UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL Sensor Technologies Progress Overview

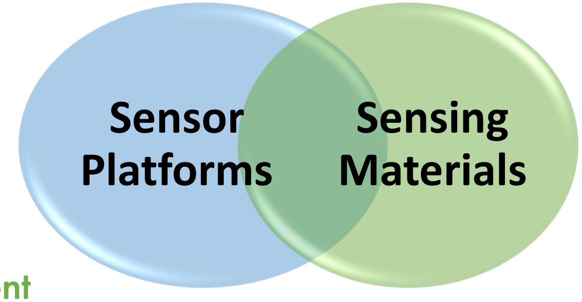
Presenter: Ruishu F. Wright, Ph.D.
Research Scientist,
Technical Portfolio Lead
NETL CORE-Sensors Capability Manager
National Energy Technology Laboratory (NETL)

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

NETL Sensor Expertise and Capabilities for Energy Infrastructure

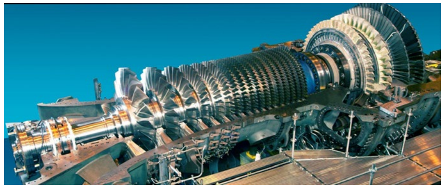
Advanced Sensors for Energy Efficiency, Safety, Resilience, and Sustainability

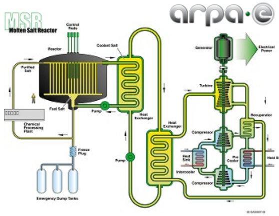
- ✓ **Monitor systems and conditions**
- ✓ **Improve performance & efficiency**
- ✓ **Enhance reliability & safety**
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films & fiber optics, sensor devices development



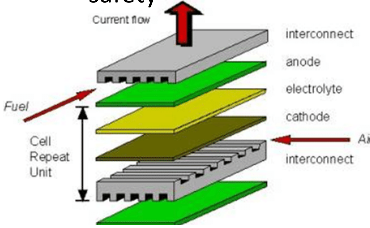
GENERATION

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





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

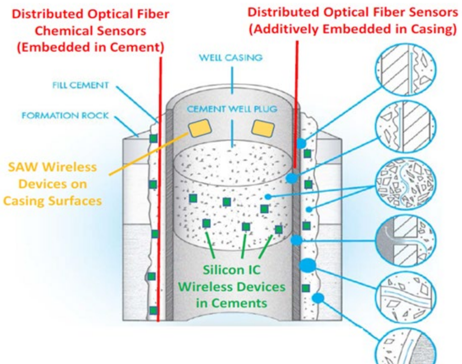


SOFCs: Fuel concentration & temperature gradients for improved lifetime and efficiency

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

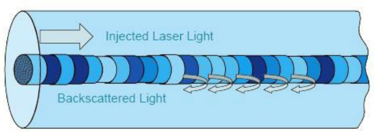


Subsurface: Wellbore integrity, failure prediction, leak detection. Geologic storage of CO_2, H_2/NG, or abandoned wells.

Multiple Sensor Technology Platforms

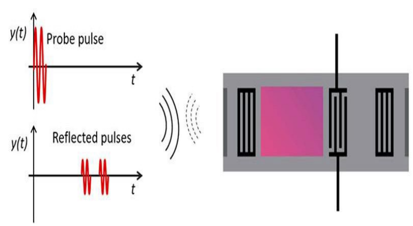
Long-distance Distributed Optical Fiber Sensors

Imperfections in fiber lead to Rayleigh backscatter:



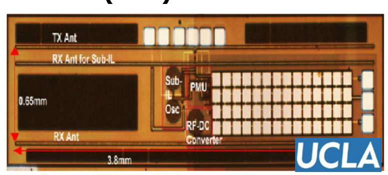
Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

Passive Wireless Sensors



Advanced Electrochemical Sensors

Wireless Miniature Silicon Integrated Circuit (SiIC) Sensors

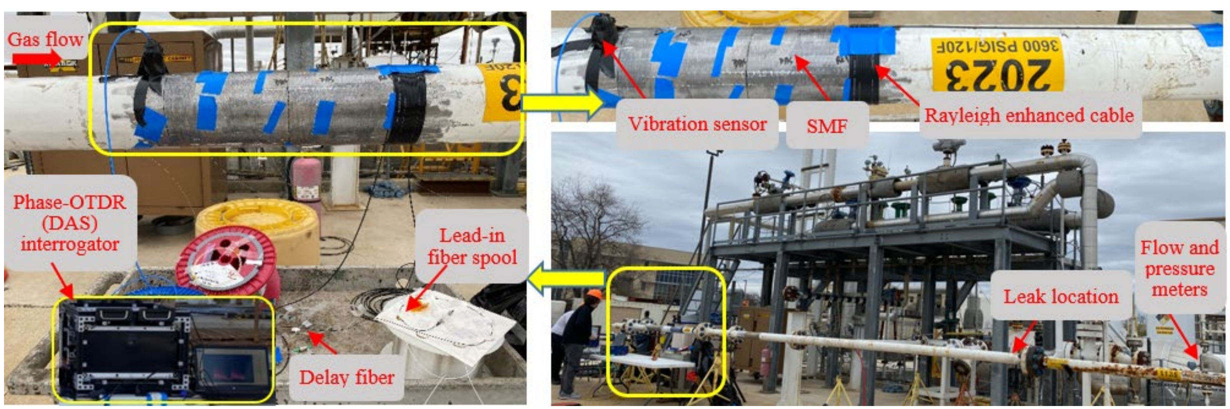


	Geospatial Attributes	Cost	Targeted Function
Distributed Optical Fiber Sensors	Linear Sensor Adjustable Distance and Resolution	Cost Per Sensor "Node" Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2,etc.) Early Corrosion/pH Detection
Passive Wireless SAW Sensors	Point Sensor	Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2,etc.) 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.**



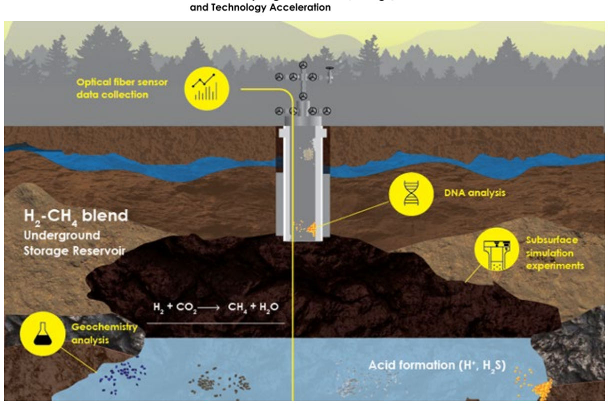
ENERGY I-CORPS
U.S. Department Of Energy

Team 188 Pipeline Sensors

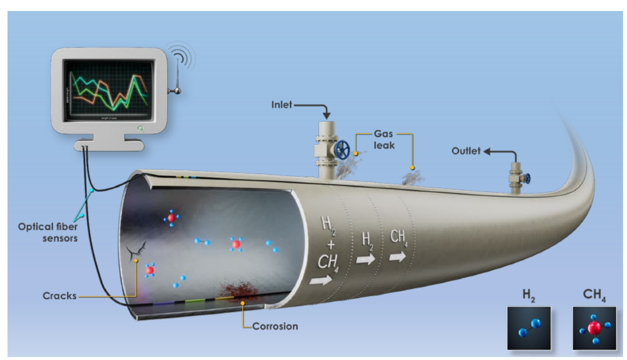
NETL Sensor Technologies Progress and Achievements
-Hydrogen Transportation and Subsurface Storage

- 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)

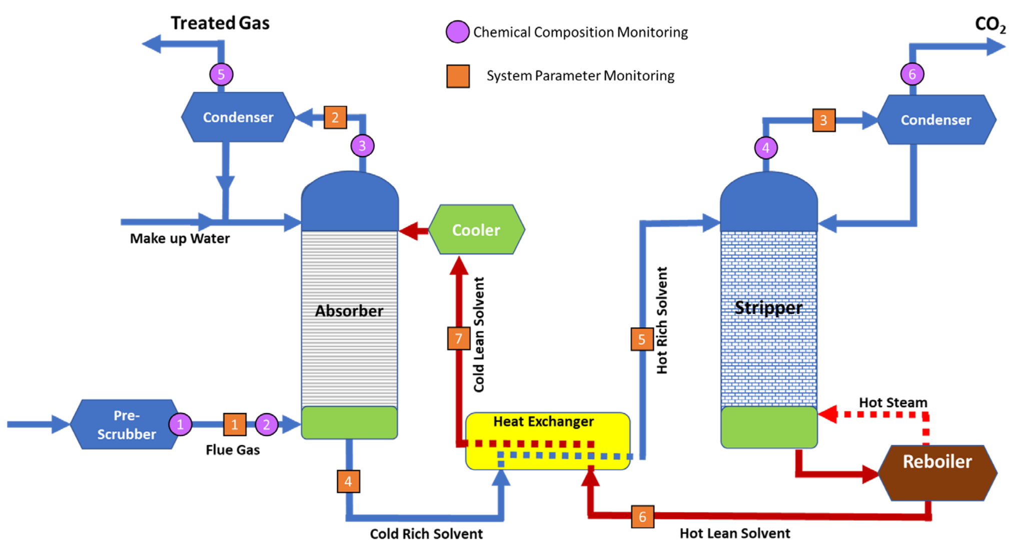


H2@Scale NREL CRADA

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).



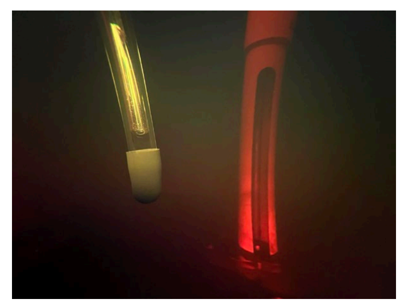
NETL Sensor Technologies Progress and Achievements
-Power Grid Modernization

- "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

Acoustic Sensing at Medium-voltage Transformer



Dissolved Gas Analysis of Transformer Oil

Temperature Sensing of Distribution Transformer

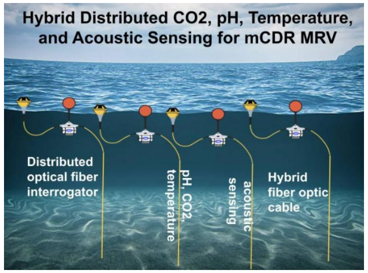
NETL Sensor Technologies Progress and Achievements
-Newly Awarded Projects in 2023

- **“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.

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

- **“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.



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.

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
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NATIONAL ENERGY TECHNOLOGY LABORATORY

PITT Sensor Technologies Updates and Overview

Presenter: Paul R. Ohodnicki, Jr.

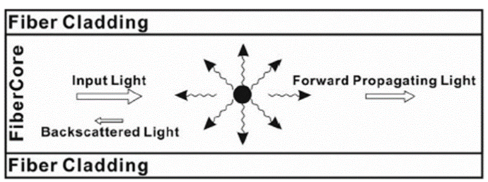
RK Mellon Faculty Fellow in Energy
Swanson School of Engineering
University of Pittsburgh (PITT)

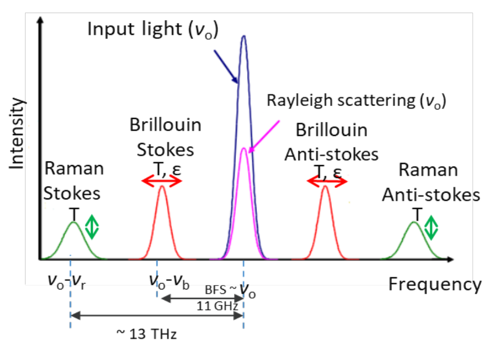
UPitt Infrastructure Sensor Collaboration (UPISC)
2023 Workshop
November 8, 2023

PITT Sensor Technologies Updates and Overview

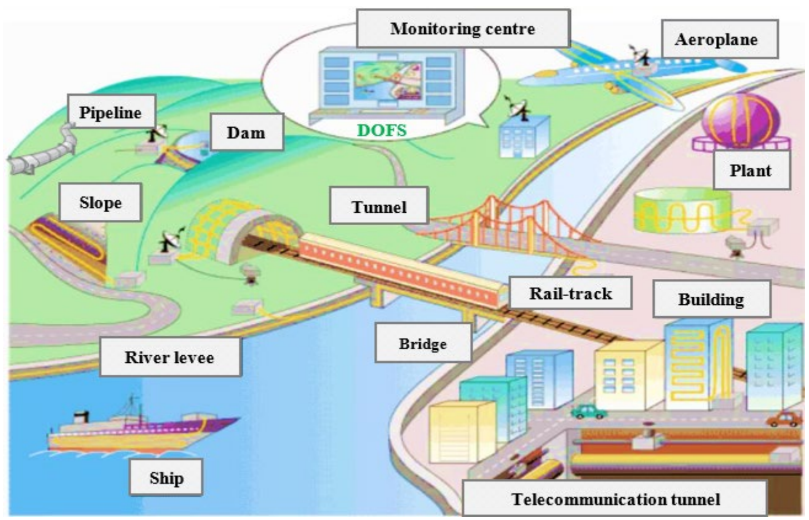
Distributed Sensing and Infrastructure Monitoring

