UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

# NETL Sensor Technologies Progress Overview


**Presenter: Ruishu F. Wright, Ph.D.**
Research Scientist,
Technical Portfolio Lead
NETL CORE-Sensors Capability Manager
**National Energy Technology Laboratory (NETL)**

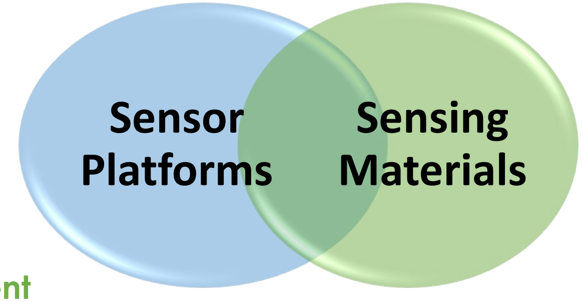


UPitt Infrastructure Sensor Collaboration (UPISC)
2023 Workshop
**November 8, 2023**

# NETL Sensor Expertise and Capabilities for Energy Infrastructure

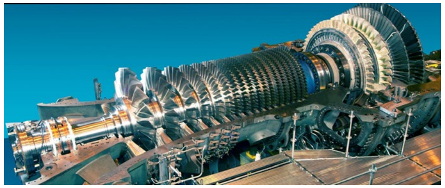
## Advanced Sensors for Energy Efficiency, Safety, Resilience, and Sustainability

- ✓ **Monitor systems and conditions**
- ✓ **Improve performance & efficiency**
- ✓ **Enhance reliability & safety**
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films & fiber optics, sensor devices development




### GENERATION

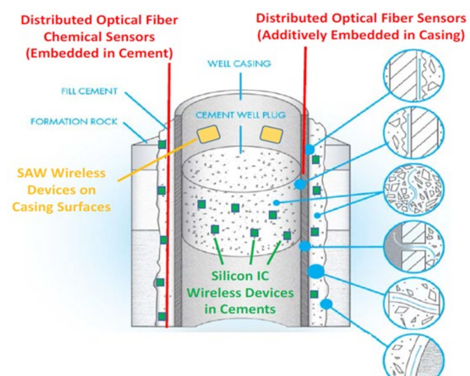
**Turbines:** Real-time fuel composition and combustion temperature for improved service life and efficiency



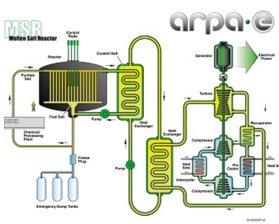
### ENERGY DELIVERY & STORAGE

**Pipelines:** Monitor corrosion, gas leaks, T, acoustics to predict/prevent failures. NG, $H_2$, $CO_2$

**Grid:** Transformer, powerline failure prediction, fault detection, state awareness

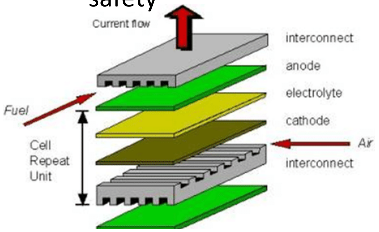



**Subsurface:** Wellbore integrity, failure prediction, leak detection. Geologic storage of $CO_2$, $H_2$/NG, or abandoned wells.




**Nuclear:** Core **monitoring and molten** salt temperatures for reactor fuel efficiency & reactor safety

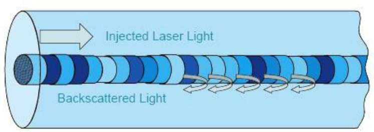
**SOFCs:** Fuel concentration & temperature gradients for improved lifetime and efficiency




# Multiple Sensor Technology Platforms

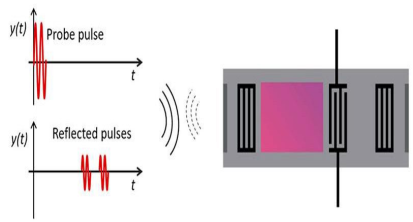
### Long-distance Distributed Optical Fiber Sensors

Imperfections in fiber lead to Rayleigh backscatter:



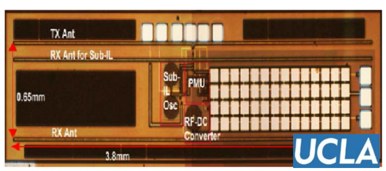

Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

### Passive Wireless Sensors




### Advanced Electrochemical Sensors


### Wireless Miniature Silicon Integrated Circuit (SiIC) Sensors

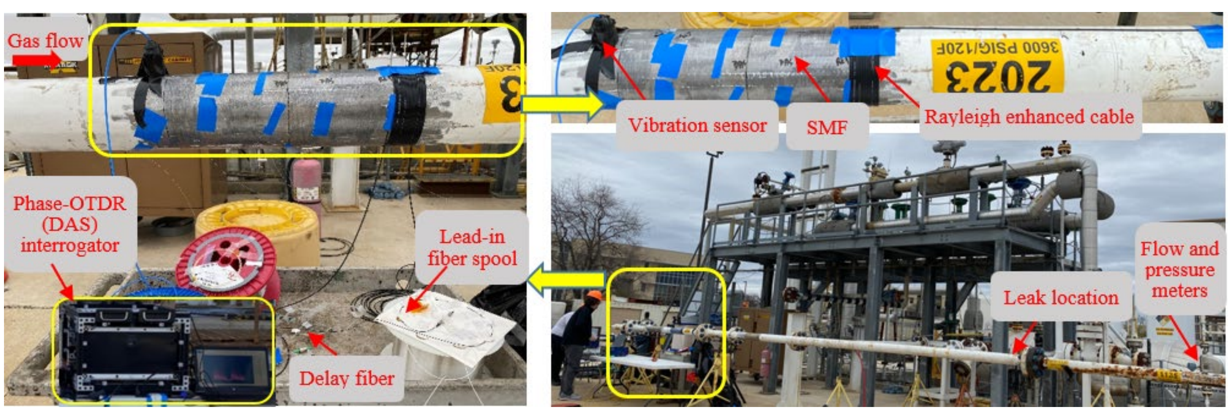



| | Geospatial Attributes | Cost | Targeted Function |
|---|---|---|---|
| Distributed Optical Fiber Sensors | Linear Sensor<br><br>Adjustable Distance and Resolution | Cost Per Sensor "Node" Low | Temperature, Strain, Gas Chemistry ($CH_4$, $CO_2$, $H_2O$, $H_2$,etc.)<br><br>Early Corrosion/pH Detection |
| Passive Wireless SAW Sensors | Point Sensor | Low | Temperature, Strain, Gas Chemistry ($CH_4$, $CO_2$, $H_2O$, $H_2$,etc.)<br><br>Early Corrosion/pH Detection |
| Advanced Electrochemical Sensor | Point Sensor | Moderate | Water Content, Corrosion Rate, T, Pitting Corrosion |
| Wireless Miniature SiIC Sensors | Point Sensor | Low | pH and Chemical Sensing |

**Multiple Sensor Platforms with Various Cost, Performance, and Geospatial Characteristics have been developed at NETL and via collaborations.**

# NETL Sensor Technologies Progress and Achievements
## -Natural Gas Infrastructure

- **Multiple pipeline sensor technologies** were tested at pilot-scale at Southwest Research Institute Testing Facility, including distributed optical fiber sensors and passive wireless sensors for gas flow, pressure, corrosion and gas leak monitoring.
- Distributed fiber/wireless sensor technologies developed at NETL awarded **DOE Energy I-Corps Program Cohort-15.**



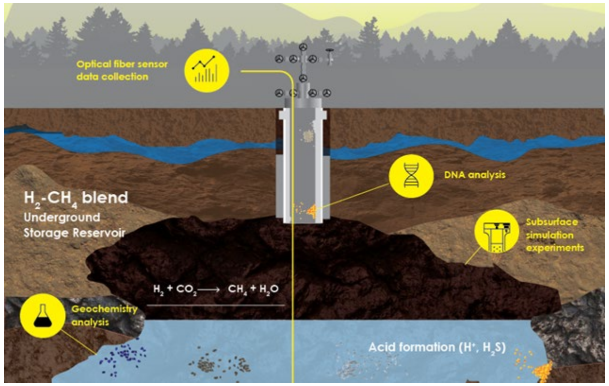

ENERGY I-CORPS
U.S. Department Of Energy

Team 188 Pipeline Sensors

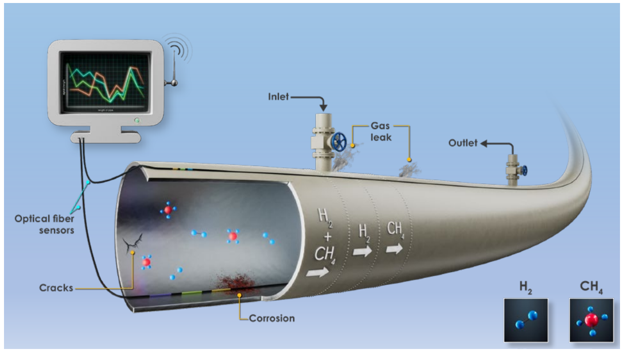
# NETL Sensor Technologies Progress and Achievements
## -Hydrogen Transportation and Subsurface Storage

- Pd nanoparticle (NP) incorporated $SiO_2$ coated optical fiber $H_2$ sensor was demonstrated for a wide range of hydrogen sensing from 0.5% to 100 %.
- A new filter layer was overcoated on the $H_2$ sensing layer to increase selectivity and mitigate humidity interference. Under 99% relative humidity, negligible cross-sensitivity from common cushion gas $CO_2$ or $CH_4$.
- Demonstrated at high pressure (~1000 psi) and high temperature (80 $^oC$), relevant for subsurface hydrogen storage.

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration




**Natural Gas Decarbonization and Hydrogen Technology FWP (NGDH2T)**

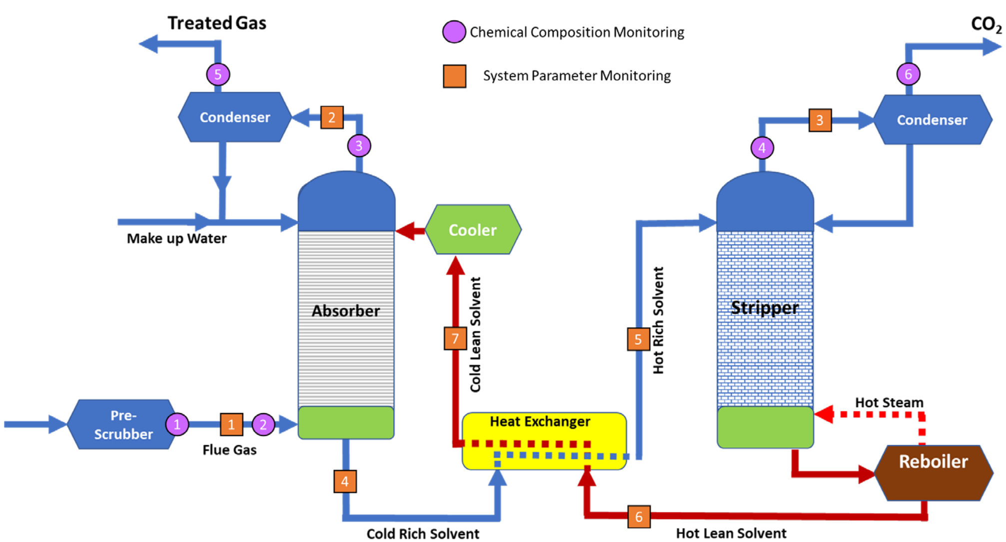



**H2@Scale NREL CRADA**

H2@Scale
U.S. Department of Energy

# NETL Sensor Technologies Progress and Achievements
## -Carbon Capture Amine Degradation Monitoring

- Completed a report reviewing monitoring needs, sensor technology survey, and recommendation for cost-effective online monitoring of amine degradation.
- Identified key indicators for amine degradation as sensing targets.
- Surveyed and selected low-cost existing sensor technologies for these targeted indicators, instead of expensive full-on laboratory chemical analysis.
- Planning for a pilot-scale field test at National Carbon Capture Center (NCCC).



## NETL Sensor Technologies Progress and Achievements
## -Power Grid Modernization

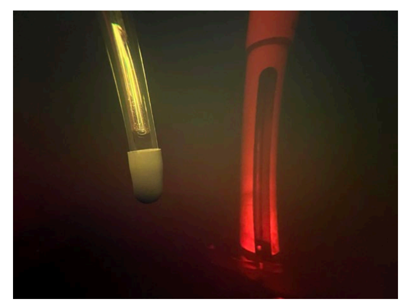
- "Transformer Watchman" developed and matured by NETL, UPitt, and Sensible Photonics won **2023 R&D 100 Award**.
- "Transformer Watchman" is an integrated fiber optics-based sensor system that can monitor dissolved gases, acoustics, and temperatures of transformers simultaneously and continuously to monitor and warn of any dangers that might be encountered.

R&D 100 AWARDS

**Transformer Watchman**

Temperature Sensing of Distribution Transformer

Acoustic Sensing at Medium-voltage Transformer



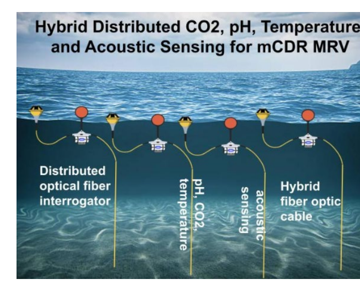
Dissolved Gas Analysis of Transformer Oil

# NETL Sensor Technologies Progress and Achievements

## -Newly Awarded Projects in 2023

- **"Advanced Methane Sensor Demonstration and Deployment"** under NETL's National Emissions Reduction Initiative (NEMRI) in support of EPA Methane Emissions Reduction Program (MERP), to quantify and mitigate methane emissions from oil and gas industry.
- "**Grid Research, Integration, and Deployment for Quantum (GRID-Q)"** funded by Grid Modernization Initiative (GMI). Multiple-lab effort led by ORNL. NETL is leading the **quantum sensing thrust for grid anomaly detection**, collaborating with UPitt.
- "**Hybrid Distributed pH, $CO_2$, Temperature, and Acoustic Sensing for Monitoring and Verification of Marine Carbon Dioxide Removal Applications**" in response to ARPA-e 2023 DE-FOA-0002989, Sensing Exports of Anthropogenic Carbon Through Ocean Observation (SEA CO2). Led by UPitt. NETL is collaborating on chemical and $CO_2$ sensing and fiber optic interrogation system.

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy



# Summary

- Multiple complementary sensor technologies are developed to leverage the advantages of optical, electrochemical, and microwave / wireless sensor platforms, to build an in-situ, multi-parameter, distributed, and cost-effective sensor network, as well as quantum sensor and networking technologies.

- A wide range of sensing materials are developed to achieve high sensitivity, selectivity, and fast response, including MOF, polymers, metallic films, and nanocomposites.

