Garcia-Ruiz, A., Pastor-Graells, J., Martins, H.F., Martin-Lopez, S., Gonzalez-Herraez, M., 2016, "Speckle analysis method for distributed detection of temperature gradients with ΦOTDR", IEEE Photonics Technology Letters, vol 28, n. 18, pp. 2000-2003.

Available at http://dx.doi.org/10.1109/LPT.2016.2578043

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Speckle analysis method for distributed detection of temperature gradients with ΦOTDR

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***Abstract*— A method to extend the operation of traditional single-frequency phase-sensitive optical time domain reflectometry (ΦOTDR) to the monitoring of distributed temperature gradients along an optical fiber is proposed and experimentally validated. The measurement principle is derived from the perturbation response of a single-wavelength ΦOTDR signal, which is analyzed as a unidimensional speckle pattern. The method could be implemented in parallel to standard ΦOTDR systems used for distributed vibration sensing with a close to zero cost and without affecting its operation, as it only requires a low computational cost post-processing of the traces which are already acquired. Frequency scanning of the laser, heterodyning or additional hardware are not required. The distributed detection of a temperature gradient of 2.5 ºC over ten minutes is demonstrated.**

***Index Terms*—distributed fiber sensing, temperature sensing, phase-sensitive OTDR, speckle theory, signal processing.**

I. Introduction

PHASE-SENSITIVE optical time domain reflectometry (ΦOTDR) is a simple and effective tool allowing the distributed monitoring of parameters, such as vibrations or intrusions, along an optical fiber in real time [1]-[5]. Standard (single-frequency) ΦOTDR allow for the monitoring of vibrations with bandwidths which can reach several kHz over tens of kilometers [1],[2]. By using direct detection, the complexity of the system is kept to a minimum [1],[3]. However, due to the nonlinear dependency of the amplitude of the received signal on the amplitude of the applied perturbations [1],[3], these systems are not suitable for the quantitative measurements of strain/temperature.

Alternatively, an implementation of the ΦOTDR using a frequency sweep of the laser source has been demonstrated to allow for static measurements, such as temperature [4] or strain [5] with high resolutions (down to the mK – 10 nε). In this case however, the measurement range is limited by the frequency scanning range. Due to the laser sweeping requirements, the complexity and cost of the technique are also increased. Furthermore, the measurement time is increased to typically a few tens of seconds or minutes, which precludes the possibility of realizing vibration measurements in parallel to the temperature/strain measurements.

A minimization of this problem was recently proposed in [5]. By sending multiple pulses to the fiber for each frequency that is scanned, vibration measurements of 1 kHz were performed in parallel to strain measurements (sampled at a lower rate). However, the vibration measurements resolution was limited to 20 Hz, due to the requirement of comparing traces acquired with pulses of the same optical frequency.

In this paper, a low cost post-processing technique is proposed and demonstrated to allow for the monitoring of distributed temperature gradients along an optical fiber in real time using standard (single-frequency) ΦOTDR with direct detection. The technique can be used in parallel to (and without affecting) the traditional vibration monitoring, and could therefore be easily implemented on existing ΦOTDR systems used in intrusion monitoring.

II. Principles of Traditional (Single-Frequency) ΦOTDR

The fundamental principle of ΦOTDR derives from the Rayleigh scattering effect [1]-[5] and can be described as a unidimensional speckle generation problem [6],[7]. Firstly, optical pulses of high coherence are launched into an optical fiber. For simplicity we consider highly coherent square pulses of constant phase, normalized amplitude 1, central frequency ω_0 and width W. Propagation is considered isotropic and losses are neglected. As the pulses propagate along the fiber, light is continuously reflected by the randomly distributed scattering centers. The m^{th} fiber scattering center, positioned in z_m and with reflectivity r_m (<<1), will generate a Rayleigh backscattered wave of amplitude r_m and with a relative phase ϕ_m, which depends on z_m [2]. Lastly, at each instant t, the ΦOTDR optical signal received at the fiber entrance (z=0), E(z) is associated to a fiber position z by $t=2n_{av}z/c$, where n_{av}

Manuscript received February XX, 2016; revised February XX, 2016; accepted March XX, 2016. Date of publication April XX, 2016; date of current version April XX, 2016. This work was supported by the European Research Council through Starting Grant UFINE (Grant no. 307441), the Spanish MINECO through project TEC2013-45265-R, and the regional program SINFOTON-CM: S2013/MIT-2790. Juan Pastor-Graells acknowledges funding from the Spanish MINECO through a FPI contract. Hugo F. Martins acknowledges EU funding through the FP7 ITN ICONE program, gr. #608099. Sonia Martin-Lopez acknowledges funding from the Spanish MINECO through a "Ramon y Cajal" contract.

