20 dB SNR enhancement in phase-sensitive OTDR using pulse stretching and recompression

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ABSTRACT

This work shows the possibility of using chirped pulse amplification concepts in order to increase the signal-to-noise ratio (SNR) of phase sensitive optical time domain reflectometry (ΦOTDR) sensors. This method allows to increase the SNR of a ΦOTDR sensor without sacrificing spatial resolution. Here, we report a ΦOTDR sensor with a spatial resolution of 3 mm (limited only by the available detection equipment) and an SNR increase of 20 dB over the traditional architecture. To our knowledge, this is the highest-resolution ΦOTDR sensor reported to date.

Keywords: Fiber optic sensors, optical time domain reflectometry, chirped pulse amplification

1. INTRODUCTION

Distributed Optical Fiber Sensors (DOFS) allow for the continuous, spatially-resolved measurement of different physical parameters (temperature, strain, birefringence, etc.) over long distances (typically tens of kilometers), in optical fiber platforms [1]. Among DOFS, Phase Sensitive Optical Time Domain Reflectometers (ΦOTDRs) are commonly used for distributed vibration detection [2]. Some variations of the traditional ΦOTDR extend its application to the monitoring of quantitative dynamic temperature or strain [3]. The range, spatial resolution, and Signal-to-Noise Ratio (SNR) of a ΦOTDR sensor are tightly related parameters. For a given resolution value (set by the temporal width of the input pump pulse), an increase of dynamic range and SNR of a ΦOTDR sensor can only be achieved by increasing the input pump peak power. However, this peak power cannot be indefinitely increased due to the onset of nonlinear effects [4-6]. To reduce these limitations, we propose a new technique that allows a substantial increase in the pulse energy in ΦOTDR, based on Chirped Pulse Amplification (CPA) concepts [7,8]. This method achieves an increase in SNR of several orders of magnitude without sacrificing the spatial resolution of the sensor.

2. OPERATION PRINCIPLE AND EXPERIMENTAL SETUP

The proposed technique is conceptually similar to CPA in ultrashort pulse amplification [7,8]. The input pulses are temporally stretched using a dispersive device. This distributes the energy carried by the input pulse over a longer temporal interval, effectively reducing its peak power. Since the fiber nonlinearities are essentially dependent on the pulse peak power [6], the energy level of the dispersed pulses can be substantially raised without triggering nonlinear effects during the propagation through the Fiber Under Test (FUT). Upon arrival of the backscattered contributions, the dispersion introduced at the input of the FUT is compensated by another dispersive device with equal dispersion magnitude and opposite sign. In the absence of nonlinearities, the system behaves essentially as a conventional ΦOTDR sensor, with a resolution given by the input pulse width. The difference is that, in this case, due to the pulse stretching, the amount of energy per pulse introduced to the FUT can be several orders of magnitude larger than the input pulse energy, hence providing a trace amplitude that can also be several orders of magnitude larger. This method achieves an increase in SNR directly given by the increase in the pulse energy introduced at the fiber input, in the absence of nonlinearities.

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The experimental setup used to demonstrate this concept (Fig. 1a) is composed by a traditional ΦOTDR scheme (as developed in [3]) and two Linearly-Chirped Fiber Bragg Gratings (LC-FBG) with opposite dispersion, in a configuration that emulates the CPA scheme. A passively mode-locked laser (working at a central wavelength of 1555.4 nm), generates transform-limited optical pulses with a duration of ~7 ps (corresponding to a 3 dB bandwidth of 55 GHz), at a repetition rate of 10 MHz. Due to the high repetition rate, the sensing range is limited to a maximum length of 10 m. For this reason, FUT used in this proof of concept, has a length of approximately 8 m (note that this limitation is only imposed by the repetition rate of the pump source, and the sensing range could be easily extended by simply choosing a lower rate pulse source). In our particular implementation, the optical input pulse is dispersed by means of an LC-FBG, so as to distribute its energy over a longer temporal duration, thus reducing its instantaneous peak power. The pulse is then amplified (up to the peak power limit given by modulation instability [4]) and injected into the fiber under test. Finally, the dispersion is compensated on the backscattered contributions using a second LC-FBG with opposite dispersion value to the input LC-FBG. In our implementation, the LC-FBGs used exhibit a total second-order dispersion magnitude of 2000 ps/nm (equivalent to ≈120 km of single-mode fiber, SMF). Fig. 1b-c shows the temporal intensity trace of the pulse emitted by the laser (b) and the broadened pulse (c). The photo-detector used in the experiment has a nominal bandwidth of 45 GHz (although the maximum usable bandwidth without distortion is 35 GHz). For this reason, the laser pulse measured by the detector presents a wider temporal width than the nominal value and ringing after the trailing edge (Fig. 1b). The maximum resolution of the sensor will be then given by the detector response, which in this case is ~30 ps, corresponding to a spatial resolution of ~3 mm [1]). The measured FWHM of the broadened pulse is ~1 ns, but as shown in Fig. 1c, the energy is distributed along almost 2 ns.