- Sensing parameters:

  **Gas**: $CO_2$, $CH_4$, $H_2$, $O_2$, CO, and other gases;
  **Chemical**: pH, corrosion, water condensation, ionic strength, salinity, REE;
  **Physical**: strain, temperature, vibration, acoustic

- Artificial intelligence-enhanced sensor network with ubiquitously embedded sensors will ultimately achieve desired visibility across the critical infrastructure.

- Advanced sensors and materials for critical infrastructure and extreme high-T environments.

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# PITT Sensor Technologies Updates and Overview


**Presenter: Paul R. Ohodnicki, Jr.**

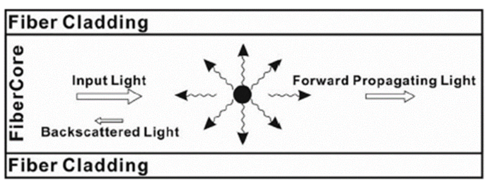
RK Mellon Faculty Fellow in Energy
Swanson School of Engineering
**University of Pittsburgh (PITT)**

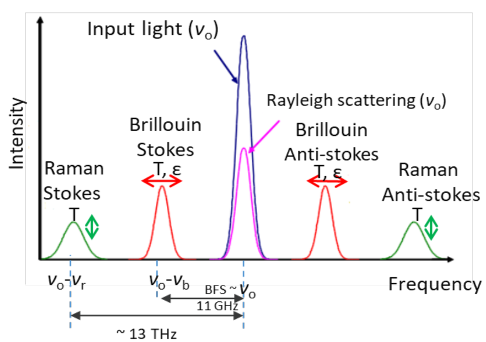

UPitt Infrastructure Sensor Collaboration (UPISC)
2023 Workshop
**November 8, 2023**

# PITT Sensor Technologies Updates and Overview

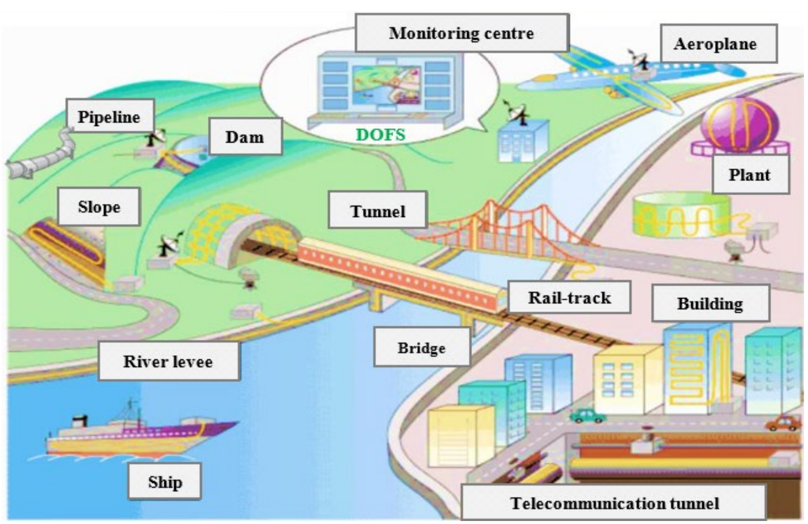
## Distributed Sensing and Infrastructure Monitoring

Scattered light spectrum of optical fiber

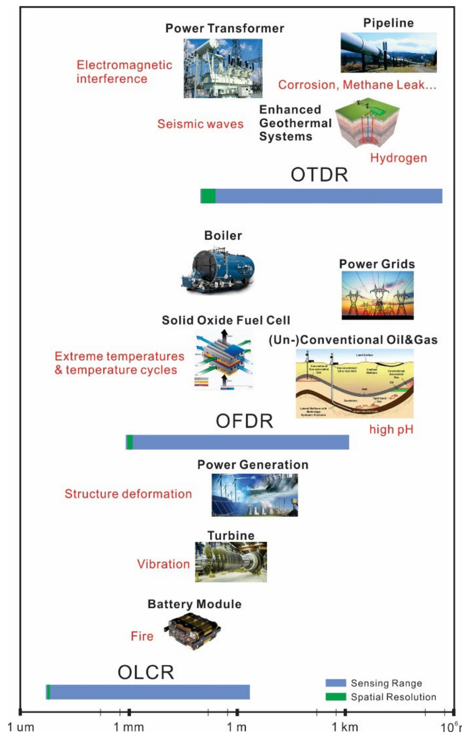



Various Applications




Applied Physics Reviews **6**, 041302 (2019);
https://doi.org/10.1063/1.5113955

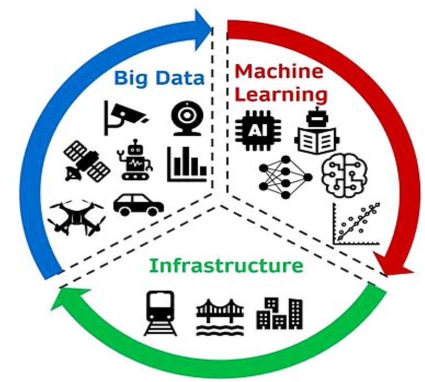


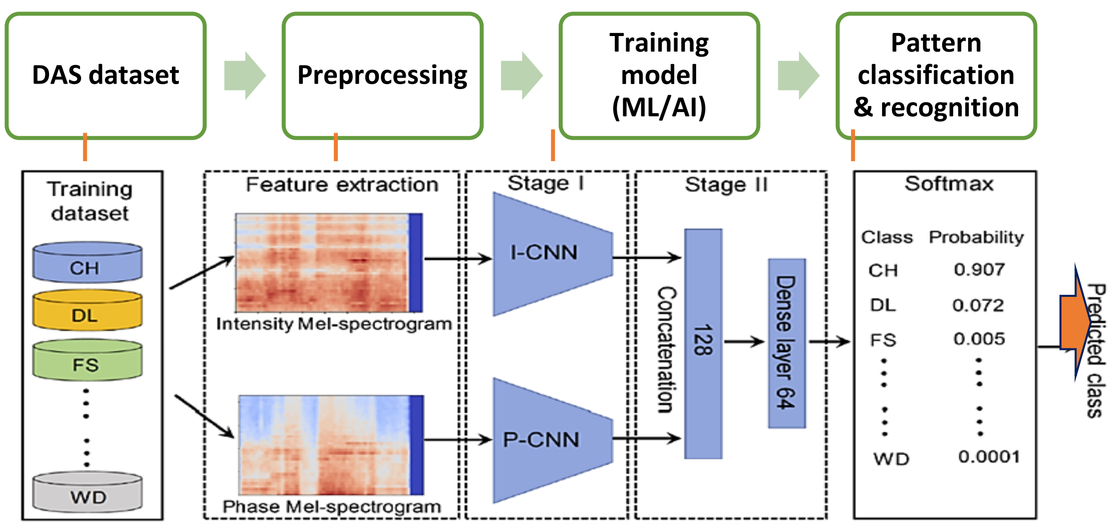

Distributed Sensing Over Different Length Scales

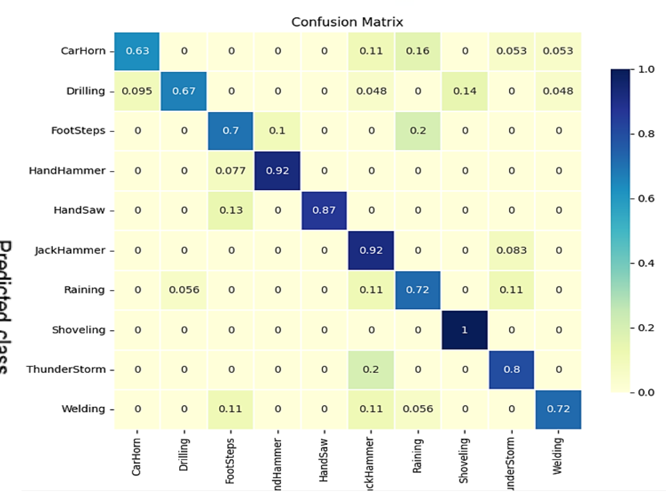

# PITT Sensor Technologies Updates and Overview

## Intelligent Fiber Sensors: A Fusion of DAS & AI

- Infrastructure type: Threats analysis
- High-quality Datasets: Acoustic signatures of various threats/events
- Data processing: Pre-processing and AI/ML models



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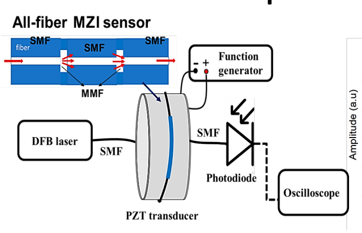
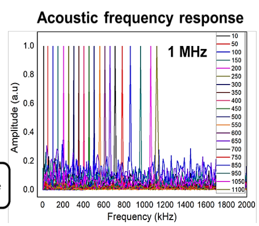
# PITT Sensor Technologies Updates and Overview

## Distributed Sensing Applications @ PITT Ohodnicki Lab

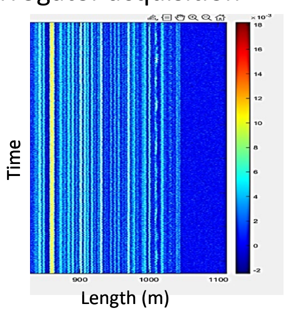
### ❑ Acoustic sensing

- **Point and Multipoint**



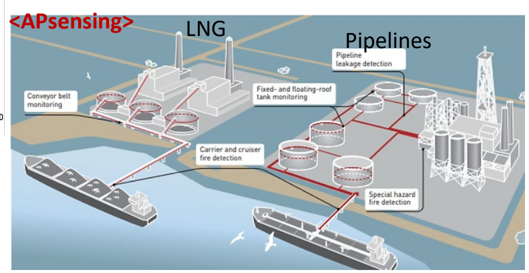



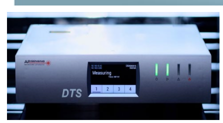

- **Distributed Acoustic Sensor (DAS):**
  - Benchtop Interrogator
  - Commercial Interrogator acquisition

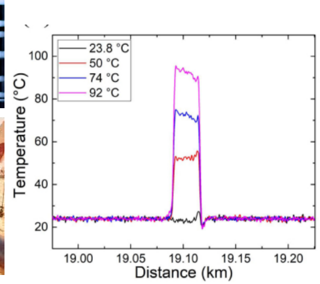

### ❑ Temperature sensing

- Distributed Temp Sensor / DTS: Commercial interrogator



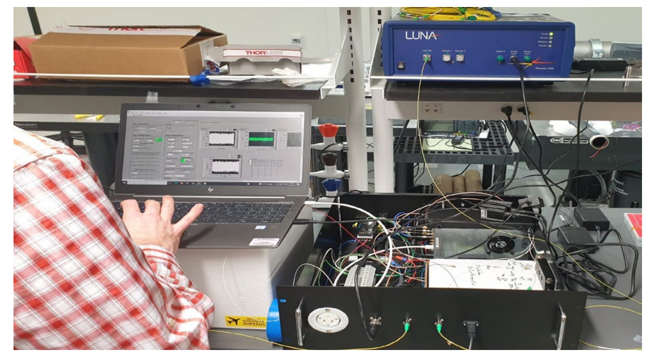



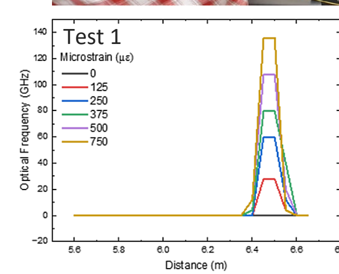


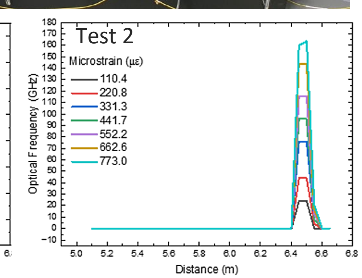



### ❑ HD Strain/Temperature

- Benchtop OFDR.....PITT/NETL



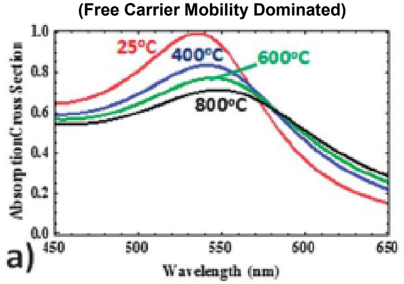

# PITT Sensor Technologies Updates and Overview

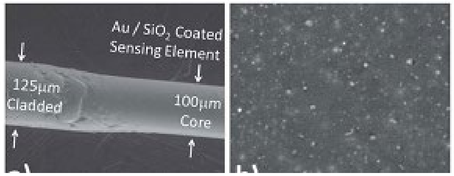
## Functionalized Optical Fiber Sensing @ PITT Ohodnicki Lab

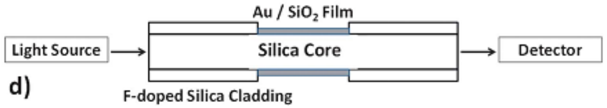
- **Temperature Sensing**

**Temperature Response**

**(Free Carrier Mobility Dominated)**

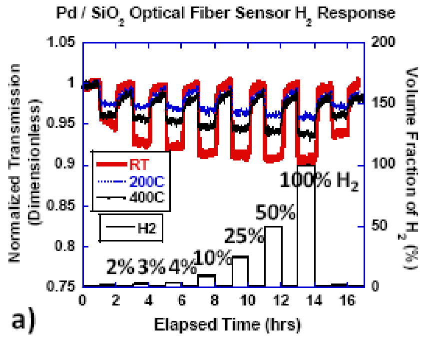


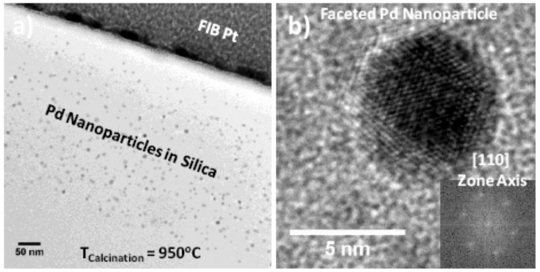




P.R.Ohodnicki et al, Nanoscale 5 (19), 9030-9039 (2013).

