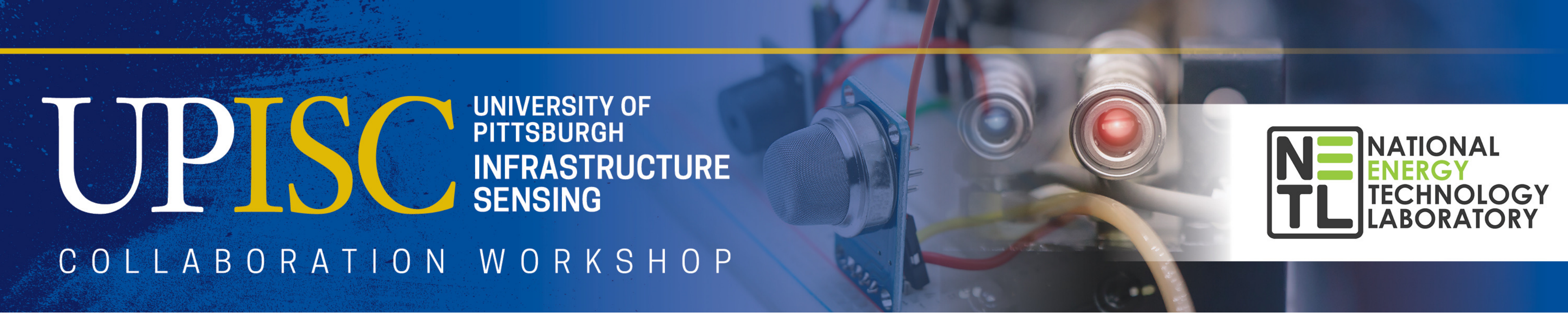
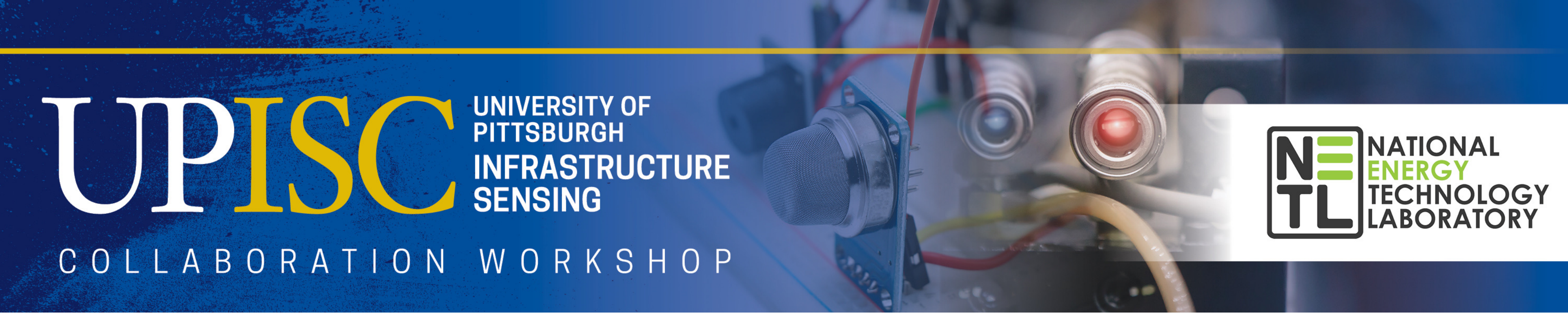


Sensor Device Technologies

Prof. Paul R. Ohodnicki, Jr.
UPISC Co-Chair; Associate Professor, Mechanical Engineering & Materials Science; Director, Engineering Science Program, University of Pittsburgh

Ruishu F. Wright, Ph.D.
UPISC Co-Chair; Research Scientist, Co-PI-MEMS Adjunct, NETL



Prof. Paul R. Ohodnicki, Jr.

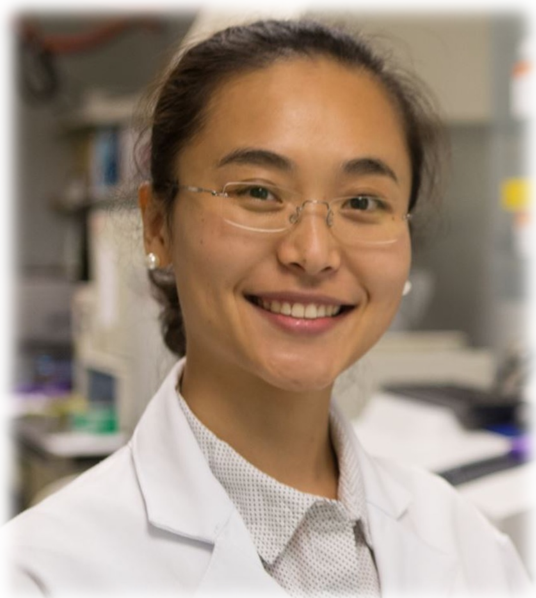
UPISC Co-Chair; Associate Professor, Mechanical Engineering & Materials Science;
Director, Engineering Science Program,
University of Pittsburgh

Paul R. Ohodnicki is an associate professor in the Department of Mechanical Engineering and Materials Science at the University of Pittsburgh. He received his Ph.D. in Materials Science and Engineering from Carnegie Mellon University in 2008, after which he joined PPG Industries R&D working on thin-film coating materials and earned the Advanced Manufacturing and Materials Innovation Award from Carnegie Science Center in 2012. Ohodnicki later continued his career at the DOE National Energy Technology Laboratory (NETL), where he eventually served as a technical portfolio lead guiding teams of materials scientists working on the development of optical and microwave sensors as well as magnetic materials and power electronics development for high frequency transformer based solar PV / energy storage inverters.

Paul has published more than 140 technical publications and holds more than 10 patents, with more than 15 additional patents under review. He is the recipient of the 2016 Presidential Early Career Award for Scientists and Engineers, the highest honor the federal government can bestow on early-career scientists or engineers. He also is the recipient of several other awards and recognitions, including the Federal Employee Rookie of the Year Award (2012), the Advanced Manufacturing and Materials Innovation Category Award for the Carnegie Science Center (2012, 2017, 2019) and in 2017 he was a nominee for the Samuel J. Heyman service to America Medal. Before joining the University of Pittsburgh as an Associate Professor, he received the 2019 R&D 100 Award owing to his work on cobalt-rich metal amorphous nanocrystalline alloys for permeability-engineering gapless inductors.

Ruishu F. Wright, Ph.D.

UPISC Co-Chair; Research Scientist, Co-PI-MEMS Adjunct, NETL



Dr. Ruishu F. Wright is a Research Physical Scientist on the National Energy Technology Laboratory's Functional Materials Team. She serves as Technical Portfolio Lead for Natural Gas Infrastructure FWP and Principal Investigator for multiple projects and coordinates R&D efforts of an interdisciplinary team to develop real-time sensors and functional sensitive materials to monitor and mitigate corrosion and gas leaks of natural gas pipelines, enable subsurface geochemical monitoring in support of subsurface hydrogen-natural gas storage, wellbore integrity monitoring of carbon storage wells, and plugging abandoned wells. Dr. Wright's expertise lies in advanced sensors development for structural health monitoring and environmental detection for energy infrastructure using distributed and nondestructive sensor technologies to ensure safe, reliable and resilient infrastructure for, among other things, natural gas and hydrogen transportation, subsurface wellbores, CO2 storage systems, and plugged abandoned wells. She has extensive experience in design and development of functional materials (e.g. metallic thin films, metal oxides, nanomaterials) to enable various sensor platforms(e.g. fiber optic sensors, passive wireless sensors, electrochemical sensors). She also has strong expertise in corrosion and materials degradation in natural gas pipelines and in deep wells with extreme conditions, such as high-temperature, high-pressure (HTHP) environments. Dr. Wright holds a Ph.D. from the Pennsylvania State University, and she has published more than 40 technical articles and given more than 30 presentations at conferences, and holds five pending and awarded U.S. patents on sensor technologies.

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

Sensing Technology Research

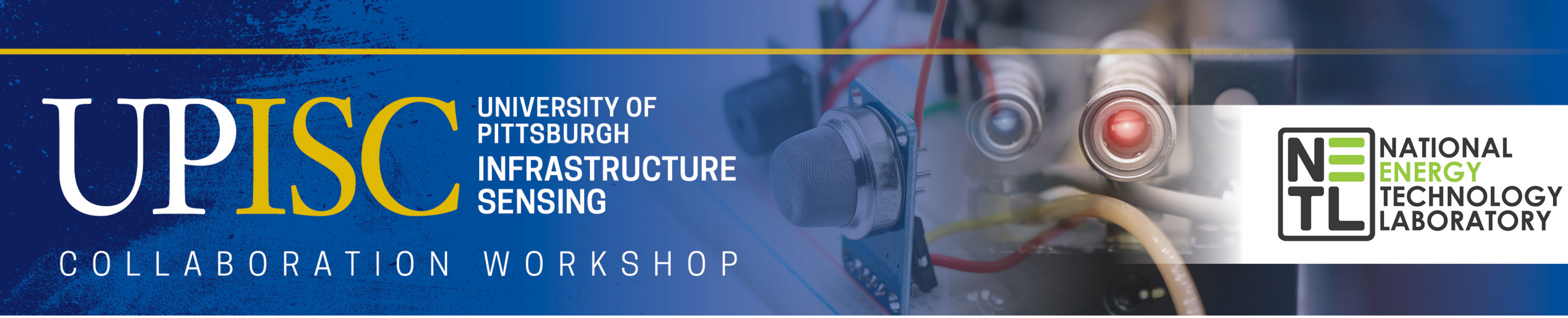
UNIVERSITY OF PITTSBURGH VERITAS 1787 VIRTUS

Cathedral of Learning
University of Pittsburgh

Date: August 25th, 2022

Prof. Paul R. Ohodnicki, Jr.
University of Pittsburgh

Ruishu F. Wright, Ph.D.
National Energy Technology Lab.



Natural Gas, Oil, & H_2 Transport & Storage

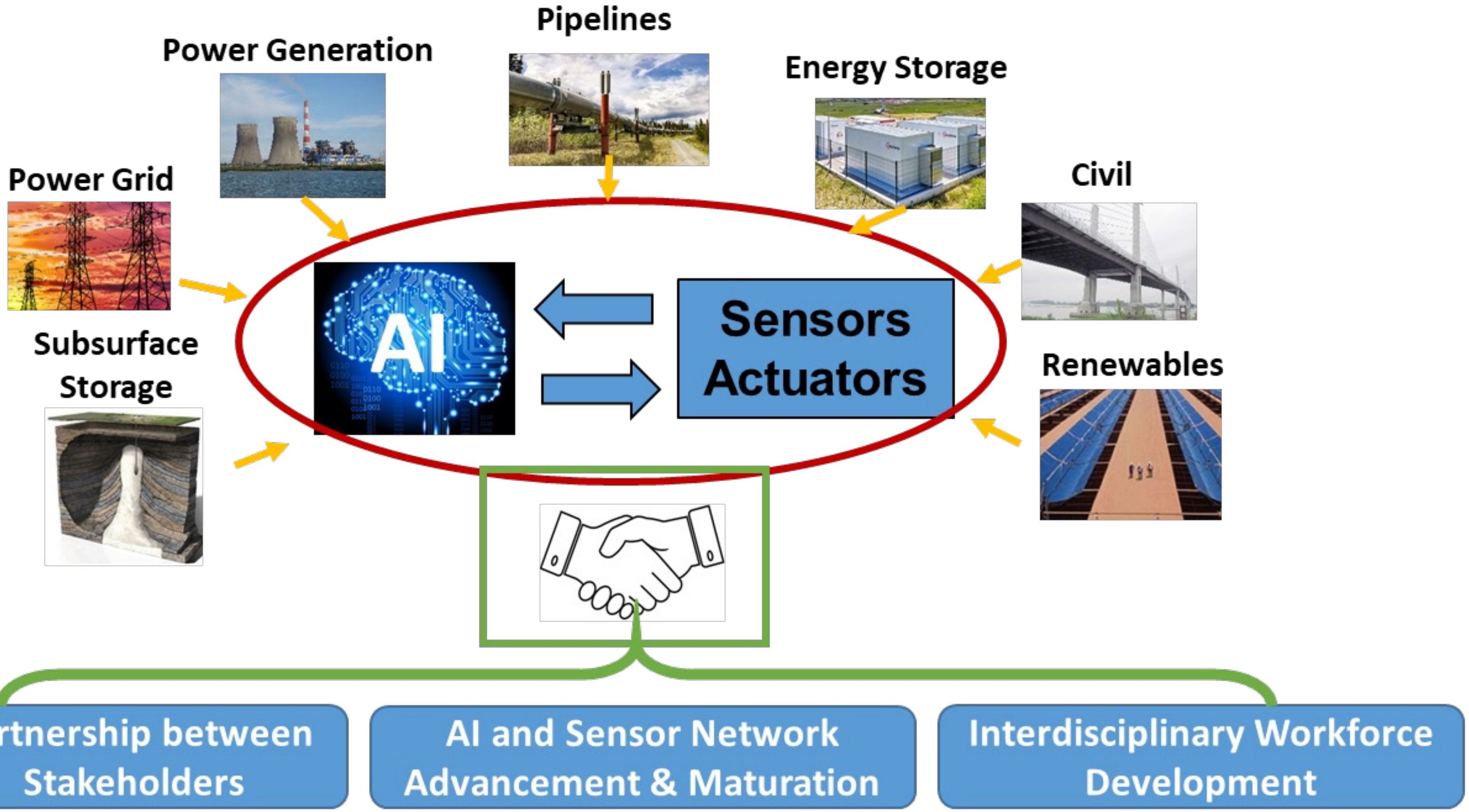
Civil (Road, Bridges, Water)

Electricity Grid Transport & Storage

Conventional & Renewable Generation

Mission: UPISC Seeks to Pursue Research and Innovation, Workforce Development, and Technology Transfer in the Area of Critical Infrastructure Sensing and Monitoring

Objective of UPISC Workshop : Community and Partnership Development

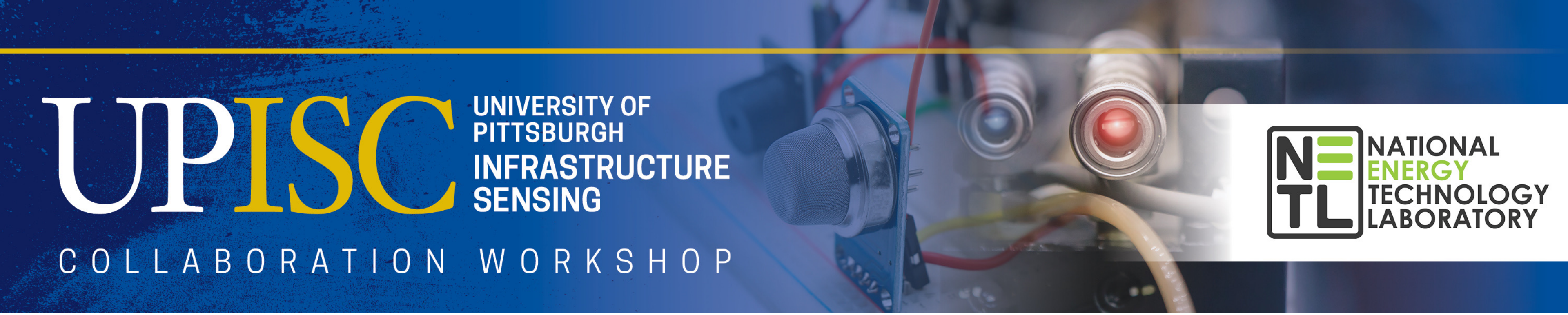


University, Lab, Industry, and Government Partnerships are Necessary to Maximize Impact

How Do We Define a Sensor?

Attributes	Example Metrics and Qualities				
Cost	Per Unit Information	Per Node		Total Installed	Total Installed w/ Communications
Information Content	Single Parameter	Multi-Parameter			Big Data
Geospatial Attributes	Point	Multi-Point	Line	Area	Volume
Telemetry and Communications	Wired (Electrical)	Wired (Optical)			Wireless
Power Requirements	Wired	Battery		Harvesting	Passive
Cybersecurity Risks	Local Data Use Only	Direct Data Transmission			Distributed Data Transmission

A Sensor is a Node Providing Information About a System That Must Be Accessed and Acted Upon to Produce Value…



What Attributes are Most Important for Applications?

Attributes	Example Metrics and Qualities				
Cost	Per Unit Information	Per Node		Total Installed	Total Installed w/ Communications
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Power Requirements	Wired	Battery		Harvesting	Passive
Cybersecurity Risks	Local Data Use Only	Direct Data Transmission			Distributed Data Transmission

Example : Natural Gas Pipelines, Electrical Transmission Lines

What Attributes are Most Important for Applications?

