Advanced Methods for Manufacturing

August 28, 2024

An Integrated Laser Approach for Fiber Sensor Embedding in Metal Parts for Nuclear Energy Applications

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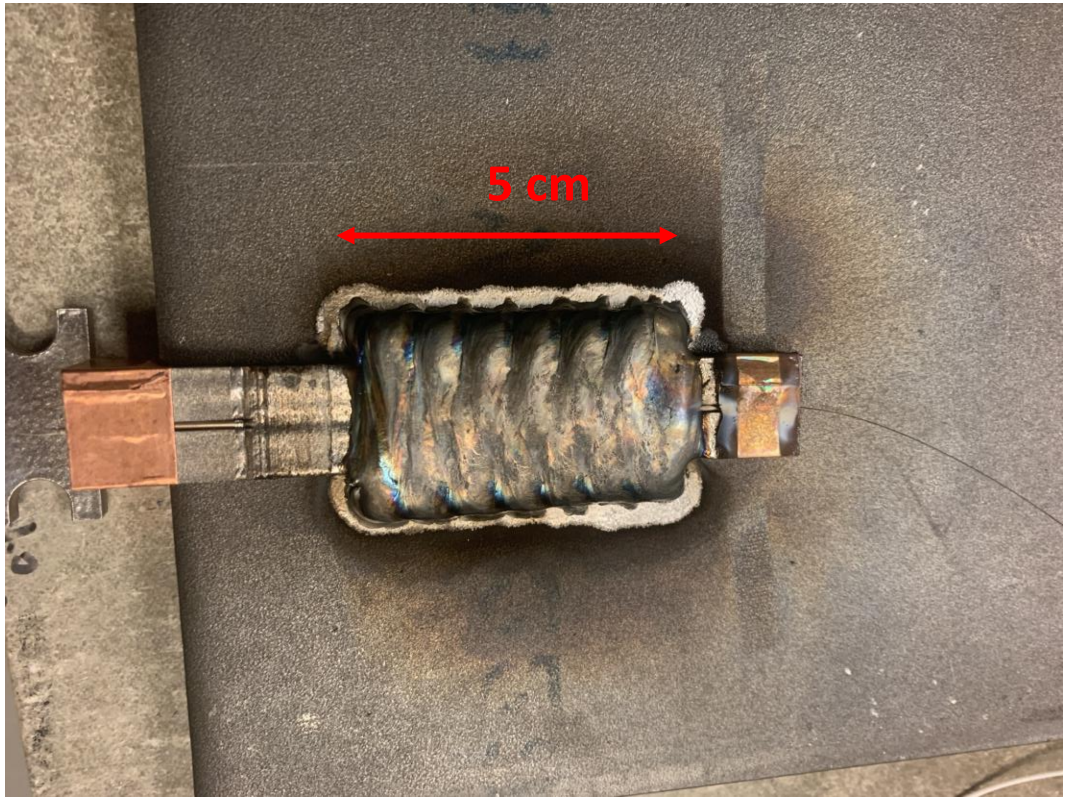
PI: Kevin P. Chen

Team Members: Professor Albert To, University of Pittsburgh

Dr. Christian Petrie, Oakridge National Lab

Dr. Moinuddin Ahmed, Argonne National Lab

Motivation



- **3D Printing: A major fabrication approach for energy, infrastructure, aerospace**
  - Special parts fabricated at 1000 per year
  - Large size (up to 5 meters)
  - Highly flexible in building materials
  - High Value added

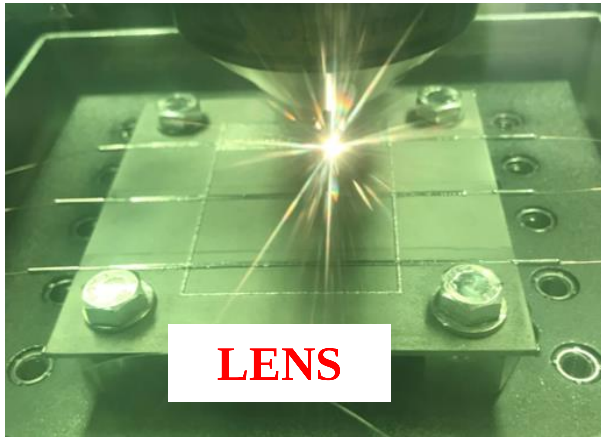
- **Can we embed distributed fiber sensors to make SMART PARTS???**
  - High-res strain measurements (1-cm)
  - Distributed acoustic and vibration
  - Temperature
  - Corrosion
  - **Condition-based Maintenance**

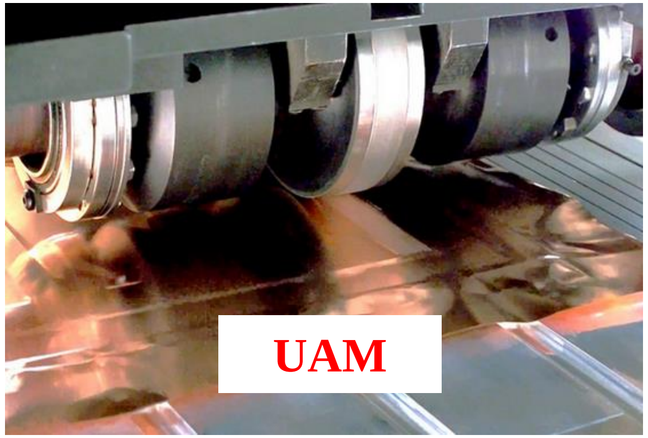
A Multi-Step Process

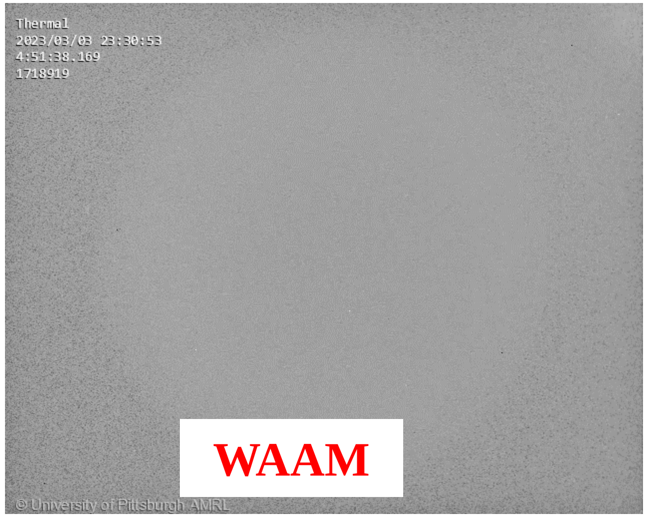
PITT | SWANSON ENGINEERING

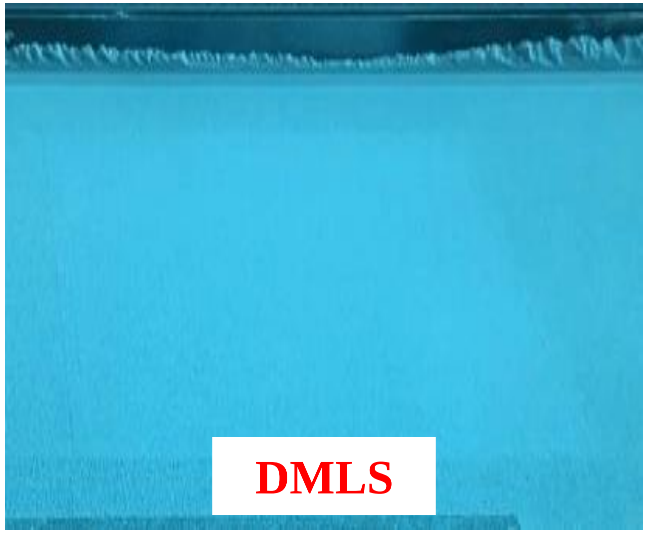
ELECTRICAL & COMPUTER

AM Processes

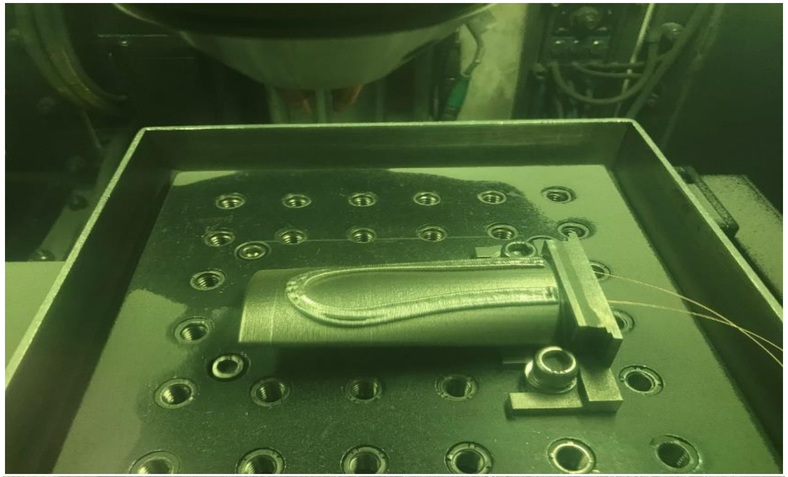


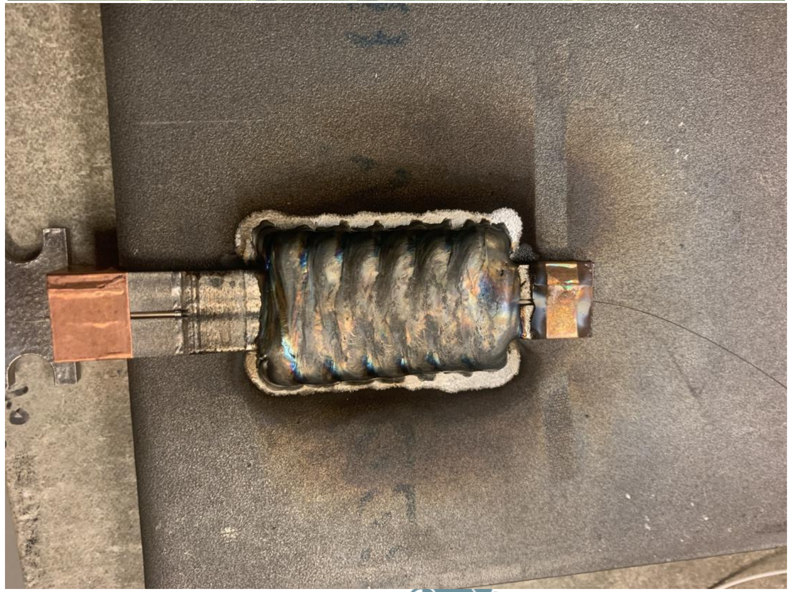






Embedded Sensors

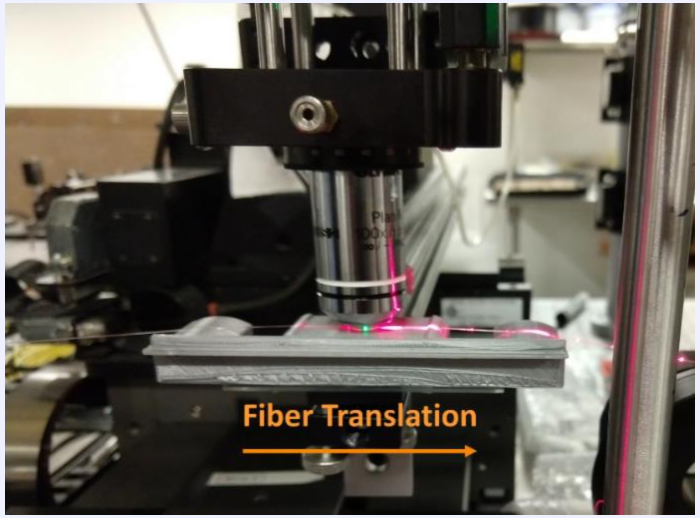


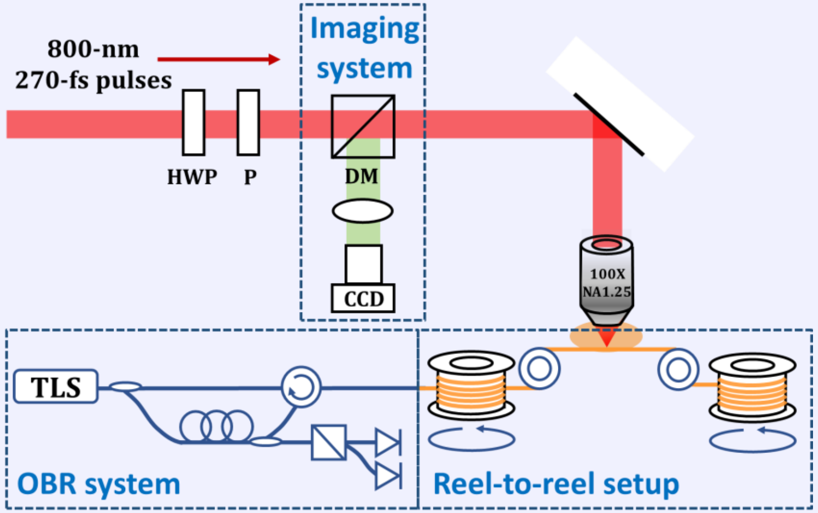


Outline of the NEET Project

- **Embed distributed fiber sensors using additive manufacturing.**
  - Direct metal laser sintering
  - Laser-energized net shaping
  - Wire-arcing (Smart parts as large as 1.5-meter)
  - Ultrasonic additive manufacturing
  - Fiber sensor packaging using glass sealants
- **Sensor-enabled digital twin modeling.**
- **New fiber and metal coating with compatible thermal expansion coefficients (TECs)**
- **Demonstration of multi-parameter measurements in radiation environments**
  - Instrumentation & algorithm developments.
  - Demonstration of high-frequency vibration measurements.
- **Irradiation test of sensor embedded by AM.**
- **Fundamental challenges/limitation of sensor-embedding using AM and partial solutions.**
- **Impacts to other fields.**

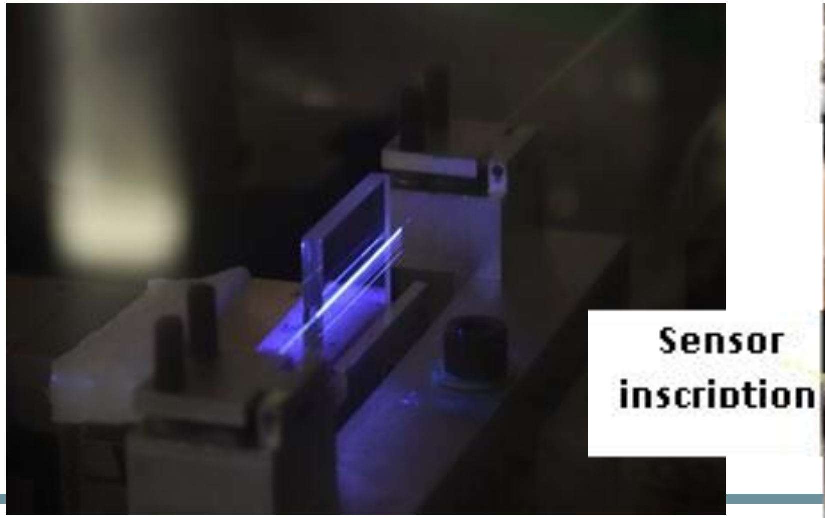
Vertically Integrated Sensor Fabrication Capability

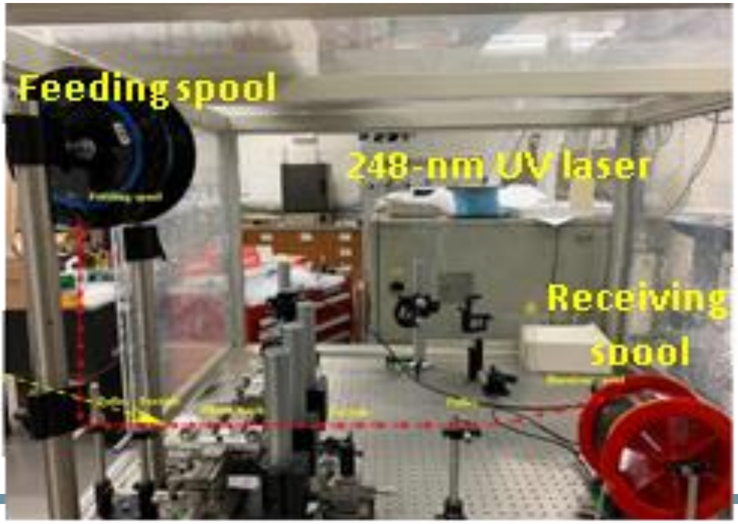




Reel-to-reel fiber writing setup

- 180-fs laser.
- Fabrication of up to 1km of fibers.
- Point-by-point writing: Flexible.
- Through fiber coating fabrication.
- FBG, distributed, IFPI.
- High-T stable distributed sensors.
- Sapphire and silica fibers

