Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

NATIONAL ENERGY TECHNOLOGY LABORATORY

Presenter: Dr. Paul R. Ohodnicki, Jr.

August 29, 2019

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

Project Team

Dr. Paul Ohodnicki,
NETL / Lead PI

Prof. Kevin Chen,
U. Pitt. PI

University of Pittsburgh
Additively Embedded Fiber Optic Sensors
Sensor Infused Wellbore Casings

Intelligent Optical Systems
Field Deployment and Wellbore Testing
Fiber Optic Chemical Sensors

Dr. Jesus Delgado,
IOS PI

NETL R&IC
Fiber Optic Chemical Sensors
Surface Acoustic Sensors
Chemical Functionalization Layers
Sensor Infused Wellbore Cements
Wellbore Materials Characterization

Prof. Aydin Babakhani,
UCLA PI

Dr. Scott Frailey,
ISGS PI

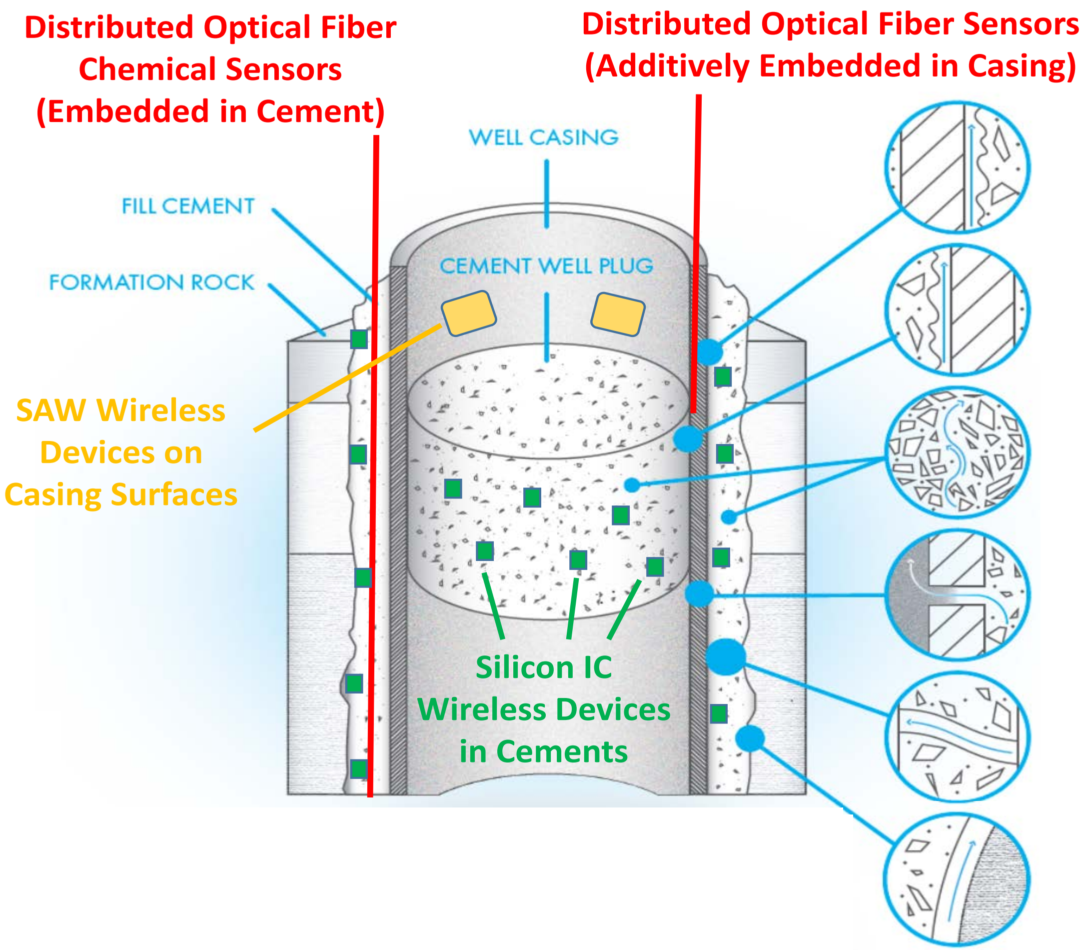
Illinois State Geological Survey
Geological and Wellbore Expertise
Industry Partnership Engagement

University of California, Los Angeles
Silicon Integrated Circuit Sensors
Wireless Energy Harvesting and Telemetry

Carnegie Mellon University
Surface Acoustic Wave Device Sensors
Wireless Telemetry in Wellbore & Geological Environments

Prof. David Greve,
CMU PI

Project Objective



Develop and Demonstrate:

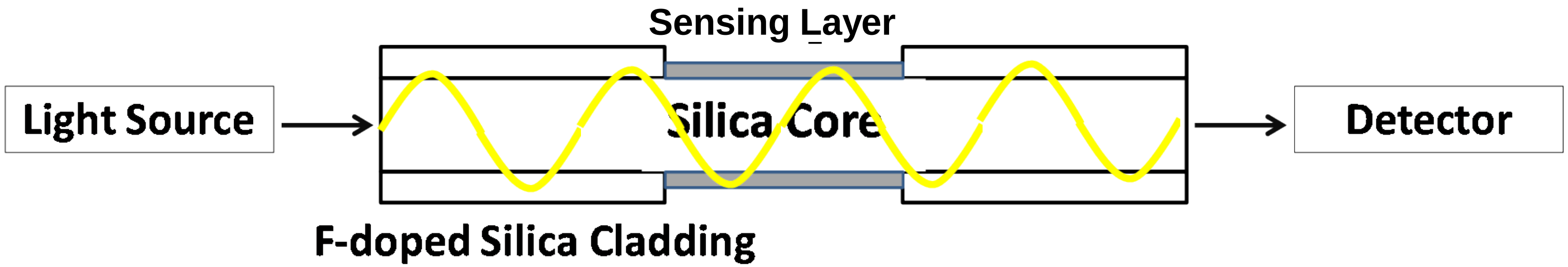
- A suite of complementary technologies for wellbore integrity monitoring
- Chemical sensing of high priority parameters (pH, corrosion onset, etc.)
- Optical fiber and passive wireless (SAW, SiIC) technologies

Overall Goal:

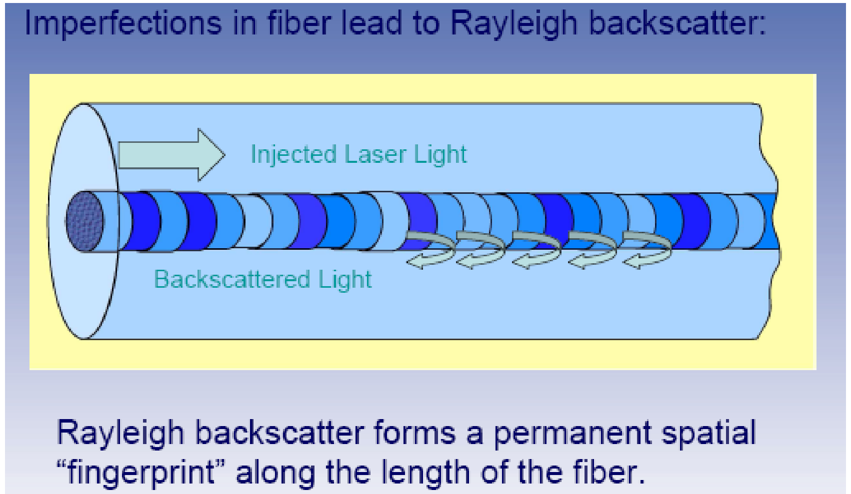
- Enable identification of wellbore integrity risks BEFORE they result in failures

Technology #1: Distributed Optical Fiber Sensors

Sensing Principle : Evanescent Wave Sensors



Distributed Sensing

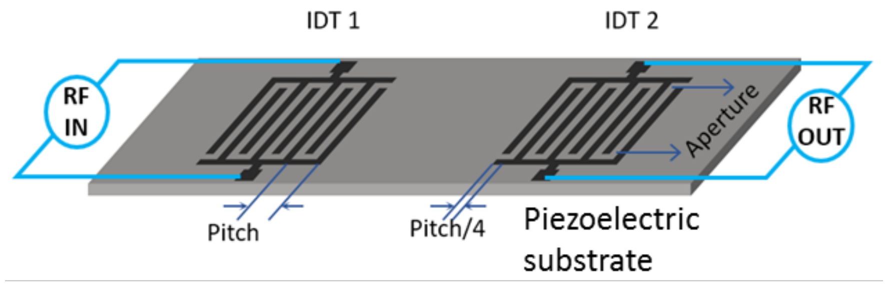


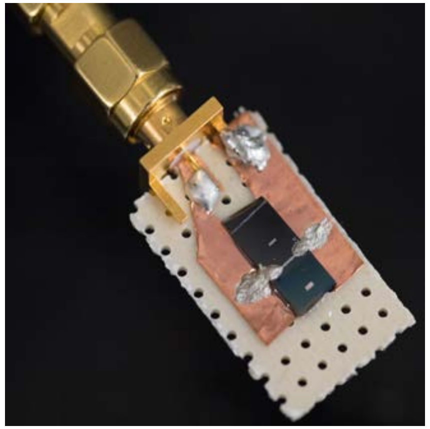
→ Eliminate Electrical Wiring and Contacts at the Sensing Location (Stability)
→ Tailored to Parameters of Interest Through Functional Materials (Functionalization)
→ Compatibility with Broadband and Distributed Interrogation (Geospatial / Multiparameter)

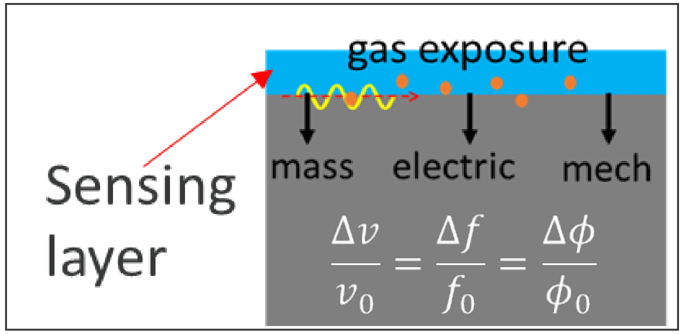
Deployment Scenario : Embedded Within Wellbore Cements and Casing Metals

