Fiber Optic Sensor Configurations

R. A. Perez-Herrera and M. Lopez-Amo
Department of Electric and Electronic Engineering, Universidad Publica de Navarra,
Campus Arrosadia s/n E-31006 Pamplona, Spain

Keywords: Fiber-Optic Sensor Multiplexing, Fiber-Optic Networks, Fiber Laser, Remote Sensing.

Abstract: The main goal of this work is to provide a brief overview of the fiber optic sensor multiplexing configurations and techniques as well as some recent advances and trends of the most important fiber optic sensor configurations. Distributed and point sensors are explained and a number of high performance networks are shown. Finally, the concept of robust fiber optic sensor is presented as well as the main records of distributed and remote sensing fiber optics topologies.

1 INTRODUCTION

The advantages of optical fiber sensor networks are well known and have been widely analyzed in the research literature on the subject. Fiber sensors appear to be very attractive in some areas where they offer innovative capabilities. At the same time, the use of nonlinear effects and amplification in sensing systems has attracted much interest in the last decade.

Technologies for fiber-optics went through a major growth period during the years 1994 to 2000. This growth came about due to the junction of several market technologies and drivers. Initially the key drivers of the demand for bandwidth were data traffic and the Internet. The second was the advent of the optical amplifier, which attended the role in optical networks that the transistor had played in the electronics revolution. The optical amplifier was the crucial issue because of the fact that it allowed the simultaneous amplification of a number of channels, as opposed to electronic regenerators that operated channel by channel. A third technology was wavelength-division-multiplexing (WDM), which made a single strand of fiber act as many virtual fibers.

WDM has permitted the capability of fibers to be increased by more than two orders of magnitude over the past few years, providing plenty of bandwidth in telecommunications to fuel the growth of data traffic and the Internet. The association with the optical amplifiers allowed the revolution related to WDM in optical networks.

Raman amplification had a slow start, but then experienced a wide distribution with increasing performance needs of optical networks. Any deployment concerns about discrete or distributed Raman amplification have been outweighed by the performance improvements permitted with Raman amplification. For example, distributed Raman amplification improves noise performance and decreases nonlinear penalties in WDM networks, in this manner improving the two main restrictions in dispersion-compensated, optically amplified systems.

All these techniques, initially developed for telecommunication systems, are now also used in sensor networks. In this way, nonlinearities will be used to provide amplification in different WDM networks, improving the overall system performance. The main concepts associated to these technologies will be described next, as well as a state of the art and future trends of modern multiplexing optical fiber sensor networks.

2 MULTIPLEXING TECHNIQUES IN SENSOR NETWORKS

Multiplexing is the simultaneous transmission of two or more information channels along a common path. A fiber sensor system includes three main parts or subsystems: the sensing elements or transducers, the optical fiber channel and the optoelectronic unit (López- Higuera, 1998). Because the last subsystem

Perez-Herrera R. and Lopez-Amo M..
Fiber Optic Sensor Configurations.
DOI: 10.5220/0005431301400146
In *Proceedings of the 3rd International Conference on Photonics, Optics and Laser Technology* (OSENS-2015), pages 140-146
ISBN: 978-989-758-092-5

uses to be the most expensive one, when it is possible to multiplex a high number of sensing points in the same network using common optoelectronic unit, the cost per sensing element decreases. Systems employing multiplexed arrays of fiber Bragg Gratings (FBGs) have performed successfully in numerous field trials and applications involving a wide diversity of structures.

The growth of the technology and components used in the optoelectronics units and multiplexing networks has been helped by the fast growing of the fiberoptic telecommunication technology. High performance tunable lasers, optical amplifiers, couplers, optical switches, filters and detectors are available for sensors multiplexing due to the major market that supposes telecommunications. Likewise, certain multiplexing techniques, as WDM comes from the telecommunications side. However, other multiplexing techniques have been developed or adapted specifically for fiber-optic sensors multiplexing (Kersey, 1991).

The sensor networks can be designed by means of only passive fibers (without utilizing optical gain) or introducing optical amplification in some key parts of the networks and hence passive or active networks can be developed (Dandridge, 2002), (Abad, 2002).

