Proliferation of Fiber Sensor Technology through Cost Reduction, Packaging, and Data Analytics

Students and PDFs of Kevin P. Chen's Group

Department of Electrical and Computer Engineering,
University of Pittsburgh

Email: pec9@pitt.edu

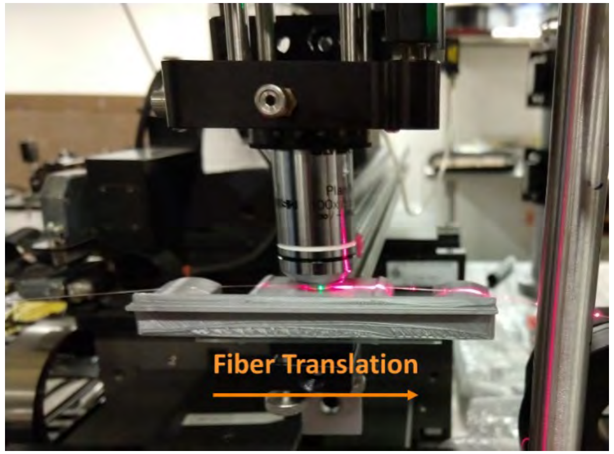
In collaboration with:

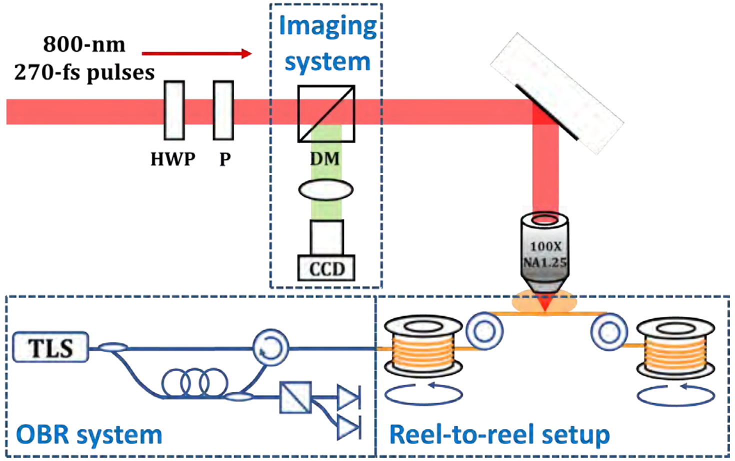
- INL
- NETL
- ORNL
- Corning Inc
- LUNA Innovation
- MITR
- Many

Fiber Sensors as ubiquitous sensor technology

- **Reduce cost of sensing fibers – Sensor Fabrications**
  - Fully exploit telecom fibers.
  - ~~Draw-tower approach~~
- **Reduce cost of sensor interrogators**
  - Fully exploit telecom gear and autonomous driving technology
  - Aided by low-cost sensing fibers
- **Develop ready-to-use packaging solutions for 10K to 1000K applications**
- **Explore new applications beyond oil/gas: Nuclear Energy (Distributed Sensors)**

Through Coating Writing Using –fs Lasers

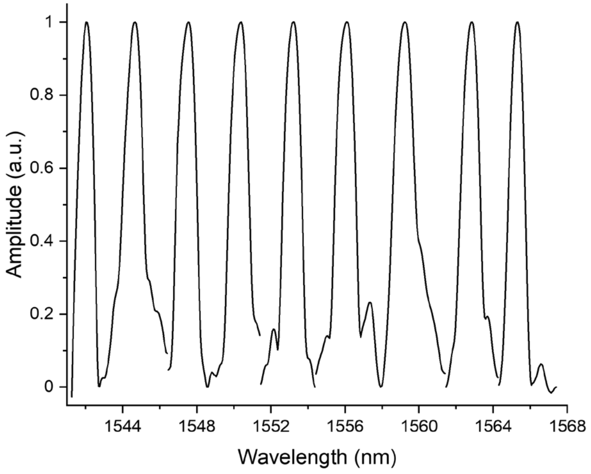




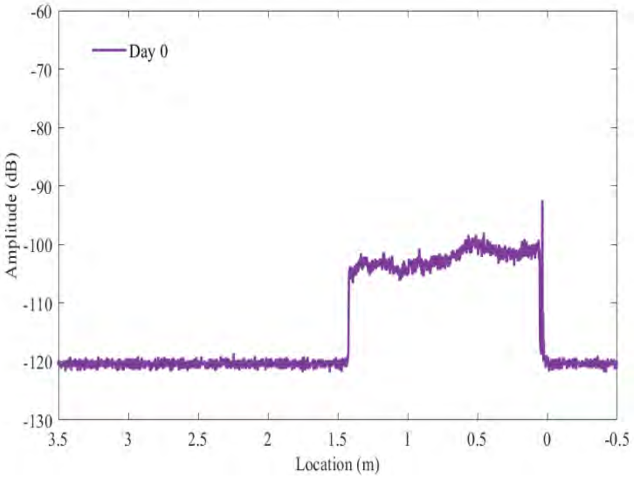
Reel-to-reel oil-immersion fiber writing setup

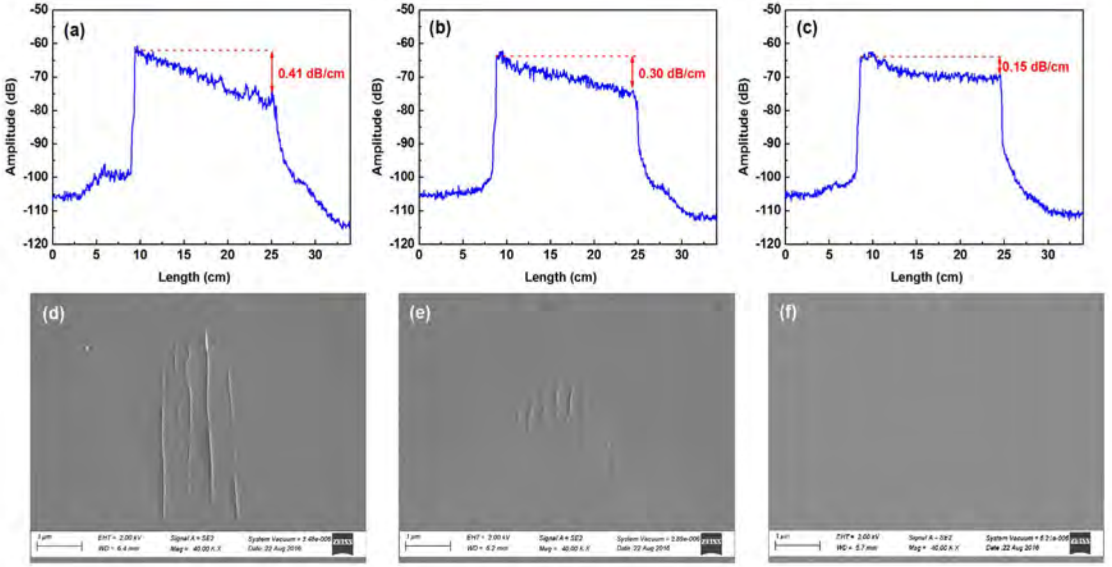
- Fast and continuous fabrication up to 1km fibers
- Point-by-point writing (not phase mask!): flexible
- High-T stable distributed sensors & point sensor array
- Applicable for wide array of optical fibers
- High-T stable tested at 900C
- Sapphire and silica

Type II: FBG Array



Laser-Enhanced Rayleigh Profile

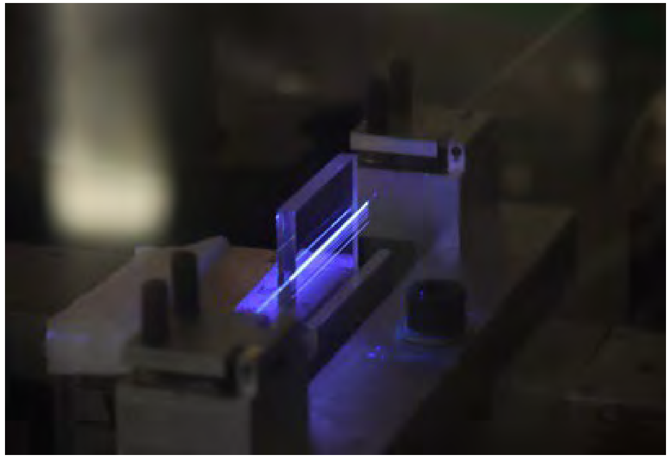




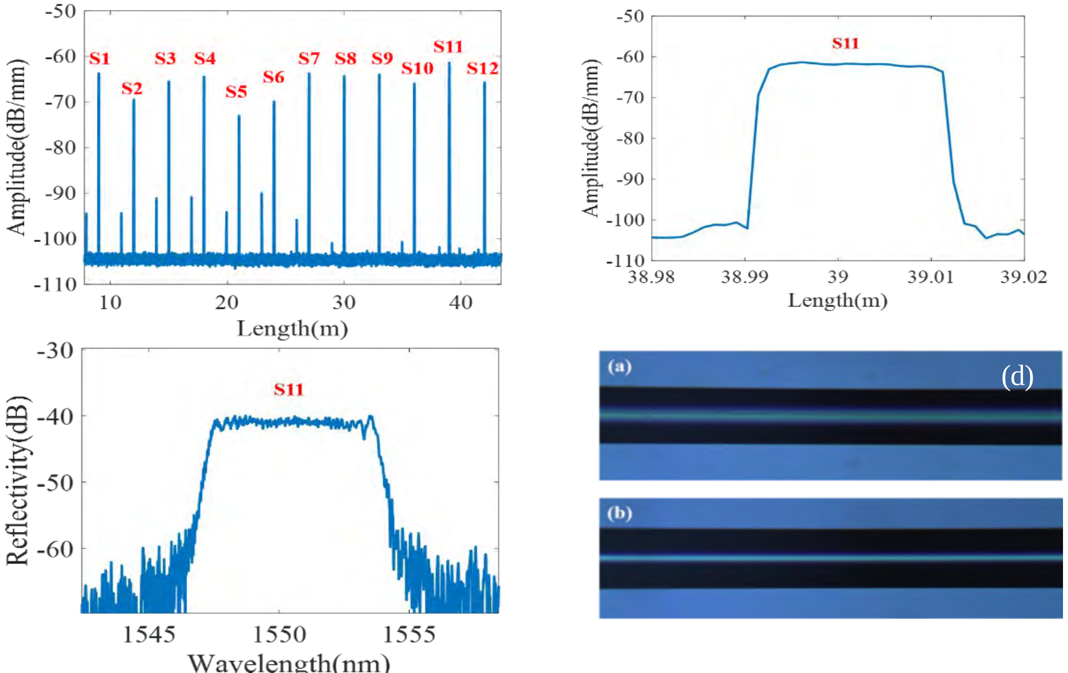
UV Laser Direct Sensing Fiber Fabrication in SMF-28

- Standard telecom fiber – through coating
- One-shot UV phase mask writing
- 10-km continuous sensing fiber fabrication possible
- Draw-tower free
- Sensing fiber cost ~$0.1-$1.0 per meter (competition: $10-30/m)

Phase Mask One-Shot Fabrications



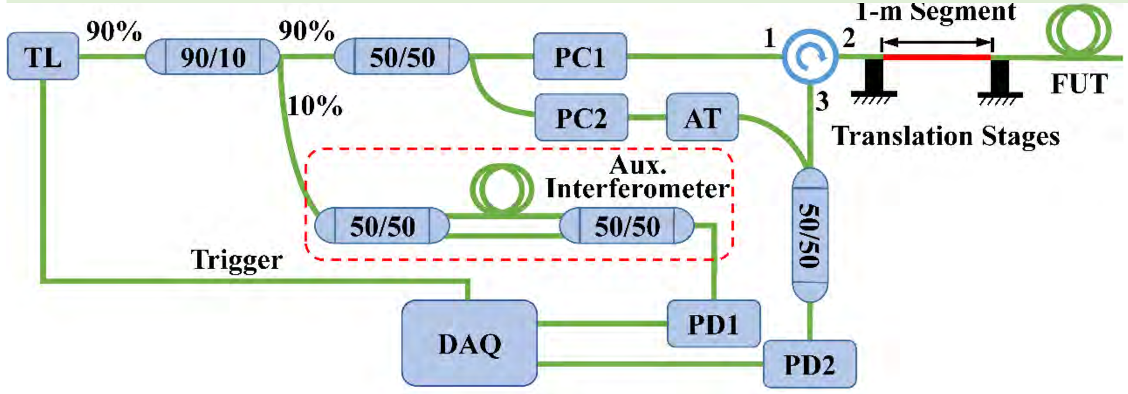
Sensing Fiber for φ-OTDR Distributed Acoustic Sensing



Reel-to-Reel Fabrications

Sensing Fiber Enabled Low-Cost or "Coarse" OFDR

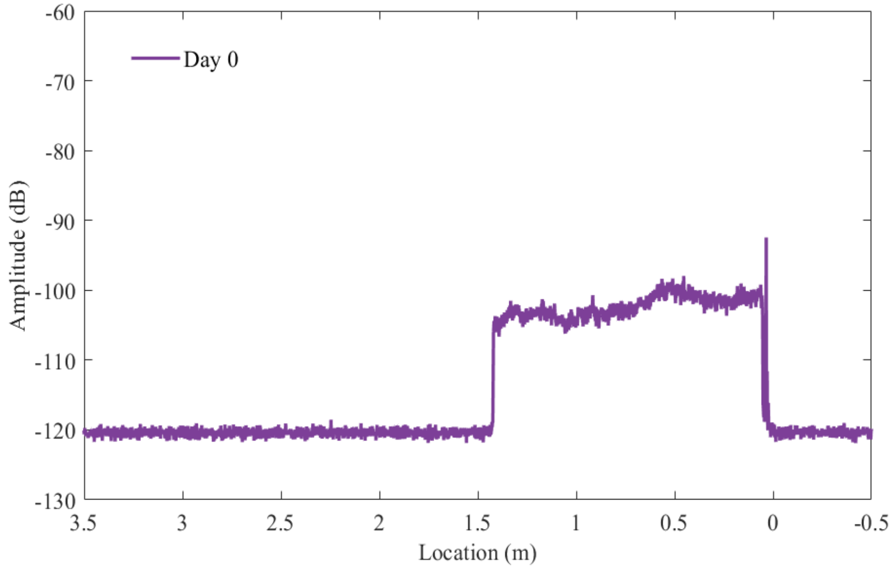
- Reduce cost of the interrogation lasers – telecom DFB
- Laser wavelength: 100 kHz – interrogation length ~ 400 m (actual ~100 m)
- Δλ tuning: 1-nm 2-point resolution drops by 80 times (but sensing backscattering signal increase by 30 dB)
- No need sensitive detectors (low-cost)
- No need high DAQ sampling rate (low-cost)



