Specialty Optical Fiber Development for Distributed Fiber Optic Acoustic Sensing

22nd Annual Center for Advanced Signal and Image Sciences Workshop

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May 23rd, 2018

LLNL-PRES-751539

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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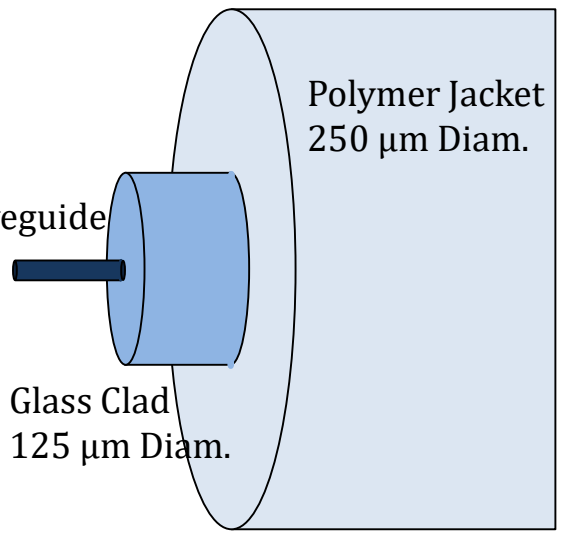
Outline

- Background and Motivation
- Fiber Fabrication and Sensing
- Testing
- Results and Next Steps

Background on Fiber Optic Acoustic Sensing

Fiber Optic Waveguide



Advantages

- Low Cost, Robust Sensor
- Well-Suited for Extreme Environments Such as Boreholes
- Enables Continuous Data Acquisition Along Borehole
- Potential to Replace Existing (Point) Sensors

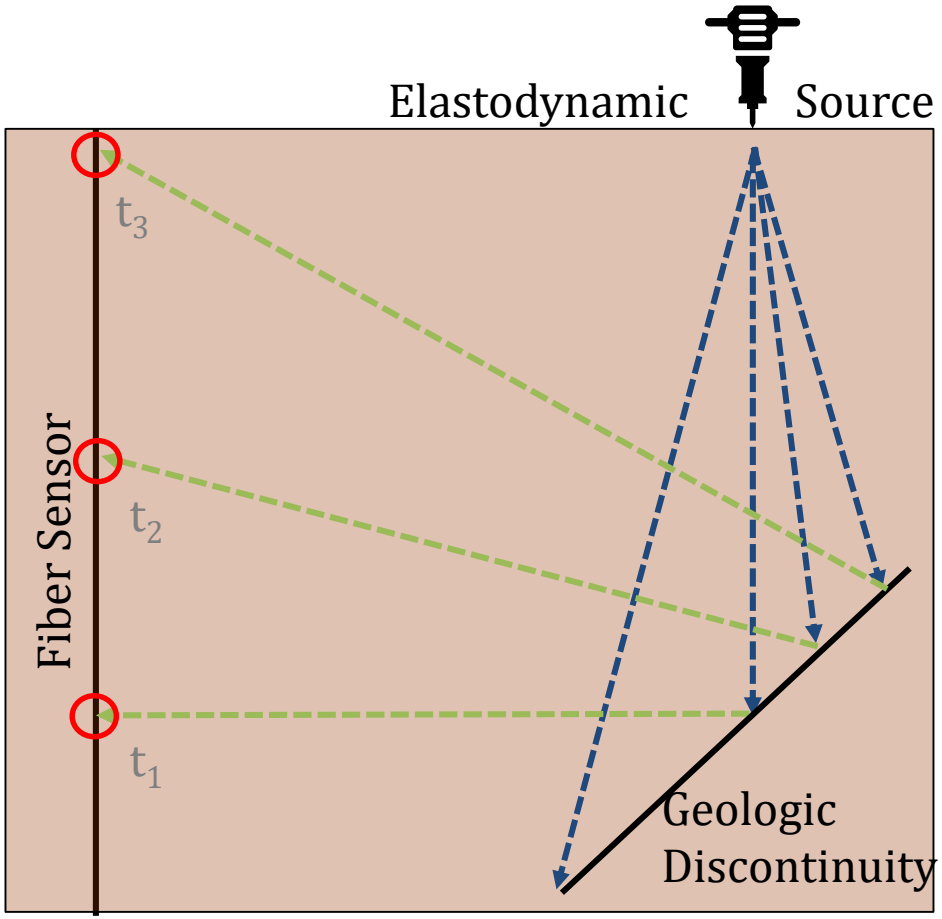
Disadvantages

- Poor Azimuthal Response
- Uncertain Systems Response

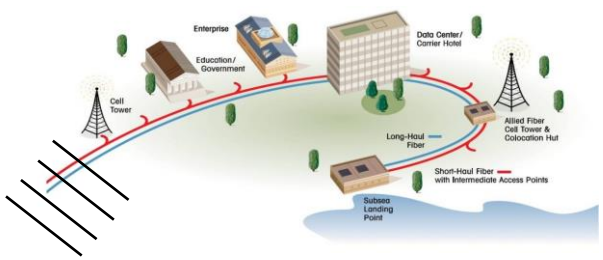
Background on Fiber Optic Acoustic Sensing

Imaging Architecture

Borehole Sensing



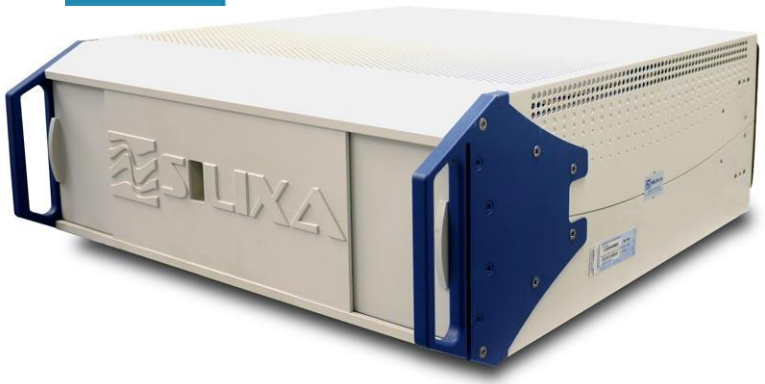
Surface Sensing



Utilizes Dark Telecom Network for Sensing

APS Physics Today, March 2018 "Earthquakes can be detected with Fiber Optic Cable," R. Mark Wilson