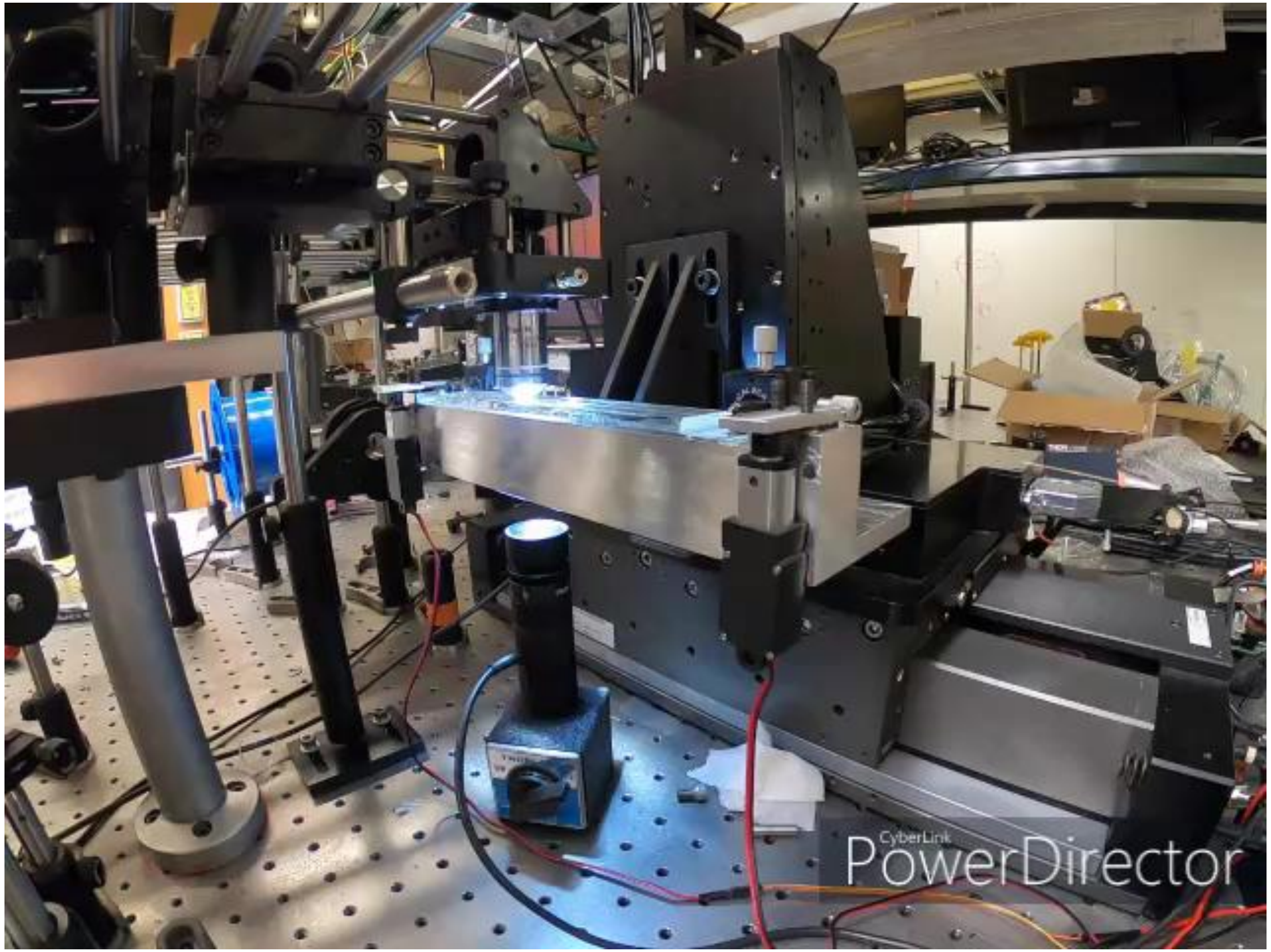




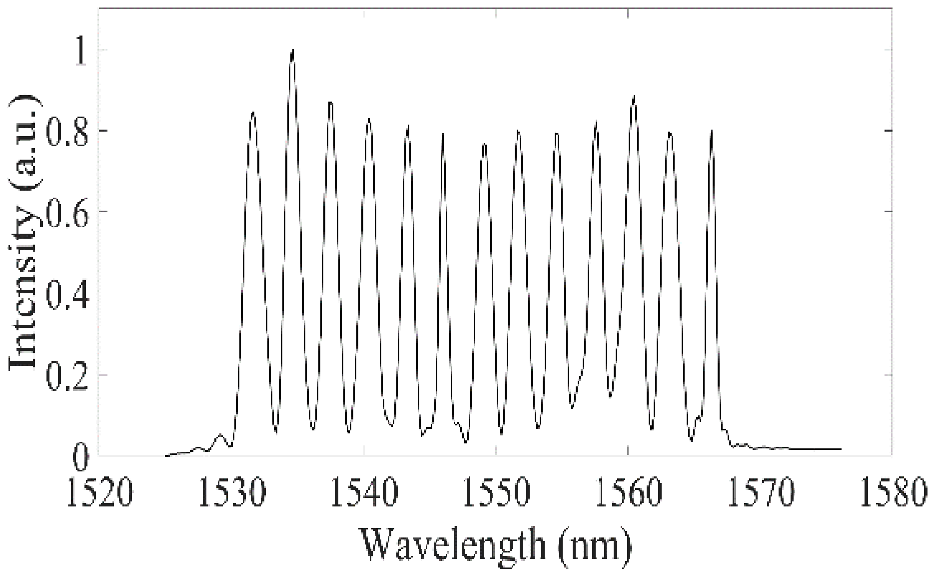
Deep UV Sensing Fiber Fabrication

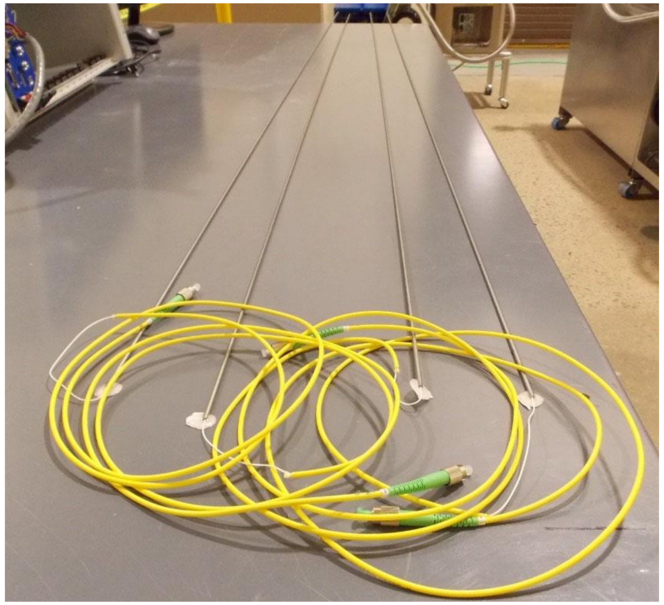
- Standard telecom fiber.
- One-shot UV phase mask writing
- 10-km continuous sensing fiber
- Draw-tower free
- Sensing fiber cost ~$0.1-$1.0 per meter (competition: $10-30/m)
- Joint pending patent with Corning

Reel-to-Reel Sensor Fabrication



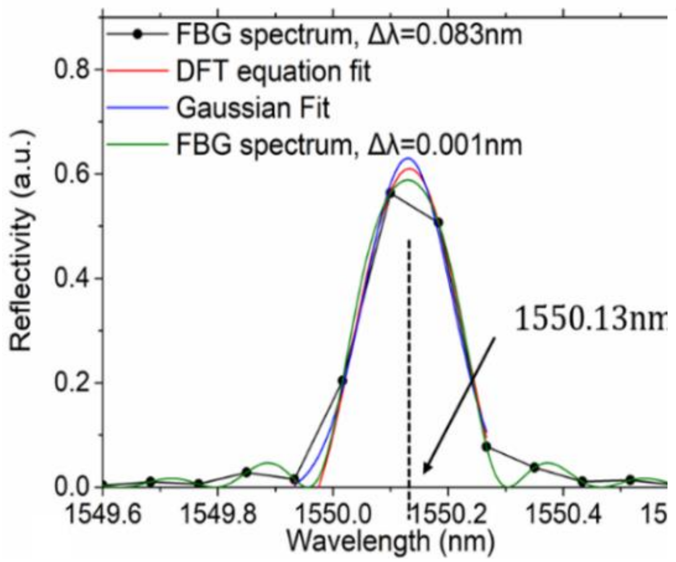
High-Temperature Stable Multiplexed Fiber Sensors

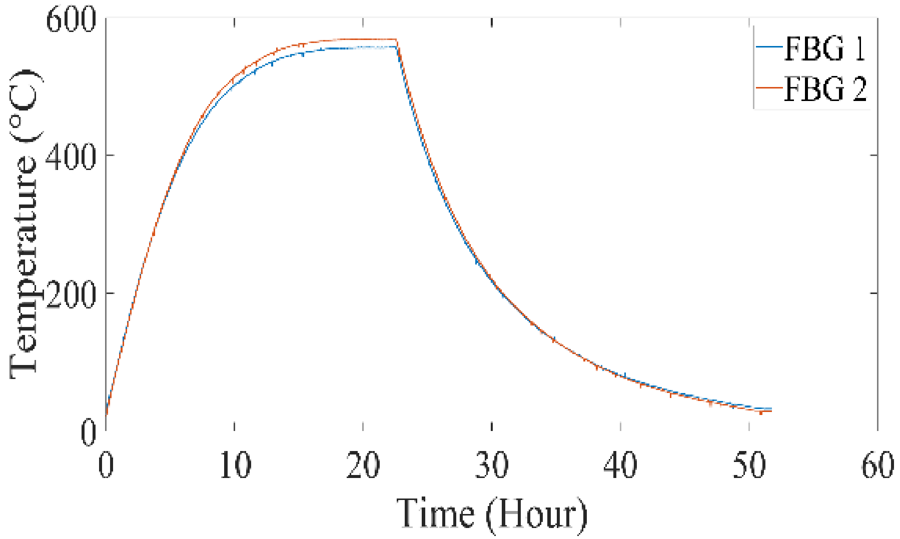


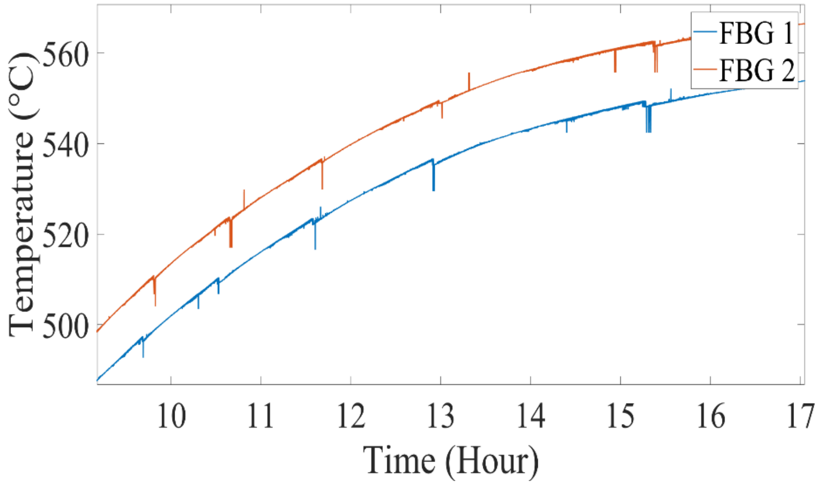


- Up to 25 high-temperature stable FBG array can be fabricated in hydrogen-resistant optical fibers.
- Packaged sensors in 316H SS tubing with polymer coating removed.
- Each sensor are pre-annealed and calibrated.
- Armored cable lead for field deployments.
- Packaged fibers can be repeated heated with consistent performance.

Robust Demodulation Algorithm







$$T = T_o + [A(\lambda - \lambda_o)^3 + B(\lambda - \lambda_o)^2 + C(\lambda - \lambda_o) + D]$$

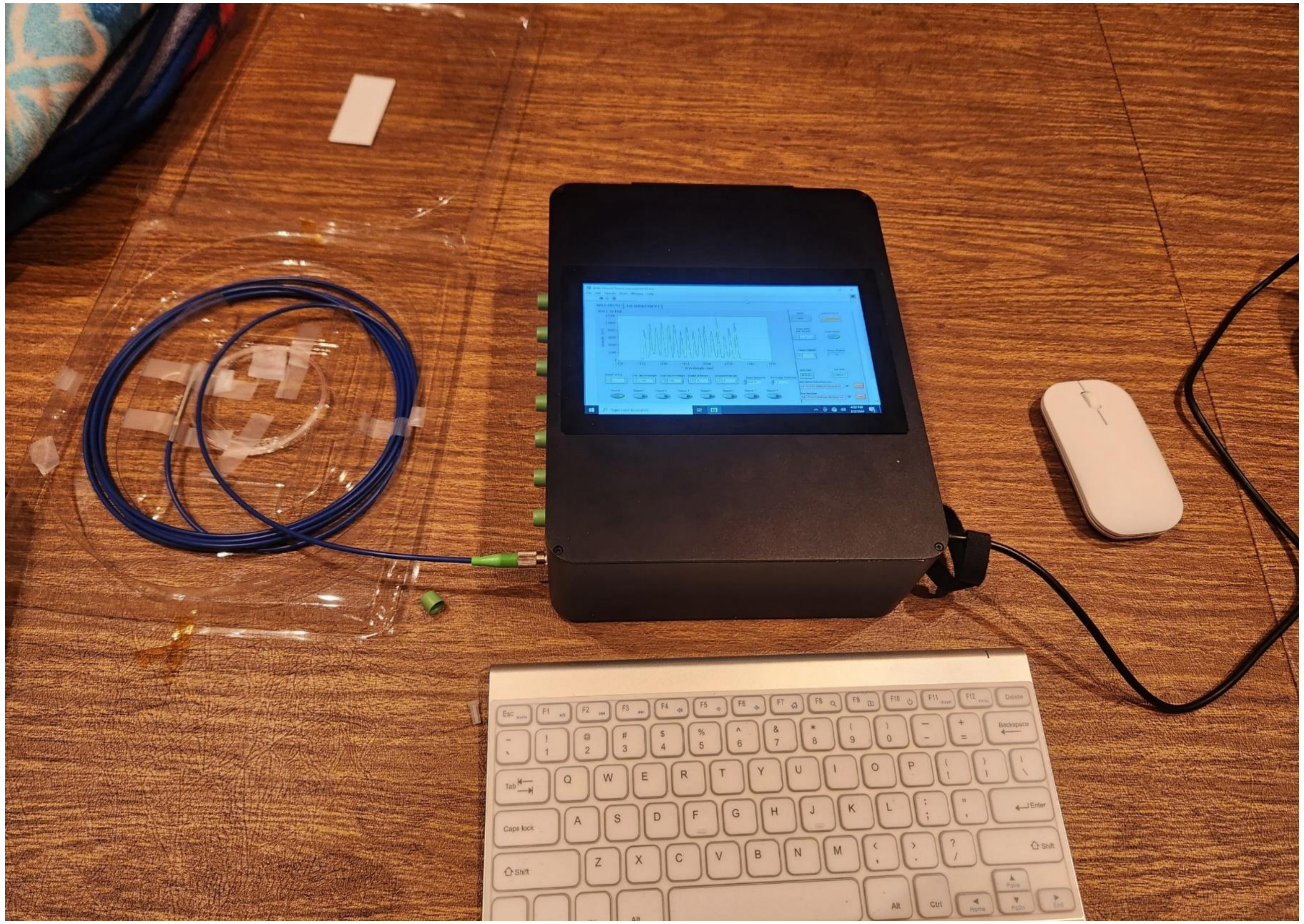
- **Demodulation algorithm key for sensor success.**
- **Four demodulation algorithm explored for accurate and reliable demodulations (avoid “peak jump”).**
- **Occasionally demodulation of FBG peak jumps are the issue (a sudden temperature change up to 8C).**
- **Computationally efficient and robust algorithm is needed to remove “peak fitting jump”.**

High-Temperature FBG Sensor Instruments

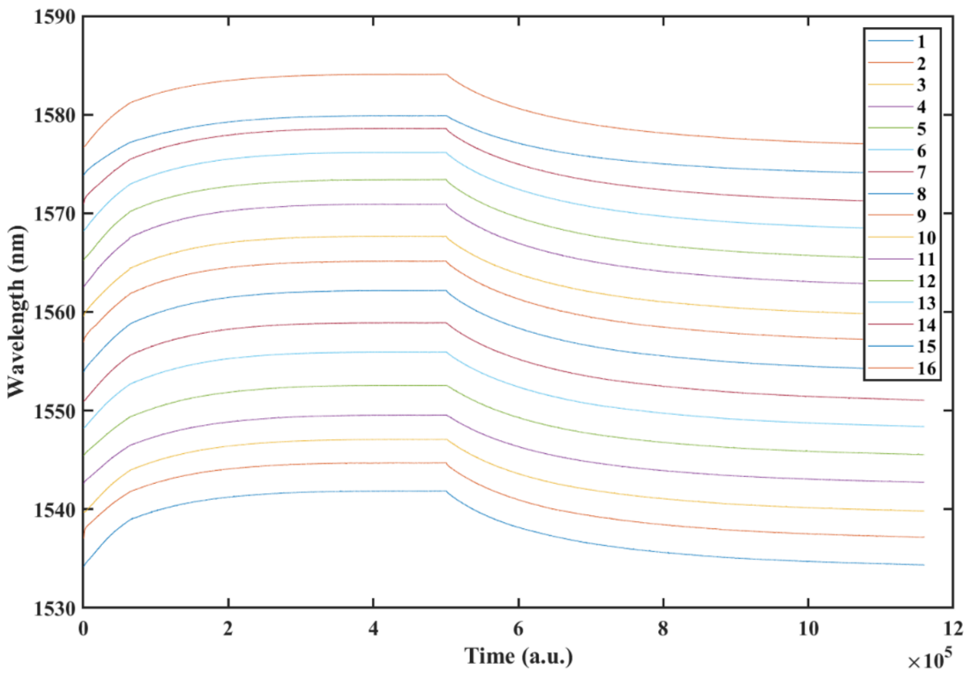
- Fully-integrated instrument (8, 16, 32, 64 channels)
- USB, Ethernet, wireless data communications.
- 5-kHz sampling rate (over total channel #).

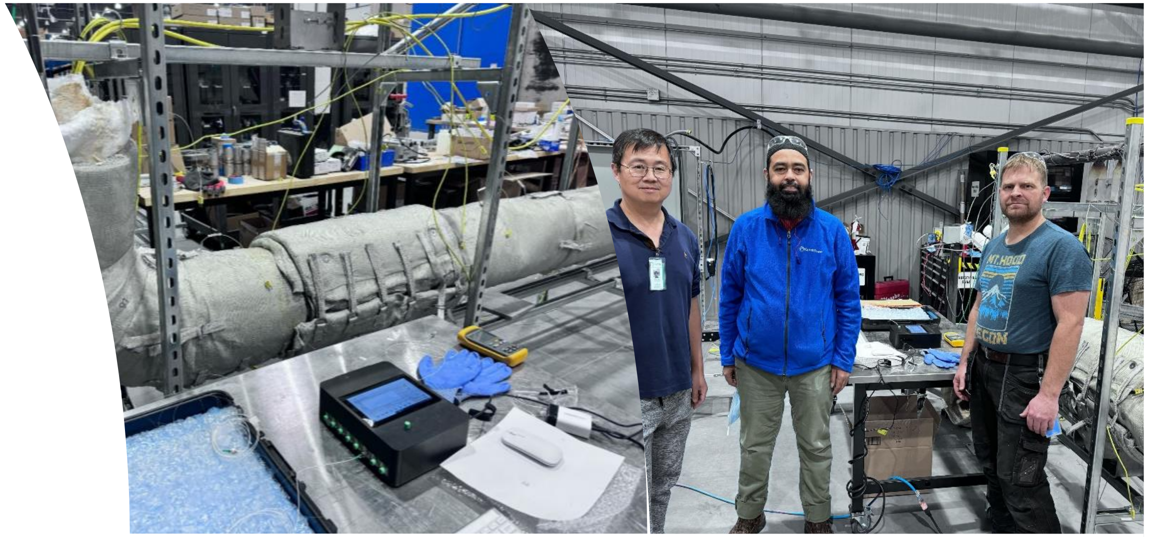
The key is the algorithm!

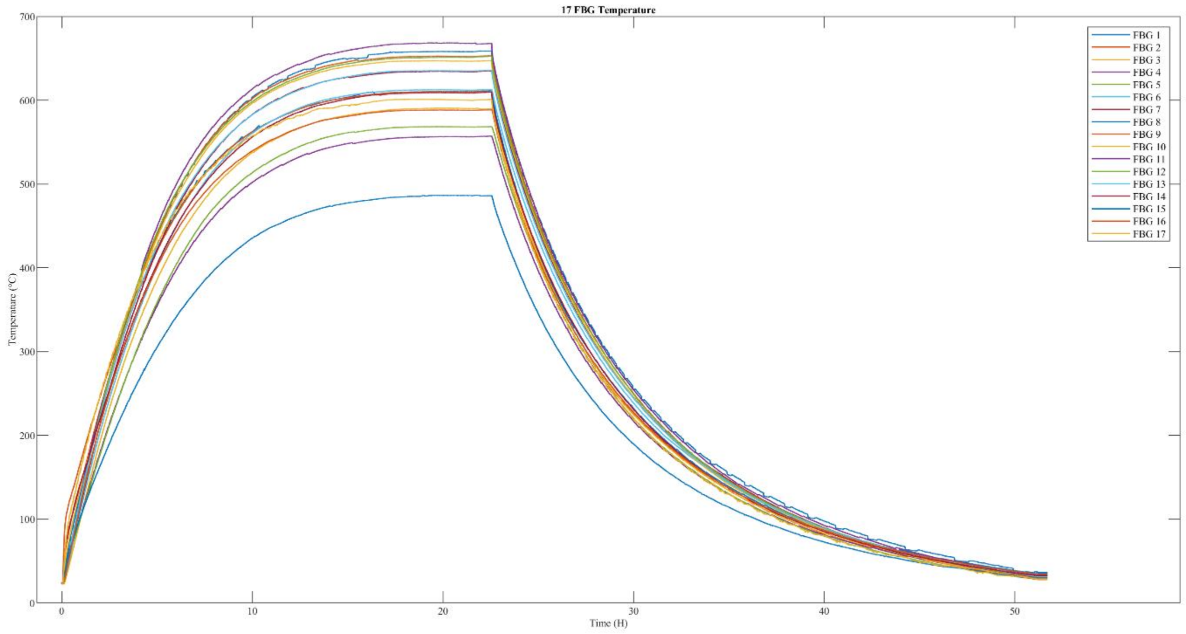
- Three algorithms to ensure accurate sensor demodulation.
- Interrogate both FBG and IFPI arrays.
- Background data screening and validation.
- Can simultaneously interrogate up to 1280 point sensors.
- **The world's first fully calibrated fiber sensors (Guaranteed at up to 650C).**
- Aiming for full calibration at 850C.
- Made in Pittsburgh.



Field Test: Molten Salt Circulation Loop





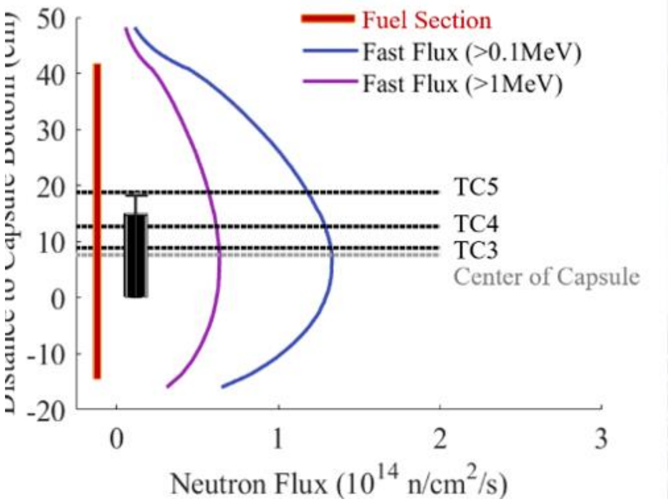


- Completed immune to EM noises
- Radiation harden
- Straightforward calibration.

