Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

FWP-1022435

Presenter: Dr. Ruishu Wright, NETL

Narciso Guzman, Intelligent Optical Systems

Prof. Aydin Babakhani, University of California, Los Angeles

Prof. Kevin Chen, University of Pittsburgh

Dr. Scott Frailey, Illinois State Geological Survey

Prof. David Greve, Carnegie Mellon University

U.S. Department of Energy

National Energy Technology Laboratory

2021 Carbon Management and Oil and Gas Research Project Review Meeting

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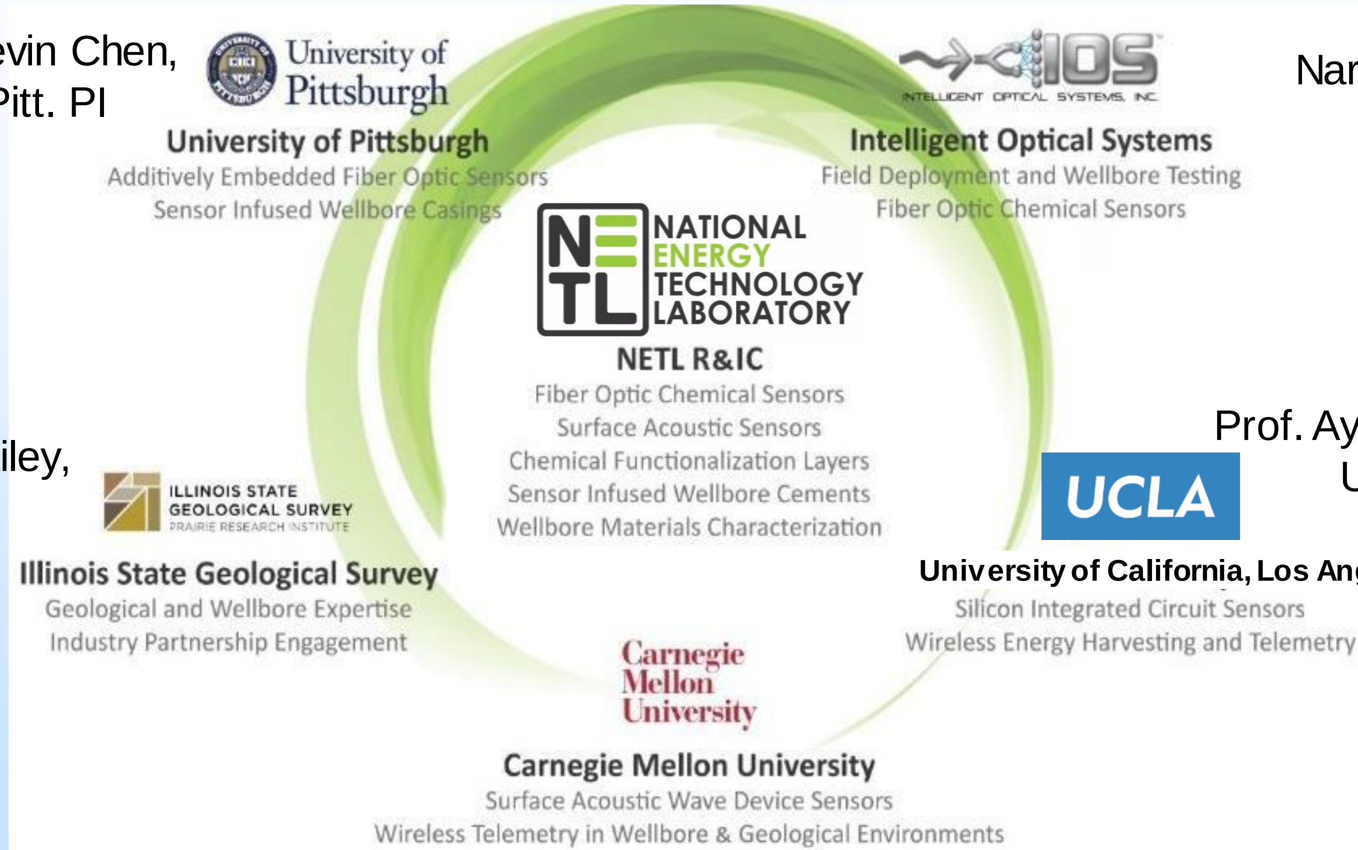
Project Team

Prof. Kevin Chen,
U. Pitt. PI

Narciso Guzman,
IOS PI



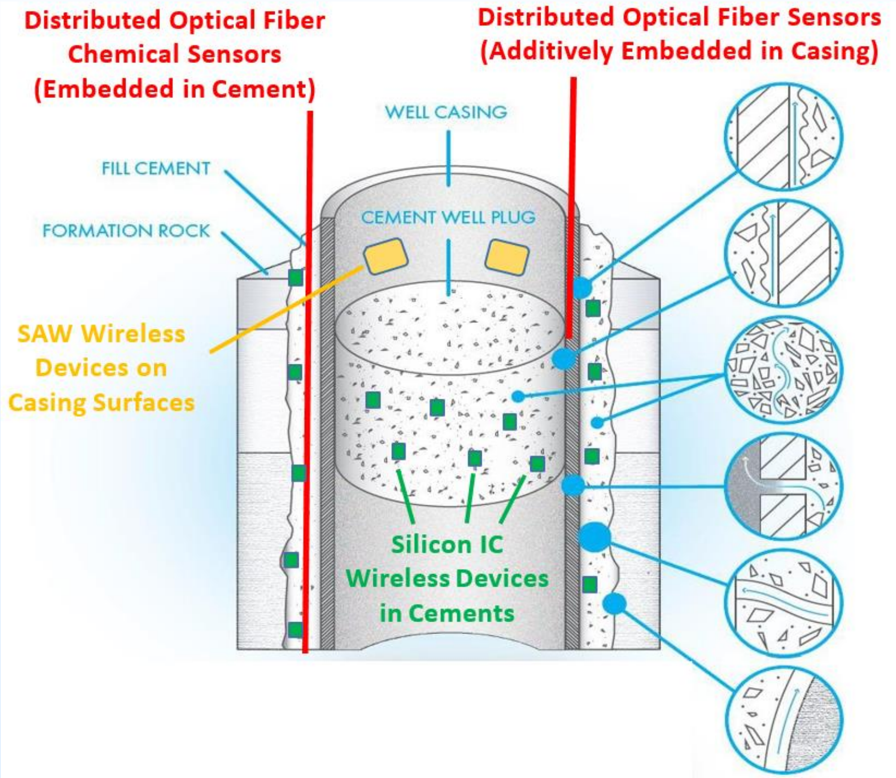
Dr. Scott Frailey,
ISGS PI

Prof. Aydin Babakhani,
UCLA PI

Prof. David Greve,
CMU PI

Overall Project Performance Dates: 04/2018-03/2022

Project Objective



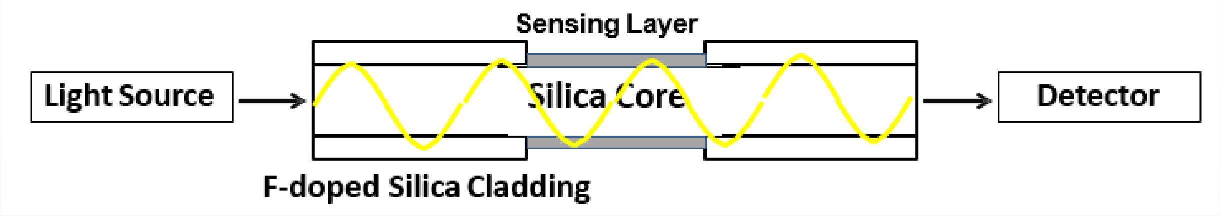
<u>Develop and Demonstrate:</u>

- A suite of complementary technologies for wellbore integrity monitoring
- Chemical sensing of high priority parameters (pH, corrosion onset, etc.)
- Optical fiber and passive wireless (SAW, SiIC) technologies

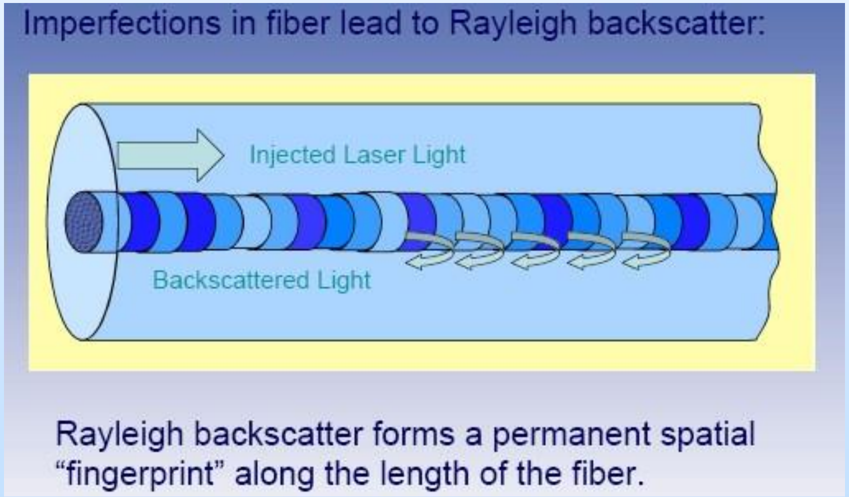
<u>Overall Goal:</u> A suite of technologies functionalized for chemical sensing and identification of wellbore integrity risks BEFORE they result in failures.

Technology #1: Distributed Optical Fiber Sensors

Sensing Principle : Evanescent Wave Sensors



Distributed Sensing

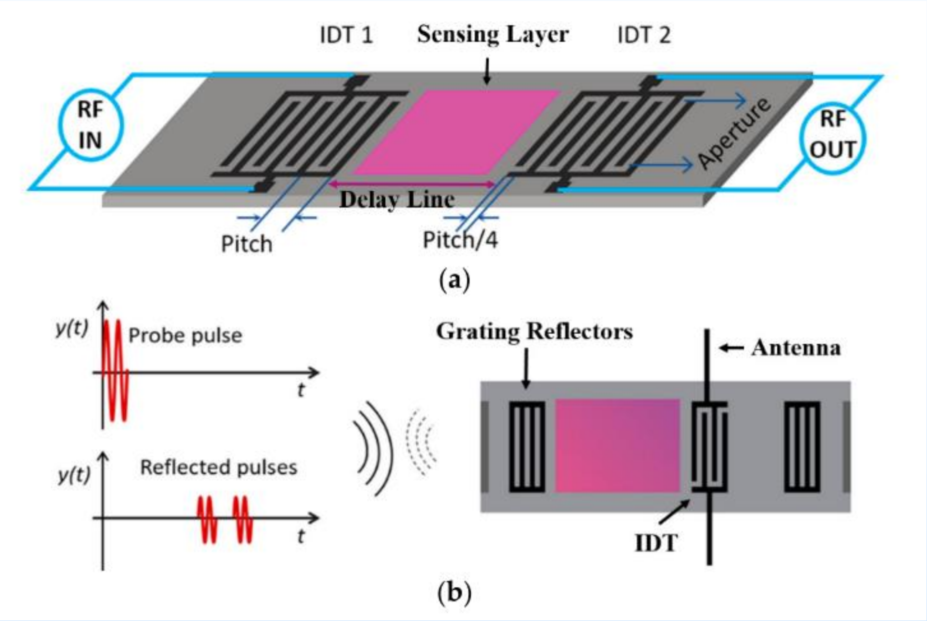


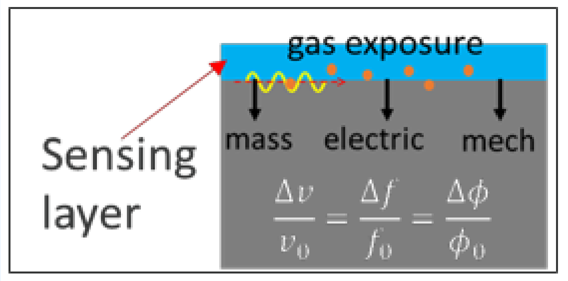
- Eliminate Electrical Wiring and Circuitry at the Sensing Location (Stability)
- Tailored to Parameters of Interest Through Functional Materials (Functionalization)
- Compatibility with Broadband and Distributed Interrogation (Geospatial / Multi-parameter)