A variety of multiplexing techniques based on different modulation formats have been developed, each one with their own benefits for a particular application. The modulation formats generally fall into one of the following categories: Wavelength Division Multiplexing, Time Division Multiplexing, Frequency Division Multiplexing, Coherence Multiplexing and Polarization Division Multiplexing. However hybrid approaches (simultaneous utilization of several modulation formats inside the same network) have been also considered. When a single fiber is devoted to each sensor, we also use the term Spatial Division Multiplexing as another multiplexing technique. Figure 1 illustrates some of these multiplexing modulation formats.

To efficiently design the most appropriate sensor network, it is necessary to take into account different aspects: the modulation and coding format of the optical signal, the network topology, the inclusion or not of optical amplification technologies, the decoding method for the received signal and the type or types of sensors multiplexed in the same network. Finally, it must be also considered the economic conditions, which would eventually determine the most appropriate network. The choice of a different multiplexing technique depends on the requirements of the sensor network. The relative importance of parameters such as cost, noise, bandwidth, and flexibility constitute the basis for making the right selection.

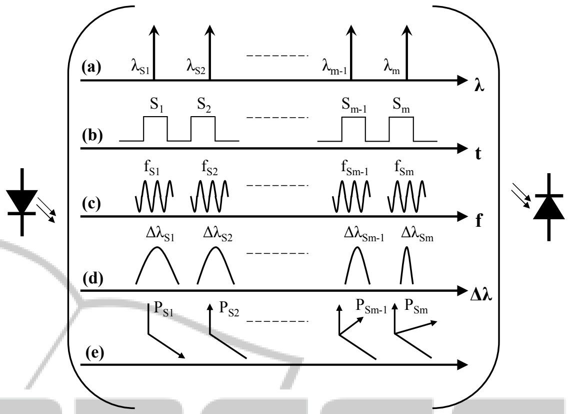

Figure 1: Multiplexing modulation formats: (a) Wavelength Division Multiplexing (WDM); (b) Time Division Multiplexing (TDM); (c) Frequency Division Multiplexing (FDM); (d) Coherence Multiplexing (CM) and (e) Polarization Division Multiplexing (PDM) (Lopez-Amo, 2011).

A first subdivision between optical fiber sensor networks will be attending on the type of the multiplexed sensors. They could be a simple o hybrid networks, terms used for the networks where only one or more than one type of multiplexed sensors in that order. Secondly, another subdivision that must be done in order to clearly define a network is based on the type of sensors used, as can be seen in Figure 2. They can be transmissive networks (based on transmissive sensors) or reflective networks (where the reflected signals in each sensor are used).

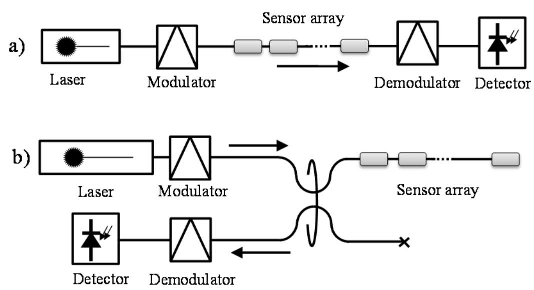

Figure 2: Serial multiplexed transmissive sensor network (a) or reflective sensor network (b).

Finally, as can be seen in Figure 3, it is common to differentiate among point and distributed sensors. On one hand, the multiplexing of point sensor is based on processing the value of the measurand corresponding to each separate sensing element. On the other hand, in the distributed sensors only one sensing element is needed and the objective of the signal processing is to recuperate the measurand as a function of position along the sensing section.

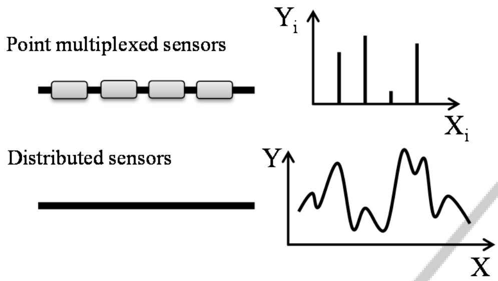

Figure 3: Point multiplexed and distributed sensors.

