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Compensation of nonlocal effects induced by the extinction ratio of pump pulses in Brillouin optical time-domain analysis sensors

JON MARIÑELARENA, HARITZ IRIBAS, JAVIER URRICELQUI, AND ALAYN LOAYSSA*

Institute of Smart Cities, Universidad Pública de Navarra, Campus Arrosadia s/n, 31006 Pamplona, Spain
*alayn.loayssa@unavarra.es

Abstract: We demonstrate a technique to compensate the nonlocal effects that appear in Brillouin optical time-domain analysis sensors when pump pulses with limited extinction ratio are deployed. These recently discovered nonlocal effects are originated in the interaction between the probe wave and the pulse pedestal. Hence, their compensation method is based on deploying a modulation (dithering) of the optical frequency of the probe and pulse pedestal waves that provides a reduction of the effective interaction length between them. This is implemented by taking advantage of the chirp associated to the direct current modulation of a semiconductor laser used as common source for both waves. The net effect of this procedure is that the probe and pulse pedestal waves display efficient Brillouin interaction just at correlation peaks along the fiber where the frequency difference between both waves remains constant. Proof-of-concept experiments in a 25-km sensing link demonstrate the performance of the technique, where large errors of more than 10 MHz in the measurement of the Brillouin frequency shift are completely compensated by introducing a sinusoidal dithering to the laser source.

1. Introduction

Brillouin Optical Time Domain Analysis (BOTDA) sensors have the potential to become an enabling tool for the monitoring of the health of large structures such as oil and gas pipelines, high voltage power lines, railways or civil engineering structures (bridges, viaducts, tunnels, etc.). These sensors provide the capability to perform distributed measurements of temperature and strain along structures with high spatial resolution and at a large number of simultaneous measurement positions.

However, several effects constrain the performance of BOTDA sensors. One of the main limitations are the so-called nonlocal effects (NLEs), which restrict the maximum probe wave power that can be deployed in the sensing fiber and, hence, the received signal to noise ratio (SNR) and measurement performance. This detrimental effect is due to the continuous transfer of energy between the probe and pump pulse waves along the fiber, which modifies the pump power by introducing a wavelength dependence that leads to errors in the Brillouin frequency shift (BFS) measurements [1]. Different solutions have been proposed to mitigate this impairment by using special configurations of the BOTDA sensor, such as the use of a double probe wave [2] or using a RF phase-modulated probe wave [3], which compensate NLEs to first order. However, there are second-order effects that originate in the spectral distortion experienced by the pump pulse when it interacts with the double sideband probe wave [4]. Nevertheless, solutions have been also proposed to mitigate these second order nonlocal effects [4–6]. In this line, we have demonstrated a mitigation method that relies on modulating the wavelength (dithering) of the probe wave either by modulation of the optical source deployed to generate both pump and probe waves [7], or by introducing the wavelength modulation just on the probe wave [5]. The modulation of the probe wave has the benefit of spreading the Brillouin interaction to a larger frequency range

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along the fiber, thus reducing the depletion of the pump pulse while transversing the sensing fiber. Moreover, when a double probe wave is deployed, both waves induce a broad gain and loss spectrum upon the pump pulse that compensate each other, thus avoiding the spectral distortion of the pump pulse [5, 8]. Furthermore, another advantage of modulating the wavelength of the probe is to increase the effective Brillouin threshold of the fiber, which allows to further increase the probe power injected in the fiber.

Another significant constrain for BOTDA sensors comes from the limited extinction ratio (ER) of the deployed pump pulses, which means that the pump pulse is on top of a pedestal. In fact, we have recently studied two ER-related impairments that had probably been observed in experiments many times by other researchers, but whose origins and implications for the performances of the sensor remained unanalyzed [9]. The first impairment is due to the increased depletion of the part of the pedestal following the pump pulse (trailing pedestal) by probe wavefronts amplified by the pulse itself. This effect has been shown to introduce a distortion in the measured Brillouin spectrum that is similar to that induced by the depletion of the pulse by the probe wave [9]. The other impairment is due to the interplay between the pulse pedestal and the transient response of the erbium-doped fiber amplifiers (EDFA) that are normally deployed to amplify the pump wave before injection in the sensing fiber. The transient response of these devices also distorts the trailing pedestal of the pulse inducing another NLE. The net result of both effects is an error in the determination of the BFS along the fiber that increases for smaller ER of the pump pulse [9].

