Impact of the probe pulse shape on the performance of phase-sensitive optical time-domain reflectometry sensors

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ABSTRACT

In this communication, the effect of the probe pulse shape on the backscattered power trace of phase-sensitive (φ-) OTDR is analyzed. In particular, the power traces obtained with rectangular and Gaussian-like probe pulses are compared, both numerically and experimentally. Our analysis reveals that the use of Gaussian-like pulses can increase the operation range and sensitivity of φOTDR-based sensors in at least two-fold as compared with that obtained from traditionally-employed rectangular-like pulses.

Keywords: Distributed optical fiber sensors, phase-sensitive optical time-domain reflectometry, pulse-shaping.

1. INTRODUCTION

The interest in fiber optic sensors has increased significantly over the last decade due to their intrinsic properties, such as immunity to electromagnetic noise, lightweight, relatively low cost, possibility of remote operation and multiplexing capability[1]. Moreover, distributed optical sensors represent a cost-effective solution for monitoring of large infrastructures such as bridges, railways, gas and oil pipelines, etc.[1] Recently, significant progress has been achieved in the field of distributed optical sensors exploiting Rayleigh scattering-based time-domain reflectometry (OTDR)[2-7]. OTDR has been traditionally used for measuring the fiber attenuation, splice and connector losses of optical fibers. OTDR systems expanded their applicability toward sensing of mechanical variations (e.g., vibration or displacement) with the use of coherent lasers[2], leading to the so-called phase sensitive (φ-)OTDR. The phase of the transmitted light is sensitive to mechanical perturbations that can be simply detected from the coherent interference of the scattered light. φOTDR technology has recently proven to have a great potential to achieve temperature, strain and birefringence sensing in a simple, time-effective fashion[3,4]. Temperature or strain variations in the fiber induce a change in the refractive index, which can be compensated at the trace level with a frequency-shifted pulse. The use of pulses with linear chirp enables a mapping of any spectral variation into a temporal variation, producing a change in the time-domain power trace[3]. Distributed birefringence profile of optical fibers has also been achieved via polarization-resolved φOTDR measurements. Considering the broad range of applications of φOTDR technology, researchers have focused their attention into the improvement of performance of φOTDR-based sensors. The followed strategies to date have implied the addition of external processes, such as the distributed amplification of the backscattered signal via Brillouin or Raman amplification[5,6]; or the application of post-processing denoising techniques to the received trace[7]. These advances have enabled to obtain measurement ranges of up to 125 km with spatial resolutions of 10 m[6]. Moreover, the achievable bandwidth of the measurement of vibrations has reached well the kHz regime[7], while the resolution of temperature and strain may exceed in two orders of magnitude the traditionally employed Brillouin or Raman-based distributed sensors (up to 1 mK or 4 nε)[3].

In this communication, we present a simple method to increase the length range and sensitivity of φOTDR sensors without the need for additional amplification or external signal-processing algorithms. It consists on shaping the power envelope of the probe pulses, aimed at mitigating the appearance of nonlinear effects that typically affect the propagation of traditionally employed rectangular-like probe pulses. As a proof-of-concept, we perform a comparison of the received power trace from a φOTDR scheme when using a rectangular and Gaussian-like input pulse. Our numerical and experimental results indicate that the use of Gaussian-like pulses can increase the length range and the sensitivity of φOTDR sensors while maintaining their spatial resolution and signal-to-noise ratio (SNR).

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2. LIMITING FACTORS IN THE PERFORMANCE OF ΦOTDR SENSORS

Rayleigh scattering is an elastic scattering process in which light is reflected in fiber inhomogeneities much smaller than the wavelength of the propagating light. The received power trace is produced by coherent interference of the scattered light, and shows a static, noise-like interference pattern from which variations of different physical parameters along the fiber can be monitored, as introduced in Section 1. There is a well-known trade-off between spatial resolution, length range and SNR of φOTDR-based sensors. Those parameters are intimately related with the features of the probe pulse that is launched into the sensing fiber to perform the measurements. Higher spatial resolutions are achieved from narrower probe pulses. On the other hand, the probe pulses need to have high energy to achieve the best possible SNR in detection. This situation leads to the need for high peak powers, which makes the propagating pulses be subject to nonlinear impairments that negatively impact on the visibility of the received trace[8].

Typically, rectangular-like pulses with pulse-widths in the hundreds of ns range are employed in φOTDR. This quasi-continuous-wave (CW) propagation induces modulation instability (MI) in the propagation, caused by a joint effect of Kerr-nonlinearities and anomalous dispersion[9]. Under certain conditions, such as the propagation of a continuous level of power over certain temporal width (e.g., rectangular pulses) and in the absence of competing nonlinear effects (e.g. Brillouin scattering), MI fosters the Fermi-Pasta-Ulam (FPU) recurrence, which causes an oscillatory energy transfer between the signal of interest and the noise at the MI gain bandwidth. This effect leads to the appearance of visibility fading in certain positions of the power trace[8], reducing the sensitivity of the sensor at these locations and limiting the length range for trustable measurements. To avoid this undesired effect, the probe pulse peak power has to be kept below a certain value, which has traditionally limited the SNR and, consequently, the length range of these sensors. Here we show that FPU recurrence can be mitigated if the probe pulse envelope is modulated, avoiding the propagation of quasi-CW light. Next, we present a numerical and experimental study of the effect of launching a pulse with Gaussian-like envelope in the φOTDR received power trace, as compared with the traditional case (i.e., use of rectangular pulse).

