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Distributed detection of temperature gradients with single-wavelength phase-sensitive OTDR and speckle analysis methods

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ABSTRACT

A method to evaluate distributed temperature gradients along an optical fiber using phase-sensitive optical time domain reflectometry (ΦOTDR) with direct detection is proposed and experimentally validated. The measurement principle derives from the perturbation response of a single-wavelength ΦOTDR signal, which is analyzed as a unidimensional speckle pattern. Our method can be implemented in real-time, relies solely on a low-cost post-processing of the standard ΦOTDR traces and requires no scanning of the laser frequency. This post-processing method can be implemented over a conventional ΦOTDR system used for distributed intrusion detection, without affecting its operation or requiring any additional hardware.

Keywords: distributed fiber sensing, temperature sensing, phase-sensitive OTDR, speckle theory, signal processing.

1. INTRODUCTION

ΦOTDR is a distributed sensing technique which allows for the distributed monitoring of parameters along an optical fiber in real time [1,2,3]. The technique has been widely established as an effective method for the distributed monitoring of vibrations or intrusions [1], with bandwidths of detection which can reach several kHz over tens of kilometers. By using a frequency sweep of the laser source, ΦOTDR can also be used for high resolution (down to the mK level) distributed temperature sensing [2]. In this case however, the measurement time is increased (typically to at least a few tens of seconds or minutes), and therefore, the detection of vibrations is not possible in parallel to the temperature measurements. The complexity and cost of the technique is also increased, due to the laser sweeping requirements.

In this work, a method is proposed to extend the operation of standard (single-frequency) ΦOTDR to the monitoring of distributed temperature gradients along a fiber without affecting the vibration monitoring or requiring any additional hardware. This method could be easily implemented on existing ΦOTDR systems used in intrusion monitoring.

2. PRINCIPLE OF THE MEASUREMENT

We start by describing a ΦOTDR and the new proposed operation for temperature gradient detection. The fundamental principle of ΦOTDR derives from the Rayleigh scattering effect [1,2,3] and can be described as a unidimensional speckle generation problem [4,5]. 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 mth 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} is the average refractive index of the fiber and c the velocity of the light in the vacuum. E(z), is the interference pattern generated by the superposition of the M ($M\rightarrow\infty$) Rayleigh backscattered waves reflected from a fiber section of length W/2 and centered around a position $\bar{z}$ which depends on *t* [1,2]. The normalized ΦOTDR signal intensity, I(z), will be given by:

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

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The relative phase differences ϕ_i-ϕ_j will be twice the optical path difference between the scattering centers *i,j* [2]:

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

Where n is the fiber local effective refractive index between [z_i,z_j]. Note that z_i-$z_j \in [0,W/2]$. 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.

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 the intensity recorded at position z will be recorded (ΔI(z)). For a large Δn, such that for z_i-z_j<W/2 and ϕ_i-ϕ_j>2π, then the dependency of ΔI on Δn will be highly nonlinear (eq.1). However, for small enough values of Δn, such that ϕ_i-ϕ_j<<2π, then the intensity changes ΔI(z) will be linearly proportional to the refractive index changes. 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),…,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 ϕ_i-ϕ_j<<2π. This is the only way to maximize the linearity of the measurement. As a reference, note that, for e.g., using a pulse of 20ns and 1550nm wavelength, n=1.467, then ϕ_i-ϕ_j≈2π (using the maximum z_i-z_j=W/2), for ΔT≈0.04K (eq 2,3). As the sampling rate of these sensors may lie in the kHz level, this restriction does not really pose much limitations on the achievable temperature range.

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:

$$\Delta n(t_n, z) \propto \sum\nolimits_{k=1}^{n} \left| I(t_{k+1}, z) - I(\mathrm{t}_k, z) \right| = \sum\nolimits_{k=1}^{n} \left| \Delta I(t_k, z) \right| \tag{4}$$

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, however 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 as well.