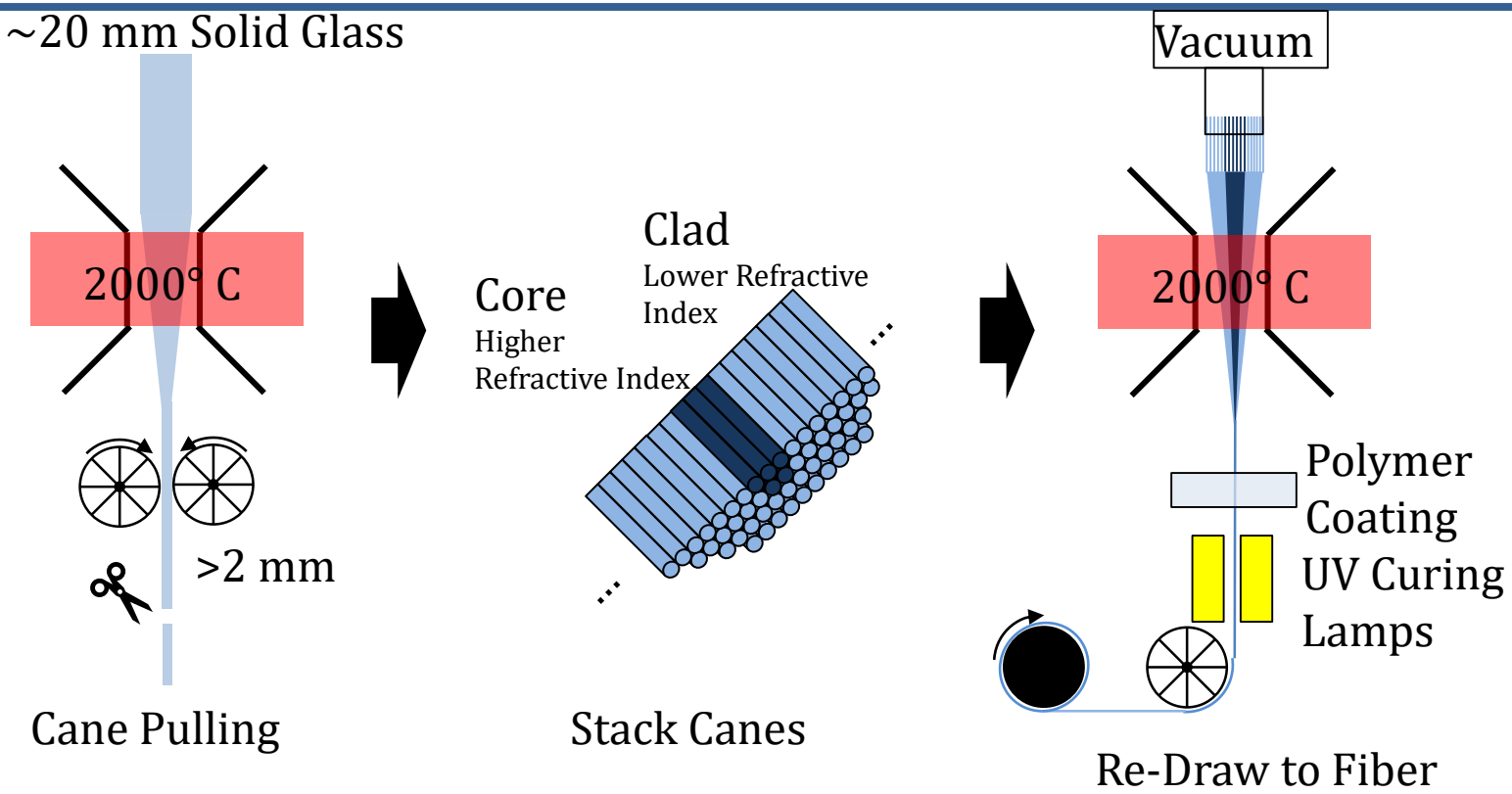
Motivation

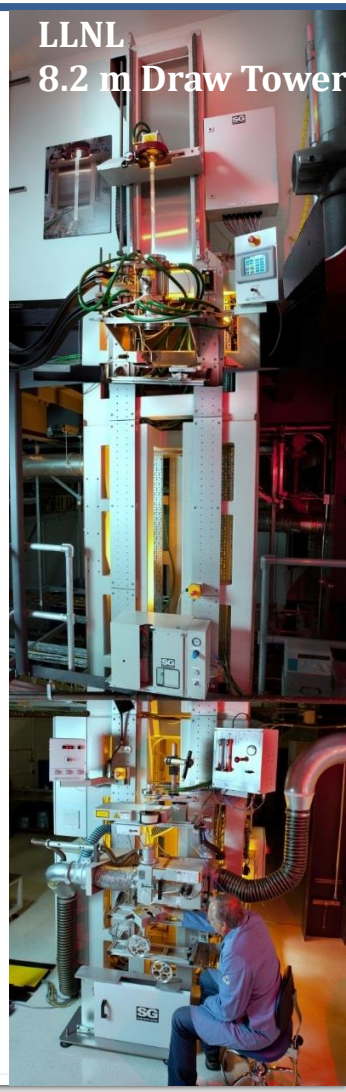


- Commercial Systems Exist, But Data Processing Routines Are Proprietary
- Custom Optical Fibers Designed For Enhanced Responsivity Are Rare
- Mechanical & Optical Physics of Elastodynamic Coupling Not Well Understood

