Fully Distributed Acoustic and Magnetic Field Monitoring via a Single Fiber Line for Optimized Production of Unconventional Resource Plays

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U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

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Project Overview (1-2 Slides)

- Goals and Objectives: Develop a fiber-optic sensing system capable of real-time simultaneous and distributed magnetic field and acoustic measurements via a single sensing fiber
- Benefits: Provide operators with a tool with unprecedented sensing density for high resolution subsurface imaging
- DOE Funding: $1,500,000 Cost Share:$375,000
- Project Duration: 10/1/2019 – 9/30/2023
- Project Participants: Virginia Tech, Sentek Instrument

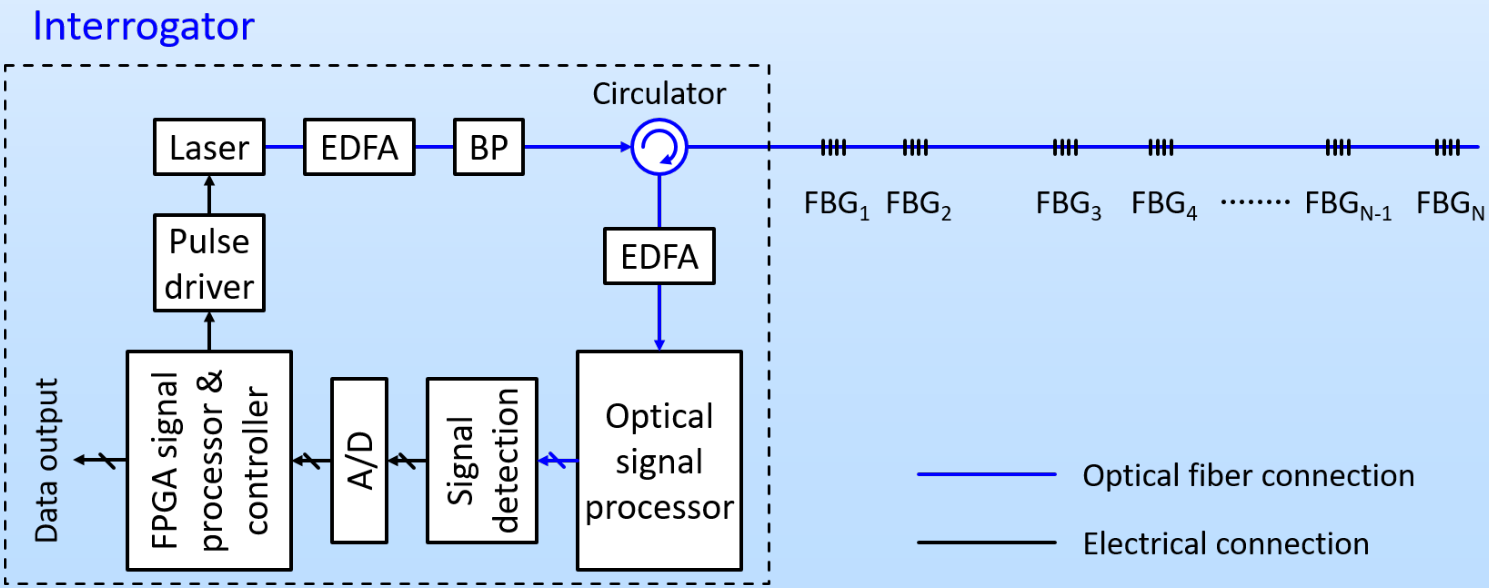
Technology Background

- Describe how the technology is envisioned to work in operation, including a simple schematic labeled with preferred operating conditions (e.g., pressures and temperatures), and any other requirements

Technical Approach

picoDAS™ Fiber Optic Sensing Technology

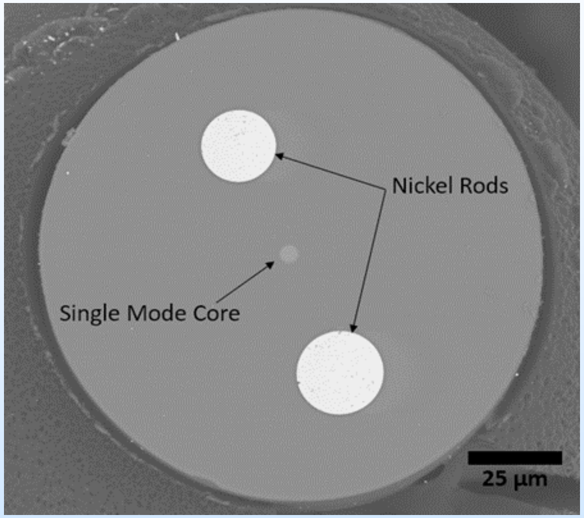
- Relies on an elegant marriage between a special type of FBG device and a time-division-multiplexing (TDM) signal processing scheme
- Superior performance
  - 100 times more sensitive than traditional DAS systems
  - Uniform sensitivity distribution across entire sensing range
  - Capable of multi-parameter measurements.