Scattered light spectrum of optical fiber

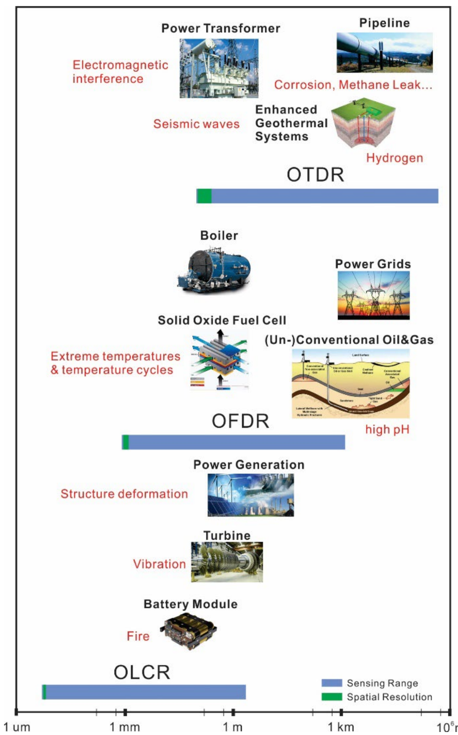




Various Applications



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

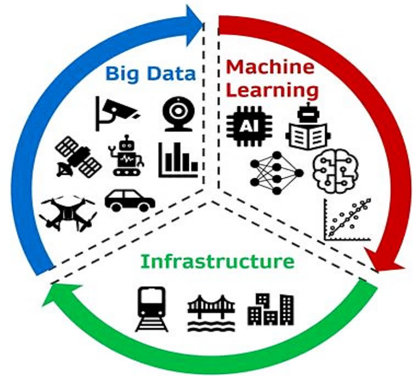


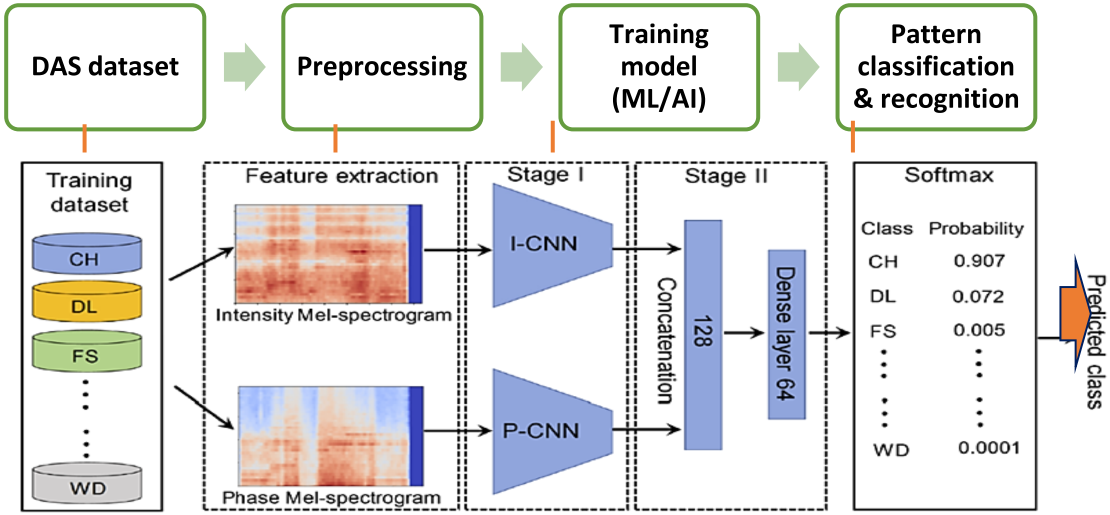
Distributed Sensing Over Different Length Scales

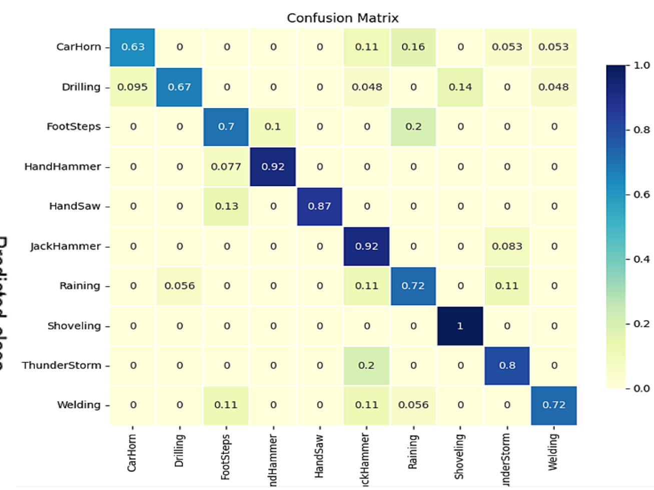
PITT Sensor Technologies Updates and Overview

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







UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

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COLLABORATION WORKSHOP

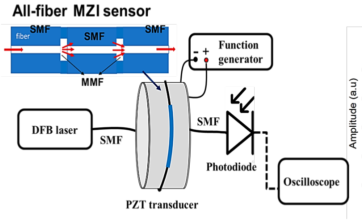
NATIONAL ENERGY TECHNOLOGY LABORATORY

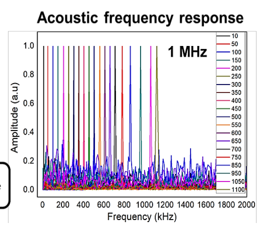
PITT Sensor Technologies Updates and Overview

Distributed Sensing Applications @ PITT Ohodnicki Lab

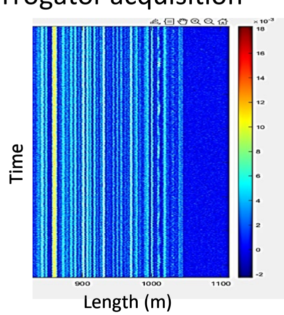
❑ Acoustic sensing

- **Point and Multipoint**



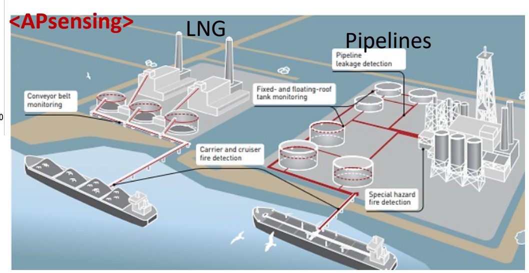


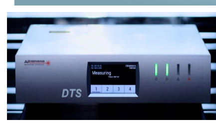
- **Distributed Acoustic Sensor (DAS):**
  - Benchtop Interrogator
  - Commercial Interrogator acquisition

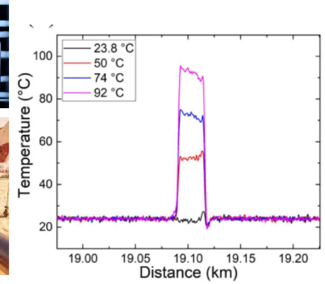


❑ Temperature sensing

- Distributed Temp Sensor / DTS: Commercial interrogator

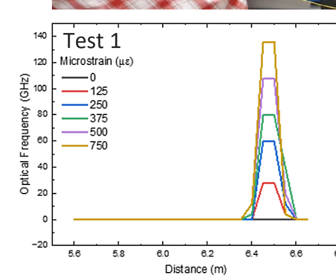


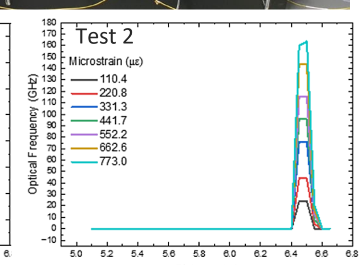




❑ HD Strain/Temperature

- Benchtop OFDR.....PITT/NETL





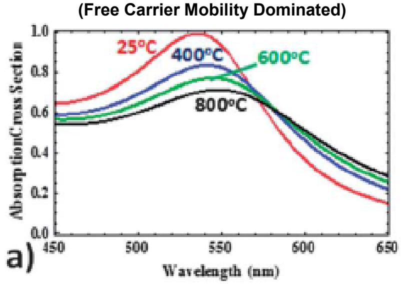
PITT Sensor Technologies Updates and Overview

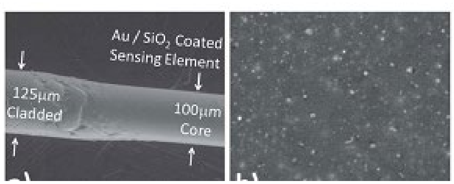
Functionalized Optical Fiber Sensing @ PITT Ohodnicki Lab

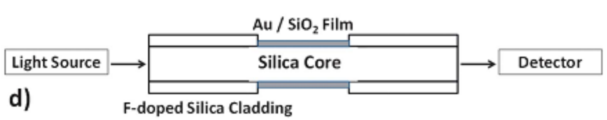
- Temperature Sensing
- Chemical Sensing
- Magnetic Field Sensing

Temperature Response

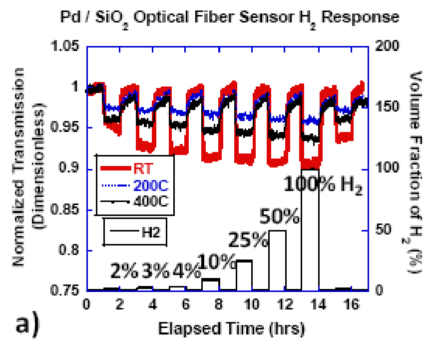
(Free Carrier Mobility Dominated)

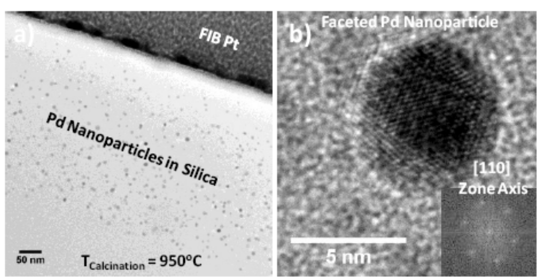




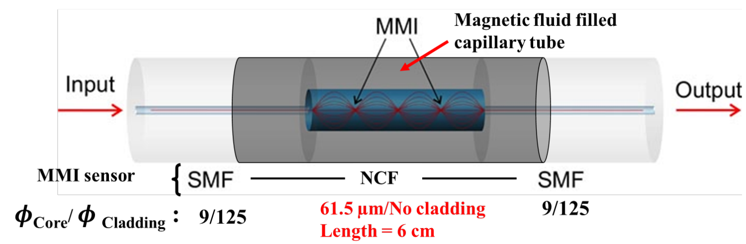


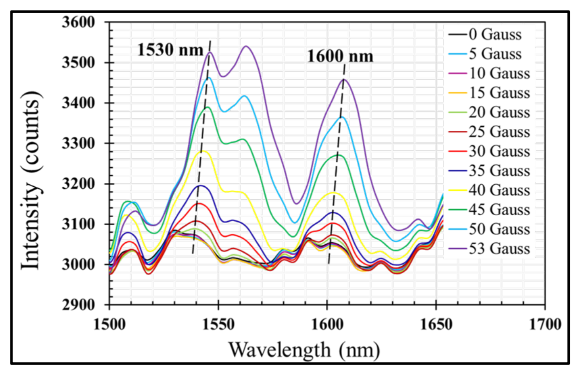
P.R.Ohodnicki et al, Nanoscale 5 (19), 9030-9039 (2013).





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



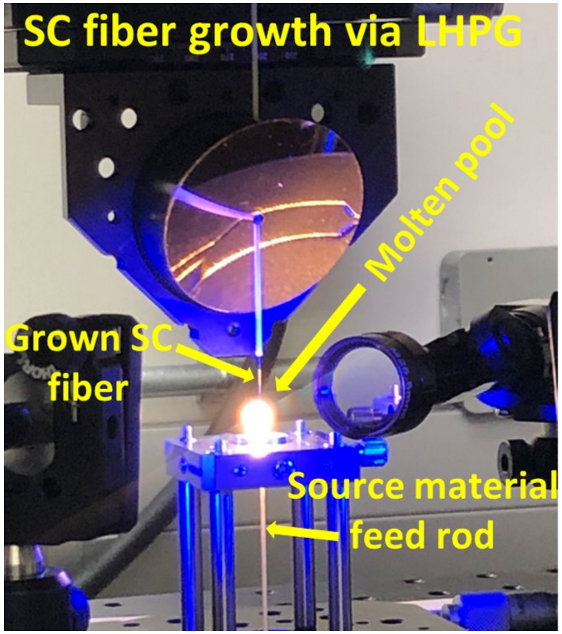


D. Karki et al, Presented at SPIE DCS 2023.

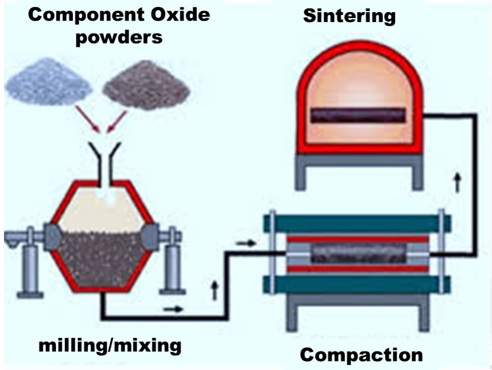
PITT Sensor Technologies Updates and Overview

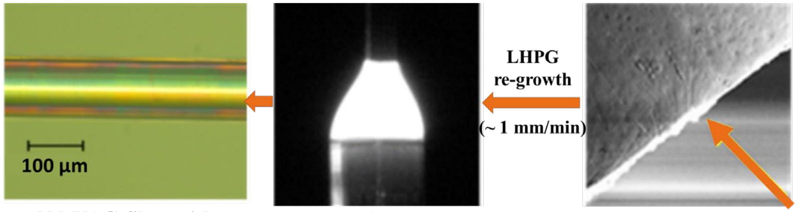
Single Crystal Oxide Fiber Sensing @ PITT Ohodnicki Lab

