Invited Paper

Advanced end-to-end fiber optic sensing systems for demanding environments

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ABSTRACT

Optical fibers are small-in-diameter, light-in-weight, electromagnetic-interference immune, electrically passive, chemically inert, flexible, embeddable into different materials, and distributed-sensing enabling, and can be temperature and radiation tolerant. With appropriate processing and/or packaging, they can be very robust and well suited to demanding environments. In this paper, we review a range of complete end-to-end fiber optic sensor systems that IFOS has developed comprising not only (1) packaged sensors and mechanisms for integration with demanding environments, but (2) ruggedized sensor interrogators, and (3) intelligent decision aid algorithms software systems. We examine the following examples:

- Fiber Bragg Grating (FBG) optical sensors systems supporting arrays of environmentally conditioned multiplexed FBG point sensors on single or multiple optical fibers: In conjunction with advanced signal processing, decision aid algorithms and reasoners, FBG sensor based structural health monitoring (SHM) systems are expected to play an increasing role in extending the life and reducing costs of new generations of aerospace systems. Further, FBG based structural state sensing systems have the potential to considerably enhance the performance of dynamic structures interacting with their environment (including jet aircraft, unmanned aerial vehicles (UAVs), and medical or extravehicular space robots).
- Raman based distributed temperature sensing systems: The complete length of optical fiber acts as a very long distributed sensor which may be placed down an oil well or wrapped around a cryogenic tank.

Keywords: Fiber Optic Sensors, Fiber Optic Sensor Systems, Fiber Bragg Grating Interrogators, Raman Temperature Sensor Systems, Photonic Crystal Spectrometers, Avionics Sensors, Medical Sensors, Energy System Sensors

1. INTRODUCTION

Optical fiber sensors have the potential to deliver new and effective measurement in many applications aided by the following properties: (a) immunity to and non generation of electromagnetic interference (EMI), (b) electrical passivity and thus safety in explosive environments, (c) transmission of sensed information over long distances and through difficult to access regions, e.g., through small holes, down oil wells, etc., (d) small size (diameter) allowing integration into smart materials, (d) highly durability in many environments, (e) minimal mass, particularly important in aerospace applications, (f) capability of being installed with less labor than comparable electronics sensors.

For practical application a fiber optic sensing system needs to include: sensors, fiber optic link, interrogator (comprising photonics, electronics and firmware/software that converts, for example voltages to measurands such as strains, temperatures or pressures), data interpretation and decision-aid algorithms/software (Fig. 1).

In Section 2, we provide some examples of such “end-to-end” sensor systems. Then in Section 3, we discuss example demanding environments in which such sensors can be used.