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Digital Object Identifier XXXXXXXXXXXX

is the average refractive index of the fiber and c the velocity of the light in the vacuum. E(z) is the result of the interference pattern generated by the superposition of the M (M→∞) Rayleigh backscattered waves reflected from a fiber section of length W/2 and centered around a position z [1,2]. Since Rayleigh scattering derives from fiber defects that are smaller than the wavelength, it can be envisaged that the number M exceeds several millions in meter-scale pulses. The normalized ΦOTDR signal intensity, I(z), will be given by:

$$I(z)=\left|E(z)\right|^2=\left| e^{i\omega 2n_{av}z/c}\sum\nolimits_{m=1}^{M} r_m e^{i\phi_m}\right|^2 \\ =\sum\nolimits_{m=1}^{M} r_m^2+2\sum\nolimits_{i=1}^{M-1}\sum\nolimits_{j=i+1}^{M} r_i r_j\cos(\phi_i-\phi_j). \tag{1}$$

The relative phase differences $\phi_{i,j}=\phi_i-\phi_j$ will be twice the optical path difference between the scattering centers *I,j* [2]:

$$\phi_{i,j}=\phi_i-\phi_j=\omega_0(\mathrm{z_i}-\mathrm{z_j})2\,n/c \tag{2}$$

Where n is the fiber local effective refractive index between $[z_i,z_j]$. Note that $z_i\text{-}z_j\in[0,W/2]$. Since the relative positions z_i,z_j of the scattering centers are random, the evolution of I(z) is a random process which turns out to be equivalent to a unidimensional speckle generation process. In speckle problems, the evolution of the pattern cannot be deterministically predicted, but the statistics of the pattern may follow deterministic rules as long as a sufficiently large ensemble is considered.

III. PROPOSED ΦOTDR METHOD FOR GRADIENT DETECTION

Let us now consider the application of a small temperature gradient ΔT on a given position of the fiber. In this case, a variation of the local refractive index of the fiber Δn will occur, being approximately given by [2]:

$$\Delta n\approx -n\left(6.92\cdot 10^{-6}\right)\Delta T\approx -10^{-5}\Delta T \tag{3}$$

In this case, a variation of $\phi_{i,j}$, $\Delta\phi_{i,j}$, and consequent variation of the intensity recorded at position z, ΔI(z), will occur. For a large Δn, such that for $z_i\text{-}z_j<W/2$, $\Delta\phi_{i,j}>2\pi$, then the dependency of ΔI on Δn will be highly nonlinear (eq. 1). However, for small enough values of Δn, such that $\Delta\phi_{i,j}<<2\pi$, then the intensity changes ΔI(z) will be linearly proportional to Δn. This linearity can be directly derived from eq. 1. Note that cos(x+y)=cos(x)*cos(y)-sin(x)*sin(y) and for a small x, cos(x)≈1, sin(x)≈x. In this case, ΔI(z) is given by:

$$\Delta I(z)\propto\sum\nolimits_{i,j} r_i r_j \cos(\phi_{i,j})-\cos(\phi_{i,j}+\Delta\phi_{i,j}) \\ \approx\sum\nolimits_{i,j} r_i r_j\sin(\phi_{i,j})\cdot\Delta\phi_{i,j}\propto\sum\nolimits_{i,j} r_i r_j\sin(\phi_{i,j})\cdot\Delta n \tag{4}$$

The smaller the value of Δn, the higher the linearity between Δn and ΔI [1, 3]. To perform a temperature measurement, ΦOTDR traces should be consecutively acquired over time, $I(t=t_1,z),\ldots,I(t=t_n,z)$, with a sampling time that is small enough to guarantee that the Δn(z) changes between two consecutive traces ensure $\phi_i\text{-}\phi_j<<2\pi$. This is the only way to maximize the linearity of the measurement. As a reference, note that, e.g., using a pulse of 20 ns and 1550 nm wavelength, n=1.467, then $\phi_i\text{-}\phi_j\approx 2\pi$ (using the maximum $z_i\text{-}z_j$=W/2) for ΔT≈0.04 K (eq 2,3). The trigger rate and trace averaging in this scheme has thus to be tuned to avoid errors due to this limitation while eliminating as much noise as possible in the measurement.

