Fiber Optic Sensors: Fundamentals, Principles & Applications

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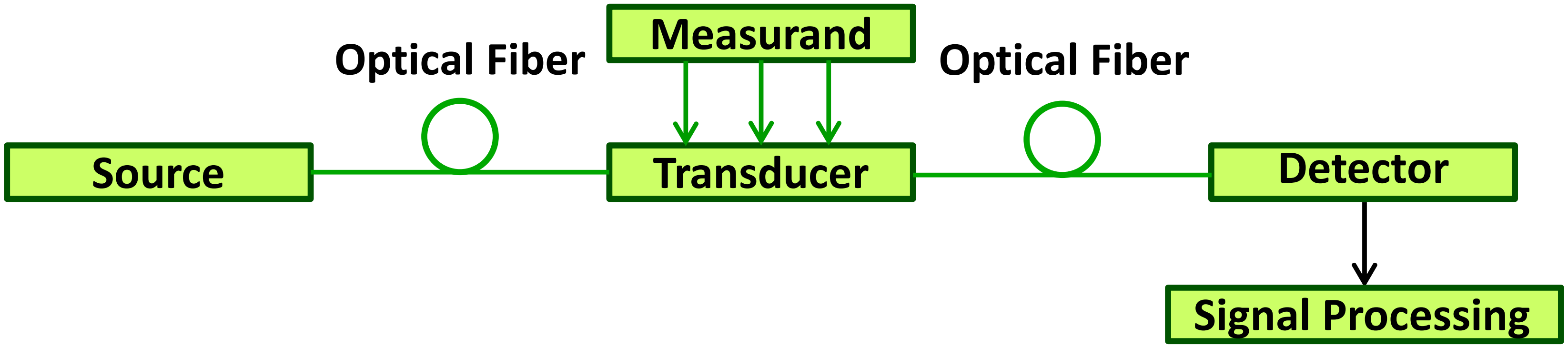
Overview

- Definitions and Classifications
- Fiber Optic Rotation Sensor
- Fiber Optic Current Sensor
- Fiber Optic Radiation Sensor
- Fiber Optic Biosensors
- Fiber Optic Distributed Sensors

Fiber Optic Sensor – Definition



- Light Injection into the Optical Fiber
  - Source (Laser, LED etc.)
- Transmission of Modulated Light to a Monitoring Point
  - Detector (PIN Diode, Avalanche Diode)
- Optical Fiber (Transmission Medium, Sensing Element)
  - Light modulated due to interaction with parameter of interest (Measurand)
- Signal Processing Device (OTDR, OSA, Oscilloscope, etc.)

Fiber Optic Sensors – Measurands/Applications

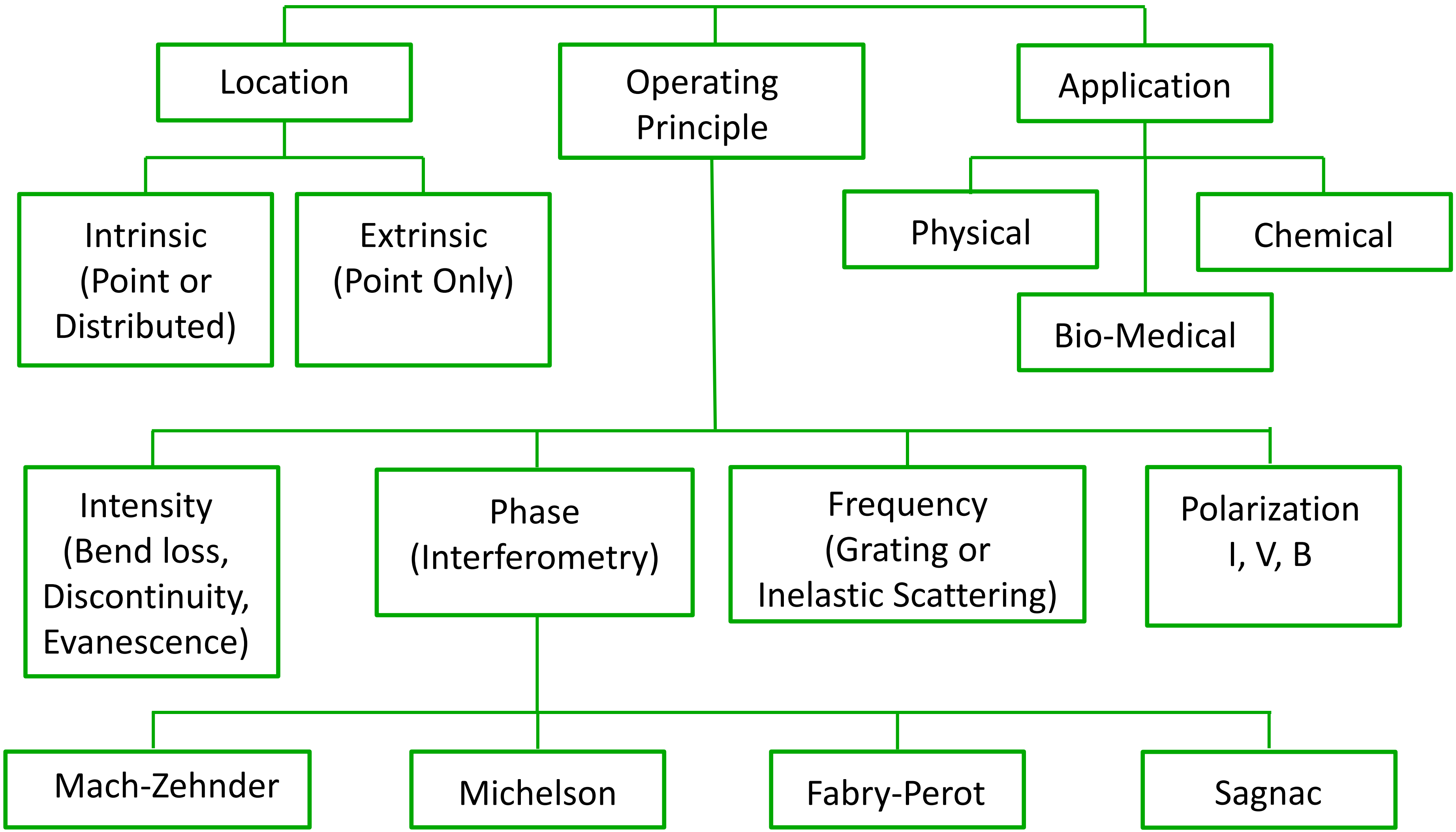
Measurands

- Temperature
- Pressure, Force, Strain, Vibration
- Displacement
- Velocity
- pH, Chemical Species
- Radiation
- Acoustic Field
- Rotation, Acceleration
- Magnetic/Electric Field

Application Areas

- Civil Engineering
- Nuclear Power Industry
- Electric Power Industry
- Navigation/Guidance
- Fly-by-Light Applications
- Oil/Gas Industry
- Biomedical
- Environmental

