Brillouin optical time-domain analysis sensor assisted by Brillouin distributed amplification of pump pulses

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Abstract: We demonstrate the extension of the measurement range of Brillouin optical time-domain analysis (BOTDA) sensors using a distributed Brillouin amplifier (DBA). The technique is based on injecting a DBA pump wave in the fiber to generate an additional Brillouin interaction that amplifies the BOTDA pump pulses and compensates optical fiber attenuation. This amplification does not introduce any significant noise to the BOTDA's probe wave due to the inherent directionality of the Brillouin gain. Additionally, we deploy a differential pulse-width pair measurement method to avoid measurement errors due to the interplay between the self-phase modulation effect and the changes in the temporal shape of the pulses induced by the transient behavior of Brillouin gain. Experimental proof-of-concept results in a 50-km fiber link demonstrate full compensation of the fiber's attenuation with no penalty on the signal-to-noise ratio of the detected signal.

OCIS codes: (290.5900) Scattering, stimulated Brillouin; (060.2370) Fiber optics sensors.

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1. Introduction

Brillouin optical time-domain analysis (BOTDA) sensor technology has evolved during the last years to such an extent that it has become a powerful tool to monitor temperature and strain over large structures. These measurements are of great value for diverse field applications such as ensuring the structural health of oil and gas pipelines or assessing the operating conditions of high voltage transmission lines, all of which have a common need for large monitoring distances.

However, the sensing range of this technology is essentially limited by the attenuation of the optical fiber, which reduces the amplitude of the optical signals involved in the stimulated Brillouin scattering interaction that underpins BOTDA sensors. Specially important is the attenuation of the pump pulses, because the Brillouin gain experienced by the probe wave exponentially drops as the pump pulse propagates along the fiber. As a consequence, the signal–to–noise ratio (SNR) of the detected Brillouin gain becomes too small at distant locations to provide measurements with the required accuracy. This problematic scenario can be compensated to some degree by the use of signal averaging, but at the cost of increasing the measurement time, which becomes impractically large. Moreover, this deterioration of performance cannot be counteracted by indefinitely increasing the pulse power injected in the fiber, because this is ultimately limited by the onset of other non-linear effects such as modulation instability, Raman scattering and self-phase modulation [1, 2].

The obvious solution is to amplify the pulses to compensate the attenuation of the fiber. This has been demonstrated by the use of erbium-doped fiber amplifiers (EDFA) as pulse repeaters along the fiber length [3]. However, distant EDFAs need to be powered, whereas an all-passive sensing network is much more attractive and practical. A more elegant solution is to use distributed Raman amplification (DRA) by injecting a Raman pump in the sensing fiber [4, 5]. However, this requires the use of very high power (of the order of Watts) in the fiber, which can become an eye-safety concern in the installation and operation of real systems. Moreover, using DRA, the relative intensity noise of the Raman pump laser is translated to the detected signal, significantly degrading measurement performance [5].

In this paper, we present an alternative and more efficient approach: a BOTDA sensor assisted by a distributed Brillouin amplifier (DBA) used to increase the pump pulse power along its propagation through the fiber. This technique has the advantage of requiring much lower DBA pump power than DRA, because stimulated Brillouin scattering is intrinsically much more efficient than stimulated Raman scattering, with just milliwatts of pump power required to obtain large gain in typical lengths of fiber. Furthermore, the DBA gain bandwith can be electronically controlled to precisely fit the pulse spectrum, instead of wasting the tens-of-nanometers bandwidth of a DRA to amplify a narrow-band signal [6]. Finally, the DBA noise added to the BOTDA signal is shown to be negligible due to the inherent directionality of Brillouin gain.

