M. R. Fernández-Ruiz, J. Pastor-Graells, H. F. Martins, A. Garcia-Ruiz, S. Martin-Lopez, and M. Gonzalez Herraez, 2018 , "> 10 dB SNR Enhancement in Distributed Acoustic Sensors through First Order Phase Noise Cancellation," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2018), paper W1K.2.

Available at https://doi.org/10.1364/OFC.2018.W1K.2

> 10 dB SNR Enhancement in Distributed Acoustic Sensors through First Order Phase Noise Cancellation

María R. Fernández-Ruiz[1], Juan Pastor-Graells[1], Hugo F. Martins[2], Andres Garcia-Ruiz[1], Sonia Martin-Lopez[1], and Miguel Gonzalez-Herraez[1]
[1] *Grupo de Ingeniería Fotónica, Universidad de Alcalá (UAH), Ctra. Madrid-Barcelona, s/n, Alcalá de Henares, 28805, Spain*
[2] *FOCUS S.L., C/ Orellana, 1, 1º Izda., Madrid, 28804, Spain*
Author e-mail address: rosario.fernandezr@uah.es

Abstract: The performance of Rayleigh-based distributed acoustic sensors (DAS) is strongly dependent on the coherence of the laser source. We present a simple methodology to reduce the impact of the laser phase noise in chirped-pulse DAS.

OCIS codes: (290.5870) Scattering, Rayleigh; (280.0280) Remote sensing and sensors; (060.2630) Frequency modulation; (030.0030) Coherence and statistical optics.

1. Introduction

Rayleigh based optical-time domain reflectometry (OTDR) has been used since the early 80's for probing the integrity of optical fiber links. This technique consists in launching a train of incoherent optical pulses into the fiber under test (FUT) and analyzing the resulting backscattered trace [1]. Aimed at the increase of OTDR signal-to-noise ratio (SNR), research efforts started to investigate on the use of coherent sources and trace coherent detection [2]. The use of coherent lasers revealed novel applications of OTDR technology towards the sensing of vibrations, strain or temperature variations over the fiber, leading to so-called phase-sensitive (Φ)OTDR [3,4]. In this kind of sensors, any perturbation in a section of the FUT that affects the fiber refractive index (e.g., temperature, strain) induces a change in the optical path difference between the scattering centers, in turn affecting the received interference pattern. Hence, by comparing consecutive traces, distributed sensing of those perturbations is readily possible.

The coherence of the probe light source is a fundamental factor in the practical viability of ΦOTDR sensors, mainly due to the elevated cost of highly coherent lasers. As such, much effort has been done to analyze the impact of the coherence of the probe light on the sensor performance [5]. In traditional ΦOTDR, the coherence length of the source has to be at least longer than the probe pulse width for vibration monitoring via direct detection of the backscattered trace. For a better performance in terms of SNR, techniques such as pulsing the source light using a semiconductor optical amplified (SOA) have been proposed, as the SOA increases the spectral purity of the laser in the active state and reduces the intraband coherent noise [5]. However, when direct detection is applied to the received trace, the resulting profile varies nonlinearly with the undergone perturbation. Therefore, the perturbation applied onto the FUT can be detected but not quantified. In order to obtain the absolute value of the perturbation, the most effective method is to acquire the trace phase using coherent detection [6]. In those cases, the need for mixing the trace with a local oscillator leads to the sensing range being limited by the coherence length of the laser. As a consequence, highly coherent lasers (i.e., with very narrow linewidth) are desired, substantially increasing the system cost. Recently, a novel technique to interrogate ΦOTDR sensors has been proposed, which is based on linearly chirping the probe pulse [7]. It has been demonstrated that using this kind of probe, any refractive index variation over the FUT translates into a proportional temporal shift over the corresponding positon of the received power trace, which can be detected simply via direct detection. The temporal shift is obtained by applying trace-to-trace correlations. Since only direct detection is required, the coherence requirements of this technique are the same as in the traditional case, i.e., the coherence length must be longer than the probe pulse width. However, in chirped pulse ΦOTDR, there is a direct relationship between the SNR and the coherence of the laser source, which has been thoroughly analyzed and evaluated in [8]. The reason is that the linear chirp induced in the pulse also translates the frequency fluctuations of the laser (caused by the finite linewidth of the laser) into temporal shifts along the resulting trace, inducing an error in the measurement.

In this work, we present a simple technique to mitigate the laser phase noise in chirped-pulse ΦOTDR. The proposed procedure enables to detect perturbations with high SNR even when using relatively conventional linewidth lasers. Up to 17 dB increase in SNR is experimentally achieved by applying the proposed technique.