The importance of these ER-related constrains lies on the requirements that it imposes on the devices that are used to shape the pulses, which are primarily of two types: semiconductor optical amplifiers (SOAs), which are used as optical switches, and Mach-Zehnder electro-optic modulators (MZ-EOM). SOA switches have large ER; hence, the impairments related to ER-induced measurement errors can be negligible in many sensor configurations. However, the rise time of commercially available SOAs is typically limited to around 1ns, which limits the spatial resolution of the sensor, particularly when spatial resolution below 1 m is targeted by deploying high-resolution techniques such as differential pulse pair [10]. The other alternative is the deployment of MZ-EOM to generate the pump pulses, which tend to be more cost-effective than SOA, have a broad modulation bandwidth and are able to generate extremely sharp pulses. However, the ER of standard MZ-EOMs is in the 20 to 30-dB range, which has been shown to be insufficient to get rid of ER-related detrimental effects [9]. In the market, there are available specialty MZ-EOM with higher ER; however, their cost is increased by the need to fine tune the device to obtain maximum suppression of the output signal for the off state. This is undesirable, as cost-effectiveness is going to be of paramount importance to provide widespread adoption of the BOTDA technology outside current niche applications.

In this paper, we demonstrate a new technique to reduce the impairments induced by the ER of the pump pulses that is based on the dithering of the optical source used to generate the pump and probe waves. The optical frequency modulation induced in both waves, apart from mitigating conventional NLEs originated by pulse depletion, also serves to restrict the effective interaction between the pulse pedestal and the probe wave to specific locations along the fiber, in much the same way as the principles followed in Brillouin optical coherence-domain analysis (BOCDA) sensors to localize measurements. Proof-of-concept experiments in a 25-km sensing link are introduced to demonstrate the mitigation of ER-related impairments as well as conventional NLE due to pump depletion.

2. Fundamentals of the method for ER-related NLEs mitigation

The NLEs related to the ER of the pump pulses in BOTDA sensors are ultimately originated in the interaction between the pump pulse pedestal and the probe wave [9]. Therefore, we propose a method to mitigate ER-related NLEs that is precisely based on reducing this interaction, which is parasitic to the desired interaction between the pump pulse and the probe wave that is used

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for sensing. The fundamentals of the technique are schematically depicted in Fig. 1. As it is shown in this figure, the method relies on the simultaneous modulation of the wavelength (optical frequency) of the pump and probe waves with the same signal. One way to perform this modulation is to take advantage of the chirp (wavelength modulation) associated to the direct current modulation of a semiconductor laser used as common source for both waves.

Assuming that the pump and probe waves have their optical frequency modulated with a tone of frequency f_m before being counter-propagated in the sensing fiber, their frequency separation at any given instant t at a location z along the fiber can be expressed as:

$$\Delta f(t,z) = \Delta f_0 + \Delta f_p \cdot cos\left[\pi f_m\left(2t - L/v_g\right)\right] \cdot sin\left[\pi f_m\left(L-2z\right)/v_g\right] \quad (1)$$

where Δf_p is the peak frequency deviation of the FM modulation introduced on the pump and probe waves, Δf_0 is their static frequency difference, which is sweep during the measurement process in order to scan the Brillouin spectra, L is the length of the sensing fiber and v_g is the group velocity of the waves. Therefore, the frequency difference between the pump pedestal and probe becomes a sinusoidal function of distance along the fiber that behaves like a standing wave; there are nodes (correlation peaks) where the frequency difference between both waves is constant. The Brillouin interaction between the pump pedestal and the probe at these correlation peaks is highly efficient, whereas it becomes inefficient outside these locations. In other words, each of the probe wavefronts have a significant Brillouin interaction with the pedestal of the pump wave just at given locations of the fiber. At all other locations in the fiber, the pedestal and the probe wavefronts become uncorrelated, thus reducing the energy transfer between both waves via Brillouin interaction. The net effect is that the total Brillouin interaction between the pump pulse pedestal and the probe wave is reduced, as it is confined mainly to the correlation peaks.

