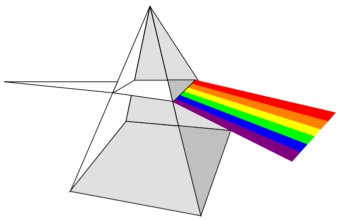
David Krohn
Light Wave Venture LLC



- David Krohn has over 55 years' experience in the photonics industry with an emphasis on fiber optics and fiber optic sensing systems
- Managing Partner of Light Wave Venture LLC
- Chair of the IEEE Working Group on Fiber Optic Sensor Standards
- Assisted over 133 companies and government agencies with activities in product development, marketing, commercialization, and management functions
- David Krohn started CITE (Commercialization of Innovative Technology through Entrepreneurship) which is a training program for technology commercialization
- He is author of the book: Commercialization Basics for the Photonics Industry, SPIE (2013). He is a co-author of the book "Fiber Optic Sensors: Fundamentals and Applications", Fourth Edition, SPIE (2014)
- David Krohn attended Rutgers University as an undergraduate (BS 1965) He obtained his MS from Case Western Reserve University in 1967 and his Ph.D. from Lehigh University in 1973. All degrees are in material science
- He has written 6 books (4 on fiber optic sensors), over 80 papers and holds 28 patents relating to photonics

Standardization of Sensing, Data, and Analytics Across Infrastructure Segments (Fiber Optic Sensors)

David Krohn, PhD

IEEE Fiber Optic Sensor Standards Working Group Chair

Managing Partner, Light Wave Venture LLC

Fiber Optic Sensor Standards Overview

- There are several organizations working on fiber optic sensor standards. However, each activity is of limited scope which results in a fragmented landscape
- There is no central organization tracking all the standards activities
- However, IEEE has focused on standardization gaps

Fiber Optic Sensor Standards Activities

Photonic Sensors Consortium
SEAFOM™ - International Joint Industry Forum to promote the growth of fiber optics in subsea applications.
ISIS Canada: Civionic Standards
NSF/NIST: FOS Standard for SHM
POSC: DTS Standard
IEEE Std. 952-1997: IFOG Standard
ASTM:
- **Subcommittee E13.09 (Fiber Optic chemical sensing)**
- **Electrical strain gage tests**
- **ASTM F3079-14 Standard Practice for Use of Distributed Optical Fiber Sensing Systems for Monitoring the Impact of Ground Movements During Tunnel and utility Construction on Existing Underground Utilities**

IEC:
- **60044-7 & 60044-8 (Optical CT & VT)**
- **IEC 61757-1 Fiber Optic Sensors – Part 1: Generic Specification**

ISA: SP12.21 (FOS for hazardous locations)
SAE: ARD 50024 (FOS for Avionic use)
SIIS (Subsea Instrumentation Interface Standard)
IWIS (Intelligent Well Information Standard)
POSC/WITSML (Petrotechnical Open Standards Consortium/ Wellsite Information Transfer Standard Markup Language)
IDOPTS (International Distributed Optical Performance Testing Standard)
Telcordia GR-63 – operating conditions tests
Fire detection
- **EN 54-5 or EN 54-22 (Europe)**
- **FM (USA)**
- **CUL521 (Canada)**

SEAFOM Participating Companies

AFL | BRUGG CABLES Well connected. | DE REGT MARINE CABLES | Gooch & Housego | NUFERN | Schlumberger | TELEDYNE OIL & GAS Everywhereyoulook | Wellstream

AkerSolutio | Chevron | FAZ TECHNOLOGY | HALLIBURTON | ofs | TE SUBCOM connectivity | woodside

Alcatel·Lucent | CITY UNIVERSITY LONDON | FBGS DRAW TOWER GRATINGS | LANCER | omnisens Securing asset integrity | SIEMENS | TNO | YOKOGAWA

