Fiber Optic Sensors: Fundamentals and Applications

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Presentation Focus

• The major focus of this presentation will be on distributive fiber optic sensors which has seen the greatest usage
• However, key applications for point sensors will be discussed
• The market dynamics will be covered briefly
# Fiber Optic Sensor Commercialization Evolution

<table>
<thead>
<tr>
<th>Year</th>
<th>Sensors</th>
<th>Telecom</th>
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<tbody>
<tr>
<td>1975</td>
<td>R&amp;D- Military and Industrial</td>
<td>R&amp;D- Telecommunications</td>
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<tr>
<td>1980</td>
<td>Laboratory Devices</td>
<td>Multimode Systems; Mb/s transmission</td>
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<td>1985</td>
<td>1st Industrial Applications and Military Systems</td>
<td>Advent of Single Mode Systems; Major Infrastructure Build</td>
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<td>1990</td>
<td>1st Commercial Gyroscope; Medical Applications</td>
<td>EDFA; Undersea Systems; Gb/s transmission</td>
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<td>1995</td>
<td>1st Oil &amp; Gas Field Trials and Smart Structures. First FBG interrogators.</td>
<td>Optical Component Advancements and DWDM</td>
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<td>2000</td>
<td>1st Commercial Oil &amp; Gas Systems</td>
<td>Optical Networks; Market Peak at $18B; Tb/s transmission</td>
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<td>2010</td>
<td>Broad commercialization of sensors &amp; instrumentation</td>
<td>Trials for 100Gb systems. R&amp;D on multi-core fibers</td>
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<td>2014</td>
<td>Key enabling technology for North American energy independence</td>
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Advantages of Fiber Optic Sensors

- Nonelectrical
- Explosion proof
- Often do not require contact
- Remotable
- Small size and light weight
- Allow access into normally inaccessible areas
- Potentially easy to install (EMI)
- Immune to radio frequency interference (RFI) and electromagnetic interference (EMI)
- Solid state reliability
- High accuracy
- Can be interfaced with data communication systems
- Secure data transmission
- Resistant to ionizing radiation
- Can facilitate distributed sensing

- Can function in harsh environments
Light Modulation Effects Used by Fiber Sensors to Detect a Physical Parameter
Classification of Optical Fiber Sensors by Transducing Approach

**DIRECT (intrinsic)**
- Fiber itself is the transducer

**INDIRECT (extrinsic)**
- Transducer acts on the fiber

**HYBRID**
- Fiber carries light in and out of the device
Classification of Optical Fiber Sensors According to their Topology

Single-point sensor

Multi-point (quasi-distributed) sensor

Distributed sensor

Fiber

Sensing element

Multiple sensing points

Continuous sensing element
Phase Modulated Sensors
Interferometers

Mach-Zehnder interferometer configuration

Michelson Interferometer configuration
Interferometers

Fabry–Perot interferometer configuration

Sagnac interferometer configuration
Phase Detection

- Change in length due to mechanical or thermal strain will cause a phase change (Mach-Zehnder interferometer)
  \[ \phi + \Delta \phi = \frac{2\pi}{\lambda_0} [\eta L + \eta \Delta L] \]
  
- Provides extremely high resolution
- Noise issues such as phase noise and multimode noise are addressed in the detection schemes
Fabry-Perot Interferometric Sensor Concepts

Air Gap

Reflections

Bragg Grating

Fiber

L L L
Distributed Interferometric Sensor Configurations

- **Performance**
  - Resolution - < 0.01 microstrain
  - Long term accuracy - <1%
  - Position Resolution - 1 meter in 10 Km length
  - Can monitor dynamic strain
Interferometric Sensing Performance

• Long term accuracy - <1%
• Resolution - < 0.01 microstrain
• Position Resolution – 1 meter in 10 Km length
• Can monitor dynamic strain over a broad range of frequencies – vibration signature
• There is a trade-off between distance range and frequency bandwidth (due to time-of-flight limitations).
How Does a Fiber Optic Hydrophone Work?

