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Random DFB Fiber Laser for Remote (200 km) Sensor Monitoring Using Hybrid WDM/TDM

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***Abstract*— In this work, a random distributed feedback (DFB) fiber laser is proposed as a multiplexing scheme for ultra-long range measurements (up to 200 km). Optical fiber sensors are time and wavelength multiplexed overcoming one of the main limitations of long-range sensing setups, which is their limited multiplexing capability. The direct modulation of the laser's cavity allows the interrogation of sensors by measuring the reflected power for different wavelengths and distances. Fiber Bragg gratings (FBGs) placed at different fiber locations and wavelengths have been interrogated in two different sensor networks. In addition, in order to improve the performance of the system, some features have been analyzed.**

***Index Terms*— Random Distributed-feedback fiber laser, Multiplexing, optical fiber sensors, time division multiplexing, wavelength division multiplexing.**

I. Introduction

A variety of multiplexing techniques based on different modulation formats have been developed, each one with its own specific advantages for each particular application [1]. These modulation formats generally fall into one of the following categories: Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM), Coherence Multiplexing (CM) or Polarization Division Multiplexing (PDM) [2]-[4]. Likewise hybrid approaches (simultaneous utilization of two modulation formats inside the same network) have been also considered. The multiplexing capability of WDM schemes can be limited by the available bandwidth, less than 100 nm [5]. On the other hand TDM schemes have been shown to own simple system structure and high sensitivity [6]. Researches in the recent years have been concentrated on the system expansion by incorporating EDFAs or Raman amplification in the array with hybrid approaches that include more than one multiplexing technique. For example, hybrid TDM/WDM systems that can multiplex hundreds of sensors in a single network have been validated theoretically. Simulations show that up to 1000 weak-reflection fiber Bragg gratings can be inserted in a single fiber using optical wavelength time-domain reflection (OWTDR) technology [7]. Large-scale interferometric sensor multiplexing schemes have been also published recently, theoretically proving the inclusion of 4096 sensors in an amplified network [8]. Other approach based on chaotic laser sources provides fault detection with a spatial resolution of 2.8 cm at the cost of lower multiplexing capability [9].

In addition, Optical Time Domain Reflectometry (OTDR) has been demonstrated to achieve fully distributed sensing systems which are be able to find the positions of any backscattered/reflected event along the length of a fiber. These systems are based on an optical pulse which is launched into the fiber under test. A high sensitivity photodetector detects the backscattered light intensity produced by the pulse along the fiber. Light backscattering/reflections occur due to optical fiber discontinuities and also because of small variations of the refractive index of the fiber known as Rayleigh backscattering [10]. Taking advantage of this technology, another simple but effective hybrid approach uses an OTDR to achieve TDM in combination with a tunable filter used for the wavelength selection [11]. OTDR techniques have been also used in ultra-long remote sensor systems demonstrating a sensing distance limit of 253 km for a single sensor [12]. It must be emphasized that the tradeoff between the pulse width and sensing distance is one of the main drawbacks of this technique in order to interrogate long distances. Up to date, few sensing proposals have surpassed 150 km of sensing range [13] but the majority of them present limited multiplexing capability in terms of position, number and type of sensors (most can interrogate just FBGs at a single location). In this manner, many works have focused on maximizing the number of sensors multiplexed and others have looked for interrogating a sensor located as far as possible. However, in this work, the particular properties of random distributed feedback (DFB) lasers have been explored in the design of a new ultra long-range sensor system, with higher multiplexing capability than others long range setups (in terms of type of sensors and its location along the cavity).

Manuscript received December, 13, 2015. This work was supported by the Spanish Government project TEC2013-47264-C2-2-R and the FEDER funds.

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2016.2547868, Journal of Lightwave Technology

Random DFB fiber lasers have been subject of intense theoretical and experimental investigations [14] during the last years due to their potential differences when compared to conventional lasers. In this work, its mode-less behavior [15], high power and stability [16], together with the capability of being internally modulated without frequency restrictions [17] are used in the design of a scheme for quasi-distributed fiber optic sensors multiplexing.

Exploiting these singular properties, a new random DFB laser has been designed to achieve ultra-long range sensor interrogation in a multiplexing scheme. Several FBGs have been remotely monitored up to 200 km away from the monitoring station with approximately 44 m of spatial resolution. Preliminary results presented in [18] have been extended by modifying the filtering process and studying the influence of different parameters such as the laser bandwidth, modulation values, etc. Results show that random DFB fiber lasers can have a great potential for remote sensing applications when combined with OTDR techniques.