2. Fundamentals of DBA–assisted BOTDA

Figure 1 schematically highlights the fundamentals of the technique depicting the various optical waves involved in the DBA-assisted BOTDA and their spectra. As shown in the figure, two

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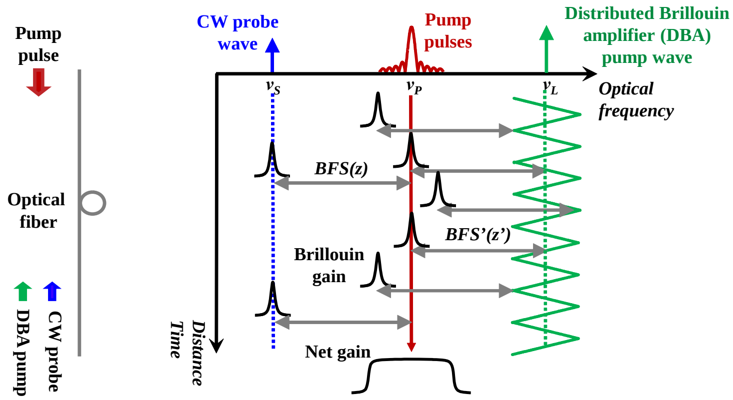

Fig. 1. Fundamentals of the technique, showing the spectra of the optical waves present in the fiber for a DBA-assisted BOTDA.

Brillouin interactions co-exist in the sensing fiber. The first one is for sensing purposes, where the conventional BOTDA interaction between a CW probe wave and a counter-propagating pump pulse provides a distributed measurement of the Brillouin frequency shift (BFS) in the fiber, which is directly related to temperature or strain. The second interaction, between the DBA pump wave and the pump pulse, is deployed to amplify the power of the latter as it propagates through the fiber. This requires that the DBA pump wave is offset from the pump pulse by an optical frequency difference that is around the mean Brillouin frequency shift (BFS) of the sensing fiber. However, the Brillouin gain spectrum generated by a CW DBA pump would be very narrow, just the intrinsic Brillouin linewidth (aprox. 30 MHz), which would severely distort the pump pulse spectrum.

Therefore, there is a need to increase the DBA bandwidth beyond the natural Brillouin linewidth to properly amplify all optical spectral components of the pump pulse so as to avoid distortion. This increment can be obtained modulating the wavelength of the DBA pump wave, as it is schematically depicted in Fig. 1. This makes the center wavelength of the Brillouin gain spectra experienced by the pump pulses to vary along the fiber as it meets the counter-propagating wavelength-modulated DBA pump wavefront, so that the pulse experiences a broad total integrated gain spectrum. The wavelength modulation of the DBA pump is additionally synchronized to the injection of the pump pulses in the fiber, so that successive pump pulses experience the same gain at the same location; thus making the gain stable and avoiding the addition of noise to the BOTDA signal. Furthermore, the net gain can be made to have a flat frequency response with a judicious choice of wavelength modulation shape and frequency [7].

The theoretical model for the interaction of the three waves depicted in Fig. 1 is based on the solutions of the steady-state coupled wave equations that define the evolution of their power along the fiber [8]:

$$\frac{dP_P}{dz} = \left[g_B(\Delta\nu_{DBA})P_L - g_B(\Delta\nu)P_S\right]\frac{P_P}{A_{eff}} - \alpha P_P \tag{1a}$$

$$\frac{dP_S}{dz} = -\frac{g_B(\Delta\nu)}{A_{eff}}P_P P_S + \alpha P_S \tag{1b}$$

$$\frac{dP_L}{dz} = \frac{g_B(\Delta\nu_{DBA})}{A_{eff}}P_P P_L + \alpha P_L \tag{1c}$$

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where P_S, P_P and P_L are the optical powers of probe, BOTDA's pump pulse and DBA pump wave, respectively, at each position z of the fiber, A_{eff} is the effective core area, and g_B is the Brillouin gain spectrum, which depends either on $\Delta\nu$ or $\Delta\nu_{DBA}$, the detuning of the pump pulse and probe wave wavelengths or the pump pulse and DBA pump wavelengths, respectively, from the center of the Brillouin gain spectrum. As in a conventional BOTDA sensor, it can be noticed that the pump pulse power is depleted by the Brillouin gain transferred to the probe wave and by the optical attenuation. However, in the present technique it also receives an additional energy transfer from the DBA pump wave, that is going to compensate its attenuation. This model assumes pulses that are longer than the acoustic phonon lifetime (10ns).

