Gonzalez-Herraez, M., Pastor-Graells, J., García-Ruiz, A., Fernández-Ruiz, M.R.R., Martins, H.F., Martin-Lopez, S., 2017, "Chirped-pulse phase-sensitive reflectometry: hearing behind the walls with high fidelity", Proc. SPIE 10323, 25th International Conference on Optical Fiber Sensors, 1032302 (April 23, 2017).

Available at http://dx.doi.org/10.1117/12.2272461

Chirped-pulse phase-sensitive reflectometry – hearing behind the walls with high fidelity

M. Gonzalez-Herraez*[a], J. Pastor-Graells[a], A. García-Ruiz[a], M. R. Fernández-Ruiz[a], H. F. Martins[b], S. Martin-Lopez[a],
[a] Dept. de Electrónica, Universidad de Alcalá, C. Universitario, 28871, Alcalá de Henares, Spain;
[b]FOCUS SL, C/ Orellana 1, 28004, Madrid, Spain

ABSTRACT

We review our recent work on chirped-pulse phase-sensitive optical time-domain reflectometry along optical fibers and its application in the measurement of true nanostrain variations in the kHz frequency range over km-long fibers. We also show how this technique can be used to perform distributed photothermal measurements of gas presence in suitable microstructured fibers.

Keywords: Distributed fiber-optic sensor, phase-sensitive reflectometry, distributed acoustic sensor, temperature sensor, strain sensor.

1. INTRODUCTION

Distributed optical fiber sensing using phase sensitive optical time domain reflectometry (ϕOTDR) [1] is gaining increasing attention due to its potential application in pipeline surveillance and perimeter protection [2]. In ϕOTDR a pulse of highly coherent light is injected into a conventional single-mode fiber and the Rayleigh backscattered light is monitored in the time domain, which is then associated with fiber position using the time of flight of the light pulses in the fiber. As coherent pulses are used, the ΦOTDR signal will be the result of the coherent interference between the fields which are Rayleigh backscattered from multiple scattering centers along the fiber [1]. Typically, the resulting detected intensity will present a random noise-like shaped pattern. This pattern will remain constant and reproducible if the fiber and measuring conditions do not change over time. Perturbations in the fiber (typically linked to temperature or strain variations) can be detected by monitoring local changes in the ΦOTDR trace [3]. The signal-to-noise ratio (SNR) of the detected trace can be engineered to be fairly large, hence allowing for single-shot measurements. Traditional phase-sensitive ΦOTDR (single frequency, without phase recovery) can then allow for distributed vibration measurements with a high bandwidth, only limited by the fiber length. The acoustic bandwidth detectable in each case is 10's of kHz for a few kilometers [3], up to 100's of Hz for more than 100 km [4,5]. These measurements however, are based on intensity variations of the ΦOTDR signal, which do not show a linear variation with the applied perturbation.

While the intensity variations of the ΦOTDR signal cannot be predicted for a given perturbation, the changes in optical path difference between the scattering centers induced by a uniform refractive index change Δn can be compensated by a shift of the pulse frequency $\Delta\upsilon$, which allows the recovery of the original ΦOTDR pattern. Assuming small refractive index changes ($\Delta n << n$), the necessary $\Delta\upsilon$ to compensate for a given Δn can be derived from [6]:

$$\frac{\Delta n}{n} = \frac{\Delta \upsilon}{\upsilon_0} \tag{1}$$

Where υ_0 is the central frequency of the pulse and n the effective refractive index of the fiber. Based on this principle ΦOTDR systems have been demonstrated to allow for very sensitive, quantitative measurements of temperature/strain [6] and birefringence [7] with high measurand resolutions. With these techniques, the demonstrated temperature resolutions (typ. <10 mK) [6] are two orders of magnitude below the typical resolutions of ≈1 ºC provided by Brillouin or Raman sensors. However, in this case, a frequency sweep of the pulse is required, which greatly increases the measurement time, typically up to a few seconds or a few minutes. The system turns out then to present similar tradeoffs to traditional Brillouin temperature sensors, having a temperature resolution and range which is dependent on the used frequency scan step and range. High measurand resolutions over long ranges can therefore be highly time consuming. The maximum achievable resolution is also limited by the pulse spectral content [7], in a somewhat similar manner to the temperature resolution limitation imposed by the spectral width of the Brillouin gain curve in Brillouin sensors.

