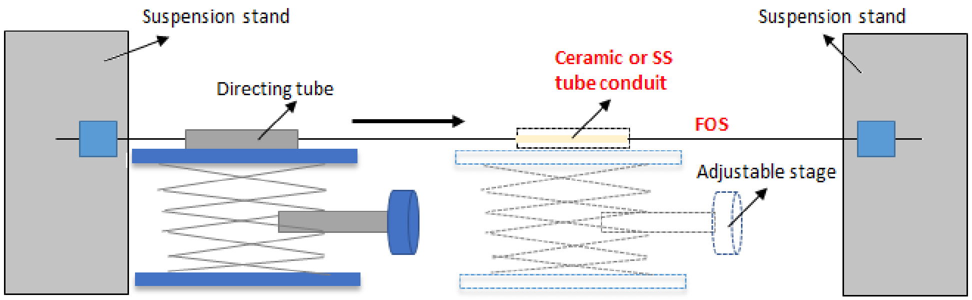
EDS line scan across the SS/alumina interface/fiber interfaces indicated no significant solid state reaction or diffusion at 1000$_{o}$C over extended period.

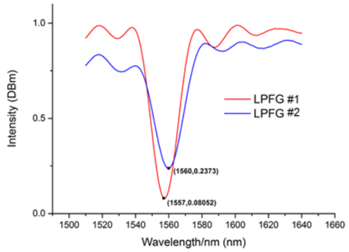
Sensor Protection by ceramic adhesive in ceramic capillary tube

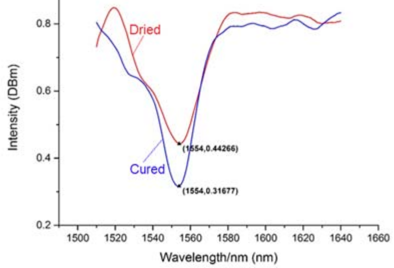
Results: pre-packaging of fibers in ceramic capillary tubes *(e.g. porous zirconia and α-alumina) has been demonstrated using ceramic adhesion and tested at 1000°C stable over extended periods.*

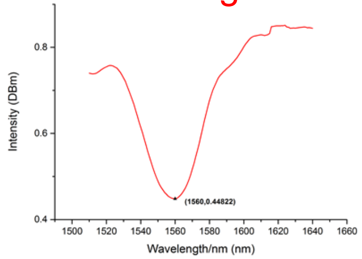


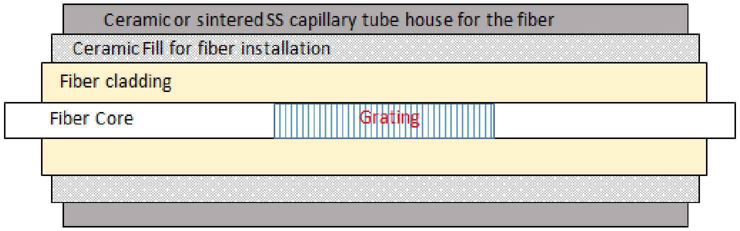
Packaging of Fiber Optic Sensor in Host Ceramic (or SS) Capillary Tubes

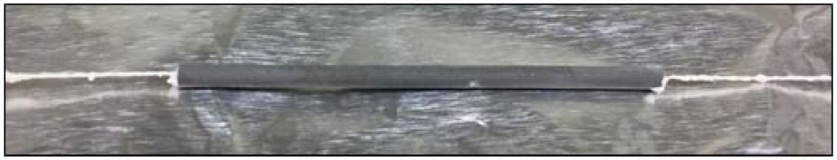


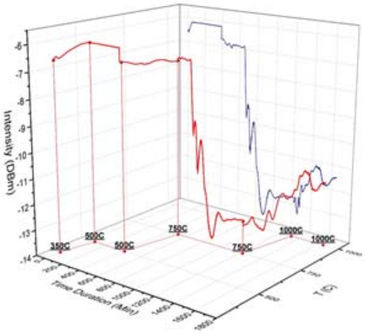


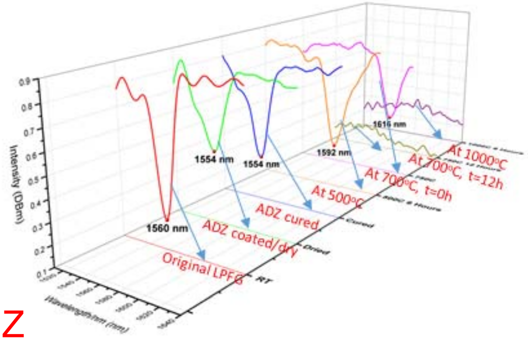

ADZ


ZAlMg







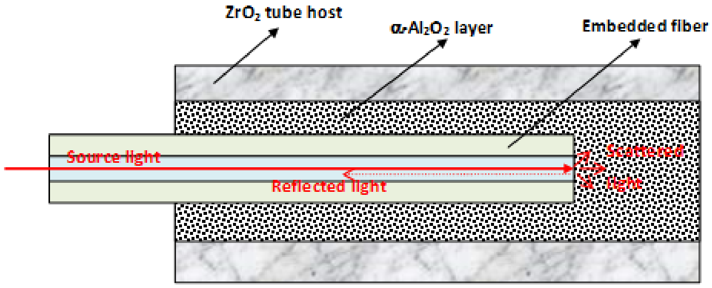


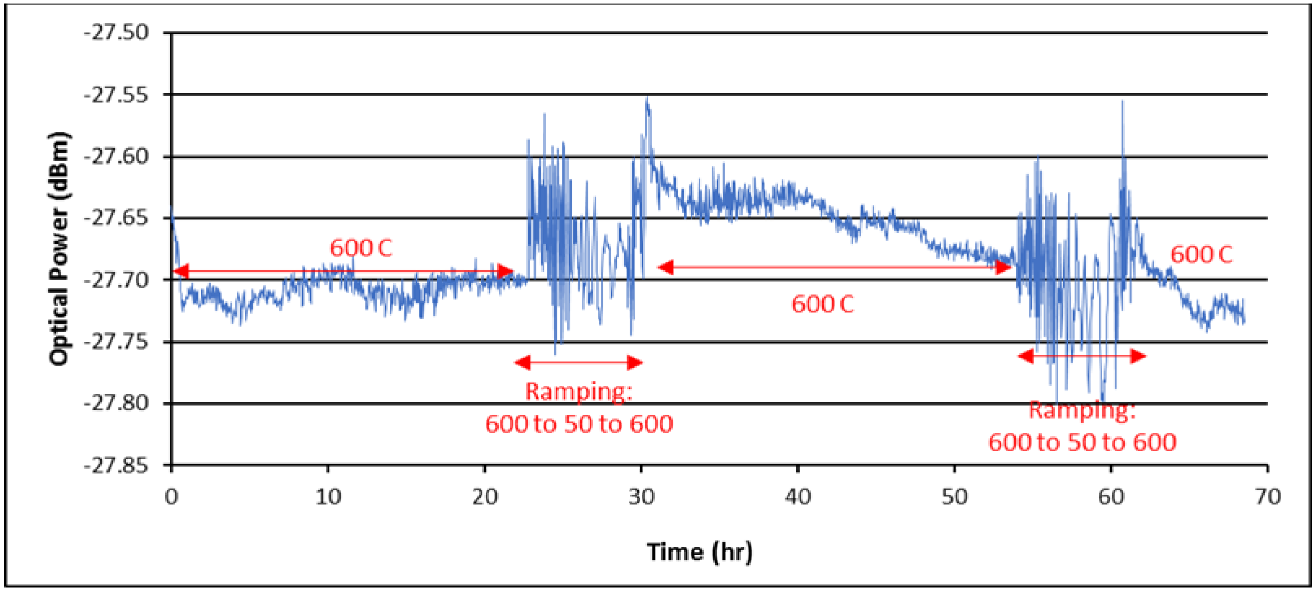
ADZ

Optical Functionality Tests for the Fiber Sensor in Capillary Tables

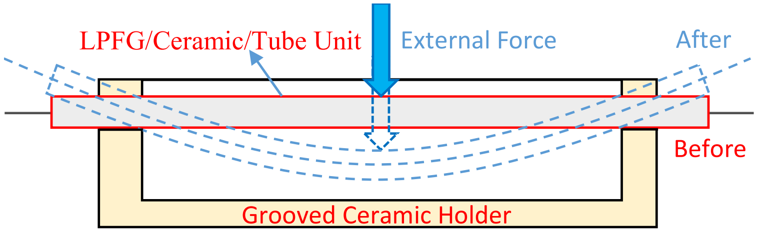
UNIVERSITY OF Cincinnati

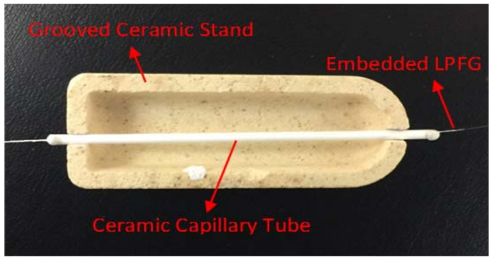
<u>Results:</u> *The fibers pre-packaged in the host tubes have been verified to be optically functional for signal generation and transmission at high temperatures*

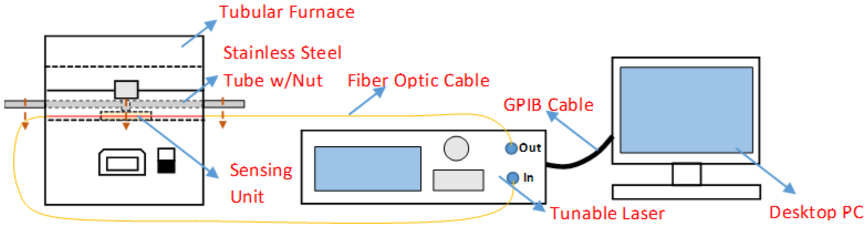


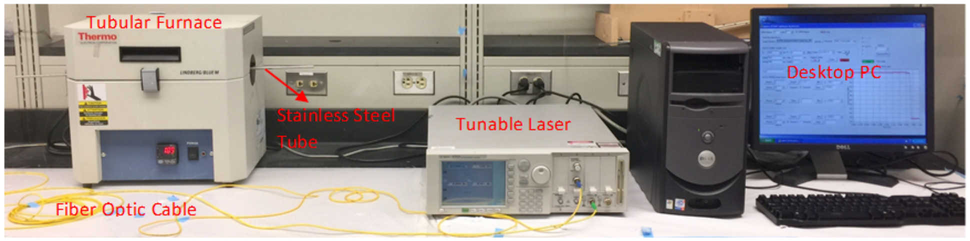


Test of Packaged Fiber Sensor (LPG) for Monitoring Strain and breakage

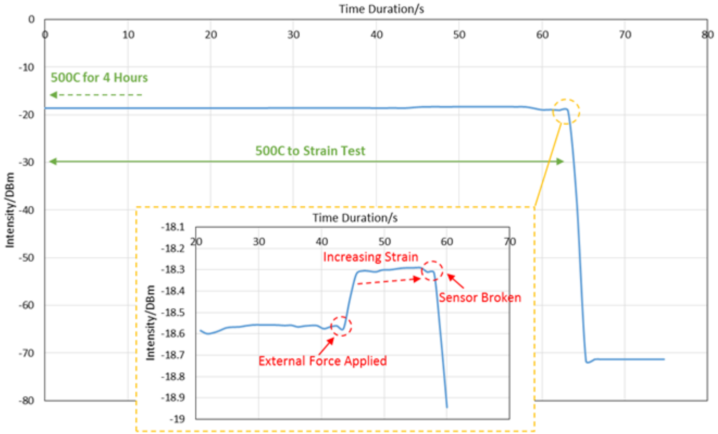








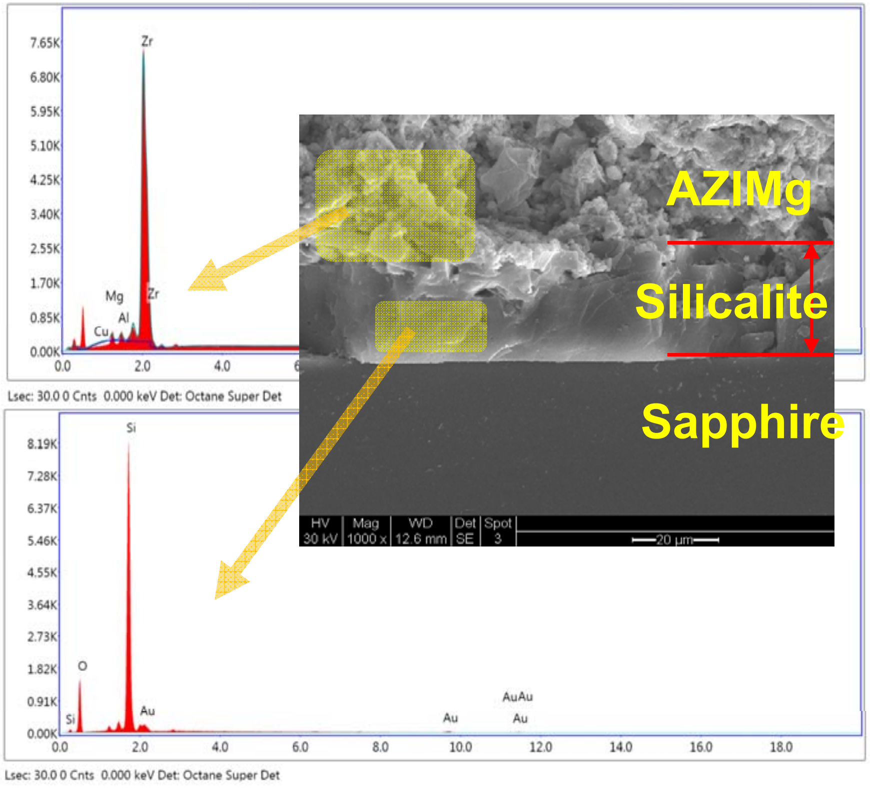
A fused silica LPFG sensor was packaged in a ceramic capillary and connected to a tunable laser for monitoring strain and structure damage at high temperature. The packaged sensor was able to detect the external force induced strain and fracture of the packaged unit that indicate promise for installation in refractory liners for structural health monitoring.