Notice that this frequency modulation, and its associated localized coherence process, is identical to the method that is used in BOCDA sensors to provide distance discrimination [11].

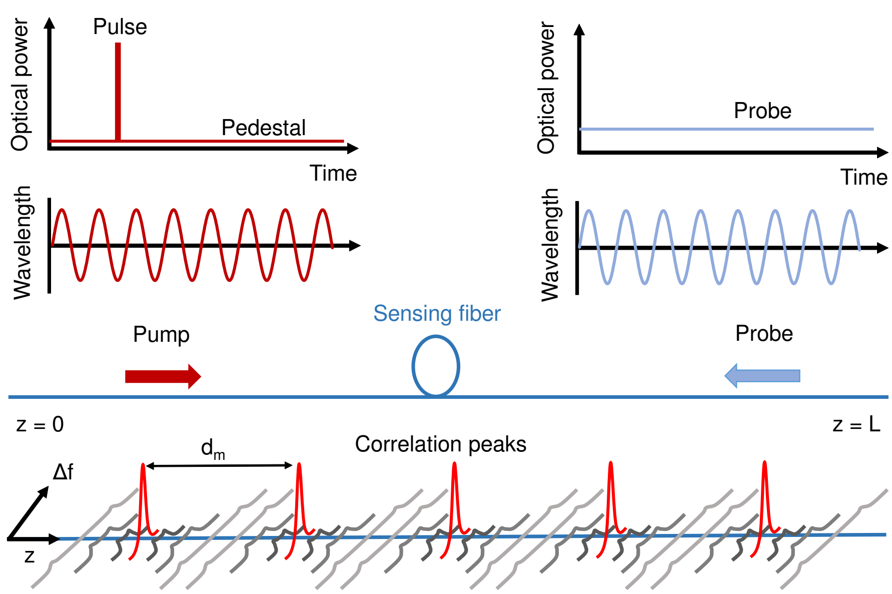

Fig. 1. Fundamentals of the light source wavelength modulation technique to compensate ER-originated NLEs.

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Hence, the width of the correlation peak, δz, and the distance between peaks, d_m, are given by [11]:

$$\delta z = \frac{v_g \cdot \Delta\nu_B}{2\pi f_m \cdot \Delta f_p} \tag{2}$$

$$d_m = \frac{v_g}{2 f_m} \tag{3}$$

where $\Delta\nu_B$ is the Brillouin gain linewidth. Therefore, the ratio between both quantities can be regarded as a measure of the reduction of the total interaction between the pump pedestal and the probe wavefronts as they cross the fiber:

$$\frac{\delta z}{d_m} = \frac{\Delta\nu_B}{\pi \cdot \Delta f_p} \tag{4}$$

This expression conveys the fact that the larger the frequency deviation of the FM modulation of the pump and probe waves, the larger the mitigation of ER-related impairments. However, the maximum Δf_p is constrained by the increment it brings on the measurement time. Indeed, the modulation of the frequency of the probe wave has been shown to have an equivalent effect to the synthesis of a virtual BFS profile along the fiber [7]. For instance, in the case of a tone modulation of the probe wave, the BFS distribution of a fiber with uniform BFS measured with a BOTDA would appear as if it had sinusoidal shape along the fiber distance. Therefore, increasing Δf_p leads to a need to increase the frequency scan range of the sensor over the range that would be measured otherwise. Then, the measurement time penalty factor is given by:

$$T = \frac{2\Delta f_p + \Delta f_T}{\Delta f_T} \tag{5}$$

where Δf_T is the frequency range that would be swept in the conventional BOTDA without probe dithering. However, for realistic scenarios this penalty can be rather small. For instance, if we assume a typical long-range measurement with Δf_T=1 GHz, which can be quite realistic in a long range link made of several fiber types, and Δf_p=100 MHz, as it is deployed in the experiments below, then penalty would be just a 20% increment in the measurement time. Regarding the value of the modulation frequency, f_m, its value is conditioned by the interaction between the probe and the pump wave along the fiber, involving trade-offs identical to those that arise when probe dithering is deployed to mitigate conventional NLE [7]. The proposed technique is valid for fibers with different BFS, but if the difference is great it may be necessary to deploy another technique that we have recently deployed for tracking BFS changes [12].

Finally, note that, apart from reducing NLEs originated by the limited ER of the pump pulses, our source optical frequency modulation (dithering) method retains the advantages in terms of mitigation of NLEs originated by pump depletion and increased Brillouin threshold that we have previously demonstrated [7].

3. Experimental setup

Figure 2 depicts the dual-probe BOTDA setup that was deployed to experimentally demonstrate the compensation of the NLE caused by the limited ER of the pump pulses and the effect of the transient response of the EDFA. Note that this is a conventional dual-probe BOTDA setup with the only addition of the chirp modulation of the optical source.

The optical source was a 1560-nm distributed feedback laser whose injection current was modulated by a 80-kHz sinusoid from a signal generator that was synchronized to the pulse generator. The amplitude of this modulation was set to get a peak frequency deviation for the laser chirp of 100 MHz. The modulated optical signal was divided by a coupler into two branches. In the upper branch, the pump pulse wave was shaped by using either a SOA, when deploying pulses

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with a high ER of 45 dB, or a MZ-EOM, when generating pulses with 26-dB ER. In both cases the corresponding optical device was driven by an electrical pulse generator. Then, the pump pulses were amplified in an EDFA whose output was filtered to reduce the amplified spontaneous emission, and directed to a polarization scrambler (PS) before launching into the sensing fiber. Two different EDFAs were deployed in the experiments presented in section 4. The first one, which we will denominate EDFA I, was a specialty EDFA designed for pulse amplification (Amonics Ltd. Pulsed EDFA) that offered minimal transient response and hence negligible trailing pedestal distortion [9]. The other EDFA, EDFA II, was a conventional commercial amplifier (MPB Communications Inc.) with significant transient response. In both cases, the pump peak power was limited to 20 dBm, in order to avoid modulation instability effects in the fiber [13], and the pump pulse duration was set to 20 ns, corresponding to approximately 2-m spatial resolution for the sensor.

In the lower branch of the setup, the probe wave was generated using another MZ-EOM driven by a RF generator that provided frequencies close to the BFS of the fiber. This modulator was biased for minimum transmission so as to generate a double-sideband suppressed-carrier modulation. In this way, a dual-probe wave with a power of -3 dBm per sideband, which is the threshold for the onset of significant second-order NLE [4], was injected into the fiber. Finally, the probe wave exiting the fiber was filtered to retain just the highest wavelength probe wave and captured in a detector followed by an oscilloscope.

In our proof-of-concept experiments, two standard single-mode (ITU G.652) fiber spools of 5-km and 20-km length with fairly uniform BFS distribution, but slightly different Brillouin gain coefficient, were deployed as sensing fiber. In addition, two hotspots were prepared along the sensing link using a climatic chamber: one after the first spool, at z=5 km, and another at the end of the link at z=25 km. These hotspots were held in a thermal bath at a temperature 10°C over the rest of the fiber.