3. EXPERIMENTAL SETUP

The experimental setup used in this work is shown in Fig.1a. It is a traditional ΦOTDR using direct detection such as the one presented in [1]. The light source was a highly coherent tunable laser diode (LD) with a linewidth of 1.6 MHz emitting around 1547 nm. The LD was working in continuous emission and was driven by a standard current and temperature controller. An isolator is used to avoid possible reflections in the next elements, which could affect the laser stability. The light was pulsed using a semiconductor optical amplifier (SOA) 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 created pulses have a duration of 20 ns which determines a spatial resolution of the system of 2 m. Before sending the optical pulses into the fiber, an erbium doped fiber amplifier (EDFA) is used to increase their power. A fiber Bragg grating (FBG) working in reflection is used to filter the amplified spontaneous emission (ASE) added by the EDFA. The FBG has a spectral width of 0.8 nm. The pulse is then injected in the fiber after passing through another tunable attenuator, in order to control 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. These were placed inside an oven, allowing to control their temperature during the experiment. The temperature inside the oven was recorded with a thermometer which had a resolution of 0.1 K. 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 a high-speed digitizer.

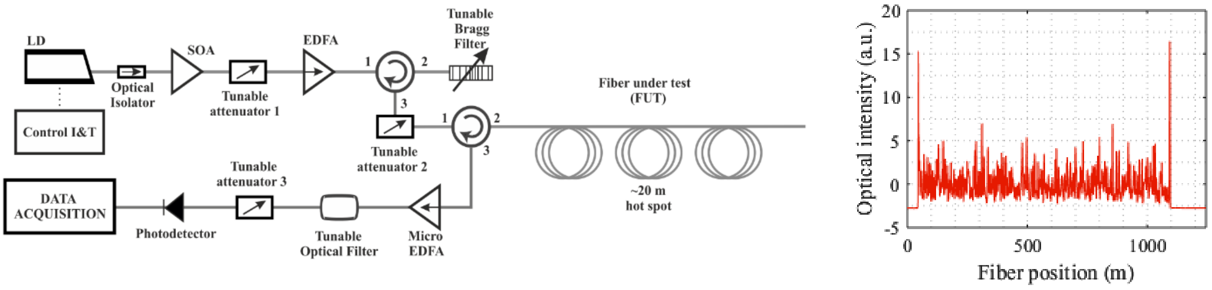

Figure 1. a) Experimental Setup ΦOTDR setup. b) E.g. of a ΦOTDR trace of the FUT, $I(t_i,z)$ (averaged 3000 times).

The optical pulses were sent to the fiber with a frequency of 3 kHz, which should allow the monitoring of a FUT of up to ≈33km [1]. The received ΦOTDR traces were then averaged by 3000 times in real time, resulting in the acquisition of one averaged ΦOTDR trace of the FUT per second, $I(t_i,z)$. The existence of temperature gradients in the fiber was then monitored using eq. 4. The number of averages was chosen as to suppress the expected trace variations resulting from vibrations (typically occurring at frequencies well above 1Hz) and enhance the trace variations resulting from temperature variations (typically occurring at frequencies lower than 1Hz). In any case, different numbers of averaging (or even more than one type of averaging processed separately) can be used, depending on the type of perturbation which is intended to be monitored. Fig. 1b shows an example of a $I(t_i,z)$, measured with the setup of Fig. 1a.

4. RESULTS

To test the detection of temperature gradients, the temperature of the hot spot was decreased at a constant rate from 52.8ºC to 50.3ºC over 600s Fig. 2a shows the evolution of the traces $I(t_i,z)$ around the position of the hot spot over 4s. Due to the high number of averages (3000), the noise is greatly decreased and the trace was observed to be very stable outside the hot spot, which was observed to be placed between 980m and 1000m of the FUT. In the hot spot however, $I(t_i,z)$ was observed to vary from trace to trace. These variations were small in comparison to the values of $I(t_i,z)$, as it was expected since the phase variations along the pulse size from trace to trace with this temperature gradient should be in the order of $\approx 2\pi/10$ (eq. 2,3). Fig. 2b shows the $\Delta I(t_i,z)$ for the traces $I(t_i,z)$ presented in Fig. 2a. When analyzing $\Delta I(t_i,z)$ at a fixed time t_i, it is observed that different positions z can present positive, negative or even null intensity variations. The evolution of $\Delta I(t_i,z)$ at a fixed position can also vary randomly over time. It was therefore observed that for small measurement ensembles, despite the constant rate and uniformity over 20m of the temperature variation, the evolution of $\Delta I(t_i,z)$ was unpredictable, as expected, due to the speckle nature of the ΦOTDR signal. However, the distributed monitoring of temperature gradients was still possible for a large enough ensemble of measurements over time and fiber positions, as demonstrated in Fig. 3.

