Fiber Optic Sensors: Fundamentals and Applications

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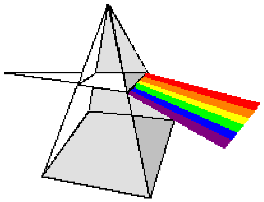


Presentation Focus

- 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

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

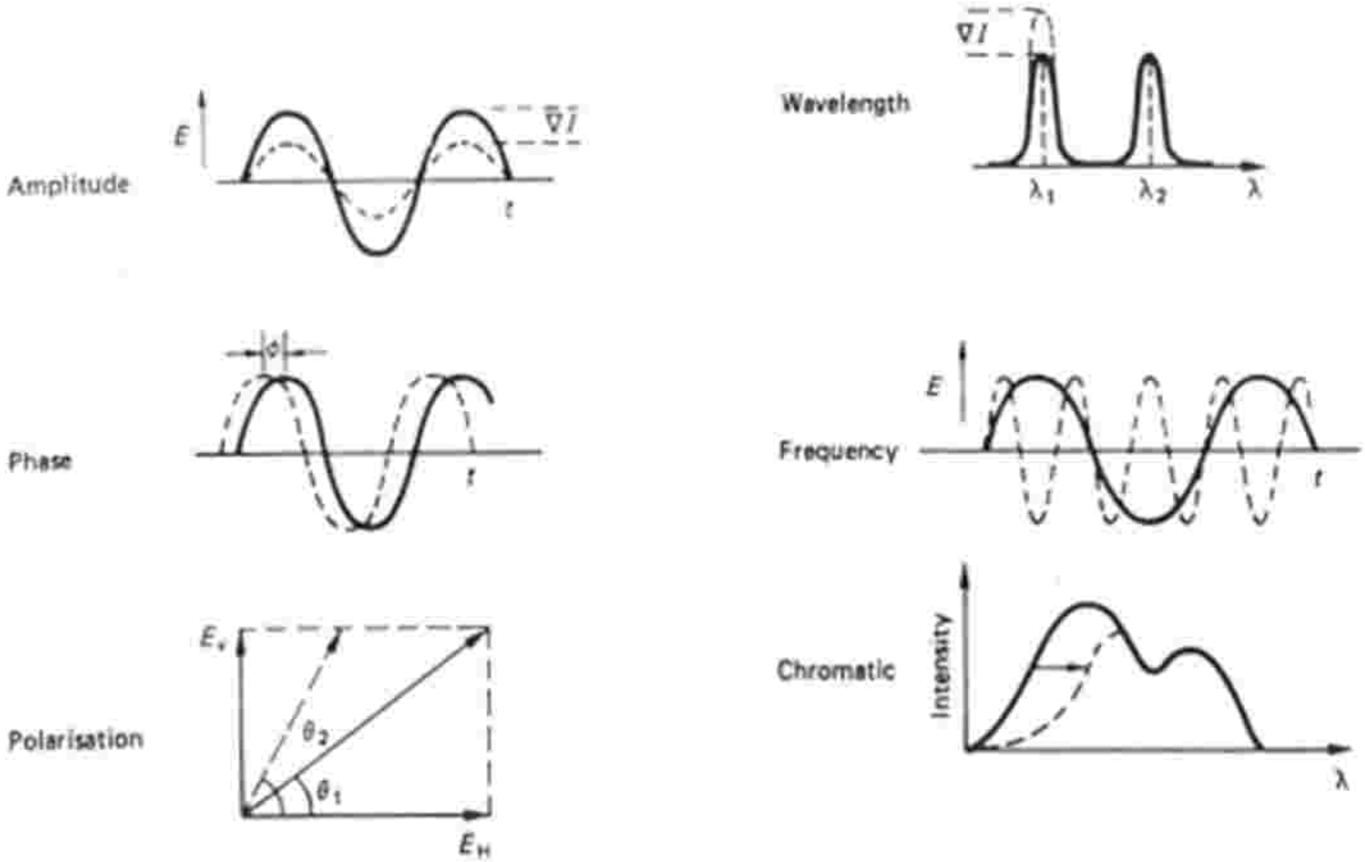
Advantages of Fiber Optic Sensors

- 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

↓

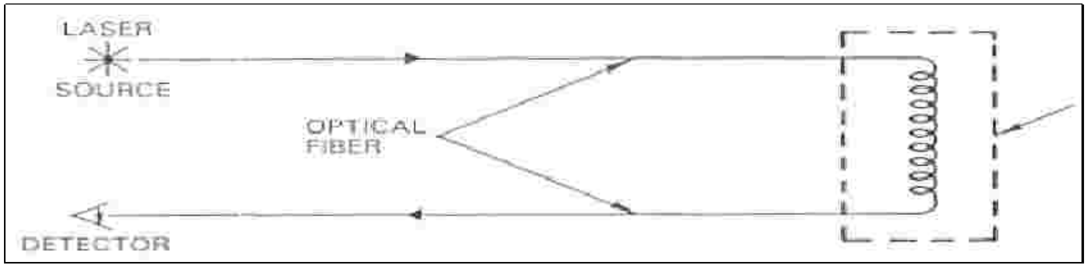
- Can function in harsh environments

Light Modulation Effects Used by Fiber Sensors to Detect a Physical Parameter



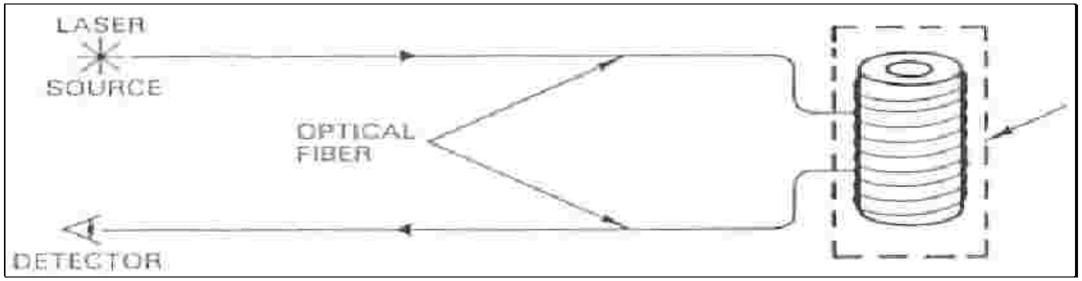
Classification of Optical Fiber Sensors by Transducing Approach

DIRECT
(intrinsic)



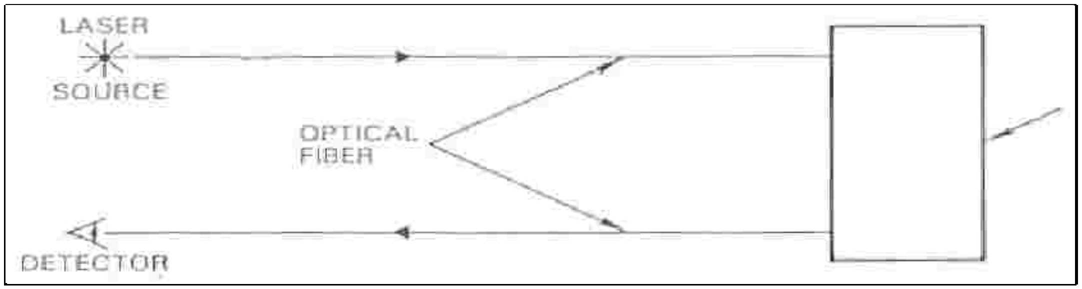
Fiber itself is the transducer

INDIRECT
(extrinsic)



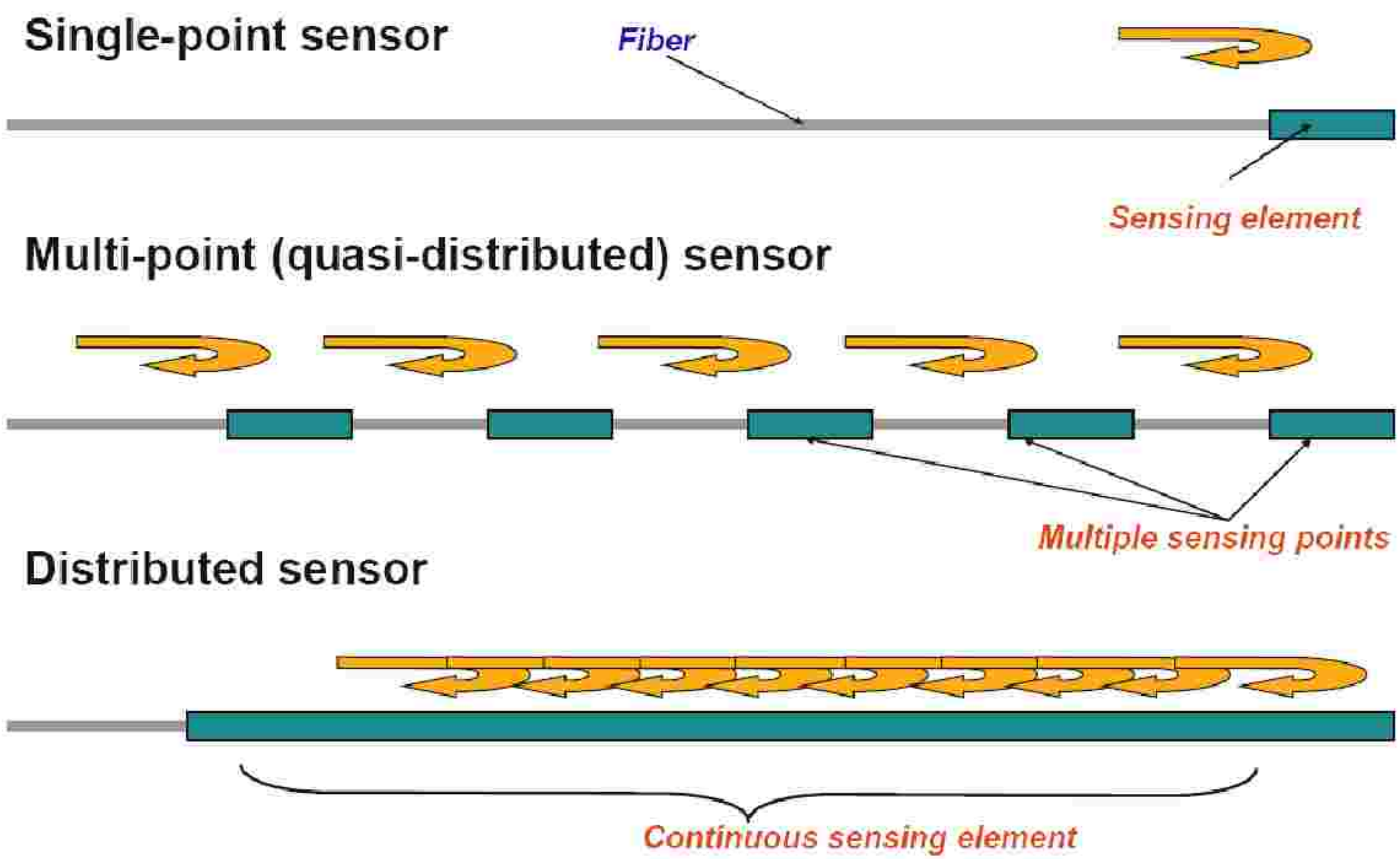
Transducer acts on the fiber

HYBRID

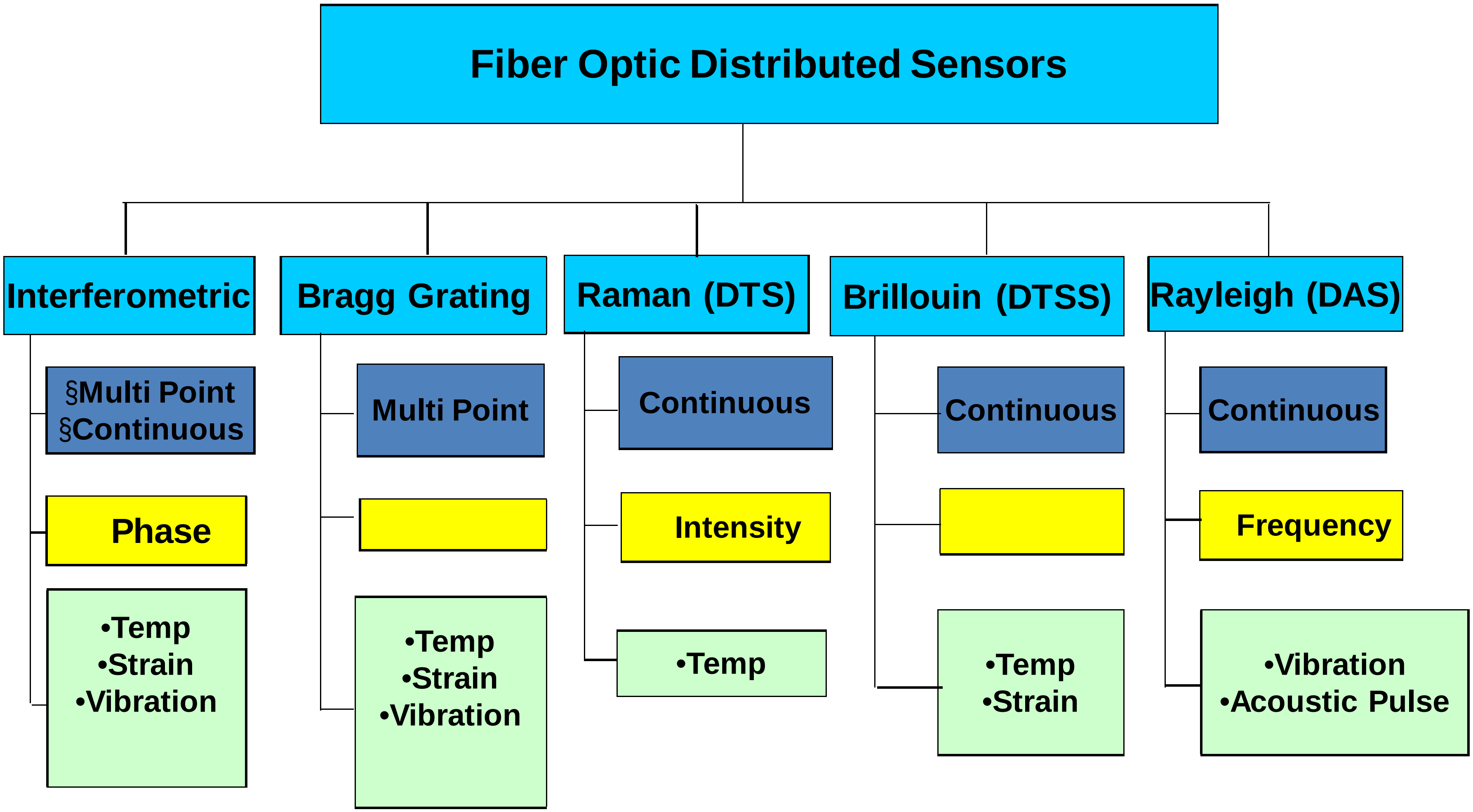


Fiber carries light in and out of the device

Classification of Optical Fiber Sensors According to their Topology

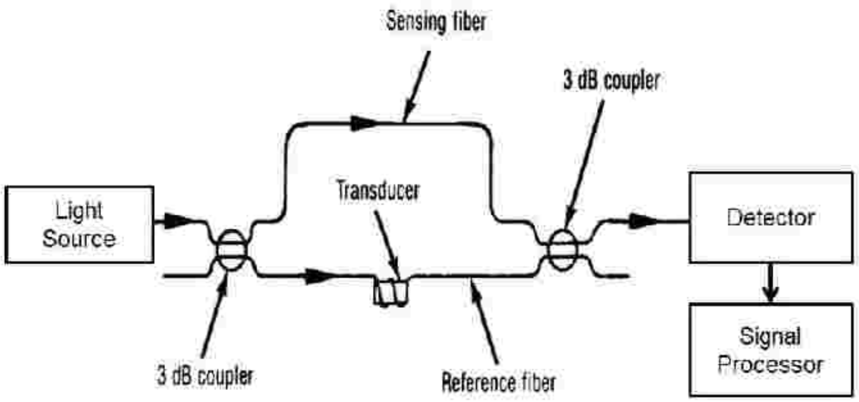


Fiber Optic Distributed Sensors

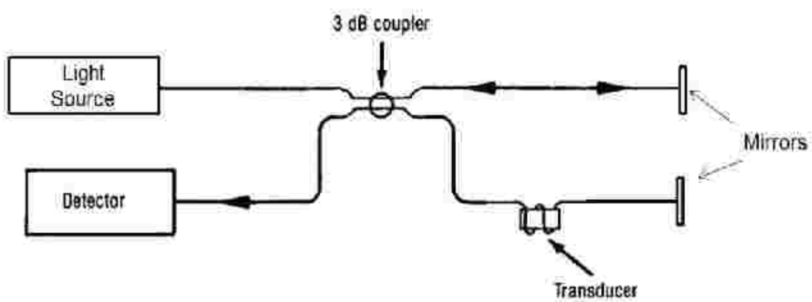


Phase Modulated Sensors

Interferometers

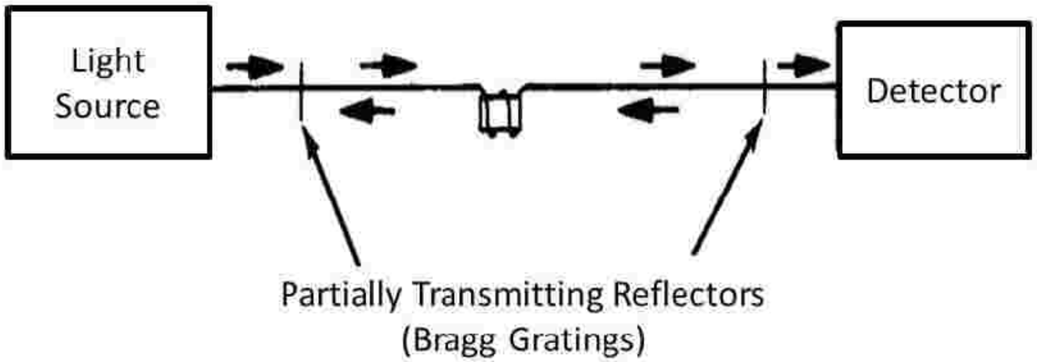


Mach–Zehnder interferometer configuration

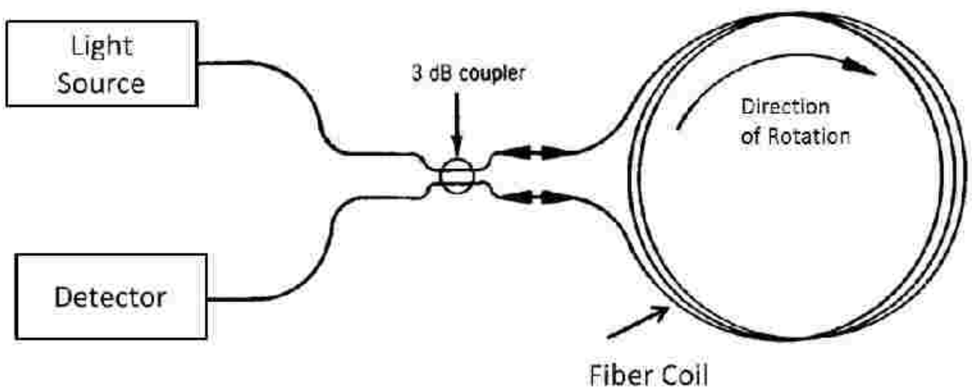


Michelson Interferometer configuration

Interferometers



Fabry–Perot interferometer configuration

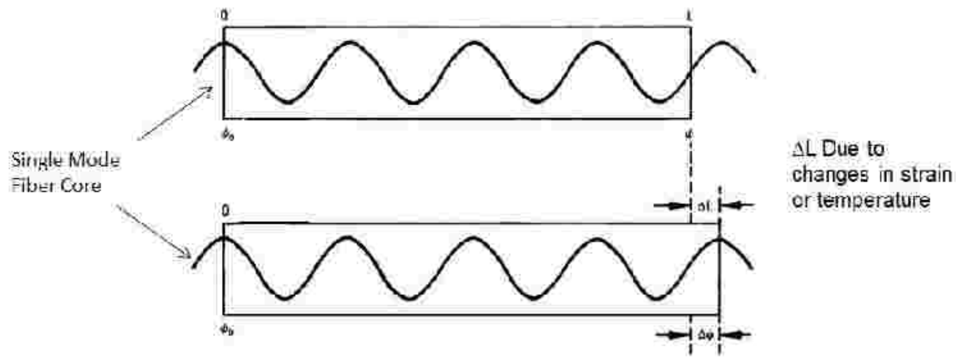


Sagnac interferometer configuration

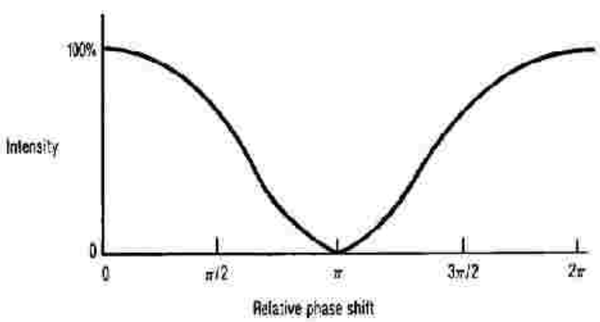
Phase Detection

- Change in length due to mechanical or thermal strain will cause a phase change (Mach-Zehnder interferometer)