4. Experimental results

Experimental measurements were performed to demonstrate the capabilities of the optical source modulation technique to overcome the impairments caused by the limited ER of the pump pulses in BOTDA sensors. Figure 3 depicts measurements of the probe gain profile along the fiber for a frequency separation between pump and probe waves close to the mean BFS of the sensing fiber. Different measurements are shown for the two EDFAs (EDFA I and EDFA II) deploying either high or medium ER pulses. The two graphs include the measurement of the probe gain profile for pulses with a high ER of 45dB generated using the SOA switch to serve as reference (blue line), as the high ER warranties that they are not distorted by ER-related NLEs [9]. Notice that there is a small discontinuity in gain at z=5 km, which is due to a slight difference of the

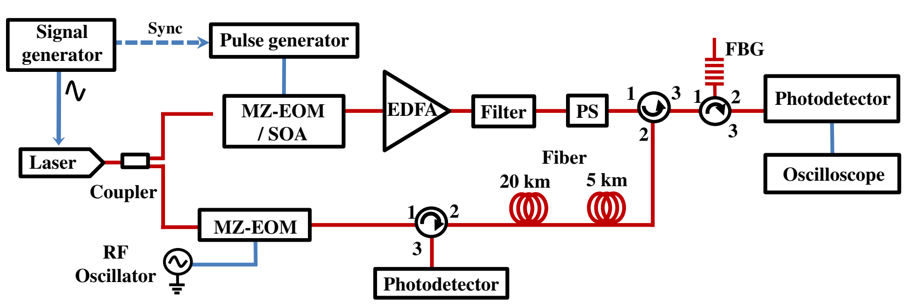

Fig. 2. Experimental setup deployed to demonstrate the capabilities of the technique to mitigate ER-originated NLEs.

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Brillouin gain coefficient for the two fiber spools deployed in the sensing link. Figure 3(a) depicts the measurement without using optical source dithering. The measurement (green line) for a pump pulse ER of 26 dB amplified using EDFA I, which has a negligible transient response, shows the detrimental effects of the increased depletion of the pump pulse and pulse pedestal by the probe [9]. This manifests as a gradual reduction of the gain along the fiber and also by the existence of a gain variation (sharp reduction followed by slow recovery) for probe wavefronts even after the pulse has exited the fiber. The gain reduction along the fiber is partly due to the increased depletion of the pulse by the interaction with a probe wave that has been previously amplified by the leading pedestal of the pulse, and partly due to the depletion of the trailing pedestal; whereas the sharp variation feature at the end of the fiber is solely originated by the depletion of the trailing pedestal of the pulse [9]. As it is shown below, these distortions of the measured probe gain lead to great errors in BFS measurements, particularly at the second hotspot where the gain profile is more distorted. The distortion of the gain profile is even stronger for the measurement (red line) in which 26-dB ER pulses are amplified by the conventional EDFA (EDFA II). In this case, the gain measured along the whole fiber is severely affected by distortion from the very first kilometers. This is due to the distortion of the trailing pedestal of the pulse by the transient response of the EDFA [9]. The effects on the BFS measurement, as shown below, are dramatic.

In contrast to these results, Fig. 3(b) depicts the measurement of the distributed gain when the optical source frequency is dithered. It can be observed that the measurements for the low ER pulses are identical in this case for either EDFA. Notice that the measurements display a

