Development of Distributed Sensors for Waste Plastics Gasification toward Clean Hydrogen Production

Kevin P. Chen

Department of Electrical and Computer Engineering, University of Pittsburgh

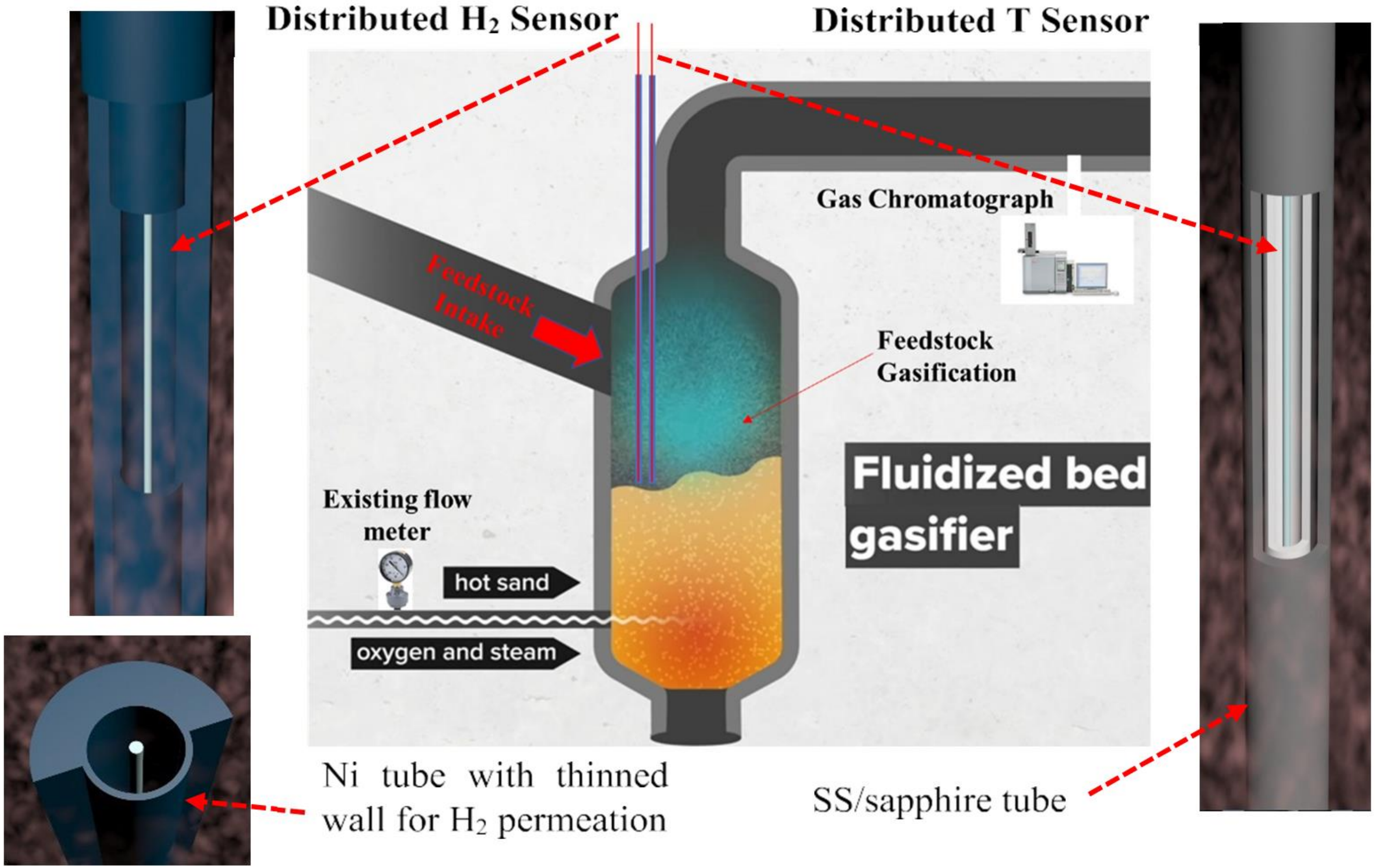
Email: pec9@pitt.edu

Jordan Klinger

Idaho National Lab, Idaho Falls

Email: jordan.klinger@inl.gov

Proposed Sensor Technology



Project Objectives

Objective I – T Sensors: Use -*fs* laser direct writing technique to fabricate distributed fiber temperature sensors stable in high-T (up to 900C) hydrogen environments (5-cm spatial resolution, across 6 meters).

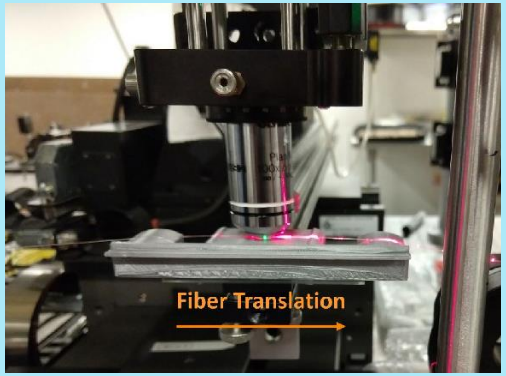
Objective II – H_2 Sensors: High-T stable functional nano-material high-T stable sensory materials enabled multiplexed hydrogen sensors.

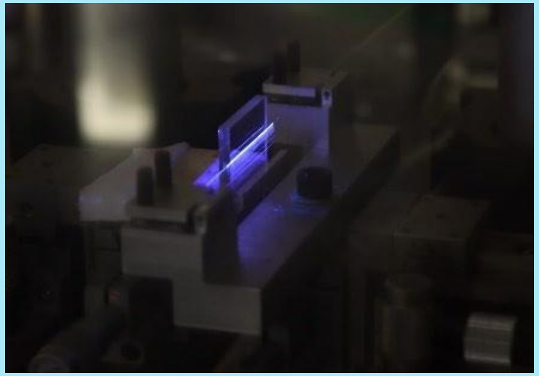
Objective III – Packaging: Unique sensor packaging enable direct, high-spatial resolution, in-vivo measurements of hydrogen and temperatures.

T2M – Works: Low-cost telecom gear enabled Optical Frequency Domain Reflectometer (OFDR) sensor interrogator that will trigger wide adaptation of this novel sensor technology for the industry.

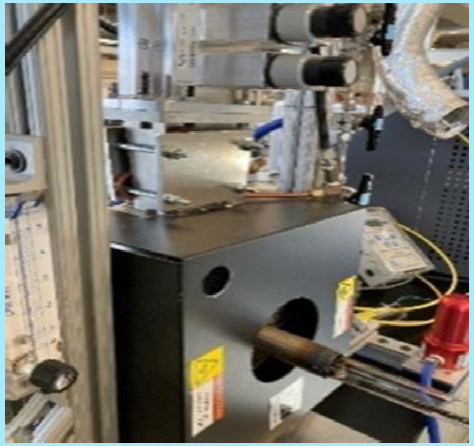
Team Members

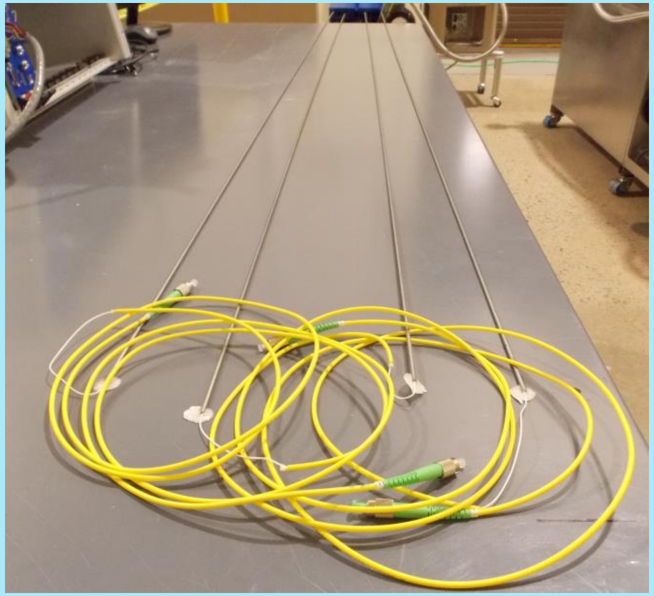
University of Pittsburgh: Sensor fabrication, sensor testing, and interrogator developments.



