AMM
Advanced Methods for Manufacturing

DEC 2 – 3, 2020

Fiber Sensor Fused Additive Manufacturing for Smart Component Fabrication for Nuclear Energy

Award Number: DE-NE0008994
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Team Members: Professor Albert To, University of Pittsburgh
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Project Objectives

- **Development Digital Twin of AM process supported by sensor measurements.**
- **Optimization of AM processing to embed distributed fiber sensors**.
  - Direct Metal Laser Sintering
  - Laser Energized Net Shaping
  - Powder Binding and Sintering process
  - Ultrasonic Process
- **New optical fibers with high TEC for sensor-fused smart components**
  - New materials for NE (Zr, Invar, Inconel, SS)
  - Material properties (high T, corrosion, radiation resilience)
- **Demonstration of multi-parameter measuring in radiation environments**

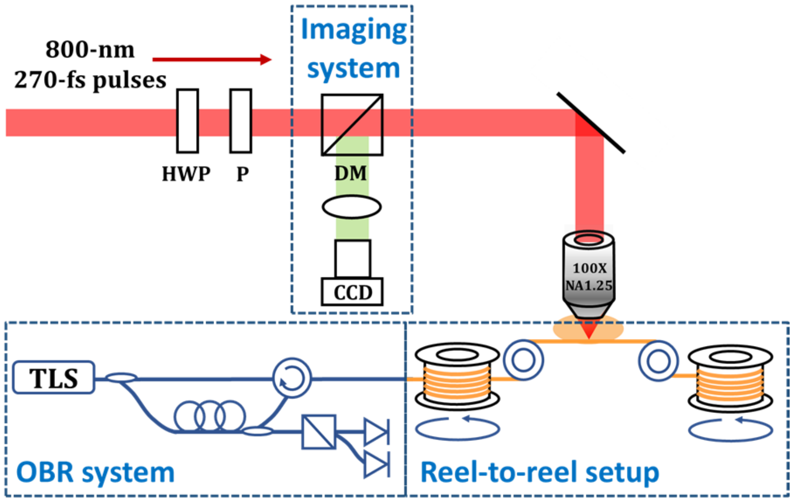
Technical Progress/Accomplishments

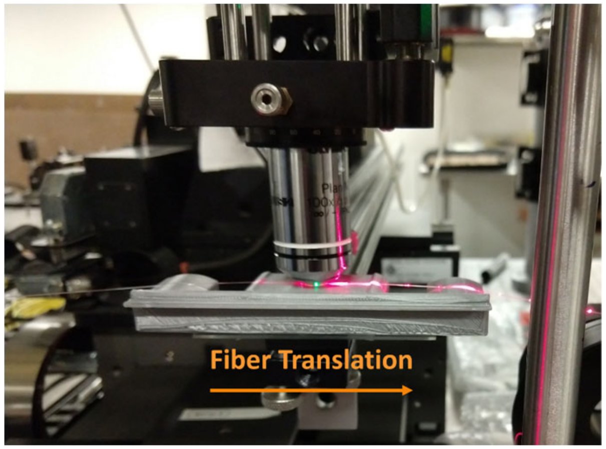
Why is this important?

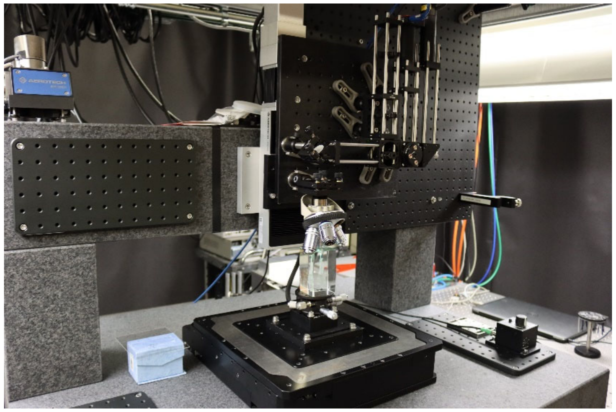
Development of radiation harden distributed and multiplexable sensors for NE

- Femtosecond laser reel-to-reel sensor fabrications
- Interrogation systems readily to be integrated with I&C
- Computationally efficient sensor demodulation algorithm
- High-resolution sensor data enabled artificial intelligence
- Improve overall TRL for fiber sensor for near-future deployment