II. Experimental setup and principle of operation

A. Laser design

The experimental setup of the sensor multiplexing system can be divided in two different parts: the fiber laser itself and the sensor network to be monitored. A random distributed feedback fiber laser design is employed due to its particular properties such as good stability, high power inside the cavity and outstanding performance when modulated. Additionally, the half-open cavity architecture allows the laser cavity to be used as part of the sensor network. Random DFB fiber lasers are based on the distributed amplification of the Rayleigh backscattering along the fiber. In this context, random DFB schemes typically consists of two single mode fibers (SMF) branches which act as distributed mirrors [14]. In the case of using Raman amplification, the SMF of the cavity also acts as the active medium for the amplification due to the Raman scattering effect. Similar performance can be achieved using a single-arm configuration, obtained by replacing one of the fiber arms by a reflector [16]. In this work, the single-arm configuration is used. Thus, the fiber cavity also serves as the sensing network in which numerous sensors can be monitored.

Moreover, the reflector used in the setup is designed to modulate and select the wavelength of operation of the laser. It consists of a fiber loop formed by an optical circulator. Two different techniques have been used to select the wavelength of operation of the laser. In the first experiment, a tunable FBG is connected using a four-port circulator as depicted in Fig. 1(a) with the aim of filtering and consequently selecting the wavelength of the laser. Another approach is used in the second experiment with the aim of automating the measurement process and increasing the wavelength range of the laser. In this case, a programmable filter is placed at the port 3 of the circulator as can be seen in Fig. 1(b). An optical coupler is used to extract a 30% of the power circulating inside the loop to be detected and analyzed in an oscilloscope. The remaining 70% of the light is forwarded into the loop to be modulated by an electro-optical amplitude modulator. A signal generator is connected to the modulator creating a pulse train with a pulse repetition rate of 450 Hz and a pulse duration of 0.83 μs and 0.44 μs for the first and second experiment respectively. Finally, the light passes through the circulator into the laser's cavity where it is combined with the 1445 nm pump laser. The single-mode fiber cavity consists of 170 and 200 km of SMF (for the first and second experiment respectively) as shown in Fig. 1.

As a result, a tunable and amplitude-modulated random DFB fiber laser emission is obtained.

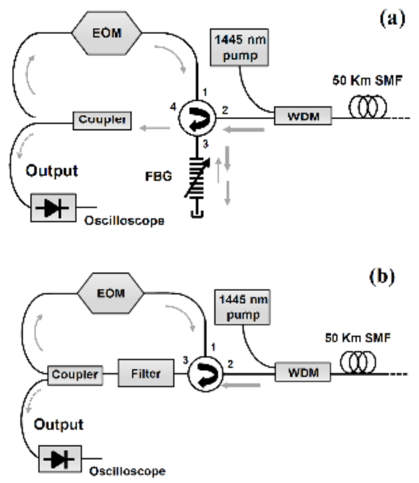

Fig. 1. Experimental setup of the proposed fiber laser in the (a) first and (b) second experiment. EOM: Electro-optical modulator, WDM: Wavelength division multiplexer, SMF: Single mode fiber, FBG: Fiber Bragg grating.

B. Sensor network configuration

The second part in which the sensing system can be divided is the sensor network itself. As previously stated, the single mode fiber of the laser's cavity is also used as a channel where different fiber optic sensors can be multiplexed. The proposed system can interrogate optical sensors operating in reflection and monitor them using time and wavelength-division multiplexing. Therefore, to validate the system as long-range sensor multiplexing scheme, the sensor network will include fiber Bragg gratings located at different wavelengths and distances from the monitoring station.

The design of the network can include sensors at any position of the cavity up to 200 km. Optical couplers are inserted in the fiber channel to extract a percentage of the light to interrogate sets of sensors. An exception is the last group of sensors, which are directly placed at the end of the cavity. It is important to note that the coupling ratio *k* of the optical couplers selected is an essential aspect in the performance of the setup. Higher *k* values will increase the power extracted from the main cavity and the reflected signal; but the system's maximum range will decrease. It must be also taken into consideration that a random DFB fiber laser requires a distributed reflector (SMF fiber in our case) to operate. In this work, the system detects the peak reflections given by the sensors along the cavity. Consequently, including a strong

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reflection in the cavity will change the laser's behavior from a Random DFB to a standard Raman fiber laser with a Fabry-Pérot cavity. This situation must be avoided by limiting the strongest reflection (choosing the appropriate *k* for each optical coupler) to a value in which the laser remains stable in the random regime. In addition, every fiber end was immersed in refractive index matching gel to avoid undesired reflections.