Two-point resolution $\Delta z = \frac{L}{N} = \frac{c}{2n\Delta F}$

Gauge Length resolution $R = W\Delta z = W\frac{c}{2n\Delta F}$

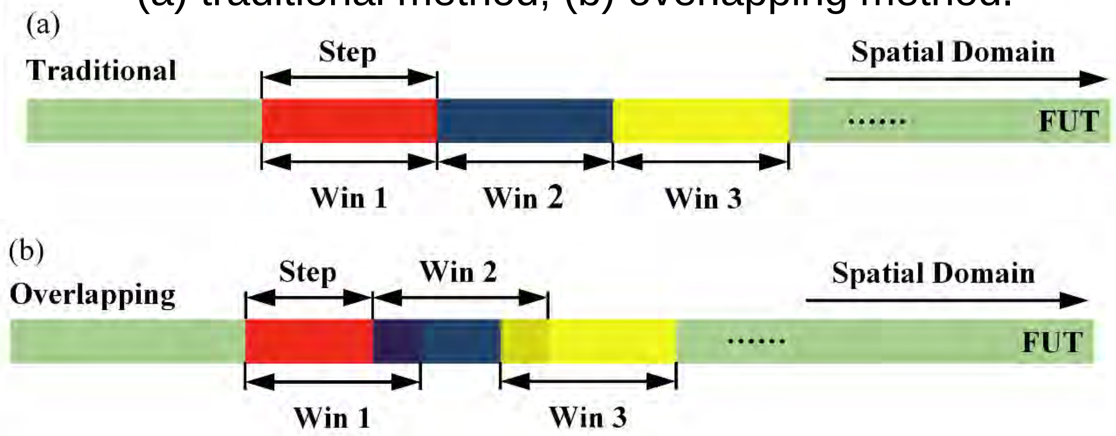
Parameter	Our Laser Source	Commercial OFDR
Wavelength sweep range	1 nm (telecom DFB)	80 nm
Laser linewidth (coherence length)	100 kHz (~800 meter)	~1 kHz (>10 km)
Two-point resolution	0.8 mm	10-µm
Gauge length	24 mm	5-mm



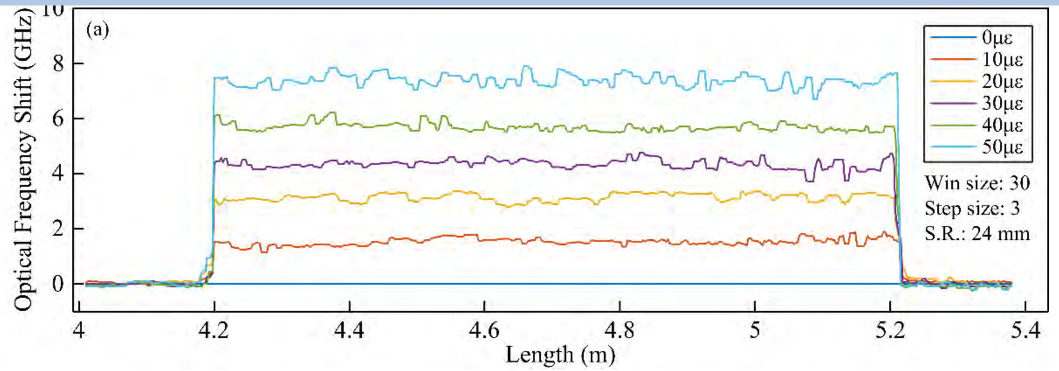
Sensing Fiber Enabled Low-Cost or “Coarse” OFDR

- Implementing denoise algorithm
- Polarization diversity reduce interrogation length from 400-m to ~100 m
- Spatial resolution 2.5-cm is achievable (Strain resolution: 1-με, Temperature: 1C)
- Mode-hopping only cause small additional errors (can be averaged out)

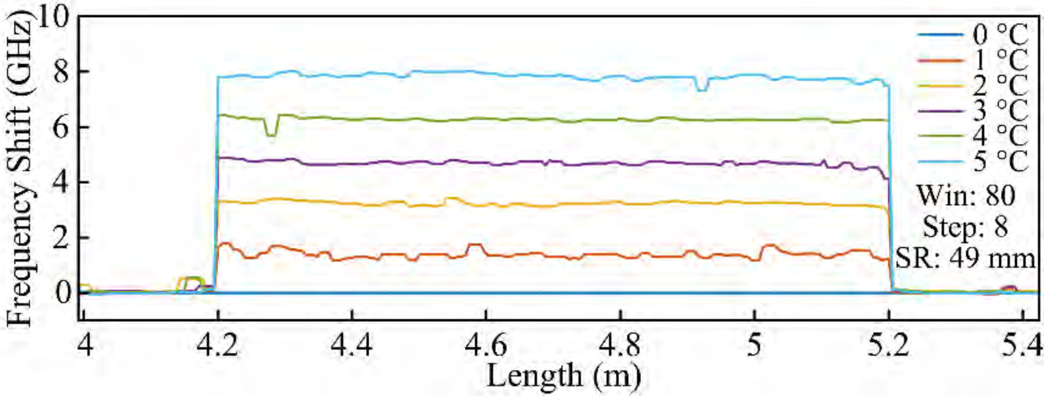
(a) traditional method; (b) overlapping method.



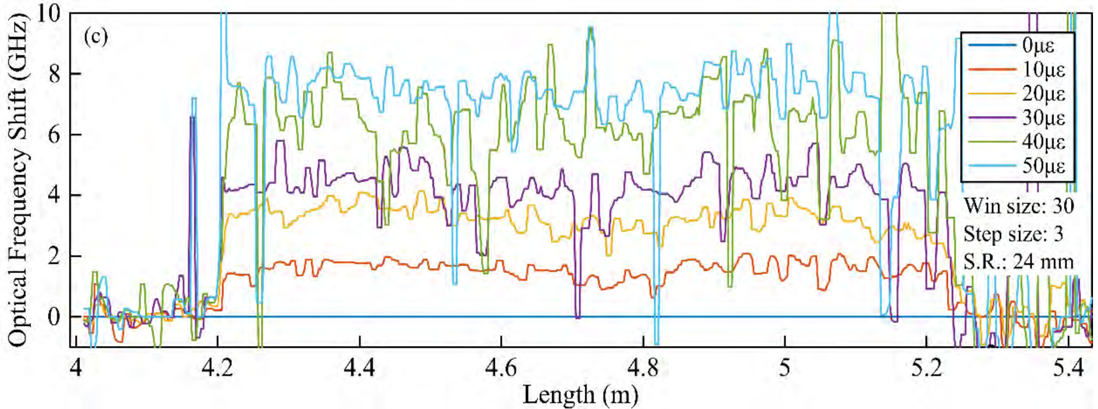
Strain: Rayleigh Enhanced Fibers



Temperature: Rayleigh Enhanced Fiber

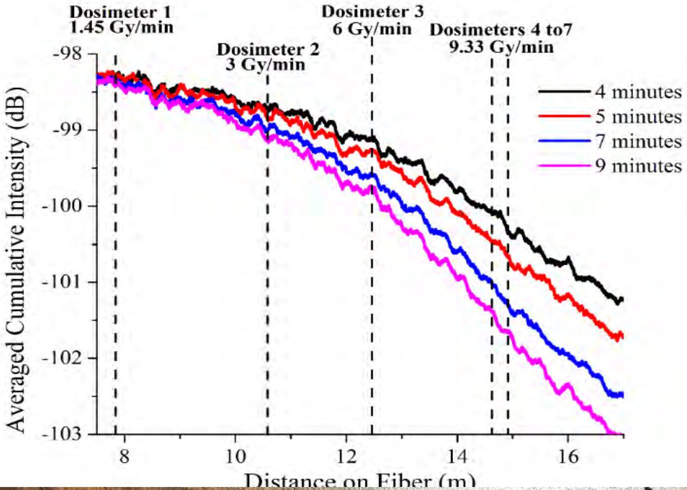


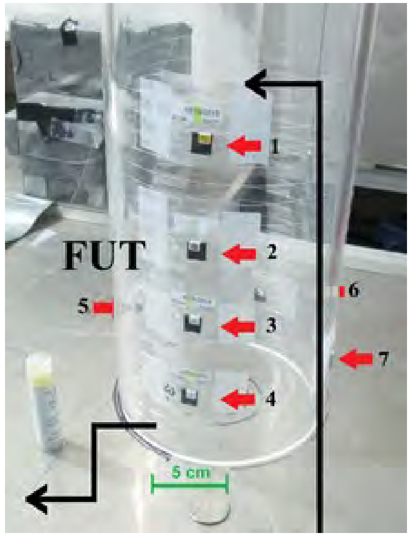
Strain: Pristine Fibers

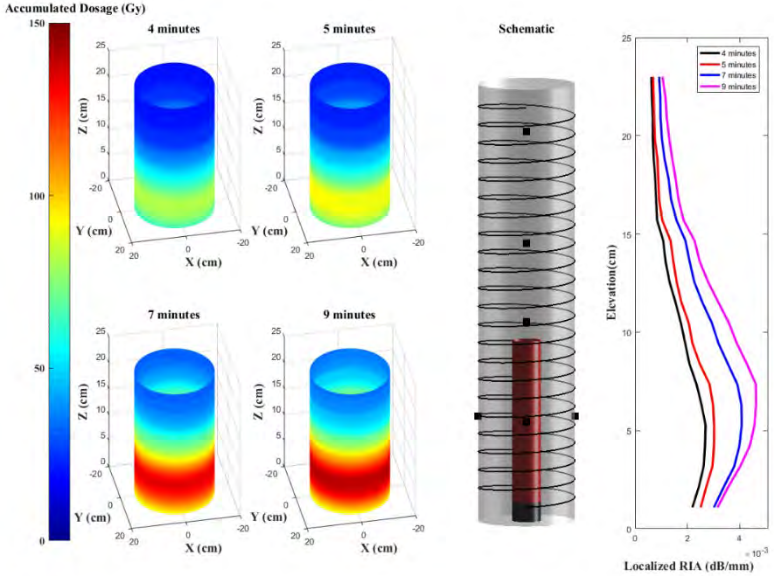


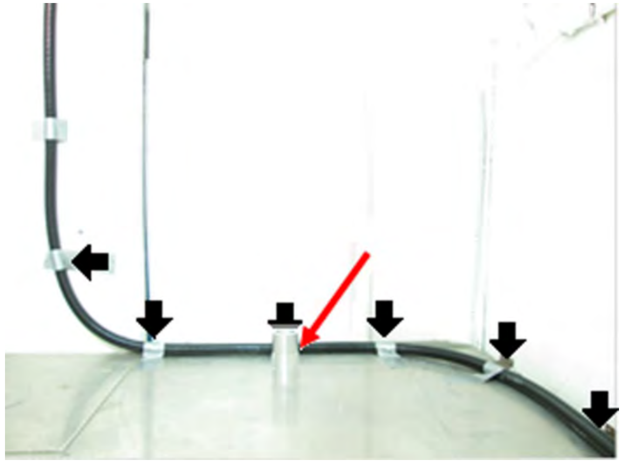
Potential Application: Coarse-OFDR for Distributed Radiation Sensing

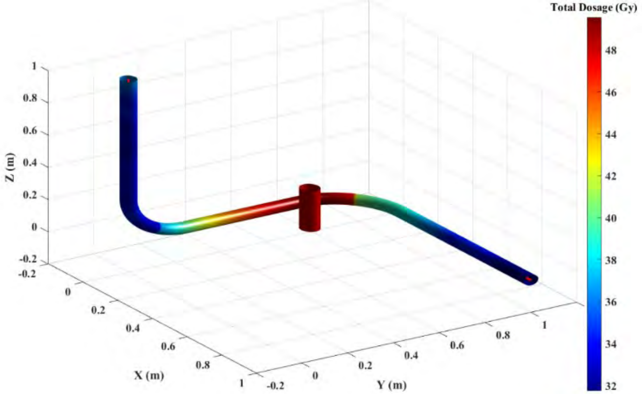
- Distributed Loss Measurements: RIA
- Spatial resolution: 2-cm
- Corning aluminum-doped Fiber