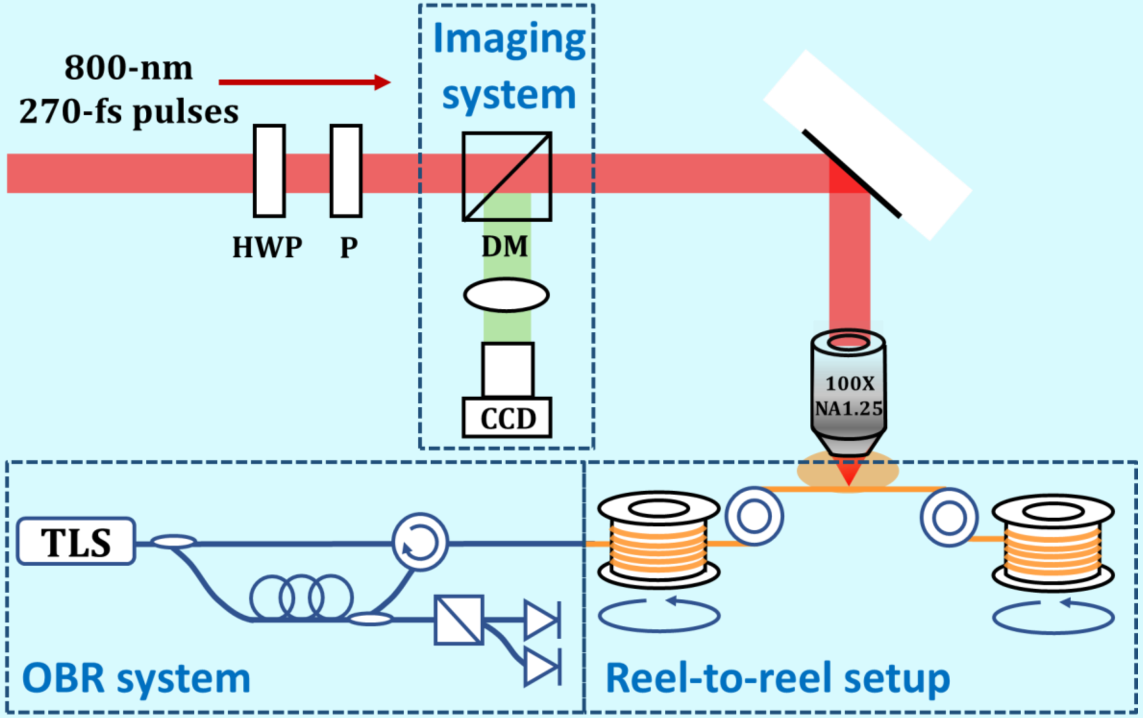


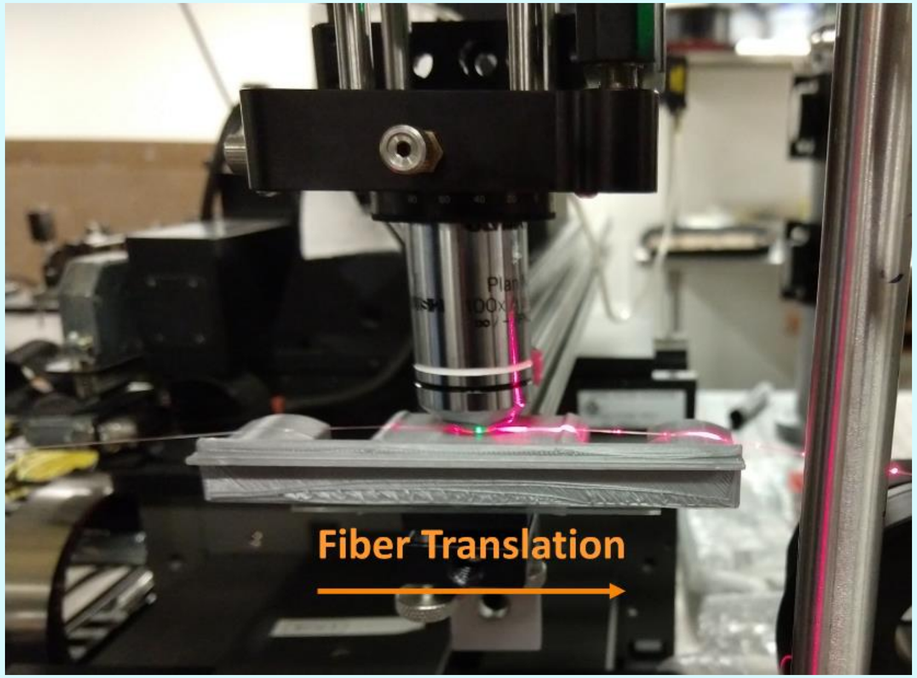
Idaho National Lab: sensor testing in plastic waste gasifiers.

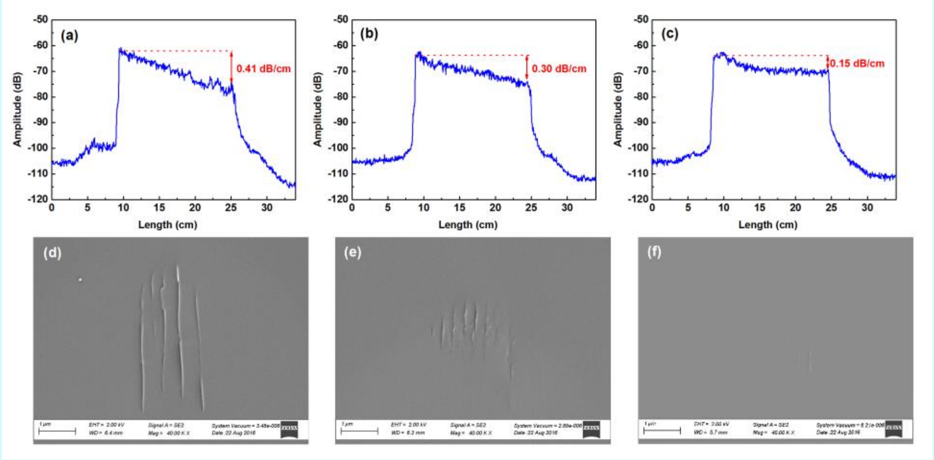




Task 1: Distributed Temperature Sensors





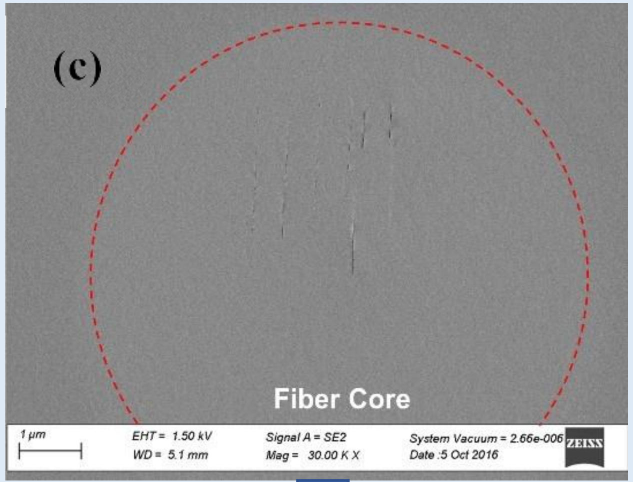


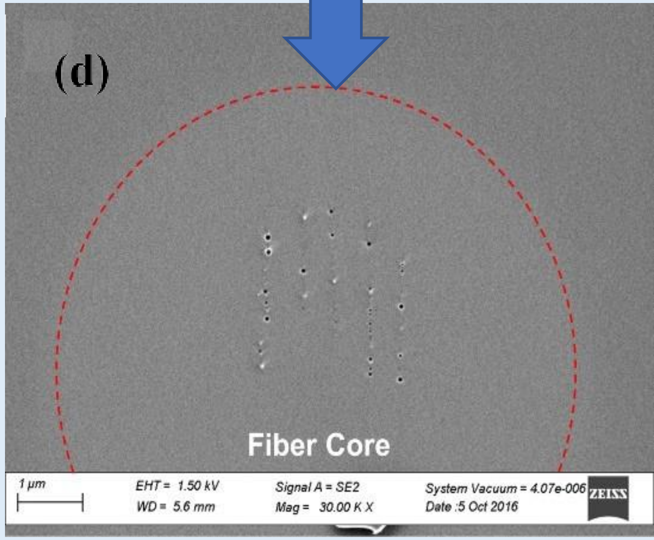
Reel-to-reel oil-immersion fiber writing setup

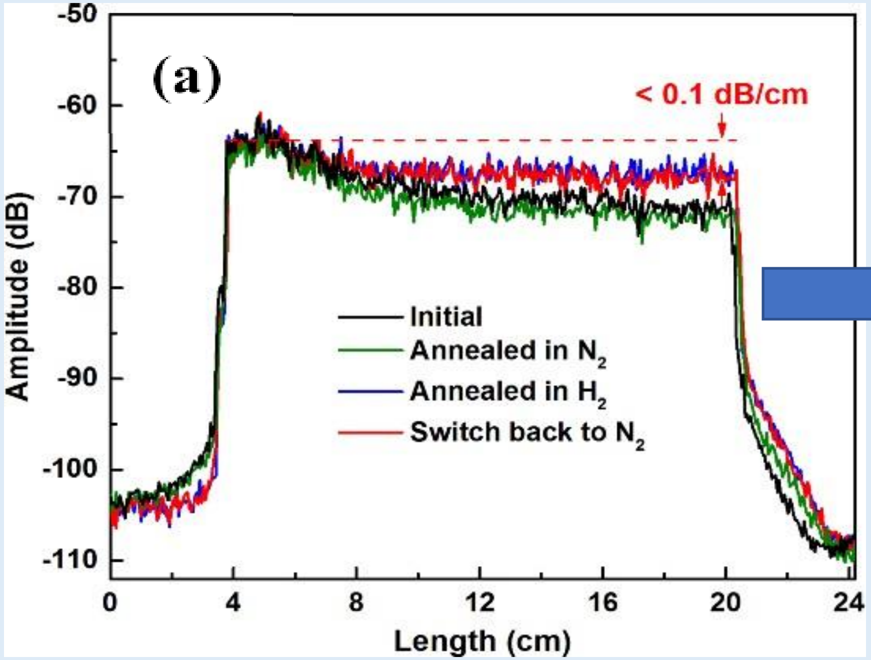
- Fast and continuous fabrication over 20-m fibers
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Point-by-point writing (not phase mask!): flexible
- Through coating sensor fabrications.

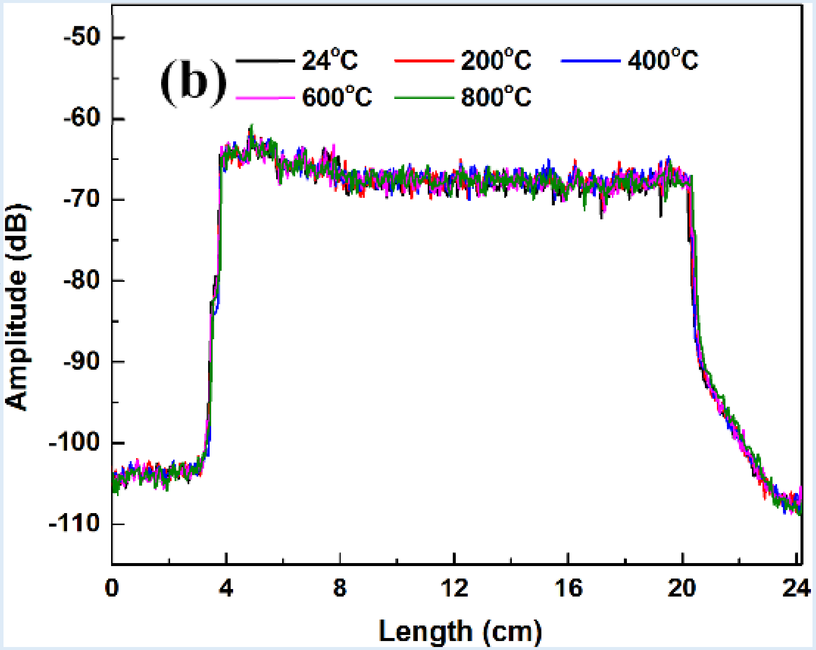
Task 1: H_2 Resilience

- Hydrogen exposure decreases loss < 0.1dB/cm (reaction fast < 10min, Temperature > 700C, Hydrogen > 5%)
- Scattering amplitude increase in hydrogen.
- The scattering change is permanent according to long-term tests.
- Stable at high temperatures.

