# Fiber Loop Mirror Sensors Interrogated and Multiplexed by OTDR

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***Abstract*—In this paper, two techniques for interrogation and multiplexing of fiber loop mirror (FLM) intensity sensors based on optical time domain reflectometer (OTDR) are proposed. These configurations enable series and parallel FLM sensor interrogation. A fiber taper characterized as a displacement sensor was used as the intensity sensor. The OTDR parameters were optimized in order to obtain the best results. The optimized parameters were 100-ns pulse width and 10-dB input signal attenuation which permitted to attain ∼18 dB dynamic range in the operating wavelength of 1550 nm. The results show a linear behavior for both configurations with similar slope, −15.3 dB/mm, in the normalized displacement range of 0.2 to 0.7 mm. It was also achieved a displacement resolution of 0.027 and 0.093 mm, for the series and parallel configurations, respectively. Sensors multiplexing are demonstrated for both configurations and the systems do not present crosstalk. Based on the experimental results, the best configuration is the parallel one. The proposed approach is a viable alternative for multiplexing and interrogation of remote fiber sensors.**

***Index Terms*—Fiber loop mirror (FLM), optical fiber sensor, OTDR, sensor interrogation.**

## I. Introduction

OPTICAL time domain reflectometer (OTDR) is the most utilized equipment to measure distributed losses in optical fibers. It uses Rayleigh scattered light to determine the attenuation of optical fiber links. OTDR is also useful to localize events, breaks and to evaluate splices and connectors [1]. Due to these advantages and since OTDR is a simple, easy and ready to be used tool, it has also been the starting point of distribution sensing techniques [1]. As interrogation system, OTDR has been utilized in different configurations. One of the most common is to use fiber Bragg grating (FBG) and/or long period grating (LPG) with OTDR [2]–[4]. Recently, it was proposed a multi-point strain measurement system based on OTDR for FBG sensors [2], [3]. Another approach employs OTDR to interrogate Fabry–Perot cavities sensors [5], [6]. Finally, a significant function of the OTDR is to enable multiplexing [7]–[9] and remote sensing [8]–[10] interrogation. OTDR trace loss [8], [11]–[13] or reflection peak variation [7], [10] are the most attractive techniques for interrogation when OTDR is used. In the case of the OTDR trace loss and considering multiplexing and remote sensing, there is a compromise between the number of sensors to be multiplexed and the distance between sensors since the loss introduced by the sensors will be a serious limitation to the system. OTDR reflection peak variation does not present such limitation.

An optical fiber mirror is a device necessary in several applications. The most important application is to be used as sensing element. One of the solutions is to utilize a fiber loop mirror (FLM) which is straight forward developed using a 3 dB optical coupler. In this case, the output ports of the coupler are spliced together forming a loop. All light input to the loop is reflected back to the coupler input port due to constructive interference which occurs in the coupler after the counter waves propagate inside the loop [14]. The optical losses are merely a result of the 3 dB coupler insertion loss and the splice loss. Fiber ring combined with LPG is an alternative solution to interrogate such structure in reflection using an OTDR as the interrogation system [15]. The FLM sensor could operate both in transmission and reflection, and its functioning does not depend on the light polarization at the input port. When compared with other temperature sensors, this configuration presented higher sensitivity [16], [17]. Strain sensor based on a Hi-Bi FLM was also investigated [18]. In 2004, temperature dependence of a polarization maintaining (PM) photonic crystal fiber in a FLM was also demonstrated. Comparing with a standard PM fiber, reduced temperature sensitivity was obtained [19]. In 2005, the characteristics of a Hi-Bi FLM composed of a standard 3 dB fiber coupler with one or more sections of Hi-Bi fibers were discussed. Displacement and temperature sensors were theoretically and experimentally analyzed. Using the characteristics of the Hi-Bi FLM, a strain-temperature sensor was proposed and demonstrated as an interrogation system for new applications [20].