In this work, two different experiments have been carried out to validate the system as sensor multiplexing scheme. In accordance, two sensor networks have been designed. The first one, depicted in Fig. 2(a), consists of four sets of sensors located at the kilometers 50, 100, 150 and 170. The coupling ratios used in the first experiment are 1%, 5% and 30% for the optical couplers located at the kilometer 50, 100 and 150 as displayed in Fig. 2 (a). In order to demonstrate the TDM feature, the sensors are composed by four pairs of FBGs with the same Bragg wavelengths: λ_1=1545.6 nm, λ_2= 1550 nm, λ3= 1547 nm and λ_4= 1548.6 nm. It is also placed a single FBG which has a Bragg wavelength of λ_5= 1545.1 nm. The reflectivity of the FBGs is higher than 90% and the full width at half maximum (FWHM) is 0.2 nm except for the tunable FBG used in λ_4 that is 0.3 nm.

In the second experiment, the main purpose is to use a wider wavelength range and to monitor the sensors at longer distances. In accordance, the coupling ratios chosen for the optical couplers located at the kilometers 50, 100 and 150 are 1%, 5% and 10% respectively as depicted in Fig. 2 (b). In this case, the FBGs used have the following Bragg wavelengths: λ_1=1545.6 nm, λ_2= 1550 nm, λ_3= 1547 nm, λ_4= 1548.6 nm, λ_5= 1542.4 nm. The Bragg wavelengths of the two FBGs located at the end of the channel illustrated in Fig. 2 (b) are λ_6= 1541.2 nm and λ_7= 1543.6 nm.

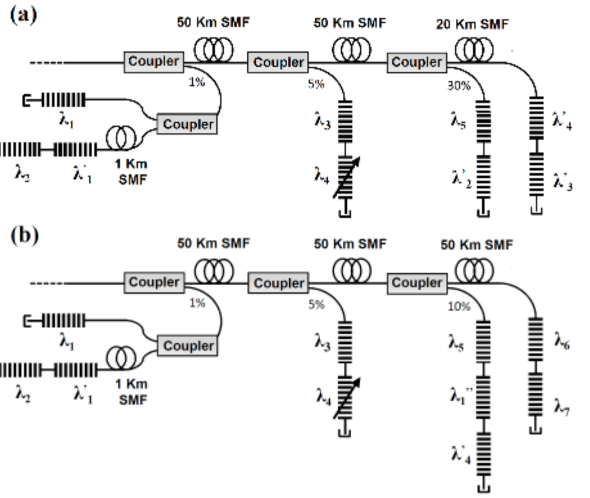

Fig. 2. Experimental setup of the sensor network to be monitored in the (a) first and (b) second experiment.

C. Principle of operation

The principle of operation of the multiplexing system relies on the particular properties of random DFB lasers such as its outstanding performance when modulated internally [17]. Additionally, high peak power values are achieved inside the cavity [19], reaching the laser's maximum power around the 40^{th} kilometer in our scheme. High power and wavelength stabilities are also attained due to the absence of longitudinal modes [14]. The laser is wavelength-tuned by the filter placed in the loop mirror and the EOM modulates the light before re-entering into the cavity again. In the same manner as an optical time-domain reflectometer, due to the pulse modulation, the reflected power along the fiber can be measured using an oscilloscope. Therefore, a voltage vs time (i.e. distance) profile is obtained for the wavelength set. This measurement can be repeated for different wavelengths by tuning the laser's wavelength, getting the reflected power along the fiber for a wavelength range. In this manner, reflections can be detected in the cavity at different wavelengths. Consequently, if a FBG is placed in the cavity, a reflection peak will arise when the laser's wavelength matches the FBG wavelength. Since the reflected wavelength of the FBGs vary with physical parameters (e.g. temperature or strain), the wavelength of the reflections will encode the information of the sensors. Therefore, fiber optic sensors can be interrogated at any position in the cavity (if they operate in reflection). That implies that sensors can be wavelength and time-multiplexed since for identical wavelength, sensors can be identified by their position along the fiber. Likewise, FBG sensors placed at a close location (given by the pulse duration) can be wavelength-multiplexed. The main factor to be taken into account for an adequate performance of the system is, as previously mentioned, the control of the reflection peaks to keep the laser operation in the random regime.

As a proof-of-concept of the proposed system, two sensor networks have been remotely interrogated for different sensor configurations and distances (170 and 200 km).