$$\phi + \Delta\phi = \frac{2\pi}{\lambda_0}\left[n_1 L + n_1 \Delta L\right]$$



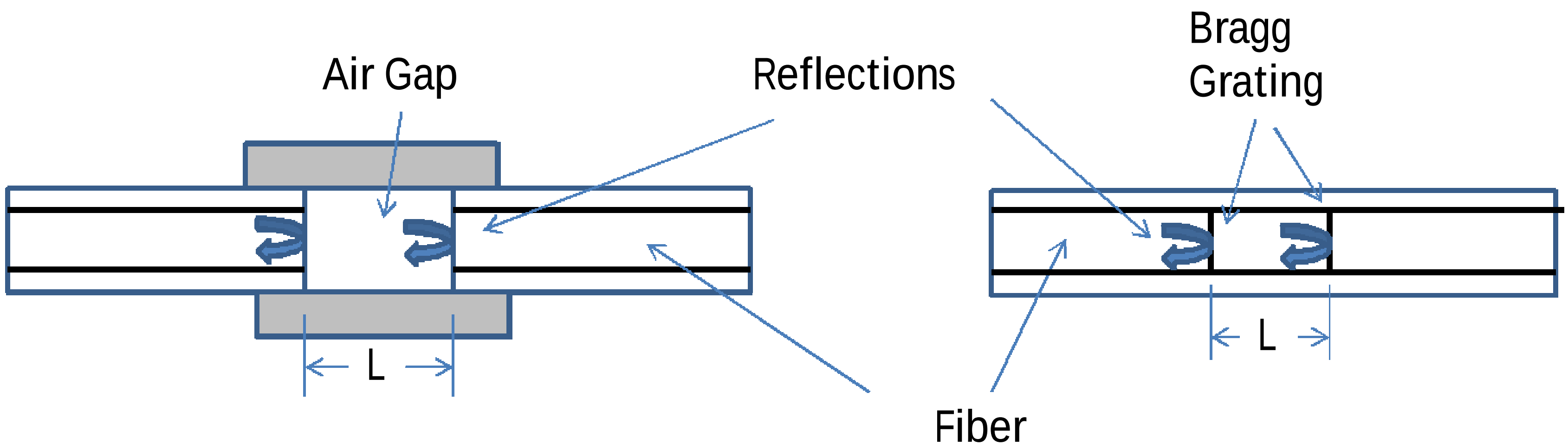
Phase change of a light wave through an optical fiber of original length *L* that has been stretched by a length ?*L*



Intensity versus relative phase shifts due to constructive and destructive interference

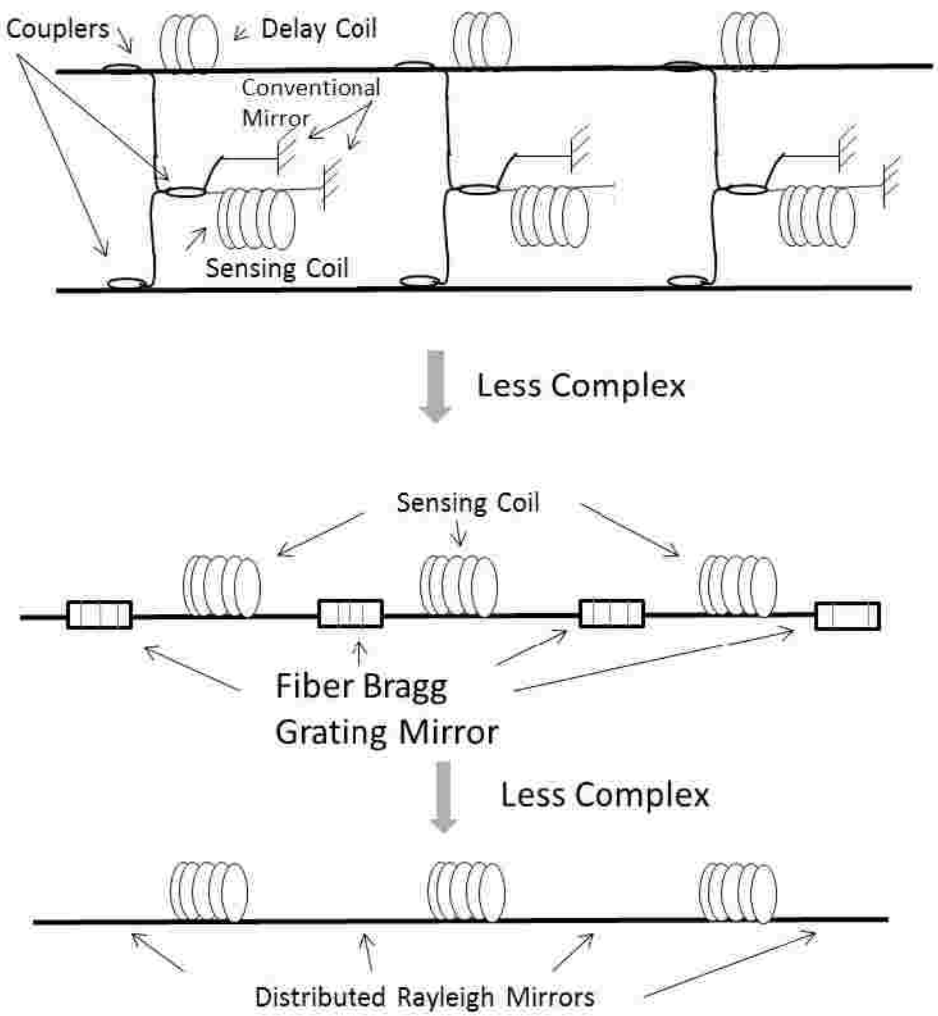
- Provides extremely high resolution
- Noise issues such as phase noise and multimode noise are addressed in the detection schemes

Fabry-Perot Interferometric Sensor Concepts



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

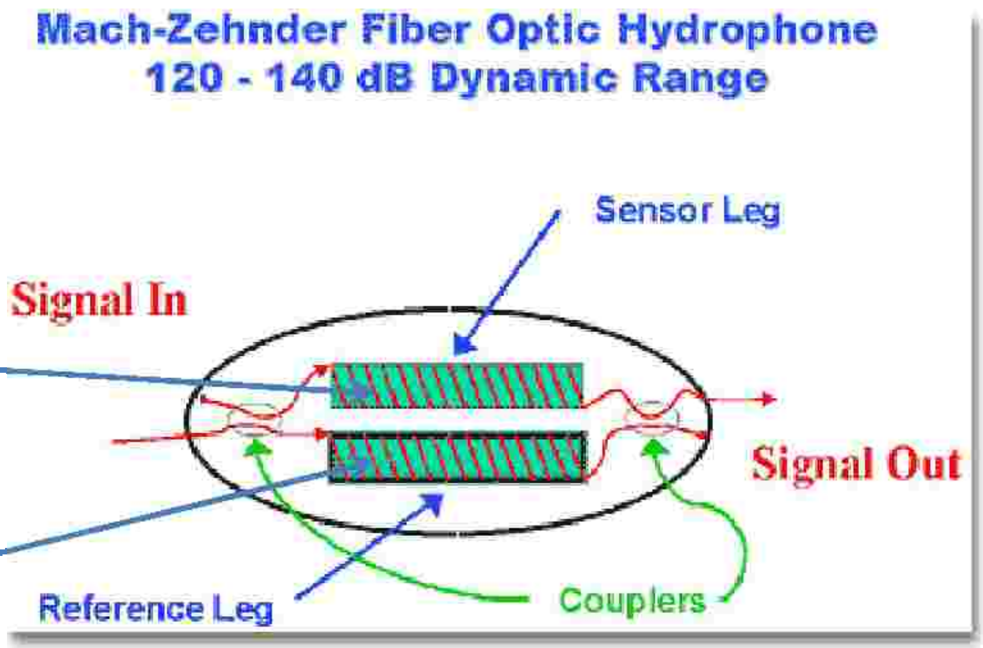
Interferometric Sensing Performance

- 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?

Hollow Mandrel – sensitive to Pressure Variations

Solid Mandrel – Insensitive to Pressure Variations



Source: Northrop Grumman

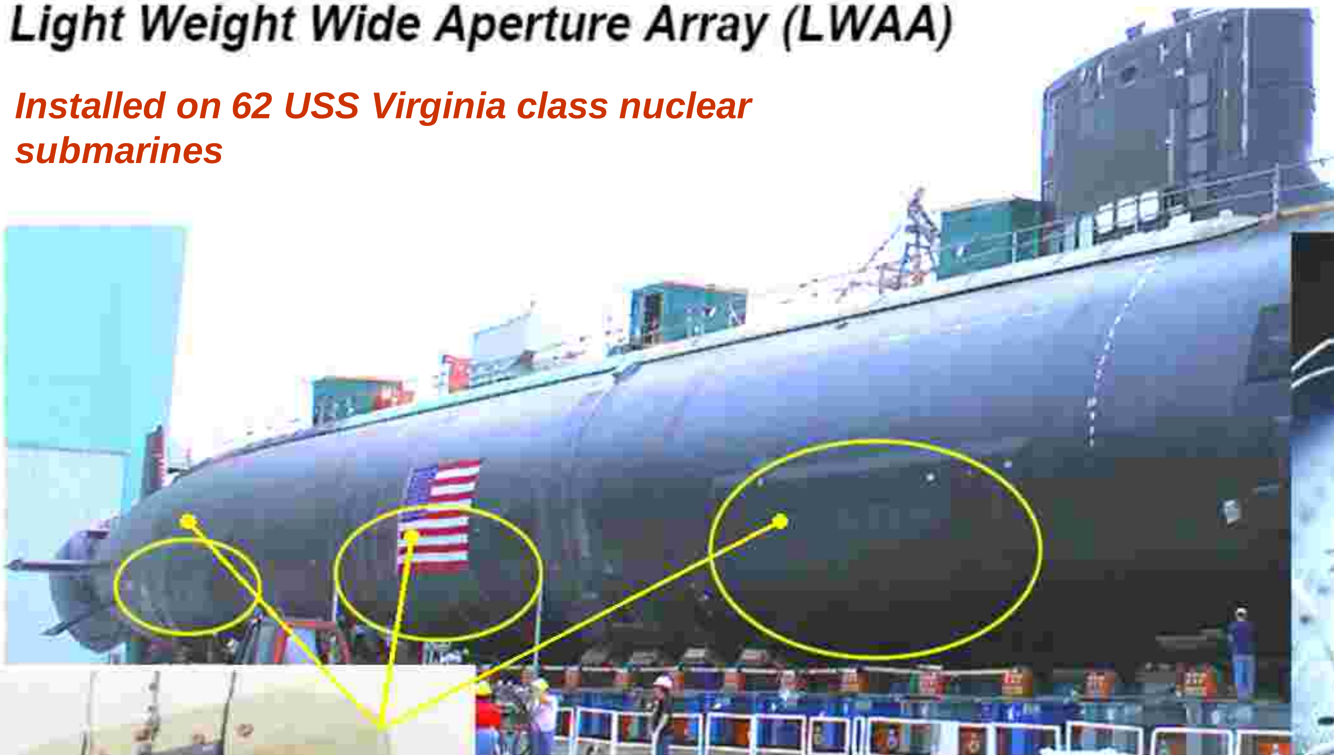
FOS Milestones:
Hydrophone Development

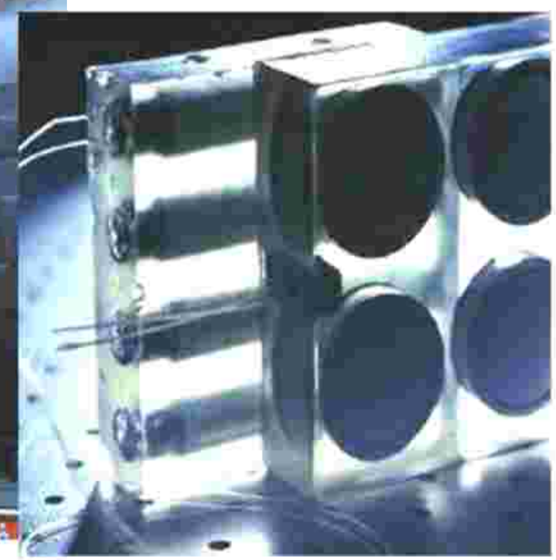
NORTHROP GRUMMAN

NAVAL RESEARCH LABORATORY
WASHINGTON, DC

Light Weight Wide Aperture Array (LWAA)

Installed on 62 USS Virginia class nuclear submarines



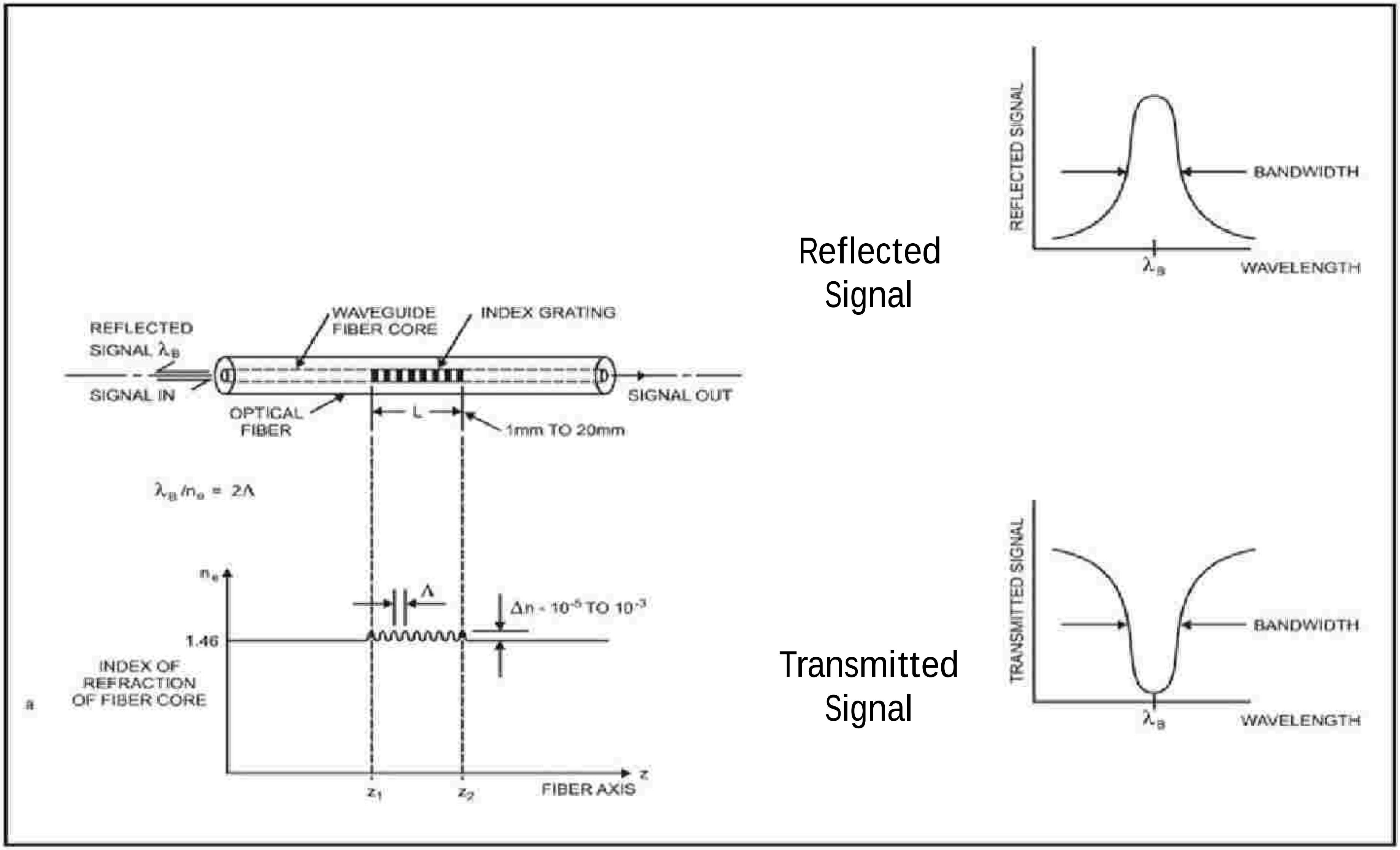


FO Planar hydrophone Arrays (three flat panels mounted low along either side of the hull), as well as two high frequency active sonars mounted in the sail and keel (under the bow).

