Long-Range (>100km) Distributed Vibration Sensor based on Φ-OTDR Technique with Spread Amplification and Detection of Probe Pulses

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Abstract: This paper presents a set of results to demonstrate a long-range (>100km) distributed vibration sensor (DAS) based on the Coherent Optical Time Domain Reflectometry (Φ-OTDR) technique using distributed amplification of the probe pulses and detection of the backscattered traces, which demonstrates great capability to achieve long-range distances with great sensitivity. In this case, optical amplifiers have been placed along the sensing optical fiber, each one followed by a detection stage. Results for some traces detected in each of the spans along the sensing fiber, and some measurements of stimuli produced by a vibration at the end of each of the sections of the sensing fiber, are showed here. This work, framed in the project SACOH (Long-range Distributed Vibration Sensing by Coherent Rayleigh Backscattering), has been carried out in collaboration between the University of Zaragoza and the company APL (Aragón Photonics Labs).

1 INTRODUCTION

Distributed vibration sensing technologies have greatly expanded their use in the recent years due to the wide range of applications that they offer (Bao and Chen, 2012). Among these applications (monitoring of the integrity of civil engineering structures and power plants, detection of leaks, control of railways, traffic control...), it stands out perimeter surveillance of infrastructures with a large perimeter to be monitored. Surveillance strategies based on conventional technologies (video surveillance or conventional motion sensors…) are no longer viable after a few kilometers due to the large increase in their cost, because of the enormous growth in complexity and in management problems of monitoring such infrastructures when the length to be monitored is increased. Therefore, the development of new long-range detection strategies such as those based on distributed optical sensing technologies, in particular distributed vibration sensing techniques, has great interest.

Distributed optical sensing technologies use different measurement strategies, and their operation is based on the use of a wide variety of physical phenomenologies, mainly Rayleigh, Brillouin and Raman optical dispersion. Systems based on Raman and Brillouin scattering are mostly employed in the monitoring of the integrity of large structures (Barrias et al., 2016) through temperature and mechanical stress measurements, while systems based on Rayleigh scattering are mostly used in dynamic scenarios typical of perimeter surveillance (Rao et al., 2008).

Measurement systems based on coherent optical reflectometry base their operation on Rayleigh backscattering to detect disturbances due to stimuli (vibrations or pressure changes) produced on the fiber environment, by sensing local phase changes (Muanenda, 2018). A pulsed laser with a highly stable emission frequency and high coherence is used to

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inject pulses that will produce Rayleigh backscattering as they propagate along the optical fiber. Interference patterns are detected, due to the coherent sum of the backscattered wave fronts throughout the pulse time, which is dependent on the relative phase between the different backscattered waves within the pulse itself. Variations in the phase relationships between the elements that remain inside the pulse at a point of the fiber, caused by some disturbance at that point, have a direct effect on the detected interference pattern and, therefore, on the instantaneous optical power corresponding to that position. This allows the localized detection of the stimulus with a high sensitivity and resolution, allowing a dynamic localized detection of the presence of intruders even with a buried fiber optic cable (Lu et al., 2010), being possible to use dark buried fibers (greatly reducing the costs of the system implementation), and in addition, isolating the cable from external noise and protecting the cable from environmental deterioration or manipulation by intruders.

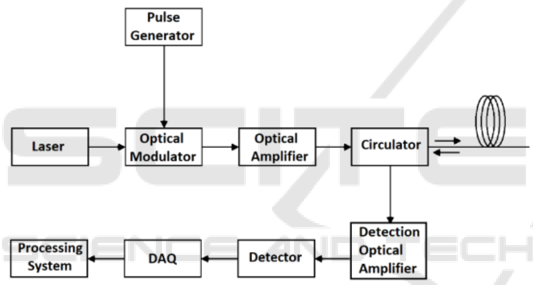

Figure 1: Direct-detecting Φ-OTDR measurement system.

According to literature, modulation instability (MI) is one of the main phenomenons that limit the maximum pump power that can be injected into the sensing fiber (Martins et al., 2013), reducing, therefore, the maximum distance at which the systems based on the Φ-OTDR technique can locate a stimulus in a distributed manner. High intensity optical pulses are a way to achieve better measurement conditions with a Φ-OTDR sensor: improved resolution, more dynamic range and a high quotient between signal and noise (SNR-Signal-to-Noise-Ratio). MI is a non-linear phenomenon resulting from an anomalous dispersion and the Kerr effect that depends on the peak power of the injected pulses and the optical noise generated when the pulsed probe is amplified. The effect of MI appears when injected optical intensity goes beyond certain threshold, producing a fading at some regions of the measured interferences and decreasing its visibility hence, which implies a decrease in the sensitivity of the detector system at corresponding positions in the sensed optical fiber.