Technology #2: Passive and Wireless SAW Devices

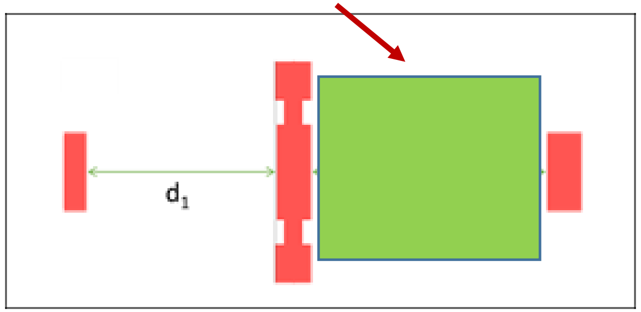
Sensing Principle : Functionalized Surface Acoustic Wave Devices







Sensing Layer

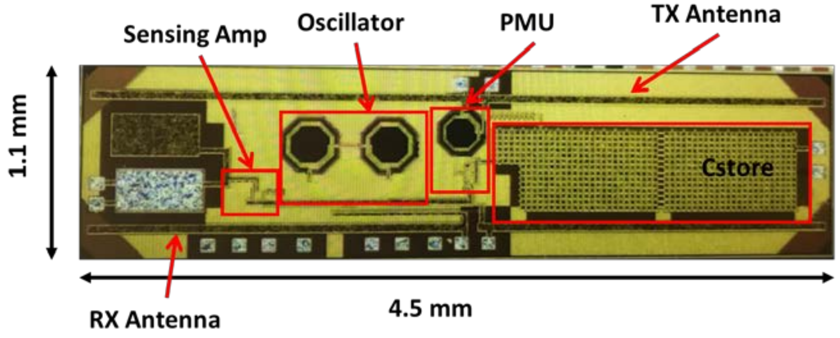


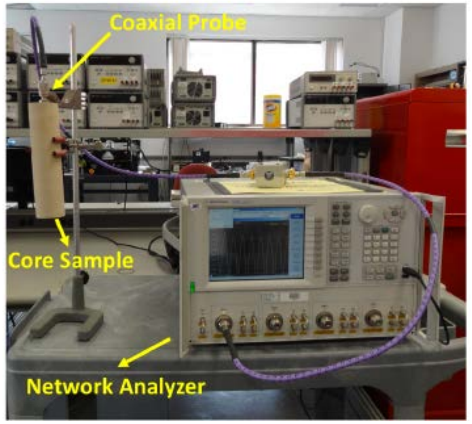
- → Passive and wireless operation
- → Rugged and stable for harsh environment applications
- → Telemetry is a primary challenge, must be addressed in parallel

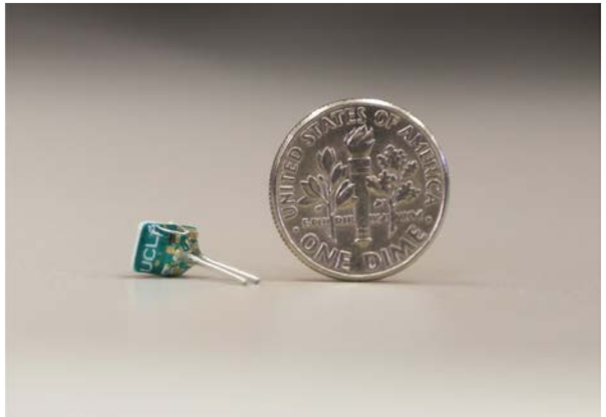
Deployment Scenario : Embedded on Interior and Exterior Casing Surfaces

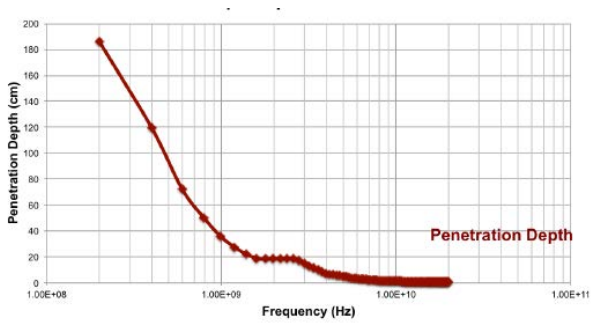
Technology #3: Wireless Miniature SiIC Devices

Sensing Principle : Functionalized Silicon Integrated Circuit Devices









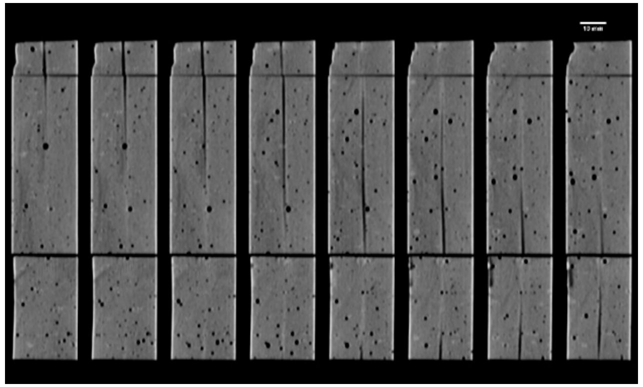
- →Miniaturized devices with active functions through IC processing
- →Wireless energy harvesting and storage to eliminate batteries
- →Telemetry is again a major challenge to be addressed

Deployment Scenario : Embedded Within the Wellbore Cements

Additional Efforts: Sensor Embedding

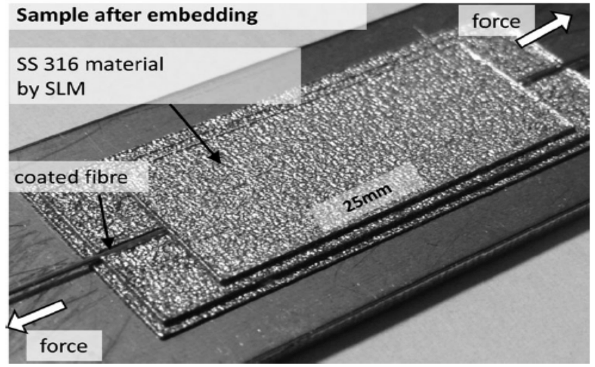
Wellbore Cements

CT Scans of Embedding



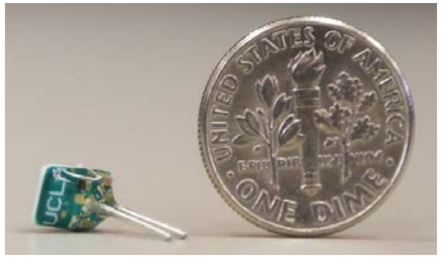
Optical Fibers

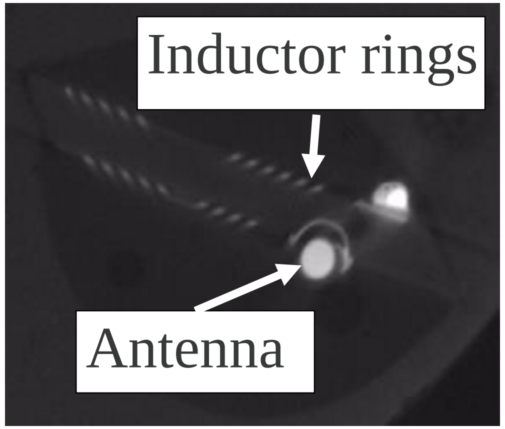
Casing Alloys

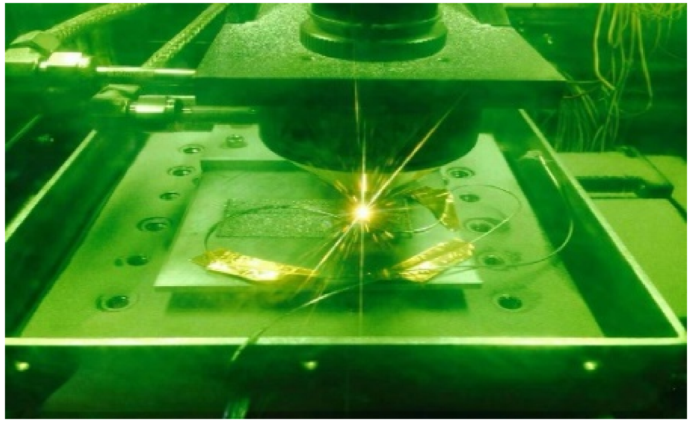


Mechanical Testing

SiIC Sensors







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

Project Structure : Tasks and Outcomes

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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 Deliverable and Outcomes

#1: New Chemical Sensing Layers for High Alkalinity / High Temp.

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

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

Project Structure : Project Timing and Status

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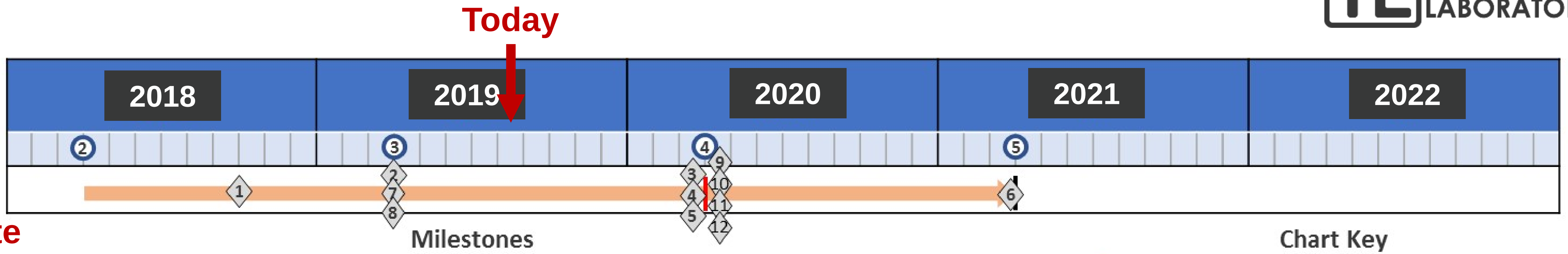


Complete

Milestones

1. Delivery of Technology Maturation Plan to FPM
2. Industry Feedback Regarding Chemical Species and Use Cases Identified as Primary Targets of R&D
3. Demonstration of Fiber Optic Sensor Coating for pH at 80C, 1atm, for 1 day with stability within 25% using self-referencing
4. Demonstration of corrosion proxy capable of early on-set detection at 80C, P=1atm
5. Demonstration of fiber optic sensor prototype with up to 4 sensing segments at ambient temperature
6. Demonstration of fiber optic sensing prototype with up to 4 sensing segments at T=80C
7. Simulation demonstrating potential for successful SAW operation in wellbore fluids
8. First Proposed SiIC Device Design Compatible with Fluid and Cement Wellbore Media Applications
9. Successful Wired SAW Device Response in Fluid Phase at ambient conditions
10. Successful Wired SiIC Device Response in Fluid Phase at ambient conditions
11. Demonstration of adequate technical performance properties of optical fiber integrated cements and casings
12. Demonstration of adequate technical performance properties of SiIC Integrated cements and casings

