Pastor-Graells, J. , Fernández-Ruiz, M.R., Martins, H.F., Garcia-Ruiz, A., Martin-Lopez , S. Gonzalez-Herraez, M., 2017, , "Impact of the laser phase noise on chirped-pulse phase-sensitive OTDR", Proc. SPIE 10323, 25th International Conference on Optical Fiber Sensors, (April 23, 2017), 103238T.

Impact of the laser phase noise on chirped-pulse phase-sensitive OTDR

Juan Pastor-Graells*[a], María R. Fernández-Ruiz[a], Hugo F. Martins[b], Andres Garcia-Ruiz[a], Sonia Martin-Lopez[a] and Miguel Gonzalez-Herraez[a]

[a]Departamento de Electrónica, Universidad de Alcalá, Escuela Politécnica Superior, 28805 Madrid, Spain; [b]FOCUS S. L., C/ Orellana, 1, 1º Izqda, 28004 Madrid, Spain

ABSTRACT

In this work, the impact of the laser phase noise on chirped-pulse phase-sensitive OTDR signals is theoretically and experimentally analyzed. In particular, it is shown that the noise in the readings of strain/temperature changes along the fiber scales directly with the frequency noise power spectral density of the laser. The effect of the pulse chirp on the signal to noise ratio is also investigated. Three lasers with different linewidths (5 MHz, 50 kHz and 25 kHz), i.e., with different phase noise, were used for the experimental study, confirming the validity of the theoretical model.

Keywords: Fiber optics sensors, optical time domain reflectometry, linear chirp, distributed acoustic sensor

1. INTRODUCTION AND OPERATION PRINCIPLE

Distributed Acoustic Sensing (DAS) technology is especially well suited for continuous monitoring of mechanical variations (e.g., vibration, displacements) over long distances or intrusions over large perimeters. In particular, phase-sensitive optical time-domain reflectometry (ΦOTDR) is an interesting solution that is gaining considerable attention in recent years [1], mostly within the framework of distributed vibration detection [2].

Recent progress in ΦOTDR has extended its applications to temperature or strain measurements using linearly chirped pulses [3]. Chirped-pulse ΦOTDR allows for the linear and single-shot strain measurements along several tens of kilometers in the kHz frequency range with nε resolutions, thereby enabling acoustic sensing [3]. In this technique, as in traditional ΦOTDR, a highly coherent optical probe pulse is injected into a single mode fiber and the backscattered signal is analyzed in the temporal domain. Thus, when no perturbation is applied onto the fiber, the detected trace remains constant over the time. In the traditional case (non-chirped probe optical pulse), when a refractive index change Δn (i.e., temperature or strain change) occurs in a fiber section, the corresponding section of the power trace varies nonlinearly with the undergone change. In contrast, when a linearly chirped pulse is launched into the fiber, a refractive index change translates into a proportional temporal shift in the corresponding section of the power trace [3,4]. The relationship between Δn suffered by a fiber section and the temporal shift [3] is

$$\frac{\Delta n}{n} = \left(\frac{1}{\nu_0}\right) \cdot \left(\frac{\Delta \nu_p}{\tau_p}\right) \cdot \Delta t \,, \qquad (1)$$

where ν_0 is the central frequency of the probe pulse, τ_p the temporal length, $\Delta\nu_p$ the chirp spectral content and Δt the measured temporal shift, obtained by means of temporal correlations. Finally, Δn is related with the temperature change ΔT or strain $\Delta\varepsilon$ with the expression $\Delta n/n = -6.92 \cdot 10^{-6} \cdot \Delta T = -0.78 \cdot \Delta\varepsilon$ (n being the effective fiber refractive index), as given by Koyamada in [5].

2. IMPACT OF THE LASER PHASE NOISE ON THE MEASUREMENT UNCERTAINTY

To realize a theoretical analysis of the impact of the laser phase noise in the sensor, we first introduce a general expression for the employed optical pulse. The complex envelope of the pulse $P(t,z)$, with rectangular intensity profile of amplitude E_0, temporal length τ_p and instantaneous angular frequency profile $\nu(t) = \nu_0 + (\Delta\nu_p/2 - \Delta\nu_p \cdot [t/\tau_p])$, is [3]:

*Contact author: juan.pastorg@uah.es; phone +34 91 885 6914

$$P(t,z) = E_0 \cdot rect\left[{(t - t_z)}/{\tau_p} \right] e^{j \cdot 2\pi \cdot \nu(t) \cdot (t - t_z)} e^{j\varphi_r(t)}, \quad (2)$$

where t_z is considered the time taken by the pulse to reach the position z in the fiber and $\varphi_r(t)$ is the random phase noise induced by the laser. The random instantaneous frequency due to $\varphi_r(t)$ is defined as

$$\nu_r(t) = \frac{1}{2\pi} \frac{d\varphi_r(t)}{dt}. \quad (3)$$

Following a similar derivation as in [3], it can be easily demonstrated that $\nu_r(t)$ induces a local temporal shift in the trace

$$\Delta t(t) = \left(\frac{\tau_p}{\delta \nu} \right) \cdot \nu_r(t). \quad (4)$$

Using Eq. 1, it is possible to relate a temporal shift in the trace with a variation in the refractive index. Thereby, the induced error in the strain measurements is related with $\nu_r(t)$ as

$$S_\varepsilon = \frac{S_{\nu_r}}{(0.78 \cdot \nu_0)^2} \propto \Delta f, \quad (5)$$

where S_ε and $S_{\nu r}$ are the strain and the random instantaneous frequency noise power spectral densities (PSD), respectively. This expression gives us a clear idea about the relationship between the laser linewidth and the strain uncertainty of the sensor. Since $S_{\nu r}$ is proportional to the laser linewidth [6], it can be concluded that S_ε is also proportional to Δf. Hence, choosing a laser with low phase noise will be essential to realize low uncertainty measurements.

In addition, Eq. (4) indicates that, when the laser phase noise is the limiting factor (as in our setup) the higher the probe pulse chirp, the lower the uncertainty in the determination of the delay. On the other hand, the nominal delay induced by the refractive index variation to be measured is also inversely proportional to the pulse chirp (Eq. 1). Eventually, this analysis allows us to conclude that the chosen pulse chirp will have basically no effect on the accurate determination of the measurand in chirped-pulse ΦOTDR schemes (i.e. both signal amplitude and laser phase noise effects scale inversely with the chirp). However, considering that for a linear relationship between delay and refractive index variation, the delay must be sufficiently short (within 2-3% of the probe pulse width, see [3]), a higher vibration amplitude between two consecutive traces will be measurable for higher pulse chirp (see Eq. 1). As such, the most convenient choice appears to be that the selected chirp value is as high as the system detection bandwidth can accommodate.

3. EXPERIMENTAL SETUP

The experimental setup used in this work (Fig. 1) is composed by a traditional ΦOTDR scheme, as the one developed in [2], but introducing a linear chirp in the pulse acting on the current control of the laser.

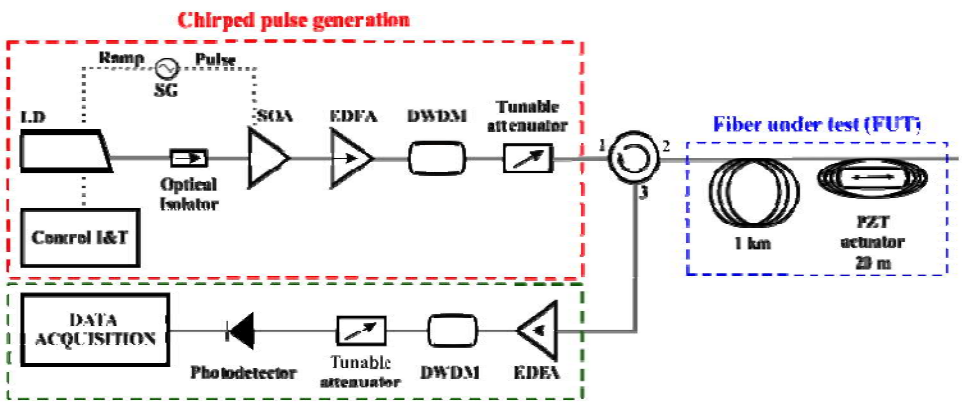

Figure 1. Experimental setup used in the experiment. Acronyms are explained in the text.

The setup is divided in three main blocks. In the chirped pulse generation block, a Laser Diode (LD) working in continuous emission is driven by a current and temperature controller to select the central wavelength. A secondary current control applies a repetitive electric ramp signal in the laser driver in order to apply a linear chirp in the outputted laser light. Three lasers with different linewidth (5 MHz, 50 kHz and 25 kHz) were employed to study the relationship between the measurement uncertainties and the laser phase noise. A Semiconductor Optical Amplifier (SOA) gated the chirped signal creating square optical pulses of 100 ns width with three different chirp spectral contents of 350 MHz, 589 MHz and 859 MHz. The secondary current slope, used to create the linear chirp, had to be adapted for each laser in order to obtain the same chirp spectral content. An Erbium-Doped Fiber Amplifier (EDFA) is used to boost the power of the optical pulses before injecting them into the fiber. In order to minimize the effect of the Amplified Spontaneous Emission (ASE) added by the EDFA, we insert a Dense Wavelength Division Multiplexer (DWDM) filter after the EDFA. The bandwidth of this DWDM is 0.8 nm.