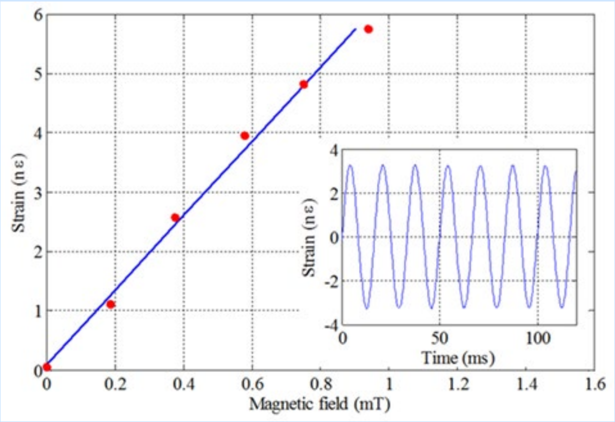


Research Approach

Multi-Material Magnetic Sensing Fiber

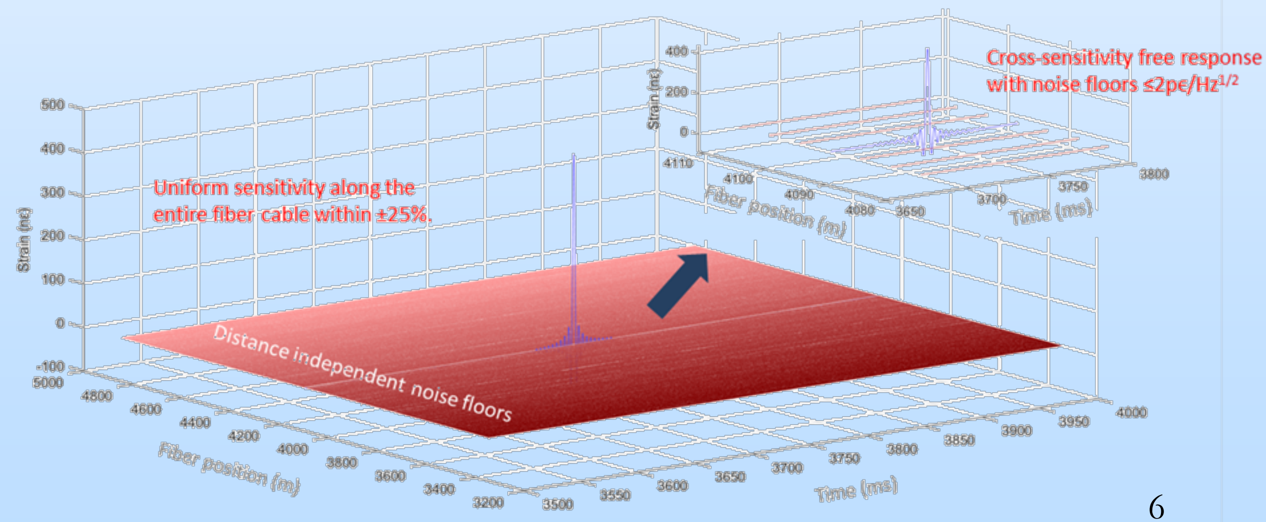
- Single mode optical fiber core with a magnetostrictive material in the cladding
  - The magnetostrictive material expands or contracts upon exposure to a magnetic field causing fiber vibration which is sensed via the FBG based interferometers
  - Stack-and-draw technique utilized to incorporate dissimilar materials in the fiber via optical fiber draw
- Magnetostrictive materials
  - Metglas 2605®, Nickel, Cobalt
- Other sensing schemes require bonding of the magnetostrictive material to the fiber, including it in the coating, and/or utilizing other post-processing schemes
  - Challenges related to reliability and performance