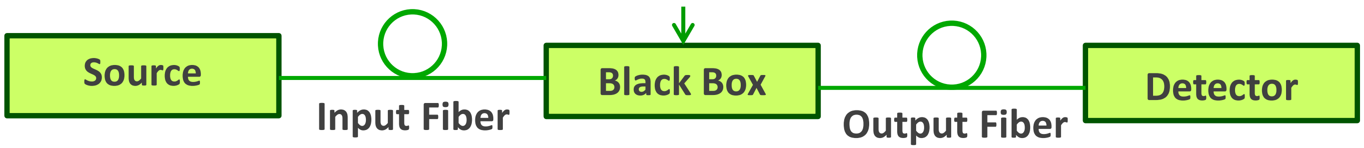
Fiber Optic Sensors - Classification

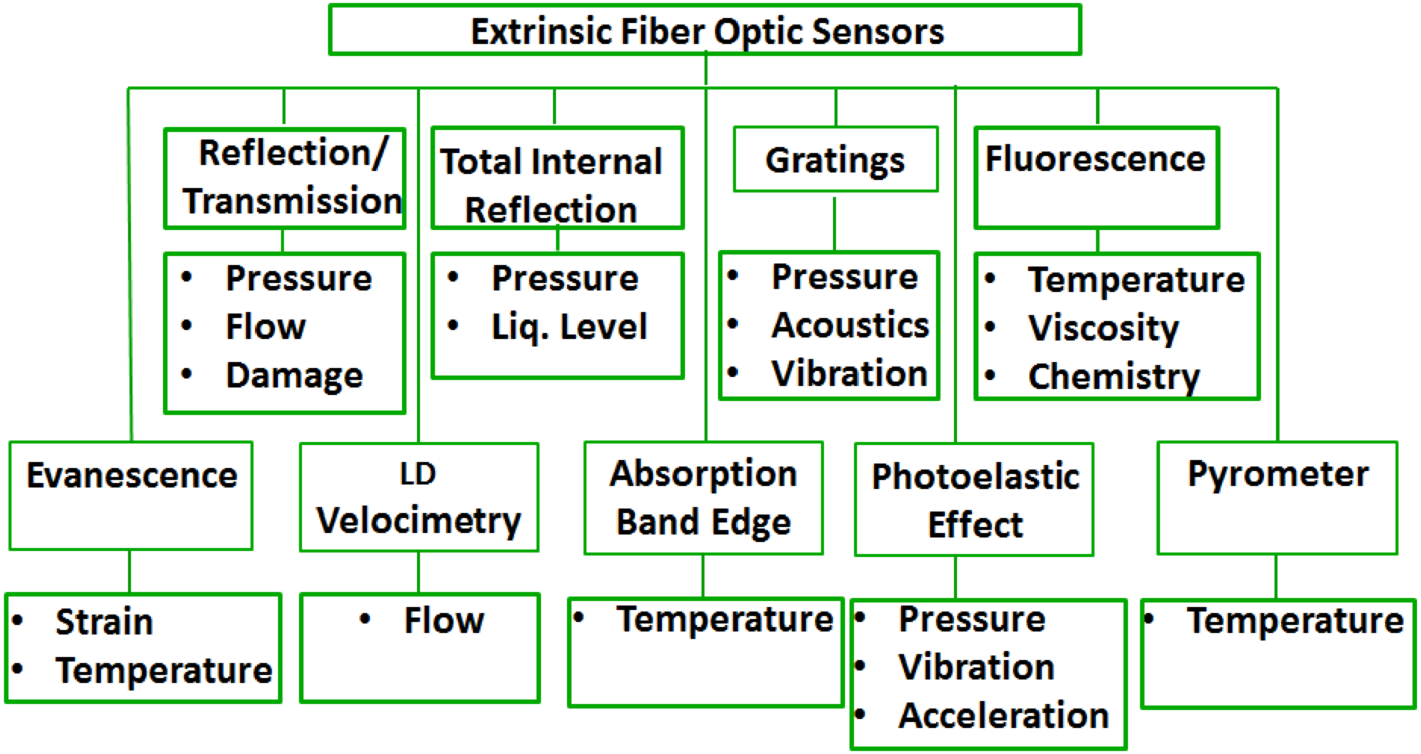


Extrinsic Fiber Optic Sensors

Fiber is Only an Information Carrier To and From a Black Box

Light Signal Generation in Black Box Depending on the Arriving Information

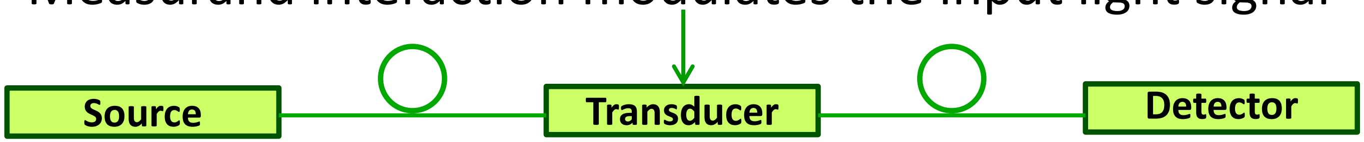


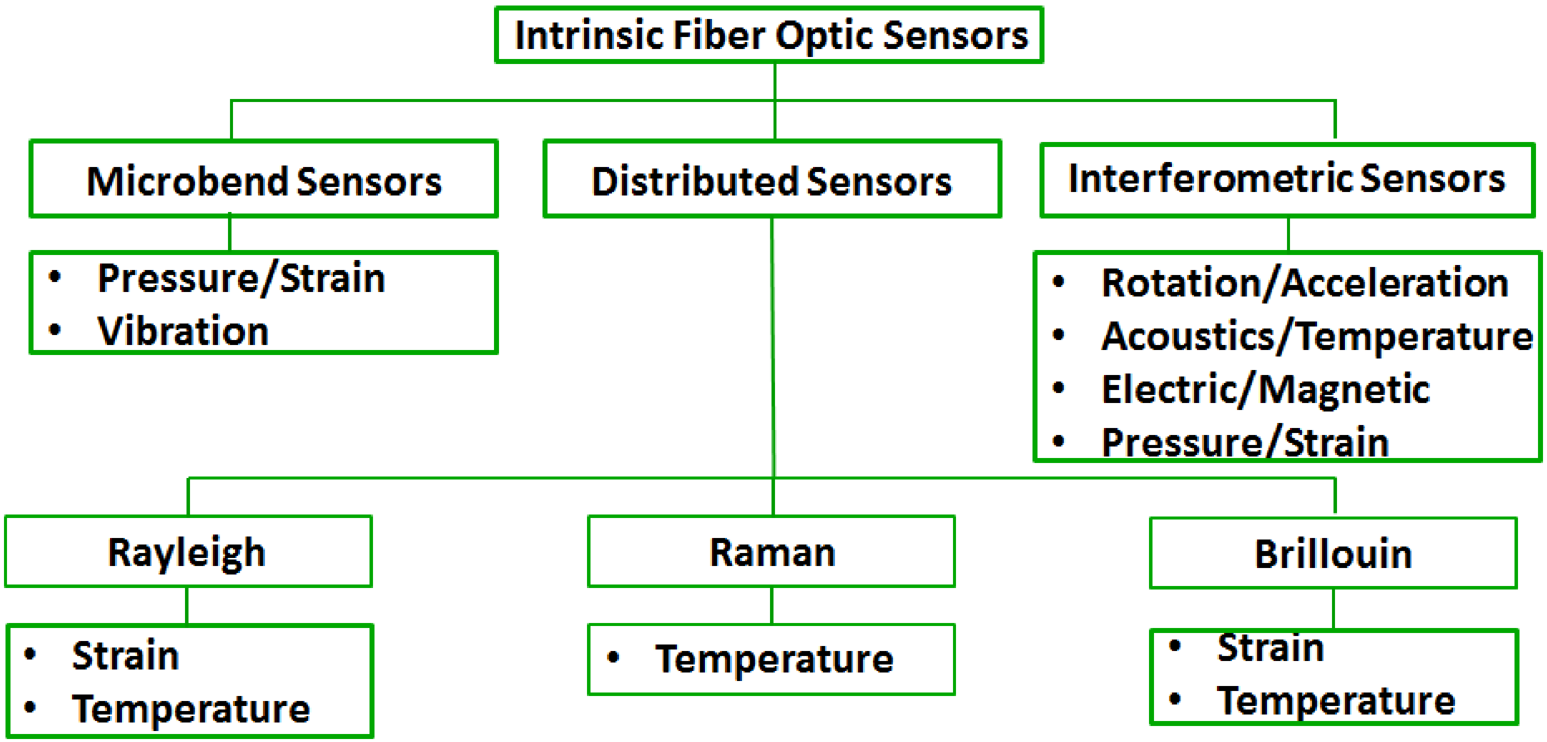


Intrinsic Fiber Optic Sensors

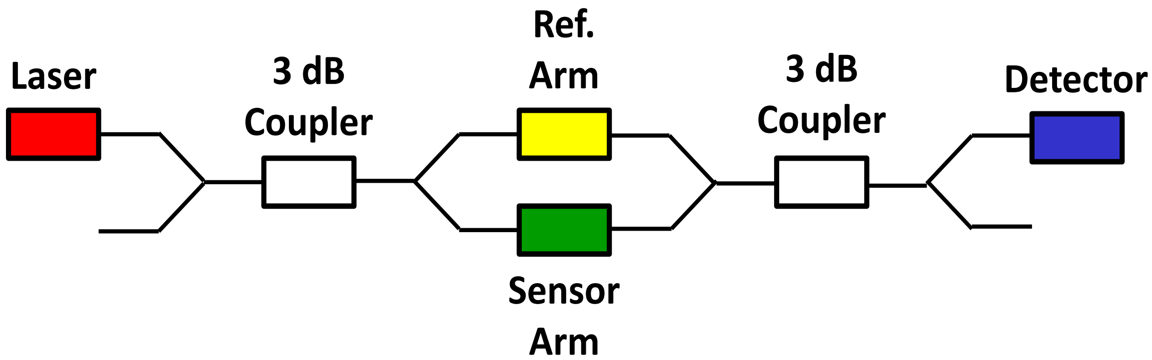
Sensing region within the fiber (Light Never Leaves the Fiber)

Measurand interaction modulates the input light signal



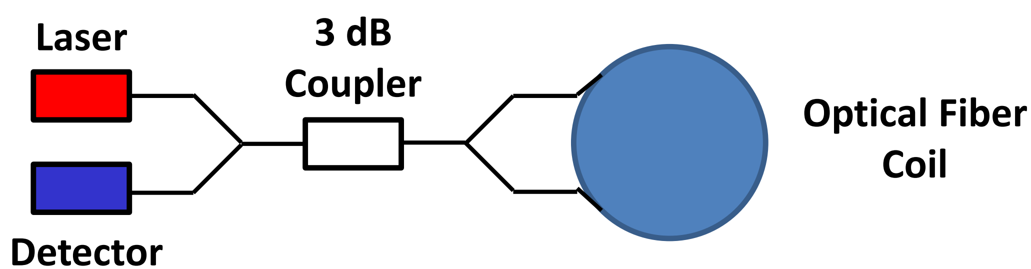


Fiber Optic Interferometer Configurations



Mach-Zehnder

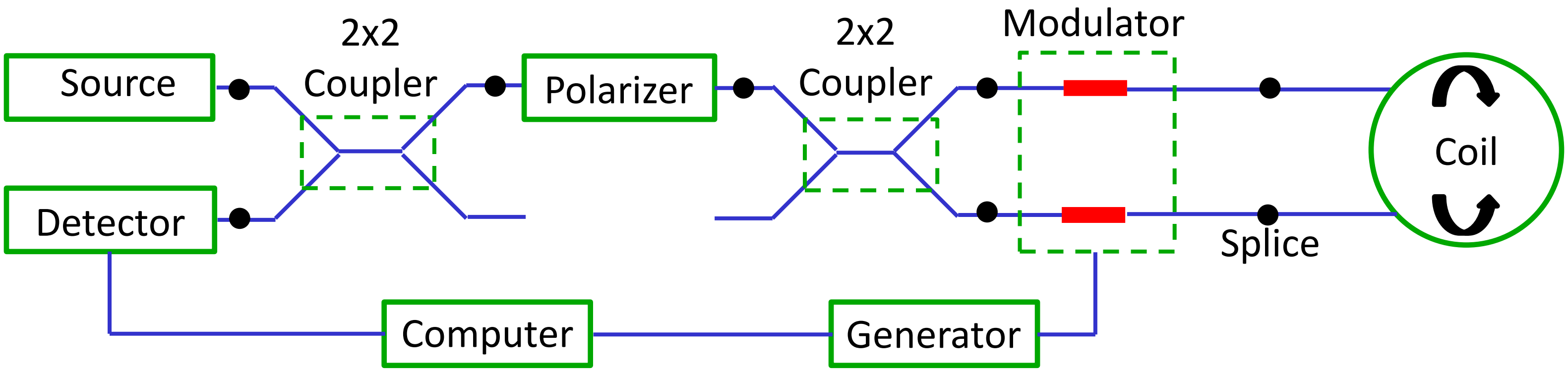
- Ref. arm isolated from external variation
- Variation in the sensing arm induces changes in the OPD
- Phase modulation of interference signal is detected
- T, P, ε, Acoustic



Sagnac

- Light is split, polarized and injected in the two ends of an optical coil
- External variations of interest
  - Rotation rate
  - Magnetic field

Rotation Rate Sensor: Fiber Optic Gyroscope



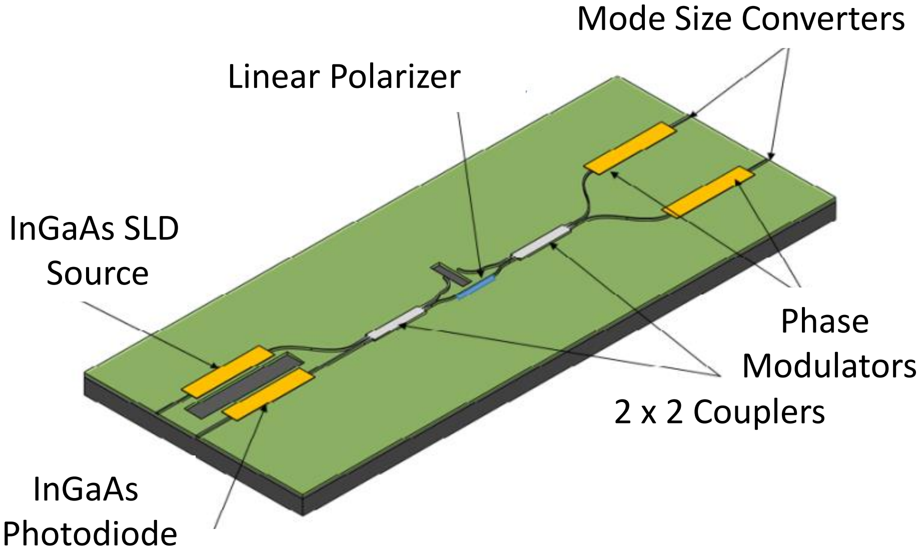
Counter rotating waves traveling through the same circular path exhibit a phase difference

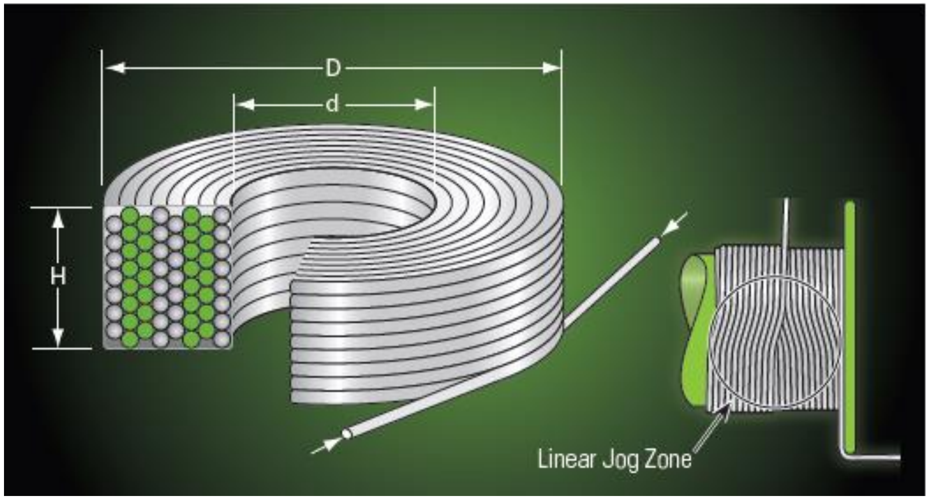
$$\Delta\phi = (2\pi LD/\lambda c)\Omega$$