There are diverse topologies for locating sensors in a network. They can be divided into five basic configurations, shown in figure 4 (where each one in turn can be of a transmissive or reflective type): serial, dual bus or ladder, star, tree or mesh topologies (Lopez-Amo, 2011).

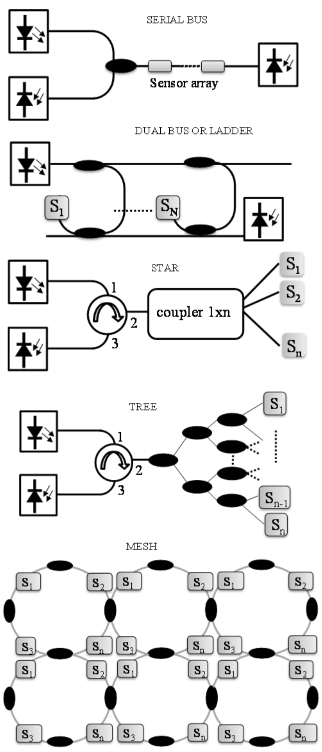

Figure 4: Multiplexing topologies for fiber optic sensors: bus, ladder, star, tree and mesh.

3 DISTRIBUTED AND POINT SENSORS

A great variety of physical and chemical parameters can be measured by using point sensors. However, here are hundreds of applications in structural health monitoring (SHM) were the key parameters to be measured are temperature and occasionally strain and vibration. In those cases, distributed sensing is an appropriate choice when many measurement points are needed along a serial or linear multiplexing topology. It is worth noticing the difference between distributed and multi-point sensing. Distributed refers to the ability to simultaneously detect scale and location of a measurand anywhere along a continuous length of sensing fiber. Nevertheless, multi-point sensing refers that the measurement is done at specific locations with point sensors (Perez-Herrera, 2013).

Distributed measurements are also based on non-linear scattering effects to evaluate a number of different parameters. Rayleigh scattering comes from the interaction between the light with refractive index fluctuations in the fiber core that appear in spatial scales much shorter than the light wavelength. Because of that, Optical Time Domain Reflectometry (OTDR) was developed initially as a network diagnostic tool for optical fiber telecommunication systems. Different means of measuring this delay time leads to other time domain techniques, like Optical Frequency Domain Reflectometry (OFDR) or polarization domain reflectometry (POTDR) (Jones, 1988).

Stimulated Raman scattering (SRS), for example, is generated by the interaction of the propagating light with molecular vibrations in the medium. On the other hand, stimulated Brillouin scattering (SBS) involves acoustic phonons. In this respect, both scattering processes involve three-waves in which the incident (pump) light is converted into (Stokes) light of longer wavelength with an unavoidable excitation of a molecular vibration (SRS) or an acoustic phonon (SBS). However, there are a number of significant differences between SBS and SRS that lead to markedly diverse systems.

Raman backscatter systems have found real applications niches such as monitoring tunnels and have been also commercially presented from several decades ago. These sensors are mostly simple to install and provide temperature resolutions of the order of 0.1 to 1 ºC within resolution lengths of order of one meter over interrogation lengths extending to tens of kilometers (Culshaw, 2004). Brillouin scatter in contrast is usually used in the frequency domain. The peak offset frequency for Brillouin scattering is measured and is a unique function of the acoustic velocity (and therefore temperature and strain) in the optical fiber (Perez-Herrera, 2013).

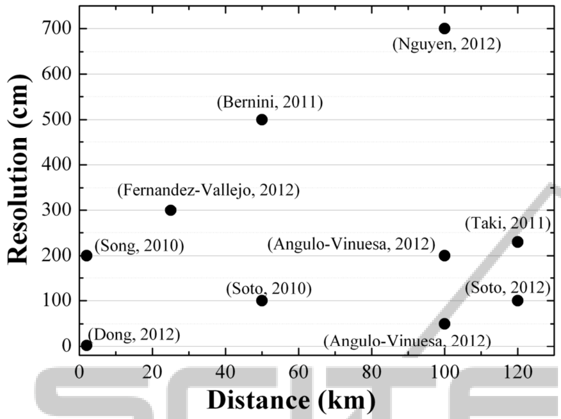

Figure 5: state of the art of long-range BOTDA sensors.