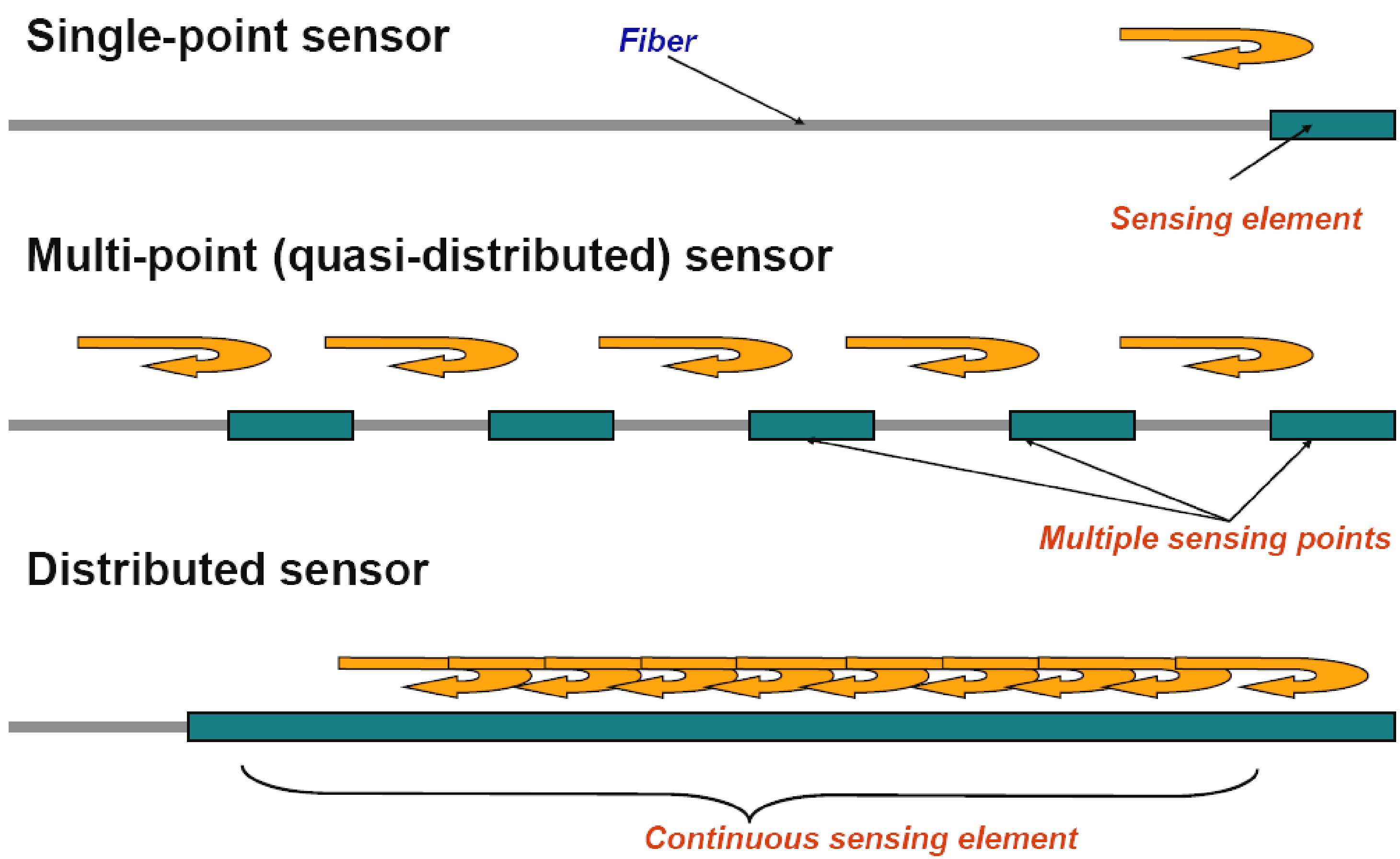
AMETEK | cmr Christian Michelsen Research | FIBERCORE | LIOS TECHNOLOGY | OneSubsea | SILIXA | TOTAL

AP SENSING advanced photonic | ConocoPhillips | FMC Technologies | MAERSK OIL | OptaSense a QinetiQ company | SMART FIBRES | UNIVERSITY OF CAMBRIDGE