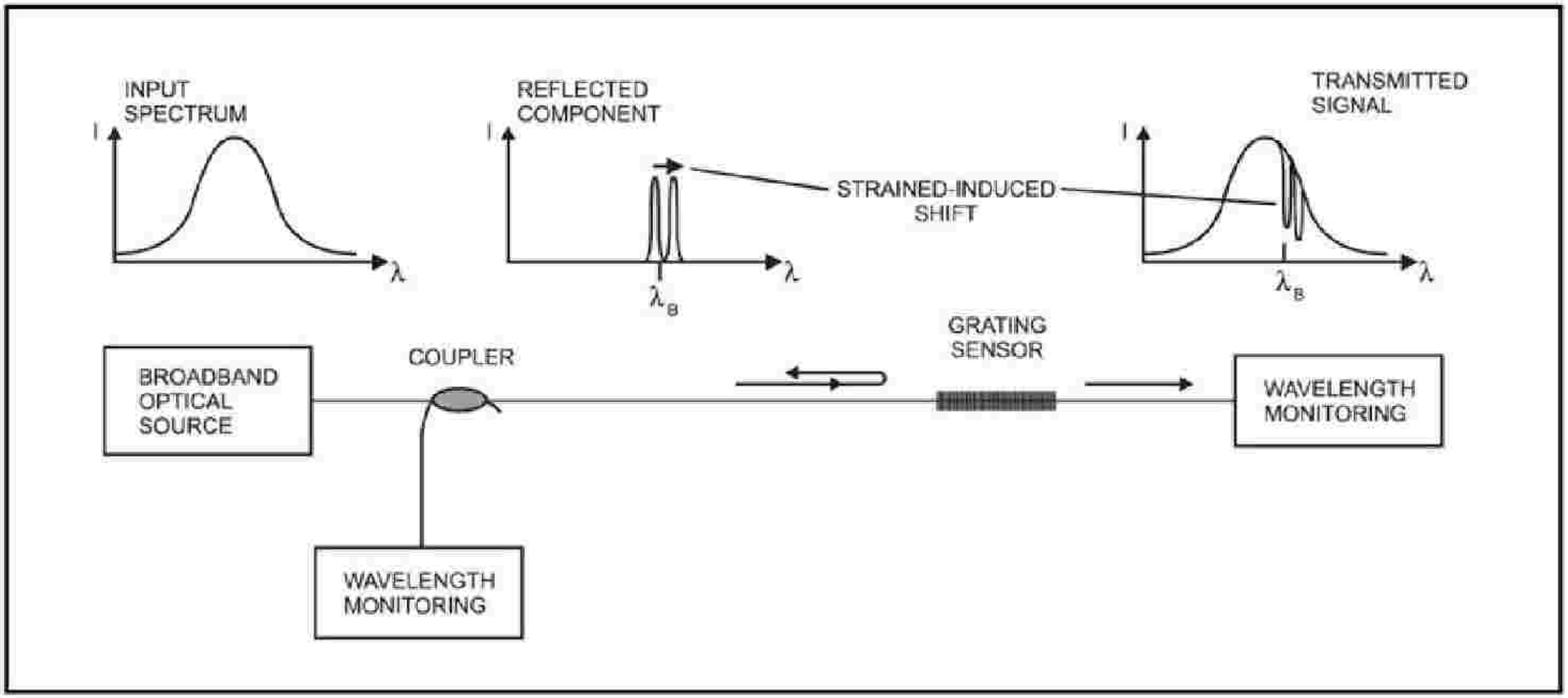
The result of 15+ years of R&D and $140M of investment!

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:

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

where:
e = the applied strain,
P_{11}, P_{12} = the stress optic coefficient,
a = the coefficient of thermal expansion,
? = Poisson's ratio,
n = the refractive index of the core, and
?*T* = the temperature change.

For constant temperature

n

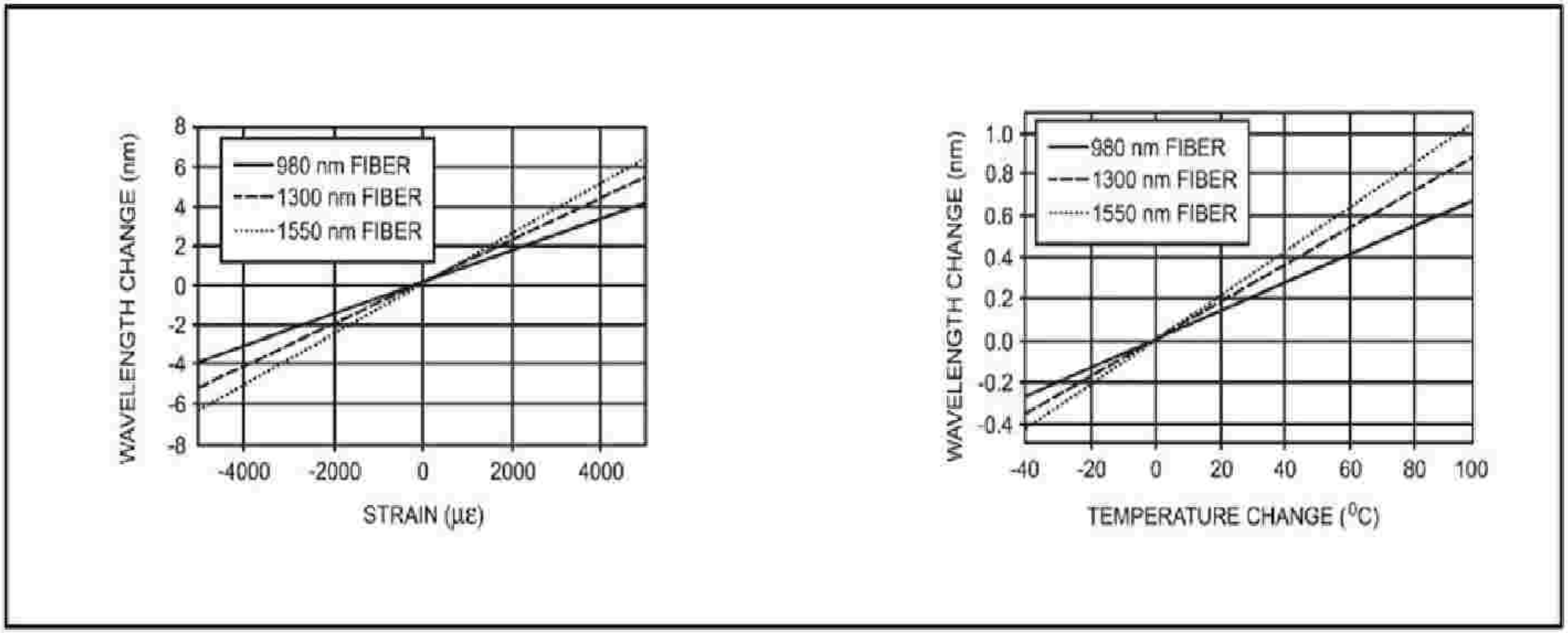
This relationship corresponds to 1 nm of wavelength change for 100 microstrain at a wavelength of 1300 nm.

For the case of zero applied strain

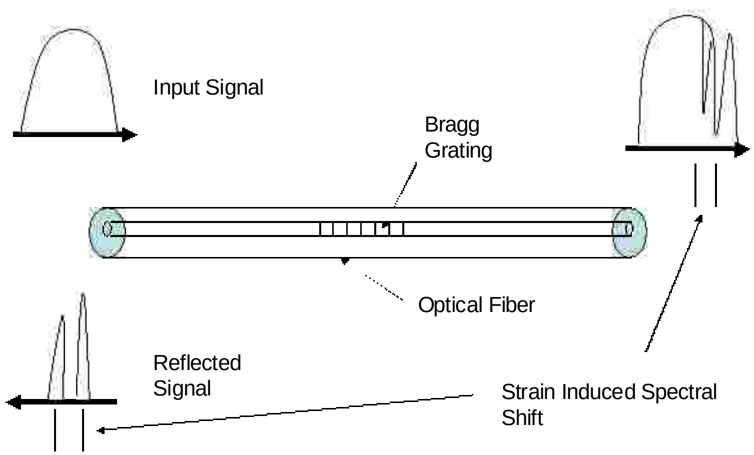
$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta T} = 6.67\times10^{-6}\ /\ ^\circ\mathrm{C}$$

At 1300 nm, a change in temperature of 1 °C results in a Bragg wavelength shift (??$_B$) of 0.01 nm.

Bragg Grating Sensor Response

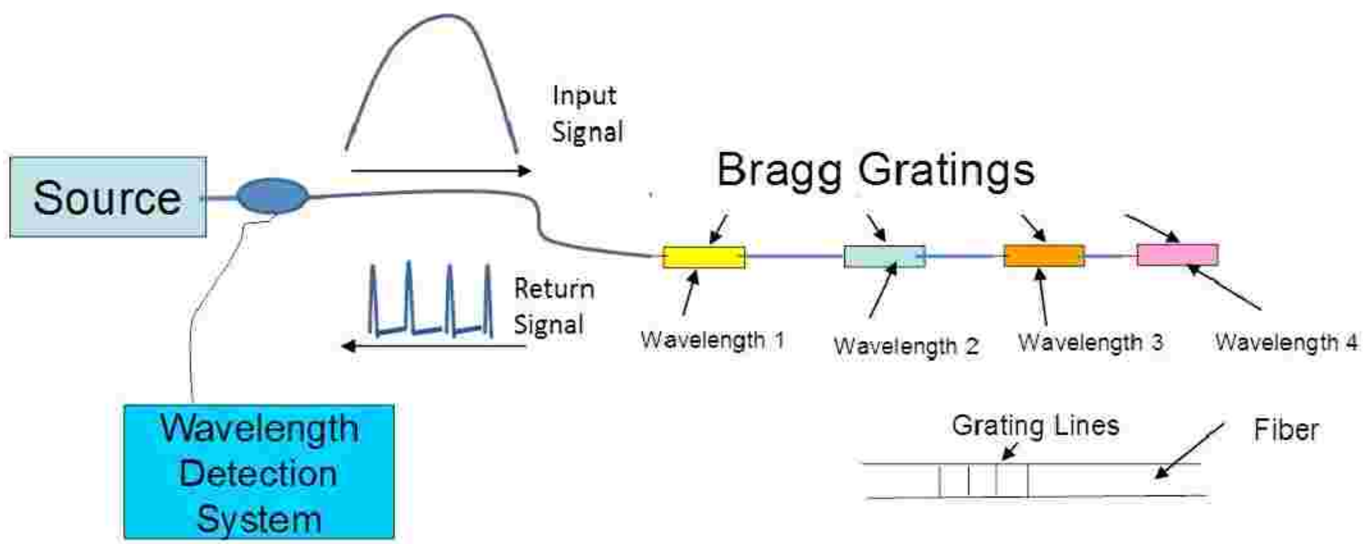


Bragg Grating Sensors

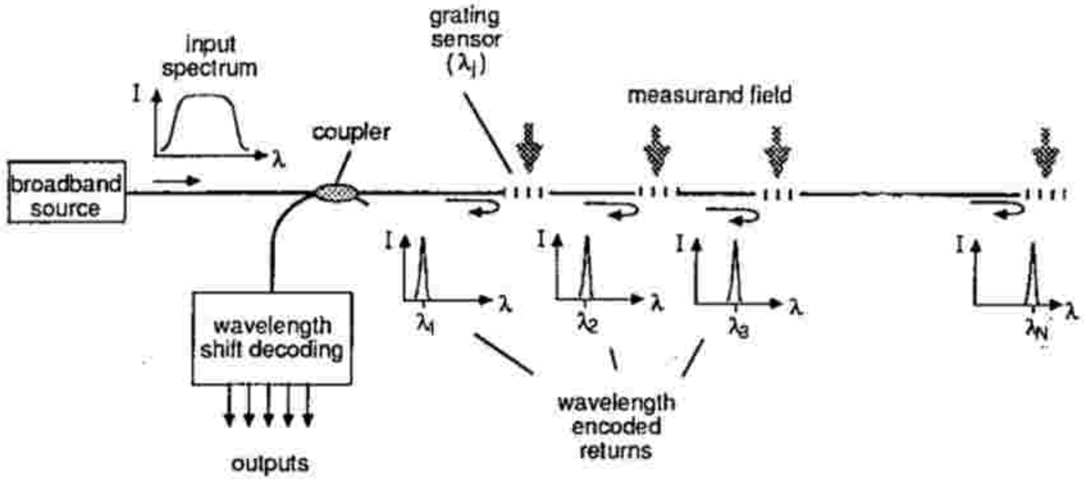


Performance

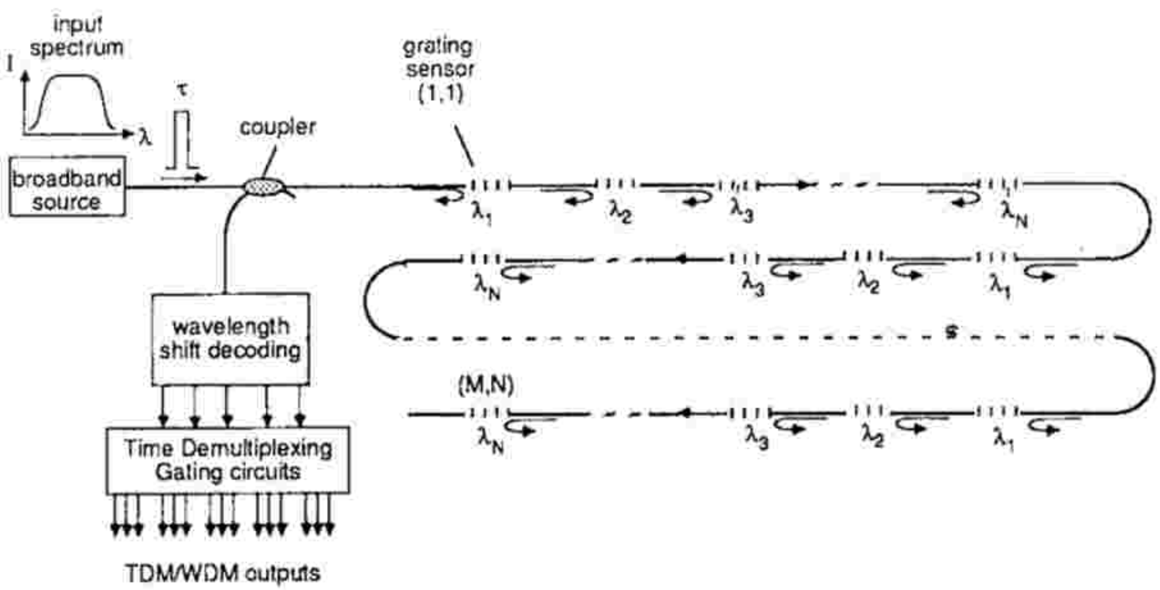
- Resolution - < 0.5 microstrain
- Long term accuracy - <1%
- Up to 20 sensing points in C band
- Can monitor low frequency dynamic strain
- Temperature resolution of 1°C
- Strain / temperature discrimination is required