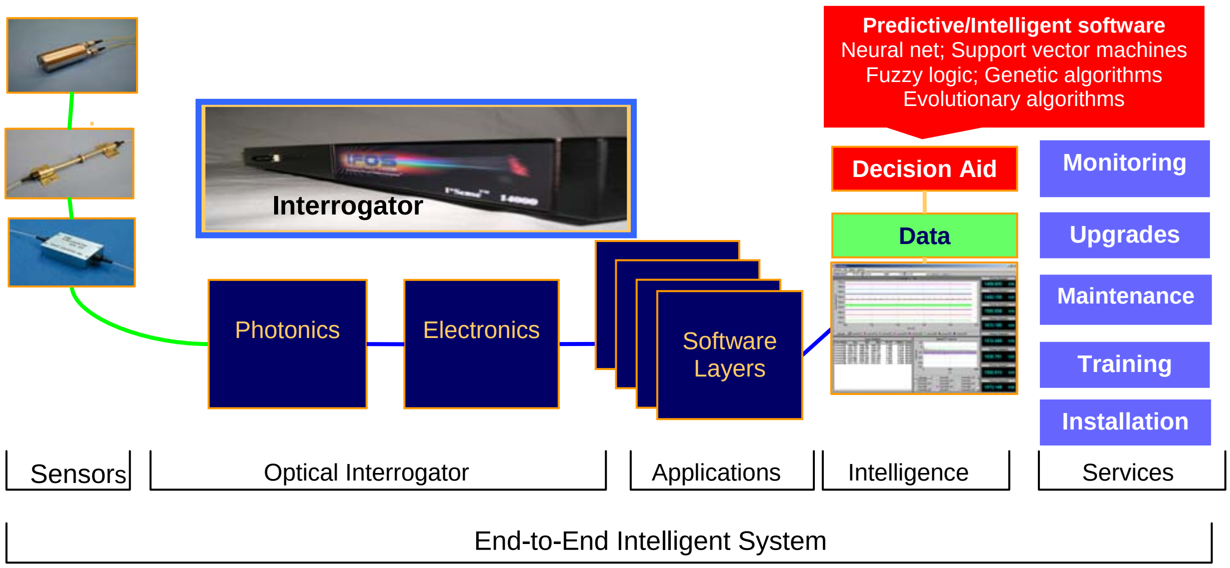

Fig. 1 End-to-end intelligent fiber optic sensor system.

2. END-TO-END FIBEROTIC SENSING SYSTEMS

In this section, we discuss two examples of end-to-end sensors systems: (1) fiber Bragg grating (FBG) sensor and (2) Raman-based distributed temperature sensor (DTS) systems. Another example, (3) a fiber optic gyroscope (FOG) sensor system, consisting of a rotation sensing fiber optic coil together with Sagnac phase sensing interrogation optics and electronics is discussed in a companion paper [1] in this proceedings volume.

2.1 Fiber Bragg Grating Sensor (FBG) Systems

The writing of FBGs [2] into select regions along an optical fiber provides a means of creating discrete high-sensitivity, high-resolution sensing sections along the fiber. Furthermore, FBGs are highly multiplexable: many FBGs can be written into a single optical fiber to provide multipoint sensing along that fiber; then, one or more fibers can be integrated as a "nerve(s)" providing "feeling" for "smart" structures. Given these properties, FBG sensing systems are being deployed in a wide variety of applications for structural health monitoring (SHM [2]-[5]) for the measurement of parameters such as such as strain, temperature, fracture, vibration or simultaneously sensing multiple parameters ([4]-[31]) with diverse applications including, for example, aerospace and robotics [43], nuclear reactors, wind turbines [6], concrete structures [9], bridges [4]-[5], MRI compatible medical devices [45] as well as oil & gas and geothermal wells. FBGs have been established as a particularly important sensor component for static and dynamic strain measurements in smart structures. This is chiefly due to their precision, resolution and reliability, tolerance of extreme conditions and immunity to RF electromagnetic interference. In many applications, arrays of FBG sensors along a single fiber at multiple locations are required to collect data samples at high speed with micro-strain resolution. However, traditional approaches to processing the optical signals either lack in sampling rate speed or are cost-prohibitive as the number of optical sensors increases. On the other hand, recent advances in interrogation technology are opening up the possibility of supporting a large number of FBG sensors (on the order of a hundred per fiber) at high speed (hundreds of kHz to MHz).

As shown schematically in Fig. 2, a fiber Bragg grating operates by acting as wavelength selective filter that reflects a narrow band of wavelengths centered on the grating's characteristic wavelength referred to as the Bragg wavelength, λ_B. The Bragg wavelength is related to the grating pitch, Λ, and the mean refractive index of the core, n, by $\lambda_B = 2\Lambda n$. Both the fiber refractive index and the grating pitch vary when strain is applied to the FBG and/or the temperature is changed. Wavelength change measurement then provides a basis for strain and temperature sensing. For example, high-resolution strain sensing operation can be achieved by precise measurement of the wavelength.