Fiber Fabrication

Stack-and-Draw

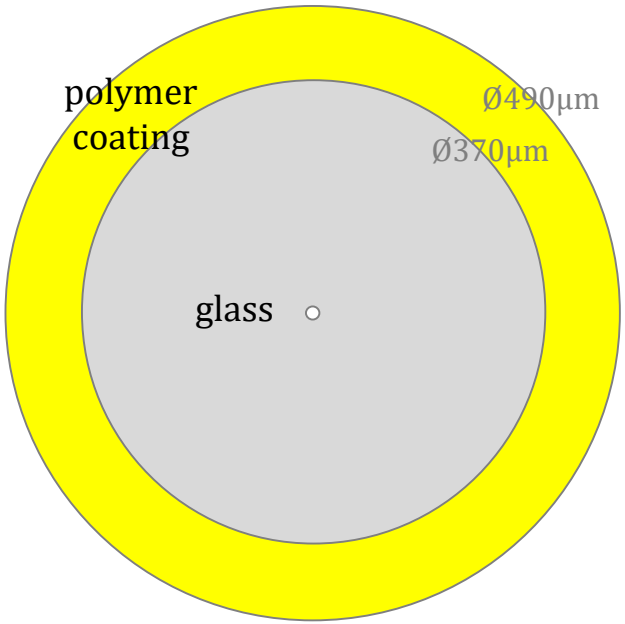




Fiber Fabrication

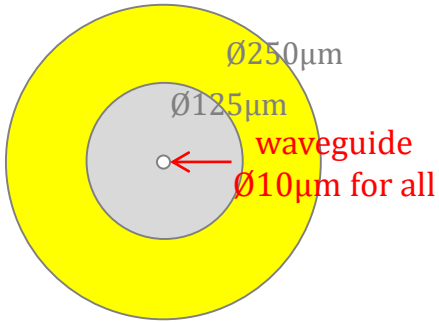
Fibers Under Investigation

Expected Sensitivity, $\sim A_{core}/A_{glass}$



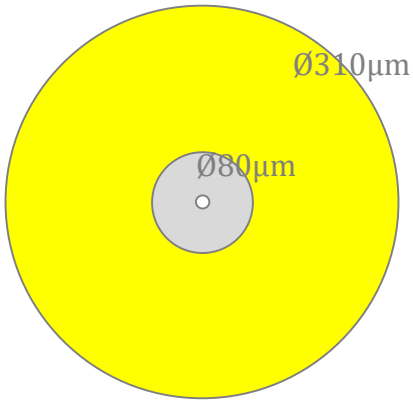
Custom fiber #1

$A_{coating}/A_{glass} = 0.75$



Telecom fiber

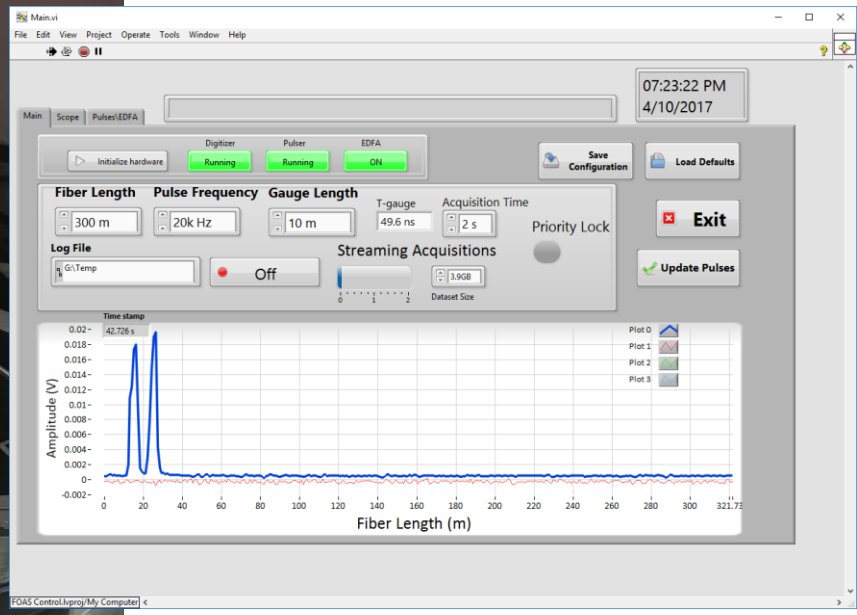
$A_{coating}/A_{glass} = 3.0$



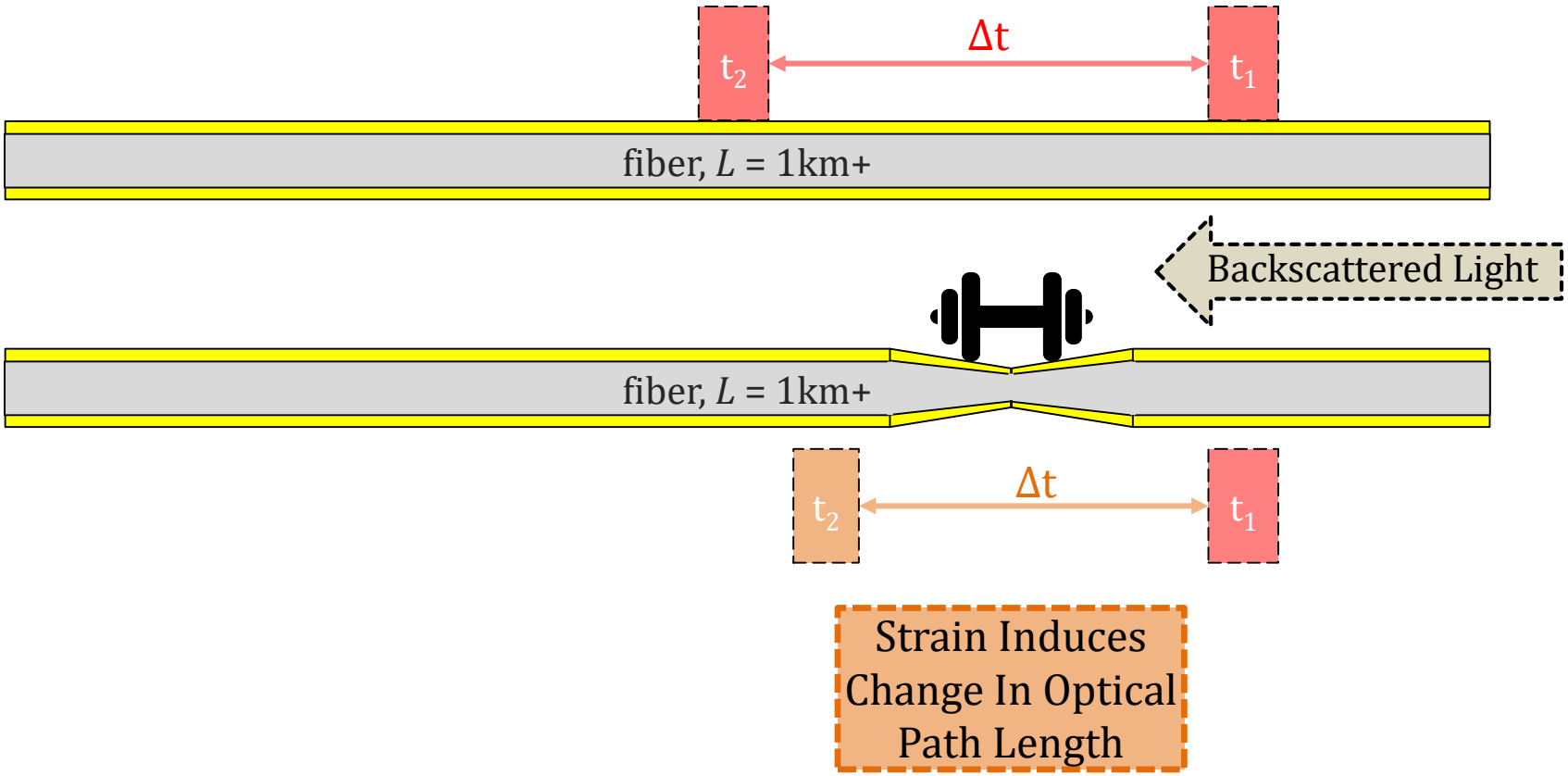
Custom fiber #2

$A_{coating}/A_{glass} = 14.0$