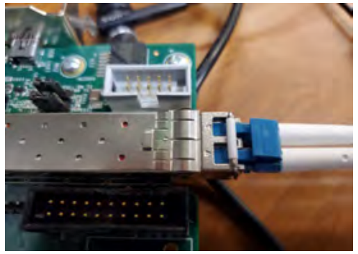






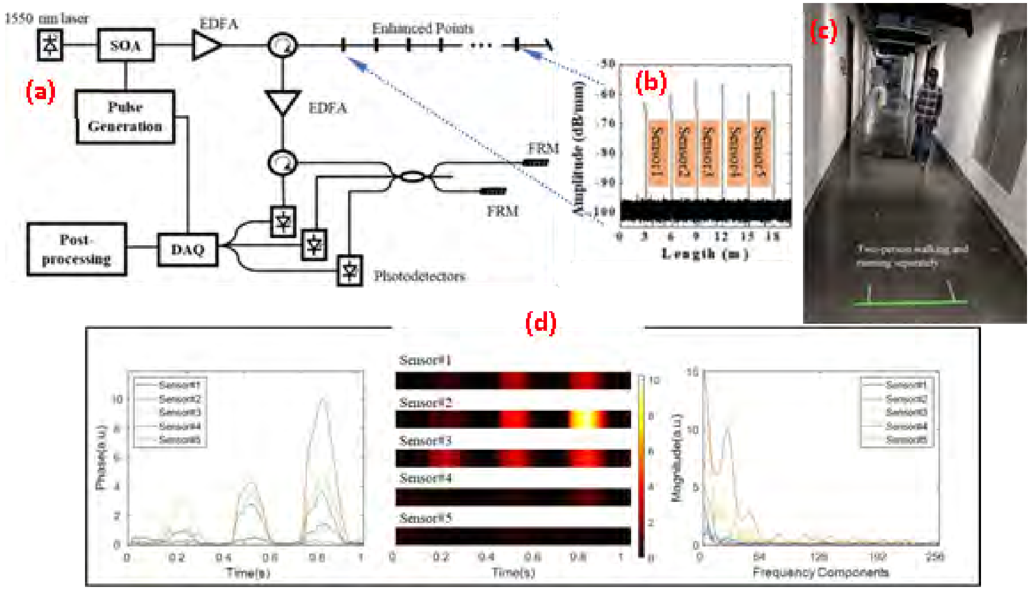


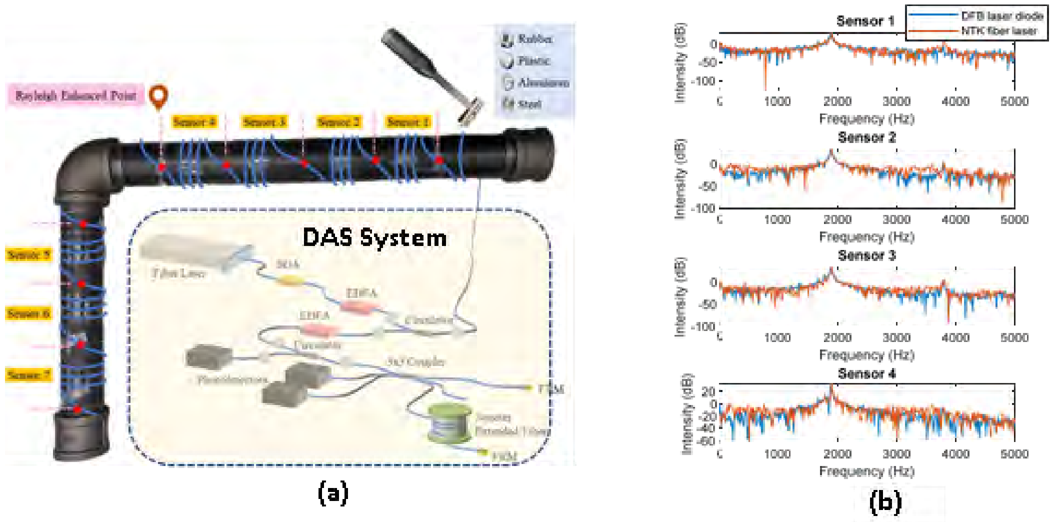
Low-Cost DAS: Distributed Fiber Sensors - 10× cost Reduction



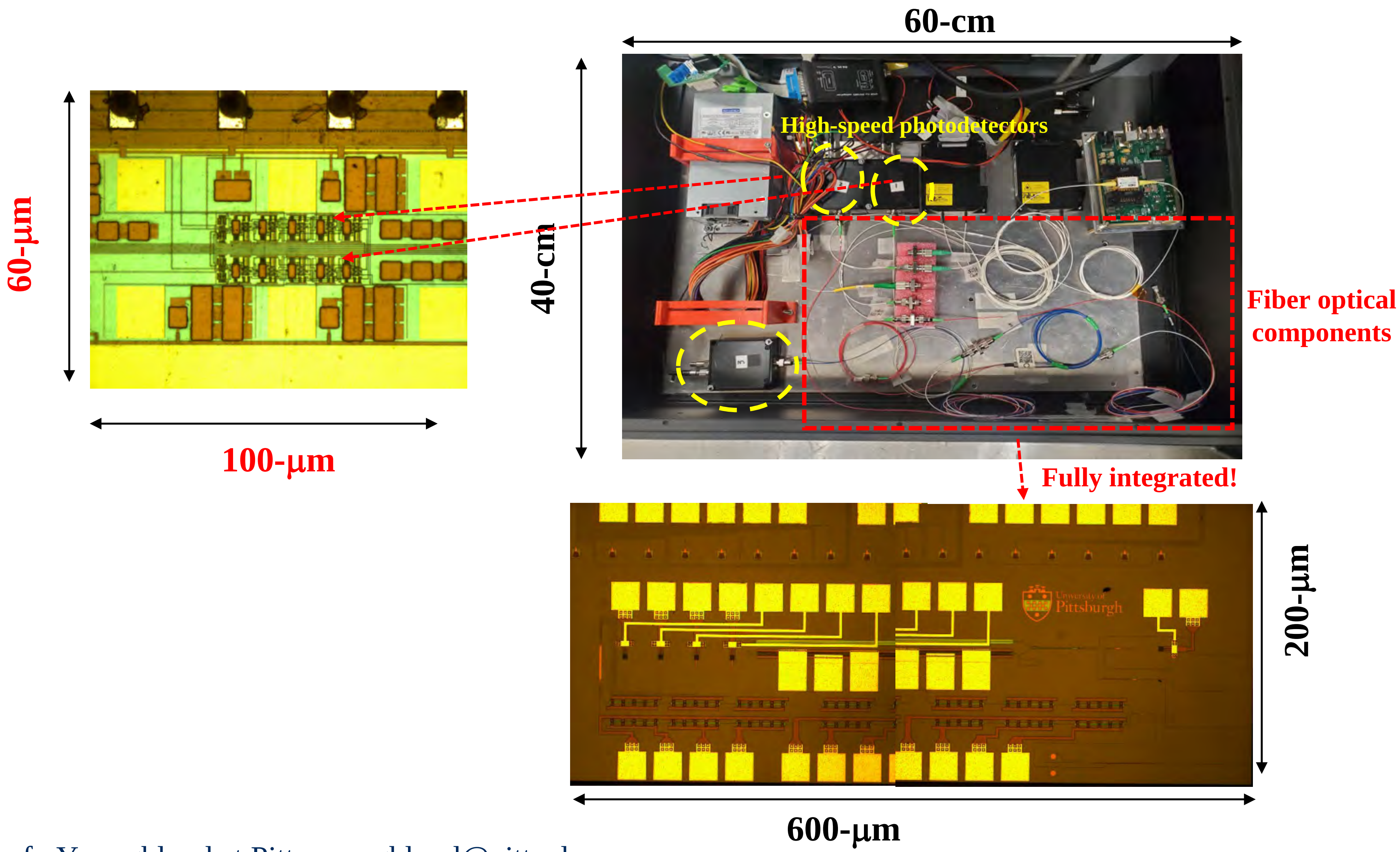
	Conventional Fiber Sensing Schemes	Optical Transceivers
Optical Sources Requirement		
Optical Coherence	100 meter to 20 km	Not required or up to 1 m
Optical Wavelength Tunning	10-nm or more	No required or up to 0.4-nm (achievable through current tuning)
Cost	\$8,000-\$20,000	\$20-\$250
Modulation Requirements		
Need dedicated modulator	Yes	NO – Already built-in!
Modulation Speed	40-250 MHz	10GHz-25 GHz
Cost	<\$5,000	Integrated with Transceivers
Network Integratable	No	Yes

DAS Based NPS 3×3 Scheme





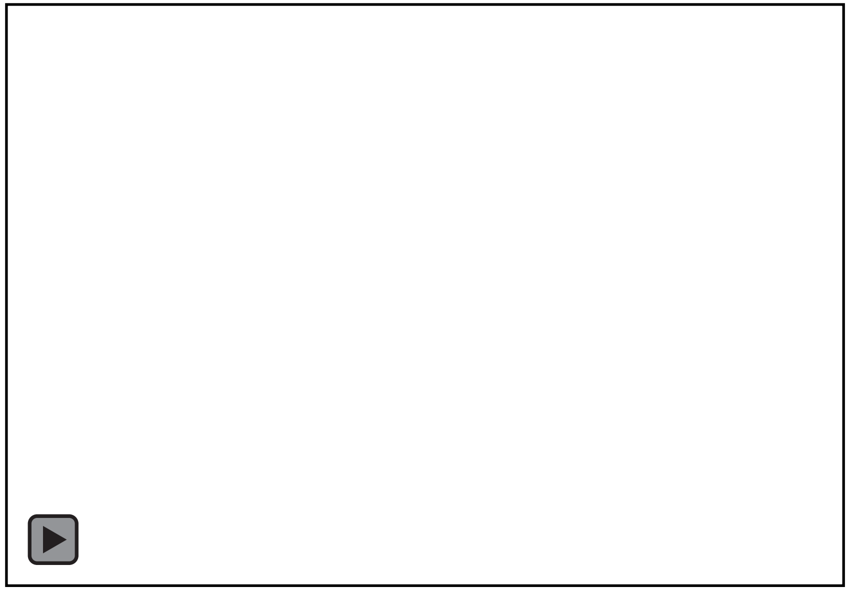
Silicon Photonics: DAS Interrogator

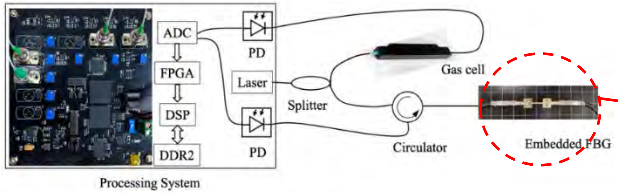


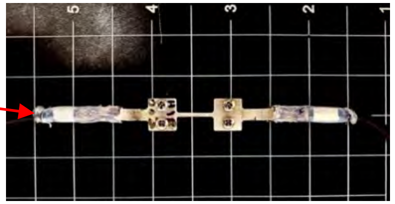
In Collaboration with Prof. Youngblood at Pitt: youngblood@pitt.edu

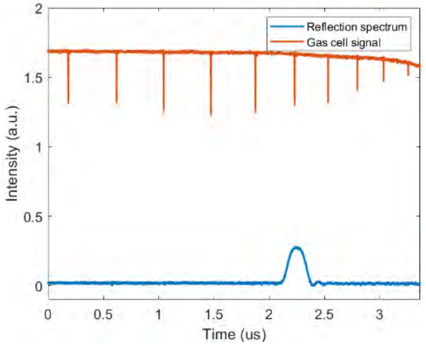
Telecom laser enable FBG Interrogation

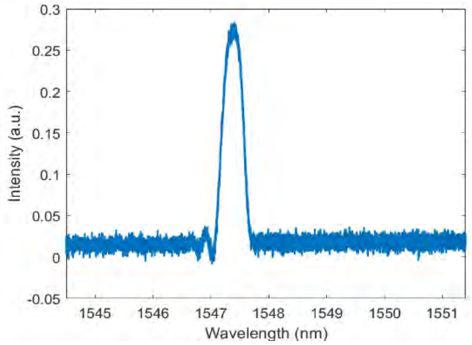
- Wavelength tuning stitching
- Gas-cell wavelength reference
- High-speed interrogation possible
- Heterogeneous multi-core architectures: FPGA+ DSP
- Rapid sensor data demodulation via DSP
- Static wavelength variation better than ± 2pm