III. Experimental Results

A. First experiment

In order to validate the system as ultra-long range remote sensor multiplexing scheme, two different experiments have been carried out. The first one uses a tunable FBG as filtering element (Fig. 1(a)) to interrogate the sensor network depicted in Fig. 2(a). In this case, the FWHM of the filter is 0.2 nm and the wavelength range for the laser is limited between 1545-1550 nm. The pulse-width of the modulation is 0.83µs.

Before carrying out the experiment, the operation under random regime of the laser was confirmed for the whole wavelength range. Fig 3 illustrates the optical spectrum of the emission line measured at an optical spectrum analyzer (OSA) when the tunable FBG was set to 1545 nm for a pump power of 1.4 W. To validate the random operation of the laser, the self-beating of the line was detected by a photo-detector and measured with an electrical spectrum analyzer (ESA). The absence of longitudinal modes in Fig. 4 indicates that the laser keeps operating in random regime even if the laser's wavelength matches the Bragg wavelength of the sensors. That indicates that the behavior of the laser is not noticeably affected by the FBGs of the sensor network.

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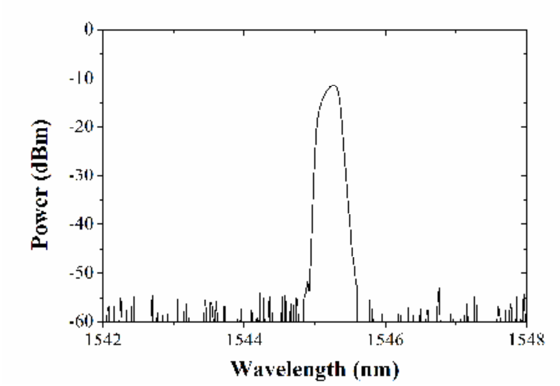

Fig. 3. Optical spectrum of the random DFB fiber laser (resolution= 0.01 nm).

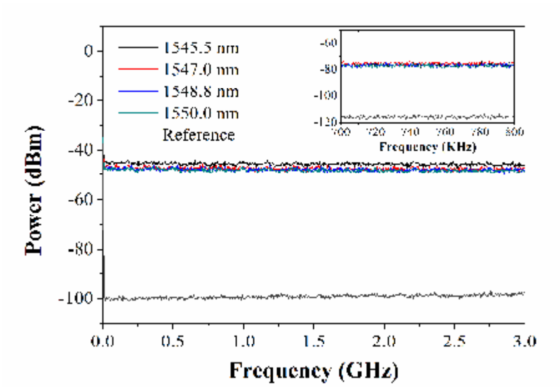

Fig. 4. Self-beating signal of the emission line for different wavelengths. ESA resolution= 300 kHz (300 Hz Inset).

After confirming the adequate performance of the laser for the wavelength range under study (1545-1550 nm), the measurements were taken with a spatial resolution of 85 m and a wavelength step of 0.05 nm (longer steps were used at the sensor-free zones to shorten the measurement process). The results obtained are presented in Fig. 5(a) and (b). It can be clearly seen that every sensor can be unambiguously identified by their position and wavelength in the network. In this manner, FBGs located at the same wavelength can be identified by its position along the fiber and sensors located at the same point can be wavelength-multiplexed. The inset in Fig. 5(b) shows a zoom in which the two sensors located 1 km away at 1545.6 nm can be easily identified.

A simple validation of the appropriate operation of the system under sensor variations has been also carried out. An axial strain of 1000 με was applied to the sensor located at λ_3'. Figure 6 shows the wavelength variation of FBG(λ_3) and FBG(λ_3') located at kilometer 100 and 170 respectively when the strain was applied to FBG(λ_3'). It is evident that the wavelength shift of FBG(λ_3') behaves correctly and it does not affect the behavior of FBG(λ_3). Therefore, as a proof of concept, the system has been validated as sensor-multiplexing network with a spatial resolution of 85 m and a maximum distance of 170 km.