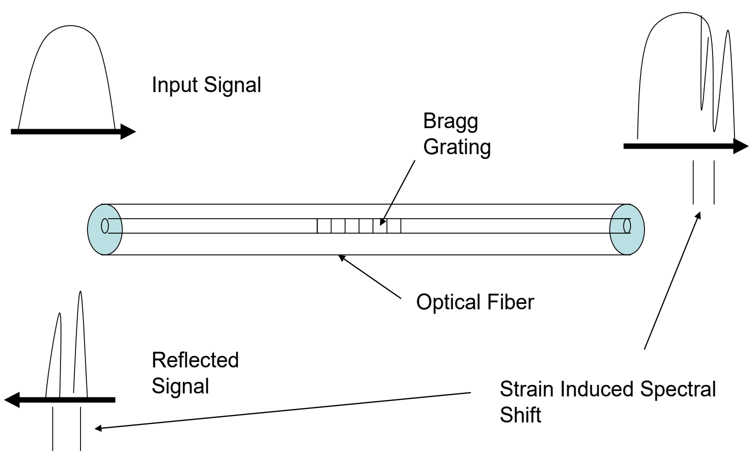
BAKER HUGHES | CORNING | Fotech SOLUTIONS | MagiQ | BR PETROBRAS | Statoil | Verrillon an AFL company

