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Authors: M. Bravo, J.M. Baptista, J. L. Santos, M. López-Amo, and O. Frazão
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250 km ultra long remote sensor system based on a Fiber Loop Mirror interrogated by an OTDR

M. Bravo^{1*}, J. M. Baptista^{2,3}, J. L. Santos^{2,4}, M. Lopez-Amo¹, O. Frazão²

¹Departamento Ingeniería Eléctrica y Electrónica—Universidad Pública de Navarra, Campus Arrosadía S/N, Pamplona, 31005, Spain

²INESC Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal

³Centro de Ciências Exactas, Universidade da Madeira, Campus da Penteada, 9000-390 Funchal, Portugal

⁴Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal

*Corresponding author: mikel.bravo@unavarra.es

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A 253 km ultra long remote displacement sensor system based on a fiber loop mirror interrogated by a commercial OTDR is proposed and experimentally demonstrated. The use of a fiber loop mirror increases the signal to noise ratio allowing the system to interrogate sensors placed 253 km away from the monitoring system without using any optical amplification. The displacement sensor was based on a long period grating spliced inside of the loop mirror, which modifies the mirror reflectivity accordingly to the applied displacement. © 2011 Optical Society of America

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The fiber optic sensor systems, unlike electric sensors systems, provide the possibility to develop remote sensing without the requirement of local biasing for the remote components. This feature results quite attractive for applications where it is not possible or it is very expensive to place active equipment, such as tsunamis predicting systems, oil pipes monitoring, landslides detection, etc. Nowadays, it has been achieved ultra large measuring distances (>100 km [1-3]) by using fiber optic lasers based on Raman non-linear effects with cavities that include fiber Bragg gratings (FBG) which act as the sensing elements. One of the main problems detected in ultra long sensor systems based on Raman amplification, is the Rayleigh backscattering which masks the optical sensor signal. T. Saitoh *et. al.* using erbium doped fibre amplification and time-domain reflectometry with a swept-wavelength light source for detecting the Bragg grating reflection spectrum achieved a 230 km distance record [4]. T. Saitoh *et. al.*, also proposed, one year before, a similar setup without amplification achieving a 120 km sensor system. To our knowledge is the longest distance achieved without amplification until this letter [5].

Other authors have proposed different solutions to achieve ultra long optical sensors systems with expensive and complicate setups, most of them using optical amplification launched from the sensing head [6-9]. Table

1 shows an actualized summary (August 2011) of different ultra long sensor systems. In this table are compared the principal characteristics of the ultra long sensor systems as well as the technologies used, length, year and number of sensing heads. As it can be seen from the table, for fiber lengths higher than 150 km, optical amplification based on erbium doped fiber amplifier (EDFA), semiconductor optical amplifier (SOA) or non linear effects (Raman and Brillouin) is required.

In this letter, the high reflectivity of a fiber loop mirror is used as a pulse reflector and this pulse can be easily observed at 253 km away without any amplification or complex setup, only with a commercial OTDR. This reflection is utilized for sensing by means of a hybrid configuration based on a fiber loop mirror (FLM), combined with a long period grating (LPG). The LPG is characterized as a displacement sensor via curvature. In what concerns the FLM and comparing to a good metalized end facet of the fiber, the FLM has a simpler implementation, since it only requires a coupler and a splice. Moreover, it is a more robust device, because it is not so prone to any undesirable mechanical or chemical damage and does not degrade with time, being its performance very stable. Accordingly to the knowledge of the Authors, it is the first time that an OTDR interrogates an optical fiber sensor system that incorporates a FLM.

