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Review

Non-Local Effects in Brillouin Optical Time-Domain Analysis Sensors

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Received: 5 July 2017; Accepted: 24 July 2017; Published: 27 July 2017

Abstract: Brillouin optical time-domain analysis (BOTDA) sensors have great potential to provide distributed measurements of temperature and strain over large structures with high spatial resolution and measurement precision. However, their performance ultimately depends on the amount of probe and pump pulse power that can be injected into the sensing fiber, which determines the signal-to-noise ratio of the detected measurement signal. The probe wave power is constrained by the generation of noise induced by spontaneous Brillouin scattering and at lower power by the so-called non-local effects. In this work, we focus on the latter. We review the physical origins of non-local effects and analyze the performance impairments that they bring. In addition, we discuss the different methods that have been proposed to counteract these effects comparing their relative merits and ultimate performance. Particularly, we focus on a technique that we have devised to compensate non-local effects which is based on introducing an optical frequency modulation or dithering to the probe wave. This method is shown to provide a comprehensive solution to most of the impairments associated with non-local effects and also to enable some side benefits, such as amplification of the pump pulses to compensate the attenuation of the fiber.

Keywords: stimulated Brillouin scattering; Brillouin optical time-domain analysis; non-local effects

1. Introduction

In the last two decades, distributed fiber optic sensors [1] have been the subject of an intensive research effort due to their unique capability to provide a multitude of measurement locations along an optical fiber. Among the different distributed sensor types, Brillouin-based distributed optical fiber sensing systems have been one of the most widely studied, particularly those based on the Brillouin optical time-domain analysis (BOTDA) measurement principle. These sensors provide high precision distributed temperature and strain measurements along hundreds of thousands of measurement positions over large structures. This renders BOTDA sensors highly useful for a number of structural health applications in several industrial sectors, such as ensuring the integrity of oil and gas pipelines, the structural health of bridges, tunnels, roads, railways and dams, the detection of fire in tunnels and industrial facilities, or assessing the temperature of sub-sea and underground electric power cables [2].

Owing to their importance, many research advancements have been made in recent years on BOTDA sensors. Indeed, different works have been focused on the improvement of the spatial resolution of the sensor [3], the enhancement of the signal-to-noise ratio (SNR) of the analyzer for long-range measurement [4] and on the simplification and reduction of the final cost of the setup [5], among other research lines.

We focus here on techniques to improve the SNR of long-range BOTDA sensors, which directly determines their performance in terms of measurement time and precision. The SNR of the probe wave detected in a BOTDA depends on the power of the pump and probe waves that can be injected in the fiber under test. The pump pulse power is fundamentally limited by the onset of nonlinear effects such as modulation instability (MI), self-phase modulation and Raman scattering [6,7]. As for the probe wave, its power is first limited by the onset of so-called non-local effects. These are due to the transfer of energy from the pump pulse to the probe wave during their interaction along the sensing fiber. This transfer has been shown to introduce an additional transfer function in the measurement due to optical frequency-dependent pump depletion, which induces a systematic error in the measurement of the Brillouin frequency shift (BFS) [8,9]. A second higher-power limit for the probe power that can be injected in the sensing fiber link would be the Brillouin threshold of the fiber, over which significant noise is added to the detected probe signal due to spontaneous Brillouin scattering [10].

In this paper, we carry out a review of the physical origins of non-local effects and their consequences to BOTDA measurements. In addition, the different techniques that have been presented in recent years to mitigate the appearance of non-local effects are introduced, with special emphasis on a technique that we have introduced based on the modulation or dithering of the optical frequency of the probe wave.