Attributes	Example Metrics and Qualities				
Cost	Per Unit Information	Per Node		Total Installed	Total Installed w/ Communications
Information Content	Single Parameter	Multi-Parameter			Big Data
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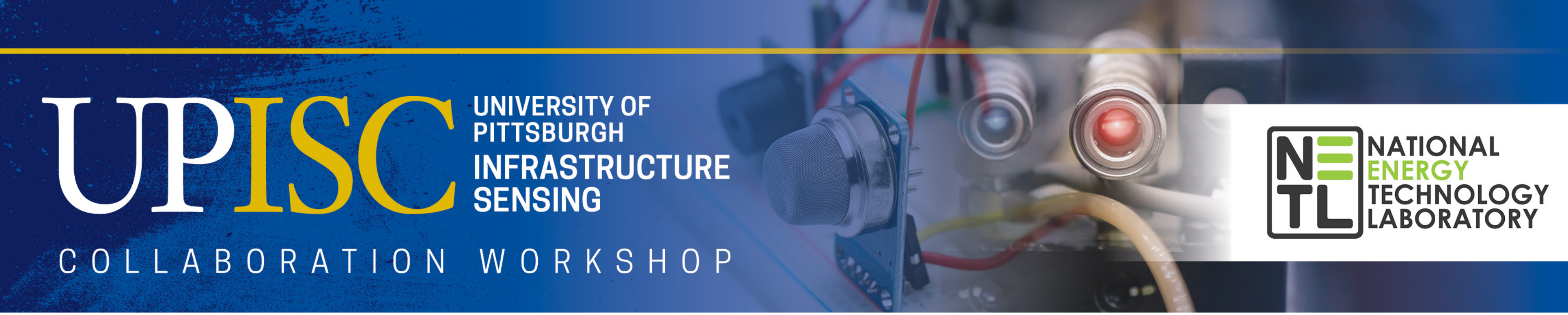
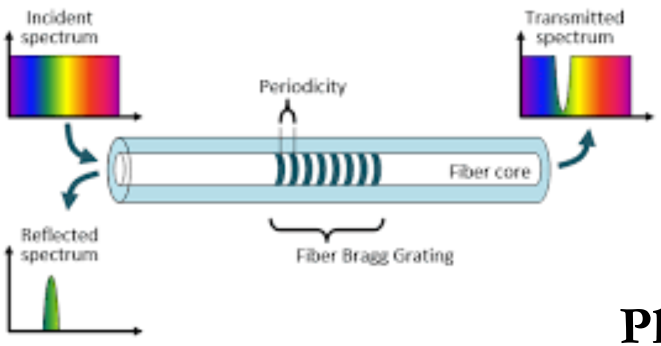
Power Requirements	Wired	Battery		Harvesting	Passive
Cybersecurity Risks	Local Data Use Only	Direct Data Transmission			Distributed Data Transmission

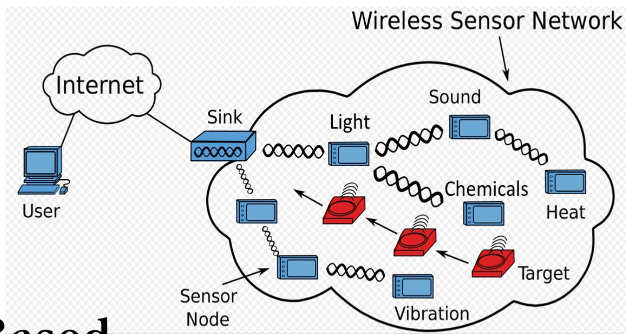
Example : Electrical Assets in Distribution System



Optical Fiber Sensing

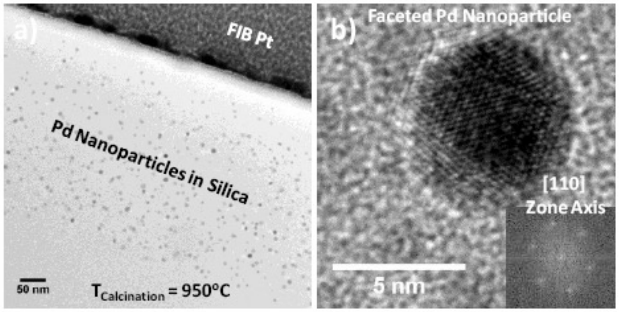


Passive Wireless Sensing

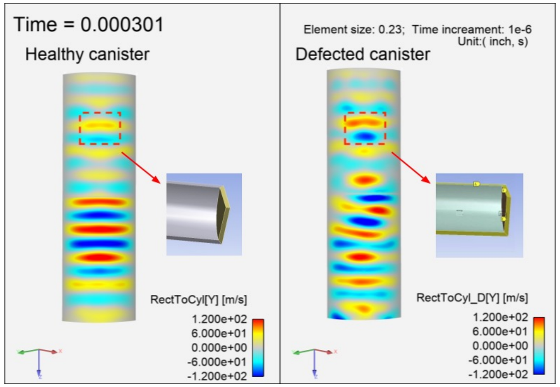


https://en.wikipedia.org

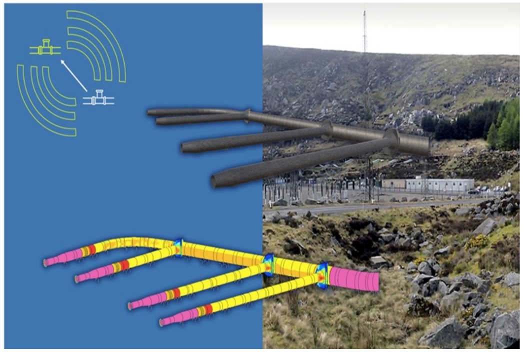
Novel Sensing Materials



Physics Based Machine Learning & AI



Digital Twin Models



Enabling Technologies: UPISC Scope Encompasses all Aspects of Critical Infrastructure Sensing Spanning Enabling Technology, Hardware, Communications, Data, and Analytics.

"Attributes" of Passive Wireless Sensors

Attributes	Example Metrics and Qualities				
Cost	Per Unit Information	Per Node		Total Installed	Total Installed w/ Communications
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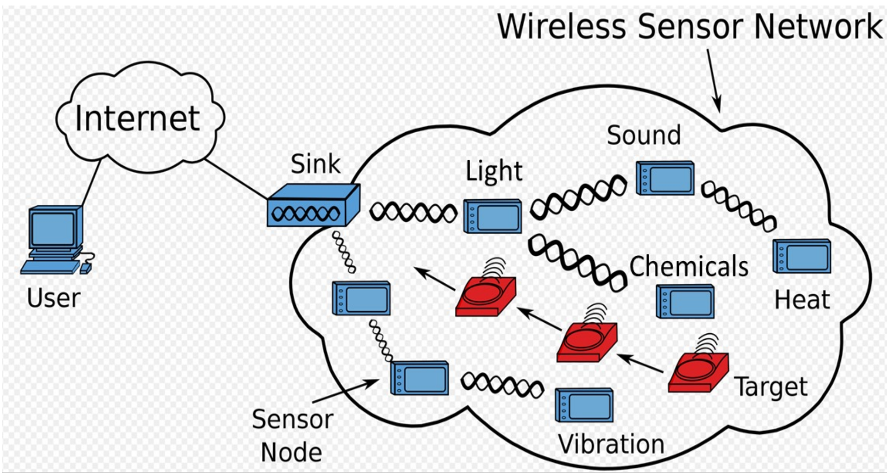
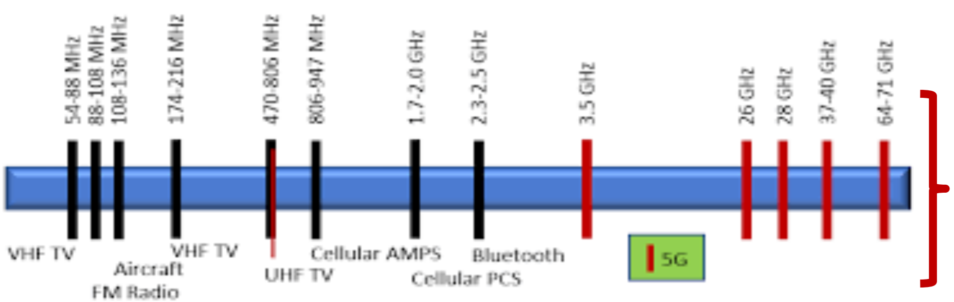
Optical Fiber Sensors are of Particular Interest for a Range of Infrastructure Monitoring Applications (Stability, Reliability, Harsh Environment Compatibility, etc.)

Wireless Sensors and Internet of Things (IoT)



https://en.wikipedia.org

- Sensors are the end devices and are indispensable enablers of IoT.

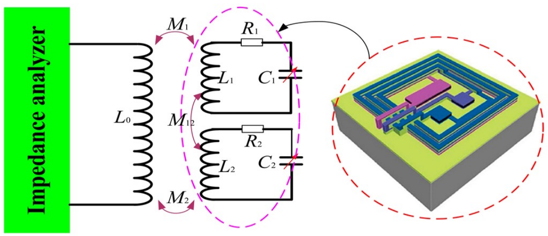


Wireless Sensors:

- Dominate most IoT applications.
- Collect data about local environment and wirelessly transmit
- Simple circuitry, small power, and low level of maintenance
- Wireless Passive sensors overcome need for local power
- Telemetry is a primary challenge.
- Emerging 5G Wireless Networks

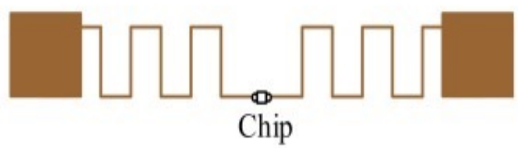
Passive Wireless Sensors

Oscillating Circuit Sensors



Li et al., Sensors 2015, 15, 13097

RFID Antenna Tags

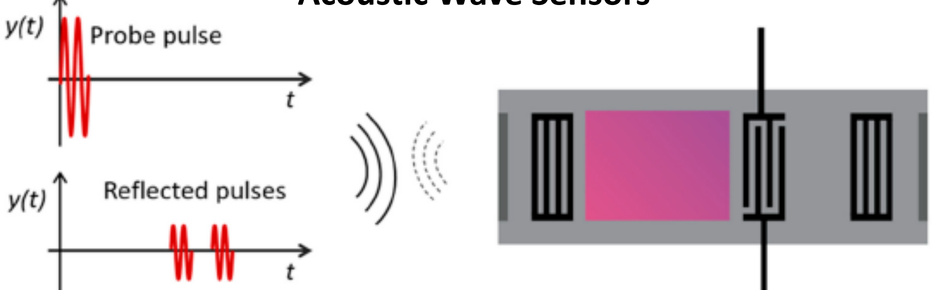


Cui et. al., Sensors 2019, 19, 4012

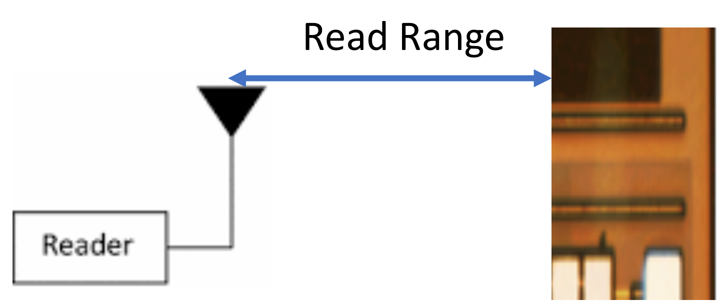
Telemetry for Wireless Passive Sensors

Antenna Gain
Thermal Noise
Insertion Losses
Radiated Frequency
Radiated Power

Acoustic Wave Sensors



Ohodnicki et. al., Sensors 2017, 17, 801



Examples of Various Passive Wireless Sensor Platforms

“Attributes” of Optical Fiber Sensors

Attributes	Example Metrics and Qualities				
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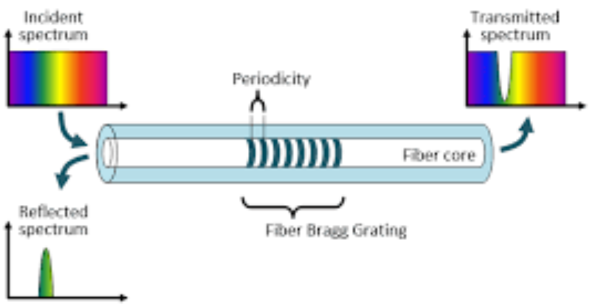
Optical Fiber Sensors are Also of Particular Interest for a Range of Energy Infrastructure Monitoring Applications (Stability, Reliability, Harsh Environment Capability, etc.)

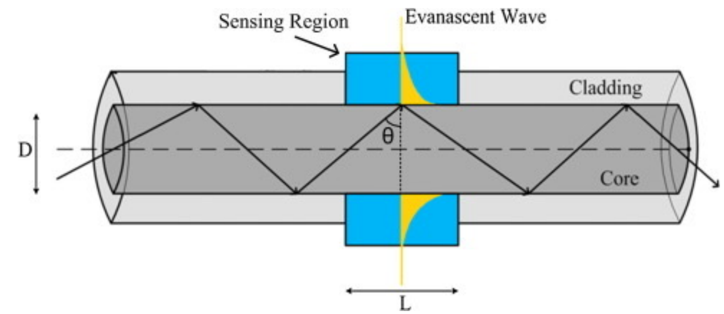
Optical Fiber Sensors

Point Sensors (FBG, FPI)



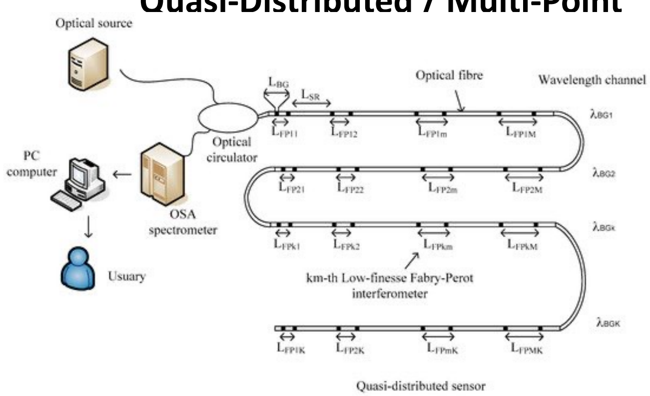
https://hittech.com/de/portfolio-posts/noria-the-fiber-bragg-grating-manufacturing-solution/

Point Sensors Evanescent, Fluorescent



A. Sharma, J.Gupta, R. Basu, Optics & Laser Technology, 98, 291 (2018)

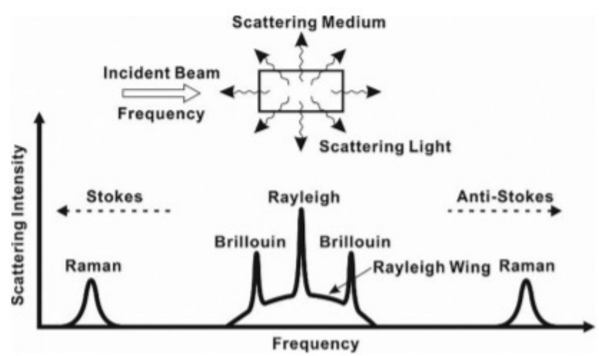
Quasi-Distributed / Multi-Point

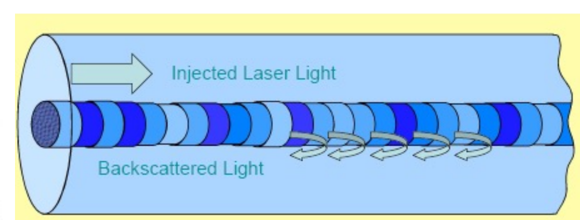


J. Bonilla et al., Sensors 2019, 19, 1759 (2019)

Distributed Optical Backscattering Based

- Rayleigh Scattering
- Raman Scattering
- Brillouin Scattering

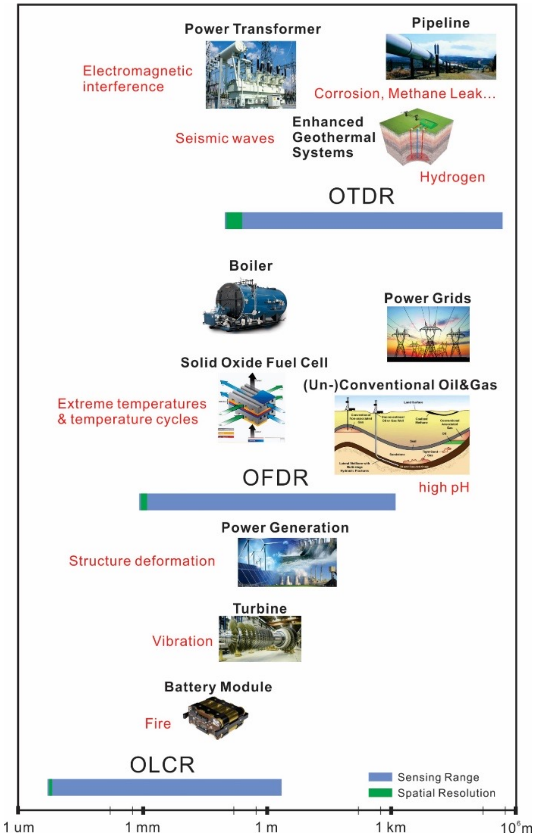




P. Lu et al., Applied Physics Reviews **6**, 041302 (2019)

Examples of Optical Fiber Sensor Types and Modalities Including Distributed Sensing

Optical Fiber Sensors and Sensor Networks



Distributed Sensing Over Different Length Scales

P. Lu et al., Applied Physics Reviews **6**, 041302 (2019)

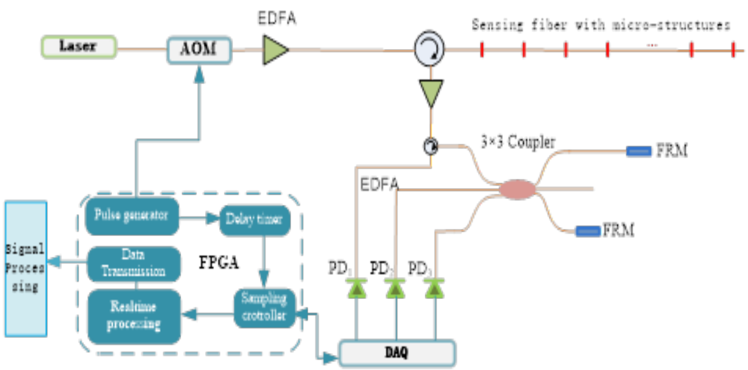
Optical Fiber Sensors:

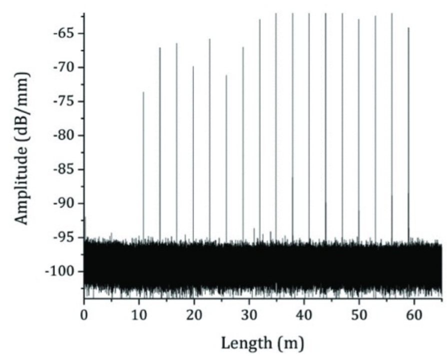
- Signal transmission medium and sensor are integrated
- Elimination of sensor node power and electronics
- Compatible with "distributed" sensing
- Harsh environment compatible
- No need for local power
- <u>**Cost**</u> tends to be a primary challenge for distributed sensors.
- A broad range of energy applications envisioned.