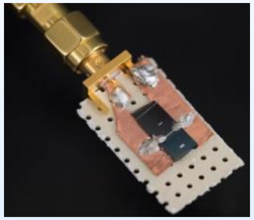
Deployment Scenario: Embedded Within Wellbore Cement and Casing Metal

Technology #2: Passive and Wireless SAW Devices

Sensing Principle : Functionalized Surface Acoustic Wave Devices





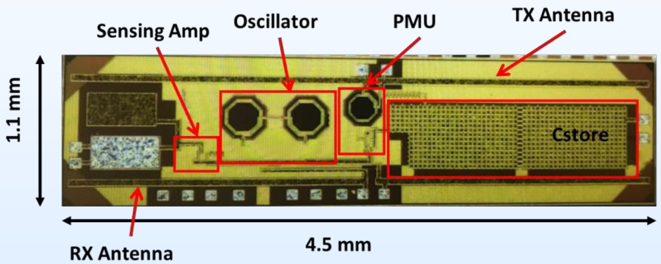


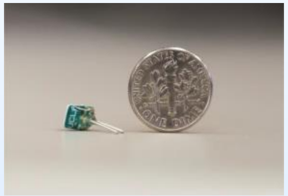
- ➢ Passive and wireless operation
- ➢ Rugged and stable for harsh environment applications
- ➢ Telemetry is a primary challenge, must be addressed in parallel

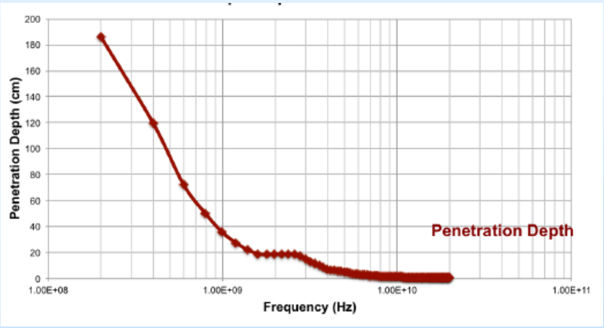
Deployment Scenario: Embedded on Interior and Exterior Casing Surfaces

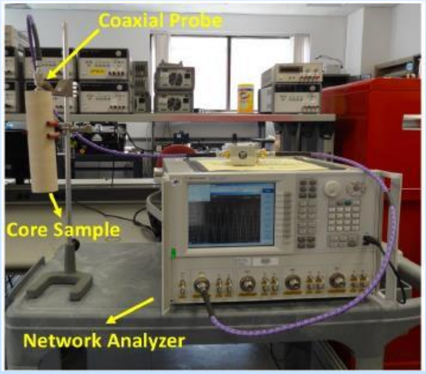
Technology #3: Wireless Miniature SiIC Devices

Sensing Principle : Functionalized Silicon Integrated Circuit Devices









- Miniaturized devices with active functions through IC processing
- Wireless energy harvesting and storage to eliminate batteries
- Telemetry is again a major challenge to be addressed

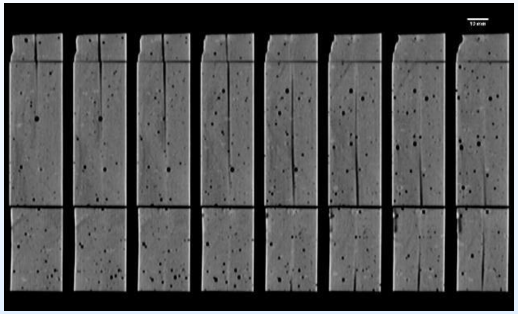
Deployment Scenario: Embedded Within the Wellbore Cement

Additional Efforts: Sensor Embedding

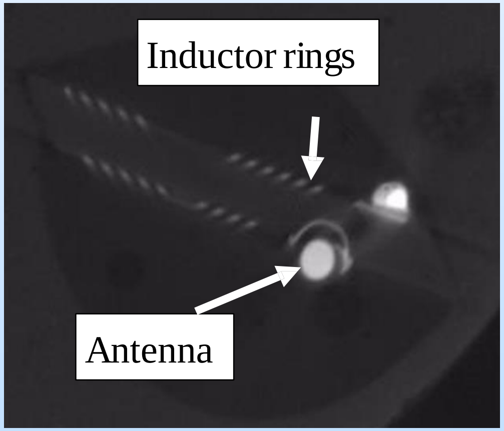
Optical Fibers Embedded in Wellbore Cement

Mechanical Testing

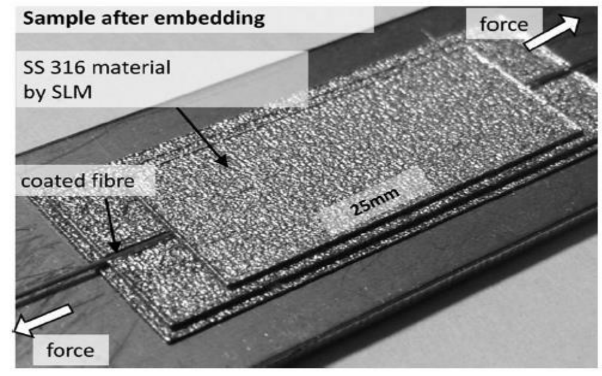
CT Scans of Embedded Optical Fibers



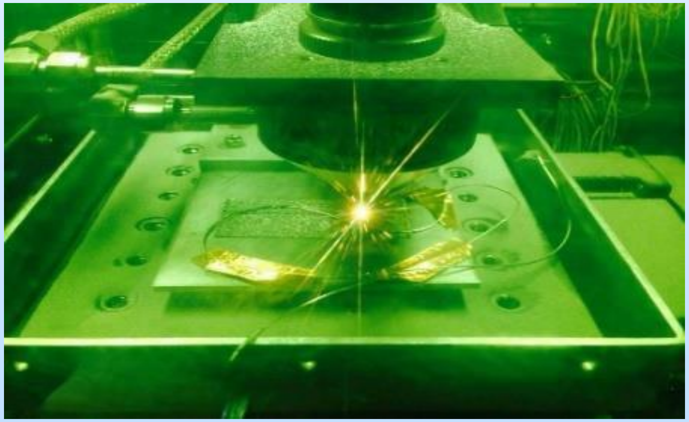
Embedded SiIC Sensors



Optical Fibers Embedded in Casing Alloys



Laser engineered net shaping (LENS)



Proof-of-Concept Sensor Embedding Efforts Combined with Structural and Performance (CT scans, Permeability, Porosity, Corrosion) Benchmarking.

Project Structure: Tasks and Outcomes

Overall Task Structure

Task 1: Project Management

Task 2: Technology Maturation Plan & Industry Engagement

Task 3: Chemical Sensing Layer Research & Development

Task 4: Multi-Functional Optical Fiber Sensor Development & Deployment

Task 5: Multi-Functional Wireless Based Sensor Device Development

Task 6: Sensor-Infused Wellbore Material Performance Characterization

Key Project Deliverables and Outcomes

#1: New Chemical Sensing Layers for High Alkalinity / High T in Wellbore Relevant Conditions

#2: Maturation of New Wireless / RF Sensing Technology for Subsurface

#3: Field Validation of New Fiber Optic pH Sensing Technology

Project Progress: Industry Advisory Group

Advisory Group Members

Name	Company	Expertise
Glen Benge	Benge Consulting	Wellbore isolation & well cementing
Dennis Dria	Myden Energy Consulting, PLLC	Fiber-optic technology development & implementation
George Koperna	Advanced Resources International, Inc.	CO_2 EOR & storage, reservoir engineering
Igor Kosacki	WellDiver	Sensor development
John Lovell	MicroSilicon Inc.	Temp & pressure measurement systems, Wellhead asphaltenes sensor
Tim Ong	BHP Billiton	Strategy planning-technology & innovation
Pierre Ramondenc	Schlumberger	Coiled tubing well interventions, real-time fiber-optics
Austin Vonder Hoya	Pioneer Natural Resources USA	Geophysical technology
David Wagenmaker	Southern Company Gas	Reservoir engineering

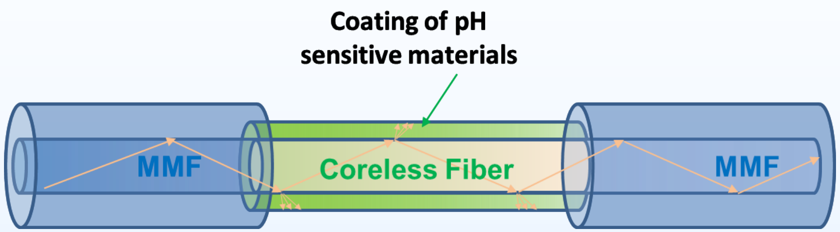
Ranking of Geochemical Parameters to Be Monitored

Rank	Geochemical paramters
1	pH
2	H_2S, HS^-
3	Dissolved CH_4 and CO_2
4	Corrosion ions (Mn^{2+}, Fe^{2+}, etc.)
5	Ionic strength, Solution conductivity
6	TDS
7	Dissolved oxygen
8	Cl^-
9	Na^+
10	Ca^{2+}

- Advise on matters that directly concern the technology developed for industry:
  - Wellbore environment for different applications
  - Hierarchy of sensing applications to industries represented
  - Deployment challenges
  - Wellbore integrity
  - Longevity (sensor and power)
- Industries represented:
  - CO_2 Storage
  - Geothermal
  - Waste Water Disposal
  - Oil Industry
- Field demonstrations are still in early stages

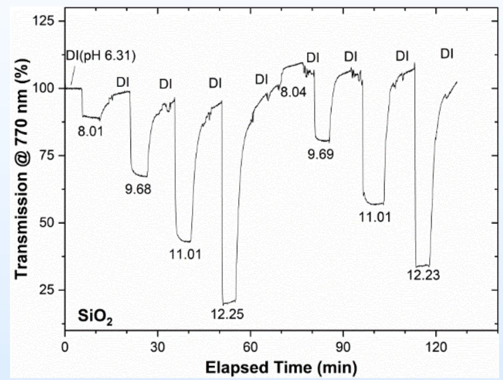
Regular Meetings Have Occurred with the Industry Advisory Group to Provide Feedback and Guide Technology Maturation Plans for the Overall Project.