$\Delta\phi$	=	Phase difference between the counter propagating beams (radians)
L	=	πND = Total length of fiber in the coil (meter)
N	=	Loops of fiber in the gyro coil
D	=	Diameter of each loop of fiber in the coil (meter)
λ	=	Wavelength of the propagating light (meter)
c	=	Speed of light in vacuum (3×10^8 meter/second)
Ω	=	Rotation rate of the coil along its axis (radian/second)

Fiber Optic Gyroscope: Components

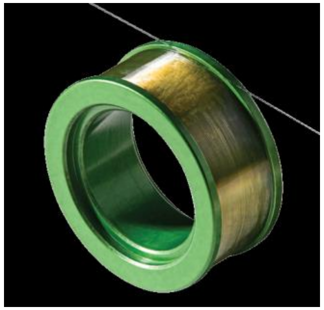
- Bulk fiber optic components spliced together
- All components on a single Photonic Integrated Chip (PIC)
  - Fiber coil attached via V- Groove
- Fiber (PM or SM)
  - PM design is more common
  - Coil – Quadrupolar winding pattern

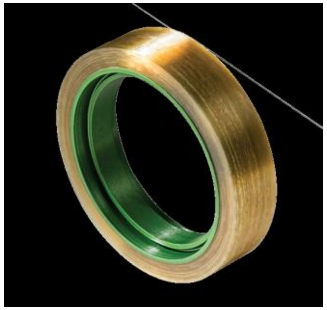




Fiber Optic Gyroscope – Optical Coil Design

$$\Delta\phi = (2\pi LD/\lambda c)\Omega = (\text{Scale Factor})\Omega$$

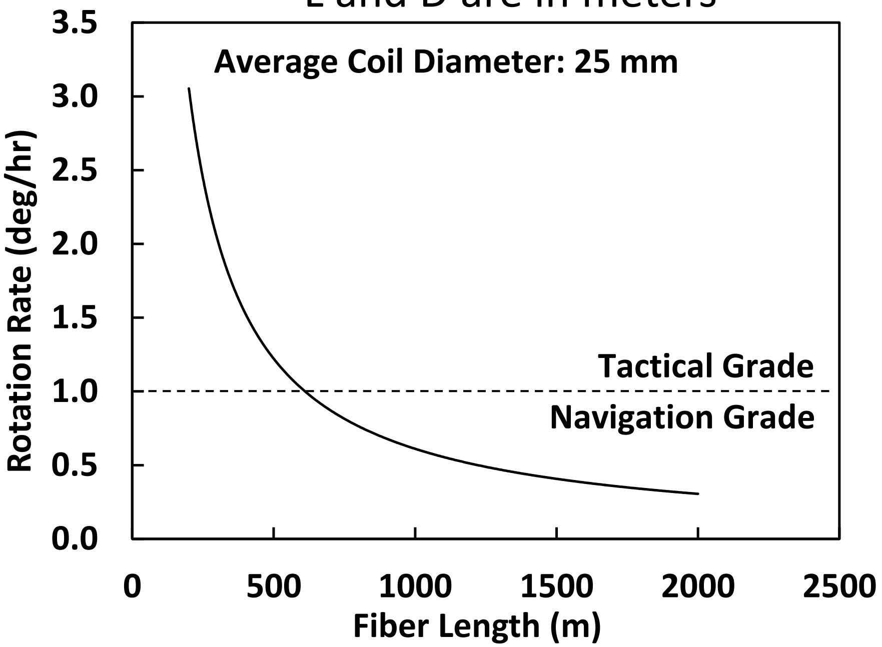


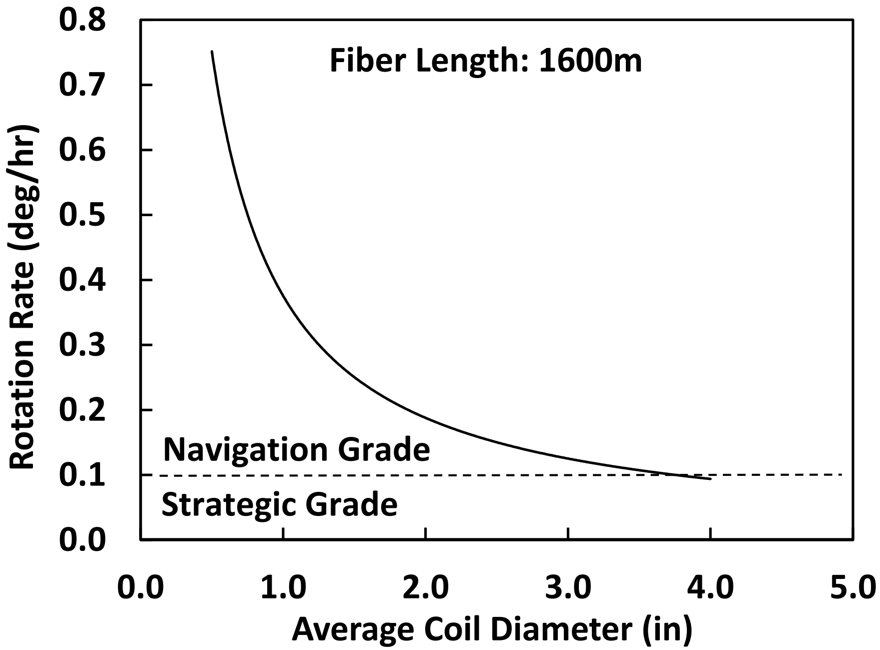


- Fiber Length in the coil: 100m – 6000m
- Diameter of the coil: 0.5” – 4.5”
- Operational wavelength: 850nm – 1550nm
- 850nm based gyros are more sensitive - fiber length is limited
  - Components are readily available and cheaper
- Smaller footprint is a major driver
  - Interest in smaller diameter fiber without penalty
    - ✓ D_f = 170 µm, ID = 2”, H = 1”, t = 0.2” → 936.4 m
    - ✓ D_f = 125 µm, ID = 2”, H = 1”, t = 0.2” → 1693.8 m

Fiber Optic Gyroscope - Sensitivity

- What rotation rate can be measured?
  - Limited by detection of phase difference via interferometry
  - Interferometers can detect $\Delta\phi \sim 1$ μradian
- For a 1550nm FOG
  - $\Omega = (\Delta\phi)(\lambda c/2\pi LD) = (74\times10^{-6}/LD)$ radian/s $= (15.27/LD)$ deg/hr
  - L and D are in meters

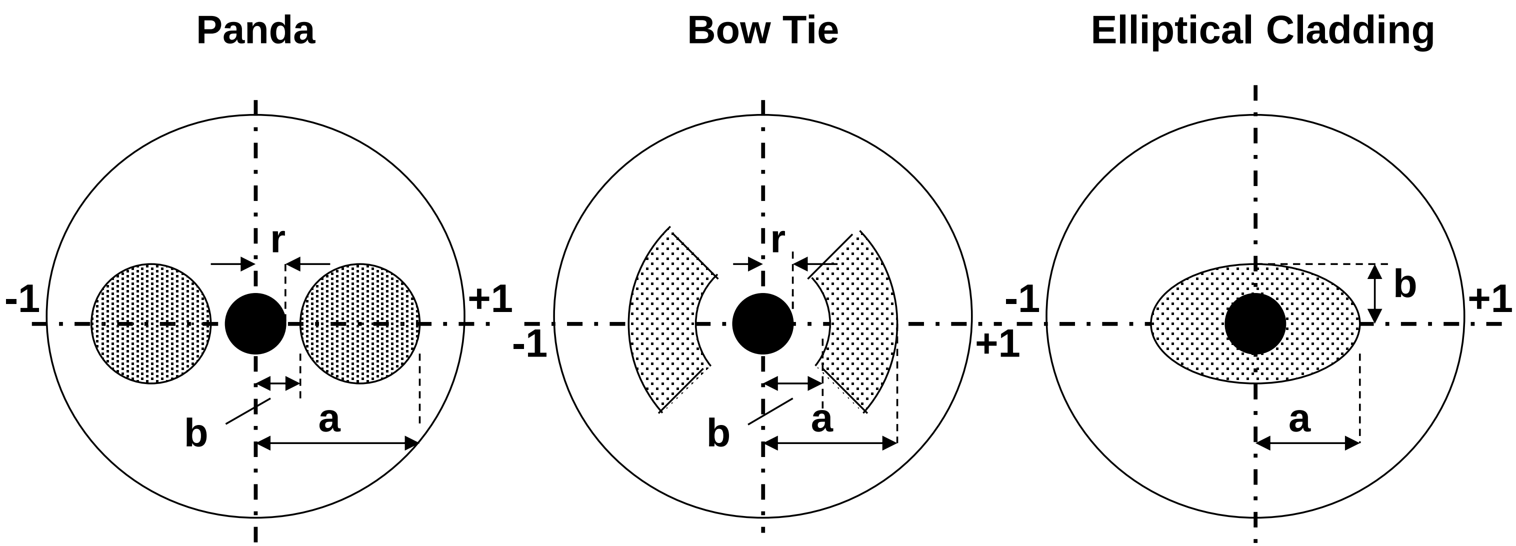




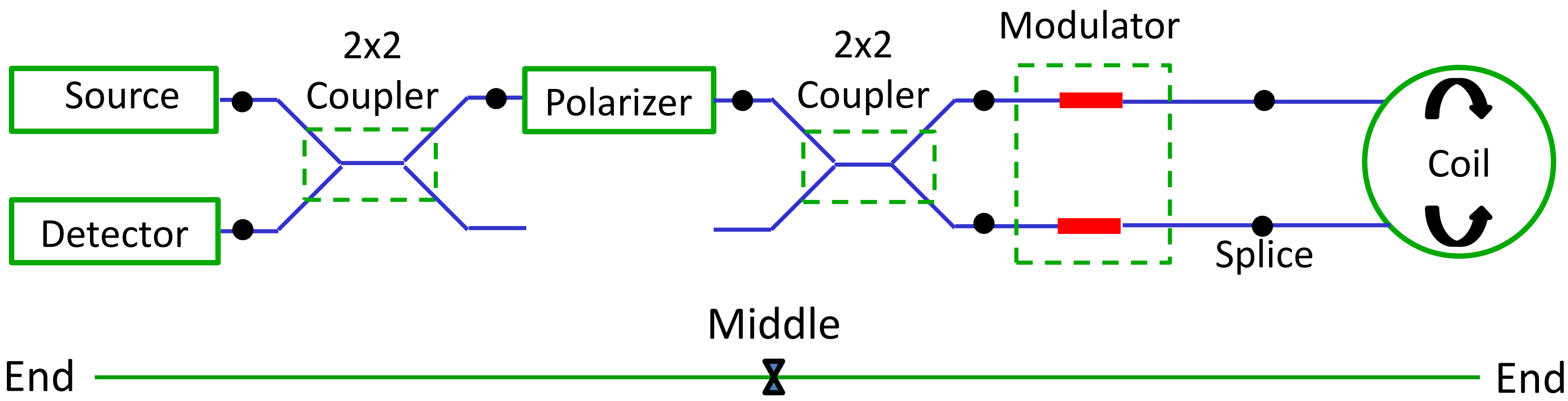
Fiber Optic Gyroscope – Nufern Fibers

PM & SM Gyro Grade Fibers

PM850G-80, PM1310G-80, PM1550G-80	80/170
PM850G-SC, PM1310G-80-SC, PM1550G-80-SC	80/125
PM1550G-40	40/90
PM-ECG-1300-80	80/170
PM-ECG-850-40	40/100
S1550-80	80/130