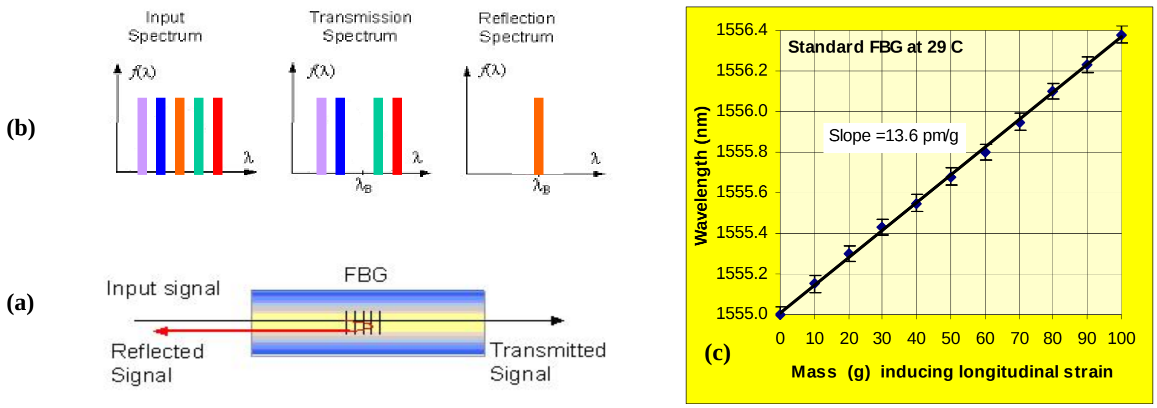

Fig. 2 (a) Fiber Bragg grating (FBG) consists of length of the fiber core (typically several mm) where the refractive index varies periodically with the grating pitch, Λ, about a mean refractive index of the core, n. (b) Given a broadband input spectrum the FBG removes a narrow wavelength band from the transmission spectrum. This wavelength band appears in the reflection spectrum and is centered on a wavelength characteristic of the FBG and known as the Bragg wavelength $\lambda_B = 2\Lambda n$. (c) The reflected wavelength is linearly proportional to strain ε on the grating providing the basis for strain sensing – In particular, the fractional change in wavelength is related to the strain by $\delta\lambda_B / \lambda_B \approx 0.78\varepsilon$ for a silica fiber. In the graph the strain is induced by hanging on the fiber weights whose mass is given in grams – We refer to [32] for detailed relationships between wavelength change, wavelength and weight for a range of optical fibers.

A key element in any FBG sensing system is the optical interrogator. Interrogators can be constructed to measure the wavelength change with sub-picometer resolution, thus allowing sub-microstrain resolution strain sensing. A general schematic for parallel processing interrogator system to measure the wavelengths reflected by the grating sensors as a basis for determining strain as shown below in Fig. 3. Therein we show a schematic of an FBG interrogation system supporting multiple grating sensors on multiple optical fibers capable of reaching hard-to-access regions via bending paths with immunity to electromagnetic interference and possibly over several kilometers. The interrogator sends out light along each fiber to each grating and analyzes the reflected spectra to determine changes in the Bragg wavelength of each grating.