Fiber Sensor Fabrication





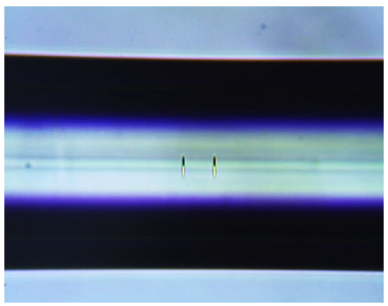


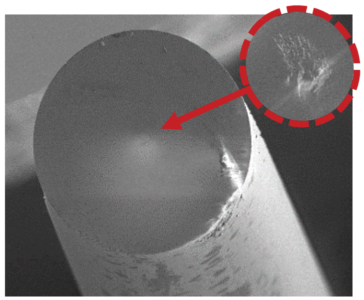
Reel-to-reel oil-immersion fiber writing setup

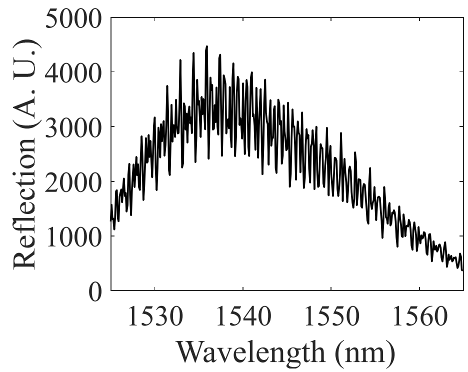
- Fast and continuous fabrication over >tens meters
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Sensors fabrication over 20 m continuously
- Applied to wide array of rad-hard fibers
- Real-time monitoring
- New laser system comes online

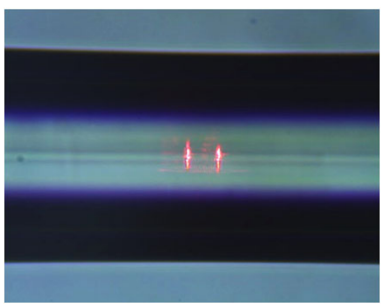
Sensor Fabrications

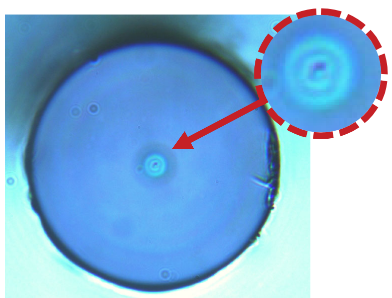
Fs-laser inscription of Type-II Nanograting and IFPI Sensor Array