Mach-Zehnder Fiber Optic Hydrophone
120 - 140 dB Dynamic Range

Hollow Mandrel – sensitive to Pressure Variations

Solid Mandrel – Insensitive to Pressure Variations

Source: Northrop Grumman
FOS Milestones:
Hydrophone Development

*Light Weight Wide Aperture Array (LWAA)*

Installed on 62 USS Virginia class nuclear submarines

FO Planar hydrophone Arrays (three flat panels mounted low along either side of the hull), as well as two high frequency active sonars mounted in the sail and keel (under the bow).

The result of 15+ years of R&D and $140M of investment!
Wavelength Modulated Sensors
Fiber Bragg Gratings
Fiber Bragg Grating Sensor
Bragg Grating Sensor

The change in wavelength, associated with both strain and temperature effects, is given by:

\[
\Delta \lambda_B = \left\{ 1 - \left[ \frac{n^2}{2} \right] P_{12} - v(P_{11} + P_{12}) \right\} \varepsilon + \left[ \alpha + \frac{dn}{dT} \right] \Delta T, \]

where:
- \( e \) is the applied strain,
- \( P_{11}, P_{12} \) is the stress optic coefficient,
- \( \alpha \) is the coefficient of thermal expansion,
- \( v \) is Poisson's ratio,
- \( n \) is the refractive index of the core, and
- \( \Delta T \) is the temperature change.

For constant temperature

\[ n \]

This relationship corresponds to 1 nm of wavelength change for 100 microstrain at a wavelength of 1300 nm.

For the case of zero applied strain

\[ \frac{1}{\lambda_B} \frac{\Delta \lambda_B}{\Delta T} = 6.67 \times 10^{-6} \text{ / } ^\circ\text{C} \]

At 1300 nm, a change in temperature of 1 °C results in a Bragg wavelength shift \( \Delta \lambda_B \) of 0.01 nm.
Bragg Grating Sensor Response

- 980 nm FIBER
- 1300 nm FIBER
- 1550 nm FIBER
Bragg Grating Sensors

Performance
• Resolution - < 0.5 microstrain
• Long term accuracy - <1%
• Up to 20 sensing points in C band
• Can monitor low frequency dynamic strain
• Temperature resolution of 1°C
• Strain / temperature discrimination is required
Bragg Grating Distributed Sensing System Configurations

WDM

TDM/WDM
High Capacity WDM Distributed Sensing System Using Bragg Gratings

Source: Micron Optics
Bridge Failure in Minneapolis MN

Critical Joint *
(Gusset) – Point of Failure

Failed Bridge Structure
Conceptual Use of Static and Dynamic Strain Monitoring in a Bridge Application

Input Vibration Signal

Distributed Interferometric sensors can monitor vibration

Vibration Signature – No Crack at Joint

Damped Vibration Signature – Crack at Joint

Critical Joint (Gusset*)

Static Strain Sensors can measure strain and deflection

Span 1

Span 2

* Suspected failure point in Minneapolis bridge failure
Strain change with Time Associated with Bridge Traffic

Source: Micron Optics
Scattering Based Sensors
Distributed Sensing Applications

The fiber is the sensor

Measurements all along a 10km fiber = 10,000 sensors!!

Standard multi-mode optical fibre

Backscattered light provides measurement point every 1m

1m pulse of light
Distributed Sensing System Based on Scattering
Emission from Raman, Brillouin and Rayleigh Scattering
Raman Scattering Process in Optical Fiber

Source: Sumitomo & LIOS
Raman Scattering Distributed Temperature Sensing (DTS).

- Temperature value = Anti-Stokes/Stokes
- Location = travel time
Temperature and Strain Sensitivities for Various Scattering Effects in Optical Fiber

<table>
<thead>
<tr>
<th></th>
<th>Temp Sensitivity</th>
<th>Strain Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>Rayleigh</td>
<td>weakly</td>
<td>weakly</td>
</tr>
<tr>
<td>Raman</td>
<td>strong-antistokes/ (intensity)</td>
<td>weakly</td>
</tr>
<tr>
<td>Brillouin</td>
<td>Strong (wavelength)</td>
<td>Strong (wavelength)</td>
</tr>
</tbody>
</table>
Raman Scattering Performance