The evolution of Δn(z) over time, Δn(t,z), can then be estimated by accumulating the intensity changes over a sufficiently large ensemble of measurements:

$$\Delta n(t_n,z)\propto\sum\nolimits_{k=1}^{n}\left|I(t_{k+1},z)-I(\mathrm{t}_k,z)\right|=\sum\nolimits_{k=1}^{n}\left|\Delta I(t_k,z)\right| \tag{5}$$

Temperature gradients ΔT(t,z) can then be calculated from Δn(t,z) using eq. 3. The use of absolute values of the differences between the consecutive traces is justified by the fact that for a given Δn, ΔI can be arbitrarily positive or negative, and is in fact bound to change sign for a large enough Δn. Thus, note that although absolute temperature changes can be quite well detected and quantified with this method if they are monotonic, the sign of the temperature change cannot be determined using this simple method.

Note that, as mentioned before, a sufficiently large ensemble of measurements is necessary in order to average the sensitivity variations from point to point. This requires the use of a sufficiently large number of spatial points in the measurement, so that the system will tend to stabilize around an average sensitivity. In this case, the overall evolution of Δn (and correspondent ΔT) can be determined without a big impact of the statistical fluctuations. Thus, apart from the temporal integration of the |ΔI(z)| for each position of the fiber, a moving longitudinal average (i.e., along a fiber section) has to be used. In our case, the "tsmovavg" function in MATLAB is used [8].

IV. EXPERIMENTAL SETUP

The experimental setup used in this work to measure temperature changes is a traditional ΦOTDR using direct detection such as one presented in [1]. A laser diode (LD) with a linewidth of 1.6 MHz working in continuous and emitting at around 1547 nm was used as the light source. The LD was driven by a standard current and temperature controller. An isolator is used to avoid possible reflections from the next elements, which could affect the laser stability. A semiconductor optical amplifier (SOA) was driven by a

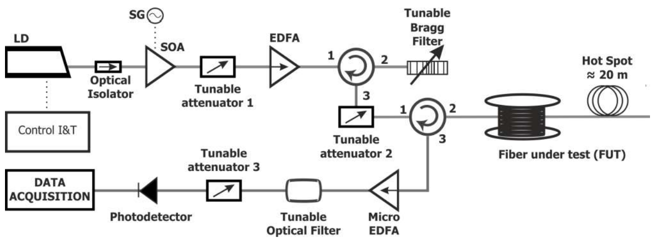

Fig. 1. Experimental ΦOTDR setup.

waveform signal generator (SG) to pulse the light in the time domain in order to meet the required extinction ratio (ER) in this system. The ER has a high impact in the SNR of the detected signals [1] and a SOA can achieve ERs >50 dB. The resolution of the system is determined by the duration of the pulses. The system uses optical pulses of 20 ns which corresponds to a spatial resolution of 2 m. The pulse power is increased with an erbium doped fiber amplifier (EDFA). Before sending the optical pulses into the fiber, a fiber Bragg grating (FBG) working in reflection is used to filter the amplified spontaneous emission (ASE) added by the EDFA. The spectral width of the FBG was 0.8 nm. The pulse is then injected in the fiber after passing through another tunable attenuator, thus controlling the input power to the fiber and avoiding possible nonlinearities such as modulation instability (MI). The fiber under test (FUT) was a single mode fiber (SMF) with a length of 1 km which was immersed in water to maintain its temperature constant. Near the end of the FUT, 20 m of fiber were used as a hot spot for the temperature measurements. The 20 m fiber section was placed inside an oven, allowing to control its temperature during the experiment. A thermometer was placed inside the oven to record the temperature with 0.1 ºC resolution. Before detection, the signal reflected from the fiber is amplified with another EDFA and filtered with an optical filter with a spectral width of 0.5 nm. The signal is detected in a p-i-n photodetector with a bandwidth of 125 MHz and sampled with a high-speed digitizer (with a 100 MS/s sampling rate). To test the detection of temperature gradients, the temperature of the hot spot was decreased at a constant rate from 52.8 ºC to 50.3 ºC over 600 s. Since this ~4 mK/s gradient is well below the 40 mK/s stated above, we can be confident that our averaging procedure is by no means spoiling the linearity of eq. 4.

V. ΦOTDR TRACES EVOLUTION

Firstly, the evolution of the ΦOTDR traces I(z) over time is analyzed. The traces are acquired as in a standard ΦOTDR, so that vibrations could in principle also be monitored in this experiment [1]. The frequency with which the optical pulses were sent to the fiber was 3 kHz, which would allow the monitoring of a FUT of up to ≈33 km. In the proposed method, variations of the traces induced by vibrations introduce noise in the temperature measurements. Therefore, the traces were averaged 3000 times - by post-processing in real time - aiming to enhance (reduce) the impact of slow (fast) trace variations associated with temperature (vibrations) changes. This resulted in the acquisition of one averaged trace, $I(t_i,z)$, per second. Note that the post-processing number of averages can be adjusted to minimize the error for a given temperature gradient. Different number of averages can also be processed separately. Fig. 2 shows the evolution of an averaged trace $I(t_i,z)$ over 6 s. Due to the temperature gradients, $I(t_i,z)$ presents intensity variations in the hot spot - between 940 m and 960 m - while remaining constant outside it, as expected.