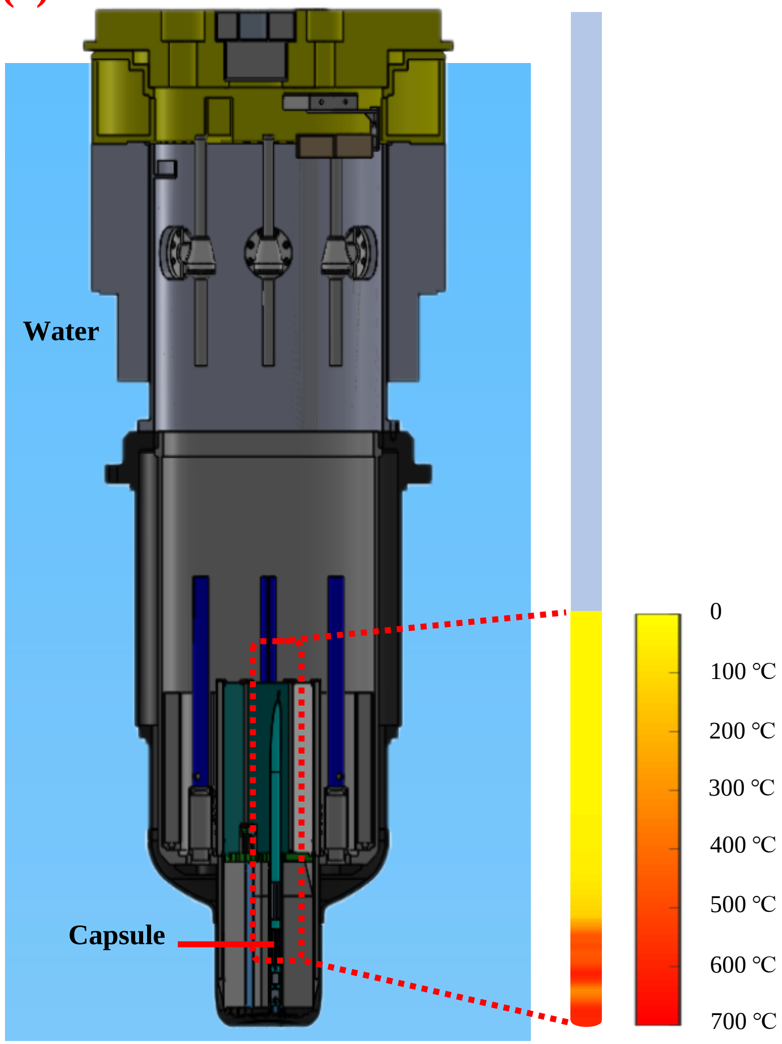
- One-fiber, 20 sensors vs. 40 lead wires – 20 sensors.

Radiation-Harden Sensors

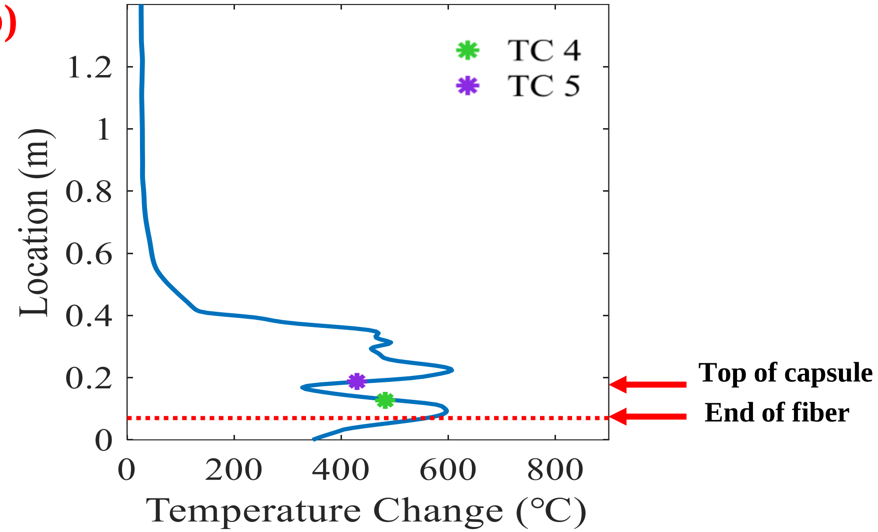
(c) (d)



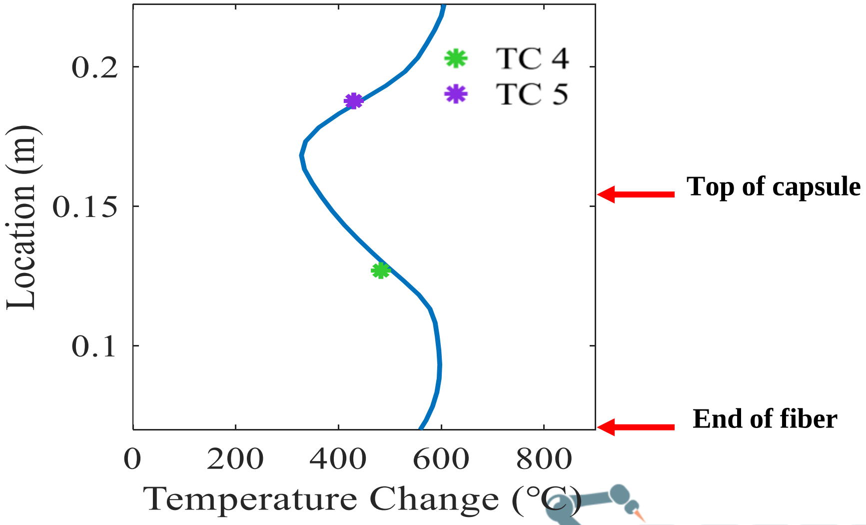
(a)



(b)



(c)

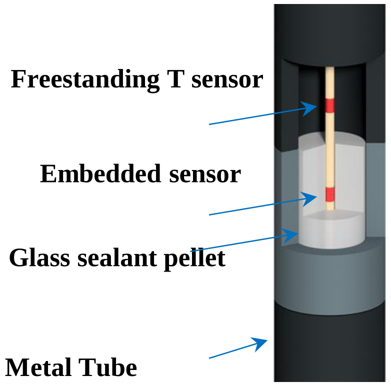


Sensor Embedding in Metal Parts

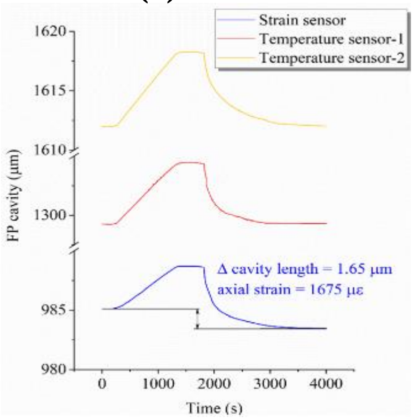
- Enable energy users for rapid and straightforward sensor deployments
- Three sensor packaging technique developed for fiber sensor embedding in metal structures
- Applicable for a wide range of temperature ranges.

Fiber Packaging Technology: High-T (800C)

(a)



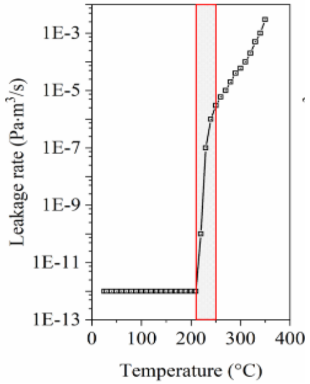
(b)



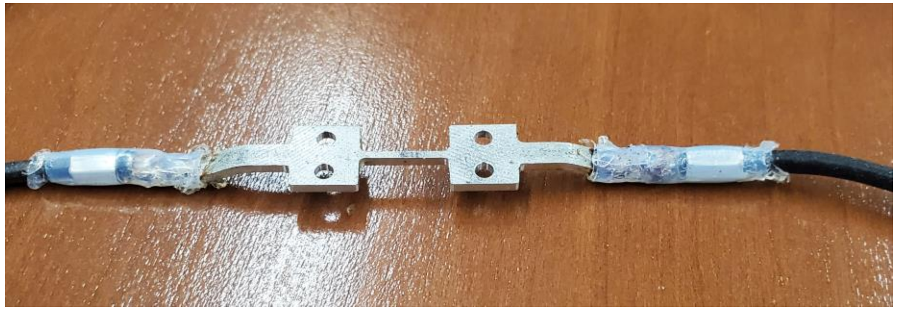
(c)

(d)

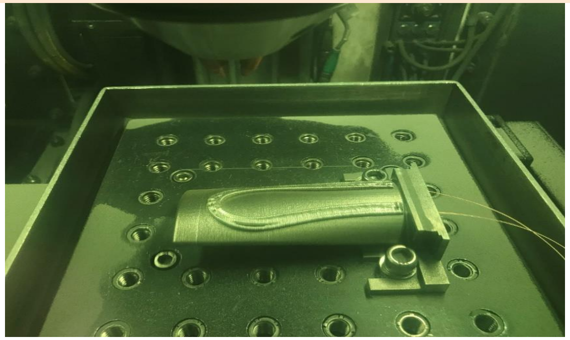
(e)



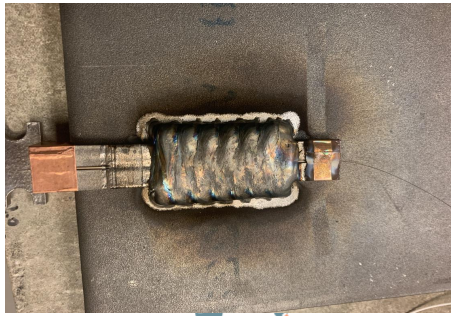
Ultrasonic AM: up to 400C



Distributed sensor in blade by LENS

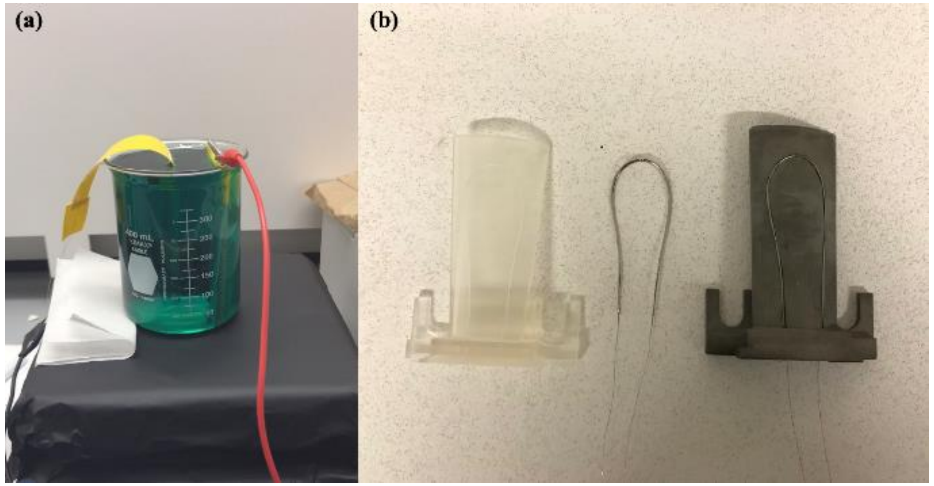


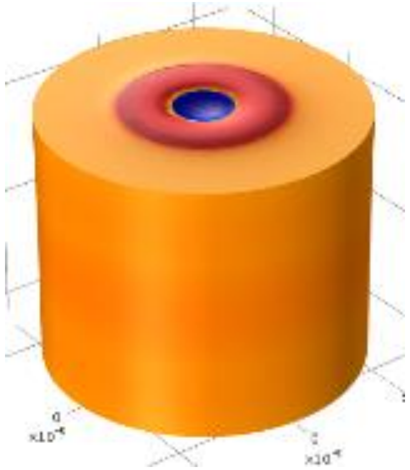
Wire-Arcing

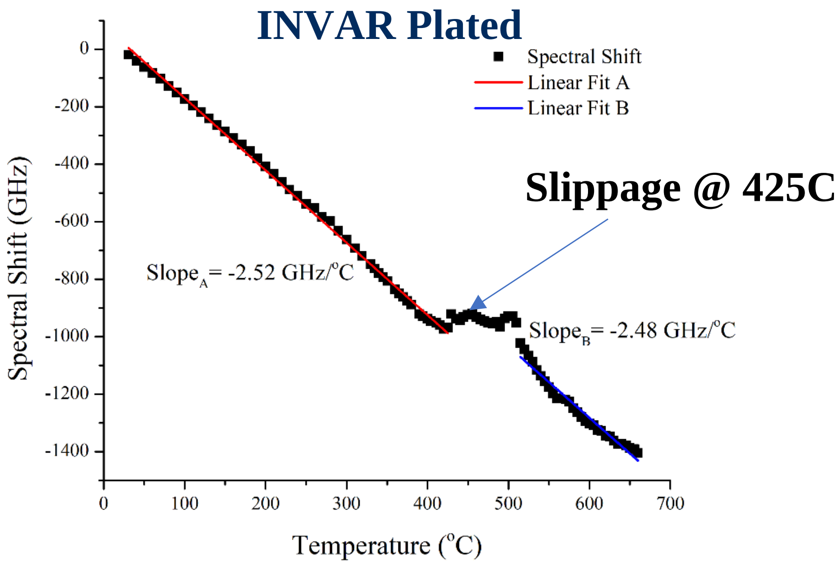


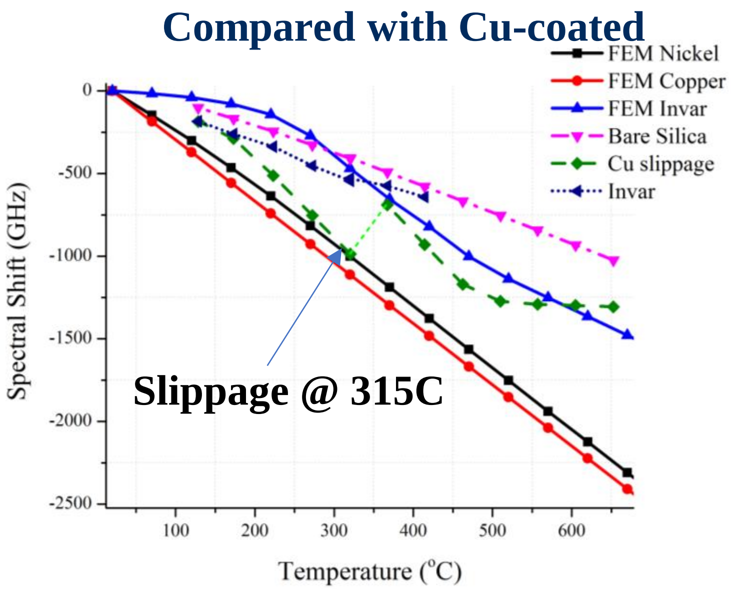
Protection and Managing TEC Mismatch

Electroplating: INVAR protective coating





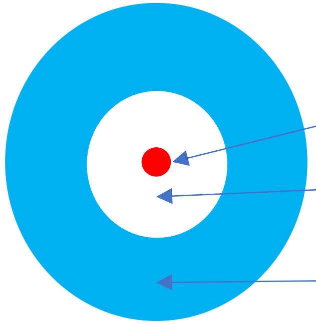




- E-beam evaporation coating: 50-nm W glue layer (TEC ~ 3.4 ppm/C).
- Electroplating of Invar-36 protective coating: 400 – 800 µm (TEC ~ 0.5 ppm).
- Electroplating in a 3D printed plastic mold to minimize residual strain.

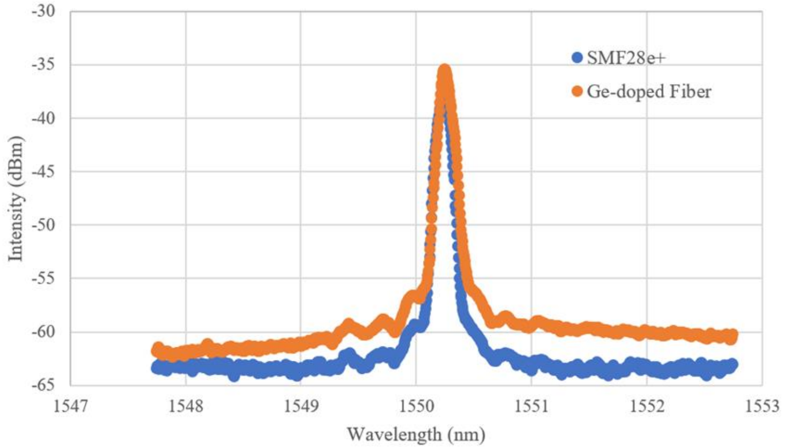
- Significant improvement in slippage temperatures.
- Still challenging to reach PWR operational temperatures.

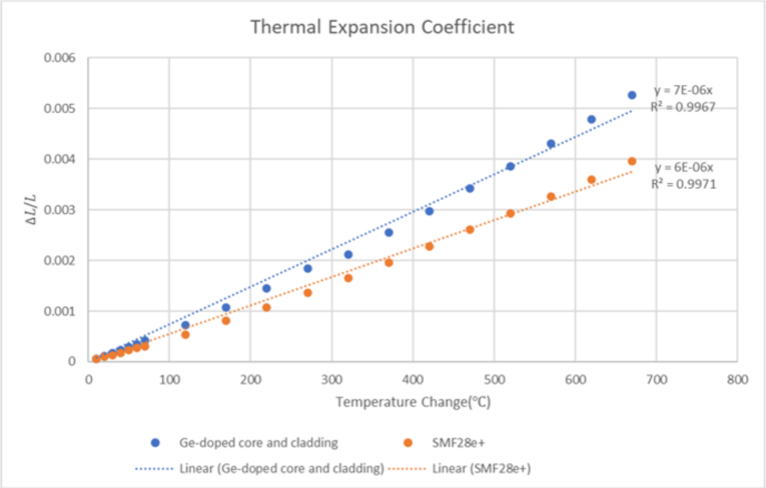
New Specialty Fiber with high TEC – with Corning



$$TEC(GeO_2) = [5.5 + 115.2 \times (GeO_2\, mol\%)] \times 10^{-7}$$

- **3% Ge-doped fiber core to maintain same thermal optical coefficient**
- **Fused silica trench to ensure optical guiding**
- **40% of Ge-doped silica outer cladding to increase TEC**
- **Successful fabrication of FBG fiber sensors**
- **TEC experimental measured by an IFPI sensors**