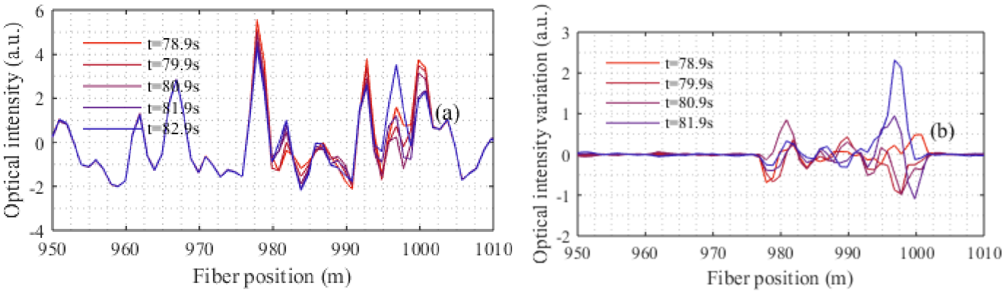

Figure 2. Evolution of the ΦOTDR traces $I(t_i,z)$ when the temperature is decreased at a constant rate uniformly between 980m and 1000m. a) Comparison of $I(t_i,z)$ acquired consecutively b) $\Delta I(t_i,z)$ for ΦOTDR traces presented in (a).

Fig. 3 shows the evolution of the integration of the absolute value of the intensity variations between consecutive traces, $\sum|\Delta I(t_i,z)|$ (eq. 4), i.e., the integration of the $|\Delta I(t_i,z)|$ presented in figure 2b. The spatial distribution of $\sum|\Delta I(t_i,z)|$ at different times (60s separation between traces) is shown in figure 3a, while the temporal evolution of the $\sum|\Delta I(t_i,z)|$ for different spatial points is shown in fig. 3b. A moving longitudinal average of 10m of $\sum|\Delta I(t_i,z)|$ was used, in order to increase the ensemble of measurements and reduce the variability of the sensitivity of I(z) at different fiber positions. Fig. 3a clearly demonstrates the feasibility of the proposed method in the detection of the temperature gradient applied in the hot spot. Fig. 3b also demonstrates a good overall linearity between the applied temperature changes and $\sum|\Delta I(t_i,z)|$.

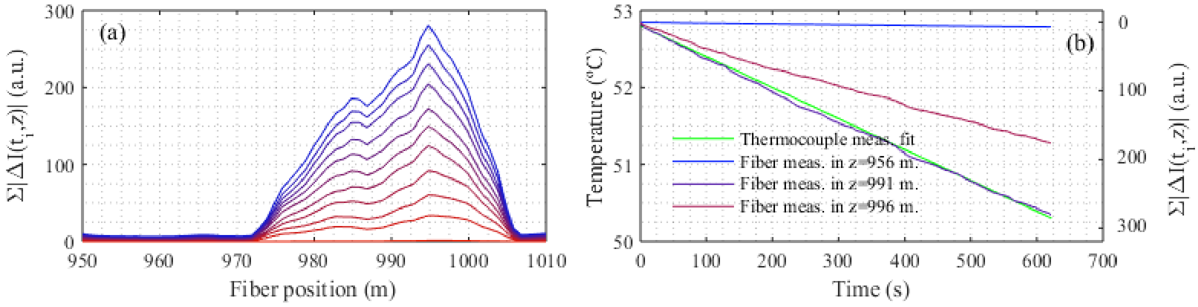

Figure 3. Evolution of the integration of the absolute value of intensity variations between consecutive traces, $\sum|\Delta I(t_i,z)|$. a) Spatial distribution of the $\sum|\Delta I(t_i,z)|$at different times (60s separation between traces). b) Temporal evolution of the $\sum|\Delta I(t_i,z)|$ for specific points, scaled to be compared with the applied temperature variations.

5. CONCLUSIONS

A low cost method derived from speckle analysis theory is demonstrated to allow for the monitoring of distributed temperature gradients along an optical fiber in real time using single-wavelength ΦOTDR. The method could be implemented in parallel to standard ΦOTDR used for distributed vibration detection with a close to zero cost, as it only requires a low computational cost post-processing of the standard ΦOTDR traces which are already acquired. The distributed detection of temperature gradients of a few degrees over several minutes is demonstrated.

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