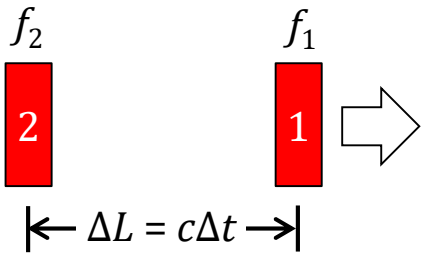
Interrogator Box Overview



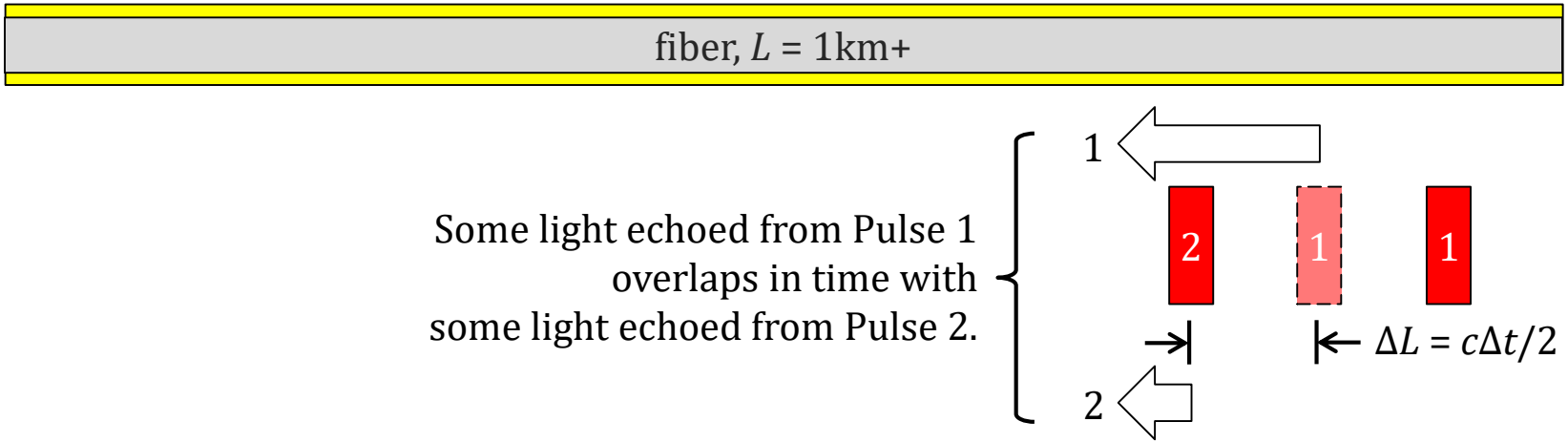
Strain Detection



Dual Pulse Interrogation Scheme



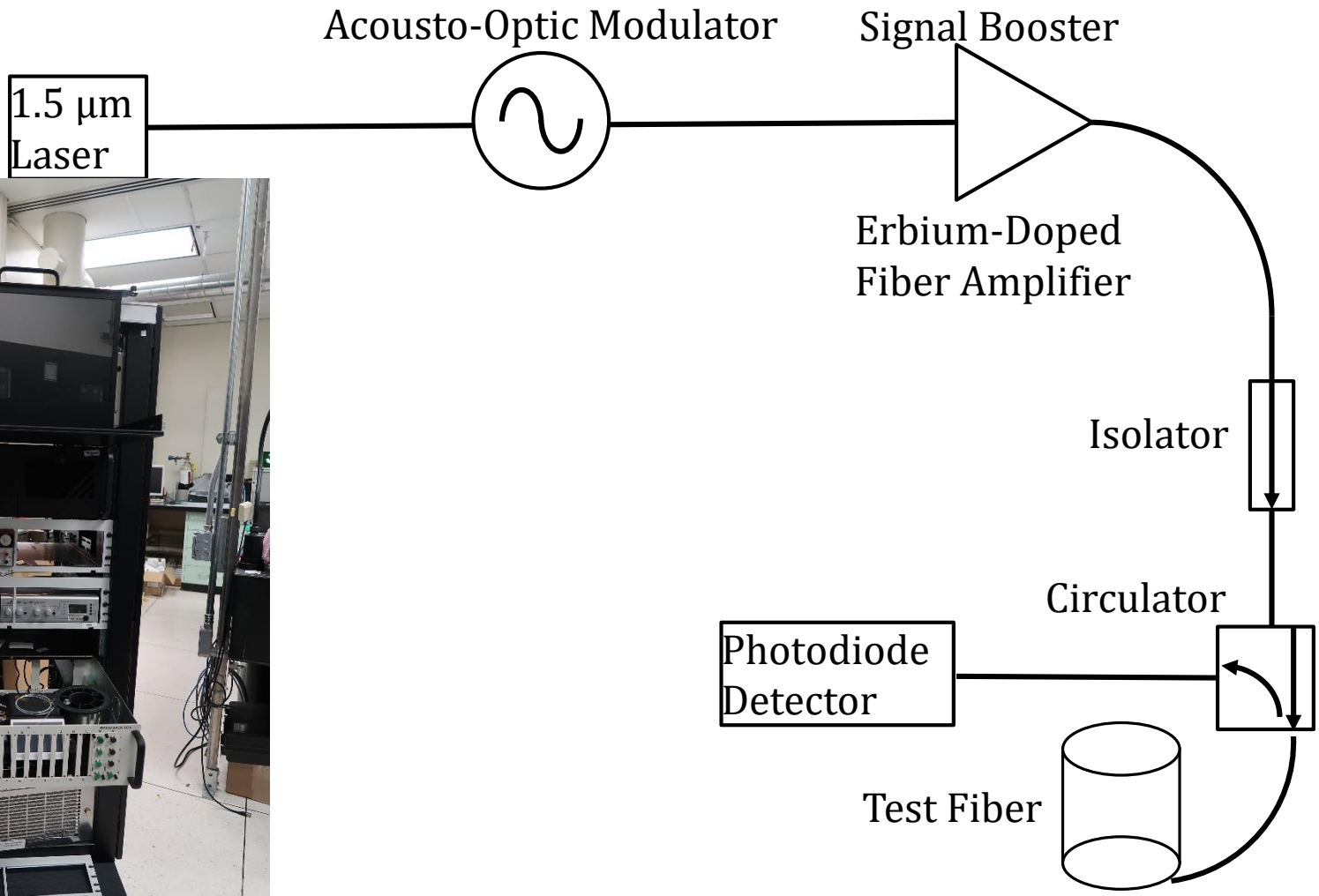
- Going into the fiber, Pulse 1 leads Pulse 2 by Δt
- Pulses are modulated at slightly different frequencies, f_1 and f_2



We electronically filter the returned signal at $f = f_1 - f_2$ and thus always isolate light that has echoed from spots separated by $\Delta L = c\Delta t/2$ (gauge length).