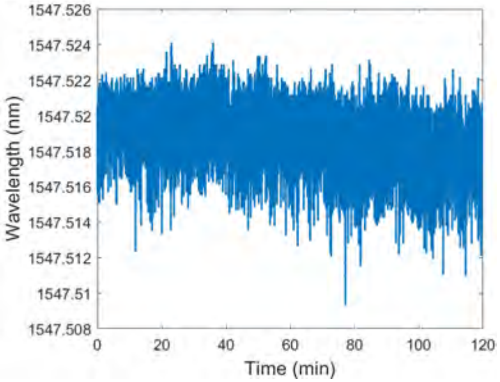


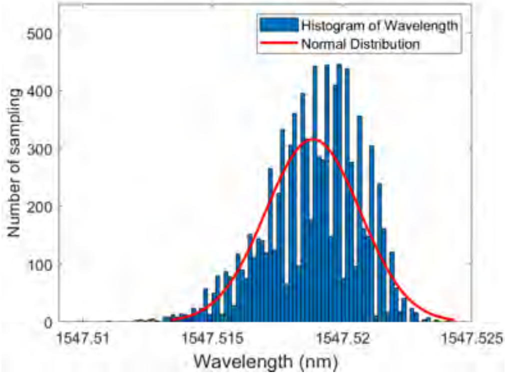






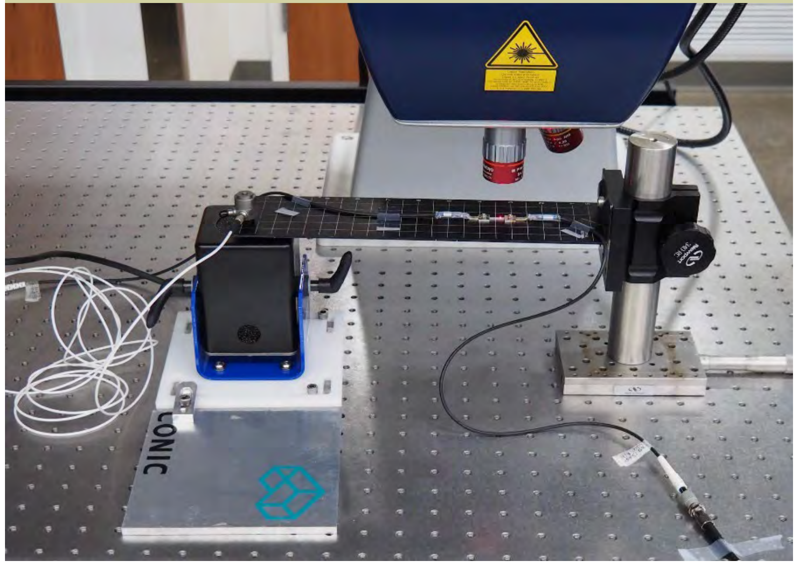
Long-Term Stability Testing

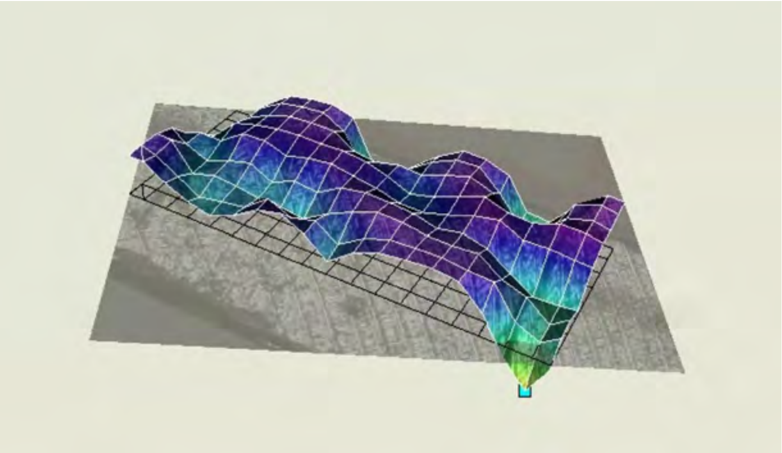




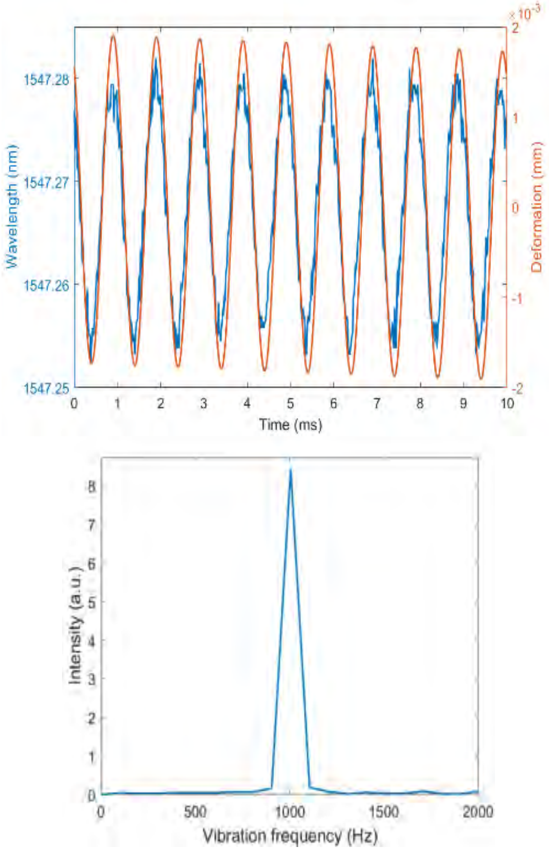
Telecom laser enable FBG Interrogation

Laser Velocimeter Comparison: 5kHz vibration



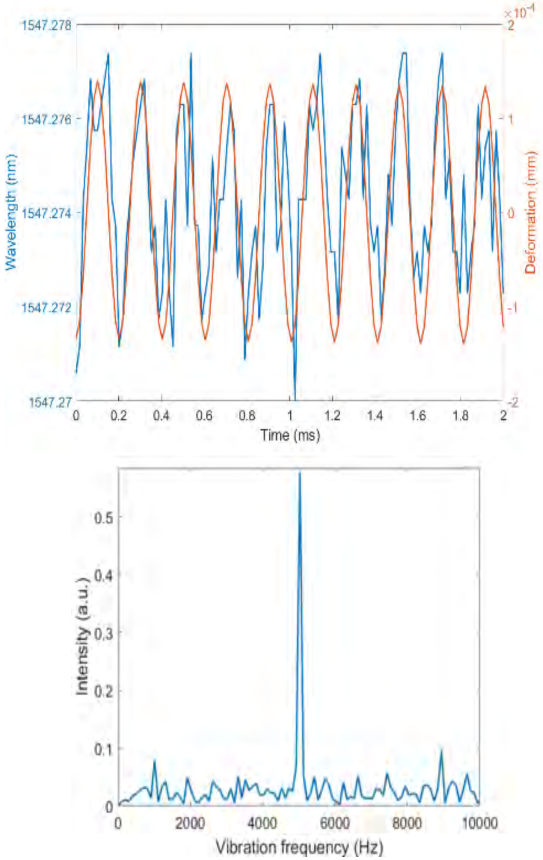


Vibration: 1kHz



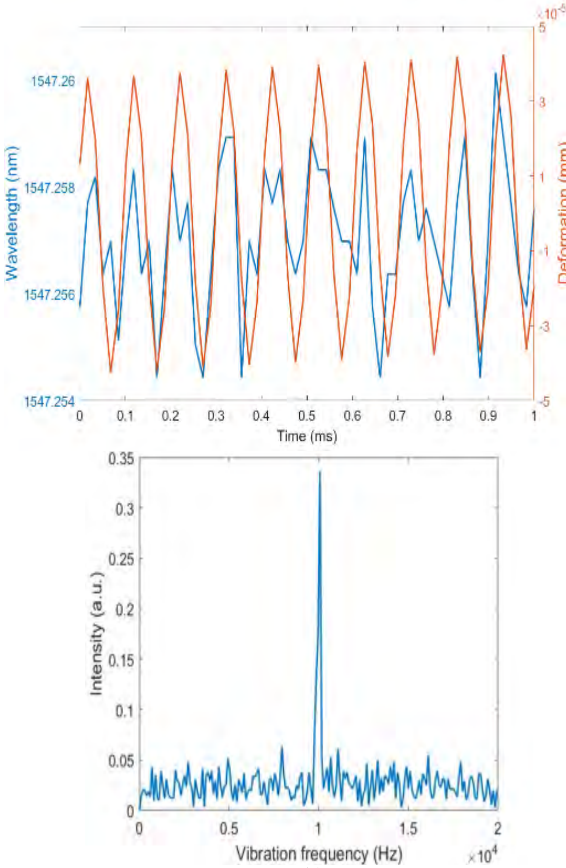
(a)

Vibration 5kHz



(b)

Vibration 10kHz



(c)

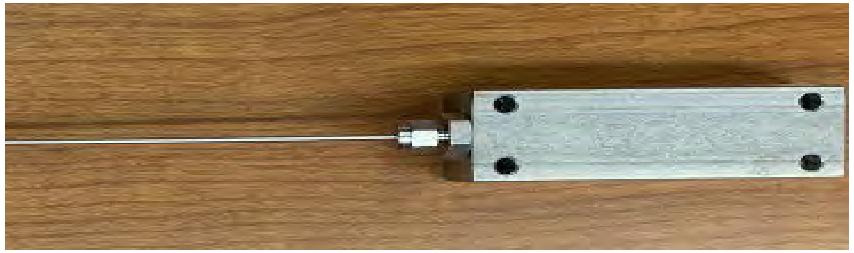
In Collaboration with Prof. Bajaj at Pitt: nbajaj@pitt.edu

Advanced Packaging Technique

Rapid and straightforward sensor deployments

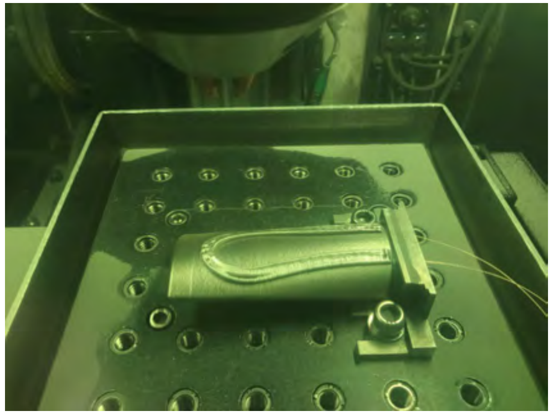
- **Smart tapes**
- **Metal additive manufacturing**
- **Glass sealants**

Glass Sealant

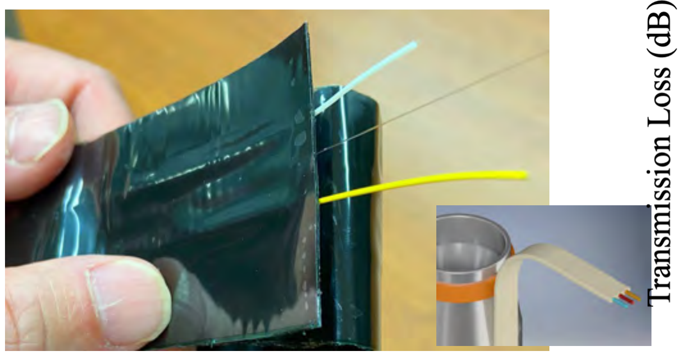


Ultrasonic Additive Manufacturing: up to 400C

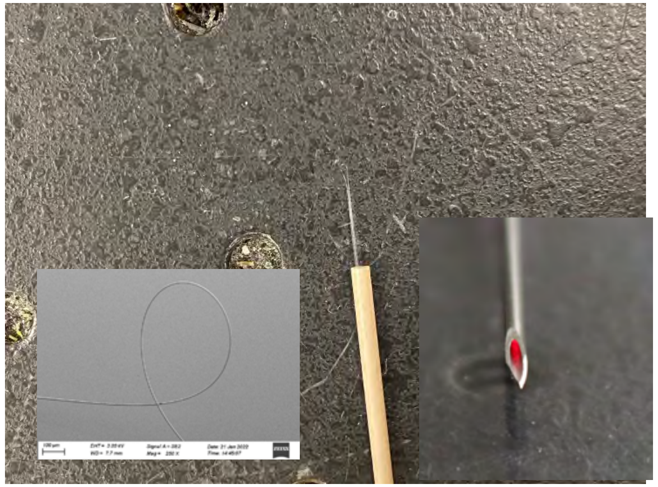
Smart Metal Components

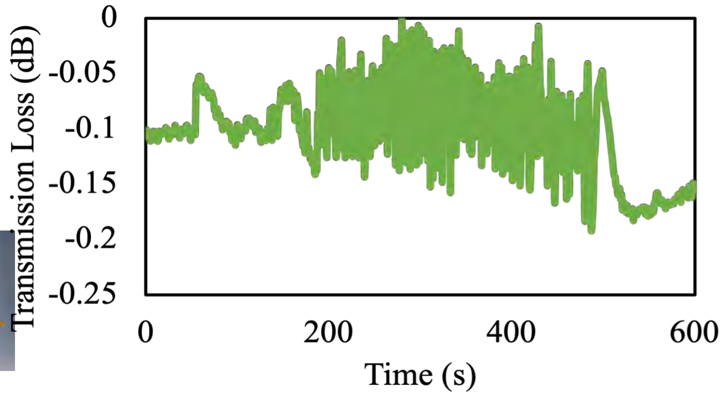


Smart Tapes

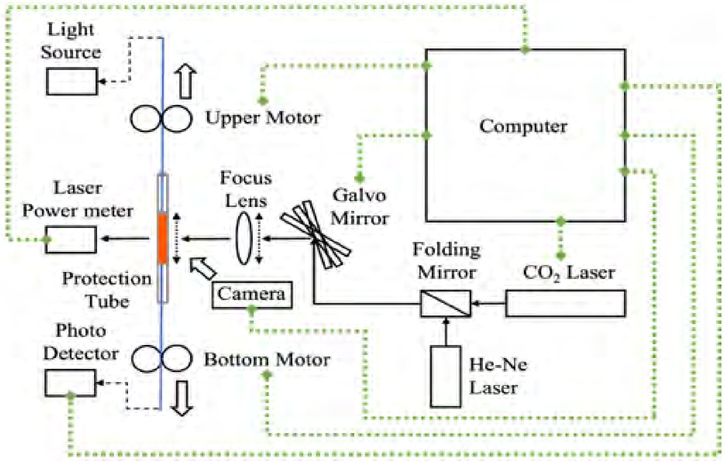


True Strain Free Sensors





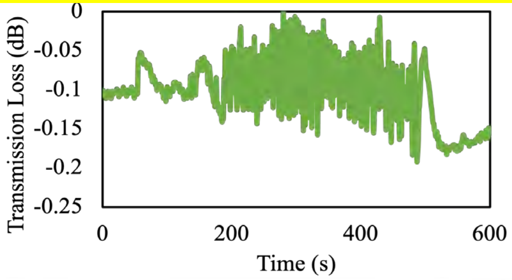
Packaging: True Strain-Free Multiplexable Sensors



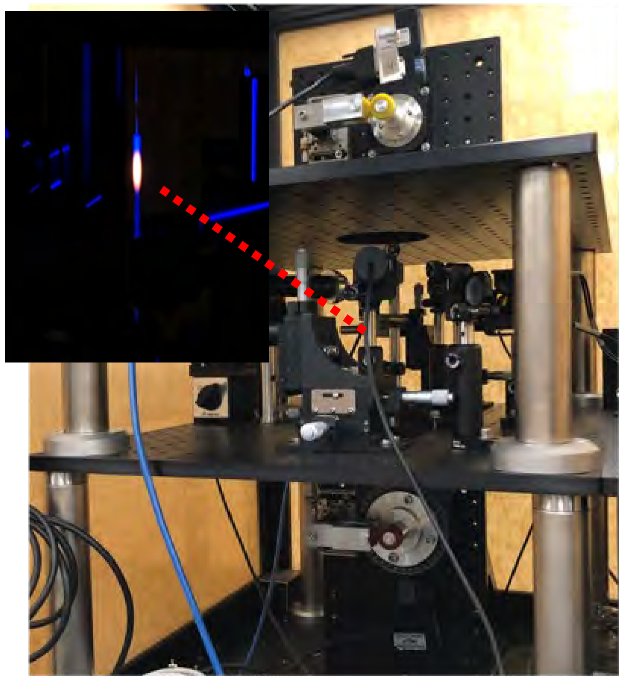
(a)