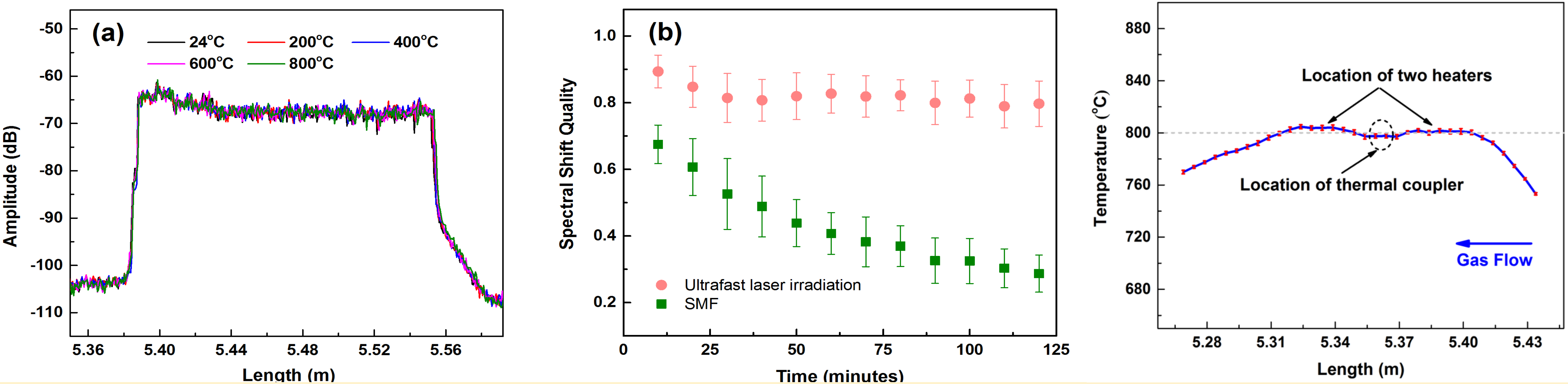








Task 1: Thermal Stability

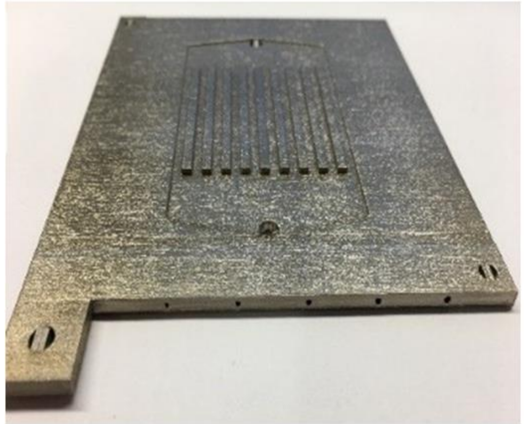


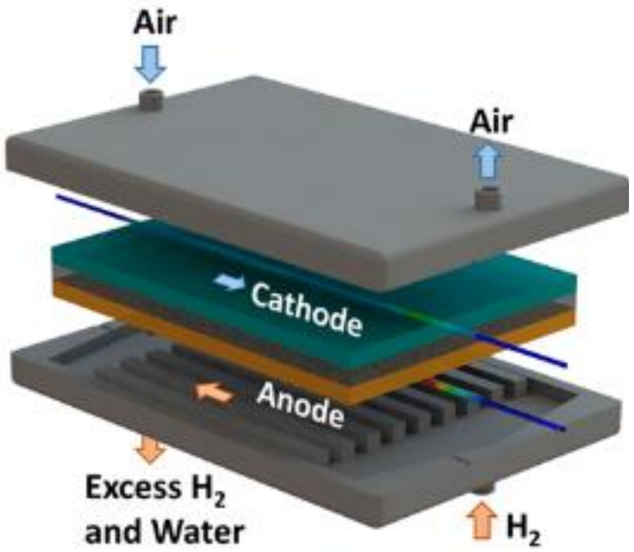
Laser-induced Scattering and Spectral Shift Quality were recorded using OBR unit

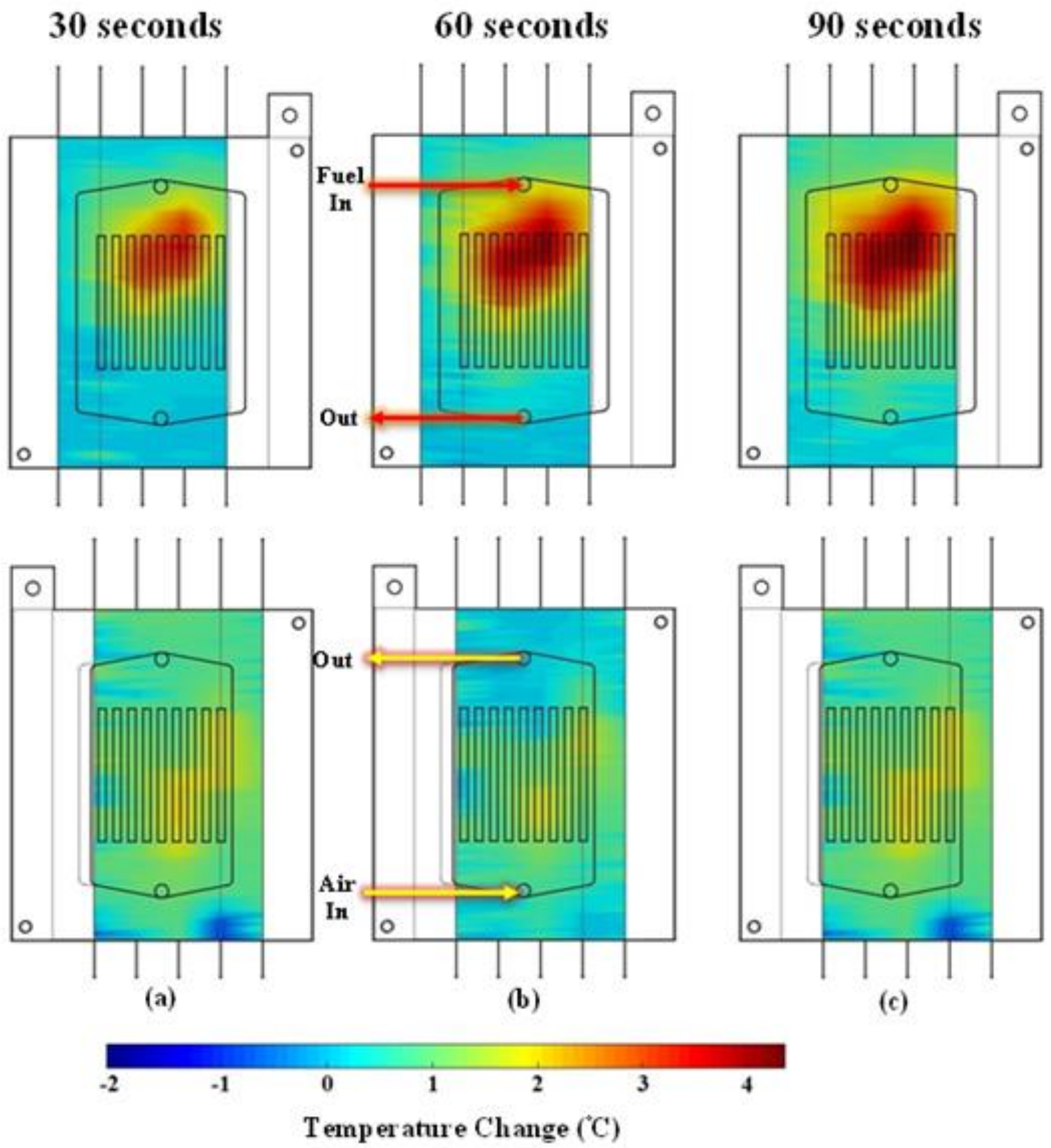
- No significant change of the amplitude in scattering from 24°C to 800°C
- Spectral shift quality was evaluated with reference at 800°C

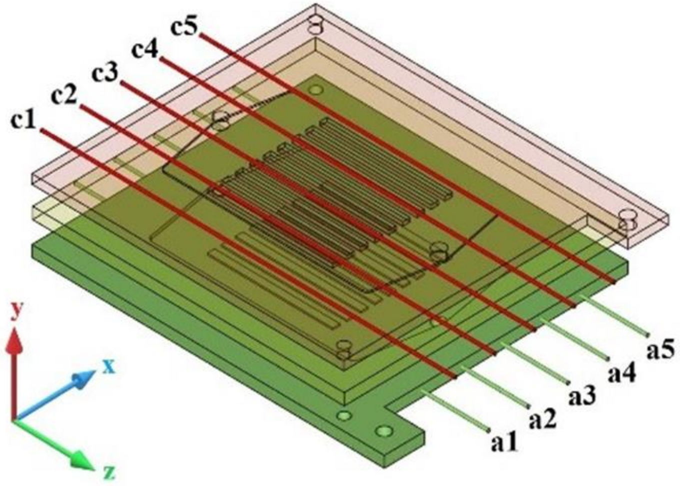
  SMF reduced to below 0.3 after 2 hours, while the enhanced fiber still around 0.8
- Long-term tests show that spectral shift quality of the fiber with enhanced scatter is above 0.7 after 2 weeks.
- Temperature measurements accuracy within 4C from 24C to 800C (thermocouple spec at 9C)