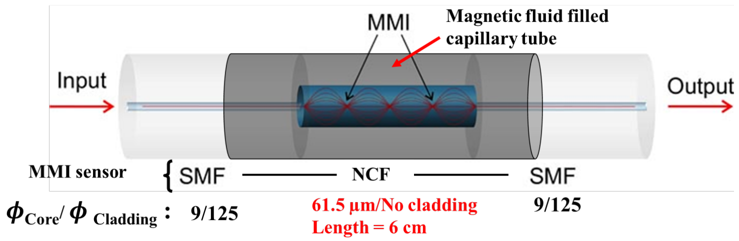
- **Chemical Sensing**

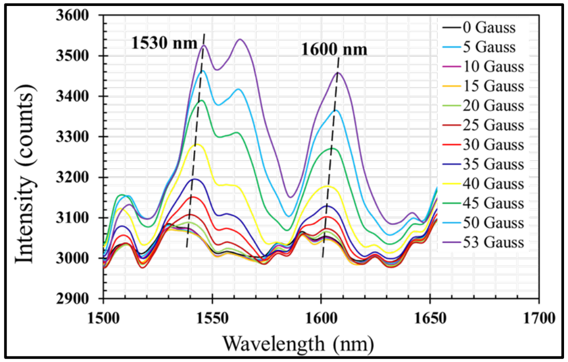



*P.R. Ohodnicki et al. / Sensors and Actuators B 214 (2015) 159–168*

- **Magnetic Field Sensing**



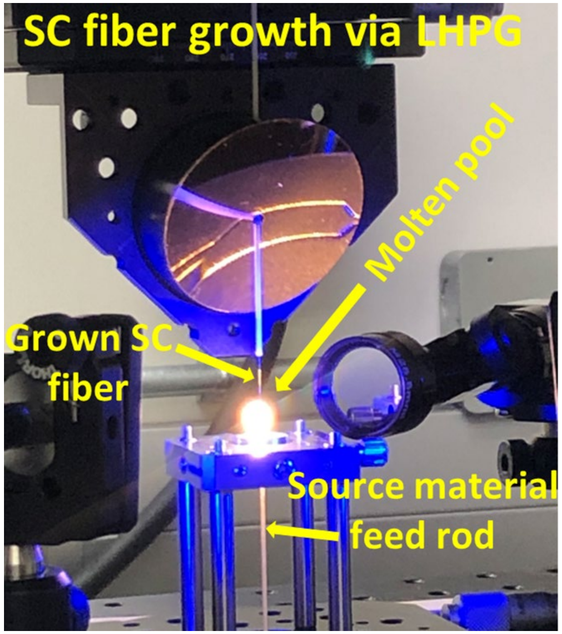




D. Karki et al, Presented at SPIE DCS 2023.

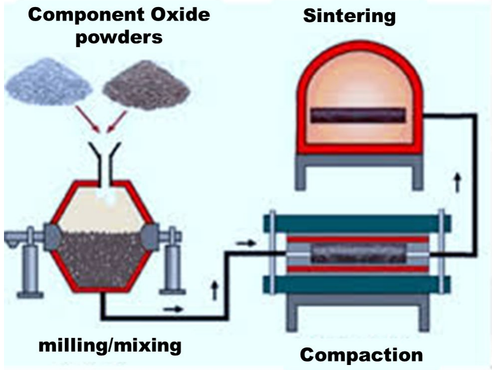
# PITT Sensor Technologies Updates and Overview

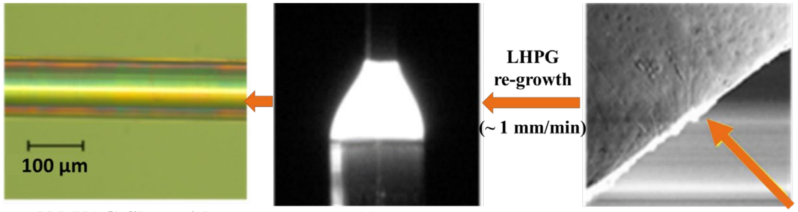
## Single Crystal Oxide Fiber Sensing @ PITT Ohodnicki Lab

- Laser Heated Pedestal Growth




- Functional Crystal Oxides



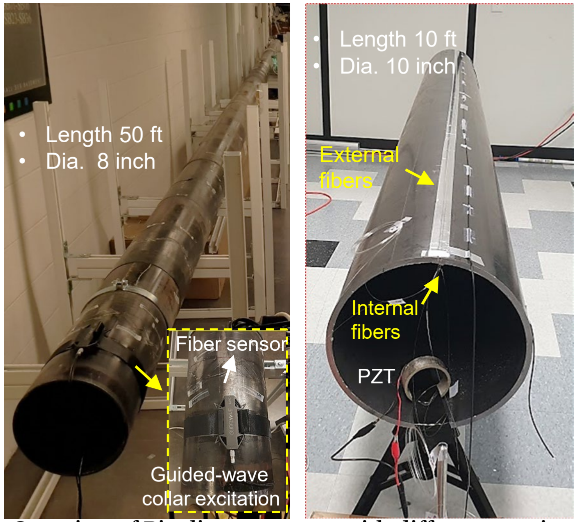




Liu, B., Ohodnicki, P. R., Fabrication and Application of Single Crystal Fiber: Review and Prospective. *Adv. Mater. Technol.* 2021, 6, 2100125. https://doi.org/10.1002/admt.202100125

# PITT Sensor Technologies Updates and Overview

## Example On-Going Work: Fusion of Acoustic NDE + Fiber Optics

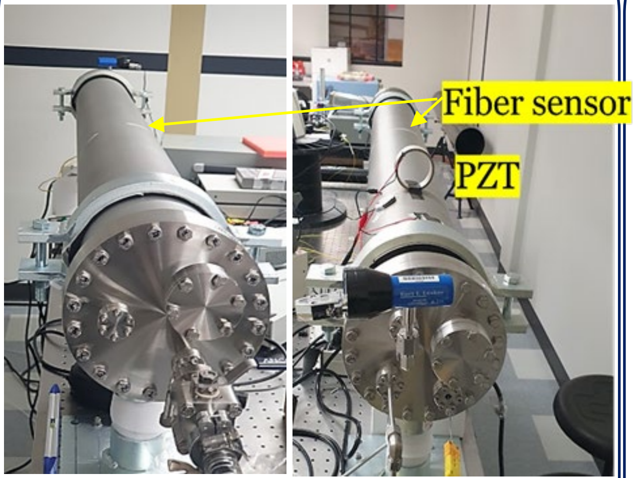
### Pipeline monitoring




Overview of Pipeline test setup with different sensing optical fibers deployed internally using robotic FODT

**Point & Distributed Acoustic Sensing:**
- Structural integrity and degradation
- Natural gas and oil leakages
- SHM: Internal state and corrosion

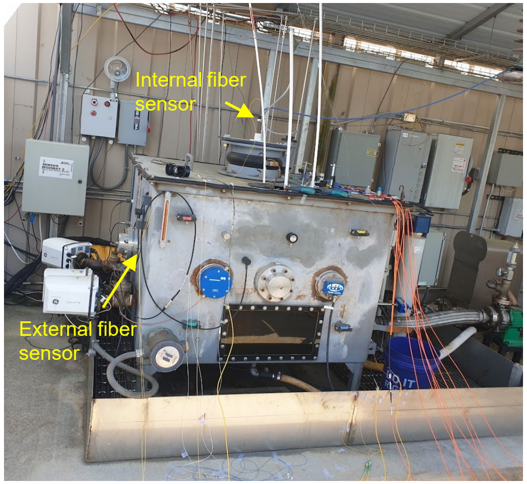
### Nuclear Canister monitoring




Dry Cask Storage System for Nuc. Canister monitoring

**Q-distributed Acoustic Sensing:**
- Internal radio-active leak detection
- Corrosion, gas phase, and temperature monitoring

### Elect. Assets monitoring



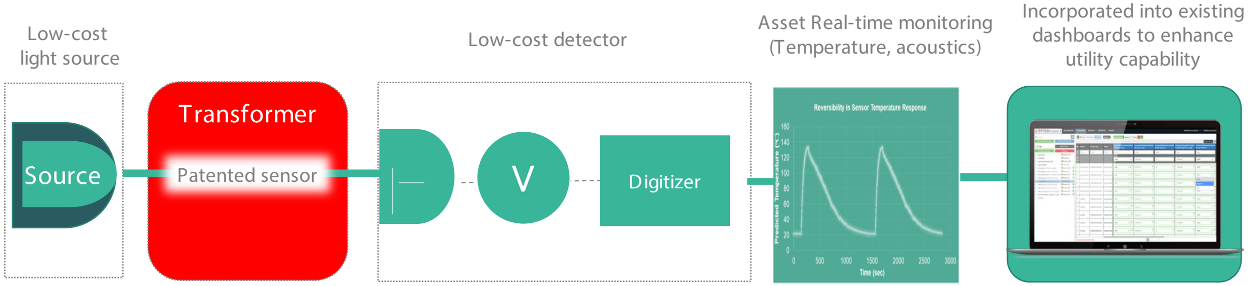

Test setup for Partial discharge detection @ EPRI

**Q-distributed Acoustic Sensing:**
- Partial Discharge detection
- Gas and temperature monitoring


# PITT Sensor Technologies Updates and Overview

## Commercialization and Technology Transfer Activities : Electrical Asset Sensing

### Low-Cost Fiber Optic Sensing Technology

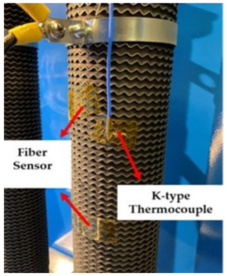


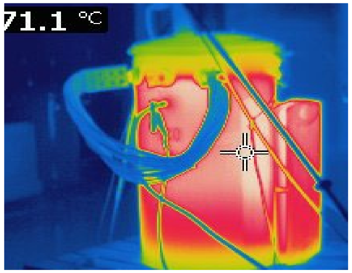

University of Pittsburgh & National Energy Technology Lab Spin-Off

SENSIBLE PHOTONICS

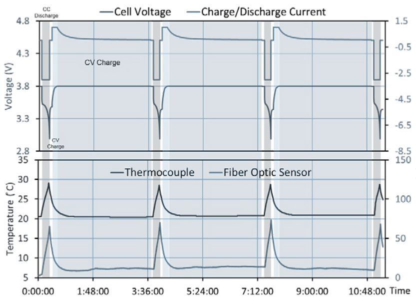
www.sensiblephotonics.com

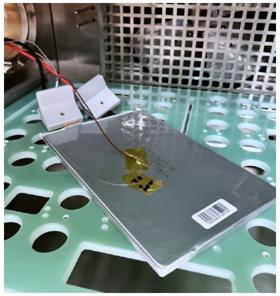
### Electrical & Magnetic Components Sensing (e.g. Transformers)




### Internal and External Battery Monitoring



Pre-Seed Stage : Initiating Fundraise

University of Pittsburgh

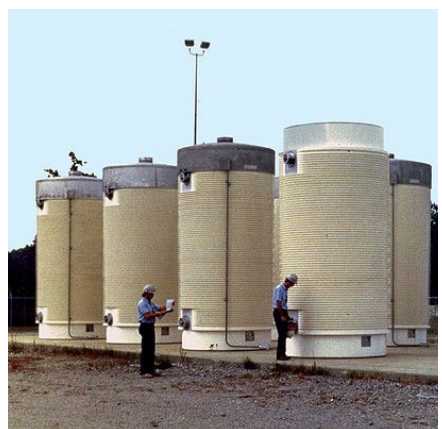
NATIONAL ENERGY TECHNOLOGY LABORATORY

2023 R&D 100 WINNER

# PITT Sensor Technologies Updates and Overview

## Example Major R&D Programs Sponsored at University of Pittsburgh

- ❑ Low-Cost Electrical Grid Asset Sensing + Grid Analytics
- ❑ Spent Nuclear Fuel Waste Facility Monitoring
- ❑ Distribution Pipeline Sensing
- ❑ Marine Carbon Capture (in Negotiaton)



SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

NEUP Nuclear Energy University Program
U.S. Department of Energy

arpa·e
CHANGING WHAT'S POSSIBLE


# PITT Poster Presentation Slide Summaries

UPitt Infrastructure Sensor Collaboration (UPISC)
2023 Workshop
**November 8, 2023**

Contact: Dr. Alexander Star
Email: astar@pitt.edu

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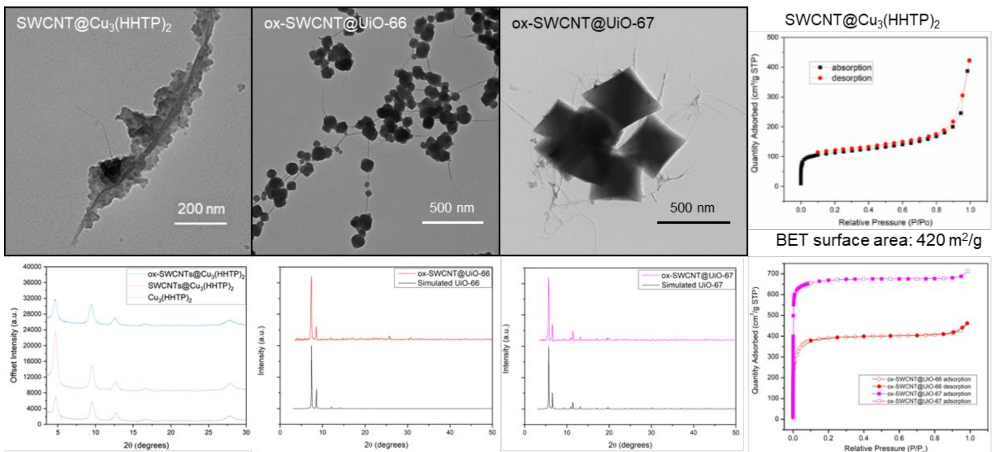
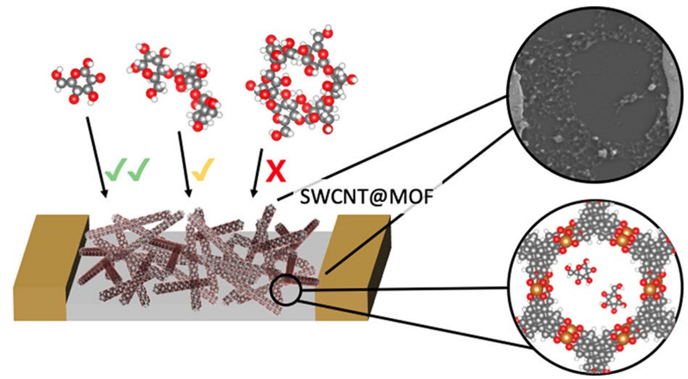
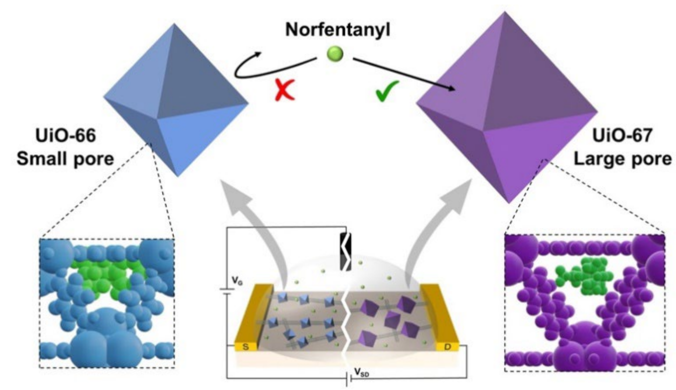
# Size-based Molecule Discrimination and Detection via Single-Walled Carbon Nanotube@Metal Organic Framework Composite Field-Effect Transistor




## Discrimination of homologous carbohydrates




## Electrical sensing of norfentanyl




- Combination of porosity and electric conductivity.
- Novel sensing mechanism for SWCNT-based field-effect transistor sensor.
- Analyte size-based sensing signal.

