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**TOPICAL REVIEW** 

## Truly remote fiber optic sensor networks

#### Verónica de Miguel Soto 10 and Manuel López-Amo

Department of Electric, Electronic and Communication Engineering and ISC Universidad Pública de Navarra, Campus Arrosadia S/N, E-31006, Navarra, Spain

E-mail: veronica.demiguel@unavarra.es

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## Abstract

An overview of truly remote fiber optic sensors is presented in this work. It starts with a brief introduction of fiber optic sensor networks, showing their advantages and multiple applications. Then, the definition of truly remote networks is provided, and their main challenges discussed, such as increasing the sensing distance and the number of sensors interrogated. Several multiplexing techniques have been compared, such as wavelength, time and coherence division multiplexing. In relation to this, the most recent works showing multi wavelength fiber lasers for wavelength division multiplexing have been grouped and their versatility analyzed. Finally, recent and relevant truly remote fiber optic networks have been gathered and some of the most representative schemes explained in detail, comparing their multiplexing capability and the remoteness of the monitored sensors. Random distributed feedback fiber lasers form part of a number of these schemes, proving the suitability of this type of lasers for their use in ultra-long truly remote sensing applications.

## 1. Introduction

## 1.1. Fiber-optic sensor networks-background

Modern optical fiber sensors were developed thanks to two of the most important scientific advances made in the 1960s: the laser and the low-loss optical fiber. The early 1970s was the period when low-loss optical fiber began to be used for sensing purposes apart from telecommunications. This revolutionary work quickly led to the growth of a few research groups, focused on the exploitation of this new technology for sensing and measurement. This field has continued making progress and has developed considerably since then due to the advantageous features offered by fiber optic sensing systems. They offer high sensitivity, a good dynamic range and reliability. In addition to these characteristics, their extraordinary resistance to high temperatures, corrosion, explosion hazards and their immunity to electromagnetic interference; allow their use in hostile environments where other types of sensors cannot operate properly.

Fiber optic technology began with the emerging need for superior performances in specific applications that the existing systems did not provide. The remarkable advantages inherent to this type of sensors, see table 1, assisted their inclusion in a great diversity of markets.

There are many criteria to classify the types of sensors that form a sensor network. The most used are their topology, their transducing approach and their modulation mechanism. Single point, quasi-distributed and distributed sensors can be found in the first category. A single-point sensor sometimes presents the sensing part located at the tip of the fiber. More often, the transduction of the measured parameter is carried out inside the fiber (fiber Bragg gratings (FBGs) or fiber gyroscopes).

A multipoint FOS consists of several detection regions along the fiber network, where each transducer can detect the same parameter or a different one. These optical fiber transducers can be physically separated from a few millimeters up to several meters away, according to the requirements of the application. The truly distributed FOS use the entire length of the fiber to detect one or more external features, achieving several tens of meters, or even tens of kilometers. This is an exclusive capability of fiber optic sensors and cannot be easily accomplished using traditional electrical detection procedures. Figure 1 shows a graphic representation of each type of sensor according to their topology.

Table 1. Advantages, possible applications and measurand of FOS.

Advantages of FOS	Passive-nonelectrical		
	• Small size, flexible, light weight		
	• Immunity to ionizing radiation, radio frequency and electromagnetic		
	interferences		
	• Environmental robustness, high reliability		
	• High sensitivity, accuracy and bandwidth		
	Multiplexing capability		
	Remote and secure data transmission		
	• Biocompatible		
	Cost-competitive		
Applications	Biomedical/biologic applications		
	Aerospace and industrial applications		
	<ul> <li>Operation in harsh environments: high temperatures, extreme vibration, high voltage</li> </ul>		
	• Health monitoring of structures: buildings, tunnels, bridges, heritage structures		
Magnitude to be measured	• Temperature	Chemical substances	
	• Pressure	• Force	
	• Flow	<ul> <li>Radiation</li> </ul>	
	• Liquid level	•pH	
	• Displacement	<ul> <li>Humidity</li> </ul>	
	Vibration	• Strain	
	• Rotation	<ul> <li>Velocity</li> </ul>	
	• Magnetic fields	<ul> <li>Electric field</li> </ul>	
	Acceleration	<ul> <li>Acoustic field</li> </ul>	



Another way to classify fiber optic sensors is by considering the transduction approach. First, intrinsic or 'all fiber' sensors carry out the detection process in the fiber itself. The second type is formed by extrinsic sensors which use fiber only to guide the light to a detection region. Then, the optical signal leaves the cable and is modulated in another medium. Fiber simply records and transmits the detected signal.

Finally, the modulation mechanism of the sensors is intimately related to the multiplexing technique which must be used in order to interrogate several of them in the same network. Previous reviews presenting the state of the art regarding the different types of FOS can be found in [1-7].

However, the main difference when comparing fiber-based sensor networks with other sensing technologies lies in the dual functionality of fiber. Optical fiber may not be only part of the sensor structure, but it can also form the communication channel between the detection site and the central station. Thus, it removes the logistical inconvenience of electrical power supply in remote locations which is a desirable feature in longdistance applications. However, increasing the interrogation distance can become a challenge due to fiber loss.