bp | DEEPLINC | GE | nexen | roxar | TE SEACON DEUTSCH | Weatherford

Classification of Optical Fiber Sensors According to their Topology

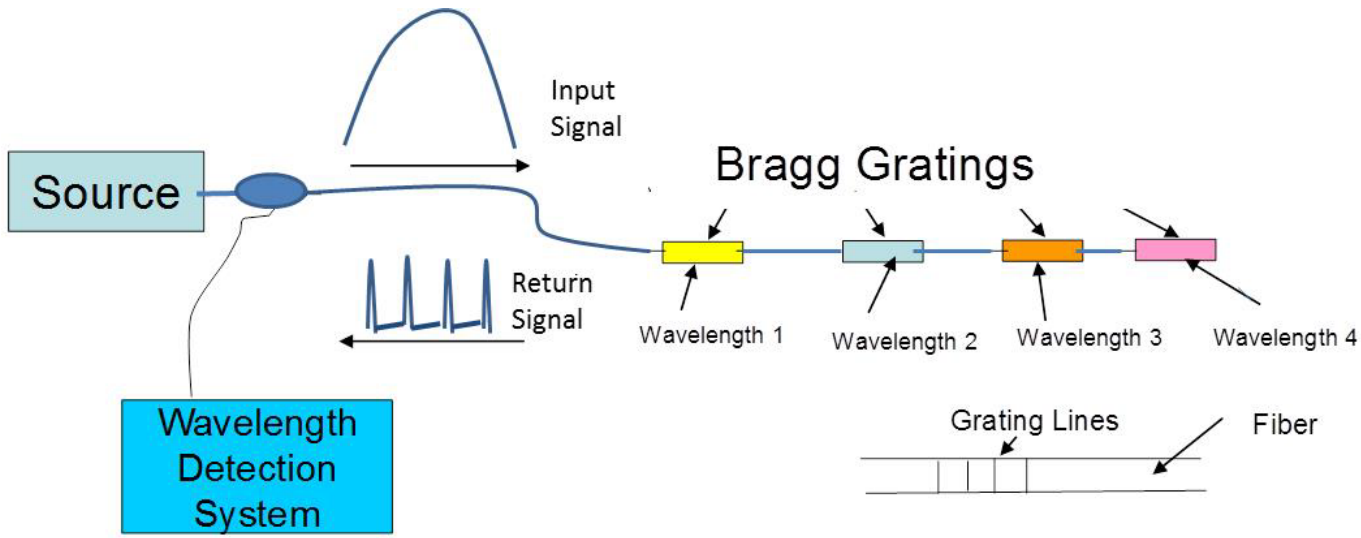


Bragg Grating Sensors

