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Single-Shot True Distributed Strain Variation Measurements Over >10 km Using Phase-Sensitive OTDR with Chirped Pulses

A. Garcia-Ruiz,[1,*] H. F. Martins,[2] J. Pastor-Graells,[1] S. Martin-Lopez[1] and M. Gonzalez-Herraez[1]
[1]Departamento de Electrónica, Universidad de Alcalá, Escuela Politécnica Superior, 28805, Madrid, Spain
[2]FOCUS S. L., C/ Orellana, 1, 1º Izquierda, 28804, Madrid, Spain
Author e-mail address: [*]andres.garciaruiz@uah.es

Abstract: Single-shot, true strain dynamic measurements with few nε resolution over >10 km are achieved with a ΦOTDR employing linearly chirped pulses. Strain variations at frequencies up to 4 kHz can be monitored over this distance.

OCIS codes: (060.2370) Fiber optic sensors; (060.2430) Fibers, single-mode (290.5870) Scattering, Rayleigh.

1. Introduction

Distributed acoustic sensing (DAS) using phase-sensitive OTDR (ΦOTDR) has attracted interest from both research and industry centers around the world due to its potential for security applications, such as monitoring activities over long linear ranges or intrusions over large perimeters. While ΦOTDR allows for detection of distributed vibrations with high bandwidths, the traditional intensity-based detection provides a nonlinear transfer function between trace intensity variations and fiber applied strain. Therefore, the detection of vibrations with a linear transfer function, i.e, the detection of true dynamic strain, would be of great interest to improve the performance of DAS systems, particularly for the interpretation of the recorded vibrations using pattern recognition systems [2].

By precisely changing the frequency of the pulses, step by step, phase-sensitive OTDR has been shown to allow for true temperature/strain measurements with high sensitivity [3]. However, due to the requirement of a frequency sweep, the measurement time is typically limited to a few seconds/minutes [3]. By recovering the phase of the ΦOTDR signal, the measurement of dynamic strains has been demonstrated [4,5]. In this case, however, the phase of the signal reflected from a certain fiber position does not depend only on the local strain variations, but rather on the accumulated phase variations until that point. While the local strain can be retrieved by comparing the relative phase variations between closely-spaced points of the fiber, the overall detection system is more complex. The measurement of true dynamic strain has also been successfully demonstrated using slope-assisted Brillouin Optical Time Domain Analysis (BOTDA) [6]. Since the measurement does not require a frequency sweep, high bandwidths of detection can be achieved, although in this case the measurable strain range is limited by the Brillouin gain curve.

Recently, a new technique using ΦOTDR with chirped pulses and intensity detection was demonstrated to allow for single-shot (i.e., no sweep, no averaging) distributed measurements of strain/temperature with sensitivities of up to three orders of magnitude higher than those provided by Brillouin based sensing [7]. While higher detection bandwidth is required, the technique allows for highly linear, rapid and sensitive measurements [7]. In this paper, following previous work from the same authors [7], the preliminary results for the characterization of the performance of a ΦOTDR using chirped pulses over medium/long ranges is presented. Dynamic strain is measured over 11 km while operating with 8 kHz pulse repetition rate i.e., close to the limit set by the time of flight of pulses in the fiber. Strain variations at frequencies up to 4 kHz (i.e., the limit set by the Nyquist sampling theorem) are successfully measured and a high linearity between detected and applied strain is observed.

2. Working principle

The basic idea of the use of ΦOTDR with chirped pulses for single-shot distributed measurements of strain derives from the idea that a linearly chirped pulse can translate a variation of frequency into a variation in time.