2. Non-Local Effects Induced by Pump Pulse Depletion

Two optical waves are used in a BOTDA sensor: a continuous wave (CW) probe and a counter-propagating pump pulse. When these two waves have an optical frequency detuning close to the BFS of the fiber, they interact exchanging energy via stimulated Brillouin scattering (SBS) [11]. In a gain-based BOTDA, a pump pulse at higher optical frequency transfers energy to the probe wave that undergoes amplification at the cost of the pump pulse being depleted. The probe wave only interacts with the pump pulse over a small length of the fiber, which is delimited by the pulse duration, which provides the spatial resolution of the sensor. Therefore, the probe gain, which is used for sensing, is rather small. On the other hand, the pump pulse is subjected to a continuous interaction with wavefronts of the probe wave as it crosses the fiber, losing a small percentage of energy at every step, so that the total accumulated depletion can be significant. The longer the fiber, the higher the pulse depletion. In a fiber with a constant BFS, the depletion of the pulse can be characterized by a dimensionless depletion factor which is given by [9]:

$$d = 1 - exp\left(-\frac{g_B}{A_{eff}} P_{Si} L_{eff}\right) \tag{1}$$

where g_B and A_{eff} are the Brillouin gain coefficient and the effective area of the fiber, respectively, P_{Si} is the probe wave power at the input of the fiber and $L_{eff} = (1 - exp(-\alpha L))/\alpha$, being α the attenuation of the fiber and L its total length. This expression conveys the fact that the pulse depletion depends on the probe power injected into the fiber: the larger the probe wave, the larger the energy transferred to it to attain a given amplification and, hence, the larger the pump depletion. On the other hand, the depletion is shown not to depend on the power or duration of the pump pulse itself.

Figure 1 schematically depicts the impairment brought by pulse depletion to the measurement. A worst-case scenario is assumed in which a uniform BFS fiber is followed by a small section with different BFS, where the gain spectrum is measured. The pump depletion depends on the frequency detuning between pump and probe optical waves along the fiber and this frequency dependence induces an additional transfer function being superimposed on the measured gain spectrum. This distorts the measured spectrum and introduces a bias in the obtained BFS that entails a systematic error in the measurement performed [9]. Notice that this measurement impairment is a non-local effect in the sense that the BFS measurement at a particular location in the fiber is affected by the Brillouin interaction between pump and probe at other locations. In fact, the shape of the transfer function associated with pump depletion at a particular location in the fiber depends on the BFS distribution along all previous locations.

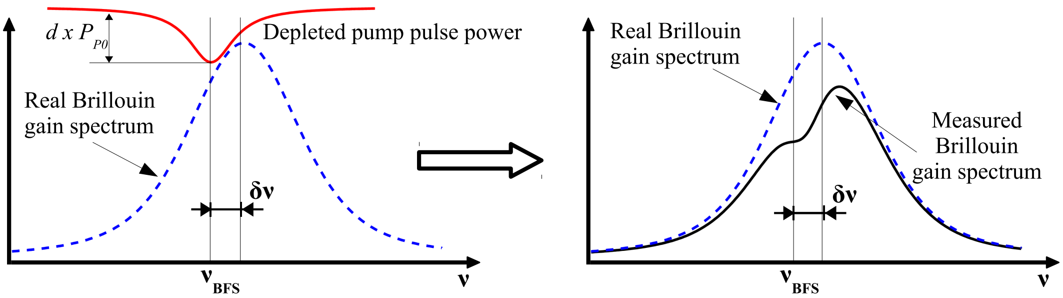


Figure 1. Effect of pump pulse depletion frequency dependence on a Brillouin gain spectrum, when scanning a fiber section displaced $\delta\nu$ MHz from the Brillouin frequency shift (BFS) of the fiber.

It has been found that, in the worst-case scenario, the BFS measurement error is maximum when the BFS difference between the long uniform BFS section and the short final section is around a quarter of the full width at half maximum of the gain spectrum [9]. Moreover, the error increases as the depletion factor increases. For a maximum 1-MHz error in the BFS measurement, the maximum tolerable depletion factor is $d \leq 0.2$, which, for typical standard single-mode fiber, translates to an upper limit of -14 dBm on the maximum probe power that can be injected into a long-range BOTDA sensing link [9].