A single-shot alternative for performing true temperature/strain measurements in ΦOTDR is achieved by performing phase recovery of the backscattered signal [8]. This phase depends linearly and predictably on the temperature/strain applied to the

fiber. However, recovering the phase of the backscattered field is fairly complex and strongly polarization dependent. Fading positions are expected to yield points of no sensitivity. Moreover, in this case, the system is more complex and laser coherences of at least the fiber size are required in order to avoid noise when beating the signal with the local oscillator. The long term-stability of such systems (i.e. after several minutes or hours) has not been clearly addressed either.

Here we review our recent work on chirped-pulse ΦOTDR systems [9]. These systems use linearly chirped pulses in a ΦOTDR to achieve a frequency-to-time mapping of the fiber response over long lengths and in a single-shot. The technique uses only intensity detection, and no frequency scan or local oscillator is needed. The system does not present fading positions unlike the phase-measuring ΦOTDR. With the proposed method, it is possible to combine the best features of ΦOTDR which had been previously demonstrated by separate: fast measurements with a bandwidth only limited by the fiber size, and measurement of temperature/strain variations with resolutions which can be several orders of magnitude below those provided by e.g. Brillouin. Since the measurement is relative, the total range of temperature/strain variation is in principle not limited, being in practice determined only by how the cumulative errors are handled. The technique allows measurements at kHz rates, while maintaining reliability over several hours. The sensitivity can also be tuned by acting on the chirp of the pulses. Temperature/strain resolutions of mK/(4nε) have been readily demonstrated.

2. WORKING PRINCIPLE

Chirped-pulse phase-sensitive reflectometry originates from the principle described in (1) that a refractive index change Δn in the fiber can be compensated (in terms of the shape of the trace) by a frequency shift Δυ of the pulse sent into the fiber. This is the same principle as used in [6], and is typically implemented by performing a laser frequency sweep. In the chirped-pulse case, however, instead of requiring a time-consuming frequency sweep to determine Δυ and calculate Δn, a single pulse which has linear chirp is used. Since different positions of the pulse have different frequencies, when a Δn is applied, the same trace pattern at a given position can be generated by a temporally-shifted region of the pulse, leading essentially to a longitudinal shift Δt of the local ΦOTDR trace. It is then possible to calculate Δυ (and consequently Δn and the temperature or strain shift) from Δt, which is obtained directly from the time-domain trace measurements. Thus, in our method, a single trace measurement should be sufficient to determine temperature/strain changes [9].

In summary, while traditional ΦOTDR systems measure intensity variations of the points along the trace over time, chirped-pulse ΦOTDR sensors analyze the local ΦOTDR trace shifts that occur along the fiber. To obtain these, the fiber is measured at consecutive times by sending the same linearly chirped pulses into the fiber. The resulting traces are divided into spatial windows of analysis. The same spatial windows in the two traces are cross-correlated to obtain the local delay at each position. The refractive index changes occurring in the fiber between consecutive traces can then be calculated using:

$$\left(\frac{\Delta n}{n}\right) = -\left(\frac{1}{\upsilon_0}\right)\cdot\left(\frac{\delta\upsilon}{\tau_p}\right)\cdot\Delta t \qquad (2)$$

Where ν_0 is the central frequency of the pulse, τ_p is the pulse width and $\delta\nu$ is the spectral content of the chirped pulse. Note that depending on how the chirp slope is defined (positive/negative along the time axis), a +or – sign will be required in eq.2. A detailed explanation of this working principle, including a full theoretical model derived from the pulse propagation equations can be found in ref. [9].