Chart Key

\# TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

Go / No-Go

1. Successful field deployment of the optical fiber based pH sensor for ambient pressure / temperature

Project on Track to Date

Impact

Key Accomplishments/Deliverables	Value Delivered
2018: Project initiated 4/2018. **2019**: **2020**:	• New sensing layers integrated with fiber optic, surface acoustic wave, and silicon integrated circuit devices for pH sensing • Field deployed fiber optic based pH sensor technology • Laboratory tested wireless surface acoustic wave and silicon IC pH sensors

Project Progress : Industry Advisory Group

Advisory Group Members

Invitees	Title	Expertise	Company
Igor Kosacki	Materials Engineering Manger	Sensor development	WellDiver
John Lovell	Vice President – Technology and Strategy	Temperature and pressure measurement systems, Wellhead asphaltenes sensor	MiscroSilicon Inc.
George Koperna	Vice President	CO_2 EOR and storage, reservoir engineering	Advanced Resources International, Inc.
Charles Gorecki	Directory of Subsurface R&D	EOR, CO_2 storage	Energy & Environmental Research Center
Pierre Ramondenc	Well Intervention Domain Manager	Coiled tubing well interventions, real-time fiber-optics	Schlumberger
Laura Nofziger	Senior Vice President and Managing Director	Geothermal Power Plant operations and maintenance	AltaRock Services, LLC
Tim Ong	Principal Strategy – Technology & Innovation	Strategy planning-technology and innovation	BHP Billiton
Dennis Dria	Petroleum Technology Advisor	Fiber-optic technology development and implementation	Myden Energy Consulting, PLLC
Austin Vonder Hoya	Senior Advisor	Geophysical technology	Pioneer Natural Resources USA

Key Practical Challenges Discussed

1) Potential Deployment Strategies for Fibers in Wellbore Cements
2) Wireless Telemetry Methods in Subsurface Environments
3) Elevated Temperatures / Pressures During Cement Hydration
4) Fiber Darkening in Subsurface
5) Vibration and Shock Tests of Sensors

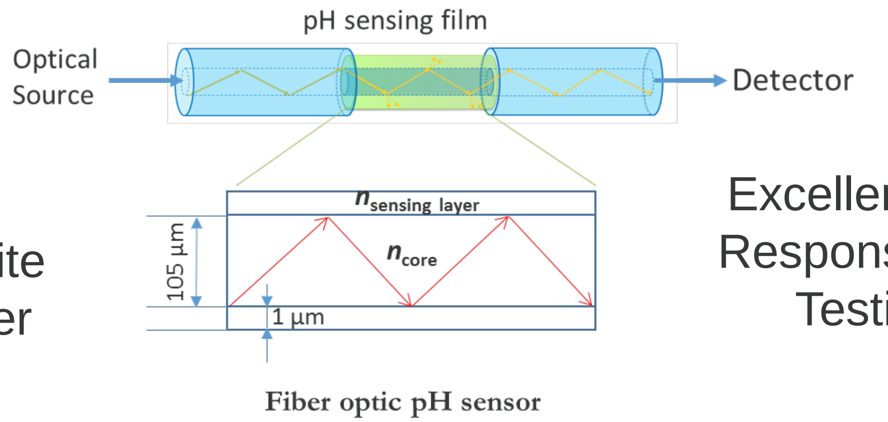
Ranking of Geochemical Parameters to Be Monitored

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+}

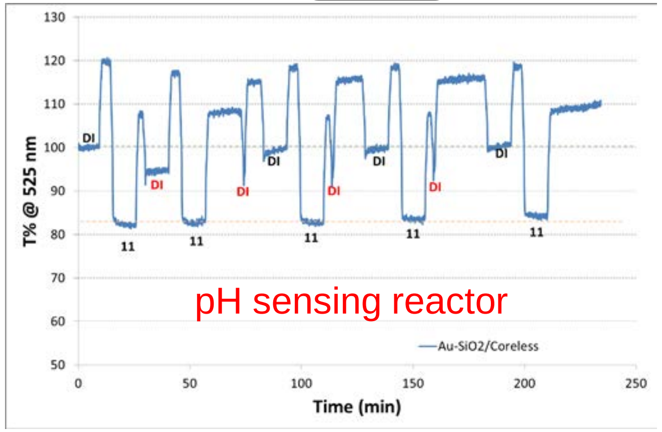
Regular Meetings Have Occurred with the Industry Advisory Group to Provide Feedback and Guide Technology Maturation Plans for the Overall Project.

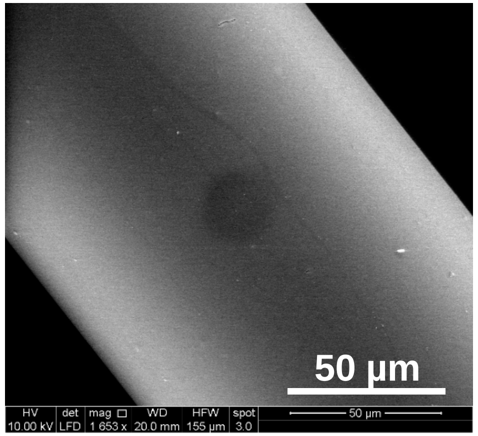
Project Progress : Chemical Sensing Layers

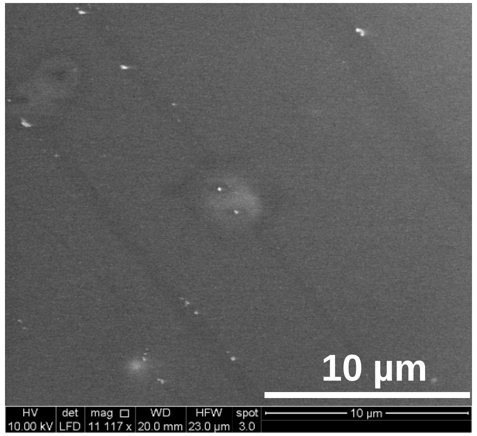
Au / SiO_2 Nanocomposite Sensing Layer

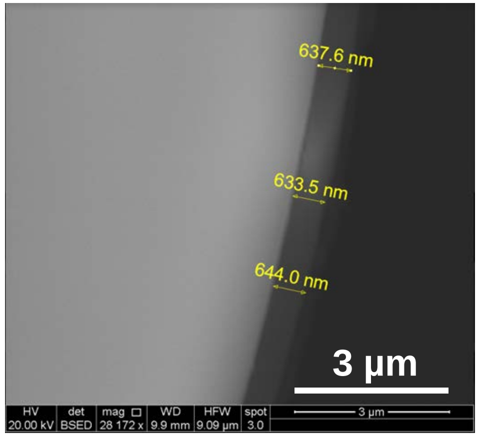


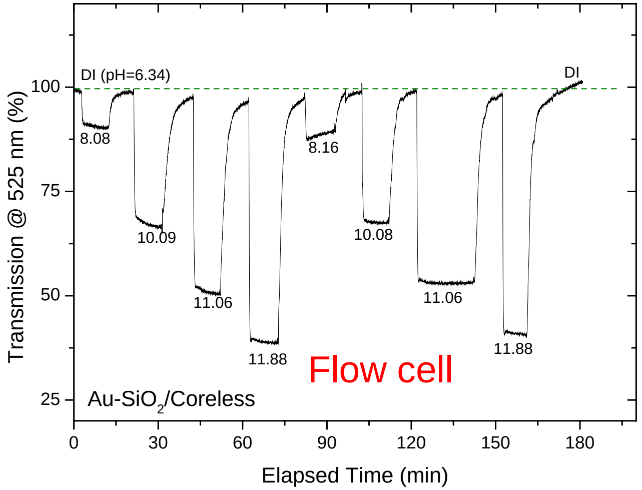
Excellent Alkaline Range Response Under Ambient Testing Conditions





