Measurement of polarization fading sensitivity in FBGs-assisted Phase-OTDR

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ABSTRACT

Distributed optical fiber vibration sensors (DOFSs) such as those based on phase-sensitive optical time-domain reflectometry (φ-OTDR) have contributed to improve structural health monitoring (SHM). φ-OTDR allows distributed vibration sensing by analysing the interference properties of the backscattered/reflected signal when an optical pulse is launched into the sensing fiber. As the Rayleigh backscattered light is relatively weak, fiber Bragg grating (FBG) arrays can be inscribed in the sensing fiber to increase the signal-to-noise ratio. However, the interference of the signals reflected by two consecutive FBGs (containing information about the locally applied vibration) is subject to a polarization fading effect as the sensing fiber presents some birefringence. Therefore the states of polarization (SOP) of the interfering reflected signals are no longer fully aligned. The present work proposes a measurement setup to quantify the polarization effects in a direct detection phase-OTDR scheme through the polarization fading sensitivity (PFS) parameter.

Keywords: DFOS, FBGs, φ-OTDR, vibration sensing, polarization effects.

1. INTRODUCTION

The evolution of scientific research and metrology enabled a massive development of distributed optic fiber sensors (DOFSs) that represent a new technological milestone among sensors. DOFSs allow the extraction of necessary data in a distributed way which is very useful in many applications such as crack detection in civil engineering, composite structural health monitoring SHM, and surface seismic surveying.[1] Among DOFSs, phase-optical time domain reflectometry (φ-OTDR) enables the monitoring of long-distance vibration and multi-point intrusion simultaneously in civil infrastructures (railroads, bridges, pipelines, optical networks...). The ultra-narrow linewidth laser (NLL) of the φ-OTDR launches probe pulses into the optical fiber and the coherent interaction of a great number of Rayleigh scattering (RS) centers within the pulse duration is sensitive to vibration or external disturbances applied to the fiber. The phase variation of the Rayleigh backscattered light (RBL) can be detected by the φ-OTDR.[2] As the RBL is relatively weak (several tens of dBs lower than FBGs reflected light), fiber Bragg gratings (FBGs) can be inscribed in the fiber to increase the signal-to-noise-ratio (SNR).[3] The interference signal between two consecutive FBGs is sensitive to external vibration applied between them, the vibration modifying the power recorded versus time at the interference signal position on the phase-OTDR trace. A double pulse interrogation technique can be used as a probe pulse. The interference signal can be observed if the delay between the two pulses corresponds in the spatial domain to twice the distance between two successive FBGs.[4,5] However, using a cascade of identical FBGs generates some undesirable effects presented in,[6] such as polarization effects. The interference of the signals reflected by two consecutive FBGs (containing information about the locally applied vibration) is subject to a polarization fading effect as the fiber presents some birefringence. Therefore, the states of polarization (SOP) of the reflected signals are no longer fully aligned.

A possible application of the FBG-assisted φ-OTDR is the localization of external stress (e.g. wind effect, presence of ice in winter) in FTTH (Fiber To The Home) Passive Optical Network (PON). In general, to

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alleviate polarization effects, a phase-OTDR scheme using a coherent detection (with a polarization-diversity stage) could be used, which requires the laser source to interfere with the signal reflected by the FBGs.[7] However, in FTTH applications, the maximum distance between the optical source and the signal reflected by an FBG at the subscriber's home can be up to 20 km. Since the laser's coherence length must be larger than the light propagation distance, using coherent detection would mean using an expensive source, which is a real issue for on-field FTTH applications. Moreover, it will be advantageous for telecommunication operators to use the telecommunication lasers (DFB lasers) as the φ-OTDR source. This is the reason why direct detection scheme is preferred for these applications. In such a case, the signals reflected by two successive FBGs do not interfere with the source but their interference signal will be directly detected by the photodiode. As a consequence, polarization fading can be an issue. In order to evaluate the resulting detriment effect, the present work aims to propose a measurement setup to quantify the polarization fading sensitivity for direct detection FBG-assisted phase-OTDR scheme.