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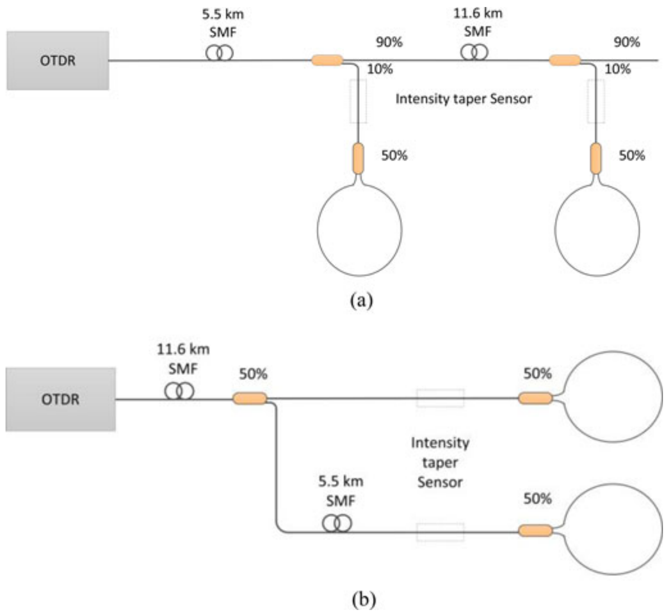


Fig. 1. Experimental setups of the (a) series and (b) parallel interrogation and multiplexing systems for FLM intensity sensors using OTDR.

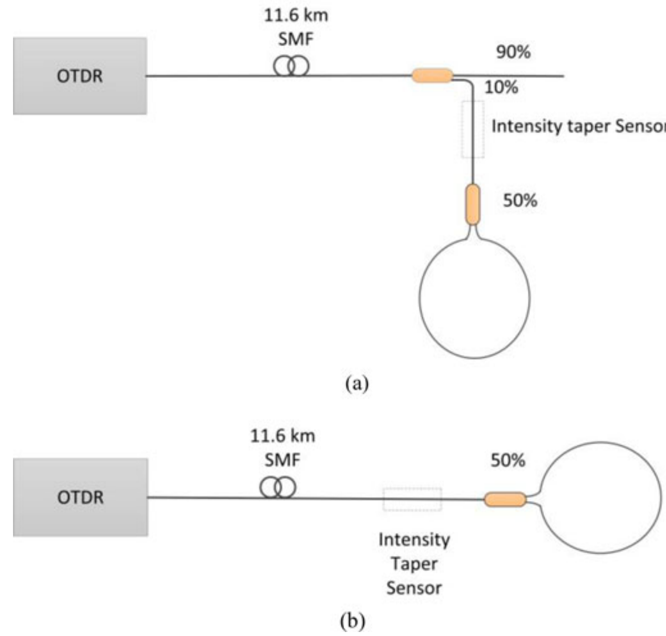


Fig. 2. Experimental setups used to build the two proposed interrogation systems when (a) series and (b) parallel multiplexing interrogation systems are concerned.

In this paper, two interrogation and multiplexing systems based on OTDR are presented to address FLM intensity sensors. The FLMs are interrogated in series or in parallel when located along the fiber line. A peak reflection is generated due to the Rayleigh scattering combined with the light reflected by the FLM. In this case, when the losses are generated by the sensors the light reflected by the peak reflection of the FLM decreases with the applied physical parameter. A fiber taper is used as displacement sensor and is located before the FLMs.

## II. Experimental Setup

The proposed interrogation techniques based on OTDR enable to multiplex several intensity sensors along the fiber. This feature is illustrated in Fig. 1(a) for the series configuration, which shows a system with two FLM intensity sensors. Considering the 2.5 dB loss originated by the $90 \times 10$ optical coupler insertion loss, it is possible to attain multiplexing of around ten sensors. For the parallel configuration, multiplexing is achieved by using a splitter which will divide the optical signal in as much sensors as needed, depending on the number of output ports of the splitter and the signal level. One interesting solution to solve this drawback is to use an optical switch instead of the splitter. In this case, the number of sensors will be dependent merely on the interrogation time. In Fig. 1(b), the splitter is a $1 \times 2$ device and therefore it is shown two multiplexed FLM intensity sensors. Note that the length of the fibers after the splitter must be different in order to allow sensors discrimination. Another interesting possibility of such proposed systems is that they allow using both configurations together in a hybrid multiplexing scheme.

