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Fiber optic displacement sensor based on a double-reflecting OTDR technique

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ABSTRACT

In this work, it is proposed a technique to implement an intensity sensor based on the generation of a double-reflecting (ghost) signal in optical time domain reflectometry (OTDR). The intensity sensor is supported by a singlemode-multimode-singlemode (SMS) fiber structure combined with a fiber loop mirror (FLM). The results of the displacement sensitivity show linear behavior for both the first-reflecting and double-reflecting signals with linear slopes of approximately −4.5 dB/mm and −6 dB/mm, respectively. The displacement resolution achieved is ~0.28 mm. It is also found that the system is able to read periodic displacement variations in the millisecond time scale applied to the sensing head. © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:1312–1315, 2015

1 INTRODUCTION

Optical time domain reflectometer (OTDR) is the most used optoelectronic equipment to measure distributed losses in single mode optical fibers [1]. The concept is based on Rayleigh scattered light, which permits to determine the attenuation of optical fiber links. OTDR is also useful to localize events, breaks and to evaluate fusion splices and optical connectors [1-3]. Due to these advantages and as OTDR is a simple, easy and ready to be used tool, it has also been the starting point when considering distributed sensing [2].

Due to the operation principle of the OTDR, if there is a high reflection from any point of the tested optical fiber, a generation of a double-reflecting "ghost" peak may appear in the OTDR trace [4]. When the OTDR sends a test pulse down the fiber, a high reflection from the far end comes back (if the pulse power is sufficiently high or the fiber is not long enough to attenuate the optical reflection below a certain level) and it shows up on the trace as an

overloaded reflection [4]. Then, it may be reflected from the OTDR fiber link connector interface back down the fiber for a second round, effectively becoming a second "test pulse" which is again reflected back from the far end, returning to the OTDR to be recorded as a second trace [4]. If the reflections are high enough, this process can go on three or more times, each one producing a ghost event on the OTDR trace [4]. The ghost event can be mitigated and even canceled if the input signal is reduced or low reflection optical interfaces are implemented. Although the ghost signal is generally harmful for the OTDR operation, it can be a useful tool in optical sensors applications. In this case, the signal propagates in two-ways down the fiber duplicating the sensitivity.

Multimode interference effects occurring in singlemode-multimode-singlemode (SMS) fiber structures have been investigated as a mechanism for sensing [5], in some cases combined with OTDR supported interrogation techniques. It is the case of a recent experimental investigation addressing temperature measurement using the SMS structure as the temperature sensor and interrogated by an OTDR [6]. Here, we proceed with this research path, but now exploring the characteristics associated with the processing of the OTDR ghost signal, enhanced by considering a fiber loop mirror (FLM) at the far end of the fiber, with the sensing device for intensity measurement based on a SMS structure.

2 EXPERIMENTAL SETUP AND DISCUSSION

Figure [1] illustrates the experimental setup of the proposed technique. A commercial OTDR from YOKOGAWA, model AQ 1200 OTDR—Multi Field Tester is used to interrogate the intensity sensor. The OTDR optical source is a multimode laser, operating at 1550 nm, with 2 µs pulse width and 2.5 dB input signal attenuation. Remote sensing is obtained connecting 11.6 km of Corning SMF-28 fiber to the OTDR port.
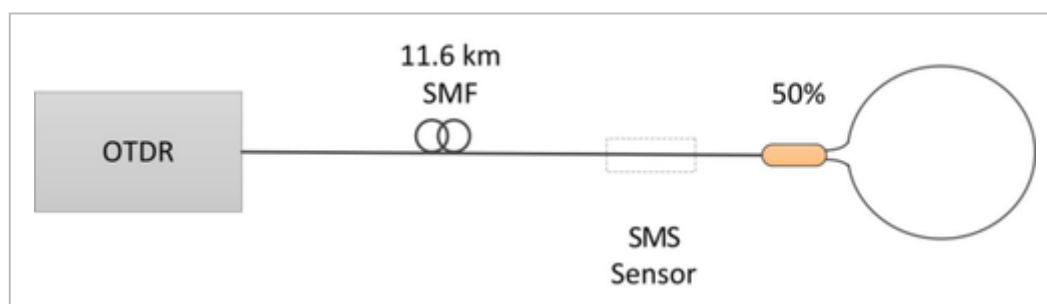