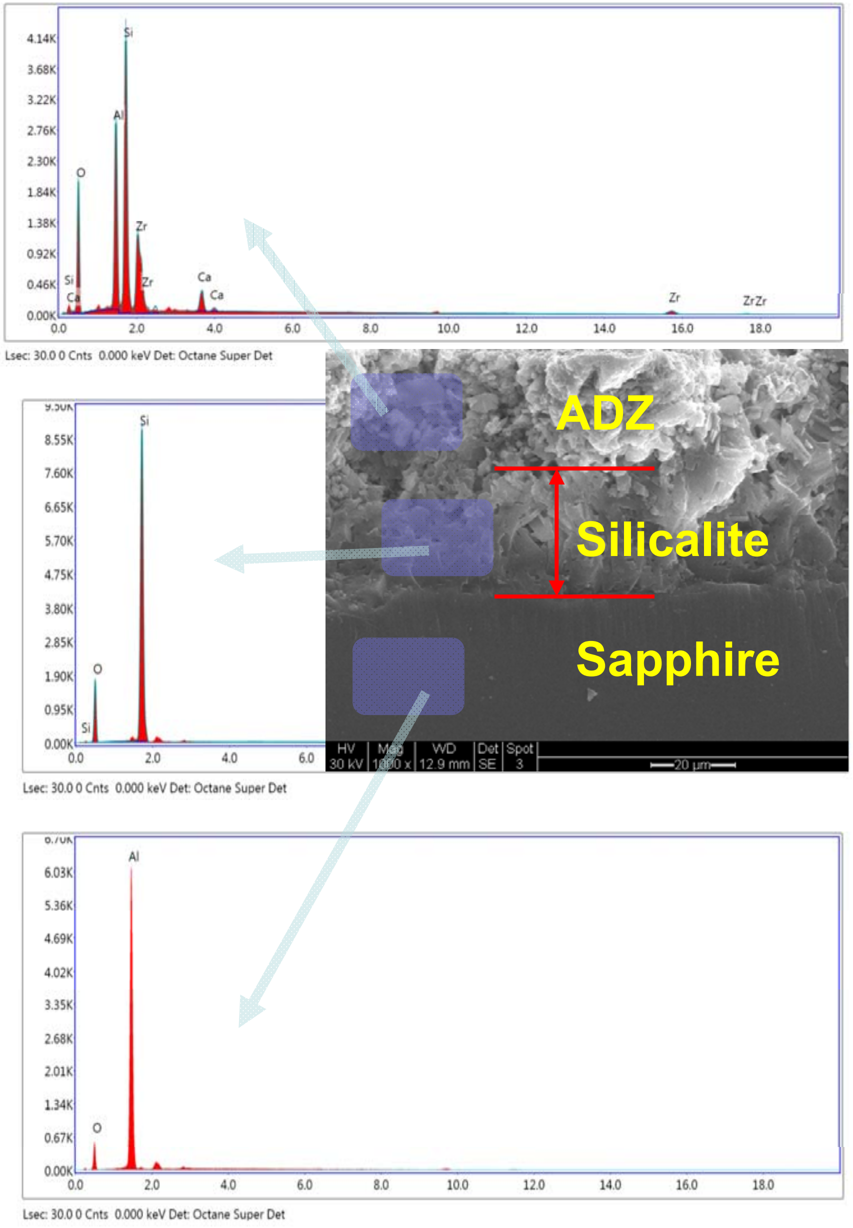


Single wavelength (λ=1612 nm) transmission intensity as a function of time at 500°C.

Long-Term Stability of Sapphire Multilayer Protection

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.



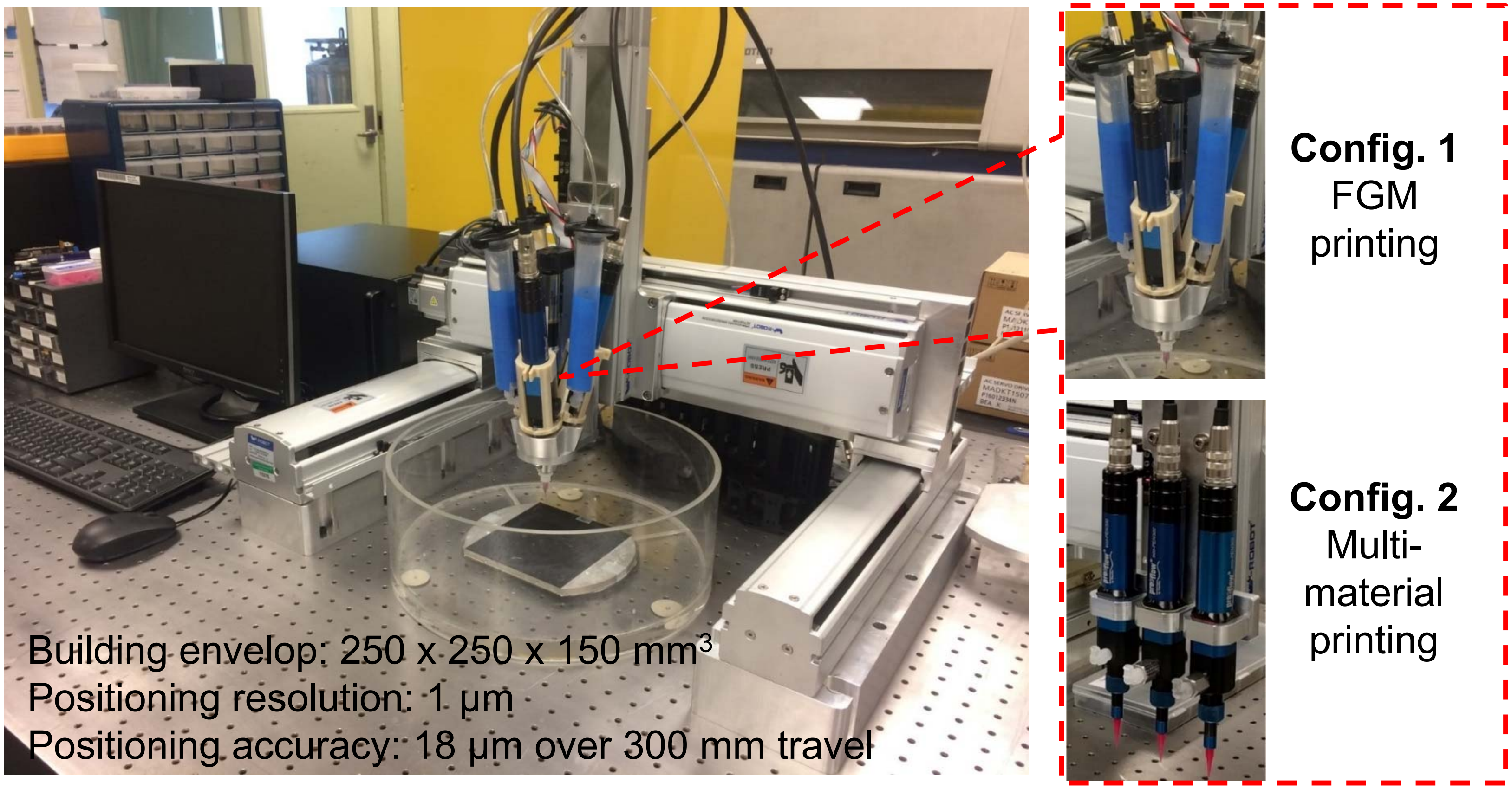


Additive Manufacturing of Ceramics

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

Ming Leu
Missouri University of Science and Technology

- A new ceramic on-demand extrusion (CODE) system has been developed to fabricate Functionally Graded parts (Configuration 1) and Multi-Material parts (Configuration 2).



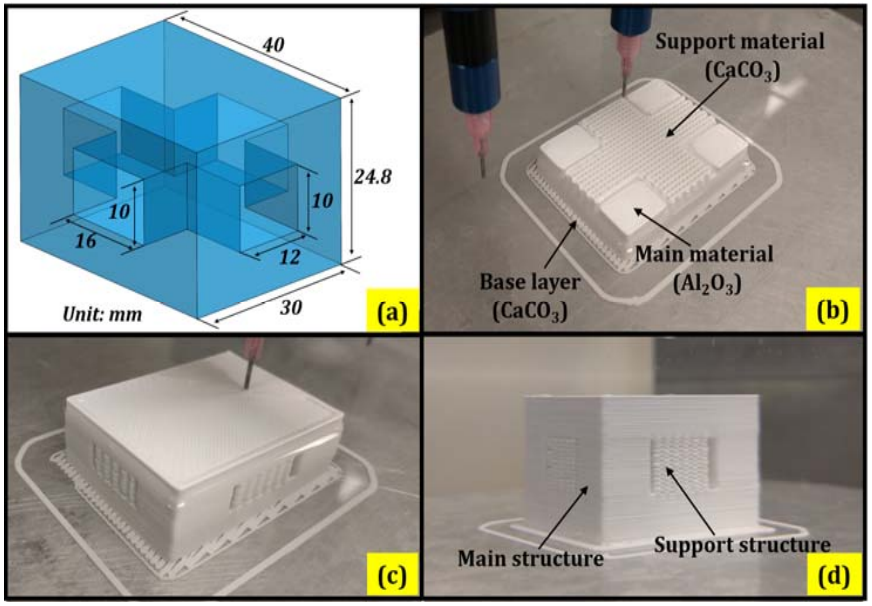
Building envelop: 250 x 250 x 150 mm^3
Positioning resolution: 1 μm
Positioning accuracy: 18 μm over 300 mm travel

Config. 1
FGM
printing

Config. 2
Multi-
material
printing

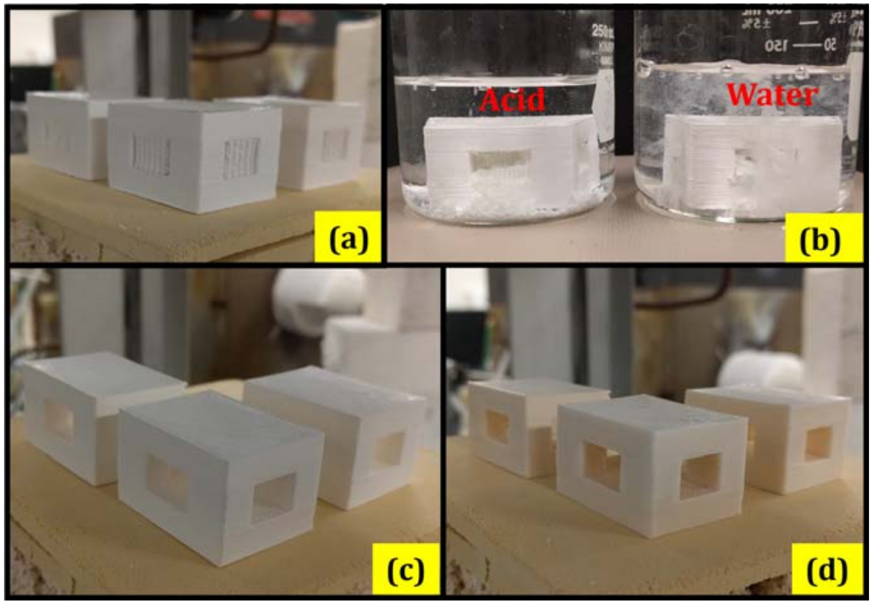
Fabricating Parts with Support Material

Printing



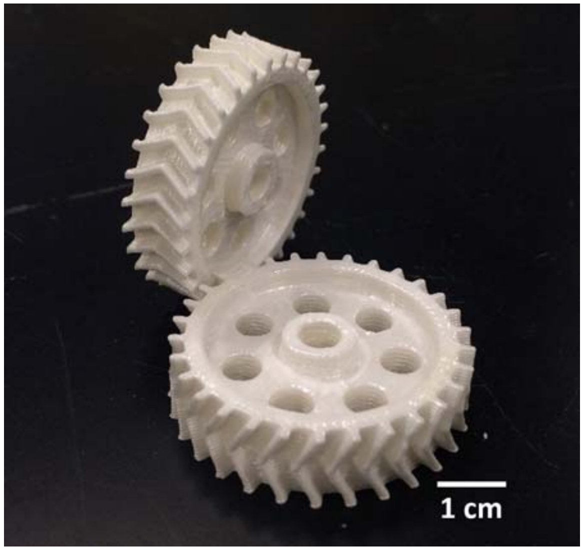
(a) CAD model
(b) Support structure being printed
(c) Overhanging structure being printed
(d) Part having been printed completely (surrounded by oil)

Post processing

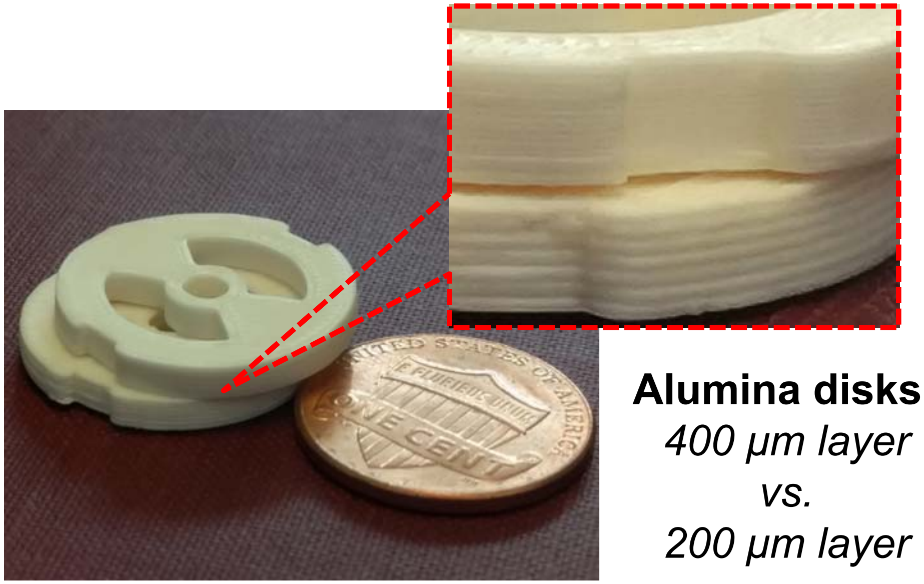


(a) Parts after 1st step sintering (1100 °C)
(b) Support structures being dissolved
(c) Cleaned parts (after support removal)
(d) Final sintered parts

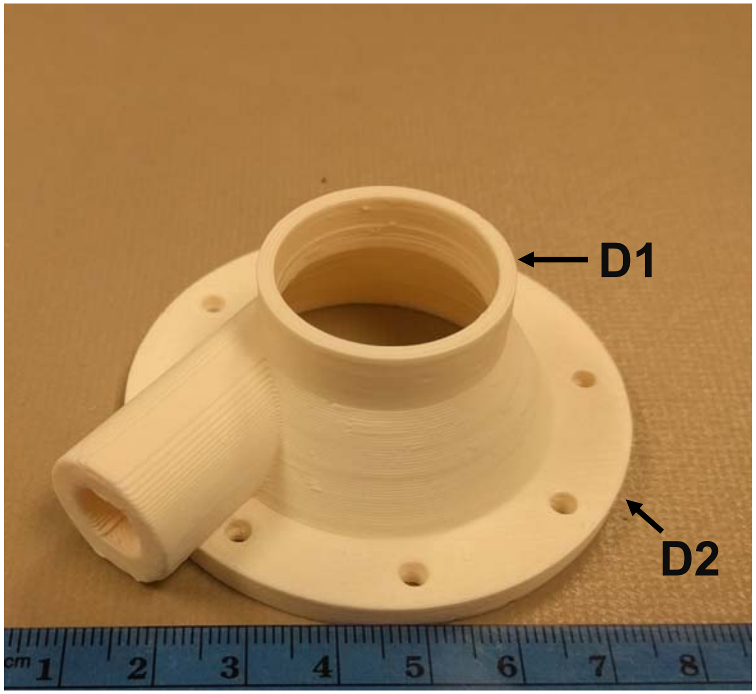
Sample Parts Fabricated with the CODE System



Zirconia gears:
400 µm layer
98.5% Density



Alumina disks:
400 µm layer
vs.
200 µm layer



Alumina turbine blower housing
400 µm layer, 97.5% density

Good circularity
D1: Mean = 29.3 mm, Std.Dev. = 0.07 mm
D2: Mean = 63.7 mm, Std.Dev. = 0.05 mm