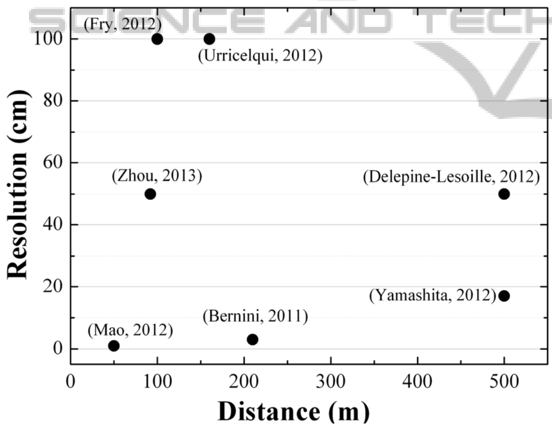

Figure 6: state of the art of high-resolution BOTDA sensors.

One of the main drawbacks of this technique is that the measurement range of these systems has a trade-off between the measurement range and the spatial resolution (Fernandez-Vallejo, 2012). Consequently, present research in BOTDA sensors has two different hot topics: long-range BOTDA sensors, which are able to perform measurements in tens of kilometers with meter resolutions, or high-resolution sensors with centimeters spatial resolution, but for relatively short-distances fibers. Figures 5 and 6 summarize some of the advances in long-range and high-resolution BOTDA sensors respectively

4 HIGH PERFORMANCE NETWORKS

The maximum measurement distance of fiber sensor systems comes out to be a practical issue due to the loss and noise and induced by the attenuation along the fiber and the Rayleigh scattering respectively. A number of diverse proposals have been experimentally carried out in order to increase the measuring distance of the fiber sensors.

For example, a 75-km long distance FBG sensor system was experimentally demonstrated by (Fu, 2008). Though, every 25 km amplification was needed which made the system more complex. An ultra-long distance fiber Bragg grating sensor system able to evaluate FBGs located 120 km far from receiver position without using amplification was demonstrated by (Saitoh, 2007). One year later, a 230 km FBTG sensor system using a high-speed swept-wave- length light source using EDF amplification was verified (Saitoh, 2008). (Leandro, 2011) presented and demonstrated a technique for remote sensing of FBGs beyond 150 km combining Brillouin, Raman, and erbium gain in a linear cavity fiber laser. A long distance fiber laser system composed by a random fiber laser with a reach of 200km able to multiple 11 optical fiber sensors based on FBGs was proposed and experimentally demonstrated by (Fernandez-Vallejo, 2013).

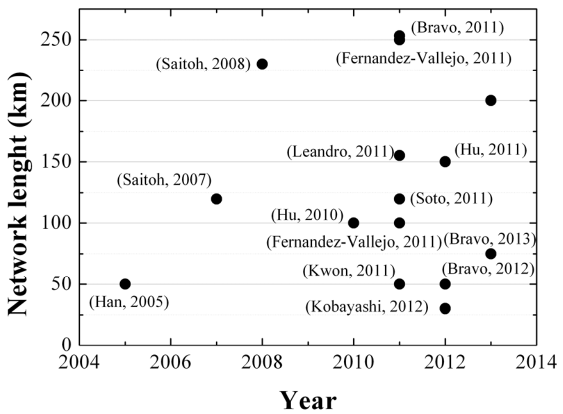

Figure 7: state of the art of the advances in remote sensing systems for optical fiber sensors.