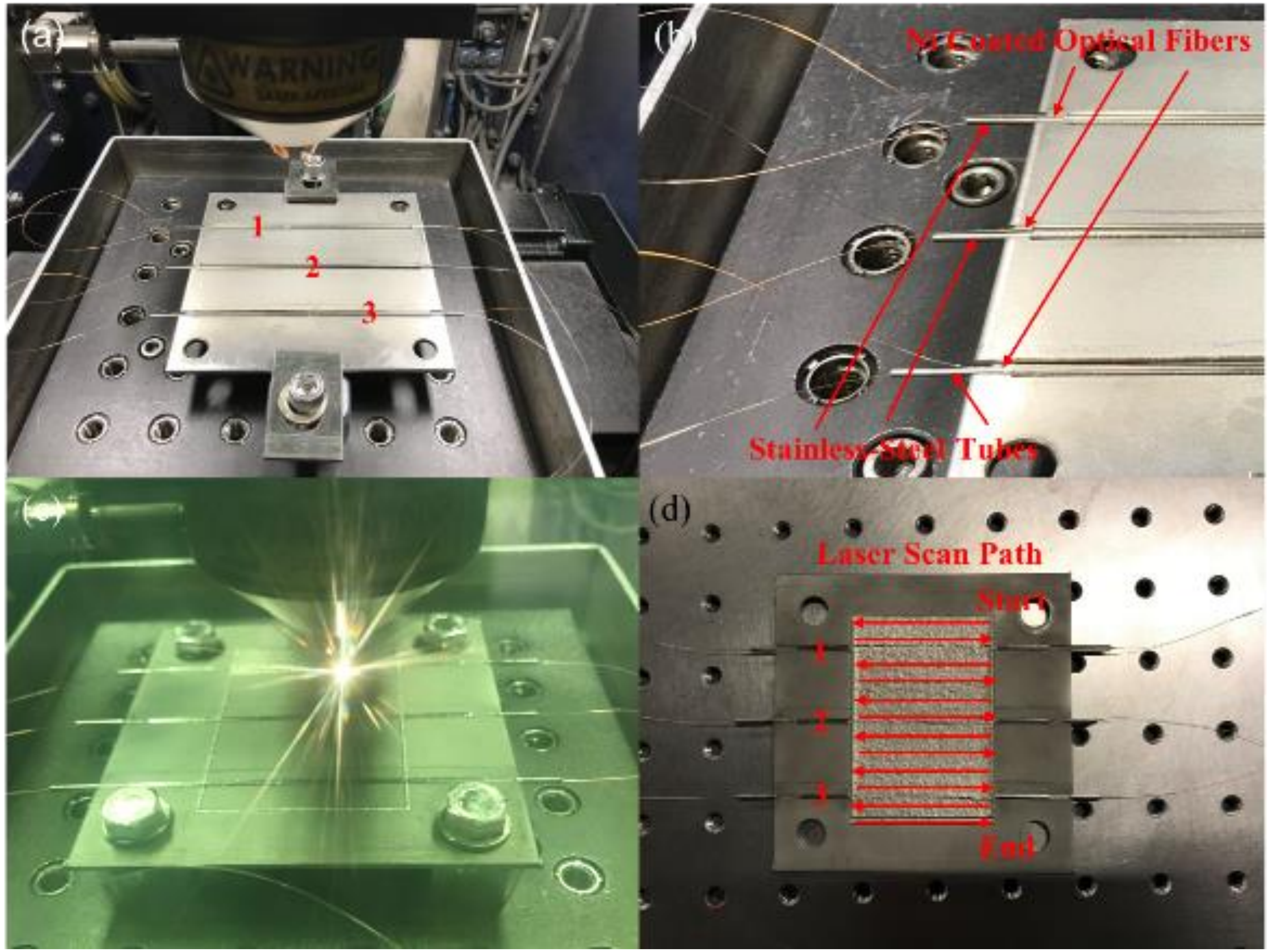




Standard Fiber: $\Delta L/L = 0.55 \times 10^{-6}\, T$

<u>*New fiber:* $\Delta L/L = 1.45 \times 10^{-6}\, T$</u>

Sensor-Fused AM Process – Metal Process



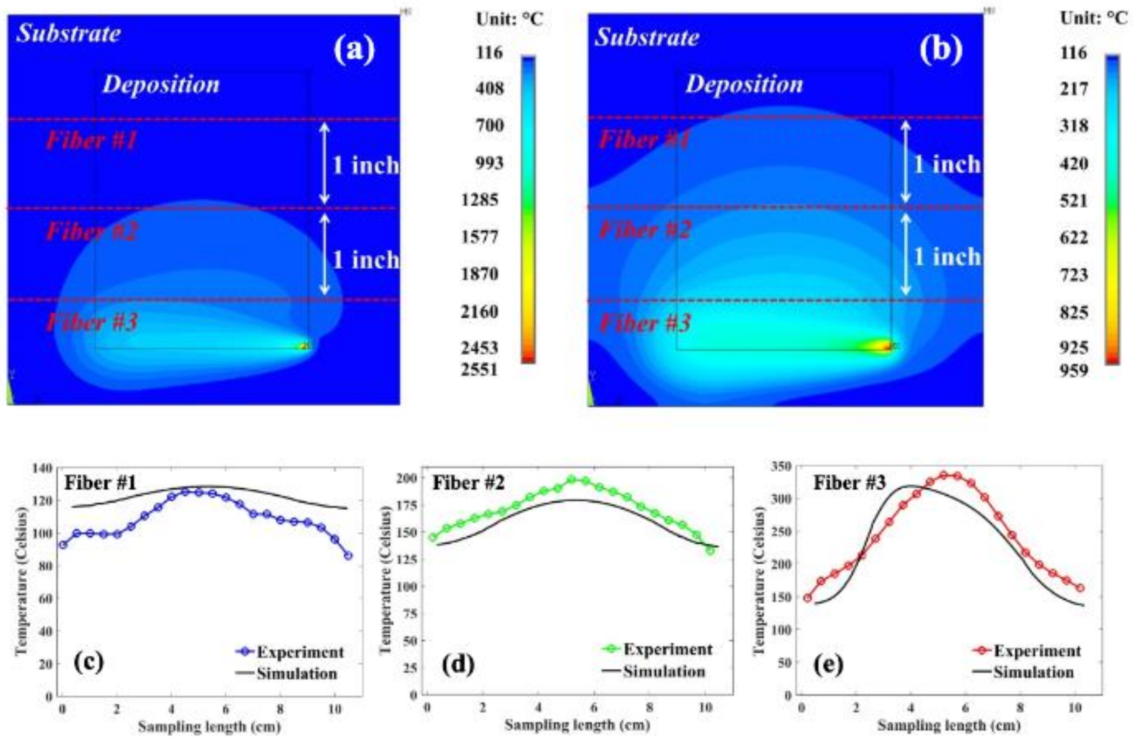
Sensor Fused AM Process

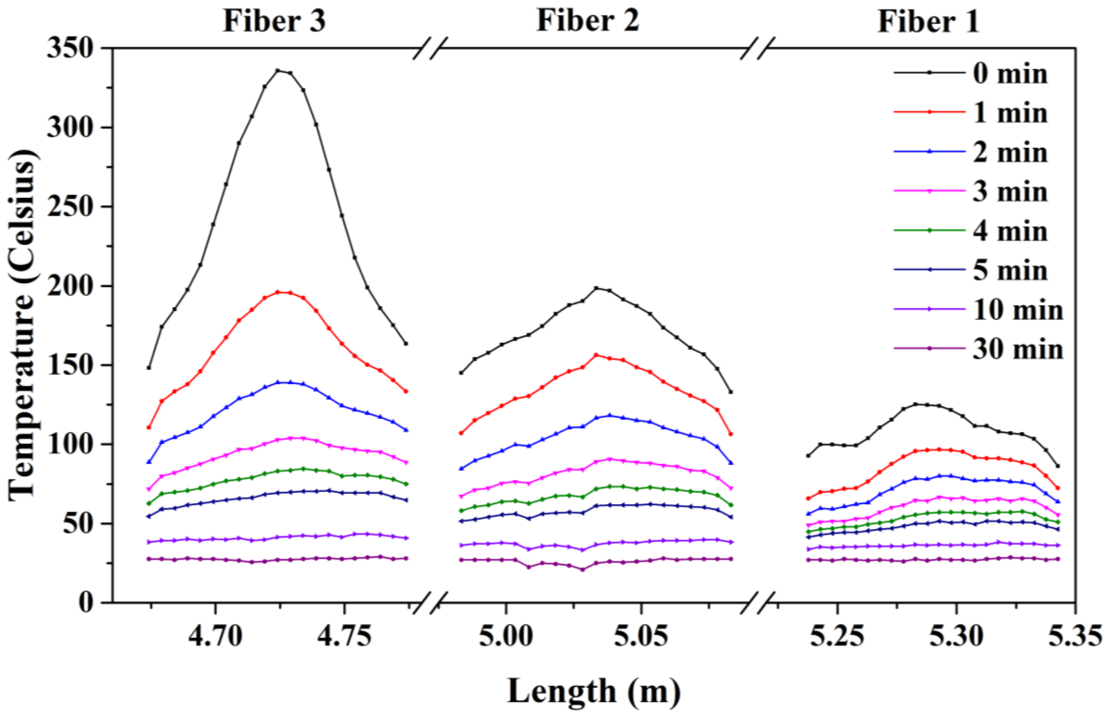
- High resolution real-time T & $\mu\varepsilon$ measurements
  - Design proper structures to embed sensors without disturbing AM process and part itself
  - Real-time measurements to study AM process itself
  - Post-process monitoring to study residual strain formation and relaxation.
  - Compare, correct, and validate DT

Temperature Measurement by Embedded Sensors

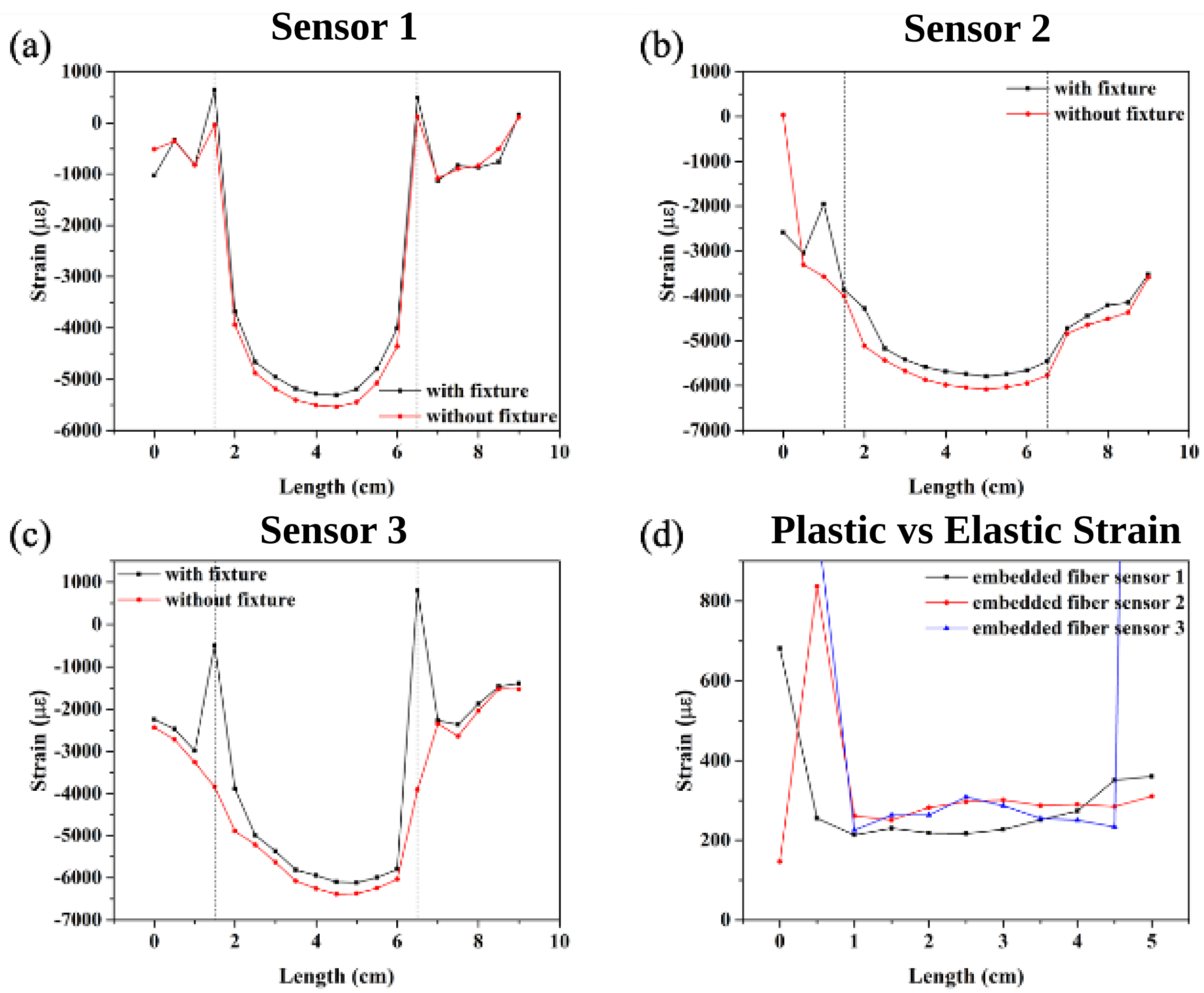
The simulated global temperature profiles of the LENS

- (a) upon the completion of the deposition
- (b) 0.5s after the deposition process.
- Measured results by fiber sensors are shown in (c)-(e).

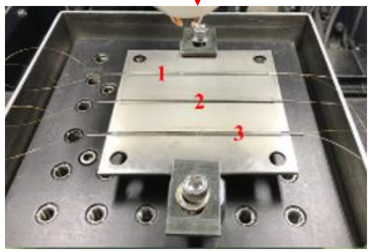




Strain Measurements vs. Simulation



Clamp



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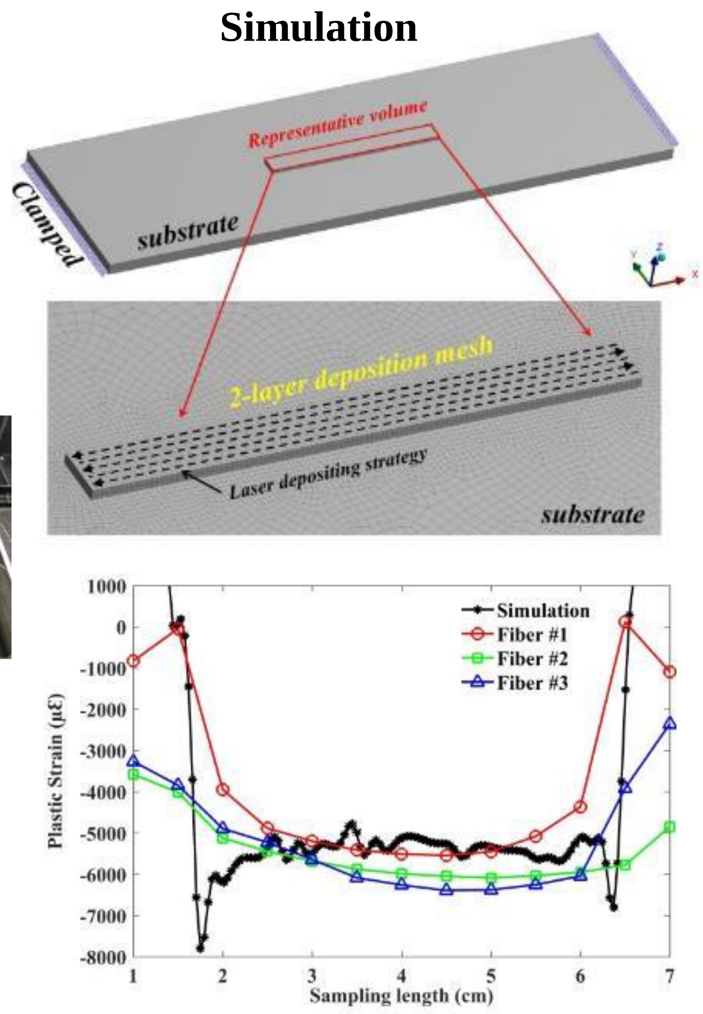
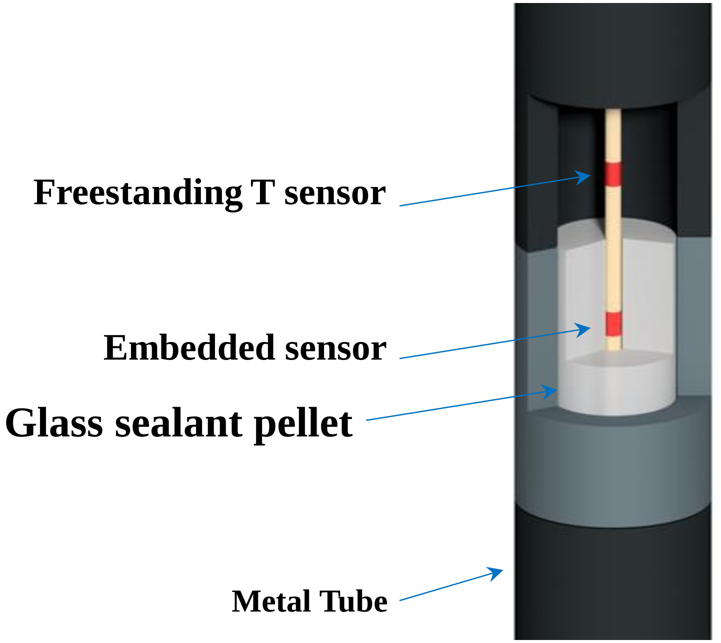
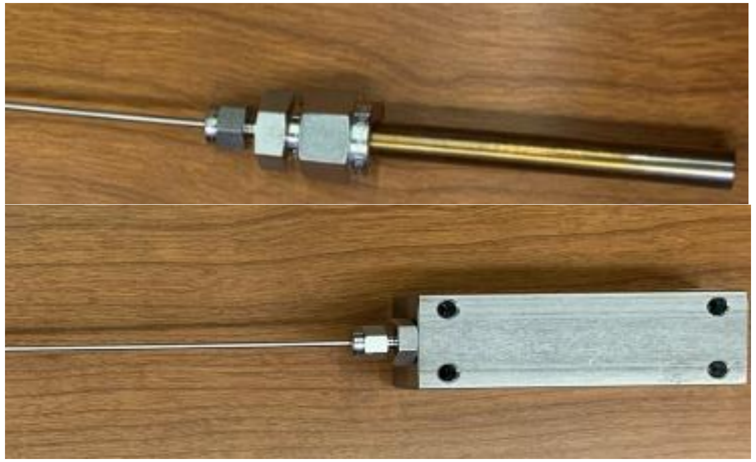
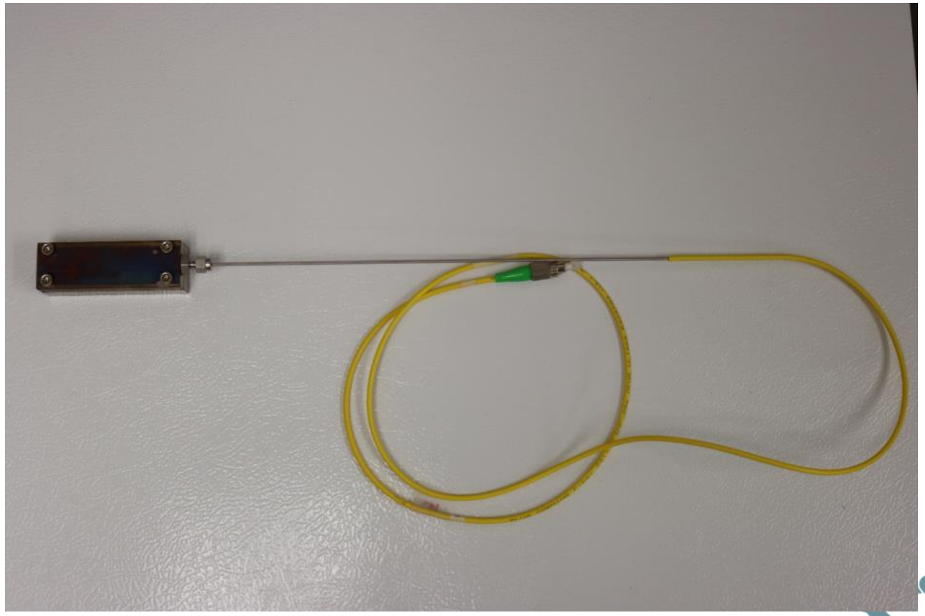


Hermetical Sensor Embedding Using Glass Sealants



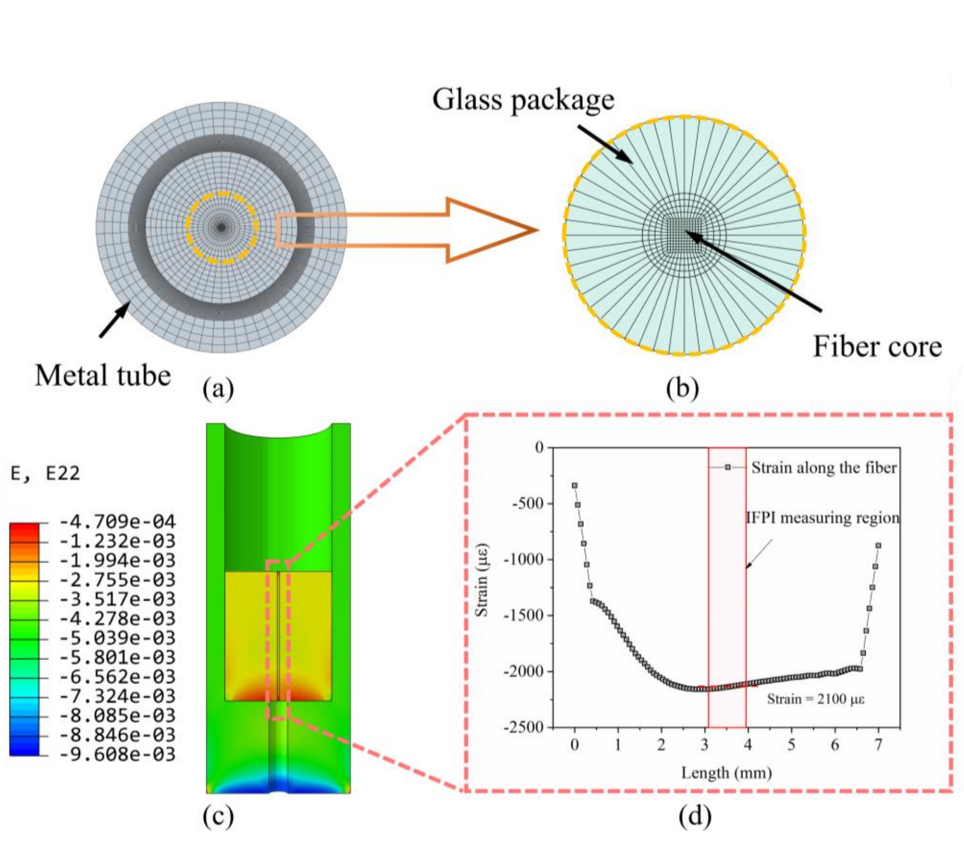


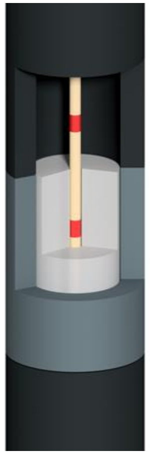
- Wide selection of sealant materials: glass and ceramics
- TEC of glass sealant ~ 5ppm/C – right in the middle between silica fiber and metal.
- Hermetical bonding on metals – enable pressure boundary penetration.
- Rapid process possible
- High-T application possible.
- Packaged sensor size > 6-mm diameter OD