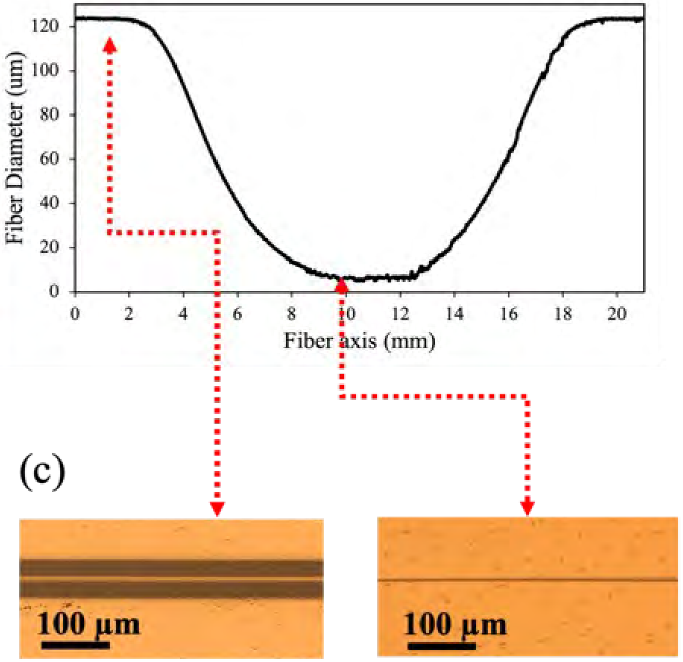
Packaging

- CO_2 laser Tapering
- Precise profile control
- Less than 0.15 dB loss

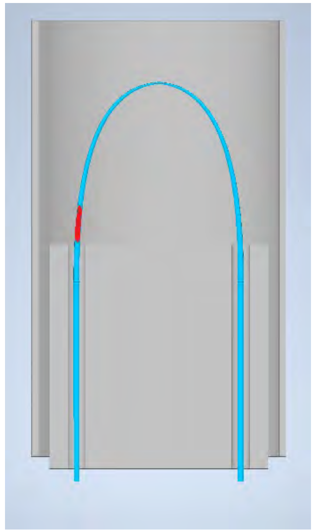


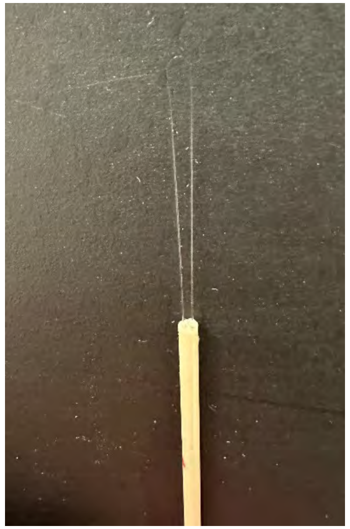
(b)

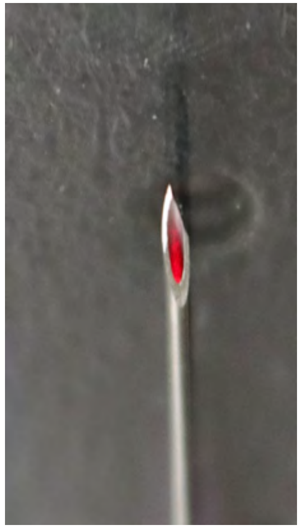




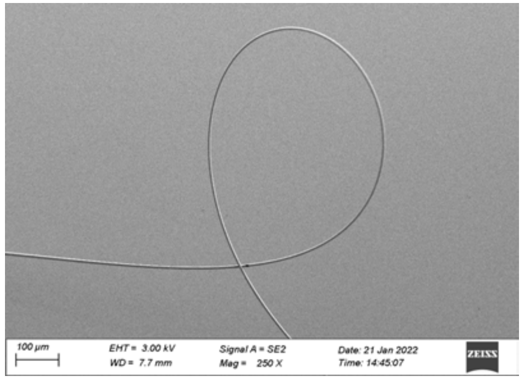
Multiplexable True Strain Free Sensors

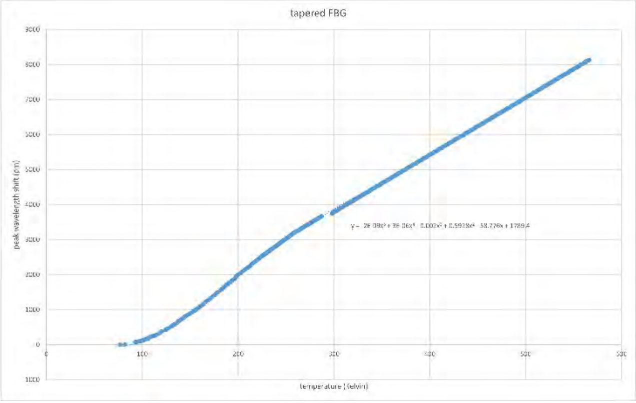






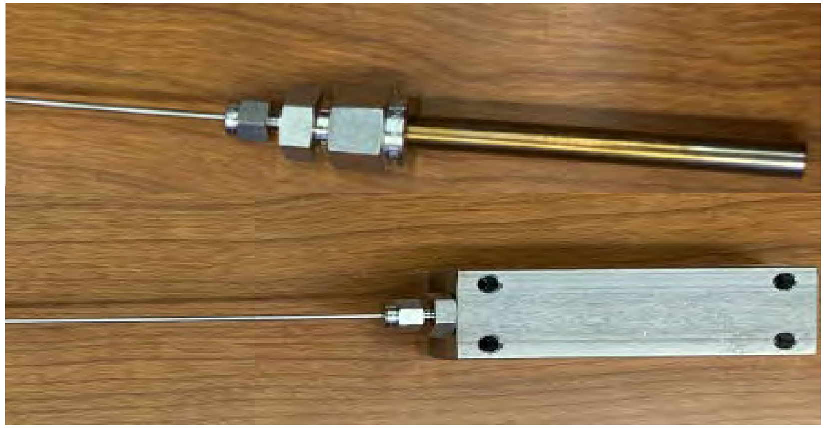
T Calibration: 77K to 600K

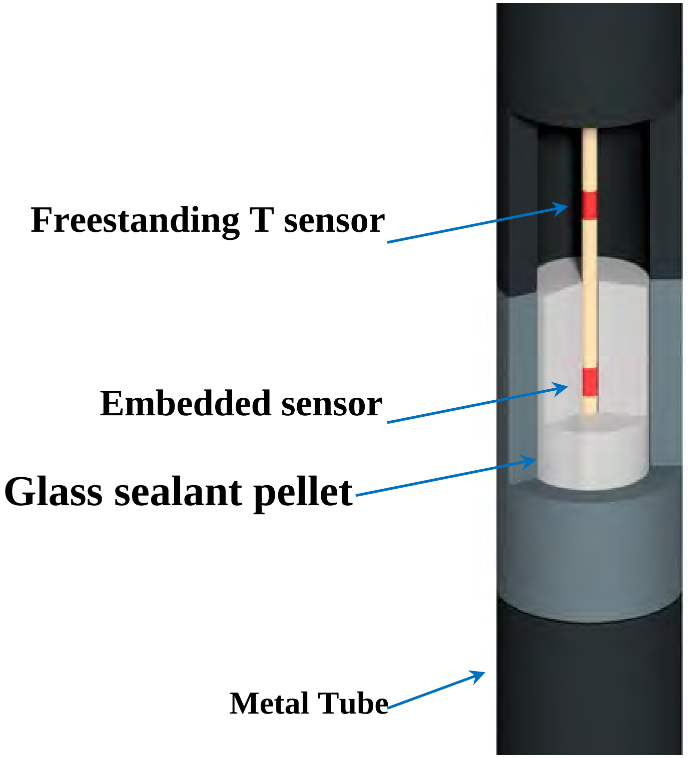


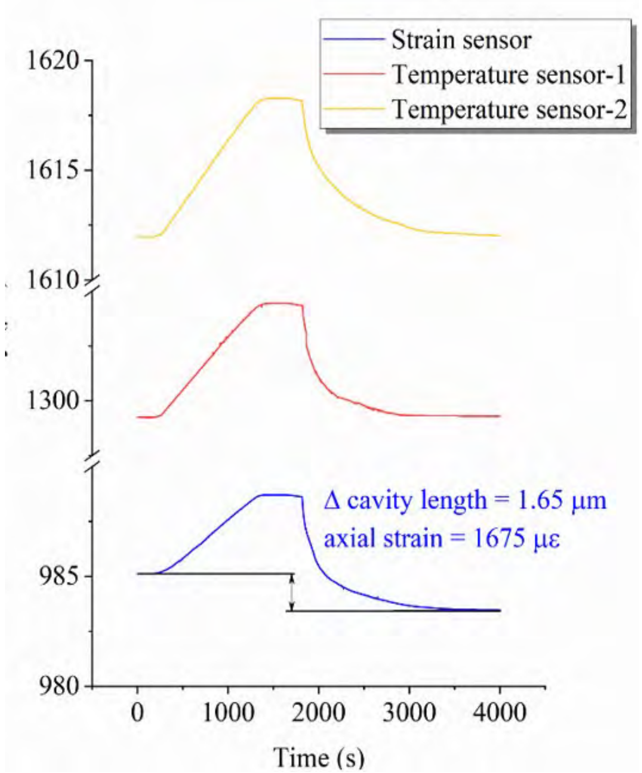


Package 2:Hermetic Fiber Sensor Packaging via Glass Sealant

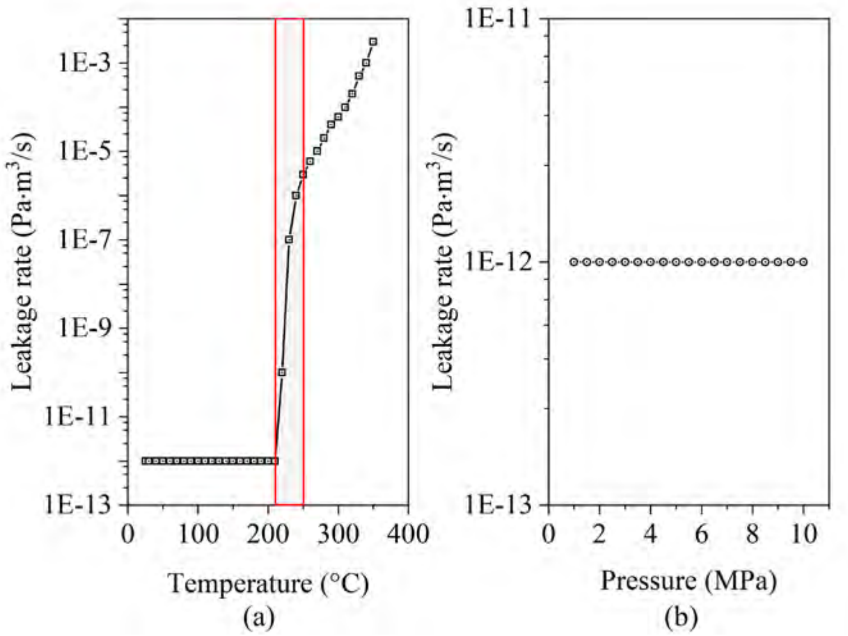
- Wide selection of sealant materials: glass and ceramics
- TEC of glass sealant ~ 5ppm/C –between silica fiber and metal.
- Hermetical bonding on metals – Compressive strain
- Rapid process possible