3. NUMERICAL AND EXPERIMENTAL RESULTS

3.1 Numerical analysis: Simulation model

The first step in our analysis is the realization of a series of numerical simulations to identify the effects of the shape of the probe pulse envelope in the power trace obtained via φOTDR. For this purpose, we have employed a simulation algorithm that has been developed as follows: first, the propagation of the probe pulse along the fiber is simulated by solving the nonlinear Schrödinger equation (NLSE)[9] using a split-step Fourier method with adaptive step size. Then, Rayleigh scattering is simulated updating temporal and spectral profile of the probe pulse along its propagation. The envelopes of the optical input pulse shapes, plotted in Fig. 1 (a) and (b) in dashed line, are described as

$$e_{rect}(t) = \begin{cases} \sqrt{P_{0,r}}, & t \le \tau_{FWHM} \\ 0, & t > \tau_{FWHM} \end{cases}; \qquad e_{Gaus}(t) = \sqrt{P_{0,G}} \cdot \exp\left(-\frac{2\ln(2) t^2}{\tau_{FWHM}^2} \right), \tag{1}$$

where τ_{FWHM} is the full width at half maximum of the pulses, which is set to 100 ns, and $P_{0,r}$ and $P_{0,G}$ are the peak power of the rectangular and Gaussian-like pulses, respectively. The values of input peak power have been selected so that the pulses have the same energy, namely 165 nJ, with the aim of generating power traces with similar SNR. This value of energy ensures the appearance of nonlinear effects in the propagation of the pulse. This corresponds to $P_{0,r}$ = 1.65 W and $P_{0,G}$ = 1.6 W. The NLSE is solved for a single-mode fiber (SMF-28) with a length of 15 km. The specifications of the fiber are: nonlinear coefficient γ = 1.1 W^{-1} km^{-1}, second order dispersion parameter β_2 = -21.7 ps^2/km, and attenuation α = 0.2 dB/km. Finally, the power trace is calculated from the resulting backscattered electromagnetic field by modeling the effect of a 125 MHz-bandwidth photodetector (PD). The visibility of the resulting power traces is calculated as $V = (T_{max} - T_{min})/(T_{max} - T_{min})$, where T_{max} and T_{min} are the maximum and minimum values of the trace over a certain distance record[8]. In this case, a window of 60 m has been employed in order to consider sufficiently high number of samples of the numerically obtained discrete power traces. The resulting visibility curves are plotted in Fig. 2 (dashed lines). From these results, we observe that the trace obtained from the propagation of a rectangular pulse presents FPU recurrence-induced fading, while the fading is significantly reduced when using a Gaussian-like probe pulse. Further discussion about these results will be carried out in Section 3.3.

3.2 Employed setup

To validate our simulation tool and numerical results, we have carried out an experimental demonstration of the proposed scheme. The setup employed is depicted in Fig. 1 (c). An external cavity laser (ECL) laser generates a CW light at a wavelength of 1550 nm. Then, the target power envelope, which is electrically generated using a signal generator (SG), is carved in the CW light using a semiconductor optical amplifier (SOA). The pulse is amplified using an Erbium-doped fiber amplifier (EDFA) up to have approximately the same peak power of the pulses employed in the numerical analysis, i.e., 1.65 W and 1.6 W for the rectangular and Gaussian shape, respectively. The synthesized pulse shapes are measured at a control arm located after the EDFA, and they are shown in Fig. 1 (a) and (b) (in solid line). The slope in the peak power of the rectangular pulse is due to the non-constant amplification gain of the SOA. A dense wavelength division multiplexer (DWDM) is employed to filter out the amplified spontaneous emission (ASE) from the EDFA, and the resulting pulses propagate through the 15 km-long sensing fiber. The received traces are amplified using a micro-EDFA and then detected using a 125 MHz-bandwidth PD. The visibility of the traces is calculated using the same window as in the numerical simulation, and the resulting visibility curves are presented in Fig. 2.

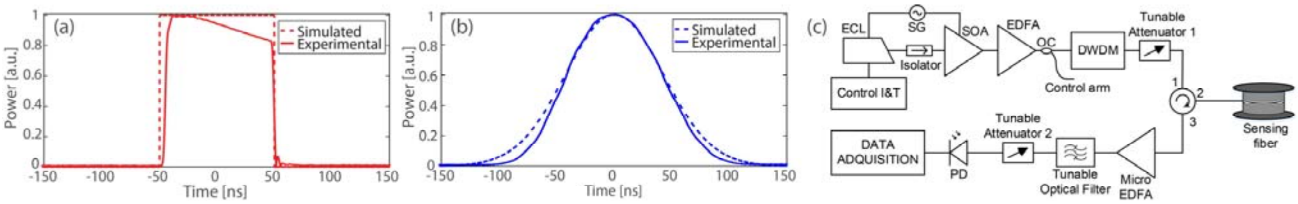

Figure 1. (a) Rectangular-like complex envelope of the input probe pulse: numerical (dashed line) and experimental (solid line); (b) Gaussian-like complex envelope of the probe pulse: numerical (dashed line) and experimental (solid line); (c) Experimental setup (acronyms are explained in the text).