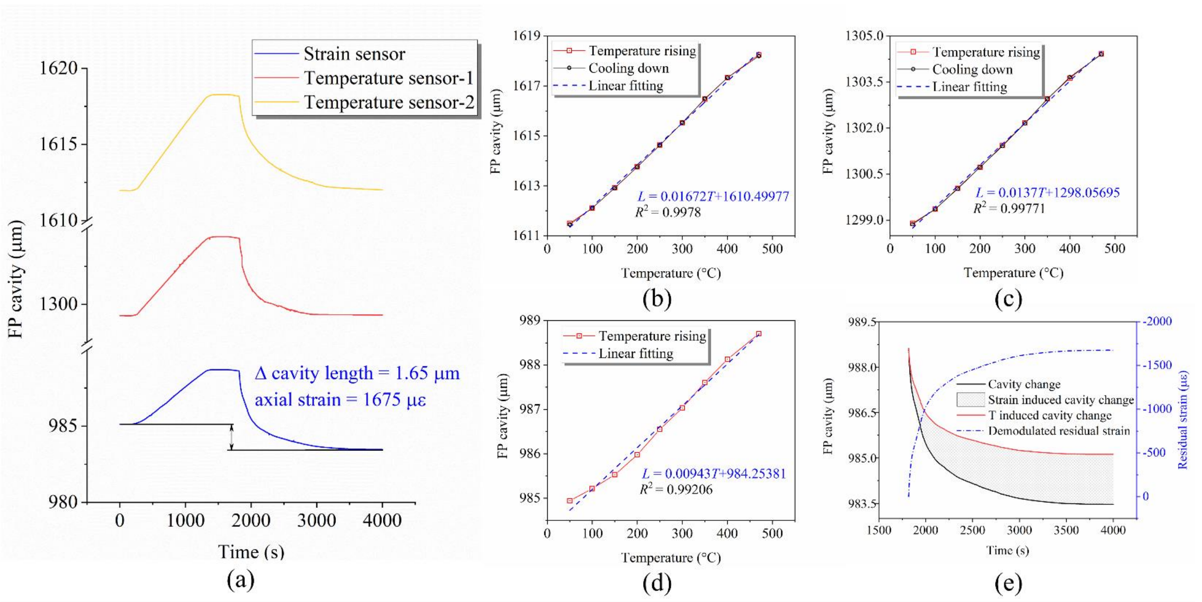
Hermetical Sensor Embedding Using Glass Sealants

FEA Simulation



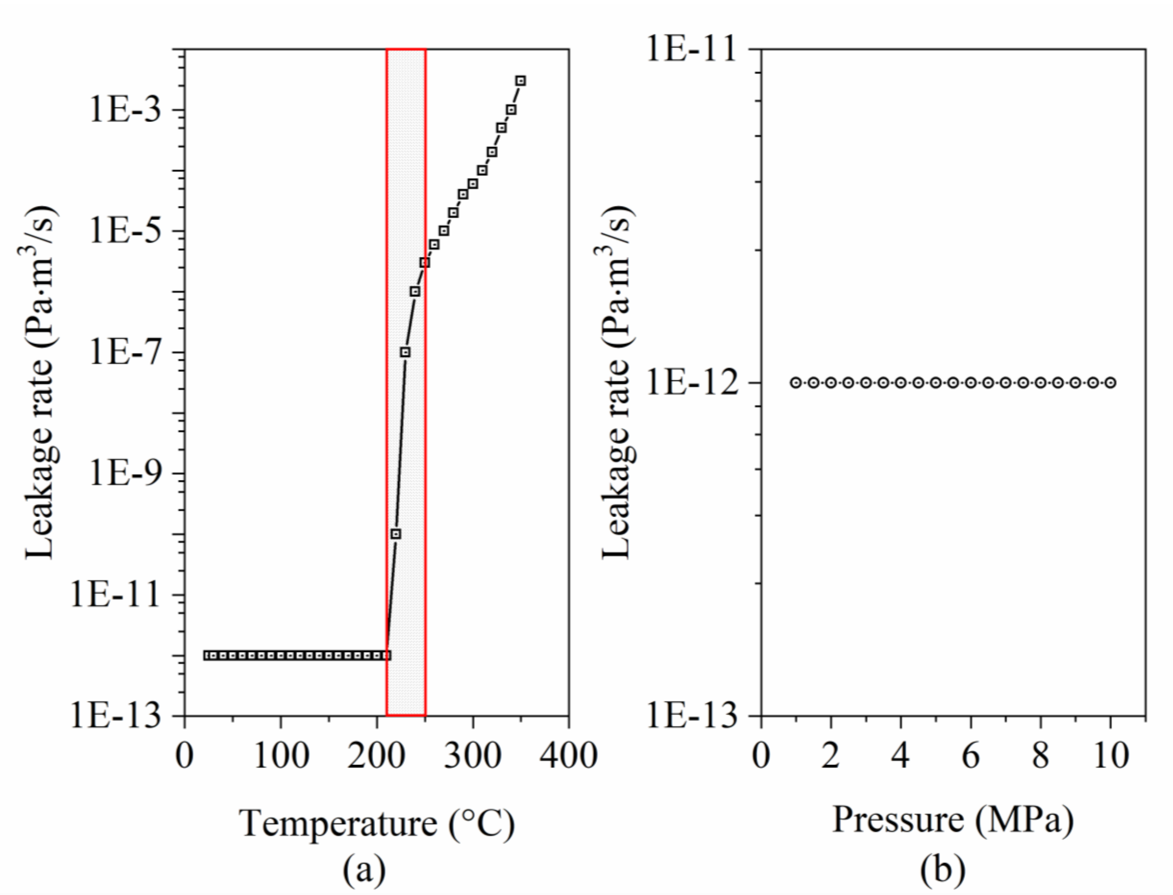


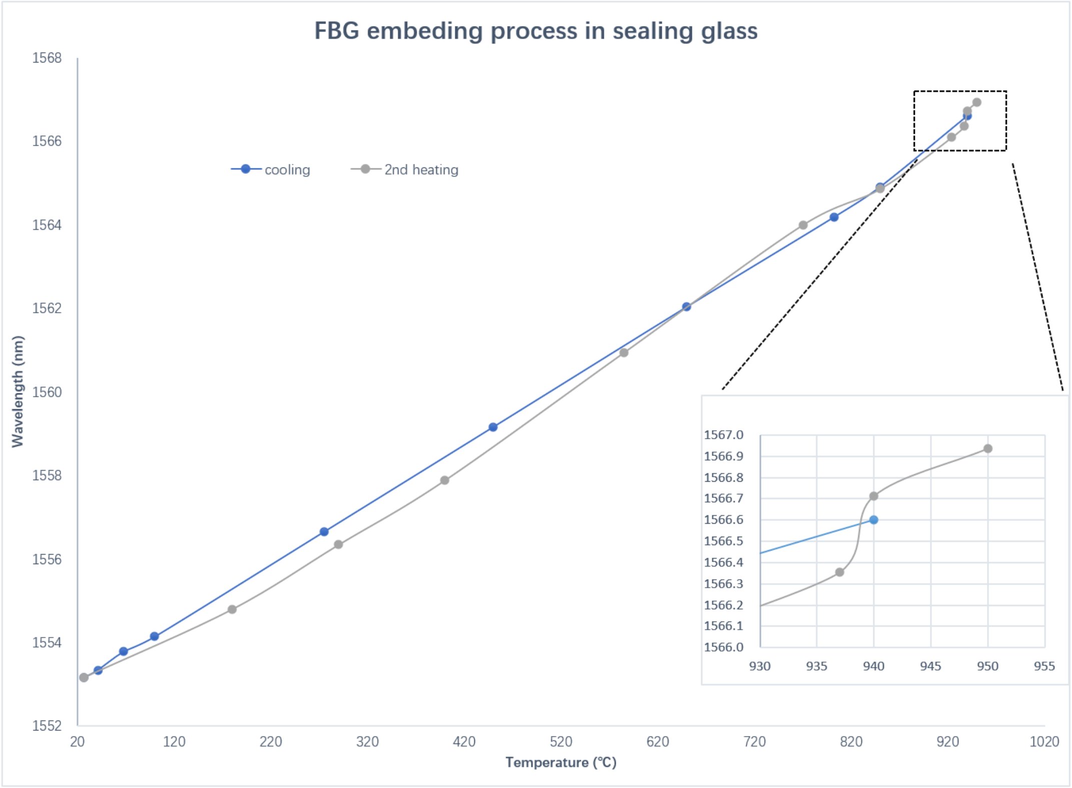
Experimental Results



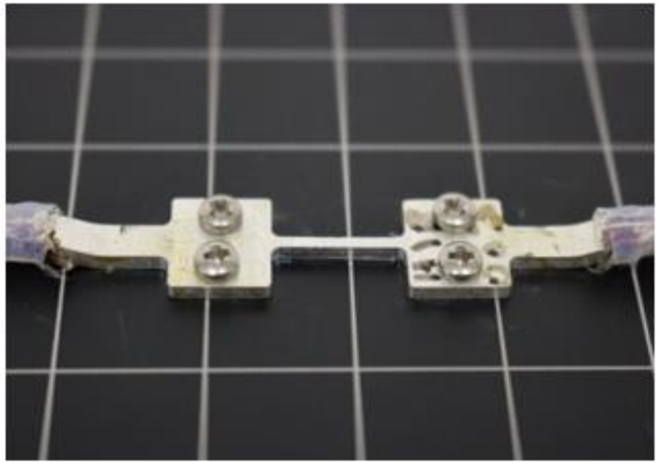
- Sealing process induced compressive strain
- Experiment match simulation: ~1500-2000 compressive strain
- Linear temperature response: non slippage
- Both FBG and IFPI sensors have been embedded

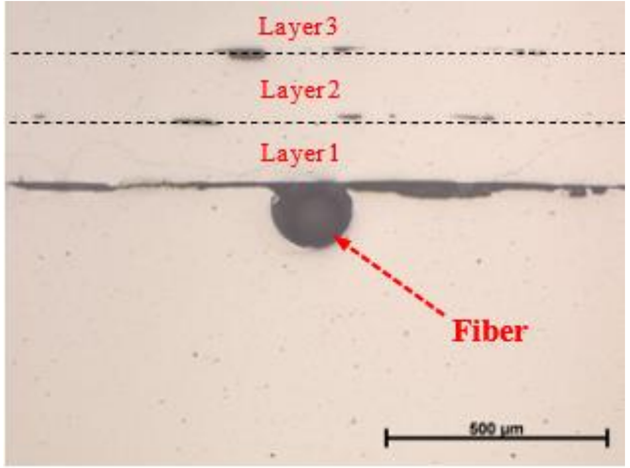
Hermeticity and High-Temperature Testing

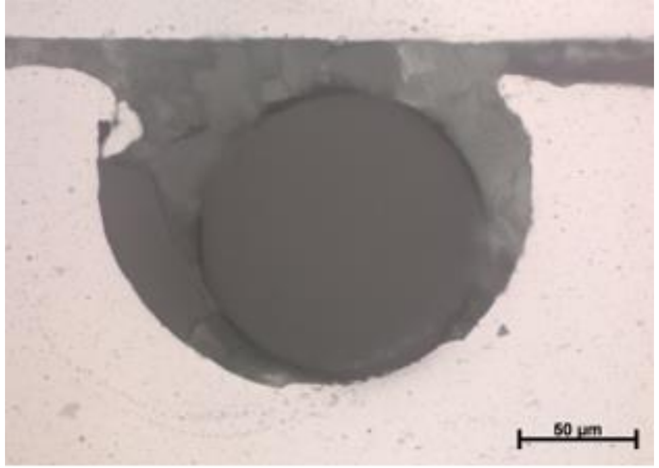




Ultrasonic Metal Additive Manufacturing





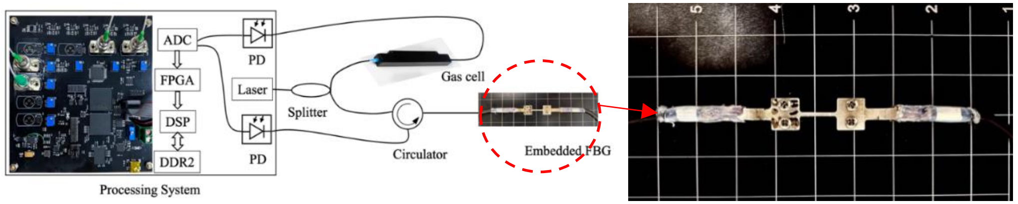


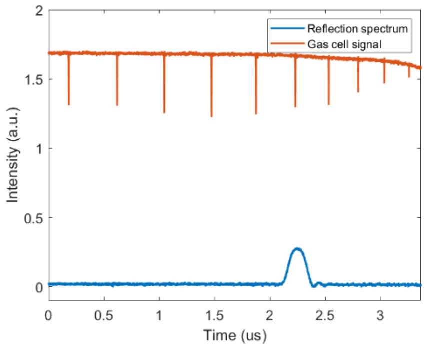
Sensor Fused UAM process

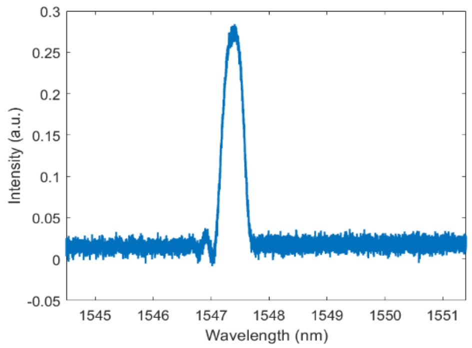
- Fs-inscribed 2-mm long FBG through polyimide coating.
- Low processing temperature ~170C for aluminum.
- AL-6061 H18 aluminum foil.
- 4 kN downforce and 32 μm peak-to-peak scrubbing amplitude.
- Repeated strain test, no slippage up to 5000 με.
- Up to 300C operation (short-term).

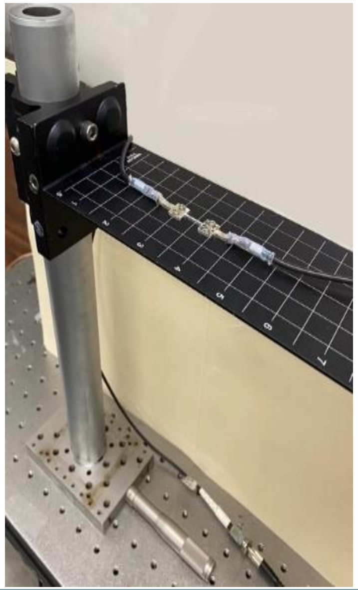
Telecom laser enable FBG Interrogation

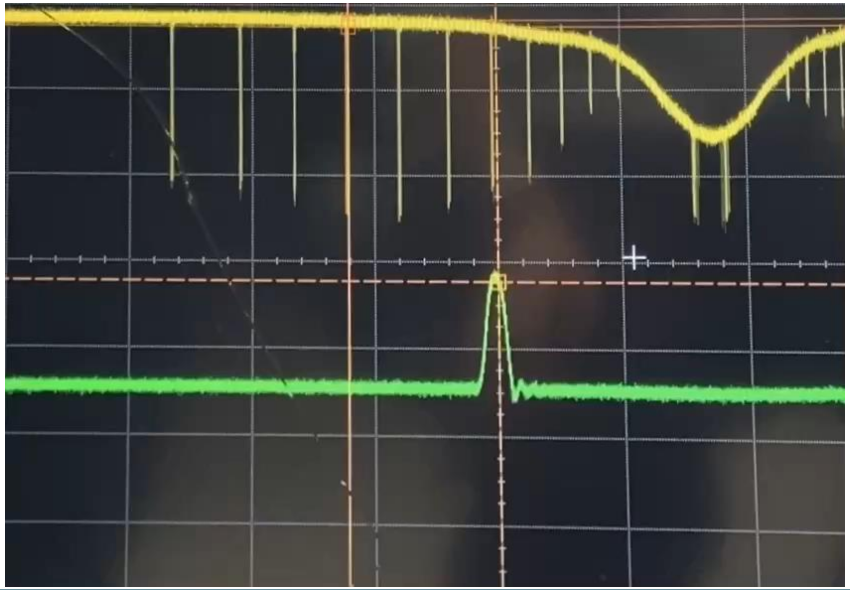
- Wavelength tuning stitching
- Gas-cell wavelength reference
- High-speed interrogation possible
- Heterogeneous multi-core architectures: FPGA+ DSP
- Rapid sensor data demodulation via DSP
- Static wavelength variation better than ± 2pm



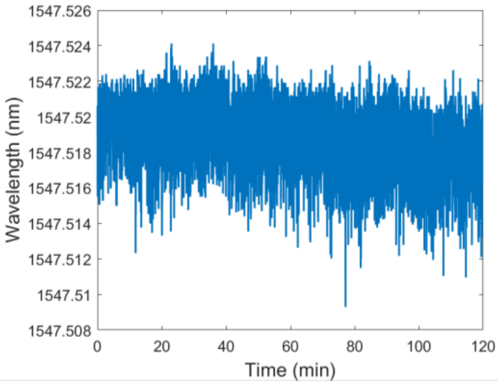


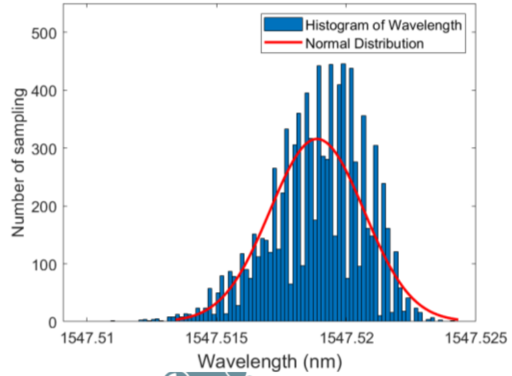






Long-Term Stability Testing

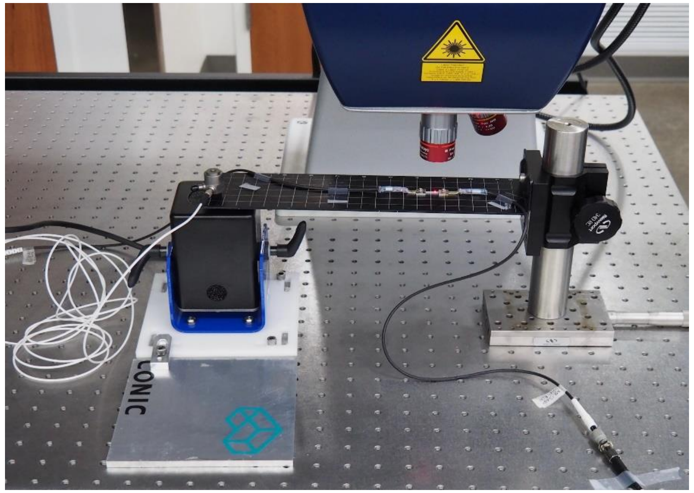


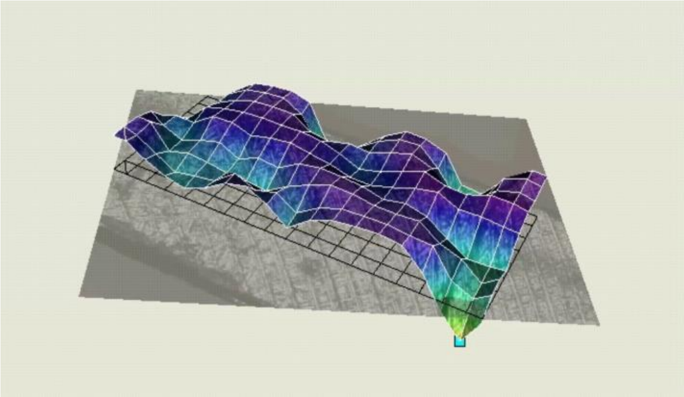


High-Frequency Vibration Sensing

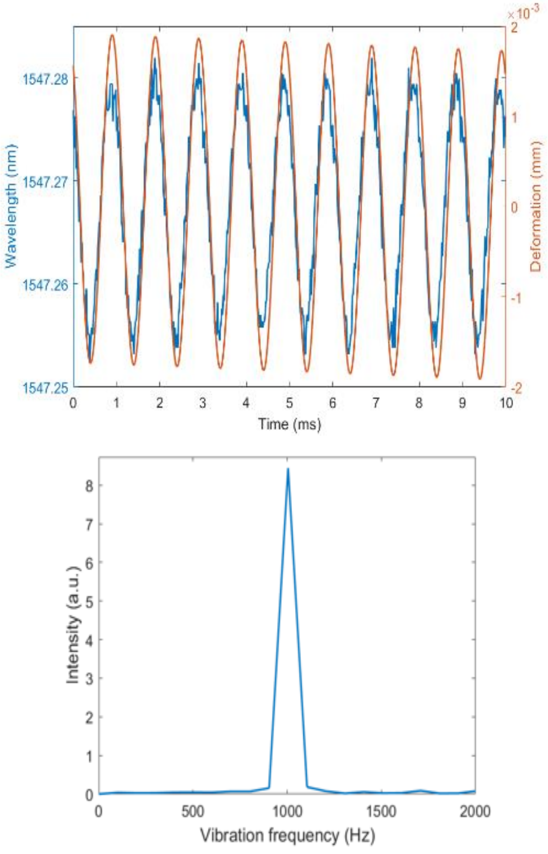
PITT | SWANSON ENGINEERING
ELECTRICAL & COMPUTER
1893–2023 130 YEARS