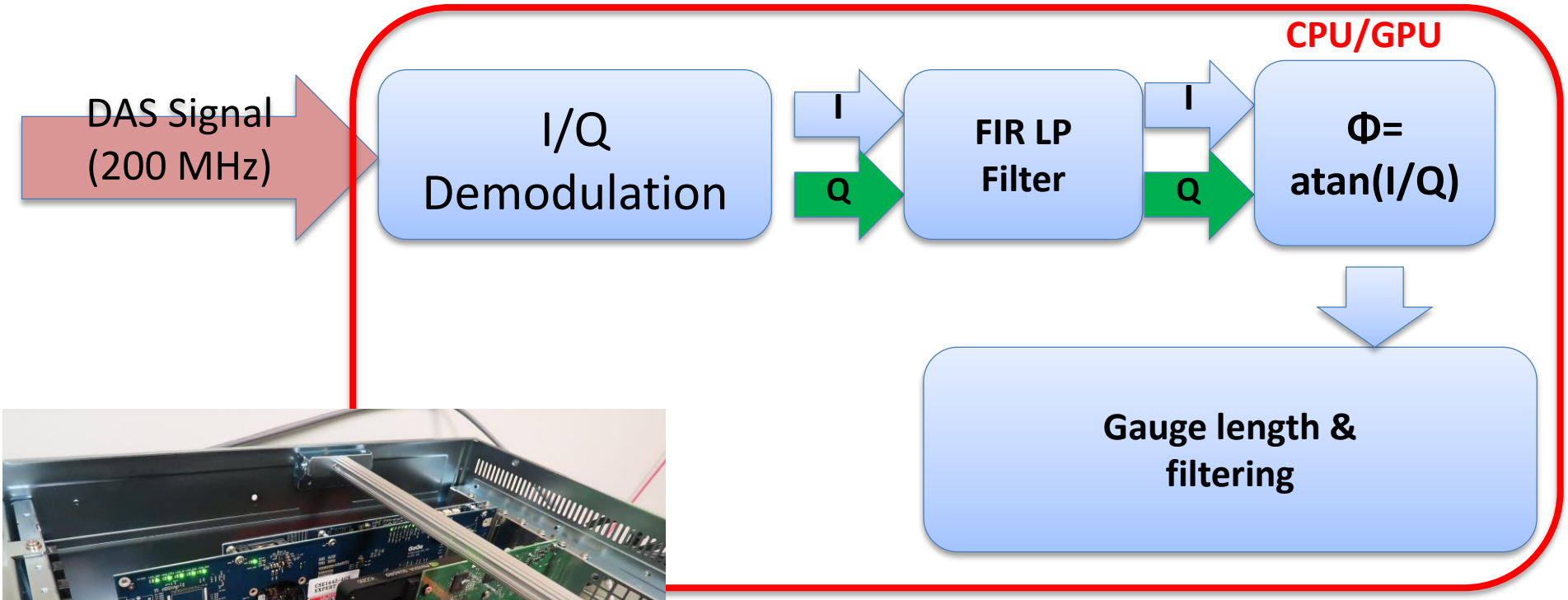
Interrogator Box Overview

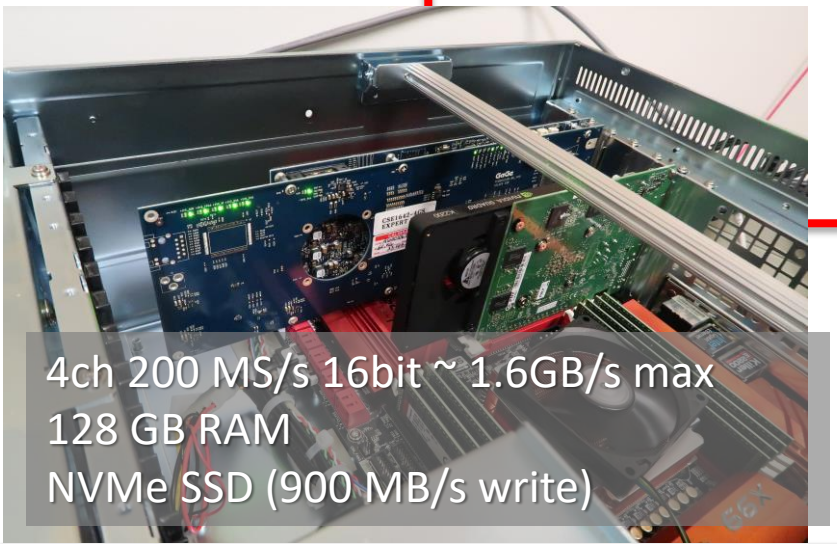
Fiber Optical Components



Interrogator Box Overview

Signal Processing





$$\frac{\Delta\varphi(z,t)}{\Delta t} \sim Strain\ at\ distance\ z\ along\ fiber$$

Strain Rate vs. time indicates elastodynamic event

Testing and Results
Environments

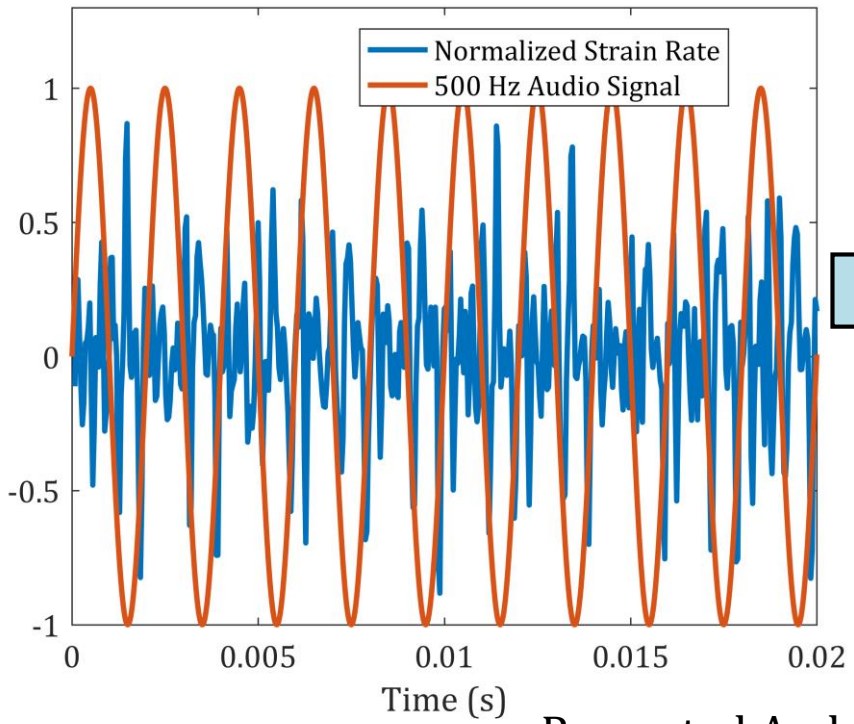
Acoustic Isolation Box

38 ft. Outdoor Water Trough

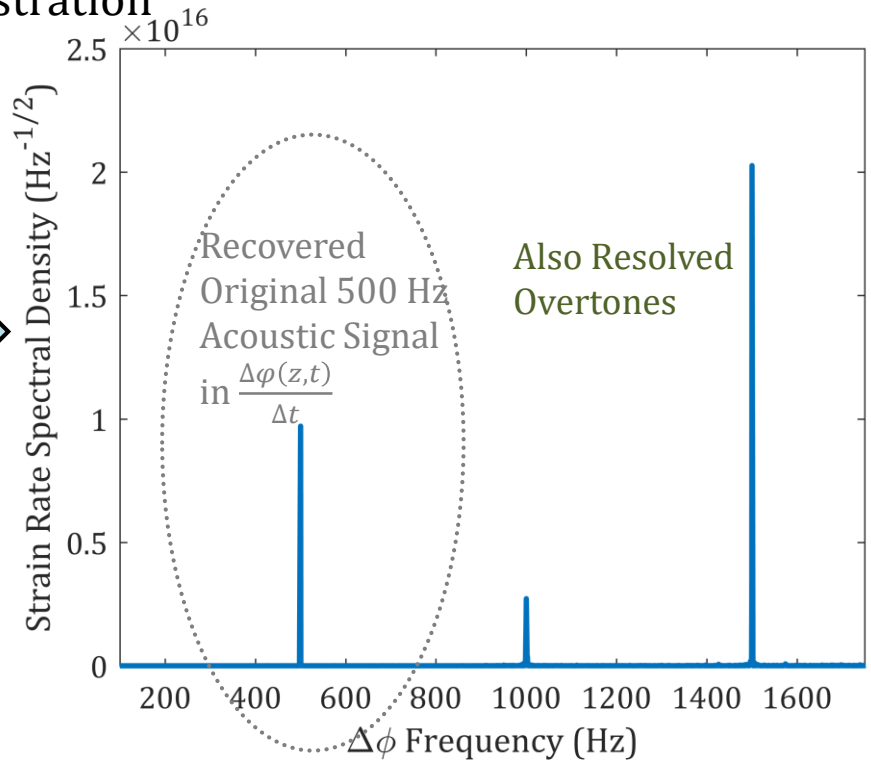
Testing and Results

Acoustic Isolation Box

Successful Demonstration



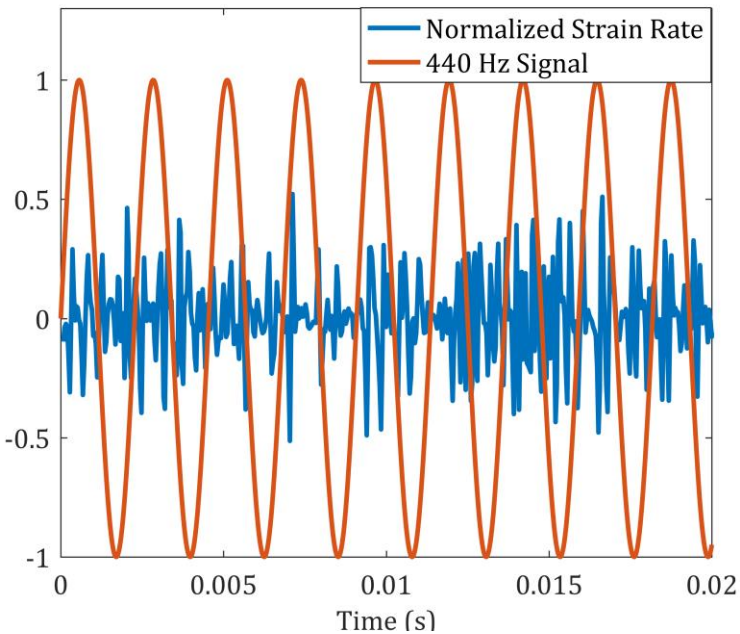
D.F.T.