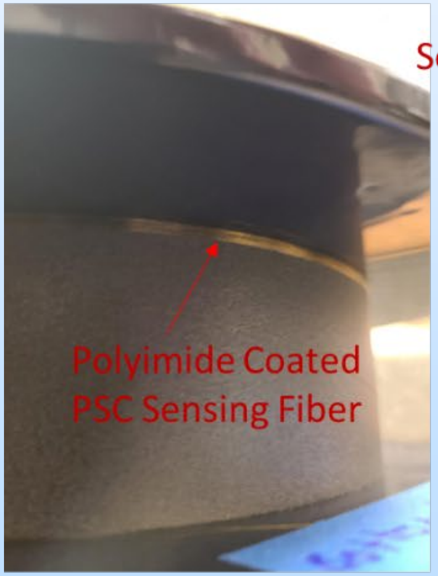
Distributed Acoustic Sensing

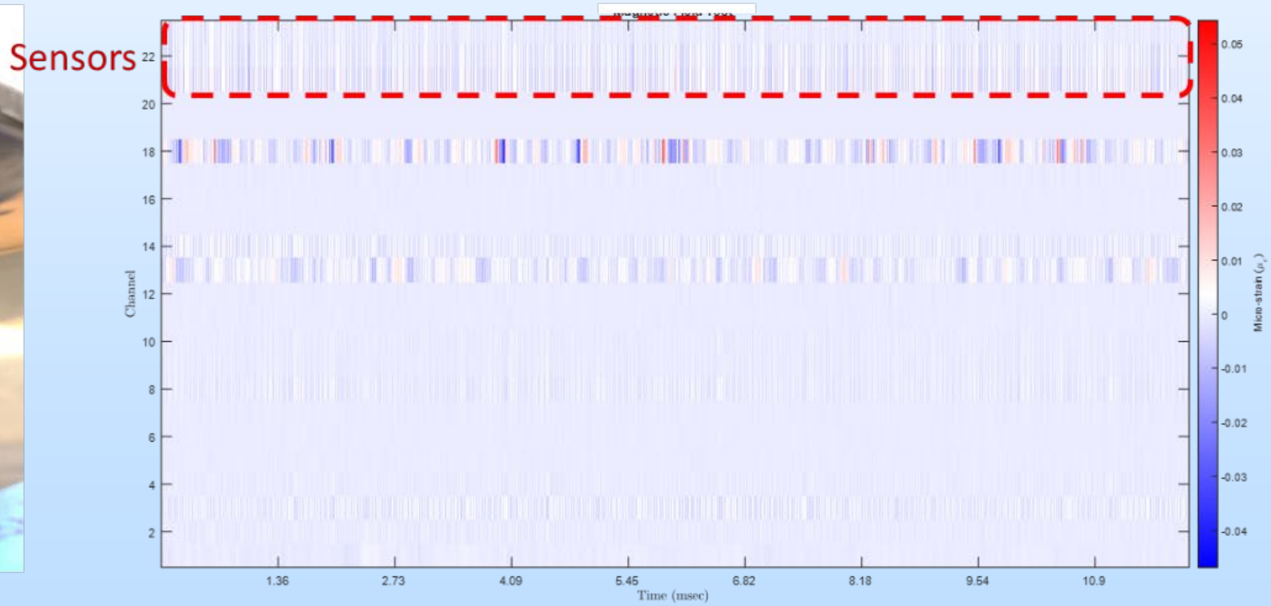
- Systematically tested and evaluated Sentek picoDAS systems
  - Demonstrated measurement resolution of 0.2 nanostrain as defined by 3σ
  - Demonstrated spatial resolutions of 2 m and 5 m
- Successfully met milestones/success criteria
- Excellent partnership between VT and Sentek
  - Systems always available for testing
  - Sentek has and continues to fabricate sensors for testing



High Temperature/Hydrogen Tolerant Acoustic Sensing

- Successfully demonstrated the ability to fabricate sensors in polyimide coated pure silica core optical fiber
  - "DrakaElite^{TM} Fluorine-doped Super RadHard single mode fiber
  - Sensors with 2 meter gauge length interrogated with Sentek picoDAS system

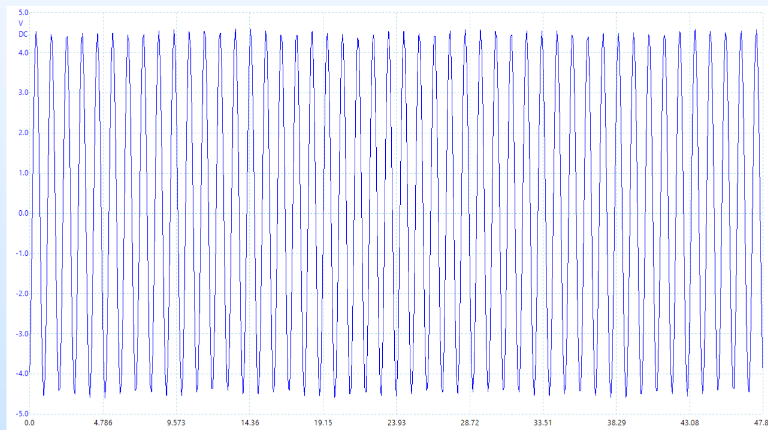




Magnetic Field Sensing

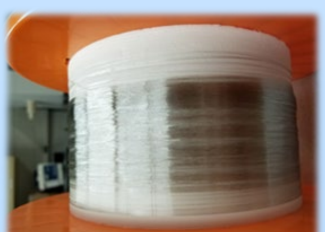
- Routinely demonstrate magnetic field measurements on one sensing fiber
  - Sensors fibers with nickel, cobalt, Galfenol, Metglas™, Permalloy cladding wires
  - Response demonstrated in transverse and longitudinal magnetic fields

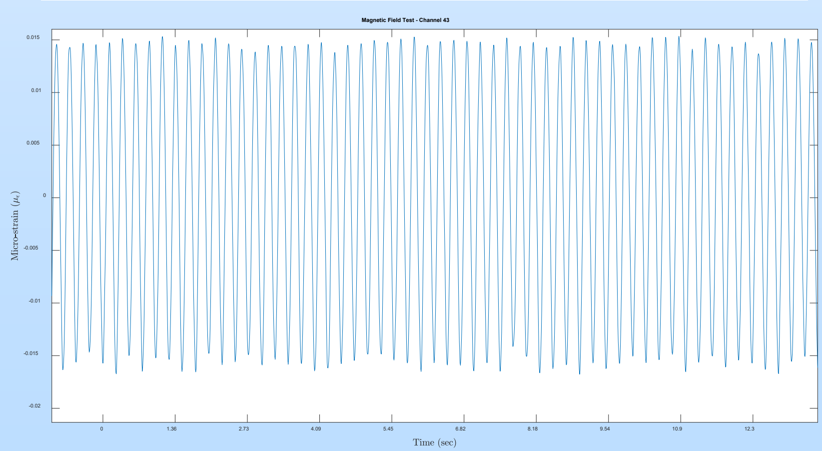
B-dot AC Magnetic Sensor (Reference)