In ΦOTDR operation using intensity-based detection, the same fiber pattern can be retrieved after a variation of strain Δε or temperature ΔT is applied to a fiber, by interrogating the fiber with a pulse with a frequency shift Δν [3]. Previous techniques using ΦOTDR for temperature/strain measurements, required a frequency sweep to measure Δν, from which Δε and ΔT was derived [3]. However, with the use of linearly chirped pulses, Δν can be translated into a local temporal shift Δt of the fiber trace, and can therefore be measured accurately once for every pulse sent into the fiber. The applied ΔT ($\Delta\nu/\nu_0 = -6.92\cdot10^{-6}\,\Delta T$) or Δε ($\Delta\nu/\nu_0 = -0.78\,\Delta\varepsilon$) can then be calculated using:

$$\left(\frac{\Delta\nu}{\nu_0}\right) = -\left(\frac{1}{\nu_0}\right)\left(\frac{\delta\nu}{\tau_p}\right)\Delta t \qquad (1)$$

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. 1. A detailed explanation of this working principle, including a full theoretical model derived from the pulse propagation equations can be found in ref. [7].

3. Experimental setup

The experimental setup used to measure strain is presented in Fig. 1. It is similar to the setup previously used by the same authors to measure temperature/strain variations [7], but the length of fiber under test (FUT) was increased from 1 km to 11 km. The setup consists of a block to generate linearly chirped pulses, which are sent to the FUT (at the end of which strain is applied), and a block for intensity detection of the Rayleigh backscattered signal.

To generate the linearly chirped pulses, the light source was a laser diode (LD) working in continuous emission and driven by a standard current and temperature controller to select the laser central wavelength. A secondary current control applied a repetitive electric ramp signal in the laser driver, which introduced a linear chirp at certain times in the outputted laser light. This light was then gated in the time domain by a semiconductor optical amplifier (SOA) – whose driver was synchronized with the secondary laser current control - thus generating linearly-chirped 100 ns squared pulses, with a total spectral content of 2.3 GHz and repetition rate of 8 kHz. After an amplification and filtering scheme, the pulses were launched into the FUT. The FUT was divided into three sections, all composed of standard SMF. First, a 10 km fiber roll was used, followed by 20 m of fiber which were wrapped around a PZT (which allowed applying controlled deformations), followed by a 1 km fiber roll. The PZT was previously calibrated, so that the transfer function between the electric signal applied to the PZT and strain applied to the fiber was known (and mostly linear in the frequency range used). The signal backscattered from the FUT was then amplified and filtered before being detected by p-i-n photodetector (9 GHz bandwidth) and recorded by a high-speed digitizer with 40 GHz sampling rate. Note that a more detailed setup description can be found in [7].

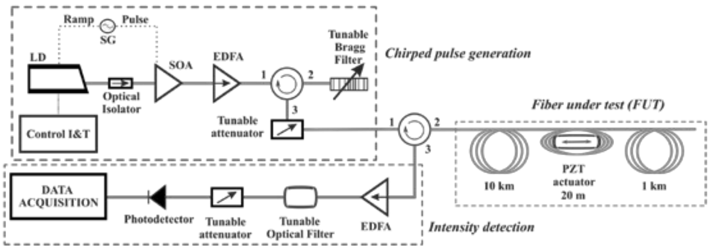

Fig. 1. Experimental setup: acronyms are explained in the text.

4. Results

The fiber trace correspondent to the 11 km of FUT is presented in Fig. 2a. Note that due to a bad connector, a high loss (≈6 dB in the backscattered signal) was observed before the fiber section wrapped around the PZT, where strain was applied. In any case, even with this loss, the system was able to accurately measure the applied strain variations, which clearly demonstrates the robustness of the technique. In Fig. 2b, two ΦOTDR traces (focused on the fiber section which was wrapped around the PZT) are shown. Since strain was applied between the two measurements, a longitudinal shift is observed between the two ΦOTDR traces. The principle of the measurement then is clearly demonstrated: when strain is applied to the fiber, the ΦOTDR trace is shifted longitudinally, with a displacement which is proportional to the amplitude of the applied strain. Note that this is a local effect, and where strain is not applied, the ΦOTDR trace will not change.