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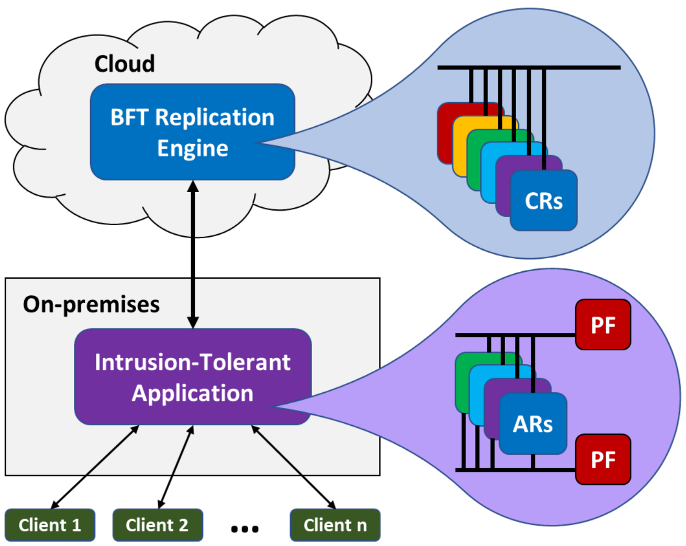
# Simplifying the Deployment of Intrusion-Tolerant SCADA by Leveraging Cloud Resources


**Maher Khan (maherkhan@pitt.edu) and Amy Babay (babay@pitt.edu)**
**Computer Science, SCI, University of Pittsburgh**


- ***Supervisory Control and Data Acquisition (SCADA)*** systems:
  - Monitor and control the power grid
  - Collect and process data from various sensors
  - Face an increasing number of nation-state-level attacks
- ***Intrusion-Tolerant*** SCADA systems:
  - Operate correctly even when partially compromised by an attacker
  - Are complex with multiple sites and many replicas
  - Are difficult to deploy and manage
- Our ***Cloud-based Hybrid Management*** approach:
  - ***System operators*** only deploy and manage their on-premises site(s).
  - ***Cloud providers*** manage additional sites
  - All data in the cloud is encrypted



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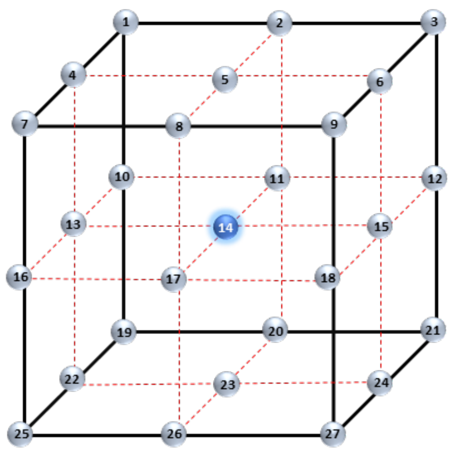
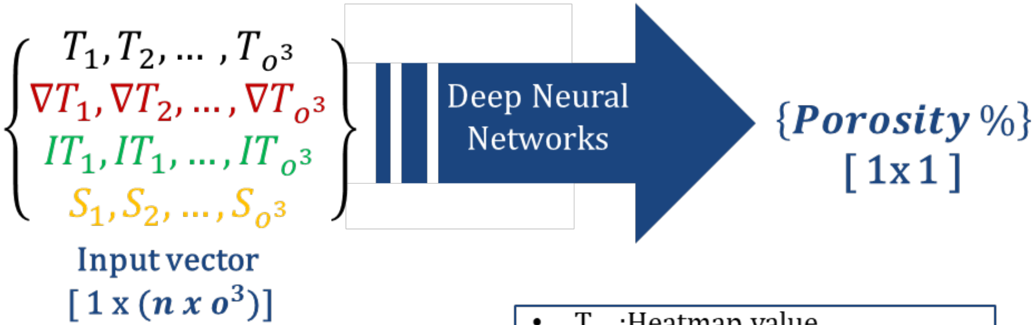
**Data-driven Local Porosity Prediction in Laser Powder Bed Fusion via In-situ Monitoring**

Berkay Bostan (beb171@pitt.edu), Shawn Hinnebusch, David Anderson, and Albert C. To

# Defect Predictor Geometry Independent DNNs




- T :Heatmap value
- ∇T : Cooling rate
- IT : Interpass temperature
- S : Spatter count
- o : Neighbor order
- n : Number of main features

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# ***Using dark fiber can improve seismic monitoring and help predict ground acceleration.***

***Monitor local region for unusual seismic activity.***

***Estimate local ground acceleration.***

***Monitor atmospheric and hydrological storm activity.***

**Monitor earthquake and tsunami activity.**

**Understand the earth system better.**

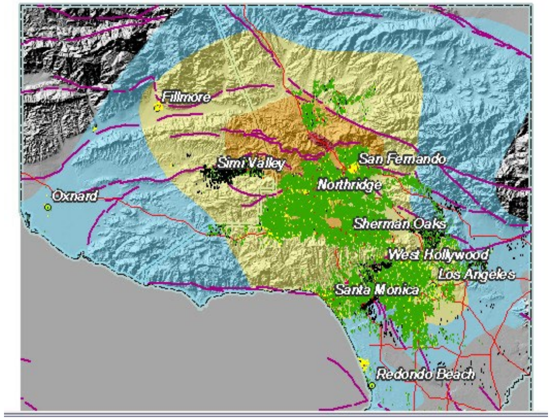
## Plate Tectonic Motion of Pittsburgh


North America
Tectonic Plate motion
Pittsburgh

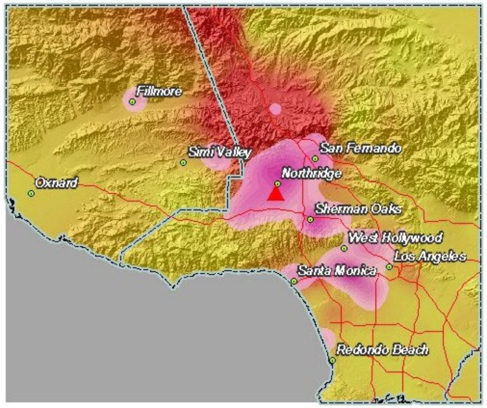
| **Rate of movement** | **Direction of movement** |
|---|---|
| **14.93 (mm/yr)** | **272.41°** |
| **(*1.24 mm/mo*)** | |

*Fingernails grow about 3 millimeters a month*

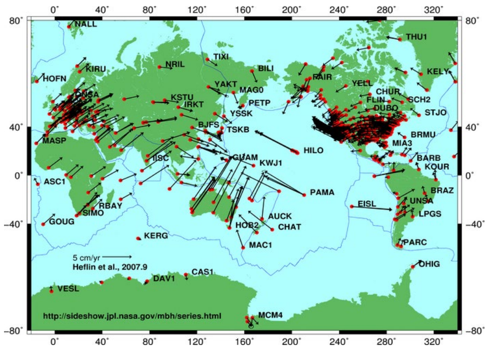
Northridge building damage



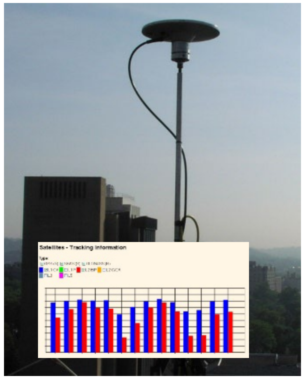

Northridge ground acceleration




Global Positioning Satellite (GPS)
Plate Motion Data




Pittsburgh CORS GPS Station: PAAP



Contact: Paul Kyros Advisor: Jingtong Hu
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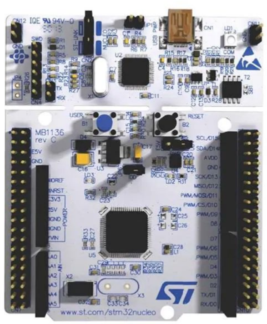
# Machine Learning on Intermittently Powered Microcontrollers

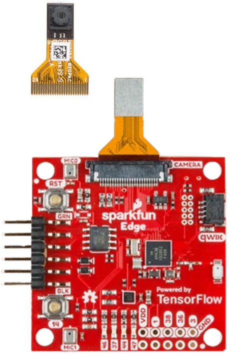
Paul Kyros, Yukai Song, Christopher Brubaker, Inhee Lee, Jingtong Hu

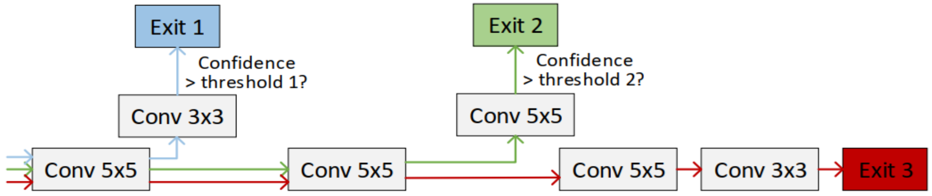


- Adapting Neural Networks to low-power microcontroller boards to perform image detection on images
- Uses a STM32 Nucleo-64 board (Top Left) to run inferences
- Uses a SparkFun Edge board (Red) to capture images
- Powered by a solar panel and charge and fire circuit
- Inferences are run using a Multi-exit Convolutional Neural Network (Shown Below)
- Chooses Exits based upon power conditions of the system

## Contributions

- ***Intermittent Inference Model*** guarantee an inference result before power failure occurs
- ***Power Trace-Aware Compression*** of multi-exit networks to fit onto MCUs while maximizing the average inference accuracy
- ***Runtime Adaptation*** selects the exit for each event, considering the EH environment and difficulty of processing each event




Multi-exit neural network

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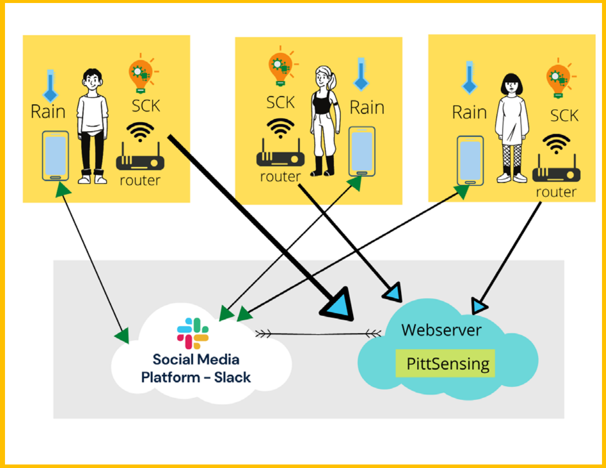
# Social Sensor Network: A distributed hyper-local network of low-cost air quality sensors and community scientists

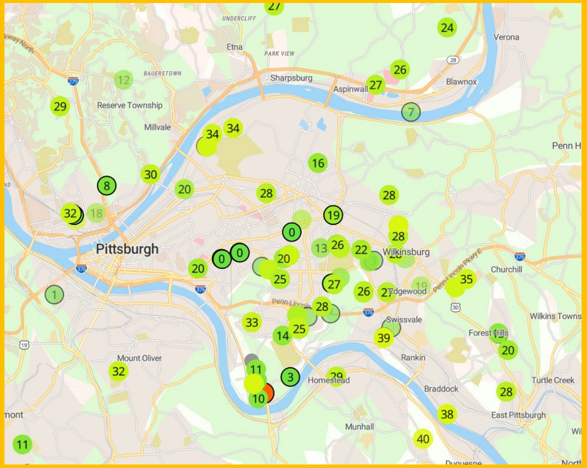
**Abhishek Viswanathan**, Amy Babay, Rosta Farzan – School of Computing and Information

Partnering with local non-profit organizations (Upstream Pittsburgh and Hazelwood Initiative) to engage residents in understanding and addressing local air quality through low-cost air quality sensors, community science, data storytelling, and science communication.




Social Sensor Network - Architecture


Part of a Data Story created by participants




PurpleAir Realtime Air Quality Map in Hazelwood

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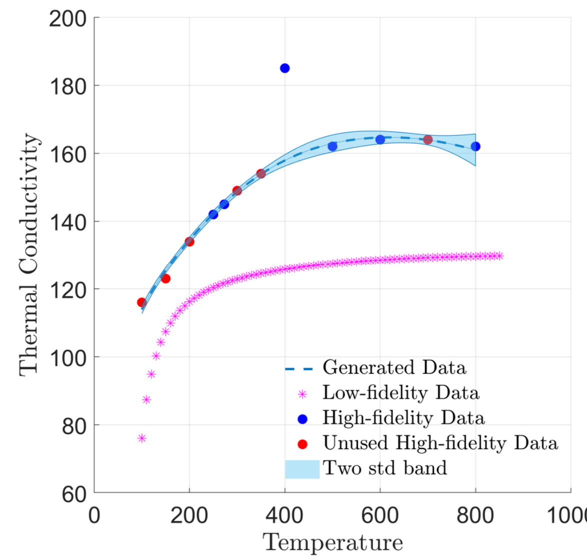
# *Multi-Fidelity Framework for Thermal Conductivity of Al−Cu*

*Sara Akhavan – Hessam Babaee*
*Department of Mechanical Engineering, University of Pittsburgh*

- Multi-Fidelity model: leverage low-fidelity (LF) and high-fidelity (HF) data sources.
- High-Fidelity data points (Experiment) : expensive but more accurate
- Low-Fidelity data points (Simulation-Approximation-Estimation) : cheap but less accurate, used to capture the trend
- LF and HF data modeled as separate Gaussian Processes (GPs) with own kernels (square exponential kernel)

$$y_L(x) = u_L(x) + \epsilon_L$$
$$y_H(x) = \rho u_L(x) + \delta(x) + \epsilon_H$$

- LF and HF combined into joint probabilistic model.
- Integrating LF and HF improves overall prediction performance.
- Optimize sensor locations to maximize prediction accuracy, minimized uncertainty, and used limited sensor.