The experimental setups used to build the two proposed interrogation systems are presented in Fig. 2. A commercial OTDR from YOKOGAWA, Inc model *AQ 1200 OTDR–Multi Field Tester* is used to interrogate intensity taper sensors. Remote sensing is obtained connecting 11.6 km of Corning SMF-28 fiber to the OTDR port. In Fig. 2(a), an optical coupler is connected at the fiber output. Ten percent optical power is used to illuminate the sensor. A 3 dB optical coupler working as a FLM is connected to the output of the displacement sensor. The 90% output port of the coupler enables multiplexing. This configuration permits a series sensor interrogation, when sensors multiplexing are concerned. Fig. 2(b) shows the other interrogation system proposed, where the intensity sensor is connected to the end of the 11.6 km Corning SMF-28 fiber directly. The FLM is also attached to the output of the displacement sensor. This configuration enables a parallel sensor interrogation, when sensors multiplexing are involved. To simulate the intensity sensor, an optical fiber taper was used as the displacement sensor. The operation mode of the sensing head consists in applying curvature in the taper region with a value that depends on the displacement to be measured. Therefore, the displacement induced curvature variation originates a change in the insertion loss of the taper. At first, both configurations are similar, but when sensors multiplexing are concerned, they behave differently.

## III. Optimization Signals

In order to optimize the OTDR parameters (optical signal) it was evaluated the dynamic range of the FLM reflection peak by varying the input signal and its pulse width. The FLM reflection peak dynamic range as a function of the input signal attenuation is shown in Fig. 3. It is observed that an input signal attenuation of 10 dB allows obtaining a maximum dynamic range of around 17 dB. The peak signal is not saturated due to the optical coupler $90 \times 10$ located before the FLM. Fig. 4 illustrates the FLM reflection peak dynamic range as a function of the OTDR

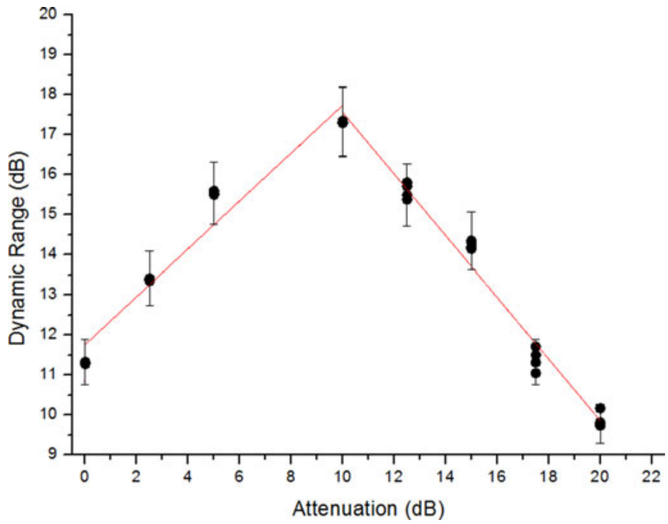


Fig. 3. Dynamic range of the FLM reflection peak as a function of the input signal attenuation.

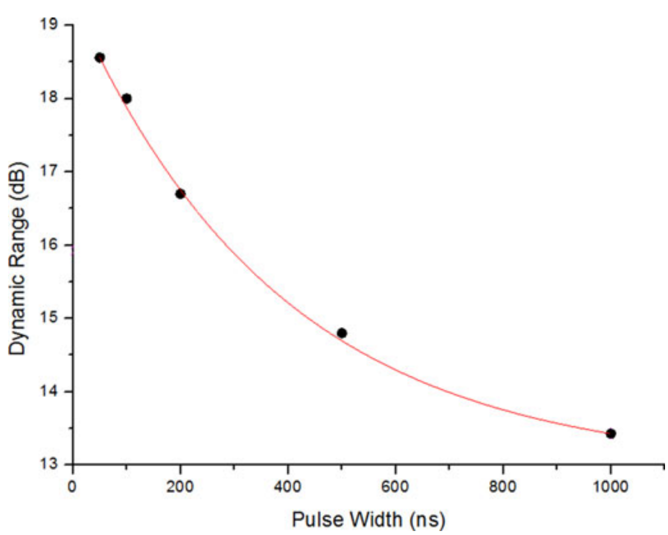


Fig. 4. Dynamic range of the FLM reflection peak as a function of pulse width.