One of the simplest ways to mitigate the appearance of pulse depletion is the use of two probe waves, equally separated in optical frequency from the pump [12]. This leads to two simultaneous Brillouin interactions (gain and loss) upon the pulse that compensate each other; hence, pulse depletion is suppressed. However, this is only true for first order approximation if the amplification and attenuation experienced by the lower and higher frequency probes, respectively, during their interaction with the pump, are neglected. When the detailed interaction is taken into account, it is found than in a dual-probe BOTDA there is still pump depletion, although it is greatly diminished. This is due to the fact that the pulse is interacting with two probe waves with a power slightly unbalanced by the interaction itself [9]. In this case, it is found that the pump depletion is no longer independent of the pulse peak power nor of its temporal duration. In particular, the greater the power and/or the longer the duration, the higher the depletion factor of the pulse.

In a long-range dual-probe BOTDA sensor, deploying 10-ns pump pulses with peak power set just below the typical MI threshold of 20 dBm, pump depletion imposes a theoretical upper limit for the probe wave injected in the fiber of approx. 7 dBm in order to have a BFS systematic measurement error of less than 1 MHz. Note that for a longer pulse duration, the limit of probe power is more stringent.

Therefore, the dual-probe BOTDA sensor configuration could be seen as greatly ameliorating non-local effects due to pump pulse depletion. However, later work showed that the probe power limitation in this setup was actually more restrictive due to the onset of so-called second-order non-local effects. These non-local effects are related to the appearance of linear distortion of the pump pulse spectrum due to its interaction with the two probe waves [13]. As is shown in Figure 2a, when the frequency detuning between pump and probe waves equals the BFS of the fiber, the loss and gain spectra generated upon the pulse perfectly compensate each other and non-local effects are largely avoided. However, in order to retrieve the full Brillouin gain spectra, it is mandatory to scan the frequency detuning between pump and probe. In this way, as is portrayed in Figure 2b,c, when the frequency difference does not match the BFS of the fiber, the Brillouin gain and loss spectra generated by both probe waves over the pump pulse do not overlap perfectly, leading to linear distortion of the pump pulse spectrum.

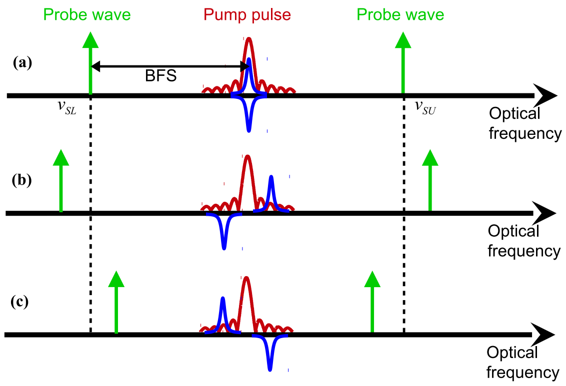
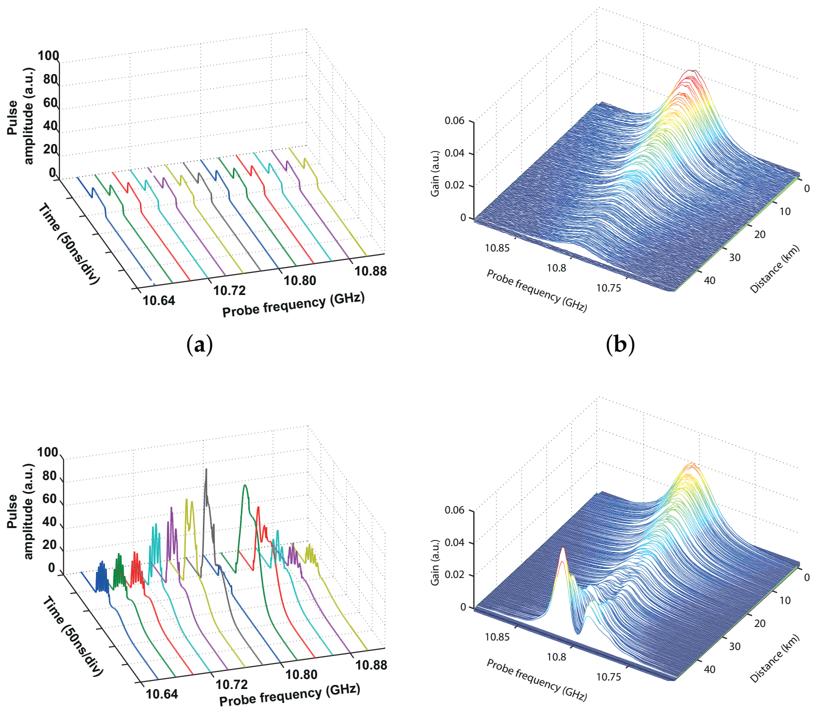