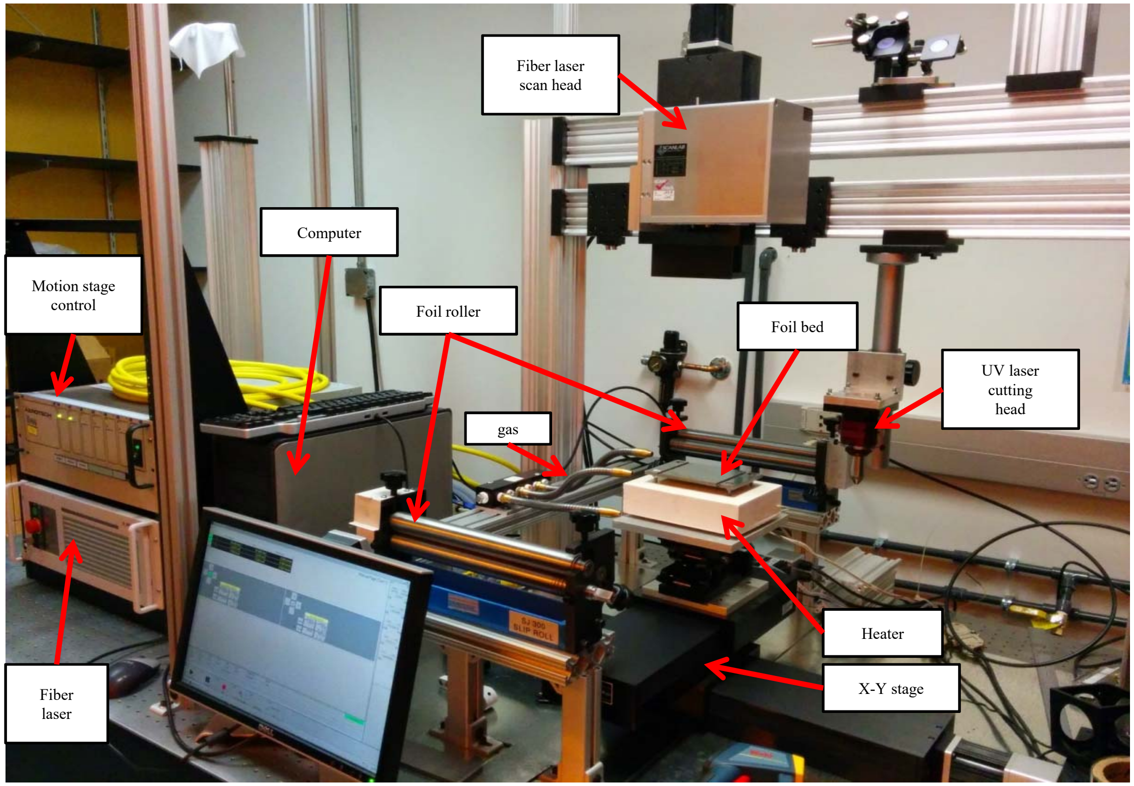
Additive Manufacturing of Metals

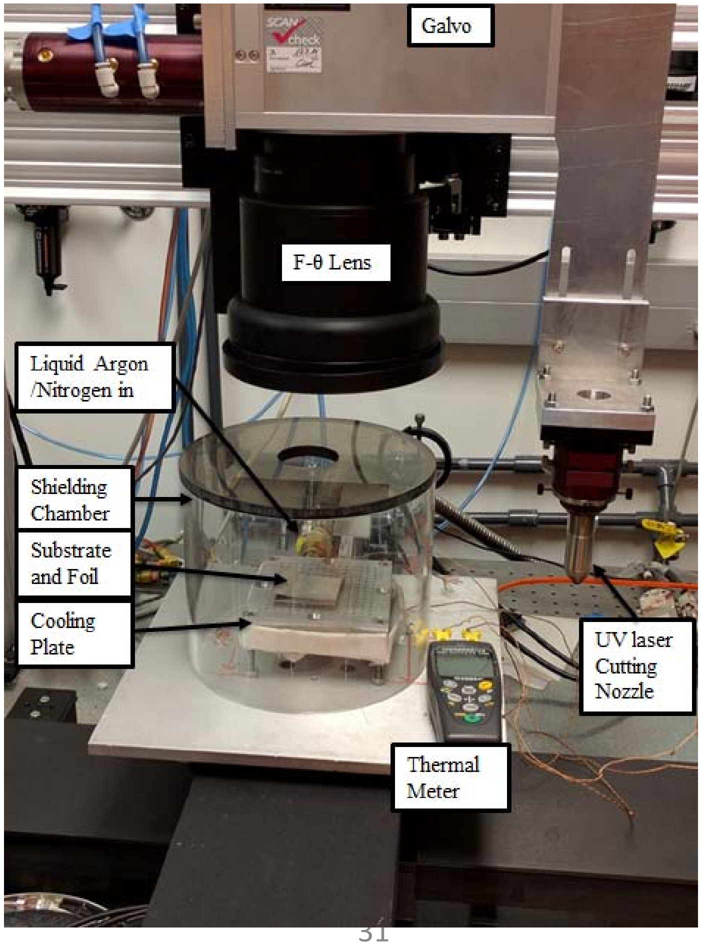
Approach: Foil-Based Dual-Laser Additive Manufacturing Technology

Hai-Lung Tsai
Missouri University of Science and Technology

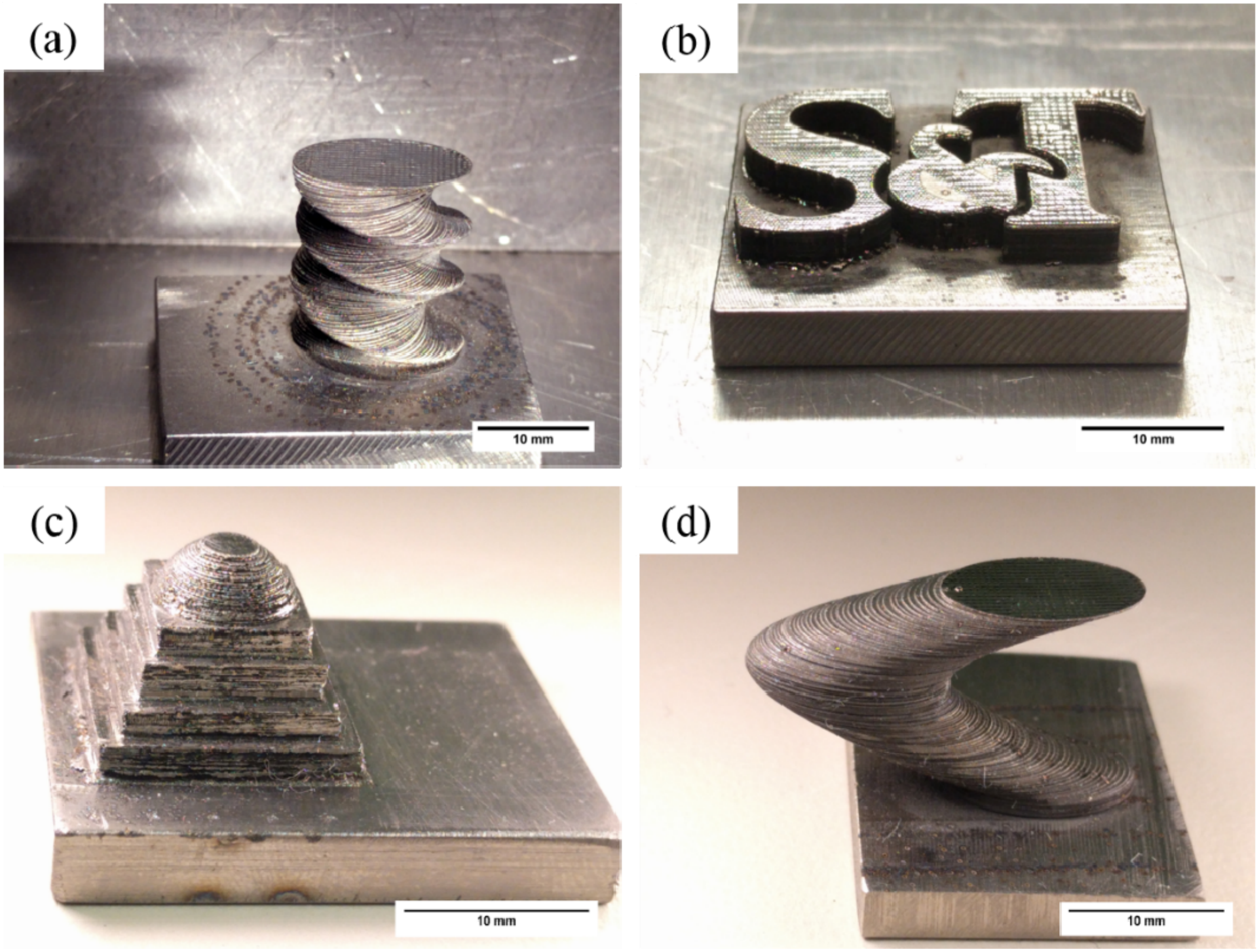
Laser-Foil-Printing AM Technology

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

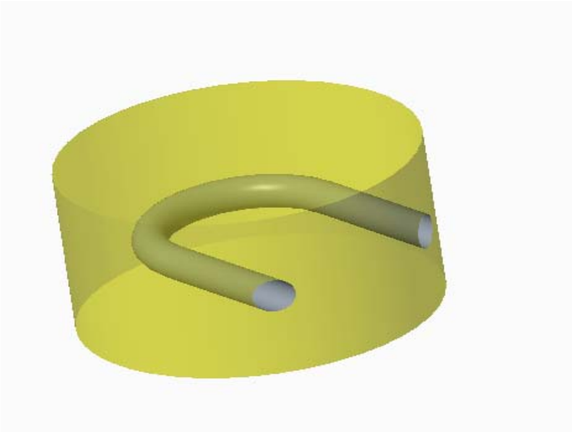




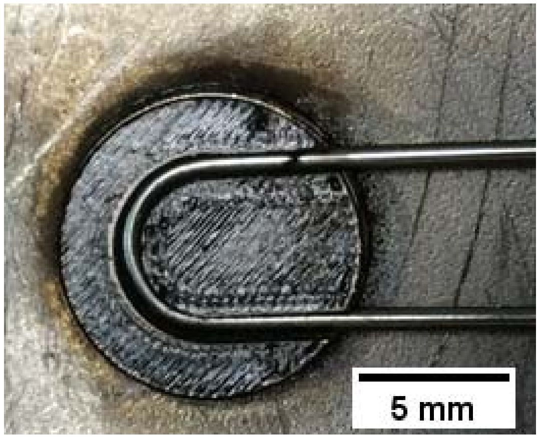
As-Fabricated Metallic Glass Samples



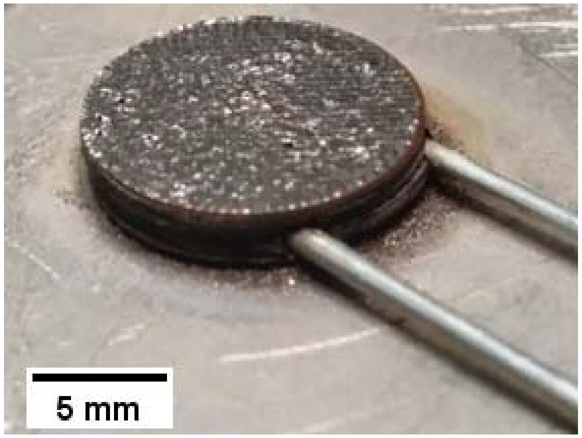
Sensor-Embedded Parts Fabrication



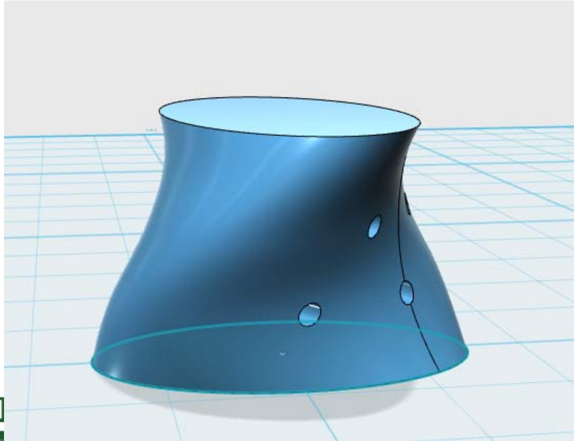
3D models for sensor embedding.

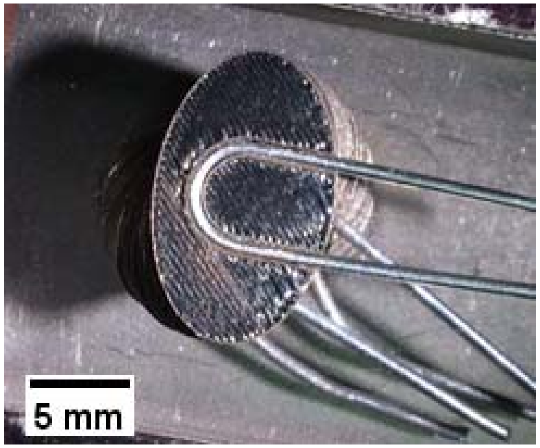


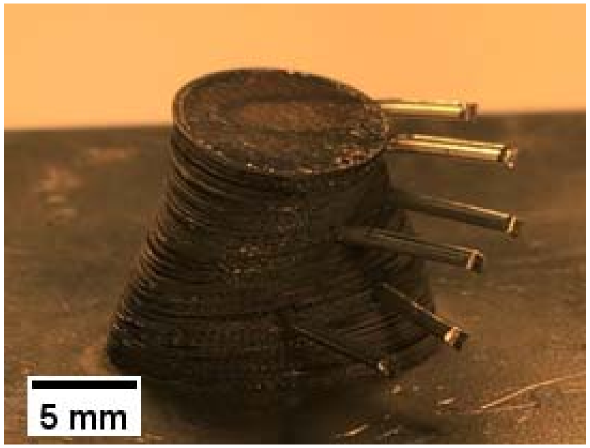
Curved sensors to be embedded in the printing process.



Sensors are embedded in the parts.

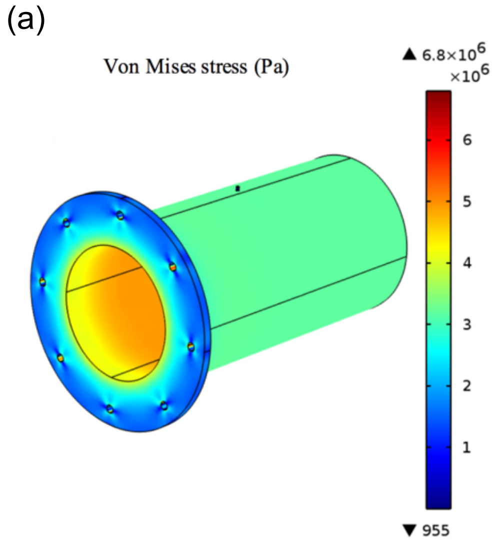




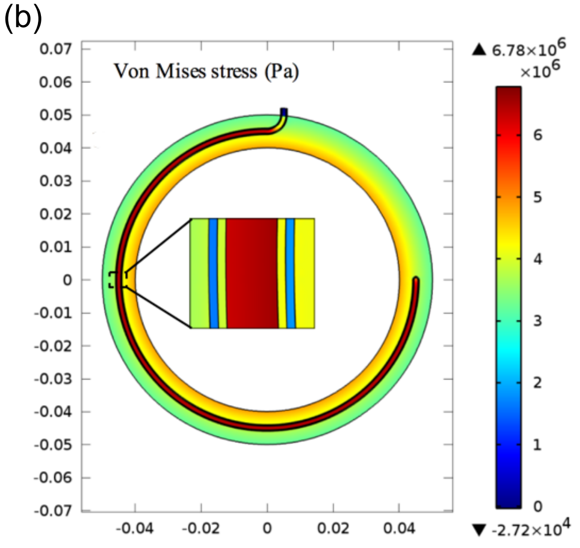


Thermal Stress-Strain Modeling of Embedded Sensors

Pressure Caused
Stress-Strain Distribution

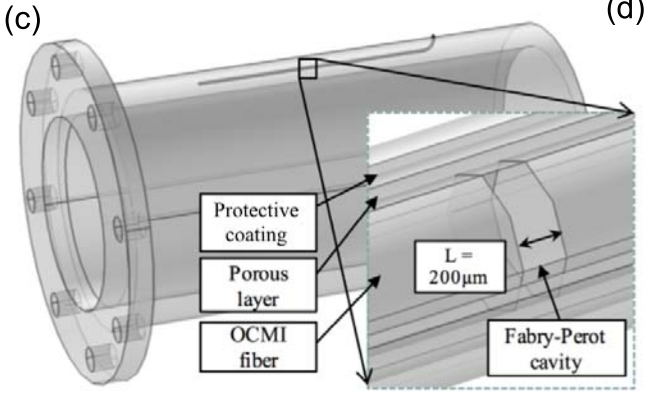


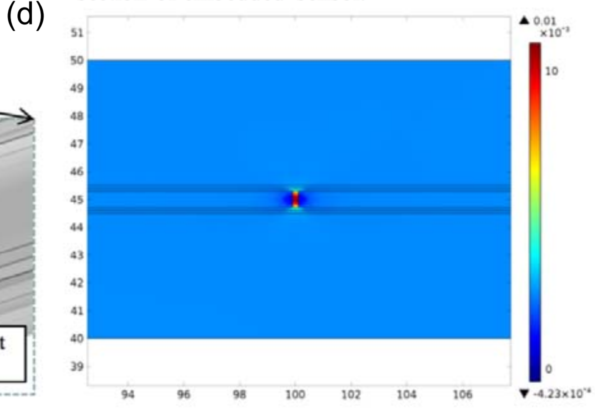
Von mises stress distribution on whole part.