Bragg Grating Distributed Sensing System Configurations

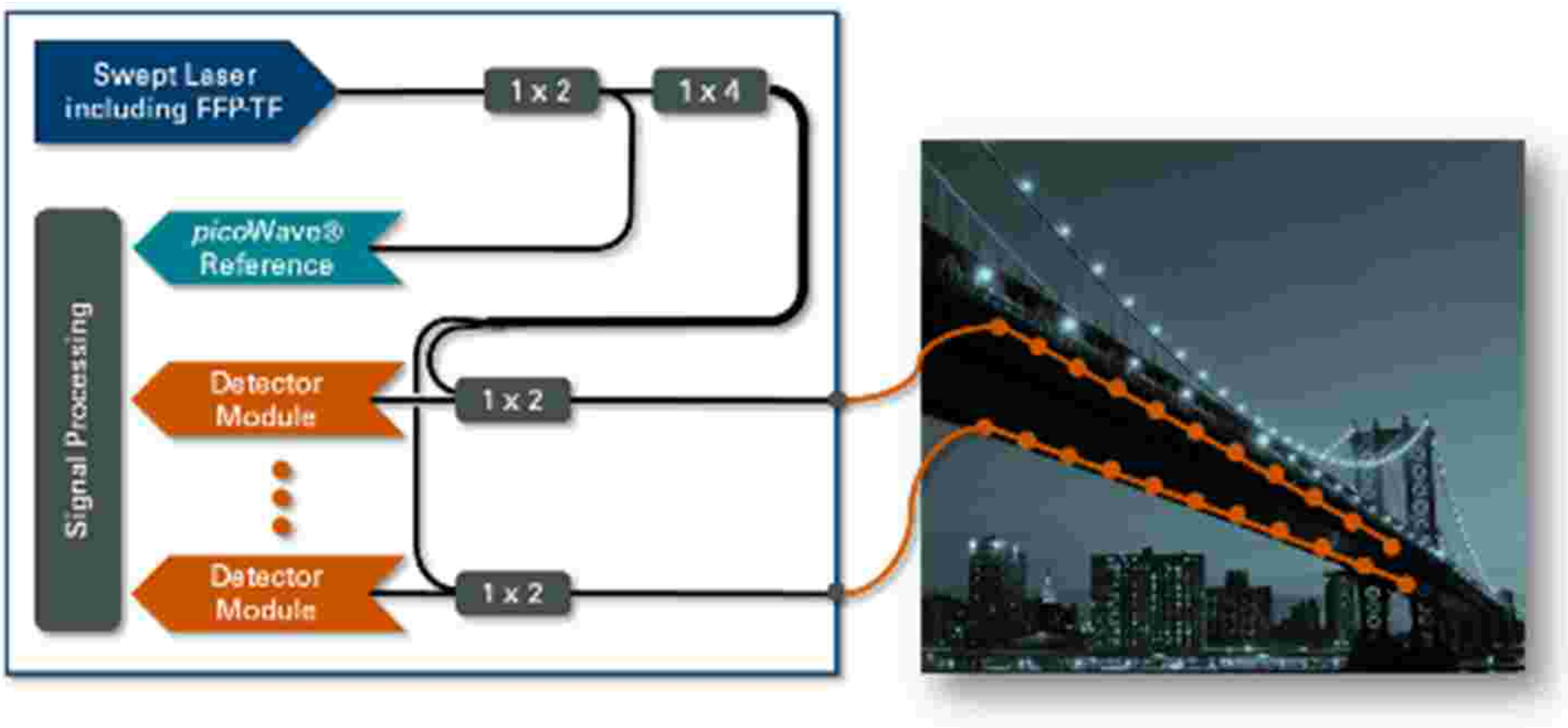


WDM



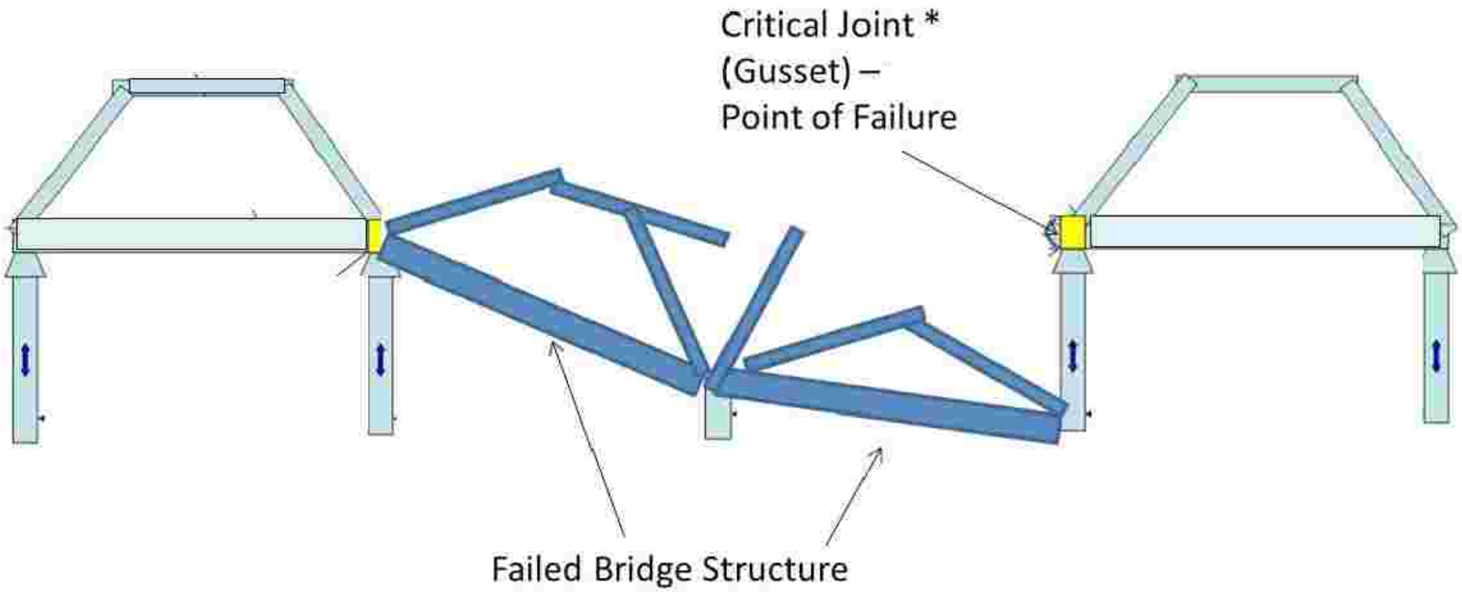
TDM/WDM

High Capacity WDM Distributed Sensing System Using Bragg Gratings

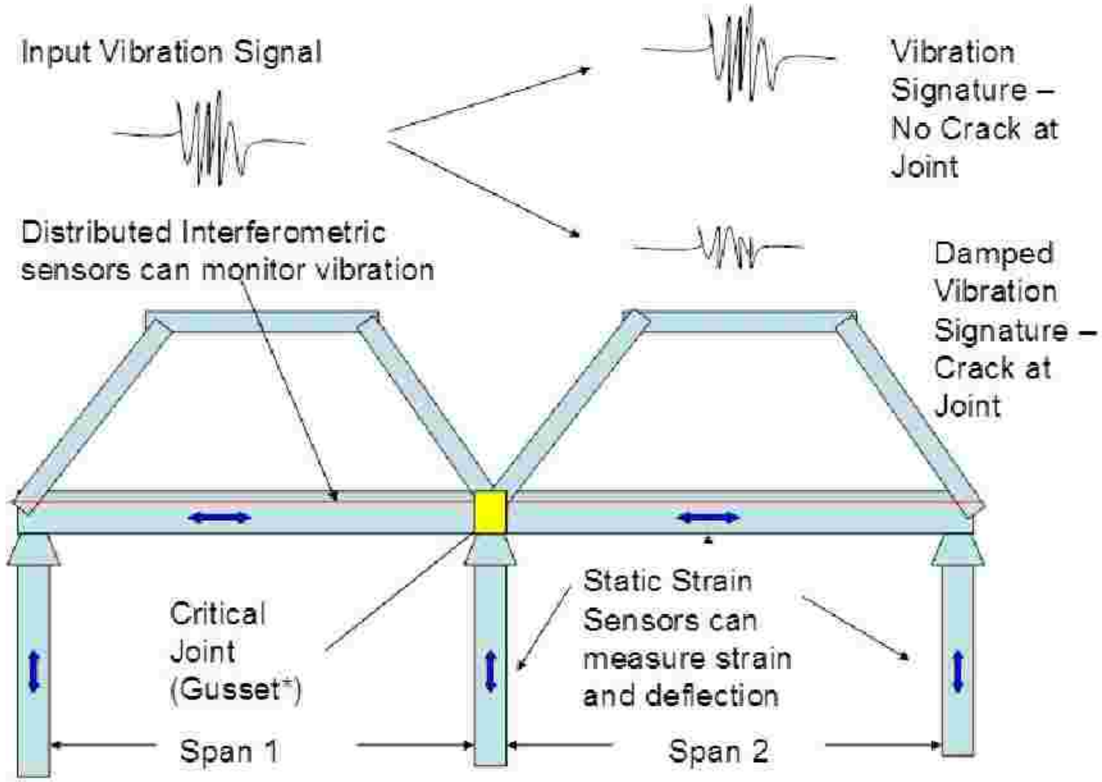


Source: Micron Optics

Bridge Failure in Minneapolis MN

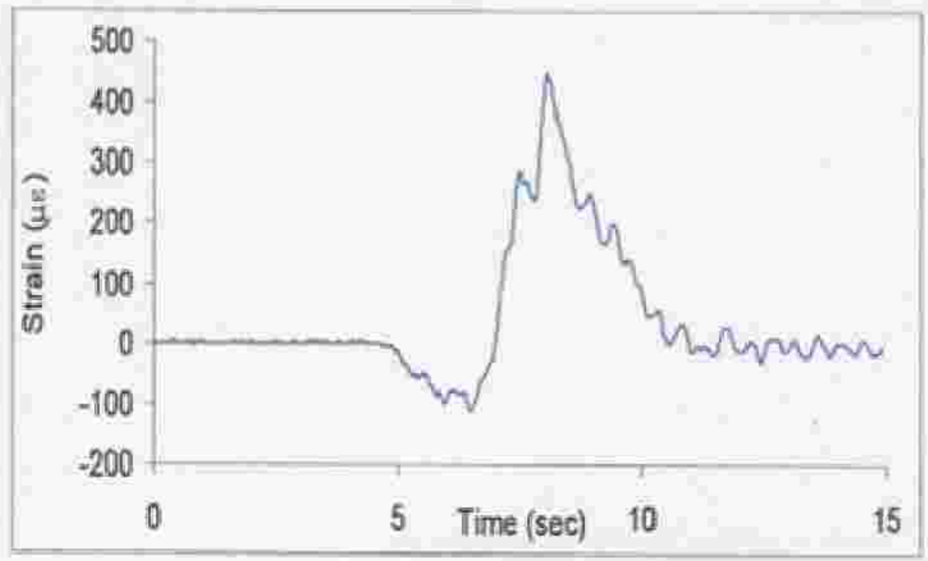


Conceptual Use of Static and Dynamic Strain Monitoring in a Bridge Application



* Suspected failure point in Minneapolis bridge failure

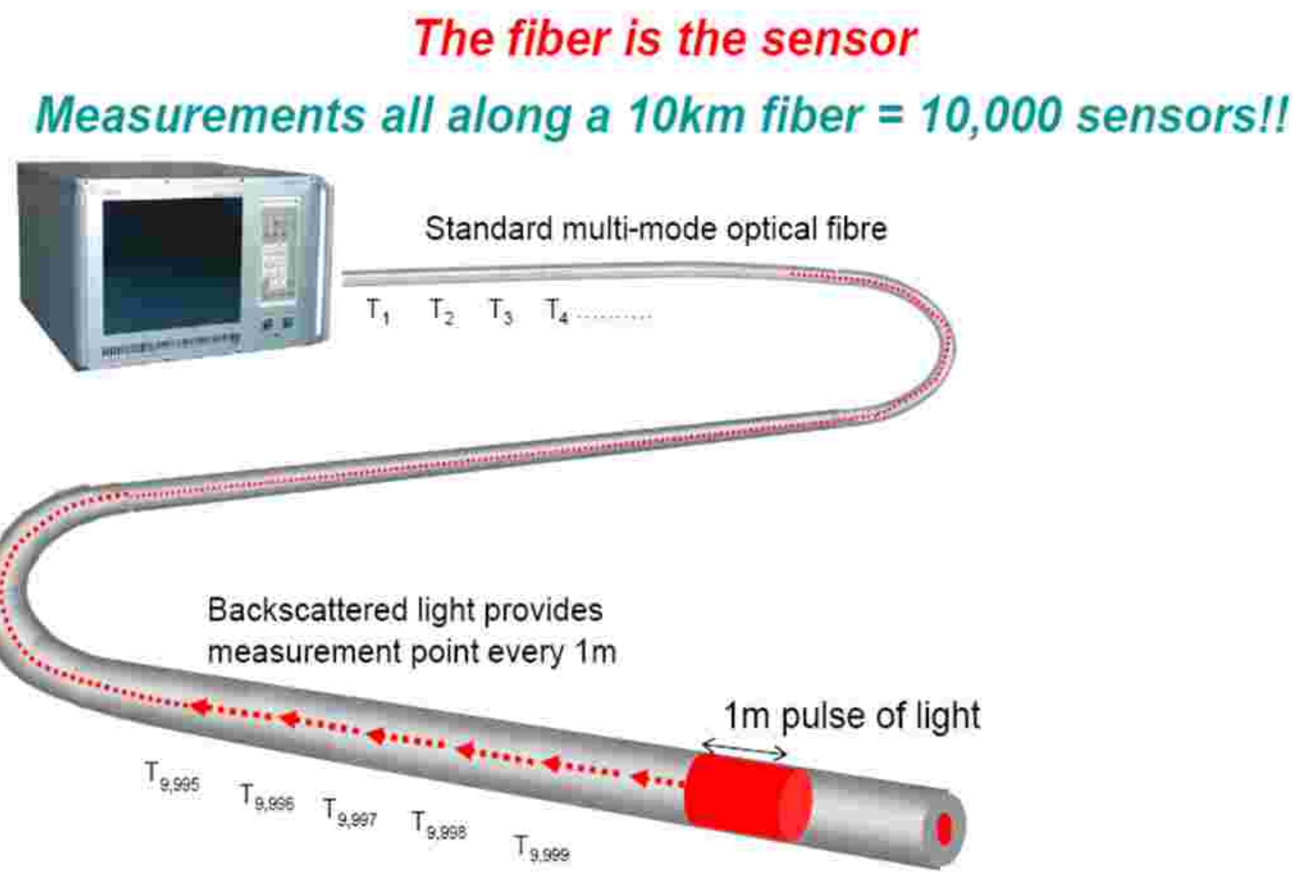
Strain change with Time Associated with Bridge Traffic



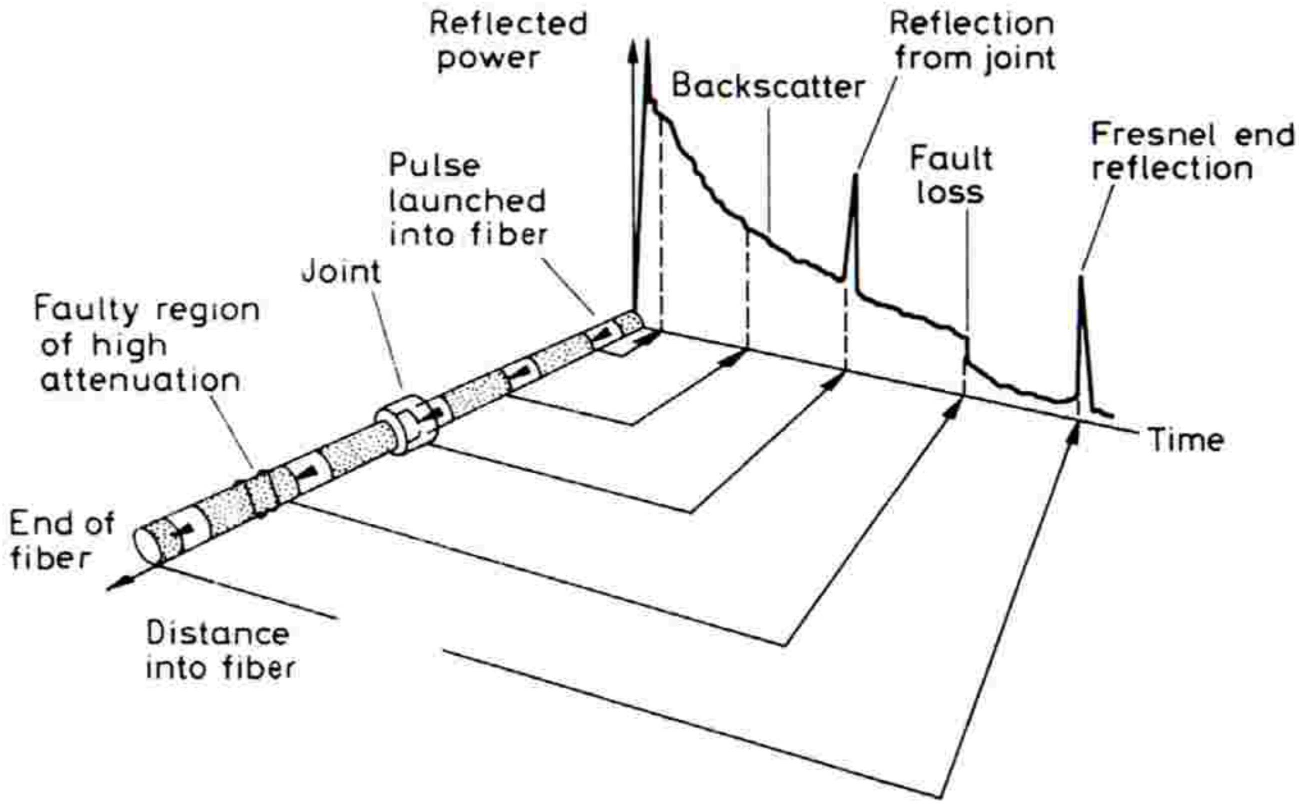
Source: Micron Optics

Scattering Based Sensors

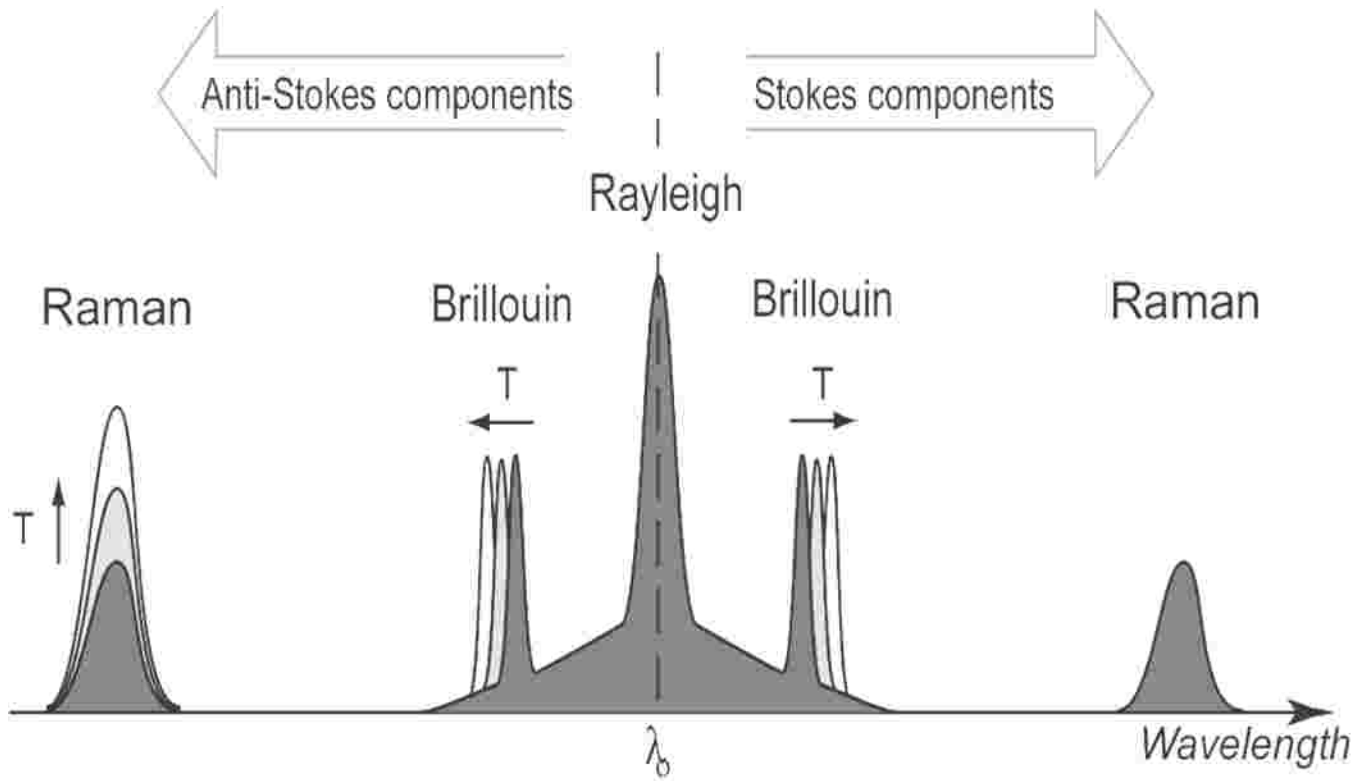
Distributed Sensing Applications



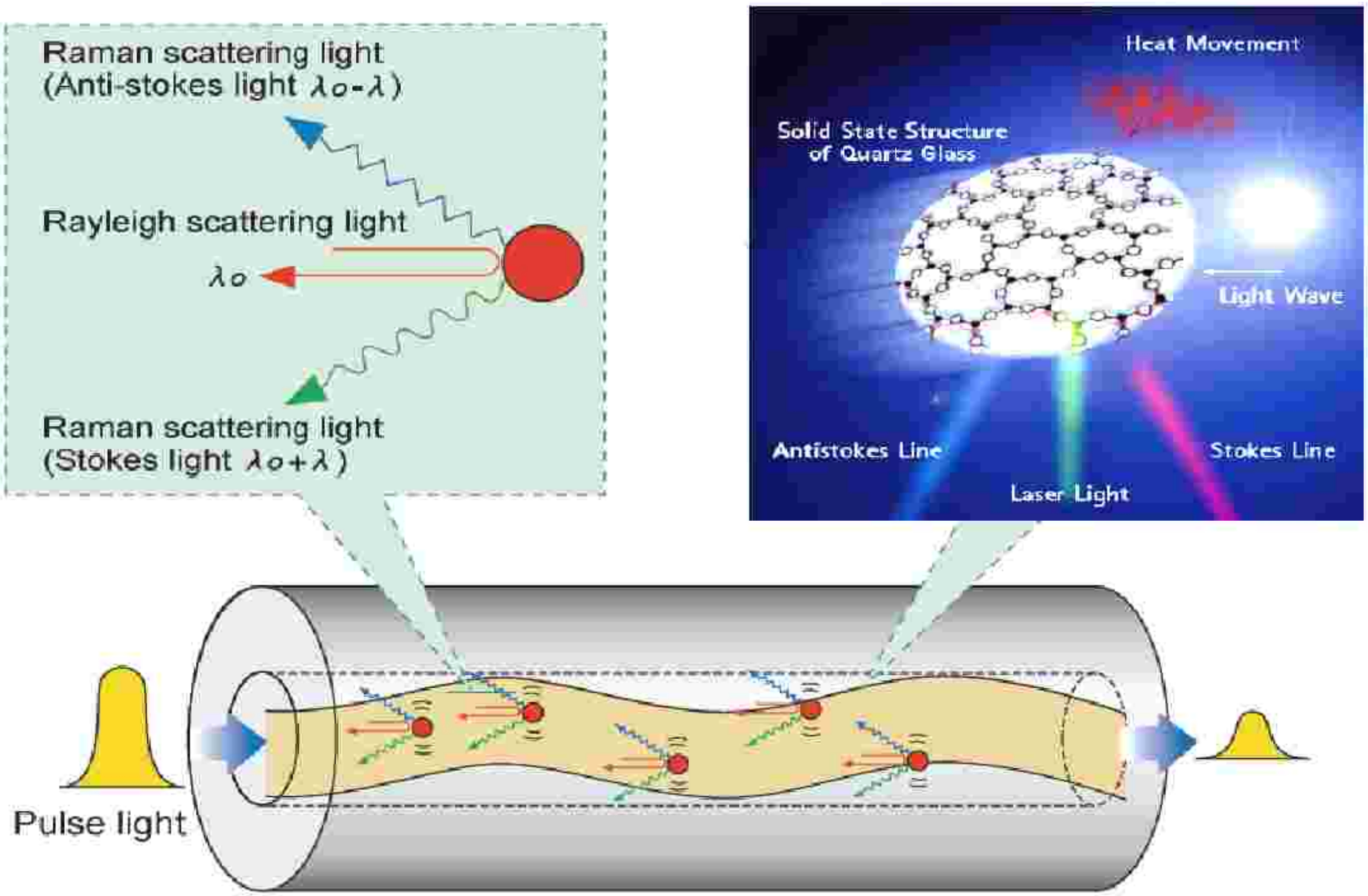
Distributed Sensing System Based on Scattering