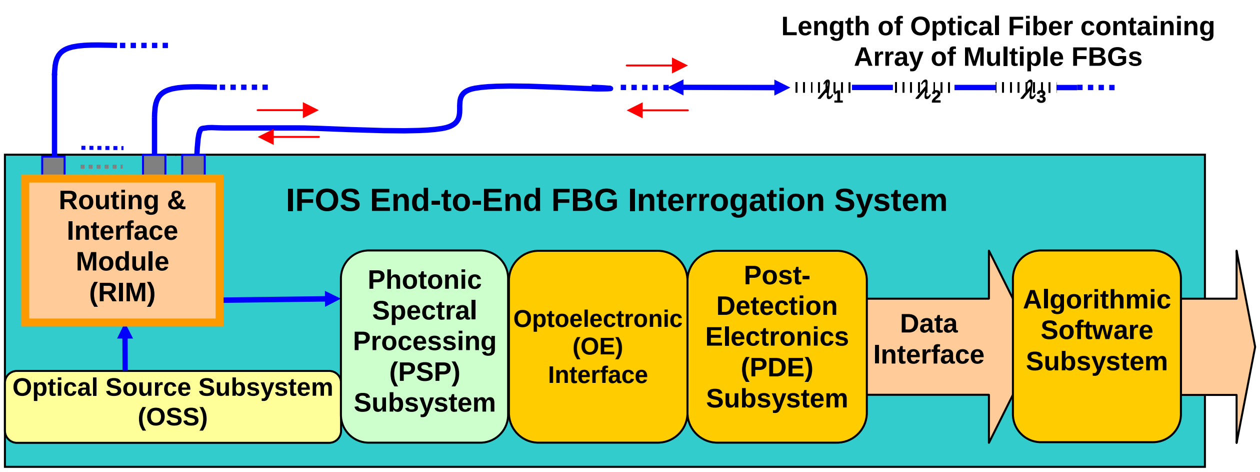

Fig. 3 IFOS parallel processing FBG interrogation supporting multiple FBG arrays.

2.2 Raman Based Distributed Temperature Sensor (DTS) Systems

In contrast to FBG sensor systems, where the sensors are discrete sensing sections (several millimeters long) that need to be written into the optical fiber, for Raman DTS sensing the whole fiber length, which can be kilometers long, acts as one giant sensor. The DTS sensing system uses a narrow-band laser source, and is based on Raman scattering caused by either absorbing a lattice phonon or emitting a lattice phonon. When this happens the scattered wavelength shifts relative to the input excitation wavelength. When a phonon is *emitted* in the scattering process, the scattered wavelength, called *Stokes light*, decreases. When the phonon is *absorbed* by the excitation light, energy increases with the scattered wavelength increase called *anti-Stokes light*. The *anti-Stokes light* scattering intensity is dependent on the upper state population, which is populated by thermal energy and is therefore *temperature dependent*. The *Stokes scattering* is dependent on the ground state population, which is *not sensitive to temperature*. By taking the ratio of intensities of anti-Stokes to Stokes scattering, one can measure the temperature at any point along the fiber. As one can collect this radiation along the entire fiber one can have thousands of independent temperature measurements along many kilometers of optical fiber. However, the scattered signal is very weak presenting a considerable challenge for interrogation.

Fig. 4 shows an example DTS system with temperature as a function of distance along an optical fiber cable measured over 2400 meters with 1 meter spatial resolution.