Tested at SOFC 30-cm Interrogation Length



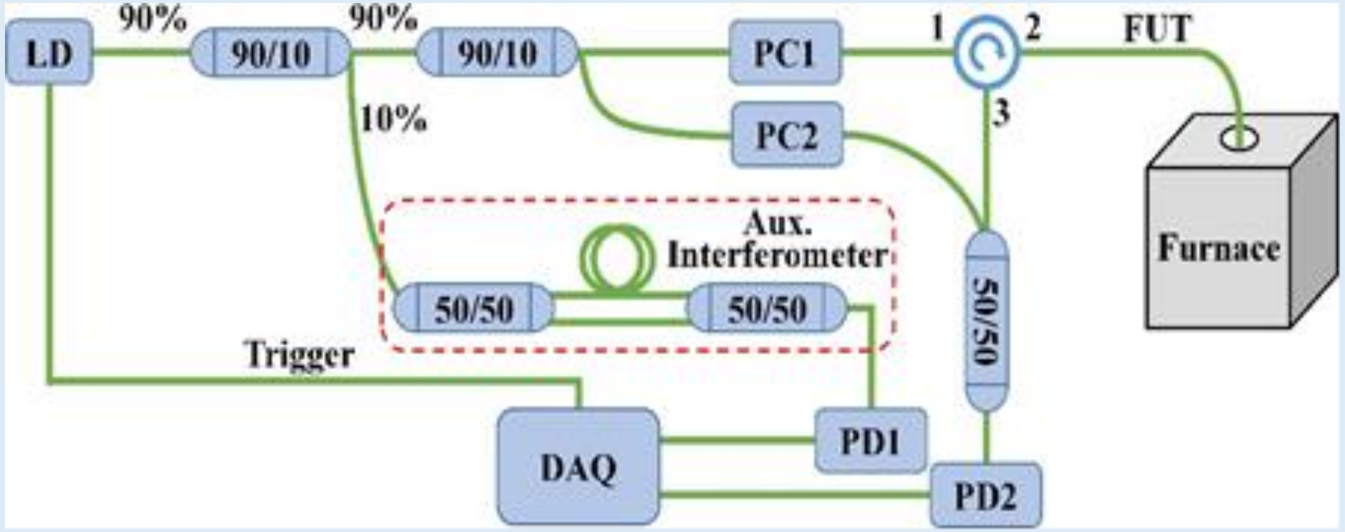






T2M: Low-Cost Sensor Interrogators

- **Commercial Interrogator: $100k**
- **A telecom DFB laser: < $1k**

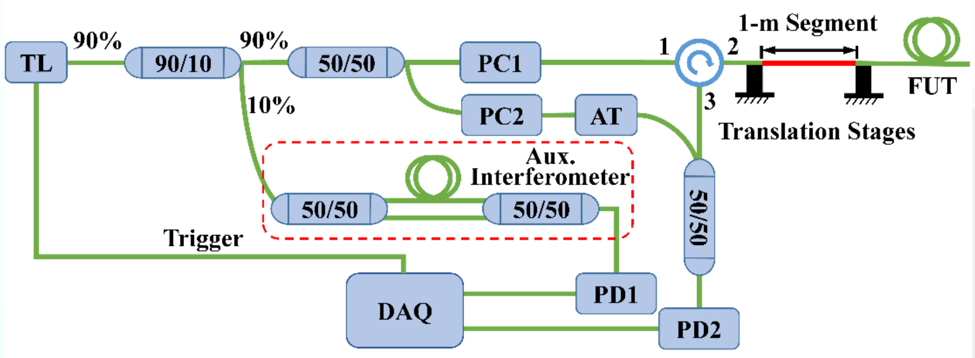


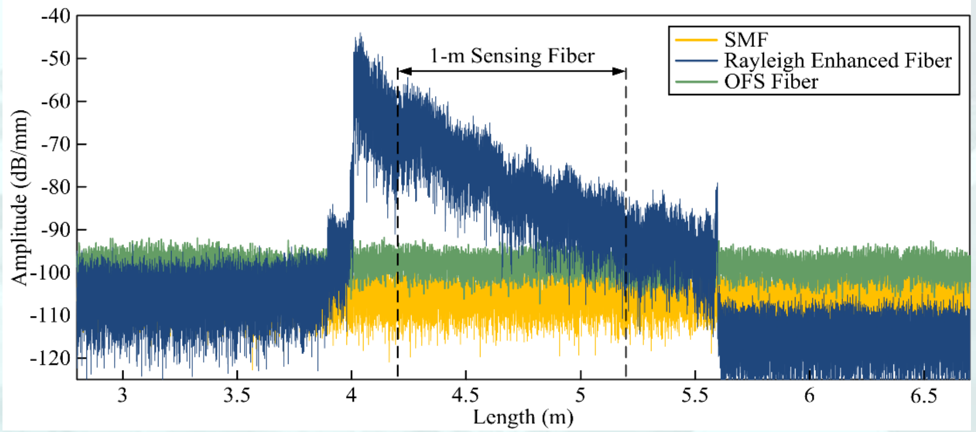
	Conventional Fiber Sensing Schemes	**This Proposal (to use Telecom Optical Transceivers)**
Optical Sources Requirement		
Optical Coherence	20 km	200 meters
Optical Wavelength Tunning	10-nm or more	1nm (current tuning)
Cost	$40,000	$250-$1000
Detector/DAQ Requirements		
Sensitivity of detector	VERY High	Low
Polarization Diversity	Required	No (only 20 m)
ADC	100MS/s	10MS/s
Data Processing Intensity	High	Low
Cost	No	Yes

T2M: Low-Cost Sensor Interrogators

Advantages of –fs point-by-point Fabrication Scheme

- Reduce cost of the interrogation system (potentially by × 5 to 10 times)





Parameter	Our Laser Source	Commercial OFDR
Wavelength sweep range	1 nm (telecom DFB)	80 nm
Laser linewidth (coherence length)	1 MHz (96 meter)	~1 kHz (>10 km)
Two-point resolution	0.8 mm	10-µm
Gauge length	24 mm	5-mm
Cost	~$1k	$40k

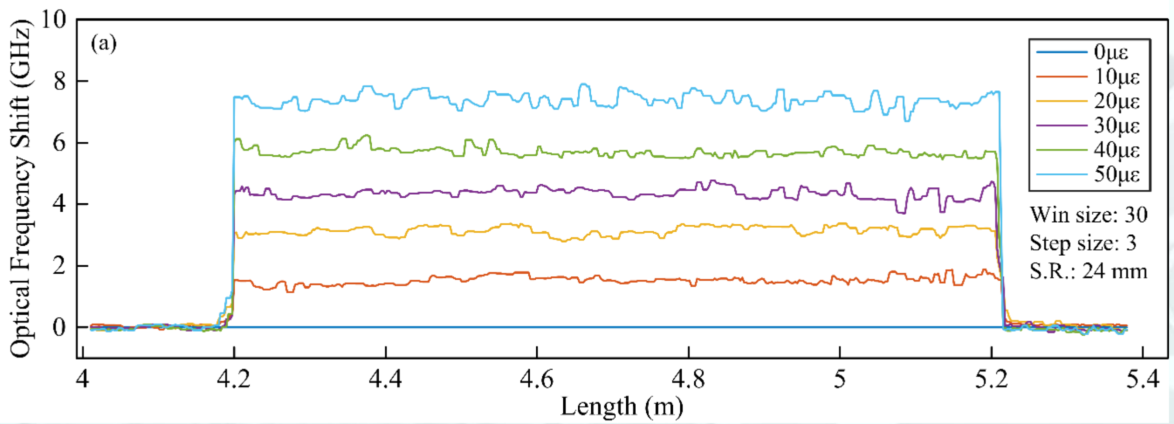
Two-point resolution $$\Delta z = \frac{L}{N} = \frac{c}{2n\Delta F}$$

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

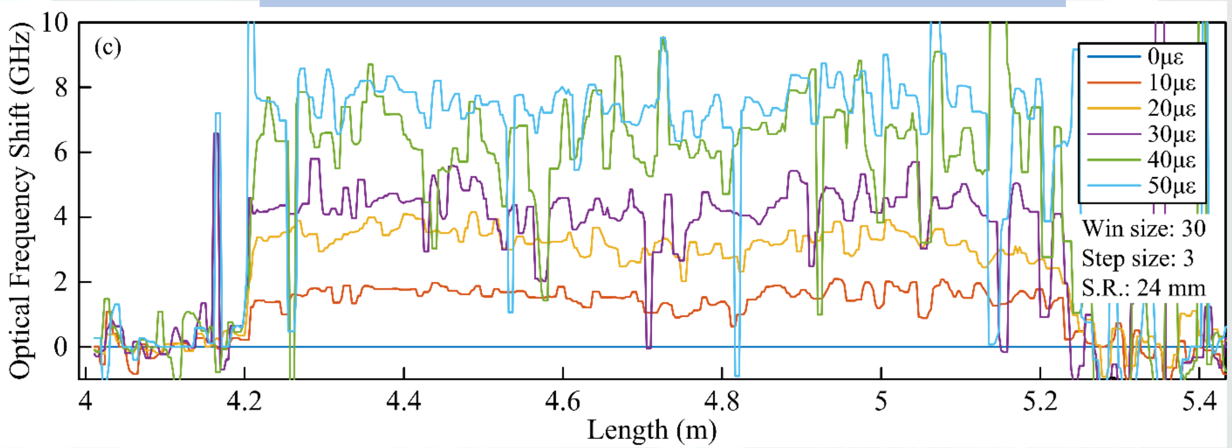
T2M: Low-Cost Sensor Interrogators

- Reduce cost of the interrogation lasers
  - **Laser linewidth: 100-kHz – interrogation length ~400-m (sufficient for energy applications)**
  - **Wavelength tuning: 1-nm two-point resolution drop by 80 times, but our backscattered signal increased by up to 30 dB! (Do NOT need many points to average!).**
- **Do NOT need sensitive detectors - Cost Reduction**
- **Reduce DAQ sampling rate – Cost Reduction**

Rayleigh Enhanced Fiber by fs laser



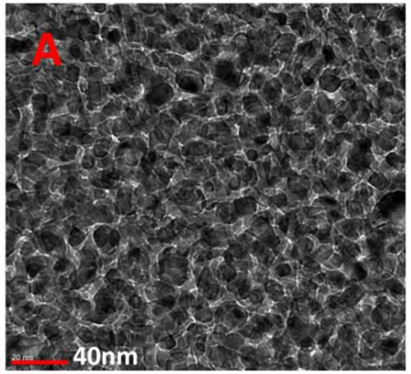
Pristine fiber



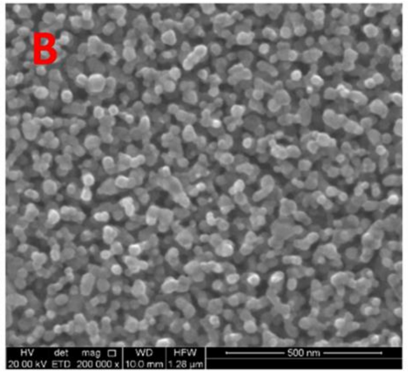
Fiber Optical Hydrogen Sensors

Co-Polymer Templating by F-127:

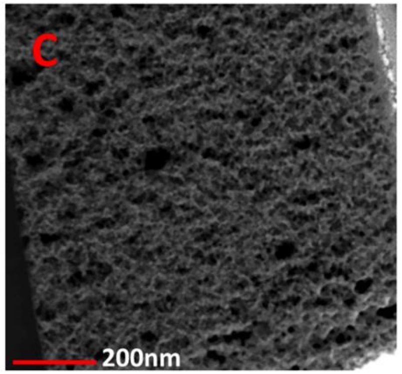
- A triblock copolymer
- Highly Compatible with the Preferred Solvents (Alcohol)
- Has better higher temperature stability



