Ultralong 250 km remote sensor system based on a fiber loop mirror interrogated by an optical time-domain reflectometer

M. Bravo,[1,*] J. M. Baptista,[2,3] J. L. Santos,[2,4] M. Lopez-Amo,[1] and O. Frazão[2]

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

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

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

[4]*Faculdade 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 ultralong remote displacement sensor system based on a fiber loop mirror interrogated by a commercial optical time-domain reflectometer 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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Fiber-optic sensor systems, unlike electric sensor systems, provide the possibility to develop remote sensing without the requirement of local biasing for the remote components. This feature is quite attractive for applications where it is not possible or it is very expensive to place active equipment, such as tsunami predicting systems, oil pipe monitoring, and landslide detection. Nowadays, ultralarge measuring distances have been achieved (>100 km [1–3]) by using fiber-optic lasers based on Raman nonlinear effects with cavities that include fiber Bragg gratings (FBGs), which act as the sensing elements. One of the main problems detected in ultralong sensor systems based on Raman amplification is the Rayleigh backscattering, which masks the optical sensor signal. Saitoh *et al.*, using erbium-doped fiber 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, this is the longest distance achieved without amplification until this Letter [5].

Other authors have proposed different solutions to achieve ultralong optical sensor systems with expensive and complicated setups, most of them using optical amplification launched from the sensing head [6–9]. Table 1 shows an actualized summary (August 2011) of different ultralong sensor systems. Compared in this table are the principal characteristics of the ultralong sensor systems as well as the technologies used, length, year, and number of sensing heads. As can be seen from the table, for fiber lengths greater than 150 km, optical amplification based on the erbium-doped fiber amplifier (EDFA), semiconductor optical amplifier (SOA) or nonlinear 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, with only a commercial optical time-domain reflectometer (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, because 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, its performance being very stable. Accordingly, to the knowledge of the authors, this is the first time that an OTDR interrogates an optical fiber sensor system that incorporates an FLM.

To achieve this sensing distance, an experimental setup is proposed, which is depicted in Fig. 1 and is formed by an FLM, which includes an 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 backreflections 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 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 (Fig. 2).

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 an LPG centered at the OTDR emission wavelength. For achieving ultralong distance measurements, it is necessary to configure the OTDR

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	30 dB	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	100 km	4	30 dB	FBG

parameters to interrogate ultralong networks. This commercial OTDR allows us to measure up to 260 km by using a 20 μs pulse time having an acquisition time of 31 s. 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 a function of displacement. An 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 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% 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 (SNR) reflectivity sensor. Thus, this sensor is well suited for ultralong 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 Fig. 2. The displacement is controlled by a computerized translation stage. The displacement steps programmed for each measurement have a value of 50 μm.

Figure 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 SNR, which is achieved using the FLM in conjunction with the OTDR, allows reaching these ultralong distances without any amplification subsystem. In the 253 km trace, shown in the inset of the upright corner of Fig. 3, the FLM/LPG sensor peak between the trace noise pulses is observed. Nevertheless, the low SNR achieved is enough to make the displacement measurements as shown in Fig. 4.

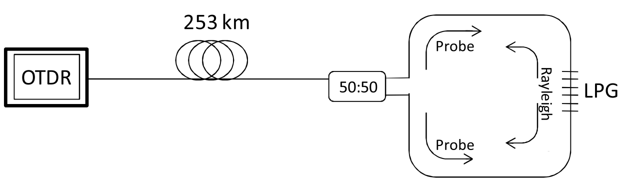

Fig. 1. Ultralong FLM/LPG sensor system setup.

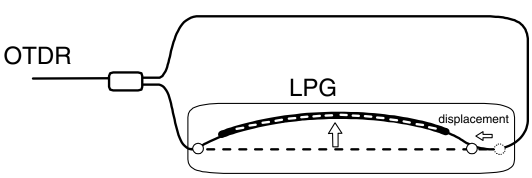

Fig. 2. FLM/LPG displacement sensing head.

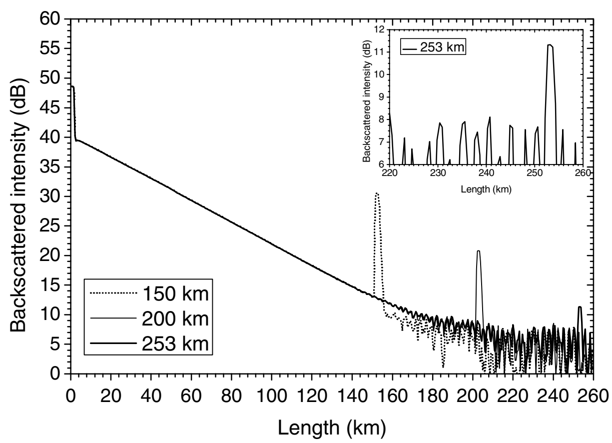

Fig. 3. OTDR acquired traces for maximum reflectivity of the sensor for 150, 200, and 253 km.

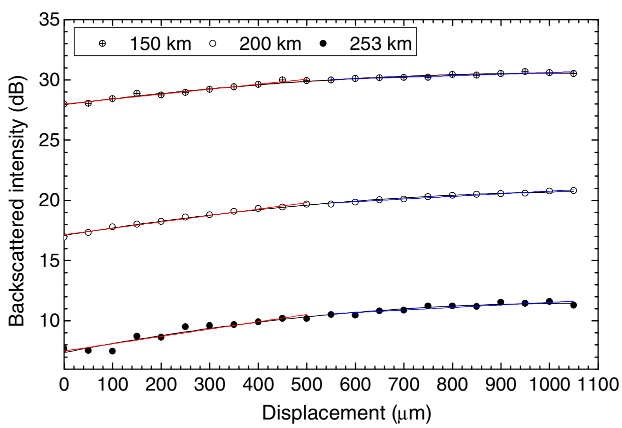

Fig. 4. (Color online) 150, 200, and 253 km sensor displacement behavior.

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 the fiber length loss measured by the OTDR that is ~ 9 dB for each 50 km (Fig. 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 $[500, 1050\,\mu\text{m}]$ it is $\sim 2\,\text{dBm}/\mu\text{m}$. The resolution of the sensing head using this configuration is $0.5\,\mu\text{m}$.

This Letter has presented and demonstrated the feasibility of measurement of 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 measurements without any kind of amplification within this ultralong-distance interrogation system, and it uses an LPG to change the reflectivity of the mirror according to the displacement applied.

This hybrid sensing head based on an FLM combined with an 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.

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