2. EXPERIMENTAL SETUP

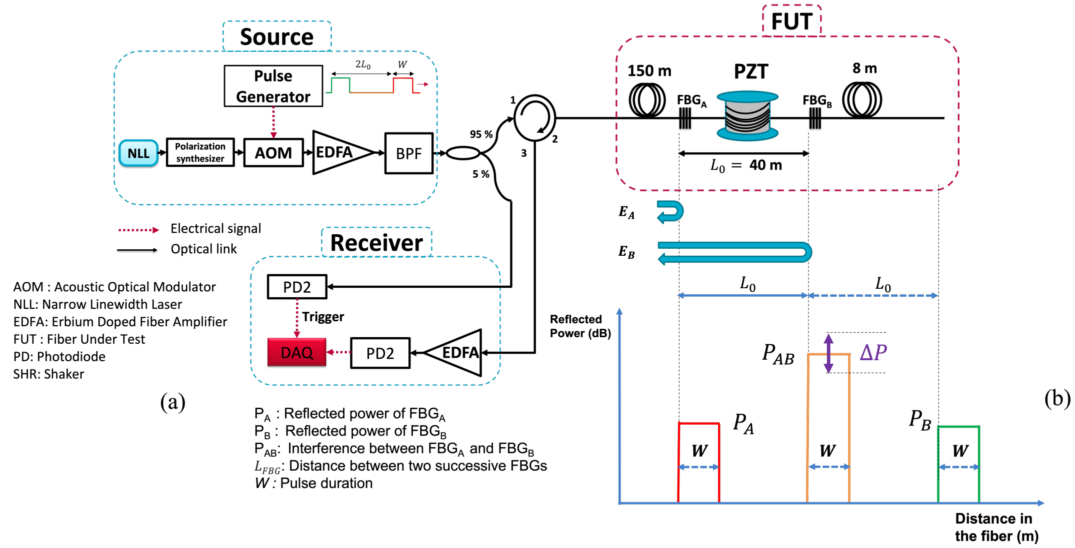

Figure 1: Experimental setup

The experimental setup is presented in figure 1a and is composed of the source, the FUT (fiber under test) and the receiver. The light source consists of an NLL emitting a highly coherent and continuous light with a linewidth of 0.1 kHz and a wavelength of 1552.5 nm. Note that the present work aims to propose a setup to measure the polarization fading sensitivity of a given sensing fiber configuration in general and not to be applied directly for FTTH monitoring. This is the reason why an NLL source can be kept. A pulse function generator (PG) enables to generate a pulsed electrical signal sent to an acousto-optic modulator (AOM) which modulates the continuous lightwave to obtain a double-pulse configuration so that the pulse duration is equal to 80 ns, and the delay is set to 400 ns with a repetition rate of 241.5 kHz. The pairs of pulses are amplified by an erbium doped fiber amplifier (EDFA) and filtered by a bandpass filter (BPF, bandwidth of 1nm) and finally launched into the FUT through the first port of an optical circulator. Two very low reflectivity FBGs (0.04 %) have been inscribed in the FUT. Both share globally the same characteristics, having a length of 4mm, a center wavelength of 1552.5nm and a 3dB bandwidth of 0.2 nm. The grating pitch is equal to 536.42 nm. FBGs are separated by $L_0 = 40$ m of single mode fiber (SMF) . The FBG is preceding by a lead-in fiber spool of 150 m and terminated by a fiber spool of 8 m length. To test the proposed setup, the fiber link under test (FUT) is made of a 40 m SMF inserted between two identical FBGs. The 40 m are coiled around a cylindrical piezoelectric (PZT) actuator having an outer diameter of 2.5 cm. The PZT plays two roles: inducing a vibration effect along the fiber and generating a controlled bending-induced birefringence. The actuator is excited by a signal generator with a sinusoidal signal having a peak-to-peak amplitude $Vpp = 40$ mV and a 10 kHz frequency. The FUT is covered by a plastic box to isolate it from the lab environment (acoustic and mechanical vibrations from lab occupants, fans and noise of various instruments, ...). The backscattered/reflected light is guided to the receiver through the port 3 of the circulator. The receiver comprises of an optical amplifier, a photodetector (PD) with a transimpedance gain amplifier and a data acquisition card with 1 GS/s sampling rate. The phase-OTDR trace records the backscattered/reflected signal as a function of the distance along the fiber. A schematic φ-OTDR trace is shown in figure 1b. P_A (P_B) represents the signal reflected by the FBG$_A$ (FBG$_B$) and P_{AB}, the interference signal between reflected signals by FBG$_A$ and FBG$_B$. ΔP represents the power difference between the maximum and the minimum power levels at the interference zone obtained over a vibration period.