Another important property of sensor networks is their competence for recovery or self-healing. Resilience guarantees the continuity of the service in case of failure of the network. This is of great importance when the

monitored structure is of high value or in critical human safety situations [8]. Some work has been done to improve this capacity [9–13], although more research should be addressed combining long distance and resilience [10].

Finally, a key concept in optical fiber networks for sensors is their multiplexing capability. Multiplexing allows interrogating two or more sensors using a single monitoring station [14–21]. It is a desirable practice since it is possible to reduce the total cost of the system by sharing several devices in the network and reduce the complexity of the network itself. In addition, some constructions present large dimensions so numerous sensors are needed to monitor the entire structure.

In this technological framework, this review wants to contribute to gathering the latest advances made in multiplexed and in truly remote interrogation of optical fiber sensor networks, highlighting the advantages and disadvantages of each proposed structure as well as its main applications.

#### 1.2. Truly remote FOS networks and their applications

A remote monitoring system presents the ability to observe and verify the performance or quality of any structure located tens or even hundreds of kilometers away from a central station. It is important to remark that a monitoring system can be considered 'truly remote' if there is no active component between the sensor network and the active headend of the system. In this case, the maximum remote distance the sensors to the last active element of the network is considered. For this reason, amplified structures composed of two opposing amplifying pumps, one on each side of the sensors network, the actual remote distance is half the length of the total fiber link.

This capability can be exploited in many applications for the control of structures as well as to avoid possible disasters. Some of the most widespread ones include structural health monitoring of bridges, tunnels and oil or gas pipelines [22–29], tsunami detection [30, 31], railway maintenance [25, 32] and geodynamic control [33, 34], to name but a few.

#### 1.3. Truly remote fiber optic networks-challenges

Three main challenges are addressed by remote fiber optic sensor networks: increasing the number of sensors interrogated, increasing the monitoring distance and assure the operation in case of failure, which is called resilience [35, 36]. In this review, we will focus on the first two challenges.

#### 1.3.1. Multiplexed remote FOS networks

In telecommunications, multiplexing is a method by which multiple signals are combined over a shared medium. Multiplexing divides the capacity of the communications channel between several logical channels, one for each multiplexed sensor. The inverse process consists of extracting the original channels in the receiver and is called demultiplexing [37, 38].

As it was mentioned before, in sensor networks, the main objective of multiplexing is to share the cost of the active devices of the network among all the multiplexed sensors. In this manner, a more efficient use is achieved and the cost per sensor is reduced. The multiplexing process in a sensor network consists of three steps.

- Generation of a signal with adequate power, spectral distribution, polarization and modulation.
- Correct detection of the signal, encoded by the sensors.
- Unequivocal identification of the information that corresponds to each sensor.

Various sensor multiplexing techniques have been proposed (see figure 2), namely, wavelength division multiplexing (WDM), time division multiplexing (TDM), coherence division multiplexing (CDM), frequency division multiplexing, space division multiplexing and hybrid combinations of the above mentioned.

It is important to emphasize that any multiplexing technique present pros and cons, but an optimal method can be chosen depending on each specific application. Cost, noise, bandwidth and flexibility are factors that should be analyzed to select the most appropriate multiplexing technique. In addition, there are several interrelated factors that influence this decision, such as:

- the modulation or coding of the optical signal used;
- network topology;
- need or not of optical amplification;
- · decoding method;



- types of sensors to be multiplexed;
- economic conditions.

One of the main drawbacks of ultra-long-range remote sensing applications is their limited multiplexing capability. WDM is one of the most used multiplexing techniques because of its many advantages. In the networks implementing WDM, the information of each sensor is allocated in a particular wavelength. For this reason, FBGs are the most employed sensors, since their information is encoded in their  $\lambda$ -Bragg. Among the advantages this technique presents, it reduces the number of fibers needed to interrogate the sensors network, the placement of the sensors is flexible and allows continuous monitoring of all of them. However, it is expensive and specialized equipment is required; and is limited by the available bandwidth of the light sources employed.

Following with other widespread multiplexing technique, TDM presents many interesting features which boost its use in remote monitoring sensor networks. For instance, TDM presents high measurement speed, high multiplexing capability and simple and efficient schemes. Contrary to WDM systems, which need a broadband light source or a  $\lambda$ -tunable one, a single optical pulsed light source is required in TDM. However, multiplexing in time requires specialized equipment, such as pulsed light sources, which desirably emit pulses of short duration, high extinction ratio and low timing jitter. Synchronization is also required. Since each sensor is identified by the time that takes the pulse to travel from the source to the sensor along the network, it is important for the sensors to be placed in separate locations. If necessary, optical delays should be introduced between them to avoid overlapping and crosstalk. Consequently, sensor networks must be carefully design in order to assure proper performance. In addition, TDM systems suffer from transmission loss, induced by the couplers that divide the signal to reach each sensor [37], and are limited by the intensity of the light source.