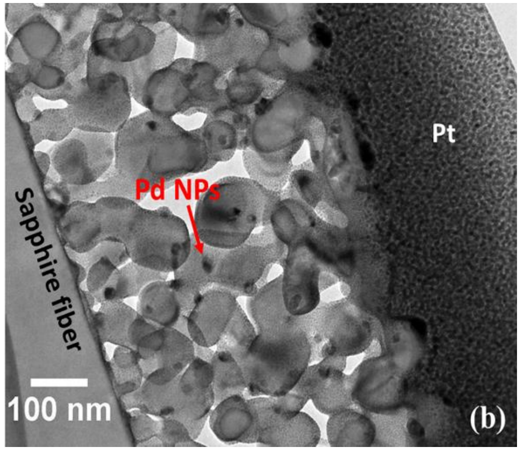
TEM of TiO_2

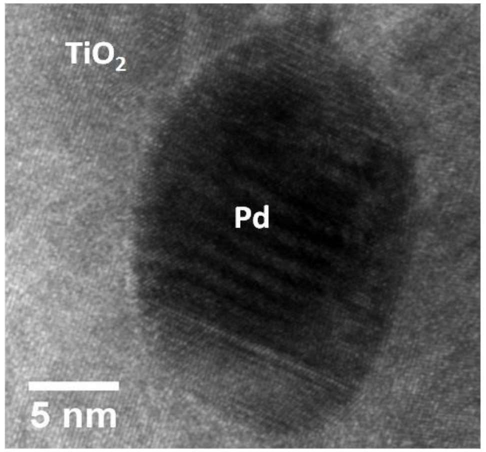


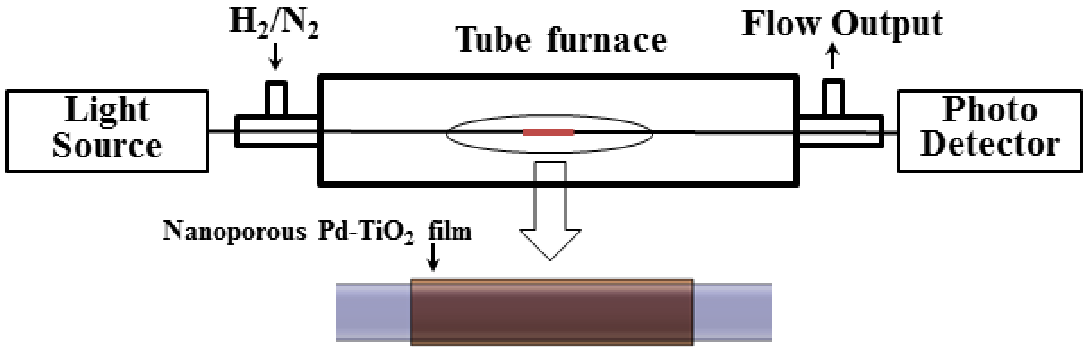
SEM of ZnO

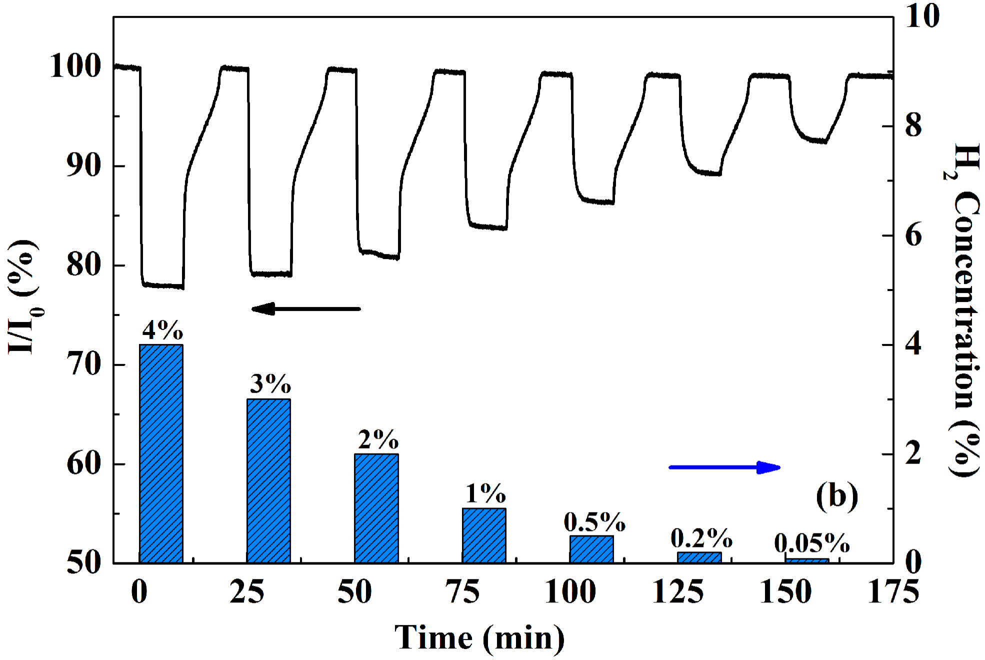


SEM of SnO_2



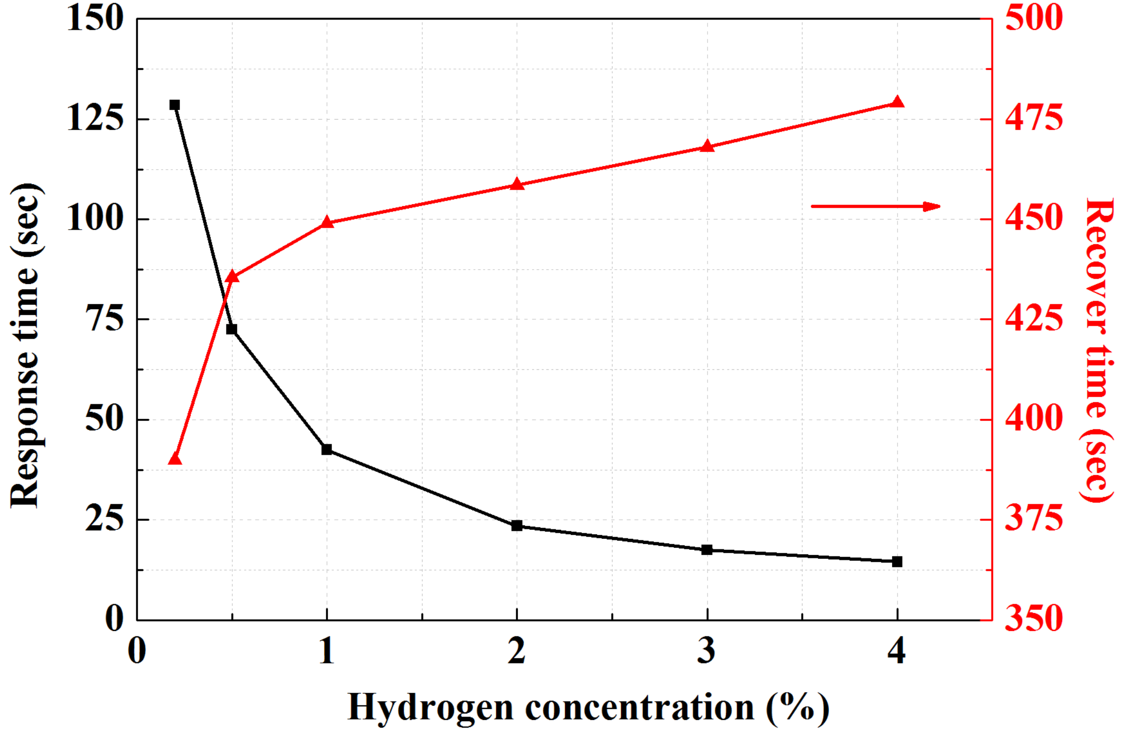


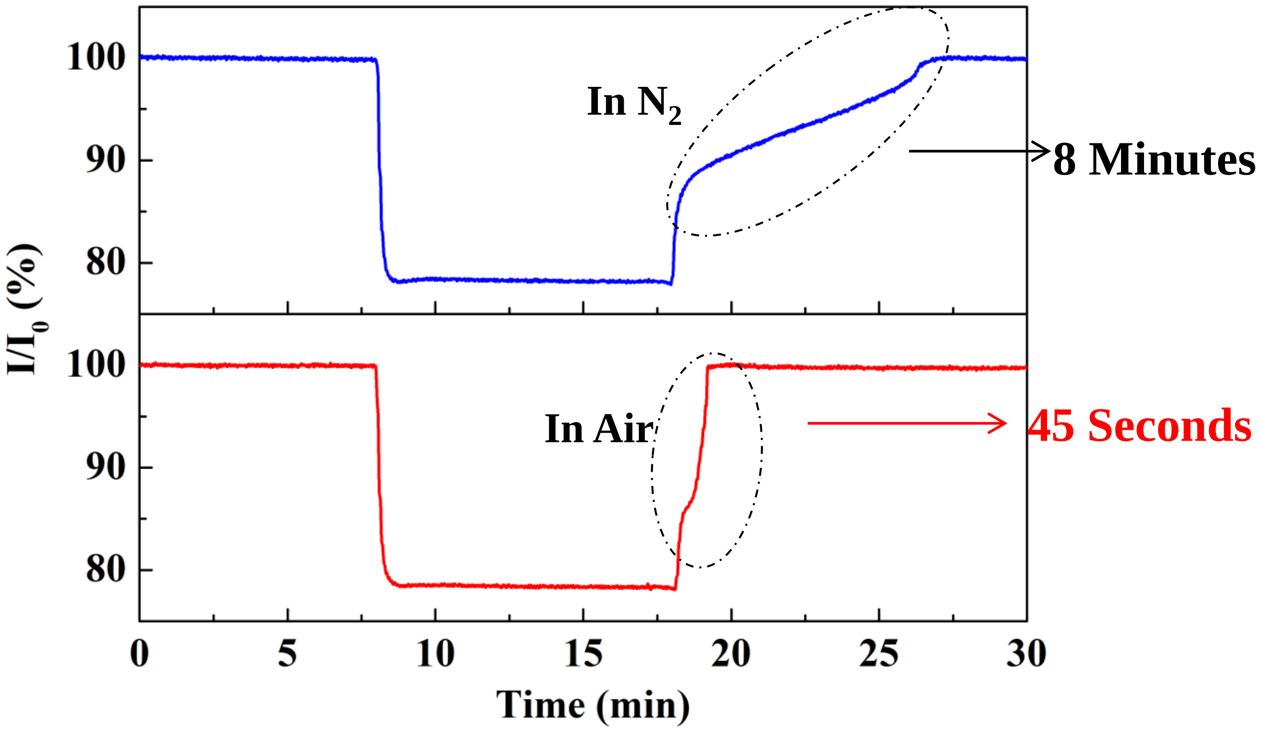




Performance of Fiber Optic Hydrogen Sensor

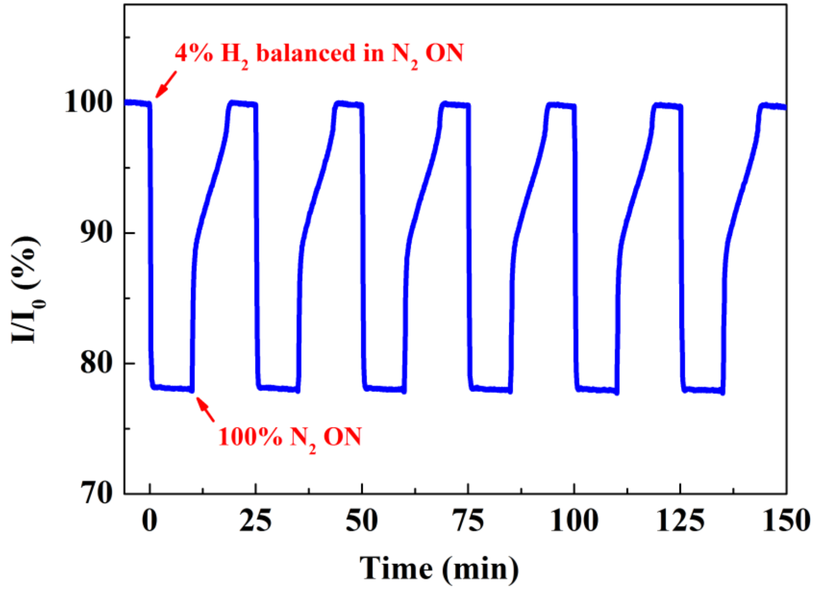
- High sensitivity at high temperatures (800°C)
- Fast response ~13s
- Quick recovery ~8 min(in N_2) , <1min(in air)

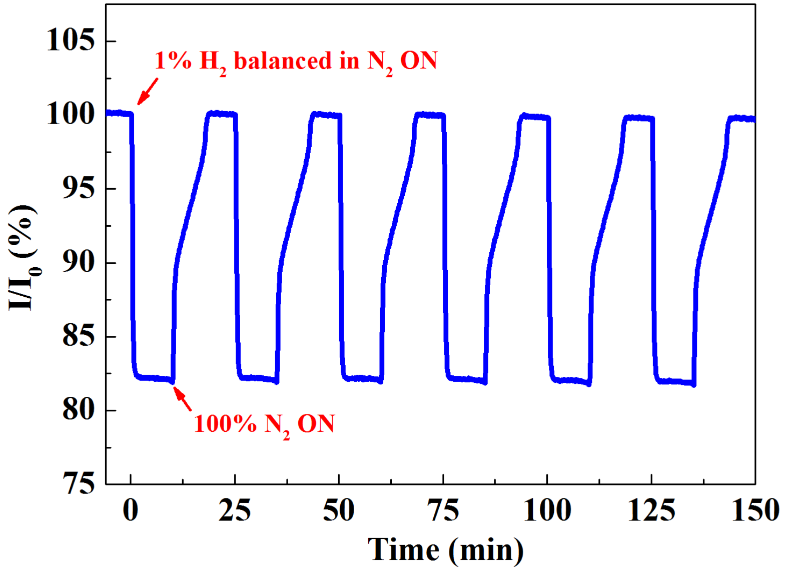




Performance of Fiber Optic Hydrogen Sensor

- **Repeatable test**
- **Stable: test at 800°C for more than 3 weeks**





H_2 Concentration	4%	2%	1%	0.5%	0.1%	0.05%