~430 μT
1 kHz

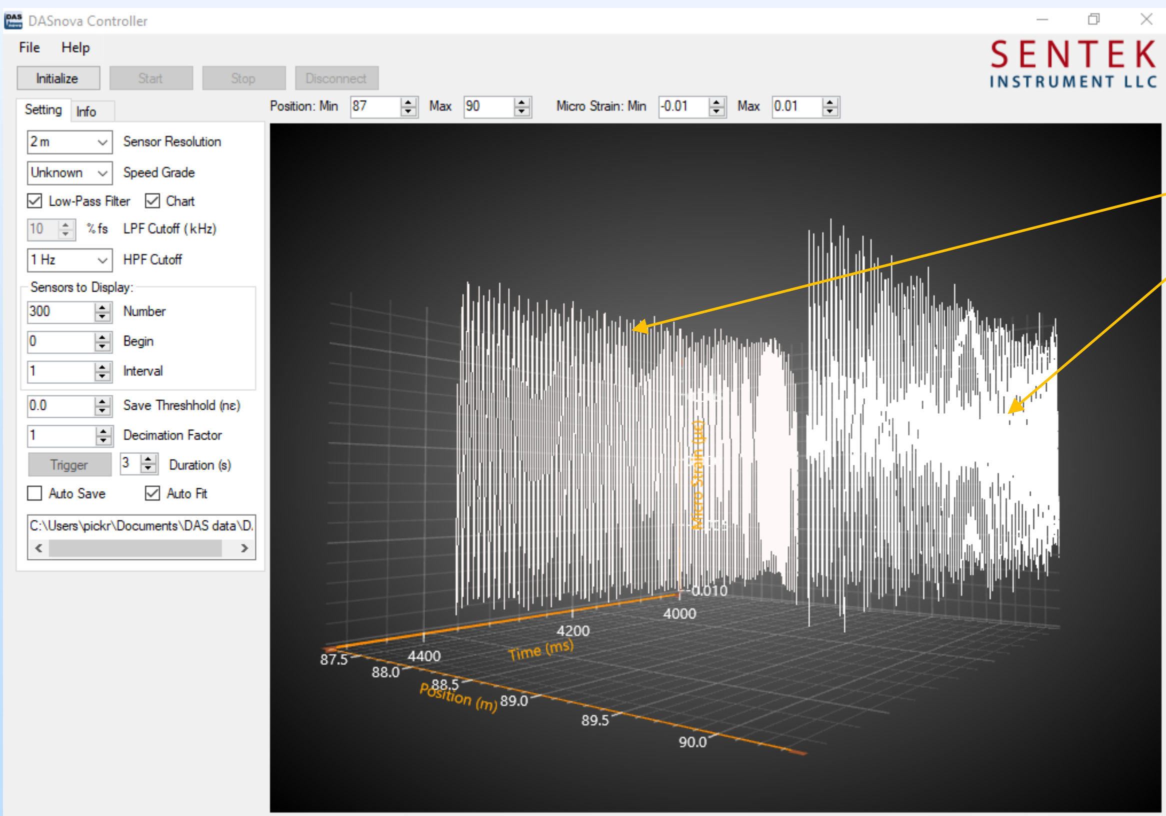
Magnetic Sensing Fiber (2Ni)





Distributed Magnetic Field Sensing

- Demonstrated multiple magnetic field measurements on one sensing fiber
  - Sensors inscribed in optical fiber with Metglas™ cladding wires
  - Performance testing in air-core solenoid