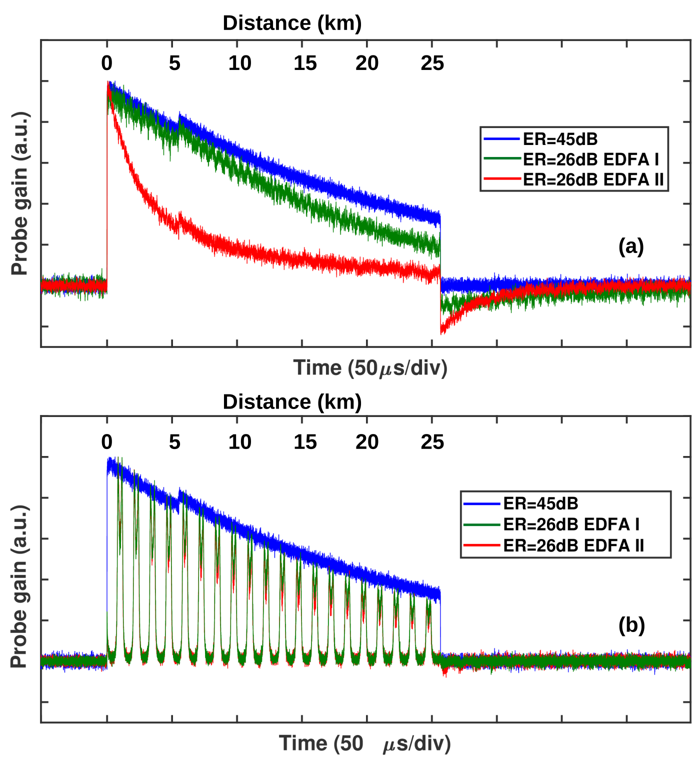

Fig. 3. Probe gain profile measured along the fiber for different ER values of the pump pulse, using either EDFA I or EDFA II, (a) without dithering of the light source and (b) when the dithering is turned on.

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series of "spikes" for the probe gain. The reason for these peaks is explained by Fig. 4, where the full Brillouin gain spectra distribution measured along the fiber is presented. This figure highlights the virtual BFS profile that is created by the probe wave wavelength modulation [7]. For a fiber with an approximately uniform BFS, this synthesized BFS profile follows the shape of the modulation, a sinusoid in this case. The correct BFS is obtained after subtraction of the known sinusoidal modulation from the measured BFS. In Fig. 3(b), we are representing just one of the frequency differences between pump and probe, which depicts peak gain at positions given by the sinusoidal variation of the BFS along the fiber. Nevertheless, it can be seen that the peak gains coincide with the gain for the measurement for high ER pulses, hence demonstrating that the gain distortion introduced by ER-originated NLEs is compensated. Furthermore, another indication that this is indeed the case, is that the probe gain after the pulse has exited the fiber is flat, with the sudden change in amplitude and slow recovery seen in Fig. 3(a) disappearing. Additionally, it was also observed that the Brillouin gain experienced by the probe wave due to the interaction with the leading pedestal of the pulse is reduced by 7.45 dB (from 18.24 dB to 10.79 dB) when the dithering method is deployed in the 26-dB ER pulse case.

Figure 5 highlights the beneficial effects of the dithering technique on the depletion of the pump pulses. The figure depicts the depletion of the pump pulses for several combinations of ER of the pump pulses, EDFA type and use or not of the dithering method. Figure 5(a) depicts the depletion of the 45-dB ER pulses generated using the SOA at the output of the fiber using EDFA I to amplify the pulses. It can be seen that the dual-probe setup is able to completely compensate the depletion of the pulses NLEs and that there are no problems related to the ER of these pump pulses. Figure 5(b) depicts the depletion of the 26-dB ER pulses generated using the MZ-EOM. Notice that, in this case, there is a depletion of the pump pulse that reaches a maximum of around 10%. This depletion is similar for both EDFAs, which means that it depends neither on the transients effects of the EDFA, nor on the trailing pedestal of the pulse. The increase depletion of the pulses is due to their interaction with probe waves that have been previously amplified by the leading pedestal of the pulse [9]. Finally, Fig. 5(c) depicts the pump depletion once the dithering of the optical source is activated. The result is that the pump depletion is almost completely suppressed with a less than 1% residual.

Finally, the BFS distribution along the optical fiber was measured in order to accurately quantify the final measurement performance improvement that can be obtained for the BOTDA sensor with the source dithering technique. Figure 6 depicts the BFS in a situation in which the transient effects of the EDFA are not significant because EDFA I is deployed. It can be seen that

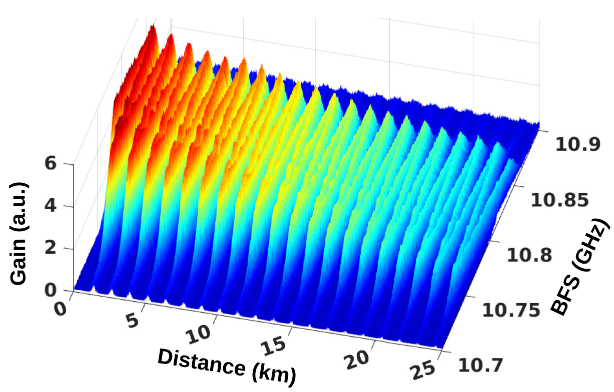

Fig. 4. Brillouin spectra distribution measured along the fiber when the source frequency is modulated with a sinusoid.