In most cases, complicated setups are employed to reduce the noise effect in order to achieve longer distance measurements. Nevertheless, (Fernandez-Vallejo, 2011) proposed and experimentally demonstrated a simple configuration able to detect four multiplexed sensors located 250 km away thanks to Raman amplification. In addition to this, a

253 km ultra-long remote displacement sensor system based on a fiber loop mirror and an OTDR without using amplification was demonstrated by (Bravo, 2011). Figure 7 illustrates some of the advances in remote sensing systems for optical fiber sensors over the last years.

5 ROBUST FIBER OPTIC SYSTEMS

As it was previously pointed out, optical fiber sensor networks provide sensing solutions for almost all kind of applications and situations: from large natural environments to large scale structures, such as bridges and other civil constructions (Majumder, 2008).They are attracting an increasing interest owing to their wide range of potential industrial application in strategic sectors such as energy, security (Fernandez-Vallejo, 2012), defense, or transportation. Nevertheless, the constant operation of the sensor network after accidental or malicious harm is of increasing importance while the structure being monitored is of high cost (power transmission lines or oil pipelines); human protection is at risk (nuclear plants or chemical storage locations) or perimeter security is a concern (banks or airports) (Li, 2004).

Four groups of protection to allow service to be restored after a failure have been defined: “dedicated” or “shared” protection, each of these has sub-categories called “path” and “line” protection. As a result, these four categories are dedicated line, dedicated path, shared line and shared path (Pérez-Herrera, 2014). The main difference between dedicated and shared protection, derives from the method the sensor unit is connected to the network. Shared protection usually uses a switch although dedicated protection employs an optical coupler.

Path protection and line protection differ in the form of protection. In line protection, the sensors are protected by the nearest switches to the failure, and such switches are located in the sensor network itself and not in the transmission/receiver node (Ramamurthy, 2003). So, if a failure happens, the network can reconfigure the path. Instead, in path protection, each sensor is protected individually by the switch positioned in the transmission or receiver node which readdresses the information in the event of a failure in the network.

Albeit most of optical sensor networks are based on linear topologies, it is worth highlighting that bus, star and ring topologies have been employed in multipoint sensing systems too to overcome system failure causing from breakpoints in the sensing system. However, the sensing area is always restricted in one dimension and not all types of breakpoints can be restored. In order to solve this disadvantage, a number of mesh sensing systems to support more comprehensive sensing regions have been recently proposed and experimentally confirmed (Wu, 2010), (Peng, 2012). In these topologies, the symmetric scheme warrants that the proposed sensing system can be accessed from any point.

Several optical sensor network based on optical add-drop multiplexer (OADM) devices with a bus configuration have been recently carried out (Bravo, 2013), (Rota-Rodrigo, 2013). These devices make it possible to increase the amount of sensors in bus networks in comparison with those that have optical couplers and each sensor can be associated with a different wavelength directly offered by each OADM. In addition to this, these devices allow networks to be developed for recovering operation after failures and it performs self-diagnosis, that is, the identification of the failed constituent(s) from the patterns of surviving end-to-end connections at its operating wavelengths (Perez-Herrera, 2012). Thanks to this configuration it is possible to coordinate self-diagnosis with protection switching so as to reduce the momentary service interruption.

6 CONCLUSIONS

This work has reviewed the key fiber optic sensor multiplexing main configurations and techniques as well as some recent advances and trends in this field of research. A summary of several high performance networks has been presented. Finally, the current trends in robust fiber optic sensor configuration have been shown as well as the main records of distributed and remote sensing fiber optics topologies.

ACKNOWLEDGEMENTS

Financial support from the Spanish Comisión Interministerial de Ciencia y Tecnología within project TEC2013-47264-C2-2-R and FEDER funds is acknowledged.

REFERENCES

López-Amo M., López-Higuera J.M., 2011 *'Fiber Bragg Grating Sensors: Research Advancements, Industrial Applications and Market Exploitation';* Bentham Science Publishers Ltd., Oak Park, Illinois, USA.

López-Higuera, J.M., 1998 *Optical Sensors: Fundamentals, current situation and future trends*, University of Cantabria, Spain.

Kersey, A.D. 1991 *Fiber Optic Sensors: An Introduction for Engineers and Scientists*, E. Udd, Wiley, Hoboken, NJ, USA.