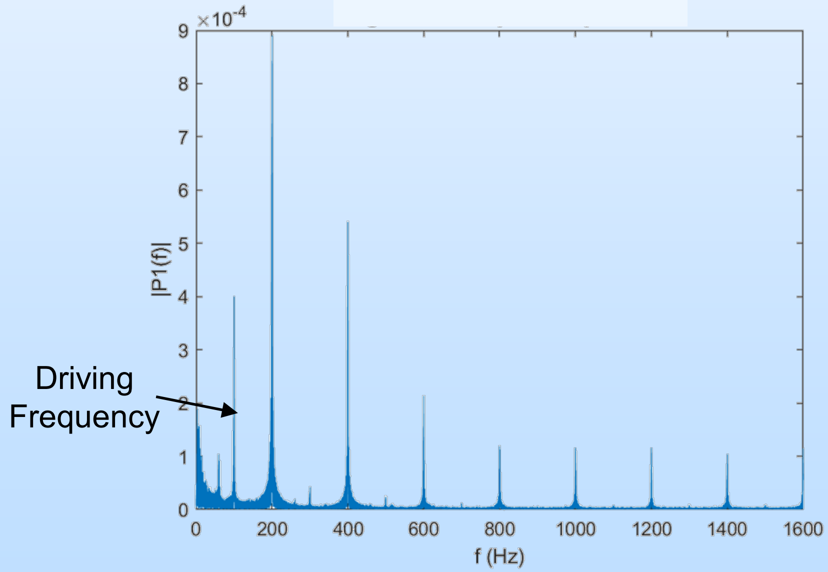
Magnetic Sensing Fiber

~620 µT
1 kHz

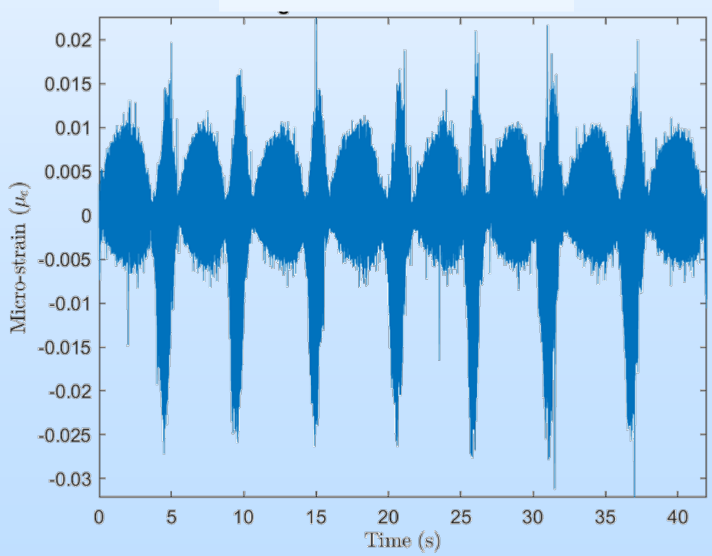
Complex Sensor Response

- Complex magnetic field sensor response will provide opportunities for enhanced function and material/process optimization
  - Driving frequency, frequency doubling, harmonics, resonance
  - Polarization control via magnetic field exposure