Furthermore, the model needs to take into account the wavelength modulation of the DBA pump, which makes the pump pulses experience a position-dependent Brillouin gain generated by the DBA pump, as it was depicted in Fig. 1. Synchronization of the DBA wavelength modulation and the pulses means that the detuning of the pump pulse wavelength from the center of the Brillouin gain spectrum, $\Delta\nu_{DBA}$, at each position along the fiber is given by:

$$\Delta\nu_{DBA}(z) = \nu_P - \nu_L(z) + BFS(z) \tag{2}$$

where ν_P is the wavelength of the pump pulses and ν_L is the local wavelength of the DBA pump. Note that the latter changes due to the wavelength modulation introduced to the DBA pump and, as a consequence, a distribution of the Brillouin spectra that follows the wavelength variations in ν_L is created [9]. The latter is factually correct when the deployed sensing fiber presents an approximate uniform BFS distribution. Although this is the typical case, it could be possible that the BFS of the fiber would vary considerably not being fully uniform. In this case, the wavelength modulation applied to the DBA laser could be adapted to compensate this effect.

The theoretical model in (1) can be easily solved either directly, through numerical integration, or analytically with some preliminary simplifications. For instance, (1c) can be simplified by neglecting the depletion induced by the short pump pulse on the DBA pump. Similarly, (1a) can be solved taking into account that the Brillouin gain provided to the probe by the pump pulse is very small. With these approximations, the pump pulse power along the fiber is found to be:

$$P_P(z) = P_P(0)\exp\left[\int_0^z \frac{g_B(\Delta\nu_{DBA})}{A_eff} P_L(L)\exp(-\alpha(L-z))\,dx\right] \cdot \exp\left[\frac{g_B(\Delta\nu)}{A_eff} P_S(L)\exp(-\alpha L)\frac{(\exp(\alpha z)-1)}{\alpha}\right]\exp[-\alpha z] \tag{3}$$

The first exponential term is the gain provided by the DBA pump and the second is just the pump pulse depletion due to the energy transferred to the probe assuming nearly uniform BFS along the fiber.

Figure 2(a) depicts the calculated local Brillouin spectrum that is experienced by the pump pulses at each location of a 50km fiber for a triangular modulation of the DBA pump with a frequency of 80 KHz and a peak frequency deviation of 125 MHz. A zoom of the z axis showing just the last 5 km of the fiber is used in Fig. 2(a) to highlight that the profile of the detuning of the Brillouin spectrum along the fiber indeed follows the same triangular profile of the DBA pump modulation. Furthermore, the modulation of the DBA pump wave must provide a DBA with a flat frequency response over the pulse's bandwidth. These parameters are directly related to the choice of wavelength modulation shape and frequency. For this particular case, a triangular shape provides a convenient flat response [7], whose gain's bandwidth can be simply set by the peak frequency deviation parameter.

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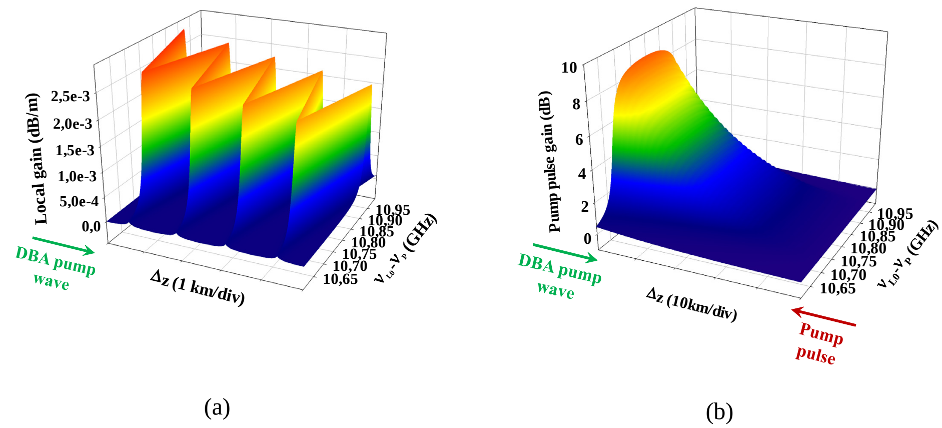

Fig. 2. (a) Local Brillouin gain experienced by the pump pulses at each location of the fiber and (b) total gain experienced by the pulses in their propagation for each location of the fiber. ν_{L0} is the wavelength of the DBA pump wave when no modulation is applied. Simulation parameters are: Brillouin gain $1.1 \cdot 10^{-11}$m/W, Brillouin linewidth 30MHz, effective area is $8 \cdot 10^{-11}$ m^2 and the injected optical pump pulse and DBA pump are 100mW and 4.7mW, respectively.