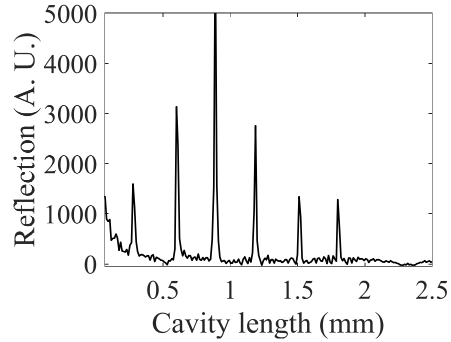




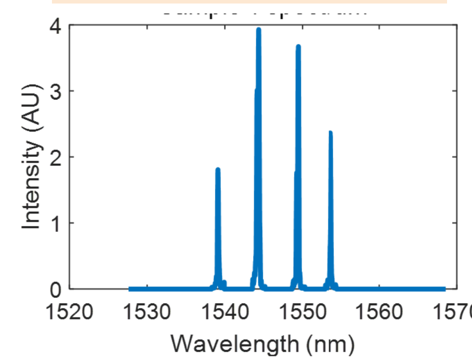




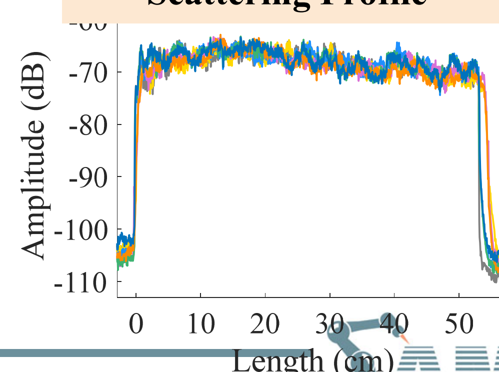




FBG Sensor String

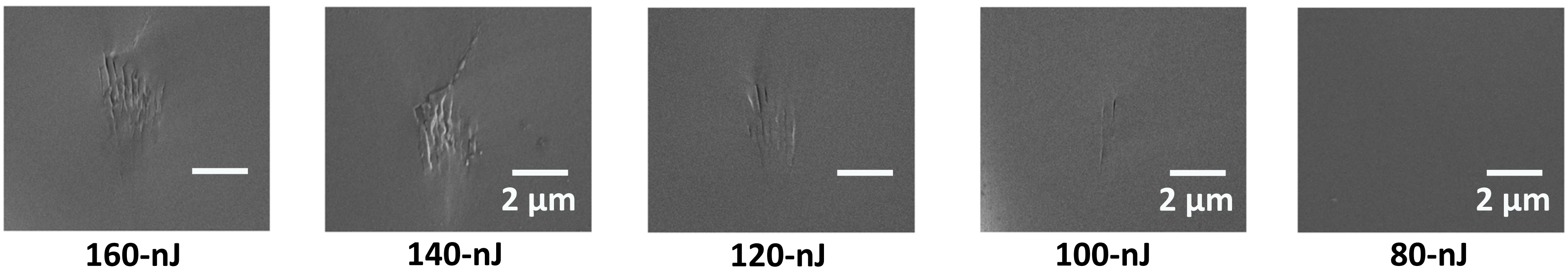


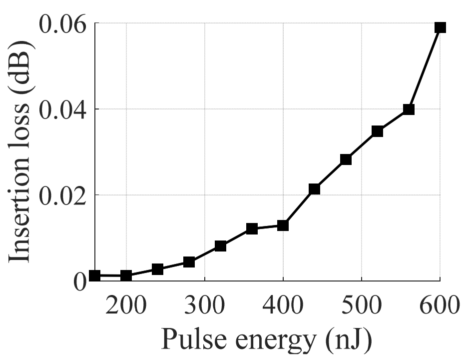
Laser Enhanced Rayleigh Scattering Profile

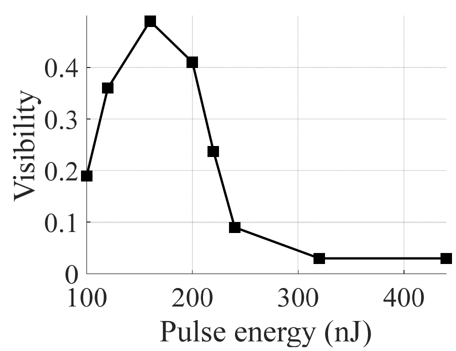


Optimization of Sensor Fabrications: IFPI arrays

Optimization of Laser Processing to Ensure High-T Stability and Low-Loss



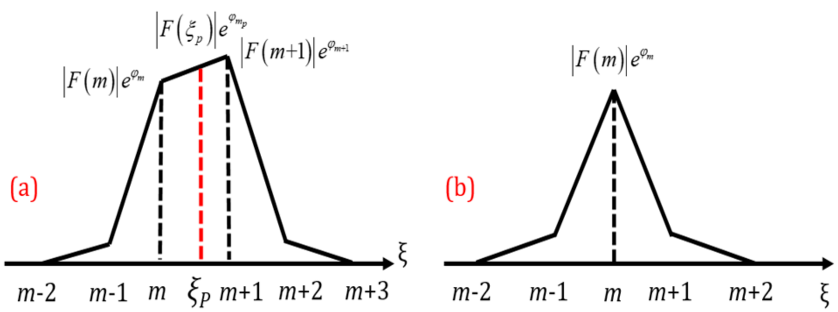




- Nanograting formation threshold at 100 nJ pulse energy
- With the increase of pulse energy, size of nanograting increases
- High visibility of 0.49 at optimized pulse energy of 160 nJ
- Low insertion loss of 0.0024 dB per sensor

Rapid Demodulation Algorithm and Interrogation Systems for NE I&C

Bunman Frequency Estimation

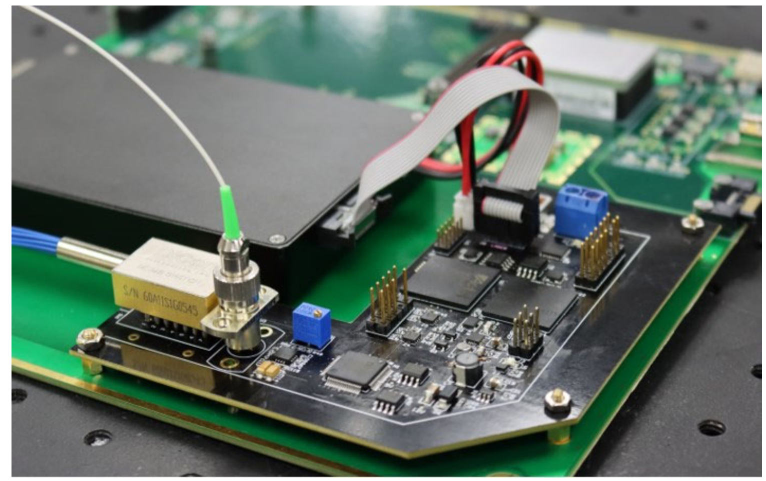


$$F(\xi)=\sum_{n=0}^{N-1}\gamma e^{i(\frac{l\Delta kn}{N}+lk_0+\varphi_0)}e^{-2\pi in\xi/N}$$

$$=\gamma e^{i[lk_0+\varphi_0+\pi(\frac{l\Delta k}{2\pi}-\xi)(\frac{N-1}{N})]}\frac{\sin[\pi(\frac{l\Delta k}{2\pi}-\xi)]}{\sin[\pi(\frac{l\Delta k}{2\pi}-\xi)/N]}$$

$$\varphi\left(\frac{l\Delta k}{2\pi}\right)=\varphi_{\xi p}+2\pi a=\varphi_m+2\pi a$$