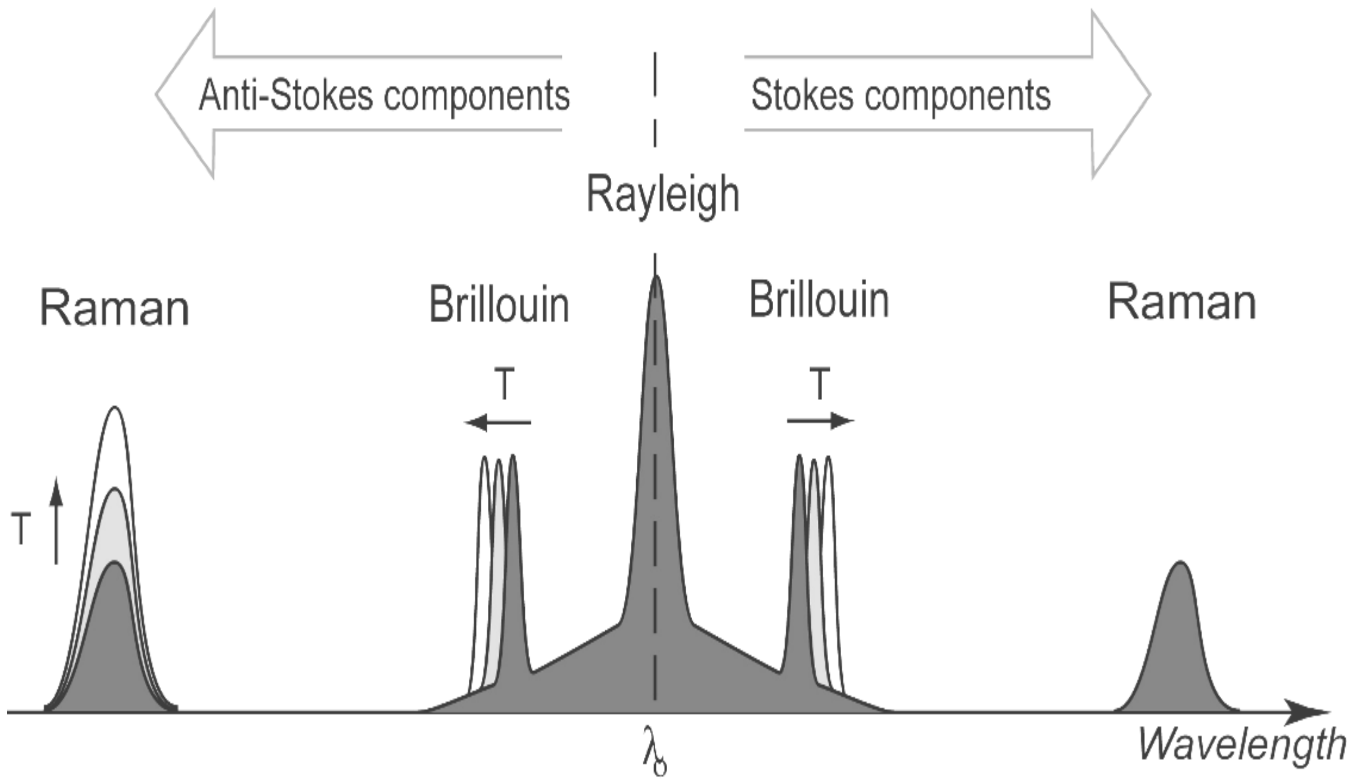


Performance

- 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



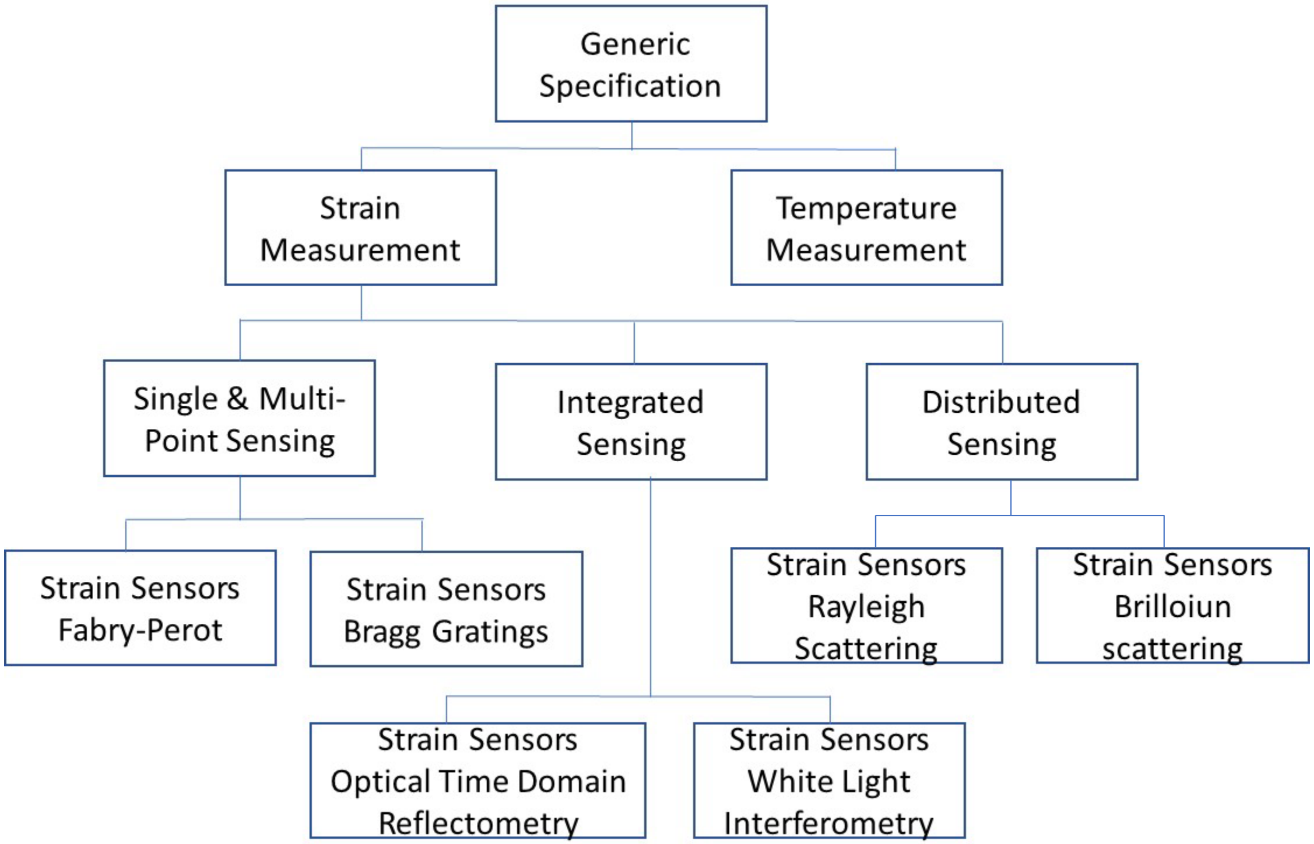
Emission from Raman, Brillouin and Rayleigh Scattering