Finally, Fig. 2(b) depicts the calculated total gain (using (3)) accumulated by the pump pulses from their entry in the fiber (at z=0) as they propagate to each particular position. This total gain is the result of the integration of the position dependent gain provided by the Brillouin spectrum at each z.

3. Experimental setup

Figure 3 schematically depicts the assembled setup to demonstrate the potential of the technique. It is based on the conventional BOTDA sensor that derives the pump and probe waves from a single laser. However, the method is perfectly applicable to BOTDA schemes using other configurations, such as those based on using two separated lasers to generate pump and probe waves [3]. In this particular case, the pump pulse is obtained by using a semiconductor optical amplifier. Then, it is amplified using an EDFA and filtered to remove amplified spontaneous emission noise. The peak pulse power injected into the fiber was 22.4 dBm. In the probe branch, a Mach–Zehnder electro–optic modulator was driven by a microwave synthesizer and biased at minimum transmission to generate a double–sideband supressed carrier signal. This provides a double probe wave, which has been shown to greatly compensate non–local effects [10]. Each of these probe waves is launched into the fiber with a power of -8dBm. Then, a polarization switch is used, as it is customary in BOTDA setups, to eliminate the polarization–dependent response of Brillouin interaction. Before detecting the optical signal, the double probe wave was filtered out to operate in gain mode and the resulting component was pre-amplified by an EDFA. The deployed fiber was a 50-km spool of standard single mode fiber.

The only addition to upgrade the conventional BOTDA technique into a DBA–assisted BOTDA sensor is highlighted in Fig. 3. It only requires the incorporation of an additional laser (DBA laser) whose output is coupled into the sensing fiber, and a signal generator to wavelength-modulate the DBA laser and synchronize the pump pulses. Note that the optical filter used to retain just one of the received probe sidebands, also filters out the remaining of the

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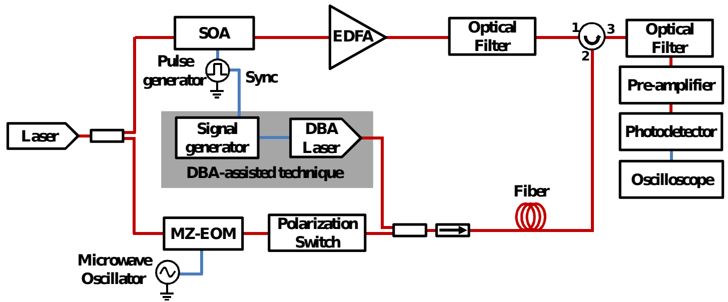

Fig. 3. Experimental setup for the DBA–assisted BOTDA sensor.

DBA laser power. The pump power for the DBA injected in the fiber was 4.7mW. Moreover, the current of the DBA pump laser wavelength was modulated with a triangular electrical signal with a frequency of 80 KHz and an amplitude adjusted to obtain a peak optical frequency deviation of 125 MHz. Note that the latter value is large enough to accommodate short pulse durations of 10 ns and to avoid also any variation of the gain induced by the DBA to the pump pulses due to a frequency drift between the deployed lasers. The resultant wavelength modulation was not perfectly triangular, but was slightly deformed due to the characteristics of the laser chirp [7]. This could be improved employing well-known methods to linearize the chirp response [7], but this was not necessary for the experiments outlined here.