Project Progress: MeO_x-based Chemical Sensing Layers

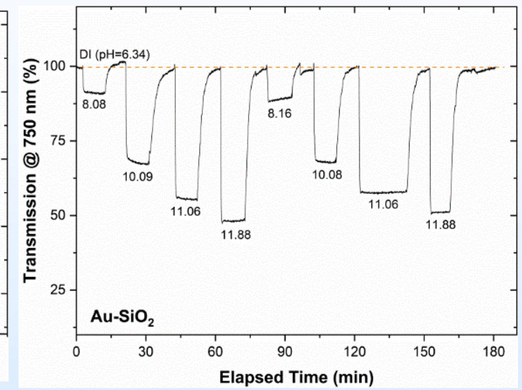


Oxides	Room Temp.	80 °C, high pH
SiO_2	✔	
Au-SiO_2	✔	
TiO_2		✔
Au-TiO_2		✔
ZrO_2		✔

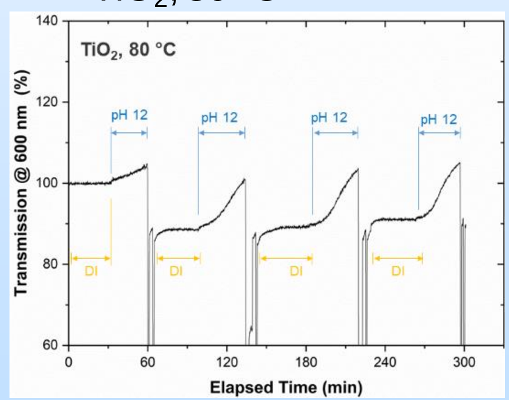
SiO_2, Room Temperature



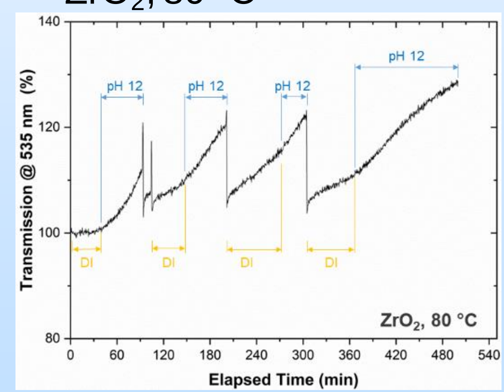
Au-SiO_2, Room Temperature



TiO_2, 80 °C



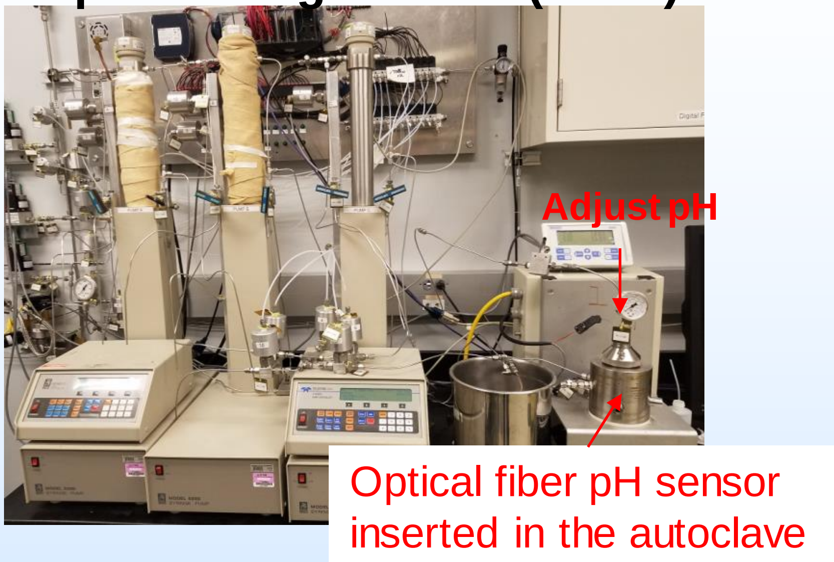
ZrO_2, 80 °C



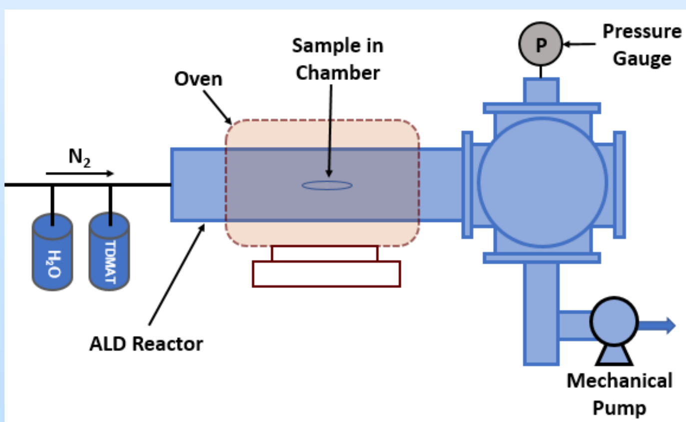
Oxide Based Sensing Layers were Developed for pH Sensing with Stability in Elevated Temperature and High Alkalinity Environments.

Project Progress: MeO_x-based Chemical Sensing Layers

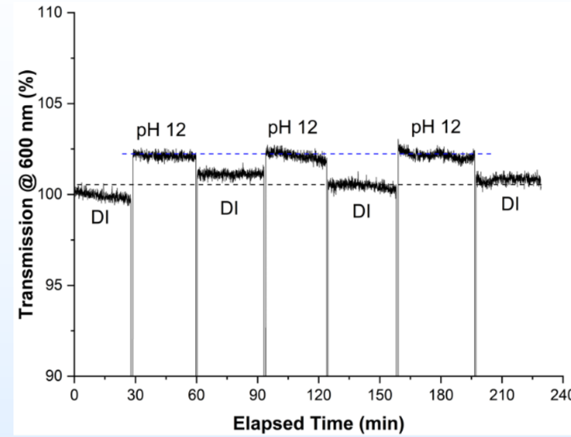
pH Testing Reactor (80 °C)



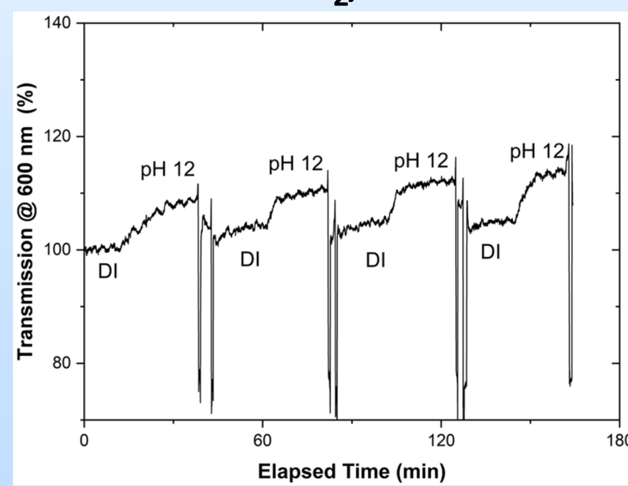
Atomic Layer Deposition (ALD)



ALD-TiO_2, Room Temperature

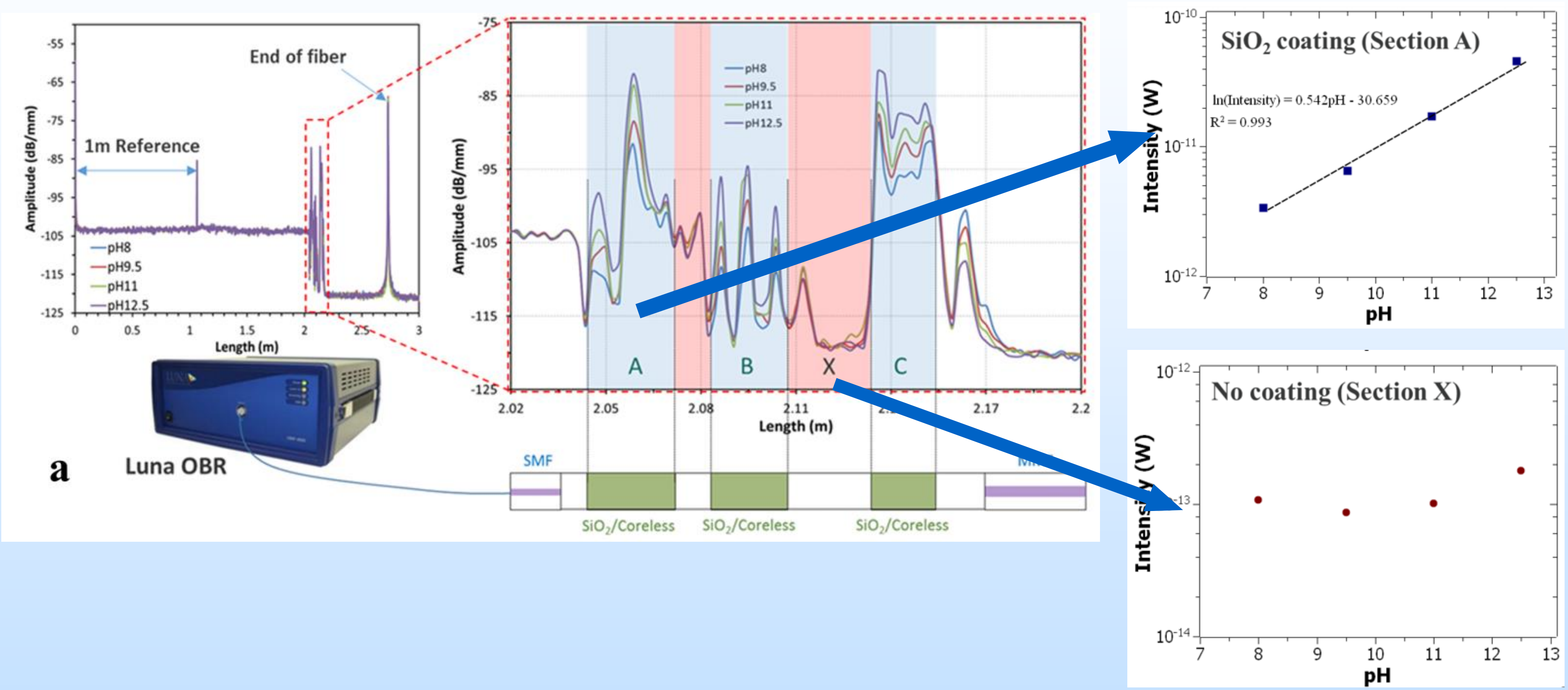


ALD-TiO_2, 80 °C



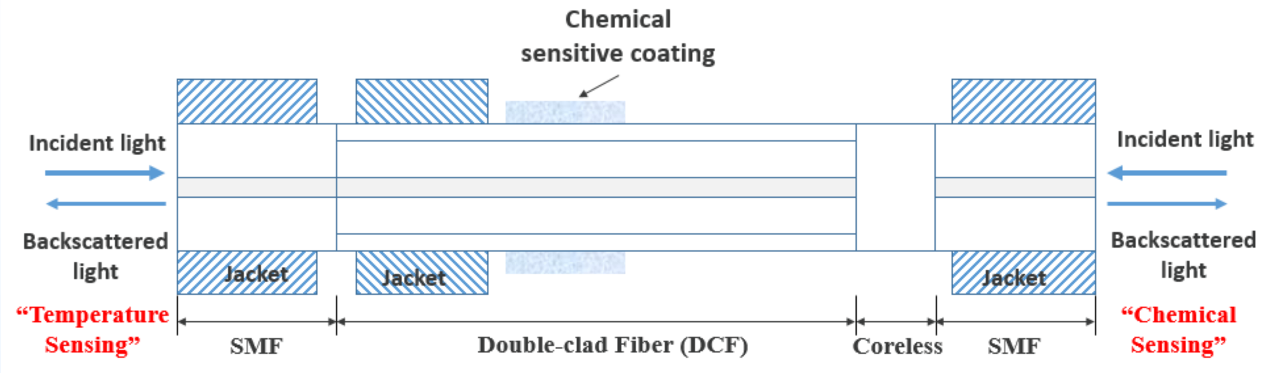
ALD-TiO_2 Coated Optical Fiber Sensors Demonstrated Improved Stability and Reversibility for pH Sensing at Room Temperature and 80 °C.