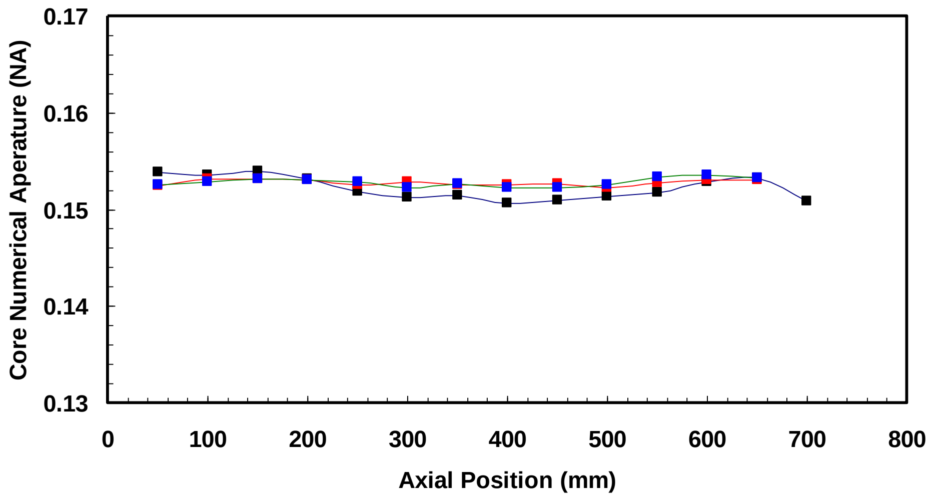


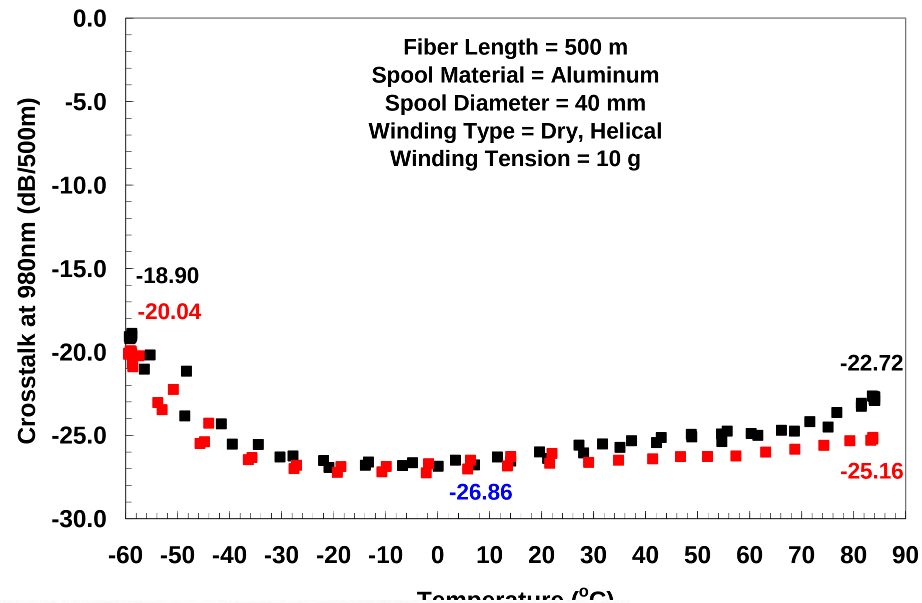
Fiber Optic Gyroscope – Critical Fiber Properties

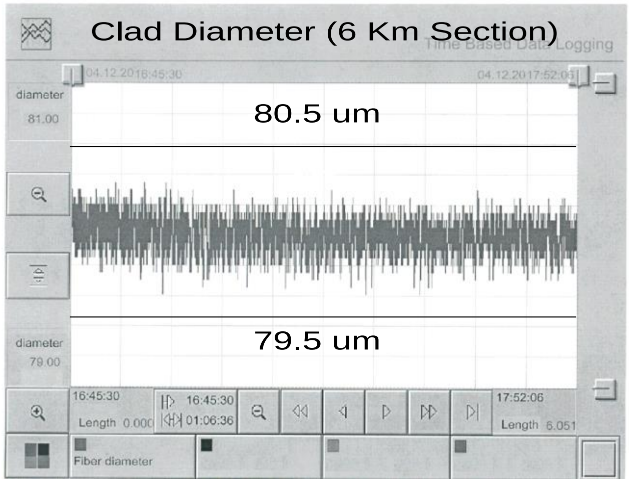


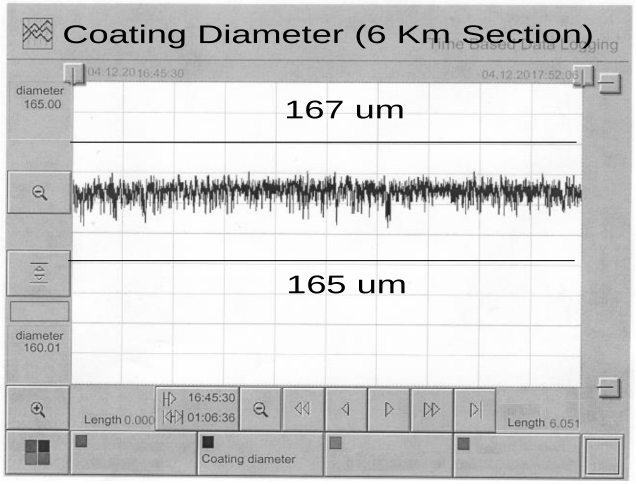
- Uniformity over fiber length in the coil (must be symmetric about midpoint)
  - Counter propagating beams must see same environment at every location
  - Phase accumulation over length – Only rotation contribution
- Tight tolerance on coating diameter over the length (tighter the better)
  - Severe impact on Sagnac coil winding - Need fixed number of turns/layer
- Fiber NA: Governs macro-bend loss
- Coating Design and Size: Minimize PER loss
- Mode Field Diameter: As large as possible to maximize signal/noise ratio

Fiber Cladding and Coating Diameter Control





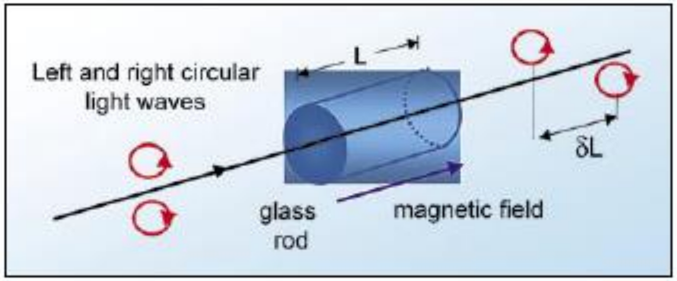




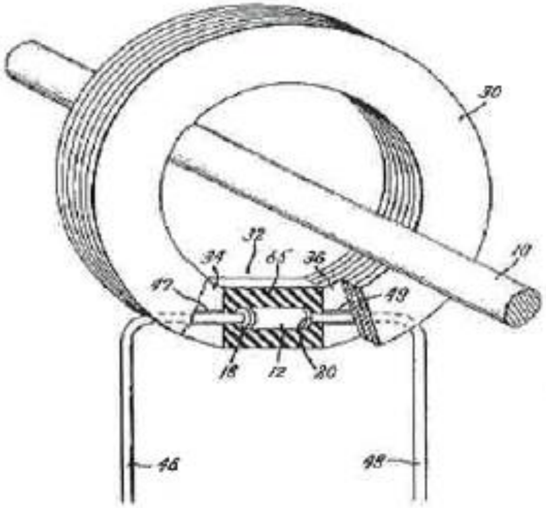
Fiber Optic Current Sensor

Faraday Effect: Magnetic Field Induced Circular Birefringence

- Linearly polarized light - A superposition of two circularly polarized waves
- In PM fibers
  - Right and Left circularly polarized light waves travel at different speeds if a magnetic field is applied along the propagation direction
- Waves accumulate a path difference δL or equivalently a phase difference
  - $\Delta\phi = V\int B.dL$
  - V: Verdet constant (Radian/m-Tesla), L: Rod length (m), B: Magnetic field density (Tesla)
- For closed optical path around a current carrying conductor, Ampere's law applies
  - $\Delta\phi = V(\mu_o NI)$
  - μ_o: Magnetic Permeability (H/m), N: # of optical path loops I: Current (A)

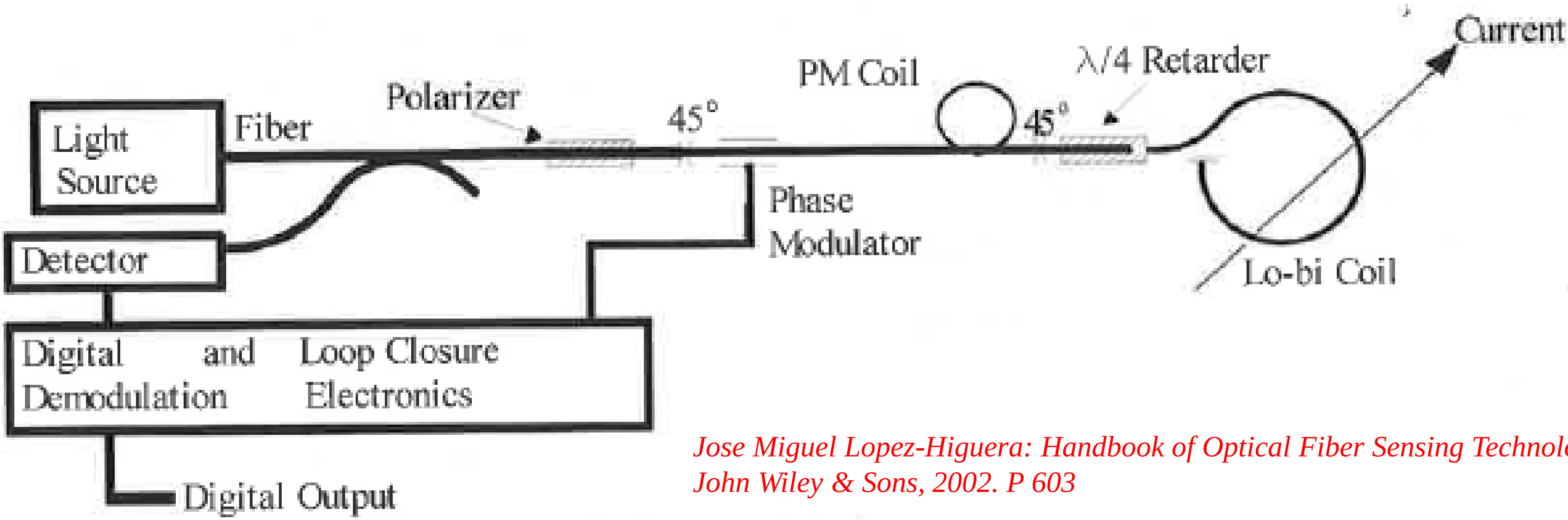


Information from ABB: Energize, Jan/Feb 2005, p 26



EJ Casey & CH Titus: US Patent 3324393, 1967

Practical Fiber Optic Current Sensors



Jose Miguel Lopez-Higuera: Handbook of Optical Fiber Sensing Technology, John Wiley & Sons, 2002. P 603