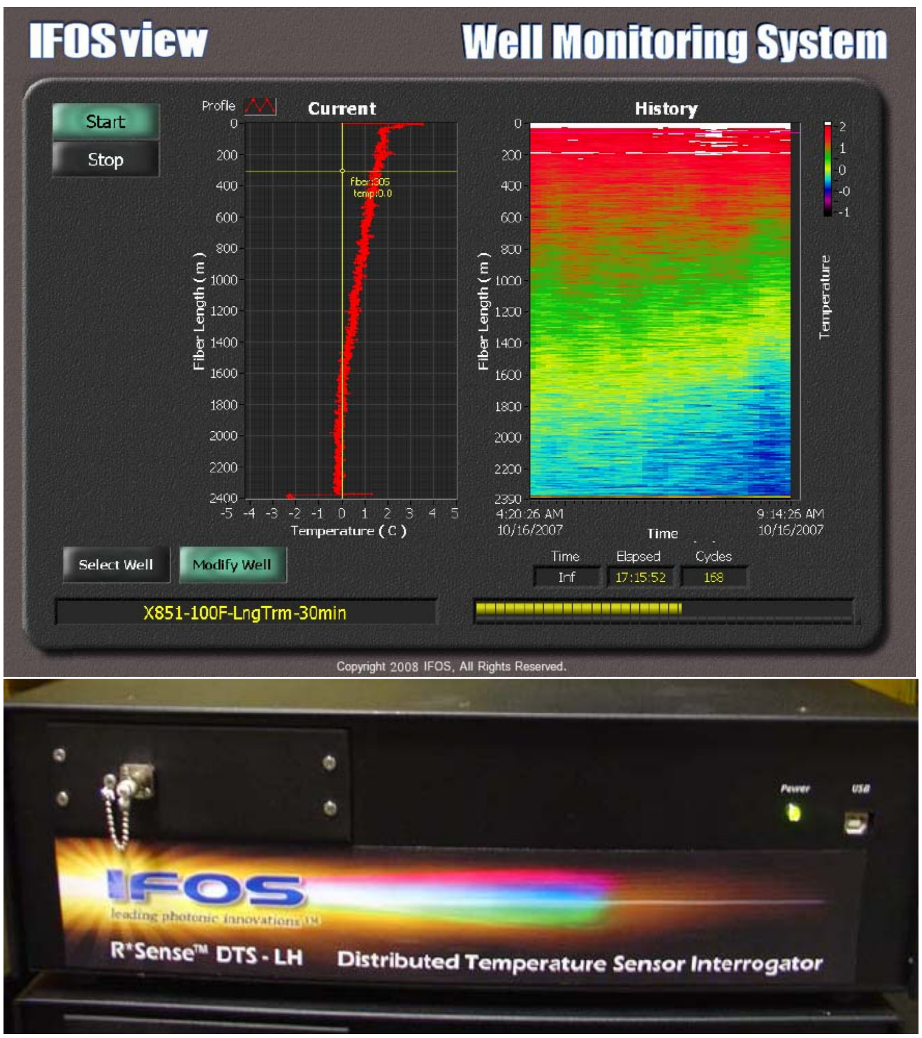

Fig. 4 IFOS DTS system with temperature as a function of distance along an optical fiber cable measured over 2400 meters with 1 meter spatial resolution.

3. DEMANDING ENVIRONMENTS

In this section, we discuss several demanding environments including (1) extreme temperatures, (2) high electromagnetic interference (EMI), (3) high magnetic field medical MRI environments, (4) high radiation, and (5) hydrogen darkening environments.

3.1 Extreme-Temperature Environments

Given appropriate coatings and/or packaging, optical fiber sensors fare relatively well in both cryogenic [37] and elevated temperature [20] environments including those encountered in aerospace, nuclear reactor and geothermal [39] applications. The following table provides considerations for their usage including the optical fiber material, coatings, tubing and attachment methods

Table 1. Optical Fiber and Coating Materials: Temperature Range Viabilities

MATERIALS	VIABLE TEMP RANGE	COMMENT
Fibers		
Silica	Close to 0 K to 1190°C when softening occurs - (Pure silica can withstand to 1800°C)	Standard optical fiber material. Can withstand strains on the order of 1% in tension & 5 % compression.
Sapphire	Melting point = 2040°C	Obtaining long lengths & adding claddings is challenging.
Polymethyl-methacrylate	-205°C (68 K) to 127°C	Have been reported to measure strains over 15% [36]
Coatings		
Acrylate	-40°C to 85°C	Standard optical fiber coating
Silicone	-40°C to 180°C	
Polyimide	-190°C (83 K) to 385°C	Most common temperature resistant coating
Nitrides		Developmental
Carbides		Developmental
Carbon		Used to prevent hydrogen ingress and thus hydrogen darkening (Sec. 3.5)
Copper	Melting point = 1083 °C	Has been used for both cryogenic and elevated temperature environments. Oxidation is an issue above about 700 °C
Gold	Melting point = 1040 °C	Most common hi-temp coating generally used up to 800°C. However gold is very soft and has been most successfully used in combination with nickel
Nickel	Melting point = 1455 °C	Commonly used under gold coatings
Platinum	Melting point = 1772 °C	Extreme hi-temp coating
Tubing (for protecting temperature sensors – but not suitable for attaching strain sensors)		
Inconel	Melting point = 1372°C	
Stainless Steel	Melting point = 1400°C to 1480°C depending on composition	
Attachment		
Epoxies	to 370°C	
Ceramic Adhesives	to 1100°C	Can have problems when attaching to metals due to thermal expansion mismatch with metals
Soldering		Promising method for attaching metal coated optical fibers to metals [38]

Fig. 5 shows an example setup for temperature monitoring with an FBG array in a thermal protection system (TPS) tile subjected to heat from one side as may be the case for a re-entry vehicle. Fig. 6 shows that, as one side of the tile was subjected to up to 540°C heat, all FBG sensors survived and tracked temperature at different depths through the TPS tile cross-section.