Once the linearly chirped pulse has been generated, it is injected into the Fiber Under Test (FUT). It consists of 1 km fiber roll, of which the last 20 m are coiled around a Piezoelectric Transducer (PZT) in order to apply controlled vibrations on the fiber. In the intensity detection block, the backscattered signal is amplified and filtered as in the first block. Finally, the signal is detected using a p-i-n photo-detector with a bandwidth of 1 GHz and a high-speed digitizer with 40 GSps sampling rate.

4. EXPERIMENTAL RESULTS

We carried out an experiment to demonstrate the extent to which the phase noise of the laser employed for the measurements affects the measurement uncertainty. For this task, 2 kHz vibrations were applied on the last 20 m of the FUT. Then, these vibrations were detected by the chirped-pulse phase-sensitive OTDR using three lasers with different linewidths: 5 MHz, 50 kHz and 25 kHz and a chirp spectral content of 859 MHz. The pulses were injected into the fiber with a repetition rate of 40 kHz. Due to the Nyquist theorem, this system is able to detect vibrations up to 20 kHz. The amplitude of the 2 kHz vibration was set to 40 nε and was subsequently measured with 1 nε resolution. The three strain measurements are presented in Fig. 2 where the noise level difference between measurements is clearly noticeable. Figure 2a shows the measurement realized using the laser with the highest linewidth, 5 MHz. The region affected by the vibration, between 70 m and 90 m in the figure (note that only the last 100 m of the FUT are shown), can be discerned but it is slightly diffuse due to the high level of noise covering the measurement. In contrast, the lasers with lower linewidths (lower phase noise) present better results, as observed in Fig. 2b-c. Here, the region affected by the vibration is clearly defined in the color map (red and blue) and the non-affected region is almost totally flat (green). As it was expected, the laser with lowest linewidth (25 kHz) presents the best results.

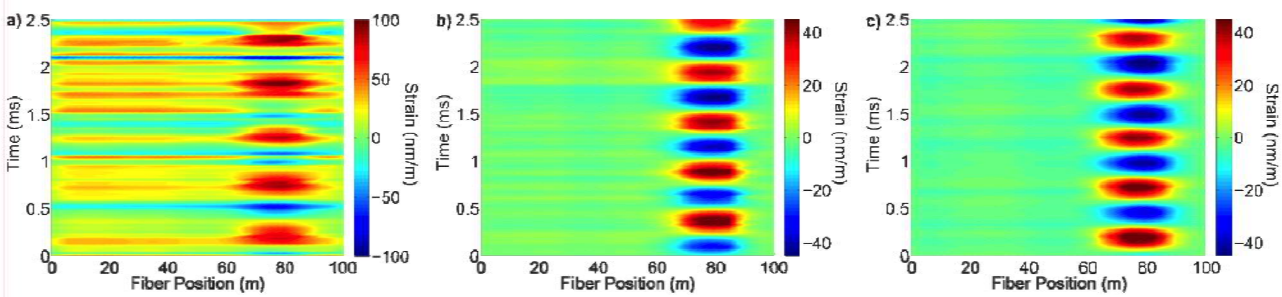

Figure 2. Strain measurements in the last 100 m of the FUT (during 2.5 ms) employing three lasers with different linewidths. (a) $\Delta f = 5$ MHz (b) $\Delta f = 50$ kHz (c) $\Delta f = 25$ kHz.

In order to quantify the signal-to-noise ratio (SNR) increase using lasers with low phase noise, the PSD of the recorded vibrations is analyzed. Fig. 3a shows the vibration PSD (around 2 kHz) at 78 m (within the last 100 m of the FUT, point with maximum amplitude) of the data plotted in Fig. 2. The three measurements present the 2 kHz peak with the same amplitude (-72 dB) but different background noise. The laser with 5 MHz linewidth (black) presents a SNR of 34.4 dB. In contrast, the one with 50 kHz (red) and 25 kHz (green) present SNRs of 54.7 dB and 56.7 dB, respectively. Thus, an SNR increase of 20.3 dB (laser with linewidth of 50 kHz) and 22.3 dB (laser with linewidth of 25 kHz) is obtained as compared with the 5 MHz-linewidth laser. These results show a good agreement with the theoretical model: considering Eq. 4, the SNR increase between the 5 MHz-linewidth laser and the 50 kHz and 50 kHz-linewidth lasers should be of 20 dB and 23 dB, respectively.