- Laser Heated Pedestal Growth



- Functional Crystal Oxides





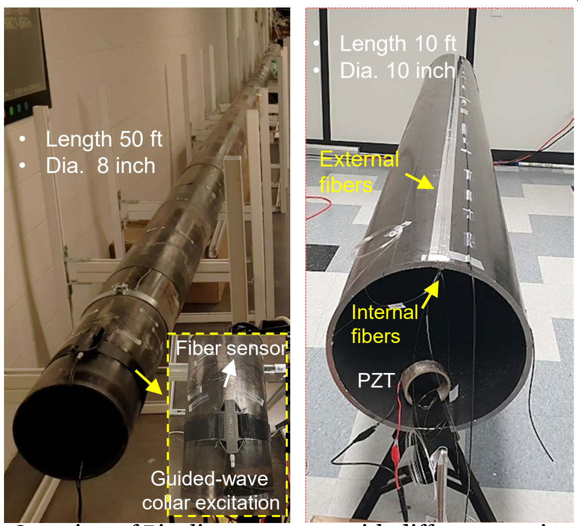
Nd:YAG fiber with HoAG cladding | 120µm Ho, Nd:YAG fiber | HoAG coated 330 µm Nd:YAG fiber

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

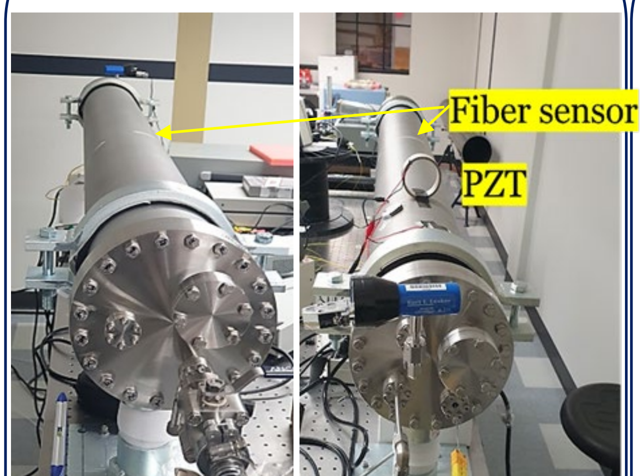
Pipeline monitoring



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

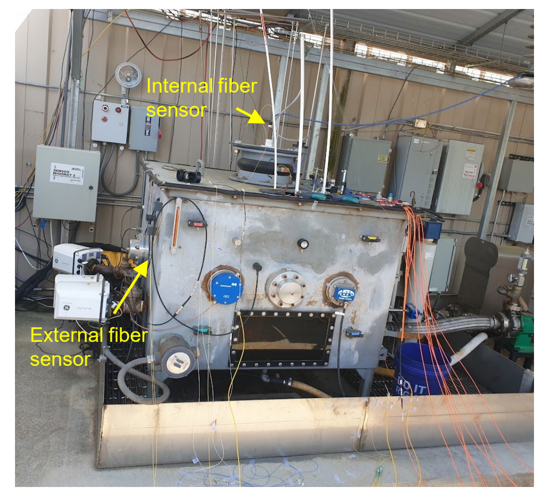
Nuclear Canister monitoring



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



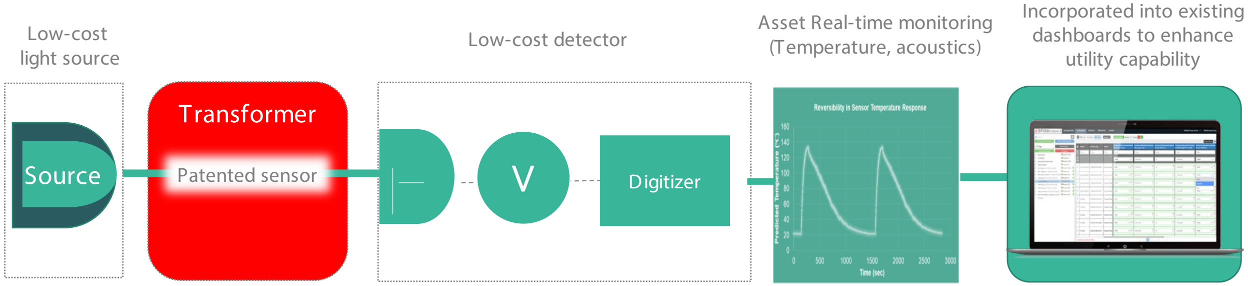
Test setup for Partial discharge detection @ EPRI

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

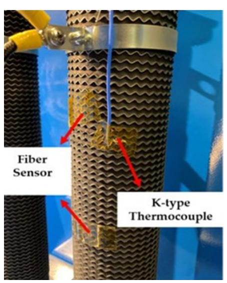
PITT Sensor Technologies Updates and Overview

Commercialization and Technology Transfer Activities : Electrical Asset Sensing

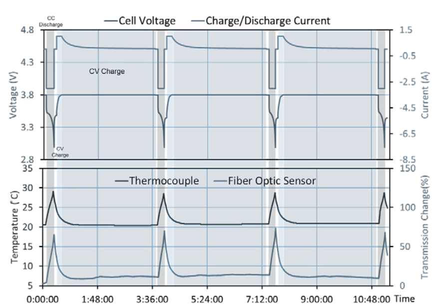
Low-Cost Fiber Optic Sensing Technology

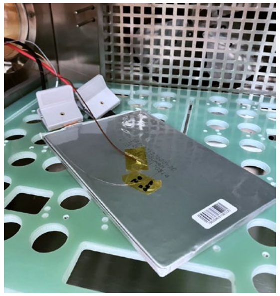


Electrical & Magnetic Components Sensing (e.g. Transformers)



Internal and External Battery Monitoring





University of Pittsburgh & National Energy Technology Lab Spin-Off

SENSIBLE PHOTONICS

www.sensiblephotonics.com

Pre-Seed Stage : Initiating Fundraise

University of Pittsburgh

NATIONAL ENERGY TECHNOLOGY LABORATORY

2023 R&D 100 WINNER

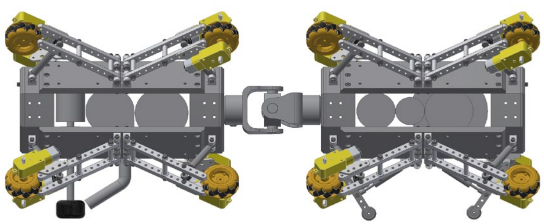
UPISC
UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
COLLABORATION WORKSHOP

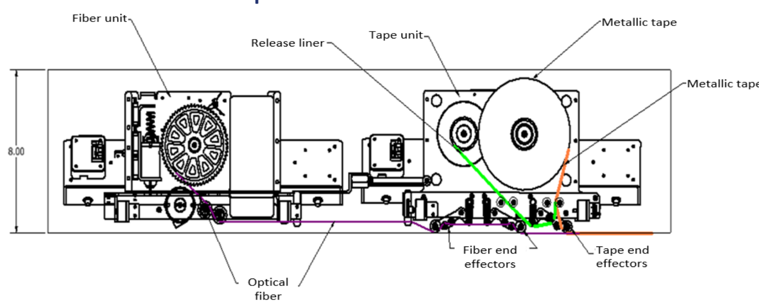
NATIONAL ENERGY TECHNOLOGY LABORATORY

PITT Sensor Technologies Updates and Overview

Commercialization and Technology Transfer Activities : Pipeline Sensing

Robotic Deployment Tool for Fiber Optic Installation

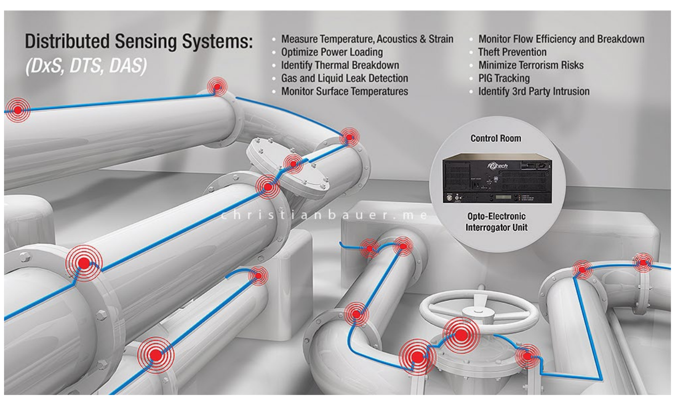




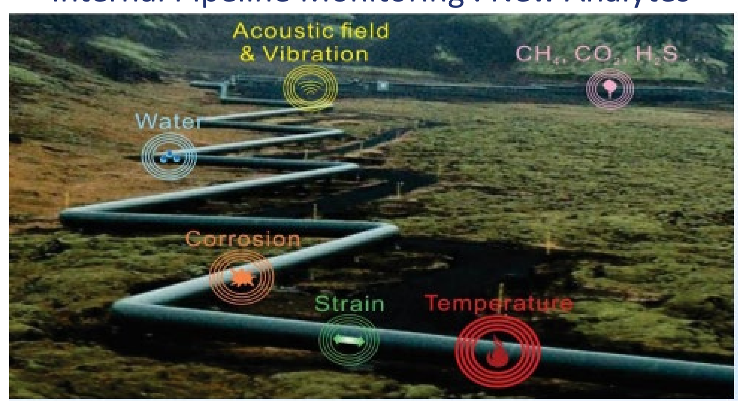
University of Pittsburgh Spin-Off

Pipeline Innervations, LLC™
Cerebral Compliance Technologies

Distributed Optical Fiber Sensing



Internal Pipeline Monitoring : New Analytes



Joint Development Partnership

University of Pittsburgh

BrainDrip™
Patently True Innovations

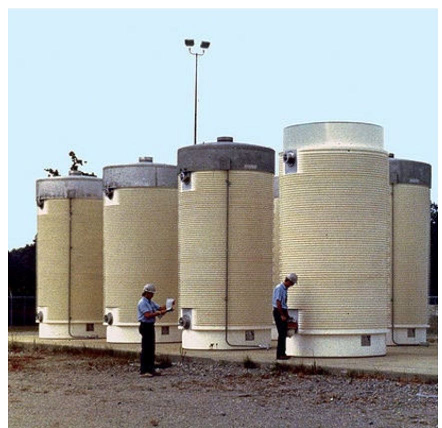
UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

UPISC
UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
COLLABORATION WORKSHOP

Contact: Dr. Alexander Star
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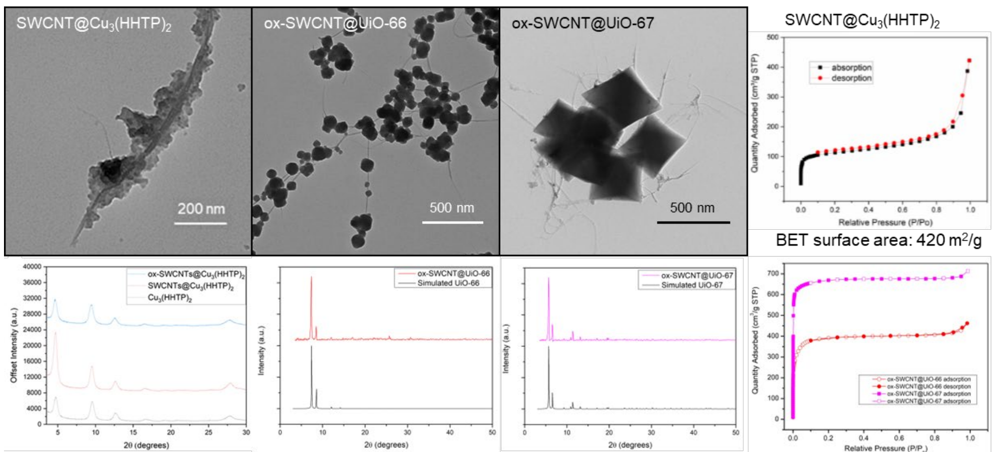
NATIONAL ENERGY TECHNOLOGY LABORATORY

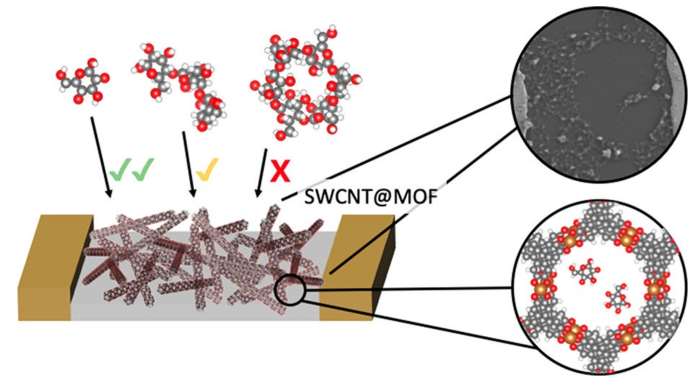
Size-based Molecule Discrimination and Detection via Single-Walled Carbon Nanotube@Metal Organic Framework Composite Field-Effect Transistor