Figure 1

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Experimental setup of the proposed sensing technique. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The intensity sensor is based on a SMS structure, formed by a short section of a multimode fiber, with 105/125 µm core/cladding diameters, a step refractive index profile and 3 mm length, sandwiched and spliced to two SMF-28 fibers, 9/125 µm core/cladding diameters.

The 3 mm length was chosen as it enables high sensitivity for the intensity sensor. Although, it is not an easy task to cleave and splice the 3 mm long MMF to the SMF fibers, the sensor is perfectly reproducible. The SMS structure is illustrated in Figure 2(a) and the setup where the SMS structure is fixed is shown in Figure 2(b).
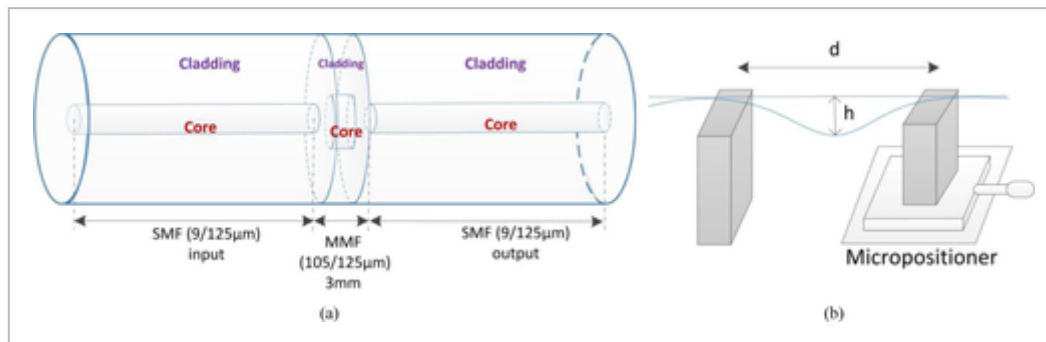