Dandridge A. and Kirkendall C. 2002 *Handbook of optical fibre sensing technology*, Chapter 21 John Wiley and Sons, (, (Baffins Lane, Chichester, UK).

Abad S., Lopez-Amo M., and Matias I.R., 2002 *Handbook of optical fibre sensing technology*, Chapter 22. John Wiley and Sons, (Baffins Lane, Chichester, UK).

Perez-Herrera, RA, Lopez-Amo, M 2013, 'Fiber optic sensor networks', *Invited Papers Optical Fiber Technology*, vol. 19, no. 6, pp 689-699.

Jones, JDC, McBride, R 1988 'Multiplexing optical fibre sensors,' *Optical Fiber Sensors Technology*, vol. 2. Chapman & Hall, London.

Culshaw, B 2004, 'Optical fiber sensor technologies: opportunities and – perhaps - pitfalls,' *J. Lightwave Technol.* vol. 22, n. 1, pp. 39-50.

Nakajima, Y, Shindo, Y, Yoshikawa T, 2003 'Novel concept as long-distance transmission FBG sensor system using distributed Raman amplification' *in Proc. 16th Int. Conf. Optical Fiber Sensors*, Nara, Japan, pp. 1-4.

Dong, Y, Zhang, H, Chen, L, Bao, X 2012, 'A 2-cm-spatial-resolution and 2-km-range Brillouin optical fiber sensor using a transient differential pulse pair' *Appl. Opt.*, vol. 51, no. 9, pp. 1229–1235.

Fernandez-Vallejo, M, et al. 2012, '46 km long Raman amplified hybrid double-bus network with point and distributed Brillouin sensors', *IEEE Sensors Journal*, vol. 12, no. 1, pp. 184-188.

Angulo-Vinuesa, X, et al. 2012, 'Raman-assisted Brillouin optical time-domain analysis with sub-meter resolution over 100 km', *Optics Express,* vol. 20, no. 11, pp. 12147–12154.

Angulo-Vinuesa, X, et al., 2012, '100km BOTDA temperature sensor with sub-meter resolution' *in Proc. of SPIE 22nd International Conference on Optical Fiber Sensors,* vol. 8421, no. 842117.

Soto, MA, Bolognini, G, Pasquale, FD, Thévenaz, L 2010, 'Long-range Brillouin optical time-domain analysis sensor employing pulse coding techniques' *Meas. Sci. Technol.,* vol. 21, no. 9, pp 094024.

Song, KY, Yang, S 2010, 'Simplified Brillouin optical time-domain sensor based on direct modulation of a laser diode' *Opt. Express*, vol. 18, no. 23, pp. 24012-24018.

Nguyen, D.M., et al. 2012, 'Sensitivity enhancement in long-range distributed Brillouin fiber sensor using an anti-Stokes single-sideband probe and a bidirectional EDFA' Photonics Global Conference, article no.6458002.

Soto, MA, et al. 2012, 'Simplex-Coded BOTDA Sensor over 120-km SMF with 1-m Spatial Resolution Assisted by Optimized Bidirectional Raman Amplification' *IEEE Photon. Technol. Lett.* vol. 24, no. 20 pp. 1823-1826.

Taki, M, Soto, MA, et al. 2011, 'Long-range BOTDA sensing using optical pulse coding and single source bi-directional distributed Raman amplification', *in proc. of IEEE Sensors 10th*, no 6127160, pp. 382–385.

Bernini, R, Minardo, A, Zeni, L 2011, 'Long-range distributed Brillouin fiber sensors by use of an unbalanced double sideband probe' *Opt. Express*, vol. 19, no. 24, pp. 23845–23856.

Zhou, DP, Li, W, Chen, L, Bao, X 2013, 'Distributed Temperature and Strain Discrimination with Stimulated Brillouin Scattering and Rayleigh Backscatter in an Optical Fiber' *Sensors* vol. 13, no. 2 pp. 1836-1845.