Finally, we experimentally prove that the chosen pulse chirp has no effect on the SNR of the measured vibrations. For this purpose, the error in the delay determination of the strain variation is calculated for three different chirp values, corresponding to pulse chirp spectral contents of 350 MHz, 589 MHz and 859 MHz, respectively, using the laser with lower phase noise. The results presented in Fig. 3b demonstrate that the amplitude and noise levels are independent on the employed chirp. However, as it was explained before, a higher pulse chirp allows to measure higher vibration amplitudes. Therefore, it is recommended to choose the highest possible chirp value in this sensor approach, ultimately limited by the available detection bandwidth of the sensor power trace.

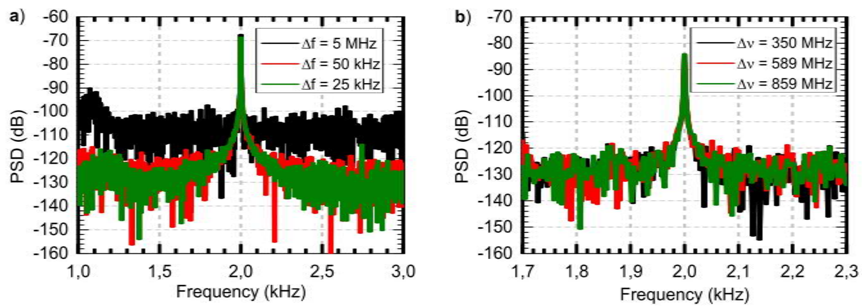

Figure 3. Spectra of 2 kHz vibration at 78 m (within the last 100 m of the FUT) (a) from measurements presented in Fig. 2 along 0.4 s (recorded time) with different lasers (5 MHz, 50 kHz and 25 kHz linewidth); (b) from measurements with 25 kHz linewidth laser and different chirp spectral contents (350 MHz, 589 MHz and 859 MHz).

5. CONCLUSIONS

In this work, the negative effects of the laser phase noise on chirped-pulse phase-sensitive OTDR measurements are demonstrated theoretically and experimentally. The use of lasers with a narrow linewidth (low phase noise) allows a significant increase in the SNR of the vibration recording, improving thus the sensor performance. This noise analysis is experimentally carried out via the measurement of vibrations using different linewidth lasers (5 MHz, 50 kHz and 25 kHz) and comparing the resulting SNR. An SNR enhancement of ~22 dB was obtained when decreasing the laser linewidth from 5 MHz to 25 kHz, in good agreement with the expected theoretical improvement. Additionally, the effect of the used pulse chirp on the SNR of the recovered acoustic signal is also evaluated, concluding that the latter is independent of the chirp. As such, the use of a chirp value adapted to the available detection bandwidth is recommended.

6. ACKNOWLEDGMENTS

This work was supported in part by: the European Research Council through project U FINE (Grant 307441); the EC Horizon 2020 program; the FINESSE project MSCA-ITN-ETN-722509; the DOMINO Water JPI project, under the WaterWorks2014 cofounded call by EC Horizon 2020 and Spanish MINECO; the Spanish MINECO through projects TEC2013-45265-R and TEC2015-71127-C2-2-R; and the regional program SINFOTON-CM: S2013/MIT-2790. The work of HFM was supported by EU funding through the FP7 ITN ICONE program, gr. #608099. The work of JPG and SML was supported by the Spanish MINECO through FPI and “Ramón y Cajal” contracts, respectively.

REFERENCES

[1] Tejedor, J., et al., "Towards Prevention of Pipeline Integrity Threats using a Smart Fiber Optic Surveillance System," J. Lightw. Technol. (2016), *in press*.
[2] Martins, H. F., et al., "Coherent Noise Reduction in High Visibility Phase-Sensitive Optical Time Domain Reflectometer for Distributed Sensing of Ultrasonic Waves," J. Lightw. Technol. 31, 3631-3637 (2013).
[3] Pastor-Graells, J., et al., "Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses," Opt. Express 24(12), 13121-13133 (2016).
[4] Pastor-Graells, J., et al., "Truly linear and dynamic distributed strain sensor using intensity-only measurements," Proc. of OSA Technical Digest (online) (Optical Society of America, 2016), SeM3D.5 (2016).
[5] Koyamada, Y., et al., "Fiber-Optic Distributed Strain and Temperature Sensing With Very High Measurand Resolution Over Long Range Using Coherent OTDR," J. Lightw. Technol. 27(9), 1142-1146 (2009).
[6] Camatel, S. and Ferrero, V., "Narrow Linewidth CW Laser Phase Noise Characterization Methods for Coherent Transmission System Applications," J. Lightw. Technol. 26(17), 3048-3055 (2008).