2. Fundamentals of laser phase-noise cancellation in chirped-pulse DAS

The phase noise power spectral density (PSD) of lasers is directly proportional to their linewidth [9]. The first term of the Taylor expansion of the laser phase noise corresponds to a random fluctuation of the instantaneous frequency of the laser. Eventually, the finite linewidth of commercially available lasers produces a deviation in the emitting frequency over the nominal central frequency, υ_0. In ΦOTDR setups, this variation must be slower than the pulse width (recall that the laser source must have a coherence time longer than the pulse width). However, the central frequency of each pulse may differ from pulse to pulse, $\upsilon_{0} + \upsilon_{r,k}$., where the subscript r refers to a random value and the subscript k stands for each pulse within the input pulse train. Due to the use of linearly chirped probe pulses, the variation in the central frequency of each pulse $\upsilon_{r,k}$ translates into a proportional temporal shift of the trace, inducing noise in the readings of the temperature/strain variations. In [8] the proportionality relationship was derived as

$$\Delta t_{r,k} = \left(\tau_p / \Delta \upsilon_p\right) \cdot \upsilon_{r,k} = -0.78 \cdot \Delta \varepsilon_{r,k} \cdot \upsilon_0 \cdot \left(\tau_p / \Delta \upsilon_p\right), \qquad (1)$$

where $\Delta t_{r,k}$ is the temporal shift of each trace, τ_p is the probe pulse width and $\Delta\upsilon_p$ is the chirp spectral content. The second equality relates the temporal shift with the strain error $\Delta\varepsilon_{r,k}$ induced by $\upsilon_{r,k}$.

Under these considerations, it is inferred that each detected backscattered trace may suffer a particular deviation (i.e. a delay) that is maintained along the whole trace, but different from the other traces. This means that the frequency fluctuations of the input laser can be, to some extent, measured with the chirped-pulse ΦOTDR scheme. This issue is the basis that allows compensation of this noise. In particular, if a portion of FUT is kept unperturbed, the trace resulting from this fiber section will only contain low frequency environmental fluctuations and the frequency fluctuations caused by the laser linewidth (which are typically much larger). The former can also be minimized e.g., by introducing this section of fiber under a mechanically-isolated water bath, although this is not strictly necessary for the proper operation of the phase noise cancellation method. The temporal pattern of laser frequency fluctuations ($\upsilon_{r,k}$) along the whole measurement time is then obtained by averaging the temporal shift induced in the trace along the unperturbed fiber section. Thus, the effect of these fluctuations can be finally compensated along the complete fiber length. The unperturbed section has to be chosen long enough so that higher order phase noise components plus additional terms of thermal and optical noise are completely averaged.

3. Experimental demonstration and discussion

The experimental setup employed to validate our proposed phase noise technique is shown if Fig. 1. First, the chirped probe pulse is generated from an external cavity laser (ECL) whose central frequency υ_0 is selected by an intensity and temperature (I&T) controller. The ECL emission is pulsed using an SOA [5] driven by 100 ns-width rectangular-like pulses from an RF signal generator (SG), and the chirp is induced by modulating the driven current of the ECL using a ramp synchronized with the rectangular pulses. The peak-to-peak voltage of the ramp is set to induce a chirp spectral content of $\Delta\upsilon_p$ = 860 MHz. The resulting signal is boosted by a stage of erbium-doped fiber amplifier (EDFA) and band pass filter (BPF). In this case a dense wavelength division multiplexer (DWDM) is used as BPF. The pulses are launched into the FUT, which is a 1 km-long spool of single mode fiber (SMF) whose last 20 m have been strapped around a piezoelectric transducer (PZT). The PZT is connected to an SG and allow us to apply controlled strain on the fiber. The backscattered trace is amplified by another set of EDFA and BPF, and it is finally detected using a 1 GHz photodetector and a 40 GSps digitalized.

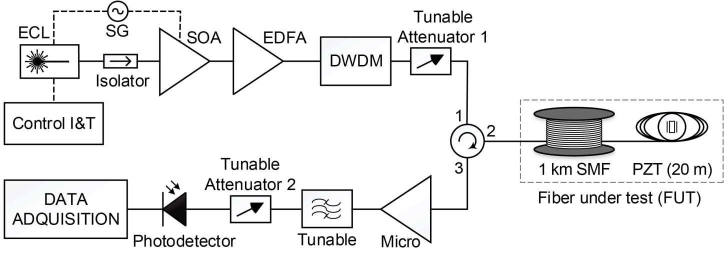

Fig. 1. Experimental setup used for the analysis of phase noise in chirped-pulse ΦOTDR. For that purpose, a strain perturbation applied in a piezo-electric transducer (PZT) is detected using three lasers with different linewidth. The acronyms are explained in the manuscript.

To test our method for different amounts of phase noise, we have used three lasers with different linewidths, namely ~5 MHz, ~50 kHz and ~25 kHz. The PZT induces a sinusoidal perturbation of 2 kHz and amplitude of 40 nε in the FUT. After applying a moving window of cross-correlation between consecutive traces, we detect the sinusoidal perturbations that are plotted in Fig. 2 in black, green and orange lines for the lasers of 5 MHz, 50 kHz and 25 kHz linewidth, respectively. Top figures show a portion of the sinusoidal perturbation in time domain, while the bottom figures show the corresponding PSDs over a measurement time of 0.4 s. The SNR of the three measurements is calculated from the PSD by obtaining the difference (in dB) between the spectral peak at 2 kHz and the average of the background noise. Hence, SNR of 34.4 dB, 54.7 dB and 56.7 dB are obtained for the lasers from the noisiest to the less noisy.