High Magnetic Field Sensor Response

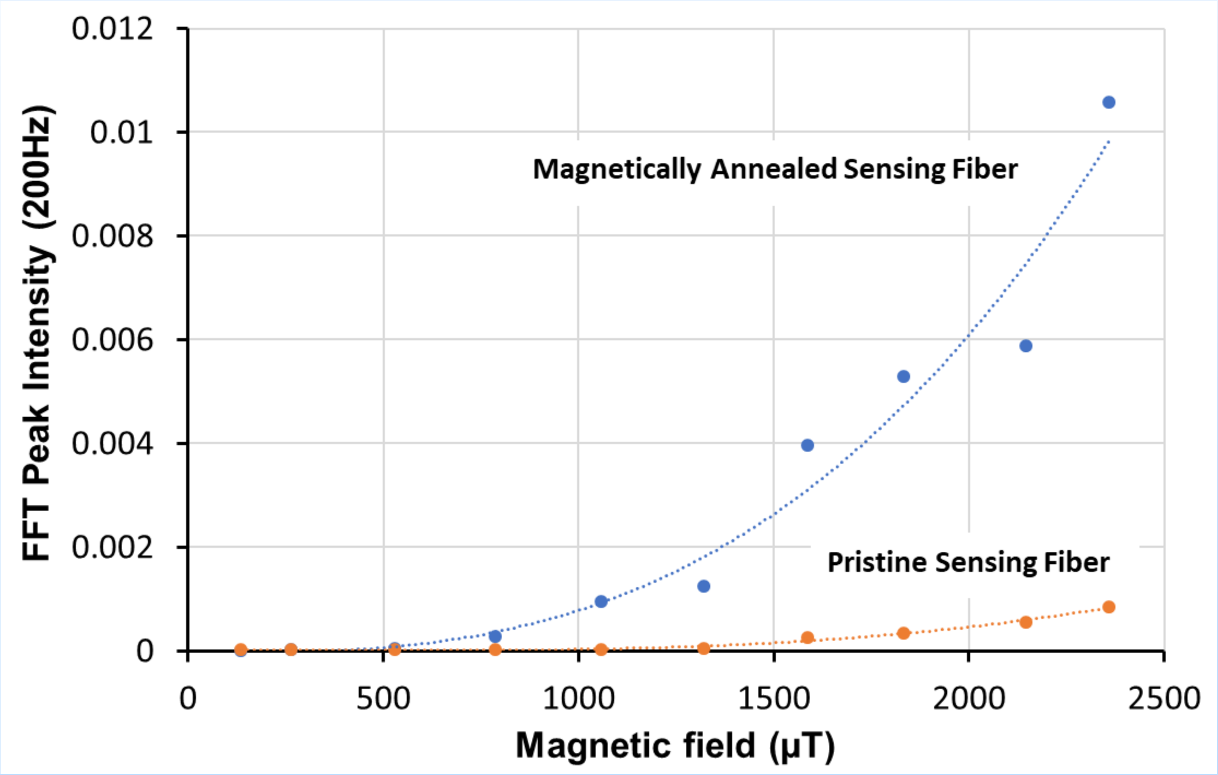


Magnetically Induced Polarization Effects



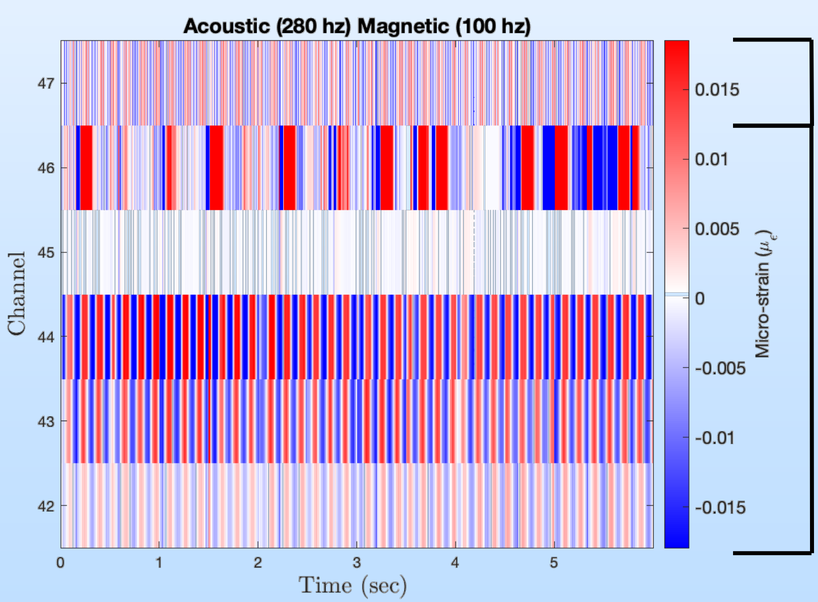
Enhanced Magnetic Field Sensing

- Demonstrated order of magnitude improvement in sensor response
- Magnetic annealing at elevated temperatures ($\sim 300℃ - 400℃$)
  - Readily scale-able for sensor manufacture polyimide coated sensing fibers
- Plan to demonstrated nano/pico Tesla sensitivity



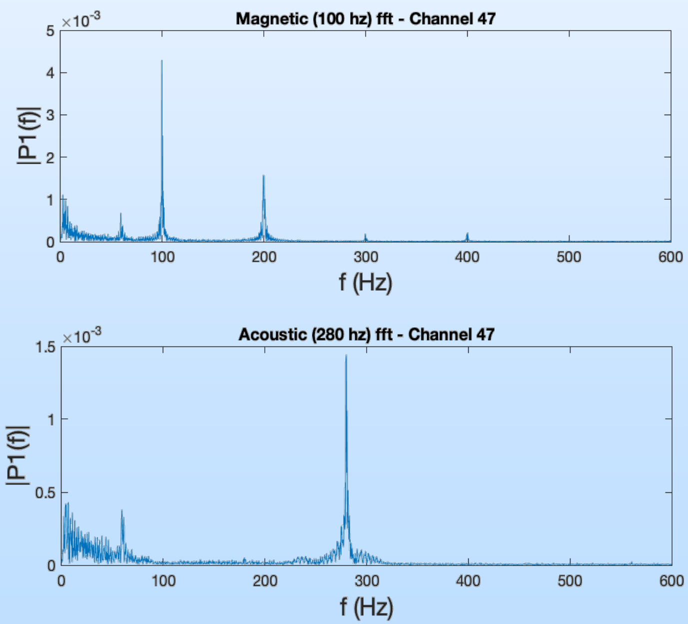
Signal Separation

- Independent Component Analysis (ICA)
  - Efficiently and automatically determine which separated signals correspond to the same individual source signal
  - Post-processing of array coherence



Magnetic sensing fiber

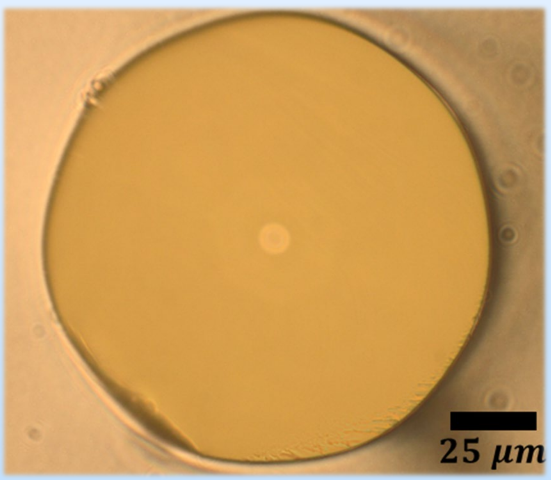
Acoustic sensing fiber



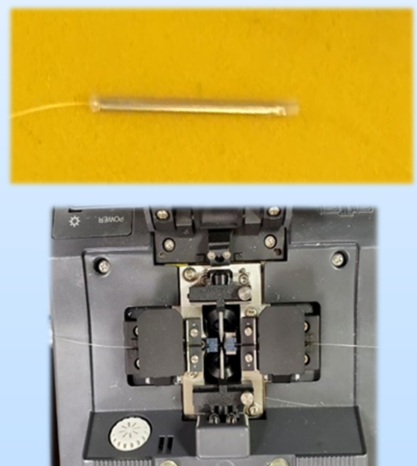
Field Deployable Magnetic Sensors

- Successfully developed sensing fibers with nano-nickel cladding wires
  - Readily splice-able to commercial single mode fiber (SMF-28)
  - “Visually” undistinguishable from traditional optical fibers