4. Experimental results

Figure 4 compares the distribution of the Brillouin gain spectra measured along the fiber using the conventional BOTDA technique, i.e. when the DBA is turned off, see Fig. 4 (a), and when is turned on to become a DBA-assisted BOTDA, see Fig. 4 (b). As it is shown in Fig. 4 (a), the measured amplitude of the Brillouin spectra exponentially decays due to the progressive attenuation of the pump pulse as it propagates through the fiber. In contrast, when the DBA is on, the amplitude of the spectra initially decays but starts to recover by mid-span. This is due to the gain generated by the DBA pump wave starting to kick-in. The latter is injected at the opposite end to the pump pulse input and the gain that it generates is proportional to its power. Therefore, the pump pulses find amplification where they need it most: at the final segment of the fiber where they have experienced more attenuation.

The net gain provided by the DBA can be simply determined by the pump pulse power at the end of the fiber, i.e. once it has interacted with the probe and the DBA pump waves. Note, that the double probe wave configuration allows to avoid the detrimental impact of non-local effects and, hence, the pump pulse power measured at the end of the fiber is only affected by the gain transferred by the DBA and the attenuation of the fiber. Figure 5 compares the pump pulse switching on and off the DBA pump for pulses of 40-ns and 55-ns. The difference between both measurements reflects a 9.2 dB increment of the pump pulse power using the DBA technique, enough to compensate the 50-km fiber attenuation. Note that the shape of the pump pulse, when the DBA is not active, is determined by the transient response of the SOA. However, when the DBA is on, the shape of the pulse acquires an exponential grow due to the excitation time of the acoustic wave. Note also in Fig. 5 that no significant temporal delay is observed between the pulses captured when the DBA is turned on or off (pulses were measured using an external trigger). However, it must be mentioned that higher DBA pump powers could induce not only amplification but a slow light effect onto the pump pulse, which would affect the spatial resolution of these systems [11].

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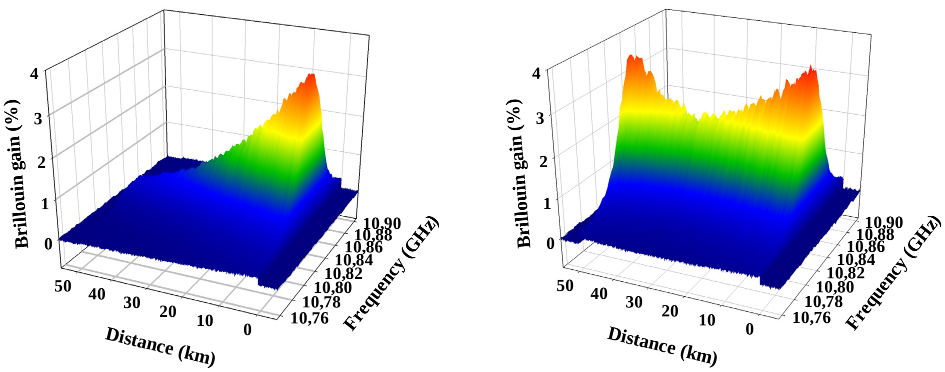

Fig. 4. Measured distribution of the Brillouin spectra when the DBA is turned (a) off and (b) on for 55-ns pulses.

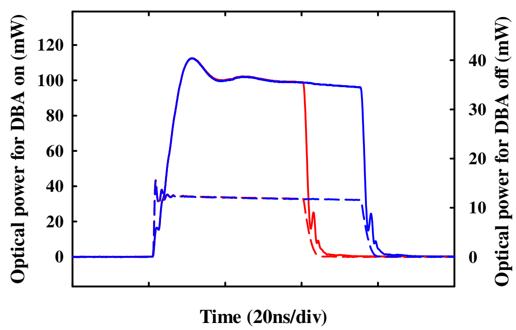

Fig. 5. Optical power of pump pulses at the output of the fiber. Two pulses of 40 ns (red) and 55 ns (blue) are depicted at the output of the fiber with the DBA turned off (dashed line, right vertical axis) and on (solid line, left vertical axis).