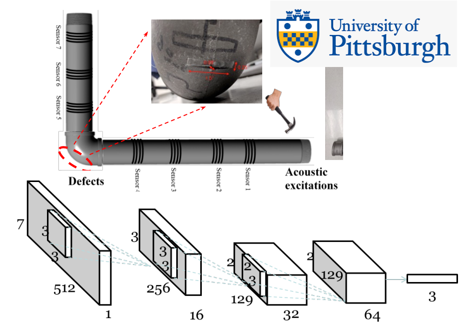
(Grant #DE-AR0001332) - $1M

arpa·e CHANGING WHAT'S POSSIBLE
University of Pittsburgh
Pacific Northwest NATIONAL LABORATORY

Distributed Fiber Optic Sensing





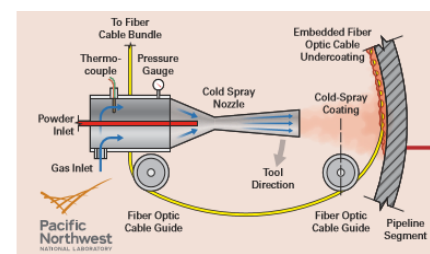


Identify and Locate Defects With Artificial Intelligence

Proposed Targets

Metric	State of the Art	Proposed
Deployed Fiber Optic Sensor Cost Per km	*>$5000 / km, external to pipe*	*< $500 / km, internal to pipe*
Deployed Internal Coating Cost	*Does Not Exist*	*< $500 / m*

Guided Wave Acoustic NDE



In-Situ Repair, Coating and Sensor Embedding with Robotic Deployable Cold-Spray

Example Major Project: ARPA-E REPAIR "Innervated Pipelines" (2021 - 2022)

UPISC — University of Pittsburgh Infrastructure Sensing

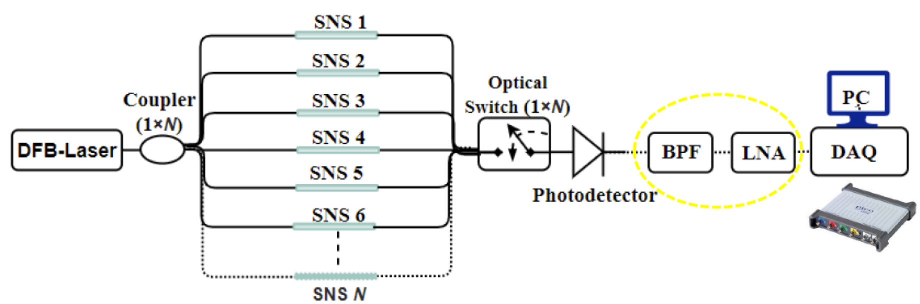
COLLABORATION WORKSHOP

NETL — National Energy Technology Laboratory

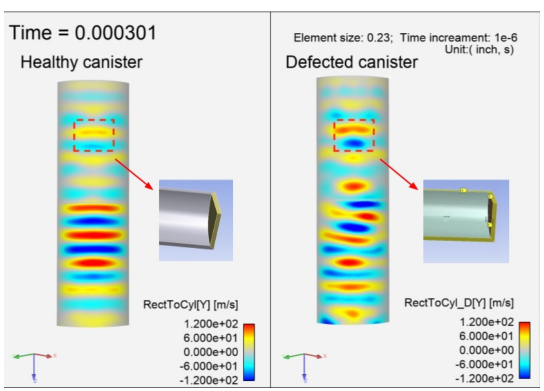
(Grant #NU-21-PA-PITT-040101-05) - $800k

NEUP Nuclear Energy University Program — U.S. Department of Energy | University of Pittsburgh | Pacific Northwest National Laboratory

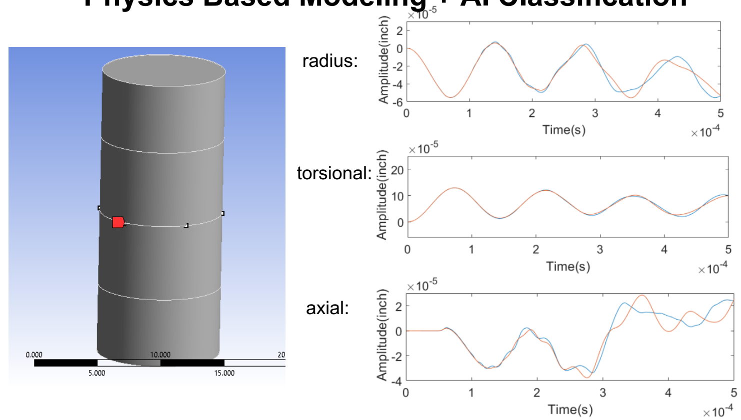
Quasi- / Fully Distributed Sensing



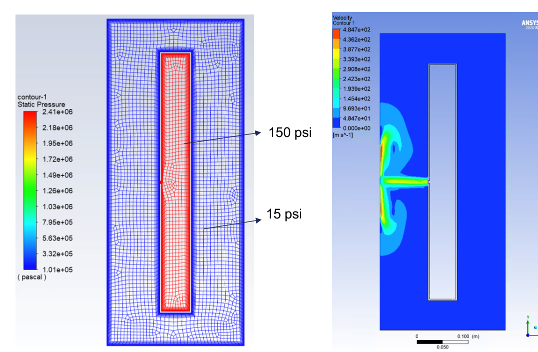
Early Corrosion Onset Detection



Physics Based Modeling + AI Classification



Active Leak Detection



Example Major Project: DOE NEUP "Nuclear Canister Monitoring" (2021 – 2024)

UPISC

UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

(Grant # DE-EE0009632) - $2.8M

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

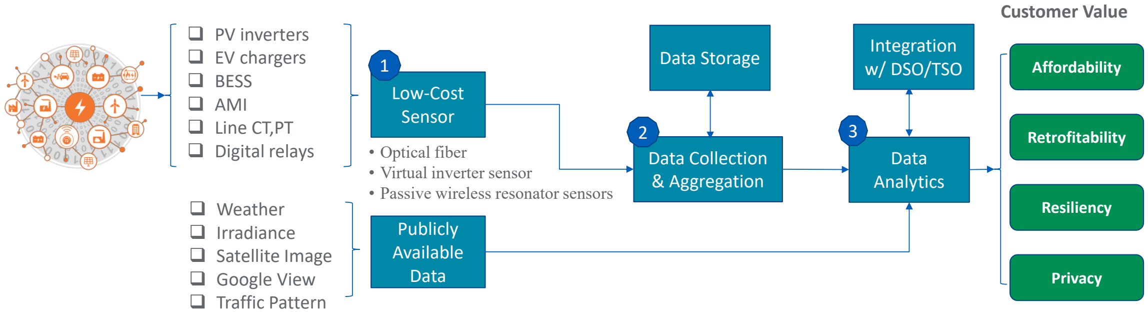
University of Pittsburgh

NRECA America's Electric Cooperatives

NC STATE UNIVERSITY

GE Global Research

Sandia National Laboratories

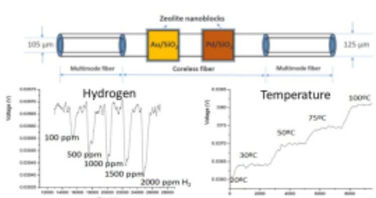


1 Low-Cost Sensor
- Lower cost by 20%
- Plug-n-play
- Waveform up to 50th harmonic

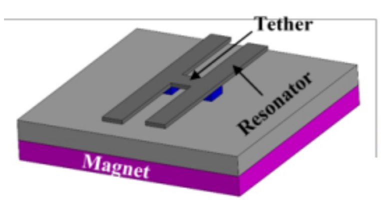
2 Data Collection & Aggregation
- IEC 61850 compliant
- Heterogeneous data
- Scalable to million nodes
- Time Synchronization
- Missing data inference
- Data cleaning
- Anomaly Detection

3 Data Analytics
- BTM PV power estimation within 5% error
- Solar hosting capacity and new installation study

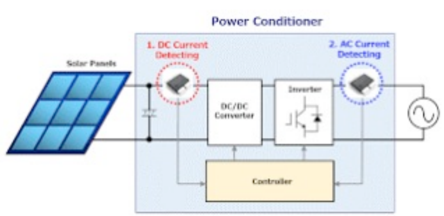
Low-Cost Multiparameter Optical Fiber Sensors



Passive Wireless Resonator Sensors

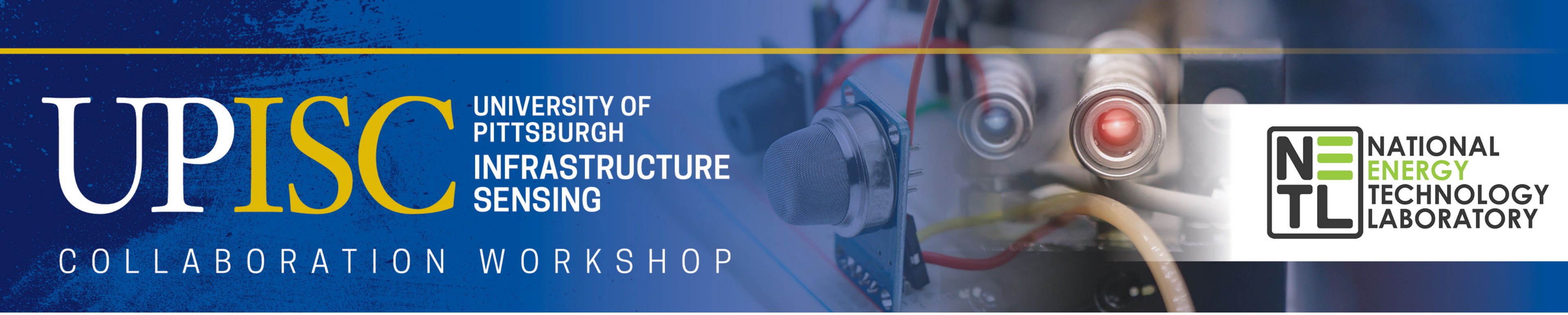


Inverter Hardware as Virtual Sensors

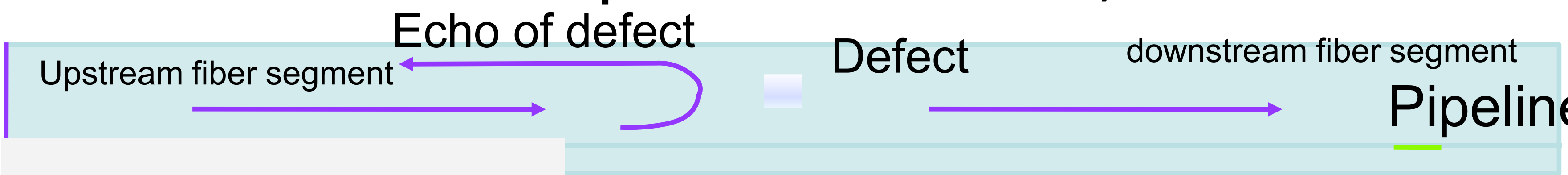


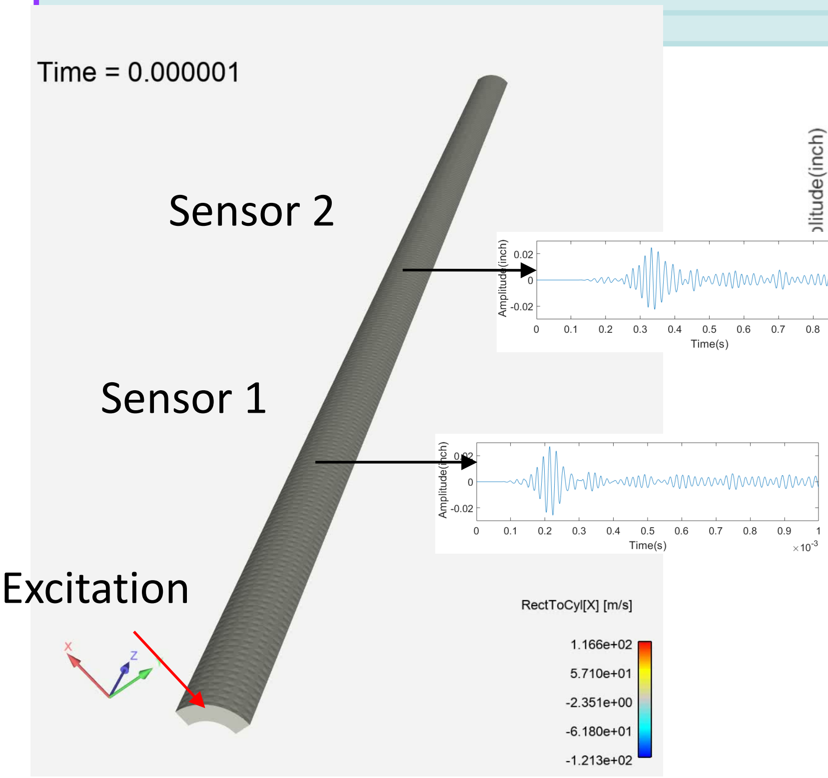
Commercial Micro-Phasor Measurement Units

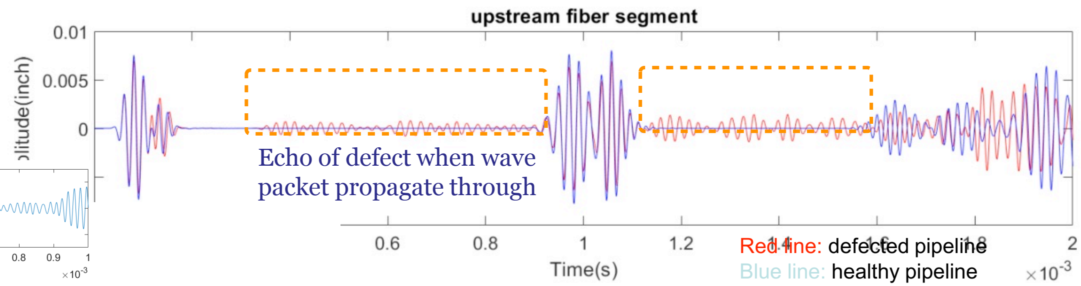
Example Major Project: DOE SETO "Rural Distribution Asset Monitoring" (2022 – 2025)

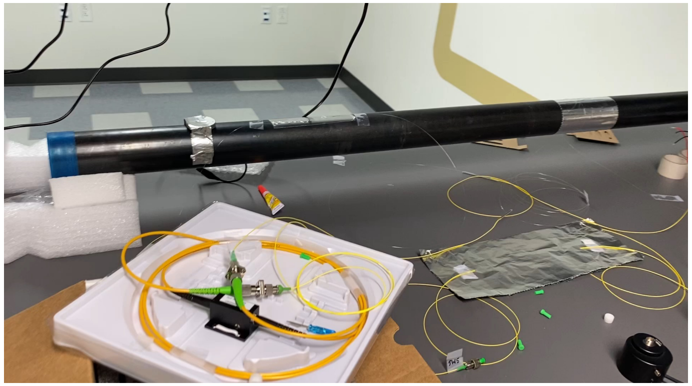


Fiber Optics + Acoustics + AI / ML









Example Area of Capability : Distributed / Quasi-Distributed Fiber Optics + AI

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

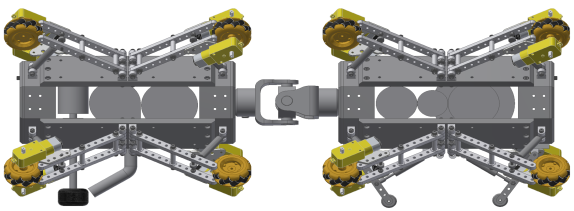
COLLABORATION WORKSHOP

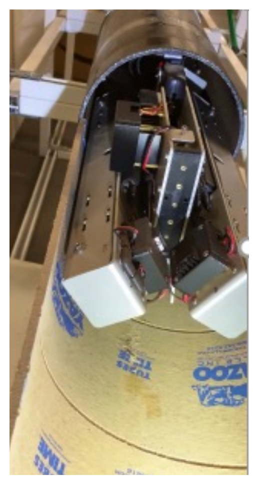
NATIONAL ENERGY TECHNOLOGY LABORATORY

Field Validation of Sensor Technology

Robotic Deployment Tool: Sensor Installation

- Self-Propelled, Remote Controlled
- Self- Contained Material Storage
- Mechanized Feed Systems



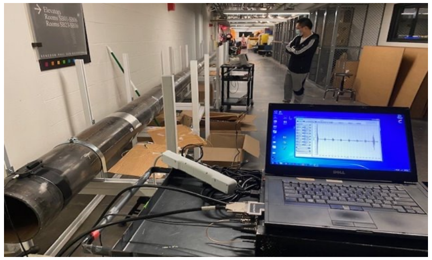


Sensor Testing in Applications:

- Electrical Assets (Transformers)
- Pipelines
- Electrical Cables

Medium Voltage (23kV/13.8kV) Transformer

Natural Gas Pipeline



Example Area of Capability : Novel Sensor Deployment, Validation, and Testing

Contact: Dr. Brandon Grainger
Email: bmg10@pitt.edu

Electric Power Technologies Laboratory

Medium Voltage Features

- 13.8kV, 4.16kV, 480V, and 208V AC voltage rails.
- Rated to handle 5MVA of power capacity.
- System is reconfigurable through Eaton reclosures to isolate parts of the lab OR create a ring architecture.