- Only measures temperature and is independent of strain.
- The temperature resolution is 0.5°C.
- The measurement range is up to 15 km with a 1 meter spatial resolution (up to 25 km with a 1.5 meter resolution) of the location of the temperature perturbation.
Brillouin Scattering Performance

• The measurement range of up to 30 km.
• The sensing point associated with a physical perturbation can be resolved to 1 meter on a 10 km length, but accuracy is reduced as distance increases.
• The strain resolution is 20 microstrain. However, more advanced detection schemes can have a strain resolution of 0.1 microstrain.
• The temperature resolution is 0.5°C.
• While Brillouin scattering is an excellent strain sensor technology, the response time is about 1 second; and therefore, is not suitable for vibration measurements.
Mach-Zehnder Interferometer Based on Rayleigh Scattering

Performance:
- Accuracy: 2 strain
- Spatial resolution: 1 cm
- Max. length: 50 meters

Diagram:
- Scanning laser
- Reference
- Detector
- Mach-Zehnder Interferometer
- Reflection 1
- Reflection 2
- Output
- Reflected Intensity
  - Reflection 1
  - Reflection 2
- Distance, Frequency
Distributed Acoustic Sensing (DAS)

- Based on Rayleigh backscattered light in an optical fiber (single mode or multi mode)
- It senses all points along the fiber and monitors acoustic perturbations to the fiber
- Specifications
  - Frequency range - 1mHz to 100kHz
  - Spatial resolution - 1 m
  - Length - 50 km
- Strong applications
  - Oil and gas – seismic
  - Pipeline monitoring
Oil & Gas Applications
FOS Milestones:

Oil & Gas Industry Adoption

- Launch in offshore platform sector - first commercial systems in 2000; growth through market adoption.
- Offered in traditional supply chain: major oilfield services companies: BHI, HAL, SLB, & WTF.
- 2014 Market Size ~$400MM (installed system hardware and retrievable surveys).
- Raman DTS most prevalent sensor.
- Operation of sensor platform to 300°C.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Offshore, Secondary &amp; Tertiary Recovery</th>
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<tbody>
<tr>
<td>Regions</td>
<td>Global</td>
</tr>
<tr>
<td>Products</td>
<td>P/T Gauges, DTS, Flow, Seismic, Acoustic</td>
</tr>
<tr>
<td>Ratings</td>
<td>150-280°C, 25kpsi</td>
</tr>
<tr>
<td>Installations</td>
<td>&gt;2,000 permanent; &gt;100,000 surveys</td>
</tr>
<tr>
<td>Operating Hours</td>
<td>&gt;20 million</td>
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Fiber Optic Sensors in Oil & Gas

Sensors for Downhole Monitoring

- Pressure
- Temperature
- Flow Rate
- Phase Fraction
- Seismic
- Strain
- Sand
- Paraffin
- Chemical
- Density

Source: Weatherford
**DTS - SAGD**

- **Steam Assisted Gravity Drainage** (SAGD) is an enhanced oil recovery technology for producing heavy crude oil utilizing steam injection.
- 80% of oil sands require enhanced recovery techniques such as SAGD.
- Optimizing steam management optimizes reservoir production, reduces costs and limits emission.
- Monitoring the temperature profile of the steam chamber growth is key to process and efficiency improvements.
- **Distributed fiber optic temperature sensing systems have provided the monitoring capability**

Source: Petrospec
Advent of Permanent Ocean Bottom Cable (OBC) Seismic Systems

• Seismic reservoir management tool to optimize production

• Major franchises formed
  – Optical System
  – Deployment
  – Interpretation
  – Oil Company Sponsors

• Fiber Optics: reach, channel count; reliability

• Early growth stage

• Between $20-50M cost per field to customer

• Large incremental growth potential

Source - Qorex
Pipeline Distributed Fiber Optic Monitoring System

- Fiber optic interferometric array monitors about 25 km.
- Interferometric and DAS systems can monitor 25 km or longer.
- Multiple arrays cover hundreds of km.
- DTS and DTSS systems have been used to monitor leaks with a wireless temperature drop.
- In evaluation trials.