Figure 2. Stimulated Brillouin scattering (SBS) interaction process over the pump pulse in dual-probe wave Brillouin optical time-domain analysis (BOTDA) configurations and its consequences on the pulsed wave for different frequency spacing of the conventional scan process (**a**) when the frequency detuning equals the BFS of the fiber (**b**) when it is higher than the BFS and (**c**) for a smaller frequency shift.

As is depicted in Figure 3, the distortion of the pulse spectrum leads to a distortion of the measured gain spectra and BFS measurement error [14]. It is found that this limits the maximum probe wave power to around −3 dBm for typical standard single-mode fiber parameters. This is well below the theoretical limit imposed by the Brillouin threshold of the fiber, which is around 7 dBm for typical single-mode fiber. Therefore, at least 10 dB of SNR is being wasted in long-range dual-probe BOTDA sensors. Therefore, the development of techniques to overcome this limit is of paramount importance to improve the performance of the sensor.



(**a**) (**b**)

(**c**) (**d**)

Figure 3. Pulses at the output of the fiber and measured Brillouin spectra for a conventional dual-probe BOTDA in two cases for probe wave powers of −6 dBm (**a**,**b**) and 5 dBm (**c**,**d**). (From R. Ruiz-Lombera, J. Urricelqui, M. Sagues, J. Mirapeix, J. M. López-Higuera and A. Loayssa, “Overcoming Nonlocal Effects and Brillouin Threshold Limitations in Brillouin Optical Time-Domain Sensors,” in *IEEE Photonics J.* **2015**, *7*, 1–9. With permission. Copyright 2015 IEEE).

3. Mitigation of Non-Local Effects

As it has been explained, dual-probe BOTDA setups mitigate non-local effects originating from pump pulse depletion. However, other methods have also been introduced over the years to mitigate this impairment. An early proposal was the use of a post-processing technique for temperature/strain profile reconstruction [15]. This was based on searching the BFS distribution that matched a given measurement data by using a multidimensional minimization algorithm to determine the coefficients of the parametrized unknown profile. However, the applicability of this method to realistic measurement scenarios is rather limited. Another proposal was a time-multiplexing method that is based on pulsing the probe wave so as to limit the interaction length with the pump pulse [16,17]. According to (1), this reduces the pump pulse depletion. The drawback of this method is that the measurement time is greatly increased as the length of the interaction lengths is reduced to achieve significant mitigation of non-local effects. Finally, we also introduced a technique tolerant to non-local effects that is based on a phase-modulated probe wave and radio-frequency (RF) demodulation [18]. The tolerance to pulse depletion-induced impairments of this method is based on the characteristics of the detection process, which generates a RF phase-shift signal that has been shown to be largely independent of the Brillouin gain magnitude. Nevertheless, probably the simplest and the most successful alternative to mitigate non-local effects due to pump depletion is the use of the dual-probe setup. In the following, we review the techniques that have been proposed to enhance dual-probe BOTDA setups so as to be able to overcome the constraints imposed by second-order non-local effects as well as other limitations.