Figure 2

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(a) SMS structure and (b) setup which permits to introduce the displacement in the sensor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Different from a multimode interference structure, the SMS sensor operation is not dependent on the wavelength and merely introduces a loss in the optical signal, as can be observed in the optical spectra shown in Figure 3. In this case, a broadband source illuminated the SMS structure and a displacement from 0 to 400 μm was applied on it. The optical spectrum is attenuated but it does not change with wavelength as the curvature is applied.
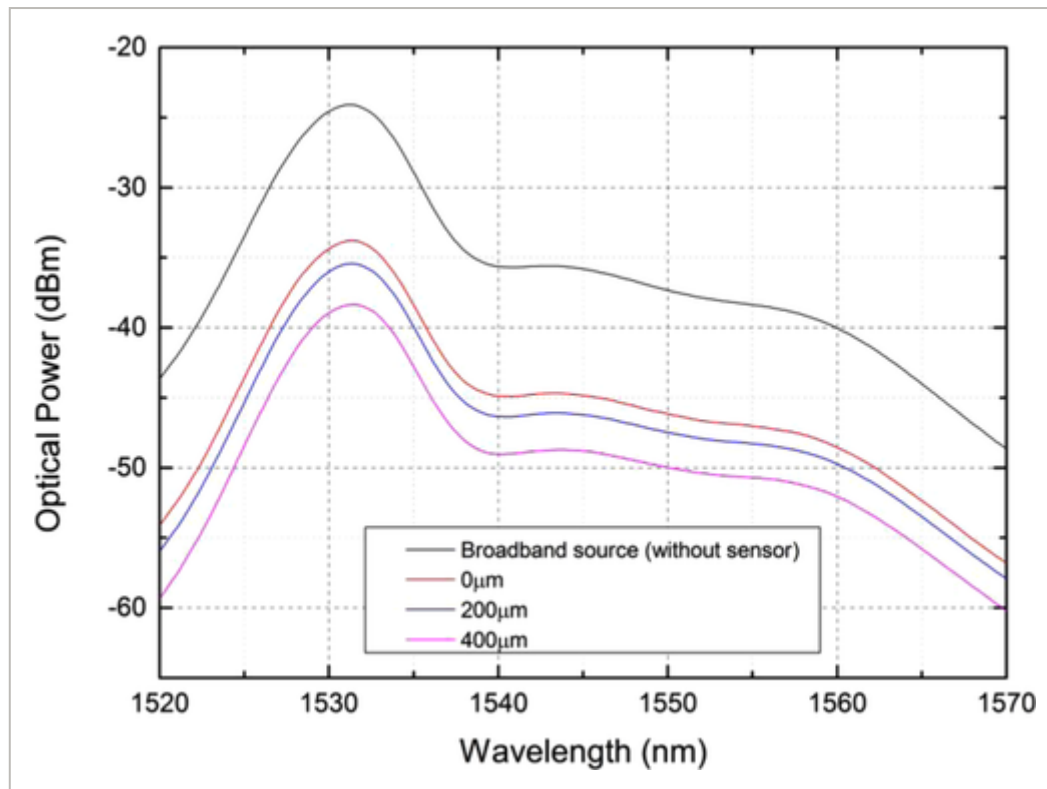
Figure 3

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Optical spectra of the SMS strucuture when a broadband source illuminates it for three different values of displacement. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

A FLM is connected to the output of the intensity SMS sensor to increase the reflected ghost signal 7. The FLM is straightforward developed using a 3 dB optical coupler. In this case, the 1.5 m 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 1, 8, 9. As the output ports present short fiber lengths and no pulse duration is altered, the FLM behaves linearly 10. The FLM permits to generate a strong reflection peak, as it provides almost 100% signal power reflection (excluding the 3 dB optical coupler insertion loss) as compared with Fresnel reflection, enabling the light to propagate 2 + 2 times, in two distinct time windows, through the SMS sensor structure where it is induced intensity modulation discernible by the OTDR. By proper interfacing, this modulation becomes associated to the variation of the targeted measurand. The signal propagates in two-ways down the fiber, duplicating the sensor sensitivity.

This concept was tested adapting the SMS structure to operate as an intensity displacement sensor. One end of the SMS structure is fixed and the other one is glued to a micro positioner, which moves (displaces) horizontally introducing a curvature and losses in the SMS structure, as can be seen in Figure 2(b). The curvature presents a radius of curvature

which is a function of the displacement [11]. When the displacement is applied to the SMS sensor, the ghost peak is reduced significantly when compared with the first reflection peak originated by the FLM.