To evaluate the polarization fading, a polarization synthesizer placed after the light source enables to sweep off all possible input SOPs. The polarization synthesizer is configured to sweep all the possible input SOPs while ensuring to maintain each SOP fixed during 12 vibration periods (to allow the φ-OTDR to detect the vibration signal and to measure ΔP for each fixed SOP. The polarization synthesizer can perform this task over 3s. Figure 2 presents the features chosen for the polarization synthesizer. Figure 2a shows how the polarization synthesizer maintains the SOP stable during Δt = 1.2 ms corresponding to 12 periods for a signal of 10 kHz vibration. The stokes S_1, S_2, S_3 parameters of the emitted light are indeed stable over Δt. Figure 2b shows on the Poincaré sphere all the swept input SOPs over 3 s.

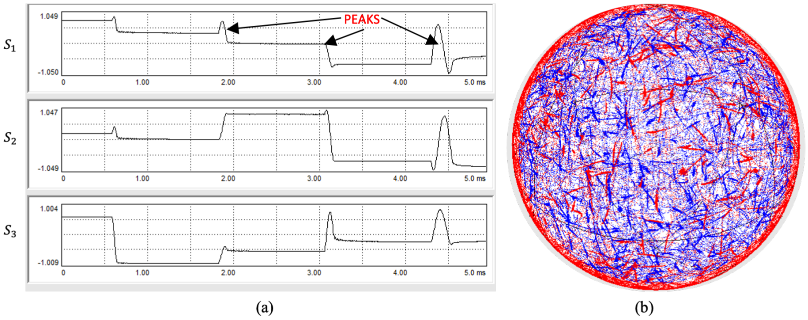

Figure 2: (a) Stokes parameters versus time of the SOP at the polarization synthesizer output for the first 5 ms (b) SOPs at the polarization synthesizer output on the Poincaré sphere over 3 s

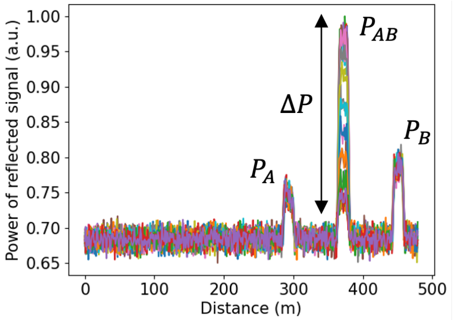

Figure 3: φ-OTDR traces with both polarization effects and vibrations for one vibration period

Due to the birefringence of the fiber (mainly induced by the bending around the PZT transducer) and the corresponding to polarization fading, the power variation ΔP depends on the input SOP. To evaluate the polarization effects based on the evolution of the power variation ΔP, it is possible to use the polarization fading sensitivity (PFS), which can be defined as:

$$\mathrm{PFS} = 10 log_{10}\left(\frac{\Delta P_{max}}{\Delta P_{min}}\right) [dB] \tag{1}$$

where $\Delta P_{max(min)}$ is the maximum (minimum) ΔP observed when sweeping all the possible input SOPs. When the SOPs reflected by FBGs are aligned whatever the input SOP, the PFS = 0 dB ($\Delta P_{max} = \Delta P_{min}$) and when the SOPs are orthogonal for at least one input SOP, $\Delta P_{min} = 0$ so that the PFS reaches infinite. The polarization fading sensitivity (PFS) enables quantifying the polarization effects in an FBG-assisted phase-OTDR.

3. RESULTS

The φ-OTDR receiver has been configured to record the traces when the PZT transducer is active and when varying the input SOP. The overlay of the recorded φ-OTDR traces is presented in figure 3 for one of the input SOPs. The P_{AB} peak clearly fluctuates, which allows to measure a ΔP.

Figure 4 shows the interference signal $P_{AB}(t)$ detected by the φ-OTDR over 3 s while the polarization synthesizer is sweeping over all possible input polarization states. In the zooms 1-2-3 made in figure 4, it clearly appears that the power variation ΔP changes every 1.2 ms, i.e. when the SOP changes. When the SOPs of the signals reflected by the gratings are aligned, ΔP is maximal. However, for some input SOPs, ΔP is weak or close to zero.

This can be explained by the fact that the reflected signals by the gratings have SOPs close to orthogonality, so that the signals can not interfere correctly. When the reflected signals have orthogonal SOPs, the signals reflected by gratings cannot interfere, and ΔP will equal to 0. For this extreme case, the PFS is infinite.
Note that a signal processing has been made to remove the effect of some undesirable peaks that occurred due to the polarization change induced by the polarization synthesizer and affected the measurement over time (see peaks in figure 2a). Figure 5 presents the evolution of ΔP measured over 3 s after removing the undesirable effect of the peaks. By taking the two extrema in figure 5 (ΔP_{max} and ΔP_{min} respectively equal to 3286.64 and 335.09 DAQ counts) it is possible to calculate the PFS, which was equal to 9.92 dB. Six different measurements have been made and the mean PFS obtained is <PFS> = 9.94 dB with a standard deviation STD = 0.26. The estimation of the PFS measurement uncertainty and the comparison with a simulated value is under progress.