Laser Velocimeter Comparison 5kHz vibration



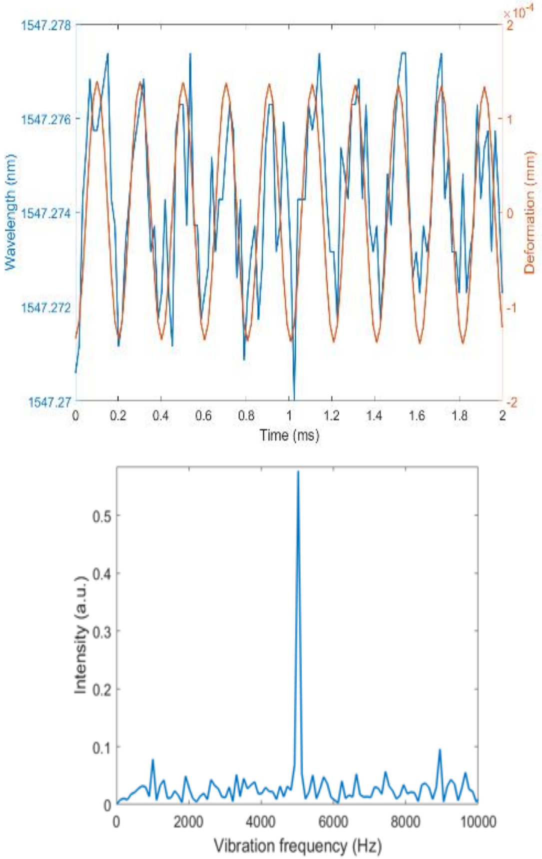


Vibration: 1kHz



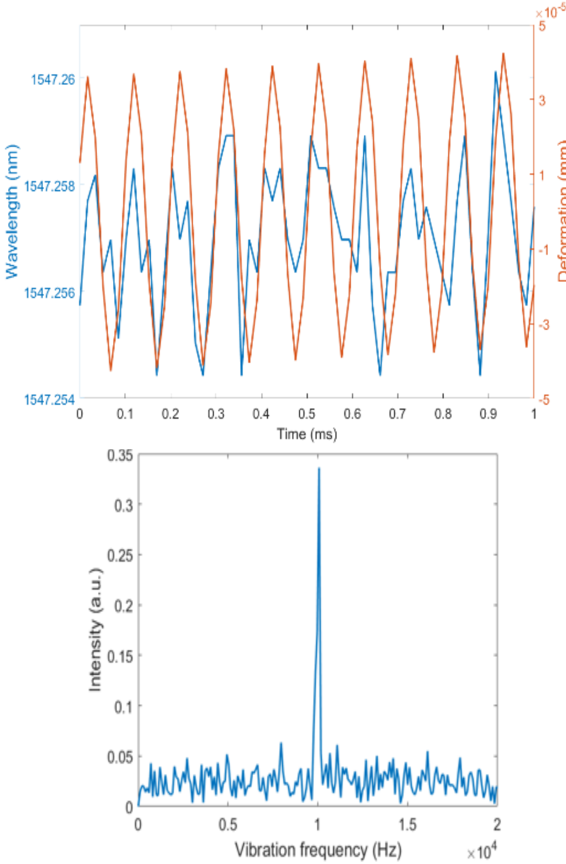
(a)

Vibration 5kHz



(b)

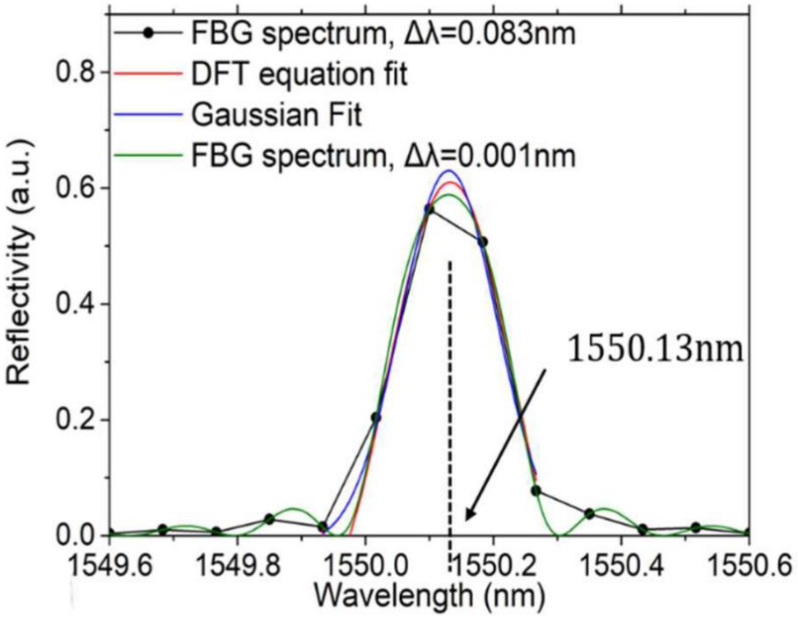
Vibration 10kHz



(c)

Demodulation Algorithm and Interrogation Systems for NE I&C

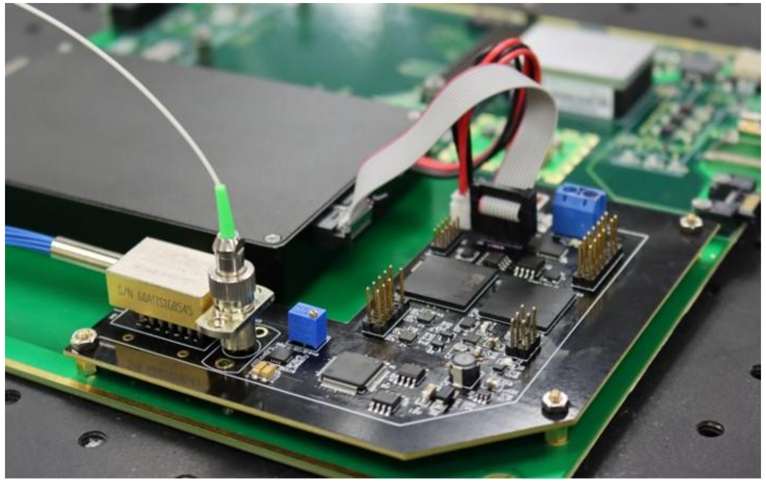
Bunman Frequency Estimation



$$R(\lambda) = \frac{\kappa^2 \sin h^2 (sL)}{s^2 \cos h^2 (sL) + \delta^2 \sin h^2 (sL)}$$

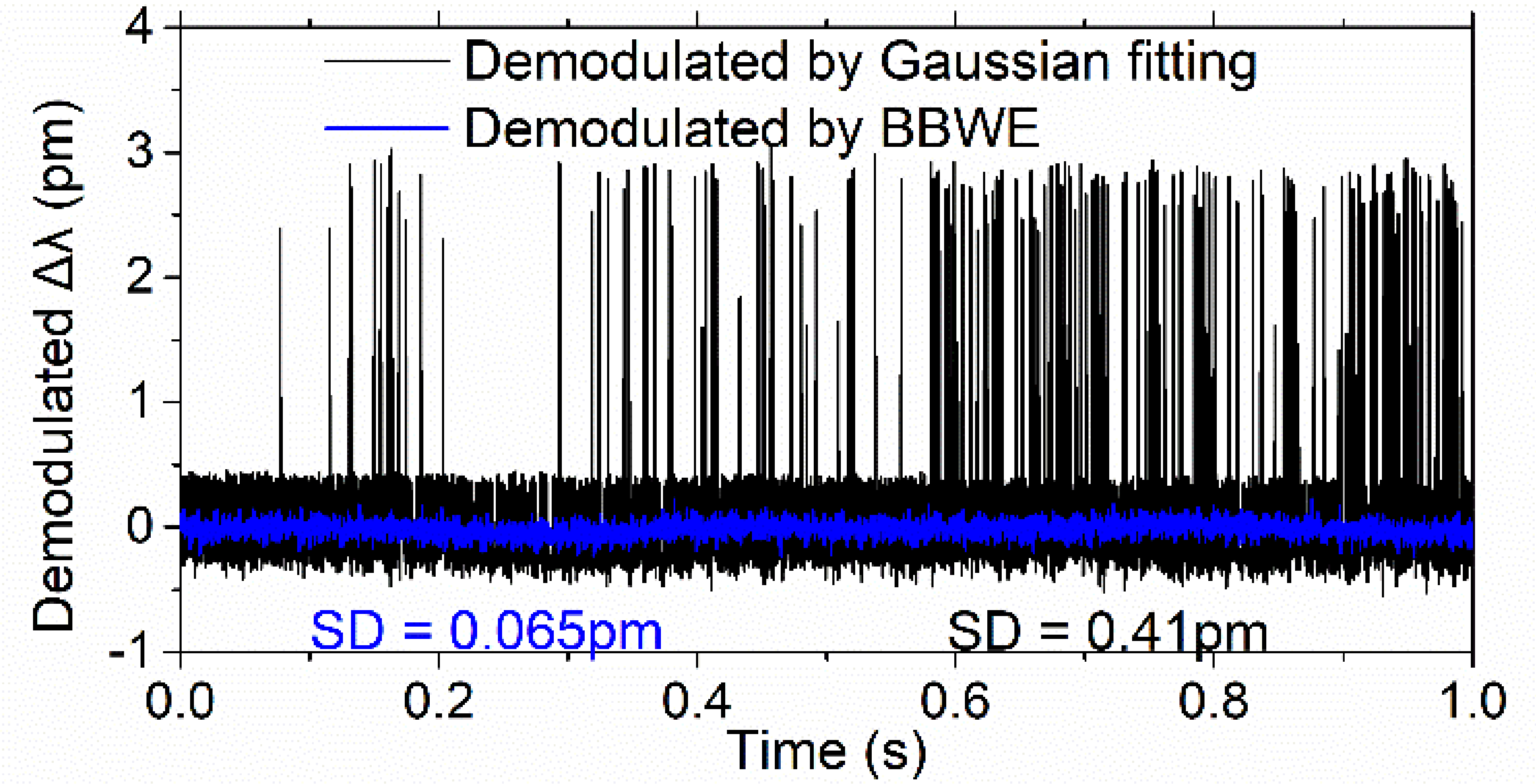
$$I_{\text{bias}} = (|I(\lambda_{n-1})| + |I(\lambda_{n+1})|)/2$$

$$\tilde{\lambda}_B = \lambda_n + \lambda_r \frac{N}{\pi} \arctan \left[\frac{\sin \frac{\pi}{N}}{\cos \frac{\pi}{N} + \frac{|I(\lambda_n)| - I_{bias}}{|I(\lambda_{n+1})| - I_{bias}}} \right]$$



- 10× more efficient than Gaussian Peak Fitting.
- Robust algorithm avoid “jump”
- Easy implementation into DSP chips
- Dedicate sensor demodulation electronics developed
- Support up to 1MHz sampling rates for acoustic/vibration sensing
- 40-nε dynamic strain
- 0.1C static measurement (temperature)
- Eight channels to support >200 sensor simultaneously

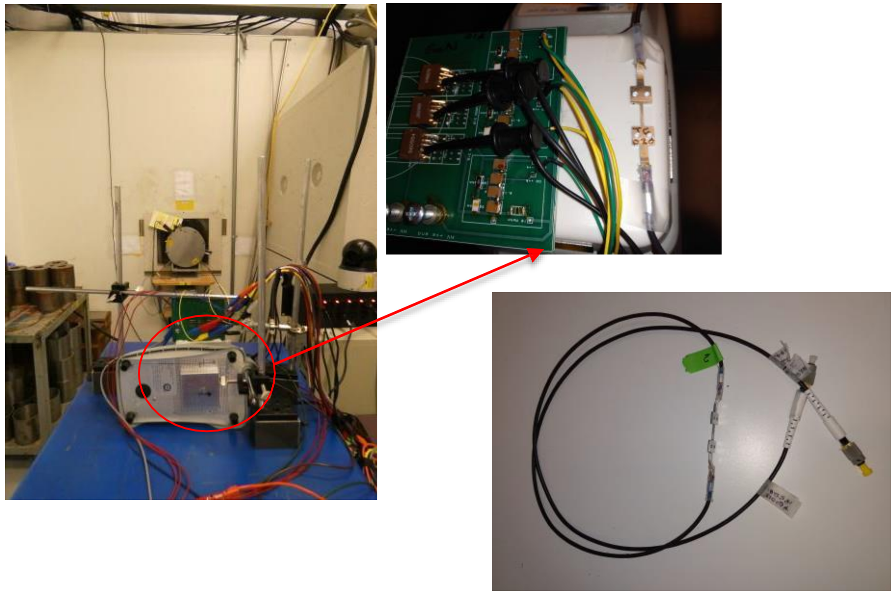
Rapid Demodulation Algorithm



Irradiation of Embedded Fiber Sensors

Carried out by Dr. Moinuddin Ahmed

- Irradiation at LANSCE (Los Alamos Neutron Science Center)
- Sensors were irradiated with neutron energy above 1.5 MeV
- Sensors were irradiated at room temperature and at 300 ^{o}C.
- Irradiation times were set at 2 hrs and 4 hrs

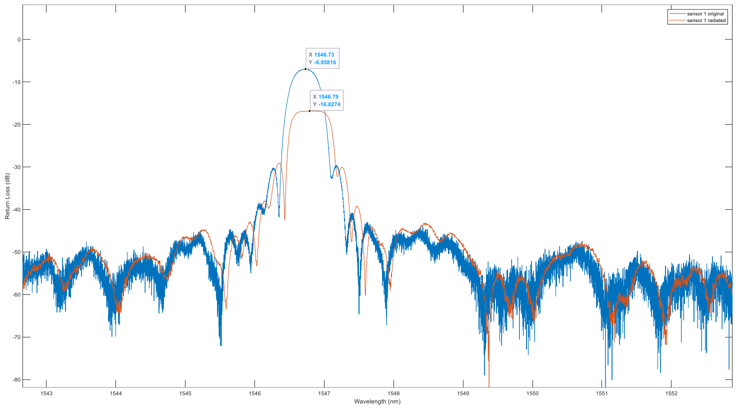


Fiber Sensor	Temperature (°C)	1.5MeV Neutrons (n/cm²)	10MeV Neutrons (n/cm²)
1	25	9.409E+09	4.682E+09
2	25	1.892E+10	9.416E+09
3	300	9.409E+09	4.682E+09
4	300	1.892E+10	9.416E+09

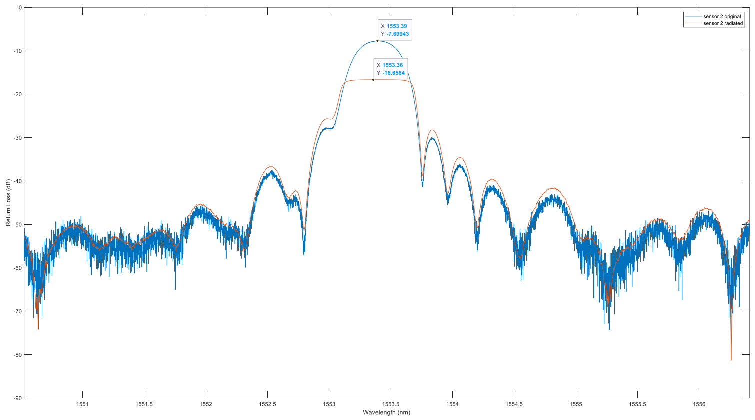
Irradiation of Embedded Fiber Sensors

Carried out by Dr. Moinuddin Ahmed

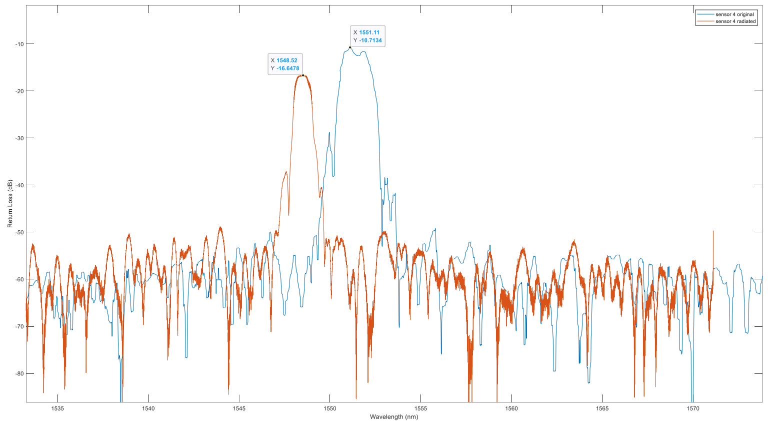
Sensor 1



Sensor 2



Sensor 4



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3	300	9.409E+09	4.682E+09
4	300	1.892E+10	9.416E+09

sensor	wave bef	wave aft	wave diff (nm)	loss bef	loss aft	loss diff (dB)
1	1546.73	1546.79	-0.06	-6.958	-16.827	9.869
2	1553.39	1553.36	0.03	-7.993	-16.658	8.665
4	1551.11	1548.52	2.59	-10.713	-16.647	5.934

What is the Challenge?