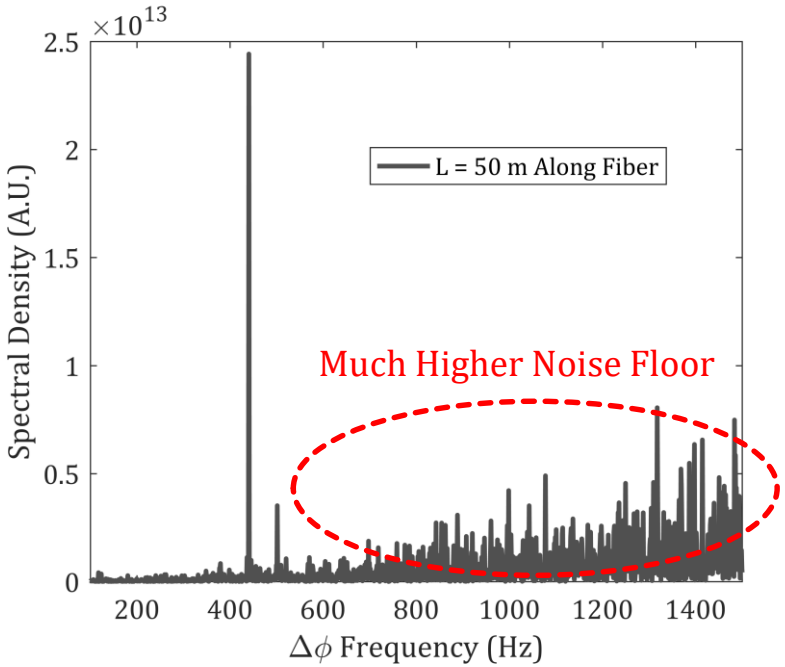
Presented Ambiguities

- Is the Fiber Reel Affecting Coupling?
- Does Fiber Wound Around a Reel Behave Differently Than A Straight Fiber?
- Acoustic Energy is Everywhere – Doesn't Mimic Point Source

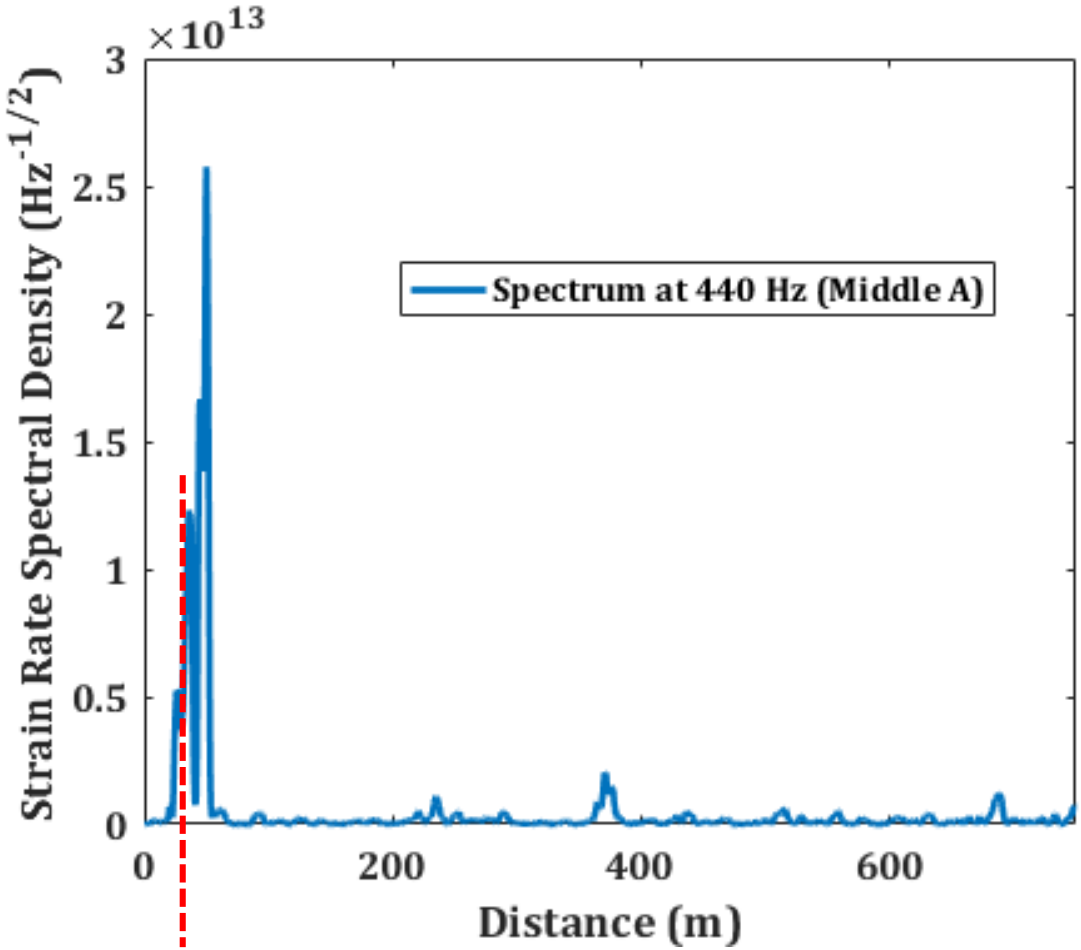
Testing and Results
Outdoor Water Trough



D.F.T.



Testing and Results
Outdoor Water Trough



Actual Epicenter

Conclusions

- Specialty Fibers for Acoustic Sensing are Needed for High Fidelity Seismic Imaging
- A Home-Built Fiber Optic Acoustic Sensing Unit Demonstrated Sensitivity to Acoustic Signals
- Methods for Quantifying Acoustic Energy (Calibrated Hydrophones, Geophones) Must be Implemented Before Data Will Become Useful for Seismic Imaging and/or Geophysics

Acknowledgements

This work was enabled through the auspices of the Laboratory Directed Research and Development Contract # 17-ERD-015-FOAS

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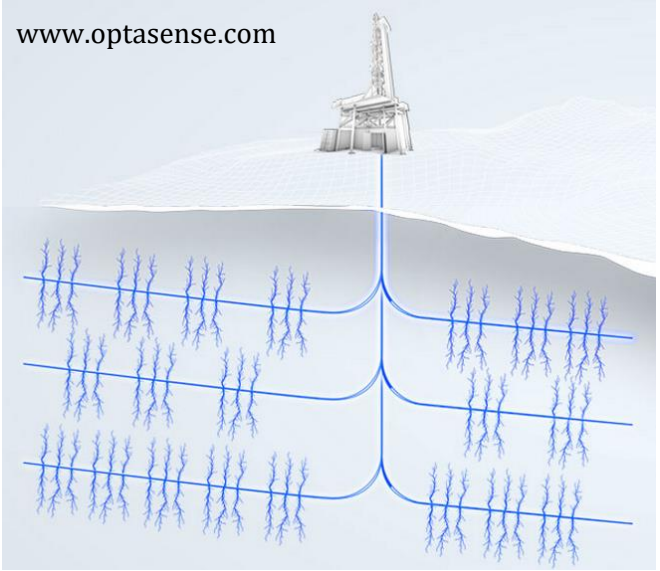
Backup Slides

