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Transforming the Fiber-Optic Network into a Dense and Ultrasensitive Seismic Sensor Array

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ABSTRACT

We show a technology capable of performing position-resolved measurement of nanostrain perturbations along a conventional optical fiber cable, with meter-scale resolution. This technology can be deployed in already existing networks to achieve a dense and ultrasensitive seismic sensor array. Applications ranging from seismic protection to chemical sensing are explored.

Keywords: Rayleigh scattering, optical time domain reflectometry, distributed fiber optics sensors, distributed acoustic sensors, seismology.

1. INTRODUCTION

Even within the photonics research community, it is a quite common believing that the only purpose of optical fibers is serving as a telecommunication channel carrying thousands of gigabytes of information over the world every second and at the speed of light. Being the main industry pushing the development of optical fiber technology, telecom is not the only application of guided light. These thin glass threads laying buried into the ground and crossing the oceans are inherently sensitive to the state of the medium surrounding them: the optical properties of fused silica depend on the fiber temperature and elongation. Providing access to the values of those physical quantities along the fiber is the aim of a vast research discipline known as distributed optical fiber sensing (DOFS), whose applications are frequently not related to telecommunications. In the last years, important achievements have been made which improve the performance and reduce costs of certain DOFS technologies. These approaches have already demonstrated great sensitivity and dynamic capabilities, especially when regarding to distributed acoustic sensing (DAS) as well as distributed temperature sensing (DTS). They have found great acceptance as solution to a wide spectrum of engineering challenges, running the gamut from oil and gas extraction and transportation, to avionics, structural health monitoring or perimeter surveillance [1-3].

In this communication, we highlight the recent interest from the seismology and geophysical sciences community on distributed optical fiber sensors. The sensors they need may be already deployed as optical fiber is present almost everywhere. Among the optical fibers holding the internet, there is a considerable amount of *dark fibers*, which lay side by side in the same trenches waiting for a greater bandwidth demand or other potential use. Providing access to these fibers for sensing purposes is something fiber owners must consider, especially if talking about preventing the effects of common natural disasters, such as earthquakes or tsunamis. Some of the areas with the highest seismic activity, such as the St. Andreas Fault or the Japanese archipelago, are highly populated. This implies an important risk for population, on one hand, but also the availability of a dense fiber optics grid. Consequently, they represent the best places to test the reliability of this new application for DOFS. The collaboration between DOFS and seismology researchers could provide a new generation of earthquake early warning systems for these areas, able to instantly warn the population even when the earthquake has been originated thousands of kilometers away. Research groups currently working in the west coast of the United States can recover seismic data almost immediately thanks to arrays of wireless seismometers scattered over a few hundreds of kilometers [4]. There, the DOFS approach would certainly represent a huge leap forward in the cost-effectiveness of such a monitoring system: the equivalent to thousands of sensors allowing for calibration, maintenance and interrogation at once, performed from a single room. This will avoid every issue related to signal multiplexing or keeping their individual power supplies over the extension of the sensor array, as DOFS *employ* the sensing fiber itself to transport the vibration information to the interrogator. The idea of having a single interrogator connected to a continuous sensing fiber would be equivalent to having multiple seismometers working much the same way a row of conventional *Benioff strainmeters* would do. To qualify as a good seismometer, the fiber sensor setup may be able to track signals in the frequency range from 0.01 to 10 Hz, or even lower to study other slower geophysical events. This is something certain fiber sensors can do, although tracking slow variations over months at the same time than registering several tens of Hz may represent a challenge. In this text, we propose a method we trust could succeed in this task, given its proved performance. We introduce the principles, last results and last explored applications of *chirped-pulse* phase-sensitive optical time domain reflectometry (CP-ΦOTDR), a recent DAS technology based on Rayleigh scattering.

Interest on DAS has emerged also in other related disciplines without a direct economic or civil interest, such as planetary sciences, where monitoring quakes or other slower, big-scale deformations of the structure of a planet (e.g. planetary tides) or a moon can shed light on their structure, geological composition and origin. These measurements could be performed provided a km-long optical fiber and an interrogating unit is deployed on their surface. This certainly represents a challenge, but it is not comparable to the idea of transporting and installing there hundreds of standard seismic stations.