*Thermal Conductivity of Al-Cu as a function of temperature*
*Generate set of data by fix Al (0.85), fix Cu (0.15), change temperature, predict thermal conductivity by multi-fidelity model*
*Low-Fidelity data are not accurate but capture the trend*
*High-fidelity data are accurate but expensive and limited in number (even have noise and outlier in high-fidelity data)*
*Best point for next sensor location is the point that multi-fidelity model has maximum uncertainty*

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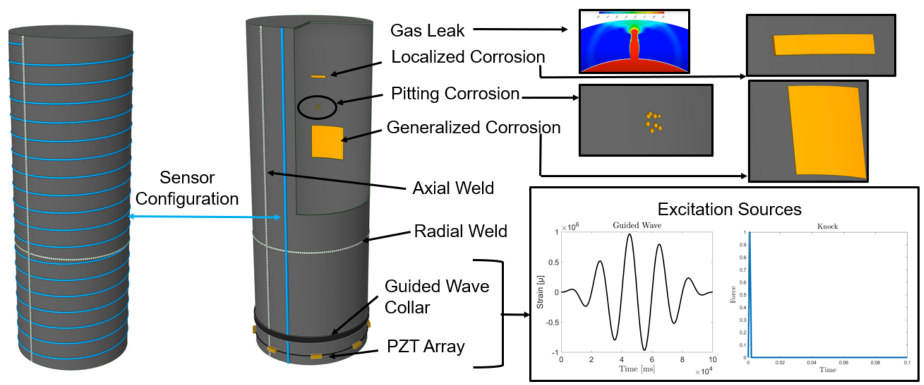
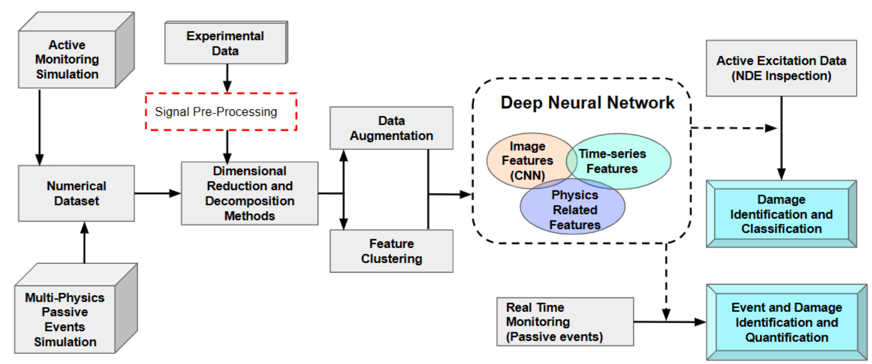
# Fusion of Distributed Fiber Optics, Acoustic NDE and Physics-Based AI for Spent Fuel Monitoring

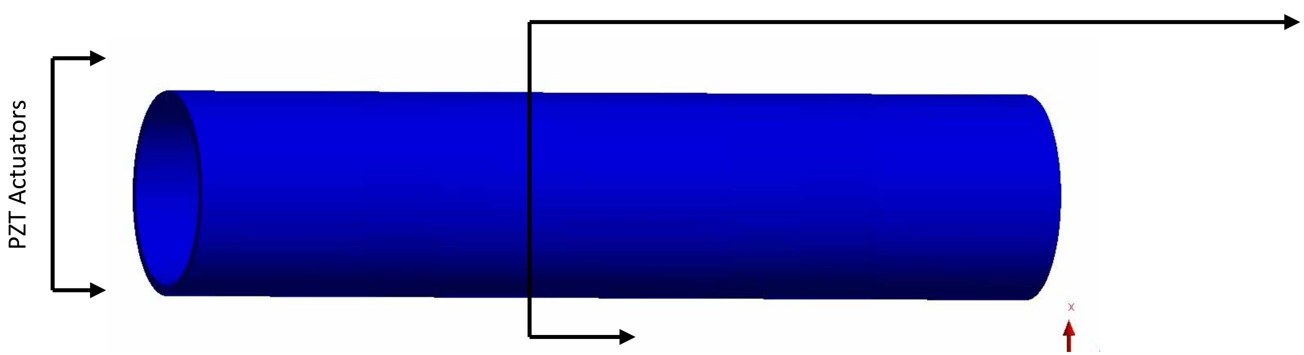
Enrico Sarcinelli[1], Pengdi Zhang[1] Abhishek Venketeswaran[2], Ruishu F. Wright[2], Khurram Naeem[1], Nageswara Lalam[2], Paul Ohodnicki[1]
[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh
[2]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA, USA 15236

## Stainless-Steel Canister Monitoring System Overview

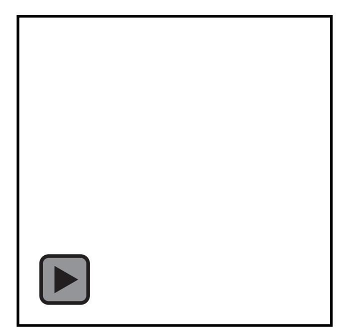



## Schematic of AI Model Development




Angular Profile (15 in)



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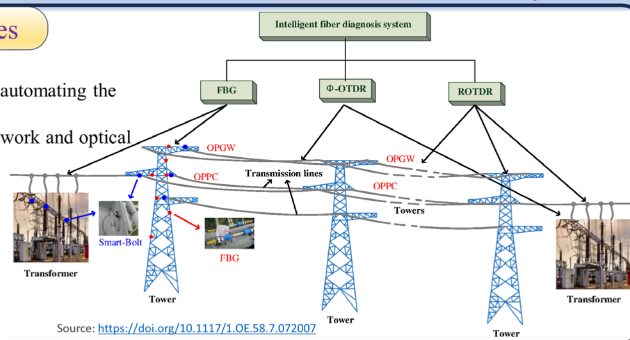
# Fiber optic current/magnetic field sensor for Power grid monitoring applications

Dolendra Karki, Tulika Khanikar, Khurram Naeem, Paul Ohodnicki
Univesrity of Pittsburgh, PA, USA

## Motivation and Objectives

- Current meter, monitor, control and automating the power grids systems
- Integration to smart grid sensing network and optical fiber communication system
- Reliable and safe delivery of power to consumer level
- Low size, weight and cost
- Immune to EMI

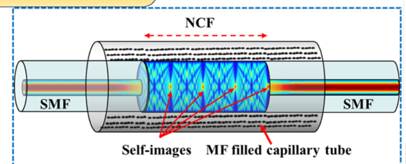



Source: https://doi.org/10.1117/1.OE.58.7.072007

## Fiber Optic current sensor architecture

*Self imaging in MMI*

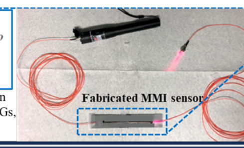
$$L_{MMF} = P\frac{n_{eff}D^2_{MMF}}{\lambda}$$

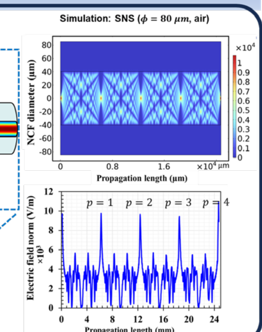



*RI of Magnetic fluid (H, T)*

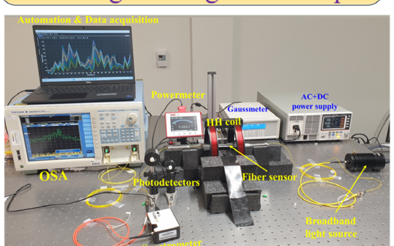
$$n_{MF} = [n_s - n_o]\left[\coth\left(\alpha\frac{H - H_{c,n}}{T}\right) - \frac{T}{\alpha(H - H_{c,n})}\right] + n_o \quad \text{for } H > H_{c,n}.$$

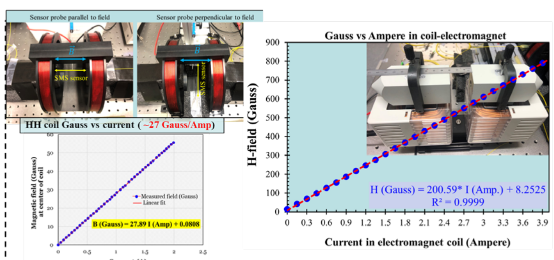
**$H_{c,n}$ - critical field strength,** $n_o$ - refractive index of MF for fields lower than $H_{c,n}$, $n_s$ - saturated value of the refractive index of MF, $H$ - field intensity in Gs, $T$ - temperature in kelvin, $\alpha$ - the fitting parameter



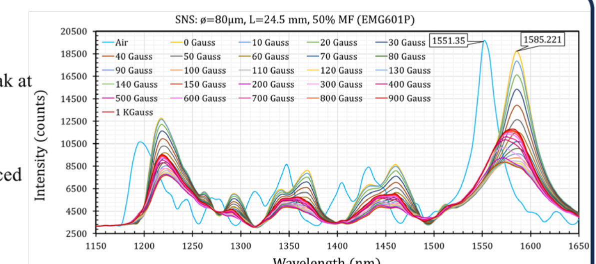

## Sensing interrogation set up




## Method of interrogation

- Sensor optimized for 4th self-imaging peak at C-L band wavelength
- Intensity based interrogation
- Change in relative intensity of 4th self-imaging peak as a function of current induced magnetic field

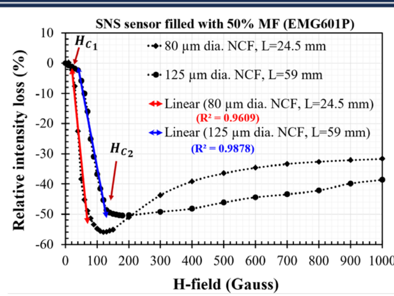



## Results

- Sensitivity > 0.5%/Gauss
- Linear response range below 130 Gauss
- Linearity $R^2 > 0.96$

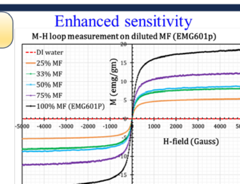
Magnetic fluid-based SMS sensor's performance metrics based on optimized 4th self-imaging condition

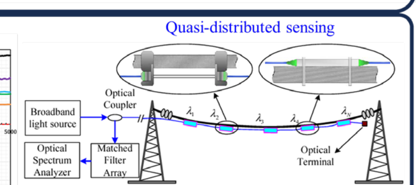
| SNS Sensor Specifications | 4th self-imaging $\lambda_{peak}$ (nm) | Response linearity | Sensing range (Gauss) | Sensitivity (S) (% intensity loss/Gauss) |
|---|---|---|---|---|
| Ø = 125μm, L= 59 mm | 1562.64 | $R^2$= 0.9878 | 40 to 130 Gauss | 0.52 %/Gauss |
| Ø = 80 μm, L= 24.5 mm | 1568.28 | $R^2$= 0.9609 | 10 to 70 Gauss | 0.82 %/Gauss |




## Conclusion and outlook

- DC magnetic field sensing ~200 Amps of equivalent current in a straight wire
- Magnetic fluid with high saturation magnetization and magnetic nanoparticles concentration for higher sensitivity
- Magnetostrictive /magneto-optic materials layers for AC field sensing




## Acknowledgement

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0009632.

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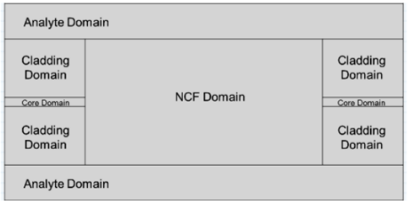
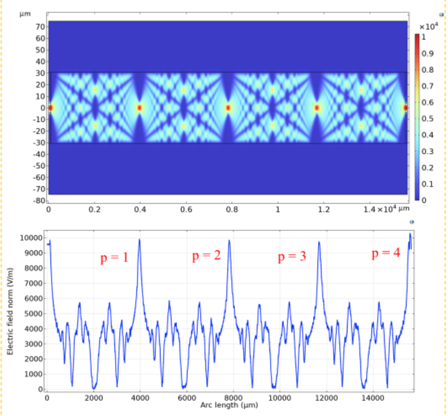
# Simulation of fiber optic Multimode Interferometer with COMSOL Multiphysics and its Application


Tulika Khanikar, Dolendra Karki, Yang-Duan Su and Paul Ohodnicki.

*Department of Mechanical Engineering and Materials Science, University of Pittsburgh, PA, USA.*

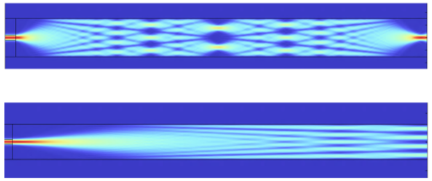




COMSOL version 6.1
Module : Wave optics
Domain : Electromagnetic Waves, Beam Envelopes (ewbe)

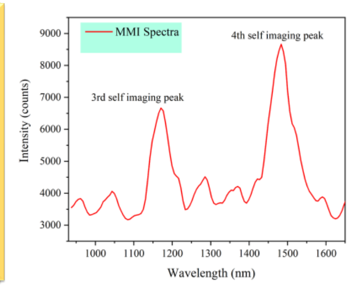
$$L_{MMF} = P\frac{n_1 D_{MMF}^2}{\lambda}$$

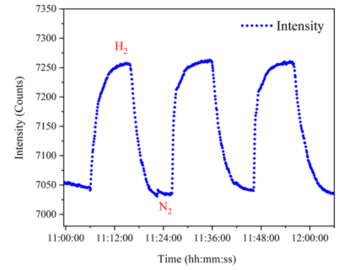
$n_1$ is the RI of core,
$D_{MMF}$ is the diameter of MMF,
$L_{MMF}$ is the MMF length,
P = 1,2,3….is an integer, representing the self-image order.



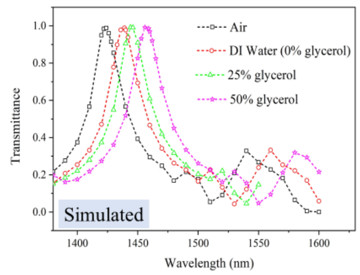
- When light is coupled from a SMF to a MMF/NCF, the modes that are supported by the MMF/NCF are excited and interferes with each other giving rise to an interference pattern along the MMF/NCF.
- At a certain length, light interferes constructively along the MMF/NCF central axis forming replicas of the input light field (self-image).
- If another SMF is connected to the MMF/NCF at the self-image point, multimode interference (MMI) information can be obtained.
- The self-imaging peaks are dependent on refractive index, wavelength, length and diameter of the MMF/NCF.