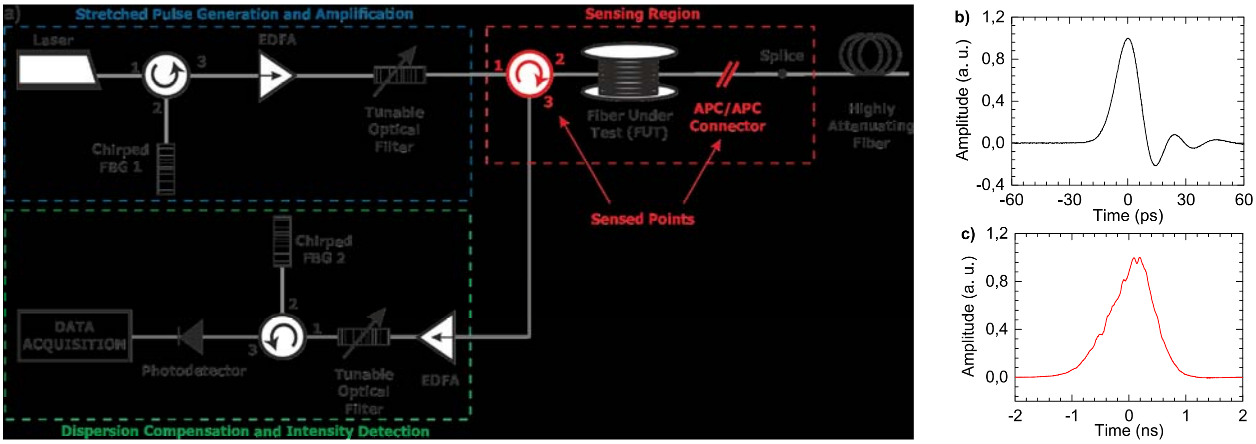

Figure 1. (a) Experimental setup used in the experiment. Acronyms are explained in the text. (b and c) Instantaneous power measurements. (b) Pulse emitted by the laser. (c) Pulse stretched by the LC-FBG. Notice the difference in the time scales in b and c.

Erbium-Doped Fiber Amplifiers (EDFAs) are used to boost the power of the chirped pulses before injecting them into the fiber and to amplify the backscattered signal by the fiber. In order to minimize the effect of the Amplified Spontaneous Emission (ASE) added by the EDFAs, tunable optical filters were inserted after each amplifying stage. An optical circulator serves to launch the signal into the fiber and to collect the backscattered response from the FUT. The final traces are detected by the 45 GHz photo-detector and recorded by a high speed Communications Signal Analyzer (Tektronix CSA8200). To generate events with reflection almost at the end of the fiber, another short fiber is connected with an APC connector. The final reflection produced by the fiber-air interface is very intense and quickly saturates the detector. To avoid such reflection, a 15 dB/cm highly attenuating fiber is spliced at the end of the FUT. Controlled connector events spaced below the chirped pulse width are inserted to demonstrate the resolution of the system.