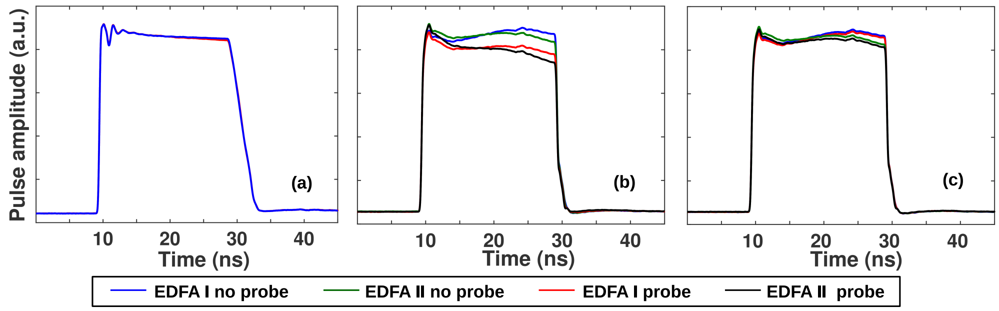

Fig. 5. Depletion of the pump pulses at the output of the fiber (a) using the SOA to generated the pulses, (b) using the MZ-EOM to generate the pulses and (c) using the MZ-EOM to generate the pulses and deploying the source dithering technique. The pulse shapes are shown with and without probe wave in the fiber and using either the low transient EDFA (EDFA I) or the conventional EDFA (EDFA II).

the BFS error, when using medium ER pulses generated with the MZ-EOM, increases along the fiber compared to the reference BFS for high ER pulses generated with the SOA. This is consistent with Fig. 3(a), which depicts an increased distortion of the measured probe gain along the fiber due to the effects of the pump pulse and trailing pedestal depletion. On the contrary, the BFS measured with the medium ER pulse once the source dithering technique is implemented coincides with the reference. This is verified in the insets of the figure, which display a zoom of the BFS measured in the two hotspots at z=5 km and z=25 km. At the first hotspot there is a small BFS error of approx. 2.5 MHz for the measurement with medium ER and no dithering. Moreover, the error drastically increases to around 7 MHz at the second hotspot. In contrast, with our source dithering method the BFS errors are perfectly compensated in both hotspots. Figure 7 displays similar measurements but when the EDFA II, i.e. the conventional amplifier with significant pulse amplification transients, is deployed. Similar trends are observed, but this time the BFS error with reduced ER pulses is dramatically increased due to the transient effects of the amplifier. Furthermore, the insets for the BFS distribution around the two hotspots highlight a very large error in both cases (10 MHz and 15 MHz, respectively). Despite this severe distortion, again the use of the source dithering method is able to compensate the BFS errors.