3. MEASUREMENT OF TRUE NANOSTRAIN VARIATIONS AT KHZ RATES

In an experiment to characterize the dynamic strain sensing capability of the sensor, the last 20 m of a 1 km long fiber section were strapped around a PZT, which applied deformations controlled by an electrical input. The ΦOTDR traces were acquired with a frequency of 4 kHz. The dynamic strain measurements are presented in Fig. 1. Fig. 1(a) presents the measured strain when a 1 Hz sinusoidal strain is applied to the fiber by the PZT, with a maximum amplitude of 100 nε. As it is clearly observed, a good agreement between the experimental measure and the applied strain is observed. Furthermore, the quantization error (set by the system minimum temporal resolution, i.e., the sampling period) is clearly observed, thus demonstrating the resolution limit of the system (in this case in the order of 4 nε). It should be mentioned that in this case, the total measured strain was calculated by simply using the strain variations calculated with reference to the first trace of the measurement (at t=0). This was possible as the frequency shift (17 MHz) correspondent to the maximum applied strain (±100 nε) was significantly lower (<1 %) than the pulse total spectral content (2.32 GHz) in this case.

Figure 1(b) presents a spectrogram of the frequencies measured by the ΦOTDR when the PZT applied a sinusoidal frequency sweep between the frequencies 450 Hz to 850 Hz with a period of 1 s. The instantaneous frequency of the spectrogram was calculated using a moving window of 40 ms width over the recovered correlation shift profile. The high

linearity of the transfer function of the sensor is clearly demonstrated as no harmonics are observed in frequencies of up to 2 kHz. The SNR of the measured frequencies is >25 dB, which clearly indicates the potential of this technique for achieving simultaneously true strain measurements, high linearity and good signal to noise ratio.

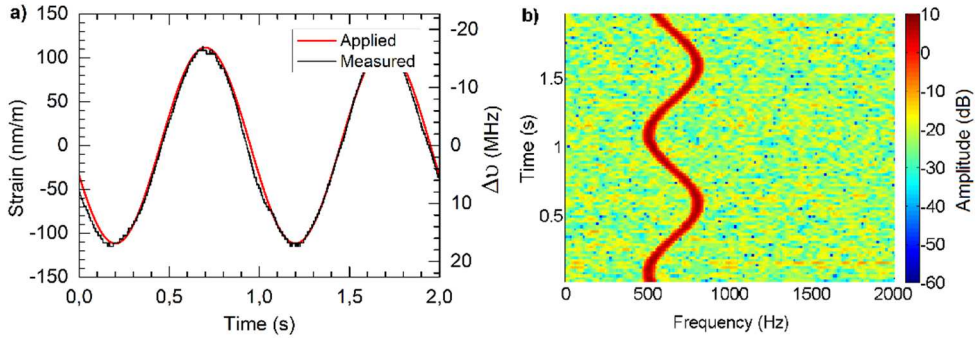


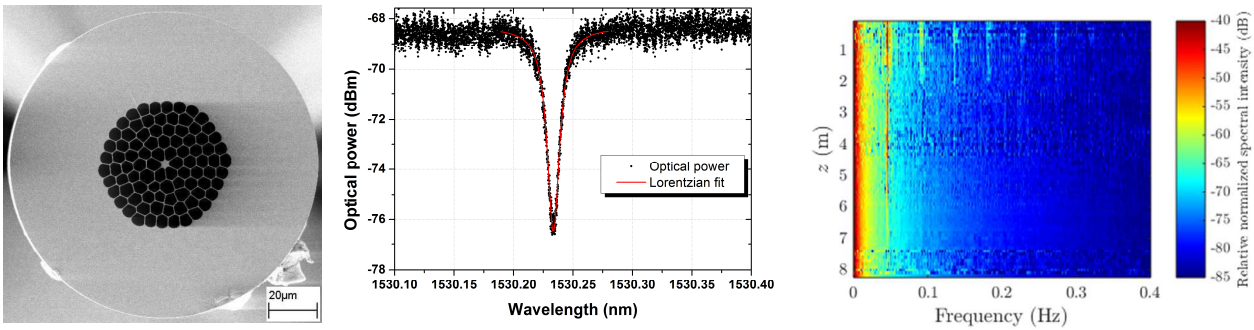
Fig. 1. Measured dynamic strain variations when strain is applied by a PZT in 20 m of fiber around meter 979 of the FUT. a) Measured strain for a 1 Hz sinusoidal strain with 100 nε maximum amplitude. (b) Spectrogram (logarithmic scale - dB) for an applied strain of a frequency sweep between 450 Hz to 850 Hz with a period of 1 s (instantaneous frequency calculated using a moving window of 40ms width of the measured dynamic strain).Figure 1. Noise power (a)-(c) and SNR evolution (b)-(d) for 100 and 200 km respectively for 1024 averaged traces.