Emission from Raman, Brillouin and Rayleigh Scattering

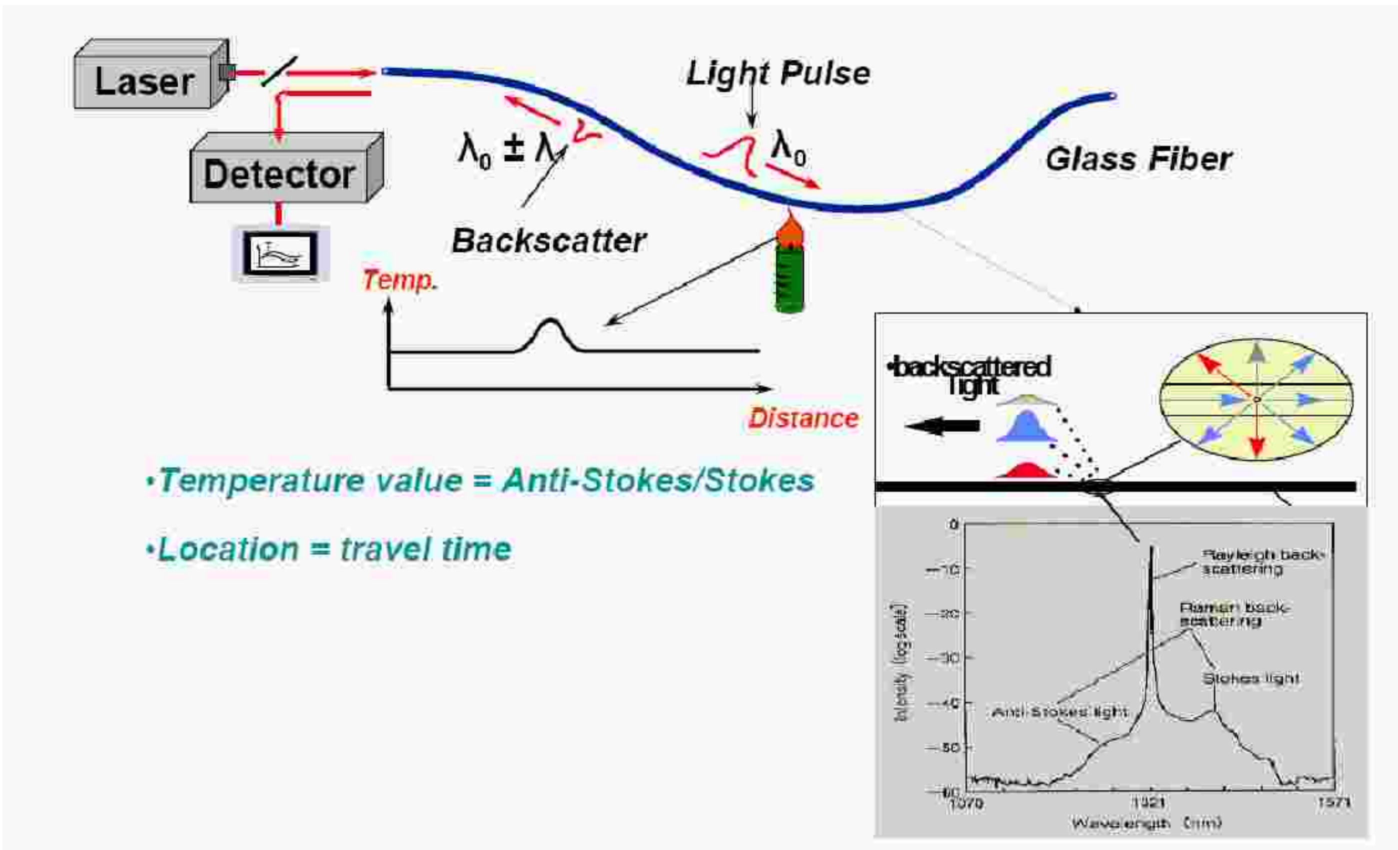


Raman Scattering Process in Optical Fiber



Source: Sumitomo & LIOS

Raman Scattering Distributed Temperature Sensing (DTS).



Temperature and Strain Sensitivities for Various Scattering Effects in Optical Fiber

	Temp Sensitivity	Strain Sensitivity
Rayleigh	weakly	weakly
Raman	strong- antistokes/ (intensity)	weakly
Brillouin	Strong (wavelength)	Strong (wavelength)

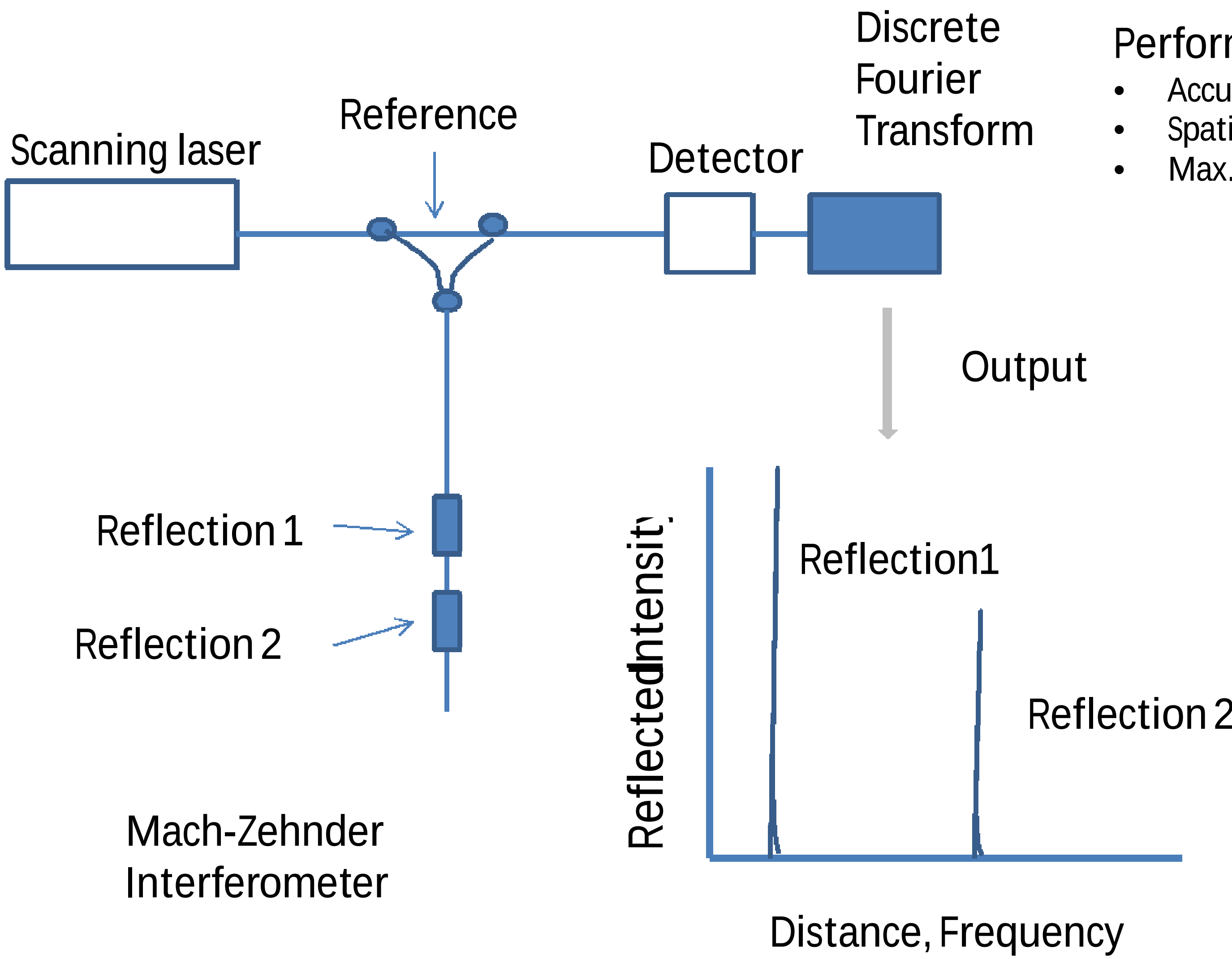
Raman Scattering Performance

- Only measures temperature and is independent of strain.
- The temperature resolution is 0.5^{o}C
- The measurement range is up to 15 km with a 1 meter spatial resolution (up to 25km 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^{o}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 Interferomter Based on Rayleigh Scattering



Performance

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

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.

Sector	Offshore, Secondary & Tertiary Recovery
Regions	Global
Products	P/T Gauges, DTS, Flow, Seismic, Acoustic
Ratings	150-280°C, 25kpsi
Installations	>2,000 permanent; >100,000 surveys
Operating Hours	>20 million

Fiber Optic Sensors in Oil & Gas

Sensors for Downhole Monitoring

- Pressure
- Temperature
- Flow Rate
- Phase Fraction
- Seismic

} Commercially Available

- Strain
- Sand

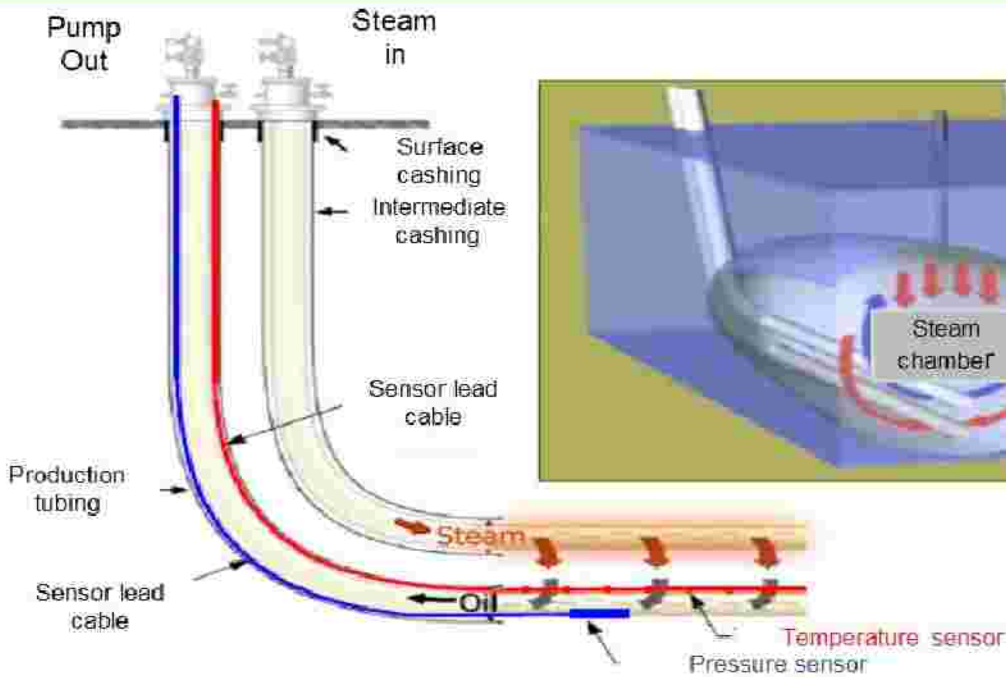
} Horizon

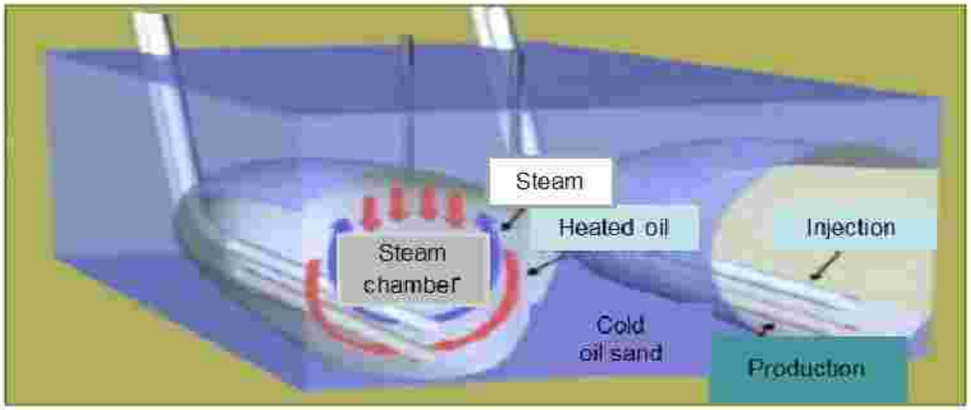
- Paraffin
- Chemical
- Density

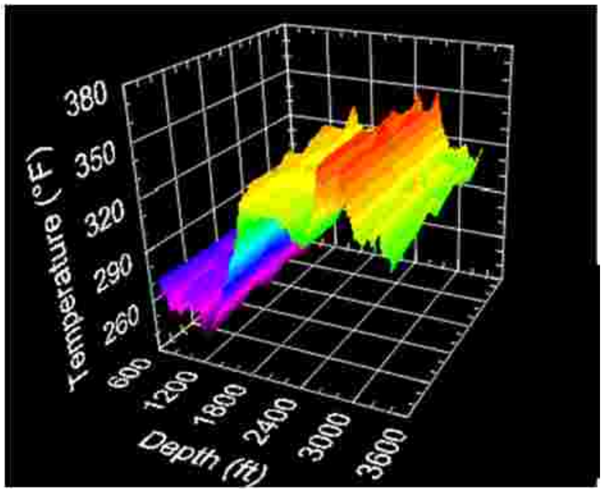
} Concept Phase

Source: Weatherford

DTS - SAGD



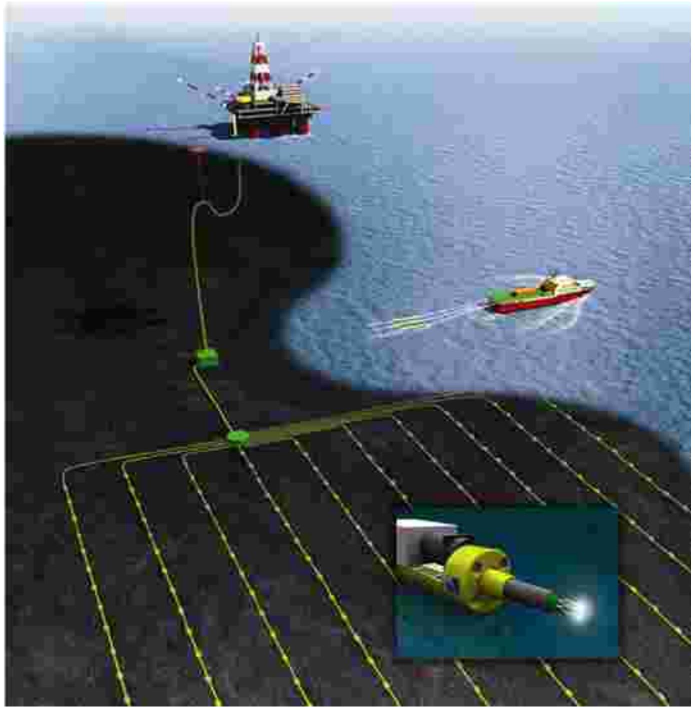




- Steam Assisted Gravity Drainage (SAGD) is an enhanced oil recovery technology for producing heavy crude oil utilizing steam injection
- 80% of oil sands require enhanced recovery techniques such as SAGD
- Optimizing steam management optimizes reservoir production, reduces costs and limits emission
- 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



Courtesy Petroleum Geo-Services

•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

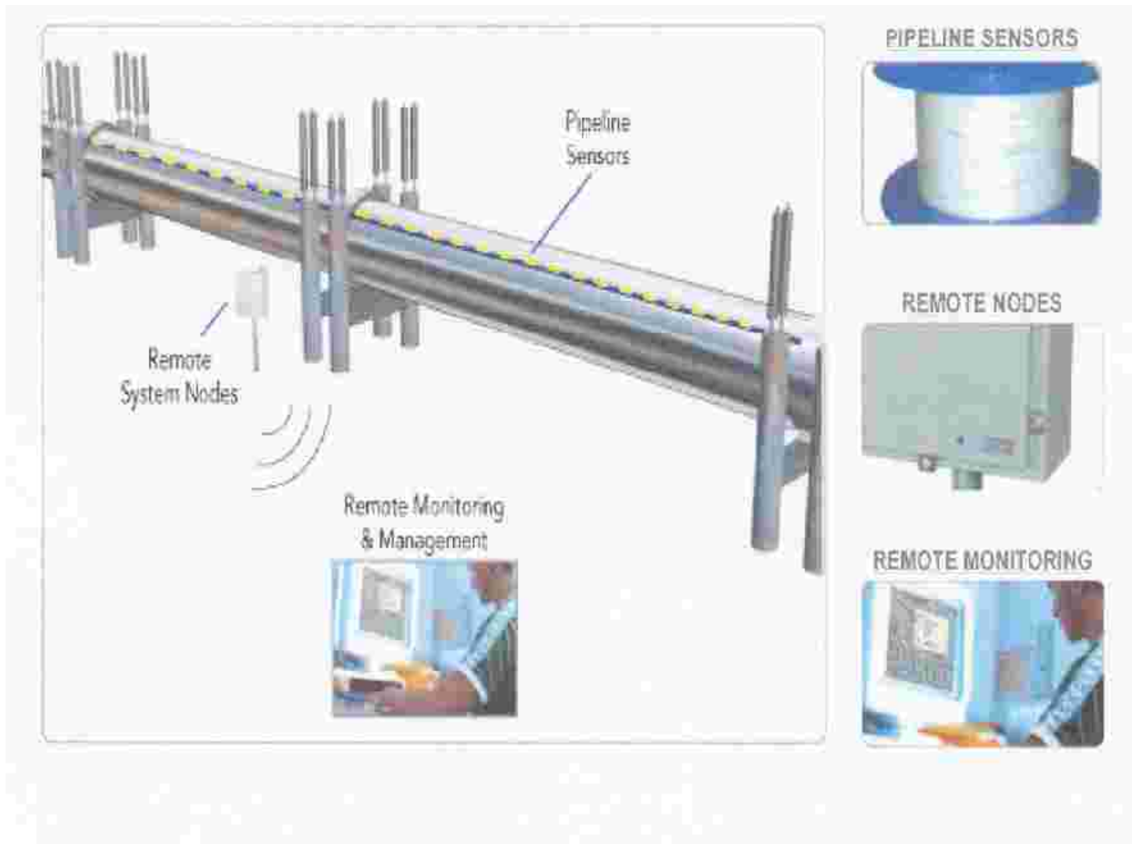
- Interferometric and DAS systems can monitor 25 km or longer
- DTS and DTSS systems have been used to monitor leaks which cause a local temperature drop