Notable Equipment Provided In-Kind

- Eaton MITS, MV circuit breakers, reclosers, power transformers, 500HP motor drive, LV motor drives, and ground fault indicator (**Donated by Eaton**).
- **Emerson Ovation** platform communicates with all major equipment.
- All equipment installed by **Sargent Electric.**

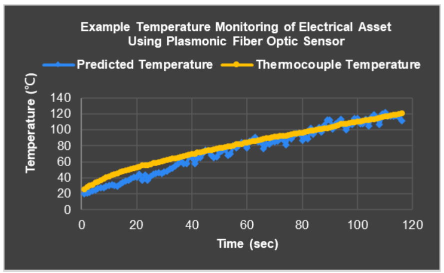
Virtual Tour of Medium Voltage Lab https://my.matterport.com/show/?m=p85qmPtaFx

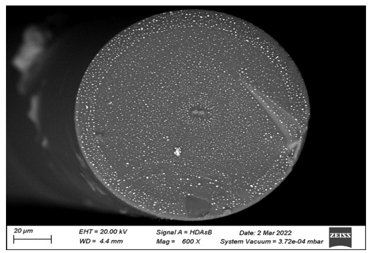
UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

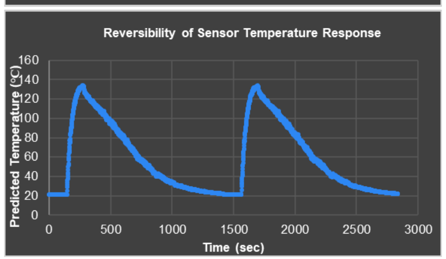
COLLABORATION WORKSHOP

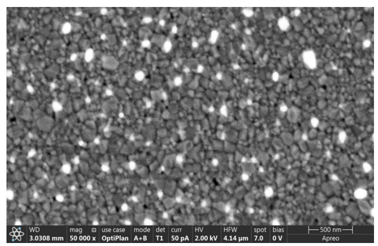
NATIONAL ENERGY TECHNOLOGY LABORATORY

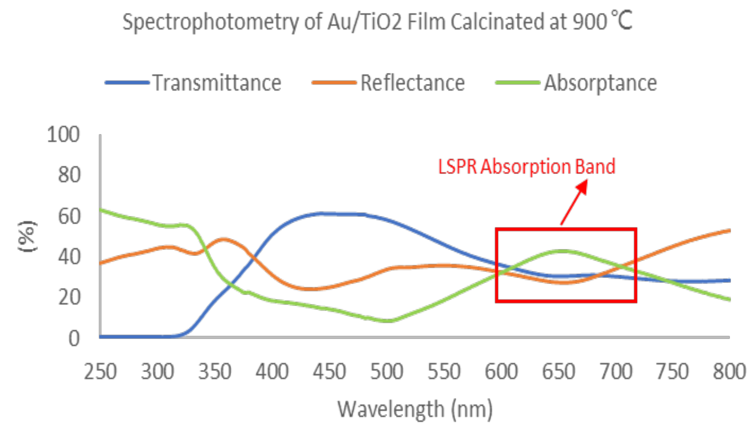
Functional Sensor Layers and Low-Cost Sensor Devices

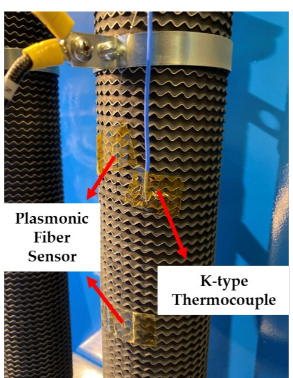


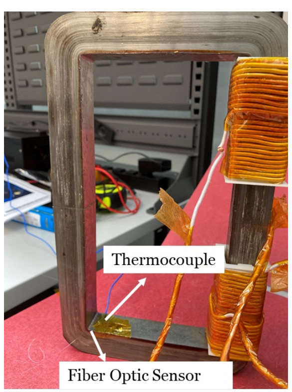


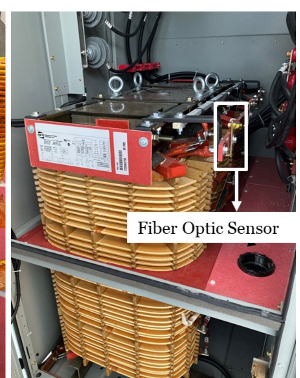




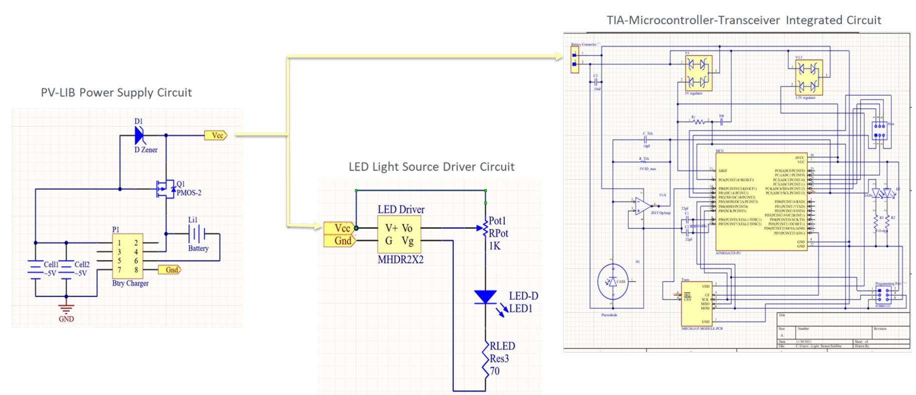




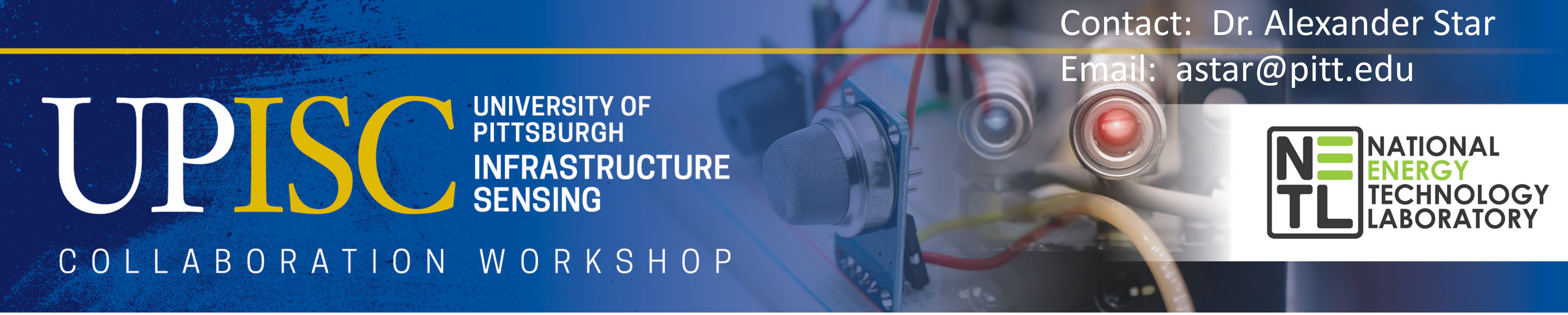




Low-Cost Light Source and Fiber Optic Interrogator



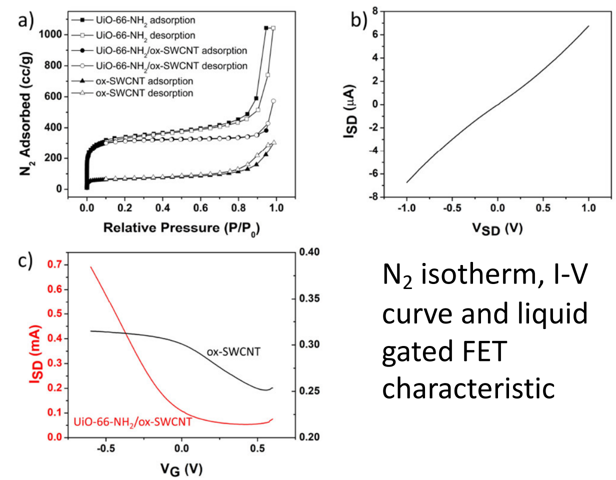
Example Area of Capability : Low-Cost Optical Fiber Probes, Interrogation, and Telemetry



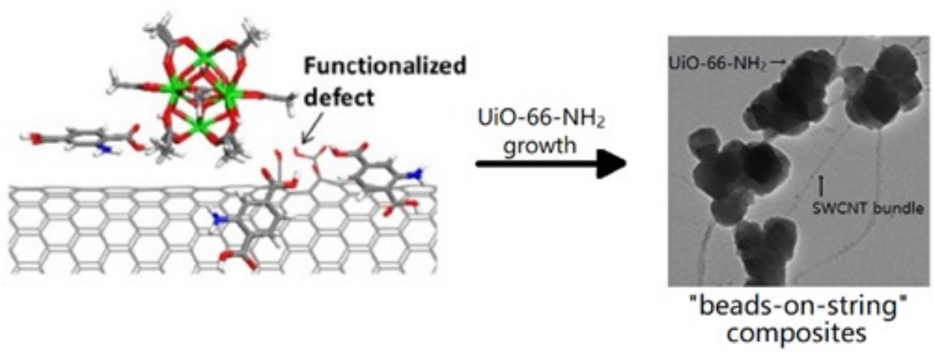
Contact: Dr. Alexander Star
Email: astar@pitt.edu

Heterogeneous Growth of UiO-66-NH_2 on Oxidized Single-Walled Carbon Nanotubes to Form "Beads-on-a-String" Composites

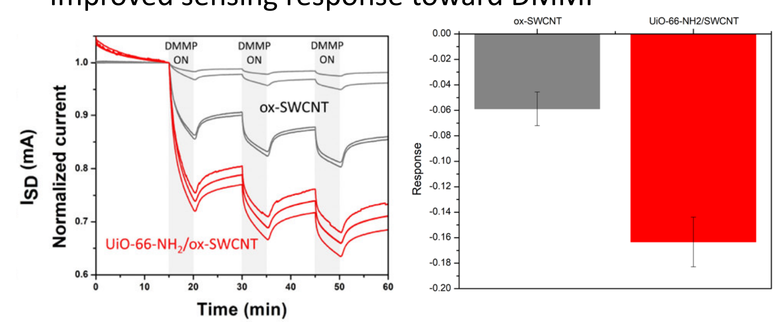
- Composites combine porosity with the electrical conductivity.
- DFT calculations to investigate heterogenous MOF growth on carbon nanotube sidewalls.
- Characterization of the interaction between CNTs and MOF metal precursors.
- Potential application as chemiresistor sensor.



N_2 isotherm, I-V curve and liquid gated FET characteristic

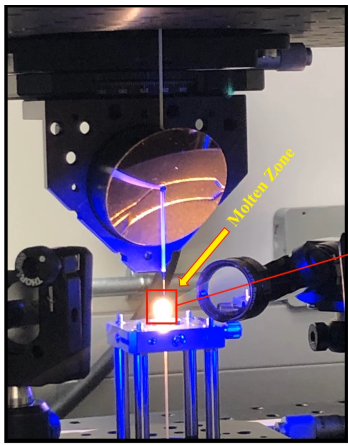


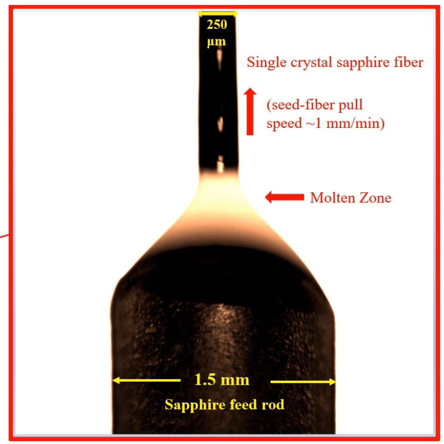
Improved sensing response toward DMMP



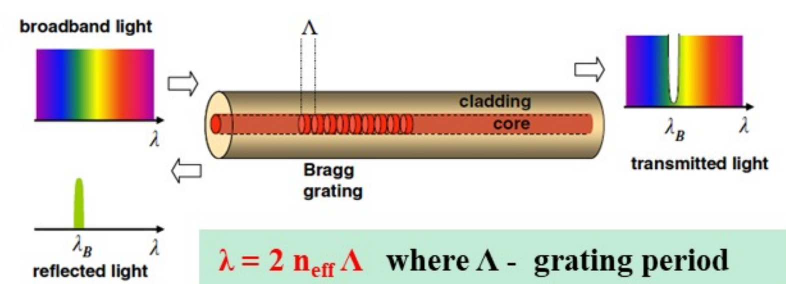
Single Crystal Fiber Based Harsh Environment Sensing

Refractory Functional Single Crystal Fibers:

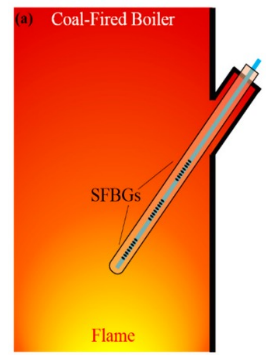


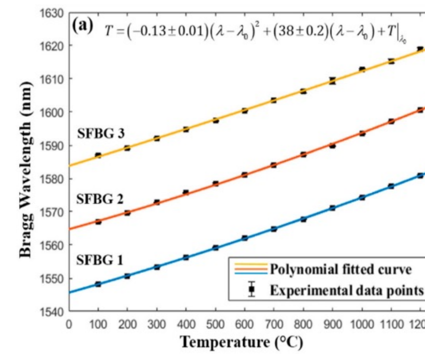


❖ **Point sensors- FBG and FPI based**



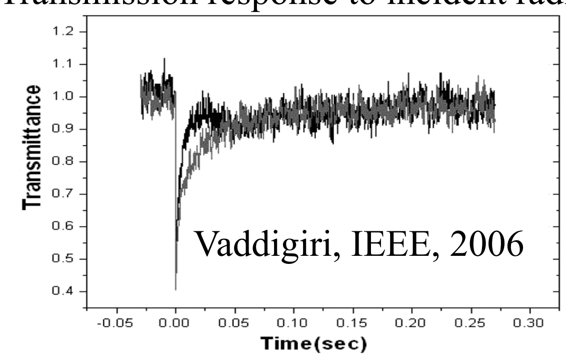
❖ **Quasi-distributed sensors (FBG and Raman scattering based)**





❖ Radiation Sensing

❖ Transmission response to incident radiation;



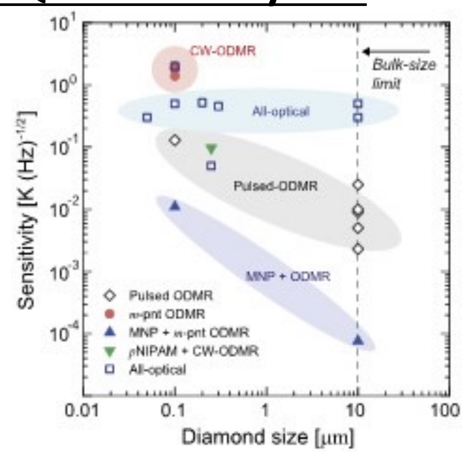
Example Area of Capability : High Temperature, Radiation Stable Sensor Technologies

Rugged, Practical Quantum Sensors

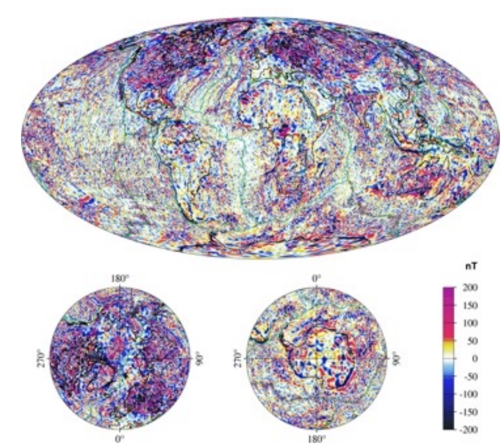
Quantum Sensing Materials and Quantum Physics:

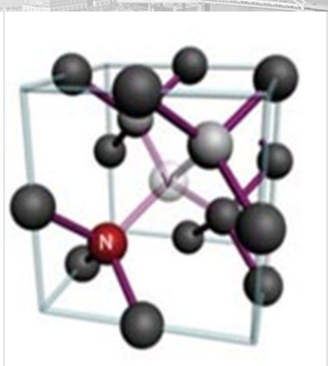
- Nanodiamonds
- Quantum Optics
- ODMR
- Microwave + Optical
- All-Optical