3.1. Mitigation of Second-Order Non-Local Effects

One approach to overcome the distortion of the pump pulse spectrum is the use of an alternative scanning method in the dual-probe BOTDA sensor configuration [19]. The method is based on changing the conventional scanning of the Brillouin spectra to ensure the continuous overlapping of the gain and loss spectra induced by both probe waves on the pump. This is achieved by maintaining a fixed frequency difference between both probe wave sidebands equal to twice the BFS of the fiber. Recently, a more elaborate solution making use of this technique but with four probe waves was also presented [20]. These methods enable an increase of the probe power over the second-order non-local effects limit, at the cost of a somewhat increased complexity of the setup. Nevertheless, the maximum probe wave power injected into the fiber is still limited by its Brillouin threshold.

We have also introduced a method to compensate second-order non-local effects that also enables dual-probe BOTDA setups to overcome the Brillouin threshold of the fiber. The basis of this technique is to introduce a modulation or "dithering" to the optical frequency of the probe waves, as it is schematically depicted in Figure 4, where the optical waves involved in the technique as well as the Brillouin interaction on the pump and probe waves are highlighted. As is depicted in Figure 4a, the optical frequency of the probe waves is modulated in the time domain following a saw-tooth shape [21]. Alternatively, sinusoidal or a triangular shape could be deployed, which have been shown to have a similar performance [14,22]. Additionally, this frequency modulation (FM) is synchronized to the pump pulses so that a series of pulses experience the same optical frequency of the probe waves at any given location. Note that in this particular experiment both, the pump pulse wave and the probe wave, are generated with the same optical source, a 1550-nm distributed feedback laser. Altogether, this makes the effective optical frequency of the probe wave vary along the optical fiber following the applied FM modulation shape. Therefore, the pump pulse, as it travels along the fiber, experiences stimulated Brillouin scattering interaction with probe wavefronts that have a different frequency detuning. The net effect is completely analogous to having a virtual BFS distribution in the fiber, in the sense of having a fiber whose BFS profile has the same shape as the FM modulation imposed upon the probe [22]. As the pulse depletion is cumulative along the fiber, interacting with different frequencies within the Brillouin spectrum leads to a decreased depletion factor of the pulse. Furthermore, as highlighted in Figure 4a, the Brillouin interaction induced by both probe waves upon the optical pulse spreads over a large frequency range. Therefore, the net gain and loss spectra induced by both probe waves broadens so that no distortion is introduced in the pump pulse spectrum and second-order non-local effects are suppressed [14]. In addition, the gain and loss spectra mutually compensate, so there is no depletion of the pulse.

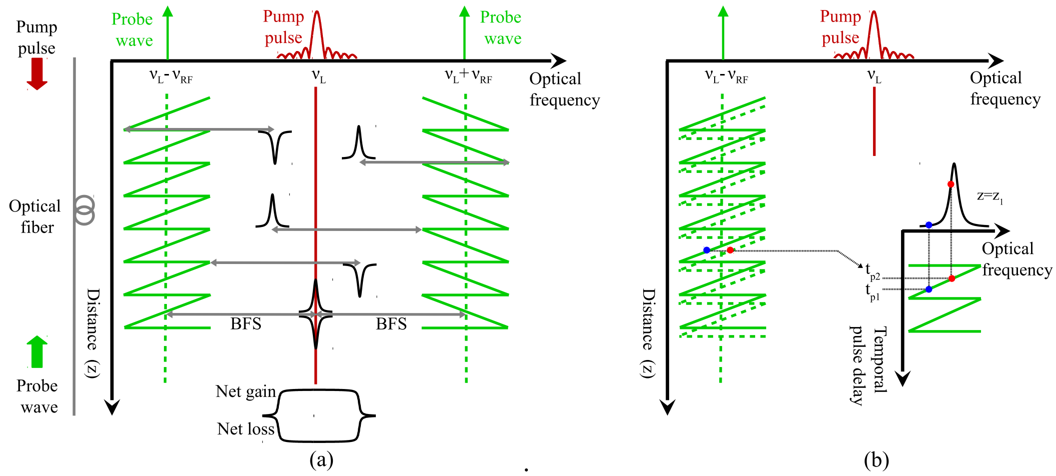


Figure 4. Fundamentals of the probe dithering technique for mitigation of second-order non-local effects: (**a**) Brillouin interaction on the pump pulse and (**b**) frequency scanning method based on the temporal delay change (t_{p1} and t_{p2}) between probe and pump waves.