3. EXPERIMENTAL RESULTS

3.1 Enhancement of SNR and avoidance of nonlinearities

We carried out an initial experiment to demonstrate that the proposed system allows to substantially increase the input pulse energy (and accordingly, the SNR of the ΦOTDR traces). To do so, we recorded the ΦOTDR traces obtained in the traditional scheme (without the LC-FBG modules) and with the proposed method (incorporating the LC-FBGs). In both cases, the pulses were amplified up to the peak power limit of modulation instability (roughly 40 W in both cases). The two detected traces are represented in Fig. 2, both detected after averaging 4000 consecutive acquisitions. Fig. 2a shows the trace obtained using the original laser pulse (FWHM of 7 ps and 40 W of peak power). Fig. 2b shows the trace detected using the stretched pulse (FWHM of 0.9 ns and 40 W of peak power) and compensating the dispersion with the second LC-FBG. It is easy to see, by comparing the same traces represented in logarithmic scale in Fig. 2c and Fig. 2d, that the proposed method increases the SNR of the sensor by ~20 dB, owing to the fact that there is 100 times more energy arriving to the detector (the pulse is roughly 100 times longer). It should be noted that we verified that the spatial resolution was the same in both cases (the connector events at the beginning and end of the fiber remained bounded to a distance given by the spatial resolution of the detected pulses, i.e. 3 mm in both cases). This idea will be illustrated in greater depth in the next subsection (3.2).

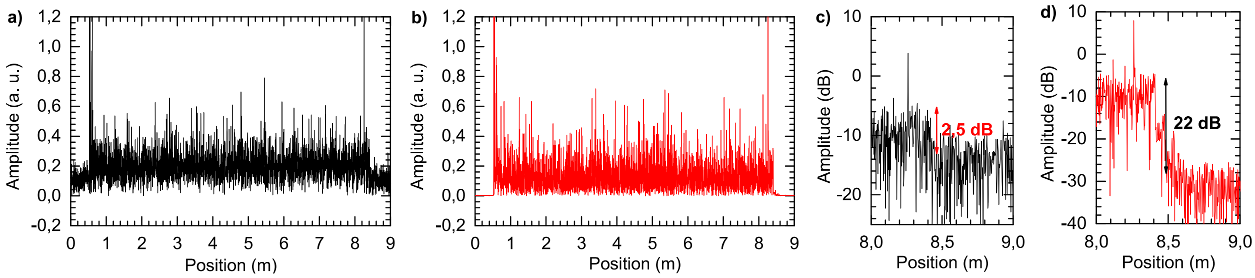

Figure 2. Detected traces with: (a) pulse without chirp (FWHM of 7 ps) with an input peak power of 40 W, and (b) stretched pulse (FWHM of 1 ns) with an input peak power of 40 W. Last meters of the same data is represented in logarithmic scale in (c) and (d).

Additionally, the system is more robust than the traditional scheme against nonlinearities. To demonstrate this, we recorded the optical spectrum of the dispersed and non-dispersed pulses after propagation along the FUT. In both cases, the pulses were again amplified up to the peak power limit of modulation instability (roughly 40 W in this case). Fig. 3 shows the spectra of both pulses after the FUT. As it can be observed in Fig. 3a, the non-dispersed laser pulse starts to suffer Self-Phase Modulation (SPM)-induced spectral broadening after 8 m of fiber propagation, increasing the bandwidth from 55 GHz to 65 GHz. In contrast, as shown in Fig. 3b, the broadened pulse maintains the original spectral width. This owes to the fact that the induced broadening due to SPM is larger for shorter pulses. Stretched pulses are therefore more robust against this effect.

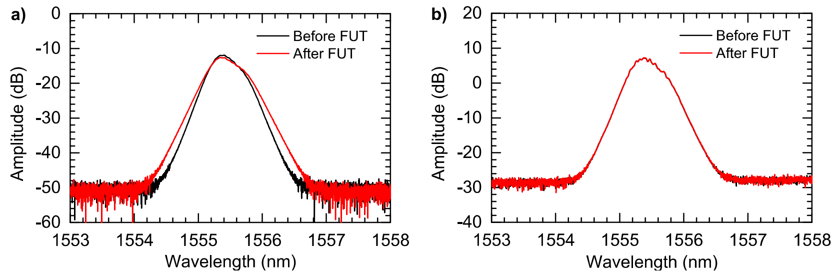

Figure 3. Signal spectra before and after propagation through 8 meters of SMF (input peak power of 40 W). (a) Pulse without chirp (FWHM of 7 ps), and (b) pulse stretched and amplified (FWHM of 0.9 ns).