However, this amplification of the pump pulse does not only occur at the final section of the fiber but during its time–flight. This effect is even more apparent in Fig. 6, where two BOTDA traces are compared in logarithmic scale. Therefore, using the conventional BOTDA technique, the detected Brillouin signal falls with a linear slope given by the attenuation coefficient of the fiber (0.184 dB/km). As a consequence, the detected signal falls by 9.2 dB at 50–km. Considering that the detected SNR is proportional to the square of the detected amplitude, the SNR degradation at the end of the fiber, compared to the start, is double the value in decibels of the extra attenuation of the pulse, i.e., 18.4 dB. In contrast, using the DBA-technique, the worst attenuation of the detected signal is experienced for this particular scenario at the mid–span of the fiber. At that location, the experienced attenuation is 2.95 dB and hence, the maximum SNR degradation is 5.9 dB.

Nonetheless, the most significant improvement obtained with the presented technique is observed at the final section of the fiber, where the conventional BOTDA technique obtains the worst results. Figure 7 compares the measured Brillouin spectra at the first and final sections of the fiber, using both techniques: the conventional in Fig. 7 (a) and the DBA-assisted BOTDA in Fig. 7 (b). With the DBA off, the measured amplitude at the last km gets into the noise floor and hence, the measurement of the BFS cannot be determined with accuracy. In contrast, using

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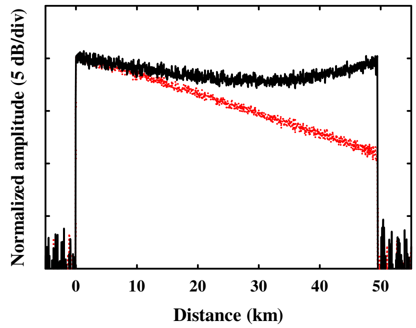

Fig. 6. Measured BOTDA traces when the DBA is switched off (red–dotted line) and on (black–solid line).

the presented technique, the measured Brillouin gain at the final section is similar in amplitude to that measured at the first km.

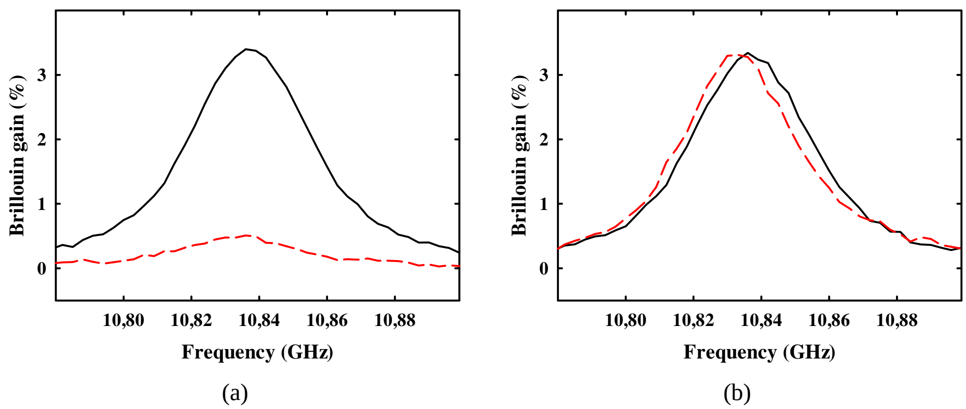

Fig. 7. Measured Brillouin spectra at the first (black–solid line) and final (red–dashed line) section using (a) the conventional BOTDA technique and (b) the DBA–assisted technique.

Furthermore, if we compare the measured spectra at the first and last sections with the DBA on, it is clear that there is no noticeable degradation of the SNR between both measurements, as both have almost the same amplitude and noise level. This is confirmed in Fig. 8, where the evolution of the SNR was calculated for both the conventional and the DBA-assisted BOTDA. As shown in the figure, once the pump pulse is amplified by the DBA, the SNR grows, instead of linearly decaying along the fiber as it happens in the conventional system. Moreover, note that the measured SNR at the start of the fiber is identical turning on and off the DBA (both measurements were performed with the same averaging number (4096) to properly compare the results). As a consequence, it can be concluded that the use of the DBA does not lead to any significant SNR penalty.