Von mises stress distribution on cross section of embedded sensor.

Temperature Caused
Stress-Strain Distribution





The component of strain along the pipe

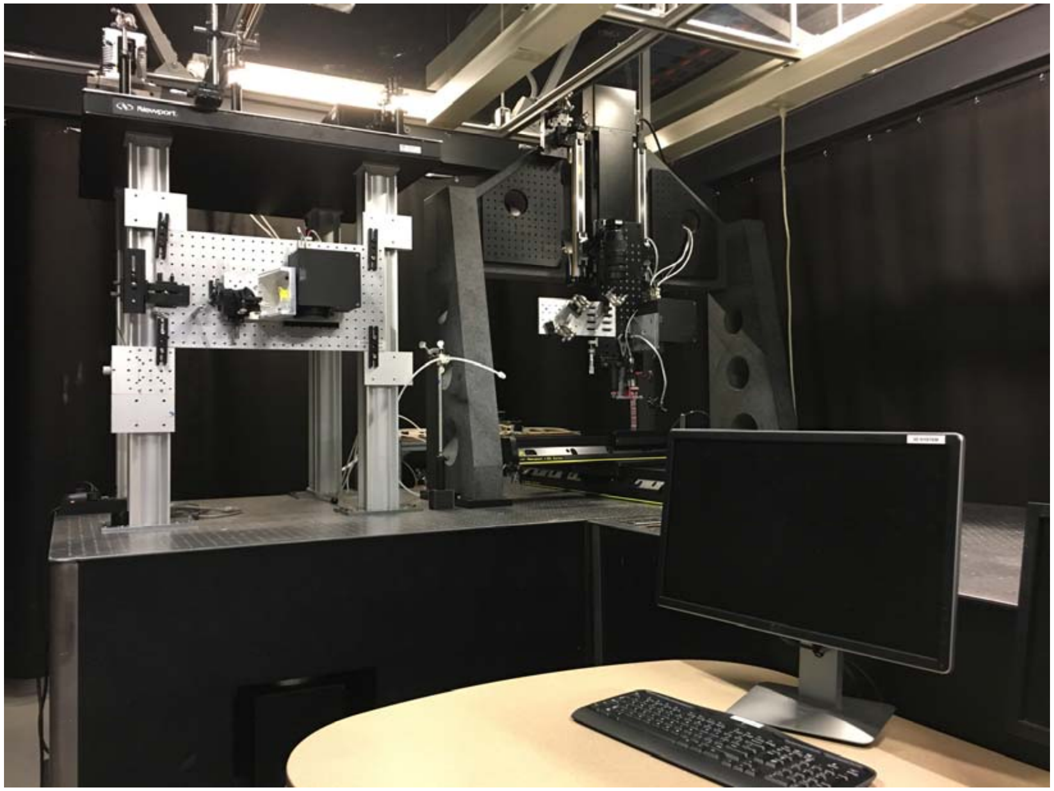
Additive Manufacturing and Test of Sensor Embedded Parts

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

Hai Xiao
Clemson University

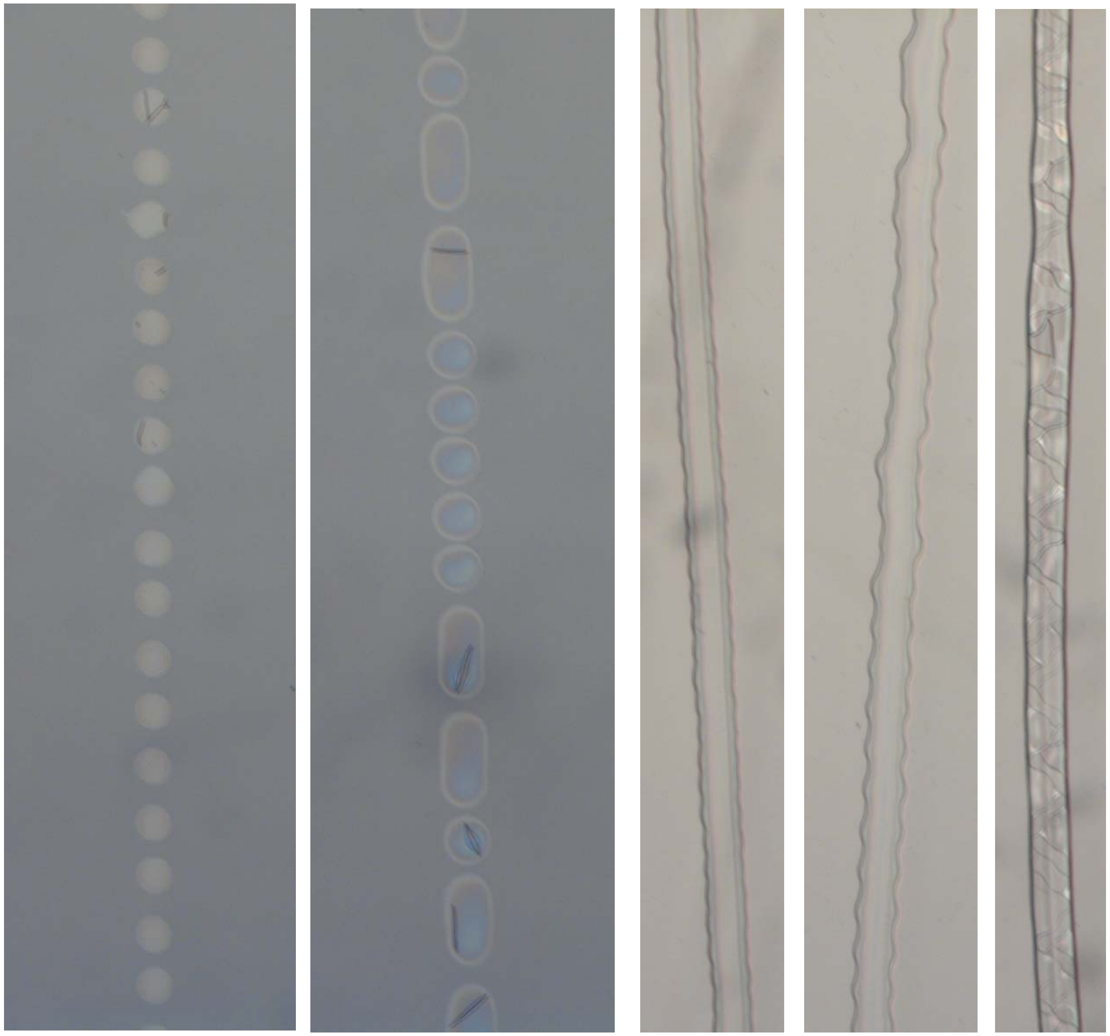
A New Manufacturing System

- An advanced manufacturing system integrates both additive and subtractive manufacturing
  - Multiple dispensers based 3D printing
  - Multiple extruders based paste 3D patterning
  - CO_2 laser based 3D heating and sintering
  - ps and fs lasers based 3D fine cutting
  - Computer controlled motion stages and CAD fusion capability
  - Ceramic, metal and plastic and composites



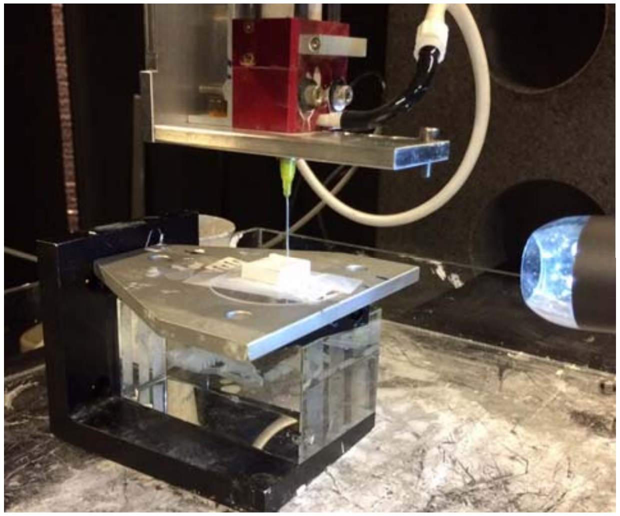
Micro dispensers

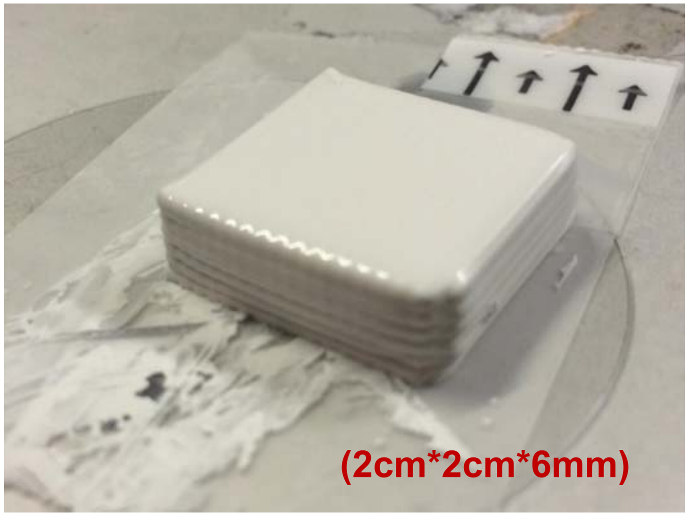
- Direct printing by dispensed sol-gel and laser in situ sintering



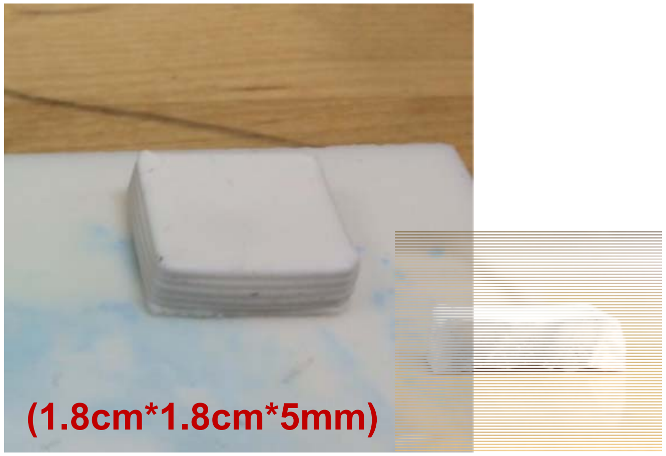
Extrusion based 3D printing

Printing ceramic block





(2cm*2cm*6mm)

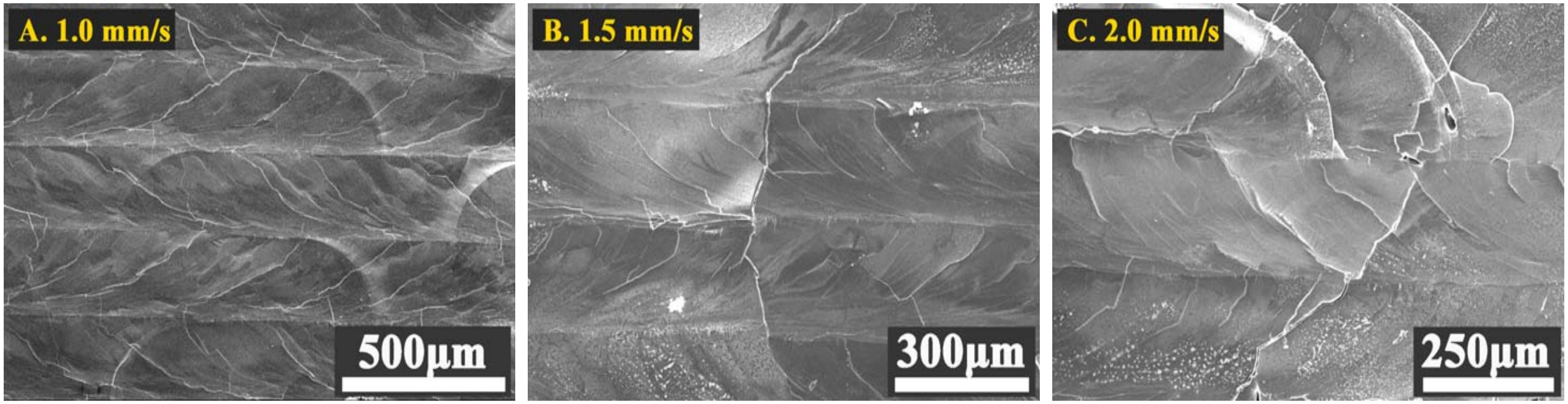


(1.8cm*1.8cm*5mm)

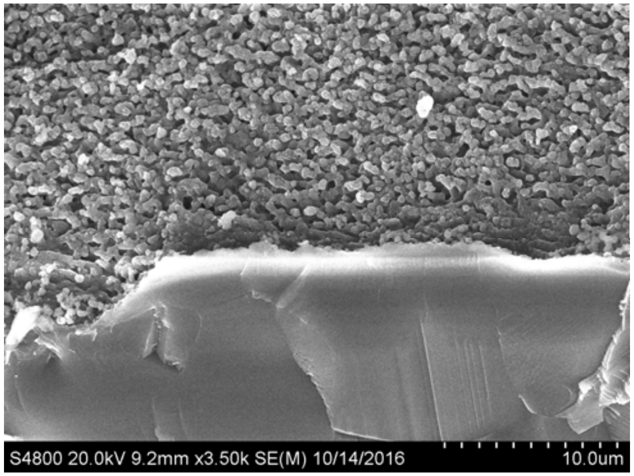
Shrinkage	Parts only
Shrinkage in length	>10%
Shrinkage in width	>10%
Shrinkage in height	>20%
Volumetric shrinkage	>32.5%
Relative density (Archimedes principle)	88%