PITTSBURGH QUANTUM INSTITUTE

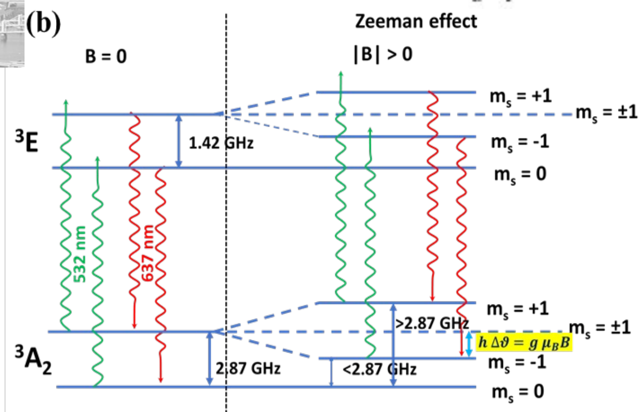


NGDC-720 Version 3.0: Bz at Earth Surface

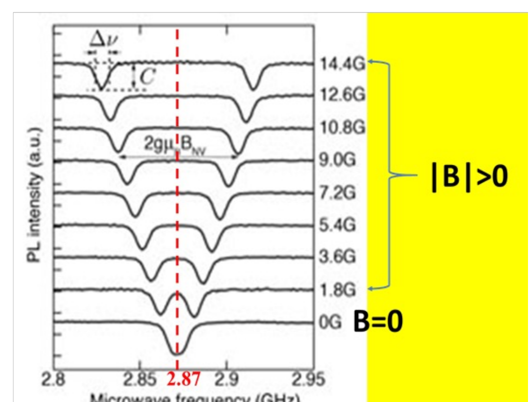




(b)



(c)



Example Area of Capability : Quantum Sensing Integrated w/ Robust, Practical Platforms

Contact: Dr. Gurudev Dutt
Email: Gurudev.dutt@pitt.edu

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

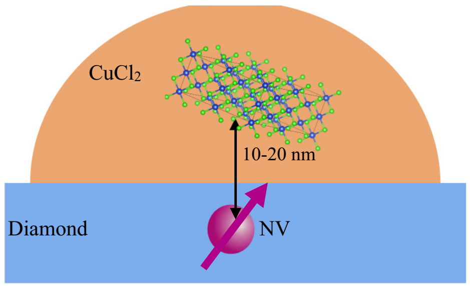
NATIONAL ENERGY TECHNOLOGY LABORATORY

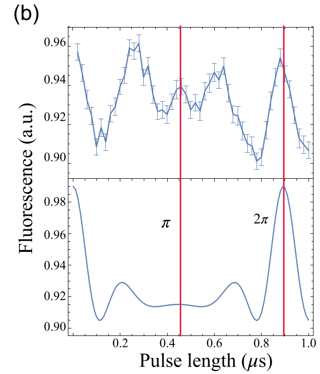
Quantum Sensors @ Pitt

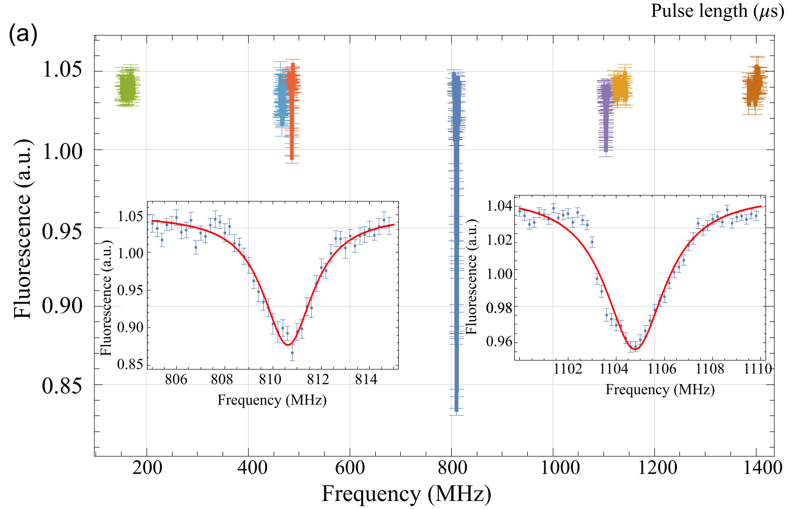
Gurudev Dutt, Dept. of Physics

- ✓ Phase estimation algorithms[1]
- ✓ Sub-shot noise scaling of sensitivity[2]
- ✓ Single spin dual-channel lock-in magnetometer[3]
- ✓ Geometric phase measurement in single spin qubits[4]
- ✓ Nanoscale electron spin resonance of molecules[5]

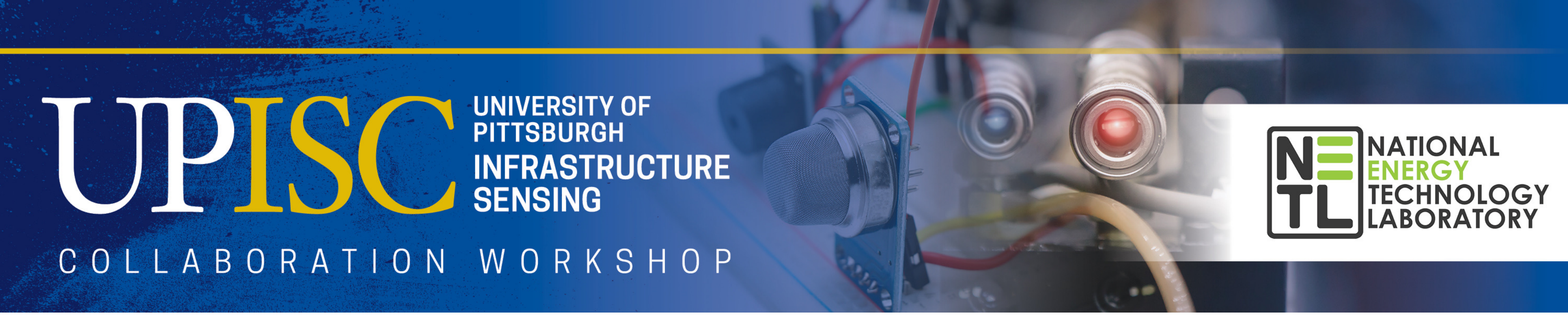
ESR of single Cu spins on diamond surface







1. N. M. Nusran, GD, Phys. Rev. B. 90, 024422 (2014).
2. N. M. Nusran, M. U. Momeen, GD, Nature Nanotechnology 7, 109-113 (2012).
3. N. M. Nusran, GD, Phys. Rev.B (Rapid), 88, 220410R (2013)
4. K. Zhang, N. M. Nusran, B. Slezak,GD, New J. Phys. 18, 053029 (2016)
5. K. Zhang, S. Ghosh, S. Saxena, GD, PRB 102, 224412 (2021)



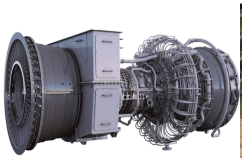
Advanced Optical Fiber Interrogation

Major Applications

Pipeline

Power cable

Transformer



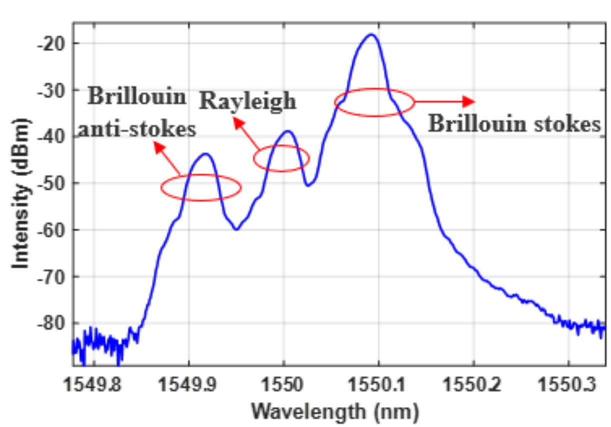
Gas turbine

Perimeter security

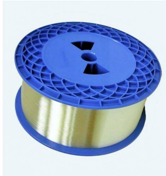
Underground cable

Brillouin stokes- Strain/temperature

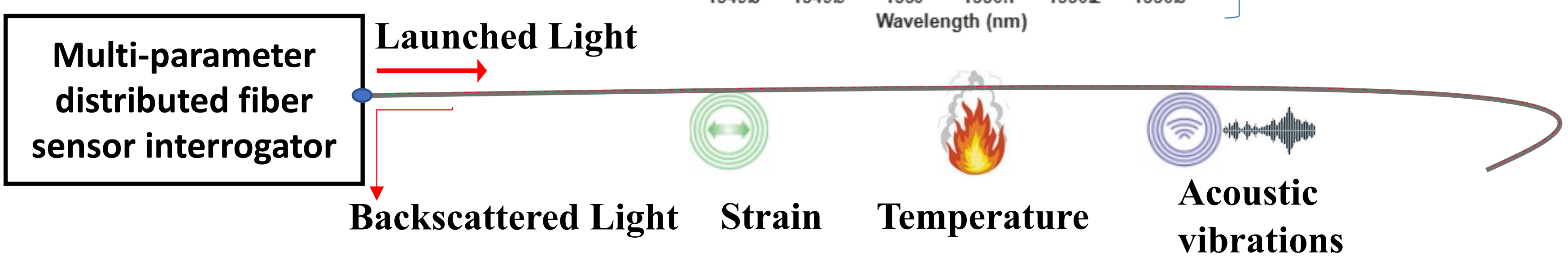
Rayleigh- Acoustics vibrations



Sensing Fiber



Single Optical Fiber



Example Area of Capability : Novel, Advanced Optical Fiber Interrogation Techniques

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL Sensor Technologies and Projects Overview

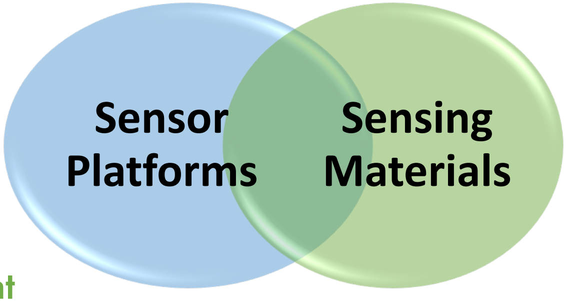
Presenter: Ruishu F. Wright, Ph.D.
Research Scientist,
Technical Portfolio Lead
NETL CORE-Sensors Capability Manager
National Energy Technology Laboratory (NETL)

UPitt Infrastructure Sensor Collaboration (UPISC)
2022 Workshop
August 25, 2022

NETL Sensor Expertise and Capabilities for Various Energy Systems

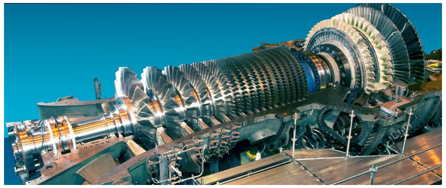
Advanced Sensors for Energy Efficiency, Safety, Resilience, and Sustainability

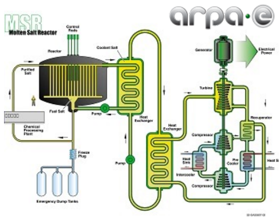
- ✓ **Monitor systems and conditions**
- ✓ **Improve performance & efficiency**
- ✓ **Enhance reliability & safety**
- ➢ **Temp, acoustics, chemical, gas, corrosion**
- ➢ **Composite nano-materials, thin films & fiber optics, sensor devices development**



GENERATION

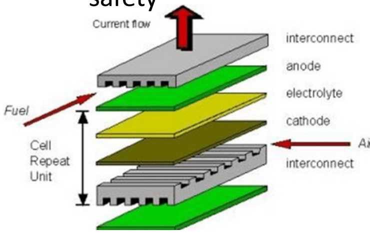
Turbines: Real-time fuel composition and combustion temperature for improved service life and efficiency





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

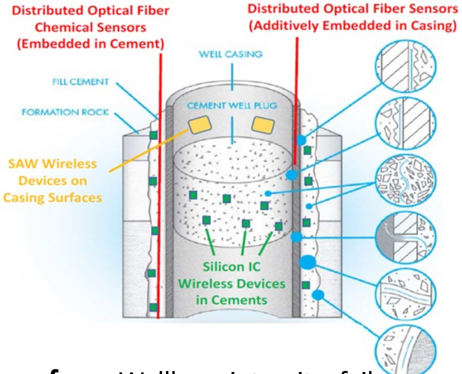
SOFCs: Fuel concentration & temperature gradients for improved lifetime and efficiency



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

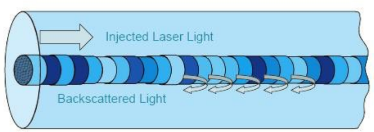


Subsurface: Wellbore integrity, failure prediction, leak detection. Geologic storage of CO_2, H_2/NG, or abandoned wells.

Multiple Sensor Technology Platforms

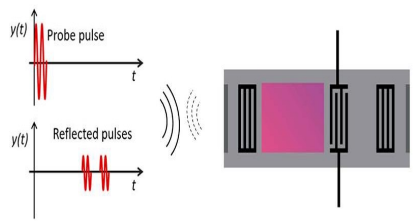
Long-distance Distributed Optical Fiber Sensors

Imperfections in fiber lead to Rayleigh backscatter:



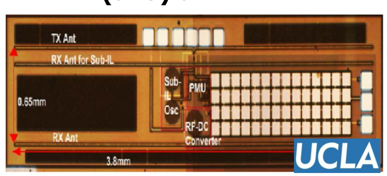
Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

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

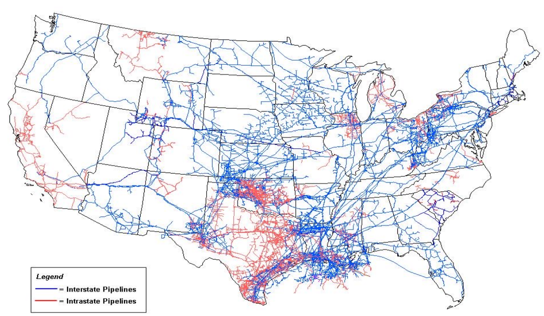
Multiple Sensor Platforms with Various Cost, Performance, and Geospatial Characteristics have been developed at NETL and via collaborations.

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

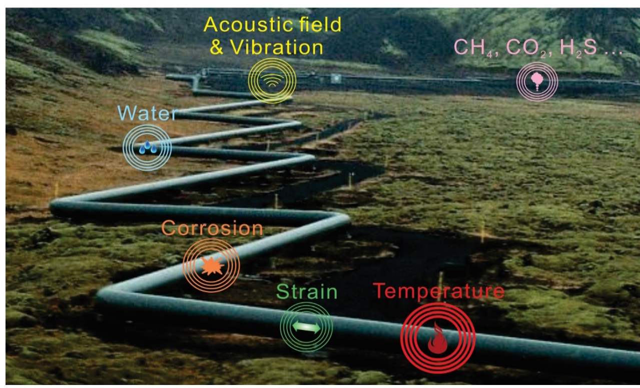
NATIONAL ENERGY TECHNOLOGY LABORATORY

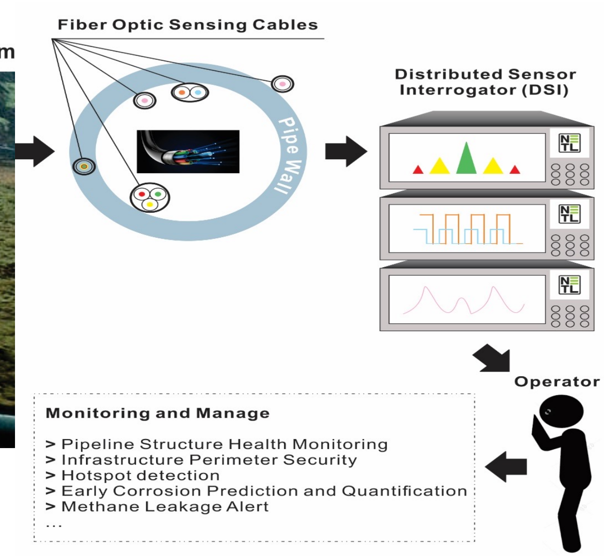
Need for Real-time Monitoring and Leak Detection/Mitigation for Aging Natural Gas Infrastructure and New Demand for Hydrogen Transportation