Mao, Y, Guo, N, Yu, KL, Tam, HY 2012, '1-cm-Spatial-Resolution Brillouin Optical Time-Domain Analysis Based on Bright Pulse Brillouin Gain and Complementary Code' *IEEE Photonics Journal*, vol. 4, no. 6, pp. 2243-2248.

J. Urricelqui, A. Zornoza, M. Sagues, A. Loayssa, 2012 'Dynamic BOTDA measurements using Brillouin phase-shift,' *Proc of SPIE 22nd International Conf. on Optical Fiber Sensors*, vol. 8421, No. 842125.

Yamashita, RK, He, Z, Hotate, K 2012, 'Spatial resolution improvement based on intensity modulation in measurement of Brillouin dynamic grating localized by correlation domain technique,' *Proc. of SPIE OFS22*, vol. 8421, No. 84219H, 2012.

S. Delepine-Lesoille, X. Phéron, J. Bertrand, et al. 2012, 'Industrial Qualification Process for Optical Fibers Distributed Strain and Temperature Sensing in Nuclear Waste Repositories' Journal of Sensors, vol. 2012, no. 369375, 9 pages.

Bernini, R, Minardo, A, Zeni, L 2011, 'Lecture notes in electrical engineering,' *16th Conference on Italian Association of Sensors and Microsystems*, vol. 109, pp. 235-239.

Fry, ES 2012 'Remote sensing of sound speed in the ocean via Brillouin scattering' *in: Proc. of SPIE,* vol. 8372, no. 837207.

Fu, HY, et al. 2008, 'A novel fiber Bragg grating sensor configuration for long-distance quasi distributed measurement', *IEEE Sensors Journal,* vol. 8, no. 9, pp. 1598-1602.

Saitoh, T, Nakamura, et al. 2007, 'Ultra-Long-Distance Fiber Bragg Grating Sensor System' *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1616–1618.

Saitoh, T, Nakamura, K, et al. 2008, 'Ultra-long-distance (230 km) FBG sensor system,' in: Proc. SPIE, vol. 7004, pp. 70046C-4.

Leandro, D, et al. 2011, 'Remote (155 km) Fiber Bragg Grating Interrogation Technique Combining Raman, Brillouin, and Erbium Gain in a Fiber Laser', *IEEE Photon. Technol. Lett.,* vol. 23, no. 10, pp. 621–623.

Fernandez-Vallejo, M, Bravo, M, Lopez-Amo, M 2013 'Ultra-long laser systems for remote fiber Bragg gratings arrays interrogation,' *IEEE Photonics Technology Letters*, vol. 25, no. 14, pp. 1362-1364.

Fernandez-Vallejo, M, et al. 2011, 'Remote (250 km) Fiber Bragg Grating Multiplexing System' *Sensors*, vol. 11, no. 9, pp. 8711–8720.

Bravo, M, Baptista, JM, Santos, JL, Lopez-Amo, M, Frazão, O 2011, 'Ultralong 250 km remote sensor system based on a fiber loop mirror interrogated by an optical time-domain reflectometer' *Opt. Lett.*, vol. 36, no. 20. pp. 4059–4061.

Han, YG, Tran, TVA, Kim, SH, Lep, SB 2005, 'Development of a multiwavelength Raman fiber laser based on phase-shifted fiber Bragg gratings for long-distance remote-sensing applications' *Opt. Lett.* vol. 30, no. 10, pp. 1114–1116.

Hu, J, Chen, Z, Yang, X, Ng, J, Yu, C 2010, '100-km Long Distance Fiber Bragg Grating Sensor System Based on Erbium-Doped Fiber and Raman Amplification' *IEEE Photon. Technol. Lett.*, vol. 22, no. 19, pp. 1422–1424.

Soto, MA, Faralli, S, Taki, M, Bolognini, G, Pasquale, FD 2011 'BOTDA sensor with 2-m spatial resolution over 120 km distance using bi-directional distributed Raman amplification,' *Proc. of the SPIE OFS21*, vol. 7753, pp. 775325.

