Overcoming high-resolution limitations in optimized long-range BOTDA sensors

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Abstract: A fundamental limitation in high-resolution and long-range Brillouin optical time-domain systems is overcome in this paper, enabling 500k resolved points over 25 km of SMF with 5 cm spatial resolution in a usual acquisition time.

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1. Introduction

Brillouin-based distributed optical fiber sensors have become an established sensing technology due to their ability to measure strain/temperature changes along tens of kilometers of fiber, making them strongly suitable to monitor large civil infrastructures. In particular, in Brillouin optical time domain analysis (BOTDA), the interaction of two counter-propagating signals, a pulsed pump and a continuous-wave (CW) probe signal allows measuring the temperature- and strain-dependent Brillouin gain response of the sensing fiber, with a spatial resolution given by the pump pulse width [1]. The probe wave is most-commonly generated by making use of a double-sideband (DSB) intensity modulation to mitigate the effect of depletion of the pump pulses, particularly in long-range schemes [2]. However, it has been recently proven that DSB schemes also bring massive spectral and temporal distortion on the pump pulse at high probe powers, inducing severe deformations in the Brillouin gain and loss spectra, and ultimately scrambling the BFS determination [3]. Such distortion results from the conventional symmetrical scanning of the probe sidebands frequency, and scales directly with the probe wave power, hence, limiting the performance of BOTDA sensors. On the other hand, the limited response time (~10 ns) of the acoustic wave generated at each fiber location imposes another fundamental limitation to the spatial resolution of BOTDA sensors, which cannot reliably provide information with spatial variations below 1 m.

In order to avoid any pump pulse distortion, two effective solutions have been recently proposed [3,4], both of them allowing to increase considerably the probe wave power. In this paper, we make use of our previously proposed solution [3], in which the probe-wave modulation frequency is fixed, matching the dominating Brillouin shift of the fiber. This way, a perfect overlap of the gain/loss processes generated by the anti-Stokes/Stokes components of the probe wave is ensured, leading to a flat net gain over the pump, and consequently, inducing no distortion on it. In this case, the pump pulse frequency is swept in order to properly scan the Brillouin gain/loss processes. By using such novel technique it has been possible to push the probe power up to the amplified spontaneous Brillouin scattering (ASpBS) threshold, which has ultimately led to achieve a state-of-the-art performance record, measuring over 100 km of fiber with a spatial resolution of 2 m on a BOTDA sensor with no extra assistance [3].

To overcome the limitations on the resolution of the sensors and achieve sub-metric spatial resolution, different approaches have been proposed based on frequency, correlation [5] or time [6] domain approaches. Frequency- and correlation-domain approaches allow very sharp spatial resolutions (in the order of mm or a few cm), however the measurement range is typically limited below a few km, with very long measurement times. Conversely, time-domain approaches are much faster and typically make use of differential pulse-width pair (DPP) measurements. The spatial resolution in this case highly depends on the rising/falling time of the used optical pulses, thus being typically limited to tens of cm along mid-range sensing distances (usually < 10 km). In the literature it can be found that, making use of a DPP-BOTDA system combined with optical pulse coding has led to 25 cm spatial resolution over a 60 km range, representing 250k independent points [7]. The differential pulse-width pair (DPP) technique [6] is based on the subtraction of two temporal traces, each of them obtained from the pump-probe interaction for different pulse widths. The resulting system spatial resolution is then determined by the width difference between the two pulses. For that reason, to maintain the resolution all along the sensing fiber, it turns critical to ensure well-shaped and non-distorted pulses all along the sensing range. Conventional DSB methods in BOTDA do not ensure this condition, as demonstrated in [3]. By combining DPP along with the above-described scanning technique [3], the pulse distortion can be significantly mitigated, allowing to increase the probe power launched into the fiber and hence the signal-to-noise ratio (SNR) of the sensor. In this paper, it is proved that the combination of these features allows maintaining a considerably high spatial resolution over a long-range BOTDA sensor, reaching values of resolved points unmatched so far by time-domain schemes, in measurement times in the order of minutes.