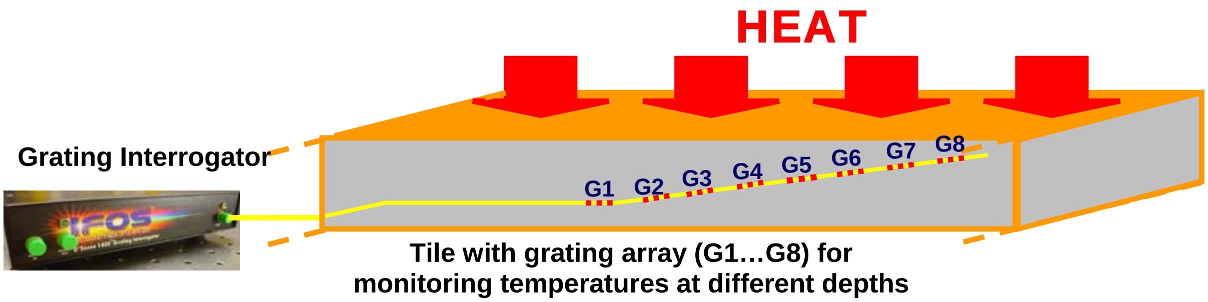

Fig. 5 Setup for measurement of temperature profiles in TPS tiles using an array of fiber Bragg gratings (G1…G8).