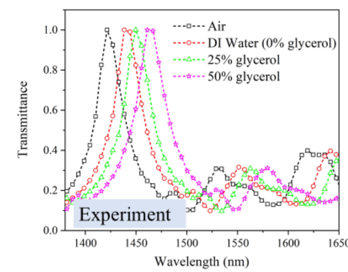
$H_2$ Sensing (80 μm NCF + Pd Thin Film)



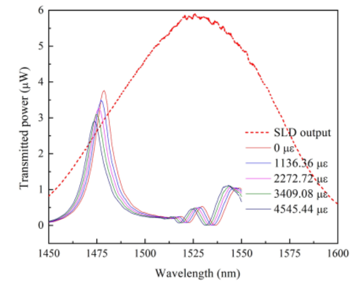



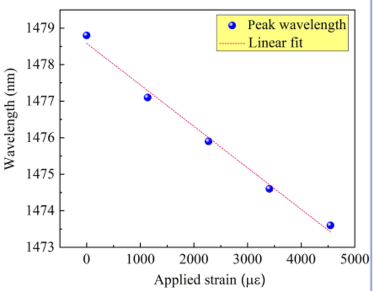

RI Sensing (61.5 μm NCF)




Axial strain Sensing (105 μm MMF)





Acknowledgement

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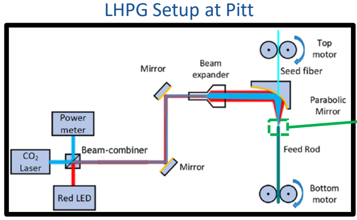
# Single crystal fiber growth via LHPG method with focus on material melting properties

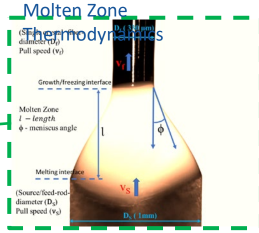

Edward Hoffman[1], Dolendra Karki[1], Jun Young Hong[1], Travis Olds[2] Paul Ohodnicki[1]

[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh, [2]Carnegie Museum of Natural History


LHPG Setup at Pitt

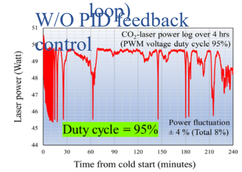



Molten Zone Thermodynamics

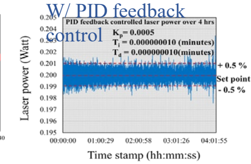



Laser power control (PID feedback loop)

W/O PID feedback control



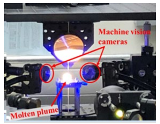

W/ PID feedback control

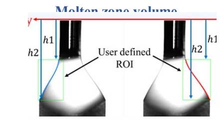



**LabVIEW machine vision based in-situ**

❖Diameter tracking and measurement

❖In-situ molten zone contour tracking and volume estimation




Varied Material Growth

❖High temperature ceramic oxides

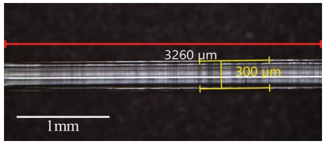
❖Versatility in growing refractory oxides fibers e.g. sapphire, YAG, MO-oxides (YIG/TGG), EO-oxides (LN, $BaTiO_3$)

❖Crucible free, high purity, diameter > 100 μm

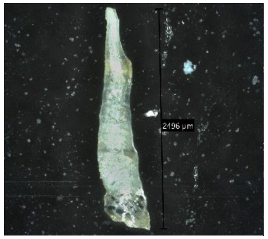
❖Specific focus on magnetic properties for novel magnetic field sensing applications

❖Greater understanding of growth characteristics of materials based on melting characteristics; e.g. congruence vs incongruence

Sapphire Fiber Grown at Pitt

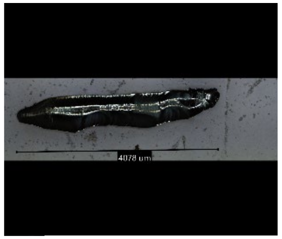



TGG Fiber Grown at Pitt

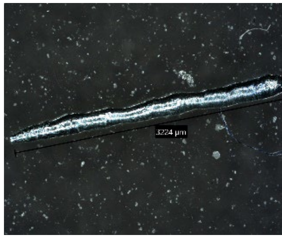


TGG Fiber Grown at Pitt

CoFe Fiber Grown at Pitt



YIG Fiber Grown at Pitt



TGG Crystal Structure

❖Overcoming the GaO evaporation issue

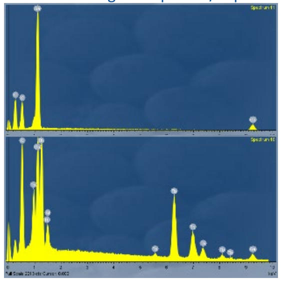
❖Fabrication of different Ga ratios via powder processing methods

❖Avoid gallium depleted regions with different crystal structures

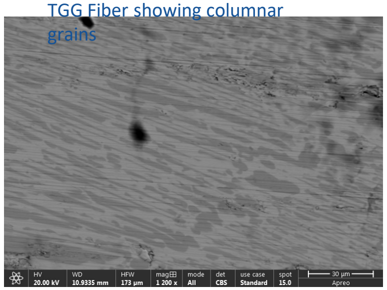
❖Evolution of elongated grain structures along the direction of growth

❖Examined by SCXRD/MicroPXRD to reveal a roughly even mixture of phases

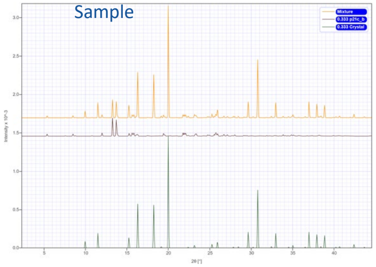
EDS revealing Ga depletion/deposition



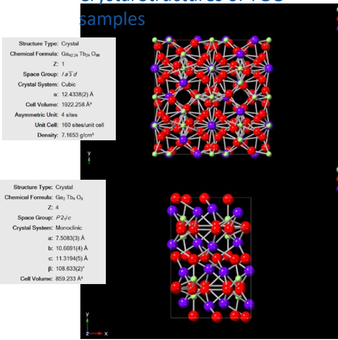
TGG Fiber showing columnar grains



XRD of Mixed Phase TGG Sample



Crystal Structures of TGG samples



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# Pipeline Health Monitoring using Fiber-optic Sensor Technology and Ultrasonic Guidedwave

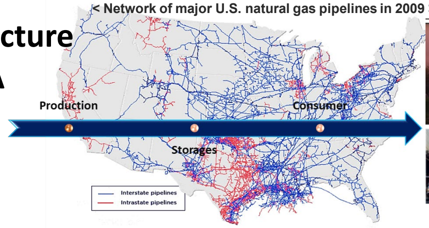
Khurram Naeem[1], Dolendra Karki[1], Pengdi Zhang[1], Enrico Sarcinelli[1], Nageswara Lalam[2], Ruishu Wright[2], and Paul Ohodnicki[1,3]

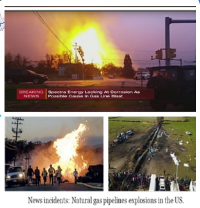
*[1]Mechanical Engineering & Materials Science, University of Pittsburgh, USA ; [2]National Energy Technology Laboratory, Pittsburgh, USA; [3]Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, USA*

NEUP Nuclear Energy University Program U.S. Department of Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

## 1 Pipelines Infrastructure Monitoring in USA

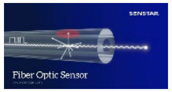


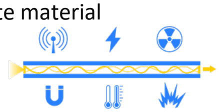

https://www.nbcnews.com/id/wbna39107965

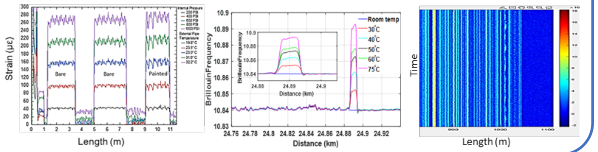
- Natural Gas, Oil Transport & Storages
- > 300k miles of distribution network
- > 50% built after World war II
- Aging and tend to deteriorate due to corrosion.
- Raptures occurs -> **Leaks** -> Explosion!!

## 2 Fiber-optic Sensor Technology

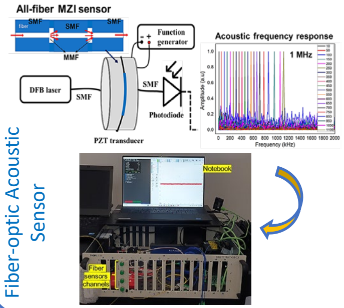


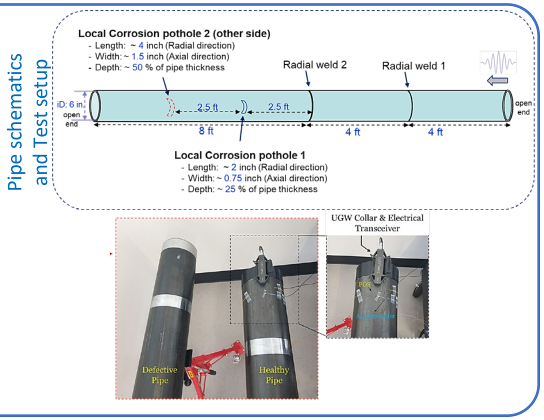

- Lightweight / embeddable in composite material
- Explosion- and electrical-proof
- Can work upto 1000 °C temperature
- Passive devices
- Point, quasi-distributed
- Fully-distributed sensing






## 3 Damage detection in Pipe



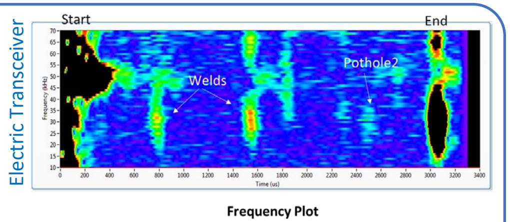



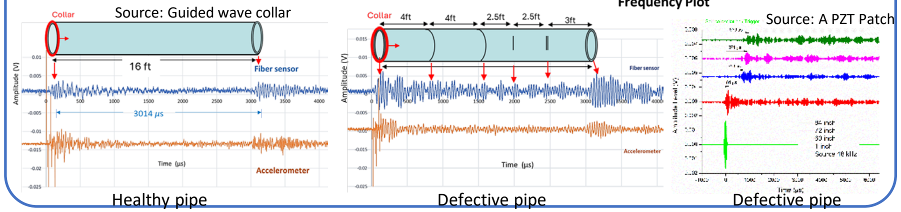

## 4 Our Results

- **Ultrasonic Source:** Guided wave collar

**-> Torsional mode (symmetric wave)** is excited by the UGW collar on the pipe surface.

< Fiber-optic Acoustic Sensor >



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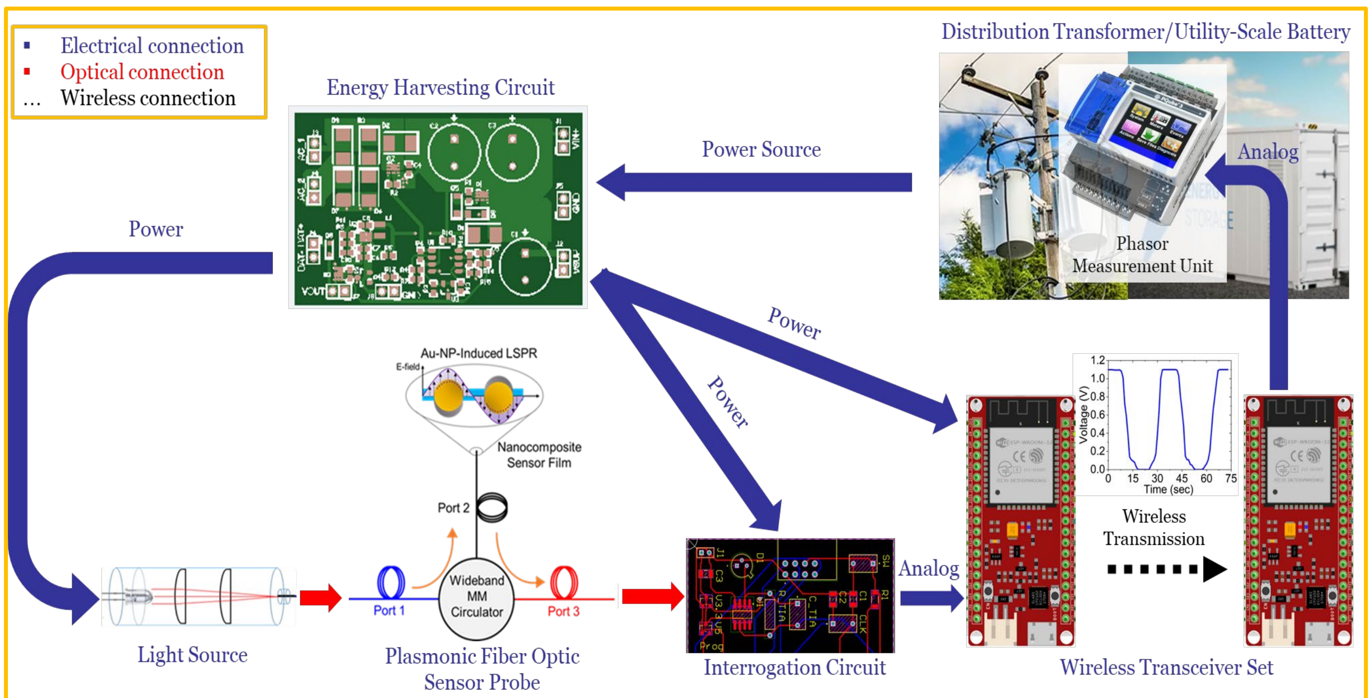
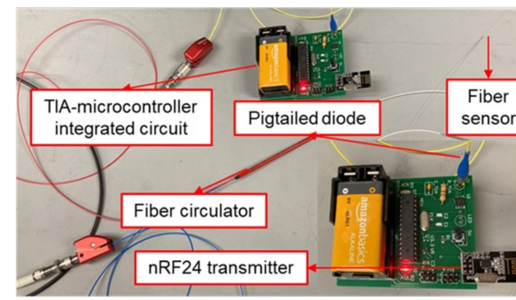
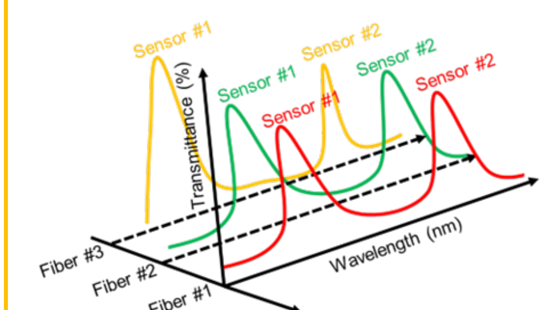
# Towards Portable and Simultaneous Gas/Temperature Fiber Optic Point Sensor Interrogator for Electrical Assets Health Monitoring

Yang-Duan Su[1], Atieh Shirzadeh[1], Heather Phillips[1], Jeffrey Wuenschell[3] and Paul Ohodnicki[1,2]
[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh
[2]Department of Electrical and Computer Engineering, University of Pittsburgh
[3]Site Support Contractor, National Energy Technology Laboratory, Pittsburgh, PA




This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office. This work is also supported by the Grid Modernization Lab Consortium, a partnership between the Department of Energy and Lawrence Livermore National Laboratories.

# NETL Poster Presentation Slide Summaries

UPitt Infrastructure Sensor Collaboration (UPISC)
2023 Workshop
**November 8, 2023**

UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

UPISC

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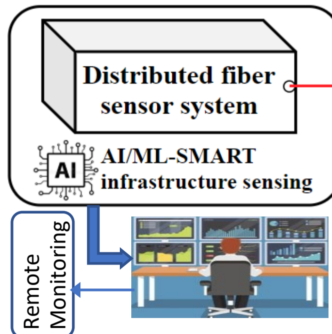
NATIONAL ENERGY TECHNOLOGY LABORATORY

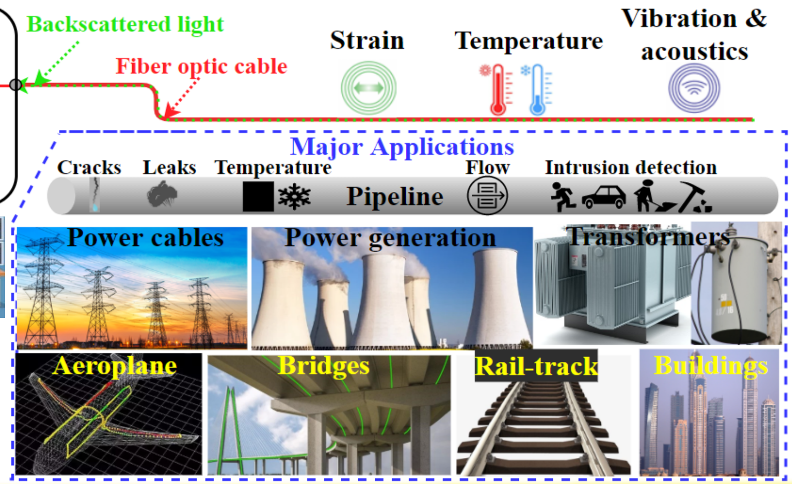
# Distributed Fiber Optic Sensor Systems for Multi-Parameter Monitoring

Nageswara Lalam (NETL), Ruishu Wright (NETL), Michael Buric (NETL), Hari Bhatta (NETL), and Paul Ohodnicki (Pitt)

Distributed fiber optic sensors allow the measurement of structural parameters; such as strain, temperature and vibrations at thousands of locations along a single fiber cable. The distributed/quasi-distributed fiber sensors include;

- Brillouin optical time domain analysis (BOTDA).
- Phase- sensitive optical time domain reflectometry (ϕ-OTDR), also called distributed acoustic sensor (DAS).
- Single-mode–multi mode–single-mode (SMS) fiber sensor.