Post-Fabrication Heat Treatments are Essential

https://www.mtixtl.com/CM-HIP-2.aspx

UAM for SS410

Yield Stress: As Fabricated: 137.5MPa
Heat treated: 337.8MPa
HIP process: 1120C, 100 MPa, 4 hours

WAAM for Inconel 718

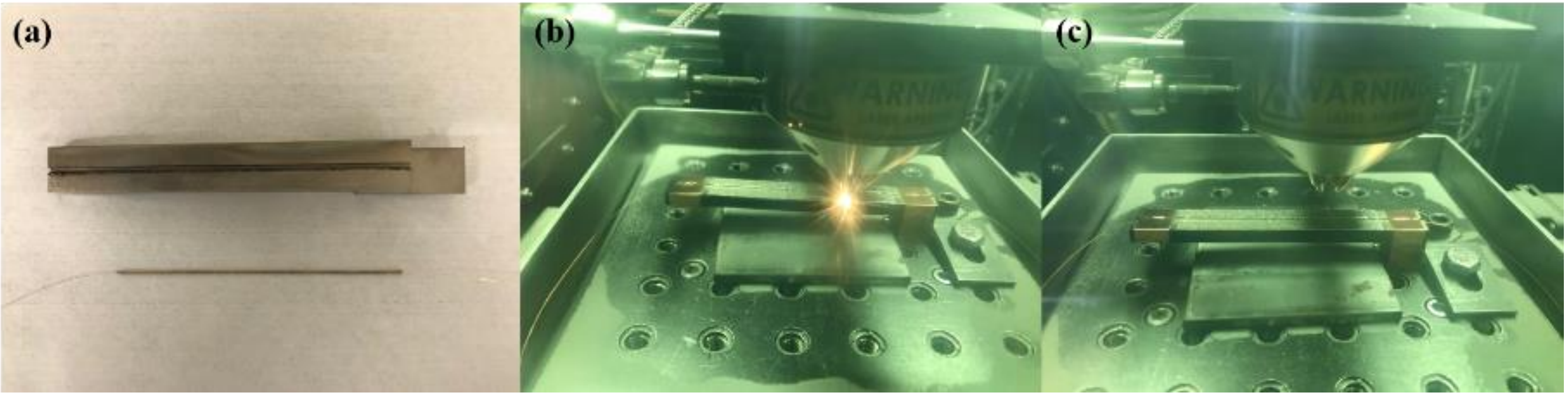
Yield Stress: As Fabricated: 430 MPa
Heat treated: 1040 MP
Heat Treatment: Multi-step, 1300C, 6 hours

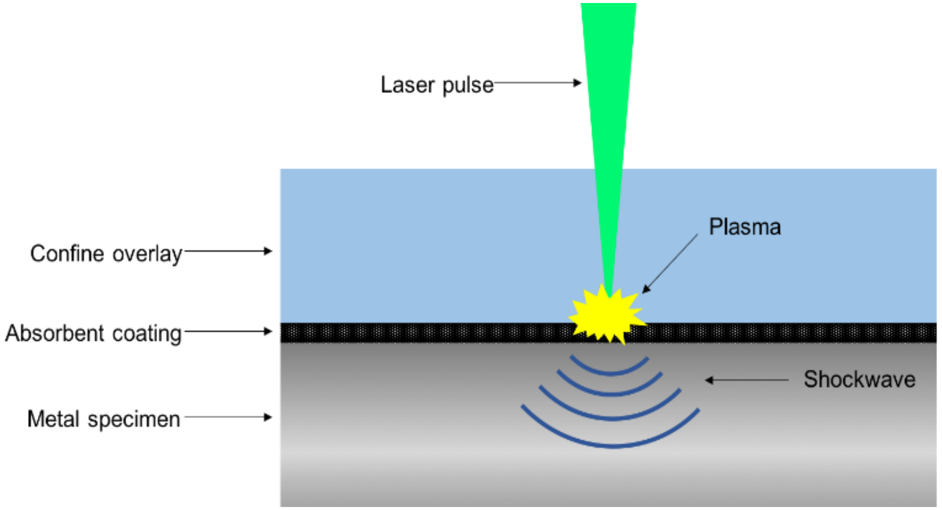
(J. Song, X. A. Jimenez, C. Russel, A.C. To, https://doi.org/10.1038/s41598-023-46674-z)

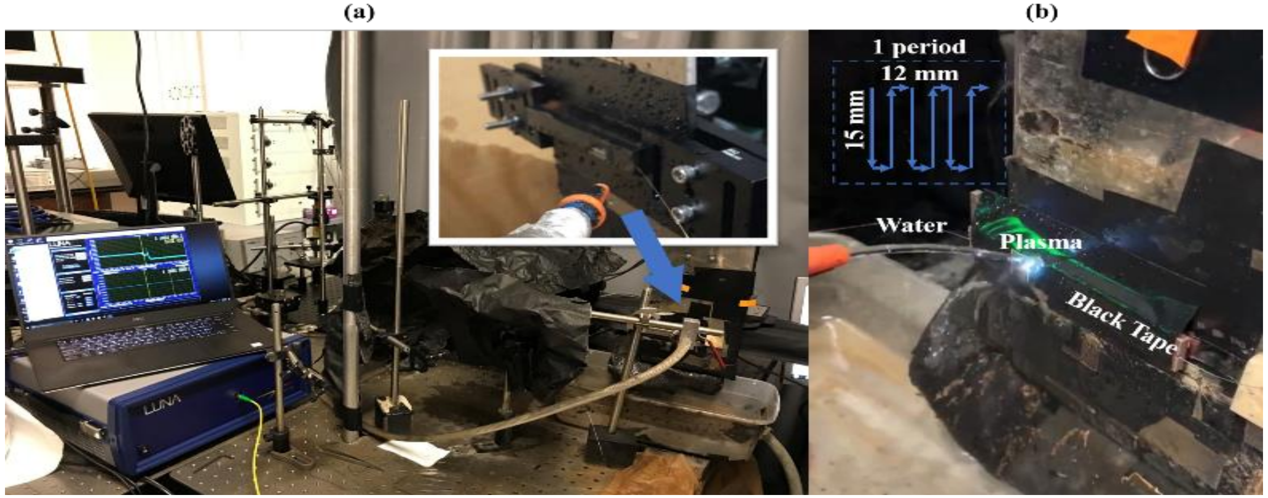
Without Post Heat Treatment?

- Drastically poorer mechanic properties.
- Prone to corrosion.
- No known sensors can withstand post-fabrication heat treatments.

A RT Post Processing Laser Shock Peening (LSP)



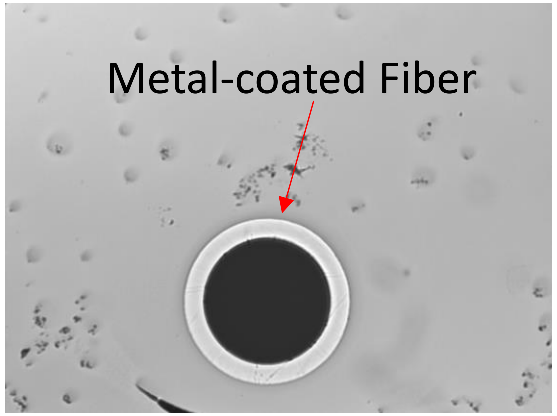


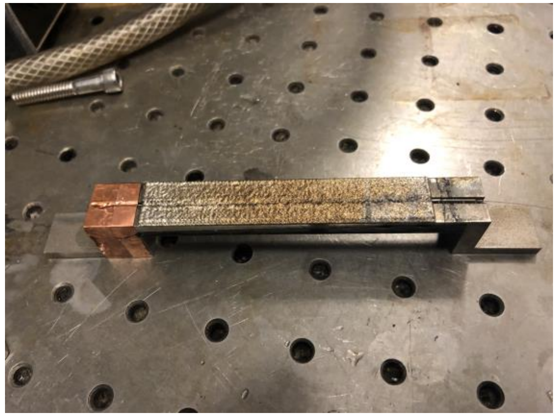


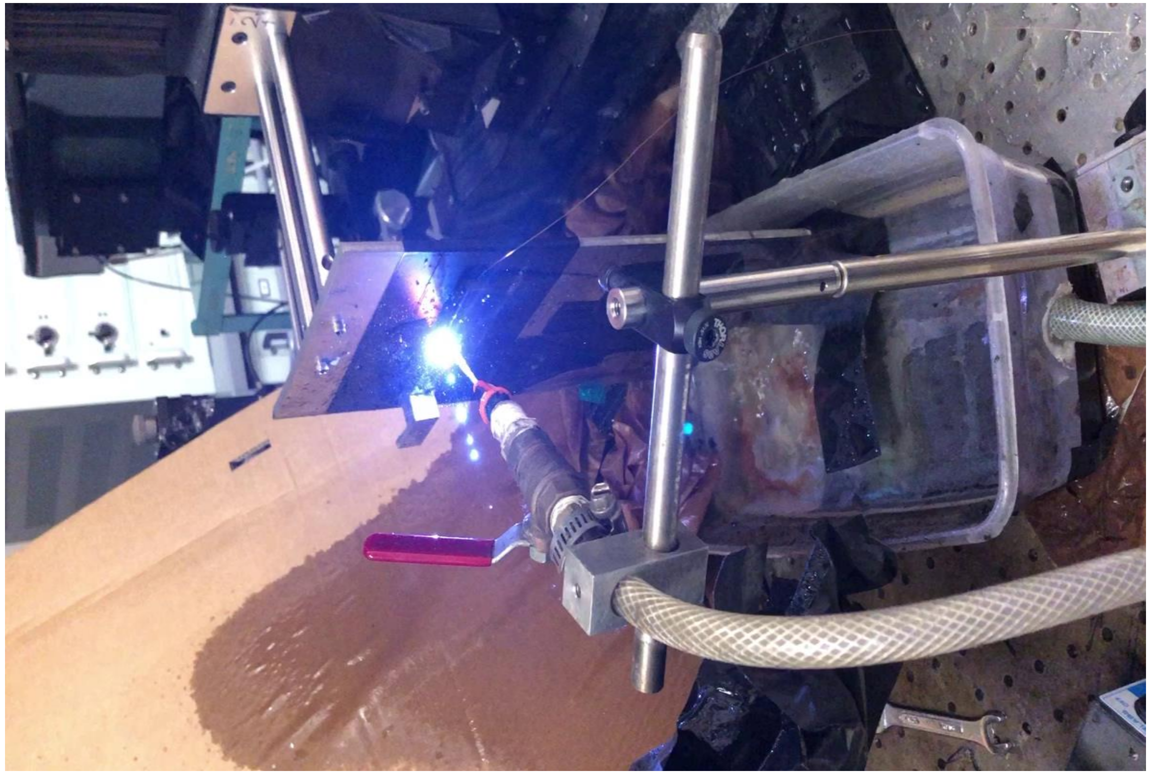
Solution
Laser Shock Peening (LPS)

A room temperature post-treatment

- A room-temperature post-process is known to improve corrosion performance.
- Simple and can be robotically deployed.
- Introducing a surface with compressive strain go as deep as 5-mm.
- Compressive strain as much as 0.1%.
- <u>Widely applicable for all AM-embedded fiber sensors</u>



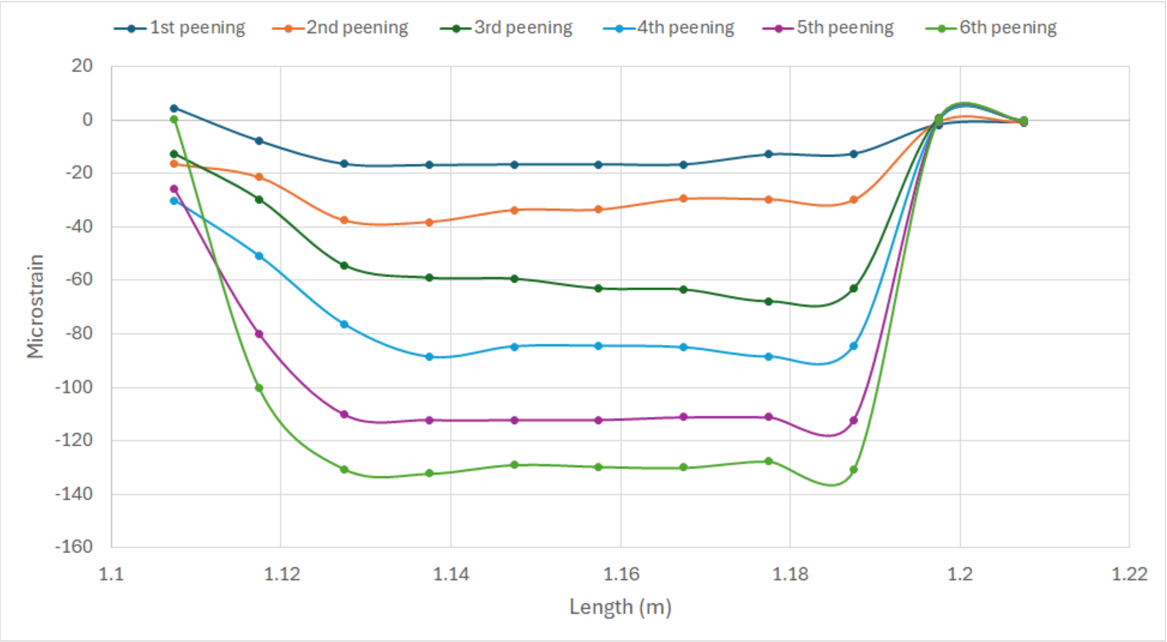




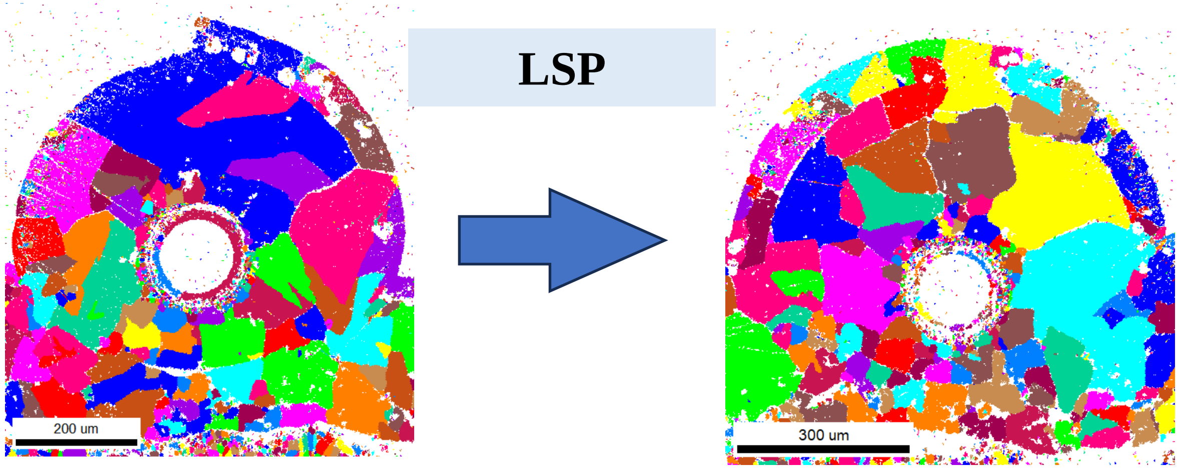
A RT Post Processing: Laser Shock Peening

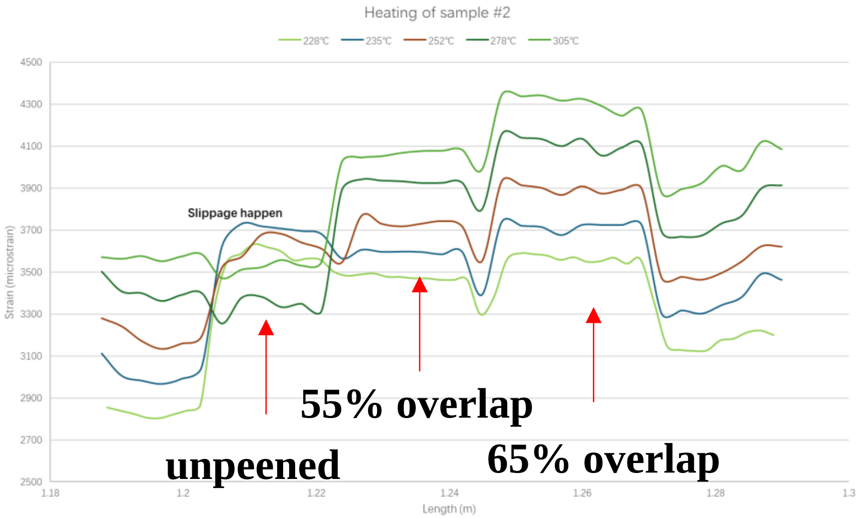
- **0.5 mJ/pulse, 10 ns, YAG.**
- **0.5 mm/s peening speed.**
- **Reach maximum compressive strain:** 130με measured by embedded fiber sensors
- **Maximum depth: 5-10 mm.**
- **Suitable for NE applications.**

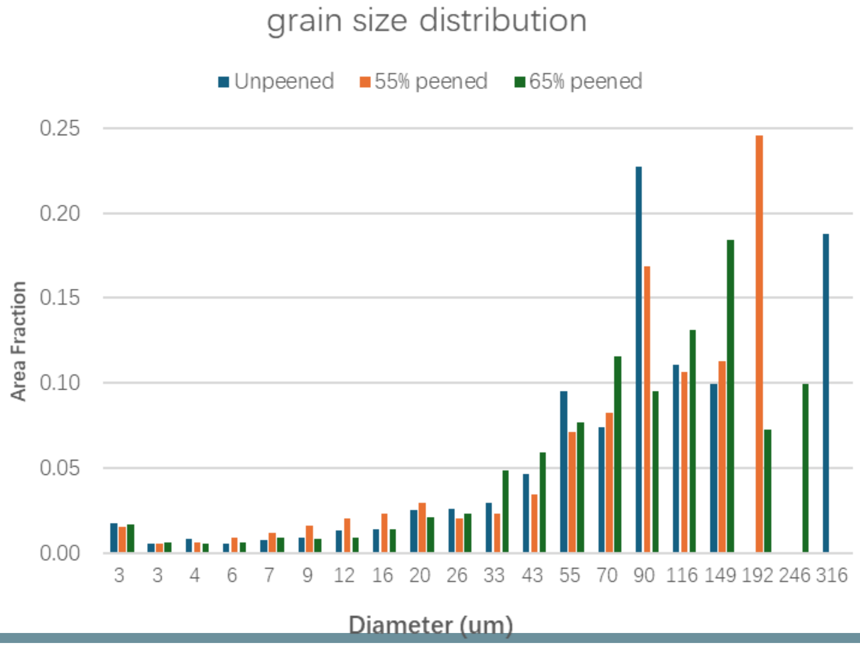
The sensor are embedded between 1.115m-1,18m

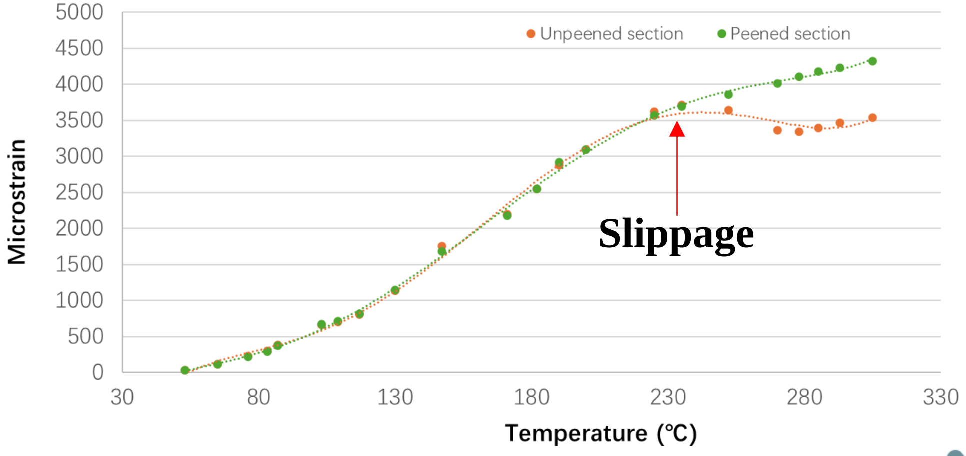


LSP: Improved Thermal Performance









Lessons Learned

- **Many AM techniques can embed fiber sensors in metal parts.**
  - LENS, DMLS, UAM, and Wire arcing.
  - No operational slippage temperature reached 800C.
  - Demonstration of temperature, strain, and vibration sensing.
  - Smart part withstand up to 20 MP pressure and through the pressure boundary.
- **Innovated optical fibers and metal coating can improve performance.**
- **Fiber sensors can NOT withstand post-fabrication heat treatment.**
- Laser shock peening can be a room-temperature alternative to post-fabrication heat treatment.
- *Fiber sensor should be embedded within 10 mm? from the surface.*
- *Multi-step process.*