•Fiber optic interferometric array monitors about 25 Km

•Multiple arrays cover hundreds of km

•Data transferred through wireless node

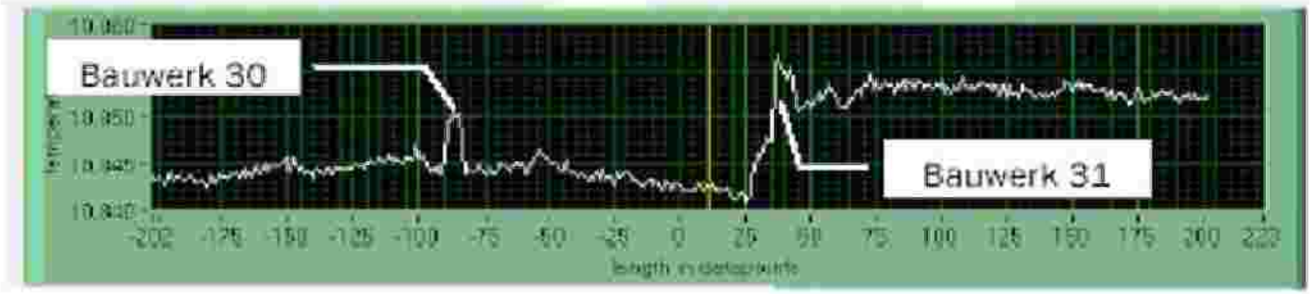
•In evaluation trials



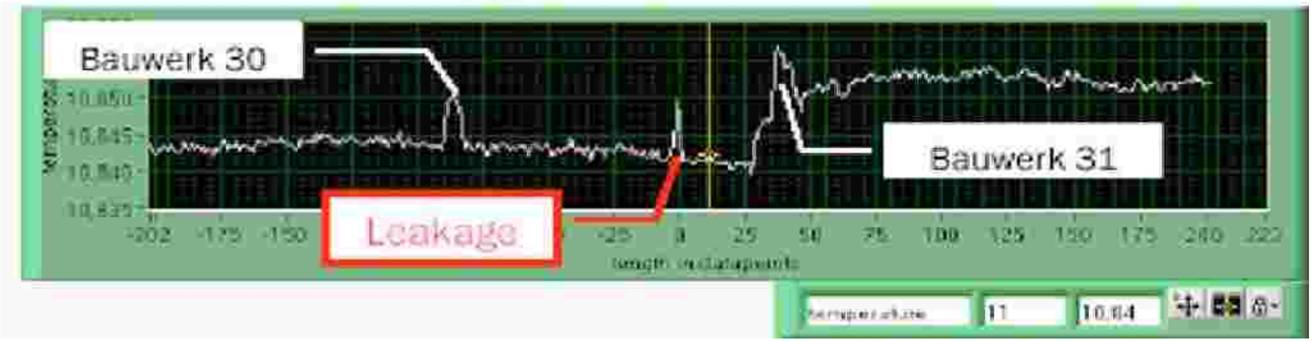
Source: Sabeus

Pipeline Leak Detection (Distributed Brillouin Scattering)

(a)

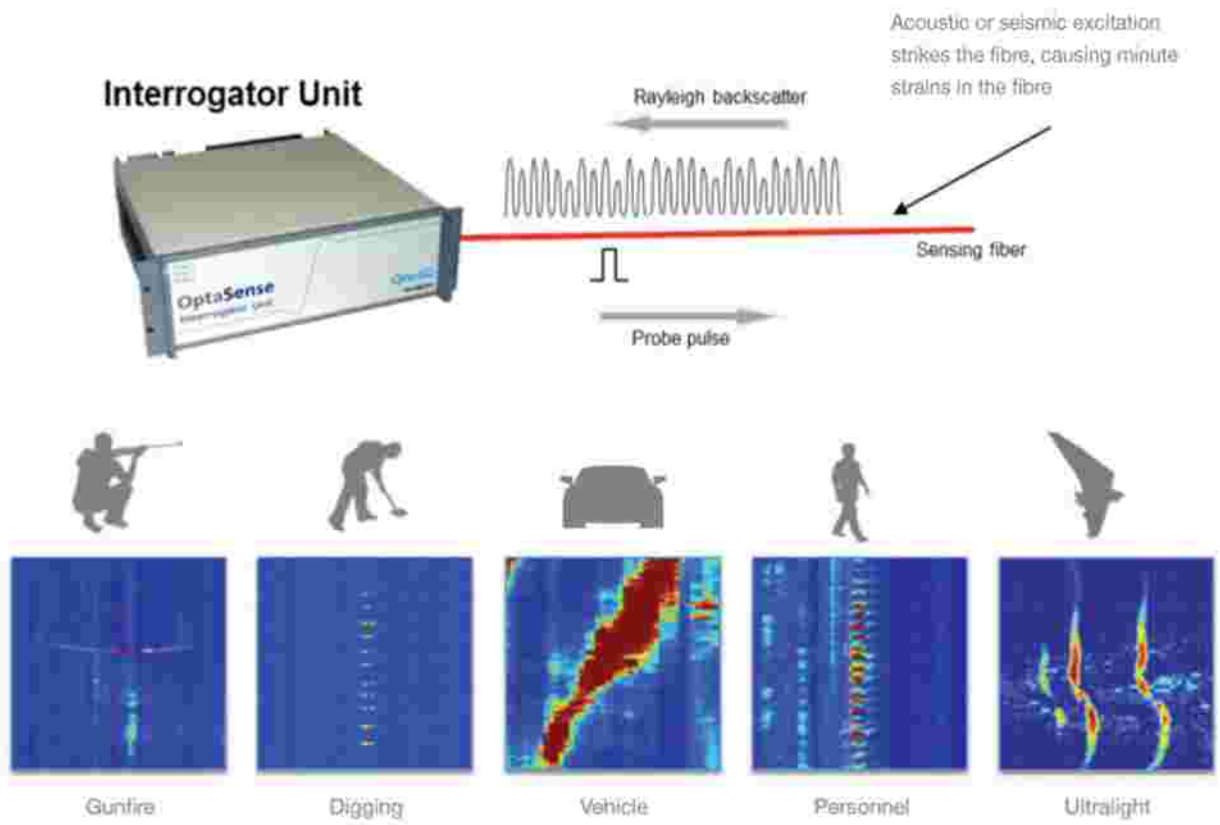


(b)



Source: Omnisens

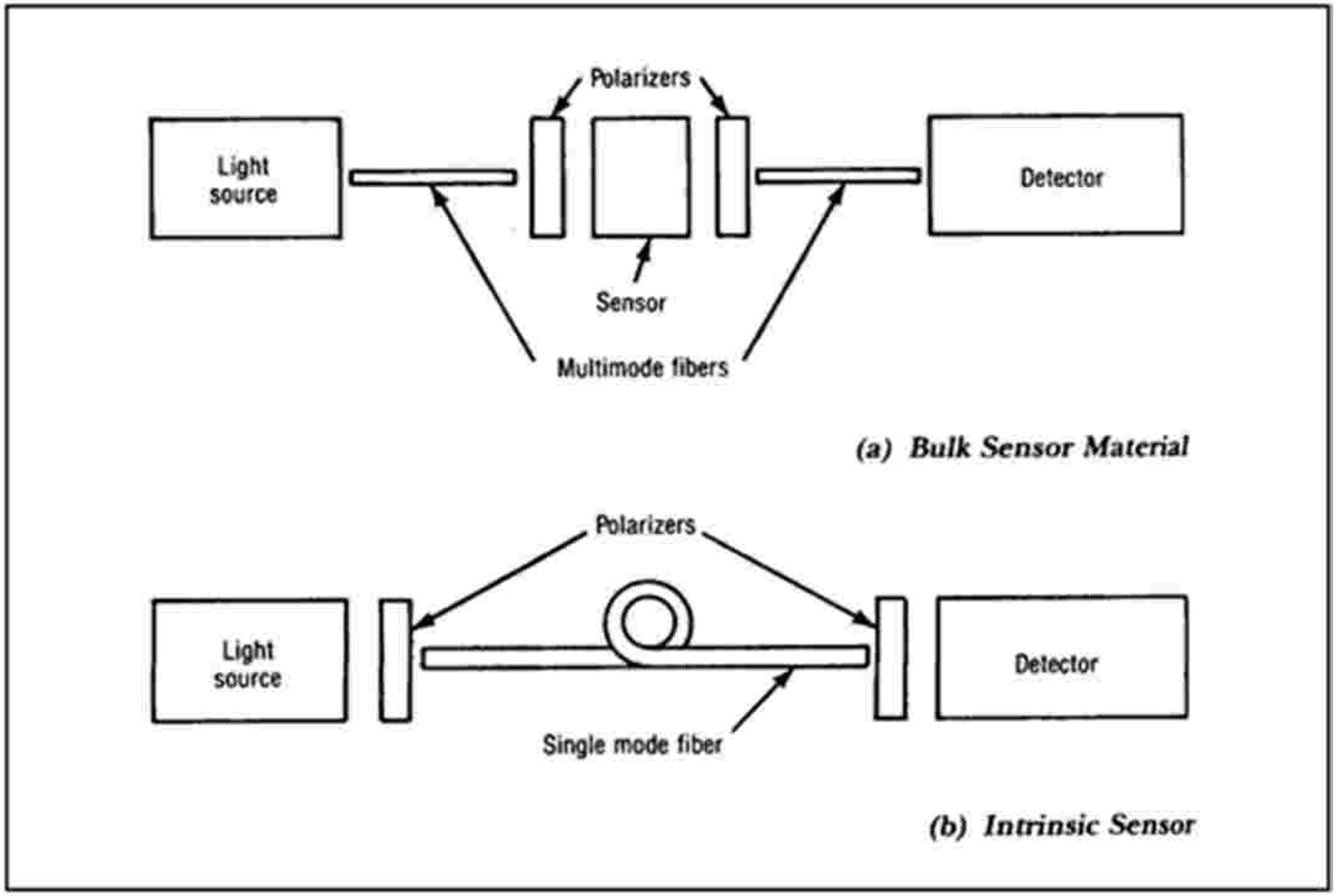
DAS Acoustic Signatures



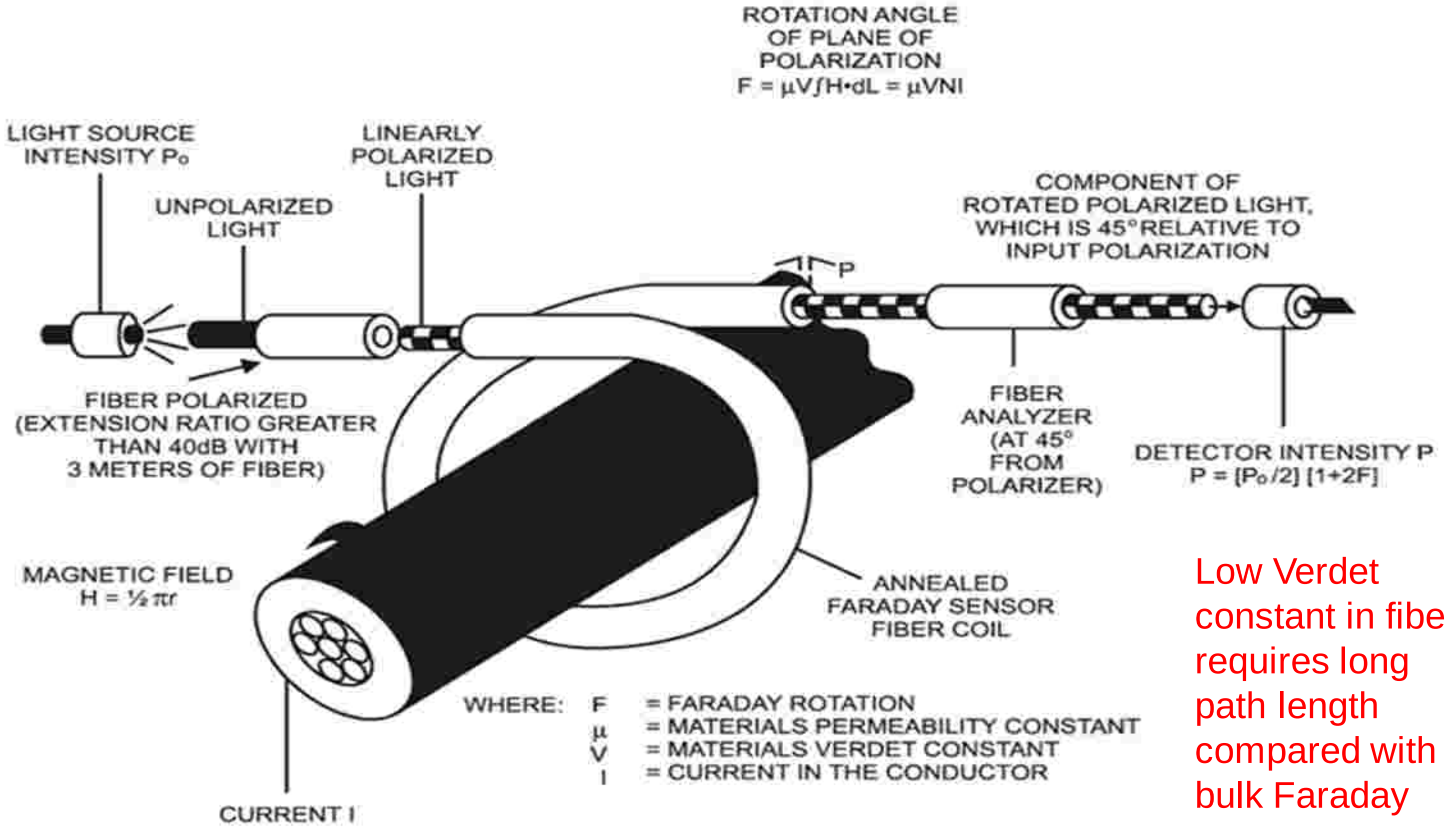
Source: OptaSense

Magnetic and Electric Field Sensors

Fiber Optic Magnetic Field Sensor Architectures

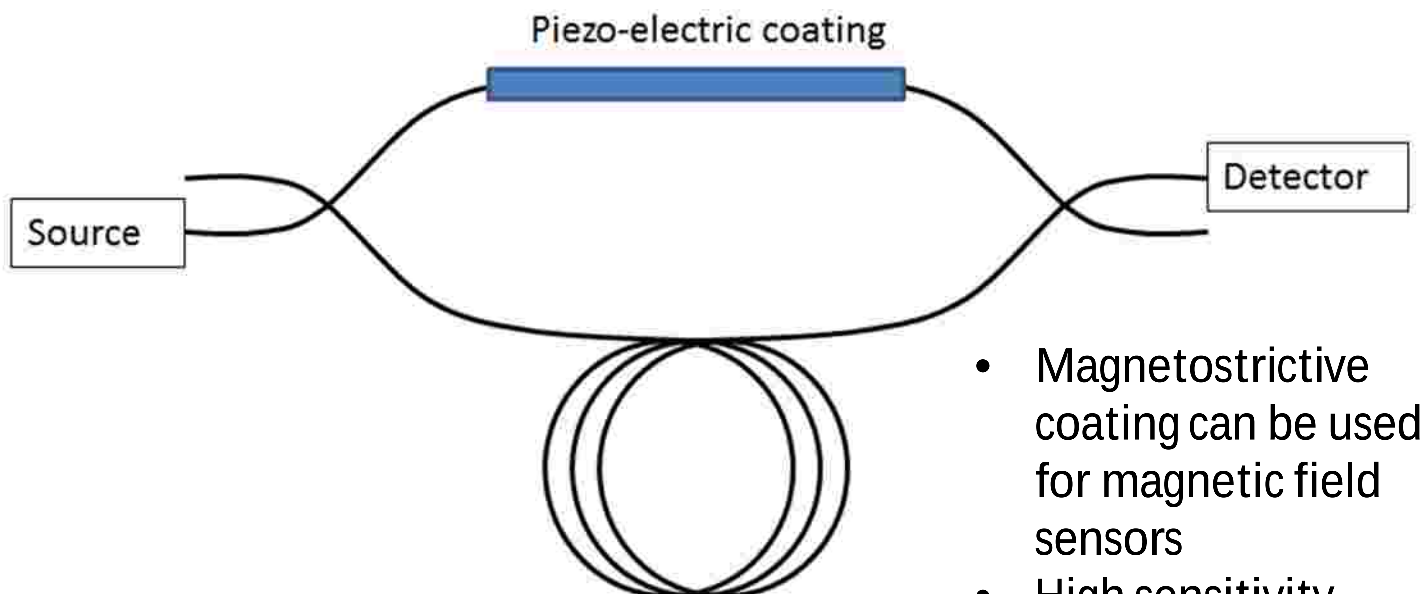


Faraday Rotating Optic
Attached Polarizing Optics



Low Verdet constant in fiber requires long path length compared with bulk Faraday rotators

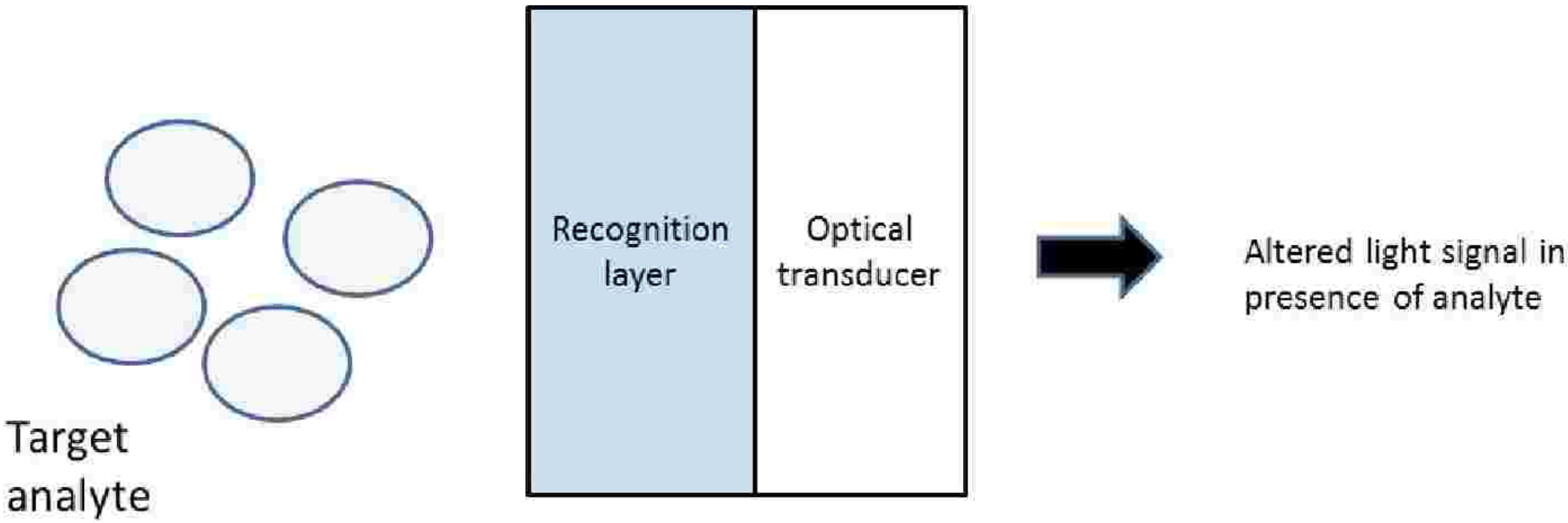
ensor with Piez
Coatings



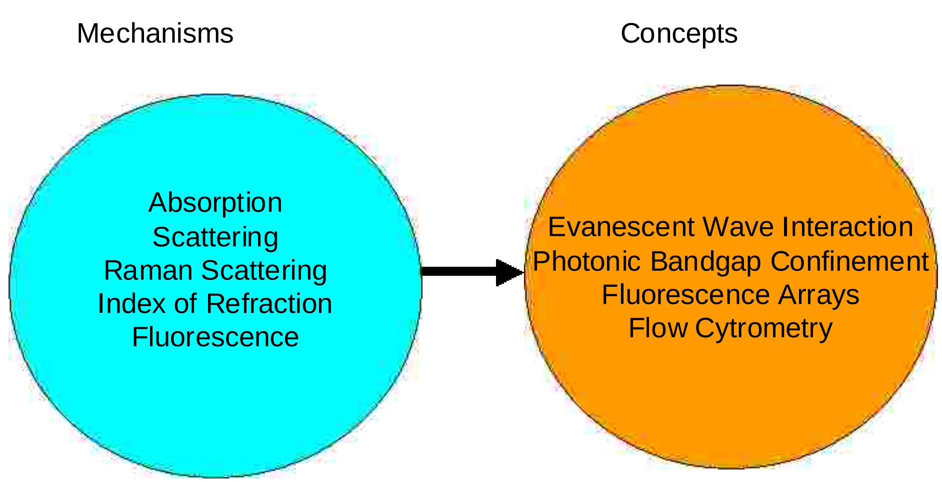
- Magnetostrictive coating can be used for magnetic field sensors
- High sensitivity potential