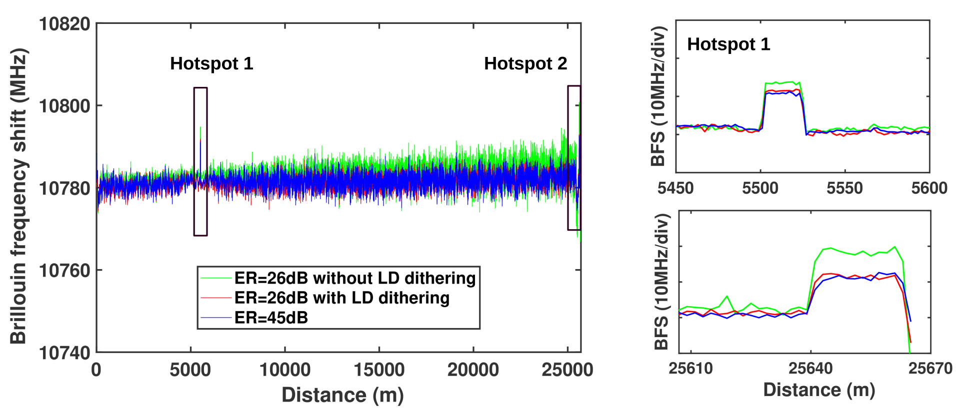

Fig. 6. Brillouin frequency shift distribution measured along the optical fiber when using EDFA I (negligible transient response) for pump pulses with ER of 45 dB (blue line), 26 dB (green line) or 26 dB with dithering of the optical source (red line). The insets highlight the details of the measurement around the two hotspots.

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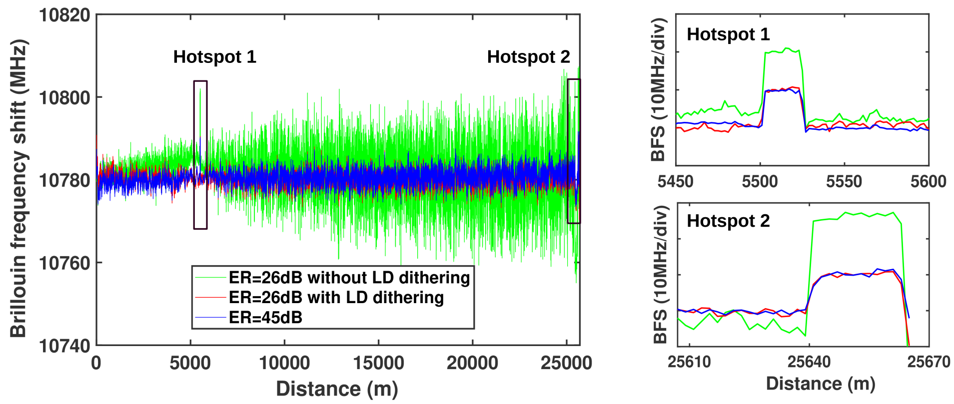

Fig. 7. Brillouin frequency shift distribution measured along the optical fiber when using EDFA II (conventional amplifier) for pump pulses with ER of 45 dB (blue line), 26 dB (green line) or 26 dB with dithering of the optical source (red line). The insets highlight the details of the measurement around the two hotspots.

5. Conclusions

In summary, a simple technique to reduce the NLEs originated by the deployment of pump pulses with limited ER in BOTDA sensors has been presented. The method is based on introducing a wavelength modulation to the common optical source used for the pump and probe waves. This technique has demonstrated that is able to compensate the three types of NLEs related to the ER of the pump pulses: First, the NLE originated in the increased depletion of the pump pulse by probe wavefronts that have been previously amplified by the leading pedestal of the pump pulse. Also, the NLE originated by the distortion of the measured probe gain due to the increment in depletion of the trailing pedestal of the pump pulse by probe wavefronts that have been previously amplified by the pump pulse. Finally, the NLE due to the distortion of the measured probe gain originated in the distortion of the trailing pedestal of the pulse by the transient response of the EDFA used to amplify the pump wave. Moreover, the source dithering technique has already demonstrated compensation of NLEs associated to the depletion of the pump pulse by the probe wave [7]. Therefore, it can be said that this technique constitutes a comprehensive tool to compensate every type of NLE that impair BOTDA sensor performance as well as to increase the Brillouin threshold of the sensing fiber. This makes it possible to deploy higher probe power in the sensing link, thus improving the detected probe SNR and enhancing the measurement precision. All with very little complexity added to the conventional setup.

The NLEs associated to the ER of the pump pulses are particularly important in BOTDA sensors that deploy moderate-ER devices, such as MZ-EOMs, to form the pulses, but further analysis is needed to know if they may be also significant even when using other high-ER devices, like SOAs, in such situations as ultra long range links or when deploying pulse coding techniques in which a large number of pulses are simultaneously launched into the fiber.

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