Project Progress: Distributed Chemical Sensing

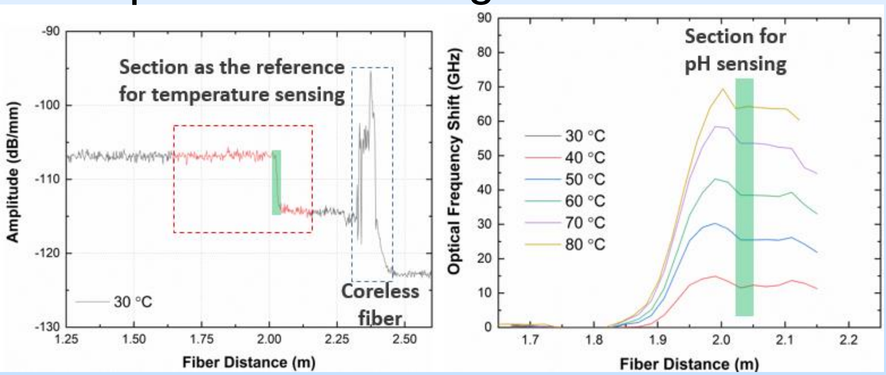


Silica Coated Optical Fiber Sensors Have Been Used to Demonstrate Multi-Point Distributed pH Sensing in High pH solutions.

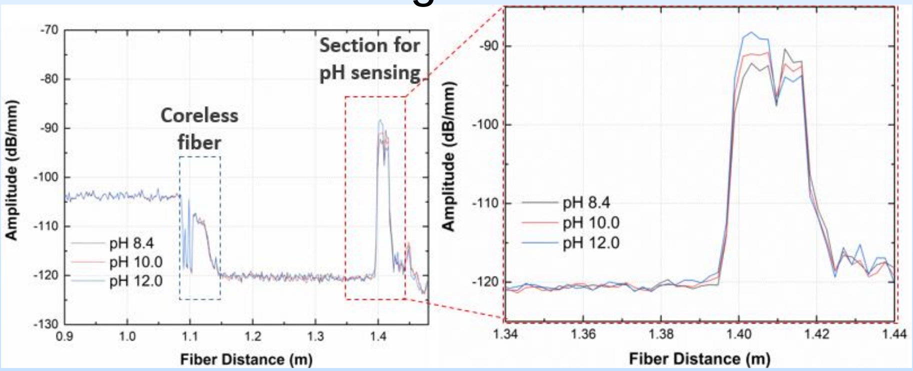
Project Progress: Distributed Chemical Sensing



Temperature Sensing



Chemical Sensing

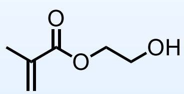


Multi-parameter sensing (T and pH) using the same optical fiber (double-clad fiber) was demonstrated for temperature compensated pH sensing.

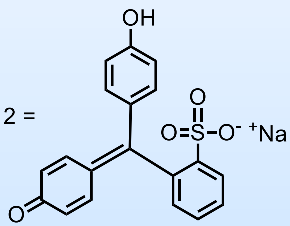
Project Progress: Polymer-based Chemical Sensing Layers

Polymer network with covalently bonded pH indicator reduces the leaching-out.

Monomer 1 =



Monomer 2 =



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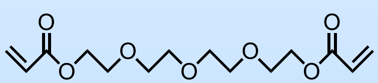
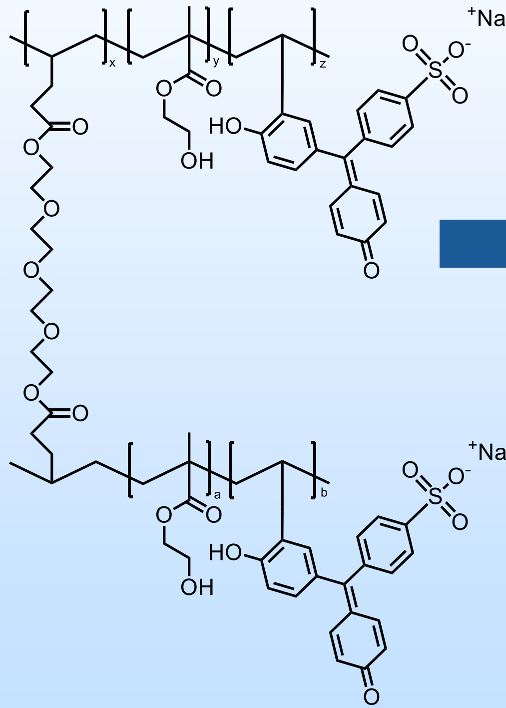
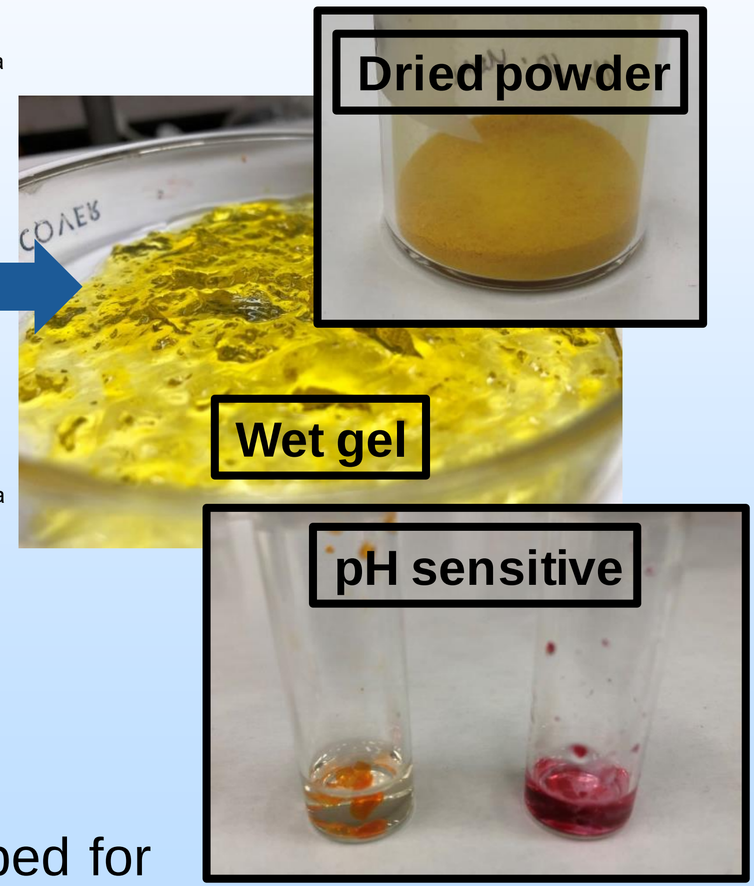


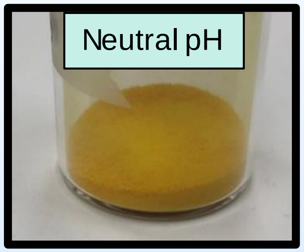


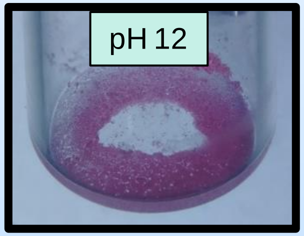


Polymers with pH Indicators are also Developed for High Temperature and High Alkalinity Environments.

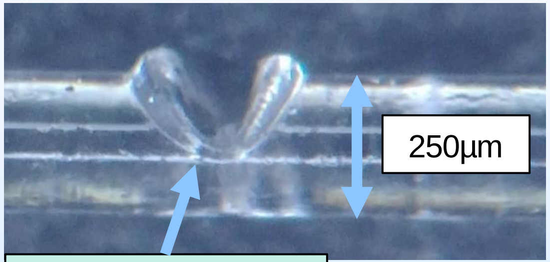
Project Progress: Polymer-based Chemical Sensing Layers

pH Sensitive Material





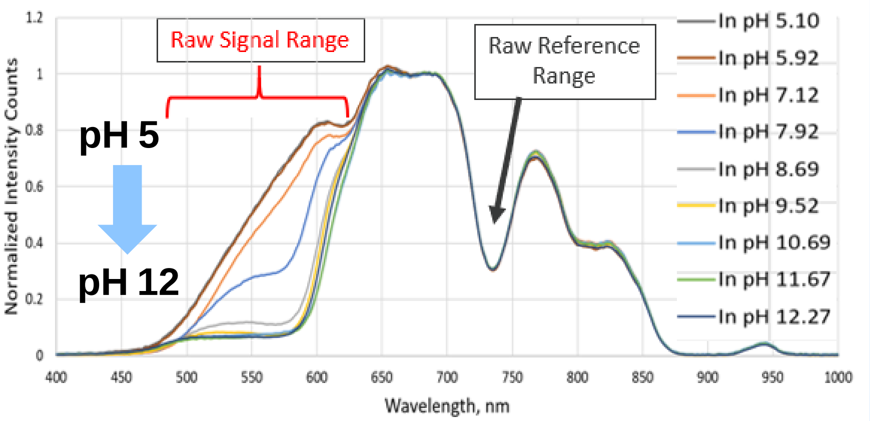
Polymer Optical Fiber (PMMA)

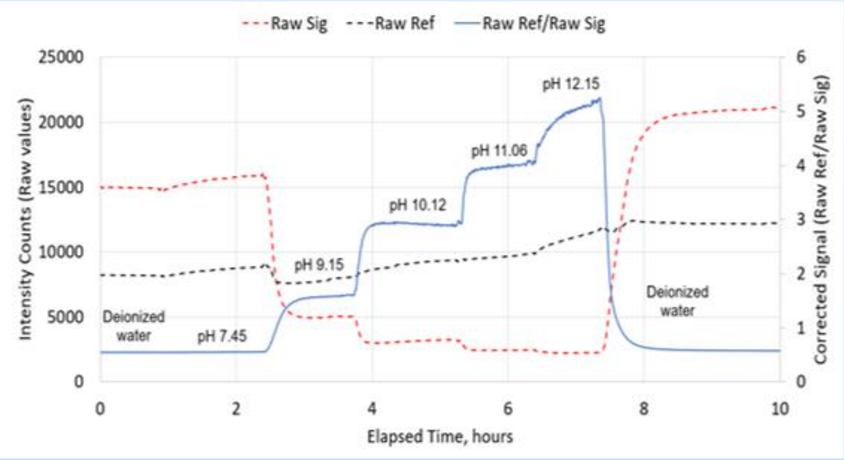


Laser created notch

Notch filled with pH indicator gel particles and coated with protective layer

Sensor fiber responding to various pH solutions



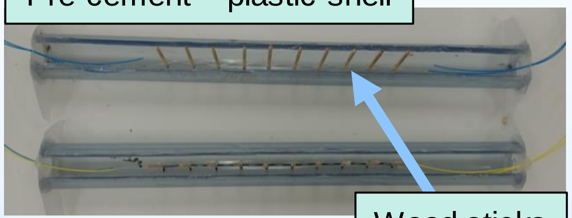


Polymer-based Sensing Layers bonded with pH Indicators are Demonstrated for pH sensing from pH 5 to 12.

