This is a postprint version of the following published document:

Available at http://dx.doi.org/10.1364/SENSORS.2016.SeM3D.5

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Truly Linear and Dynamic Distributed Strain Sensor using intensity-only measurements

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Abstract: A new dynamic distributed strain sensor is presented in this work. It is based on a phase-sensitive OTDR and linearly chirped pulses. Linear strain measurements at kHz rates with 4 nε resolution are demonstrated.

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

1. Introduction

Distributed Optical Fiber Sensors (DOFS) allow for the monitoring of different physical parameters (such as temperature or strain) over long fiber distances. DOFS are based mainly on Rayleigh, Brillouin and Raman scattering phenomena [1]. Generally, Raman and Brillouin DOFS are characterized by long measurement times, which can take several minutes [2,3]. This is due to the requirement to implement frequency sweeps and/or high averaging. There are some recent Brillouin schemes able to realize dynamic strain measurements [4], however the strain dynamic range is limited by the Brillouin gain spectral width. In contrast, Rayleigh DOFS require lower averaging than Raman and Brillouin DOFS. For this reason, Rayleigh-based sensing is better suited for dynamic measurements such as vibrations or intrusions [5].

Phase-sensitive OTDR (ΦOTDR) systems can be adapted for high-resolution strain change measurements [6], significantly lower than the typical resolutions of $\approx$20µε provided by Brillouin sensors. However, in this case the measurement times and complexity of the system are increased due to the requirement of a frequency scan. To avoid this issue, ΦOTDR with phase-recovering techniques has allowed performing dynamic measurements of strain [7]. In this case, however, the complexity of the system is increased and the behavior of these systems in terms of long-range applications has not been clearly addressed.

In the present work, it is provided a method based on ΦOTDR using linearly chirped pulses, which allows for the quantitative measurement of distributed strain changes without the requirement of a frequency scan while maintaining the simplicity of a traditional ΦOTDR using direct detection. The strain resolution is dependent on the chirp applied to the pulses and the sampling rate of the ΦOTDR trace. In this paper, we demonstrate the principle using 10 m resolution pulses over a 1 km fiber, achieving 4 nε strain resolution and sampling rates of 4 kHz. Nevertheless, the sensor should allow achieving the conventional features of a ΦOTDR in terms of range and resolution, i.e., measurement ranges over several tens of kilometers with metric spatial resolutions.

2. Fundamentals of the sensor and experimental setup

The presented new dynamic distributed strain sensor is based on ΦOTDR technique, where a highly coherent optical pulse is injected into a conventional optical fiber. The backscattered light from the different scattering centers of the fiber interferes with itself and is detected at the beginning of the fiber, yielding a temporal intensity trace. It is possible to associate the detected light to a fiber position by the time of flight of the light pulses in the fiber. Due to the random position of the scattering centers, the detected trace presents random variations, which remain constant over time if the fiber is not perturbed. Commonly, ΦOTDR works analyzing changes of intensity in the trace which indicate the presence of perturbations such as vibrations. However, the intensity variations will depend nonlinearly on the applied perturbations. Therefore, traditional ΦOTDR sensors do not recover true strain variations unless a frequency sweep [6] is performed or coherent detection [7] is used for phase recovery. In contrast, the sensor presented here can recover linear strain measurement without such need of complexity increase. Compared to traditional ΦOTDR, the need for a frequency sweep is replaced by linearly chirped pulses and the computation of simple local temporal correlations from trace to trace.

In the presented sensor, a pulse P(t) with a linear chirp is used, in which the instantaneous frequency is varied linearly by $\nu(t)=\nu_0-\Delta\nu_p/2+\Delta\nu_p\cdot[t/\tau_p]$. ν_0 is the central frequency of the pulse and $\Delta\nu_p/\tau_p$ is the frequency slope, where $\Delta\nu_p$ and τ_p are the pulse spectral content and length, respectively. In this case, it can be demonstrated algebraically that if a small Δn (refractive index change) occurs at a certain location of the fiber z, then the local ΦOTDR pattern,

E(t) will be longitudinally shifted by an amount Δt at that location, which can be translated (through the chirp value) to a value of Δv which compensates for the Δn. The associated local Δn change is then given by:

$$\Delta n = -\left(\frac{n}{v_0}\right)\cdot\left(\frac{\Delta v_p}{\tau_p}\right)\cdot\Delta t \tag{1}$$

The measurement of Δn along the fiber then allows for distributed strain variation measurements (Δε), by using the conversion relation [6]:

$$\frac{\Delta n}{n} = \frac{\Delta v}{v_0} \approx -0.78\cdot\Delta\varepsilon \tag{2}$$