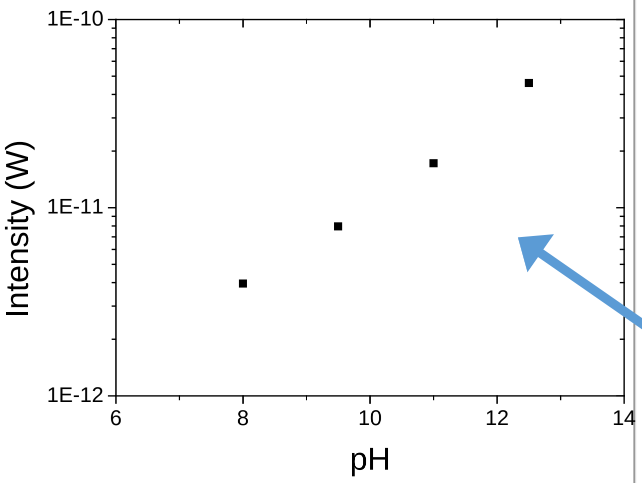


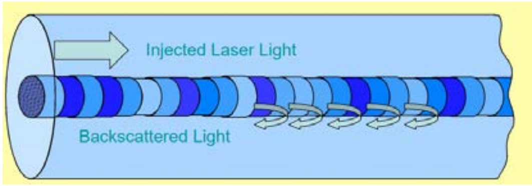




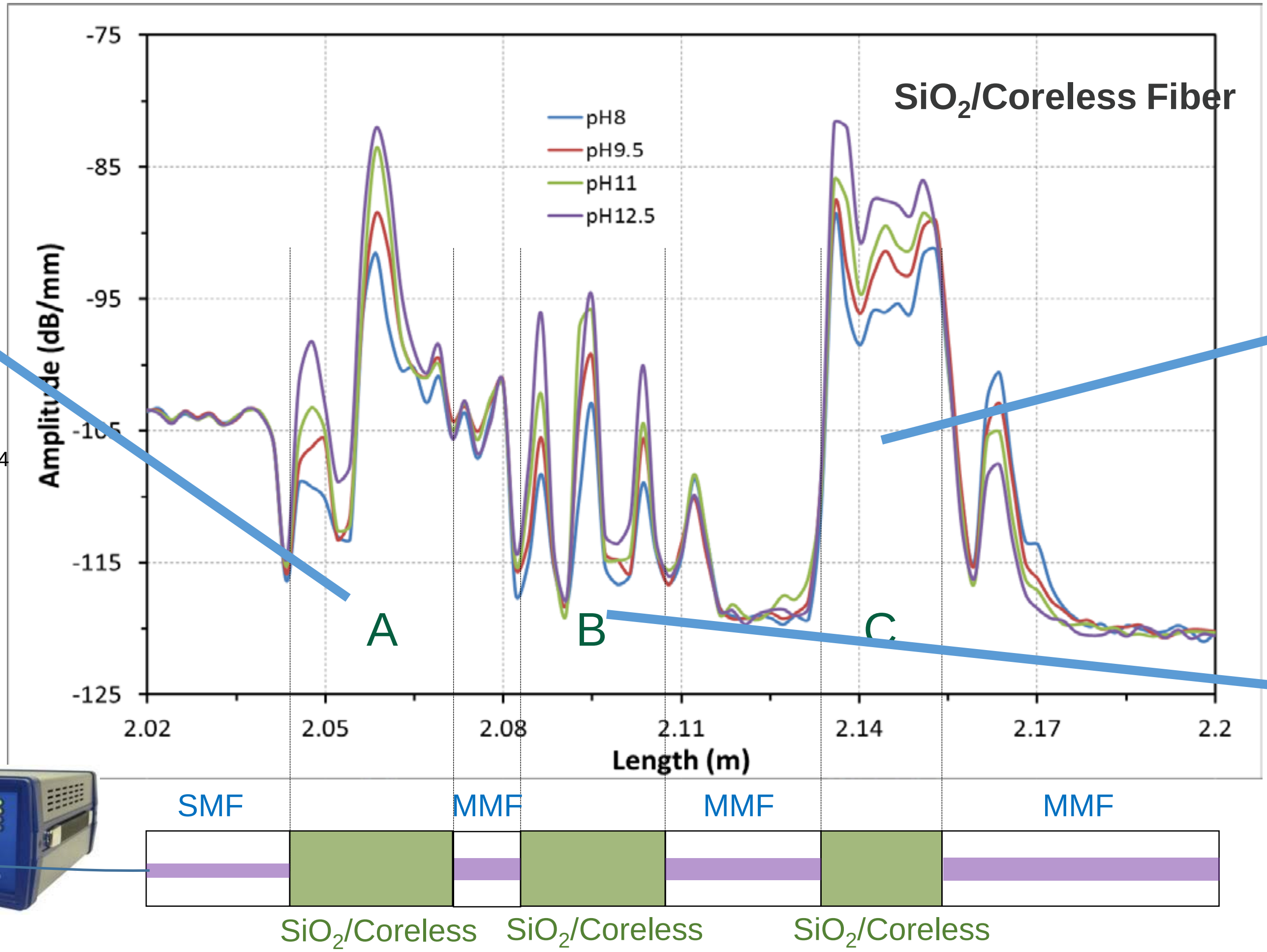
Silica and Au / Silica Films Have Been Developed and Demonstrated for pH Sensing Under High Alkalinity Environments.

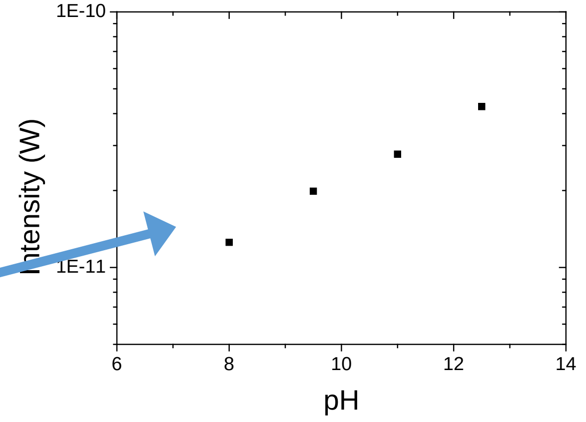
Project Progress : Chemical Sensing Layers

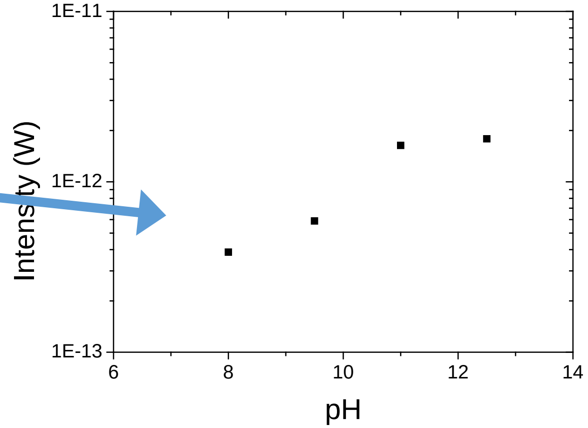




Luna Optical Backscatter Reflectometer (OBR)



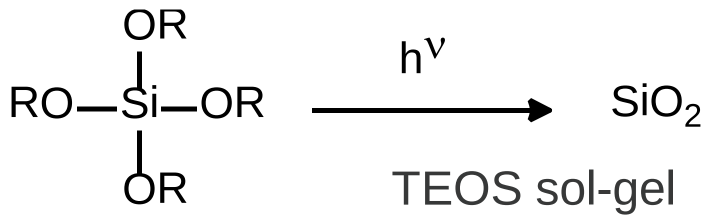




Silica and Au / Silica Films Films Have Been Used to Demonstrate Multi-Point Distributed pH Sensing .

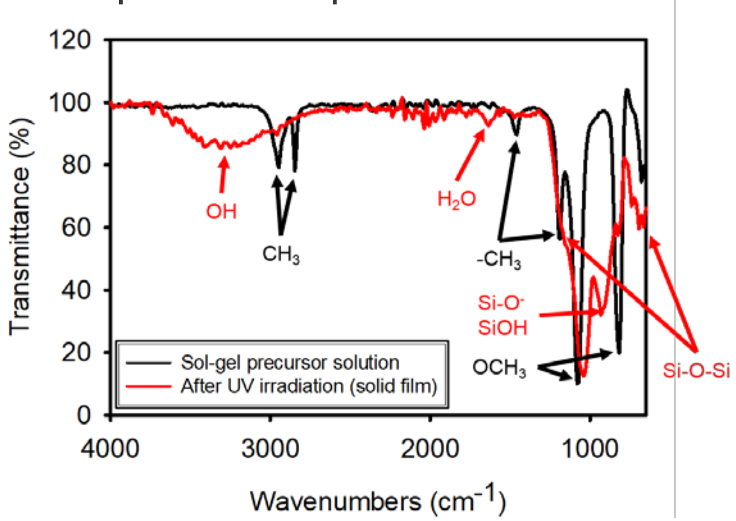
Project Progress : Sensing Layer Scale-Up

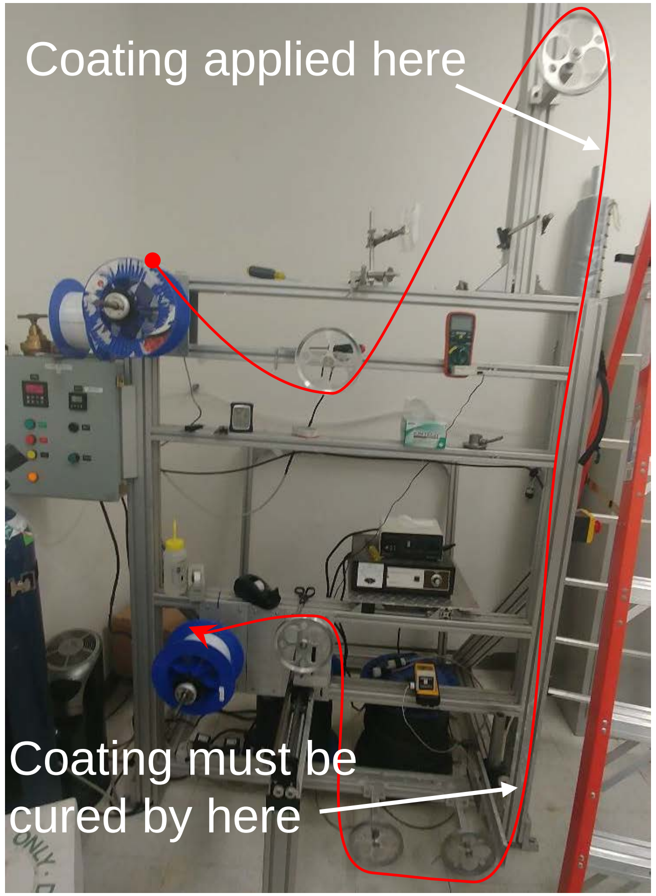
- Challenge:
  - Rapidly cure a coating in time for fiber to travel from top to bottom of rig
  - TEOS-based pH coating curing time NOT compatible with reel-to-reel coating
- Strategy: Fast Photocuring
  - Photocured hydrogels is well developed
  - Photocuring of TEOS sol-gels is being developed



- We have demonstrated production of films in the range of tens of seconds
- Calcination can be performed as a second step
- We are evaluating fiber coating protocols

IR Spectrum of photocured TEOS





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

Project Progress : Chemical Sensing Layers

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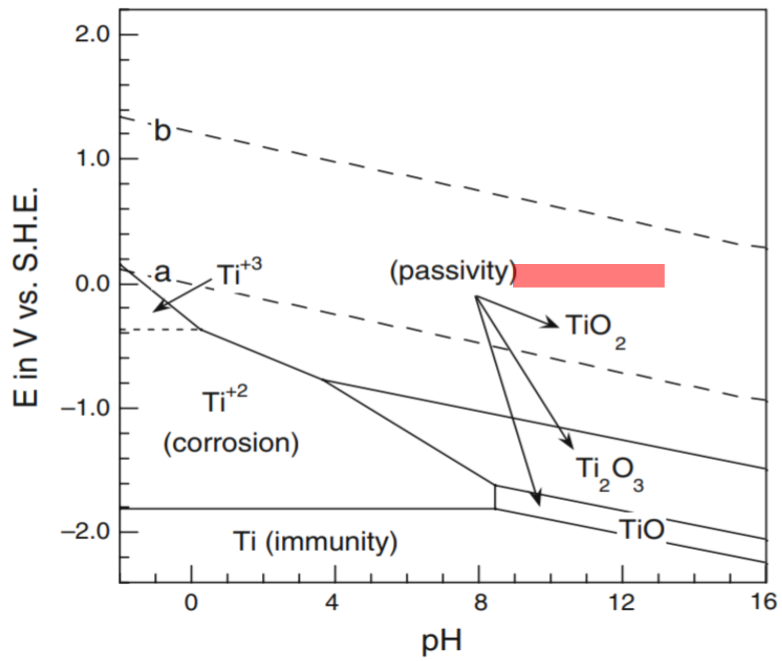
Oxides *	pH_{pzc}	Refractive index (550nm)	Refractive index (1530nm)	pH range of passivity	Melting point
TiO_2	3.9-8.2	2.6479	2.4538	0- to 14+	~2000 °C
ZrO_2	4-11	2.1661	2.1107	4 to 13	~2700 °C
α-Al_2O_3	8-9	1.7704	1.7465		~2000 °C
Ta_2O_5	2.7-3.0	2.1411	2.0580	0- to 14+	~1500 °C
NiO	9.9-11.3		2.1818	5-14+	~1950 °C
MgO	9.8-12.7	1.7405	1.7149	9-14+	~2800°C

* Incorporation with Au nanoparticles are also investigated



Alternative Oxide Based Sensing Layers are Being Explored for Maximum Stability in Elevated Temperature and High Alkalinity Environments.