It is important to point out that, as it is depicted in Figure 4b, the FM of the probe wave is also used to perform the frequency scan of the Brillouin spectra, instead of doing it by a conventional frequency sweep. At each location of the fiber, the pump pulse is made to interact with different probe wave frequencies simply by changing the relative delay between the probe wave FM modulation and the pump pulse [14]. Note that the number of relative delay steps is given by the relation between the peak-to-peak frequency deviation of the FM, which defines the range of frequencies to scan, and the desired frequency step; hence, it is exactly the same as in a conventional BOTDA scheme. Thus, there is no penalty at all regarding measurement time in comparison with a conventional frequency sweep. The final Brillouin spectra is obtained after a post-processing of the measurement to compensate the frequency shift introduced to the probe wave at each location due to the FM modulation. To do this, all measured data are introduced in a matrix, so the trace measured for each pulse delay is stored in a different row of the matrix. The method is simply to apply a shift to the elements of the columns of the matrix containing the probe wave samples (rows) for each relative delay between the FM modulation and the pump pulses [14].

A side benefit of this probe dithering method is that the optical frequency modulation of the probe waves allows to overcome the Brillouin threshold limit of the fiber, by means of reducing the effective amplification of spontaneous Brillouin scattering [22]. Therefore, a very large probe power can be deployed to enhance the SNR in detection, which in turn leads to an enhancement of the measurement precision and/or the measurement time of the BOTDA sensor. Indeed, up to 15 dBm of probe wave power [4] injected into a long-range BOTDA has been demonstrated experimentally [4], which, to the best of our knowledge, is the largest probe power ever deployed in a BOTDA setup.

An important caveat of both methods to mitigate second-order non-local effects, the alternative sweep and our probe dithering technique, is that they assume that the BFS profile of the fiber does not significantly deviate from uniformity [23]. As was mentioned before, the alternative sweep method requires the frequency difference between both probe waves during the scanning process to be constant and equal to the BFS of the fiber. However, if the BFS of the fiber changes, the gain and loss spectra generated by both probe waves no longer overlap, and second-order non-local effects reappear. Similarly, our probe dithering method is also affected by variations of the BFS along the fiber because perfect compensation of the gain and loss spectra induced upon the pulse requires a nearly uniform BFS.

However, the technique is much less sensitive to this effect than the alternative sweep method because the gain and loss spectra are broadened by the FM modulation process. In any case, the assumption of uniform BFS along the fiber is somewhat not realistic in many practical applications because in a sensing link we may have fiber from several manufacturers with slightly different nominal BFS or different fiber sections subjected to different environmental conditions. However, we have devised a technique that solves this issue. It is based on introducing an additional wavelength modulation to the probe wave so as to track the BFS changes along the sensing fiber link [23]. This technique has been demonstrated in a 120-km fiber sensing link deploying three types of single-mode fibers with different nominal BFS. The use of a 15 dBm probe wave power provided 3-m resolution and 2-MHz precision BFS measurement in the worst-contrast position.

3.2. Probe Dithering for Brillouin-Assisted Amplification of Pump Pulses

Another beneficial side effect of using the probe dithering technique is the amplification of the pump pulses propagated along the fiber [21]. This increases the Brillouin interaction and the SNR of the probe signal received from far away locations along the fiber. A hint on how to achieve this pulse gain can be obtained from observation of Figure 4a. Notice that if the lower optical frequency probe is removed, the pump pulse experiences the gain induced by the higher frequency probe. Moreover, as this gain is broad and flat, all frequency components of the pulse are equally amplified, leading to a non distorted pulse, free from second-order non-local effects. This is a BOTDA sensor operating in a loss configuration, so that the energy is transferred from the probe wave to the pump wave and the Brillouin loss spectrum experienced by the probe is finally measured.