Biophotonic Sensors

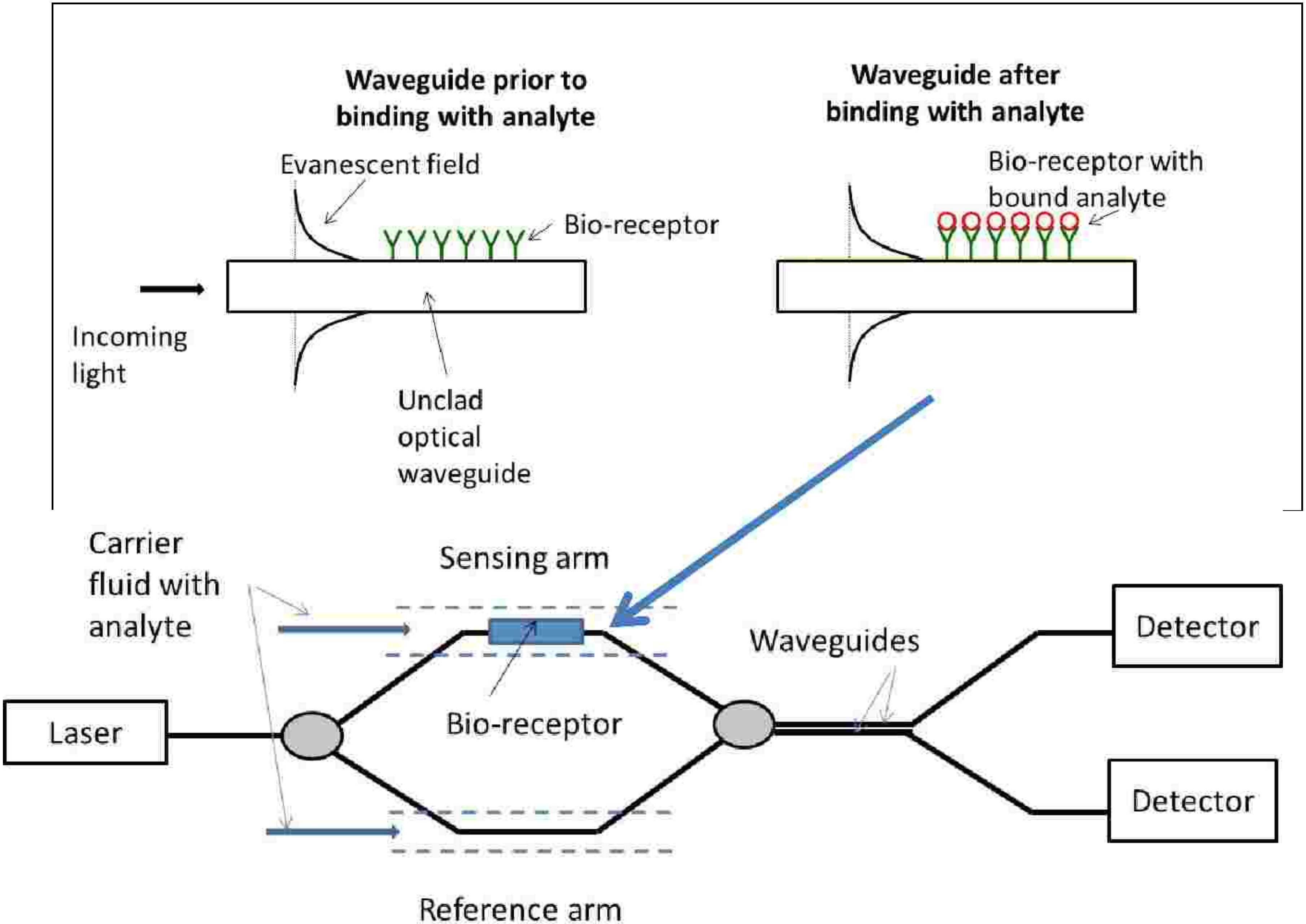
Biosensor Concept



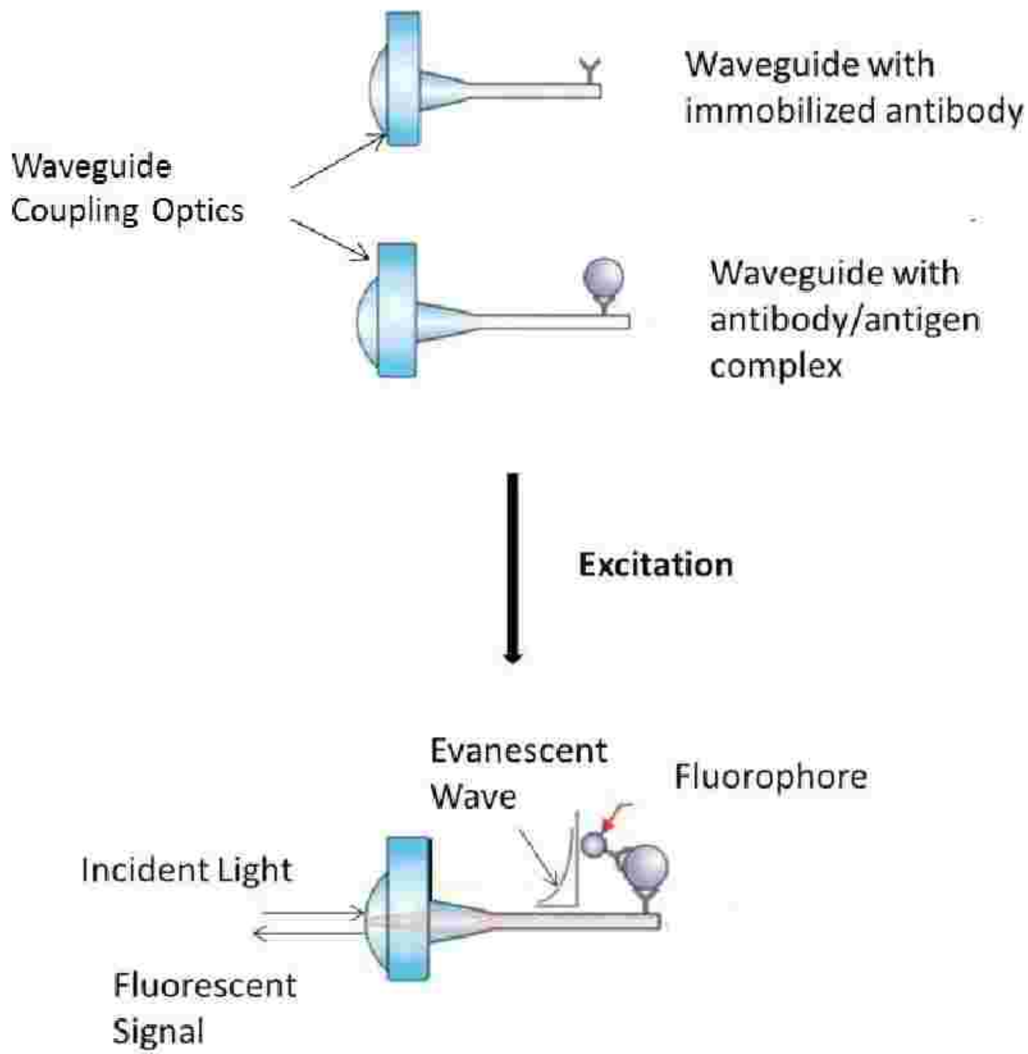
Intrinsic Biophotonic Sensors



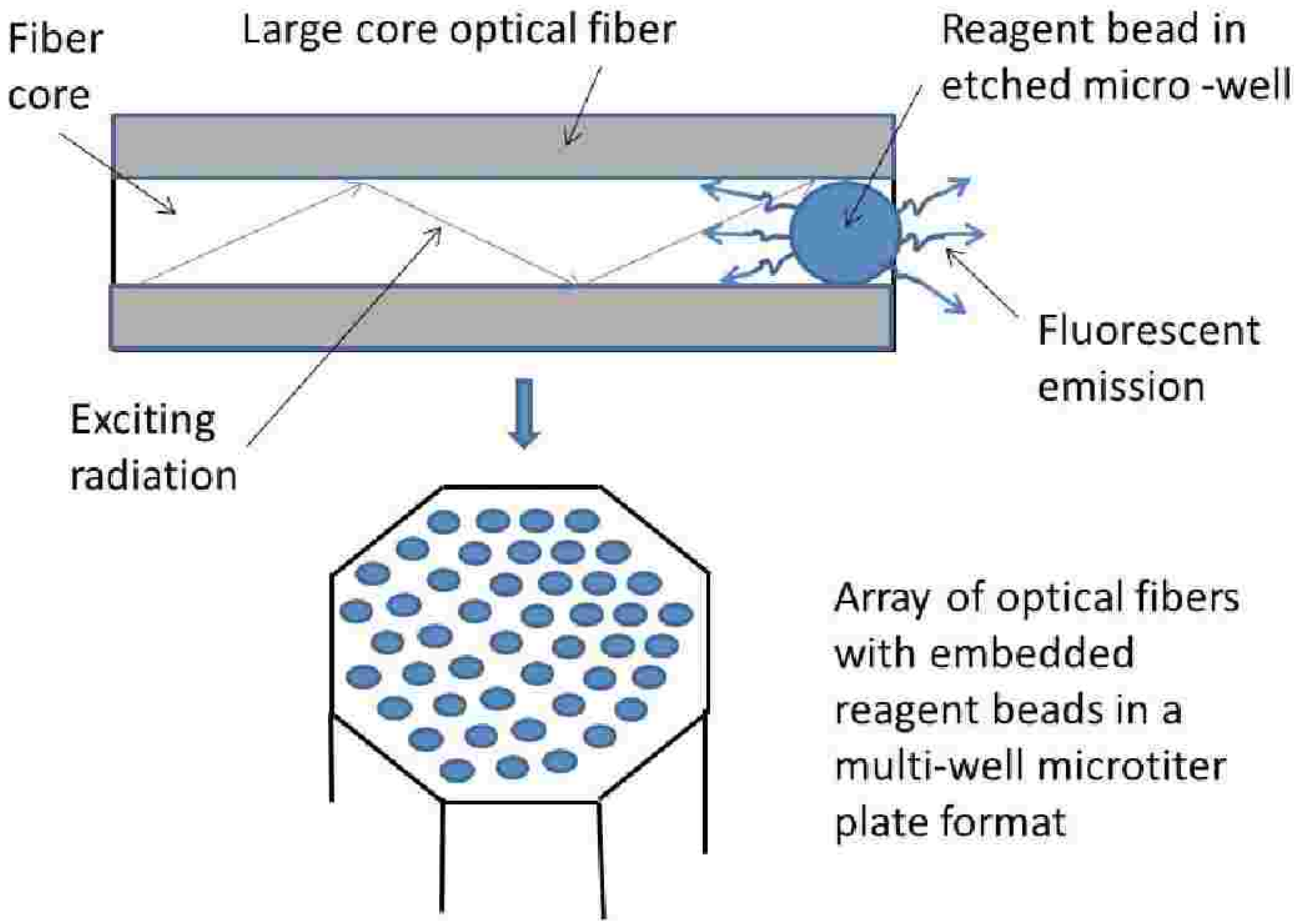
Biophotonic Interaction Modulated Mach-Zehnder Interferometer



Evanescent Wave Fluoroimmunoassay Concept



Fiber Optic Enabled Arrays using Fluorescence for High Speed Screening



Fluorescent Array Microsphere Vapor Sensors

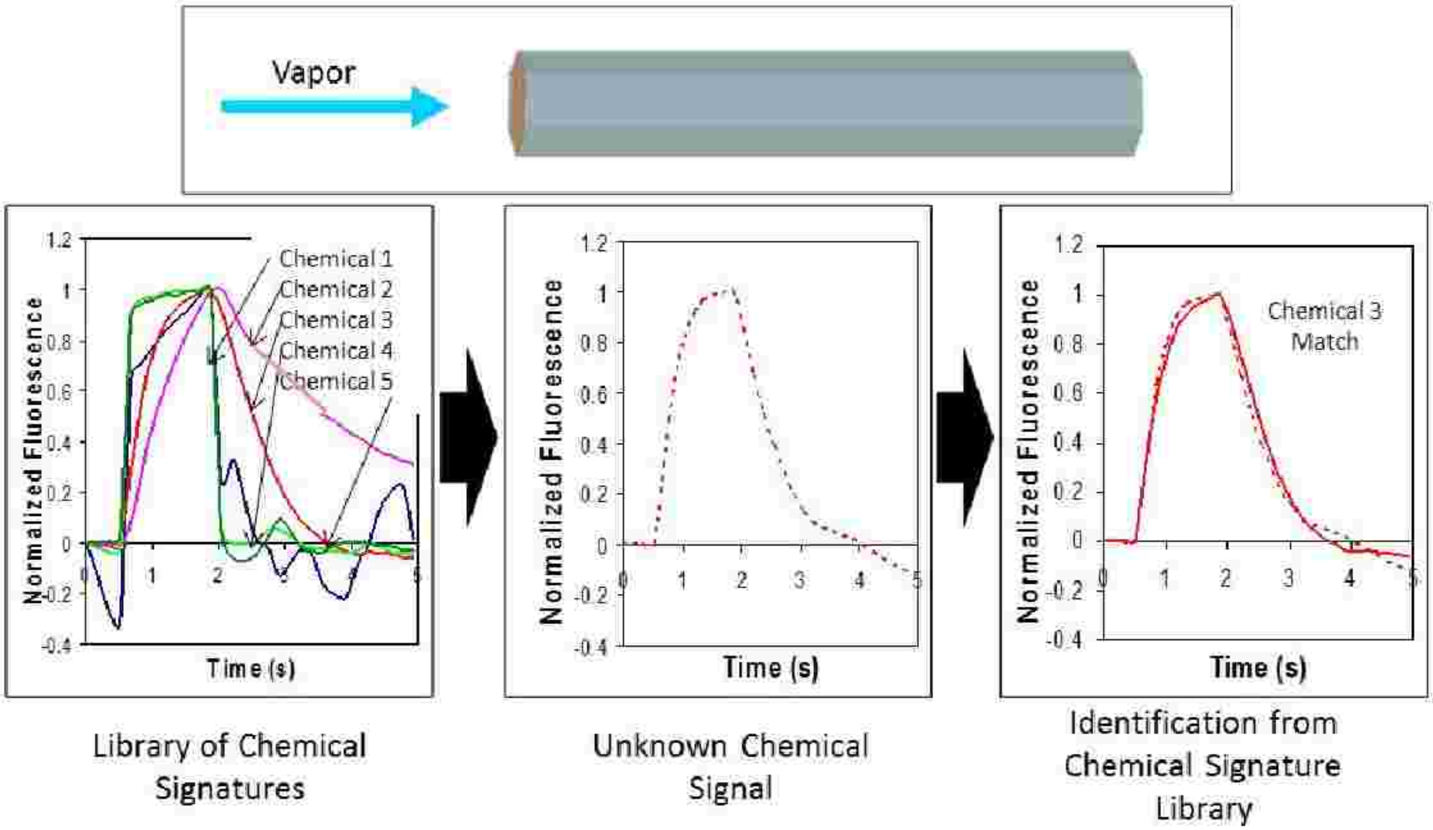
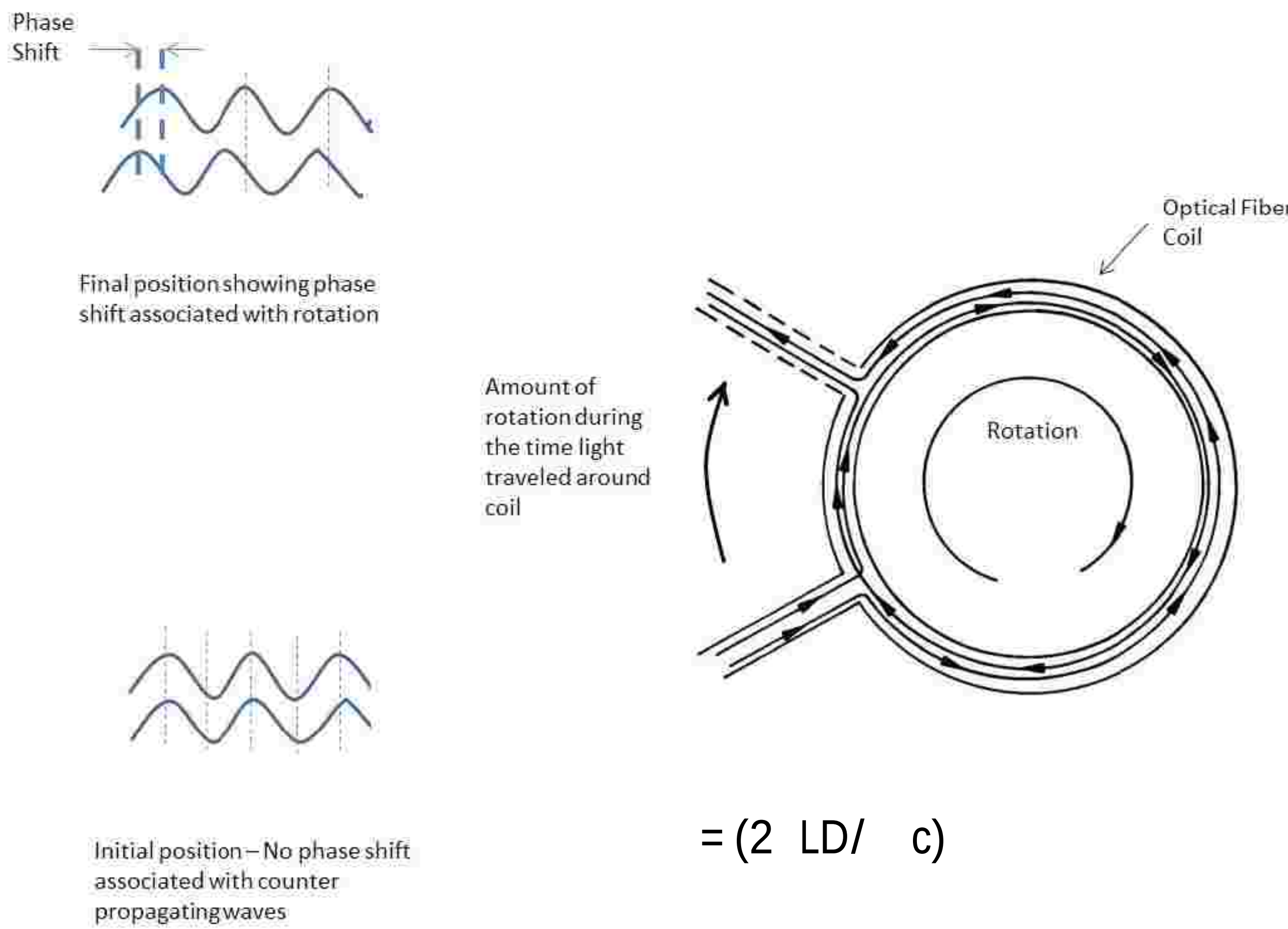


Figure 16.14 Fluorescent Array Microsphere Vapor Sensors[10]

Gyroscopes

Sagnac Effect in a Coiled Fiber Used for Rotation Rate Sensing.