2. WORKING PRINCIPLES

Since the emergence of optical fiber sensing technology, multiple tools have been demanded to test and monitor optical fiber links. One of the most important, named optical time-domain reflectometer (OTDR), has allowed to retrieve an instantaneous map of the most relevant link features, such as the location and quality of its connections, splices or other sources of undesired reflections and optical loss. This tool is based on optical reflectometry, i.e., the analysis of the light reflected inside the fiber core, being similar to a one-dimensional radar system working in the optical domain. Thanks to the Rayleigh scattering phenomenon (especially efficient along the forward and backward propagation directions), a power pulse guided by the fiber produces an optical *echo* at every refractive index imperfection of the fiber core smaller than the employed wavelength, which returns to the interrogating unit, registering a power trace along the time axis that characterizes the physical state of the fiber. These small imperfections, which are inherent to the conventional fiber drawing process, provide the core hundreds of *scattering points* per millimeter, constituting the starting point to understand the working principles of every DOFS based on Rayleigh scattering. The optical path between these points is affected by temperature or longitudinal strain changes, and the time of flight of the echoes they produce reveals where changes are occurring. If the coherence length of the light source employed is large enough, the fiber with its scattering points can be thought of as a series of highly sensitive, few-meter long interferometers, whose interferometric state is accessible in a single interrogator shot. These systems, named *phase-sensitive* (Φ)OTDR, lead to high sensitivity measurements over kilometers of fiber with spatial resolutions in the meter range.

2.1 A new ΦOTDR paradigm: *chirped* probe pulses

In a distributed temperature/strain sensor based on conventional ΦOTDR, the sensed perturbation information is extracted from the local amplitude changes of the consecutively acquired power traces. However, this results in a non-linear mapping of the perturbation amplitude. When the instantaneous frequency of the probing pulse varies at a constant rate (*linearly-chirped* pulse), the perturbation information is recovered through a linear transfer function. With this method, named chirped-pulse (CP-)ΦOTDR, the consecutive power traces suffer a local delay which is proportional to the variation of temperature or strain applied in the corresponding section of the fiber under test (FUT), and easily reaches sensitivities of a few mK/nε. This suggests a monitoring procedure that consists in detecting and digitizing the optical echoes, and computing the correlation of consecutive traces every few meters. The result of these correlations is the local time shift of the traces $\delta t(z)$, and the calculations can be easily performed for every shot in real-time, at thousands of measuring points simultaneously, thanks to the state of the art in computing based on GPU architectures. The conversion of $\delta t(z)$ to the more useful applied temperature $\delta T(z)$ or strain $\varepsilon(z)$ variations is derived from the CP-ΦOTDR theory and the thermo-optical/opto-mechanical coefficient [5,6]. This renders the CP-ΦOTDR an ultrasensitive and highly dynamic DTS/DAS.

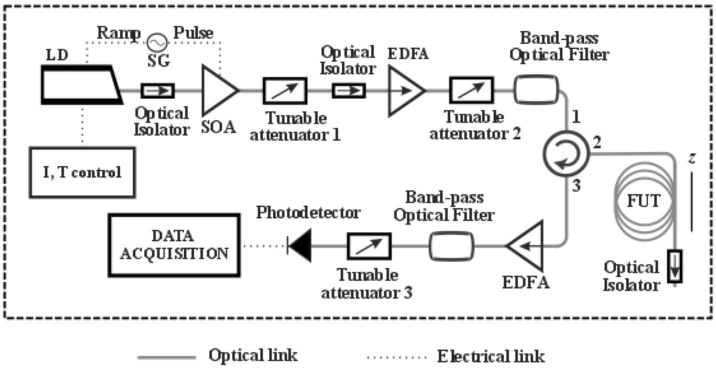

Figure 1. Optical setup of a CP-ΦOTDR sensor. Acronyms are explained in the text.