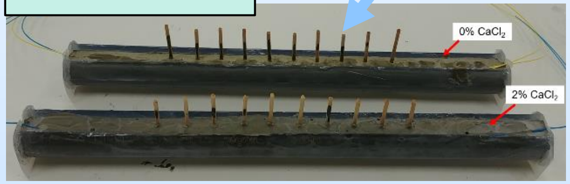
Project Progress: Fiber Optic pH Sensing when Embedded in Cement

Cement cores with man-made defects for embedding sensor fibers

Pre-cement – plastic shell

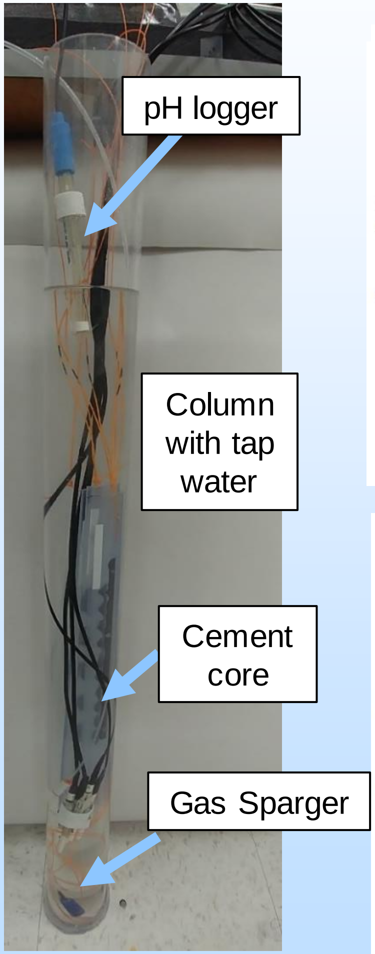


Cement added

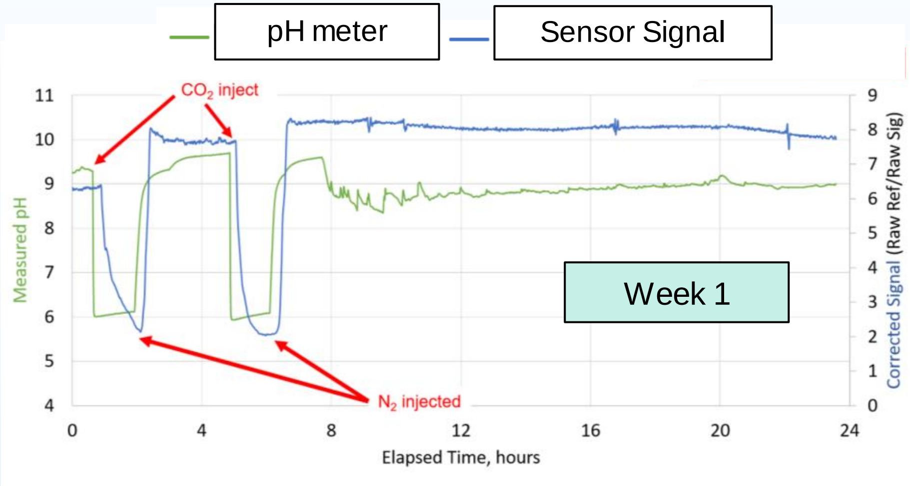


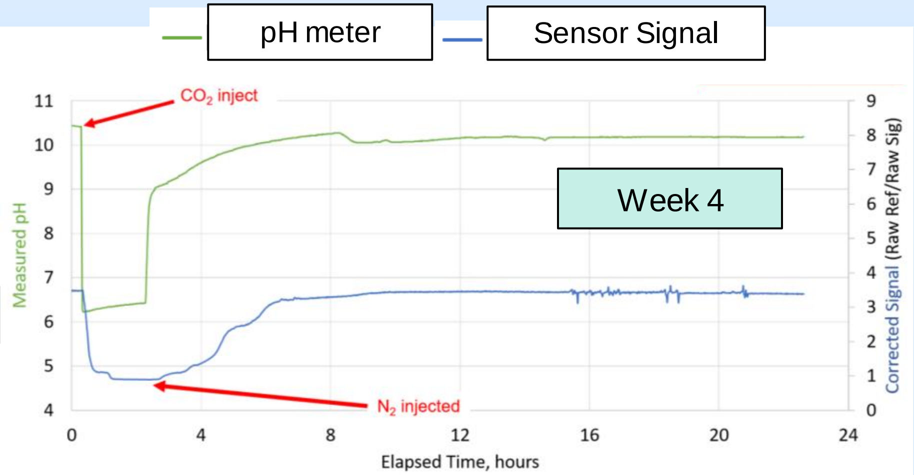
Wood sticks removed

Test setup



Sensor embedded in cement core responding to CO_2 and N_2 gas injections

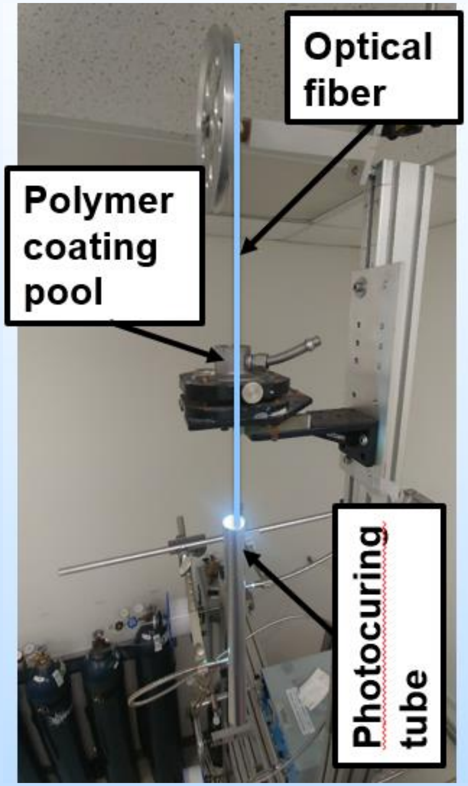


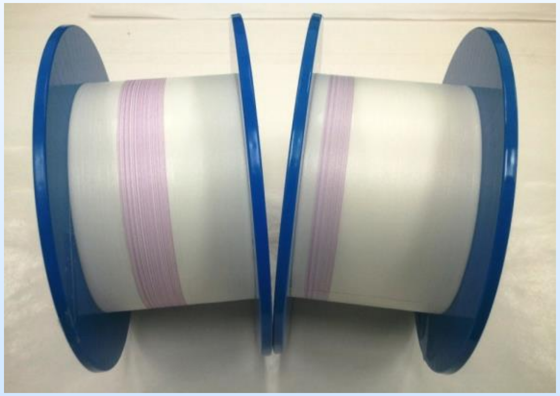


Fiber Optic pH Sensors Demonstrated pH Sensitivity for Weeks when Embedded in Cement.

Project Progress: Sensing Layer Scale-Up

Optical fibers are passed from the feed spool, through a polymer coating pool, into the photocuring tube, and rolled onto the collection spool at the base of the coating tower.





Fiber optic chemical sensor rolled on a spool.
40 m coated fiber was demonstrated in this project.

Established Fiber Recoating Facilities are Being Leveraged to Scale Promising Inorganic and Organic Sensing Layers to m- and Eventually km-Scale Lengths.

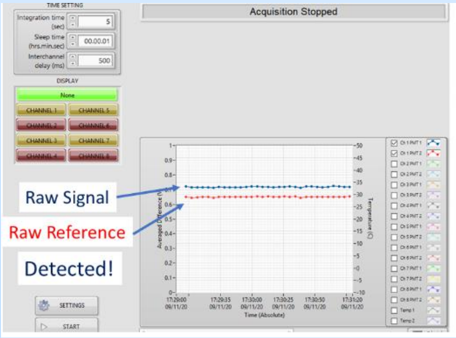
Project Progress: Optical Fiber Sensor Deployment and Field Validation

PHASE 0: Lab Studies of Sensors in Cement. Status: Completed
PHASE I: Shallow Water Well Test (20 ft. depth). Status: August 2021
PHASE II: Deep Water Well (up to 2,000 ft. depth). Status: TBD

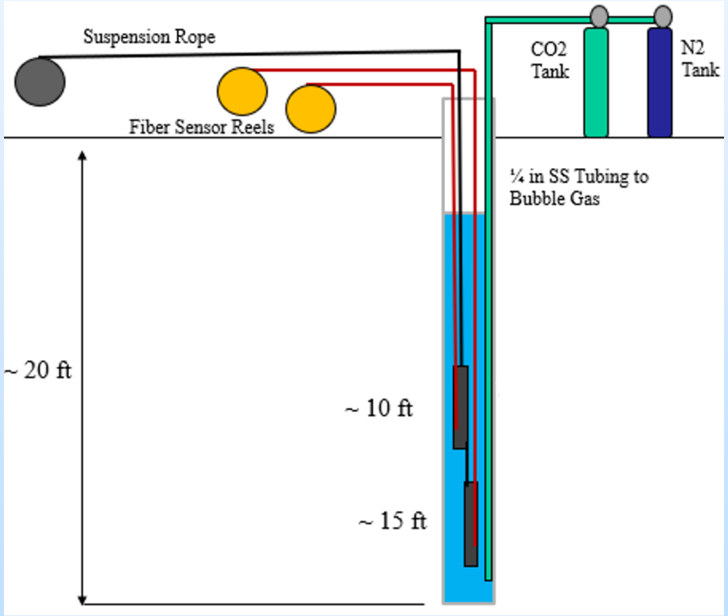
Field optoelectronic hardware

Multi-band optoelectronic light sources and detectors enable signal correction for non-pH environmental effects.