Measurements of BFS for different duration pulses with the DBA turned on and off are displayed in Fig. 9. Note that, towards the end of the fiber, the BFS for the shorter pulses deviates from that measured with the conventional BOTDA. The shorter the pulse, the larger the deviation. This effect is attributed to the interplay between the temporal shape changes in the pulse brought by the distributed Brillouin amplification and the SPM effect. Stimulated

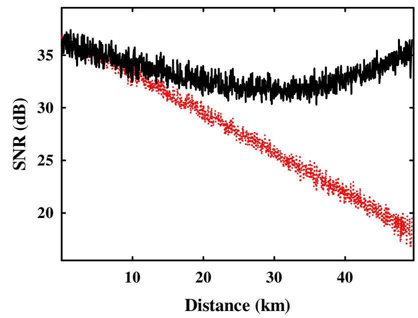

Fig. 8. SNR evolution for the DBA–assisted technique (black–solid line) and the conventional BOTDA sensor (red–dotted line).

Brillouin scattering is a dynamic phenomena that depends on the interaction of a pump and Stokes waves via an acoustic wave. The DBA pump is present at a certain location in the fiber and an acoustic wave is created and starts to grow exponentially when the pump pulse arrives, then it reaches an steady state (if the pulse is long enough) and, finally, the gain is abruptly cut-off as the pulse leaves [12]. This alters the shape of the pulse as it is amplified along the fiber and makes it asymmetrical in time. Then, SPM comes into play generating an optical phase modulation that has been shown to increase the Brillouin gain linewidth when using symmetric pulses with large rise-time [2]. In our case, with an asymmetrical pulse, SPM leads to a down-shift of the instantaneous frequency of the pulse that translates into an apparent up-shift of the measured BFS. This effect is more pronounced for shorter duration pulses because the change in shape of the pulse takes place during the acoustic wave growth, which is of the order of the acoustic phonon lifetime. Moreover, further evidence on the role of SPM was confirmed by repeating the measurements with a reduced pulse power and observing that, in this case, the BFS profile matches that of the conventional BOTDA.

We have devised a solution to compensate the BFS error due to SPM by deploying differential pulse-width pair (DPP) measurements, i.e. substracting the BOTDA traces for pulses of different duration [13], which are longer than the acoustic phonon lifetime. This takes advantage of the fact that temporal asymmetry in the pulses due to the transient behavior of the Brillouin amplification takes place at the start of the pulses during the acoustic wave growth. Furthermore, for pulses longer than the acoustic phonon lifetime, the pulse reaches quasi-steady state Brillouin amplification. Therefore, DPP measurements with two long pulses are not affected by SPM-induced shift in optical frequency and error in BFS. This was confirmed by experimental measurements of the BFS profile for DPP (purple), which is superimposed to that of the conventional BOTDA in Fig. 9. In addition, the measured Brillouin spectra using DBA amplification for a 15-ns pulse duration and the differential Brillouin spectrum using DDP of pulses 40/55-ns duration are shown in Fig. 9. Note that the frequency shift of the Brillouin peak is effectively corrected and no asymmetrical shape is observed at the differential Brillouin spectrum.

Finally, Fig. 10 compares the measured DPP gain spectra at the input and output of the fiber. As it was expected, the amplitude of both spectra is similar (no normalization is used in the figure) as fiber attenuation has been compensated by DBA. Furthermore, the noise in both measurements was also found to have the same standard deviation as the noise detected without DBA. Just to visually compare them, the detection noise without DBA is also shown in Fig. 10.