- Source light passes through a polarizer → Equally split linear states of polarization
- Quarter wave-plate converts linearly polarized light into circularly polarized light
- Mirror at the end of sensing fiber returns light in opposite mode
  - Cancel out reciprocal effects
- Faraday loop is completed at the coupler
- Modulator allows phase-locked loop operation

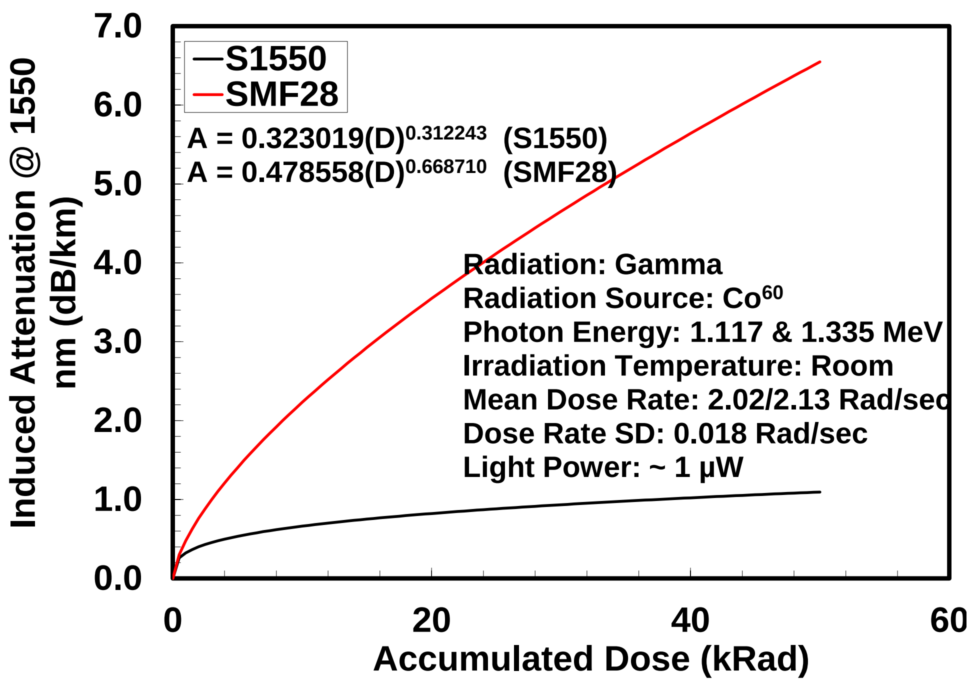
Radiation Effects in Optical Fibers

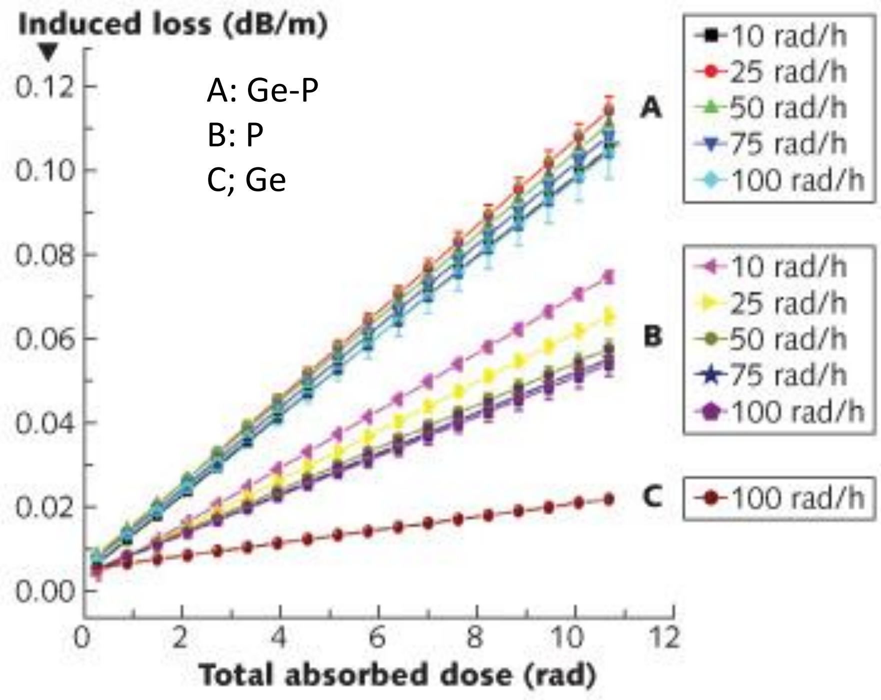
- Increased Loss - Radiation Induced Attenuation (RIA)
- Scintillation - Radiation Induced Luminescence (RIL)
  - Radiation absorption excites an orbital electron to a higher energy level.
  - Electron returns to its ground state by emitting the extra energy as a photon
- Thermoluminescence
  - Radiation absorption creates electronic excited states that are trapped by localized defects for extended periods of time.
  - Heating the material enables the trapped states to interact with phonons and decay into lower-energy states, causing the emission of photons.
- Enhanced Scattering
  - Radiation absorption creates damage sites in glass that exhibit higher degree of light scattering.

RIA Based Radiation Sensors

- Pure silica core fibers → lowest radiation sensitivity
- Dopants increase sensitivity → B, Ge, P and Pb
- Require lower to moderate loss at the expected radiation levels
  - Long Duration Sensing
- Loss → Vary linearly with accumulated dose but independent of the dose rate
- Low dose detection with high sensitivity
  - Long length probe at shorter wavelength
- High dose detection with high sensitivity
  - Small length probe at longer wavelength

Fibers for Radiation Sensing

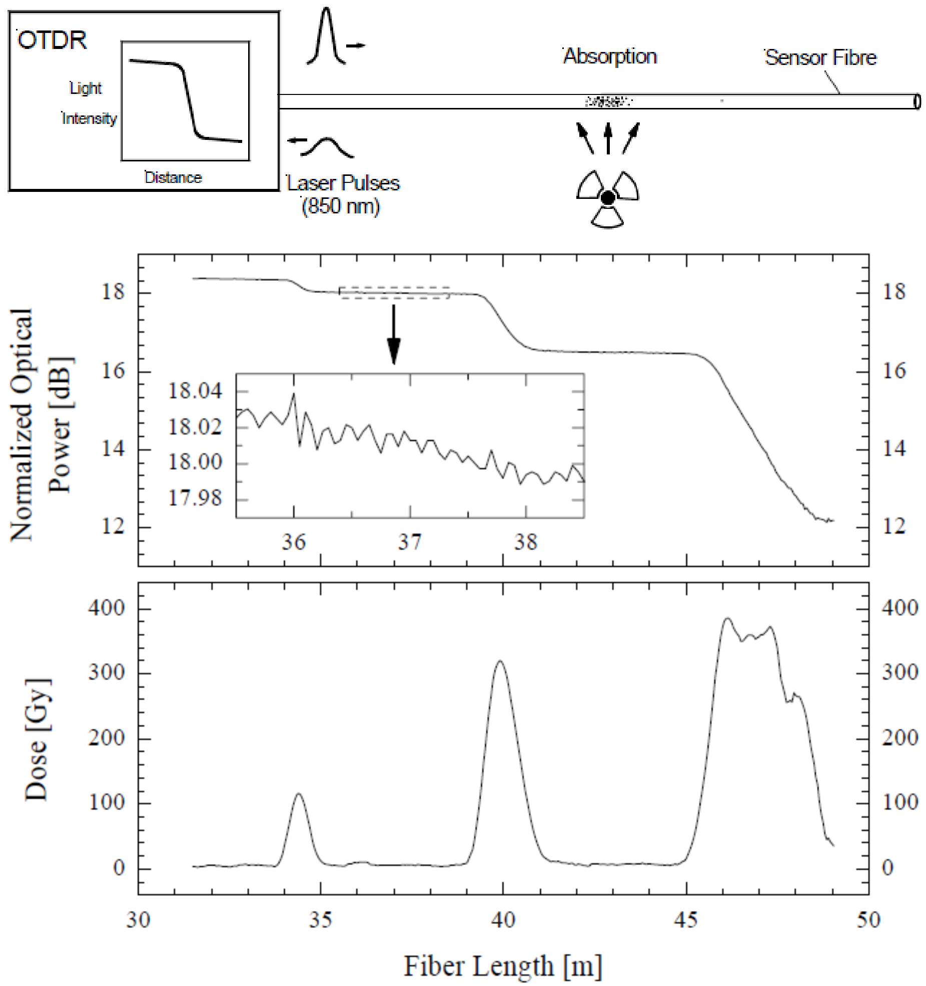




John Wallace: Laser Focus World, September 2011

Radiation Sensing Using OTDR

- Distributed measurement over length
- Radiation sensitive fiber passes through regions of varying radiation intensity
- Measure loss of signal resulting from color center formation (defects) in silica
- Ge-P doped graded index MM fiber
  - Linear Region: Up to 1000 Gy
  - Sensitivity: 5 dB/km-Gy
  - Expected Accumulated Dose: 100 Gy/y
  - Lifetime: 1000 Gy/100Gy/y = 10 y

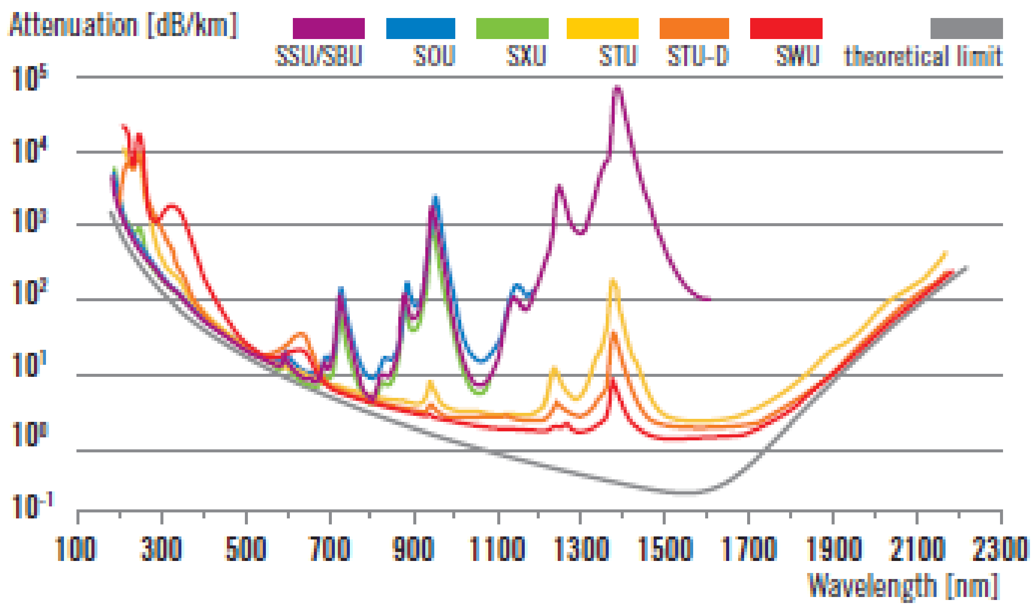


Stefan K. Hoffgen: 1st Workshop for Instrumentation on Charged Particle Therapy, Fraunhofer Institute of Tech., Germany

Luminescence Based Radiation Sensing Fibers

<u>**Requirements**</u>

- Light generated per unit fiber length
  – As high as possible
  - Light yield/Length increases with d_F (100-600 μm)
- % of generated light directed to the detectors – As high as possible
  - Higher NA fiber
- Benign and RIA in the UV – As low as possible
  - Decoupling of Cerenkov component



Heraeus Product Brochure
Specialty Fiber Preforms for the Most Demanding Applications

- Fiber bandwidth for high accuracy detection – As high as possible
  - Fiber bandwidth decreases with increasing diameter (Issue with longer sections)

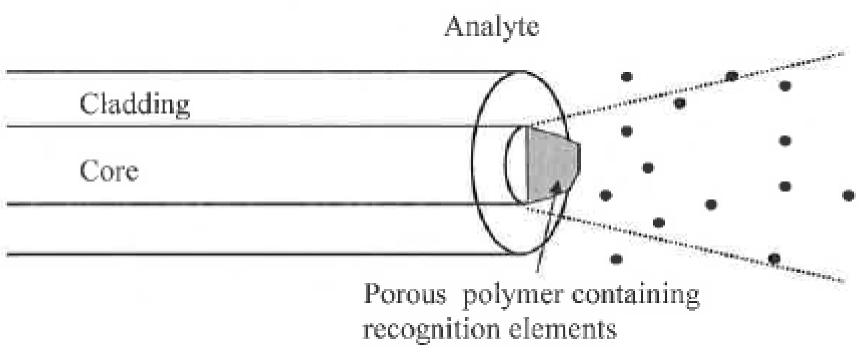
Best Choice (High OH, MM SI, Pure Silica Core)

What is Fiber Optic Biosensor?