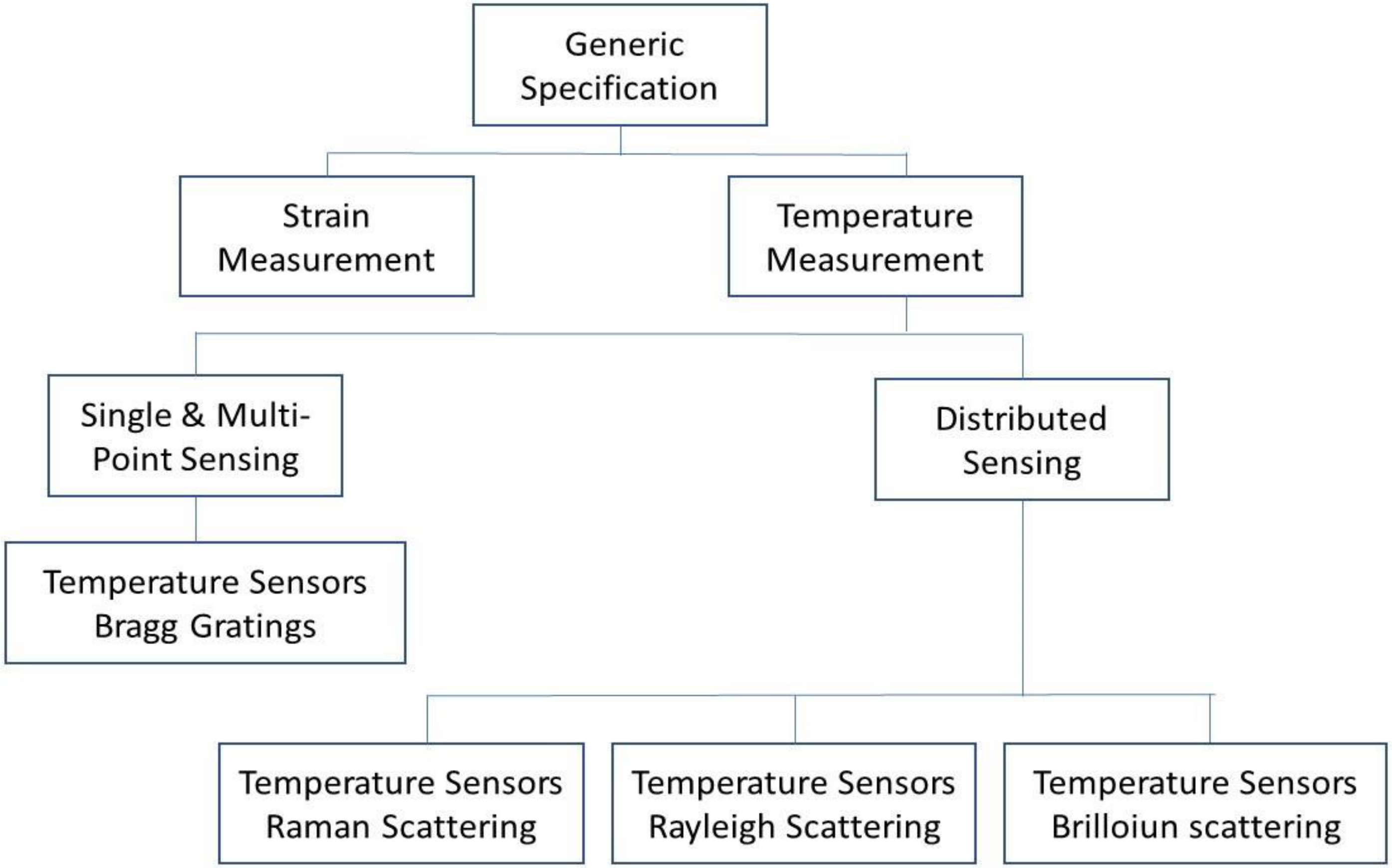
Distributed Fiber Optic Sensors

- Background
  - DTS (Distributed Temperature Sensors-Raman Scattering) – entire fiber is a sensor
  - DAS (Distributed Acoustic Sensors – Rayleigh Scattering) - entire fiber is a sensor
  - DSTS (Distributed Strain and Temperature Sensors-Brillouin Scattering) – entire fiber is a sensor
  - Interferometric – Quasi-Distributed – discrete sensing points
  - Bragg grating - Quasi-Distributed – discrete sensing points