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

Pipeline Integrated with Distributed Optical Fiber >100 km

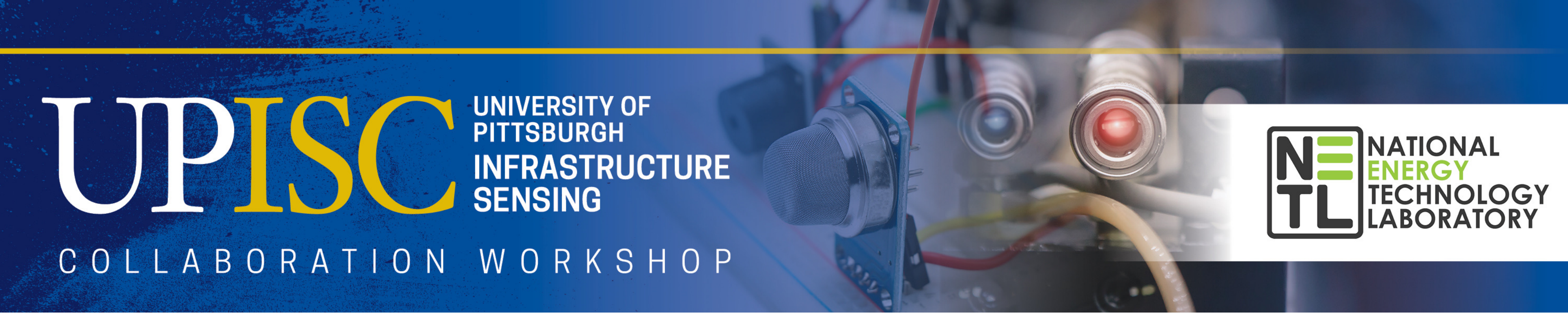




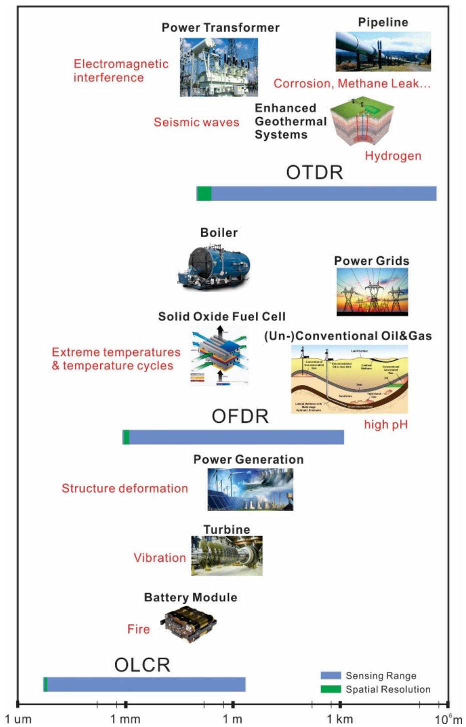
<u>PHMSA Data</u>:
NG Transmission Pipeline: 298,353 miles
NG Distribution Pipeline: 2,296,214 miles
Hydrogen Transmission Pipelines: 1,567 miles
Hydrogen Distribution Main Pipelines: 1 mile

- Optimize Interrogation System (Range, Resolution, Cost)
- Early Corrosion On-Set Detection
- Methane or H_2 Leak Detection & In-Pipe Gas Composition Monitoring

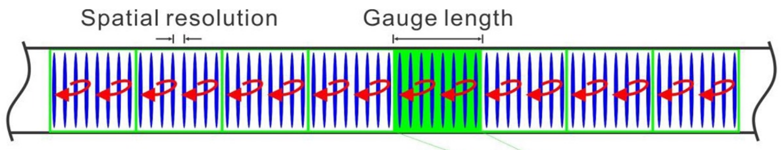
DOE Office of Technology Transitions, Energy I-Corps, Pipeline Sensor Team



Distributed Optical Fiber Interrogator Development

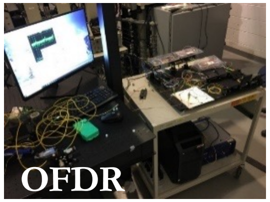


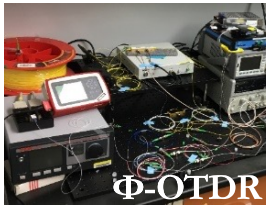
In-House NETL Distributed Optical Fiber Sensor Interrogators

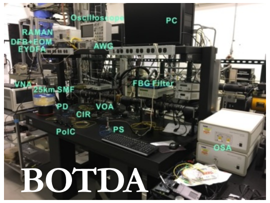


Technology	Sensing Range	Spatial Resolution	Measurement Time	Fiber Type	Sensing Performance
Coherent Rayleigh OFDR	m – km	mm – cm	seconds	SMF	Temperature, strain, vibration, chemical sensing
Coherent Rayleigh OTDR	km	m	seconds	SMF	Acoustic wave, vibration
Brillouin OTDR/BOTDA	> 100 km	cm – m	minutes	SMF	Temperature, strain,

- Multiple distributed optical fiber sensing platforms have been developed to enable structural health monitoring of pipeline and other infrastructure.
- Multiple patents have been filed.

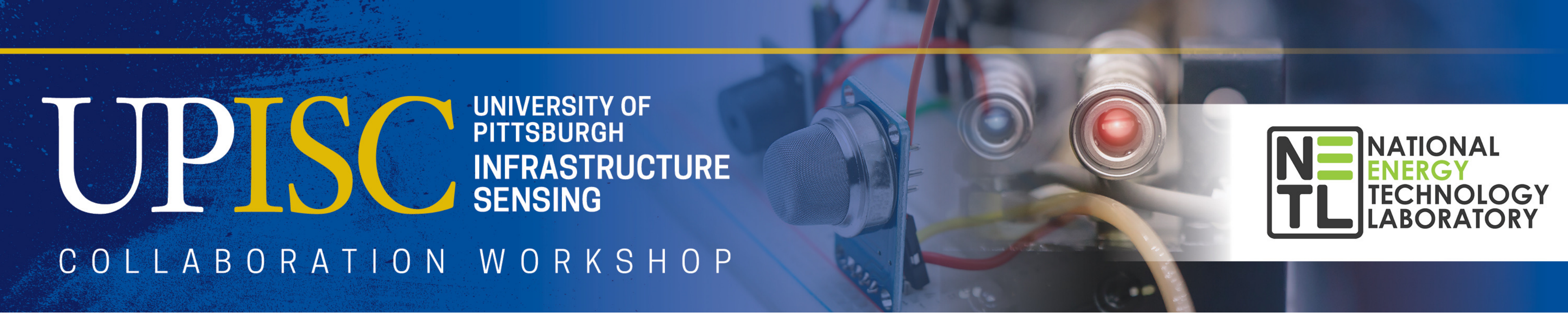






A Multi-Parameter, Distributed Optical Fiber Sensor Platform Enabling Reliability & Resilience

Target Metrics = >100km Interrogation, <1m Spatial Resolution, <$1 per meter



Field Test of Distributed Optical Fiber Interrogator: Distributed Acoustic Sensing (DAS)

BOTDA

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

ϕ-OTDR/DAS — Patented

Sensing range = >10 km;
Spatial resolution = <1 m;
Measurable parameters: vibration/acoustics

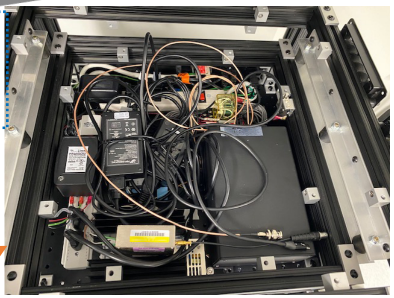
SMS — Patented

Frequency range= 1 Hz to 400 kHz;
Resolution= <1 to 2 Hz;

Operating NG Pipeline

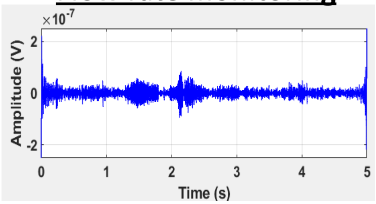
Custom Phase-OTDR Interrogator Box

Top view

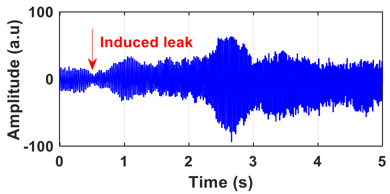


Front view

Flow rate monitoring



Leak detection

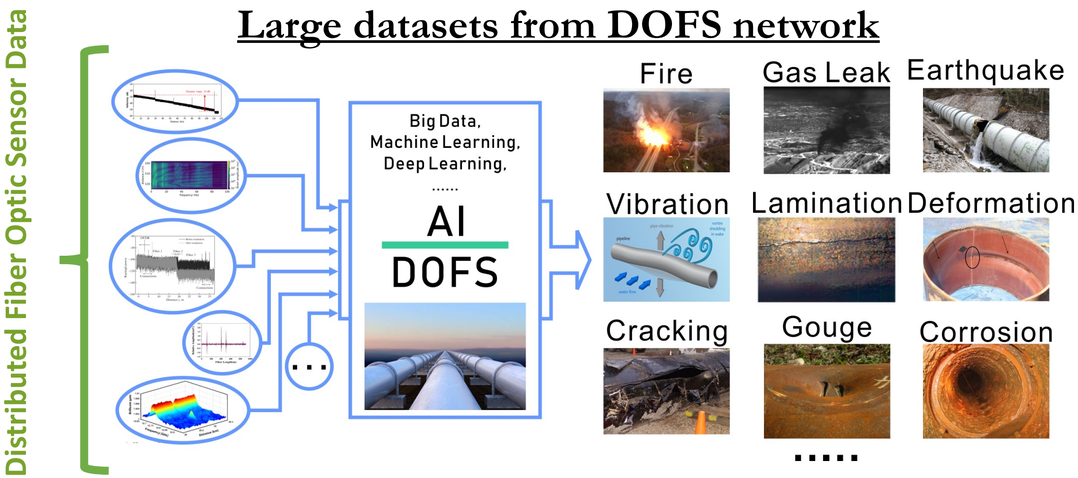


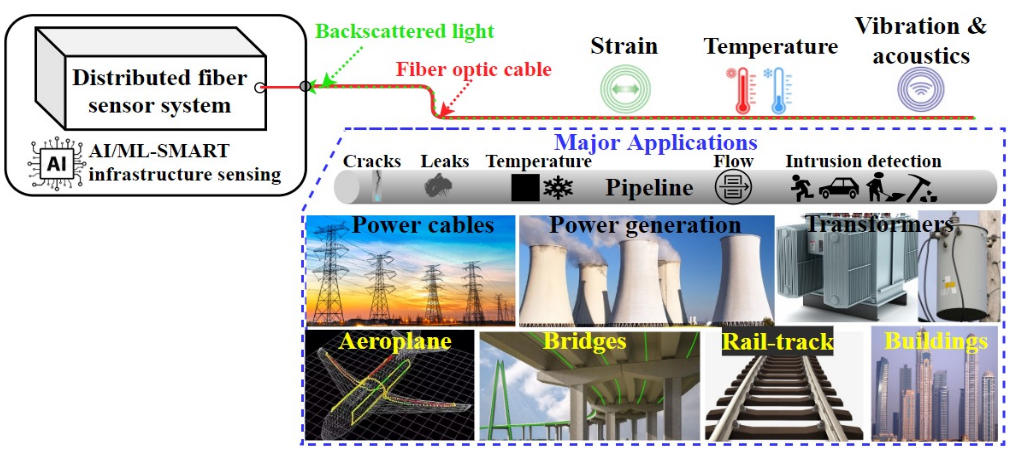
- **Flow rate monitoring**
- **Leak detection**
- **Third party intrusion detection**

NETL expertise in distributed optical fiber interrogators from system design, assembly, packaging, lab-scale, and pilot-scale demonstrations.

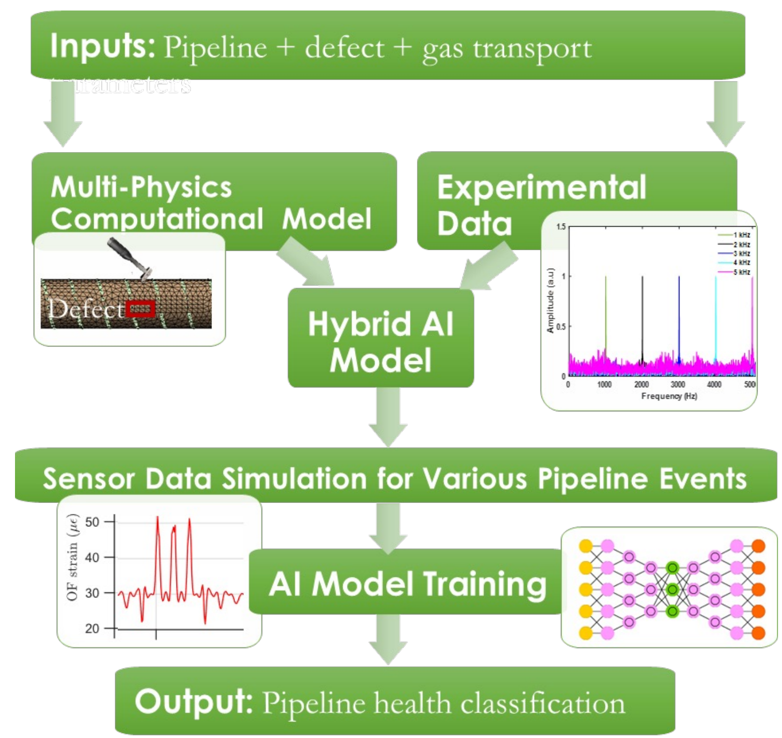
AI-enhanced Distributed Optical Fiber Sensor Network

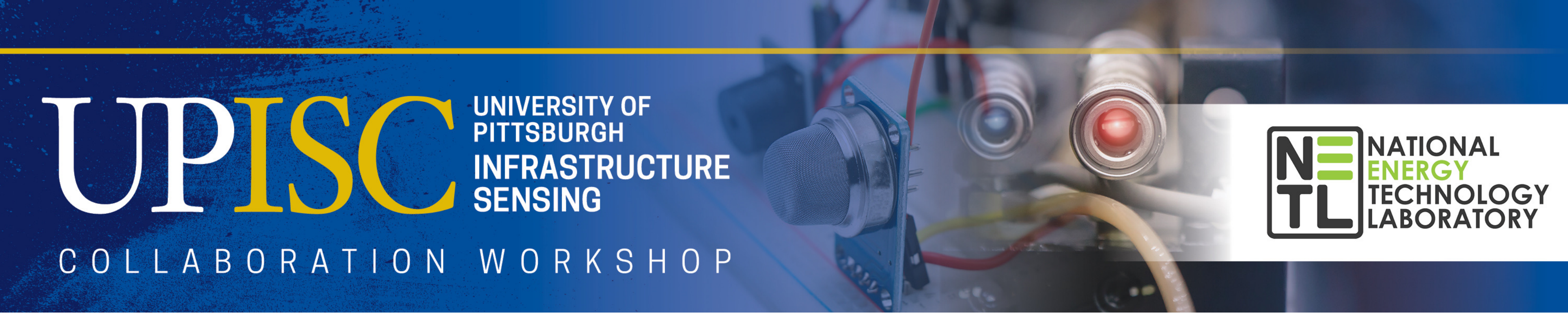
Large datasets from DOFS network





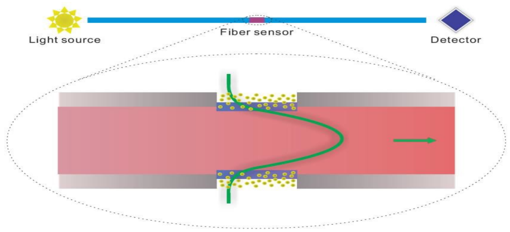
Hybrid AI Framework: Multi-Physics Modeling + Machine Learning



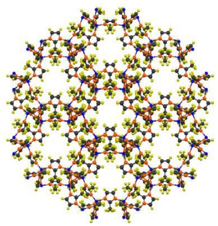


Functional Sensitive Material Coating Enabled Gas Monitoring

Functional Sensing Layer Integrated Fiber Optic



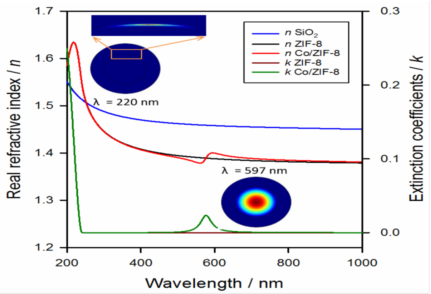
<u>Porous Metal Organic Framework (MOF)</u>



<u>Micro-porous Gas Permeable Polymers</u>

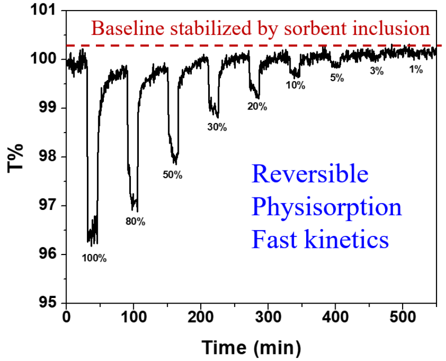
Evanescent Wave Absorption Based Sensors

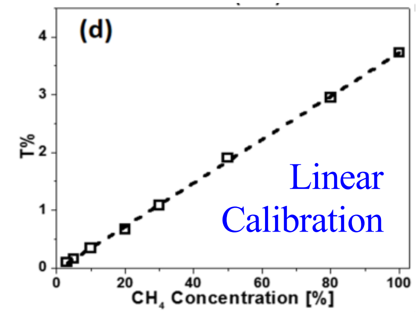
$$I_T(\lambda) = I_0 \exp[-\gamma\alpha(\lambda)CL]$$



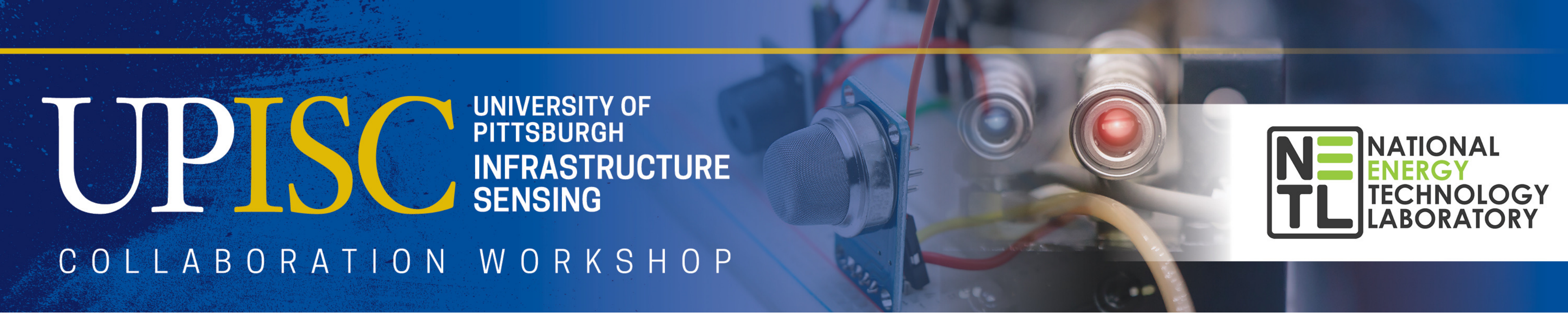
Gas adsorption in the sensor coating causes $RI_{(coating)} > RI_{(fiber)}$, inducing optical power changes.