3. Experimental results

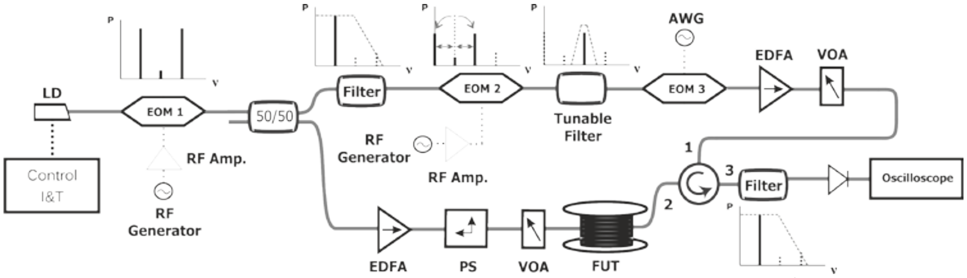

Fig. 1: Experimental setup. LD: Laser Diode; EOM: Electro-Optical Modulator; AWG: Arbitrary Waveform Generator; EDFA: Erbium Doped Fiber Amplifier; VOA: Variable Optical Attenuator; PS: Polarization Switch; FUT: Fiber Under Test.

To support the above explained analysis we implemented a DPP-BOTDA system, as shown in Fig. 1, in which the probe sidebands remain frequency fixed while the pump pulse scans the Brillouin gain spectrum. First, the laser beam is DSB-modulated by means of an intensity electro-optic modulator (EOM1), whose frequency is set to match the average BFS over the last section of the fiber (equivalent to the non-linear effective length L_{eff}) [3]. Afterwards, the modulated CW is split into two branches; one of them already constitutes the probe wave and is amplified by an Erbium-doped fiber amplifier (EDFA 1) in order to increase the probe power launched into the sensing fiber. Right before being launched into the fiber-under-test (FUT) the probe goes through a polarization switch (PS), which is used to reduce polarization fading in the measured temporal traces. The other branch is used to generate the pump pulse. To do so, it is first necessary to select either the Stokes (Brillouin gain) or anti-Stokes (Brillouin loss) modulation sidebands by means of a suitable filter. In this case, a fiber Bragg grating (FBG) of ~40 pm of bandwidth is used to select the Stokes band, which is intensity-modulated by means of a second modulator (EOM2) at a frequency difference sweeping around the BFS ($\nu_B \pm \Delta\nu$). This new frequency component, which provides the pump wave frequency, is selected through a narrow tunable filter (~ 80 pm of bandwidth), wide enough to allow a frequency tuning along the selected spectral span and narrow enough to filter out all the unwanted spectral components. Subsequently, the pulse is properly shaped by means of an intensity modulator (EOM3), and then amplified by an EDFA (EDFA 2). Then, after selecting the Brillouin gain component by means of another FBG, the signal is fed into a high transimpedance and high bandwidth (1 GHz) photo-receiver.

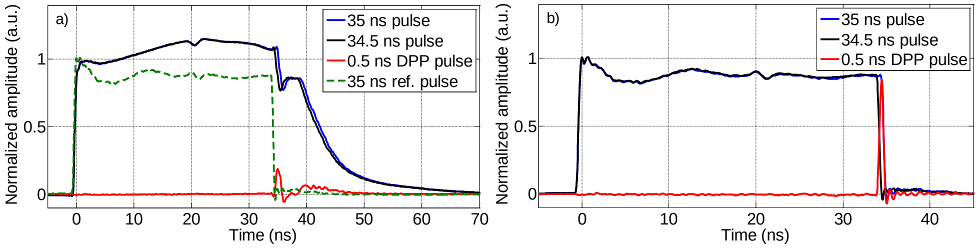

Fig. 2: Differential Pulse-Pair working principle, presenting two long pulses (34.5 ns and 35 ns), and the respective differential pulse (500 ps) at the end of the 25 km sensing range. a) DPP on the conventional BOTDA sweeping method, showing a huge distortion in the pulses for a +15 MHz pump-probe detuning, and a null differential pulse. A non-distorted 35 ns pulse measured without SBS interaction is shown as a reference in green-dashed line. b) DPP on the novel scanning procedure: both long pulses remain well-shaped after SBS interaction, and its differential pulse shows a sharp squared shape of 500 ps width.