Another technique less used but employed in one of the longest remote systems proposed up to date is CDM. As in WDM, CDM allows all the sensors to be continuously monitored, separating the signals corresponding to each sensor spatially and not temporarily. Several configurations have been proposed to carry out this technique, namely: series, extrinsic-reference ladder and intrinsic-reference ladder [15]. As in TDM, CDM sensor networks must be carefully designed so that the optical path difference of each interferometric sensor was much longer than the coherence length of the light source employed. In this manner, it is guaranteed that the signals traveling through the interferometer interfere coherently. The main drawbacks of this technique are its poor SNR and its high insertion loss, which are significant as the number of multiplexed sensors increases. Furthermore, CDM can only be implemented to interrogate interferometric sensors, which reduces the versatility of the network.

For this reason, the combination of two or more multiplexing techniques may help to overcome the limitations that each technique presents individually. For instance, hybrid WDM/TDM schemes have been validated theoretically to multiplex hundreds of sensors in a single network. In fact, it has been demonstrated through simulations that optical wave time domain reflection technology can be used to multiplex up to 10 000 Bragg gratings of weak reflection into a single fiber [39]. The use of optical time domain reflectometry (OTDR),

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Year References	Princ. operation	Number emission lines	Range (nm)	Spacing
2004 [48]	Semicond. (SOA)	17	13	Fixed (0.8 nm)
2005 [49]	Erbium	17	15	Fixed (0.8 or 1 nm)
2007 [50]	Brillouin-Erbium	70	11	Fixed (0.088 nm)
2007 [51]	Erbium	11	50	Fixed (0.8 nm)
2007 [52]	Raman + Erbium	17 (for 0.4 nm spacing)	10	Tunable 0.2, 0.4 and 0.8 nm
2008 [53]	Broadband source	8	19	1.6–9.6 nm
2009 [54]	Brillouin	5	35	Fixed (0.08 nm)
2010 [55]	Parametric Amplif.	129	25.6	Fixed (0.2 nm)
2011 [56]	Brillouin-Erbium	150	6	Fixed (0.075 nm)
2011 [57]	Random DFB-FL	160	16	Fixed (0.09 nm)
2012 [58]	Erbium	28	10	0.3–1.5 nm
2014 [59]	Random DFB-FL	18	15	Tunable
2015 [60]	Random DFB-FL	25	30	Tunable
2016[61]	Brillouin-Erbium	4	1.1	Tunable
2017 [62]	Erbium	4	8	Fixed (1.1 nm)
2017 [63]	Erbium	14	13	Tunable
2017 [64]	Erbium	4	36	Tunable
2018 [65]	Erbium	60	5	Tunable
2018 [66]	Erbium	48	13	Tunable
2018 [67]	Brillouin	7	50	Fixed (0.088 nm)
2018 [68]	Erbium	11	23	Fixed (1.9 nm)

Table 2. State of art of fixed and reconfigurable multi-wavelength fiber lasers.

which implements TDM technique, allows to achieve fully distributed sensing along a fiber. However, this method is limited in distance because of the compromise between the pulse-width and the sensing distance.

Considering the light sources employed for interrogating remote networks, multi-wavelength fiber lasers (MWFL) have attracted a lot of interest recently due to their great potential in a variety of applications. Among them are included: communications based on WDM, high resolution spectroscopy and sensor monitoring [18–26]. Several researchers have focused their attention on proposing new multi-wavelength sources which allow tuning the output spectrum for sensing purposes [27, 28]. In fact, the use of this type of fiber lasers to multiplex fiber optic sensors allows reducing the total cost of the system, by sharing costly devices of the network.

MWFL can be classified by their gain medium, as well as by the generation process of the emission lines. Some of the gain media used in previous works are erbium doped fiber [29–32], stimulated Raman scattering [25, 32, 33], stimulated Brillouin scattering (SBS) [34] or a hybrid combination of the above [40, 41]. Besides, the emission lines can be generated passively or actively. Within the first category, passive filtering systems such as FBGs [42], Fabry–Pérot filters [43], Sagnac loop mirrors [44], and Lyot filters [45]. Then, some examples that would enter the category of active generation are SBS or four wave mixing [46].

When the emission lines are generated by passive elements, the central wavelength and separation between lines can be simply configured. The reconfiguration of the distance between emission lines is very useful for the aforementioned applications of MWFL. Thus, fiber lasers that can generate a comb of multiple wavelengths with a tunable separation are suitable candidates for dense-WDM systems [47].

In table 2, recent works on fixed and tunable multi wavelength lasers are collected. It gathers parameters such as principle of operation, maximum number of emission lines and wavelength range. Finally, the spacing flexibility is also compared.

#### 1.3.2. Active remote FOS networks

A simple definition of optical amplifier could be a device that increases the power of an optical signal directly in the optical domain, without the need for electrical processing. Optical amplifiers are essential elements in sensor networks. They allow increasing the capacity, interrogation distance as well as the number of multiplexed sensors, compensating the losses of the network. Without the help of optical amplifiers, electronic amplification would be needed, which implies more expensive systems.