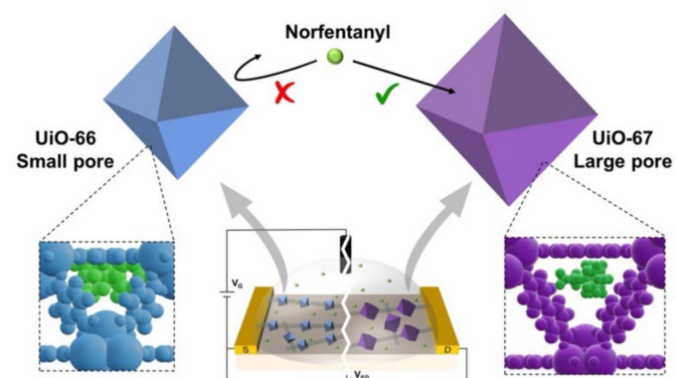
BET surface area: 420 m^2/g

ox-SWCNT@UiO-66 BET surface area: 1577 m^2/g
ox-SWCNT@UiO-66 BET surface area: 2603 m^2/g

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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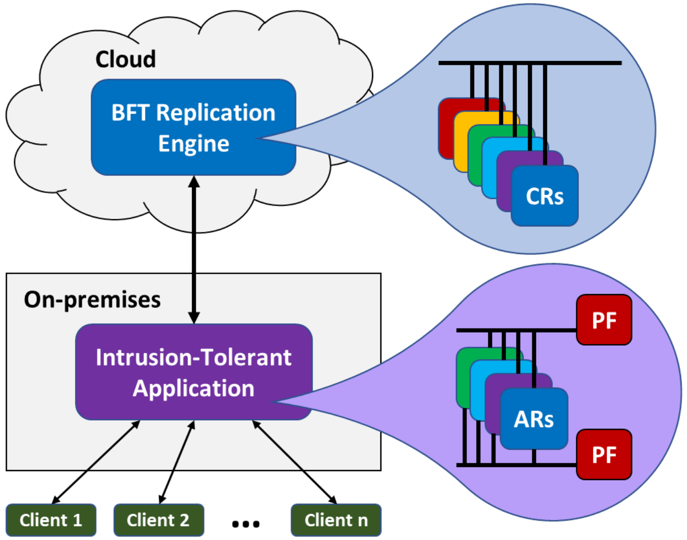
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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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LinkedIn

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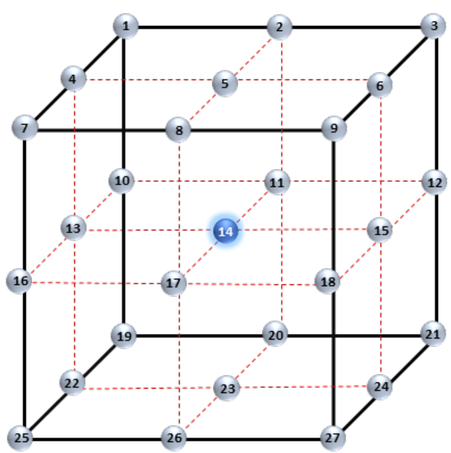
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

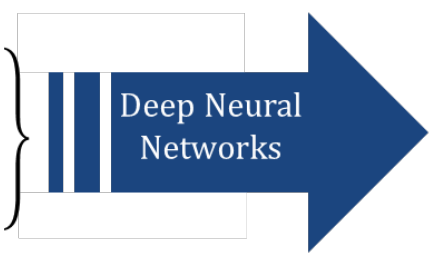
Berkay Bostan (beb171@pitt.edu), Shawn Hinnebusch, David Anderson, and Albert C. To

Defect Predictor Geometry Independent DNNs



$$\left\{\begin{matrix} T_1, T_2, \dots, T_{o^3} \\ \nabla T_1, \nabla T_2, \dots, \nabla T_{o^3} \\ IT_1, IT_1, \dots, IT_{o^3} \\ S_1, S_2, \dots, S_{o^3} \end{matrix}\right\}$$

Input vector
$[1 \text{ x } (\boldsymbol{n} \text{ } \boldsymbol{x} \text{ } \boldsymbol{o}^3)]$



$\{\boldsymbol{Porosity}\ \%\}$
$[1 \text{x} 1]$

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

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COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

Monitor local region for unusual seismic activity.

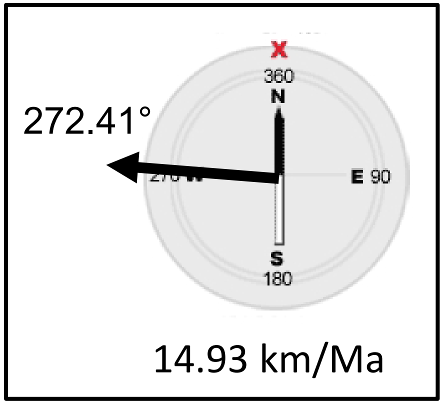
Estimate local ground acceleration.

Monitor atmospheric and hydrological storm activity.

Monitor earthquake and tsunami activity.

Understand the earth system better.

Plate Tectonic Motion of Pittsburgh

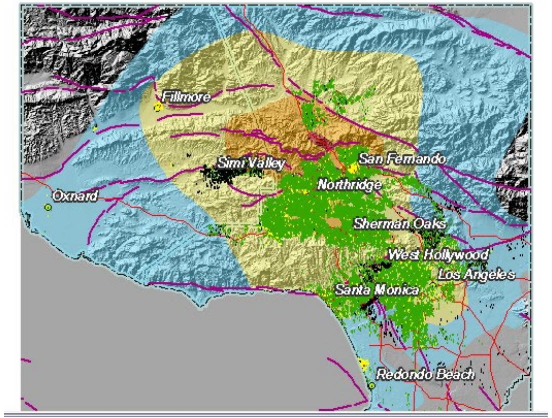


North America Tectonic Plate motion Pittsburgh

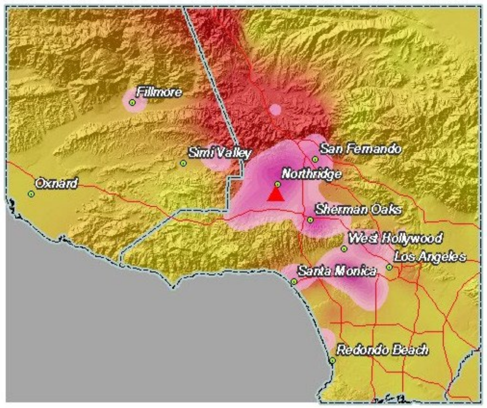
Rate of movement	**Direction of movement**
14.93 (mm/yr)	
(1.24 mm/mo)	**272.41°**

Fingernails grow about 3 millimeters a month

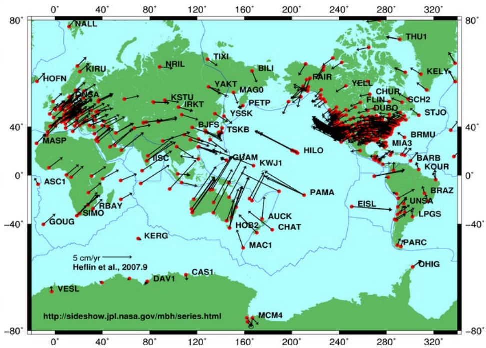
Northridge building damage



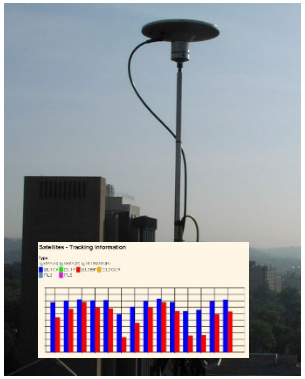
Northridge ground acceleration



Global Positioning Satellite (GPS) Plate Motion Data



Pittsburgh CORS GPS Station: PAAP



Contact: Paul Kyros Advisor: Jingtong Hu
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COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

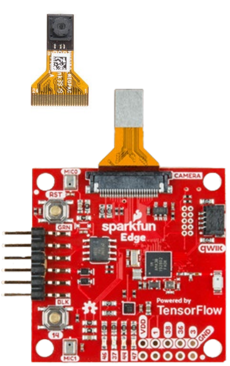
Machine Learning on Intermittently Powered Microcontrollers

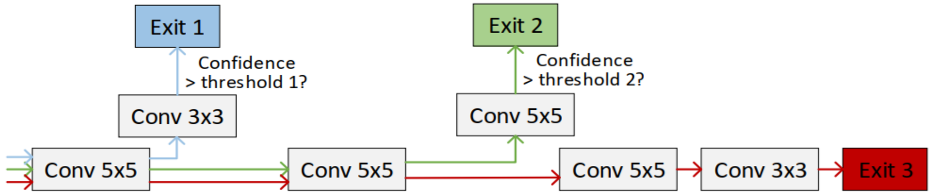
Paul Kyros, Yukai Song, Christopher Brubaker, Inhee Lee, Jingtong Hu

- 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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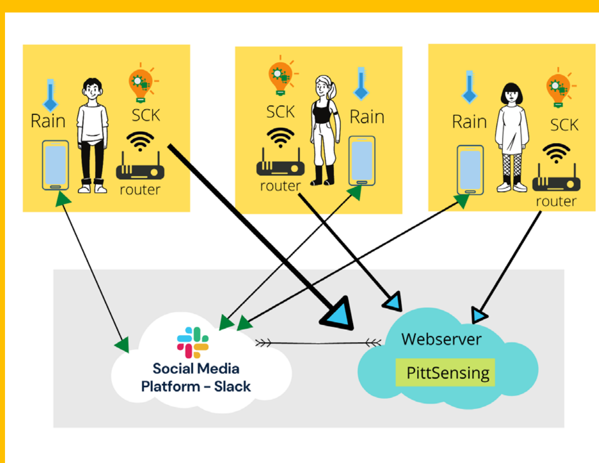
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

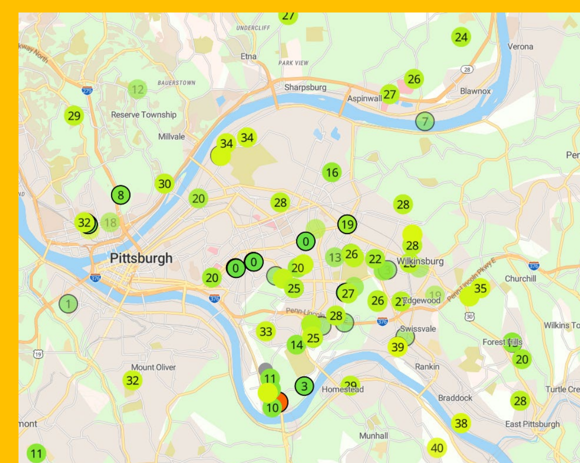
Abhishek Viswanathan, Amy Babay, Rosta Farzan – School of Computing and Information

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

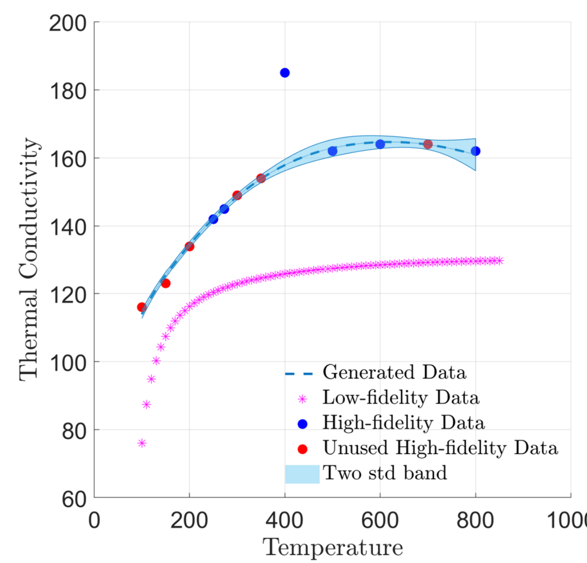
Multi-Fidelity Framework for Thermal Conductivity of Al−Cu

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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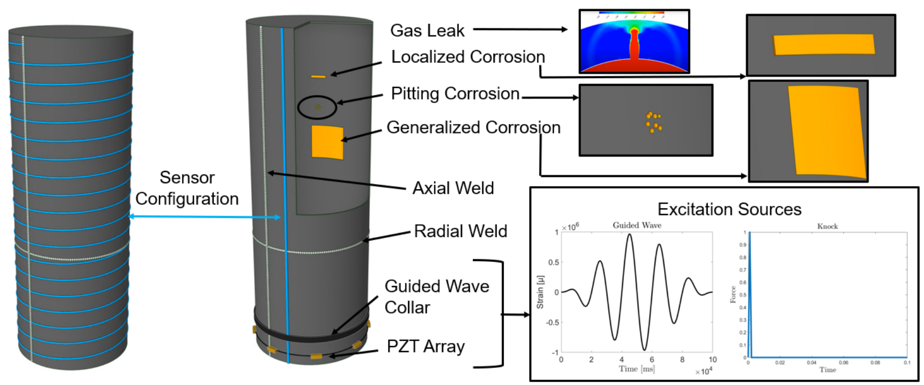
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

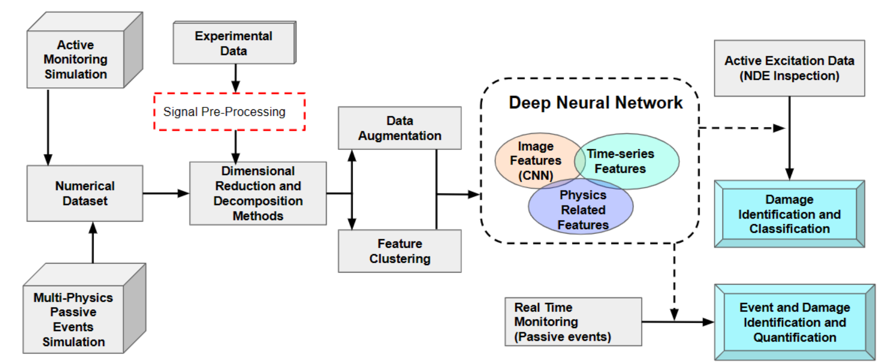
Fusion of Distributed Fiber Optics, Acoustic NDE and Physics-Based AI for Spent Fuel Monitoring

