Specialty Optical Fiber Development for Distributed Fiber Optic Acoustic Sensing

22nd Annual Center for Advanced Signal and Image Sciences Workshop

Cody Mart, Charles Yu, Graham Allen, Paul Pax, Karl Fisher, Michael Messerly, and Robert Mellors

May 23rd, 2018

Lawrence Livermore National Laboratory
Outline

• Background and Motivation
• Fiber Fabrication and Sensing
• Testing
• Results and Next Steps
Background on Fiber Optic Acoustic Sensing

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

Elastodynamic Source

Surface Sensing

Utilizes Dark Telecom Network for Sensing

Jonathan Ajo-Franklin, LBNL, Burying Fiber Cable

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

~20 mm Solid Glass

2000°C

Cane Pulling

>2 mm

Core
Higher Refractive Index

Stack Canes

Vacuum

2000°C

Clad
Lower Refractive Index

Polymer Coating
UV Curing Lamps

Re-Draw to Fiber

LLNL 8.2 m Draw Tower
Fiber Fabrication
Fibers Under Investigation

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

- **Custom fiber #1**
  - $A_{\text{coating}}/A_{\text{glass}} = 0.75$

- **Telecom fiber**
  - Waveguide
  - $A_{\text{coating}}/A_{\text{glass}} = 3.0$

- **Custom fiber #2**
  - $A_{\text{coating}}/A_{\text{glass}} = 14.0$

Dimensions:
- Ø490μm
- Ø370μm
- Ø250μm
- Ø125μm
- Ø310μm
- Ø80μm
- Ø490μm
- Ø370μm
Interrogator Box Overview
Strain Detection

Strain Induces Change In Optical Path Length

fiber, $L = 1\text{km}+$

Backscattered Light

$t_2 - \Delta t - t_1$

$t_2 - \Delta t - t_1$
Dual Pulse Interrogation Scheme

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

\[
\Delta L = c\Delta t /2
\]

Some light echoed from Pulse 1 overlaps in time with some light echoed from Pulse 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

1.5 µm Laser

Acousto-Optic Modulator

Signal Booster

Erbium-Doped Fiber Amplifier

Isolator

Circulator

Photodiode Detector

Test Fiber
Interrogator Box Overview
Signal Processing

DAS Signal (200 MHz) → I/Q Demodulation → FIR LP Filter → CPU/GPU

\[ \Phi = \tan^{-1}(I/Q) \]

Gauge length & filtering

\[ \Delta \varphi(z, t) / \Delta t \sim \text{Strain at distance } z \text{ along fiber} \]

Strain Rate vs. time indicates elastodynamic event

4ch 200 MS/s 16bit ~ 1.6GB/s max
128 GB RAM
NVMe SSD (900 MB/s write)
Testing and Results
Environments

Acoustic Isolation Box

38 ft. Outdoor Water Trough
Testing and Results
Acoustic Isolation Box

Successful Demonstration

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.

Normalized Strain Rate
440 Hz Signal

Spectral Density (A.U.)

L = 50 m Along Fiber

Much Higher Noise Floor
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
Backup Slides
Background on Borehole Seismic Sensing

Petrol/Gas Producing Wells Must 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

• Pressure/Seismic Gradients in Vicinity of Well Related to Petrol/Gas Depletion

• Seismic Profile Imaging Is Essential to Determine Well Lifetime

www.optasense.com
Motivation
Limitations on Current Commercial Optical Fibers

- Temperature: Survival Limited by Polymer Jacket $\sim 130^\circ C$
- 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
Incident Light Wave
Traveling Acoustic Wave
Reflected Stokes Wave

- Travels in Opposite Direction
- Down-Shifted in Frequency due to Doppler Effect
Background on Fiber Optic Acoustic Sensing

Signal Detection

- Pulsed Input
- Narrow Linewidth Laser
- Amplitude Modulator
- Continuous Return
- Combiner
- Analysis

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

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

Amplitude

Nominal Fringe Fields
Event Nominal

Brillouin Frequency Shift

~10 GHz
~100 kHz

Event
## Background on Fiber Optic Acoustic Sensing

### Rayleigh versus Brillouin Optical Time Domain

<table>
<thead>
<tr>
<th><strong>Rayleigh Scattering</strong></th>
<th><strong>Brillouin Scattering</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benefits</strong></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td>Higher Strain Response</td>
<td>Stronger Optical Interactions, Higher Return Signal</td>
</tr>
<tr>
<td>Phase- and Amplitude-Based Detection Possible</td>
<td>Direct Measurement of Strain is Simple</td>
</tr>
<tr>
<td>Systems Indirectly Measuring Strain are Easily Deployed</td>
<td>Only Technique Capable of Measuring Temperature</td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td><strong>Drawbacks</strong></td>
</tr>
<tr>
<td>Direct Measurement of Strain is Complicated</td>
<td>Native Silica Acoustic Bandwidth Limits Sensitivity</td>
</tr>
<tr>
<td>Phase-Based Measurement Requires Cumbersome Data Post-Processing</td>
<td>High-Speed DAQ Necessary due to &gt;10 GHz Signal and ns Sampling</td>
</tr>
<tr>
<td>High-Coherence Laser Required</td>
<td>Expensive Electronics for Detection Required</td>
</tr>
</tbody>
</table>