A device that transforms chemical information into an analytically useful signal

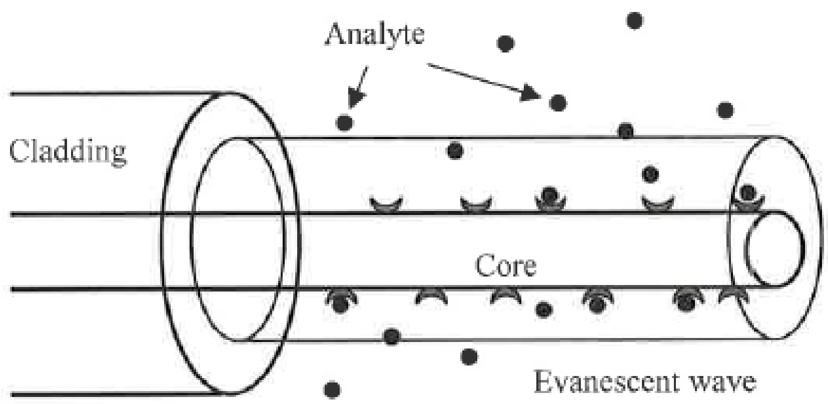
Jose Miguel Lopez-Higuera: Handbook of Optical Fiber Sensing Technology, John Wiley & Sons, 2002. PP 689-690

Optrode



- Recognition molecule immobilized at the tip
- Optical fiber as transporting medium
    - ➢ To and from the sensing region

Evanescent Wave



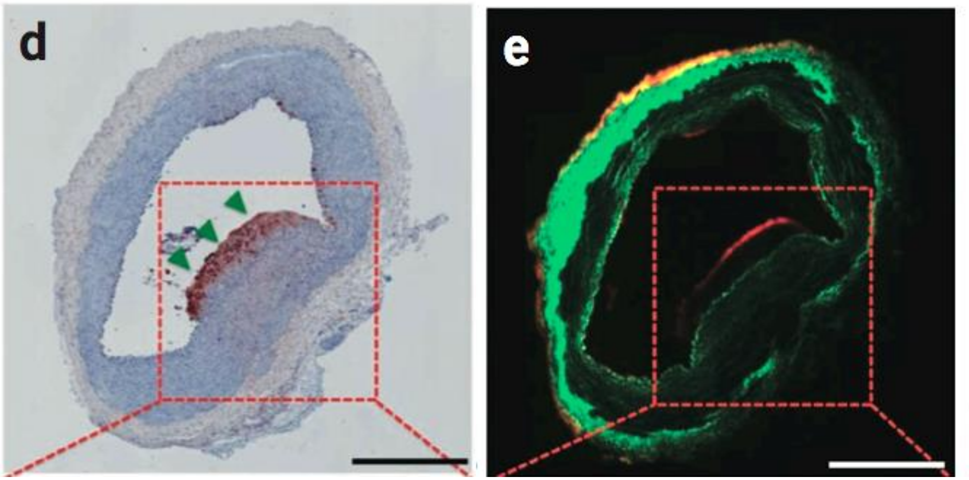
- Recognition molecule immobilized on the de-clad surface of the fiber core - RI
- Evanescent light propagation changes with RI changes

Parameters, Immobilization & Detection

- Measured Optical Parameters
  - Fluorescence
  - Absorbance
  - Bioluminescence
- Immobilization of Biological Molecules
  - Physical Adsorption
  - Encapsulation
  - Covalent Attachment
  - Bio-molecular Interactions
- Detection Methods
  - Bio-catalytic
  - Affinity Based

Optical Fibers for Imaging and Spectroscopy

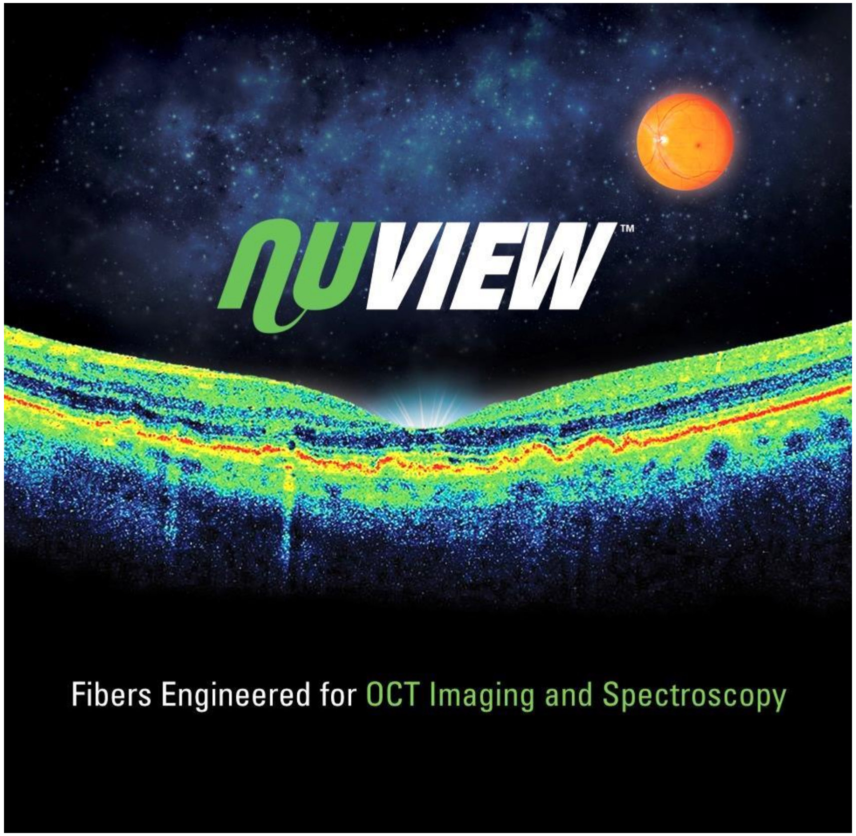
Microscope Image | OCT Image



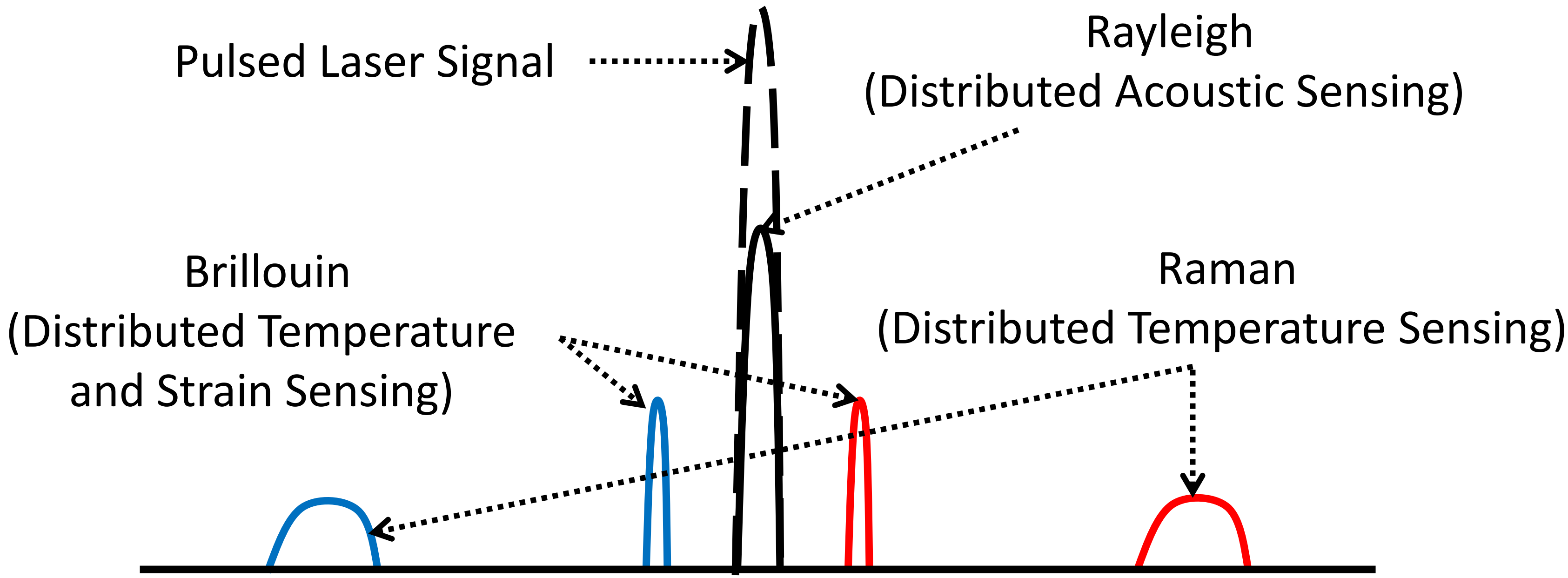
Courtesy: Wellman Center for photo-medicine, Harvard Medical School

Arterial Image obtained by optical frequency domain interferometry (OFDI)

OCT Image of Human Eye



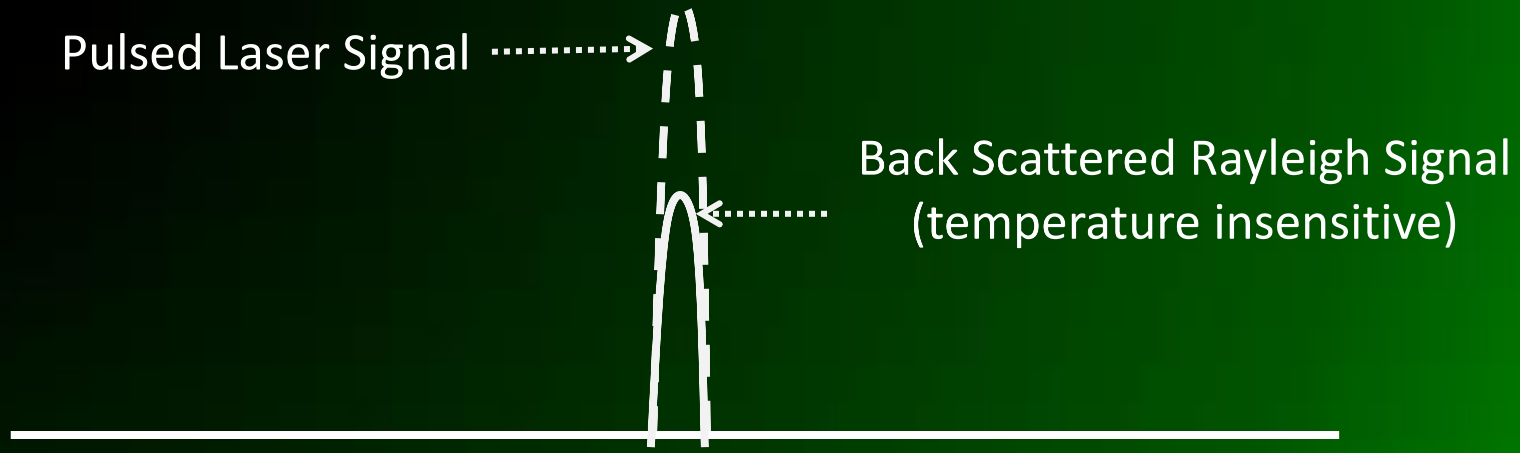
Distributed Sensing - Principles



Fiber serves as a continuous sensing element. Sensing is based on

- Elastic (Raleigh) or inelastic (Raman or Brillouin) scattering of signal
- Intensity and/or frequency shift are sensitive to temperature and strain