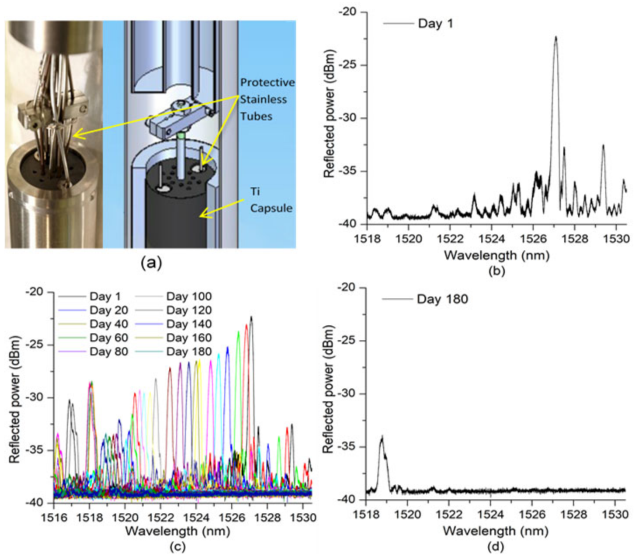
$$\xi_p=\frac{k_1-k_0}{k_0}\left(\varphi_m-\varphi_0+2\pi[a]\right)$$

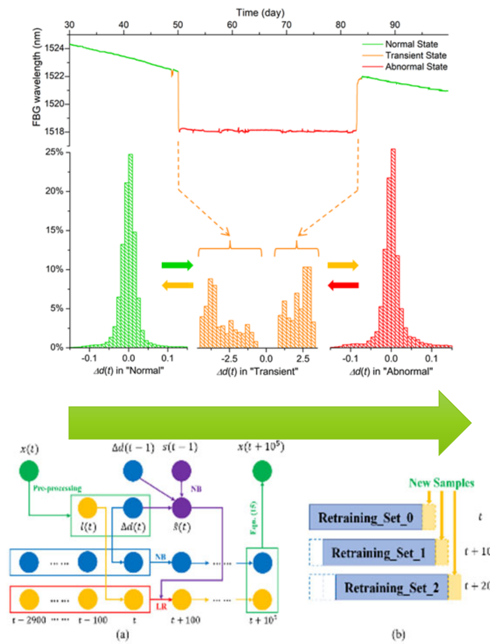


- Phase based demodulation
- Robust algorithm avoid "phase jump"
- Computationally efficient
- Easy implementation into DSP chips
- Dedicate sensor demodulation electronics developed
- Support 2 kHz sampling rates
- 40-nε or 0.01C temperature accuracy.
- Eight channels to support >200 sensor simultaneously

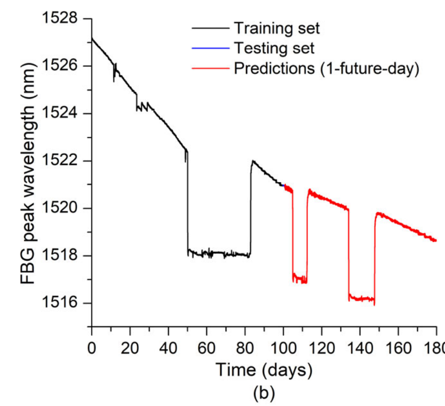
Sensor Data Enabled Artificial Intelligence