4. DISTRIBUTED PHOTOTHERMAL SPECTROSCOPY IN MICROSTRUCTURED FIBERS

Recently, chirped-pulse ΦOTDR enabled the development of a new scheme to perform fully distributed, spatially-resolved detection of gas species along holey optical fibers with spectroscopic selectivity and suitable for a variety of chemicals with a single configuration. This method is based on realizing wavelength-modulated photothermal spectroscopy in a microstructured optical fiber (MSF), and probing the resulting heat distribution along the fiber using a dynamic distributed temperature measurement with mK resolution, enabled by chirped-pulse ΦOTDR. In this scheme, the evanescent field escaping the core of the fiber due to a propagating continuous wave (CW) signal is used to thermally excite the target chemical species, present in the close vicinity of the fiber core. When tuned on a gas molecular absorption line, the laser light absorbed in the gas causes heating by non-radiative molecular relaxation. The temperature changes along the fiber are determined with a fast and high-resolution readout using chirped-pulse ΦOTDR [23]. Wavelength modulation in the heating laser allows to easily discriminate the ambient temperature variations from the actual presence of gas. The use of molecular absorption lines provides the system with spectroscopic selectivity and reduced cross-sensitivity to environmental changes. However, since the measured quantity is the temperature, the vast majority of the system can work as a conventional distributed temperature sensor, i.e. the majority of the system components can operate at the conventional telecom window of 1.55 μm. The system can thus potentially reach the performances of range and resolution already demonstrated in previous configurations.

A proof-of-concept experimental demonstration of this idea has been carried out using a 10-m long MSF with the cross-section shown in Fig1(a). The fiber holes are filled with acetylene at low pressure. The temperature distribution along the fiber core was monitored continuously and dynamically with high temperature resolution using a chirped-pulse ΦOTDR system [23]. At the same time, a laser source tuned around the P9 line (~1530.4 nm) of the acetylene gas spectrum was launched into the fiber and used as a heating pump in order to induce photothermal heating in the gas upon absorption of the evanescent field escaping from the fiber core. As the gas temperature increases, heat is transferred to the fiber core, producing a small but detectable change in its temperature. The temperature change induced by photothermal absorption in this volume is in the order of hundreds of mK. In order to eliminate the effect of the slow contribution on the temperature measurements, a periodic wavelength modulation of the heating laser was made. This modulation was generated by adding a ~1 mA amplitude sine oscillation with a frequency 50 mHz to the current of the heating pump. This additional current corresponds to a peak wavelength displacement of about 6.1 pm. The wavelength modulation of the heating pump causes a periodic heating at the same frequency, which is analyzed by means of the Fourier transform in time applied of the data registered over 30 minutes. The spectral content present in the heating map normalized for each point z, is shown in Fig. 2(a). As it is visible, we observe the modulation frequency and some of its first harmonics.

In summary, chirped-pulse ΦOTDR offers unprecedented levels of measurement speed, resolution and robustness whose applications are yet to be defined. Interesting new outcomes of this technique are expected in the future.