IEC 61757 – Generic Specification- Strain



IEC 61757 – Generic Specification- Temperature

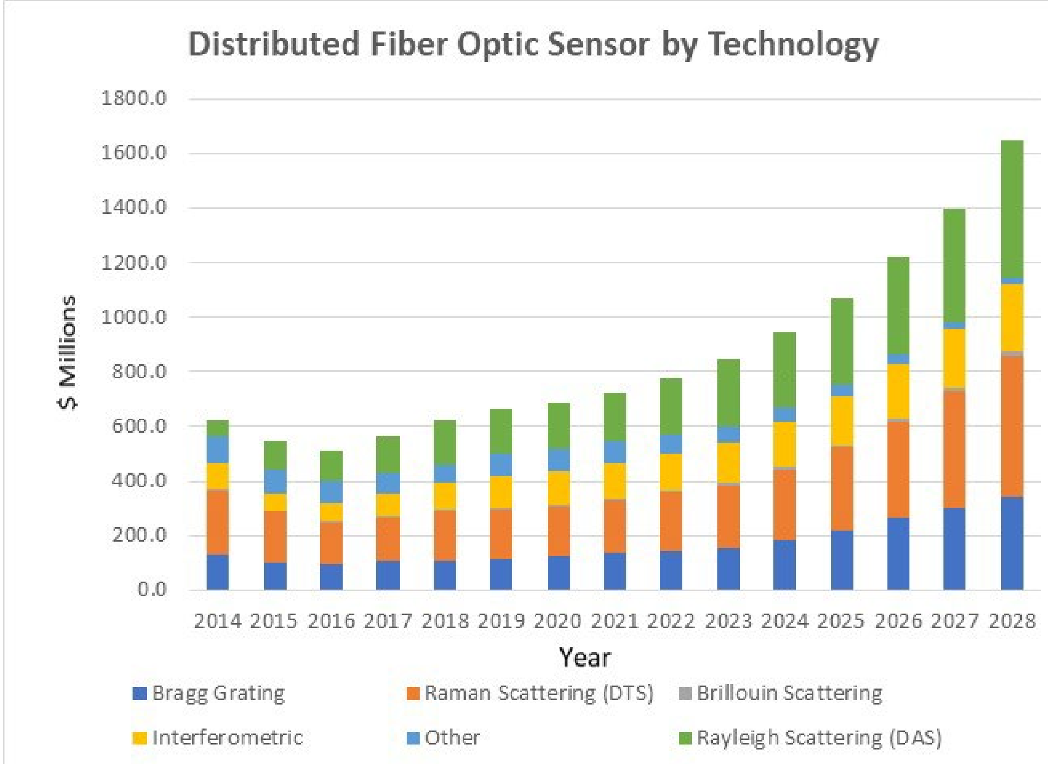


Evolution of the Distributed Fiber Optic Sensor Market

- Normally, emerging technology will move from simple to complex difficult applications
- Distributed fiber optic sensors took on one of the most difficult applications much earlier in the product development and commercialization cycle
- Oil and gas well applications
  - Advantages
    - Not price sensitive
    - Eliminated the use of electronics in a very harsh environment
    - Fully distributed or multiple point sensing capability
    - Can work over very long distances
  - Problems
    - Harsh environment with 15-year lifetime required
  - Now fiber optic sensors can meet the 15-year lifetime requirement
  - However, the integration of sensor system suppliers and oil service companies to provide a proprietary solution left gaps in specifications needed for other applications
- Key conclusion – distributed fiber optic sensors could address a broad range of applications

IEEE Standards Activity Focus

- Focus on market drivers where standards would have the greatest impact on commercialization
- Market forecasts identified the best standard targets
  - Technologies
  - Broad market applications
  - Standards – market impact for commercialization



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Bragg Grating	131.3	98.6	97.2	107.5	109.6	112.2	124.5	136.1	141.8	156.0	185.8	219.0	264.7	299.4	340.7
Raman Scattering (DTS)	233.5	187.4	150.6	160.7	177.7	180.9	181.5	193.5	214.4	228.5	256.9	303.4	353.7	427.7	517.9
Brillouin Scattering	4.3	4.4	4.7	5.1	5.5	6.0	6.3	6.5	6.9	7.4	8.2	9.3	10.6	12.1	13.8
Interferometric	95.1	63.3	67.8	81.9	101.5	117.6	124.2	130.6	138.3	150.1	167.9	177.4	198.4	217.0	247.8
Other	97.7	90.0	80.0	75.0	66.0	84.0	82.0	78.0	68.0	59.0	53.0	45.0	35.0	26.0	22.0
Rayleigh Scattering (DAS)	62.2	100.8	113.3	135.4	159.7	161.9	168.6	178.0	203.2	246.0	270.7	315.9	357.1	414.4	505.5
Total	**624.2**	**544.6**	**513.7**	**565.6**	**620.1**	**662.6**	**687.1**	**722.7**	**772.6**	**847.0**	**942.4**	**1069.9**	**1219.5**	**1396.6**	**1647.7**

Take away – In 2014 the market share was 21% for Bragg grating sensors, 54% for DTS sensors and 10% for DAS sensors. In 2028 the market share is projected to be 21% for Bragg grating sensors, 31% for DTS sensors and 30% for DAS sensors.

Source - Light Wave Venture

IEEE Standards for Bragg Grating and DAS Fiber Optic Sensors

- The purpose of these standards is to clarify definitions so that ambiguity in specifications can be eliminated to facilitate broad usage of Bragg grating and DAS sensing systems in a multiplicity of applications including smart civil structures, aerospace, security, defense, transportation, energy, and environmental monitoring.
- The two IEEE fiber optic sensor standards (P2067- Bragg Grating Interrogator Standard and P3101 DAS Interrogator Standard) are to provide definitions and explanations of terms relating to the use of distributed Bragg grating and acoustic sensor (DAS) interrogators. They also offer a list of the key performance parameters needed to describe fully Bragg grating and DAS-based sensor systems and to allow the end user readily to compare systems from different suppliers
- In addition, the two standards address the translation between strain measured in picometers versus measured in microstrain
- The IEEE Standard Spec sheets for Bragg grating interrogators and DAS interrogators follow in the next two slides