1st week	21.27%	18.52%	16.00%	13.48%	8.04%	5.78%
2nd week	23.45%	20.38%	17.66%	15.21%	10.12%	7.75%
3rd week	23.39%	20.18%	17.38%	15.02%	10.06%	7.83%

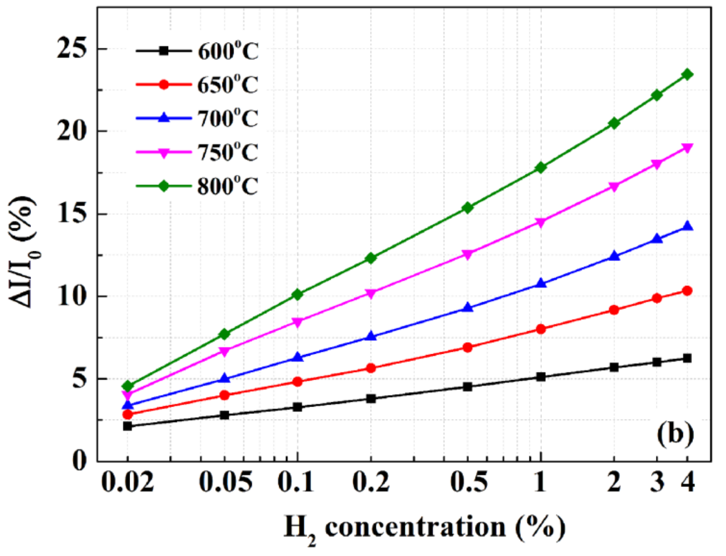
Performance of Fiber Optic Hydrogen Sensor

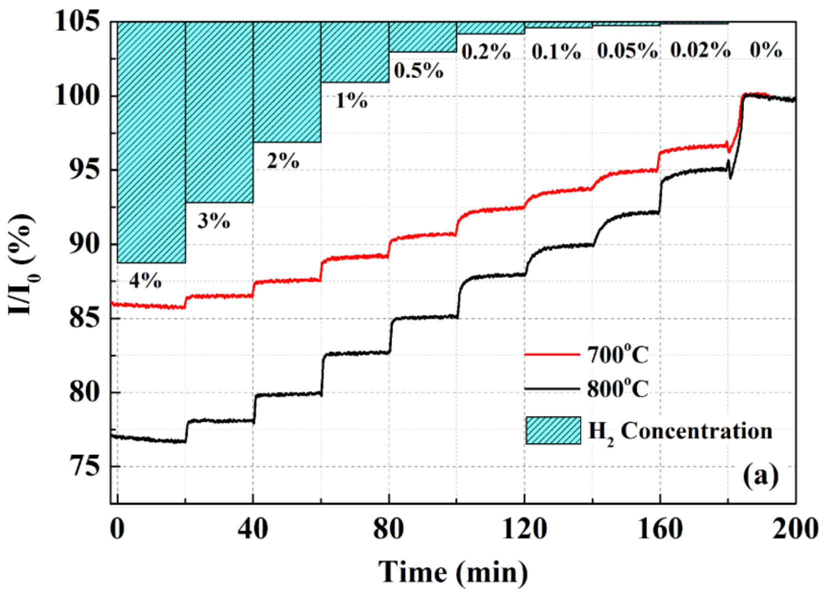
- **High sensitivity at high temperature**
- **Temperature dependency**

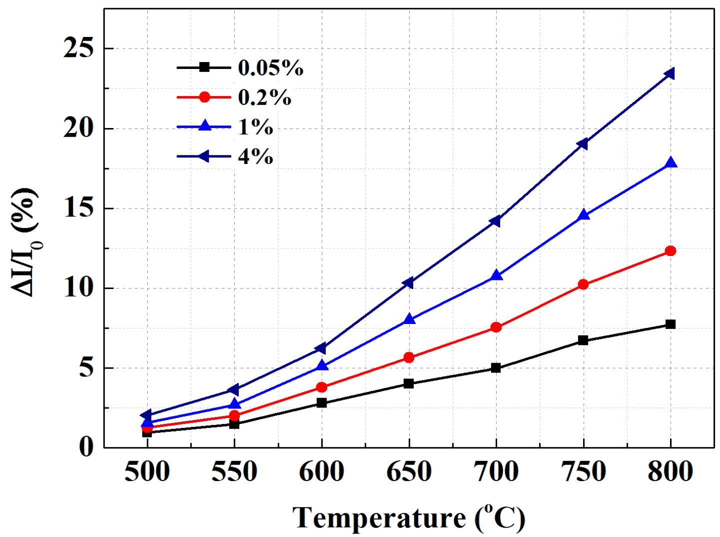
– **Comparison of sensory output for varying concentrations of hydrogen;**

– **Sensitivity of the sensor for the varying concentration of hydrogen evaluated at different temperatures;**

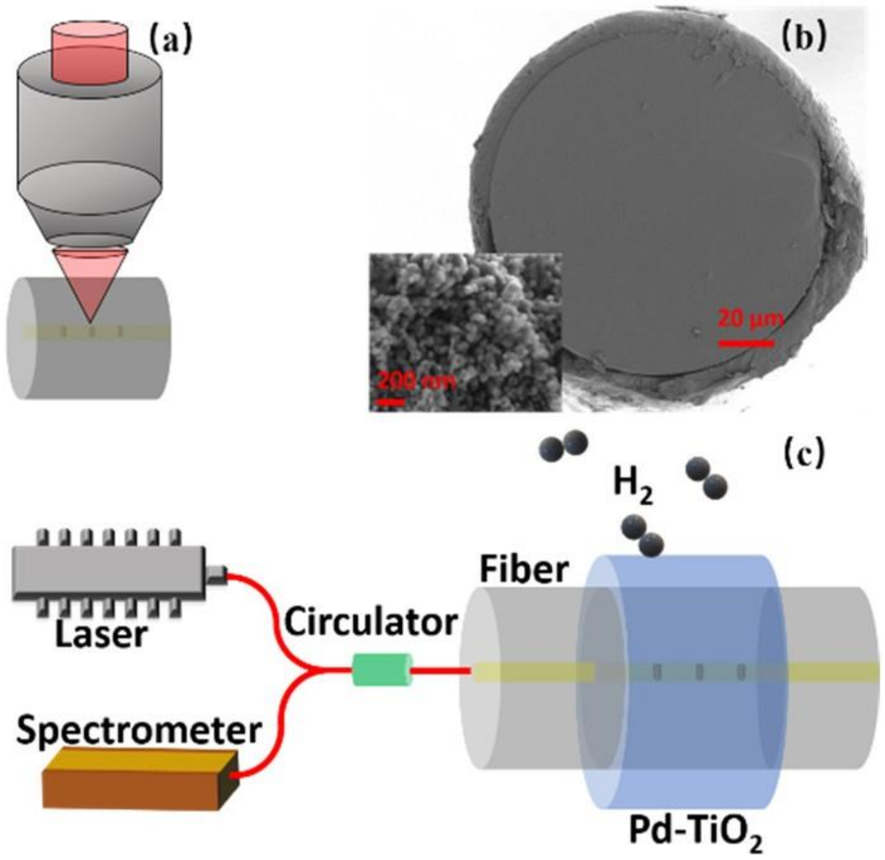
– **Sensitivity of the sensor depends on temperature.**