Project Progress : Chemical Sensing Layers

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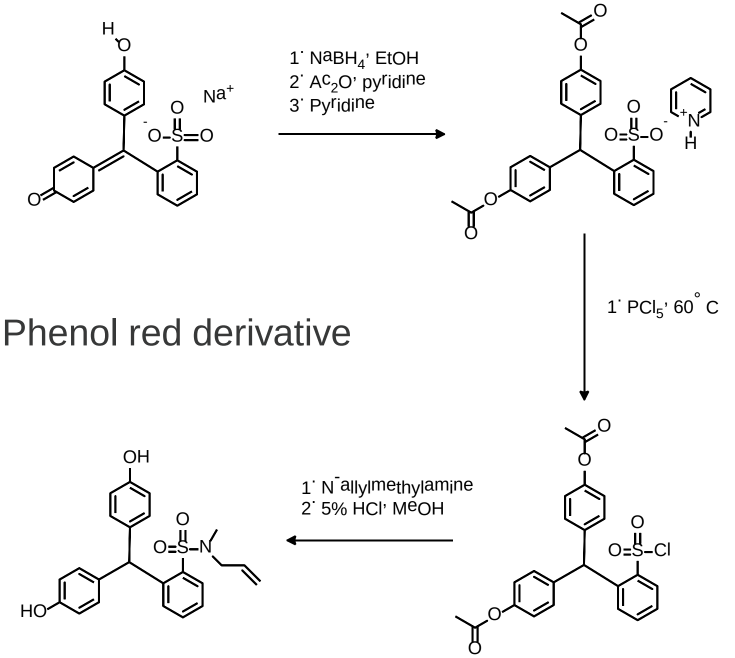
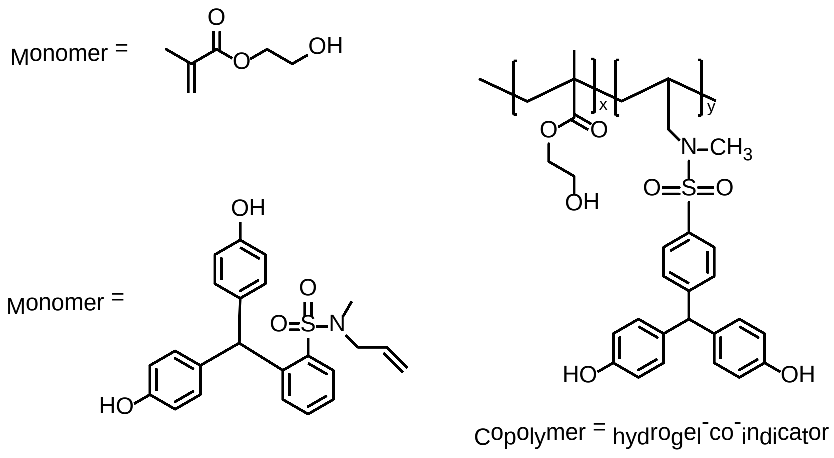
Phenol Red: Indicator functionalization follow by copolymerization with hydrogel matrix

- Phenol red has moderate pKa but synthetic strategy similar to our desired approach has been published for this indicator, and it exhibits a structure similar to that of indicator dyes successfully synthesized in our lab.



Desired Phenol red derivative



Target Organic Sensitive Coating for pH Monitoring

Polymers with pH Indicators are Also Being Explored and Developed for High Temperature and High Alkalinity Environments Relevant for Wellbore Cements.

Project Progress : Packaging Development

Challenge:

- Sensorized fibers must be robust and not break when spooled, unspooled, or embedded in cement
- Sensors must be exposed to environment

Perforated Fiber Jacket: Protection of the fiber optic sensor with a standard polymer jacket perforated with microholes for water permeation

Status:

- Optimized fabrication process
- Evaluated mechanical properties
- Investigated fiber integration into cement
- Evaluating coating protocols after jacket perforation

Permeable Fiber Jacket: Protection of the fiber optic sensor with a polymer that allows water and ion permeation

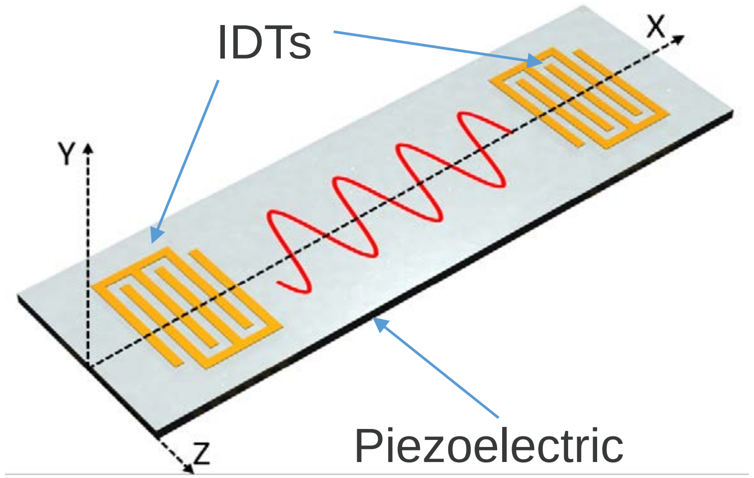
Status:

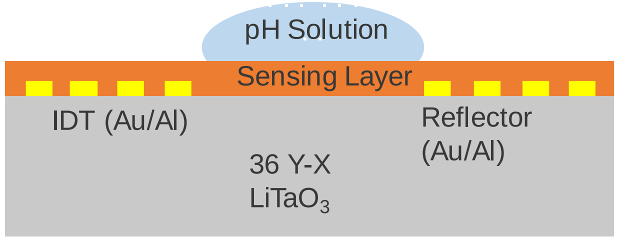
- Polymer selected

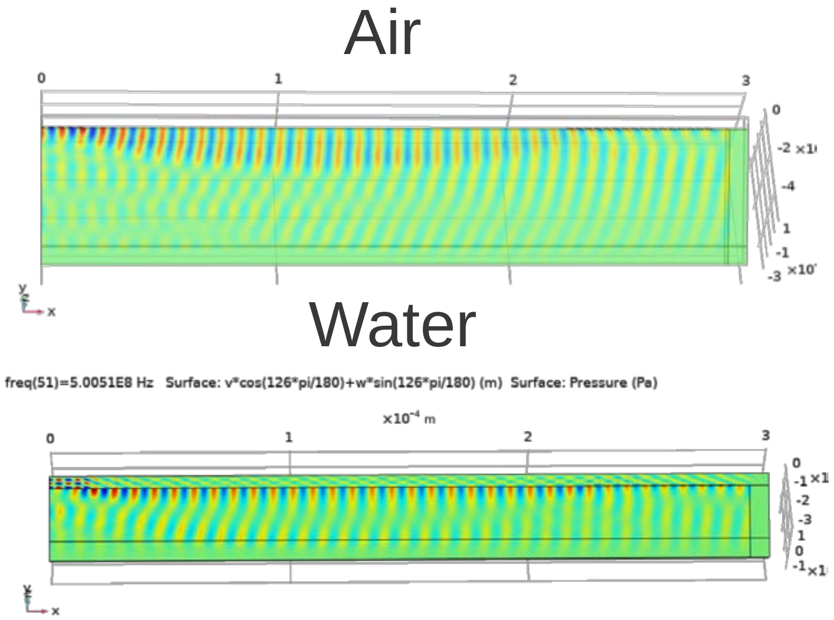
Various Techniques are Being Explored for Development of Packaging That is Compatible with Installation within Wellbore Cements for Chemical Monitoring.

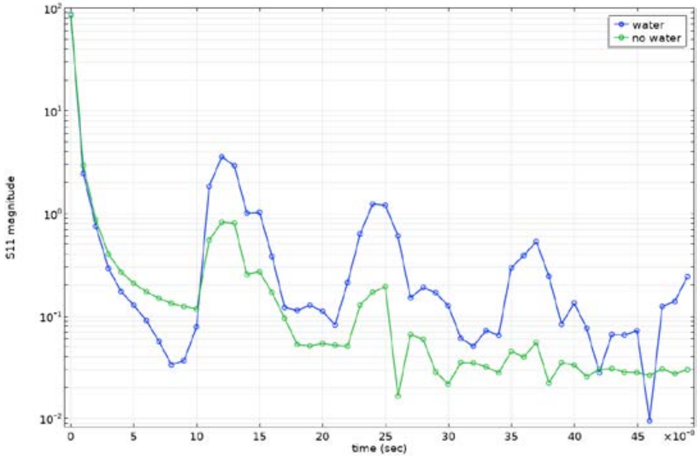
Project Progress : SAW Device Modeling

Shear Horizontal
Surface Acoustic Waves







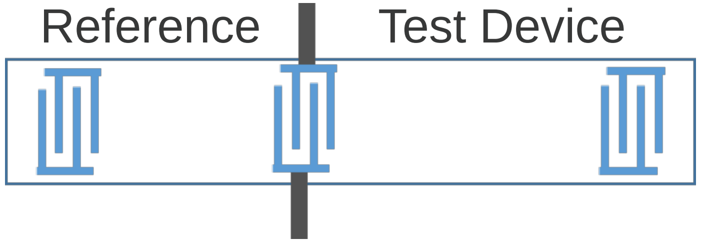


Reflector (IDT type) Reflectivity for air and water above the SH-SAW.

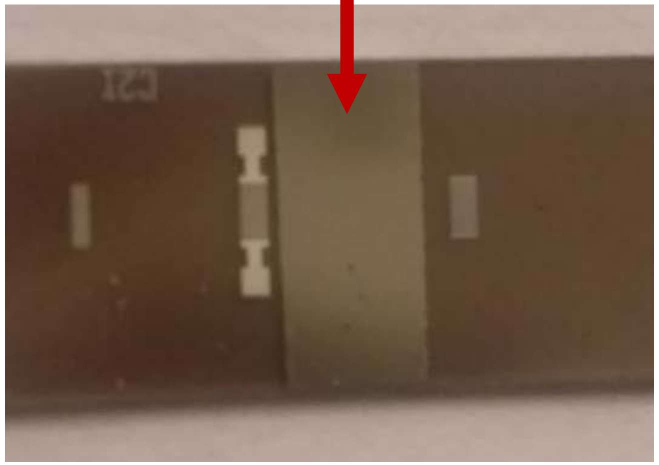
Early Efforts on SAW Device Modeling Demonstrated Proof of Concept for Aqueous Phase Operation and Identified Value in Metallization of Delay Path.