Despite their numerous advantages, optical amplifiers present several challenges. For example, they generate noise that decreases the signal-to-noise ratio (SNR) of the transmitted signals. In addition, nonlinear effects can be enhanced by high power levels in the communication channels, generating crosstalk between them. Finding the compromise between the generated noise and crosstalk is one of the main challenges of these systems [69].

Erbium-doped fiber amplifiers (EDFA) are by far the most significant fiber amplifiers in the context of longhaul fiber optic communications since their invention in the late 1980s [70]. They can efficiently amplify light in the 1550 nm wavelength region, where telecommunication fibers show their minimum loss. EDFA is based on single-mode fiber whose core has been doped with Er3+ and gain is provided by stimulated emission. The characteristics and variations of EDFAs have been widely documented in previous publications [71–79], so we will focus on their main features and use in long-range applications. Although gain can be obtained pumping at different wavelengths, the maximum efficiency of amplification is attained using 980 nm-pump lasers. The amplification band extends from 1525 to 1565 nm, which is very convenient for WDM systems. EDFAs are the optical amplifiers with the highest efficiency gain per pumping power, with values of ~8–10 dB mW<sup>-1</sup>. However, their gain spectrum is not uniform throughout the band and flattening methods are sometimes required.

The combination of EDFAs and WDM technology extends the transmission capability in long-distance fiber optic sensor networks. Many remote sensor systems implementing Erbium amplification have been proposed [80–82], reaching a maximum distance of 230 km in [80]. Other approaches have attained larger monitoring distances and the number of sensors multiplexed combining EDFA with other amplification methods such as Raman [83–85] and Brillouin amplification [86].

Nevertheless, the most widely used amplification technique for remote sensor networks is distributed Raman amplification (DRA). It has all the properties inherent to Raman amplification and has also very advantageous qualities for long distance applications. As a matter of fact, a special type of fiber is not needed to generate amplification, since Raman scattering is an inherent process of the germane-silicate fibers. The transmission fiber itself acts as the amplifier, simplifying the network. In addition, Raman gain spectrum covers a wide region, up to 150 nm (700 cm<sup>-1</sup>) in silica [87]. Moreover, the higher gain levels remain reasonably flat over a wide wavelength range (about 40 nm). Gain can be generated at any wavelength by appropriately modifying the pump wavelength, even combining several pumps to obtain a wider gain spectrum. DRA provides distributed amplification along the fiber, overcoming the losses at every point and improving the SNR.

Several works have proposed this technique for remote monitoring applications [88, 89]. The maximum distance achieved was 250 km in [90], where four sensors were multiplexed and interrogated in a remote system implementing Raman amplification.

In order to extend the monitoring distance, schemes that use two pump lasers simultaneously have been proposed [91–94]. In the same line, higher-order pumping structures [95, 96] have been proposed because this procedure reduces the difference between the gain and loss coefficients along the propagation. For instance, it has been exploited in second-order Raman amplification schemes, obtaining quasi-lossless transmission along the fiber [97, 98].

Random distributed feedback fiber lasers (RDFB-FL) [99] have been the subject of many studies and experimental investigations during the last years due to their particular properties compared to conventional fiber lasers [100]. Due to the long cavities commonly used, they are especially well suited for ultra-long remote sensing applications [101–103]. The intense research has resulted in a wide range of applications and improvements. Many studies have been carried out to enhance the already promising inherent features of RDFB-FL, for instance, the optimization of the output power [104–107], relative intensity noise transfer [108, 109] and thermal noise [110]. In addition, their spectral and statistical properties have been analyzed in [111–113] and a variety of configurations have been proposed implementing polarized pump or linearly-polarized outputs [114–117], mixing different fibers in the gain media [118], short cavities [119, 120] and tunable [121], multi-wavelength [57, 122–125] or super-continuum output [126, 127]. Finally, RDFB-FL schemes allow combining the traditionally employed Raman amplification with other amplification mechanisms such as Erbium. In fact, recent works have proposed new schemes for random distributed feedback generation based on Erbium-doped fiber or implementing Brillouin random lasing, Ytterbium-Brillouin or Erbium–Brillouin [125, 128–135].

The distinctive properties of these lasers use to include high power and long cavities, which make them especially convenient for long-haul telecommunications or sensing applications [102, 103, 136–139]. Besides, RDFB-FL present mode-less behavior, which is useful in multiwavelength and tunable laser sources [121–125] since the undesired mode competition or mode hoping are eliminated. Their ability to generate outstanding stable narrow-linewidth laser sources can be exploited in many sensing applications [140–144], being able to achieve high-resolution measurements [142]. In addition, RDFB-FLs can be internally modulated without frequency restrictions or self-mode-locking effects. Contrary to conventional lasers, the feedback does not correspond to a fixed length. As a result, the length of the laser cavity does not distort the analog internal modulation and does not determine the repetition rate of the generated pulses. An internally modulated RDFB-FL could be used to interrogate a sensor array by TDM as it was proposed in [102], where ten FBGs were monitored at 200 km applying this technique.