In Figure [4], it is exhibited the OTDR trace for two different values of displacement related to an initial straight fiber configuration: 0.1 mm (line) and 0.7 mm (bold line). Note that the ghost signal exists (at the distance of ~23 km) in both traces and is much more sensible than the original reflection peak (at 11.6 km). In this case and for the displacements considered, the variation at the ghost peak amplitude is around 3.5 dB, while for the first reflection peak created by the FLM and for the local backscatter before and after the sensor no variation exists, essentially due to OTDR saturation effects.
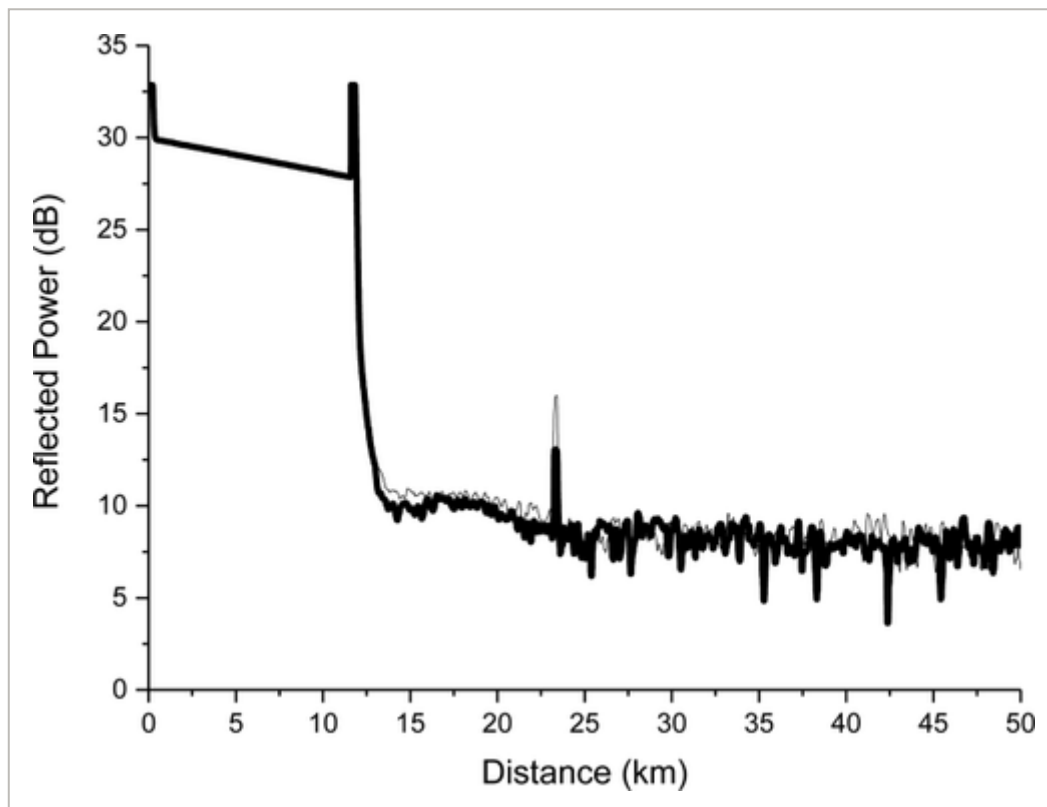

Figure 4

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OTDR traces for 0.1 mm (line) and 0.7 mm (bold line) of displacement applied to the SMS sensor

The behavior of this SMS sensor structure was characterized for displacement measurement. The optical losses in the SMS sensor for the original (black dots) and ghost (red dots) peaks as a function of the displacement are presented in Figure [5]. The results evidence that the ghost peak is much more sensible than the original peak for smaller values of displacement, while the original peak only starts to vary after 1.5 mm of displacement. This behavior is due to the saturation in the original peak. However, the operation dynamic range for the ghost curve is ~1 mm and for the original curve is ~2 mm. This occurs due the