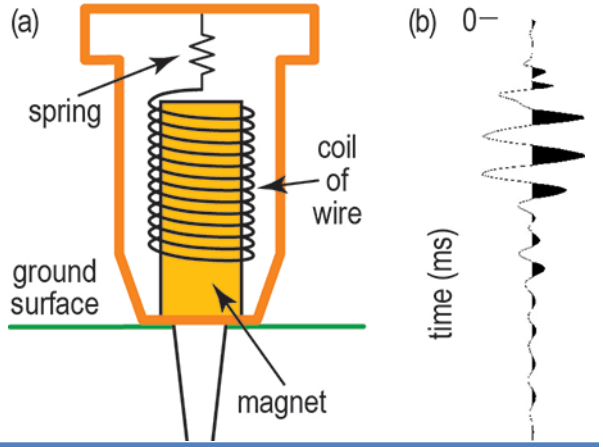
Background on Borehole Seismic Sensing

Petrol/Gas Producing Wells Must Determine Well Lifetime



- Pressure/Seismic Gradients in Vicinity of Well Related to Petrol/Gas Depletion
- Seismic Profile Imaging Is Essential to Determine Well Lifetime

Currently Reliant on Geophones



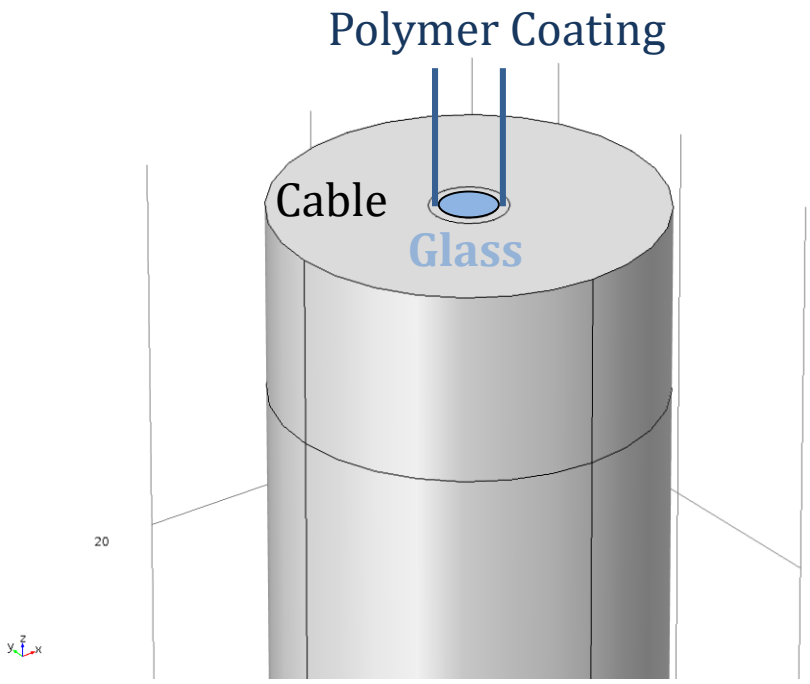
Advantages
Able to Ascertain Directionality
Individual Sensors Responsive to Longitudinal And Transverse Waves
Drawbacks
Limited Range of Detection – Must Deploy Network of Sensors
Responsivity Variations in Detection is an Inherent Limitation

Motivation

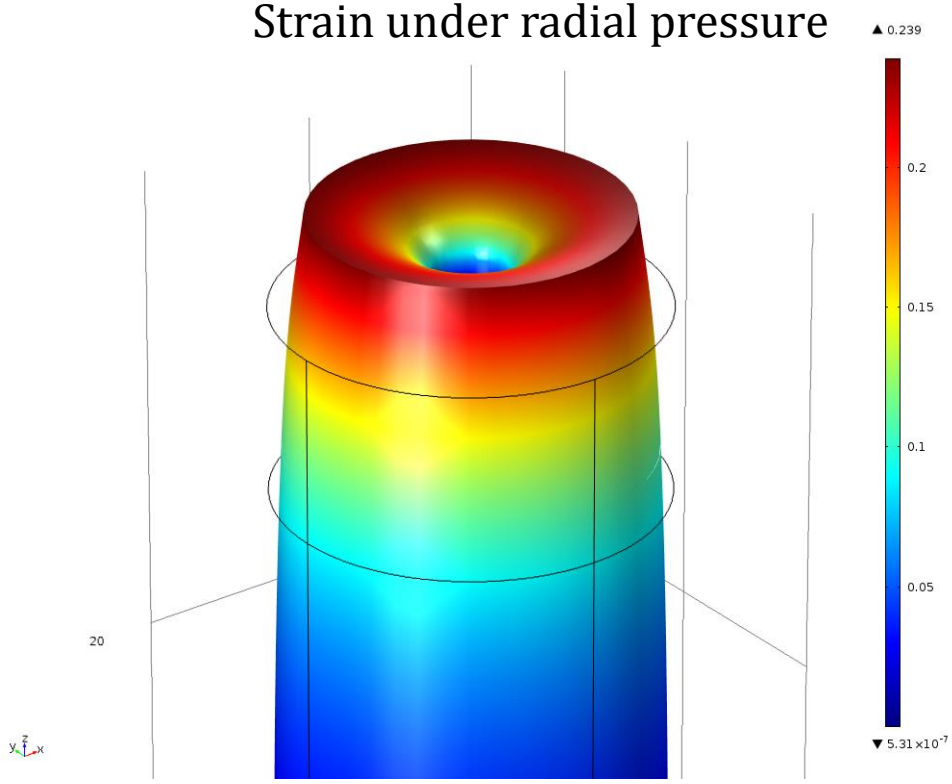
Limitations on Current Commercial Optical Fibers

- Temperature: Survival Limited by Polymer Jacket ~**130° C**
- Cladding and Polymer Coating Limited to Telecom-Standardized Dimensions
- Elastodynamic Strain Coupling Depends on Ratio of Polymer Coating to Cladding Diameter