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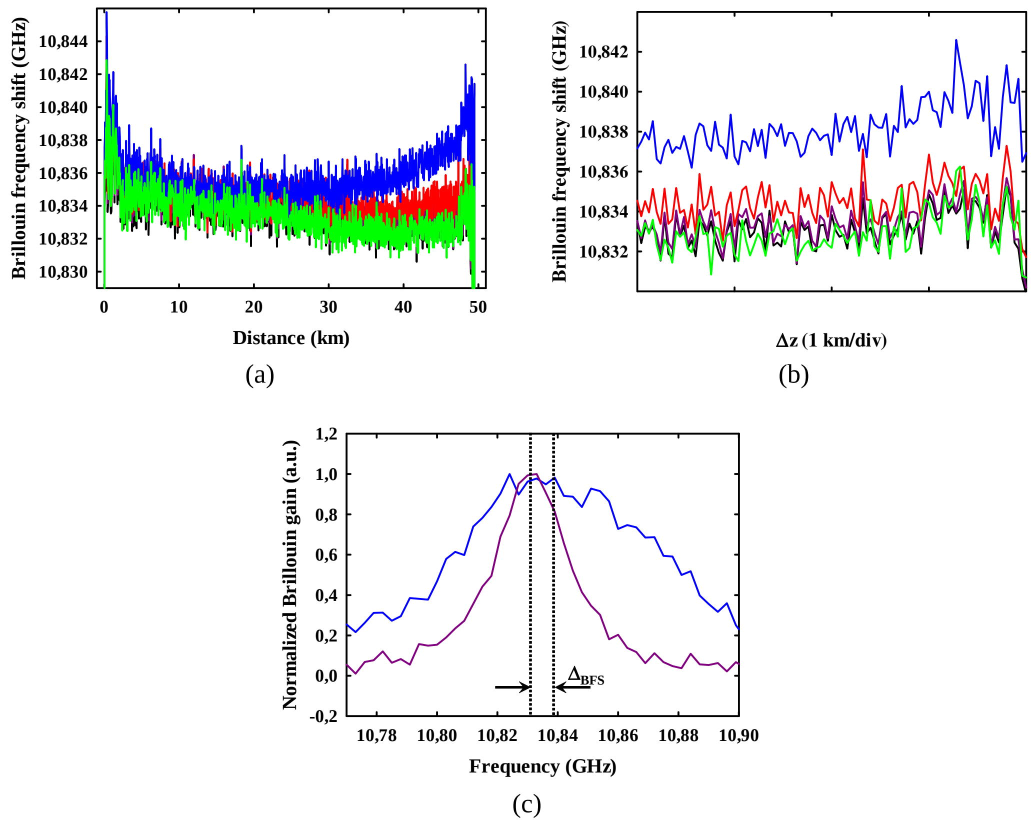

Fig. 9. BFS distribution measured (a) along the whole lenght of fiber and (b) at the last kilometers, using DBA for 15-ns (blue), 30-ns (red) and 40-ns (black) pulses and DPP of 40/55-ns (purple), and without DBA amplification for 40–ns pulses (green). Brillouin gain spectra (c) measured at the last kilometers using DBA for 15-ns (blue) and DPP of 40/55-ns (purple).

5. Conclusion

Distributed Brillouin amplification of the pump pulses in BOTDA sensors has been proven as a powerful tool to extend the measurement range of this sensors. A theoretical model has been introduced and the technique has been experimentally demonstrated over a 50-km fiber link, where the attenuation of the fiber has been fully compensated by the DBA. Moreover, it has been shown that the use of a DBA does not add any significant noise to the measurement, so that an enhanced SNR is obtained for every position of the sensing fiber. This is a remarkable result, specially compared to the use of Raman distributed amplification, which has the drawback of adding significant noise to the measurements. This feature can be explained by taking into account that Brillouin distributed amplification, despite having a large noise figure, amplifies the pulses that counter-propagate with the DBA pump, but has no effect on the probe wave. Particularly, there is no significant transfer of RIN noise to the detected signal.

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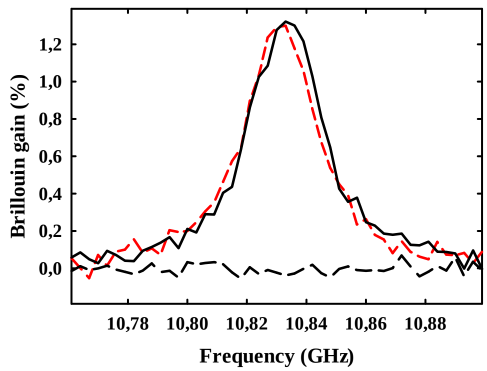

Fig. 10. Brillouin gain spectra at the input (solid–black line) and output (medium–dashed red line) of the fiber link, for the DBA-assisted BOTDA deploying DPP using 40-ns and 55-ns pulses. Detection noise (long dashed black) without DBA.

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