Sensor integrated cement core



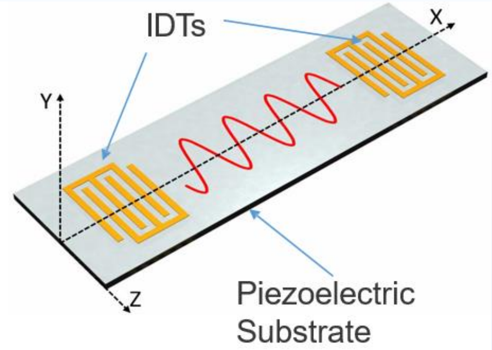
Shallow Well Deployment

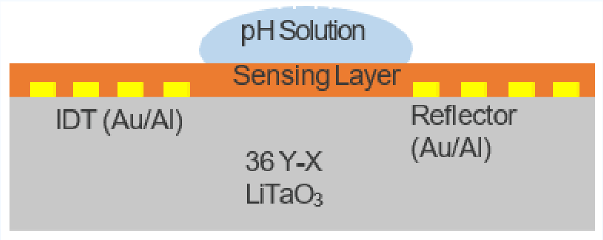


Multiple Sensor-integrated Cement Cores will be Deployed in the Wells to Demonstrate Distributed Sensing.

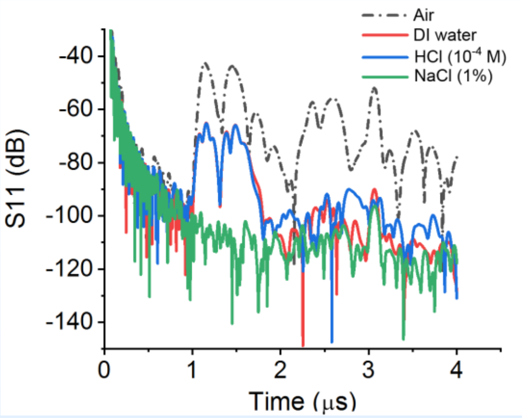
Project Progress: SAW pH and Corrosion sensing

Shear Horizontal Surface Acoustic Waves for Aqueous Phase Applications



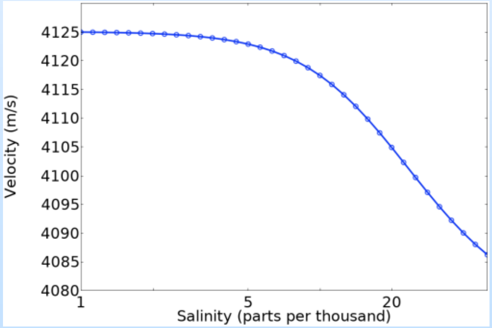


36° rot Y-cut X-propagating $LiTaO_3$

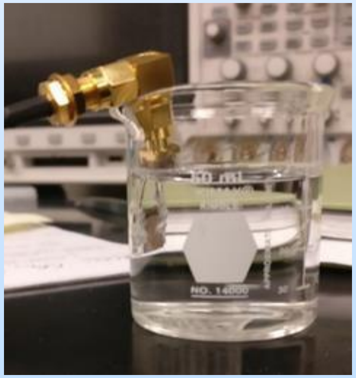


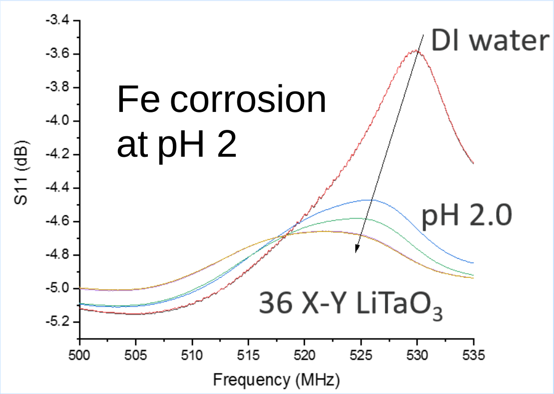
- Attenuation and velocity changes for NaCl and HCl solutions

Modeling



Experiment

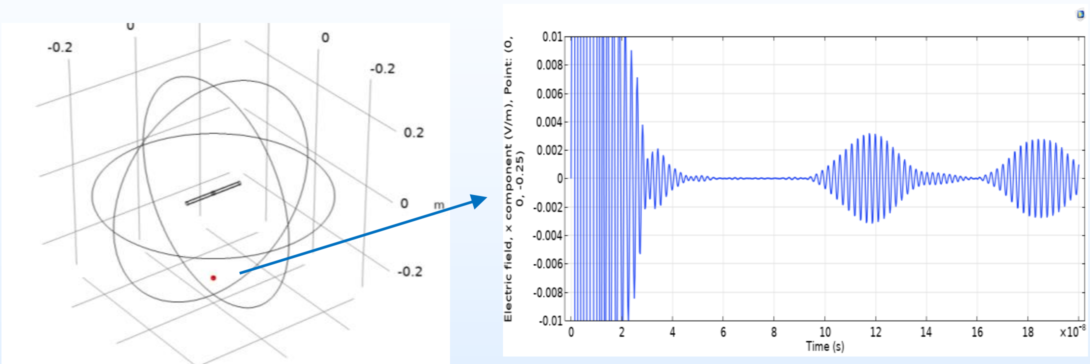




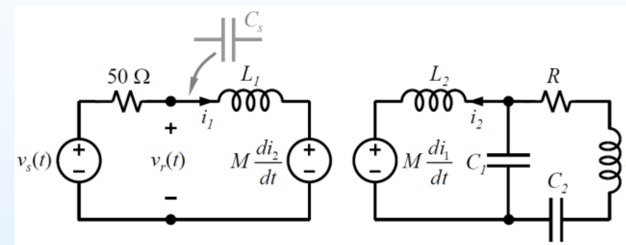
SAW Device Modeling and Experiments for Aqueous Phase Operation.
Demonstrated Velocity Changes and Attenuation with Various Salinity and pH.
Demonstrated Sensitivity to Fe Mass Loss/Corrosion at Low pH.

Project Progress: Wireless Telemetry Concepts

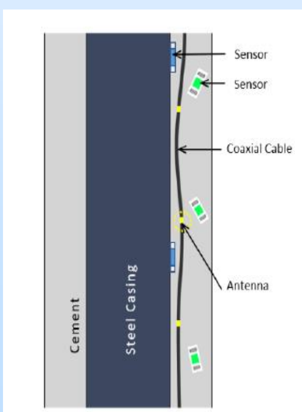
- Simulations of a Dipole Antenna + SAW in cement

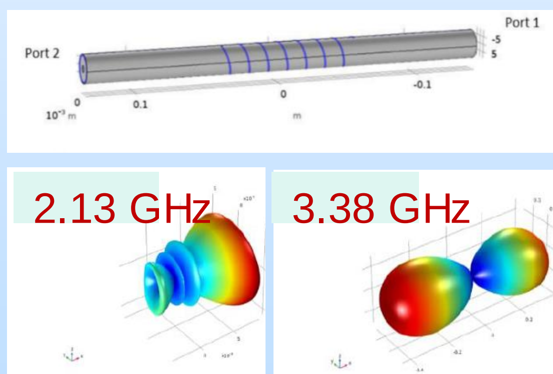


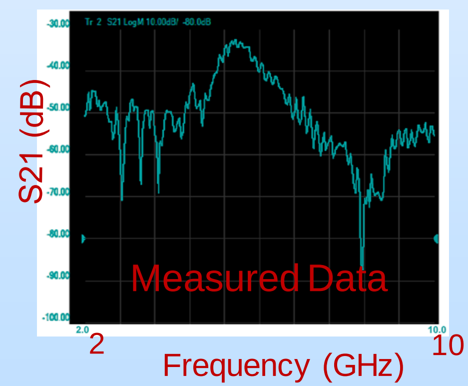
- Simulation of Inductive Coupling



- Simulations and Measurements of Helical Antenna around a Coaxial Cable



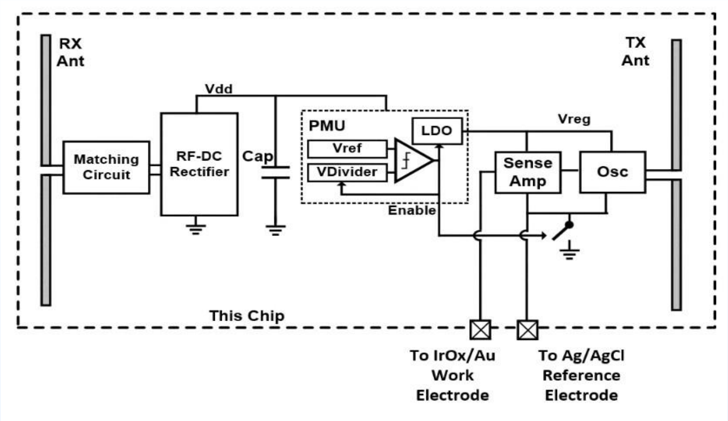


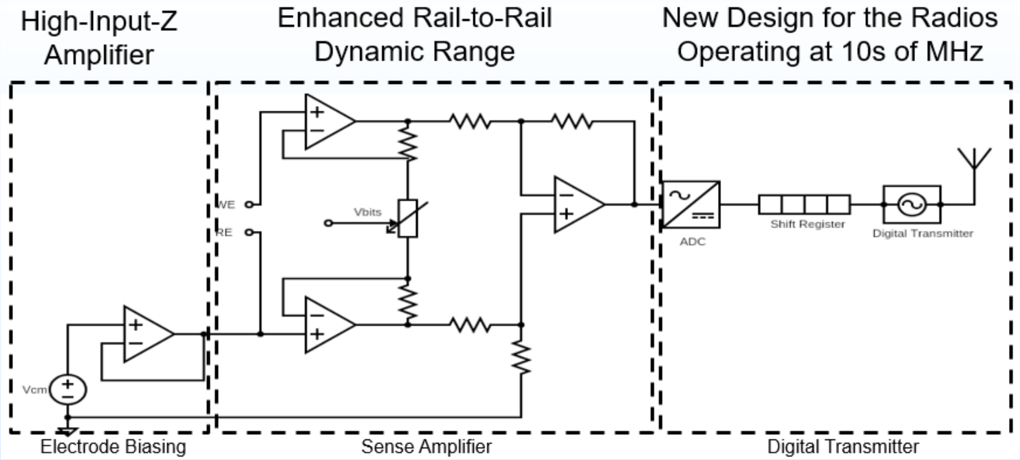


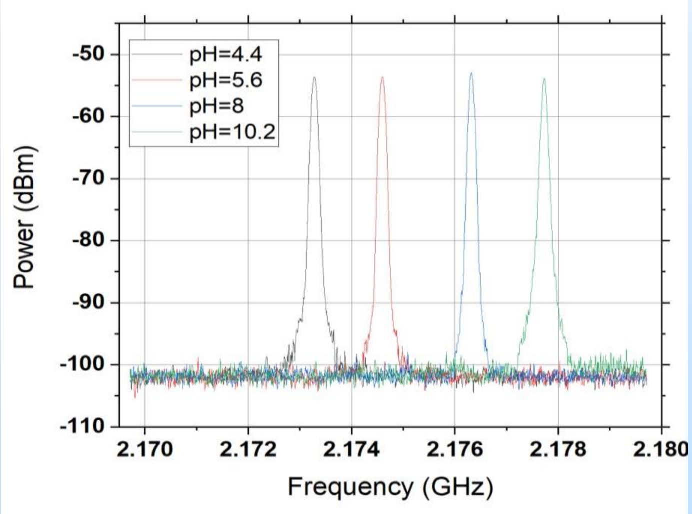
Wireless Telemetry Methods are Being Explored for Compatibility with Applications in Subsurface Media Including Novel Antenna and Coupling Designs.