Project Progress : SAW Device Fabrication / Test

Reference Test Device

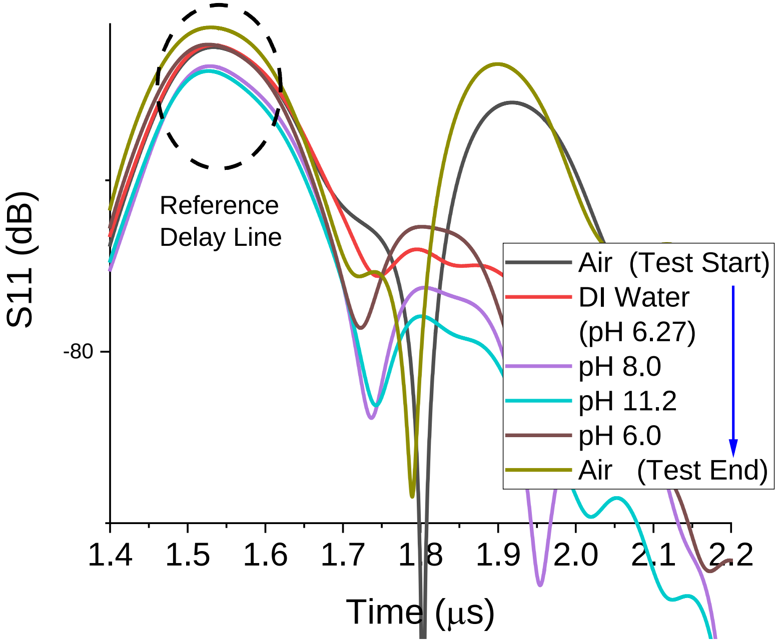


Fe Thin Film Layer



Substrate: 36 Y-X $LiTaO_3$

f_0 = 520 MHz; IDT: Al, 120 nm thick

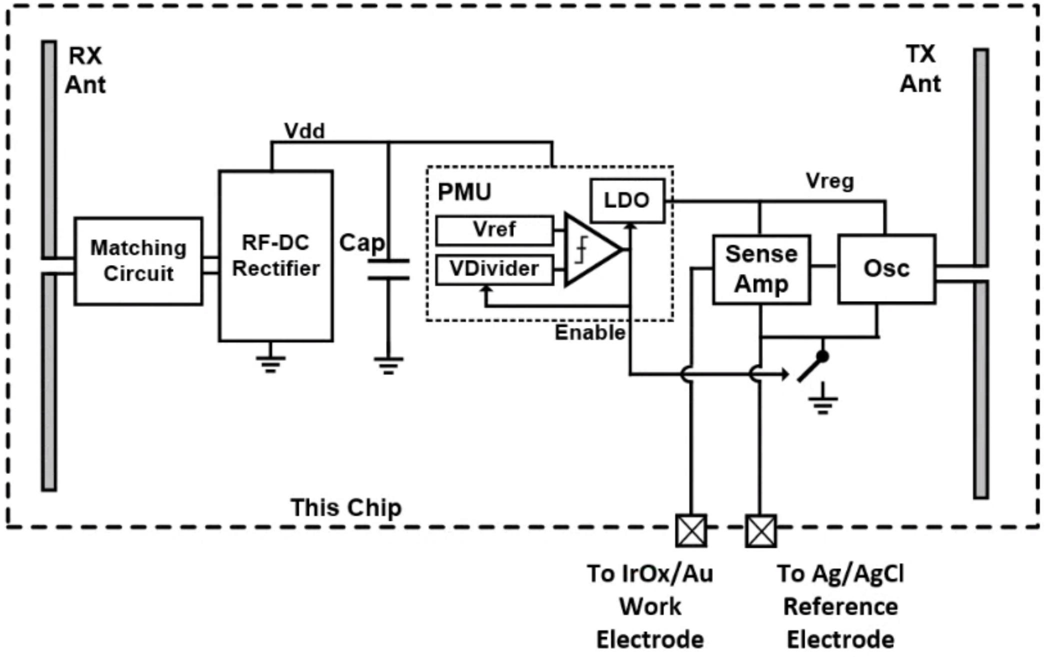


Bare device responds to pH to some extent.
Sensing layers will be applied to improve sensitivity.

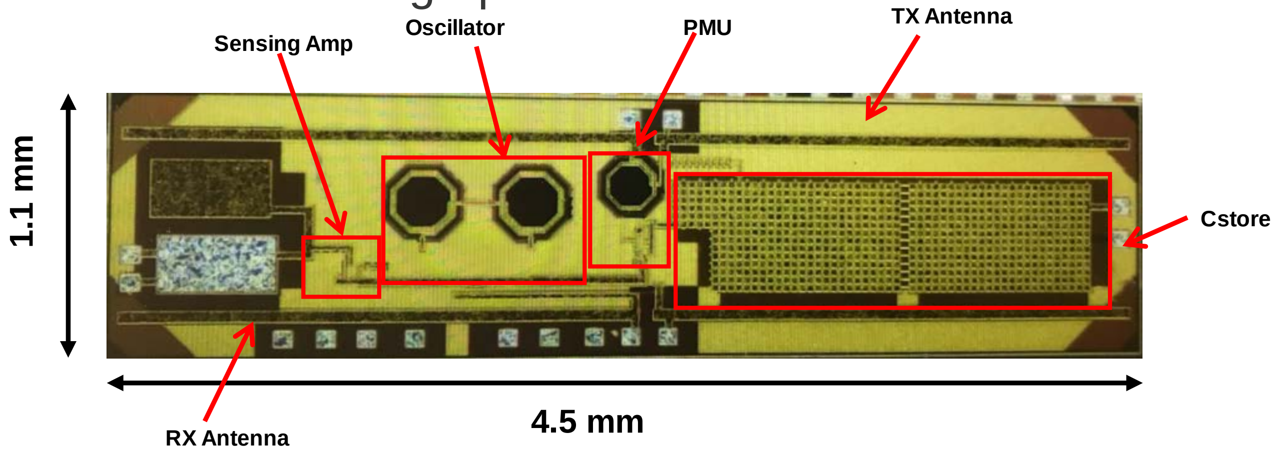
SAW Devices Have Been Successfully Fabricated and Show Stable Operation in the Context of Aqueous Phase Environments with Initial pH Sensing Underway.

Project Progress : SiIC Device Fabrication / Design

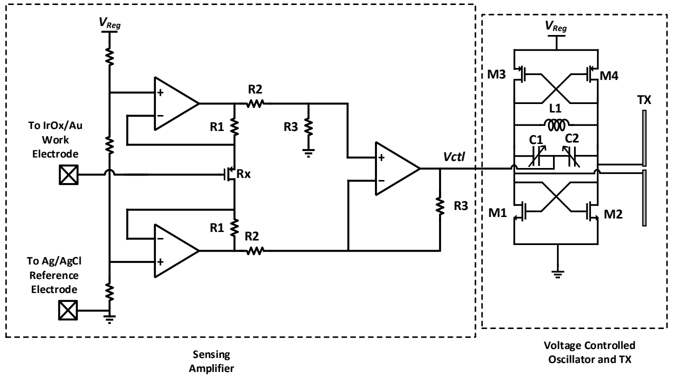
Circuit Architecture of Latest pH Sensor Designs



Latest Device Micrograph



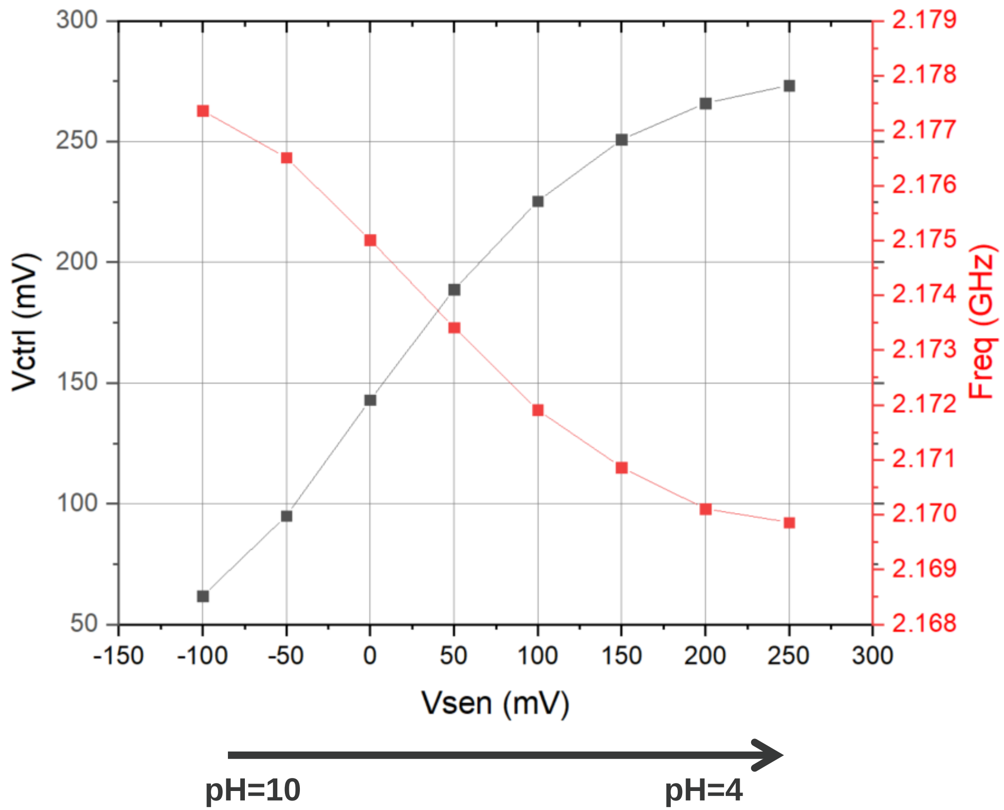
Sensing Amplifier and Voltage Controlled Oscillator