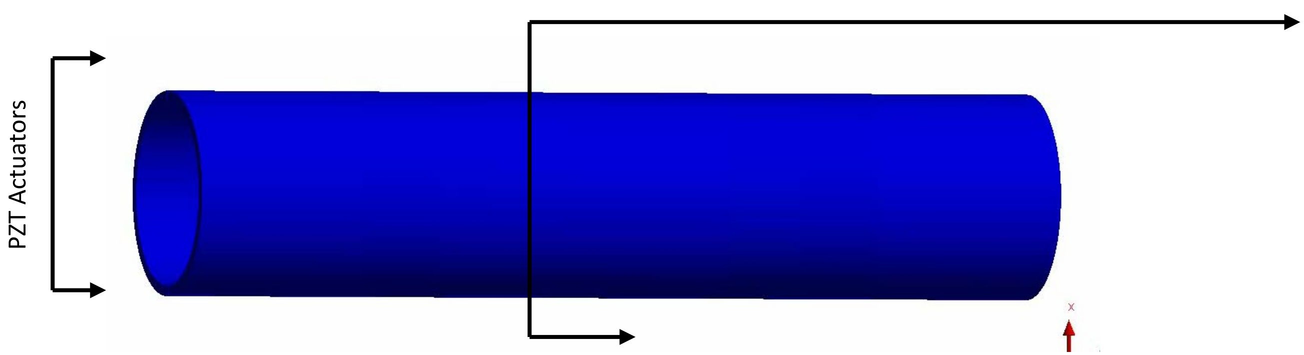
Enrico Sarcinelli[1], Pengdi Zhang[1] Abhishek Venketeswaran[2], Ruishu F. Wright[2], Khurram Naeem[1], Nageswara Lalam[2], Paul Ohodnicki[1]
[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh
[2]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh,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

Stainless-Steel Canister Monitoring System Overview

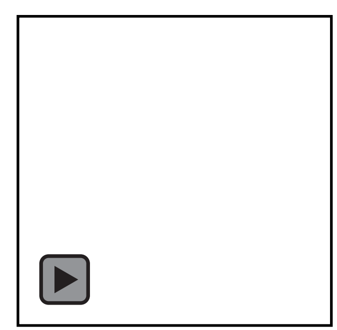


Schematic of AI Model Development





Angular Profile (15 in)



Contact: Dr. Dolendra Karki
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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

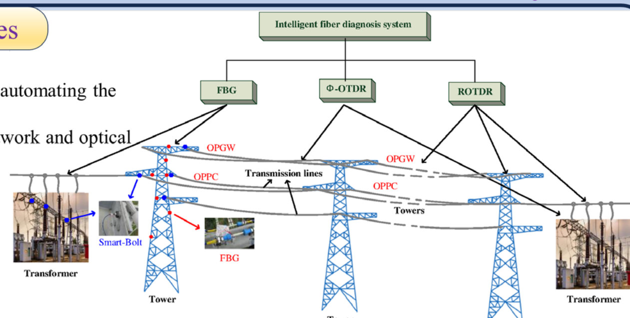
NATIONAL ENERGY TECHNOLOGY LABORATORY

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

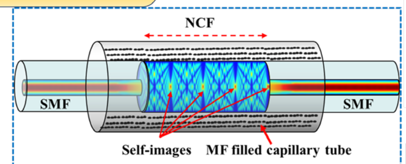


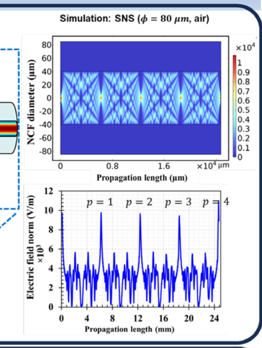
Source: https://doi.org/10.1117/1.OE.58.7.072007

Fiber Optic current sensor architecture

Self imaging in MMI

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

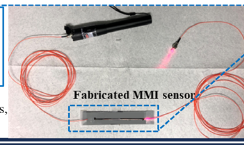




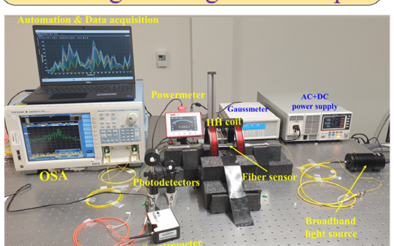
RI of Magnetic fluid (H, T)

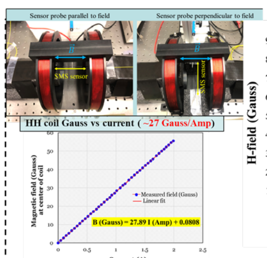
$$n_{\mathrm{MF}} = [n_s - n_o]\left[\coth\left(\alpha\frac{H - H_{c,n}}{T}\right) - \frac{T}{\alpha(H - H_{c,n})}\right] + n_o \quad \text{for } H > H_{c,n}.$$

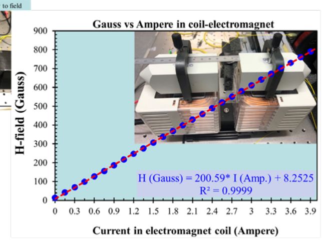
***Hc,n* - critical field strength,** *no* - refractive index of MF for fields lower than *Hc,n* , *ns* - saturated value of the refractive index of MF, *H* - field intensity in Gs, *T* - temperature in kelvin, *α* - the fitting parameter



Sensing interrogation set up

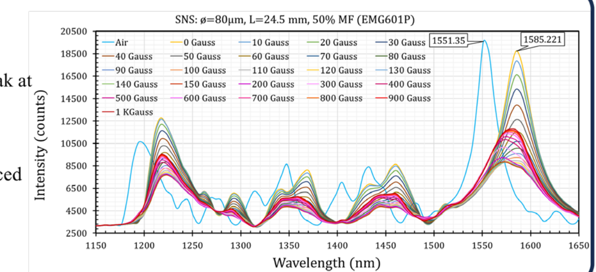






Method of interrogation

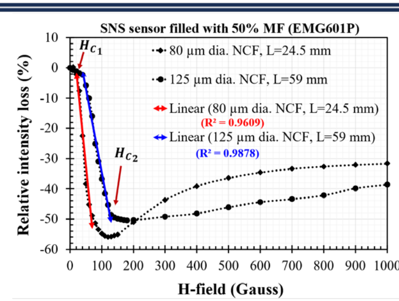
- Sensor optimized for 4th self-imaging peak at C-L band wavelength
- Intensity based interrogation
- Change in relative intensity of 4th self-imaging peak as a function of current induced magnetic field



Results

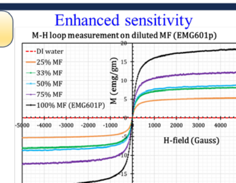
- Sensitivity > 0.5%/Gauss
- Linear response range below 130 Gauss
- Linearity $R^2 > 0.96$

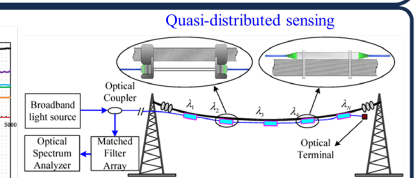
Magnetic fluid-based SMS sensor's performance metrics based on optimized 4th self-imaging condition				
SNS Sensor Specifications	4th self-imaging λ_{peak} (nm)	Response linearity	Sensing range (Gauss)	Sensitivity (S) (% intensity loss/Gauss)
Ø = 125μm, L= 59 mm	1562.64	R^2= 0.9878	40 to 130 Gauss	**0.52 %/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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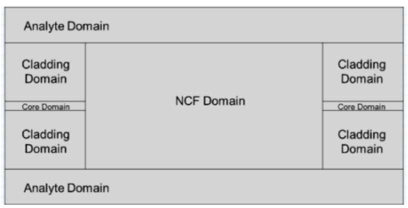
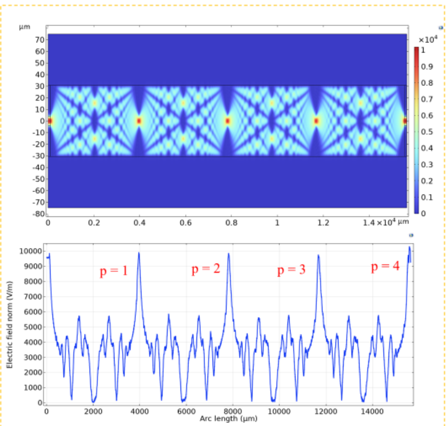
NATIONAL ENERGY TECHNOLOGY LABORATORY

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

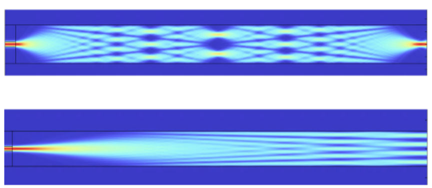
Tulika Khanikar, Dolendra Karki, Yang-Duan Su and Paul Ohodnicki.
Department of Mechanical Engineering and Materials Science, University of Pittsburgh, PA, USA.





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

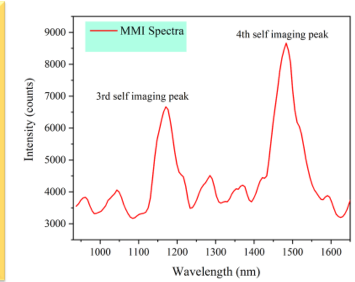
n_1 is the RI of core,
D_{MMF} is the diameter of MMF,
L_{MMF} is the MMF length,
P = 1,2,3….is an integer, representing the self-image order.

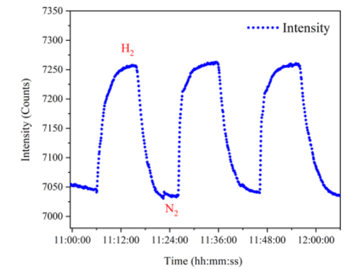


COMSOL version 6.1
Module : Wave optics
Domain : Electromagnetic Waves, Beam Envelopes (ewbe)

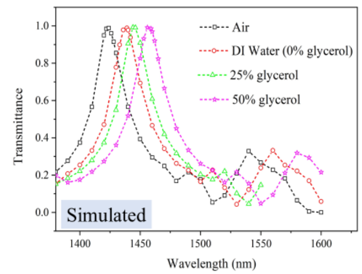
- When light is coupled from a SMF to a MMF/NCF, the modes that are supported by the MMF/NCF are excited and interferes with each other giving rise to an interference pattern along the MMF/NCF.
- At a certain length, light interferes constructively along the MMF/NCF central axis forming replicas of the 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.

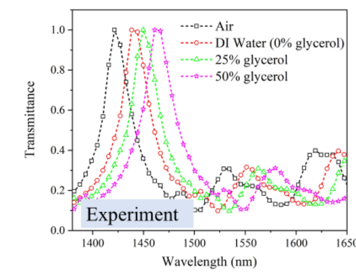
H_2 Sensing (80 μm NCF coated with 5nmTi+50 nm Pd)



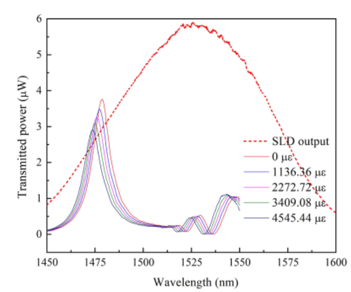


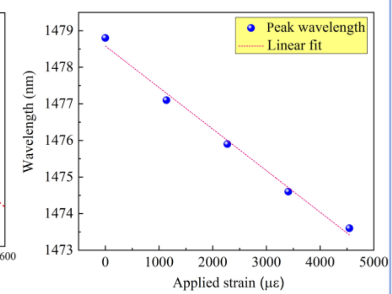
RI Sensing (61.5 μm NCF)





Axial strain Sensing (105 μm MMF)





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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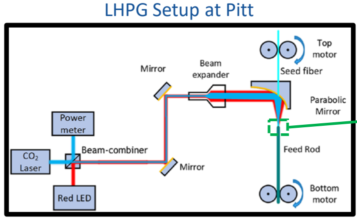
UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

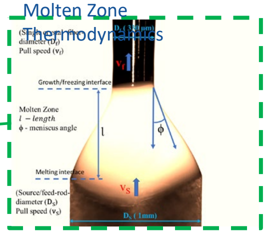
Single crystal fiber growth via LHPG method with focus on material melting properties

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



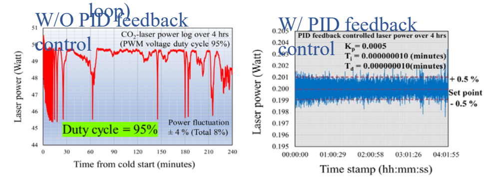
Molten Zone Thermodynamics



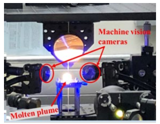
Laser power control (PID feedback loop)