In order to analyze the performance of the above explained technique, full DPP-BOTDA measurements have been carried out over a 25 km SMF, presenting a homogeneous BFS of ~ 10.848 GHz along the entire fiber. In the first set of measurements, sharp squared pulses (200 ps rise/fall time) of 35 ns and 34.5 ns have been used, thus, resulting in a spatial resolution of 5 cm (500 ps width difference). The pump pulse peak power employed is ~100 mW while the probe wave is ~1 mW per sideband. Fig. 2a shows the acquired pump pulses after going through the 25 km-long fiber and interacting with the probe wave through SBS, as well as the subtraction among them that enables the DPP technique, for the conventional scanning method. Measured shapes illustrate the huge temporal distortion that the pump pulse experiences when detuning the pump-probe frequency offset by +15 MHz from the average BFS. Such huge distortion leads to the complete cancellation of the differential pulse resulting from the subtraction of the long and short pulses (red line in Fig. 2a), turning the DPP technique not applicable for this range and powers. However, as it can be seen in Fig. 2b, by making use of the proposed scanning procedure, the obtained pump pulses maintain their original shapes along the fiber, regardless the probe power used and its frequency detuning. This secures the correct functioning of the DPP technique, having a well-shaped squared differential pulse of ~500 ps (5 cm resolution).

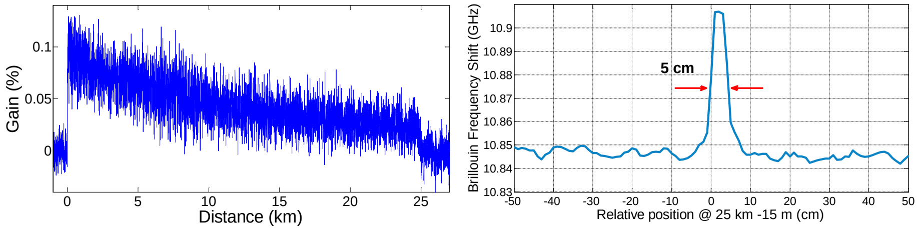

Fig. 3: a) DPP-BOTDA trace of a 25 km SMF for a differential pulse of 500 ps width (5 cm spatial resolution). b) BFS evolution at the far end of the fiber, where a 5 cm piece of fiber has been strained 1200 με.

The system performance has been evaluated by elongating a 5 cm section of the fiber located at the end of the FUT. The elongation has been precisely controlled gluing the fiber to a micro-metric translation stage, in order to induce a calibrated and known strain over the fiber. To perform comprehensive measurements a full frequency sweep has been carried out, where all of the temporal traces have been averaged 16000 times, leading to an acquisition time of a few minutes. The differential temporal traces show a sufficient signal contrast along the entire 25 km fiber (Fig. 3a) as well as a correct exponential decay. The signal-to-noise ratio (SNR) calculated at the end of the fiber is ~3 dB. In addition, the evolution of the BFS along the FUT has been obtained, and a zoom in the last few meters of fiber is presented in Fig. 3b. The measured BFS evolution demonstrates the presence of a short fiber section where positive strain is induced. The elongated piece of fiber presents a BFS of ~10.905 GHz, which implies a frequency difference of ~60 MHz when compared with a non-strained fiber section. If the conventional strain-to-frequency conversion parameter is used (~0.05 MHz/με), the estimated induced strain (~1200 με) matches the applied elongation of 60µm. The frequency uncertainty measured at the end of the fiber is ~2.1 MHz, which matches the expected theoretical value for the calculated ~3 dB SNR. The strained section is proven to be 5 cm long, which actually validates the system spatial resolution. It should be highlighted that such effective spatial resolution and sensing range corresponds to 500,000 sensing points, obtained in a conventional time-domain approach using a short acquisition time.

4. Conclusions

In conclusion, an optimized long-range and high-resolution DPP-BOTDA sensor has been demonstrated. The use of the proposed novel scanning method ensures operating with non-distorted pump pulses (time and frequency wise) while allowing augmenting the probe wave power, ultimately limited by the onset ASpSBS threshold. Such power increase improves the overall system performance of the DPP-BOTDA technique, in this case allowing to reduce the spatial resolution down to 5 cm over an extended sensing range of 25 km. This results in achieving 500,000 sensing points along the fiber, which are measured in a few minutes, representing a significant reduction of the acquisition time when compared to other methods, such as correlation-based approaches. In addition, the use of the proposed scanning procedure helps overcoming fundamental limits of high spatial resolution techniques, which had been overlooked until now. It turns out to be particularly critical for DPP schemes and this issue has probably been a fundamental hurdle preventing long-range high spatial resolution sensing. The potential of the present approach is high, as it could be also combined with other additional techniques in order to further improve the system performance.

5. References

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