### BOTDA

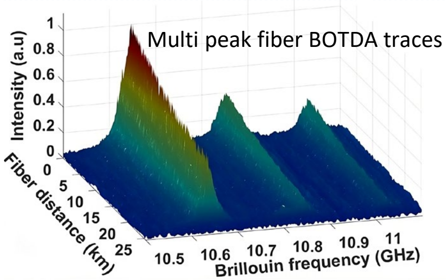
**Sensing range =** >100 km;
**Spatial resolution =** <5 m;
**Measurable parameters:** strain, and temperature

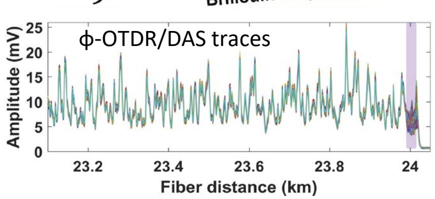
### ϕ-OTDR/DAS

**Sensing range =** >30 km;
**Spatial resolution =** <1 m;
**Measurable parameters:** vibration/acoustics

### SMS

**Frequency range=** 1 Hz to 1.2 MHz;
**Resolution=** <1 to 2 Hz;



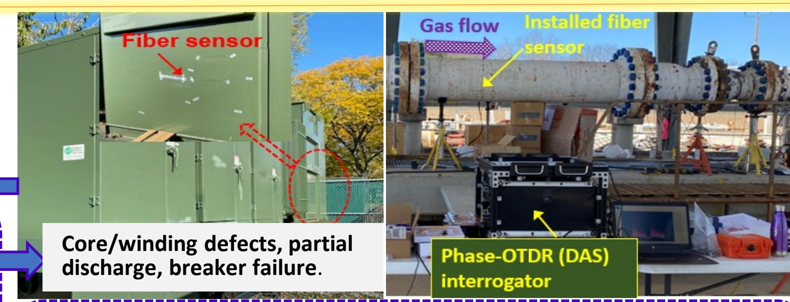



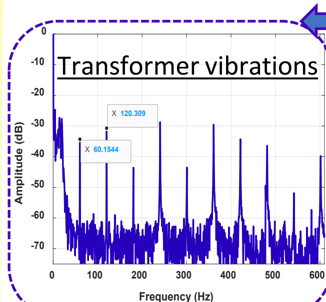

### Advantages

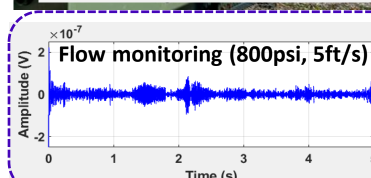
- Compact size
- EMI resistance
- Withstand harsh environment
- Real-time and remote monitoring
- High accuracy and stability
- Enhanced structural safety

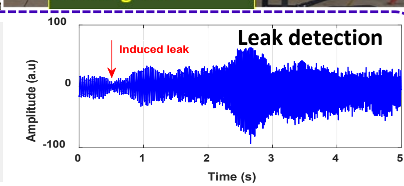
### Field validation

Power Transformer
Oil and Gas Pipeline



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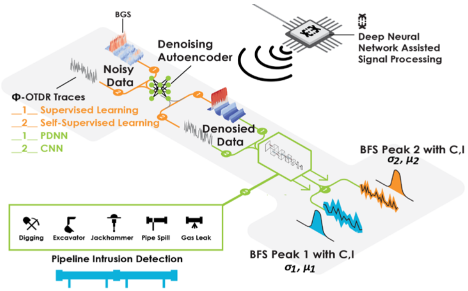
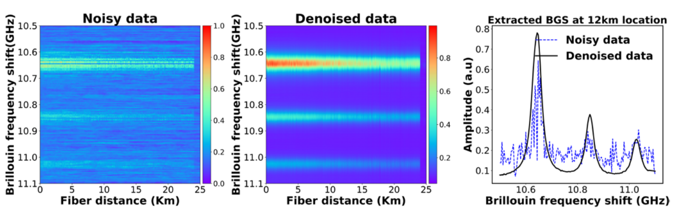
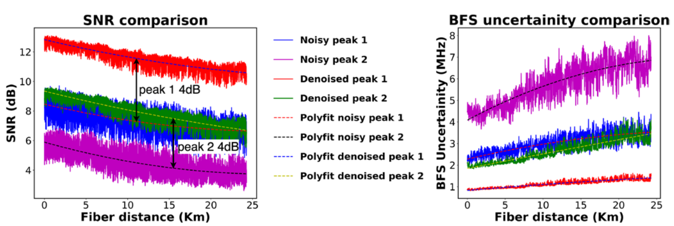
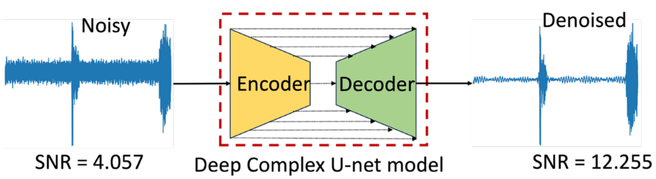
# Intelligent and Real time data analytics for fiber optic sensors using deep neural networks

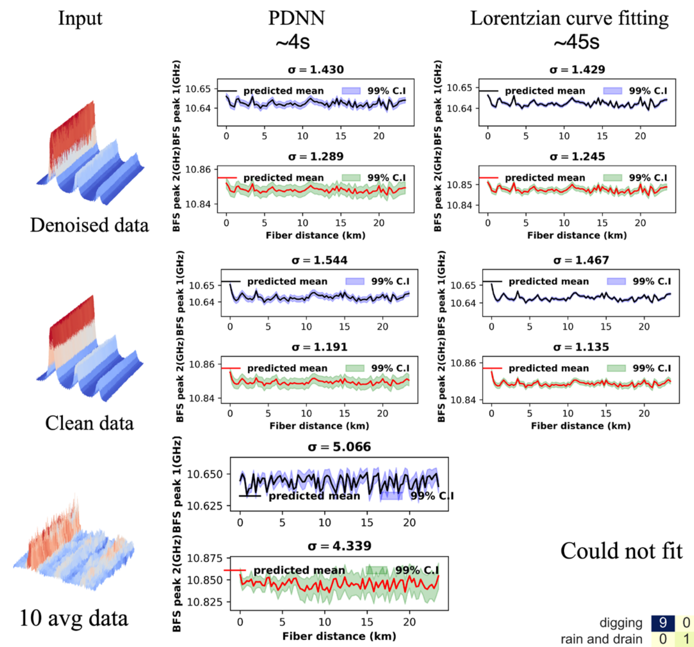

Sandeep Reddy Bukka[1], Nageswara Lalam[1] , Hari Bhatta[1] , Ruishu F. Wright[1]
[1]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA, USA 15236

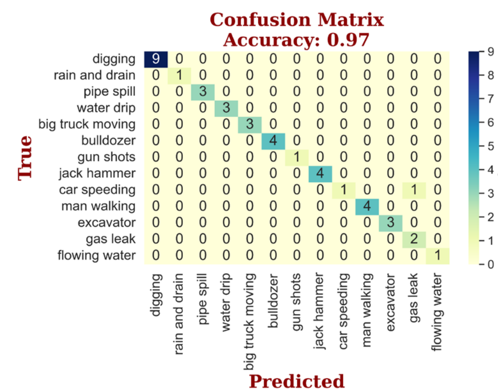



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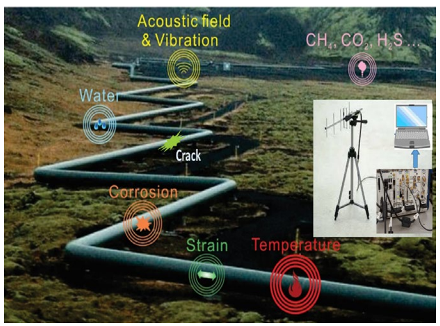
# Passive Wireless Sensing of Methane Leak and Monitoring Corrosion in Pipelines


**Jagannath Devkota[1,2]; David W. Greve[1,3]; Laura Schwendeman[1]; Richard Pingree[1,2]; Krista Bullard[1,2]; Nathan Diemler[1,2]; Badri Mainali[1,2]; Ruishu Wright[1]**

[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [3]Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

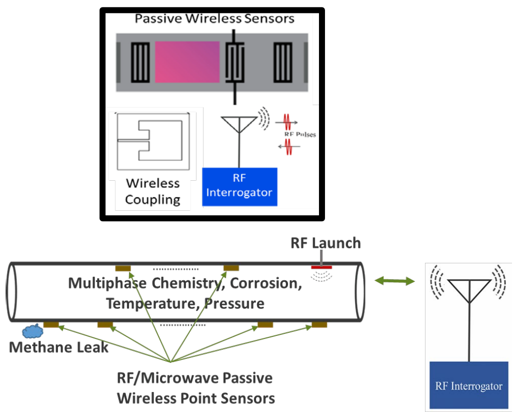
**Contact: Ruishu Wright Email: ruishu.wright@netl.doe.gov**

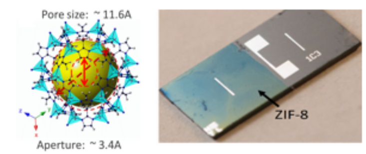

## Motivation



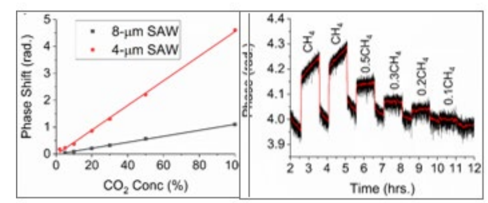

- Conventional monitoring techniques are infrequently performed making prediction of potential events difficult.
- Continuous and real-time monitoring technologies are helpful to better identify, locate, and quantify methane leaks and corrosion events.
- Passive wireless sensors and their network are emerging platforms for remote and real-time monitoring of long pipelines.

## Pipeline Monitoring with Passive Wireless Sensors




*A MOF (ZIF-8)* nanoporous material (left) and coated SAW sensor (right)




## Advantages

- Passive, Wireless, Matured Devices
- Sensitive, Cheap Point Sensors
- Possible for Multi-Parameter Operation (Chemical Species, Corrosion, Temperature, Pressure, Strain, etc.)

## Other Applicable Industries

- Subsurface Wellbores
- Harsh Environments in Energy Generation
- Automotive
- Aerospace

**Small (~5x10 $cm^2$), Low-Cost, Passive Wireless SAW Sensors to enable Ubiquitous Wireless Sensor Network for Energy Infrastructure Monitoring**

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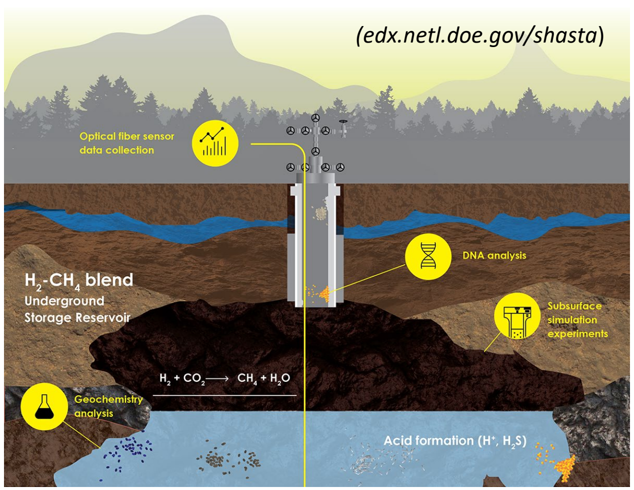
# Optical Fiber Sensors Capable of Monitoring Harsh Subsurface Conditions for $H_2$ Storage Applications

**Daejin Kim[1,2], Krista K. Bullard[1,2], Alexander Shumski[1,2], Ruishu Wright[1]**

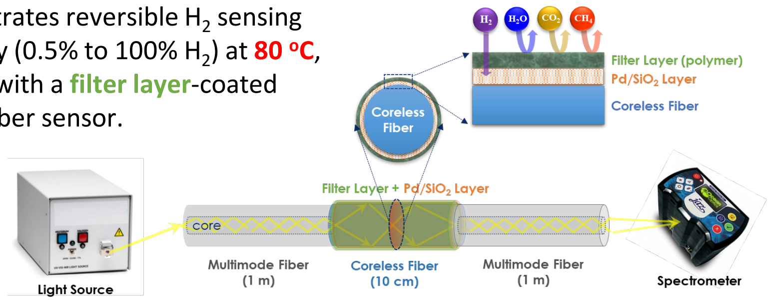
([1]National Energy Technology Laboratory; [2]NETL Support Contractor,
626 Cochran Mill Road, Pittsburgh, PA 15236, USA)




- In-situ optical fiber sensors for real-time monitoring of **hydrogen**, **methane**, and **pH** at subsurface hydrogen storage conditions.
- Ensure the integrity of the underground hydrogen storage facilities.

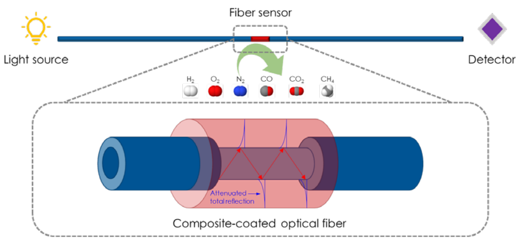
## $H_2$ Sensor

- Demonstrates reversible $H_2$ sensing capability (0.5% to 100% $H_2$) at **80 °C**, **99% RH** with a **filter layer**-coated optical fiber sensor.

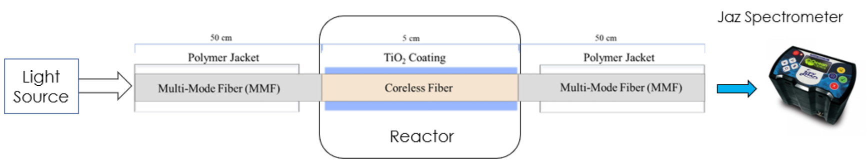



## $CH_4$ Sensor

- Successful demonstration of optical fiber methane sensor with a **polymeric composite material** at **80 °C**, **99% RH**.




