Development of an intrusion sensor based on a POTDR system

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In this paper we demonstrate the possibility of using a Polarization Optical Time Domain Reflectometry (POTDR) system as an intrusion sensor. This system measures the evolution of the light polarization state along the fiber length. If a fiber is installed on a fence, an intrusion leads to a modification of the polarization state, which appears as a flattening of the POTDR trace starting from the intrusion position, which can then be determined. Experiments show that an intrusion corresponding to a 1.5 cm displacement of the fiber can be detected, using a 5 s averaging and with a 1.1 m resolution.

Introduction

Intrusion sensors are very important in the industrial world as they can secure, amongst others, nuclear power plants, electrical power centers, prison perimeters and so on. Amongst the set of sensors, optical fibers are interesting due to their possibility to provide distributed measurement (i.e. in every position along the fiber), their insensitivity to EM disturbances, their resistance to corrosion and their possible use in harsh environments (e.g. high temperature and nuclear).

Some optical fiber-based intrusion sensors already exist, such as phase-sensitive Optical Time Domain Reflectometry (OTDR) [1], micro-bend sensors [2], interferometers [3] or more sophisticated techniques [4,5]. The main drawbacks of most of these systems are their complexity and the fact that they require a very coherent laser source, as the key parameter is the phase. This greatly increases the sensor cost.

In this paper we propose a novel kind of intrusion sensor, based on the state of polarization (SOP) of light rather than on its phase and that uses a broadband source (typical a source used in an OTDR) rather than a very narrow linewidth laser source.

This proposed intrusion sensor is based on the facts that the SOP is modified when the fiber is subject to external perturbations and that the OTDR realizes an averaging operation on the backscattered signal. These two features together lead to a flattening of the backscattered signal, starting from the intrusion position. The subsequent use of a signal-processing technique allows to detect the intrusion location.

This paper is divided as follows: in the first part the set-up as well as the sensor principle are explained. In the second section experimental results are given. The last section is dedicated to perspectives.

Sensor principle

The proposed intrusion sensor is depicted in Fig. 1 and is composed of a POTDR source (combination of a commercially available OTDR with a polarizer, which also serves as an analyzer to the backscattered signal) and the fiber under test

(FUT), which could be glued on a fence. z is the light propagation axis and an incoming intrusion happens at z_{int}.

Pulses are injected by the OTDR into the FUT with a determined (due to the presence of a polarizer) SOP and are continuously Rayleigh backscattered in the fiber. As the SOP randomly varies along the fiber (due to the intrinsic birefringence properties of the FUT), the backscattered power at the output of the polarizer (analyzer) varies and the POTDR trace presents fluctuations, as can be observed in Fig. 2.

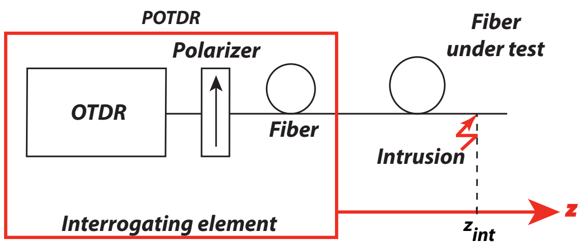

Figure 1. Intrusion set-up

An intrusion at a certain position z_{int} along the fiber can be detected as follows: for $z<z_{int}$ the SOP does not practically vary with time when considering the time scale of the OTDR acquisition. The POTDR trace has thus practically the same evolution. The OTDR averaging does not therefore induce important changes to the POTDR trace. However, at z_{int} the intrusion provokes a displacement of the optical fiber, modifying the local birefringence properties and in turn changing the SOP, starting from this position. As the intrusion is time varying, the SOP modification at z_{int} varies as a function of time. When the OTDR averaging is applied, the final signal is flattened due to this temporal variation. This phenomenon can be observed in Fig. 2. This Figure shows that the two POTDR traces are similar up to the intrusion position, at approximately 200 m, but are different between 200 m and 350 m (which corresponds to the fiber end).

Experimental results

The optical fiber used during the experiments is a 380 m single-mode fiber with an intrusion at 197 m. During the experiments, the FUT is moved back and forth so as to simulate the intrusion.

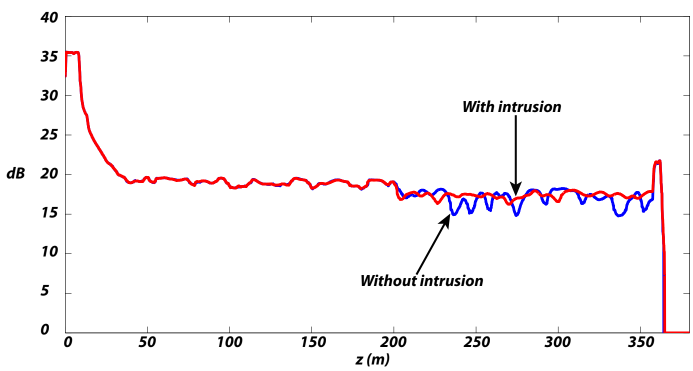

Figure 2. POTDR traces evolutions with intrusion and without intrusion

Fig. 2 shows that the intrusion position is detected via the flattening of the POTDR trace. In order to be more robust against localization errors (due to noise, for instance), an additional signal processing is applied, consisting of three steps:

- Firstly, these two successive POTDR traces are subtracted, giving an *error* trace, which is depicted in Fig. 3(a). Before the intrusion position, this signal is weak as the two POTDR traces do not significantly change, as shown in Fig. 2. Starting from the intrusion position the error trace has a sharp shape, because of the modification of the POTDR trace;

- Secondly, the variance of this error trace is calculated within a sliding 5m window. As the error trace has a higher variance after the intrusion position, the sliding variance also increases. The evolution of this sliding variance is given in Fig. 3(b);

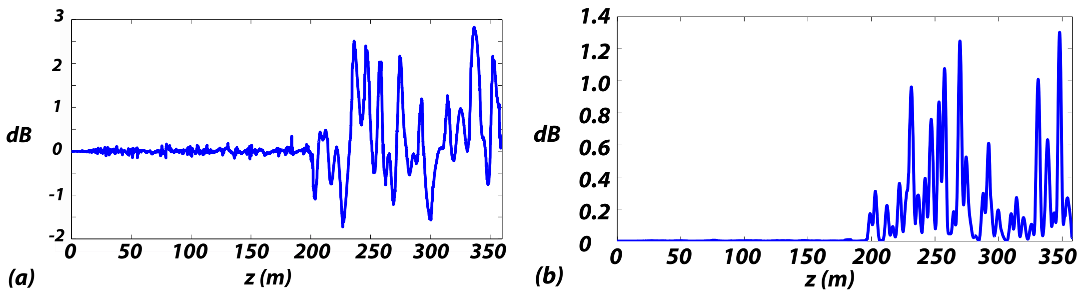

Figure 3. (a) Error trace – Selection of two POTDR traces; (b): Sliding variance of the error trace

- Thirdly, the intrusion location is detected as soon as the sliding variance is higher than a certain threshold (the threshold value is calculated from the sliding variance of the first hundred meters of fiber – which are not subject to any intrusion – multiplied by a security factor – 3, in our experiments). Fig. 4 shows the detected intrusion location.

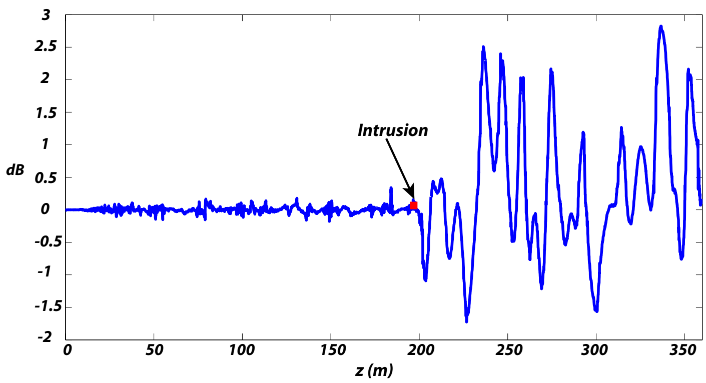

Figure 4. Determined intrusion location

Using this signal processing technique, 50 ns pulses and 5 s averaging, Table 1 gives the determined intrusion position for five different tests (repeatability), for a 1.5 cm intrusion-induced displacement.

Test number	*Detected position*
1	195.3 m
2	194.1 m
3	196.0 m
4	195.5 m
5	197.0 m

Table 1: Intrusion detections (5 tests) for a 5s averaging (50 ns pulses and 1.5 cm displacement)

From these tests, the mean determined position is 195.6 m while the standard deviation is 1.1 m while the intrusion was induced at 197 m. This result is logical as the OTDR precision is related to the pulse width, here 50 ns (5m).

Conclusion

In this paper a new POTDR intrusion sensor system has been proposed. Based on the modification of the polarization state of light due to an intrusion and on the temporal averaging processed by the OTDR the intrusion can be detected in the form of a sudden flattening in the POTDR trace. A subsequent signal processing is then applied in order to be more robust against noise. Intrusions-induced displacements as small as 1.5 cm can be detected after 5 seconds with a 1.1 m standard deviation. One of the strong points of this sensor is its low-cost as it is based on a commercial OTDR followed by a linear polarizer.
Further work includes the transition to real time detection, which still needs additional signal processing. Other aspects as non-intrusive events (wind) have still to be analyzed. An on-the-ground test could also be possible.

Acknowledgment

The authors would like to thank the financial support of the *F.R.S.-FNRS (F.R.I.A)*, the IAP program *6/10 photonics@be*. This project is within the frame of *Actions de Recherche Concertées financées par le Ministère de la Communauté française – Direction générale de l'Enseignement non obligatoire et de la Recherche scientifique*.

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