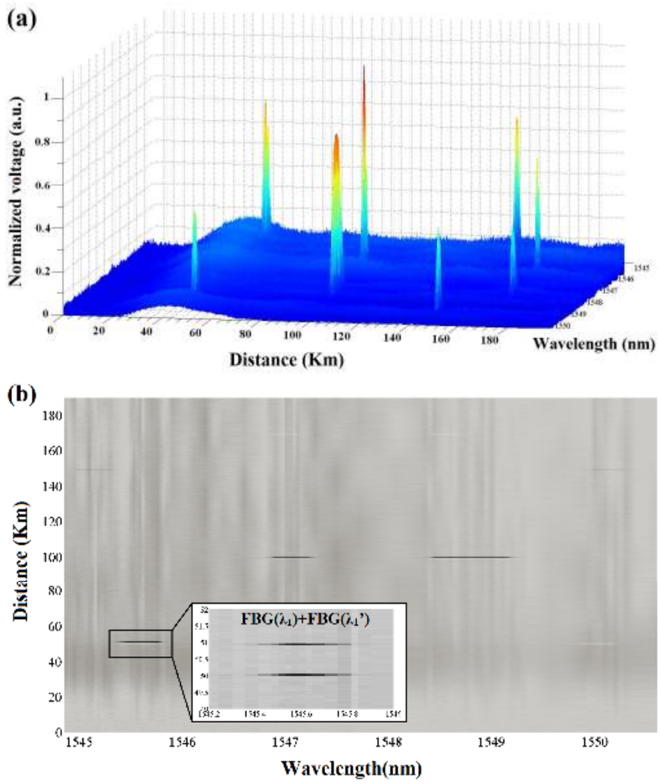

Fig. 5. Experimental results obtained for the 170 Km-setup.

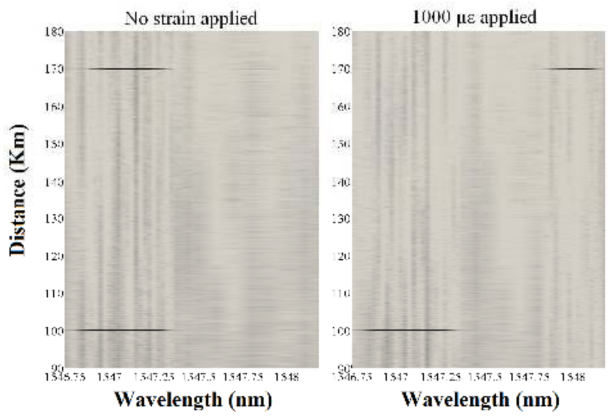

Fig. 6. FBG(λ_3) and FBG(λ_3') wavelength response when 1000 με are applied to FBG(λ_3').

B. Second experiment

In order to improve the multiplexing capability of the system by increasing the spatial resolution, the wavelength range and the maximum range of the network, a second experiment was carried out. In this case a programmable filter was used as the filtering element instead of a tunable FBG for the selection of the laser's wavelength. Initially, a study of the bandwidth of the filtering process with the aim of find the value in which the reflection of the sensors is higher was carried out. Figure 7 displays the results, showing an increment of the reflected signal with the bandwidth increment. In accordance, a FWHM of 0.38 nm was chosen for the filter, obtaining the optical spectrum displayed in Fig. 8.

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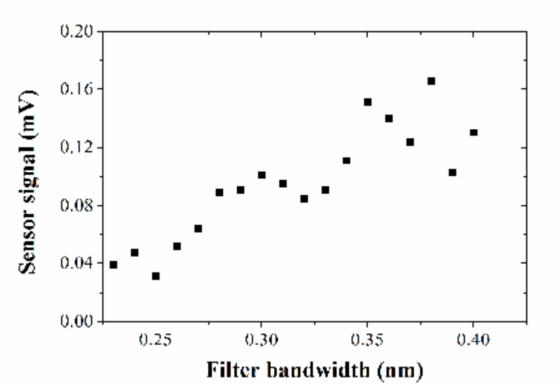

Fig. 7. Reflection given by a FBG for different filter bandwidth values.

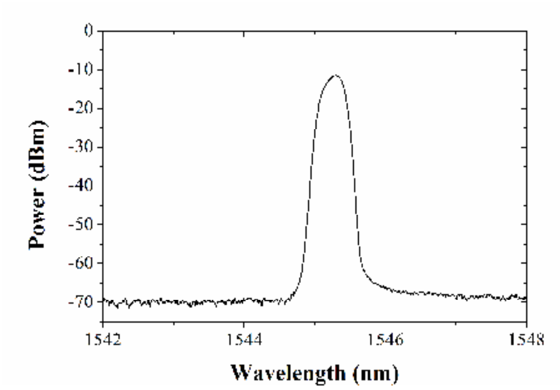

Fig. 8. Optical spectrum of the laser configuration used in the second experiment.