Fading effects, including the one induced by MI, are one of the most limiting factors of the sensing capability of systems based on coherent reflectometry (Healey, 1984a; Healey, 1984b). Reduction of such phenomenon would make it possible to greatly increase the sensitivity and range of distributed sensing systems based on Φ-OTDR technique, so study and development of new strategies to reduce the effects of MI is desirable. Since MI sets an upper constraint on the optical intensity at the input of the sensing fiber, amplifying the injected pulses in a distributed way along the fiber, should be a reliable strategy. In this work results are presented of straightforward technique by introducing amplifiers every certain distance.

2 EXPERIMENTAL SETUP

The general objective of this work is the validation of a prototype measurement equipment for long-range distributed vibration sensing based on direct-detecting Φ-OTDR with a measuring range higher than 100km, which will represent a clear advance on the current state of technology (Liu et al., 2016; Liu et al., 2018).

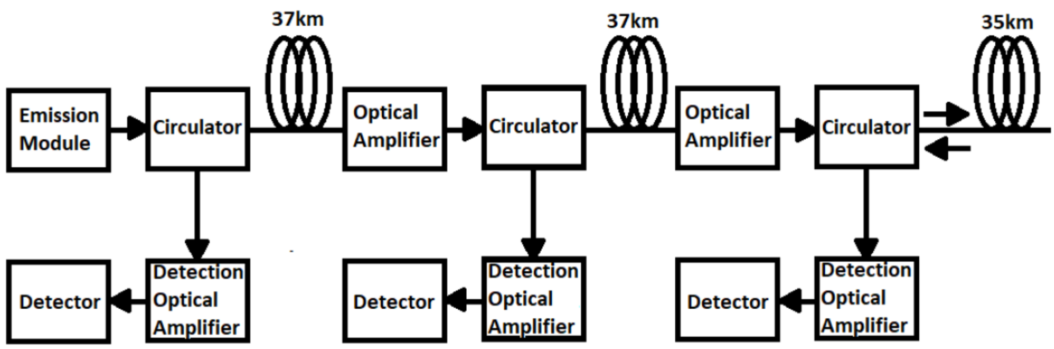

Figure 2: Experimental setup. Direct-detecting Φ-OTDR system with the addition of the distributed sensing system.

The system to be validated is based on the use of the conventional direct-detecting Φ-OTDR system shown in Figure 1, with the addition of a new architecture for the measuring set-up that allows to maintain optical probe intensity below MI threshold along the sensing fiber. The signal detection infrastructure is distributed along the sensing optical fiber to improve the range of the system without impairing the performance and detection capabilities of the system. To increase the range of the system, three optical amplifiers (the first one of them inside of the emission module) separated one from each other along three spans (two optical fiber coils with a length of 37km, and the third one with a length of 35km) are used, with each one of the optical amplifiers followed by a detection optical amplifier and a detector, so that the detection system is also distributed along the sensing line.

Figure 3: 50m coil above the mechanical vibrator used to generate the stimulus.

The basic scheme of the proposed new architecture is shown in Figure 2.

This architecture allows to improve the range of the system due to the optical amplifiers distributed along the sensing fiber and without losing the quality of the sensed signal thanks to the distributed detection. As no section of the sensing system exceeds 37km, the dynamic range of each detector does not limit the maximum detection distance. In addition, the pulse repetition period (PRP) is not limited by the maximum distance of the sensing line, allowing to have a high PRP rate, as the length of fiber that the injected pulse has to propagate through in each span is shorter, and therefore, the number of captured traces is higher for a shorter acquisition time, which can be translated as an improvement in the sensitivity of the system. The proposed setup uses a single laser source as emitter and a single optical modulation element, which simplifies the system and reduces its cost.

3 RESULTS

Below, there is a series of captures with some of the obtained results with the aim of validating the Φ-OTDR-based architecture proposed in this work.

Measurements have been made with a conventional direct-detecting Φ-OTDR system without the new architecture (Figure 1): traces along the length of the three coils in a single phase, and a measurement of the MI-induced fading by increasing the pump power of the first optical amplifier (Figures 4 and 6).

Afterward, two more measurements were carried out to validate the Φ-OTDR system with the new architecture (Figure 2): traces detected in each span (Figure 5) and sensitivity measurements (Figure 7) at the end of each span (a mechanical vibration at a specific point of sensing fiber, with well-controlled displacement amplitude and frequency, around the µm and 100Hz respectively, was used as a stimulus (Figure 3)).

Figure 4 shows the interferences in a trace corresponding to pulses with a pulse-width of 800ns obtained by a conventional direct-detecting Φ-OTDR system. As can be seen in the figure, interferences in the trace are lost along the first coil until completely disappear at 37km.

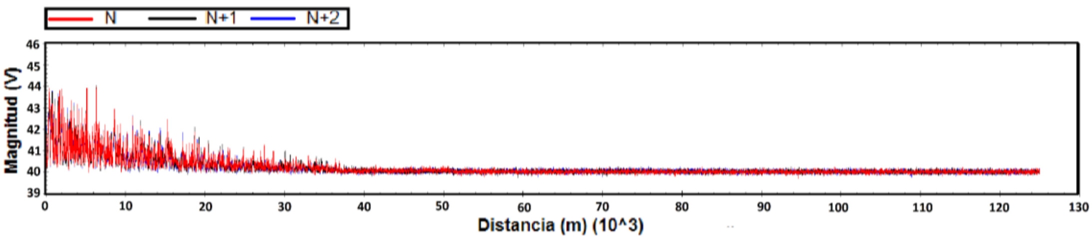

Figure 4: Detected interferences in a trace along the length (109km) of the three coils in a single phase.