The basic optical setup of the CP-ΦOTDR interrogator is depicted in figure 1, and is comparable to that of a conventional ΦOTDR. The only modifications required are the means to induce the pulse chirp in the launched pulses, and a detection bandwidth matching the chirp span. An easy way to induce chirp in the range of 10 MHz/ns is applying a sawtooth modulation in the bias current of the continuous wave laser source (LD). At the LD output, a semiconductor optical amplifier (SOA) synchronized with the modulation is used to pulsate the signal, due to its good extinction ratio (~50 dB). The pulses are then passed through an erbium-doped fiber amplifier (EDFA) and a band-pass filter to eliminate the amplified spontaneous emission (ASE) originated at the EDFA. The power backscattered by the FUT is similarly amplified and filtered before reaching a fast p-i-n photodetector. Appropriate electronics and a computer is employed to digitize and process the power traces.

In the following subsections, we present some of the last improvements and applications of the system.

2.2 Long range capabilities and laser phase noise removal

The possibility of applying DOFS techniques to the km range, where the limit is stablished by optical loss and attenuation of the light sent and reflected, is guaranteed by the compatibility of the method with a technology such as distributed Raman amplification. The CP-ΦOTDR system has demonstrated the viability of combining it with bidirectional first-order Raman amplification, showing the immunity of the sensor to long range effects such as dispersion, and reaching measurement lengths of 75 km with spatial resolution of 10 m [7]. The CP-ΦOTDR traces and noise levels obtained with and without Raman amplification are shown in figure 2 (top).

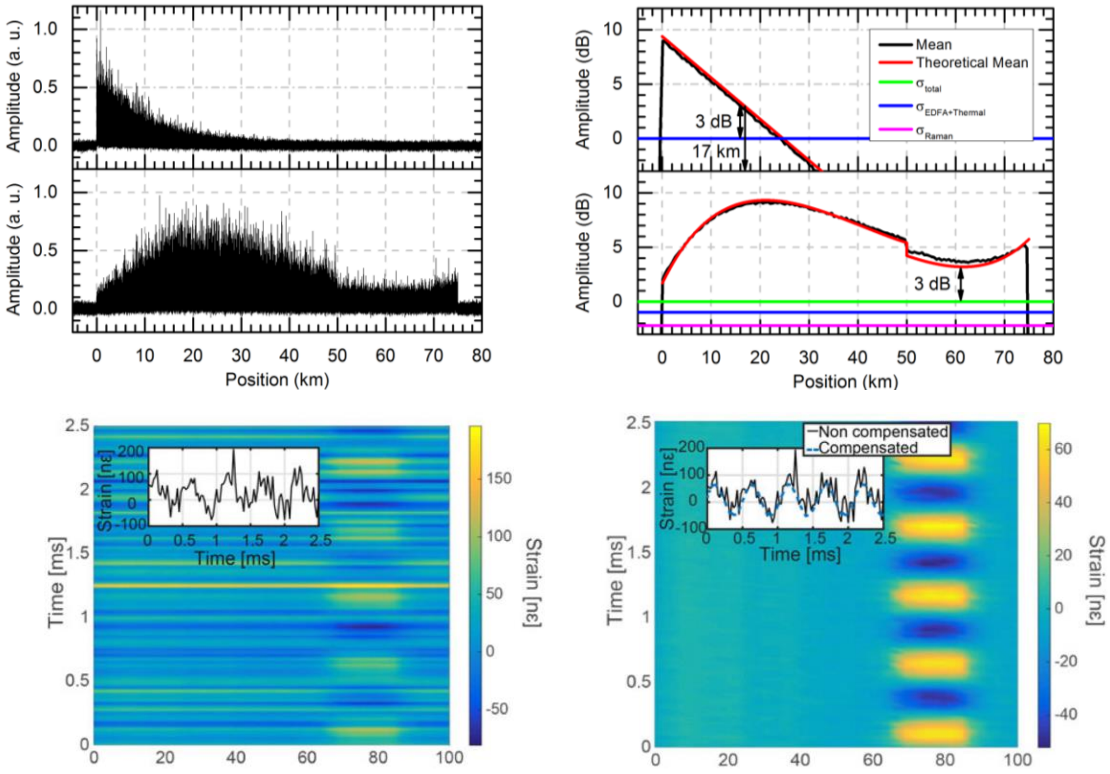

Figure 2. (Top) Distributed first-order Raman amplification applied to CP-ΦOTDR. The range is extended from 17 to 75 km; (Bottom) Denoising strategy proposed to compensate the CP-ΦOTDR laser source phase noise. The original and corrected signals are shown, for a periodic local perturbation.