In the following table, the recent works of remote sensing networks have been summarized. Their amplification method, multiplexing technique, type and number of interrogated sensors and total length are described.

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Year References	Amplif. method	Type sensor	Num. of sensor	Mux tech.	Netw. length (km)
2007 [145]	No amplif.	FBG	1	_	120
2008 [80]	EDFA	FBG	1	_	230
2009 [81]	EDFA	FBG	4	WDM	50
2009 [146]	Raman	FBG	2	WDM	50
2010 [10]	Raman	FBG	4	WDM	50
2010 [85]	Raman + EDFA	FBG	1	WDM	100
2011 [147]	Raman + Brillouin	FBG	4	WDM	100
2011 [148]	Raman + EDFA+ Brillouin	FBG	2	WDM	155
2011 [90]	Raman	FBG	4	WDM	200
2011 [90]	Raman	FBG	4	WDM	250
2011 [149]	No amplif.	Interf.	1	_	253
2011 [89]	Raman	FBG	2	WDM	75
2011 [150]	Raman	FBG	1	_	150
2012 [82]	EDFA	FBG	2	WDM	50
2012 [86]	Raman + EDFA	FBG	3	WDM	150
2012 [85]	Raman	FBG	2	WDM	100
2013 [101]	Raman	FBG	11	WDM	200
2015 [60]	Raman + EDFA	FBG + Inter.	7 + 11	WDM/TDM	50
2016 [102]	Raman	FBG	9	WDM/TDM	170
			10		200
2016 [139]	Raman + EDFA	Inter.	1	_	225
2018 [138]	Raman	Inter.	1	CDM	290
			2		270

	Table 3.	State of	art of rem	ote sensing	networks.
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#### 1.4. Recent development in remote fiber optic sensor networks

In this section, we will explain more in detail the most representative remote systems for fiber optic sensors presented in table 3. They will be ordered considering the length of the network. Their schemes will be discussed, and pros and cons highlighted.

#### 1.4.1. Remote 50 km fully switchable RDFB-FL

Bravo *et al* demonstrated in [59, 60] a reconfigurable MWFL based on a RDFB-FL which is used as the light source to interrogate a remote FOS network. The scheme of the laser structure is shown in figures 3 and 4.

The proposed forward-pumped laser scheme in figure 3 includes a filtering element in header fiber loop. This programmable filter provides this scheme of outstanding versatility. A fully switchable spectrum can be obtained by controlling dynamically the filter parameters. In [59], a deep study of this novel scheme is provided, optimizing the behavior and performance of the light source for remote multiplexing networks. In fact, the fiber laser scheme was tested with two different fibers, 50 km of SMF and 2.5 km of dispersion compensating fiber as the distributed laser cavity. If the objective is to increase the number of emission lines, a better performance is obtained using SMF fiber. Among the comparative studies presented in this manuscript, the output peak power and the stability were the authors priority. As a result, the maximum output peak power was measured varying the emission linewidth. In addition, the pump power was chosen to maximize the stability of the system and obtain better overall performance.

The main objective of multiplexing fiber optic networks is to reduce the cost per sensor ratio. For this purpose, the maximum number of emission lines needs to be generated and the amplification bandwidth extended. The authors implemented two main ideas to overcome this fact: use hybrid amplification and equalize



the peak power of the emission lines. The use of EDFA in the header fiber loop of the laser in combination with the inherent Raman amplification of the system led to double the amplified bandwidth maintaining the previous stability of the laser.

As previously advanced, the authors developed programmable filter control software which included the function of equalizing the power of the different emission lines. This is a key factor of the system, since it allowed an increase in the number of emission lines and maintain a flat multi-wavelength spectrum.

In order to prove the good performance of this novel scheme for remote monitoring, a proof of concept fiber optic sensor network was proposed. These networks were connected to the laser source in figure 3 at point A. Both sensor networks are based on completely different operation modes: 7 high birefringence photonic crystal fiber (Hi-Bi PCF) intensity-based strain sensors and an array of 11 FBG temperature/strain sensors. The sensor networks were both connected to a remote powered by light fiber optic switch which commutes and selects the network to be monitored.

On the one hand, the interferometric sensor network was monitored by a multi-wavelength spectrum composed by 8 emission lines, 7 which monitor each of the interferometers and 1 which interrogate a reference FBG. On the other hand, a single wavelength sweep was performed to interrogate the FBG sensor network, performing 1500 steps with a 0.01 nm resolution.

#### 1.4.2. Remote 200 km TDM WDM sensor network

In [102], the combination of OTDR techniques with RDFB-FL was exploited for remote sensing applications. The modulation of the cavity of a RDFB-FL with an electro-optical modulator (EOM) allowed the authors to

identify up to 10 sensors by means of time-domain reflectometry, reaching a 200 km monitoring distance. The operating principle of this multiplexing system is based on the specific properties of RDFB-FL, such as

their good performance when they are internally modulated [151] in addition to their high peak power values [152]. Furthermore, the absence of longitudinal modes allowed obtaining stable output signals both in power and wavelength.