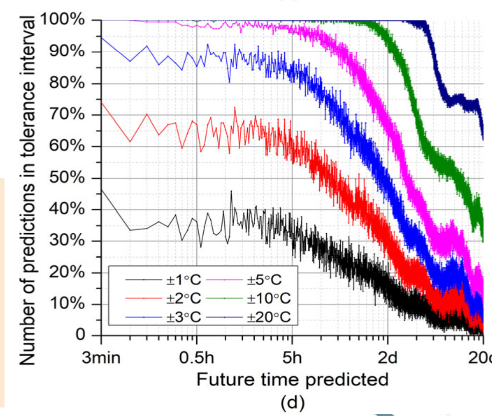
FBG Sensor In-Pile Testing





Bayesian Learner Prediction

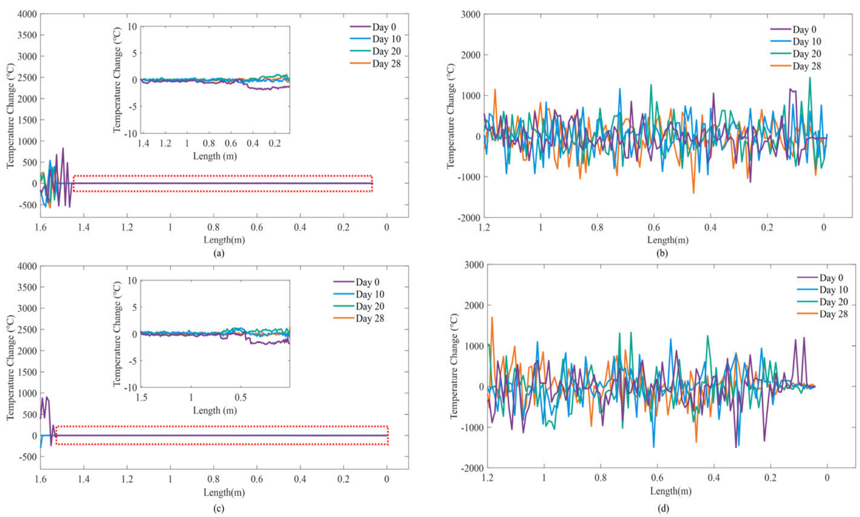




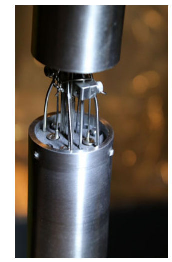
- **Machine learning mitigation of sensor drifts**
- **Bayesian learner for reactor anomaly event detection**
- **98.3% of sensor drift can be eliminated through ML**
- **Anomaly event detected if event-induced 3°C temperature variation can be detected.**
- **"Bad Sensor" is better than No Sensor!**

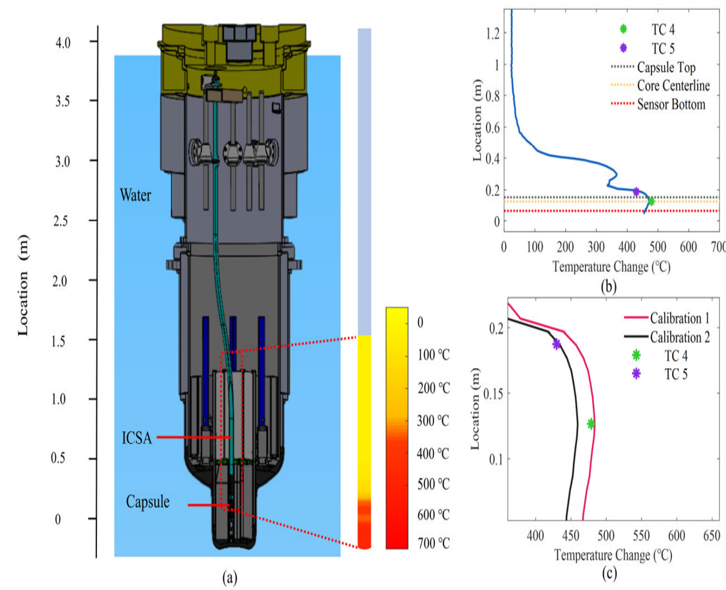
First High Spatial Resolution Temperature Profile Measurements of a Reactor Core