On the other hand, the pulse width has to be narrowed to improve the spatial resolution. In order to check that the system behavior is not affected by the narrowing of the pulse width, the results of the reflection detected for a FBG located at the km 50 for different pulse widths are presented in Fig. 9. It can be seen that the reflected amplitude is constant except for the last case. That drop, together with the pulse deformation (the pulse shape is rectangular) is due to the bandwidth limit of the oscilloscope. In any case, for the system configuration of the first experiment, the spatial resolution can be straightforwardly improved from 85 to 45 m having a slight decrease in the amplitude. Consequently, the pulse width set for this experiment was 0.44 µs.

The next factor to be improved was the wavelength range. It has to be taken into account that there is a strong dependence of the Raman gain with wavelength as depicted in Fig. 10 (triangular samples). As a result, for example, if the Raman pump is configured to measure reflections at 1544 nm (maximum gain), it is possible that a reflection located at a wavelength with smaller gain value is not detected. In the same manner, if the system is properly set for measuring sensors at wavelengths with lower gain, it might occur that the reflections located at 1545 nm are strong enough to destabilize the laser (leaving the random regime). To avoid these effects, the automated filter was programmed to apply an attenuation value that keeps the laser operating at a constant power. The results of the system with and without the attenuation control can be seen in Fig. 10 (dots and square samples). As a consequence, the pump power required in this experiment was higher, being needed 1.60 W. This power equalization allowed the wavelength increase of the network to 1540-1550 nm.

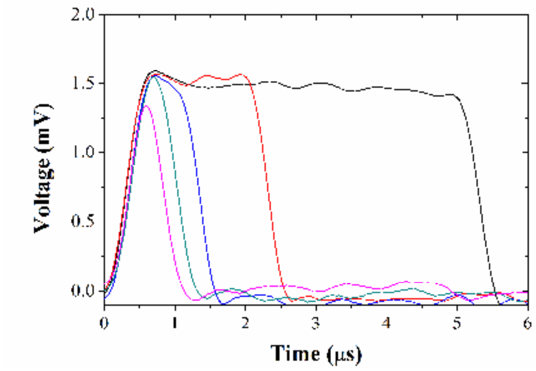

Fig. 9. Reflection given by a FBG for different pulse widths.

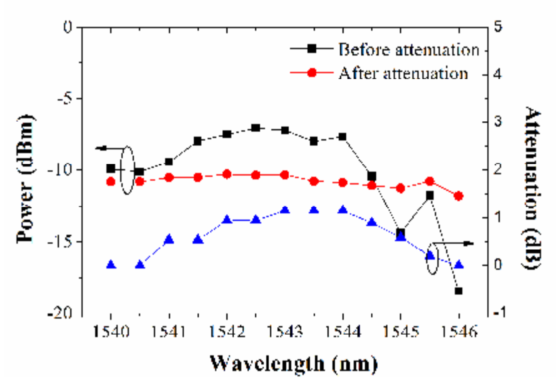

Fig. 10. Attenuation profile and optical power detected before and after the application of the attenuation control.

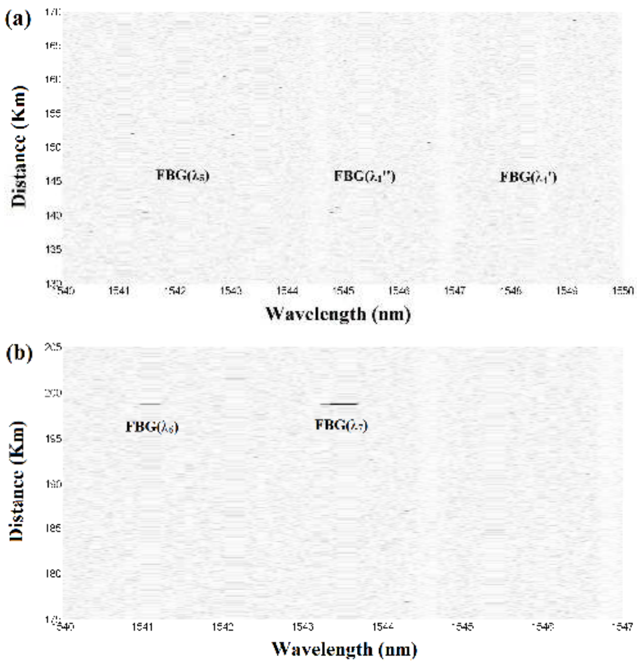

Fig. 11. Experimental results for the FBGs located at the kilometers (a) 150 and (b) 200.

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Finally, the network was measured for a wavelength range between 1540-1550 nm, a spatial resolution of 45 m and a maximum distance of 200 km. The results of the FBGs located at the km 200 and 150 can be seen in Fig. 11(a) and (b). The sensors can be identified even after improving the spatial resolution from 85 to 45m, doubling the wavelength range and increasing the sensing distance to 200 km.