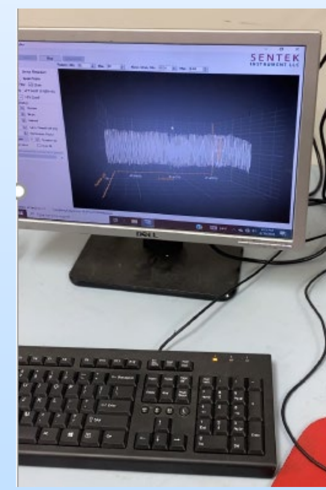
Nano-Cladding Wires



Spliced to SMF28

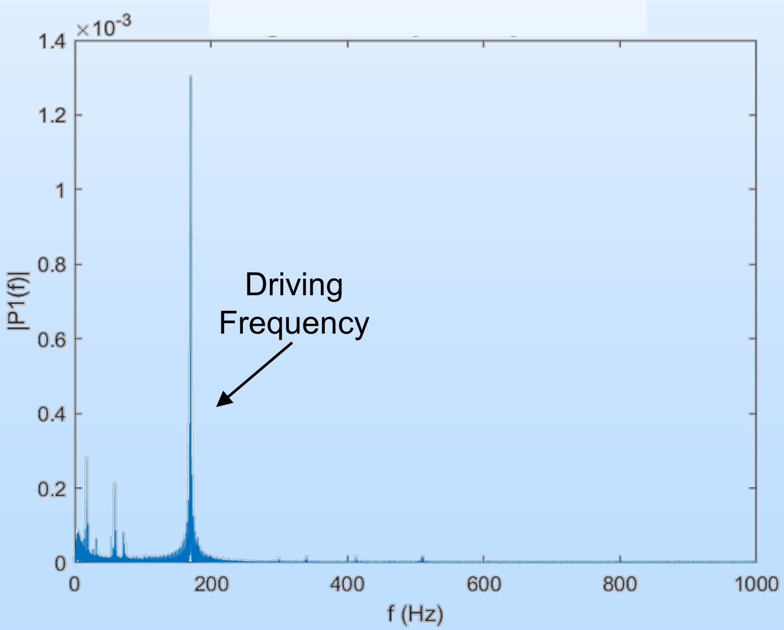


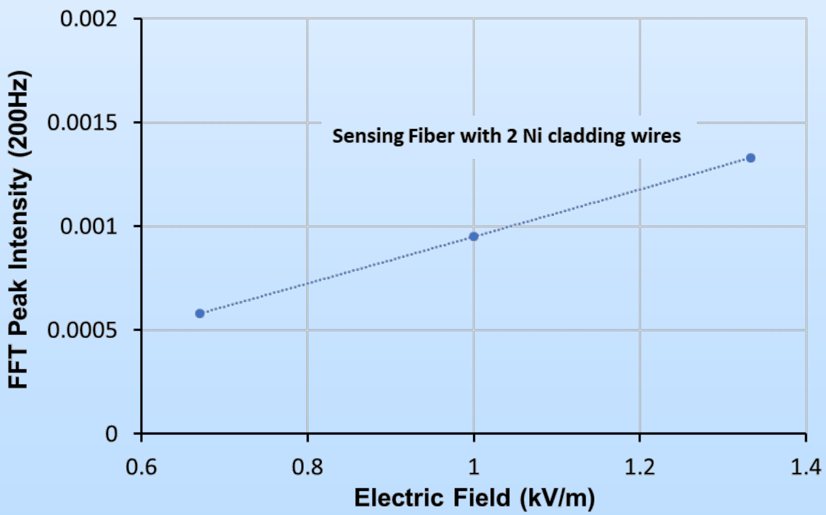
Magnetic Field Sensing



Distributed Electric Field Sensing

- Demonstrated distributed electric field sensor ($\sim kV/m$)
  - Sensing fibers with/without magnetostrictive cladding wires
- Currently evaluating PVDF buffered sensing fiber ($\leq mV/m$)
  - Sensors fabricated in Prysmian single mode fiber
  - Demonstrated fibers with $BaTiO_3$ cladding wires





Future Testing and Development

- Project Testing and Development
  - Develop thermal magnetic annealing techniques and "unique" sensor designs to enhance sensor response to lower magnetic flux (nT/pT)
  - Conduct simulated environmental testing
  - Develop electric field sensor for complete electromagnetic field sensing
  - Publish results in peer reviewed journals (4-8)
  - Prepare for field trial testing (cable design/installation techniques)
- Phase II Program
  - Develop technology for field trial testing
  - Demonstrate distributed downhole fiber optic sensing for the first time
- Commercialization
  - Sentek's picoDAS system is currently commercially available
  - Magnetic sensing fiber design and manufacturing process is extremely scale-able; technology transfer

Synergistic Opportunities

- Real-time information for optimized drilling and production
- “Turnkey” system to create a geophysical (Electromagnetic Methods) monitoring network for carbon storage site characterization and/or carbon storage
- Provide experimental options to validate theoretical feasibility studies of the design and use of an electromagnetic sensing optical fiber for geophysical applications
  - Alumbaugh, David L., Evan Schankee Um, G. Michael Hoversten, and Kerry Key. "Distributed electric field sensing using fibre optics in borehole environments." Geophysical Prospecting 70, no. 1 (2021): 210-221.
- Electrical power line/transformer continuous health monitoring
- Wireless sensing capabilities
- Energy harvesting/spintronic/quantum sensing applications
- Monitoring heart and brain activity
- Monitoring of nuclear power plants/reactors via RadHard fibers