IEEE Standard – Bragg Grating Interrogator (P2067) Example

Parameter	Value	Unit
Wavelength Range	40	nm
Number of Channels	4	
Number of Sensors Per Channel	1 - 30	
Resolution	1	pm
Wavelength Accuracy	< +/- 1	pm
Wavelength Precision	< 0.1	Pm
Linewidth	20	MHz
Wavelength Repeatability	< 0.05	pm
Laser Output Per Channel	+1 to +5	dBm
Programmable Gain Settings	4	
Optical Dynamic Range	> 25 dB	
Scan Frequency (FBG Processing)	1/2/4/8	kHz
Scan Frequency (Spectrum Mode @ 1pm)	16	Hz
Sensor Range Distance	0 - 10	km

IEEE Standard – DAS Interrogator (P3101) Example

Parameter	Value / Definition	Unit
Operating Mode	Intensity vs Phase	
Operating Wavelength	1550	nm
Range	40-100	Km
Spatial Resolution	1 - 10	m
Spatial Interval	0.025 - 5	m
Scan Frequency	>0 -20	mHz to KHz
Optical Time Interval		s
Acoustic Frequency Range	>0 -20	mHz to KHz

DAS Market Segregation

- DAS Market Segregates into two categories
  - Intensity
  - Phase
- Intensity demodulation can only detect disturbances and cannot generate a detailed waveform that characterizes vibrations. As a result, it can only provide qualitative measurements. It can detect events but cannot characterize events.
- Phase demodulation can generate a waveform that enables quantitative measurements and allows characterization of events such a vibration signature
- Initial products were intensity based. Phase based systems will increase relative market share due to their expanded versatility

IEEE Fiber Optic Sensor Standards Logistics

- The IEEE fiber optic sensor standards activity was initiated in 2017
- The Bragg interrogator standard was created and published in 2021
- The DAS interrogator standard was created and published in 2023
- The working group that establishes the standard is typically made of about 20 to 25 companies and organizations. (Membership in IEEE is not required)
- However, the be in the ballot group that votes on the standard – IEEE membership is required
- At this point, each new standard will likely be a 2 plus year development cycle
- The two existing standards can be purchased from IEEE

Possible Next Standard Targets

- Smart infrastructure (Projected 2028 market - $324M*)
- Avionic fuel level sensors (subset of projected 2028 avionic market – military & civilian - $95M*)
- Other

* Light Wave Venture Distributed Fiber Optic Sensor Market Forecast - September 2023

Possible Next Standard Targets – Smart Infrastructure

- Parameters to monitor
  - Strain
  - Vibration signature
  - Crack detection
  - Corrosion
  - Temperature
- Range < 1 km to 5 km
- Spatial resolution 1 m
- Scan frequency >0 – 20 kHz
- Accuracy +/- 1 pm → 1% microstrain
- Technology
  - Bragg grating
  - DAS
  - DTS
- Fiber/sensor attachment
- Standard must address cost
- Lifetime > 20 years

Possible Next Standard Targets – Avionic Fuel Level

- Parameters to monitor
  - Multipoint hydrostatic pressure
  - Temperature
- Range < 100 m
- Accuracy 1%
- Temperature range -40^{O}C to plus 30^{O}C
- Vibration insensitive
- Technology
  - Bragg grating
  - Other
- Fiber/sensor attachment
- Standard - moderate cost sensitivity
- Lifetime > 15 years

Summary

- There are several organizations working on fiber optic sensor standards. However, each activity is of limited scope which results in a fragmented landscape
- There is no central organization tracking all the standards activities
- However, IEEE has focused on standardization gaps
- The IEEE has developed international standards for Bragg grating interrogators and DAS interrogators that deal with a broad range of applications with a strong focus on smart infrastructure
- Next focus areas (to be determined)
  - Smart infrastructure
  - Avionic fuel level sensors
  - Other

Industry Support

- Any company or group that would like to join the IEEE Fiber Optic Sensor Standards Working Group, please contact me in my role as IEEE Working Group Chair

(You do not have to be a member of IEEE to join the working group)

- Any group, company or start-up needing assistance with market understanding and commercialization support, please contact me in my role as Managing Partner, Light Wave Venture LLC

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