Fig. 3a shows the intensity variations between consecutive traces, $\Delta I(t_i,z)$, for the $I(t_i,z)$ presented in Fig. 2 and Fig. 3b the evolution of $\Delta I(t_i,z)$ over time for two points of the fiber (inside and outside the hot spot). The average variations of $\Delta I(t_i,z)$ were observed to be relatively small (typically up to ≈10 %) in relation to the maximum values of $I(t_i,z)$. This is expected, as for a temperature variation of 0.004 ºC between traces (2.5 ºC over 600 s), the maximum phase variation along the pulse size of a 20 ns is well below 2π (≈2π/10 rad) – eq. 2,3.

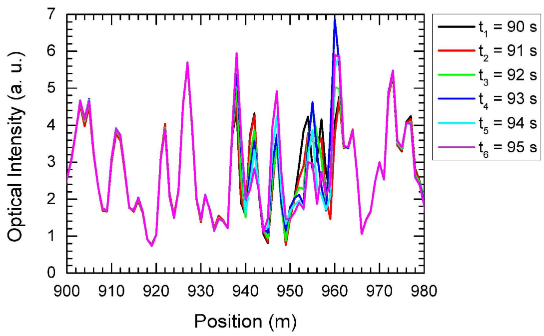

Fig. 2. Evolution of the ΦOTDR trace (averaged 3000 times), $I(t_i,z)$, around the hot spot (between 940 m and 960 m), where the temperature is uniformly decreased at a constant rate of ~4 mK/s. The factor converting voltage to a. u. depends on the particular electrical and optical setup configuration used.

VI. TEMPERATURE GRADIENT DETECTION

Due to the random speckle nature of the ΦOTDR signal, the evolution of $I(t_i,z)$ was observed to be unpredictable for small measurement ensembles, as expected. Despite the constant temperature gradient uniformly applied over 20 m, $\Delta I(t_i,z)$ presented positive/negative/null values seemingly uncorrelated over position (Fig. 3a) or time (Fig. 3b). This last figure also

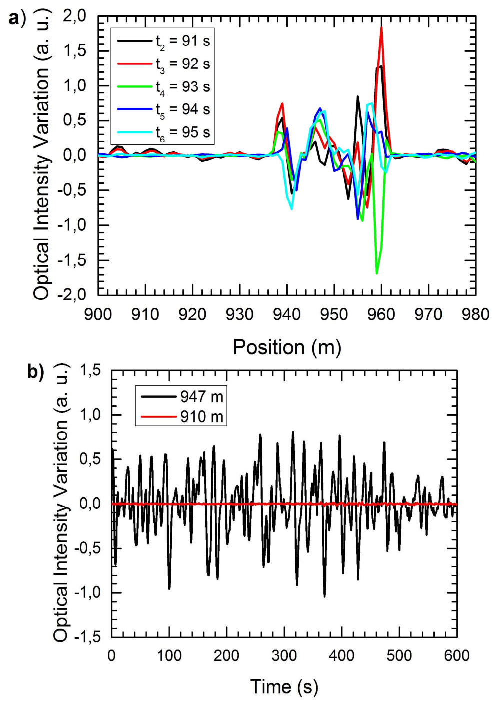

Fig. 3. Intensity variations between consecutive traces, $\Delta I(t_i,z)$. a) $\Delta I(t_i,z)$ along the fiber for the $I(t_i,z)$ presented in Fig. 2. b) $\Delta I(t_i,z)$ over time for two points of the fiber, showing a SNR greater than 10 dB.