Project Summary

- Accomplishments
  - Successfully demonstrated distributed magnetic field sensing
  - Implemented acoustic/magnetic signal separation algorithms
  - Preliminary demonstration of distributed electric field sensors
  - Successfully demonstrated splice-ability of multi-materials sensing fiber to commercial single mode fiber
  - Demonstrated enhanced sensor response upon thermal magnetic annealing
  - Demonstrated polyimide coated/hydrogen tolerant acoustic sensors for high temperature dowhole deployment
  - Successfully demonstrated sensing fiber with nano-cladding wires
- Lessons Learned
  - Magnetic sensor response is complex and requires further study to understand harmonics, resonance, etc..

Acknowledgements

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U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

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HALLIBURTON 100 YEARS

Prysmian Group

Industrial Support: Brian Risch, Ph.D.

Prysmian Group Linking the Future

Weatherford

Industrial Support: Zhuang Wang, Ph.D.

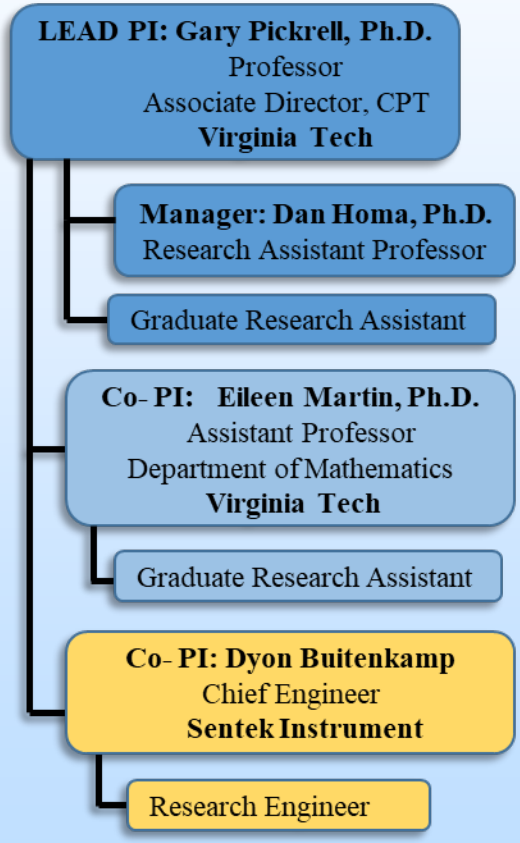
Weatherford

Appendix

– Organizational Chart
– Gantt Chart

Organization Chart

- Lead PI : Dr. Gary Pickrell
  - Provide executive management for all phases of the project, and oversee the selection, fabrication, and characterization of the fibers.
- Co-PI : Dr. Eileen Martin
  - Support all phases of the project and provide expertise in all technical aspects of the project and efforts pertaining to the testing and analysis of the selected optical fibers.
- Co-PI: Dyon Buitenkamp
  - Development and characterization of the *picoDAS* system to include sensor fabrication.
- Technical Manager: Dr. Daniel Homa
  - Daily project management, to include technical insights, under the guidance of the PI and Co-PI.



Gantt Chart

GANTT CHART		Project Year 1				Project Year 2				Project Year 3				Project Year 4			
Task #	Task Name	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	Project Management and Planning																
M1	**MILESTONE 1**																
2	Workforce Readiness Plan																
3	Data Management Plan																
4	Technology Maturation Plan																
5	Theoretical Modeling and Analyses																
M2/D1	**MILESTONE 2 / DECISION POINT 1**																
6	Construction of the Simulated Subsurface Test Facilities																
M3/D1	**MILESTONE 3 / DECISION POINT 1**																
7	Multi-Parameter Sensing Fiber																
7.1	Preform and Fiber Fabrication																
7.2	Fiber Grating Array Fabrication																
M4/D2	**MILESTONE 4/ DECISION POINT 2**																
8	Demonstration of Distributed Sensing System																
8.1	Interrogation Design and Implementation																
8.2	Distributed Sensing System Construction and Demonstration with Commercial Fibers																
M5/D3	**MILESTONE 5 / DECISION POINT 2**																
9	Fabrication of High Temperature DAS Fiber																
10	Integration of Distributed Sensing Fiber and System																
10.1	Fabrication of Distributed Magnetic Sensing Fiber																
10.2	Development of the Simulated Subsurface Test Facilities																
10.3	Demonstrate Distributed Sensing with Magnetic Sensing Fiber																
10.4	Perform Sensor Calibration and Verification																
M6	**MILESTONE 6**																
11	Prototype Sensing System Testing																
11.1	Fabrication of Prototype Distributed Magnetic Sensing Fiber																
M7	**MILESTONE 6**																
11.2	Construct Multi-Parameter Sensing System																
11.3	Test Sensing System and Evaluate Performance																
M8	**MILESTONE 8**																