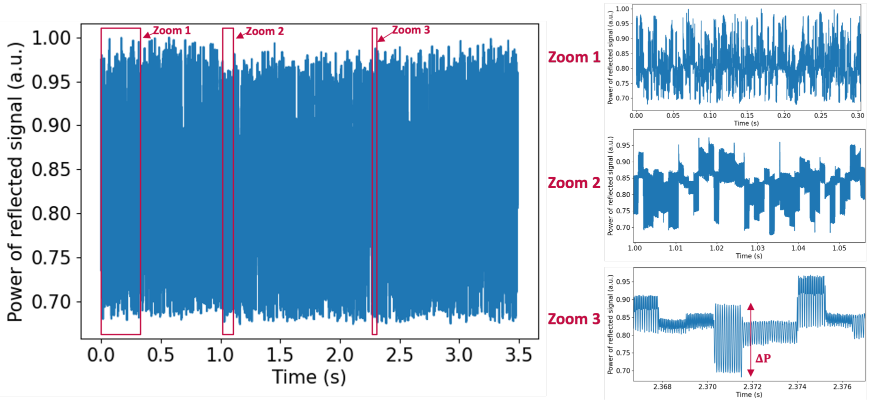

Figure 4: P_{AB}(t) at 190 m and measured over 3 s

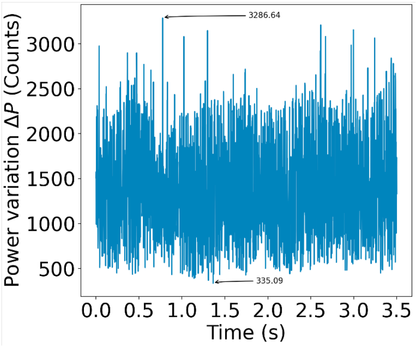

Figure 5: Power variation ΔP measured over 3 s

4. CONCLUSION

This work proposed an experimental setup to evaluate the polarization fading effect in direct detection FBG-assisted φ-OTDR. The analysis is based on the measurement of the PFS parameter. The mean PFS obtained was 9.94 dB for the proposed configuration with an STD of 0.26 obtained over 6 measurements. In a near future, the setup will then be used to measure the PFS improvement when using spun fibers.

REFERENCES

[1] Hartog, A. H., [*An introduction to distributed optical fibre sensors*], CRC press (2017).

[2] Peng, F., Duan, N., Rao, Y.-J., and Li, J., "Real-time position and speed monitoring of trains using phase-sensitive otdr," *IEEE Photonics Technology Letters* **26**(20), 2055–2057 (2014).

[3] de Miguel Soto, V., Jason, J., Kurtoğlu, D., Lopez-Amo, M., and Wuilpart, M., "Spectral shadowing suppression technique in phase-otdr sensing based on weak fiber bragg grating array," *Optics Letters* **44**(3), 526–529 (2019).

[4] Liu, T., Wang, F., Zhou, L., Zhang, X., and Zhang, L., "Phase sensitive distributed vibration sensing using double-pulse for ultra-weak fbg array," in [*Conference on Lasers and Electro-Optics/Pacific Rim*], s0978, Optica Publishing Group (2017).

[5] Sandah, F., Dossou, M., and Wuilpart, M., "Spectral shadowing compensation in double-pulse fbg-assisted φ-otdr," in [*2022 Photonics & Electromagnetics Research Symposium (PIERS)*], 530–535, IEEE (2022).

[6] Gorshkov, B. G., Yüksel, K., Fotiadi, A. A., Wuilpart, M., Korobko, D. A., Zhirnov, A. A., Stepanov, K. V., Turov, A. T., Konstantinov, Y. A., and Lobach, I. A., "Scientific applications of distributed acoustic sensing: State-of-the-art review and perspective," *Sensors* **22**(3), 1033 (2022).

[7] Yan, Q., Tian, M., Li, X., Yang, Q., and Xu, Y., "Coherent φ-otdr based on polarization-diversity integrated coherent receiver and heterodyne detection," in [*2017 25th Optical Fiber Sensors Conference (OFS)*], 1–4, IEEE (2017).