Project Progress: Wireless SiIC pH Sensor

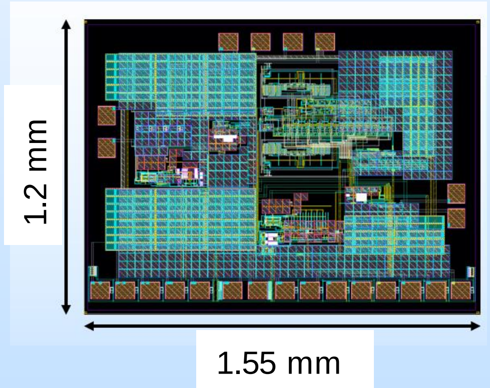
Circuit Architecture of pH Sensor Designs







- The chip successfully transmitted wireless signals at 2.173~2.178GHz when exposed to different pH values.
- Chip Radiation Frequency Changed as a Function of pH Value.

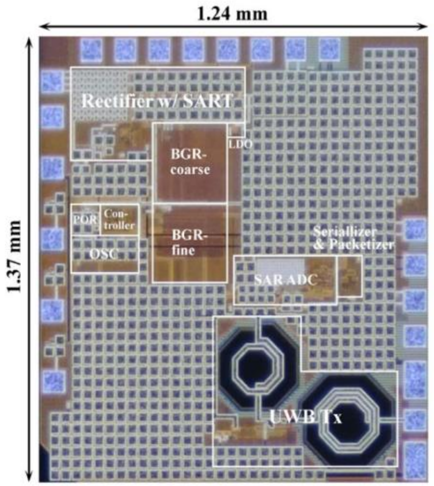


SiIC Design / Fabrication Enabled Successful Device Operation Including the Integration of Electrochemical Sensing Electrodes for pH Sensing.

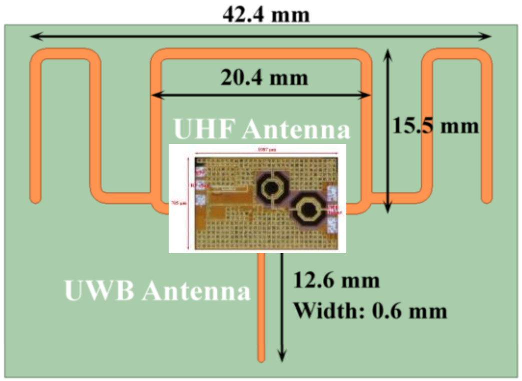
Project Progress: Wirelessly-Powered SiIC Device

Status of the New MHz Radios To Push the Operating Range

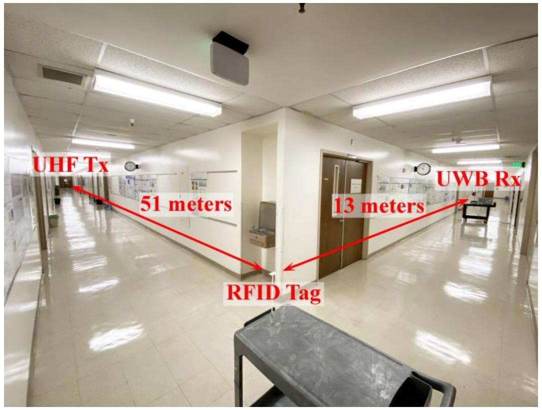
Radio 1: Power Harvester, PMU, ADC, ASIC, UWB Radio



Radio 2: PCB Antenna, Power Harvester, PMU, and UWB Radio used to demonstrate 50m operation range



Successfully Demonstrated **50m** Operating Range (**Radio 2**)

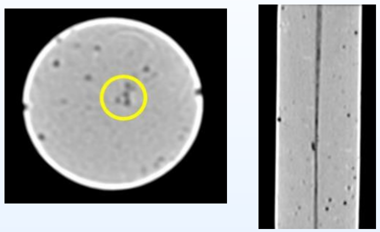


- Successfully demonstrated harvesting electromagnetic energy at 10s of MHz and used it to power the SiIC sensor.
- Demonstrated a range of 50m with a wirelessly-powered radio operating at 10s of MHz while maintaining a small antenna size (~4cm).

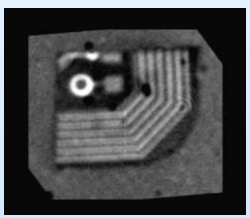
Project Progress: Sensor Embedding in Cement

Cement Cores

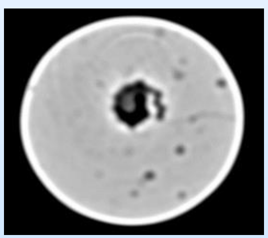
Optical Fibers



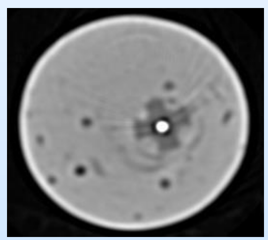
SiIC Chip



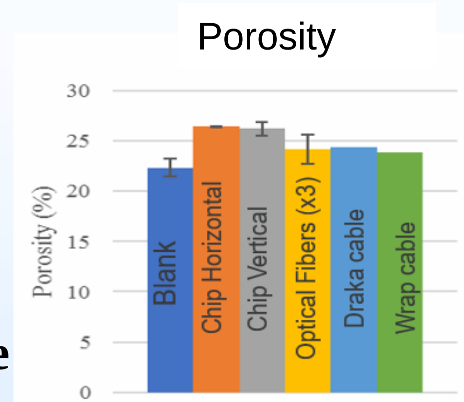
Wrap cable

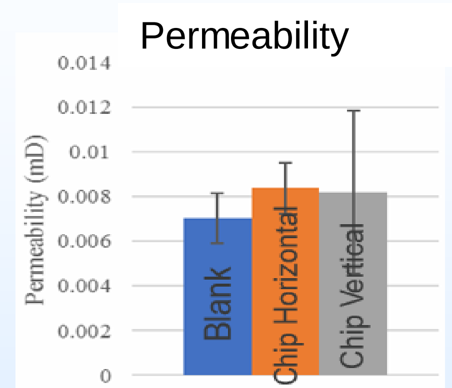


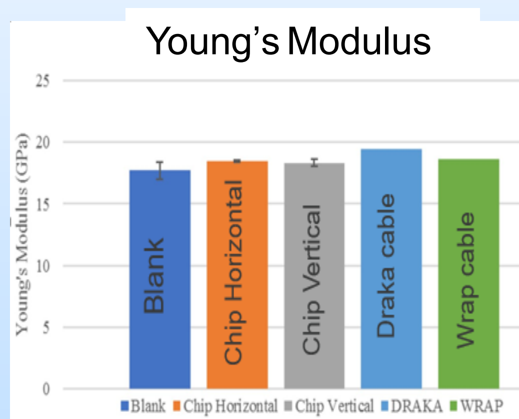
Draka cable

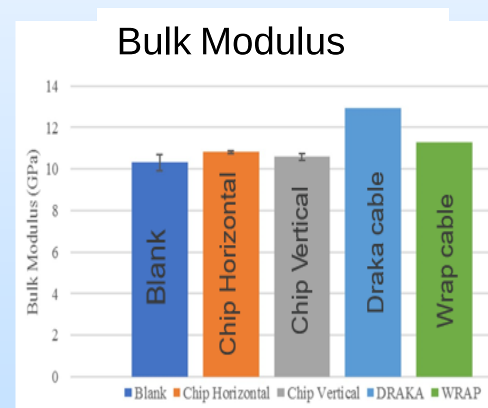


Optical fiber cables enhanced Young's and bulk moduli.





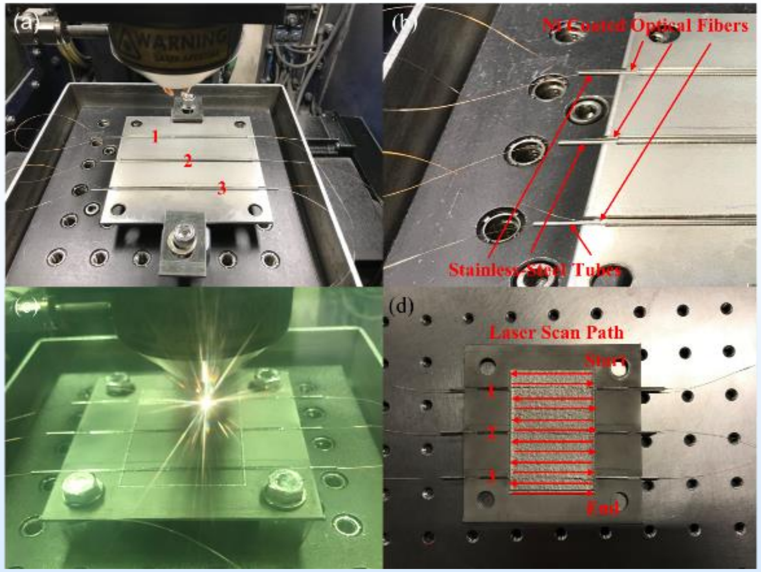


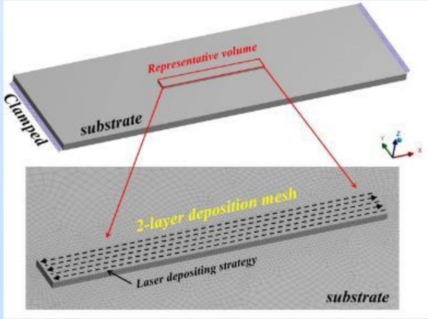


3D CT Scans and Cement Property Measurements were Performed to Understand Structural Impacts of Embedded Sensors on Cement.