In order to evaluate the repeatability of the measurements, the results obtained from a FBG sensor located at 1547 nm for nine consecutive sweeps are presented in Fig. 12. As expected, the peak of the trace varies between two adjacent samples, showing a good repeatability.

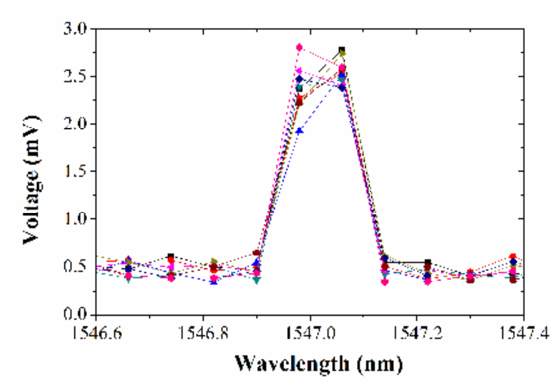

Fig. 12. Results obtained from nine consecutive sweeps to evaluate the repeatability of the measurements.

Referring to the relationship between the number of sensors that can be multiplexed using this technique and the performance of the system, there are several aspects that must be taken into account. Initially, it is worth mentioning that the spatial resolution is not affected by the number of sensors of the system. Depending on the physical parameters to be measured and the type of sensors, a different amount of FBGs can be included in each branch. The inclusion of sensors in the already set branches would not affect the performance of the system. However, if more optical couplers are placed in the main cavity to insert more sensors, the maximum distance of the system will decrease. In this manner, the maximum sensing distance depends on the amount of power extracted from the cavity. It should be mentioned that there is no limitation on the location of the sensors along the cavity. In the proposed setups the couplers have been placed at the splicing points between reels for simplicity, but the sensors can be located at any position. However, including an optical coupler will have different impact in the system depending on its location along the cavity. For example, if arrays of sensors are included before the kilometer 50 (which is the point where most part of the Raman amplification is depleted) the pump power will be critically affected. This would have an important repercussion in the amplification process, significantly reducing the maximum range of the system.

IV. CONCLUSIONS

In this study, for the first time, a random DFB fiber laser has been used to create and validate a new sensor system for time and wavelength division multiplexing. To achieve this, the particular properties of Random lasers have been exploited, like its good performance when modulated or high stability. The modulation of the laser's cavity allows the sensors to be identified by means of time-domain reflectometry. Moreover, the reflected signal vs distance profile has been measured at different wavelengths by tuning the emission wavelength of the laser. Consequently, this work overcomes one of the main drawbacks of ultra-long range remote sensing systems, that is their very limited multiplexing capability. Using this setup, sensors located at the same wavelength can be identified by their position in the network. In the same manner, sensors closely spaced can be wavelength-multiplexed.

Two different experiments were carried out. Initially, a simple proof of concept was performed, using a tunable FBG as the filtering element of the laser. As a result, 9 FBGs (located at wavelengths between 1545-1550 nm) were monitored up to 170 km away from the monitoring station with a spatial resolution of 85 m. In the second experiment, the filtering device was replaced by a programmable filter. Additionally, a study of the different properties of the system allowed several improvements over the first experiment. In this manner, 10 FBG sensors were monitored 200 km away with a spatial resolution of 45 m and a wavelength range between 1540-1550 nm. It is worth saying that the number of sensors measured was limited by the material availability but the system allows a higher number of FBG to be directly measured. However, due to the complex laser dynamics, further work is required to reliably estimate the maximum number of sensor that can be multiplexed.

More advanced reflectometry techniques and equipment could straightforwardly improve the performance of the system. For example, a wider optical spectrum can be measured by an appropriate control of the gain profile. In conclusion, a new sensing application for random DFB fiber lasers is proposed by exploiting its singular properties. Preliminary results show a greater multiplexing ability of the scheme compared to other ultra-long sensing setups. Additionally, authors consider that further work can significantly improve the capabilities of the system.

REFERENCES

[1] M. López-Amo, J.M. López-Higuera; "Multiplexing Techniques for FBG Sensors," in Fiber Bragg Grating Sensors: Research Advancements, Industrial Appli*cations and Market Exploitation*; 1st ed. Ed. Bentham Science Publishers Ltd, (2011).

[2] R.A. Perez-Herrera, M. Lopez-Amo, "Fiber optic sensor networks," *Opt. Fiber Technol.*, vol. 19, no. 6, pp. 689-699, Dec. 2013.