We have experimentally demonstrated this idea in a 100-km BOTDA sensor, obtaining a measurement uncertainty of 1 MHz at the worst-contrast position for 1-m spatial resolution. The obtained BGS with the FM modulated dual-probe BOTDA and for the BOTDA amplification of the pump pulse technique in the same conditions are depicted in Figure 5a,b, respectively. Notice that the amplitude of the measured spectra is reduced as the pulse propagates along the fiber. However, for the system with Brillouin-assisted amplification, the amplitude starts to increase and recover at mid-link when the gain provided by the probe wave starts to be significant.

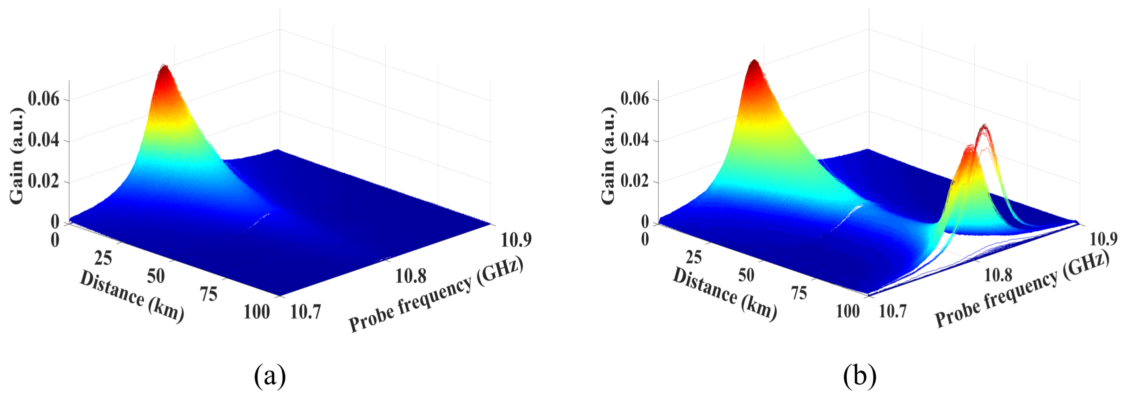


Figure 5. Brillouin gain distribution measured with (**a**) dual-probe-sideband BOTDA sensor using frequency modulation of the probe wave and (**b**) novel BOTDA with pulse amplification. A pulse duration of 45 ns was deployed in both measurements. (From Juan José Mompó, Javier Urricelqui, and Alayn Loayssa, "Brillouin optical time-domain analysis sensor with pump pulse amplification", *Opt. Express* **2016**, *24*, 12672–12681. With permission. Copyright 2016 Optical Society of America).

3.3. Probe Dithering for ER Impairments Mitigation

In the description of the BOTDA sensor thus far, it has been assumed that the pump wave is just an ideal optical pulse. However, any practical device that is used to generate the pulse is bound to have a limited extinction ratio (ER). Hence, as shown in Figure 6, in real-world BOTDA sensors there is a CW pump power that leaks and counter-propagates with the probe wave along the fiber.

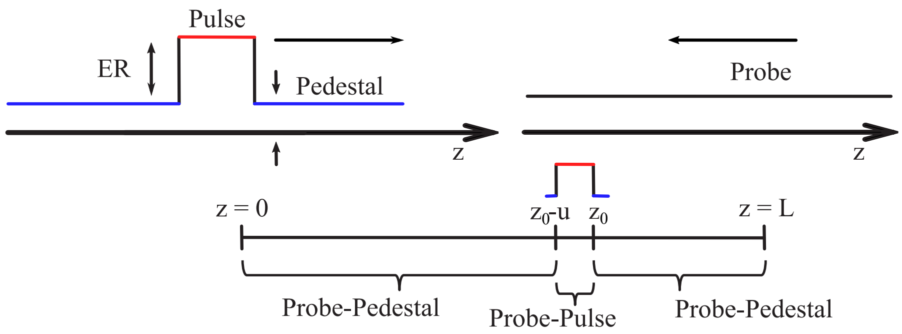


Figure 6. Schematic description of probe and pulse waveform interaction along the fiber for an extinction ratio (ER) limited pump pulse wave.