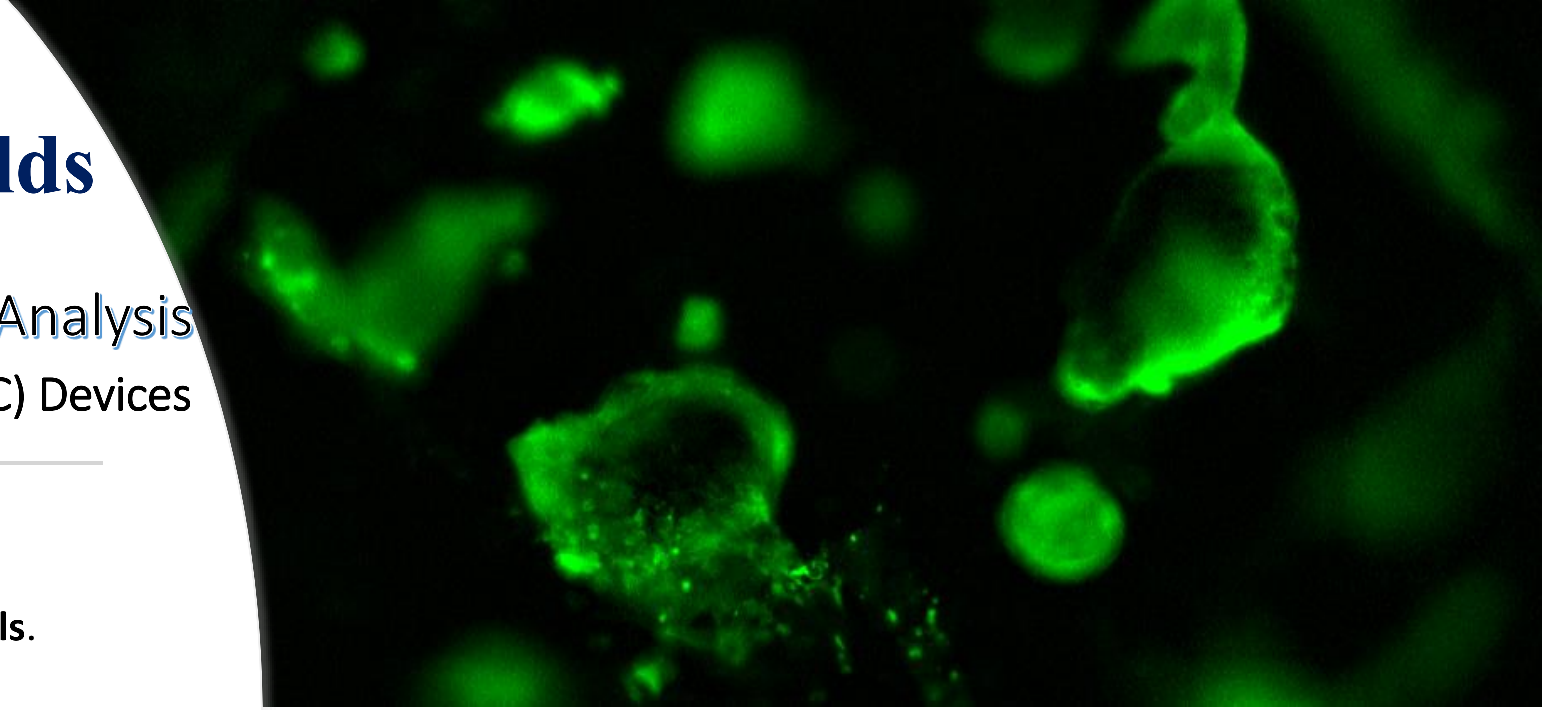
Contribution to Other Fields

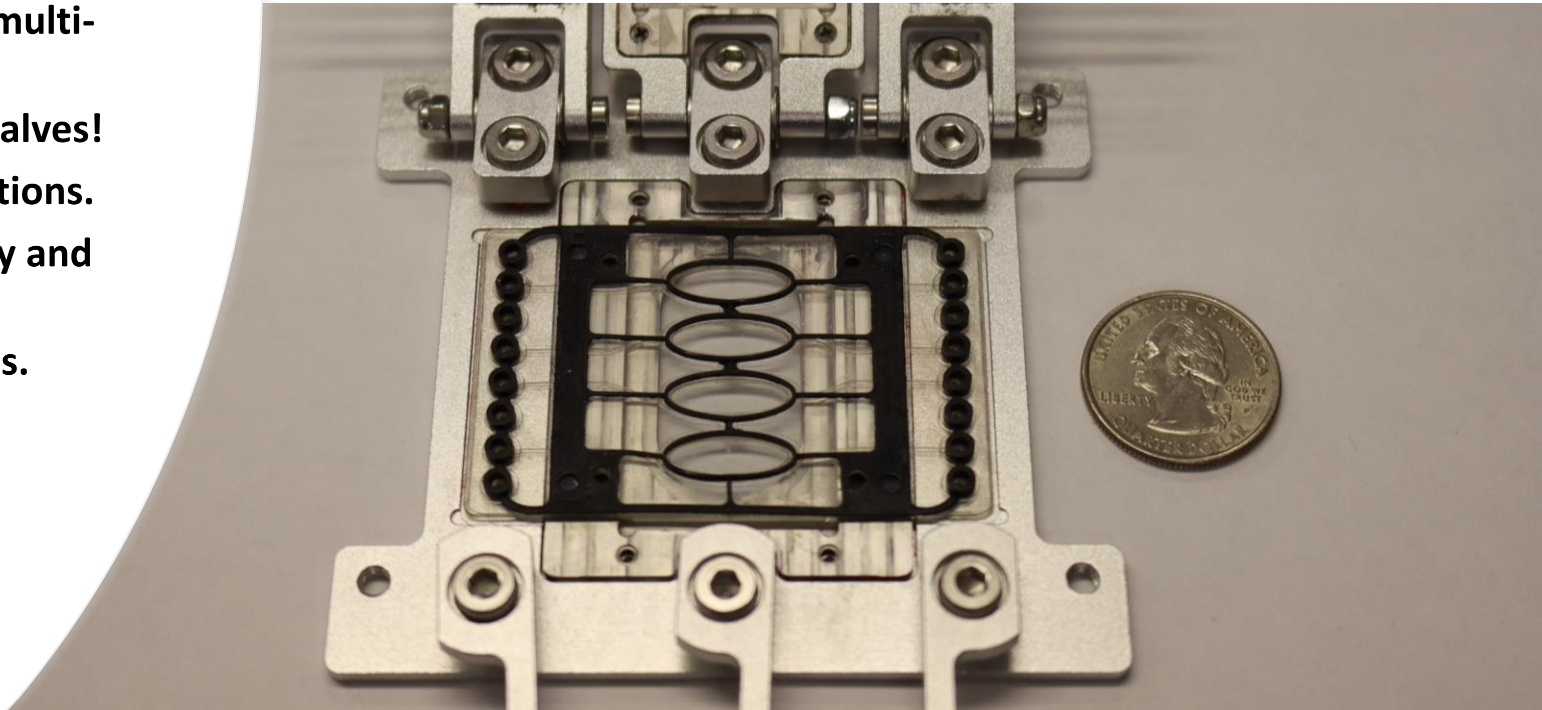
Additive Laser Integrated Systems for Analysis

The World's Most Advanced Organ-on-a-Chip (OC) Devices

Breakthrough innovation

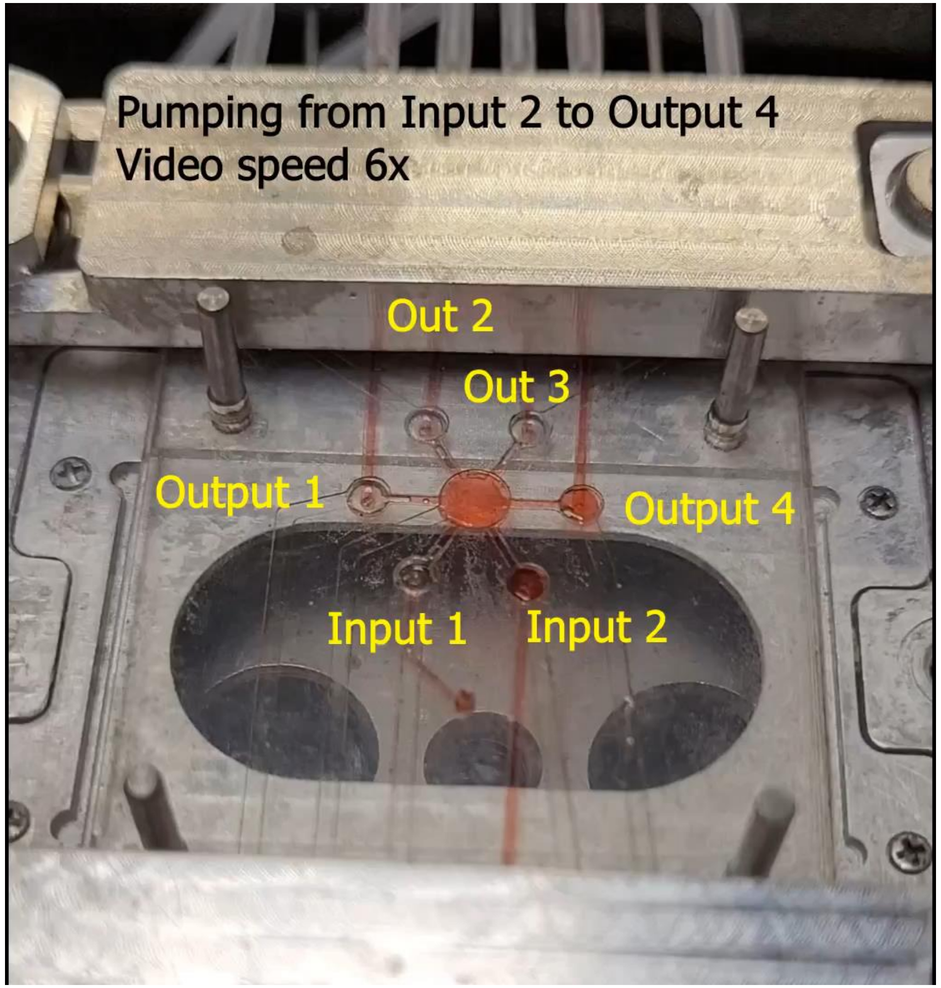
- **Achieve complete flexibility in building materials.**
- **Free from drug molecule contamination.**
- **Nature 3D structures – achieving complex and multi-functional chips.**
- **On-chip flow control integration of pump and valves!**
- **On-chip sensors embedding – rich on-chip functions.**
- **Built-in sealing layer – straightforward assembly and use – minimize bio-contamination.**
- **Eliminate 80% of expensive off-chip instruments.**



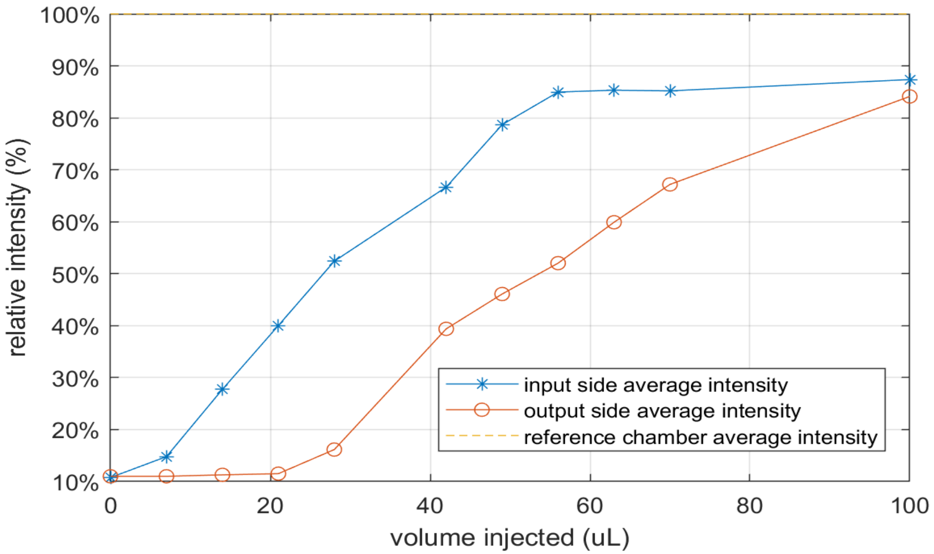


On-Chip Pump and Valves

- On-chip three-way valve and pump for complex liquid routing with no latency!
- Eliminated off-chip instruments.

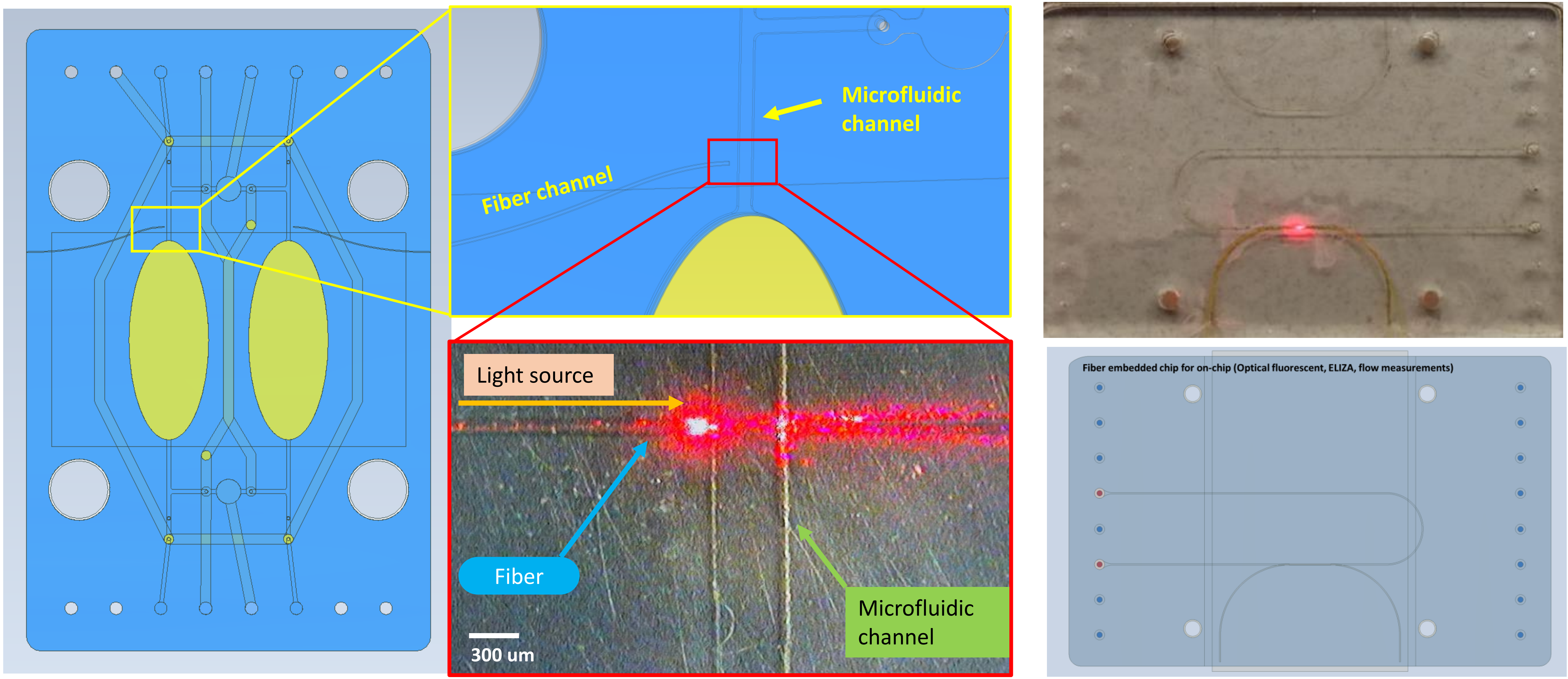


Example: Injection of 20-60 µl drug without bubble using on-chip pump/valve

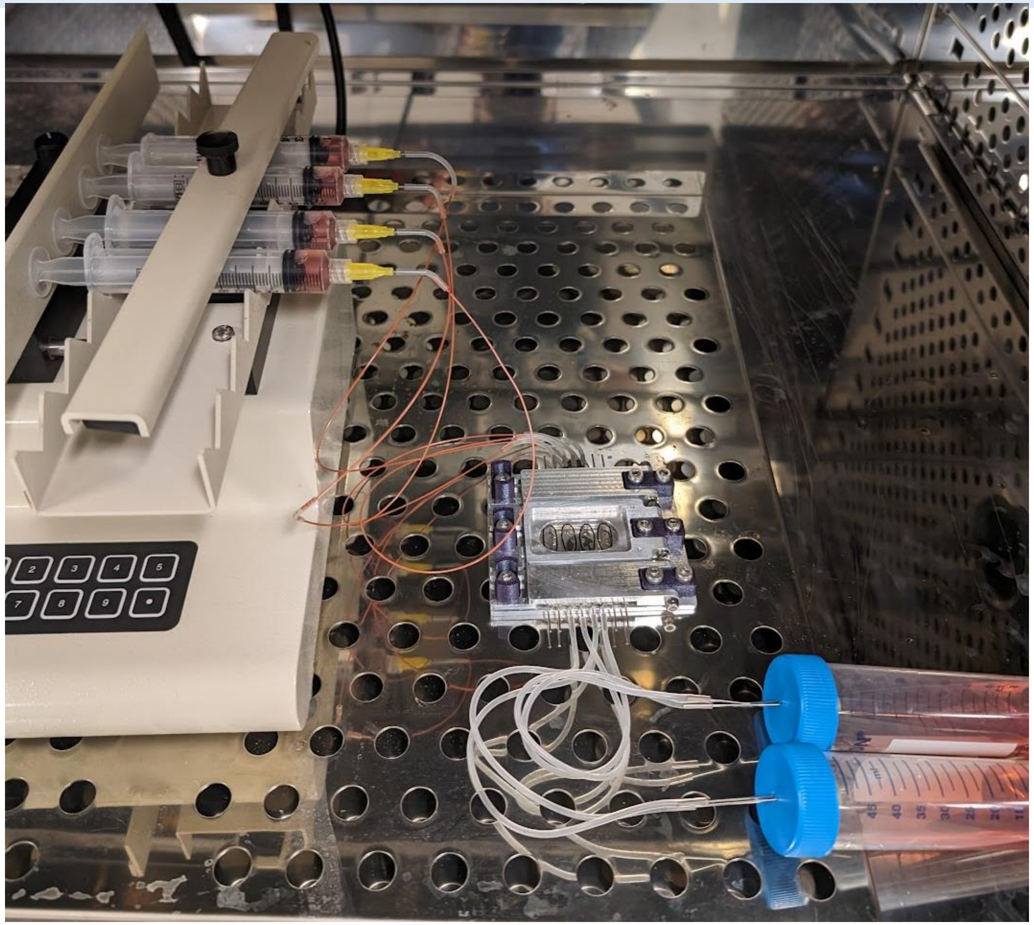


Embedding Sensors on-Chips

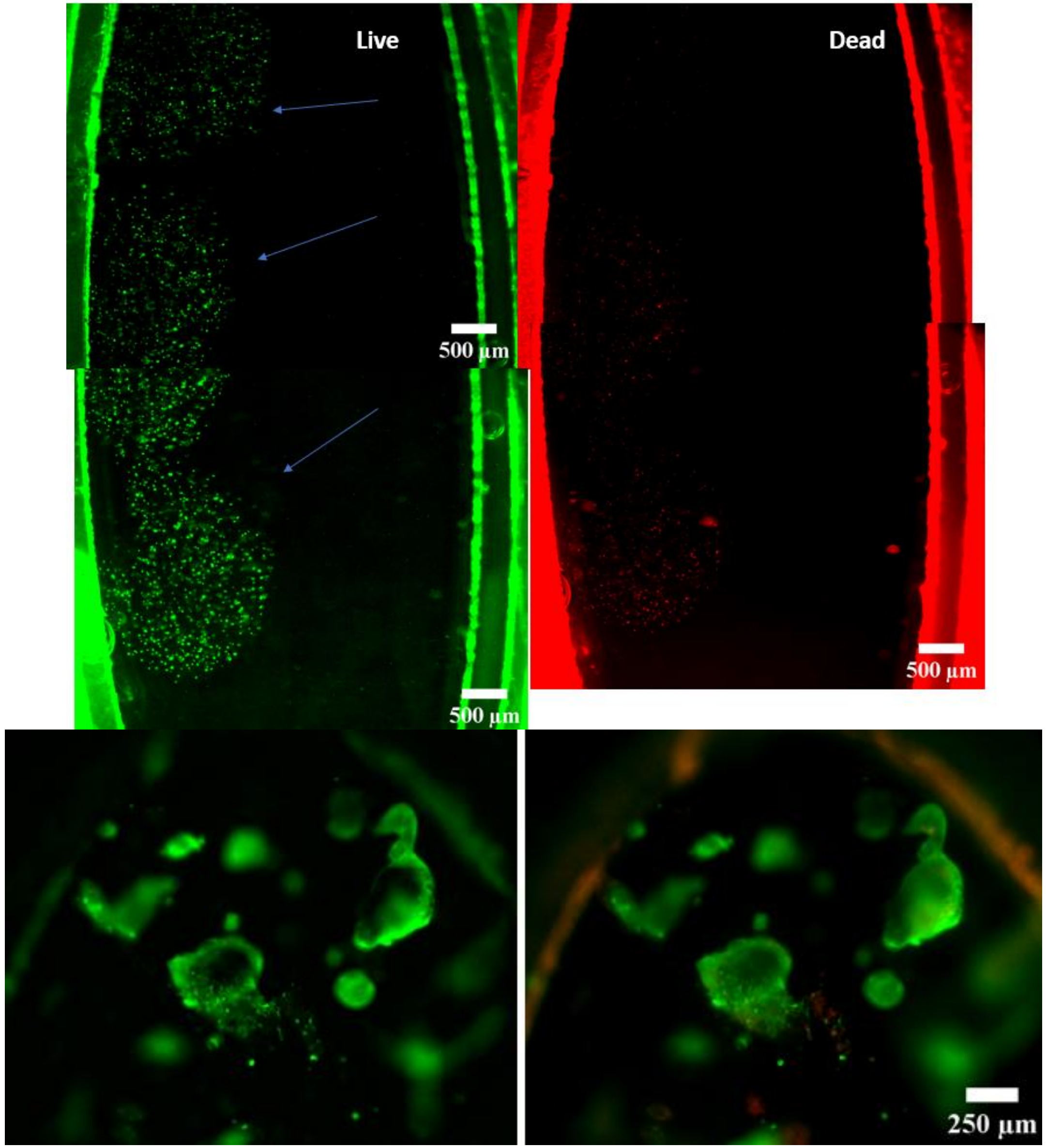
- **Antibody functionalized polymer can be integrated on-chip.**
- **On-chip ELIZA, fluorescent, Raman, and flow measurements.**



Successful Production of Pancreatic Islets using Induced Pluripotential Stem Cell (iPSc)



- Seven-day continuous cultures.
- Achieved 90% viability.
- Successful production and harness of iPSC derived pancreas islets.



Contact Information and Questions

University of Pittsburgh

- PI: Kevin P. Chen (pec9@pitt.edu, Tel. 724-6128935)
- Co-PI: Albert To (albertto@pitt.edu)

Oak Ridge National Lab

- Christian Petrie (petriecm@ornl.gov)

Collaboration Welcome!