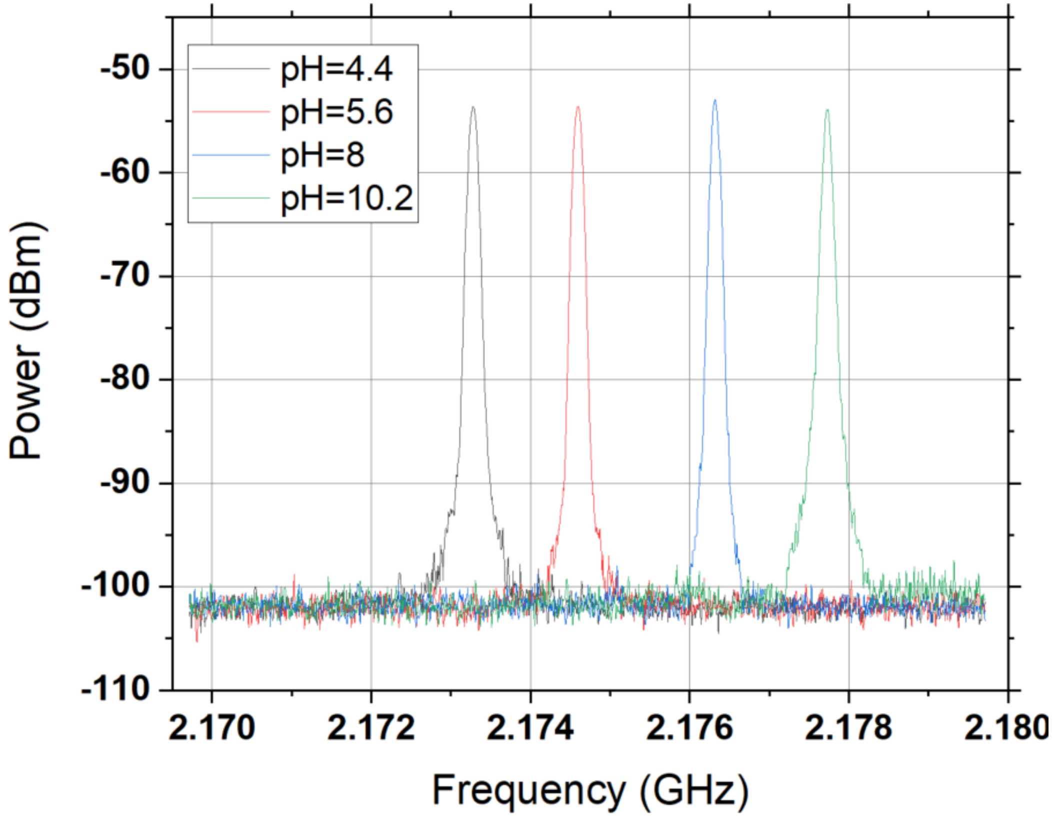


Several Rounds of Design / Fabrication Enabled Successful Device Operation Including the Integration of Sensing Layer Electrodes for pH Functionalization.

Project Progress : SiIC Device Early pH Sensing

Control Voltage and Oscillator Frequency vs. Sense Voltage





Initial Proof of Concept pH Wireless Device Sensing Responses Have Been Demonstrated with Standard Reference Electrodes, Miniaturization in Progress.

Project Progress : Wireless Telemetry Concepts

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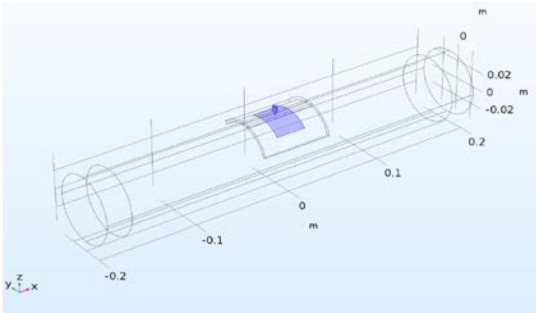
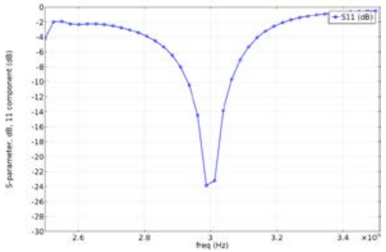
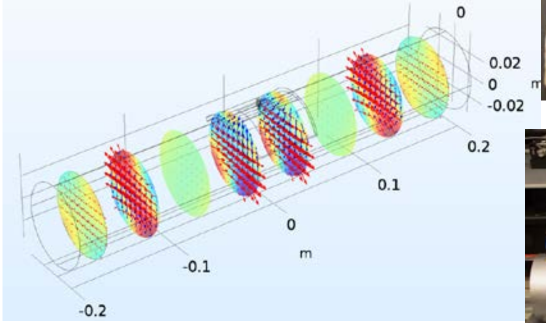
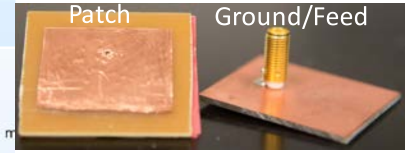
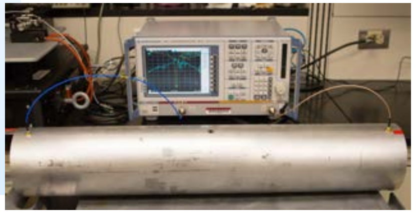




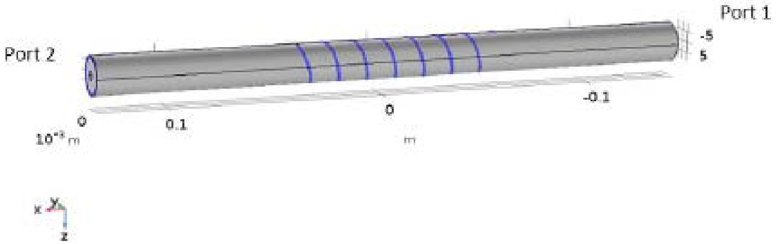


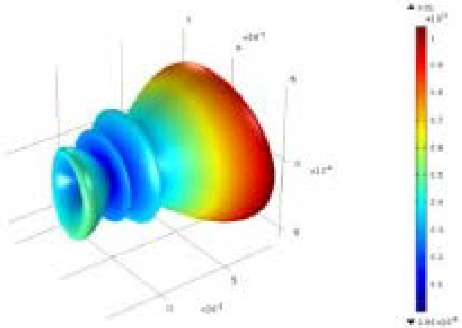


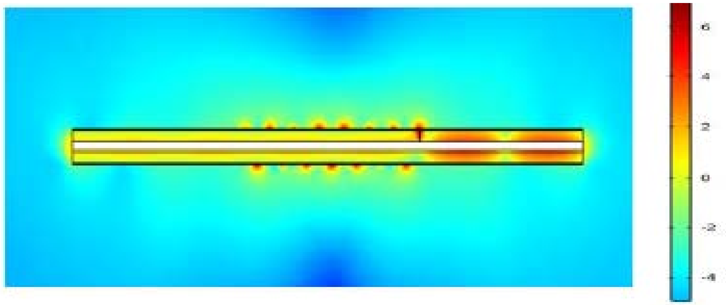


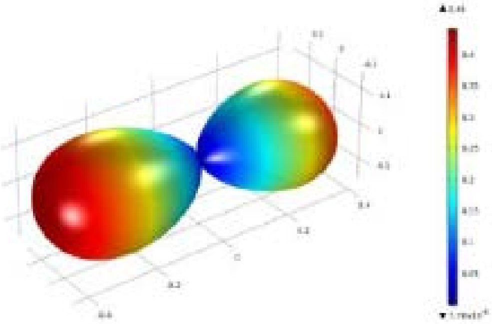
RF signal launching and propagation in metallic tubular structures with waveguiding

New Concepts in Distributed EM Interrogation Techniques With Antenna Designs









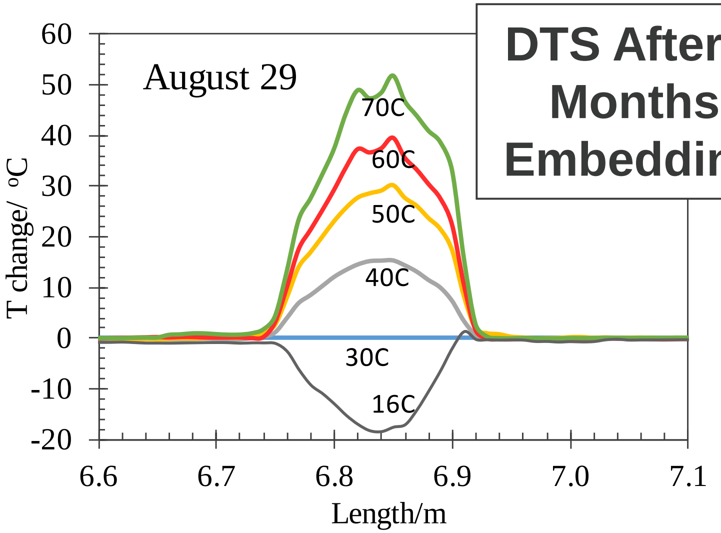
Wireless Telemetry Methods are Being Explored for Compatibility with Applications in Subsurface Media Including Novel Antennae Designs.

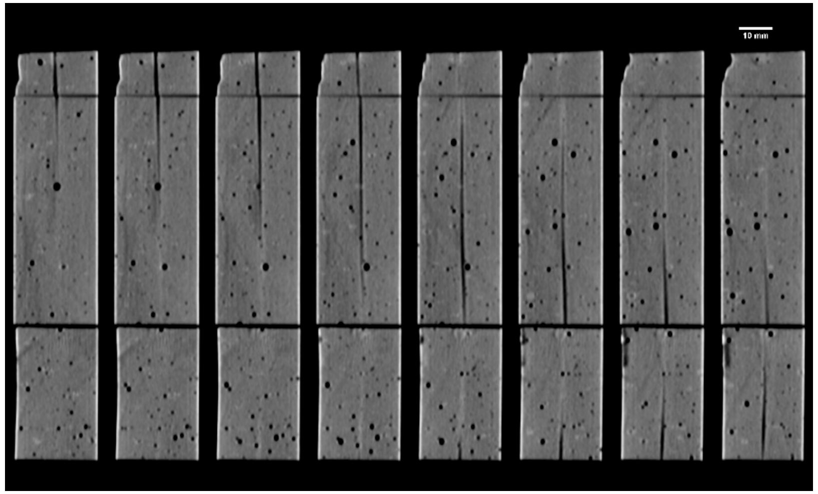
Project Progress : Sensor Embedding in Cements