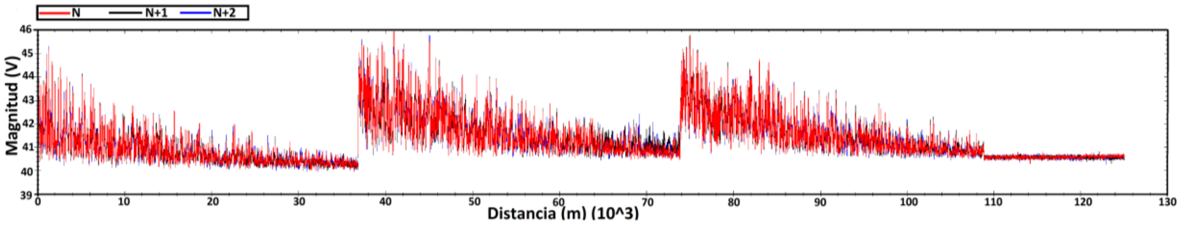

Figure 5: Interferences recovered in each span by means of the distributed amplification and distributed detection system.

To prevent interferences from being lost along the first 37km, the pump power was increased to increase the power of the pulses which are injected into the sensing fiber. Figure 6 shows how the phenomenon of the MI-induced fading appears in the trace when the input power in the fiber is increased, preventing it from rising enough to obtain interference along the 109km of sensing fiber.

Due to the appearance of the MI-induced fading, the detection range of the system is limited because MI represents a limit to the increase in the pump power of the optical amplifier until, as can be seen in the figure below, the system ends up acting like a conventional OTDR.

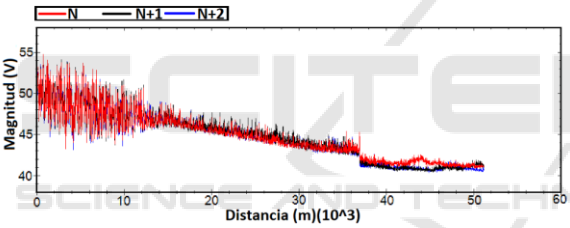

Figure 6: MI-induced fading in a trace.

Figure 5 shows how the interferences in the traces in each of the three spans are recovered by means of the distributed amplification and distributed detection system.

When the pulses (in this case with a width of 800ns) are amplified in a distributed manner along the sensing fiber and when the backscattered light is detected in a distributed manner, it is possible to reduce the pump power to avoid the negative effects of the MI and it is possible to recover the traces in each span of the distributed sensing system, as the length of the fiber that each injected pulse has to propagate through is not greater than 37km because no section of the sensing system exceeds that length.

Because the sensing system with distributed amplification and distributed detection allows to recover the traces in each span, the quality of the detected signal is recovered along the entire sensing fiber, and it is possible to extend the detection distance and detect a disturbance due to a stimulus at greater distance.

As can be seen in Figure 7, it is possible to clearly see the disturbance caused by a stimulus (in this case a mechanical vibration) at 37km, 74km and 109km (at the end of each span of the sensing line).

4 CONCLUSIONS

An analysis of the possibilities of using a distributed detection architecture to overcome the limit in the measurement range imposed by the modulation instability in conventional Φ-OTDR systems has been carried out.

Comparative results are presented between a conventional architecture and a three-stage distributed sensor scheme that includes probe pulses amplifiers at the beginning of each span and corresponding detection modules.

The capability of the distributed detection architecture to measure disturbances at distances which are higher than 100km with good sensitivity and resolution is demonstrated, with the advantage of being simpler than other architectures with distributed Raman (Wang et al., 2014a) or Brillouin amplification (Wang et al., 2014b), with offering excellent expectations for future applications in the field of long-range distributed sensing.

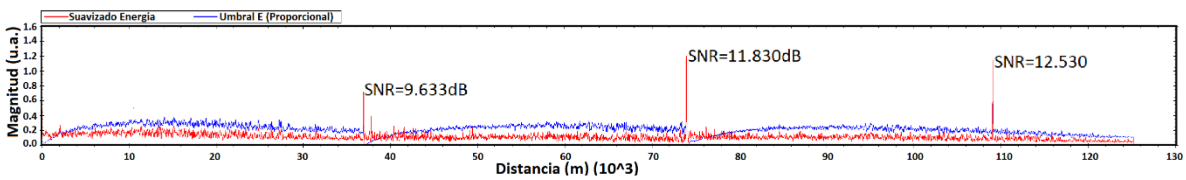

Figure 7: Mechanical vibration (100Hz, 3Vpp) at 37km, 74km and 109km.

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