Project Progress: Sensor Embedding in Casing Steel

Embedded Fibers in Steel

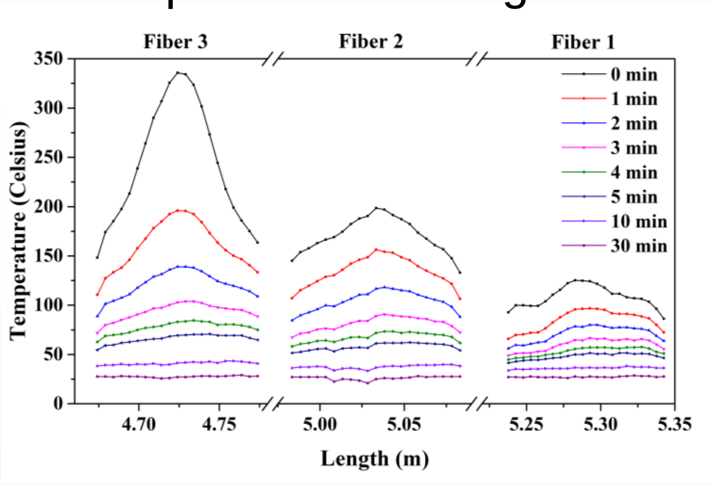




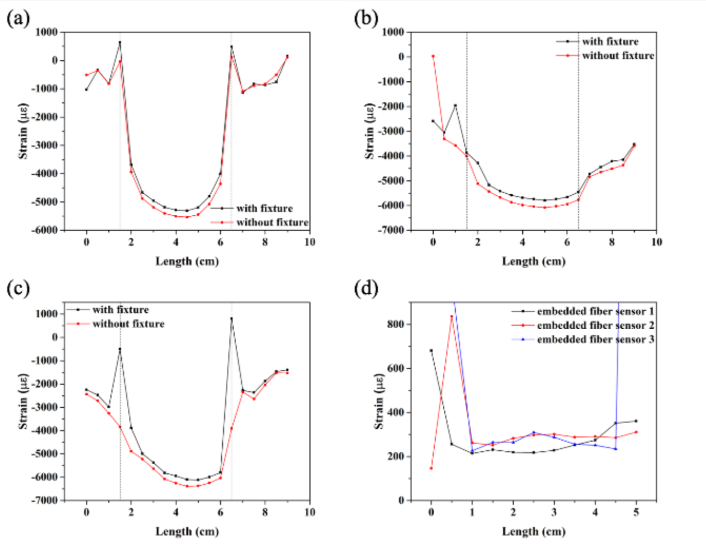
FEA simulation of 3D printing

Additive Manufacturing Methods were used for Integration of Optical Fibers Into Steel Parts with Capability of high-resolution Temperature and Strain Sensing.

Temperature Sensing

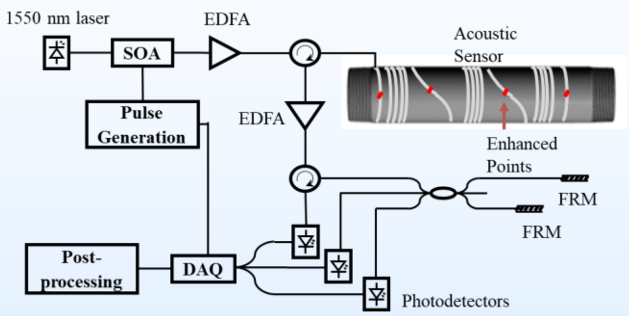


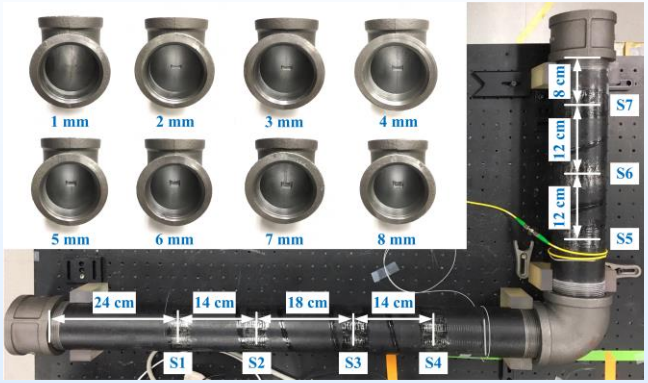
Strain Sensing

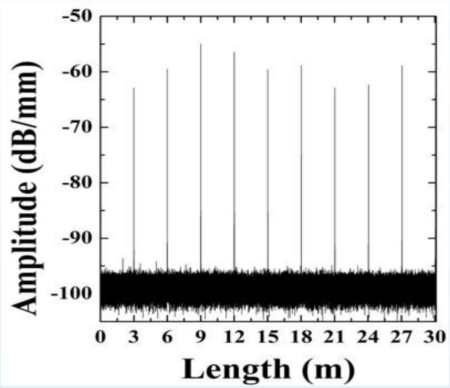


Project Progress: AI-Enhanced Optical Fiber Sensing

Distributed Acoustic Sensing (DAS) System with Sensor Enhanced Fiber



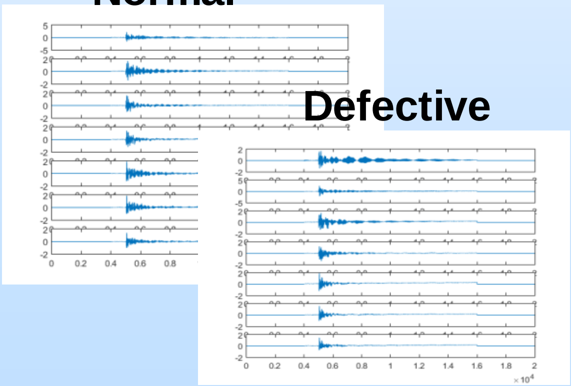


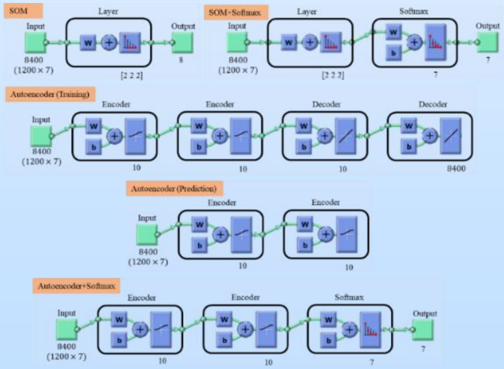


Deep Neutral Network Machine Learning to Identify Pipe Defects

Normal

Defective



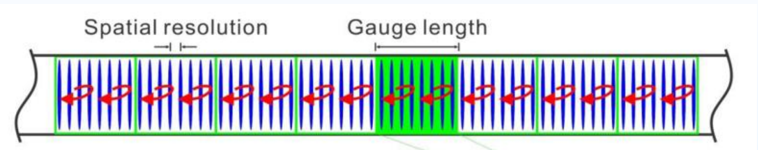


- **94% accuracy is achieved by supervised learning.**
- **71% accuracy using unsupervised learning**

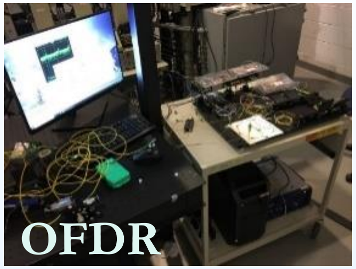
AI-Enhanced Methods to Analyze the Optical Fiber Sensing Data for Defect Identification of a Steel Pipe

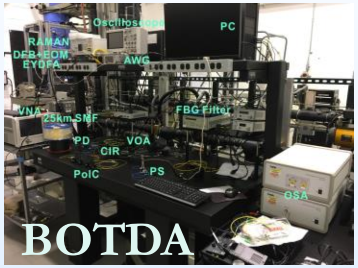
Project Progress: Low-cost Custom Interrogators

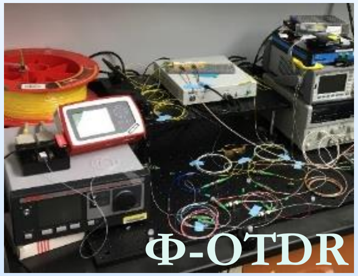
Distributed Optical Fiber Sensor Interrogators



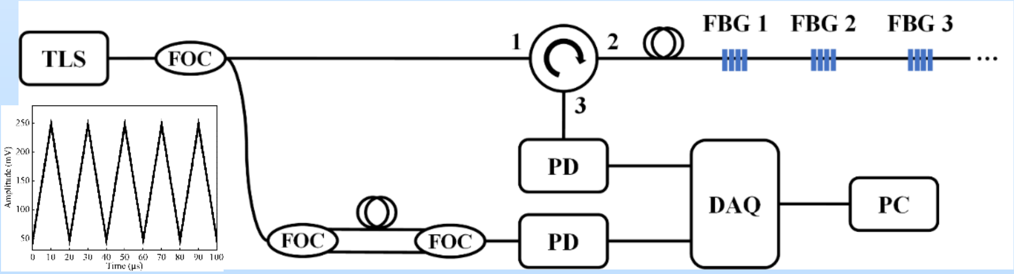
Technology	Sensing Range	Spatial Resolution	Measurement Time	Fiber Type	Sensing Performance
Coherent Rayleigh OFDR	m – km	mm – cm	seconds	SMF	Temperature, strain, vibration, chemical sensing
Coherent Rayleigh OTDR	km	m	seconds	SMF	Acoustic wave, vibration
Brillouin OTDR/BOTDA	> 100 km	cm – m	minutes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

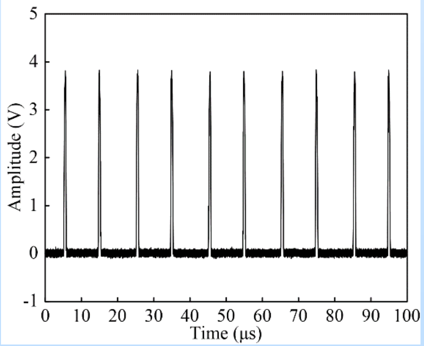






Multiplexable Fiber Bragg Grating Interrogator





Low-cost telecom tunable laser.

FBG interrogation rate at 100 kHz.

Low-cost Distributed and Multiplexable Optical Fiber Sensing Interrogators Have Been Developed.

Project Summary: Success and Next Steps

Project Success

- Fiber optic sensor technology for pH and corrosion sensing at 80°C and high pH
- Aqueous phase sensing of novel SAW devices through simulation and experiments
- Wirelessly-powered SiIC sensors for successful pH sensing in a liquid phase
- Demonstrated embedded sensors in cement to prepare for field validation
- Novel concepts of wireless subsurface telemetry methods and early lab testing
- AI-enhanced distributed optical fiber sensing for defect identification
- Impacts of sensor embedding in cement and steel were explored and evaluated
- Low-cost custom interrogators for distributed and multiplexable optical fiber sensing

Next Steps

- Field validation of embedded fiber optic pH sensors in shallow and deep wells

Accomplishments

- 5 Patent Applications and 2 Reports of Invention
- 21 Technical Journal Publications and 3 Major Literature Reviews
- 32 Presentations and Conference Papers

Acknowledgement and Team

Program Management: Darin Damiani (HQ), Anthony Armaly, Erik Albenze (NETL)

NETL
Dr. Ruishu Wright
Dr. Michael Buric
Dr. Jagannath Devkota
Dr. Ping Lu
Dr. Dustin Crandall
Patricia Cvetic
Richard Spaulding
Nathan Diemler

Wellbore Sensor Materials
Chemical Sensing Layers
SAW Devices
Wireless Telemetry
Optical Fiber Sensors
Sensor Embedding in Cement

IOS
Narciso Guzman

Optical Fiber Sensor Field Deployment

UCLA
Prof. Aydin Babakhani

Silicon IC Sensors
Wireless Telemetry

U. Pitt.
Prof. Kevin Chen

Optical Fiber Sensor Embedding in Steel

CMU
Prof. David Greve

SAW Devices
Wireless Telemetry

ISGS
Dr. Scott Frailey

Industry Partnership Group
Subsurface Sensor Deployment Review

Former Team Members
Dr. Paul Ohodnicki; Dr. Fei Lu; Dr. Nageswara Lalam; Dr. Roman Shugayev

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