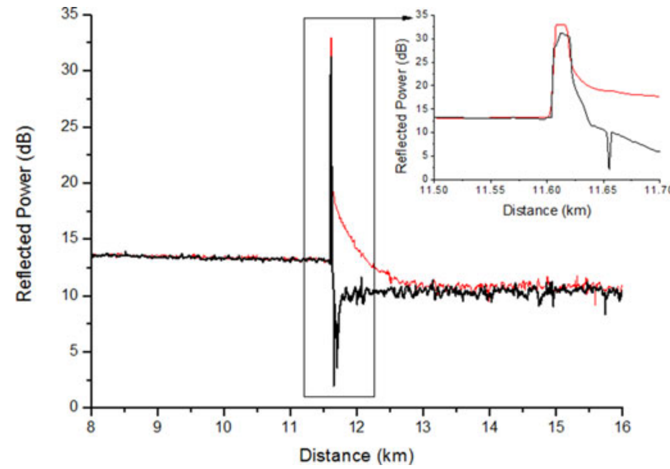


Fig. 5. OTDR traces for the parallel (line) and series (bold line) interrogation systems. Inset: better view of the OTDR peak curves.

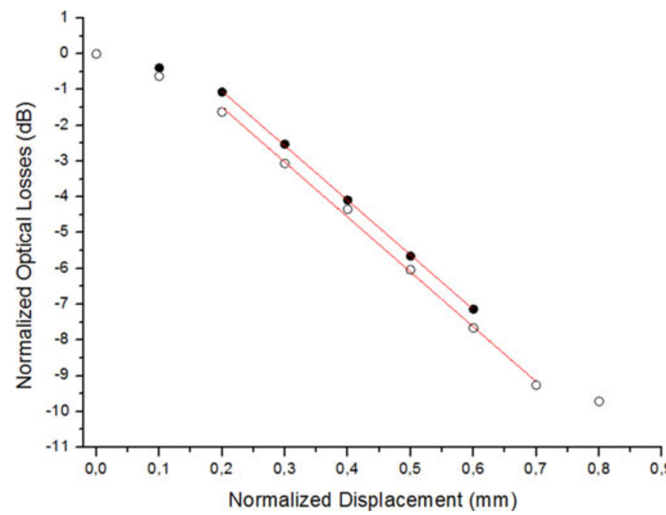


Fig. 6. Normalized optical losses in the FLM reflection peak as a function of the normalized displacement for the parallel (solid circles) and series (open circles) configurations.

input signal pulse width. It is verified that smaller pulse width results in higher dynamic range. A pulse width of ∼100 ns enabled to attain an even better dynamic range of ∼18 dB. In both curves, the dots represent the experimental results and the solid lines are the fitting curves. It was compared the behavior of both interrogation systems with the OTDR operating at 1550 and 1300 nm. Since the attenuation is lower at 1550 nm, this wavelength presented better results and was therefore used throughout this work.

The OTDR traces for the two interrogation systems configurations can be observed in Fig. 5. It is seen a 2.5 dB difference between the OTDR reflection peak curves, as better observed in the inset. Such difference is due to the $90 \times 10$ optical coupler used in the series configuration [see Fig. 2(a)] which enables only 10% of the signal to be input to the sensor and after that to be reflected by the FLM. On the other hand, the parallel configuration [see Fig. 2(b)] enables all signals to input the sensor and to be reflected. However, since this configuration reflects the entire signal, such reflected signal is intense and suffers further reflection back and forth.

## IV. Experimental Results and Discussion

The normalized optical losses in the FLM reflection peak as a function of the normalized displacement sensor for the parallel (solid circles) and series (open circles) configurations are presented in Fig. 6. The results evidence similar linear behavior within the normalized displacement range from 0.2 to 0.7 mm with a slope of around −15.3 dB/mm.

The sensing heads resolutions with the proposed interrogation systems were obtained by performing a step of 0.4 (series configuration) and 0.3 mm (parallel configuration) in the displacement sensor which corresponds to a 3.91 and 4.19 dB signal