CH_4 Detection Limit: < 5% in N_2





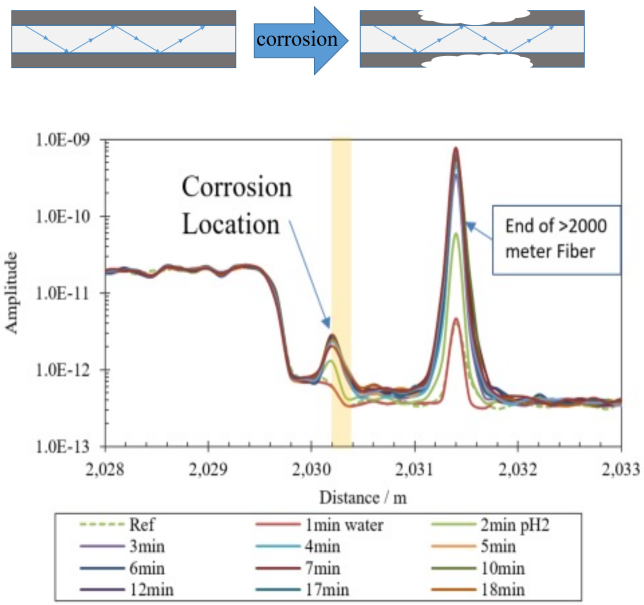
NETL Functional Materials Team with established expertise in materials development by design to functionalize different sensor platforms and enable gas sensing such as CH_4, CO_2, and H_2.



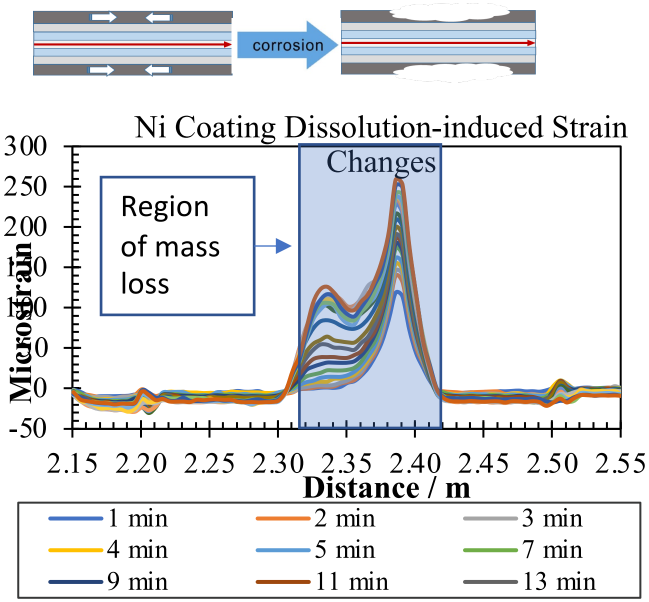
Early-stage Corrosion Detection

Metallic film coated optical fibers

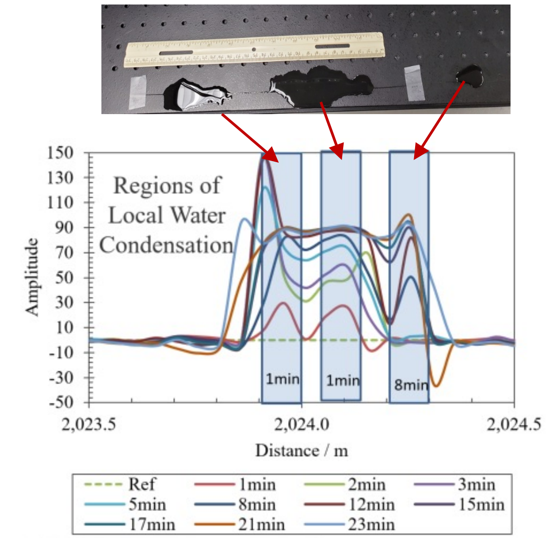
Optical Power Based



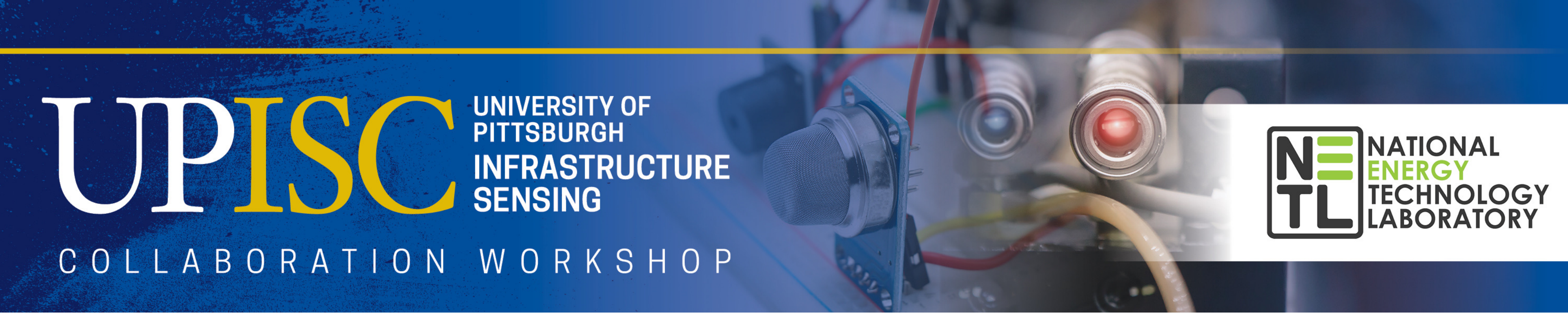
Strain Based



Water provides electrolytes for corrosion onset and is an indicator of potential corrosion.

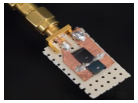


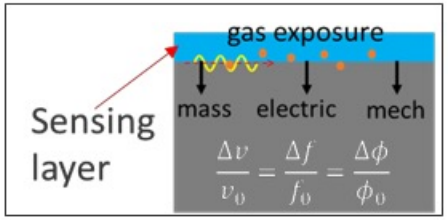
Corrosion can be detected and located along the optical fiber, which enables distributive corrosion monitoring for long-distance infrastructure.

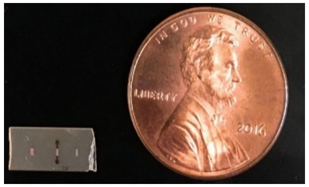


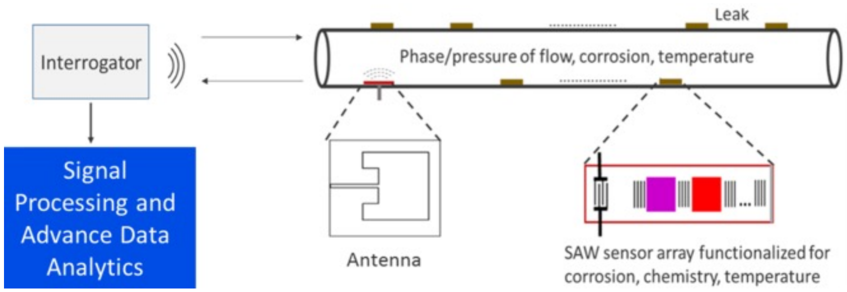
Passive Wireless Surface Acoustic Wave (SAW) Sensors

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

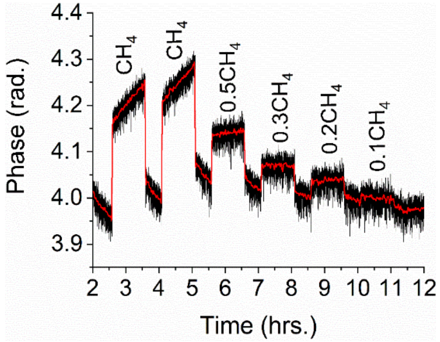




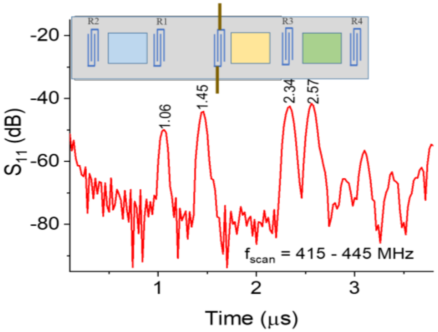




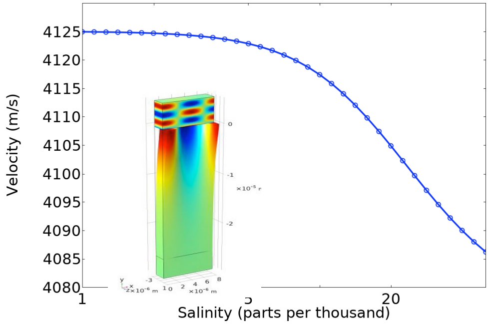
Wireless CH_4 Sensing



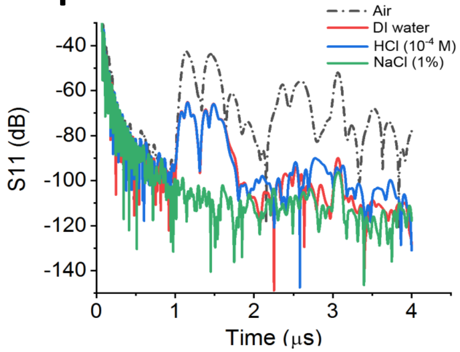
SAW Sensor Array for Multiple Gases



Simulation of Salinity Sensing

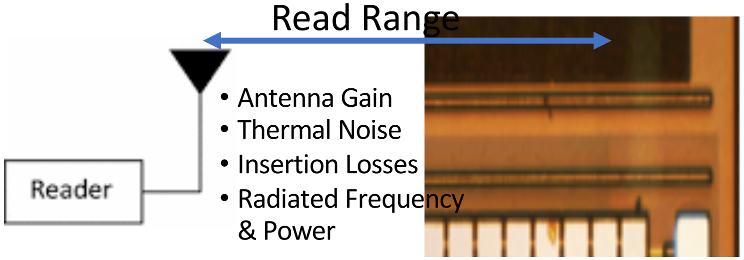


Experiment in Aqueous phase



- Ubiquitous Passive Wireless Sensors for Energy Infrastructure Monitoring
- Successful Demonstration of Wireless SAW Gas Sensor
- SAW sensor Array Devices were functionalized for simultaneous monitoring of CH_4 and CO_2

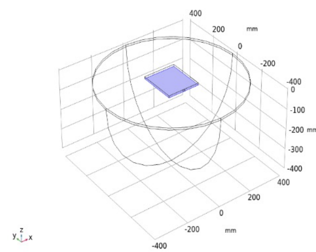
Wireless Telemetry for SAW Devices and Pipelines

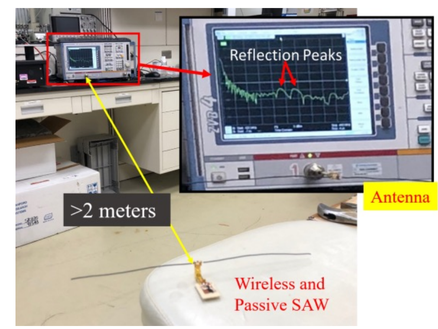


- Telemetry of wireless and passive SAW sensors is similar to radar operation.
- Low loss SAW devices and higher the radiated power to improve the range.

Wireless Coupling:

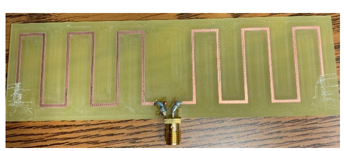
SAW Device + EM Radiator/Receiver





In-house Antenna Design and Fabrication:

Circuit Board Plotter



Compact Meander Dipole

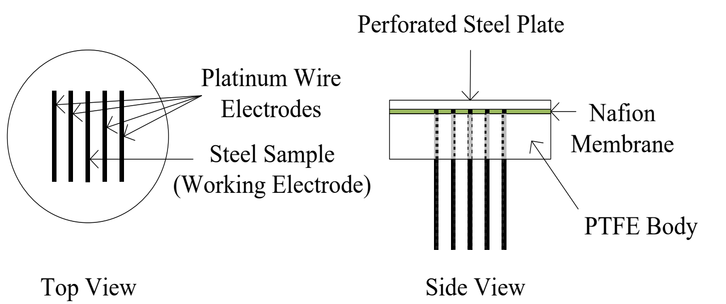
Long Range Telemetry and Interrogation

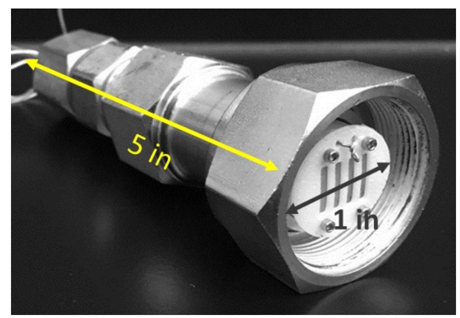
Demonstrated in the pilot-scale test Inside a metal pipe for 70 meters (230 ft).

Various Approaches have been Designed and Field-Demonstrated to Achieve Wireless Interrogation of SAW Sensors in Pipelines.

Multifunctional Advanced Electrochemical Sensors

Conductivity & Corrosion Monitoring





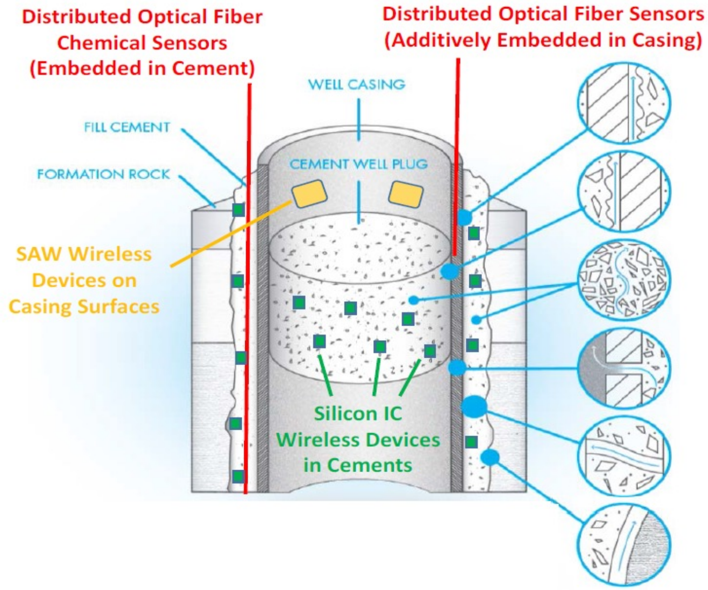
- Capable of remote in-situ monitoring
- Capable of measurements in non-aqueous phases
- Easy to install
- Successful Field Test

Electrochemical sensors for quantification of corrosion rates and environmental monitoring (humidity, water content, etc.).

PennState

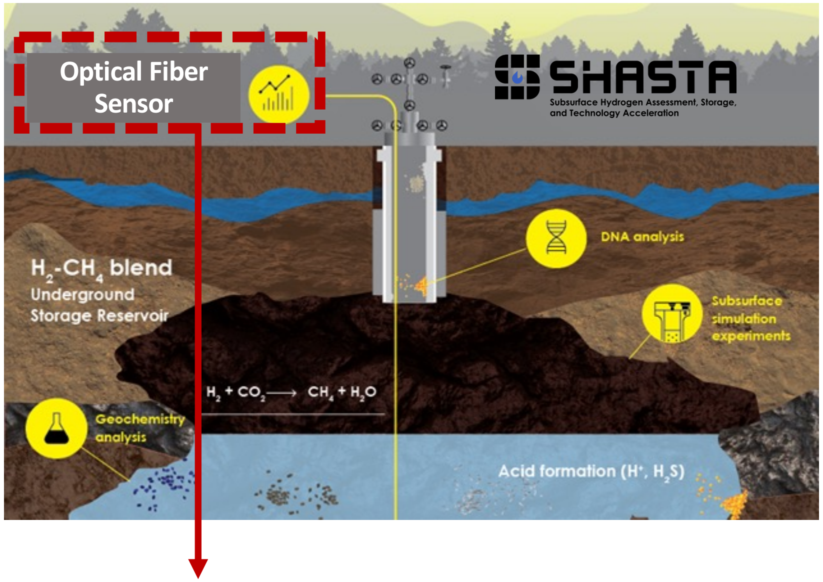
Sensor Technologies for Subsurface CO_2 or H_2-NG Storage

Wellbore Integrity Monitoring (SubTER)



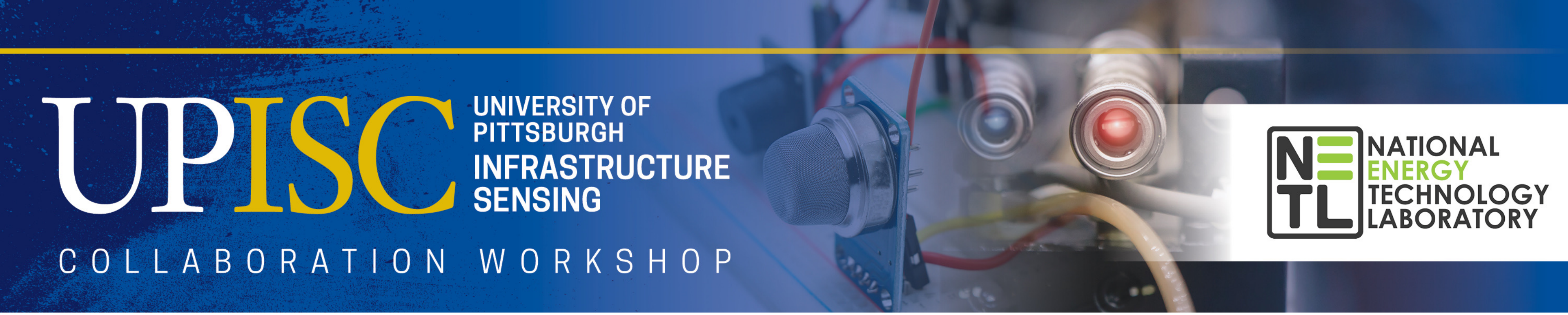
A suite of technologies functionalized for chemical sensing of high priority parameters (**pH, corrosion** onset, etc.).