Fernandez-Vallejo, M, Leandro, D, Loayssa, A, Lopez-Amo, M 2011, 'Fiber Bragg Grating interrogation technique for remote sensing (100km) using a hybrid Brillouin-Raman fiber laser,' *Proc. of SPIE OFS21*, vol. 7753, pp. 77537I-1–77537I-4.

Kwon, OJ, Kim, HJ, Yoon, MS, Park, S, Shim, Y, Lee, SB, Han, YG 2011, 'Long distance simultaneous measurement of bending and temperature based on a dual-wavelength Raman fiber laser,' *Proc. of SPIE*, vol. 7753, no. 77531D.

Hu, J, Chen, Z, Yu, C 2012, '150-km Long Distance FBG Temperature and Vibration Sensor System Based on Stimulated Raman Amplification' *J. Ligthwave Technol.*, vol. 30, no. 8, pp. 1237–1243.

Kobayashi, H, Tsuzuki, T, Onishi, T, et al. 2012, 'Suppression of Instability on Sensing Signal of Optical Pulse Correlation Measurement in Remote Fiber Sensing,' *Journal of Sensors*, vol. 2012, no.107847.

Bravo, M, Fernández-Vallejo, M, Lopez-Amo, M 2012, 'Hybrid OTDR-fiber laser system for remote sensor multiplexing' *IEEE Sens. J.* vol. 12, no. 1, pp.174-178.

Bravo, M, et al. 2013, 'Multiplexing of six micro-displacement suspended-core Sagnac interferometer sensors with a Raman-Erbium fiber laser' *Opt. Express*, vol. 21, no. 3, pp. 2971–2977.

Fernandez-Vallejo, M, Bravo, M, Lopez-Amo, M 2013, 'Ultra-long laser systems for remote fiber Bragg gratings arrays interrogation', *IEEE Photon. Technol. Lett.,* vol. 25, no. 14, pp. 1362–1364.

Majumder, M 2008, 'Fiber Bragg gratings in structural health monitoring-Present status and applications', *Sensors Act. A: Physical* vol. 147, no. 1, pp. 150–164.

Fernandez-Vallejo, M 2012, '46-km-Long Raman Amplified Hybrid Double-Bus Network With Point and Distributed Brillouin Sensors' *IEEE Sensors Journal,* vol. 12, no. 1, pp. 184-188.

Li, H 2004, 'Recent applications of fiber optic sensors to health monitoring in civil engineering', *Engineering Structures,* vol. 26, pp. 1647–1657.

Pérez-Herrera, R. A., Lopez-Amo, M. 2014 'Robust Fiber-Optic Sensor Systems' Conference Paper Optical Fiber Sensors II (SeW2C) (pp. SeW2C-1) Optical Society of America.

Ramamurthy, S 2003, 'Survivable WDM mesh networks' *Journal of Lightwave Technology,* vol. 21, pp.870-883.

Wu, CY 2010, 'Three-dimensional mesh-based multipoint sensing system with self-healing functionality,' *IEEE Photon. Technol. Lett.,* vol. 22, pp. 565–567.

Peng, PC 2012, 'Novel optical add-drop multiplexer for wavelength-division-multiplexing networks,' *Opt. Comm.*, vol. 285, pp. 3093-3099.

Bravo, M, Fernandez-Vallejo, M, Lopez-Amo, M, Kobelke, J, Schuster, K. 2013 'Fiber optical sensor networks based on OADM devices with a bus configuration', *Proceedings of SPIE,* vol. 8794, no. 87943V.

Rota-Rodrigo, S, Perez-Herrera, R.A, et al. 2013, 'Multiwavelength Fiber Ring Laser based on Optical Add-Drop Multiplexers and a Photonic Crystal Fiber Sagnac interferometer', *Optics & Laser Technology*, vol. 48, no. pp. 72–74.

Perez-Herrera, RA, Urquhart, P, Schlüter, M, et al. 2012, 'Optical Fiber Bus Protection Network to Multiplex Sensors: Experimental Validation of Self-Diagnosis,' *IEEE Sensors Journal*, vol. 12, no. 9, pp. 2737-2743.