Leandro *et al* proposed an initial scheme as proof of concept to demonstrate the feasibility of this new technique. The principle of operation can be briefly described as follows: the RDFB-FL was  $\lambda$ -tuned by the filter located inside the fiber loop mirror (FLM), see figure 5. Then, light is modulated by an EOM before being reinjected in the distributed cavity of the laser. Due to pulse modulation, the power reflected along the fiber can be measured by an oscilloscope, acting as an optical reflectometer in the time domain. Accordingly, this process can be employed to determine the reflected power at a certain wavelength range by performing a  $\lambda$ -sweep of the laser source. A reflection peak will be detected when the central wavelength of the laser source matches with the  $\lambda$ -Bragg of the FBG. In this manner, FBGs can be identified by their position in the network (TDM) and by their wavelength (WDM). This hybrid multiplexing technique allows increasing the number of multiplexed sensors.

This first approach (figures 5(a)) and 6(a))) aimed to demonstrate the validity of the system to monitor remote sensors operating in reflection using the principle of operation explained above. Besides, a modified setup (figures 5(b)) and 6(b))) was proposed to improve the results obtained in the first case. The objective of the second experiment was to increase the wavelength range of the system, the spatial resolution as well as the distance to the sensors.

The sensor multiplexing scheme developed in [102] can be divided in two parts: the laser and the sensor network. The light source is a forward-pumped RDFB-FL with a distributed laser cavity of 170 km and 200 km length in the first and second approach, respectively. The laser cavity is part of the sensor network, in which up to 11 FBG sensors were multiplexed, although this number could be further increased.

The sensor networks include FBGs centered at different wavelengths which were located at different distances from the monitoring station.

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Several optical couplers were placed throughout the cavity, which allows a percentage of the transmitted light to be extracted and interrogate each group of sensors. The coupling ratio of each coupler was one of the system design parameters needed to be considered and suitably chosen. Hence, a stable laser operation is achieved by appropriately choosing the coupling percentages.

Two main differences can be identified when comparing both laser schemes: the filtering element of the header (a tunable FBG or a programmable filter) and the maximum interrogation distance (170 or 200 km). The programable filter was a key element of the system since it provided the system with versatility and allowed power equalization along the wavelength band, maximizing the performance of the laser. However, these functionalities cannot be obtained using the tunable FBG, which worsens the benefits of it. For instance, the authors exploited this advantage in order to study the relationship between the filter bandwidth, the pulse duration and the maximum distance achieved. After the optimization studies of these parameters, considerably improvement of the system performance was achieved. As a matter of fact, the maximum distance of the sensors



increased from 170 to 200 km, the available wavelength range doubled, and the spatial resolution improved from 85 to 45 m. The strain variation applied to up to 11 gratings were monitored simultaneously and without crosstalk between sensors and the repeatability of the measurements was also demonstrated.

#### 1.4.3. Real-time 225 km remote fiber optic sensor

Despite their potential application in many fields, interferometric sensors, such as FLM, are not frequently employed in remote sensing structures owing to their limited multiplexing capacity and high loss compared to FBGs. Many approaches have been presented in previous works to multiplex interferometric sensors, such as coherence multiplexing [15], and phase carrier techniques [153]. In addition, some recent work provided other solution to solve this problem by validating multiple multiplexing topologies based on the fast Fourier transform (FFT) analysis [154–156] initially proposed in [139].

In [139], a combination of the FFT technique and an RDFB-FL was exploited to remotely interrogate a FLM located 225 km away from the monitoring station. The axial strain applied to the interferometer was measured with good linearity and a sensitivity of 1.69  $\pi$ rad/m $\varepsilon$ .

The set-up proposed in this work is shown in figure 7. It consisted of a modified forward-pumped RDFB-FL combined with a commercial interrogator of FBGs, which acted as the seed for the laser generation. Although the principle of operation of the laser was the same as in [60], it presented a relevant difference which affected the laser generation. Instead of using a filtering element to tailor the output spectrum of the laser, a commercial FBG interrogator was included in the header of the laser scheme. The signal emitted by this device acted as the seed for the generation of the distributed random laser.

This signal entered through port 2 of a 3-port circulator and was amplified using an EDFA before injecting it into the laser cavity, by a 50:50 coupler. Amplification was needed in order to equate the power generated in the laser cavity with that of the injected emission lines. By increasing the power of the latter, the random laser synchronized with the interrogator, influencing the generation of the laser. The sensing unit consisted of a highbirefringence (Hi-Bi) FLM. In this type of sensors, physical changes such as temperature or axial strain lead to a wavelength shift of the interference measured in the optical spectrum. This sensor was formed by two sections of Panda fiber, which were fused together with a 90° rotation angle and connected to a polarization maintainer coupler. The 90° angle fusion between the sections of Panda fiber eliminated the requirement of a polarization controller, as it was previously demonstrated in [157]. The obtained results validated this system to monitor in real time the strain applied to the interferometric sensor located 225 km away from the monitoring station.