An important difficulty of the CP-ΦOTDR sensor, given its high sensitivity, is related to the phase noise of its laser source. This noise translates in a global displacement of the trace representing the whole fiber, in opposition to localized temperature/strain events, and must be subtracted from the acquired signal to obtain the true measurements. For this reason, it has been proposed a simple method which takes advantage of keeping a *reference fiber* segment under controlled conditions to measure the laser fluctuations. By averaging the global signal from this fiber, the laser pattern is acquired and can be subtracted from the FUT results [8]. In fig. 2 (bottom), a perturbated area of the FUT is shown, before and after the denoising procedure has been applied. An important noise reduction has been demonstrated, achieving a signal to noise ratio improvement ranging from 14 to 17 dB, depending on the laser source linewidth.

2.3 Application to other measurands: chemicals and flow speed

The outstanding performance of the CP-ΦOTDR sensor has allowed devising other derived sensors, which indirectly measure physical quantities from the fast and high-resolution temperature measurements. One of the proofs of concept developed is related to chemical sensing. By monitoring the temperature along a holey optical fiber containing a sample gas, the identification and quantification of the chemical is possible [9]. The idea is based on injecting light from a tunable pumping source at the same time. By sweeping with it the typical range where gas absorption lines lay, the CP-ΦOTDR can selectively detect the small heating caused by photothermal absorption of the pump source by the gas, without the requirement of *analyte-tailored* coatings or transducers.

Another scheme recently demonstrated is devoted to the measurement of wind or fluid speed [10]. To do this, the temperature of a metal-coated fiber is tracked. The coating is used to intentionally heat up the fiber by Joule effect. The power delivered to the coating is dissipated by convection, which highly depends on the speed of the air flowing around the fiber, and thus it will affect the fiber temperature. By calibrating this dependence, it is possible to provide high resolution wind speed results, and reduce the power required to heat up the fiber, which would set a huge range limitation for other technologies lacking the high temperature sensitivity of the CP-ΦOTDR sensor. We show in fig. 3 the experimental setup and a demonstrative fiber temperature curve under intermittent electrical heating and subject to different wind speeds, as registered by a CP-ΦOTDR setup. The amplitude and time constant of the temperature modulation allows to calibrate the wind speed sensor.

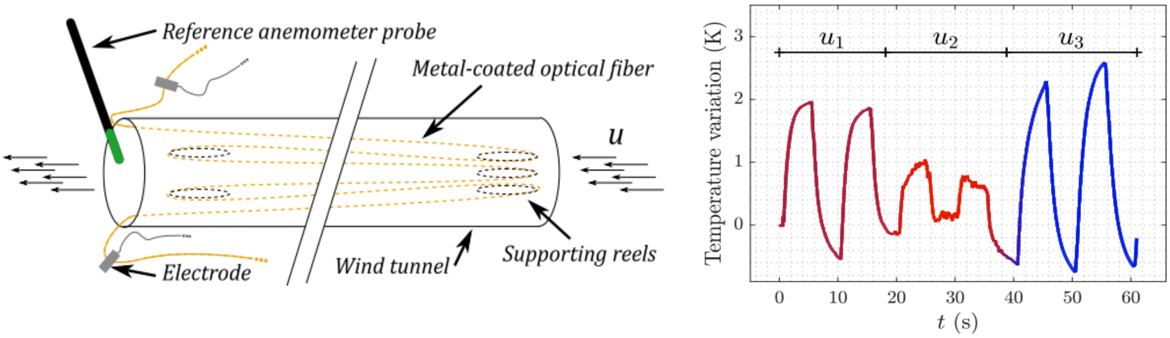

Figure 3. Setup and response of an experimental wind speed sensor based on CP-ΦOTDR operating under different wind speeds ($u_3<u_1<u_2$).

3. CONCLUSIONS

In this communication, we have presented the principles of operation, achievements and some applications of a qualitatively new approach in the field of distributed optical fiber sensing: the CP-ΦOTDR. Considering the expectations and prospect for this tool coming from geophysical sciences and seismology, and based on its proved performance and results, we expect this new application will bring important results and new opportunities for the study and monitoring of earthquakes, taking a central role in the earthquake early warning systems of the future to come.

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