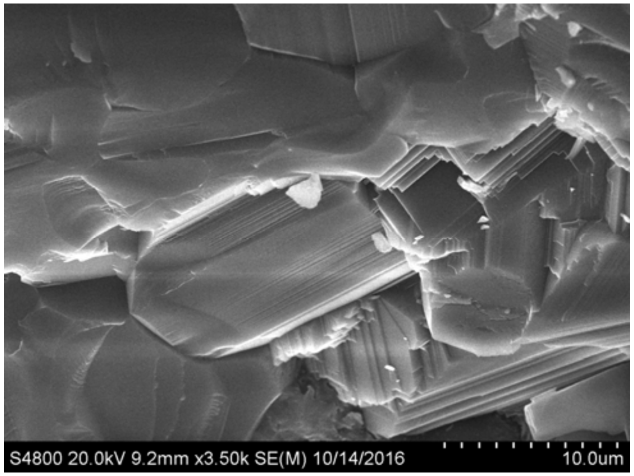
Direct laser sintering of ceramics

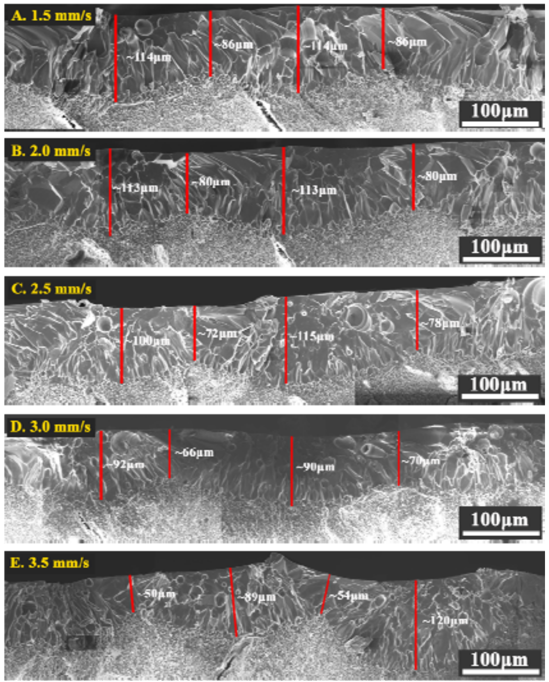
- **Surface**



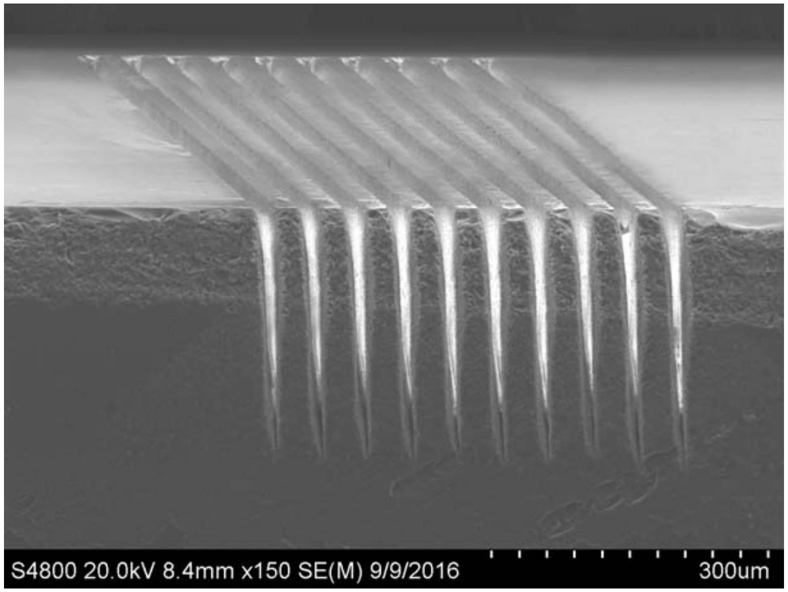
- **Cross sections**

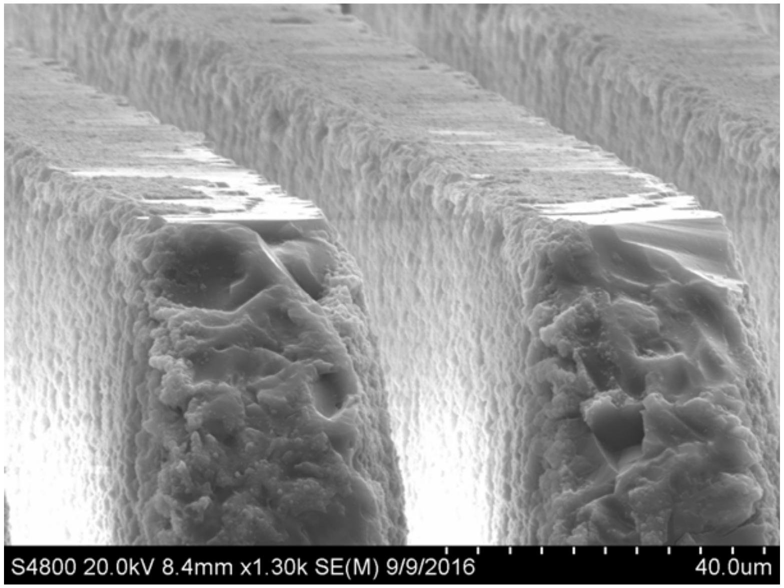


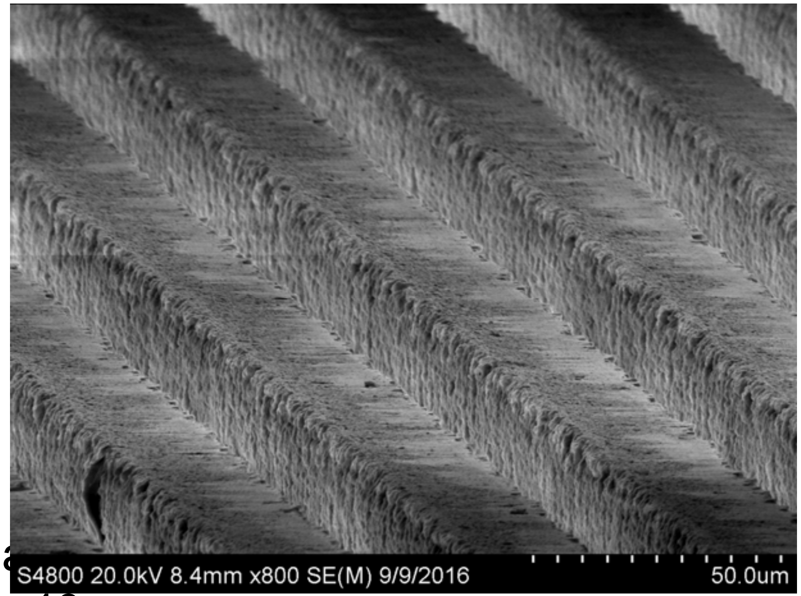


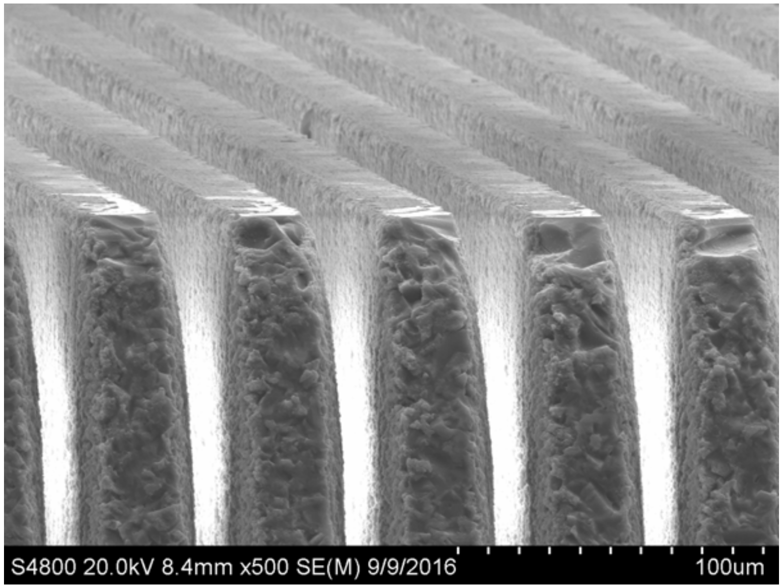


ps laser cutting

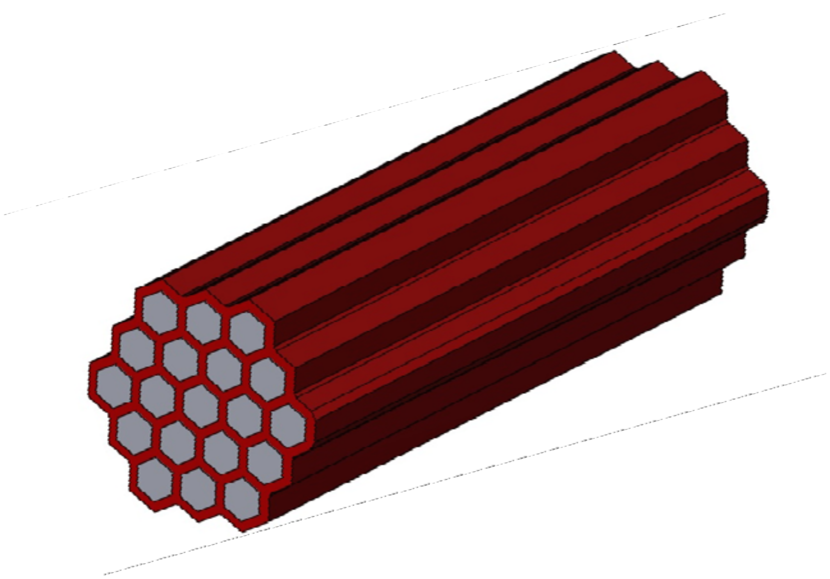


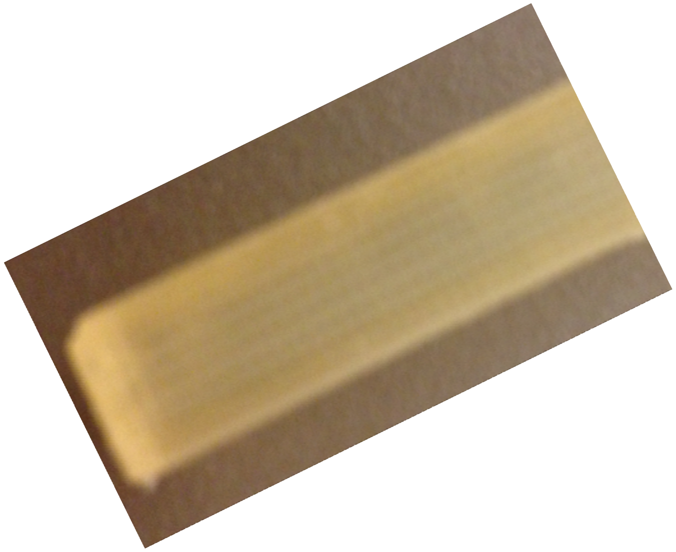


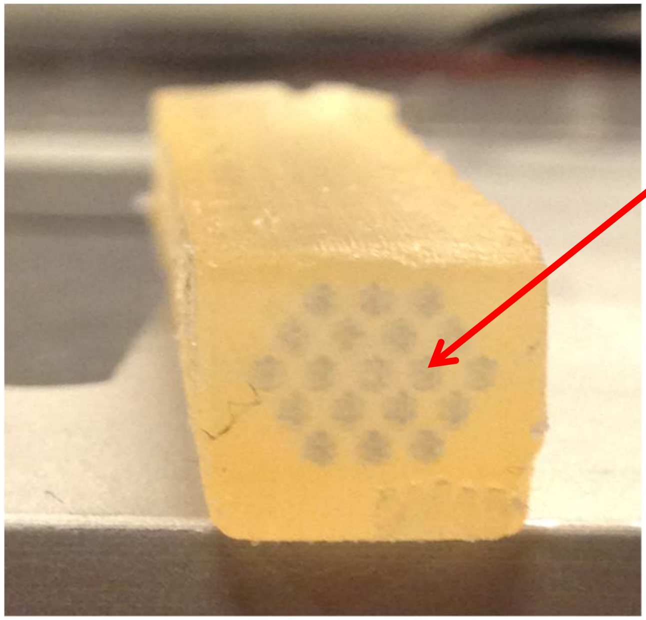




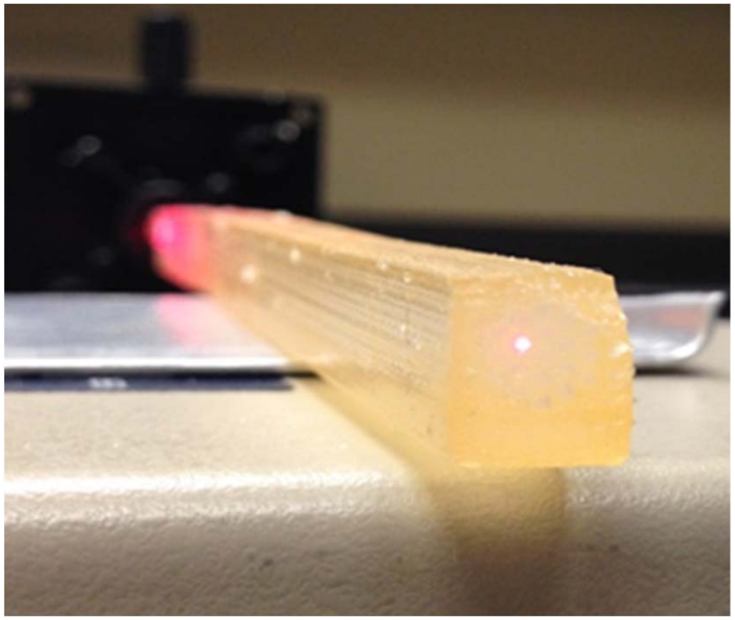
3D printing sensors inside the part