Principle of Distributed Acoustic Sensing

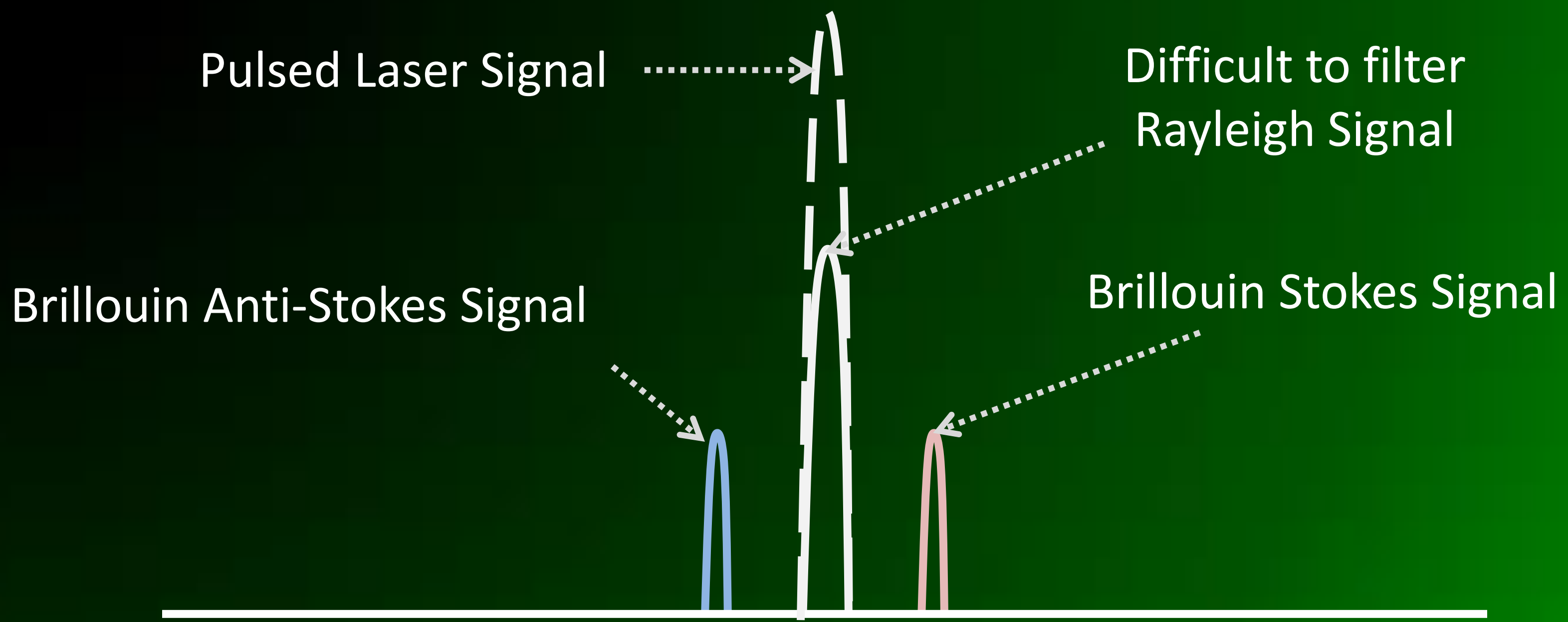


- Rayleigh signal intensity varies due to local changes in strain
  - Temperature effects can be separated from strain effects
- Pulsed signal launched into sensing fiber
  - Pulse launched only after signal from previous pulse returns
- Time of flight and repeated scans provide position and velocity

Rayleigh Based System Considerations

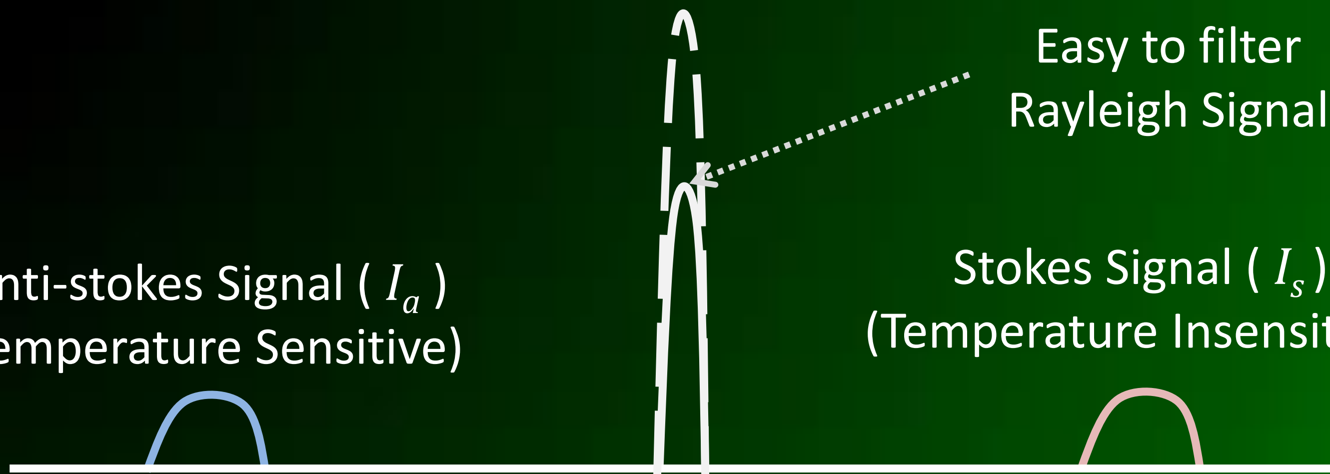
- Maximum range (L) determined by strength of returning signal
- Strain resolution depends on signal to noise ratio
  - Signal intensity can be enhanced with longer pulse duration (Δt)
- Spatial resolution, $\Delta L = c\Delta t$ (c = speed of light in fiber)
  - Longer pulses enhance range at the expense of spatial resolution
- Acquisition rate = c/2L decreases with range

Distributed Temperature and Strain Sensing



- Signal light scattered due to interaction with acoustic phonons
- Intensity and frequency of stokes and anti-stokes signals depend on temperature and strain
- DTSS systems analyze signals to determine temperature and strain

Principle of Raman DTS

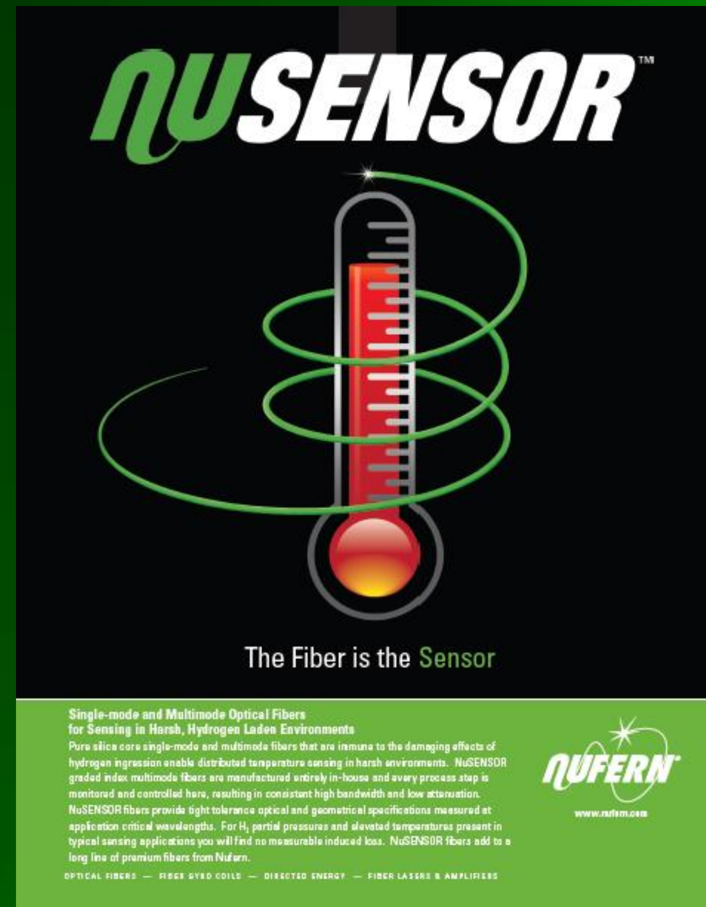


$$T(z) = T_{ref} \left\{ 1 + \frac{\Delta\alpha}{\ln(C_s/C_a)} z + \frac{\ln(I_s/I_a)}{\ln(C_s/C_a)} \right\}$$

- Pulsed laser signal launched into sensing fiber
- Ratio of stokes and anti-stokes intensities provides temperature
  - Time of flight analysis gives position information
  - Differential attenuation ($\Delta\alpha$) between stokes and anti-stokes signals needs to be considered for accurate temperature assessment

DTS Fibers for Oil and Gas

- Fibers tolerant to harsh environments
  - High temperatures and hydrogen pressures
- Fiber types:
  - Graded index multimode: GR-S50/125-20P
  - Single mode: S1310-P
- High temperature (200 - 350 °C):
  - Pure silica fibers with polyimide coatings
- Moderate Temperatures (< 200 °C):
  - Pure Silica fibers
  - Ge doped fibers with hermetic carbon
  - High temperature acrylate or Silicone/PFA