Table 1. State of the art in remote sensor systems

Year/Ref	Amplification type	Network length	Multiplexing/No sensors	SNR	Sensor technology
2005 [7]	EDWA/SOA	25 km	24	42 dB	FBG
2005 [6]	Raman	50 km	1	50 dB	Phase FBG
2007 [5]	No amplification	120 km	1	24 dB	FBG
2008 [4]	EDFA	230 km	1	4 dB	FBG
2010 [8]	Raman	50 km	4	46 dB	FBG
2010 [2]	Raman/EDFA	100 km	1	30dB	FBG
2010 [1]	Raman/EDFA/Brillouin	155 km	2	10 dB	FBG
2011 [9]	EDFA	50 km	4	25 dB	Bending/FBG
2011 [3]	Raman/EDFA/Brillouin	100 km	4	30 dB	FBG

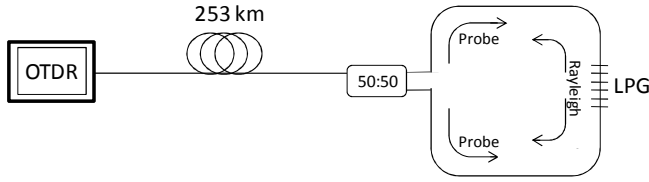


Fig. 1. Ultra long FLM/LPG sensor system setup

To achieve this sensing distance, it is proposed an experimental setup which is depicted in figure 1 and is formed by a FLM which includes a LPG as the sensing element. LPGs have been used before to measure different parameters such as strain, temperature and refractive index. These sensing heads show a high sensitivity and low back reflections and can be interrogated using low-cost signal demodulation schemes [10].

This work uses the Sagnac interference to measure displacement. The high reflectivity of the fiber loop mirror combined with the LPG allows the easy detection of displacement by using an OTDR as the interrogation unit. The displacement sensitivity of the sensor is achieved by the change of the reflection peak of the LPG at the OTDR working wavelength (Figure 2).

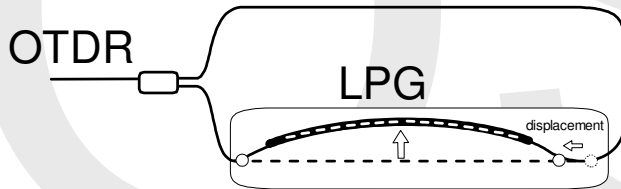


Fig. 2. FLM/LPG displacement sensing head

The commercial OTDR used in this work is an EXFO, model FTB-7423B-B. This OTDR interrogates a sensor placed 253 km away connected by a single mode fiber (SMF28). The sensing head consists of a 50:50 low insertion loss coupler and a long period grating centered at the OTDR emission wavelength. For achieving ultra-long distance measurements it is necessary to configure the OTDR parameters to interrogate ultra long networks. This commercial OTDR allows us to measure up to 260 km by using a 20 μ s pulse time having an acquisition time of 31 second. The device acquires more than 1 trace per second, which are averaged during the acquisition time to reduce the measured noise level.

This FLM/LPG acts as a variable high reflectivity mirror as function of displacement. A FLM consists of a loop of optical fiber, where the output ports of a directional coupler are connected. We assume that the coupler is balanced and when the light reaches the coupler at the input port, the coupler sends the half of the power to one of the output ports and the other half to the other output

port. Fifty percent of the remaining launched light travels, therefore, clockwise around the loop and the other 50 percent travels anticlockwise. The transmitted intensity is therefore the sum of a clockwise field of arbitrary phase Φ and an anticlockwise field having the same relative phase and equal amplitude. This results in a zero transmitted intensity and by the conservation of energy principle; all input light is reflected back along the utilized input port. This reflectivity is varied by the LPG placed inside the mirror. When a displacement is applied to the LPG, the LPG's attenuation peak is shifted in wavelength and changes the intensity of the OTDR received pulse varying the reflectivity of the mirror.

With this variable mirror we obtain a high signal to noise ratio reflectivity sensor. Thus, this sensor is well suited for ultra long sensing systems interrogated by an OTDR.

The experimental procedure to characterize this sensor is to fix both LPG extremes on two points as is shown in figure 2. The displacement is controlled by a computerized translation stage. The displacement steps programmed for each measurement had a value of 50 μ m.

Fig. 3 shows the OTDR traces obtained by measuring the FLM/LPG displacement sensing head at a distance of 150, 200 and 253 km, respectively. The signal to noise ratio, which is achieved using the FLM in conjunction with the OTDR, allows reaching these ultra long distances without any amplification subsystem. In the 253 km trace, showed in the inset of the upright corner of figure 3, it is observed the FLM/LPG sensor peak between the trace noise pulses. Nevertheless, the low SNR achieved is enough to make the displacement measurements as shown in figure 4.