high global loss experienced by the ghost signal for displacements above 1 mm, turning the optical power levels close to the OTDR noise floor, while for the original signal, larger measurand induced losses are accessible considering the initial (no displacement) power level is also substantially larger. For displacements above 3.2 mm, the original peak seems to behave nonlinearly. Such behavior may be due to the high losses that are imposed to the sensor at these displacements levels.
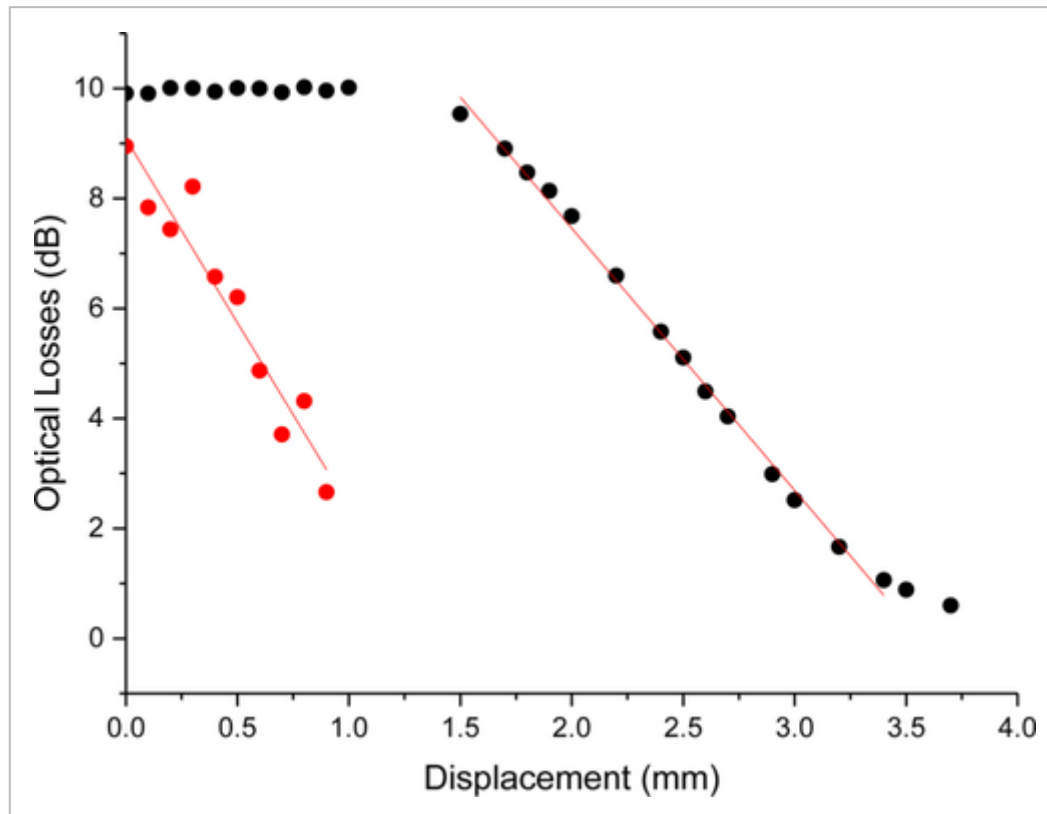

Figure 5

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Optical losses for the original (black) and ghost (red) peaks as a function of the displacement applied to the SMS sensor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Both peaks show a linear behavior with a slope of approximately −6 dB/mm for the ghost peak and approximately −4.5 dB/mm for the original peak. The resolution of the sensing head for the case of the ghost signal was evaluated by performing a step of 0.6 mm in the displacement sensor which corresponds to a 2.57 dB signal intensity variation. Considering this value and the average rms noise amplitude before and after the step change, it turns out a displacement resolution of 0.28 mm.

The results shown in Figure 5 also reveal an interesting characteristic derived from combining the processing of the sensor original and ghost signals, which is the possibility to have a larger measurement range. For smaller displacements (<1 mm), the best approach is to consider the ghost signal, while for larger values the original trace shall be considered.