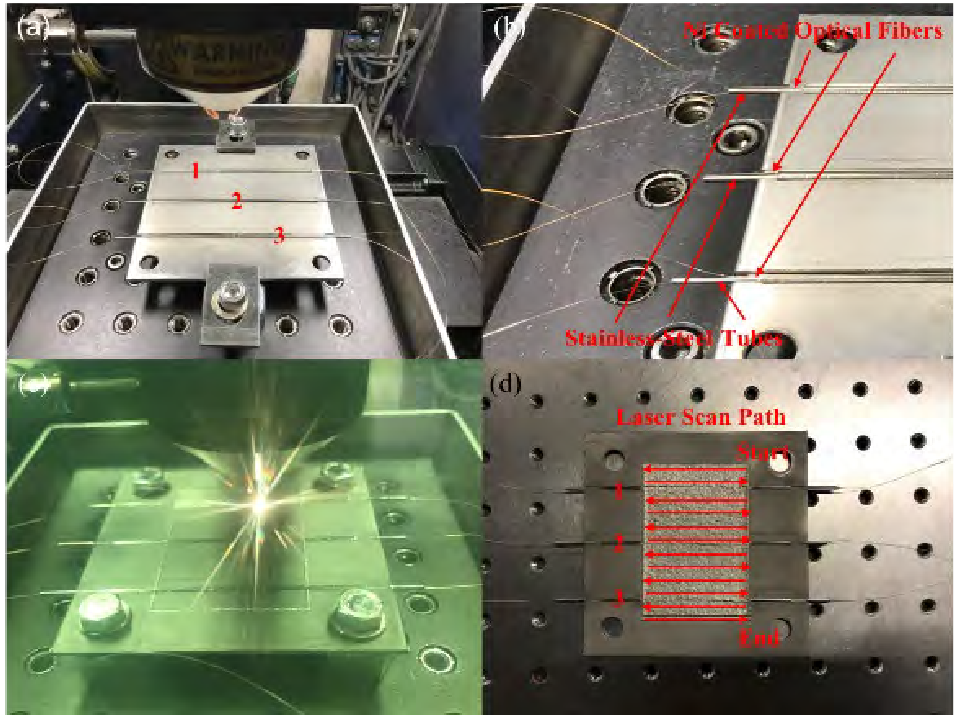
Helium Leak Test Results



Package 3: Metal Additive Manufacturing

Ultrasonic AM Sensor Embedding

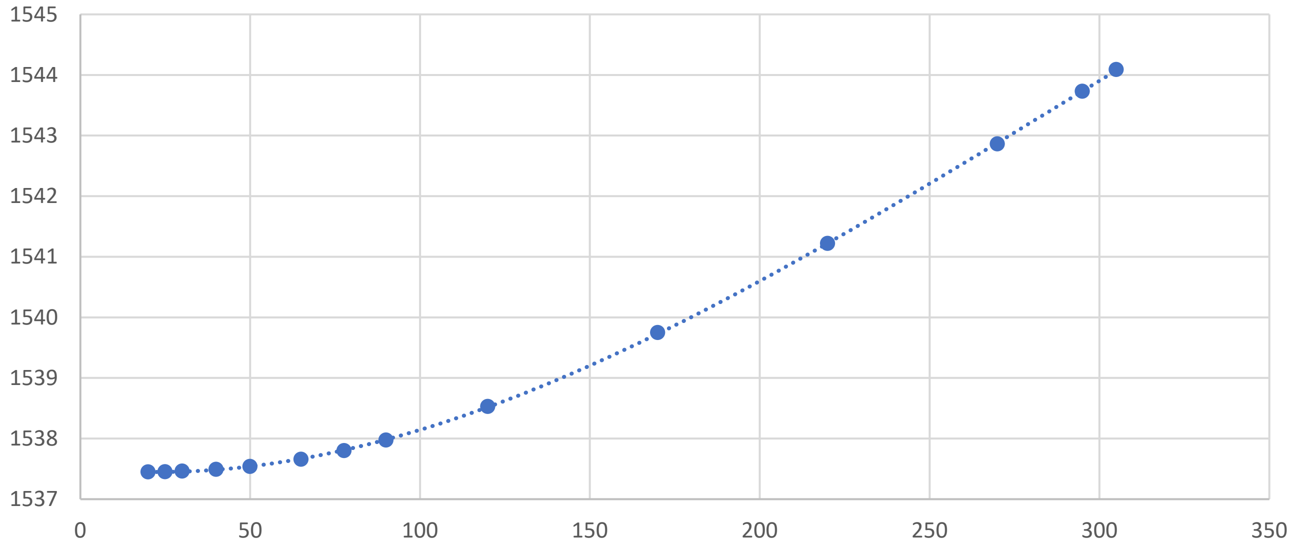
Powder-bed AM Sensor Embedding



Sensor Fused AM Processes

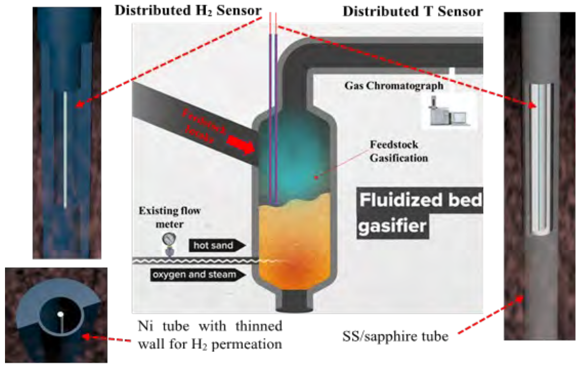
- **Enable smart components**
- **Provide feedbacks for AM processing optimization**
- **Improve sensor performance**

(In collaboration with Prof. Albert To of Pitt: albertto@pitt.edu)

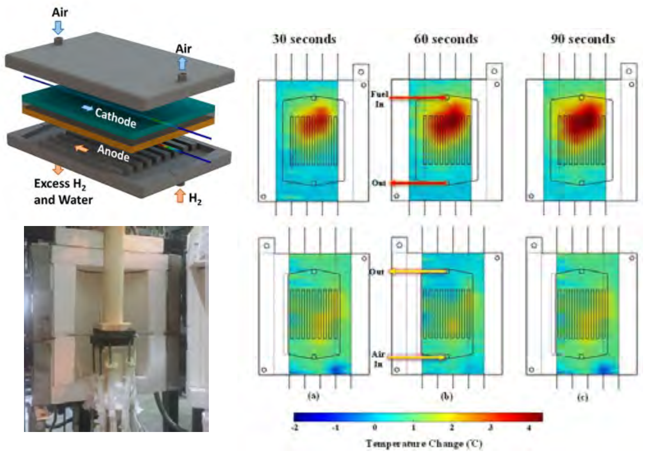


Explore New Applications: High-T Hydrogen Sensing

T and H_2 Sensor for Waste Plastic Gasification



High Spatial Resolution Sensor for H_2 SOFC

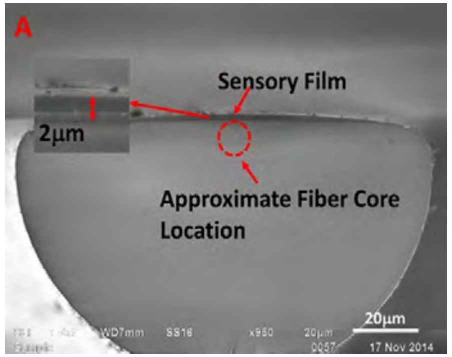


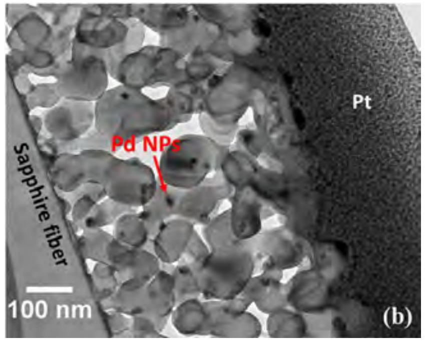
High-T Fiber Sensors for Hydrogen Applications

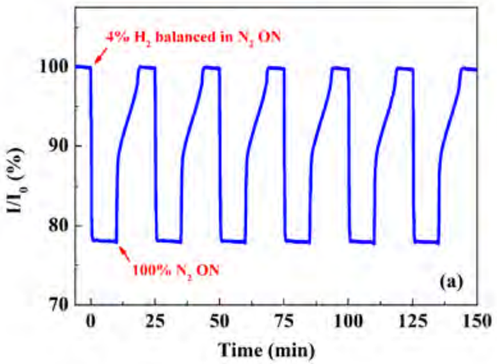
- 800^{o}C distributed H_2 and T measurements
- 1-cm T sensing spatial resolution
- 3-cm hydrogen sensing spatial resolutions
- 6-m interrogation length in harsh environments
- H2 SOFC and Waste plastic gasification process

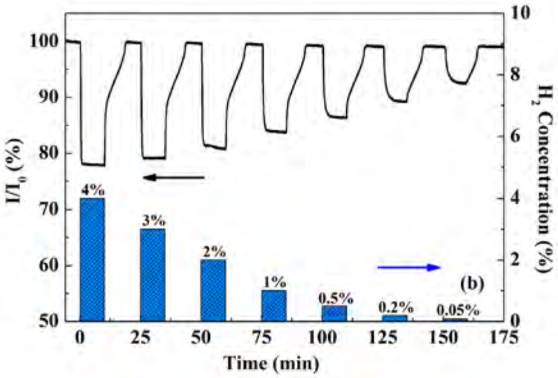
**** In collaboration with NETL***

Pd-doped Metal Oxide Porous Materials Enabled H_2 Sensors Operated at 800C





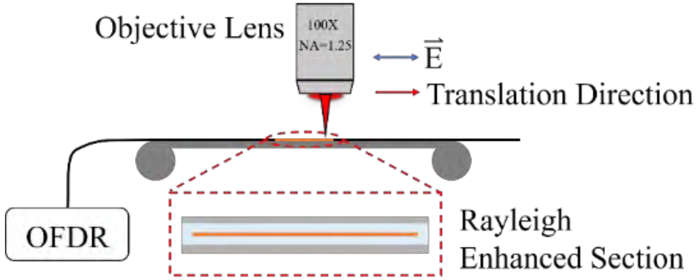




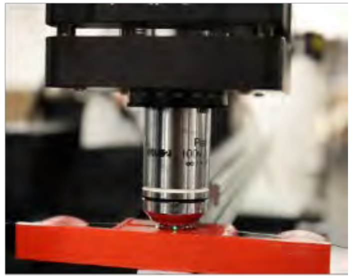
Project Objectives

- Can fiber sensors survive and function in extreme harsh in-pile conditions?
  - Types of fibers?
  - Sensor fabrication processes?
  - Type of sensors? – Rayleigh-enhanced distributed sensors
  - Sensor drifts and mitigation schemes?
- How severe is radiation contamination for fiber sensors (Possible hot sensor replacements).
- Use fiber sensors as a mean to enable Condition-Based Monitoring for NE Systems

Fabrication of High-T Stable Distributed Sensors in Rad-hard Fiber



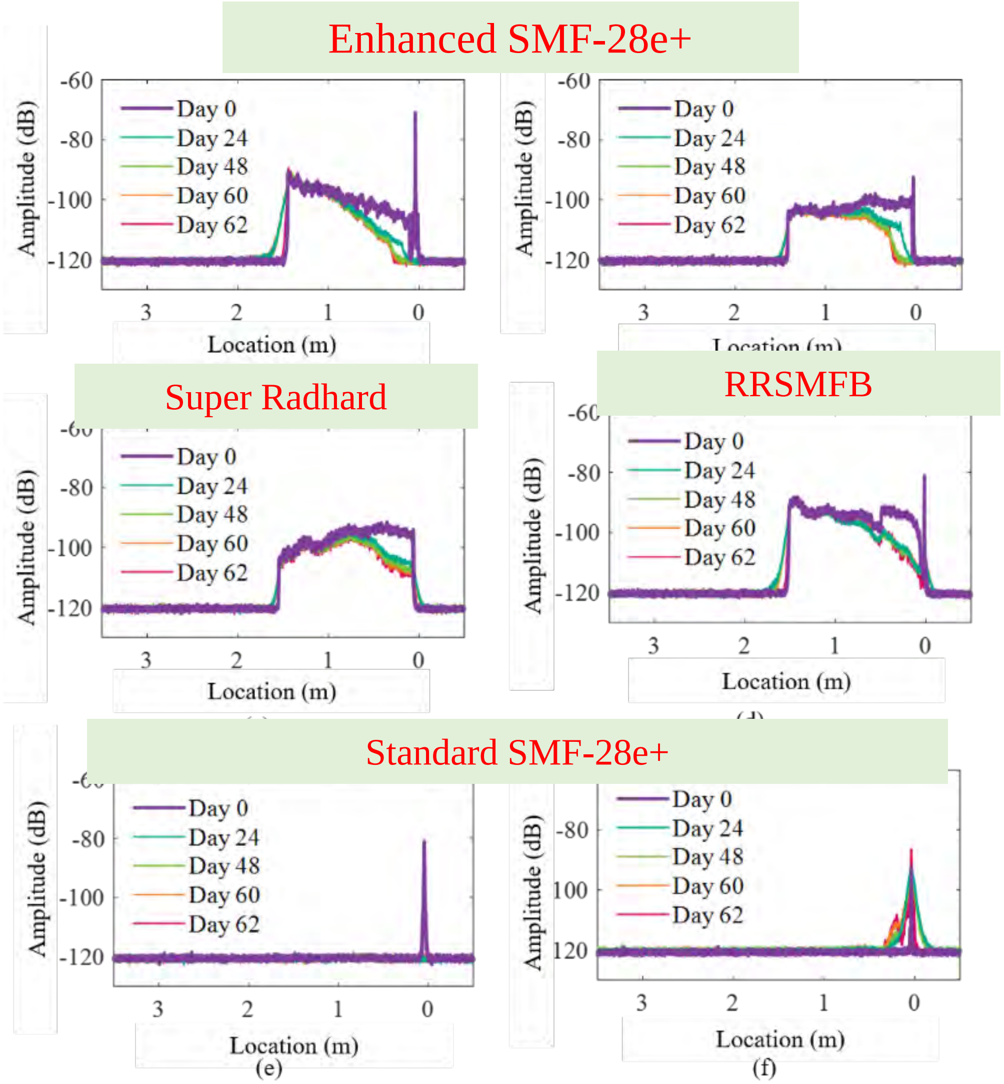
(a)



(b)