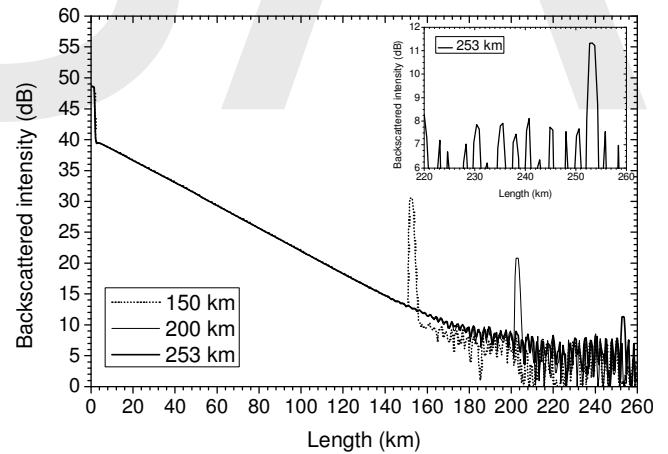


Fig. 3. OTDR acquired traces for maximum reflectivity of the sensor for 150, 200 and 253 km

Figure 4 shows the different displacement measurements obtained for the different fiber lengths connecting the OTDR and the sensing head. Each measurement has a different backscattered intensity level, which corresponds to the difference of fiber length loss measured by the OTDR that is ~ 9 dB for each 50 km (Figure 4). The achieved dynamic range for each

measurement is ~ 3 dB. The sensor polynomial behavior is similar for the different fiber lengths and results from the LPG response, when analyzed in intensity [11]. In each displacement curve, two linear regions can be found. For the range between $[0, 500 \mu\text{m}]$ the sensitivity is $\sim 5 \text{ dBm}/\mu\text{m}$ and for $[500, 1050 \mu\text{m}]$ is $\sim 2 \text{ dBm}/\mu\text{m}$. The resolution of the sensing head using this configuration is $0.5 \mu\text{m}$.

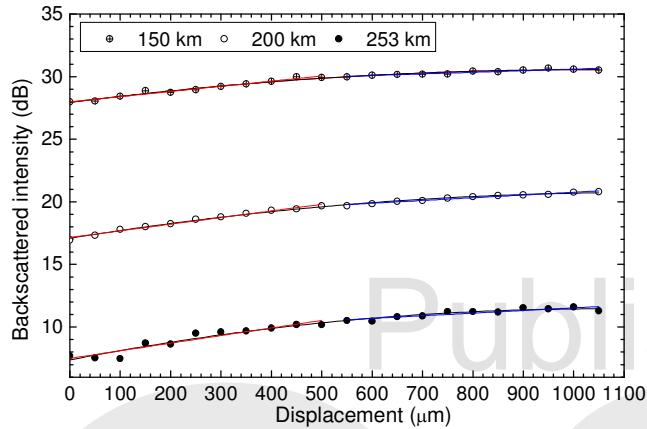


Fig. 4. 150, 200 and 253 km sensor displacement behavior.

This letter has presented and demonstrated the feasibility of measurement a remote FLM/LPG based displacement sensor. The sensor was placed 253 km away from the interrogation head using a commercial OTDR. The high reflectivity of the FLM/LPG sensor is the key feature that permits the measurements without any kind of amplification within this ultra-long distance interrogation system and it uses a long period grating to change the reflectivity of the mirror accordingly to the displacement applied.

This hybrid sensing head based on a FLM combined with a LPG can also be used to measure other physical parameters. This configuration can also use other types of intensity sensors inside of the loop mirror without changing the peak response created by the fiber loop mirror.