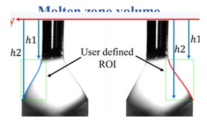
W/O PID feedback control

W/ PID feedback control



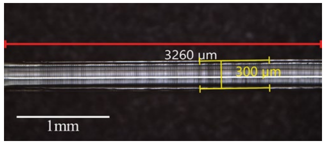
LabVIEW machine vision based in-situ
- ❖Diameter tracking and measurement
- ❖In-situ molten zone contour tracking and volume estimation



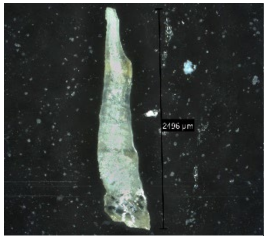


Varied Material Growth
- ❖High temperature ceramic oxides
- ❖Versatility in growing refractory oxides fibers e.g. sapphire, YAG, MO-oxides (YIG/TGG), EO-oxides (LN, BaTiO3)
- ❖Crucible free, high purity, diameter > 100 µm
- ❖Specific focus on magnetic properties for novel magnetic field sensing applications
- ❖Greater understanding of growth characteristics of materials based on melting characteristics; e.g. congruence vs incongruence

Sapphire Fiber Grown at Pitt

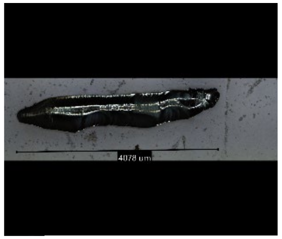


TGG Fiber Grown at Pitt

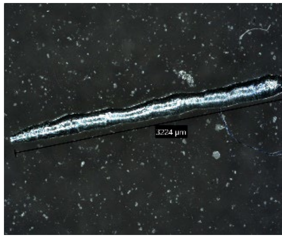


TGG Fiber Grown at Pitt

CoFe Fiber Grown at Pitt

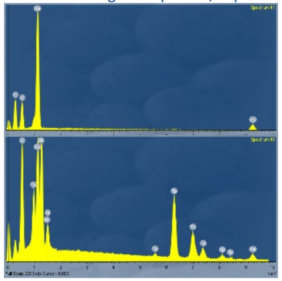


YIG Fiber Grown at Pitt

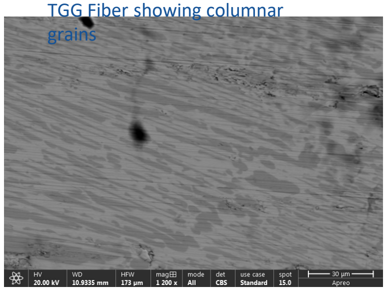


TGG Crystal Structure
- ❖Overcoming the GaO evaporation issue
- ❖Fabrication of different Ga ratios via powder processing methods
- ❖Avoid gallium depleted regions with different crystal structures
- ❖Evolution of elongated grain structures along the direction of growth
- ❖Examined by SCXRD/MicroPXRD to reveal a roughly even mixture of phases

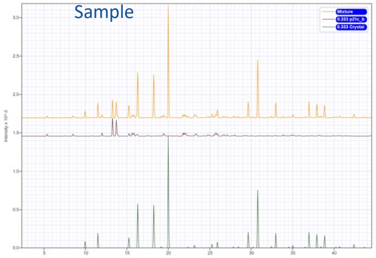
EDS revealing Ga depletion/deposition



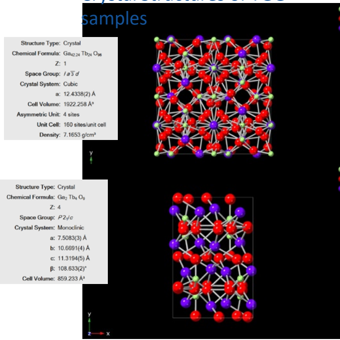
TGG Fiber showing columnar grains



XRD of Mixed Phase TGG Sample



Crystal Structures of TGG samples



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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

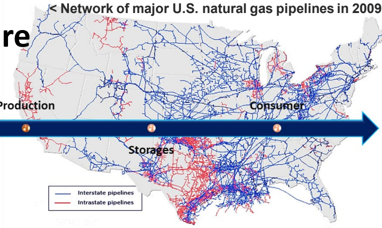
Khurram Naeem[1], Dolendra Karki[1], Pengdi Zhang[1], Enrico Sarcinelli[1], Nageswara Lalam[2], Ruishu Wright[2], and Paul Ohodnicki[1,3]

[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

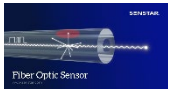
1 Pipelines Infrastructure Monitoring in USA



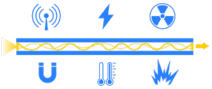
https://www.nbcnews.com/id/wbna39107965

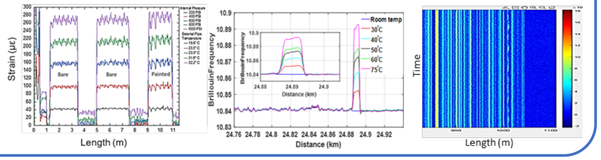
- Natural Gas, Oil Transport & Storages
- > 300k miles of distribution network
- > 50% built after World war II
- Aging and tend to deteriorate due to corrosion.
- Raptures occurs -> **Leaks** -> Explosion!!

2 Fiber-optic Sensor Technology



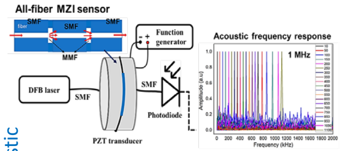
- Lightweight / embeddable in composite material
- Explosion- and electrical-proof
- Can work upto 1000 °C temperature
- Passive devices
- Point, quasi-distributed
- Fully-distributed sensing

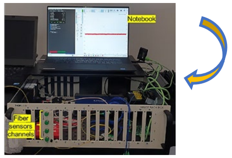




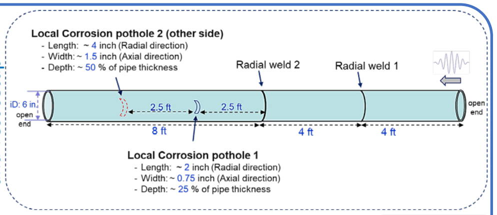
3 Damage detection in Pipe

Fiber-optic Acoustic Sensor





Pipe schematics and Test setup



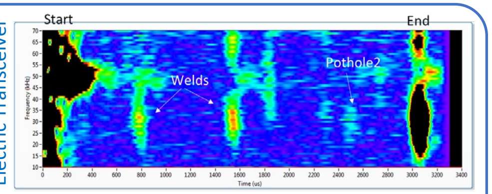
4 Our Results

- **Ultrasonic Source:** Guided wave collar

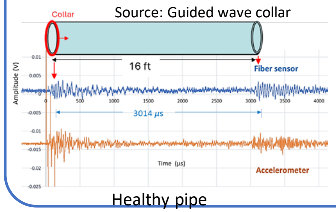
-> Torsional mode (symmetric wave) is excited by the UGW collar on the pipe surface.

< Fiber-optic Acoustic Sensor >

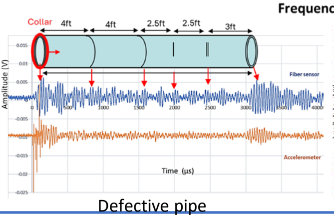
Electric Transceiver



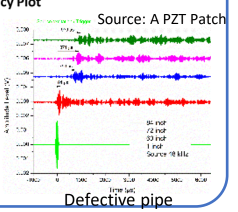
Frequency Plot



Healthy pipe

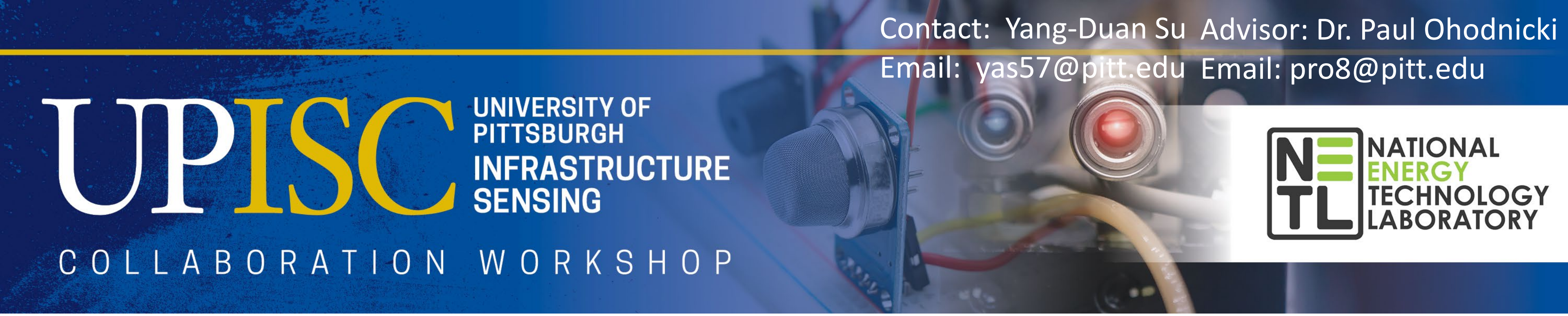


Defective pipe



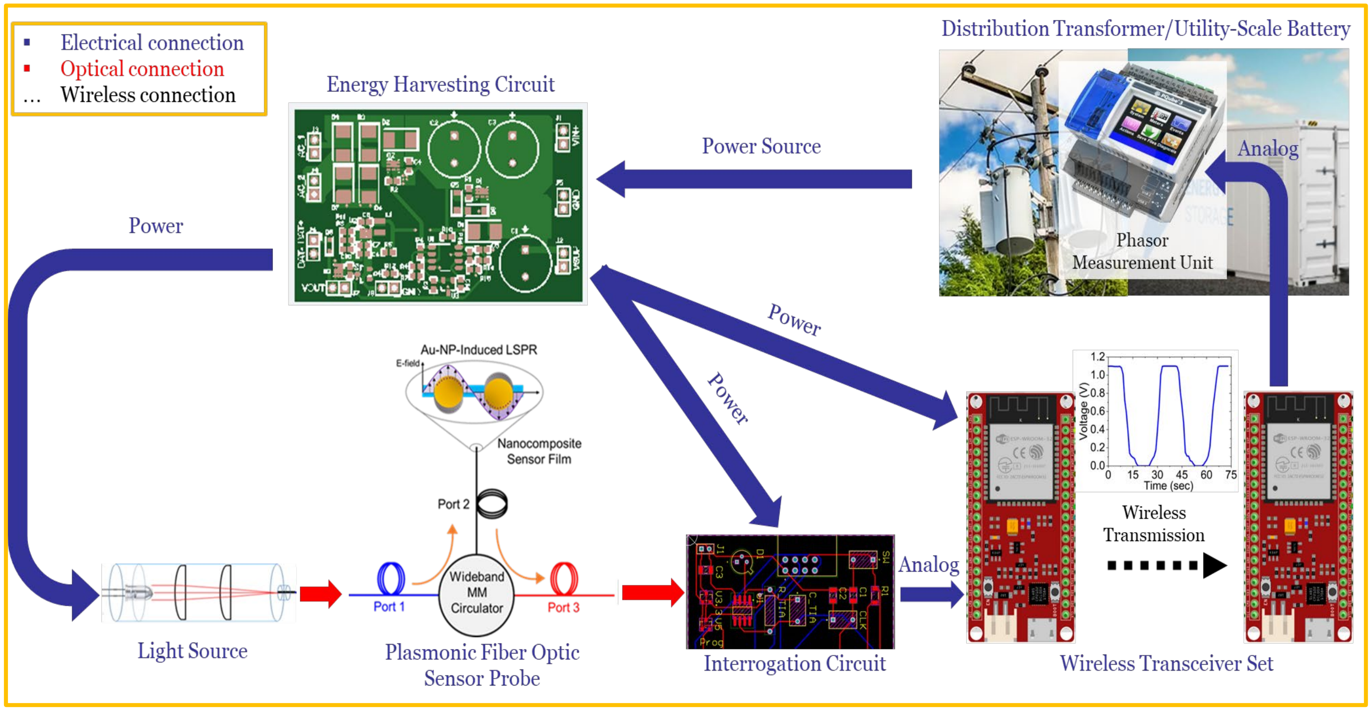
Defective pipe

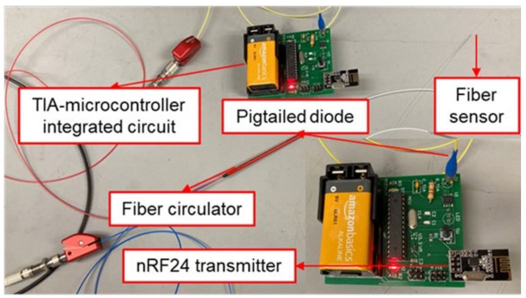
Contact: Yang-Duan Su Advisor: Dr. Paul Ohodnicki
Email: yas57@pitt.edu Email: pro8@pitt.edu

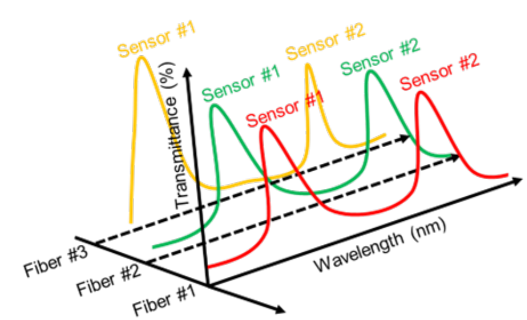


Towards Portable and Simultaneous Gas/Temperature Fiber Optic Point Sensor Interrogator for Electrical Assets Health Monitoring