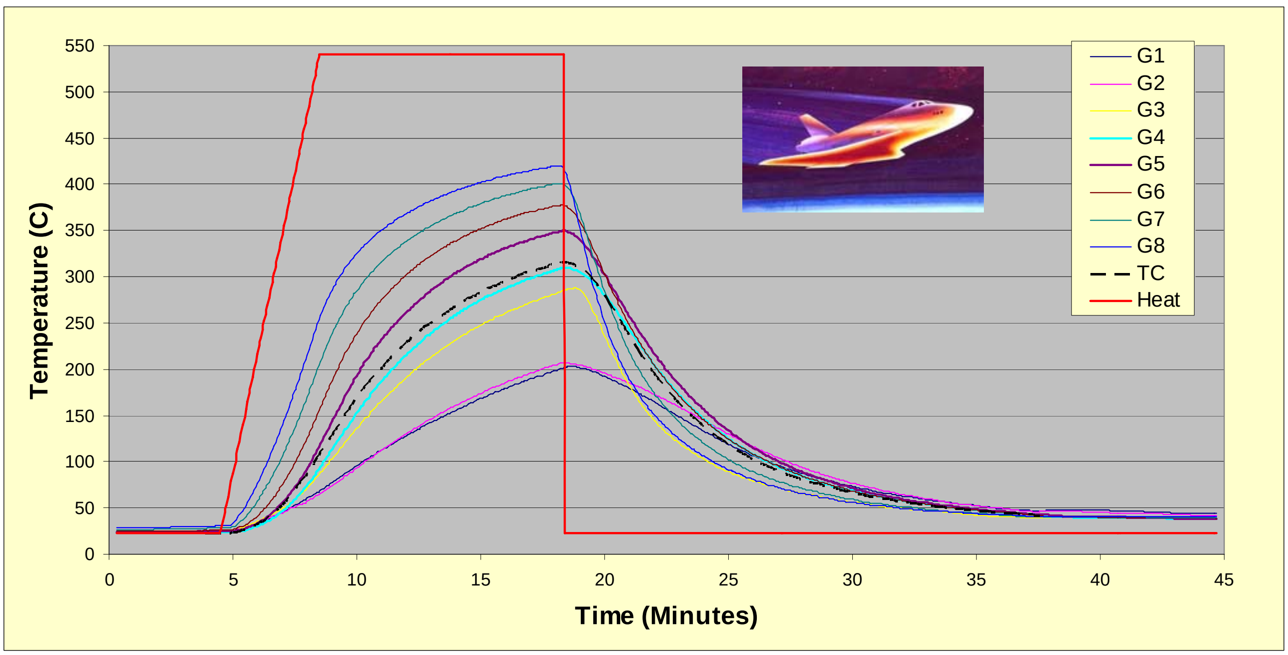

Fig. 6 Temperature profile tracking at different depths in TPS with FBG array (G1…G8) and thermocouple (TC) near G4.

3.2 High-EMI Environments

The electromagnetic interference (EMI) resistance of optical fibers is advantageous when making measurements close to electromagnetic actuators or power lines. For example in robotics, electromagnetic actuators can result in noisy signals when using traditional sensors such as resistive foil strain gages whilst optical fiber sensors perform well [43].

3.3 MRI Medical Environments

Magnetic fields up to several tesla are experienced in nuclear Magnetic Resonance Imaging (MRI) environments which prohibit the use of ferrous metals and the majority of sensors – Optical fiber sensors (fabricated from silica with operation based on light) are one of the few sensor types compatible with MRI. Accordingly IFOS has instrumented medical instrumentation including biopsy needles with FBG sensors for measuring needle shape [44]-[45].

3.4 High-Radiation Environments

For applications such as space and nuclear power plants high radiation tolerance is extremely important. Optical fibers are being developed for space [41] and other high radiation environments. Pure Silica Core (PSC) SM fiber can be highly radiation insensitive. As reviewed in reference [42], the incremental loss of these fibers after 10 years with total dose of 100 krad is as low as 0.05 dB/km.

3.5 Hydrogen Darkening Environments

In underwater and oil well environments [46]-[49], one effect that can result in a decrease in optical performance is hydrogen darkening [48]-[49]. Hydrogen ions, naturally present at low partial pressures in the subsea environment, or from more intense sources such as corrosion, or from a cathodic protection system, can be absorbed by glass fiber causing an increase in attenuation in the affected length of fiber. When good engineering practices are used, umbilical constructions provide a barrier to the ingress of hydrogen, usually in the form of a hermetically welded steel or copper tube, filled with a buffer gel that has hydrogen getter properties. If the optical fiber is run through a jumper with a non-corrosive construction (thermoplastic hose), the long-term performance will not be affected by hydrogen darkening. Carbon coating can also be used to protect against hydrogen ingress – The manufacture of "carbon coated fiber" typically involves sputtering of a 50 nm thick coating is sputtered directly onto the glass surface of the fiber. However, this fiber, although proof against hydrogen darkening, has considerably worse fracture characteristics and fatigue properties, particularly when under strain. This is due to the carbon granules bedded in the surface of the glass acting as a multitude of crack initiators. For almost all applications, hermetically welded tube technology is more than sufficient to provide 25-year lifetimes for installed fiber systems. PSC fiber provides another potential solution. PSCs have been used for DTS in the harsh environment of a Steam-Assisted Gravity Drainage (SAGD) well [49] in which in which steam is injected into heavy oil reservoirs to reduce the viscosity of the hydrocarbon fluid so that it can flow more freely to a producing well.

4. CONCLUSIONS

Optical fibers are small-in-diameter, light-in-weight, electromagnetic-interference immune, electrically passive, chemically inert, flexible, embeddable into different materials, and distributed-sensing enabling, and can be temperature and radiation tolerant. With appropriate processing and/or packaging, they can be very robust and well suited to demanding environments. In this paper, we reviewed FBG and DTS sensor systems as examples of complete end-to-end fiber optic sensor systems that IFOS has developed comprising not only (1) packaged sensors and mechanisms for integration with demanding environments, but (2) ruggedized sensor interrogators, and (3) intelligent decision aid algorithms and software systems.

5. ACKNOWLEDGEMENTS

We thank all members of the IFOS team for their support.

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