The experimental setup used in the new proposed technique is depicted in Fig. 1a. It is based on a traditional ΦOTDR scheme [5] but introducing a linear chirp in the pulse simply acting on the current control of the laser. The light source was a laser diode (LD) with a linewidth of 1.6 MHz emitting at 1546.66 nm and working in continuous emission. The LD was 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 in the outputted laser light. Optical square pulses of 100 ns were carved on the chirped laser signal using a semiconductor optical amplifier (SOA). The resulting pulse spectral content is Δv_p=2.32 GHz and the instantaneous frequency profile ω_{inst}(t) of the pulse is presented in Fig. 1b, where the chirp profile of the pulses showed a good linearity. The phase profile has been characterized using balanced phase reconstruction using optical ultrafast differentiation (balanced PROUD). The details of the used balanced PROUD detection scheme can be found in a previous work by the same authors [8]. The trace is detected using a p-i-n photo-detector with a bandwidth of 13GHz and a high-speed digitizer with 40Gsps sampling ratio. For more information on the rest of the setup elements, an interested reader is invited to consult [5]. The fiber under test (FUT) was a 1 km single-mode fiber and the last 20 m of the FUT were strapped around a PZT which allowed the controlled application of deformations.
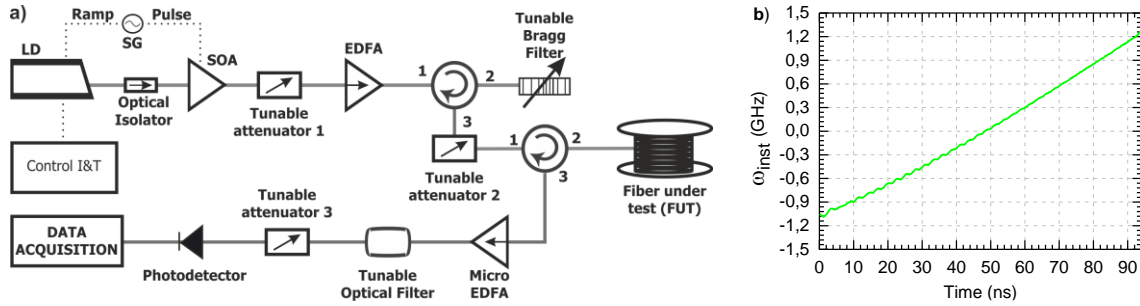

Fig. 1. a) Experimental setup: Acronyms are explained in the text. b) Instantaneous frequency profile of the chirp induced in the 100 ns square optical pulse employed (2.32 GHz).

3. Acoustic measurements

This work demonstrates the capability of this sensor for performing truly linear and dynamic strain measurements using the presented technique. For this purpose, different sounds were applied to the PZT in order to create controllable dynamic strain variations on the fiber, which is controlled by an electrical input. The ΦOTDR traces were acquired with a frequency of 4 kHz. Firstly, we applied three pure tones with known amplitudes onto the fiber and recovered the applied strain. The results are presented in Fig. 2. The applied signal has a duration of 3.5 seconds and contains three frequencies of 523 Hz, 659 Hz and 784 Hz. Fig. 2a shows the full measurements, with a maximum amplitude of 80 nε. As it is clearly observed, a good agreement between the experimental measure and the applied strain is observed. The small amplitude disagreement at 784 Hz is caused by the amplitude response of the PZT element and not the optical sensor. In Fig. 2b it is shown a zoom of the first tone in Fig. 2a where a good correspondence between the measured and applied strain variation is visible. To demonstrate the linear behavior of the sensor, Fig. 2c presents the spectrogram of the recorded signal. The spectrogram was calculated using a moving window of 90 ms width over the recovered signal. The high linearity of the transfer function of the sensor is clearly demonstrated as no harmonics are observed in frequencies up to 2 kHz. The signal-to-noise ratio (SNR) of the measured frequencies is >25dB, which clearly indicates the potential of this technique for achieving simultaneously true strain measurements, high linearity and good SNR. Finally, the first 5 seconds of the 5th symphony of Beethoven were applied to the fiber. The recorded signal is presented in Fig. 3. Again, there is a good agreement between the experimental measure and the applied strain, the small disagreements coming more from the non-flat

spectral PZT response and fiber mechanical coupling than from the ΦOTDR response. The signal recorded by the ΦOTDR was also perfectly understandable by human hearing when played by a speaker.
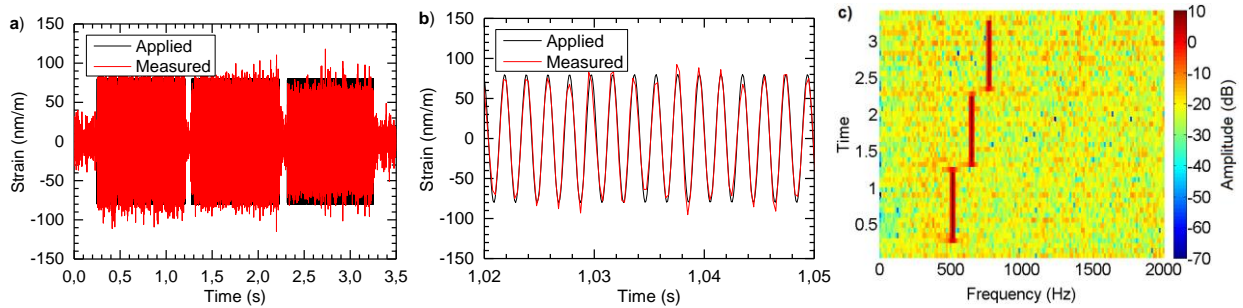