[3] G.A. Cranch, P.J. Nash, "Large-scale multiplexing of interferometric fiber-optic sensors using TDM and DWDM," *J. Lightw. Technol.*, vol. 19, no. 5, pp. 687–699, May. 2001.

[4] G. Fang, T. Xu, F. Li, "Heterodyne interrogation system for TDM interferometric fiber optic sensors array," *Opt. Commun.,* vol. 341, pp. 74-78, Apr. 2015.

[5] H. Chenyuan, W. Hongqiao, B. Wei, "A Novel Interrogation System for Large Scale Sensing Network With Identical Ultra-Weak Fiber Bragg Gratings," *J. Lightw. Technol.*, vol. 32, no. 7, pp. 1406-1411, Apr. 2014.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2016.2547868, Journal of Lightwave Technology

[6] C.K. Kirkendall, A. Dandridge, "Overview of high performance fiber-optic sensing," *J Phys. D Appl. Phys.*, vol. 37, no. 18, pp. R197-R216, Sept. 2004.

[7] M. Zhang, Q. Sun, Zi W., X.Li, H. Liu and D. Liu, "A large capacity sensing network with identical weak fiber Bragg gratings multiplexing," *Opt. Comm.*, vol. 285, no. 13–14, pp. 3082-3087, Jun. 2012.

[8] Y. Liao, E: Austin, P.J. Nash, S.A. Kingsley, D.J. Richardson, "Highly Scalable Amplified Hybrid TDM/DWDM Array Architecture for Interferometric Fiber-Optic Sensor Systems," *J. Lightw.Technol.*, vol.31, no.6, pp.882-888, Mar., 2013.

[9] Y. Luo, L. Xia, W. Li, Z. Xu, Q. Sun, and D. Liu, "Optical Chaos and Hybrid WDM/TDM Based Large Capacity Quasi-distributed Sensing Network with Real-time Fiber Fault Monitoring," *Opt. Express*, vol. 23, no. 3, pp. 2416-2423, Jan. 2015.

[10] N. Niharika, M. Basu, S.K. Ghorai, "Detection and monitoring of multiple cracks using distributed fiber optic sensor" in *Proc. SPIE ICACCCT 7019204*, 2014, pp. 809-812.

[11] L.C.G. Valente,.M.B. Braga, A.S. Ribeiro, R.D. Regazzi, W. Ecke, C. Chojetzki, R. Willsch, "Combined time and wavelength multiplexing technique of optical fiber grating sensor arrays using commercial OTDR equipment," *IEEE Sens. J.* , vol.3, no.1, pp.31-35, Feb. 2003.

[12] M. Bravo, J. M. Baptista, J.L. Santos, M. Lopez-Amo, et al, "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, Oct. 2011.

[13] M. Fernandez-Vallejo, M. Lopez-Amo, "Optical fiber networks for remote fiber optic sensors," *Sensors*, vol. 12, no. 4, pp. 3929-3951, Mar. 2012.

[14] S.K. Turitsyn, S.A. Babin, A.E. El-Taher, P. Harper, D.V. Churkin, S.I. Kablukov, J.D. Ania-Castañon, et al., "Random distributed feedback fibre laser," *Nat. Photonics*, vol. 4, no. 4, pp. 231-235, Feb. 2010.

[15] M. Fernandez-Vallejo, S. Rota-Rodrigo, M. Lopez-Amo, "Comparative study of ring and random cavities for fiber lasers," *Appl. Optics*, vol. 53, no. 16, pp. 3501-3507, Jun. 2014.

[16] S.K. Turitsyn, S.A. Babin, D.V. Churkin, I.D. Vatnik, M. Nikulin, E.V. Podivilov, "Random distributed feedback fibre lasers," *Phys. Reports*, vol. 542, no. 2, pp. 133-193, Sep. 2014.

[17] M. Bravo, M. Fernandez-Vallejo, M. Lopez-Amo, "Internal modulation of a random fiber laser," *Opt. Lett.,* vol. 38, no. 9, pp. 1542-1544, May. 2013.

[18] D. Leandro, R. Perez-Herrera, M. Bravo, et al., "Time and wavelength division multiplexing scheme for ultra-long sensing based on a cavity-modulated random DFB fiber laser," in *Procc of SPIE,* 2015. pp. 9634-963415.

[19] D.V. Churkin, A.E. El-Taher, I.D. Vatnik, et al., "Experimental and theoretical study of longitudinal power distribution in a random DFB fiber laser," *Opt. Express*, vol. 20, no. 10, pp. 11178-11188, May. 2012.

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