## pH Sensor




- **$TiO_2$**-coated optical fiber pH sensor was demonstrated at **80 °C**, **1000 PSI**.

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NATIONAL ENERGY TECHNOLOGY LABORATORY

# Review of Sensors for In-Situ Amine Degradation Monitoring in Post-Combustion Carbon Capture


**Matthew M. Brister[1,2]; Alexander Shumski[1,2]; Chet R. Bhatt[3,4]; Jeffrey Culp[1,2]; Krista Bullard[1,2]; Dustin McIntyre[3]; Benjamin Chorpening[3]; Nicholas Siefert[1]; Ruishu F. Wright (PI)[1]**

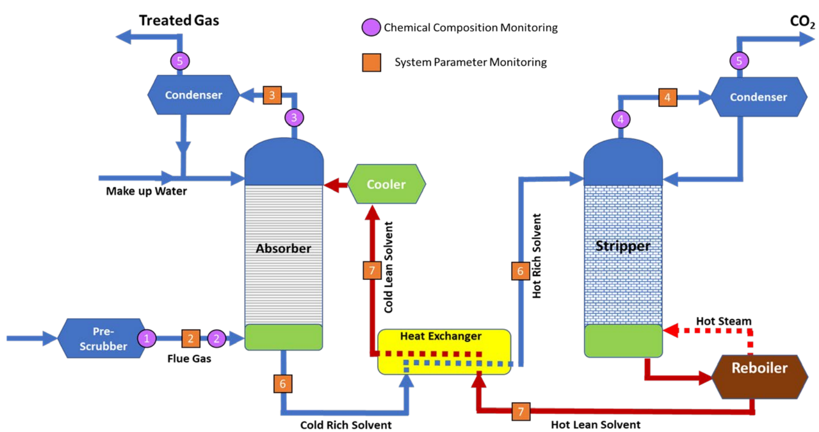
[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [3]National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26505, USA; [4]NETL Support Contractor, 3610 Collins Ferry Road, Morgantown, WV 26505, USA


## Solvent Darkens with Degradation and Lightens when Regenerated

Flø et al. Energy Procedia **114**, 1307–1324, Elsevier Ltd (2017)

- Solvent monitoring is needed for carbon capture plant operation due to continuous **thermal** and **oxidative** degradation.
- Current solvent monitoring hardware is **expensive** and **requires sampling**.
- Degraded solvents form dark colored **heat stable salts (HSSs)** which reduce carbon capture efficiency.

## Post Combustion Carbon Capture Design




## Current Physical Sensing Technology

| Location | Equipment | System Parameter Monitoring |
|---|---|---|
| 1,2,3 | Pressure Gauge | Pressure of Gas and Liquids |
| 1,2 | Volumetric Flow Rate | Rate of Gaseous Flow |
| 4,5,6,7 | Viscosity | Flow Rate of Solvent |
| 4,5,6,7 | Temperature | Temperature of Solvent |

## Current Chemical Sensing Technology

| Location | Equipment | Chemical Composition Monitoring |
|---|---|---|
| 1 | pH Meter | Basicity |
| 1 | UV | $SO_2$, $NO_2$ |
| 1 | Total Organic Carbon Analyzer | $CO_2$ |
| 2,5,6 | FTIR | $CO_2$, $H_2O$, $NH_3$, NO, $NO_2$, $SO_2$, $CH_2O$, $C_2H_4O$, Amines |
| 2,5,6 | NDIR | $CO_2$ |
| 2 | Paramagnetic | $O_2$ |
| 3,4 | GC/MS | $CO_2$, $O_2$, $N_2$, $H_2O$ |
| 3,4 | LC/MS | $CO_2$, $O_2$, $N_2$, $H_2O$ |
| 2,4 | Electric Conductivity | $O_2$ content |
| 5,6 | Single Ion Monitoring | Mass Spectrometry |
| 5,6 | Electric Low-Pressure Impactor | Aerosol Measurements (Size Distribution and Count) |

Simultaneously **Low-Cost** and **Continuous** Degradation Monitoring is Not Currently Available

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# Multi-parameter Optical Fiber Sensor for Simultaneous Monitoring of Humidity, Pressure, $CO_2$, and Corrosion

**Badri P Mainali[1,2]; Alexander Shumski[1,2]; Nathan Diemler[1,2]; Ruishu Wright[1]**

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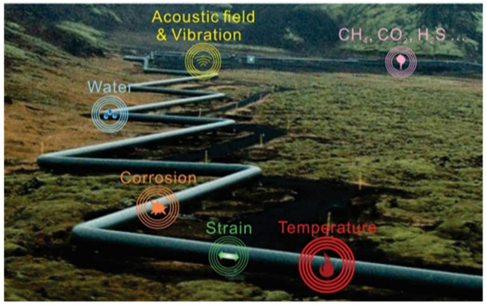
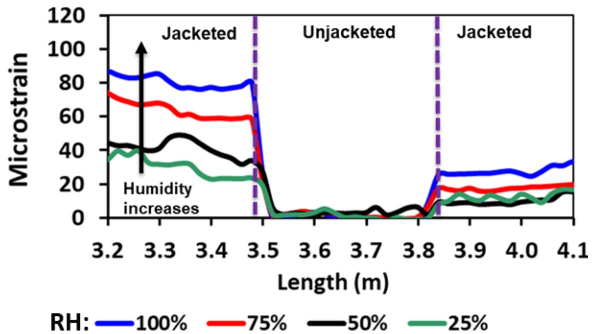
## Pipeline Monitoring Concerns

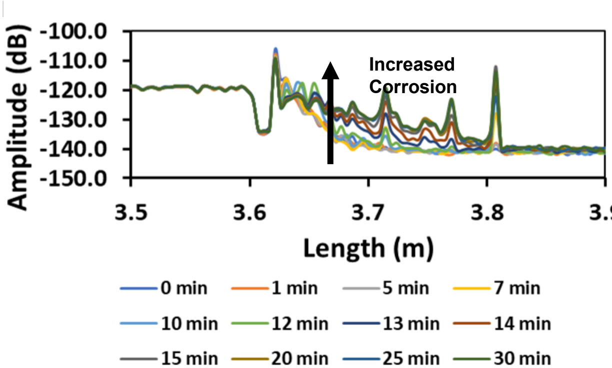
**Pipeline Integrated with Distributed Optical Fiber > 100 km**




- Pipeline corrosion costs billions of dollars annually.
- Increased humidity and $CO_2$ can predict corrosion favoring conditions, and pressure drops can indicate leaks.
- Periodic methods like couponing collect average corrosion rates over a long period of time.

## Humidity and Corrosion Monitoring




- Single-mode fiber (SMF) jacket detects humidity and $CO_2$ concentration using swelling-induced strain.
- Unjacketed fiber detects only pressure-induced strain.
- Changes in backscattered light intensity of a thin Fe coating acts as a continuous distributed proxy for pipeline corrosion.

**Optical fiber sensors provide long distance distributed sensing of humidity, pressure, $CO_2$, and corrosion in natural gas pipeline conditions.**

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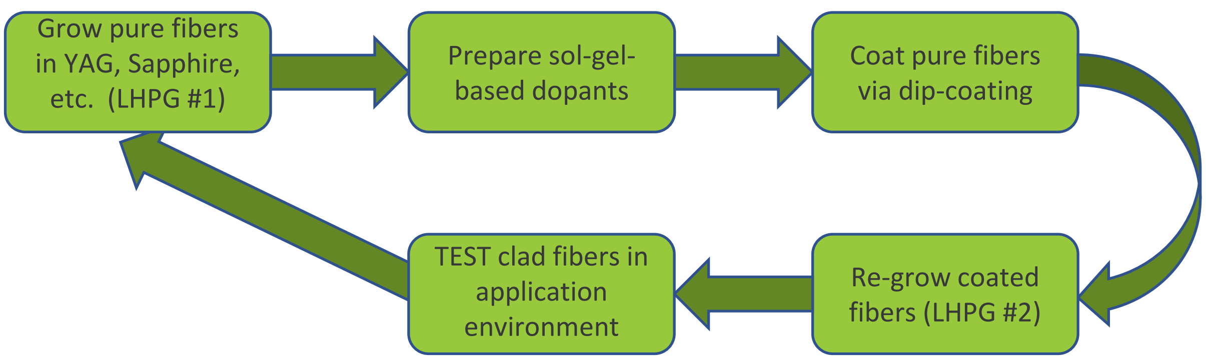
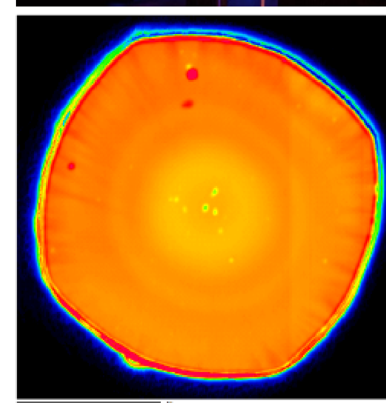
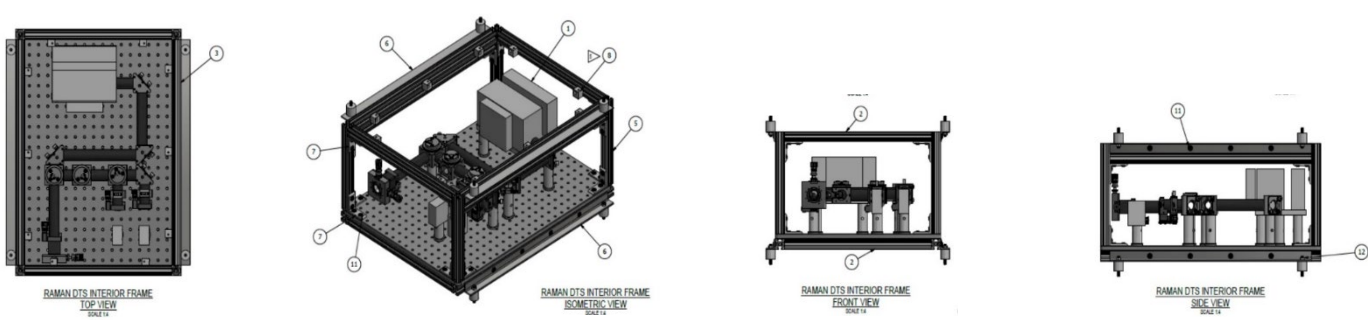
## Laser-heated Pedestal Growth and Raman DTS for Harsh-environment Applications

- Single crystal fiber (SC) superior to silica fiber in regard to stability under harsh conditions.
- Grow SC fiber via laser-heated pedestal growth (LHPG).
- Sol-gel coated fiber used in two-step LHPG process to create cladding layer.
- Raman DTS system can use grown fiber for distributed temperature sensor.





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# Modeling and Experimental Testing of High-Temperature Stable Sensor Materials for Gas Monitoring

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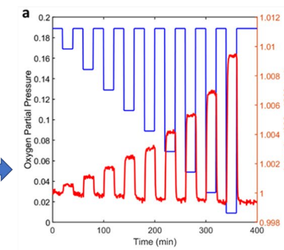
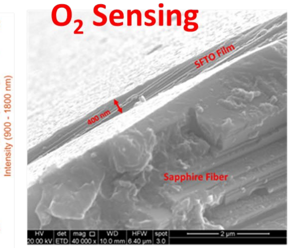
- Doped perovskite oxide thin films on the optical fiber platform show promise for gas detection in extreme environments (paired with single crystal fiber, may exceed 1000 °C operation for some applications). **Provides a pathway to distributed gas sensing via approaches such as OTDR.**
- La-doped $SrTiO_3$ demonstrated for $H_2$ sensing up to 900 °C on sapphire fiber. "p-type" doped systems ($SrFe_xTi_{1-x}O_3$) demonstrated for $O_2$ sensing up to 900 °C.
- **Density functional theory (DFT):** PAW-PBE(+*U*) exchange-correlation in generalized gradient approximation (GGA) used to evaluate optical properties of doped $SrTiO_3$ systems.
- Better understanding of (1) impact of dopants, (2) impact of defects (e.g., vacancies, interstitial H), and (3) diffusion pathway energetics needed for **fast, stable, selective, and high sensitivity gas sensors.**

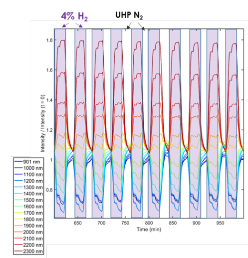
## $O_2$ Sensing

SFTO-based sensor Using single crystal sapphire fiber 0-19% $O_2$ at 800 °C

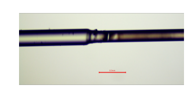


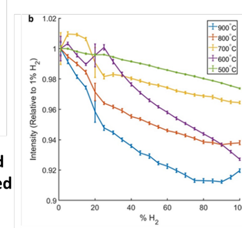



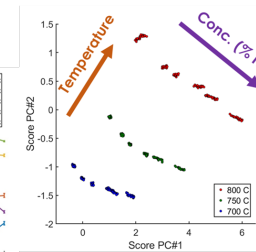

## $H_2$ Sensing

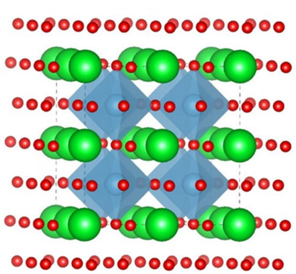


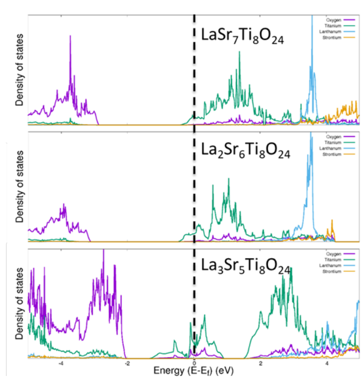

LSTO-based conductive and plasmonic optical fiber-based hydrogen sensing 0-100% $H_2$, 500-900 °C

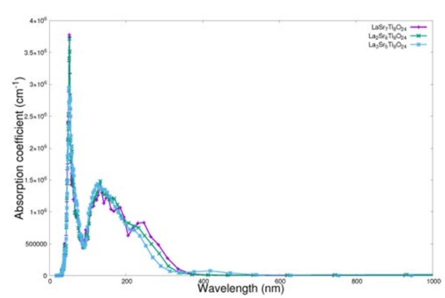







## Disclaimer

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- Published three open-access comprehensive review articles on quantum computing, quantum networking, and quantum sensing for energy sector applications, with a fourth in preparation.
- Constructed apparatus capable of optically detected magnetic resonance and spin relaxometry using NV centers in nanodiamonds for ultra-sensitive magnetic field, electric field, temperature, and pressure sensing.
- Perform *ab initio* density functional theory (DFT) calculations on the bulk and surface properties of the N and NV defective bulk and diamond surfaces.