H_2-NG Subsurface Storage Wells (SHASTA)

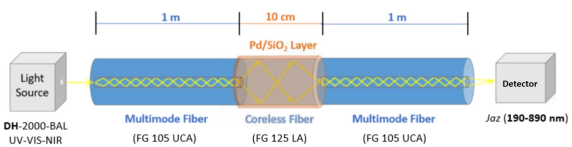


- Subsurface **H_2, CH_4, and pH** monitoring
- Gas Leak and Wellbore Integrity Monitoring

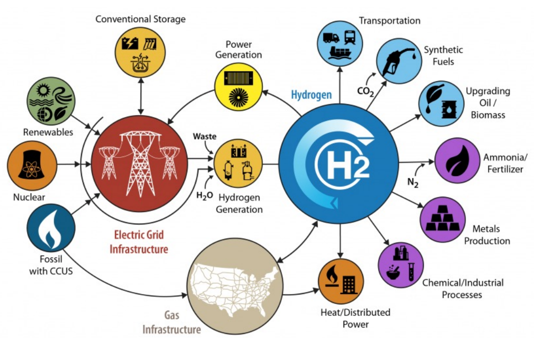
- Challenging harsh conditions in subsurface require reliable and durable sensor technologies.
- Applicable to abandoned wells, geothermal wells, and aquifer.



H_2 Sensors for Hydrogen Infrastructure to Support Decarbonization

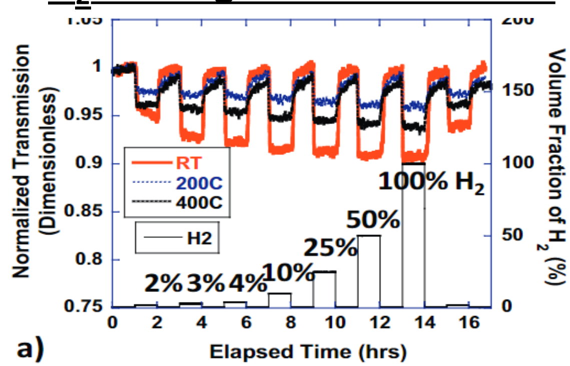


Pd Nanoparticle-Incorporated SiO_2 Thin Film coated Optical Fiber Sensor

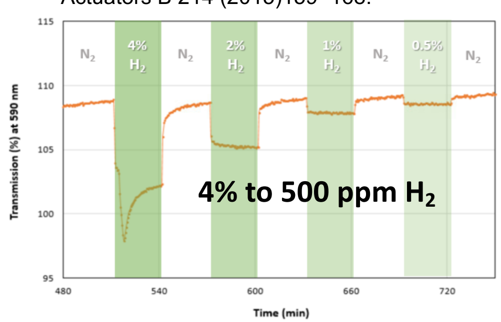


H_2@Scale

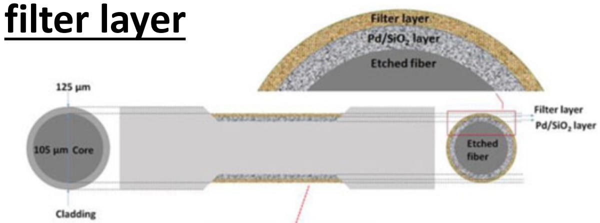
H_2 Sensing from RT to 400 °C



Ref: Ohodnicki et al, Sensors and Actuators B 214 (2015)159–168.

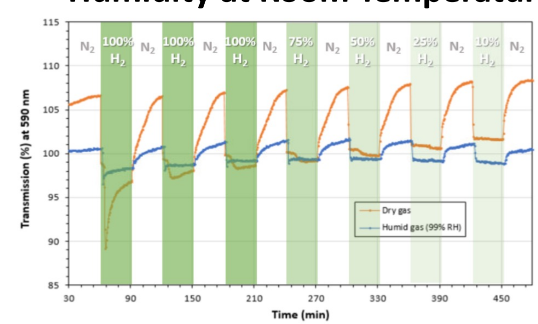


Selective H_2 Sensing with nano-filter layer



Ref: Sun et al, IEEE Sensors Letters, Vol. 1, No. 5, October 2017.

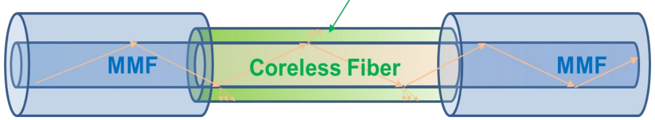
H_2 Sensing in 99% Relative Humidity at Room Temperature



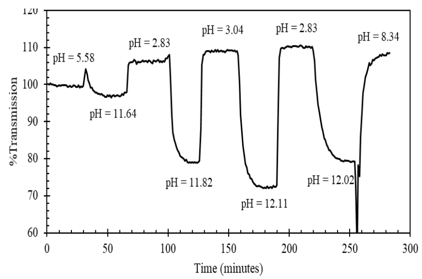
- Pd/SiO_2 coated optical fiber H_2 sensor demonstrated reversible sensitivity for a wide range of H_2 concentrations (100s ppm to 100%).
- H_2 blend composition monitoring for operation and early-stage H_2 leak detection for safety.

pH Sensing Layer enabled Optical Fiber pH Sensors

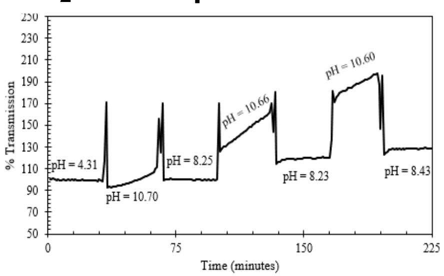
Coating of pH sensitive materials



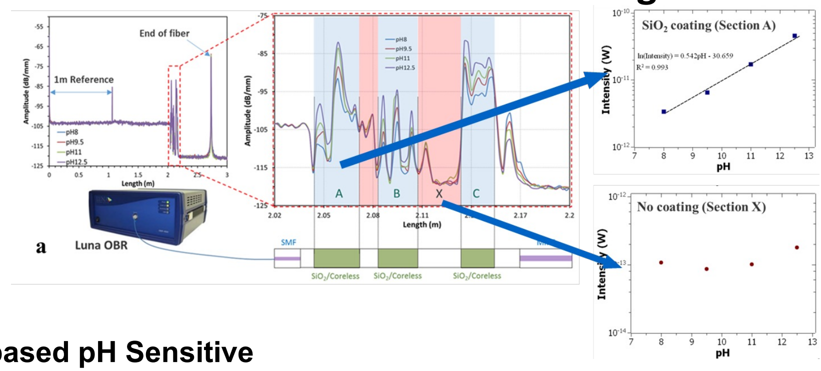
SiO_2 coated pH OFS at room temperature



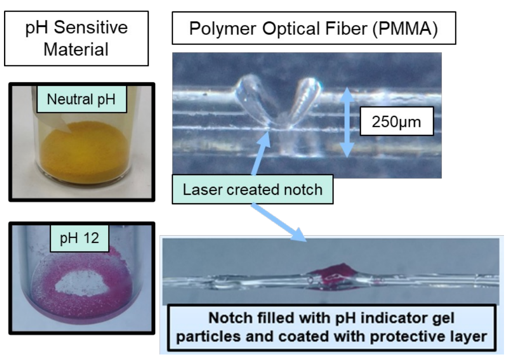
TiO_2 coated pH OFS at 80°C



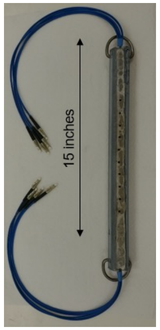
Distributed Chemical Sensing



Polymer-based pH Sensitive Materials



Embedded in Cement and Field Test

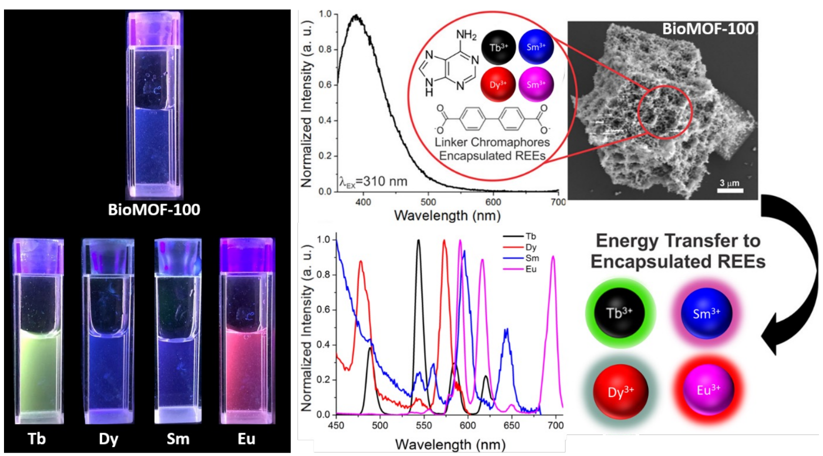


INTELLIGENT OPTICAL SYSTEMS, INC.

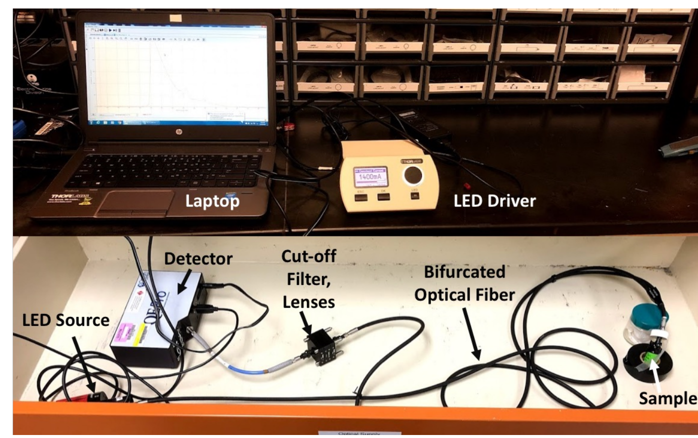
In-situ chemistry monitoring to increase visibility and optimize operations

Portable Low-cost Photoluminescent Fiber Optic Sensors for Rare Earth Element (REE) and Critical Metal Detection

BioMOF-sensitized Fluorescence Emissions from Rare Earth Elements (REE)



Low-cost Portable Sensor in Development



- **Compact and Portable**
- **Low part-per-billion** detection limits for a range of high value elements (<u>rare earths, cobalt, aluminum)</u>
- Quick analysis time ~**3 minute**.
- Significant **cost savings** versus current state-of-the-art ($20,000 vs. $180,000 for ICP-MS)
- Intended applications include **process stream characterization** for critical metals extraction, field-deployable metals **prospecting**, and **wastewater quality monitoring**.

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

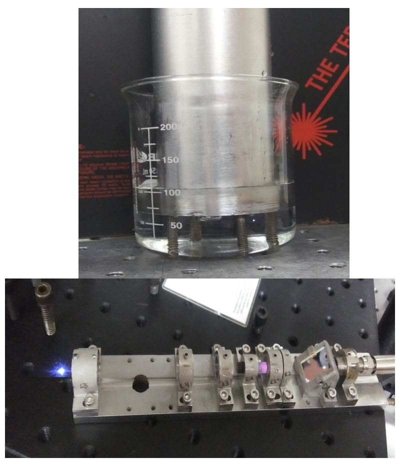
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

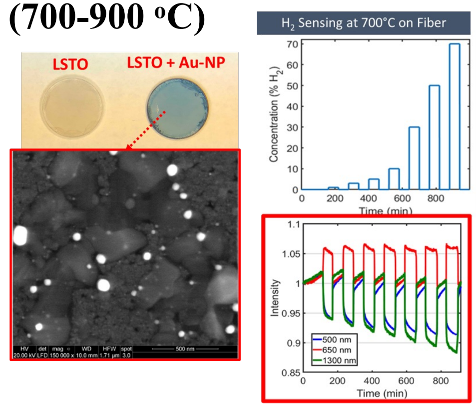
A Variety of Sensor Technologies and Capabilities at NETL

Fast Raman Gas Analyzer (RGA) for Real-time Gas Analysis

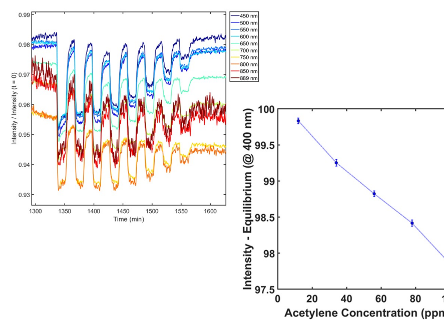
Laser Induced Breakdown Spectroscopy (LIBS)



High-Temperature Plasmonic Films for Harsh Environment (700-900 °C)

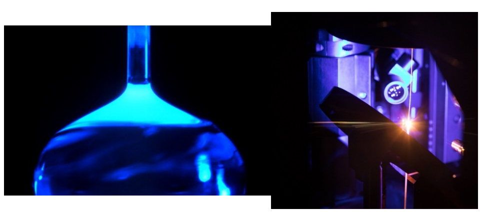


Nanocomposite thin film for Dissolved Gas Analysis in Transformers



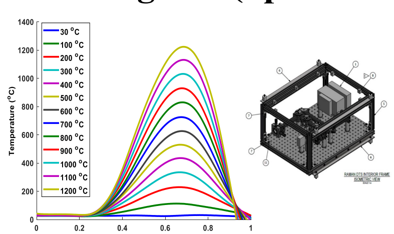
NETL's Science-based AI/ML Institute

Novel cladded single-crystal optical fiber for molten salt reactors

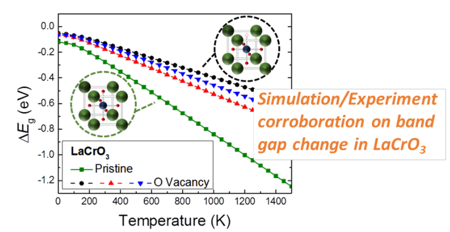


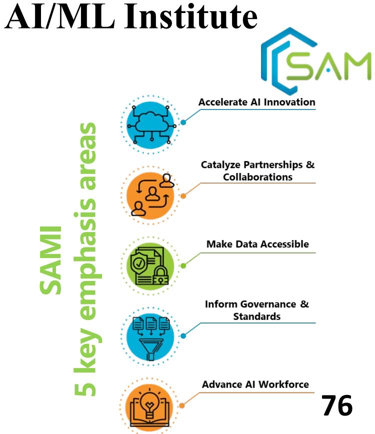
Laser-heated pedestal growth

Raman Distributed Temperature Sensing Interrogator (up to 1200 °C)



Computational Modeling of Sensing Materials/Quantum Computation

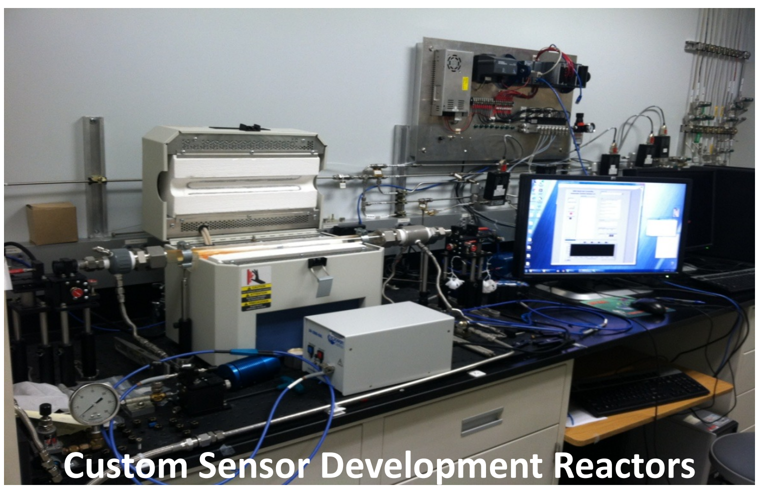




NETL R&IC Facility: Sensor Preparation and Test Equipment

Custom Sensor Development Reactors Simulate:

- → **Power Generation and Combustion Systems**
- → **Subsurface / Geological Environments**
- → **Pressurized Gas and Oil-Based Systems**



Automated High Pressure High Temperature (HPHT) Reactors

Reel-to-Reel Coating for Optical Fiber Sensors

NETL has established capabilities and well-equipped laboratories to enable new sensor material and device research & development activities.

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.
- 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.