Next, we apply our frequency noise cancellation method. For this purpose, we measure the temporal pattern $\Delta t_{r,k}$ corresponding to the laser frequency noise perturbation ($\upsilon_{r,k}$) from 20 m of the unperturbed fiber previous to the location of the PZT. This pattern is translated into strain variations following Eq. (1). The resulting curve is subtracted from the measured strain perturbation, obtaining the curves shown in pink, red and blue lines in Fig. 2 for each laser. Once again, the PSD of the three curves is calculated (bottom of Fig. 2, same color code) where we can observe a reduction in the phase noise PSD of 14.1 dB for the 5 MHz-linewidth laser; 17.1 dB for the 50 kHz-linewidth laser; and 16.4 dB for the 25 kHz-linewidth laser. The reason for the noisiest level presenting the lowest frequency-noise compensation is that this laser has higher values of higher-order phase-noise components, which are not compensated by our proposed technique.

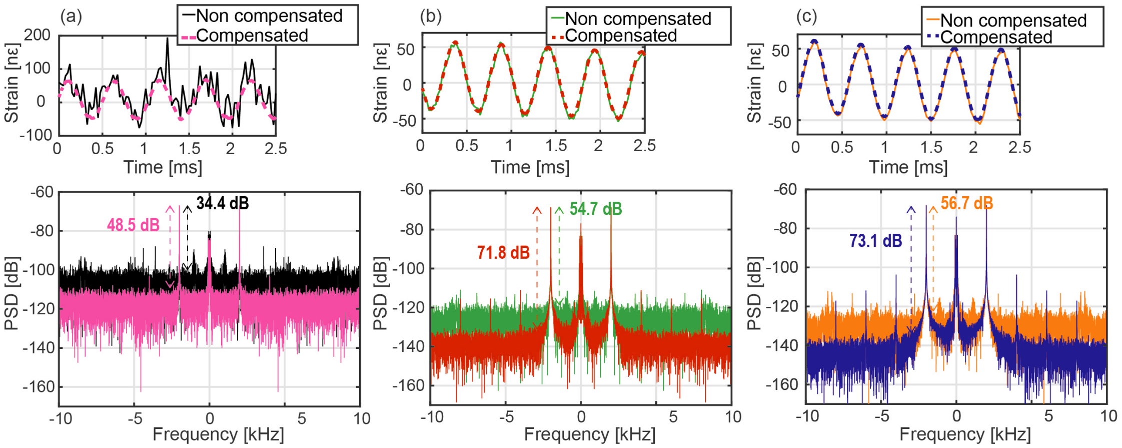

Fig. 2. Strain measurements employing three lasers with different linewidths: (a) 5 MHz (b) 50 kHz (c) 25 kHz. Top figure shows the time-domain perturbation before and after compensation. Bottom figure shows the corresponding power spectral densities (PSD).

4. Conclusions

A simple and efficient technique to reduce the first-order term of laser phase noise (i.e., the frequency noise) in chirped pulse ΦOTDR sensors has been proposed and experimentally validated. Up to 17 dB SNR enhancement has been achieved by using this technique. The presented results discloses the great robustness of chirped-pulse ΦOTDR, enabling the achievement of single-shot, quantitative, high SNR strain measurements even with relatively low coherence laser sources (always with coherence times longer than the pulse width) and direct detection.

5. Funding

This work was supported in part by: The European Research Council through project U-FINE (Grant 307441); the EC Horizon 2020 program through 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). The work of AGR was supported by the UAH (FPI contract).

6. References

[1]. M. K. Barnoski, et al., "Optical time domain reflectometer," Appl. Opt. **16**, 2375-2379 (1977).
[2]. P. Healey, "Fading in heterodyne OTDR," Electron. Lett. **20**, 30-32 (1984).
[3]. J. Park, et al., "Fiber optic intrusion sensor with the configuration of an optical time-domain reflectometer using coherent interference of Rayleigh backscattering," in Proc. SPIE, 1998, pp. 49–56.
[4]. J. Tejedor, et al., "Toward prevention of pipeline integrity threats using a smart fiber-optic surveillance system," J. Lightw. Technol. **34**, 4445-4453 (2016).
[5]. H. F. Martins, et al., "Coherence noise reduction in high visibility phase-sensitive optical time domain reflectometer for distributed sensing of ultrasonic waves," J. Lightw. Technol. **31**, 3631-3637 (2013).
[6]. Z. Wang, et al., "Coherent Φ-OTDR based on I/Q demodulation and homodyne detection," Opt. Express **24**, 853-858 (2016).
[7]. J. Pastor-Graells, et al., "Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses," Opt. Express **24**, 13121-13133 (2016).
[8]. J. Pastor-Graells, et al. "Impact of the laser phase noise on chirped-pulse phase-sensitive OTDR," in 25th Optical Fiber Sensors Conference (OFS), 2017, pp. 1-4.
[9]. S. Camatel, et al., "Narrow linewidth CW laser phase noise characterization methods for coherent transmission system applications," J. Lightw. Technol. **26**, 3048-3055 (2008).