Source: Sabeus
Pipeline Leak Detection
(Distributed Brillouin Scattering)

Source: Omnisens
DAS Acoustic Signatures

Source: OptaSense
Magnetic and Electric Field Sensors
Fiber Optic Magnetic Field Sensor Architectures

(a) Bulk Sensor Material

(b) Intrinsic Sensor
Faraday Rotating Optic Attached Polarizing Optics

Low Verdet constant in fiber requires long path length compared with bulk Faraday rotators.
Sensor with Piez Coatings

- Magnetostrictive coating can be used for magnetic field sensors
- High sensitivity potential
Biophotonic Sensors
Biosensor Concept

Target analyte

Intrinsic Biophotonic Sensors

Mechanisms
- Absorption
- Scattering
- Raman Scattering
- Index of Refraction
- Fluorescence

Concepts
- Evanescent Wave Interaction
- Photonic Bandgap Confinement
- Fluorescence Arrays
- Flow Cytometry

Altered light signal in presence of analyte
Biophotonic Interaction Modulated Mach-Zehnder Interferometer
Evanescent Wave Fluoroimmunoassay Concept
Fiber Optic Enabled Arrays using Fluorescence for High Speed Screening
Fluorescent Array Microsphere Vapor Sensors

Figure 16.14 Fluorescent Array Microsphere Vapor Sensors\textsuperscript{10}
Gyroscopes
Sagnac Effect in a Coiled Fiber Used for Rotation Rate Sensing.

\[ = \left( \frac{2 \cdot LD}{c} \right) \]
Noise Sources in an Optical Fiber Gyroscope
Typical Precision FOG Design
Northrop Grumman Commercial Inertial Measurement Unit (IMU) with Three Fiber Optic Gyroscopes
Market
FO Sensor Market:
Single-Point Sensing

2008
- Military: 4%
- Oil & Gas: 2%
- Power: 3%
- Medical: 4%
- Industrial: 8%
- Civil Infrastructure: 25%
- Gyro: 54%
Total: $194 Million

2014
- Military: 4%
- Oil & Gas: 2%
- Power: 4%
- Medical: 3%
- Industrial: 8%
- Civil Infrastructure: 29%
- Gyro: 50%
Total: $302 Million
Distributed Fiber Optic Sensor Applications

- Oil & Gas Wells
- Pipelines
- Wind Energy Turbines
- Geothermal
- Military
- Shipboard Monitoring
- Avionic
- Homeland Security
- Process Control
- Infrastructure
Distributed Fiber Optic Sensor Market Forecast: By Application

Take away

• The oil and gas market segment will see a contraction lasting through 2015 as illustrated in the projections above.

• Price dips are typically short lived; and, the average price has moved back to an upswing in typically 12 to 18 months or less.
Future Market Opportunities:

- **Low cost sensors/instruments** all applications & markets
- **Disposable sensors** medical & health care
- **Distributed sensors** oil & gas, smart structures
- **Smart fabrics** geotechnical, medical, aerospace
- **Food industry** water & food safety
- **Environmental** gas sensing/emissions monitoring, pollution detection and monitoring
Future Possibilities: Optical Integrated FOS

More:
- Functionality
- Capability
- Reliability

Less:
- Space
- Power
- Cost

Multiple complementary optical systems can be placed on a single chip and packaged into a small size, light weight, low power package:

TFT-FOS
TechnoFibre Technologies
Fibre Optic Sensing
Conclusions

• The FOS field initiated the transition from lab to commercialization since the early 80’s.

• Initial products have targeted military and harsh environment applications (gyro, hydrophones, oil & gas, HV sensing).

• Commercialization cycles are long, needing 5-20yrs of development.

• Several FOS products have reached maturity and reached commercial success: FOG, DTS, DAS, FBG sensors, etc.

• The Distributed FOS market was ~$630 million in 2014 and projected to be $1042 million in 2019. The oil and gas sector represents 46% of the total market.

• The FOS Industry, in general, was blind-sided by the sudden surprise drop in oil prices in early 2015.
Contacts

• David Krohn
  – dkrohn@lightwaveventure.com
  – 203-248-1475

  – Available at www.spie.org

• **Photonic Sensor Consortium Market Survey - Distributed Fiber Optic Sensing Systems Forecast**
  – Available at Information Gatekeepers - hpan@igigroup.com