#### 1.4.4. 250 km remote FBG WDM system

In 2011, Fernandez-Vallejo *et al* proposed an ultra-long range FBG sensor interrogation system, which allowed to multiplex up to 4 FBG located 250 km away from the monitoring station (see figure 8).

The system was based on a laser performing a wavelength sweep and scanning the FBGs reflection spectra. The basic design of this laser, depicted in figure 9, included a tunable FBG and provided the system of tunable capability. The grating presented a bandwidth of 0.6 nm and offered an extinction ratio of 65 dB, being able to sweep the whole wavelength span.

The transmission channel consisted of two identical optical paths, which caused an improvement in the signal to noise ratio (SNR) of the detected signal when compared to a single-path scheme, The first path launched the amplified laser signal by means of discrete Raman amplification and the second one was employed to guide the reflection signal back to the monitoring system. A maximum SNR of 6–8 was obtained, being able to remotely monitor the temperature of four FBGs located 250 km away from the header.







#### 1.4.5. 253 km remote system based on a FLM

The same year, Bravo *et al* experimentally demonstrated a 253 km ultralong remote displacement sensor system. Their system was based on a FLM interrogated by a commercial optical time-domain reflectometer (OTDR) [149]. Figure 10 shows the proposed experimental set-up which included a long period grating (LPG) spliced inside of a FLM. The LPG modified the mirror reflectivity accordingly to the applied displacement. Then, the combination of the high reflectivity of the FLM with the inscribed LPG allowed using an OTDR as the interrogation unit of the system. In this particular work, displacement detection was carried out using LPGs. However, this type of sensor has been also used for strain, temperature, and refractive index measurements. The main benefit of this remote sensor system is that the remote sensor has been monitored without any optical amplification. The natural high reflectivity of the FLM was used as a pulse reflector, being easy to detect event at 253 km away of the monitoring station. Nevertheless, it presented a low multiplexing capability, which limited its applicability.

## 1.4.6. Low-coherence interferometry-based remote 270 and 290 km sensor systems

CDM employs light sources with short coherence length in interferometric configurations to multiplex numerous sensors into a single optical signal [15]. This multiplexing technique avoids the quite complex requirements of or WDM [158] or TDM [159], such as frequency ramping of the optical light source or synchronization, correspondingly. Nevertheless, the geometry of the interferometer sensor must be carefully designed in CDM schemes to avoid crosstalk between the sensing interferometers (SI). As a result, the optical path differences of the SI must differ so the sensing signal can be de-multiplexed by selecting its optical path difference in the local receiving interferometer. CDM systems have been widely used in fiber optic sensing applications, multiplexing up to 10 sensors in [160] and measuring physical parameters such as temperature, displacement and strain [161–163].

Generally, CDM is used in fiber optic low-coherence interferometry (FOLCI) sensor systems [164, 165]. Temperature [166], pressure [167], strain [168] and refractive index [169] are among the parameters that can be





measured using this technique. One the advantages of FOLCI is that the measurement accuracy is ideally insensitive to fluctuations in optical power between the monitoring station and the location of the sensor. Then, higher resolutions can be obtained if compared to conventional intensity-based sensors. The intrinsic requirement for short-coherence length light sources in FOLCI systems makes broadband light sources the most advisable choice. However, their low output power, if compared to laser sources, makes these systems not suitable for long-haul applications.

The experiments performed in [138] demonstrated that the natural coherence length of RDFB-FLs can be used in low-coherence interferometry and CDM schemes since it is short enough to be suitable for FOLCI. Besides, the remote interrogation of an interferometric sensor was achieved 290 km away from the header. This was the longest distance achieved in a remote fiber optic sensing system.

In order to show the potential of this technique in conjunction with an RDFB-FL, two different experiments were carried out. Accordingly, two different schemes were developed for this purpose and three differentiated parts were identified: the laser source, the transmission channel and the sensing unit (see figures 11 and 12).

The light source used to interrogate the sensor unit was the same in both cases. It was formed by two pump lasers (1360 and 1445 nm), separated by 50 km of SMF, which injected 3 W each into the cavity of a single-arm forward-pumped RDFB-FL.

The transmission channel consisted of two identical optical paths of 290 km in the first and 270 km in the second experiment. The first path was part of the distributed cavity of the laser, which illuminated the sensor unit. The second path guided the signal modulated by the sensor unit back to the detection system. The counter-propagating noise in the arm of the laser was higher than the sensor response. For this reason, both the illuminating signal and the response of the sensors could not share the same transmission channel.

In the first scheme, figure 11, two Mach–Zehnder interferometers (MZI) composed the FOLCI sensing scheme (one local receiving interferometer (LCI) and a SI). On the contrary, the second scheme, figure 12, was formed of three MZI: two SIs and one LRI, with longer arms than in the previous case, which interrogated both SI within the same displacement sweep.

The aim of the first experiment was to evaluate the feasibility of monitoring an optical fiber interferometer at 290 km as a displacement sensor. In the second test, a set of measurements were performed to validate the proposed system as a coherence multiplexing scheme, interrogating two MZI at 270 km.