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

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

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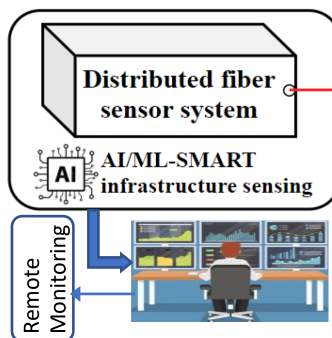
NATIONAL ENERGY TECHNOLOGY LABORATORY

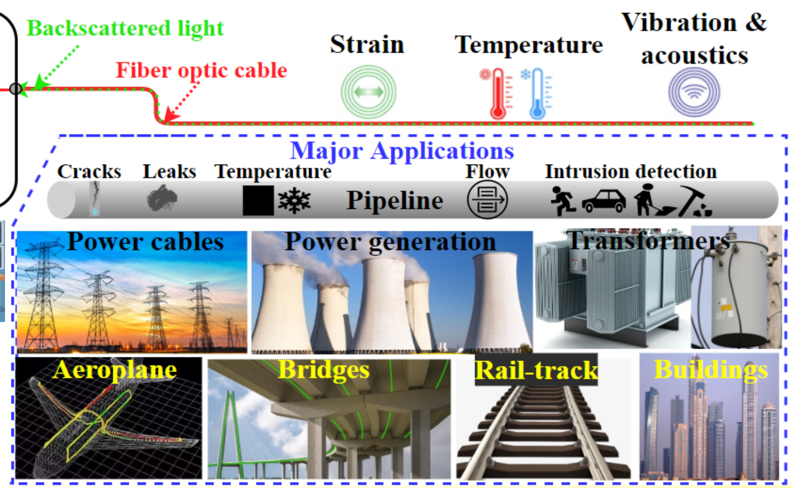
Distributed Fiber Optic Sensor Systems for Multi-Parameter Monitoring

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

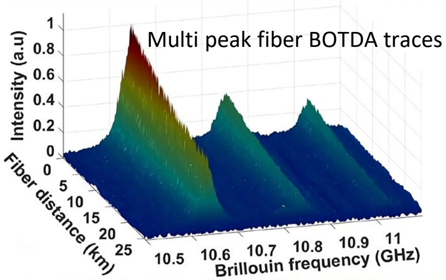
Sensing range = >100 km;
Spatial resolution = <5 m;
Measurable parameters: strain, and temperature

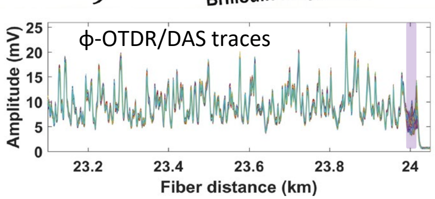
ϕ-OTDR/DAS

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;



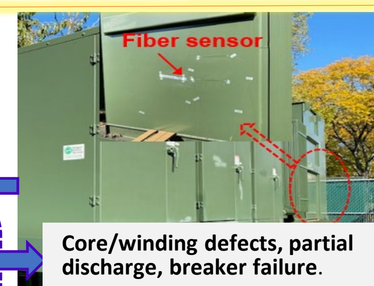


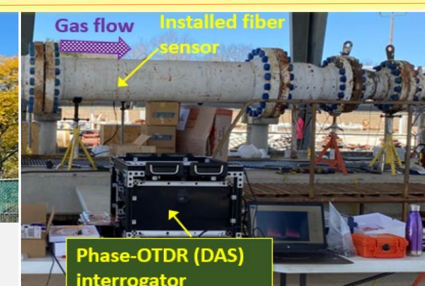
Advantages

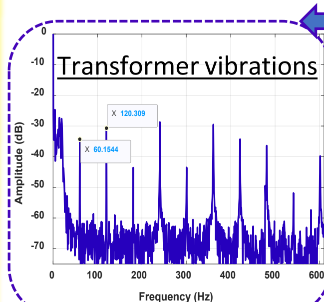
- Compact size
- EMI resistance
- Withstand harsh environment
- Real-time and remote monitoring
- High accuracy and stability
- Enhanced structural safety

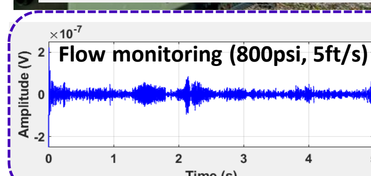
Field validation

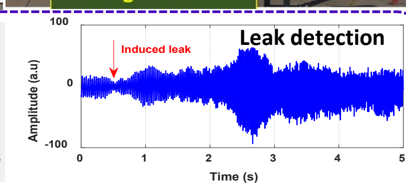
Power Transformer
Oil and Gas Pipeline











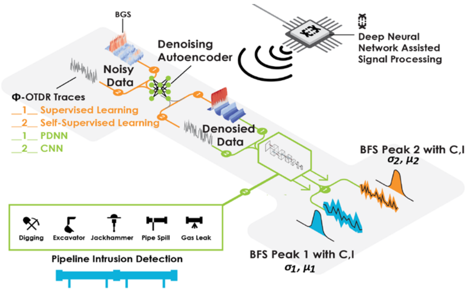
Contact: Sandeep Bukka
Email: Sandeep.bukka@netl.doe.gov

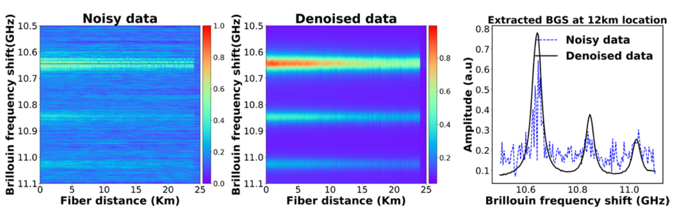
UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING COLLABORATION WORKSHOP

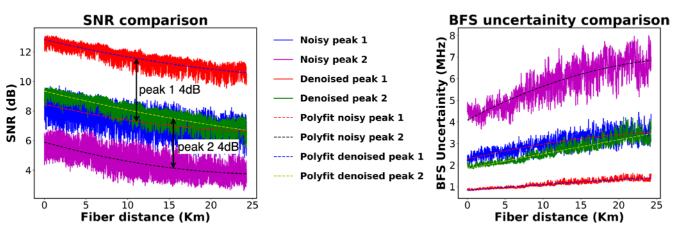
NATIONAL ENERGY TECHNOLOGY LABORATORY

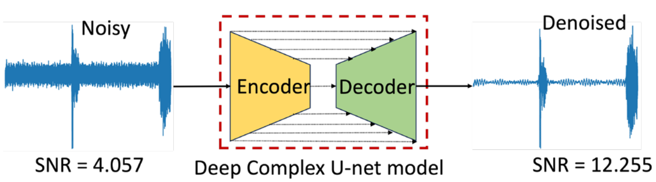
Intelligent and Real time data analytics for fiber optic sensors using deep neural networks

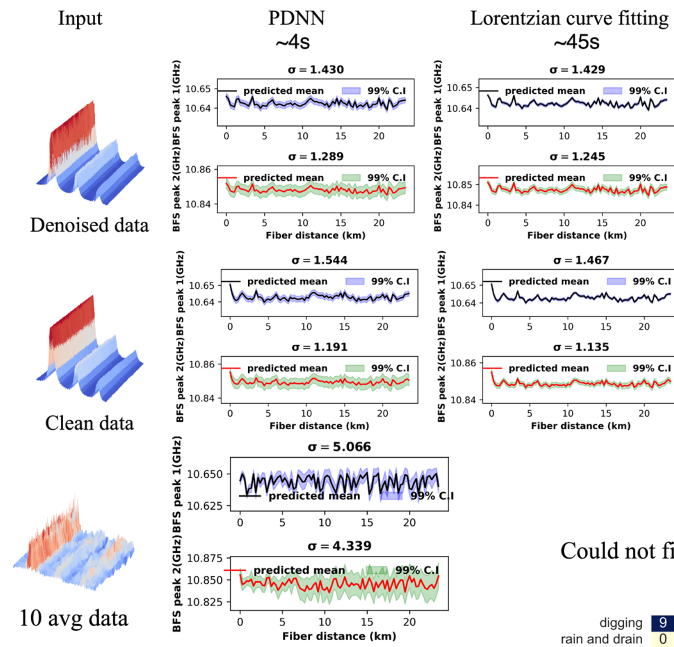
Sandeep Reddy Bukka[1], Nageswara Lalam[1] , Hari Bhatta[1] , Ruishu F. Wright[1]
[1]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA, USA 15236

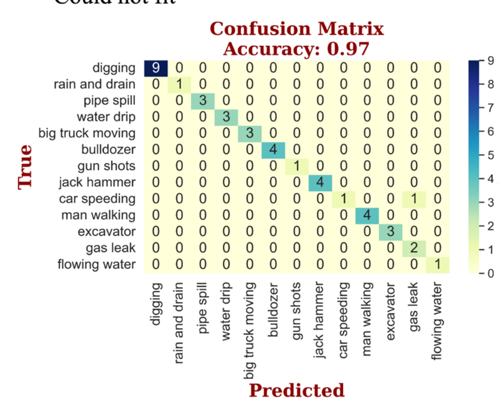












Passive Wireless Sensing of Methane Leak and Monitoring Corrosion in Pipelines

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

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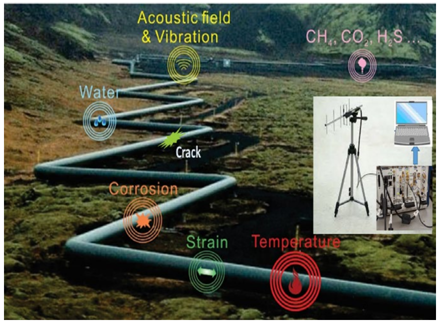
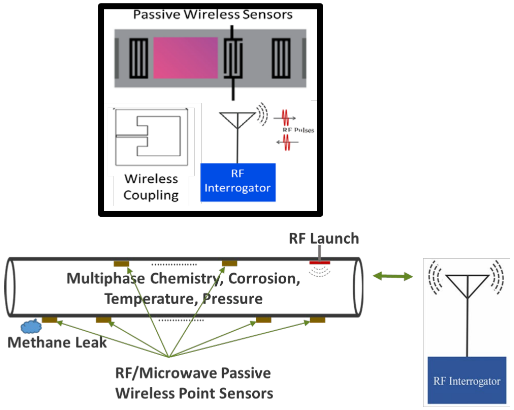
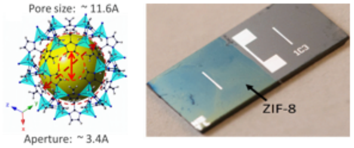
Motivation



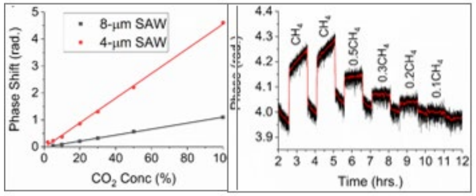
- Conventional monitoring techniques are infrequently performed making prediction of potential events difficult.
- Continuous and real-time monitoring technologies are helpful to better identify, locate, and quantify methane leaks and corrosion events.
- Passive wireless sensors and their network are 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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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

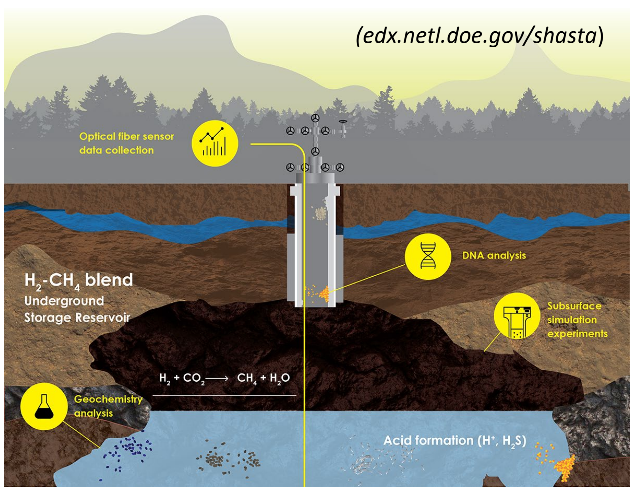
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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]

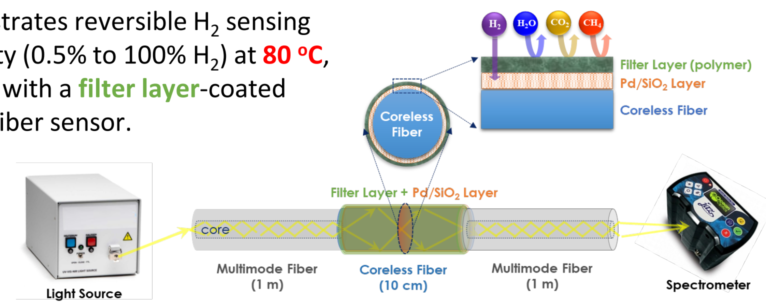
([1]National Energy Technology Laboratory; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA)



- 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.

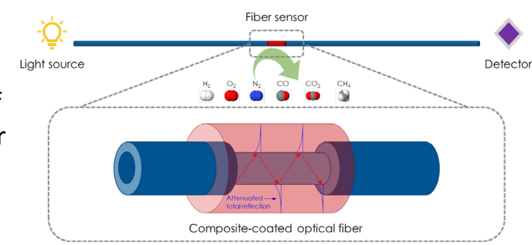
H_2 Sensor

- 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.