Laser Enhanced Fibers | **Pristine Fiber**



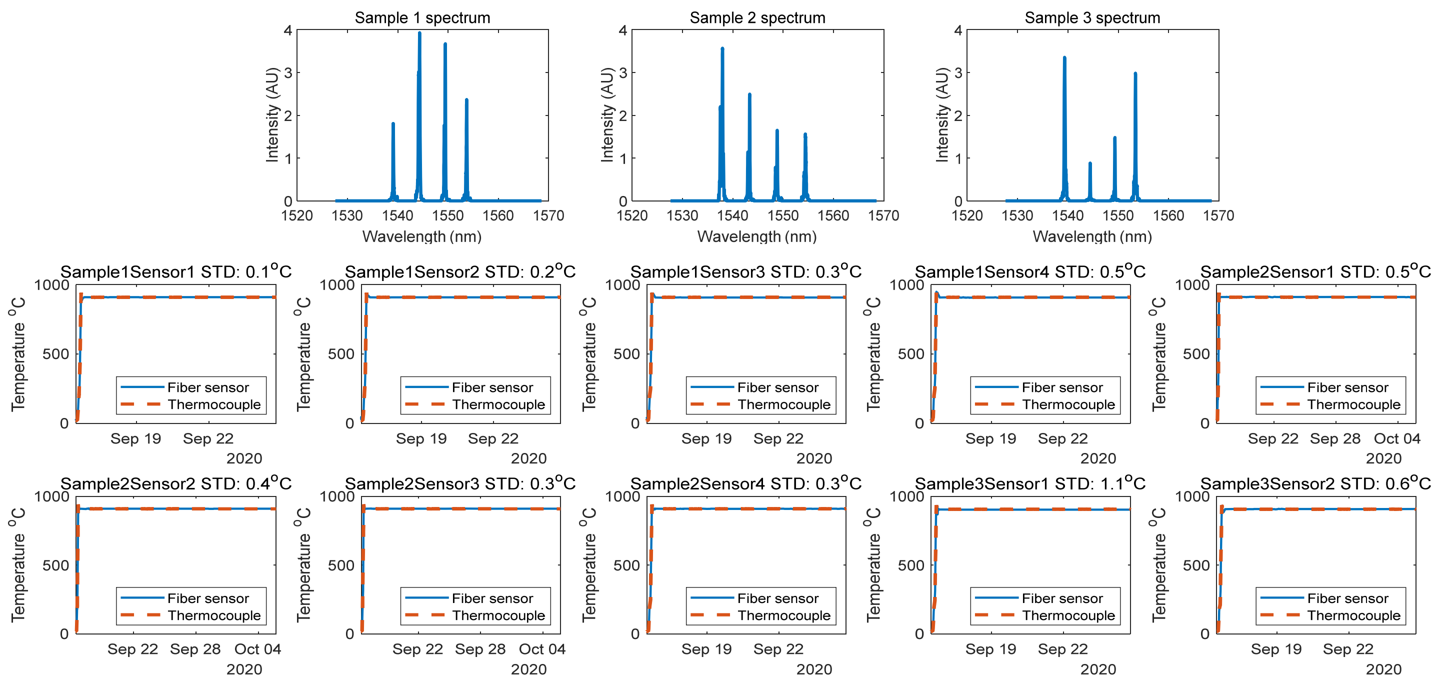
- **In-pile measurements at (560°C, 1.4×10^{14} f n/s/cm^2)**
- **1.6-m core profile, 3-cm resolution, 1-s update rate.**
- **Femtosecond laser fabrication critical**
- **High resolution data useful for VR and Digital Twin**





Improving TRL for Reactor Deployments

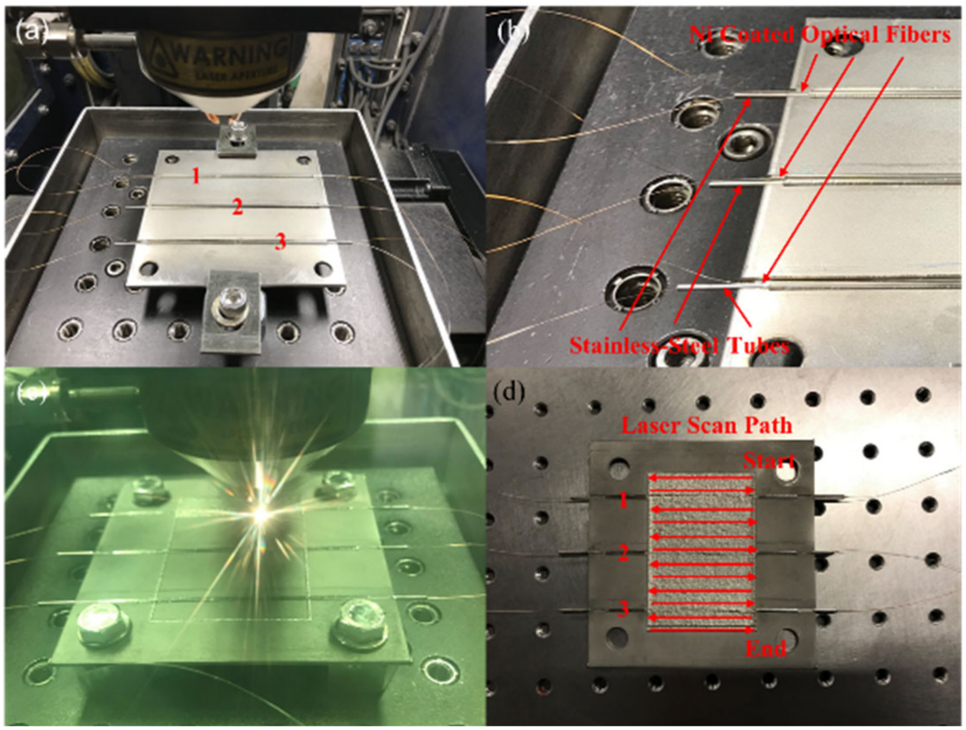
- **Comprehensive FBG sensor array high-T testing (900°C-1000°C)**
- **Interrogation electronics and algorithm used for demodulation**
- **Average STD <0.6°C over 10 days spans at 900°C (comparing with TC)**
- **Further increase sensor counts (200) and testing duration (2 months) in 2021.**



Challenge: How to embed these sensors into NE Systems?