Both experiments proved the good overall performance of the systems proposed. The displacement applied to the sensors versus the measured displacement showed a linear tendency with a slope near the unit and a resolution of 0.02 mm.

#### 1.5. Results and discussion

In the previous section, the most important parameters in the design of long-distance fiber optic sensor systems for remote network monitoring have been discussed. In the following, we will discuss briefly the most important points.

Regarding the amplification technique, the most part of the approaches for remote sensors monitoring are based on Erbium [60, 80, 82, 85, 86, 166] and Raman distributed amplification [2, 10, 89, 90, 138, 146, 150]. A few schemes implement Brillouin amplification [147, 148] and even fewer schemes no amplification at all [145, 149]. Amplification is key in remote monitoring applications. Fiber network loss must be compensated if the response of the sensors wants to be detected. Erbium amplification fiber region. However, DRA presents an important advantage when compared with other amplification techniques. Not only can Raman gain be generated in any wavelength range by correctly choosing the Raman pump, but we can expand the amplification band as much as we want by using several pumps at the same time. This enhances the multiplexing capabilities of the system, which is another challenge a fiber optic network must face. In addition, Raman gain needs long fibers for its generation. This requirement may be undesirable for many other applications, but it makes Raman amplification very well-suited for long-haul ones.

Among the most recent remote systems proposed and gathered in table 3, Raman amplification is used in the longest systems, alone or combined with Erbium amplification. The longest distance achieved using only one Raman pump laser is 250 km, and four FBGs were interrogated by the scheme showed in [90]. Many works proposed double pumped [91–94] and higher-order amplification schemes [95, 96] to increase the fiber network length. The latter procedure diminishes the difference between the gain and loss coefficients along the propagation, thus obtaining quasi-lossless transmission along the fiber [97, 98]. Thanks to the implementation of these techniques in a RDFB-FL system, the longest distance in remote sensor monitoring was achieved in [138]. It is worth mentioning that this type of laser is present in the longest schemes achieved up to date. RDFB-FL outstanding features allow their adaptation to a great variety of remote applications. In fact, their capability to interrogate sensors of different nature (FLM [139], MZ interferometers [138] and FBGs [102]) has been demonstrated.

Actually, the 2nd longest remote monitoring set-up is based on a RDFB-FL and interrogates a remote interferometric sensor. This type of sensor has attracted great interest for many applications due to their simple structure and manufacture and because of their environmental robustness [170]. However, their low multiplexing capacity did not make them attractive for use in sensor networks. This limitation was solved when multiplexing techniques based on the FFT were proposed. Since then, many schemes interrogating remote interferometric sensors have been presented and distances of more than 200 km have been reached [138, 139].

Nevertheless, among the different types of sensors that can be interrogated in remote fiber networks, FBGs have been the most employed for their advantageous properties [171–177]. Not only because they present the inherent advantages of FOS, but because their simplicity and versatility make them stand out from another type of sensors. FBGs are inscribed directly on the fiber and the information is encoded in an absolute parameter: the resonance wavelength of the structure. As a result, these sensors can be self-referenced and easily multiplexed implementing WDM techniques and MWFL. Lately, several approaches have been presented to achieve multi wavelength operation. The most versatile ones implement dynamical filtering, which allows modifying the width and separation between emission lines in real-time. Up to 18 sensors have been multiplexed in a proof of concept network, but a higher number of sensors could be straightforwardly interrogated using this

configuration [60]. Another dynamically filtered fiber laser was shown in [102] combined with the internal modulation of the cavity. Again, a RDFB-FL-based system allowed to implement a hybrid combination of WDM and TDM. Exploiting this characteristic, 11 gratings were interrogated, differentiating them both by their wavelength and by their position in the sensor network.

As it has been previously stated, there is no ideal solution for all remote sensing scenarios. Although DRA seems to be most advantageous technique, it is limited by Rayleigh backscattering noise accumulated and amplified along the transmission channel formed by hundreds of kilometers of fiber. Several factors need to be considered in order to choose the most suitable technique, which is also influenced by the type of fiber optic sensors that compose the network. RDFB-FL have demonstrated a great versatility in terms of multiplexing techniques and type of sensors multiplexed. For this reason, these lasers have been proposed as the light source in the longest remote fiber optic systems up to date.

#### 1.6. Conclusions

In this review, the main challenges of remote sensor networks have been discussed. The schemes implemented in the most recently developed solutions in remote sensing have been analyzed and compared between them.

On the one hand, and with the aim of increasing the interrogation distance, the different amplification mechanisms most used in remote sensor networks have been compared, standing out erbium and DRA for their advantageous features. On the other hand, several multiplexing approaches (wavelength, time and coherence division) have been confronted, highlighting their advantages and drawbacks. The principle of operation of the latest proposed schemes reaching the longest distances has been explained in more detail. Most of them have the implementation of RDFB-FL lasers in common, which proves how promising the properties of this type of lasers are for their use in ultra-long remote sensor networks.

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## **ORCID** iDs

Verónica de Miguel Soto 6 https://orcid.org/0000-0003-3299-6829

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