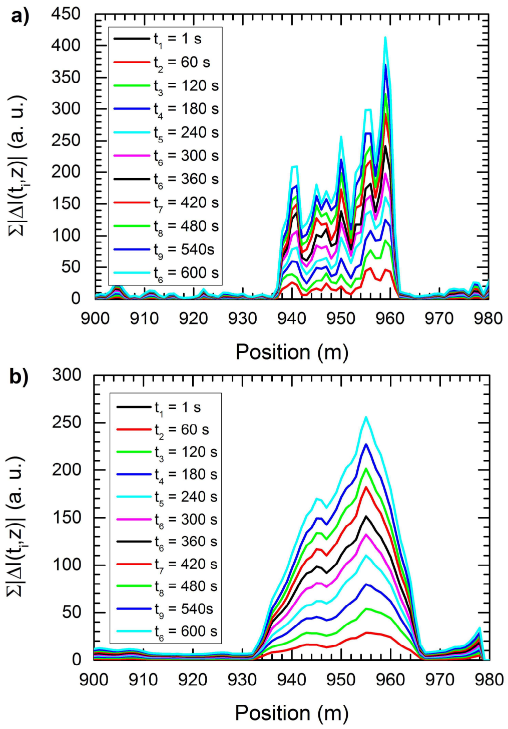

Fig. 4. Spatial distribution of the evolution of the integration over time of the absolute value of intensity variations between consecutive traces, $\sum|\Delta I(t_i,z)|$. a) $\sum|\Delta I(t_i,z)|$ using integration for each individual point of $|\Delta I(t_i,z)|$. b) $\sum|\Delta I(t_i,z)|$ using integration of a 10m moving spatial average of $|\Delta I(t_i,z)|$.

shows a SNR well above 10 dB achieved in part due to the average aforementioned. However, for a large enough ensemble of measurements the statistics of $\Delta I(t_i,z)$ showed a predictable behavior, and the distributed monitoring of temperature gradients was possible.

Fig. 4 shows the spatial distribution of the evolution of the integration of the absolute value of the intensity variations between consecutive traces, $\sum|\Delta I(t_i,z)|$ (eq. 5). Fig. 4a shows the integration of $|\Delta I(t_i,z)|$ done over time for each individual spatial point, i.e., the temporal integration of the $|\Delta I(t_i,z)|$ presented in figure 3a. Fig. 4b shows the integration of $|\Delta I(t_i,z)|$ over time using a 10 m moving spatial average, i.e., Fig. 4a after applying a 10 m moving spatial average filter.

Fig. 4 clearly demonstrates the feasibility of the proposed method in the detection of temperature gradients. The values of $\sum|\Delta I(t_i,z)|$ in the hot spot clearly rise above the background noise of the fiber. As for the quantification of the detected temperature gradients, 4a seems to indicate that different points may present different sensitivities, as expected due to the random speckle nature of the ΦOTDR signal. However, by using a moving spatial average (Fig. 4b) the ensemble of measurements is increased and the variability of the sensitivity of $I(t_i,z)$ at different fiber positions is reduced, thus obtaining a higher linearity between $\sum|\Delta I(t_i,z)|$ and the temperature variations along the fiber.

Fig. 5 shows the temporal evolution of the $\sum|\Delta I(t_i,z)|$, using the same integration parameters as in Fig. 4b, for specific spatial points. A good overall temporal linearity between the applied temperature changes and $\sum|\Delta I(t_i,z)|$ is observed.

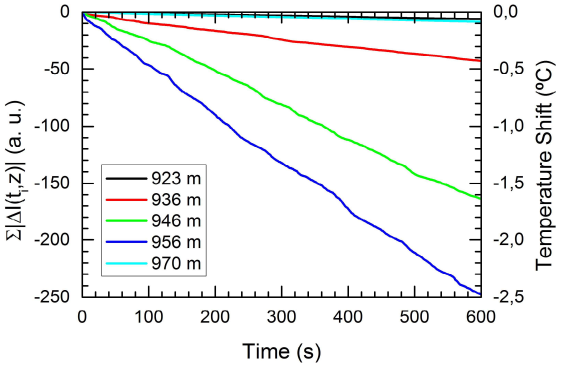

Fig. 5. Temporal evolution of the $\sum|\Delta I(t_i,z)|$ for specific points (inside and outside the hot spot), using the same integration parameters of Fig. 4b and scaled to be compared with the applied temperature variations.

VII. 5. CONCLUSIONS

A method, derived from speckle analysis theory, is proposed to extend the operation of traditional (single-frequency) ΦOTDR used for distributed vibration sensing, to the monitoring of distributed temperature gradients. Since the proposed method relies solely on a low-cost post-processing of the standard ΦOTDR traces, it could be implemented without affecting the distributed vibration detection and with a close to zero cost.

The temporal and spatial statistical variability of the ΦOTDR trace response to temperature changes is studied and observed to be predictable for large enough measurement ensembles. The distributed detection of temperature gradients of a few degrees over several minutes is demonstrated. The method is only capable of quantifying absolute temperature gradients, with upper limits in the range of <1 ºC/min for high SNR measurements. This is generally enough for most applications in which the fiber is buried.

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