(a) (b) (c)

Fig. 2. (a) SEM image of the MSF cross-section; (b) Detail of the absorption spectrum of the fiber around the P9 absorption line of acetylene. The estimated absorption of the fiber at the P9 wavelength is 1 dB/m, confirming the presence of the gas inside the fiber. (c) Spectral response of the temperature modulation measured along the fiber. A stronger temperature modulation is observed at the beginning of the fiber.

ACKNOWLEDGEMENTS

This work was supported in part by: the European Research Council through project U-FINE (Grant 307441); the EC Horizon 2020 program; the FINESSE project MSCA-ITN-ETN-722509; the DOMINO Water JPI project, under the WaterWorks2014 co-founded call by EC Horizon 2020 and Spanish MINECO; the Spanish MINECO (projects TEC2013-45265-R and TEC2015-71127-C2-2-R); and the regional program SINFOTON-CM: S2013/MIT-2790. The work of JPG and SML was supported by the Spanish MINECO (FPI and "Ramón y Cajal" contracts, respectively).

REFERENCES

[1] X. Bao and L. Chen, "Recent progress in distributed fiber optic sensors," Sensors 12(12), 8601–8639 (2012).

[2] J. Tejedor, H. F. Martins, D. Piote, J. Macias-Guarasa, J. Pastor-Graells, S. Martin-Lopez, P. Corredera, F. De Smet, W. Postvoll, and M. Gonzalez-Herraez, "Towards Prevention of Pipeline Integrity Threats using a Smart Fiber Optic Surveillance System," J. Lightwave Technol. 34(19), 4445-4453 (2016).

[3] H. F. Martins, S. Martin-Lopez, P. Corredera, M. L. Filograno, O. Frazao, and M. Gonzalez-Herraez, "Coherent noise reduction in high visibility phase sensitive optical time domain reflectometer for distributed sensing of ultrasonic waves," J. Lightwave Technol. 31(23), 3631-3637 (2013)..

[4] H. F. Martins, S. Martin-Lopez, P. Corredera, M. L. Filograno, O. Frazão, and M. Gonzalez-Herraez, "Phase-sensitive optical time domain reflectometer assisted by first-order Raman amplification for distributed vibration sensing over >100km," J. Lightwave Technol. 32(8), 1510–1518 (2014).

[5] H. F. Martins, S. Martin-Lopez, P. Corredera, J. D. Ania-Castanon, O. Frazao, and M. Gonzalez-Herraez, "Distributed Vibration Sensing Over 125 km With Enhanced SNR Using Phi-OTDR Over a URFL Cavity," J. Lightwave Technol. 33(12), 2628–2632 (2015).

[6] Y. Koyamada, M. Imahama, K. Kubota, and K. Hogari, "Fiber-Optic Distributed Strain and Temperature Sensing With Very High Measurand Resolution Over Long Range Using Coherent OTDR," J. Lightwave Technol. 27(9), 1142- 1146 (2009).

[7] M. A. Soto, X. Lu, H. F. Martins, M. Gonzalez-Herraez, and L. Thévenaz, "Distributed phase birefringence measurements based on polarization correlation in phase-sensitive optical time-domain reflectometers," Opt. Express 23, 24923-24936 (2015)

[8] H. F. Martins, K. Shi, B. C. Thomsen, S. Martin-Lopez, M. Gonzalez-Herraez, and S. J. Savory, "Real time dynamic strain monitoring of optical links using the backreflection of live PSK data," Opt. Express 24, 22303-22318 (2016).

[9] J. Pastor-Graells, H. F. Martins, A. Garcia-Ruiz, S. Martin-Lopez, and M. Gonzalez-Herraez, "Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses," Opt. Express 24(12), 13121–13133 (2016).

[10] A. García-Ruiz, J. Pastor-Graells, H. F. Martins, K. Hey Tow, L. Thévenaz, S. Martin-López, M. González-Herráez "Distributed photothermal spectroscopy in microstructured optical fibers: towards high-resolution mapping of gas presence over long distances" Opt. Express (to appear)

*miguel.gonzalezh@uah.es; phone +34-91-885-65-43