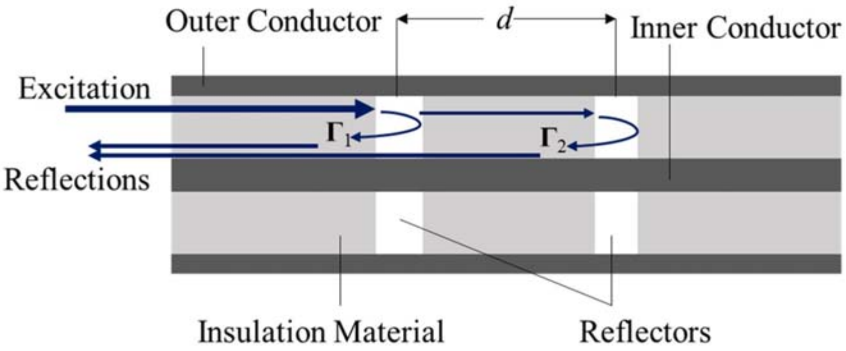


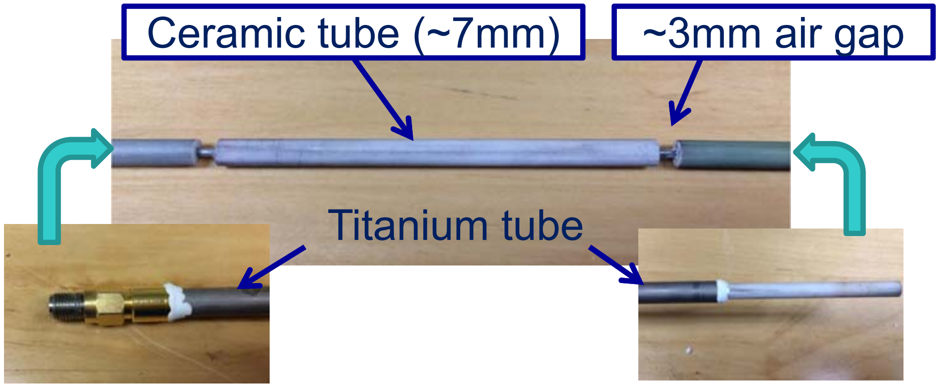
800 µm hexagons

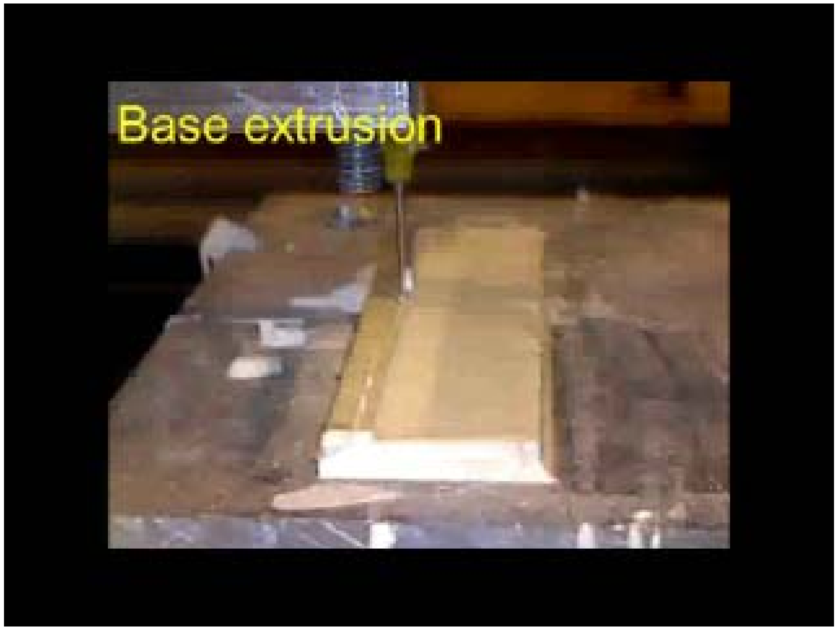


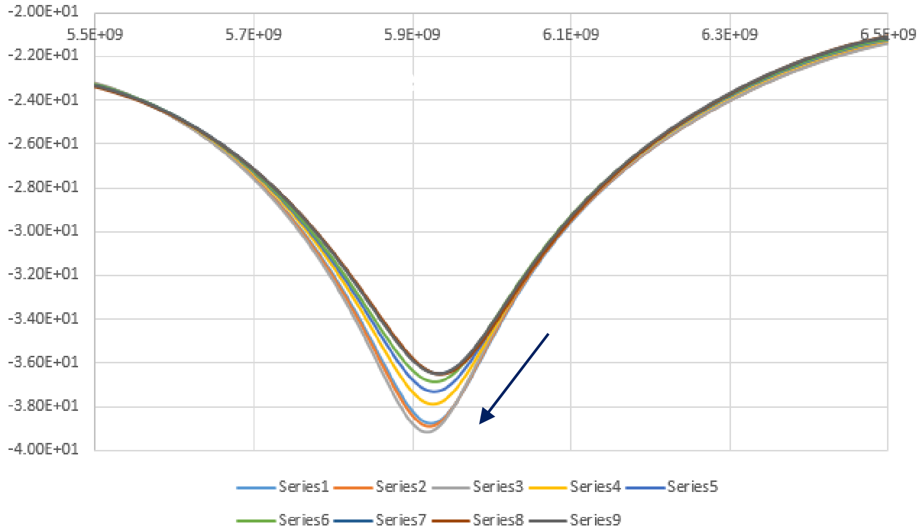
Embedded Coaxial Cable

- **Embedded cable for strain test**

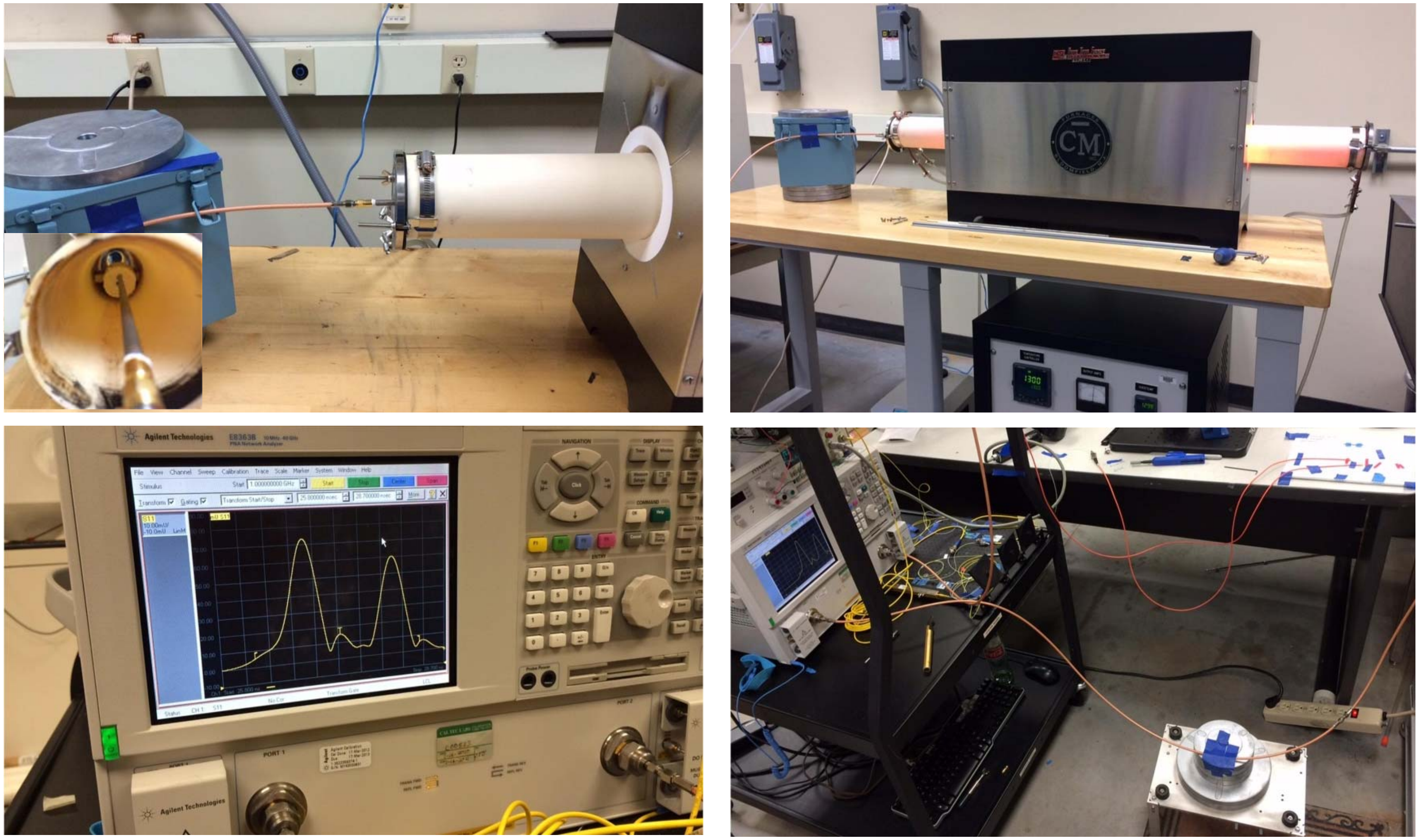






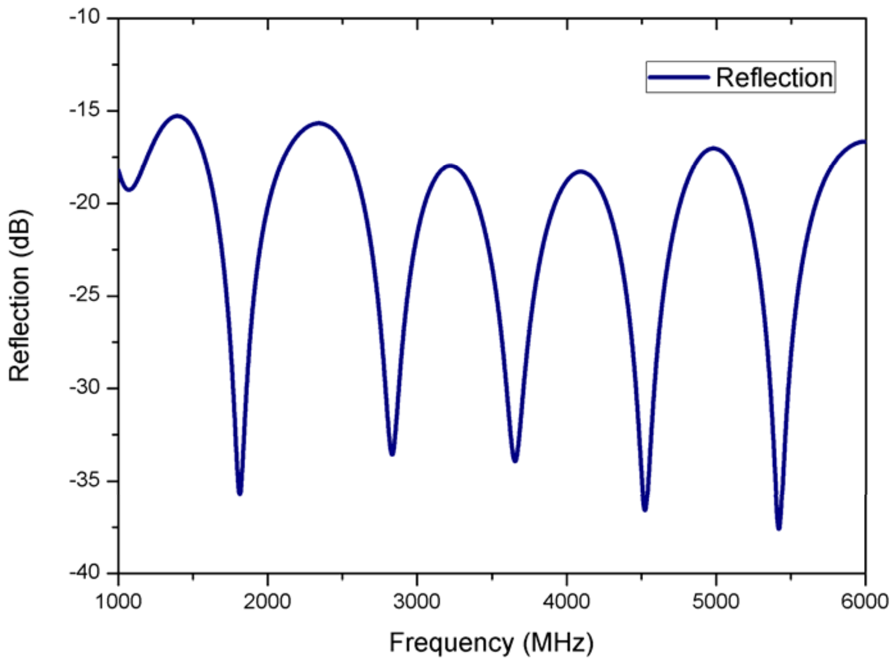


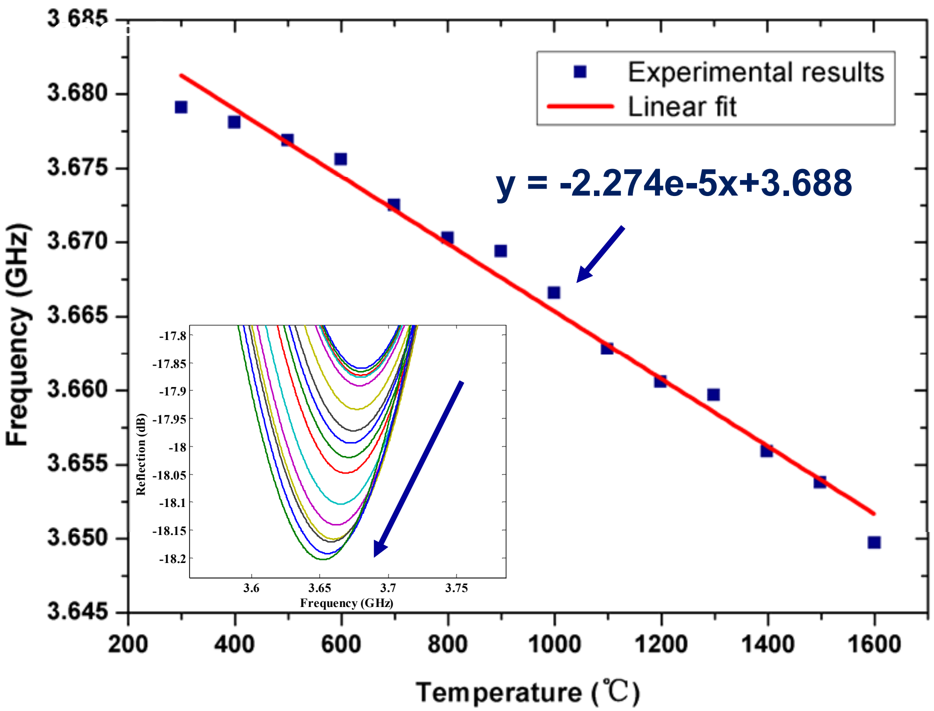
High temperature test of the smart part embedded with a metal-ceramic coaxial Cable (MCCC) Sensor



Embedded Coaxial Cable

- **Embedded Metal-Ceramic Coaxial Cable (MCCC) Fabry-Pérot Interferometric Sensor**