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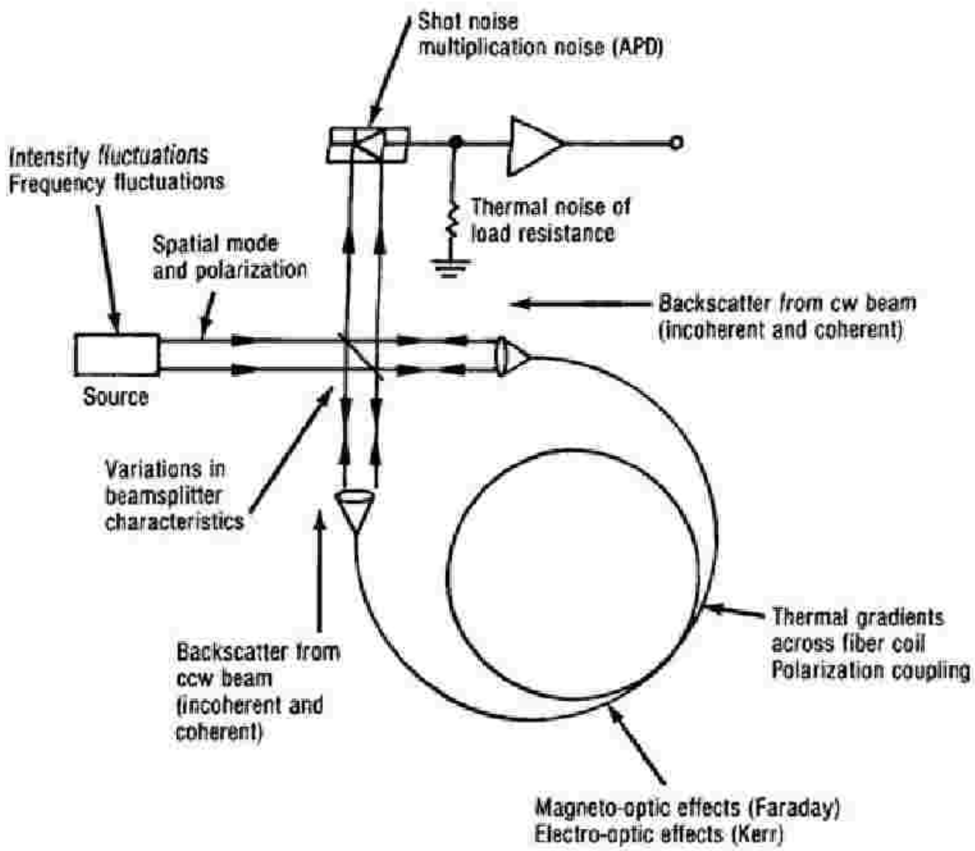
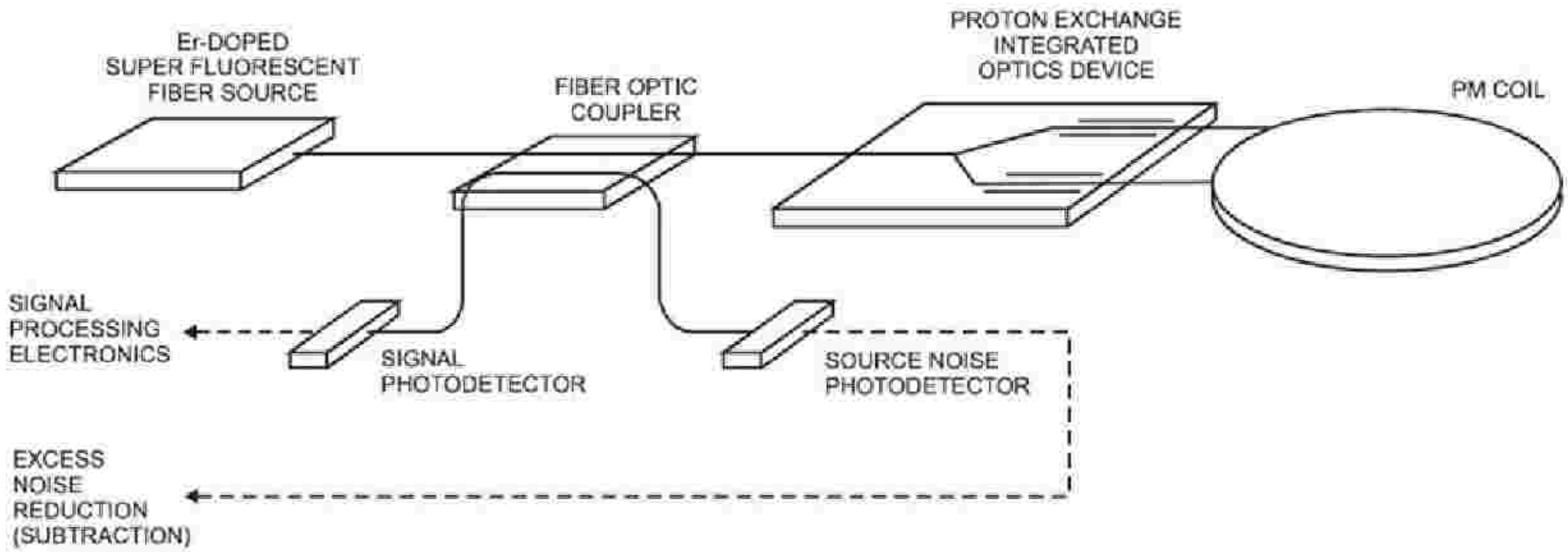
Noise Sources in an Optical Fiber Gyroscope



Typical Precision FOG Design



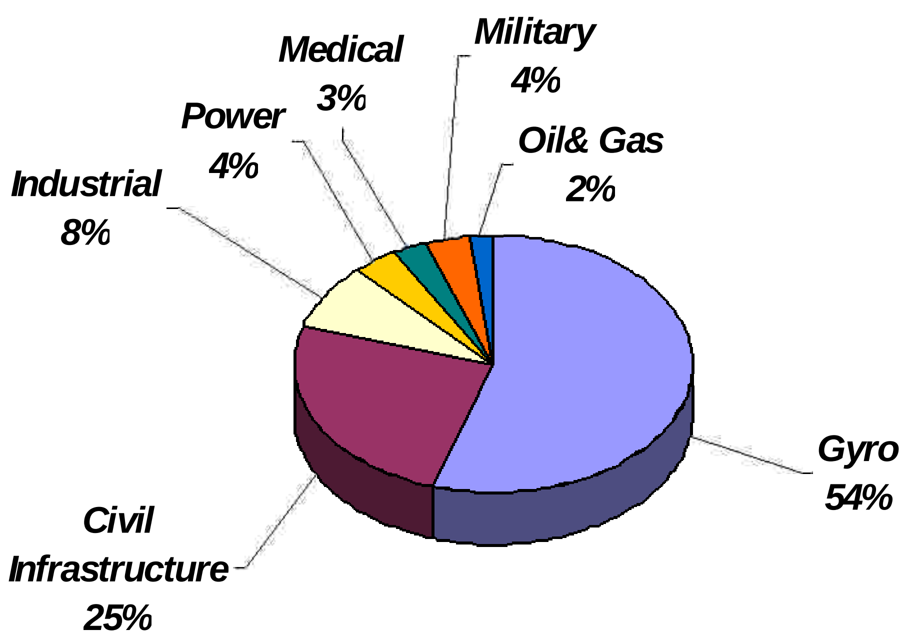
Northrop Grumman Commercial Inertial Measurement Unit (IMU) with Three Fiber Optic Gyroscopes

Market

FO Sensor Market:

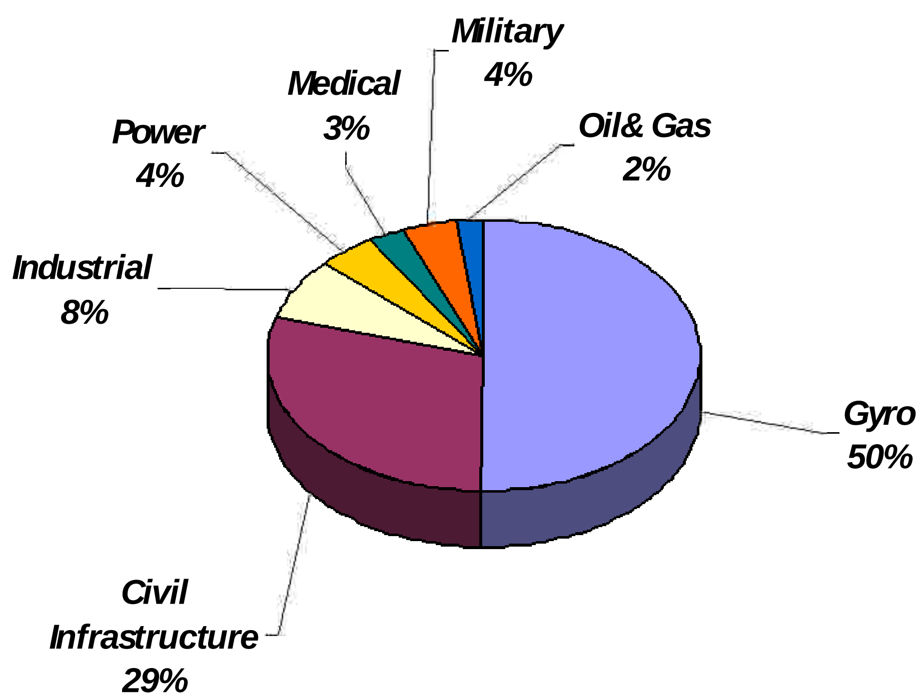
Single-Point Sensing

2008



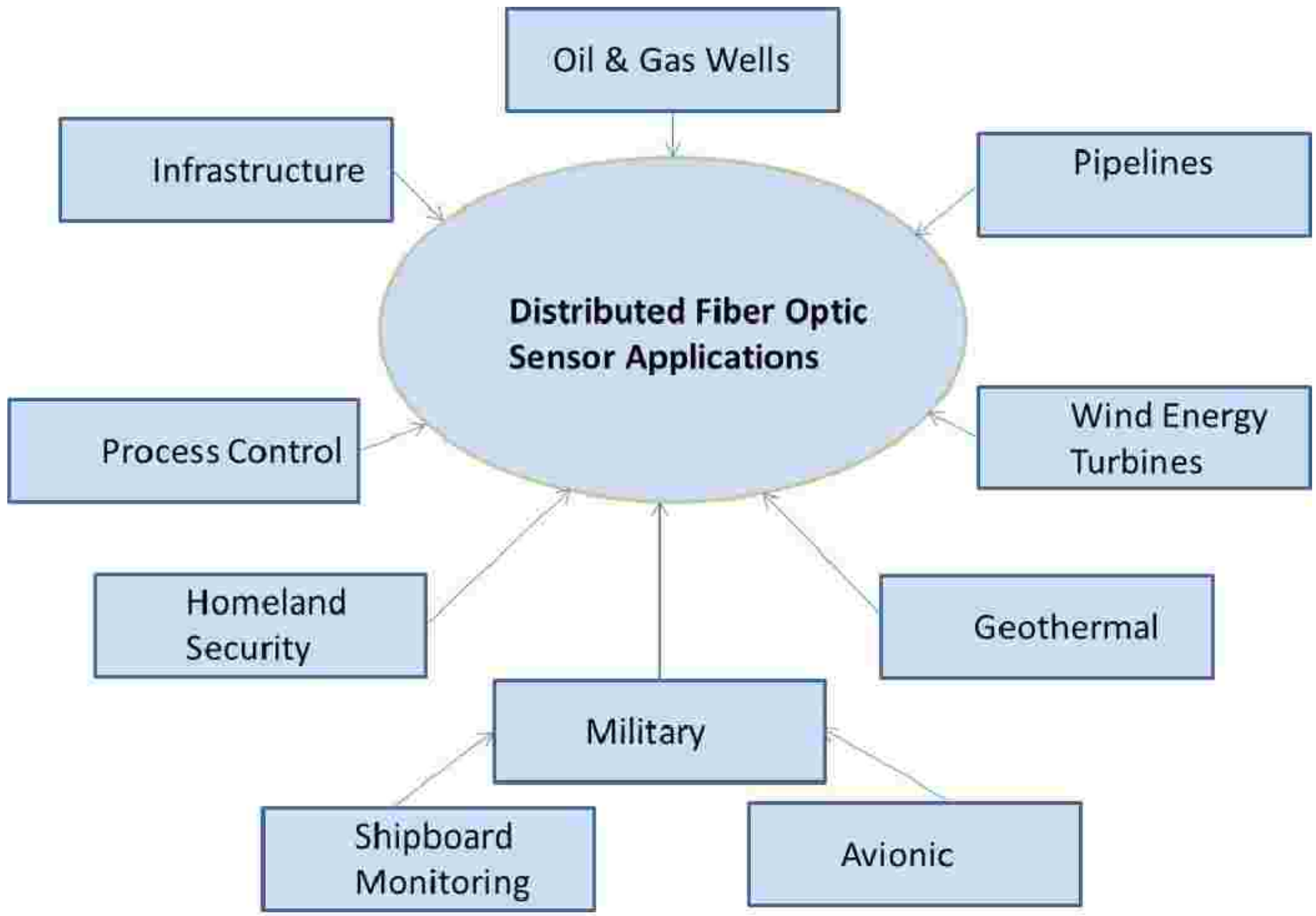
Total: $194 Million

2014

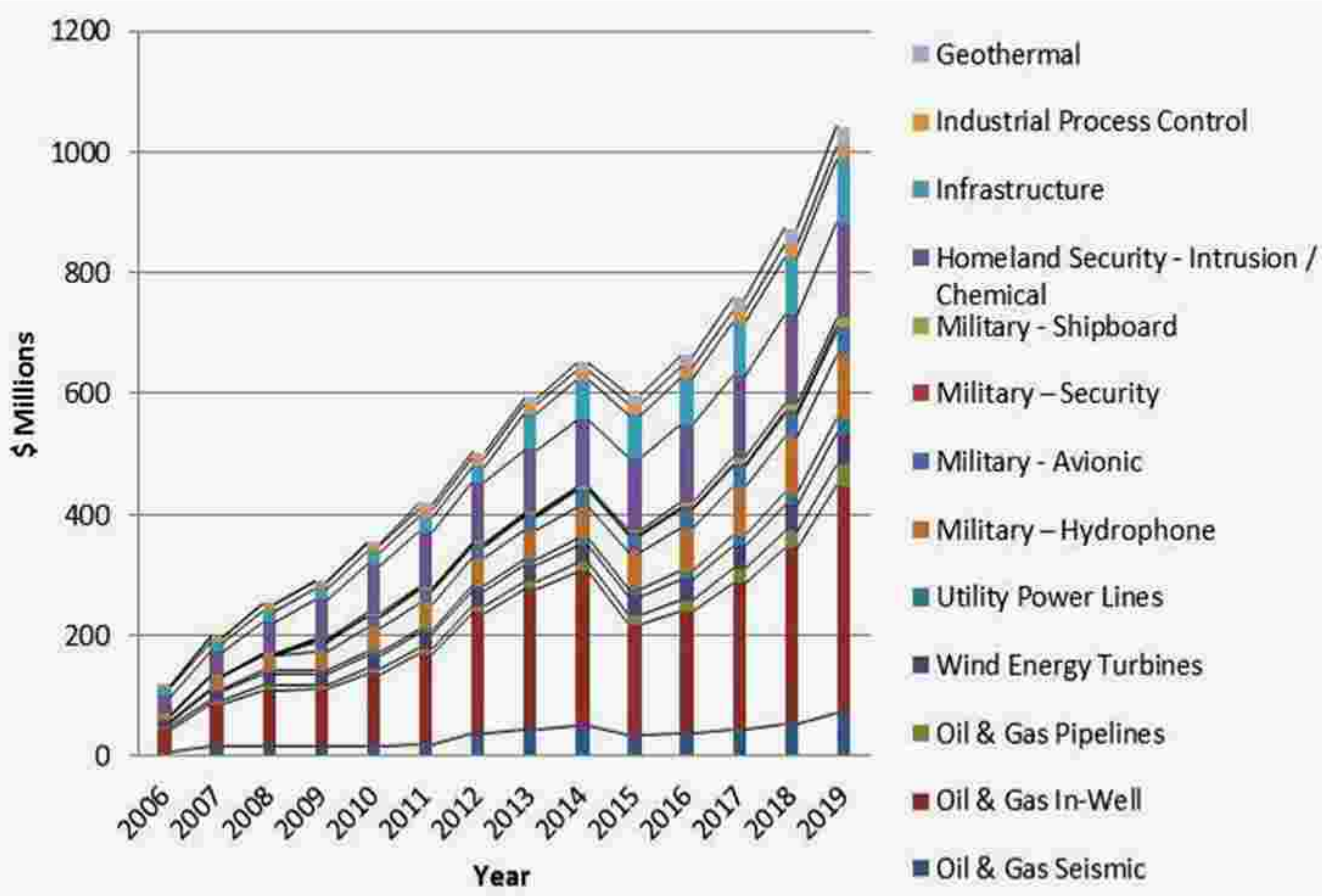


Total: $302 Million

Distributed Fiber Optic Sensor Applications



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 à *all applications & markets*
- Disposable sensors à *medical & health care*
- Distributed sensorsà *oil & gas, smart structures*
- Smart fabrics à *geotechnical, medical, aerospace*
- Food industry à *water & food safety*
- Environmentalà *gas sensing/emissions monitoring, pollution detection and monitoring*

Future Possibilities:
Optical Integrated FOS

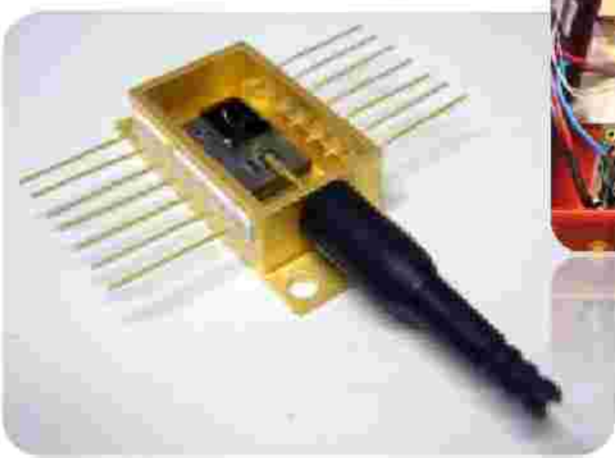
More:

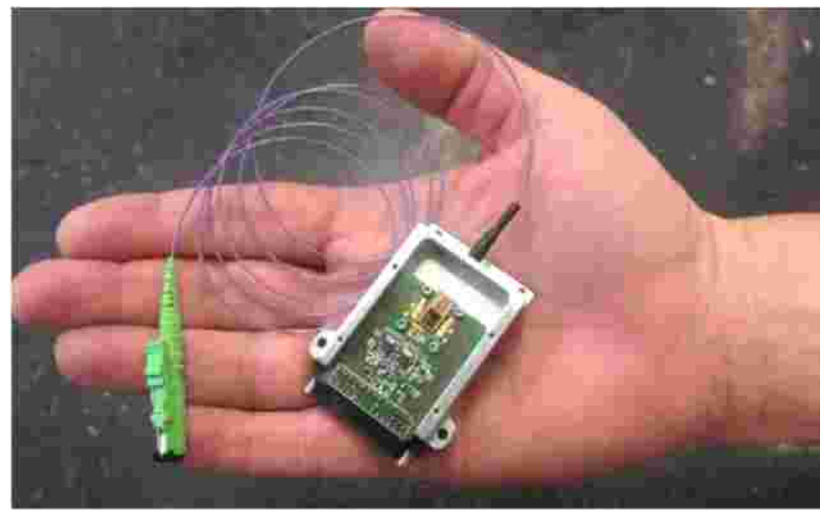
- Functionality
- Capability
- Reliability

Less:

- Space
- Power
- Cost

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





TFT-FOS
Technobis Fibre 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
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  - 203-248-1475
- Fiber Optic Sensors Fundamentals and Applications, Fourth Edition, 2014
  - Available at www.spie.org
- Photonic Sensor Consortium Market Survey - Distributed Fiber Optic Sensing Systems Forecast
  - Available at Information Gatekeepers - hpan@igigroup.com