Geometry



Strain under radial pressure

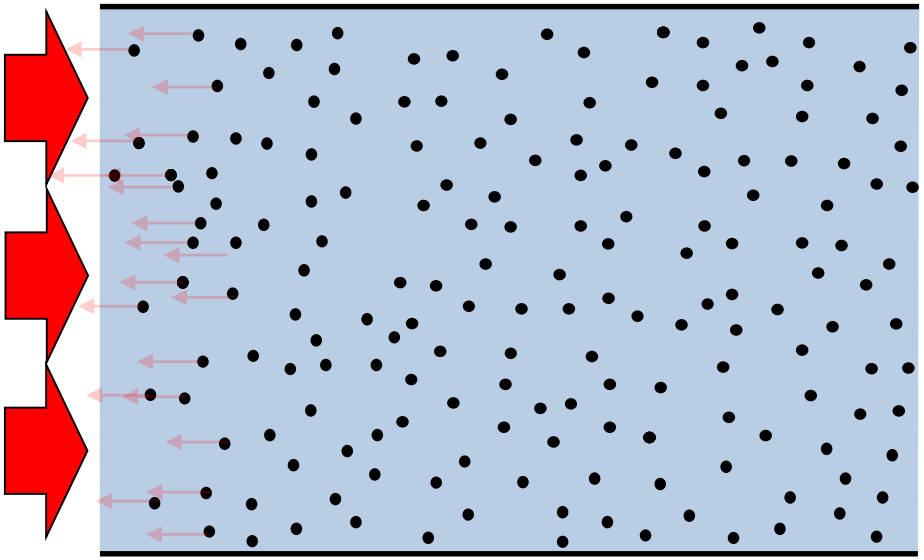


Background on Fiber Optic Acoustic Sensing

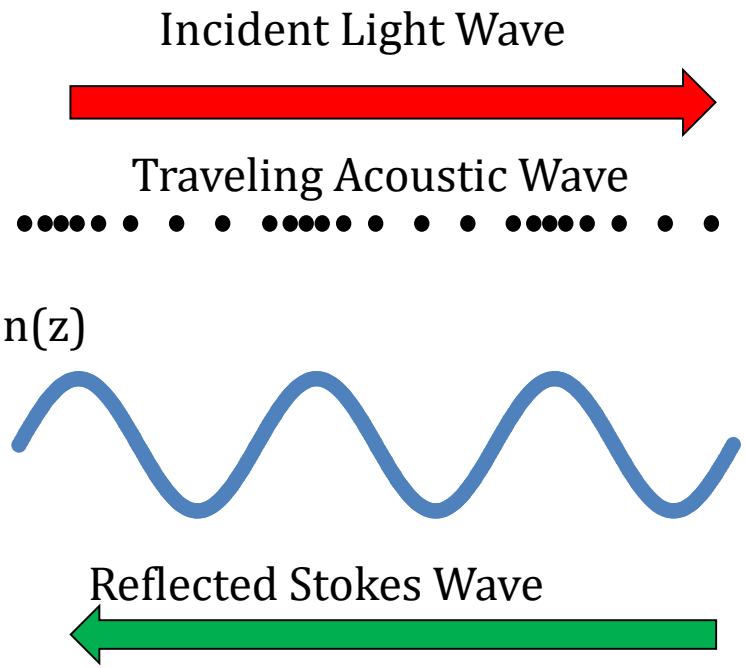
Rayleigh Scattering
(Like Sunlight Diffusing in the Sky)

Microscopic Defects Cause Inelastic Scattering

- ~-90 dB/m compared to Forward Wave
- Same Frequency as Original Wave



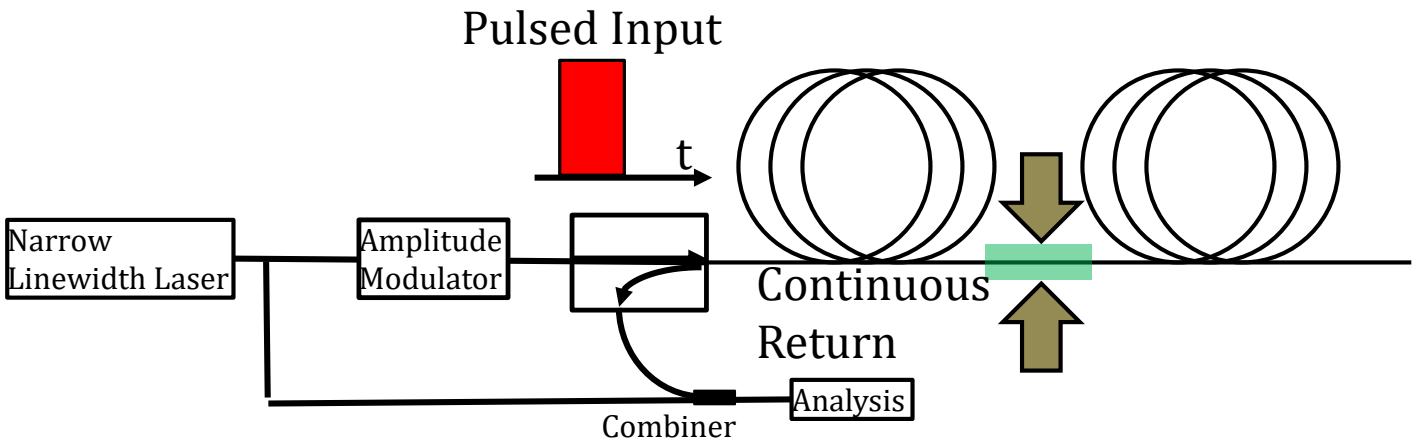
Brillouin Scattering



- Travels in Opposite Direction
- Down-Shifted in Frequency due to Doppler Effect

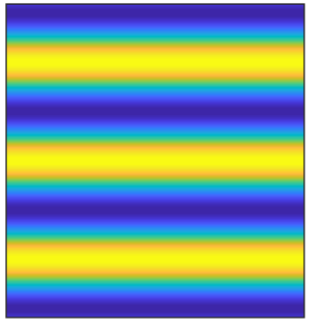
Background on Fiber Optic Acoustic Sensing

Signal Detection

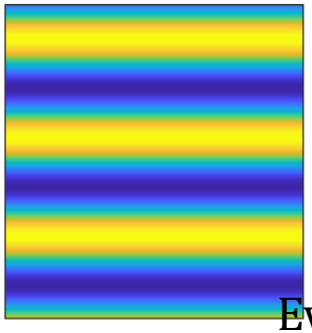


Rayleigh Scattering

- Strain Modifies Local Refractive Index
- Change in Fringe Pattern of Interferogram = Event



Fringe Fields

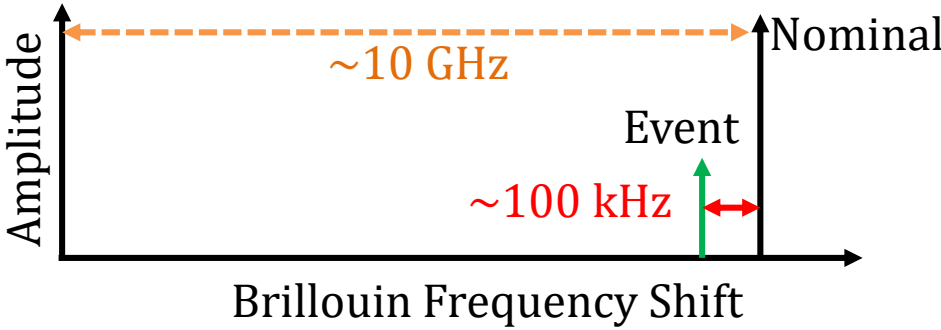


Nominal

Event

Brillouin Scattering

- Strain Modifies Acoustic Wave Velocity
- Stokes Frequency Shift = Event



Background on Fiber Optic Acoustic Sensing

Rayleigh versus Brillouin Optical Time Domain

Rayleigh Scattering

Benefits
Higher Strain Response
Phase- and Amplitude-Based Detection Possible
Systems Indirectly Measuring Strain are Easily Deployed

Drawbacks
Direct Measurement of Strain is Complicated
Phase-Based Measurement Requires Cumbersome Data Post-Processing
High-Coherence Laser Required

Brillouin Scattering

Benefits
Stronger Optical Interactions, Higher Return Signal
Direct Measurement of Strain is Simple
Only Technique Capable of Measuring Temperature

Drawbacks
Native Silica Acoustic Bandwidth Limits Sensitivity
High-Speed DAQ Necessary due to >10 GHz Signal and ns Sampling
Expensive Electronics for Detection Required