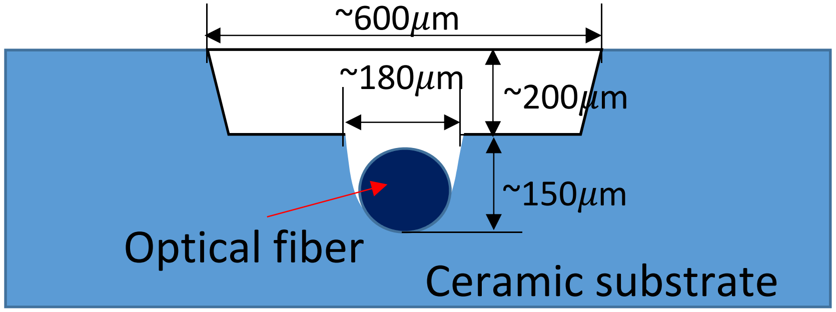


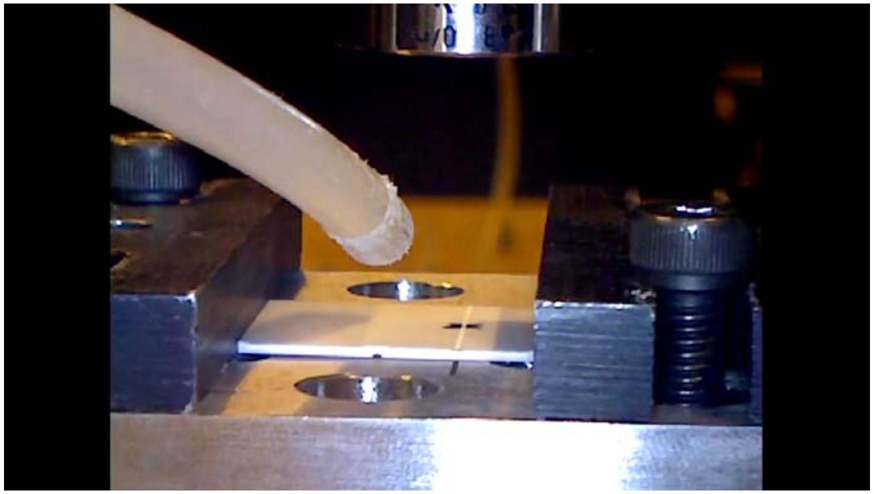
- Such cable can be operated at 1600℃

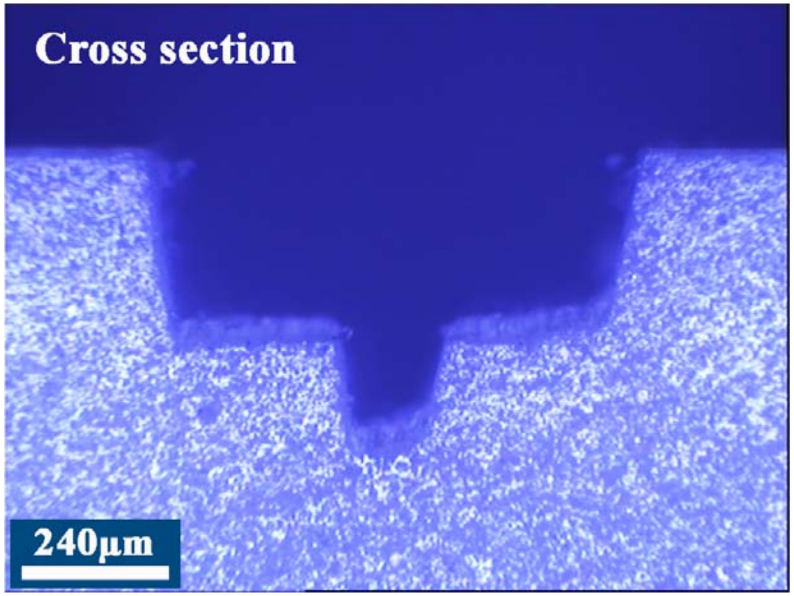
Sensitivity = -2.274e-5 GHz/℃

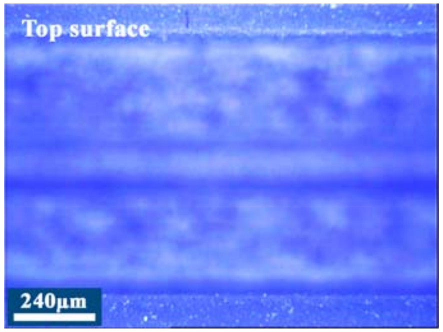
Embedded Photonic Sensor

1. Fabricate the channel on the ceramic substrate with designed shape for fiber embedding

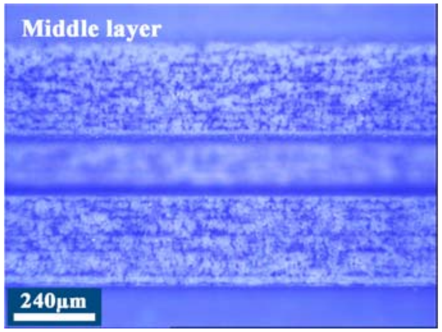


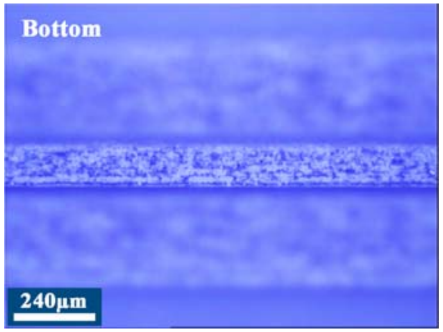




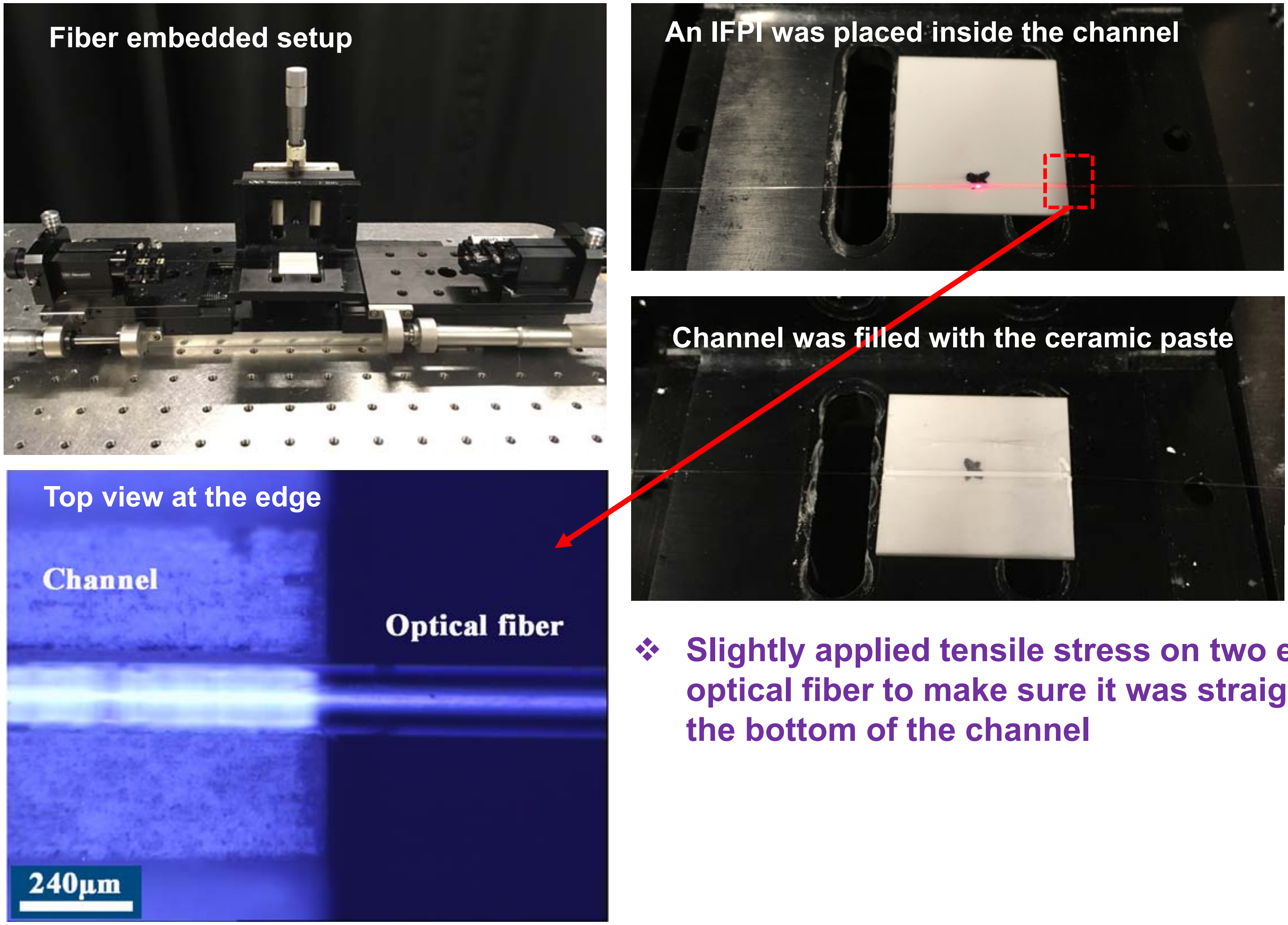


- Easy to fabricate by ps-laser with high resolution
- Confining the fiber into the small channel can provide more protection to the optical fiber
- Control the thickness of the ceramic filler by controlling the depth of the channel





2. Place the optical fiber sensor into the channel and filled the channel with the ceramic paste



- Slightly applied tensile stress on two ends of the optical fiber to make sure it was straight and touch the bottom of the channel

Embedded Photonic Sensor

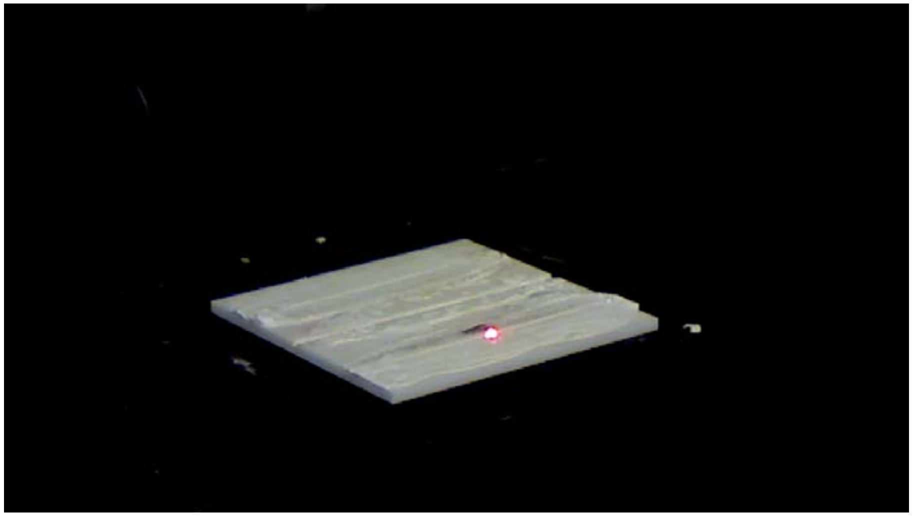
3. Use a CO_2 laser to process the filling materials and seal the fiber inside

❖ **Laser operating parameters:**

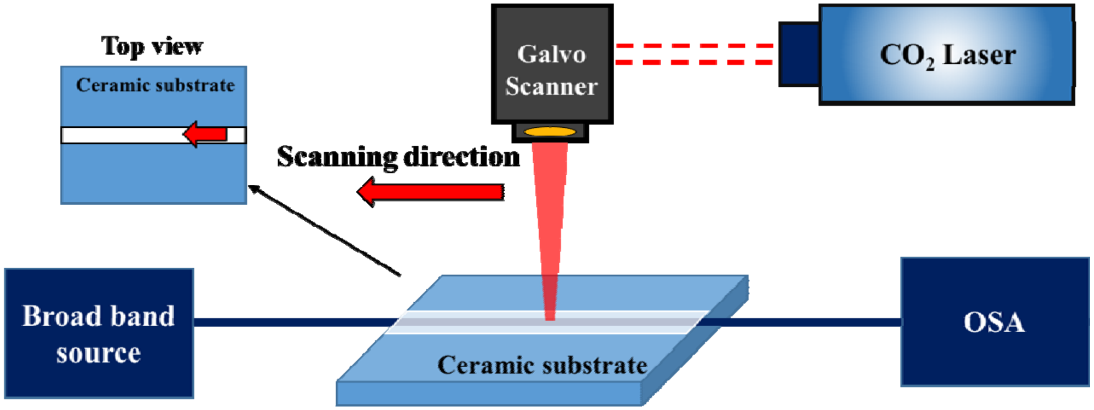
- Laser output power: 9 W
- Scanning speed: 0.2 mm/s
- Spot size: 1.1 mm

❖ **high speed scanning at low power to pre-heat the materials before high power processing**

❖ **The optical fiber was monitoring by the OSA during the whole embedding process**



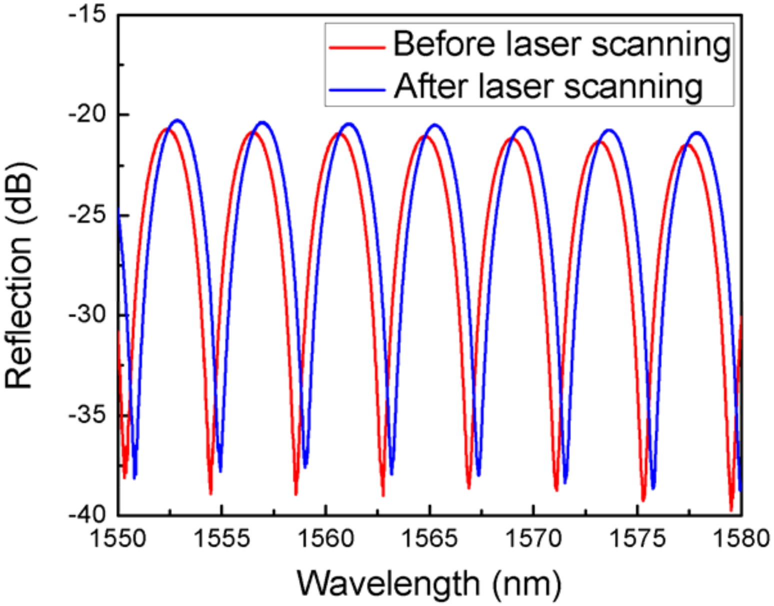
Max Output Power	20W
Operation	Continuous wave (CW)
Mode Quality	TEM_{00}, $M^2 < 1.1 \pm 0.1$
Beam Diameter before focusing	2.5mm ± 0.5mm
Beam Diameter after scanner	~1.0 mm
Wavelength	10.6 µm
Polarization	Linear (Horizontal)



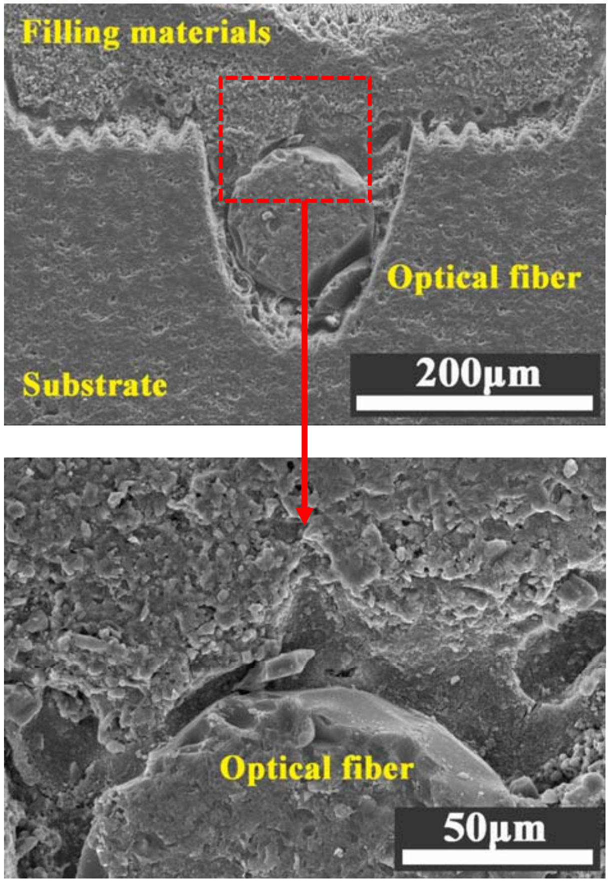
Embedded Photonic Sensor

3. Use CO_2 laser to process the filling materials to seal the fiber inside

(2) Embed an IFPI optical fiber sensor into the ceramic substrate and seal it by the CO_2 laser



- For the IFPI sensor, after laser processing, the spectrum slightly shifted to longer wavelength for about 1 nm
- Known from the cross-sectional image, the channel was filled well but it seems that there were still pores at the part that was close to the optical fiber



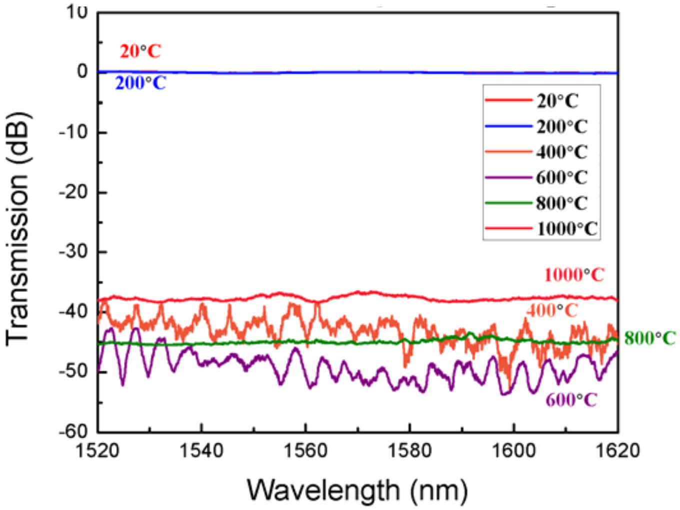
the cross section after laser scanning on the surface

Embedded Photonic Sensor

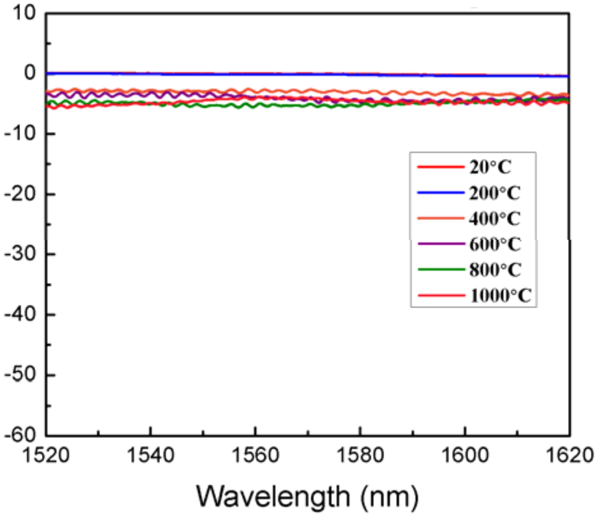
4. Test the high temperature stability of the embedded optical fiber sensor