Optical Fiber embedded in cement

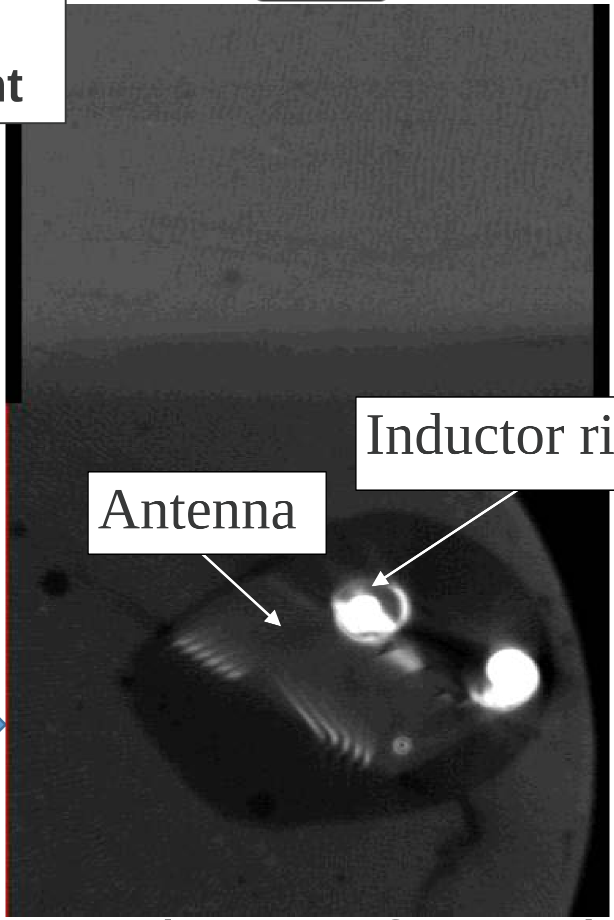
SIlC chip (5-7mm) embedded in cement

DTS After 2 Months Embedding





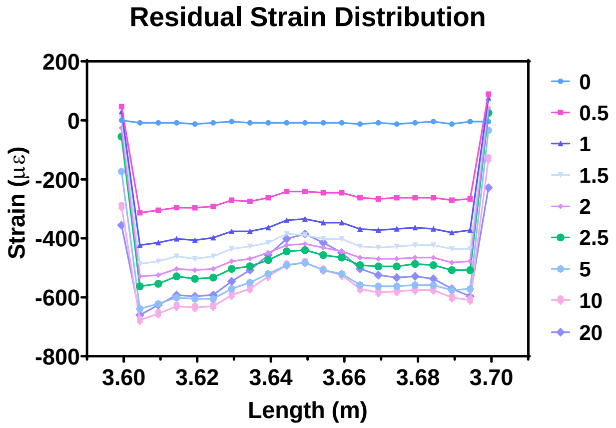
Video

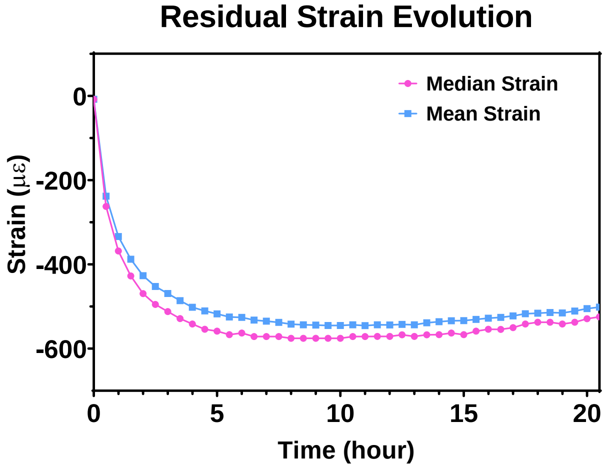


CT Scanning and Property Performance Measurements are Being Performed to Understand Structural / Chemical Impacts of Cements After Sensor Embedding.

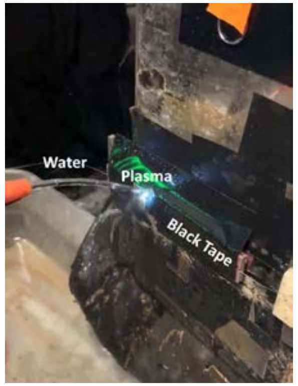
Project Progress : Sensor Embedding in Casing

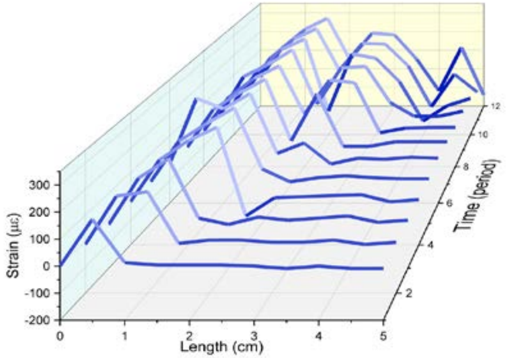
Embedded Fibers in Curved Parts





Shot Peening to Reduce Residual Strain

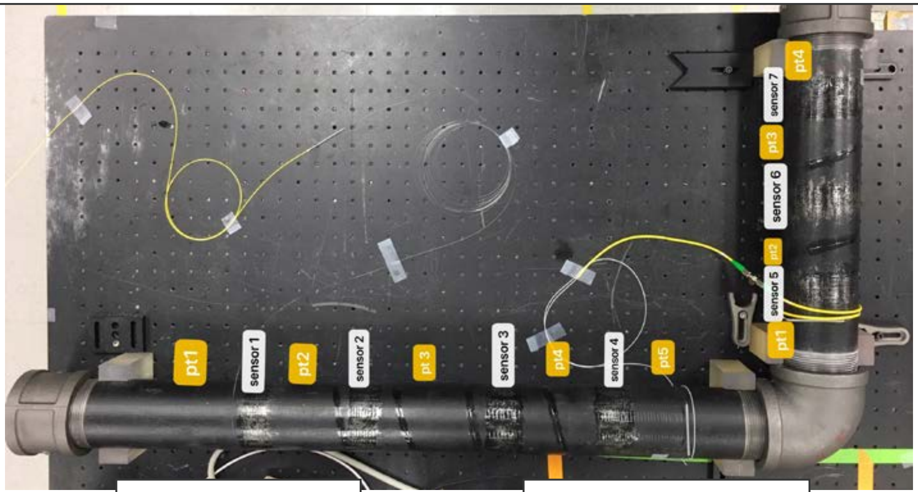




Additive Manufacturing Methods are Being Explored for Integration of Optical Fibers Into Curved Parts with Minimized Residual Strains Such as Casings.

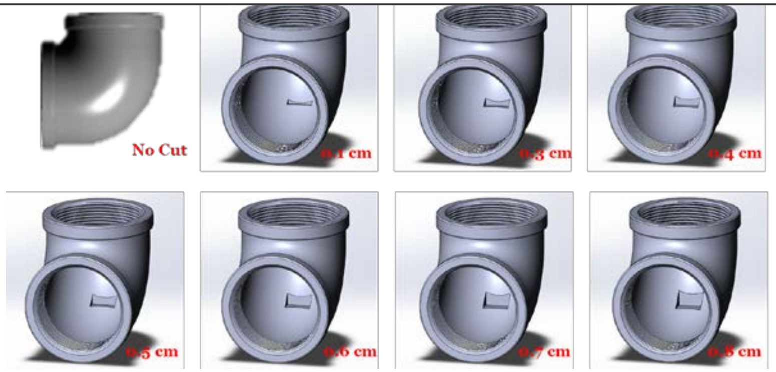
Project Progress : AI-Enhanced Optical Fiber Sensing

Defect Distribution in Metallic Structures

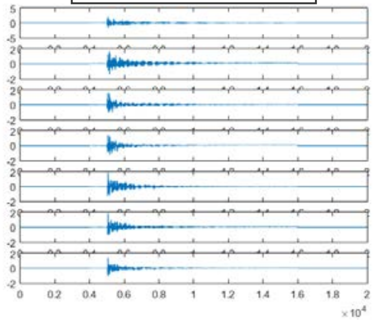


- Seven acoustic sensors
- Defects on elbow
- Various defect sizes
- Acoustic sensors detection / classification

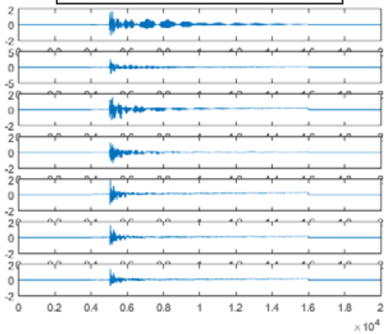
Various Types of Defects to Classify



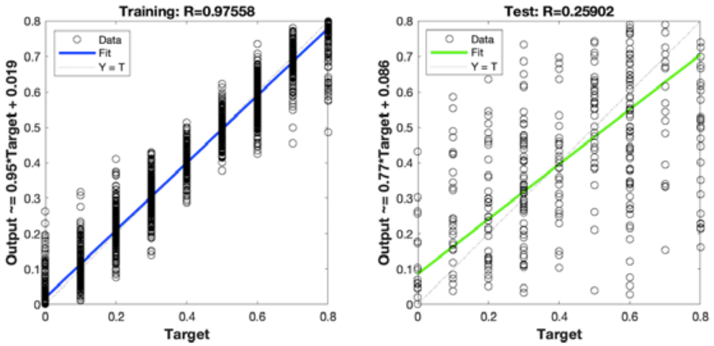
Normal



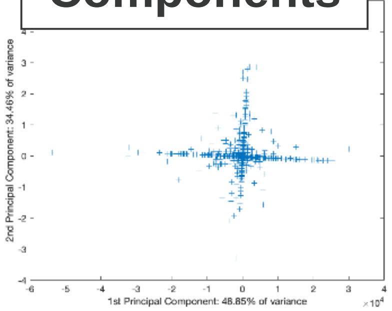
Defective



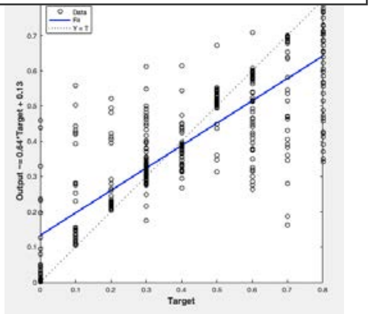
Linear Regression



Principle Components



Shallow Neural Network



Efforts are Underway to Prepare for 2nd Year Field Testing Which Serves to Help Prepare for More Extensive Field Testing in the 3rd Year of the Project.

Project Summary : Successes and Next Steps

Project Successes to Date

- Successful design, fabrication, and testing of SiIC wireless pH sensors
- Demonstrated aqueous phase sensing of novel SAW devices
- First demonstration of distributed pH sensing using optical fiber platform
- Novel concepts in wireless subsurface telemetry methods
- AI-enhanced distributed optical fiber sensing for defect identification

Next Steps

- Miniaturization of pH sensor electrodes for wireless SiIC sensing
- Integration of pH sensing layers with wireless SAW sensors
- First field deployment for cement embedded fiber optic pH sensors
- Demonstrated wireless interrogation of SiIC devices embedded in cement