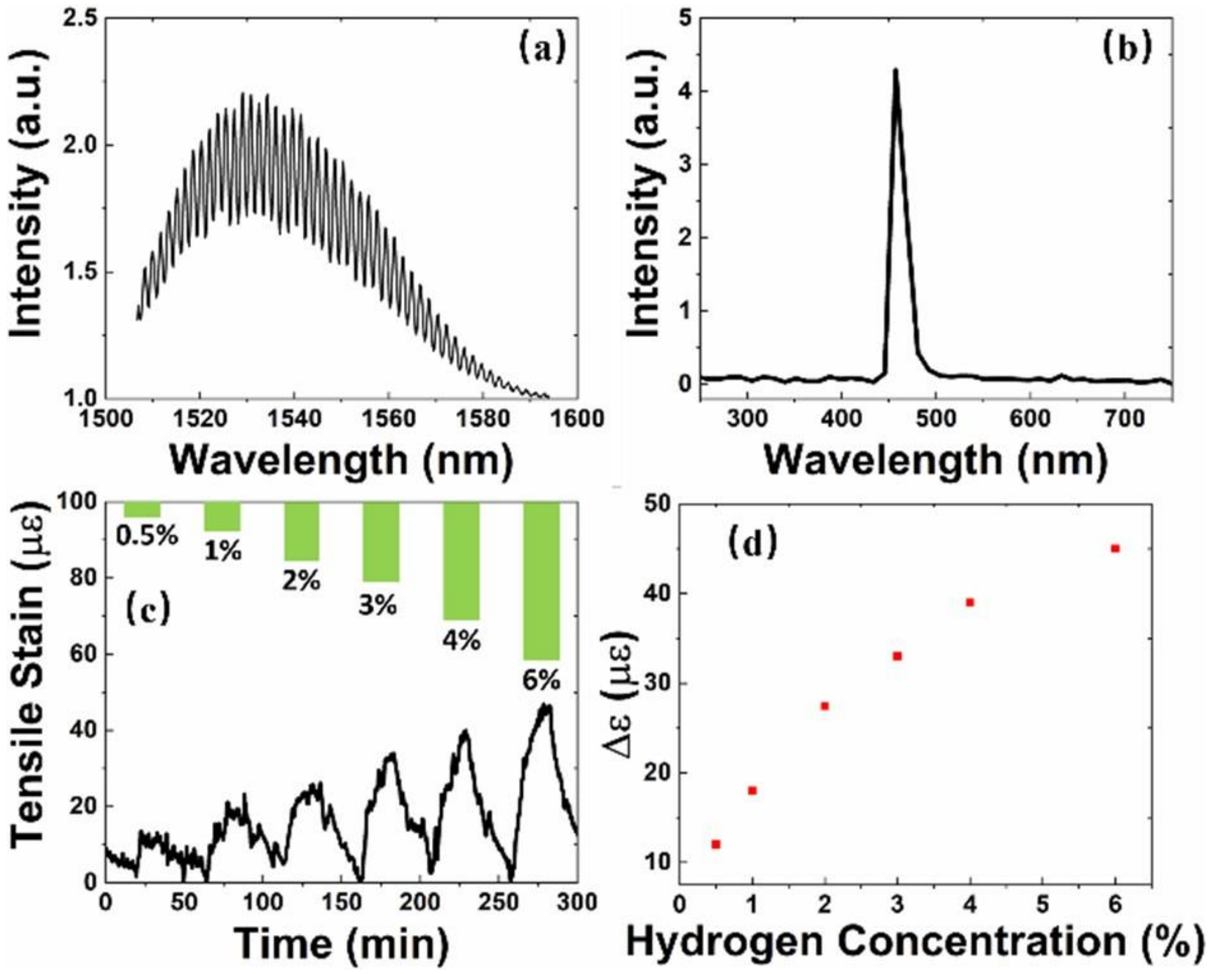






Multiplexed Fiber Sensors: Strain-Based Sensors

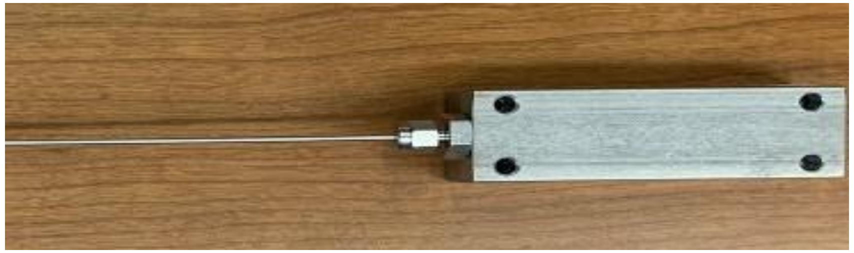




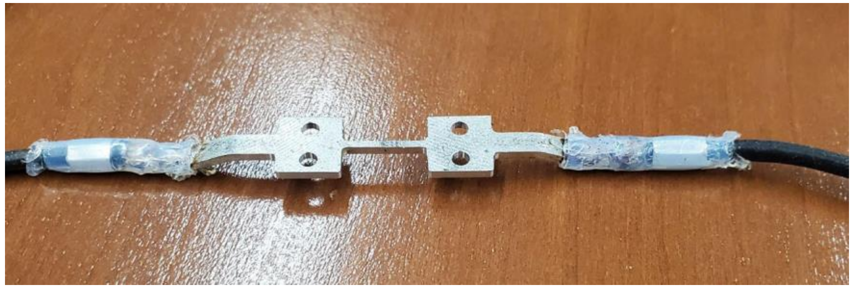
Advanced Sensor Packaging

- **Enable energy users for rapid and straightforward sensor deployments**
- **Smart tapes for pipeline deployments: three sensors for vibration, temperature, and acoustic measurements**
- **Two sensor packaging technique developed for fiber sensor embedding in metal structures**
- **Applicable for a wide range of temperature ranges.**

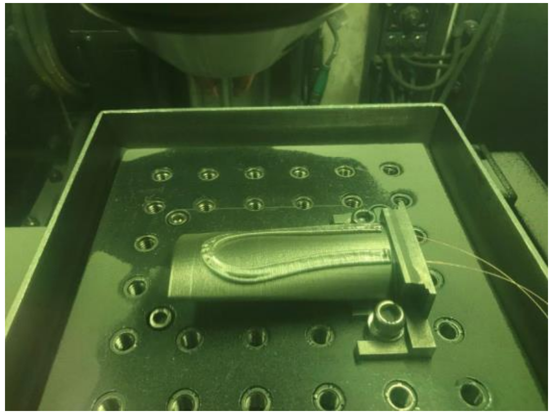
Glass Sealant: High-T up to 800C



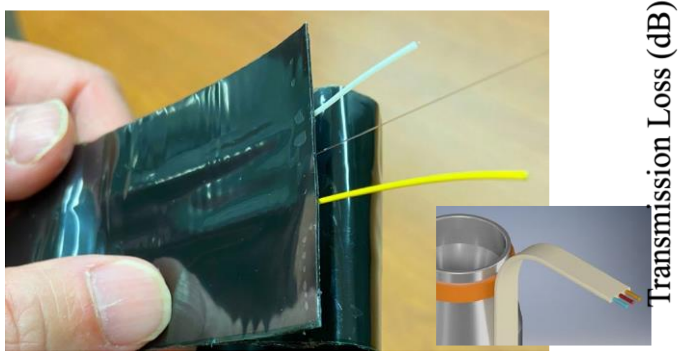
Ultrasonic Additive Manufacturing: up to 400C