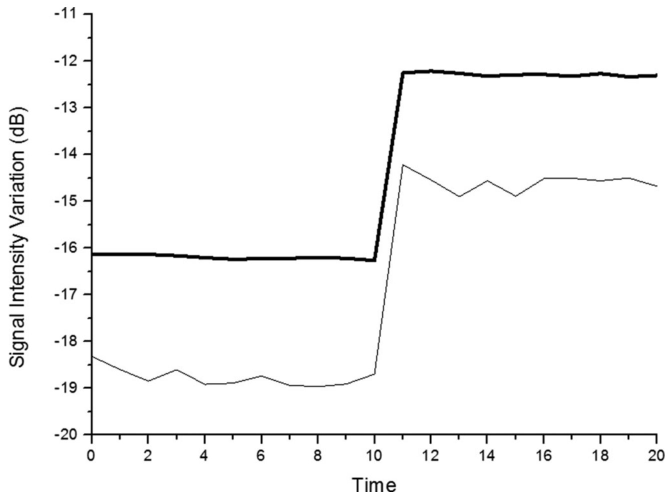


Fig. 7. Step procedure to obtain the resolution for the parallel (line) and series (bold line) interrogation systems.

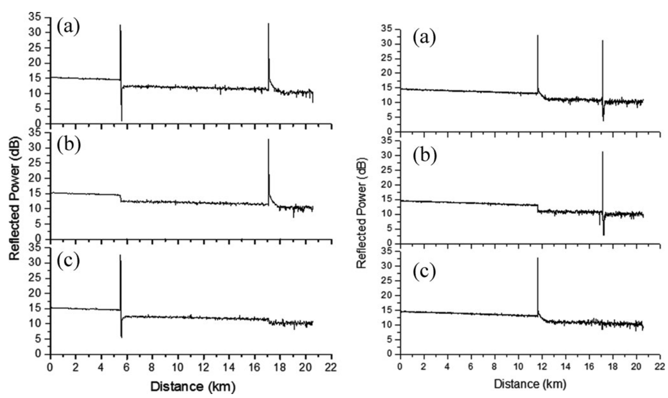


Fig. 8. OTDR traces for series (left) and parallel (right) configurations with (a) two multiplexed sensors, (b) in the absence of the first sensor and FLM and (c) in the absence of the second sensor and FLM.

intensity variation, respectively, as shown in Fig. 7. Considering these values and the average *rms* noise amplitudes before and after the step change, it turns out a displacement resolution of 0.027 and 0.093 mm, respectively.

## V. Multiplexing and Sensing

Fig. 8(a) presents the OTDR trace of two multiplexed sensors in the series (left) and parallel (right) configurations. Crosstalk between the two sensors in both configurations was analyzed. Fig. 8(b) shows the OTDR trace when the first sensor followed by a FLM is absent. The dynamic range of the second FLM reflection peak is still the same in both configurations.

Finally, Fig. 8(c) illustrates the OTDR trace when the second sensor ($\sim$17 km) followed by a FLM is not present. The dynamic range of the first reflection peak is about the same as shown in Fig. 8(a), also for both configurations. Therefore, crosstalk is not an issue in both configurations. The signal observed between the sensors is kept constant along the fiber. Using this type of OTDR, the sample interval is 2 m what corresponds to the minimum distance between the two FLMs.

## VI. Conclusion

In this paper, it was proposed two interrogation and multiplexing systems based on OTDR for FLM intensity sensors. The sensing zones are located before the FLM setup. This configuration based on FLM allows using any type of intensity sensors. In this work a fiber taper was used as a displacement sensor. The FLM structure when is monitored through the OTDR generates an intense peak reflection which is observed in the OTDR display. The schemes were characterized in order to obtain the maximum dynamic range of the reflection peak. It was achieved a maximum value of 17 dB when input signal attenuation of around 10 dB is used. Pulse width of $\sim$100 ns enabled to attain an even better dynamic range of $\sim$18 dB. Both configurations demonstrated similar and good linearity in a specific region of the dynamic range with a $-15.3$ dB/mm slope and a 0.027 mm resolution for the series configuration and 0.093 mm for the parallel one. The series configuration presents three times more noise comparing to the parallel configuration. This result was expected due to the intense reflected signal, which suffers further reflection back and forth. Furthermore, the parallel configuration presents a 2.5 dB increase in the OTDR reflection peak power. Therefore, the parallel configuration may be considered the best one.

Finally it was demonstrated that the two configurations can be used for remote sensing. The choice between both configurations will always depend on the number of sensors that we want to interrogate and the distance between them. However, a hybrid configuration is also one solution for a low number of sensors. The proposed interrogation systems showed to be feasible alternatives techniques for sensor multiplexing and remote sensing when compared with other conventional interrogation systems.

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