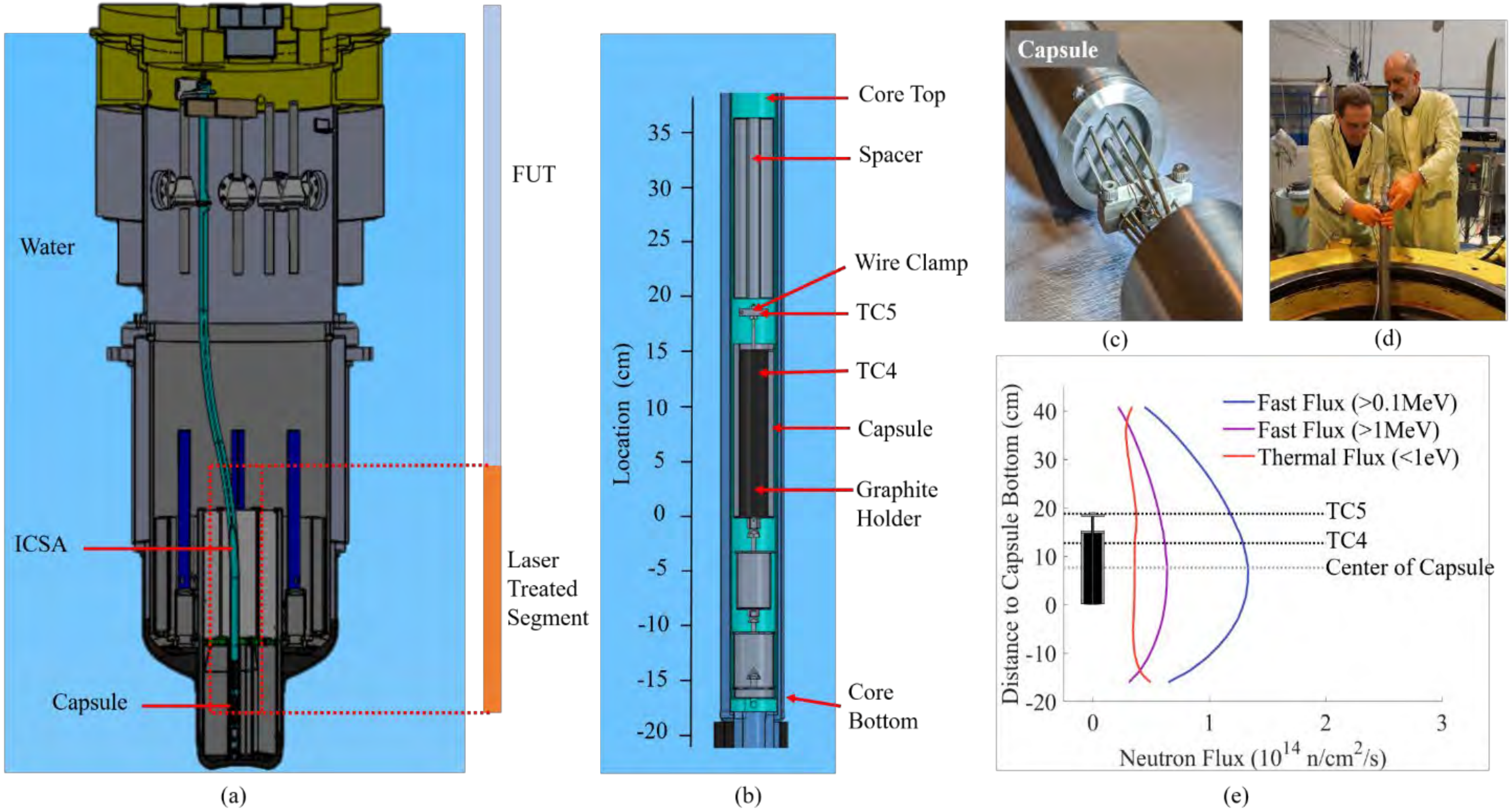
Sample #	Fiber Type & Vendor	Single-mode Fiber Specifications	Laser Enhancement
1, 2	SMF28e+, Corning	NA=0.14, Ge-doped core	Yes
3			No
4, 5	Super RadHard, Draka	≥ 0.41 wt% and 1.2 wt% fluorine doped in core and cladding	Yes
6			No
7	RRSMFB, Fujikura	Fluorine-doped silica core and cladding, chlorine concentration of core ≥ 1ppm	Yes

In Collaboration with LUNA Innovation: Dr. Derek Rountree (rountreed@lunainc.com)



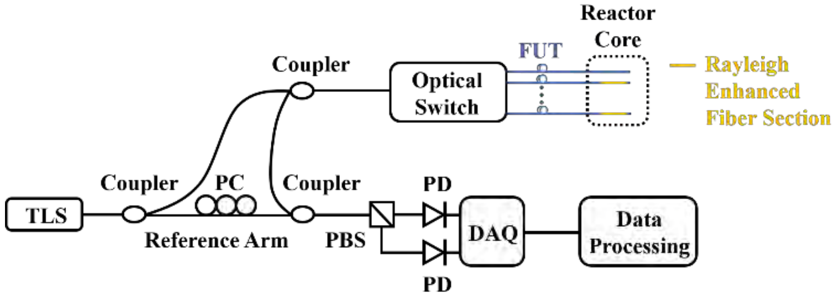
In-Pile Fiber Sensors Testing

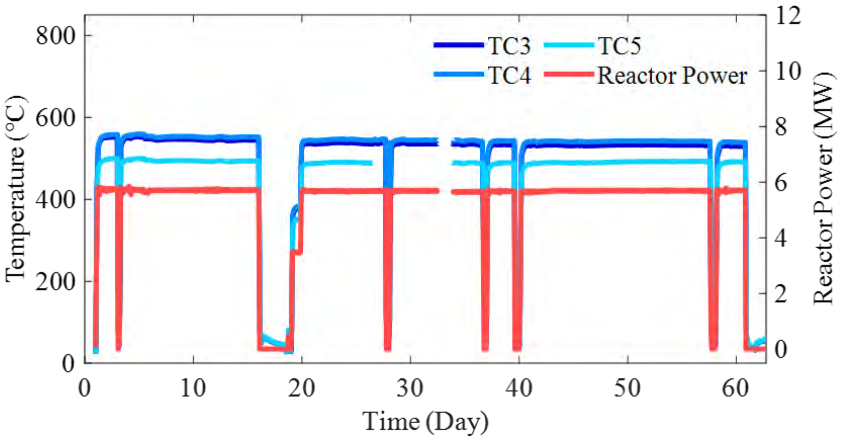
- MITR Tests: 560C to 650C, total fast neutron flux 4.4×10^{21} n/cm^2 Per Year

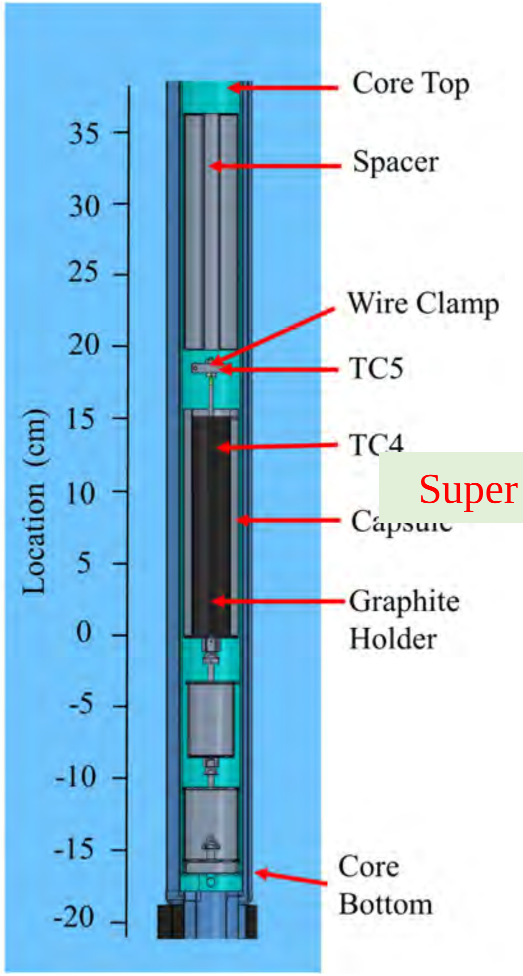


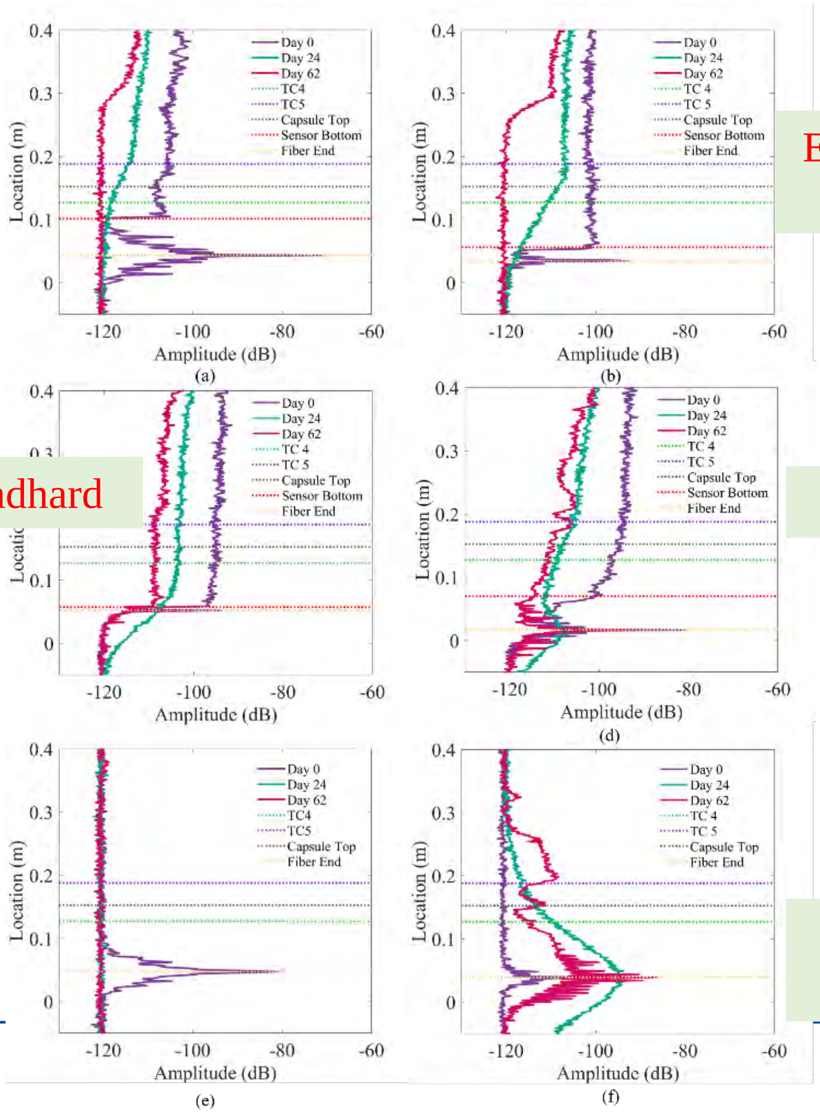
Fiber Sensors for Nuclear Applications

Irradiation Effects of Distributed Fiber Sensors









Enhanced SMF-28e+

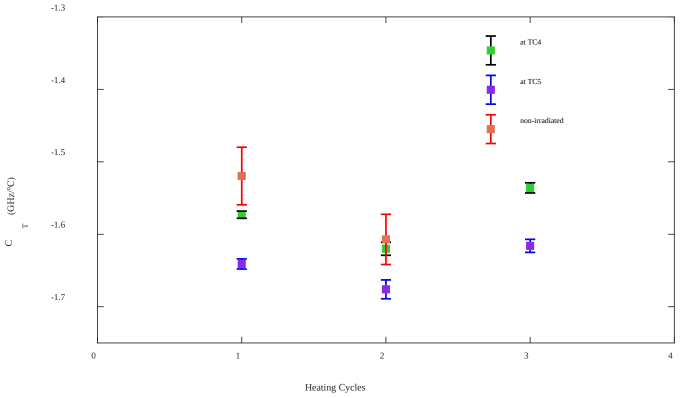
Super Radhard

RRSMFB

Pristine SMF28e+

Evolution of C_T

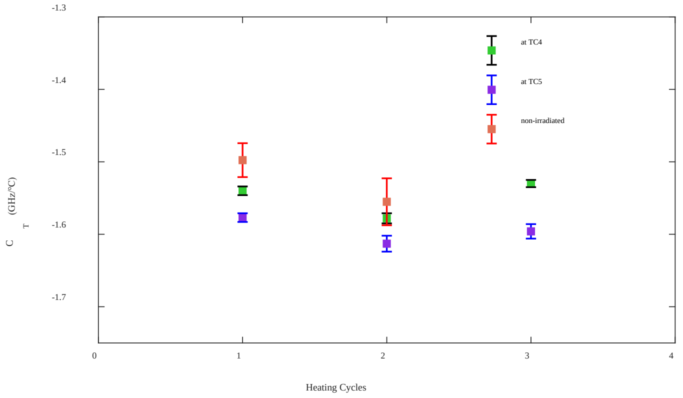
One coefficient can be used
(~2.5% error for all locations, fast neutron flux variation ~8%)



SMF28e+ fiber

One coefficient, 2.7% error for all locations

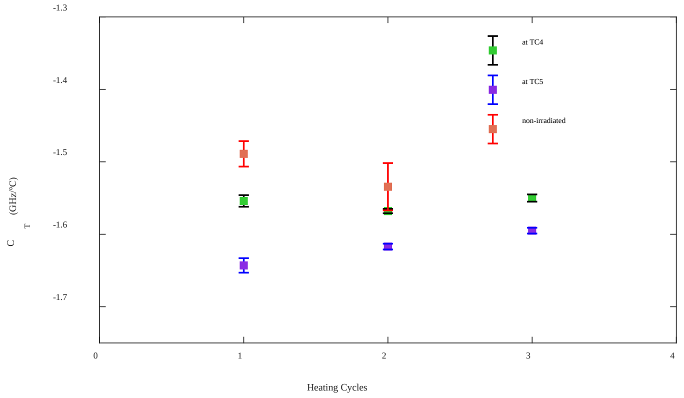
Heating Cycle #	Location	Temperature Coefficient C_T (GHz/°C)	R-square
1st (Non-irradiated)		-1.519±0.040	0.997
2nd (Non-irradiated)		-1.607±0.035	0.998
1st (Day 1, Under Radiation)	at TC4	-1.573±0.005	0.999
	at TC5	-1.641±0.007	0.999
2nd (Day 3, Under Radiation)	at TC4	-1.620±0.009	0.999
	at TC5	-1.676±0.013	0.997
3rd (Day 19, Under Radiation)	at TC4	-1.536±0.007	0.999
	at TC5	-1.616±0.009	0.998
Aggregated Linear Fit	at TC4&5	-1.604±0.004	0.998