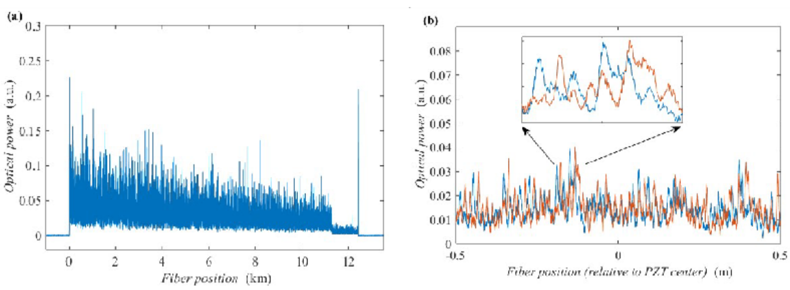

Fig. 2. a) ΦOTDR trace along the 11 km FUT. b) Longitudinal shift of the ΦOTDR trace in a fiber section around the PZT when strain variations are applied to the fiber by the PZT.

To test the bandwidth of the dynamic strain sensing of the system, a sinusoidal strain signal with an amplitude (peak-to-peak) of 400 nε and frequency which was linearly varied over time was applied on the PZT. Due to scope memory limitations, (note that the trace acquisition rate is 8 kHz and the trace is sampled at 40 GHz), it was only possible to record 0.6 s. Figure 3a and 3b present the spectrogram of the measured dynamic strain variations around the location of the PZT when the applied frequency was linearly swept between a) 500 Hz to 1500 Hz b) 3000 Hz to 4000 Hz. The possibility of the technique to perform measurements with high linearity (no harmonics are observed), high SNR (>15 dB) in frequency ranges which can reach the limit set by the Nyquist sampling theorem (i.e., up to 1/2 the trace acquisition rate) is clearly demonstrated over 11 km.

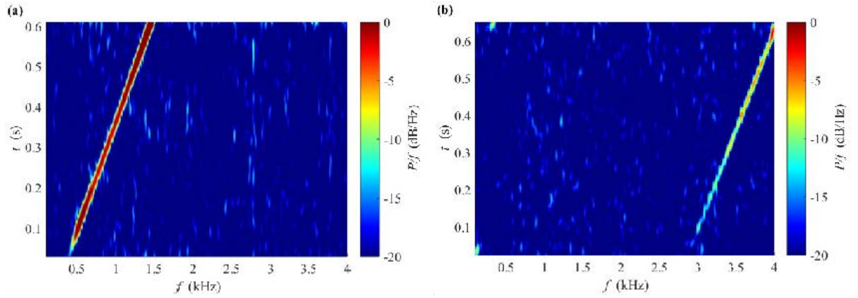

Fig. 3. Spectrogram (logarithmic scale - dB) of the measured dynamic strain variations applied to 20 m of fiber wrapped around the PZT (instantaneous frequency calculated using a moving window of 60 ms width of the measured dynamic strain). The applied strain signal was a sinusoidal strain with an amplitude (peak-to-peak) of 400 nε and frequency swept over periods of 0.6 s between a) 500 Hz to 1500 Hz b) 3000 Hz to 4000 Hz.

5. Conclusions

Following previous work from the same authors, the preliminary results for the characterization of the performance of a ΦOTDR using linearly chirped pulses over medium/long ranges were presented. It was demonstrated that true dynamic strain could be monitored with a strain sampling frequency only limited by the time of flight of the pulses in the fiber. The performed tests show that high linearity, high sensitivity and ultimate sampling rate performance can be achieved with this system, even over >10 km of fiber.

As it is visible in the results, the system presented a high linearity (no harmonics were observed for the applied frequencies) and high SNR, with at least 15 dB between the applied frequencies and background noise, despite the rather small integration window (60 ms). Given the good overall performance of the sensor and taking into account that the results were obtained despite a 6 dB signal loss (owned to a bad connector), the possibility of further extending the sensing range is readily envisaged.

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