A further test involved to subject the sensor to a low-frequency dynamic displacement regime and to observe the detected signal. Six cycles with a peak-to-peak displacement variation of 0.6 mm (displacement from 0.1 to 0.7 mm and the way back) were applied to the sensor during two time periods, one with an extension of 350 s and the other with a time span of 700 s (corresponding to excitation frequencies of 16.7 and 7.6 mHz, respectively). For the first case the system acquisition time was set to 10 s while for the second one this value was adjusted to 20 s. The results obtained are shown in Figure 6.
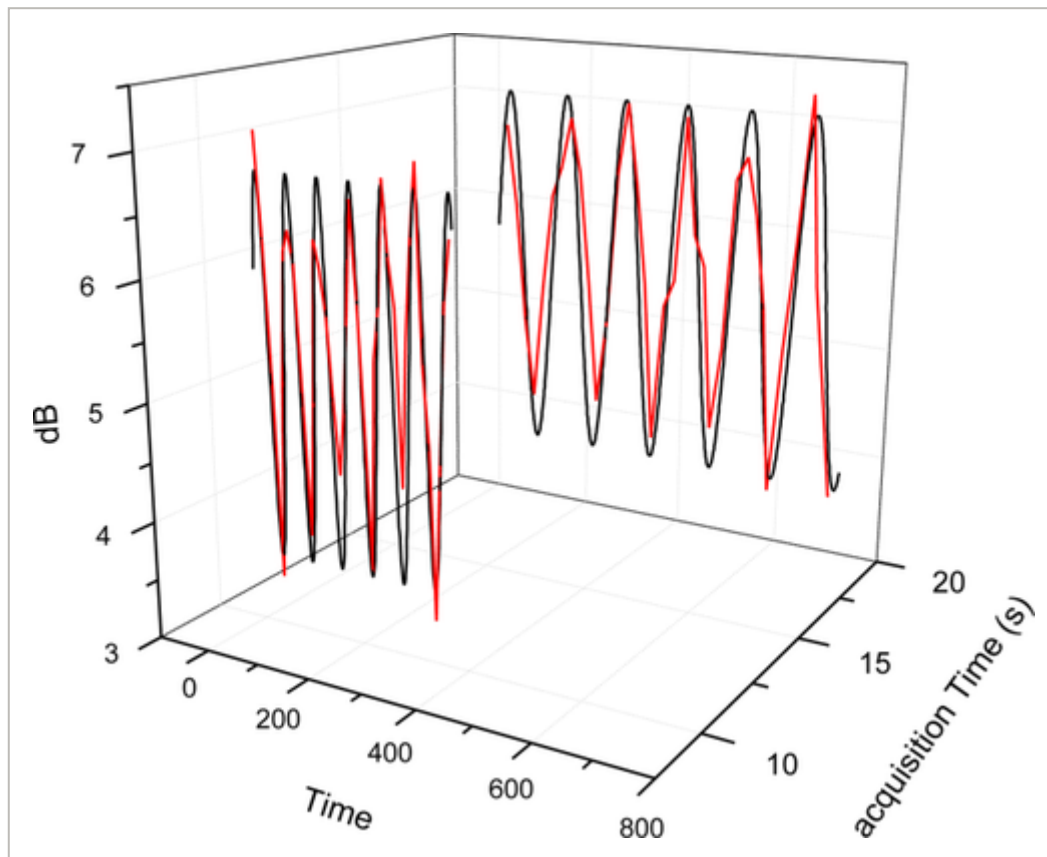

Figure 6

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Response of the SMS intensity sensor associated to 6 displacement cycles with peak-to-peak amplitude of 0.6 mm occurring in time spans of 350 s and 700 s (acquisition times of 10 and 20 s, respectively). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

It can be observed the displacement cycles originate a periodic sensor loss with a peak-to-peak amplitude of 3.5 dB, in both cases. Therefore, by adjusting the OTDR operating conditions it is possible to read time variations of the measurand (displacement in the case) within certain limits, indicating this readily applicable technique is also compatible with some level of dynamic measurement.

3 CONCLUSION

In this work, it was proposed an intensity sensor based on the ghost signal in OTDR and supported by a fiber SMS structure. To increase the ghost signal a FLM was used. The results obtained showed a linear behavior for both the original and double-reflecting signal with slopes of approximately −4.5 dB/mm and −6 dB/mm, respectively, as well as a displacement resolution of 0.28 mm. It was also found that the system is able to read periodic displacement variations in the millisecond time scale applied to the sensing head. This technique can be readily applicable in a large spectrum of situations involving remote displacement measurement, such as impact and damage detection and structural health monitoring.

ACKNOWLEDGMENT

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