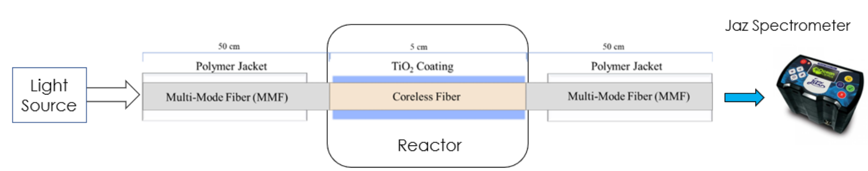


CH_4 Sensor

- 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**.

Contact: Matthew Brister
Email: matthew.brister@netl.doe.gov

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

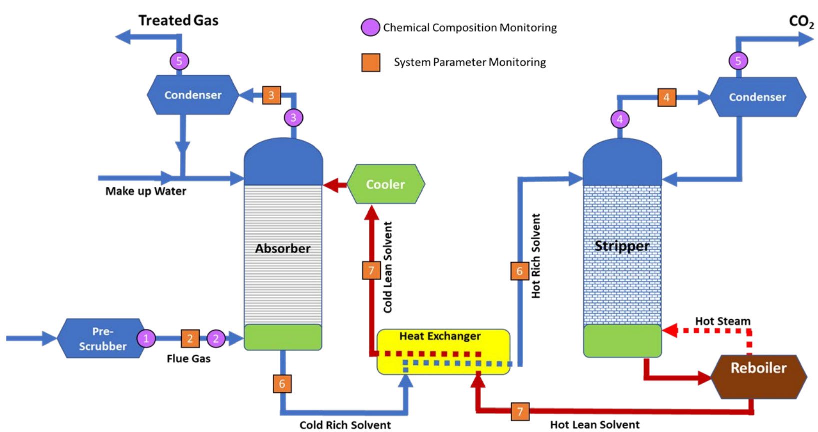
Matthew M. Brister[1,2]; Alexander Shumski[1,2]; Chet R. Bhatt[3,4]; Jeffrey Culp[1,2]; Krista Bullard[1,2]; Dustin McIntyre[3]; Benjamin Chorpening[3]; Nicholas Siefert[1]; Ruishu F. Wright (PI)[1]

[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)

Post Combustion Carbon Capture Design



- 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.

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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NATIONAL ENERGY TECHNOLOGY LABORATORY

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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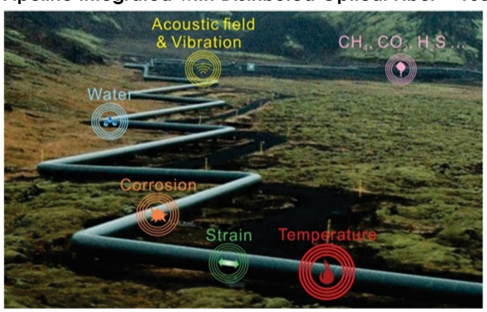
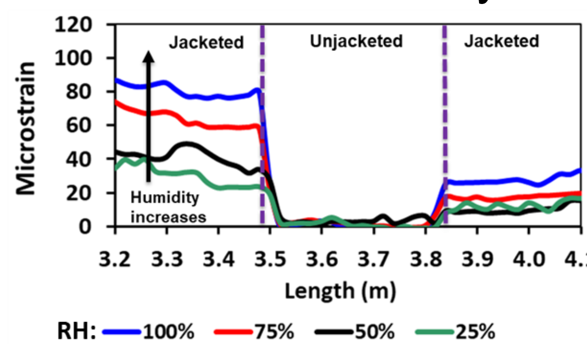
Pipeline Monitoring Concerns

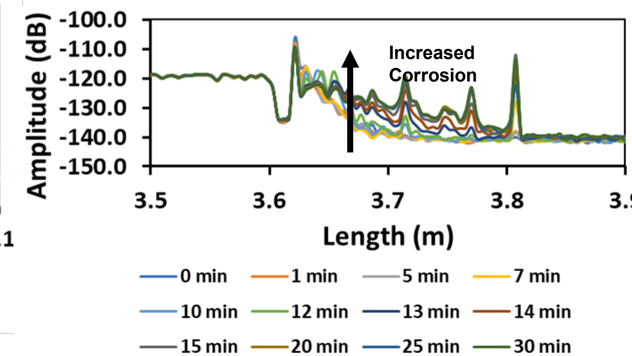
Pipeline Integrated with Distributed Optical Fiber > 100 km



- 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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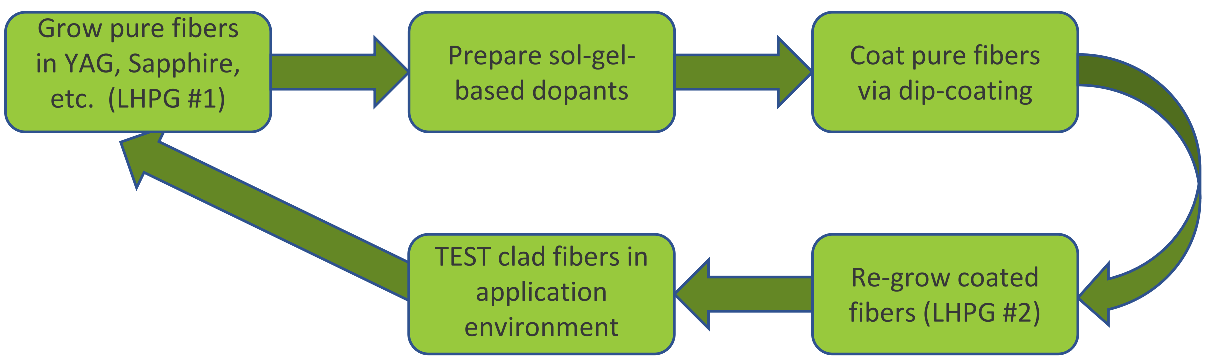
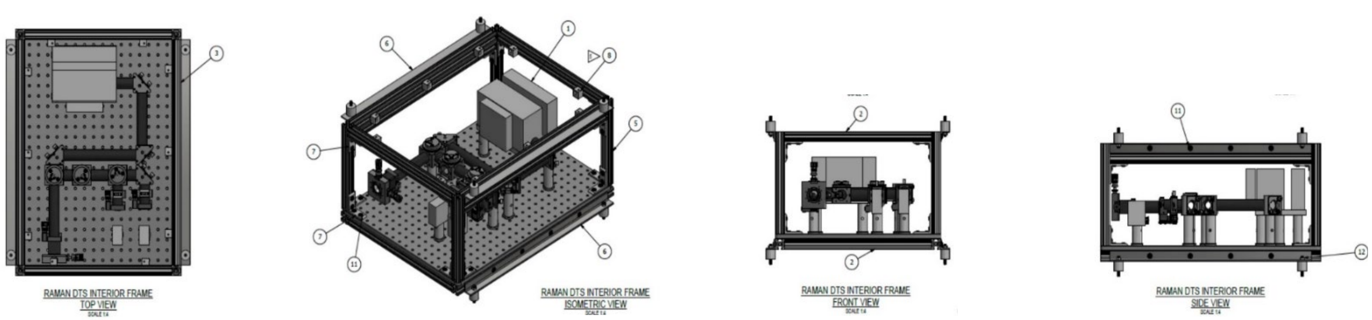
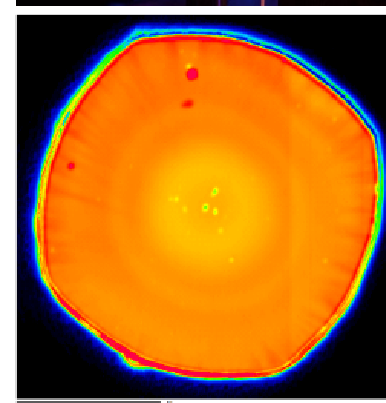
NATIONAL ENERGY TECHNOLOGY LABORATORY

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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NATIONAL ENERGY TECHNOLOGY LABORATORY

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

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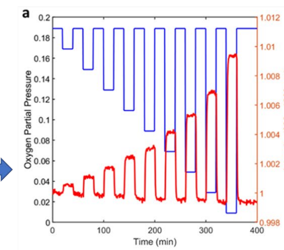
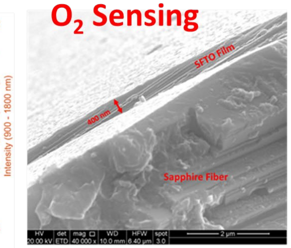
[1]National Energy Technology Laboratory, Pittsburgh PA /Morgantown WV; [2]NETL Site Support Contractor, Pittsburgh PA / Morgantown WV

- 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.**

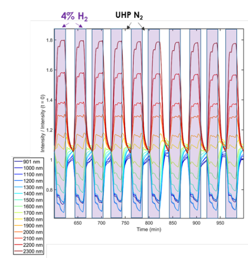
O_2 Sensing

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

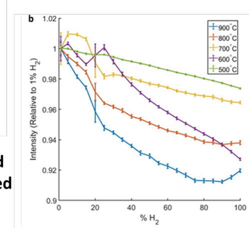


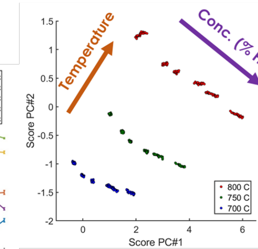


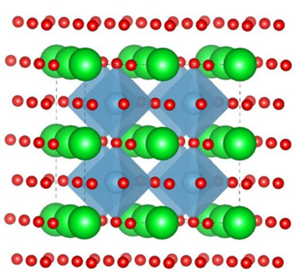
H_2 Sensing

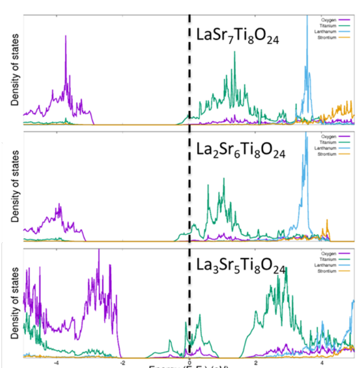


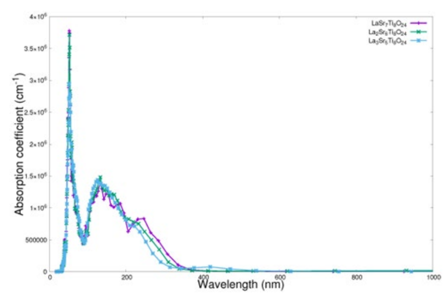
LSTO-based conductive and plasmonic optical fiber-based hydrogen sensing 0-100% H_2, 500-900 °C











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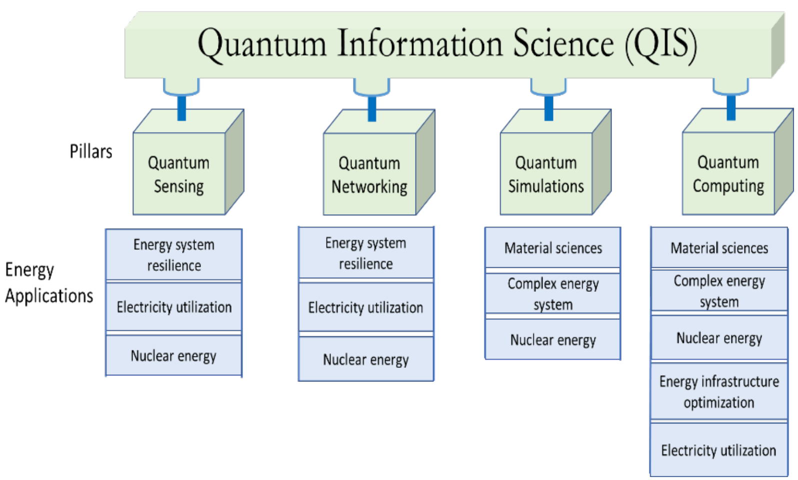
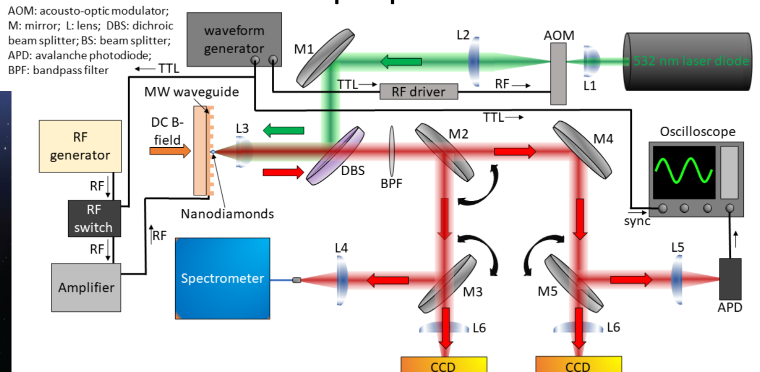
NATIONAL ENERGY TECHNOLOGY LABORATORY

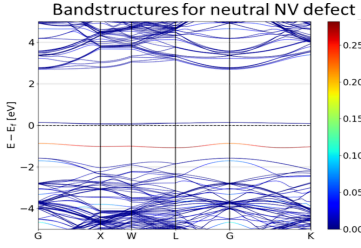
Quantum for Energy Systems and Technologies

- Growing interest in quantum sensing, quantum computing and quantum networks for processes pertaining to energy production, distribution, and consumption.
- 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.





Bandstructures for neutral NV defect



Bandstructures for negative NV defect