Fig. 2. Measured strain variations when strain applied by a PZT in 20 m of fiber around meter 979 of the FUT. Three pure tones of 523 Hz, 659 Hz and 784 Hz have been applied. a) Full vibration b) A detail of 0.03 s of figure (a) c) Spectrogram for the full vibration (instantaneous frequency calculated using a moving window of 90 ms).
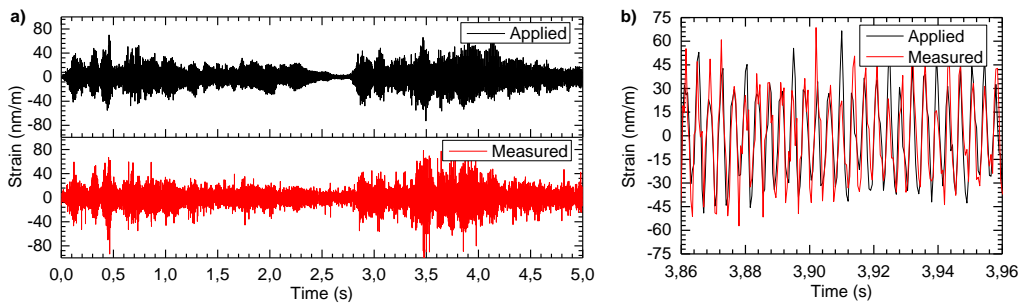

Fig. 3. Measured strain variations when strain applied by a PZT in 20 m of fiber around meter 979 of the FUT. First 5 seconds of 5th symphony of Beethoven has been recorded. a) Full vibration b) A detail of 0.1 s of figure (a).

4. Conclusion

In this work, we have presented a novel distributed fiber sensor which allows for the dynamic measurement of true strain variations using intensity only measurements and no sweep. It is based on phase-sensitive OTDR using linearly chirped pulses. Compared to traditional ΦOTDR, the need for a frequency sweep is replaced by the computation of simple local temporal correlations from trace to trace. With the proposed system, real acoustic strain variations have been experimentally recorded at kHz update rates and nε strain resolution. The strain resolution can be adapted by acting on the chirp profile of the pulses and the bandwidth and sampling rate of the digitizing scheme.

6. References

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

[2] Bolognini, G., Park, J., Soto, M. A. and Di Pasquale, F., "Analysis of distributed temperature sensing based on Raman scattering using OTDR coding and discrete Raman amplification," Meas. Sci. Technol. 18(10), 3211-3218 (2007).

[3] Angulo-Vinuesa, X., Martin-Lopez, S., Nuño, J., Corredera, P., Ania-Castañon, J. D., Thévenaz, L. and Gonzalez-Herraez, M., "Raman-Assisted Brillouin Distributed Temperature Sensor Over 100 km Featuring 2 m Resolution and 1.2 °C Uncertainty," J. Lightwave Technol. **30**, 1060-1065 (2012).

[4] Peled, Y., Motil, A. and Tur, M., "Fast Brillouin optical time domain analysis for dynamic sensing," Opt. Express 20(8), 8584-8591 (2012)

[5] Martins, H. F., Martin-Lopez, S., Corredera, P., Filograno, M. L., Frazão, O. and González-Herráez, M. "Coherent Noise Reduction in High Visibility Phase-Sensitive Optical Time Domain Reflectometer for Distributed Sensing of Ultrasonic Waves," J. Lightwave Technol. **31**, 3631-3637 (2013).

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

[7] Wang, Z., Zhang, L., Wang, S., Xue, N., Peng, F., Fan, M., Sun, W., Qian, Rao, J. and Rao, Y., "Coherent Φ-OTDR based on I/Q demodulation and homodyne detection," Opt. Express **24**, 853-858 (2016).

[8] Martins, H. F., Pastor-Graells, J., Romero Cortes, L., Piote, D., Martin-Lopez, S., Azaña, J., and Gonzalez-Herraez, M. "PROUD-based method for simple real-time in-line characterization of propagation-induced distortions in NRZ data signals," Opt. Lett. **40**, 4356-4359 (2015).