3.2 Demonstration of high spatial resolution

Since the pulses propagating along the fiber are temporally stretched, it is important to clarify that the spatial resolution of the measurement still corresponds to that of the un-chirped pulse. To demonstrate this, several connectors/interfaces have been measured that demonstrate this resolution: two initial reflections separated by ~2 cm and generated by the interfaces inside the circulator placed at the fiber input (circulator 2 in Fig. 1a), and a final one produced by a fiber connector (APC/APC) (connector 2 in Fig. 1a) before the highly attenuating fiber.

Fig. 4 represents the detailed measurements of these reflections. Fig. 4a shows the reflections produced by the 40 W peak power laser pulse. The two reflections produced by the circulator are represented in black; the reflection produced by the last connector is represented in red and superimposed on the first reflection. It can be seen that this reflection fits perfectly with the first black reflection (intensity levels have been adjusted, so as to show the correspondence of the two pulses). This shows that there is no broadening or resolution loss along the fiber. Since the resolution of the system is 30 ps (corresponding to 3 mm), it is possible to clearly identify the two interfaces. Fig. 4b represents the same results using the chirped-pulse principle (stretching the pulse at the input of the FUT, and re-compressing the trace at the output). The pulse input peak power is again 40 W. As it can be seen, the same resolution is obtained, as compared with Fig. 4a. The two input interfaces are clearly resolved, even though the stretched pulse covers both of them. As expected, the last connector also fits perfectly with the first connector, showing no distortion along the propagation. Thus, it can be concluded that nonlinearities are not generated. Finally, Fig. 4c shows the results obtained in this last case without compensating the dispersion. The two reflections regenerated by the input interfaces are now indistinguishable (black). The optical pulse is superimposed in red, showing that the resolution with the uncompensated signal is ~1 ns (10 cm), corresponding to the temporal length of the pulse.

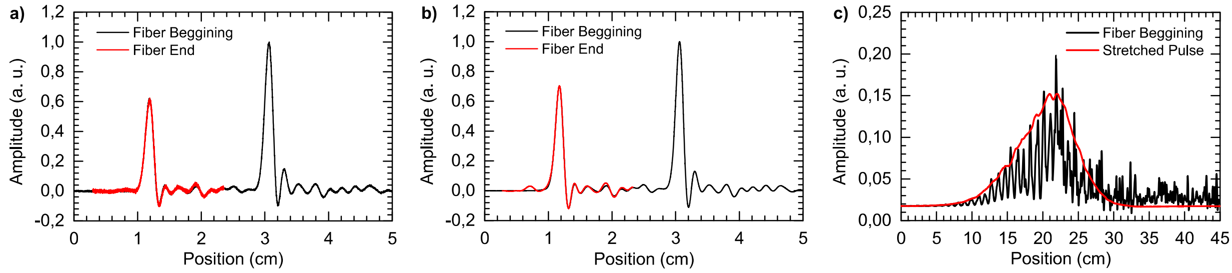

Figure 4. Connectors observed in the trace obtained with: (a) pulse without dispersion (FWHM of 7 ps), (b) pulse stretched and amplified (FWHM of 0.9 ns) and then re-compressed, and (c) pulse stretched and amplified (FWHM of 0.9 ns), not re-compressed. In all cases, the input peak power is 40 W.

4. CONCLUSIONS

In this work, we have demonstrated a novel technique to increase the SNR of ΦOTDR signals using chirped-pulse amplification concepts. The input pulses are temporally stretched by a suitable dispersive device, and the backscattered traces are re-compressed prior to detection. This allows to substantially increase the input pulse energy, while avoiding nonlinear interaction with the fiber under test, resulting in an increased SNR without compromising the spatial resolution of the sensor. The reported experimental demonstration shows an SNR increase of 20 dB over the traditional ΦOTDR architecture in a system with 3 mm spatial resolution.

5. ACKNOWLEDGMENTS

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