Acknowledgments

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References

1. D. Leandro, A. Ullan, A. Loayssa, J. M. López-Higuera and M. López-Amo, IEEE PTL, 23, 10 (2011)
2. J. Hu, Z. Chen, X. Yang, J. Ng, and C. Yu, IEEE PTL, 22, 19 (2010).
3. M. Fernandez-Vallejo, D. Leandro, A. Loayssa and M. López-Amo, SPIE 21st OFS, 7753-8, (2011).
4. T. Saitoh, K. Nakamura, Y. Takahashi, H. Iida, Y. Iki and K. Miyagi, SPIE 19th OFS, 7004, 70046C (2008).
5. T. Saitoh, K. Nakamura, Y. Takahashi, H. Iida, Y. Iki and K. Miyagi, IEEE PTL, 19, 20 (2007).
6. Y. Han, T. V. A. Tran, S. Kim and S. B. Lee, Optics Letters, 30, 10 (2005)
7. P. Peng, K. Feng, W. Peng, H. Chiou, C. Chang, S. Chi, Optics Communicatios, 252, 127-131 (2005).
8. M. Fernandez-Vallejo, S. Diaz, R. A. Perez-Herrera, D. Passaro, S. Selleri, M. A. Quintela, J. M. López-Higuera, and M. López-Amo, Meas. Sci. Technol., 21, 094017, (2010)
9. M. Bravo, M. Fernández-Vallejo and M. López-Amo, Proc. SPIE, 7653, 765340-1-4, (2010).
10. V. Bhatia and A. M. Vengsarkar, Optics Letters, 21, 9, 692-694 (1996)
11. O. Frazão, R. Falate, J. M. Baptista, J. L. Fabris, J. L. Santos, Optical Engineering, 44, 11, (2005)

1. D. Leandro, A. Ullan, A. Loayssa, J. M. López-Higuera and M. López-Amo, "Remote (155 km) fiber Bragg grating interrogation technique combining Raman, Brillouin and Erbium gain in a fiber laser" IEEE PTL, 23, 10 (2011)
2. J. Hu, Z. Chen, X. Yang, J. Ng, and C. Yu, "100-km Long Distance Fiber Bragg Grating Sensor System Based on Erbium-Doped Fiber and Raman Amplification" IEEE PTL, 22, 19 (2010).
3. M. Fernandez-Vallejo, D. Leandro, A. Loayssa and M. López-Amo, "Fiber Bragg Grating interrogation technique for remote sensing (100km) using a hybrid Brillouin-Raman fiber laser", SPIE 21st OFS, 7753-8, (2011).
4. T. Saitoh, K. Nakamura, Y. Takahashi, H. Iida, Y. Iki and K. Miyagi, "Ultra-long-distance (230 km) FBG sensor system", SPIE 19th OFS, 7004, 70046C (2008).
5. T. Saitoh, K. Nakamura, Y. Takahashi, H. Iida, Y. Iki and K. Miyagi, "Ultra-Long-Distance Fiber Bragg Grating Sensor System", IEEE PTL, 19, 20 (2007).
6. Y. Han, T. V. A. Tran, S. Kim and S. B. Lee, "Development of a multiwavelength Raman fiber laser based on phase-shifted fiber Bragg gratings for long-distance remote-sensing applications", Optics Letters, 30, 10 (2005)
7. P. Peng, K. Feng, W. Peng, H. Chiou, C. Chang, S. Chi, "Long-distance fiber grating sensor system using a fiber ring laser with EDWA and SOA", Optics Communications, 252, 127-131 (2005).
8. M. Fernandez-Vallejo, S. Diaz, R. A. Perez-Herrera, D. Passaro, S. Selleri, M. A. Quintela, J. M. López-Higuera, and M. López-Amo, "Resilient long-distance sensor system using a multiwavelength Raman laser", Meas. Sci. Technol., 21, 094017, (2010)
9. M. Bravo, M. Fernández-Vallejo and M. López-Amo, "Hybrid OTDR-fiber laser system for remote sensors multiplexing", Proc. SPIE, 7653, 765340-1-4, (2010).
10. V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors", Optics Letters, 21, 9, 692-694 (1996)
11. O. Frazão, R. Falate, J. M. Baptista, J. L. Fabris, J. L. Santos, "Optical bend sensor based on a long-period grating monitored by an optical time-domain reflectometer", Optical Engineering, 44, 11, (2005)