(1) Improved high temperature stability of the embedded optical fiber by laser sintering

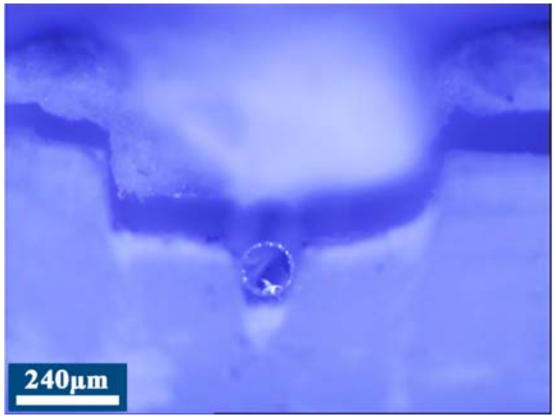
Furnace sintering (failed)



Direct laser sintering (successful)



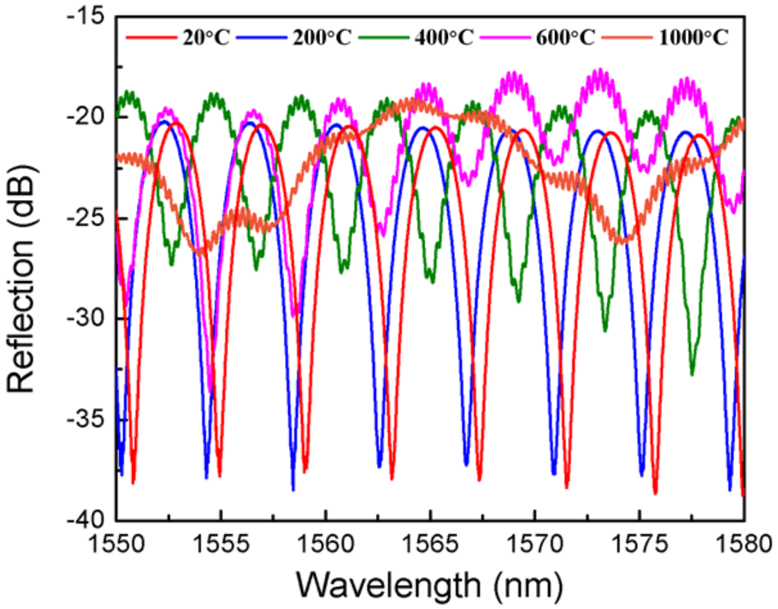
Furnace sintering (failed)

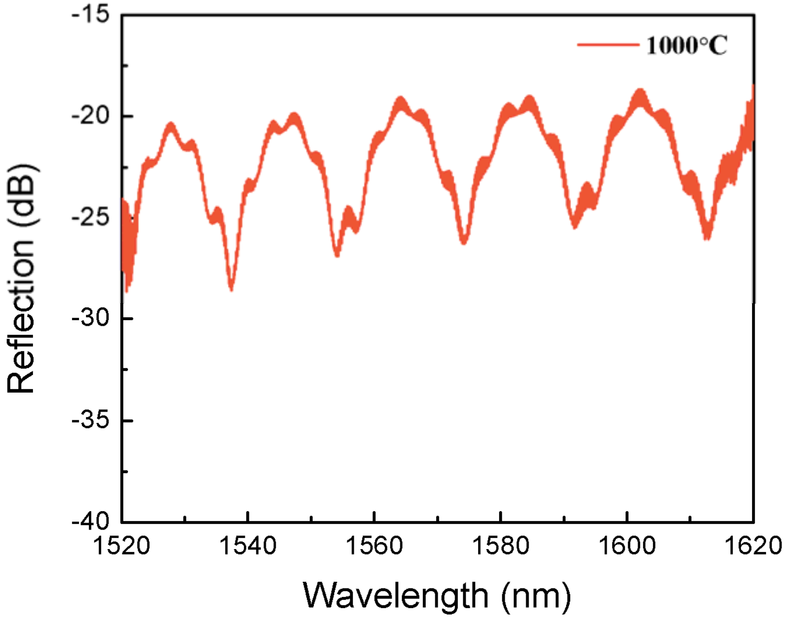


- Traditional furnace based sintering, the embedded optical fiber had a huge loss (~45 dB) when the temperature reached 400℃
- Direct laser sintering, though small ripples occurred after 400℃, the transmission spectrum generally maintain straight and only 5 dB loss when the temperature reached 1000℃

4. Test the high temperature stability of the embedded optical fiber sensor

(2) High temperature stability of the embedded intrinsic Fabry-Perot interferometer (IFPI)





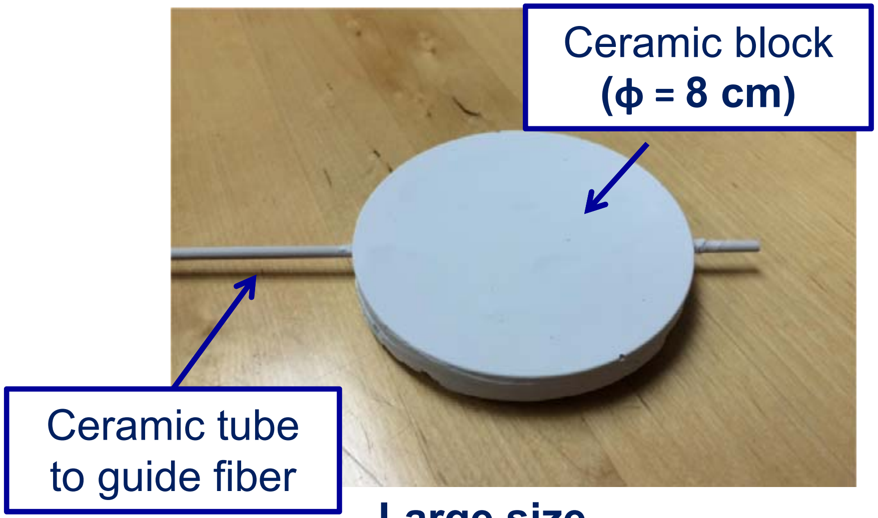
- **Survived 1000℃ and still produced good signals**
- **Slightly compression of the optical fiber that reduced the cavity length of the IFPI**
- **Need further improvement and optimization**

Manufacturing of smart parts

- **Manufacturing of sensor embedded smart parts (a smart ceramic washer)**

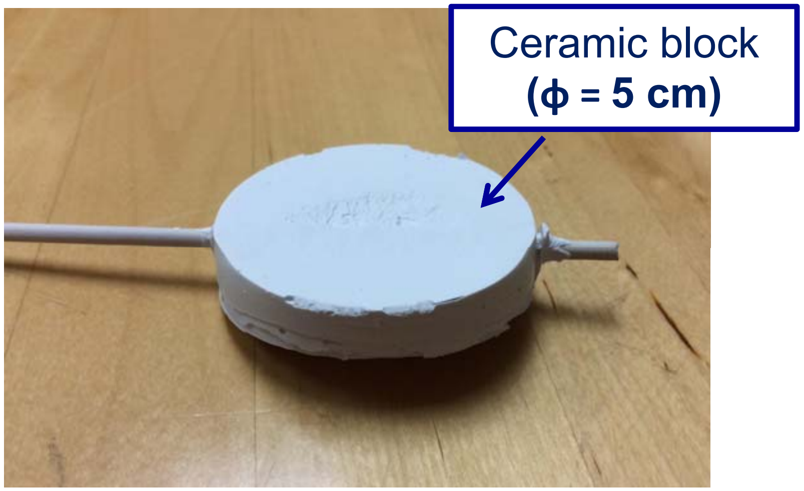
Embedded Photonic Sensor

● Embedment and experimental setup

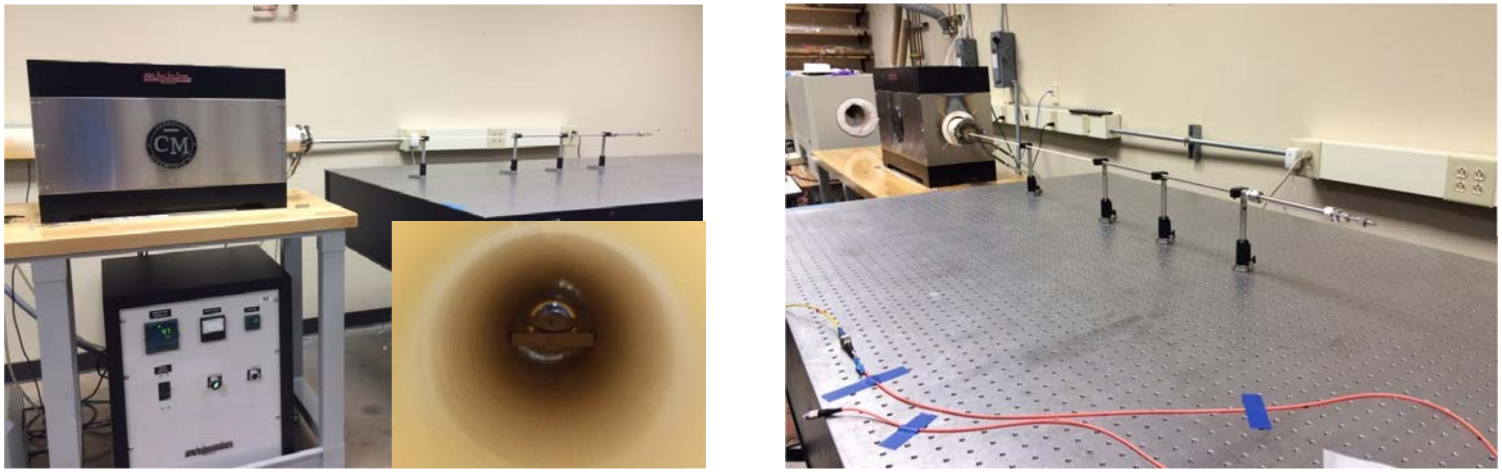

Ceramic block (ϕ = 8 cm)

Ceramic tube to guide fiber

Large size

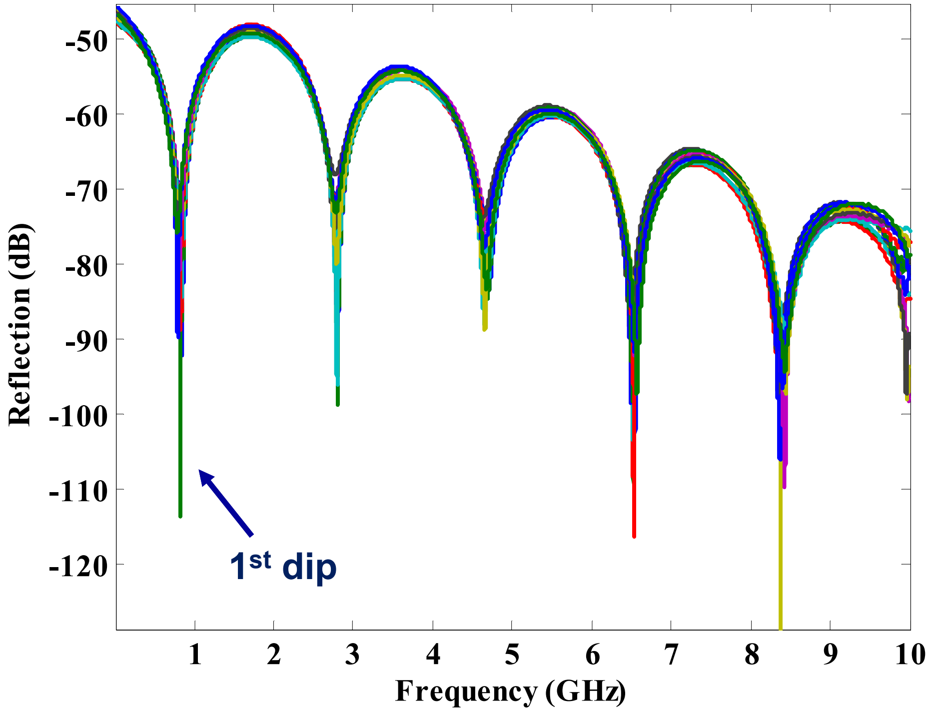

Ceramic block (ϕ = 5 cm)

Small size

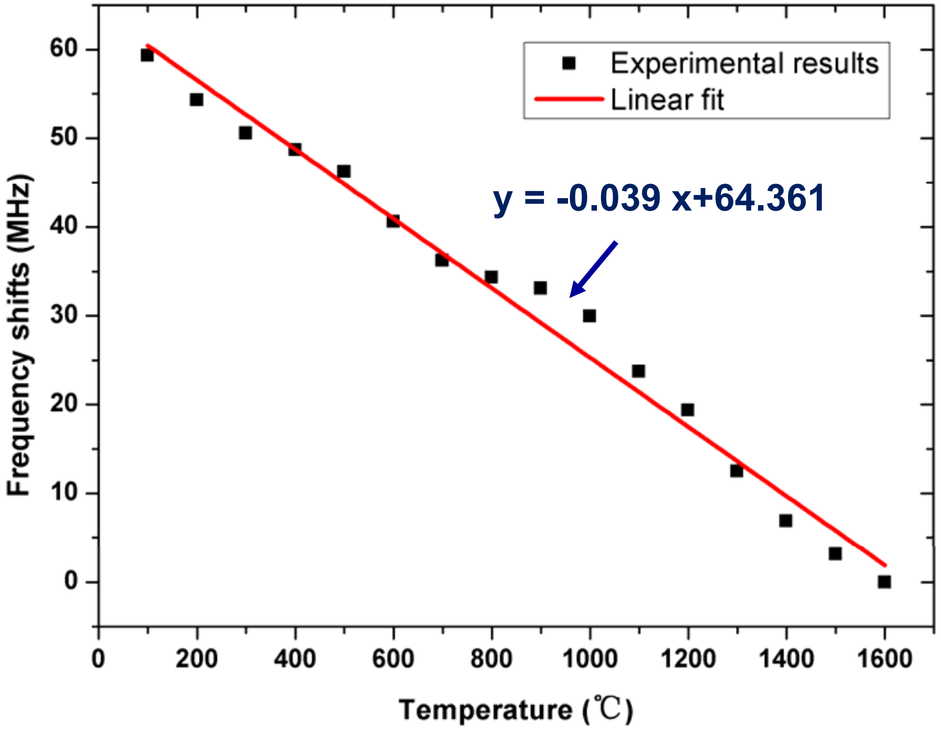

Experimental setup

- **Embedded Sapphire Fiber Michelson interferometer**

High temperature results
(100-1600℃)



Frequency domain



Frequency response VS temperature

Summary of Progresses

- **Distributed microwave and photonic sensors and instrumentation have been developed and proven**
- **Protective coating materials have been identified and successfully coated on silica and sapphire optical fibers**
- **Additive Manufacturing techniques have been developed for fabrication of metal and ceramic parts**
- **Smart parts with embedded sensors have been fabricated using advanced manufacturing and preliminarily tested**

Future Work

- **Manufacture more smart parts**
- **Comprehensive tests of the smart parts**

Acknowledgement

- **NETL Managers and Engineers (current and former)**
  - Robert Romanosky
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  - Robie Lewis
  - Steve Seachman
  - Barbara Carney
  - Sydni Credle
  - Paul Ohodnicki
  - Benjamin Chorpening
  - Richard Dunst
  - Jessica Mullen
  - Otis Mills