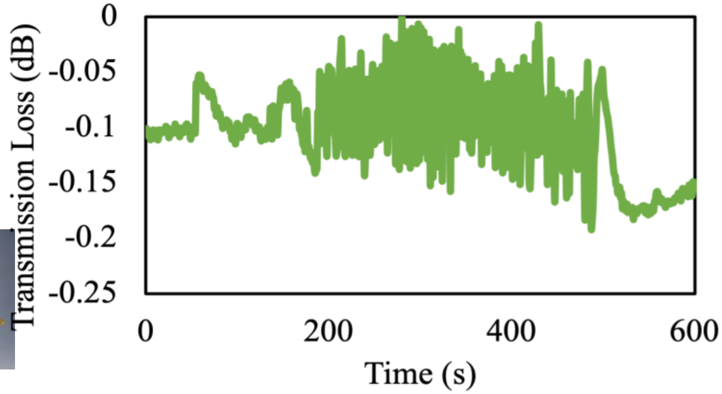
Smart Metal Components



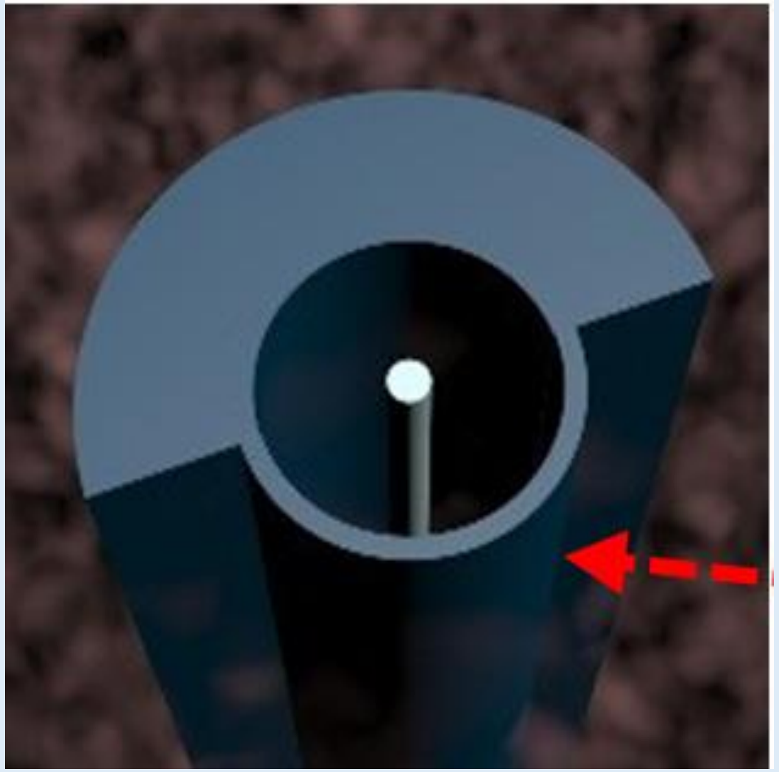
Smart Tapes

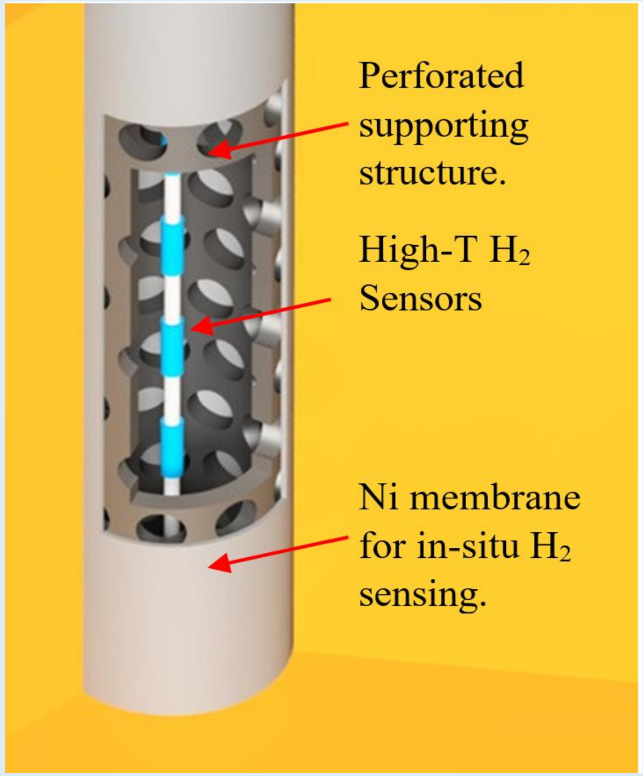


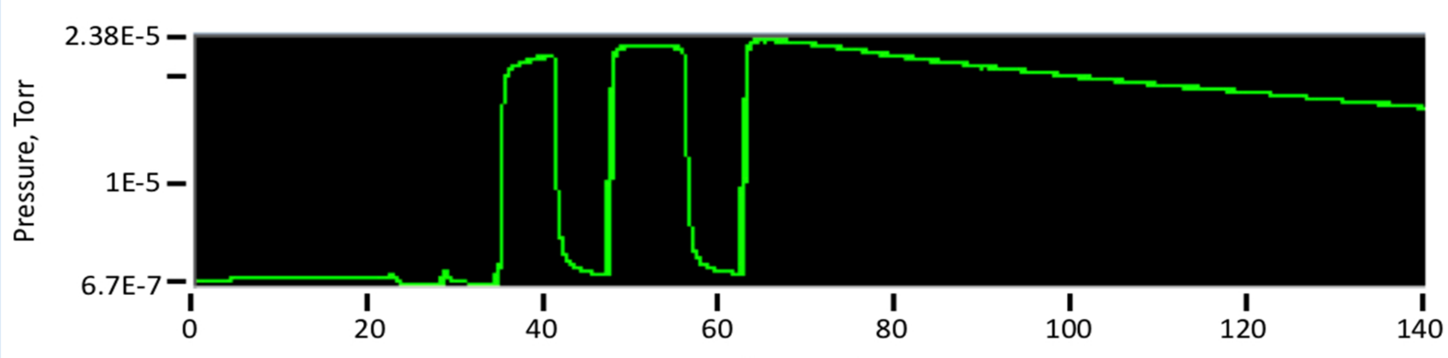
True Strain Free Sensors



Innovative Fiber Packaging







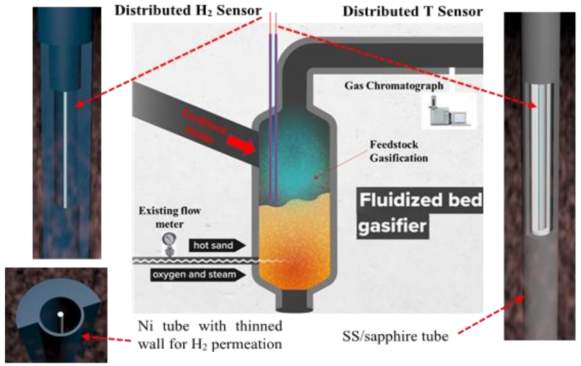
- Gasifiers produce extraordinarily harsh gas environments.
- A large variety of gas species, including strong corrosive gas.
- Nickel membrane machined out of Nickel tube.
- Take advantage of hydrogen high diffusivity.
- Create highly controlled gas environments for hydrogen measurements.
- ANL validated this design for NE applications.

Project Timelines

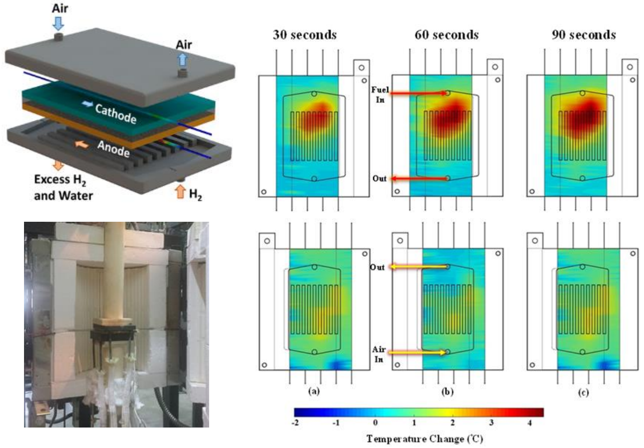
	Year 1			Year 2		
	2	9	12	16	20	24
Task 2.0: Development of stable distributed fiber temperature sensors						
Milestone 1: Successful developments of distributed fiber sensors at least 6-m long to perform high spatial resolution and reliable temperature sensing from 400^{o}C to 900^{o}C.						
Milestone 2: Successful developments of a low-cost sensor interrogation system to meet required specifications (5-cm spatial resolution, 1^{o}C resolution) across 6-m Rayleigh enhanced fibers.						
Task 3.0 – Development of highly stable distributed fiber hydrogen sensors.						
Milestone 3: Successful fabrication of fiber sensors to perform distributed hydrogen measurement from 600 to 900^{o}C across a 2-meter-long sensing fiber. Successfully detects H_2 from 0.5% to 20%.						
Milestone 4: Successful demonstration of H_2 measurements using packaged fiber sensors in a complex gas mix including at least four gas species (e.g., SO_2, H_2, NO_x, CH_4 etc.).						
Task 4.0 – Studies of gasification process using distributed temperature and H2 sensors.						
Milestone 5: Complete fiber sensor testing in an experimental test gasifier.						
Milestone 6: and Final Project Success Criteria: Completing Milestones 1-5 and reaching TRL4.						

Sensors for H_2 **Production, Gasification**, SOFC, Turbines, Infrastructures

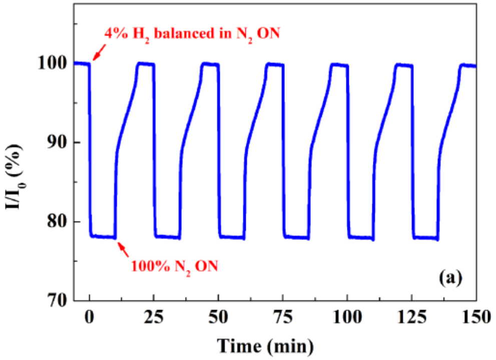
T and H_2 Sensor for Waste Plastic Gasification

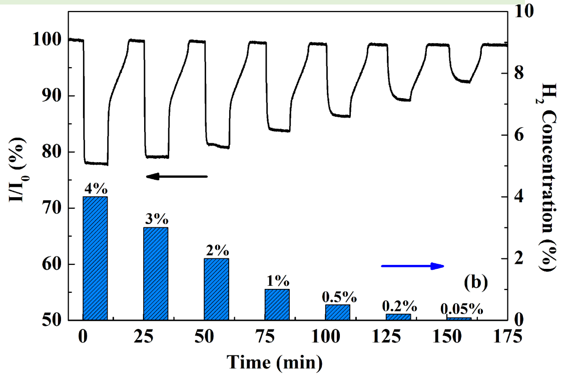


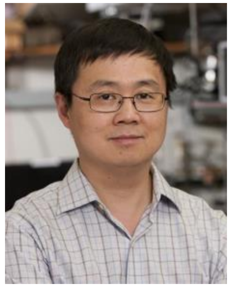
High Spatial Resolution Sensor for H_2 SOFC



Distributed H_2 Sensor: the world-record Operation T (800°C)

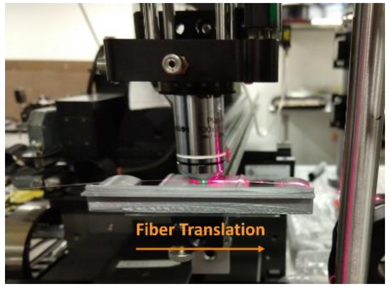






- **Unique distributed fiber sensor technology**
  - 900°C distributed H_2 and T measurements
  - 1-cm T sensing spatial resolution
  - 3-cm hydrogen sensing spatial resolutions
  - 6-m interrogation length in harsh environments
  - Three US patents
  - In-house ultrafast laser sensor fabrication
- **Unique Sensor Packaging for High-T Uses**
- **National Lab Collaborations**
  - INL (plastic waste gasification)
  - NETL (H_2 for SOFC and H_2 generators)
  - ORNL and ANL (H_2 sensing in molten salts)
- **FPGA-base Sensor Interrogation Systems**

_fs_-laser sensor writing



Packaged Sensor

FPGA Sensor Interrogator