3.3 Discussion on the obtained results

In this Section, the numerical and experimentally obtained results are presented and compared. For a clearer analysis, we just compare the visibility of the obtained traces instead of the traces themselves. Figure 2 shows all the obtained results, following the same color code than in Fig. 1. A comparison between numerical and experimental results is performed in Figs. 2 (a) and (b). Figure 2 (c) shows the superposition of the curves previously presented for comparison purposes.

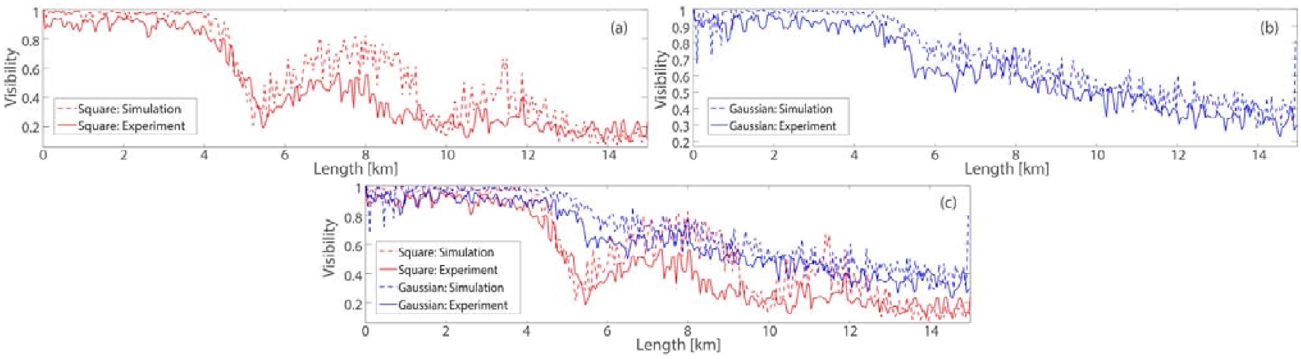

Figure 2. Visibility of the power trace, simulated (dashed line) and experimental (solid line): (a) from a rectangular input pulse; (b) from a Gaussian input pulse; (c) Superposition of the previously presented curves.

From Fig. 2 (a) and (b), we can verify the proper functionality of the employed simulation tool. Both the numerically and experimentally obtained visibility curves present the same behavioral pattern. In particular, the resulting trace from the propagation of a rectangular pulse (Fig. 2 (a)) presents the expected fading at localized positions, after which the trace visibility is partly recovered due to FPU recurrence[8]. We can observe how in the experimental result the power recovery at the bandwidth of interest is reduced as compared with the ideally expected (numerical) curve. The reason may be attributed to the fact that the FPU recurrence requires a delicate balance of power, which is not easily satisfied in practical conditions. In the case of propagation of a Gaussian-like pulse (Fig. 2 (b)), there is an excellent matching between the numerical and experimental results. The comparison between these two results (Fig. 2 (c)) proves that the modulation of the probe pulse using a Gaussian-like power envelope can mitigate the fading occurred when using a rectangular-like pulse. The reason is that Gaussian pulses have a continuous distribution of intensity levels associated with different MI gains and frequencies, which essentially destroys the FPU process. Still, we can observe that the trace visibility smoothly decays from a distance of ~5 km due to MI (the signal of interest pumps optical components outside the PD bandwidth), but the rapid depletion of the signal of interest due to FPU recurrence that occurs when using rectangular pulses is not evident when Gaussian pulses are employed. We have verified through simulations that, contrary to the case of Brillouin-based sensors[10], the effect of self-phase modulation (SPM) of the pulses barely affect the final power trace as long as the spectral broadening of the pulse lies within the bandwidth of the PD. Otherwise, the decaying of the trace visibility is simply slightly more pronounced. Thus, the length range and sensitivity of the sensing system can be increased without the need for any external amplification stage or post-processing methods.

4. CONCLUSIONS

To sum up, in this communication we have analyzed the impact of the beamshape of the probe pulse on the received power trace of φOTDR. We have demonstrated that the smooth modulation of the complex envelope of the input probe pulse can increase the length range as well as the overall sensitivity of φOTDR sensors. In particular, the use of a Gaussian-like input pulse mitigates the localized fading induced by FPU recurrence. This enables an increase of the range of more than two-fold while maintaining the spatial resolution and SNR of the measurements, without the need for external amplification or application of post-processing algorithms.

5. ACKNOWLEDGMENTS

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