- Additive manufacturing: make sensor part of smart component design and fabrications from get-go!
- Can sensors survive extreme AM process?
- What is the best AM fabrication strategy?
- Can sensor be embedded in components with complex shape?
- Can we ensure quality of sensor-fused smart components (corrosion, high-T durability, radiation-resilience…)?
- What kind of measurement functions can we achieve, what are benefits?

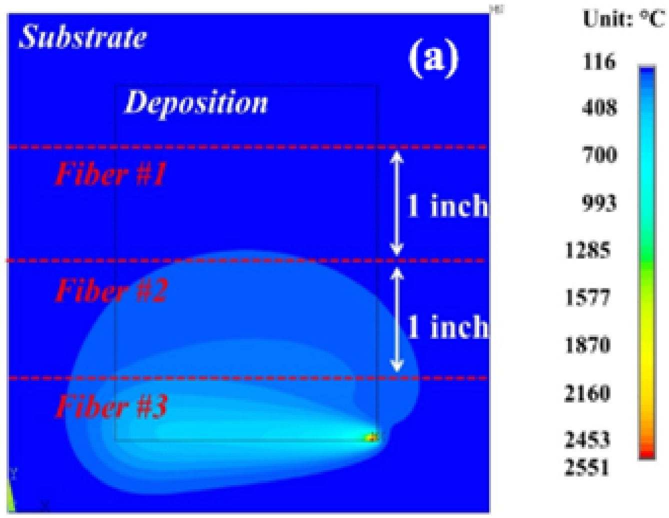
Sensor-Fused AM Process

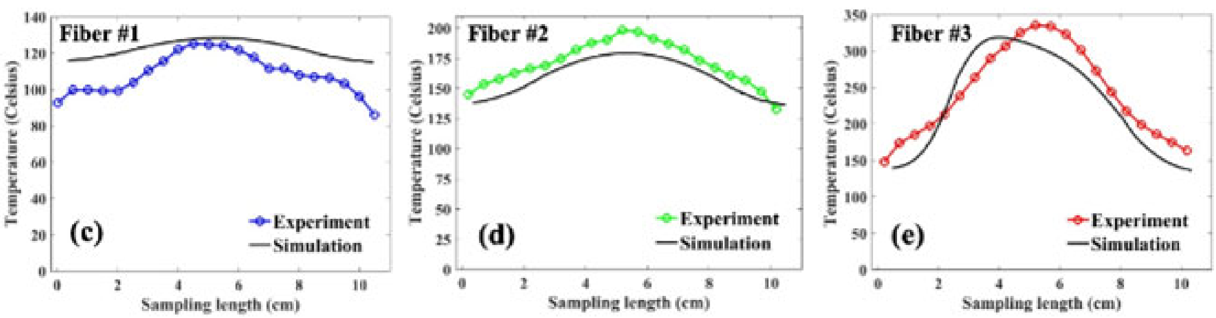


Sensor Fused AM Process

- 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 Modeling vs. Measurement





$$\rho C_p \frac{dT(\boldsymbol{r},t)}{dt} = -\nabla \cdot \boldsymbol{q}(\boldsymbol{r},t) + Q(\boldsymbol{r},t), \boldsymbol{r} \in \boldsymbol{V}$$

Dirichlet boundary conditions

$$T = \bar{T}, \qquad \boldsymbol{r} \in S_D^T$$

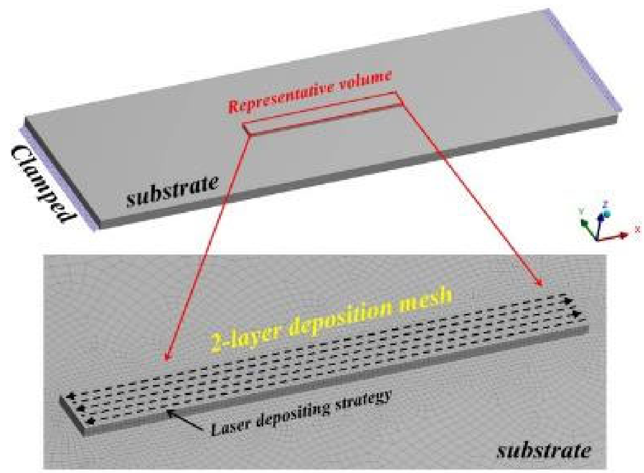
Neumann boundary conditions:

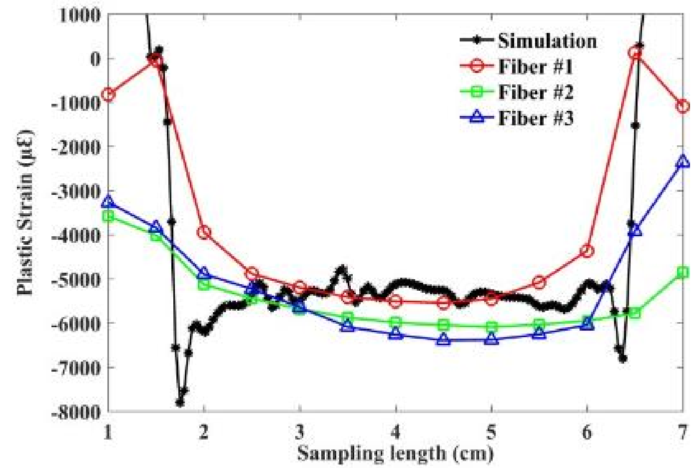
$$-k\nabla T \cdot \boldsymbol{n} = \overline{q}, \boldsymbol{r} \in S_N^T$$

Robin boundary conditions:

$$-k\nabla T \cdot \boldsymbol{n} = h(T - T_a), \boldsymbol{r} \in S_R^T$$

Strain Modeling vs. Measurements





- Two-layer deposition (red box) as the representative volume of the large deposition area (upper).
- Laser scanning strategy in the laser fusion process (lower) Modelled.

- Measurements performed at 4-mm spatial resolution.
- Simulation consistent with modeling, provide confidence for model-based optimization.

Project Impacts

- Patents

1. (Pending) Kevin Peng Chen, Zsolt Poole, Michael Buric, and Kirk Gerdes, Thomas Brown, P. R. Ohodnicki "**System and method for monitoring a reactor system using optical fiber-based sensors**," US Patent Pending 15/501,443 (2020).
2. (To be awarded) Kevin Peng Chen, Mohamed A. Bayoumy, Aidong Yan, Rongzhang Chen, "**Optical fiber-based sensing for smart electrical cable and distributed radiation detection**," US Patent to be awarded in (2020).
3. Kevin Peng Chen, Albert To, and Shuo Li, "**Laser Systems enabled by additive manufacturing**," US Patent 10,811,835 (2020).
4. Kevin Peng Chen, Aidong Yan, Michael Buric, and Paul Ohodnicki, "**Method of making a distributed optical fiber sensor having enhanced Rayleigh scattering and enhanced temperature stability and monitoring systems employing same**," US Patent 10,670,802 (2020).

- Involvement
  - Engage with both national labs and industry to explore commercialization pathway.

Milestones and Deliverables for FY-20

- Development of simulation framework and code to perform temperature and stress profile for both sensor fused LENS and DMLS AM processes.
- Development of comprehensive sensing scheme to monitor AM process
  - Embedded fiber sensors
  - Optical monitoring
- Develop new sensor fabrication technique using femtosecond laser
  - Establish reel-to-reel continuous fabrication
  - Validate sensor performance based on radiation-harden fibers

Issues and Concerns

- COVID-19 Limits Lab Access and Travel
- No yet to receive account number from the University (due to COVID?)

Milestones and Deliverables for FY-21

- Development of simulation framework and code to perform temperature and stress profile for both sensor fused LENS and DMLS AM processes.

- Develop new specialty optical fibers and innovative fiber metal coating
  - Collaboration with Corning to develop germanosilica based fiber (both core and cladding to achieve TEC 5ppm, silica fiber TEC 0.5ppm)
  - New metal/ceramic coating scheme (heat laser pedestral approach, cold spray, plating)
  - Embedding in relevant metal materials
    - Inconel
    - Zr
    - Invar

Possible Areas/Industries/Programs (and Readiness) for Adoption

Turn-key solutions of fiber sensor being developed that is affordable and customizable for NE.

- Sensor TRL-6 and going up
- Sensor embedding process: TRL-2 aiming to TRL-6 (*Thank you for this NEET project!*)

- **Idaho National Lab: SMR and micro-reactors**
- **ORNL**
- **Industry**

Cross-cutting nature!

- Solid Oxide Fuel Cell
- Natural gas pipelines
- Naval applications

Contact Information and Questions

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Collaboration Welcome!