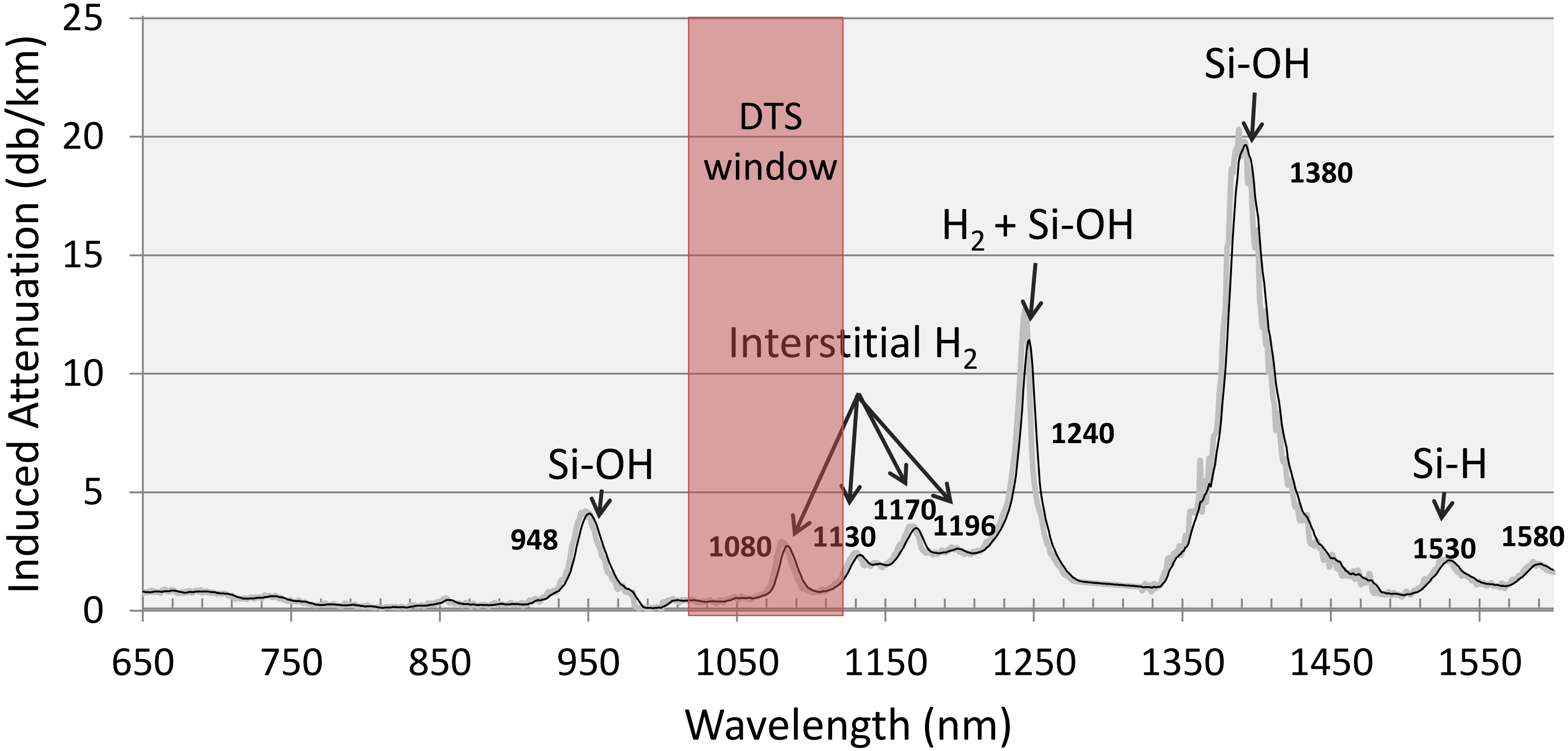
Fiber Test and Characterization Facility

- Monitor changes in spectral attenuation (600 to 1600 nm)
  - Periodic in-situ logging with OSA
  - Source power monitored with reference fiber outside H_2 vessel
- Parallel testing of up to 4 fibers
  - Pure H_2 or H_2/He gas mixtures
  - Pressures $\leq$ 150 atm.
  - Temperature $\leq$ 300 ^{o}C
- 24x7 operation for monitoring long term effects
- Equipped with safety features and remote fault monitoring.

<u>Dedicated Fiber Test Facility for Oil and Gas Industry</u>

Nufern offers hydrogen and other environmental test services

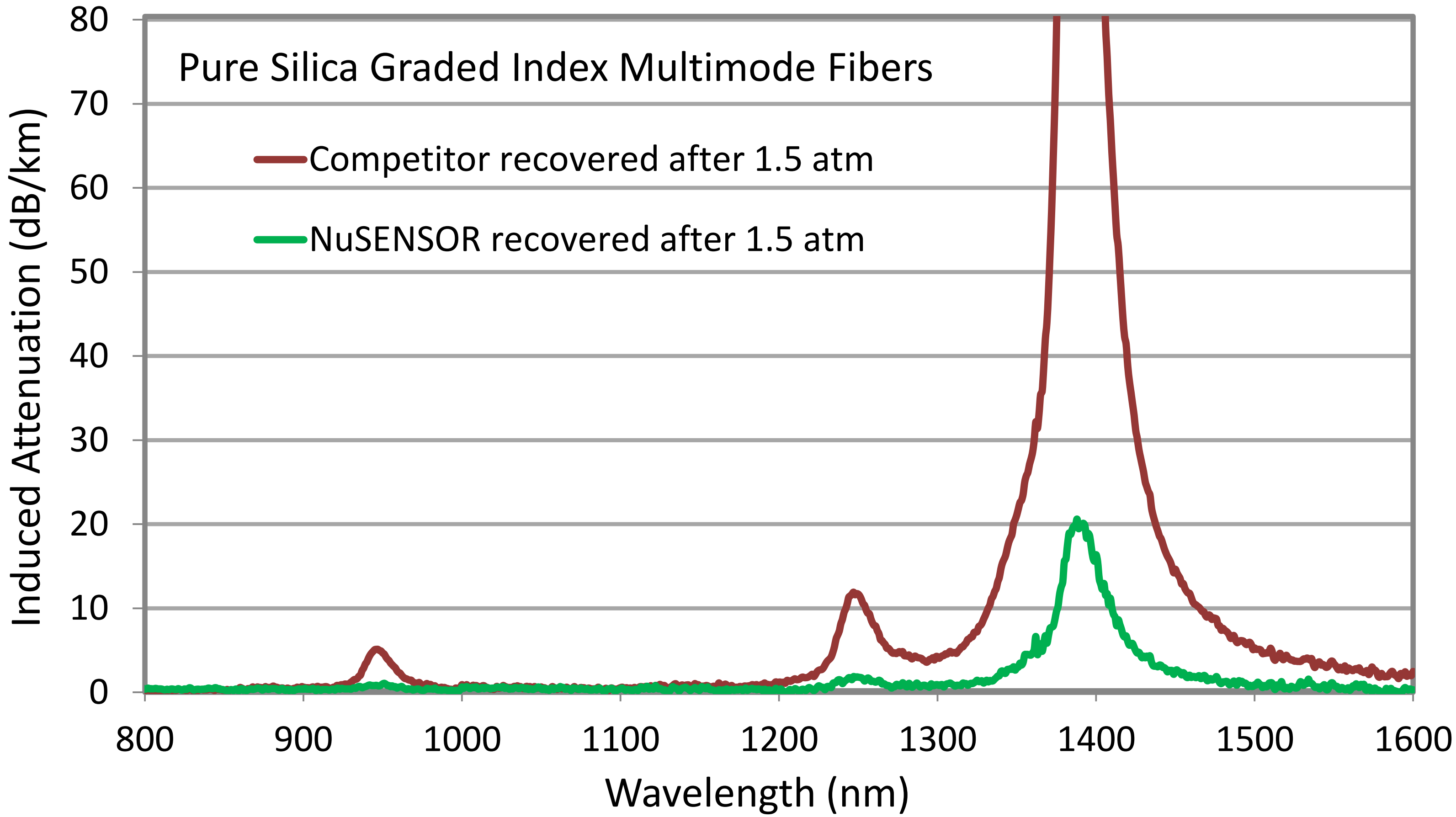
Fiber Attenuation in Down Hole Environment



High temperature and hydrogen environments induce losses

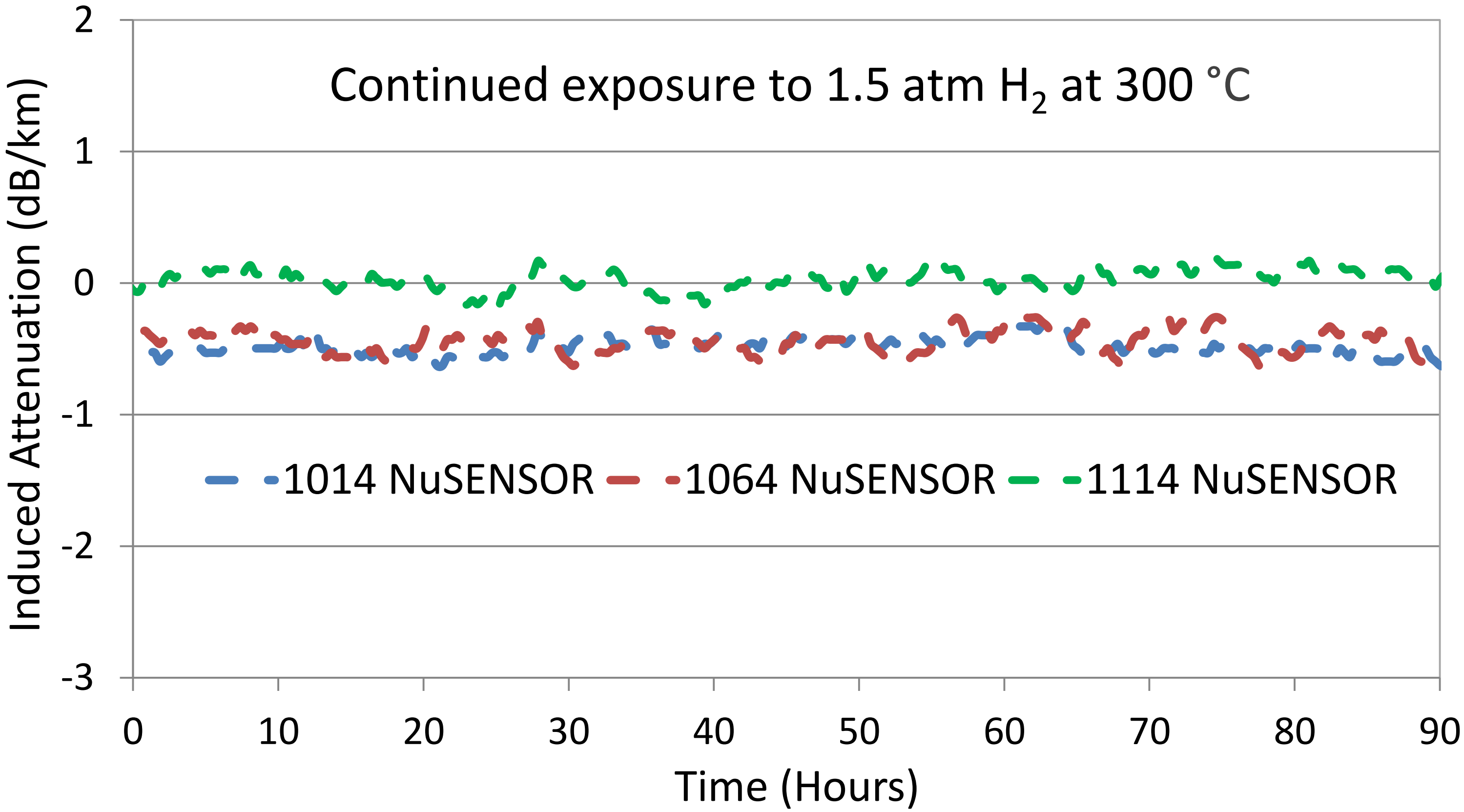
- Attenuation of signal and stokes and anti-stokes signals limits range
- Changes in differential attenuation effects temperature accuracy

Si-OH Related Losses in Typical Well Environments



Significant differences in hydrogen induced-attenuation can be observed in nominally pure silica fibers due to processing differences

Polyimide Coated Pure Silica Core Fiber



- Polyimide coating provides thermal stability up to 300 °C
- Pure silica glass provides resistance to hydrogen induced losses
- No significant attenuation induced at typical DTS wavelengths

Polyimide Coating Quality

Polyimide coating show excellent resistance to temperature & chemical resistance

– Microscopic examination shows no signs of degradation

Summary

- Optical fibers are being widely used for a variety of sensing applications
- Fiber optic sensors enable remote sensing capabilities
- Truly distributed sensing is achievable when the fiber is used as an intrinsic sensor
- Specialty fibers can be engineered to meet specific sensing applications and environments

Nufern

Brighter Fiber Solutions

Thank you