Super RadHard fiber

One coefficient, 2.4% error for all locations

Heating Cycle#	Location	Temperature Coefficient C_T (GHz/°C)	R-square
1st (Non-irradiated)		-1.498±0.023	0.999
2nd (Non-irradiated)		-1.555±0.032	0.998
1st (Day 1, Under Radiation)	at TC4	-1.540±0.006	0.999
	at TC5	-1.577±0.006	0.999
2nd (Day 3, Under Radiation)	at TC4	-1.578±0.007	0.999
	at TC5	-1.613±0.011	0.998
3rd (Day 19, Under Radiation)	at TC4	-1.530±0.005	0.999
	at TC5	-1.596±0.010	0.998
Aggregated Linear Fit	at TC4&5	-1.567±0.003	0.998

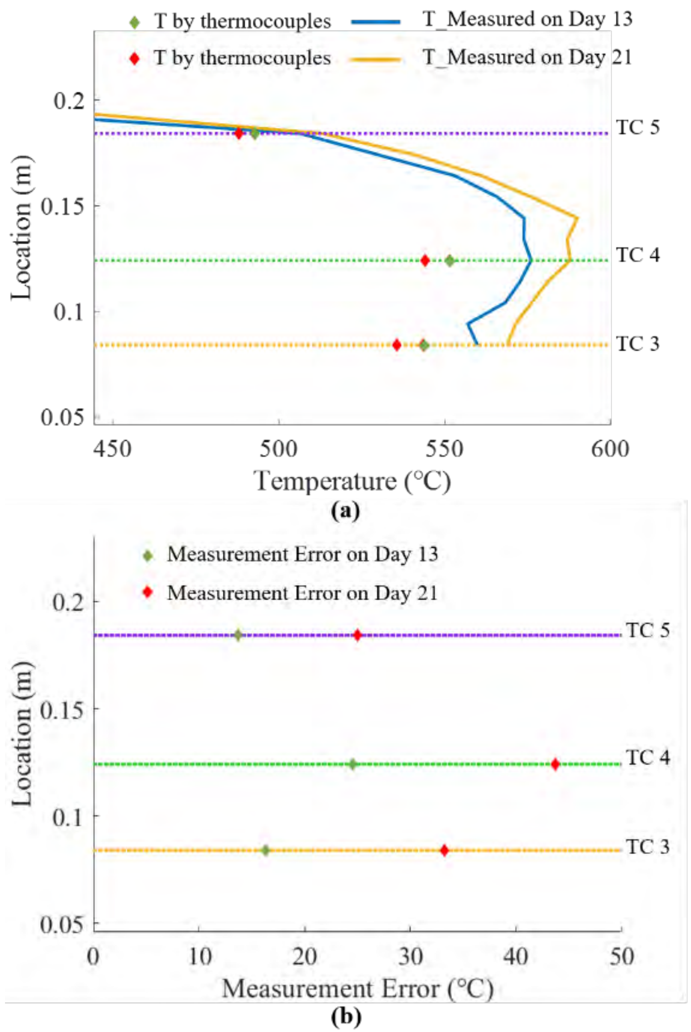


RRSMFB fiber

One coefficient, 2.5% error for all locations

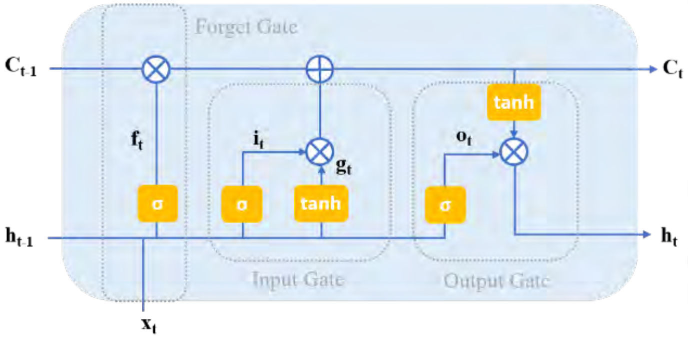
Heating Cycle#	Location	Temperature Coefficient C_T (GHz/°C)	R-square
1st (Non-irradiated)		-1.489±0.018	0.999
2nd (Non-irradiated)		-1.534±0.033	0.998
1st (Day 1, Under Radiation)	at TC4	-1.554±0.008	0.998
	at TC5	-1.643±0.010	0.997
2nd (Day 3, Under Radiation)	at TC4	-1.568±0.003	0.999
	at TC5	-1.617±0.004	0.999
3rd (Day 19, Under Radiation)	at TC4	-1.550±0.005	0.999
	at TC5	-1.595±0.004	0.999
Aggregated Linear Fit	at TC4&5	-1.588±0.003	0.999

Radiation-induced Sensor Drifting and Mitigations: Sensor Fusion



Mitigation Strategy:

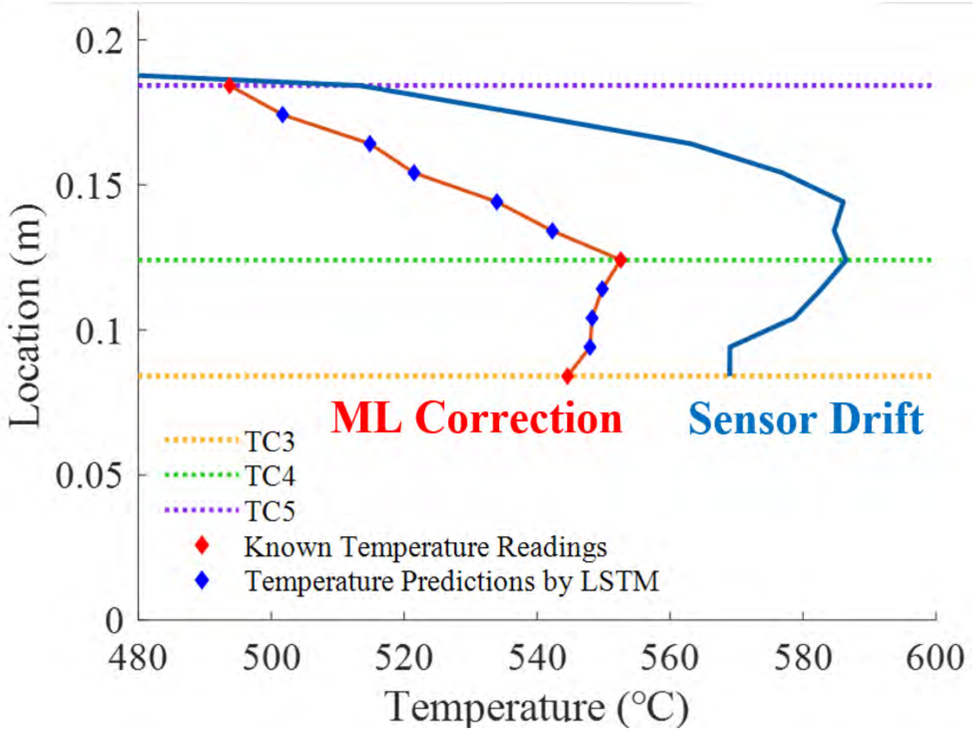
- Single Thermocouple as "gold standard" TC4
- LSTM neural network apply to the fiber sensor at TC4 location: harness temporal knowledge
- kNN neural networks pass knowledge to other fiber sensors located in different spatial position
- Absolute error within 4C



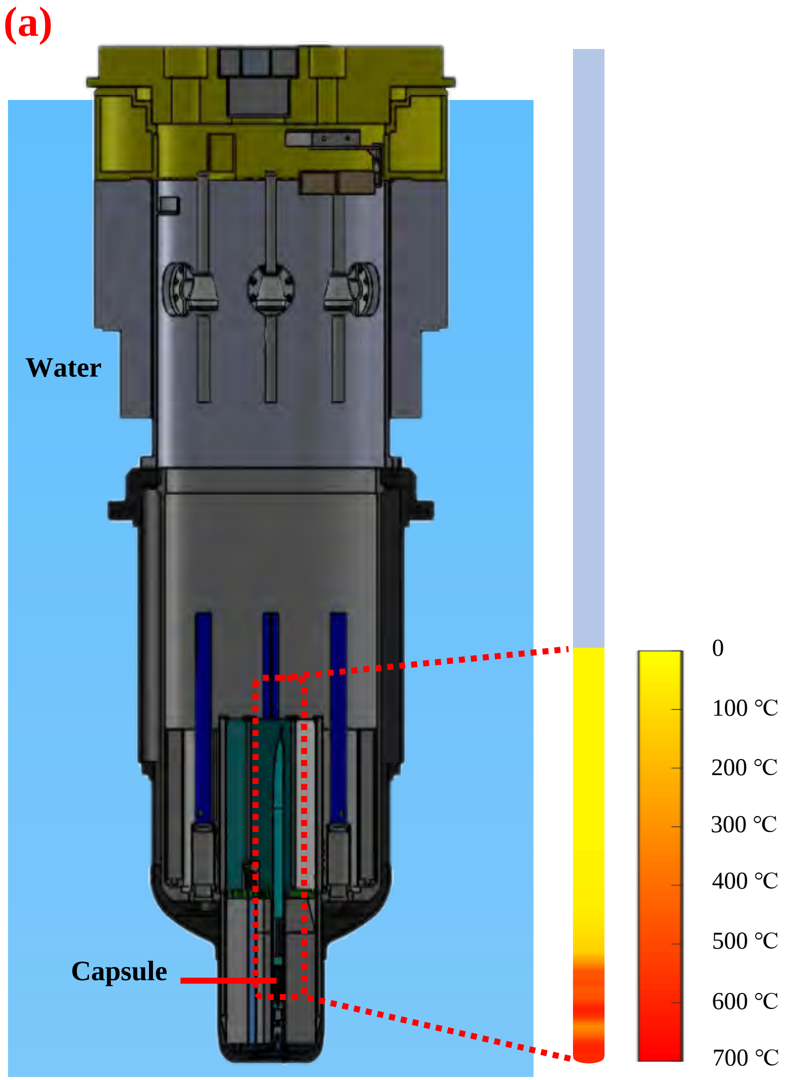
$$\begin{pmatrix} i_t \\ f_t \\ o_t \\ g_t \end{pmatrix} = \begin{pmatrix} \sigma \\ \sigma \\ \sigma \\ \tanh \end{pmatrix} \left(\begin{pmatrix} W & U \end{pmatrix} \begin{pmatrix} x_t \\ h_{t-1} \end{pmatrix} + B \right) \quad (5)$$

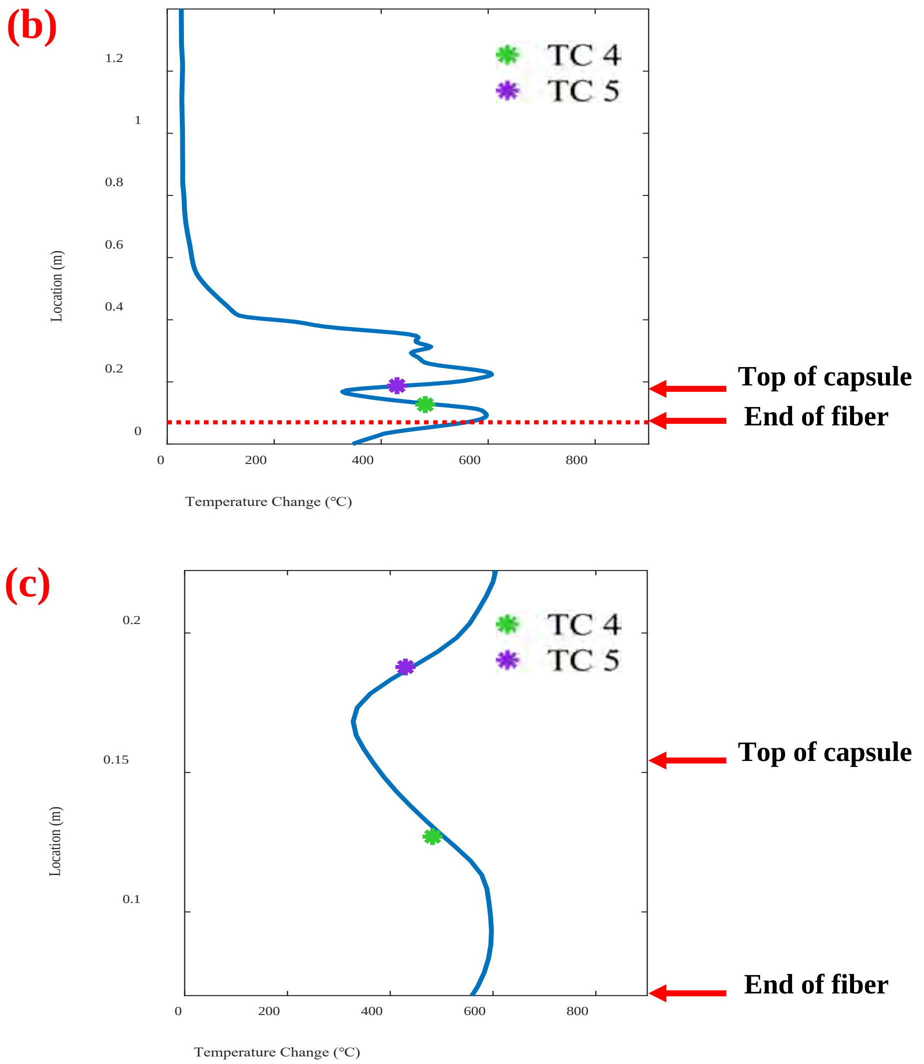
$$C_t = f_t \otimes C_{t-1} + i_t \otimes g_t \quad (6)$$

$$h_t = o_t \otimes \tanh(C_t) \quad (7)$$



Temperature Profile of MIT Research Reactor Core





Summary

- It is possible to reduce cost of sensing fibers by ×10 times.
- It is possible to reduce cost of sensor interrogators by ×10 times.
  - Not the best performance but good enough.
- Expand applicability of fiber sensors
- Scale-up deployments for energy infrastructures

Thank you!