In this way, as shown in Figure 6, there are three regions of interaction with the pump wave that the probe wave finds as it travels along the fiber. The first interaction section extends from the probe entrance in the fiber at $z = L$ to the location of the pulse at a particular z_0. In this region, just the pedestal of the pump pulse and the probe wave interact, leading to Brillouin amplification of the probe wave. Then, the probe wavefront meets the pulse and is amplified during the width u of the pulse (half the spatial width of the pulse in the fiber, which equals the spatial resolution). Finally, after leaving the pulse location, there is another interaction area, from $z = z_0 - u$ to $z = 0$, where the probe wave is again amplified by the pump pedestal.

Therefore, the net effect of the presence of the pump wave pedestal is that the probe wave experiences more gain than just that due to the pulse itself. A gain that is not useful for sensing. On the contrary, the extra power amplification of the probe wave aggravates the appearance of pump pulse depletion since the pulse meets a higher probe power along the entire sensing fiber than would be met in the case of no pump pulse pedestal [24]. This effect takes place even in BOTDA setups deploying two probe waves. In this case, the power of the probe waves becomes unbalanced owing to the interaction with the pedestal: one probe wave is amplified while the other one is depleted. Thus, gain and loss processes induced by the probe waves over the pump pulse no longer compensate each other, leading to pulse depletion, which in turn introduces a more stringent limitation of the total probe wave power that can be deployed in the sensor. Figure 7 displays the numerically calculated frequency-dependent depletion factor of the pump pulse in a dual-probe BOTDA configuration for different ER of the pulse. It can be observed that the use of a 25 to 30 dB ER of the pump pulses, which is typical of pulses shaped using electro-optic modulators, seriously increases the depletion factor and, hence, the error in the measurement of the BFS.

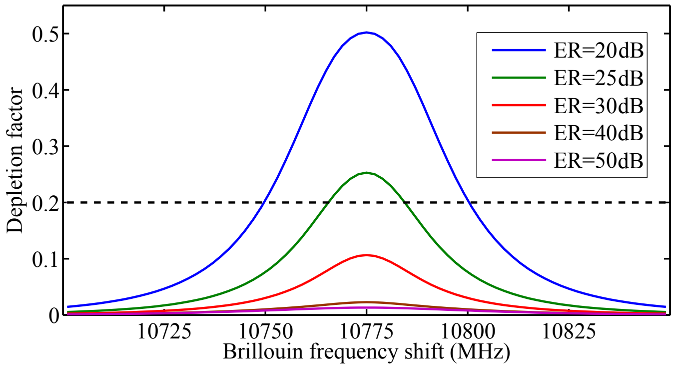


Figure 7. Depletion spectrum of the pulse for different ER pulses of 20 dBm counter-propagating to a −3 dBm probe wave power per sideband in a 25-km length single-mode fiber.

To obtain a higher ER of the pulses, acousto-optic modulators (AOM), optical switches or cascaded Mach-Zehnder modulators (MZM) can be used. However, AOMs and optical switches are limited in the rise time of the pulses that they can produce so it is not possible to generate short pulses. Furthermore, the use of cascaded MZMs increases the complexity and final cost of the sensor. Thus, in order to use a single MZM, which provides short pulses at a reduced setup complexity and cost of the sensor, we have devised a method to deploy the probe dithering technique to reduce the detrimental effects of the use of limited ER pulses in BOTDA sensors [25]. In this incarnation of the technique, the modulation of the optical frequency of the probe wave is performed by taking advantage of the chirp of the source laser under direct current modulation. The theoretical underpinnings of the method are similar to those of the interaction between pump and probe waves in Brillouin optical correlation domain analysis sensors. As the laser used for generating not only the probe wave but also the pump pulse is FM modulated, the pulse pedestal and the probe wave have their optical frequencies modulated with the same sinusoidal shape. Thus, as they counter-propagate, their wavelength difference is correlated just at certain locations in the fiber (correlation peaks), where there is efficient Brillouin interaction. Therefore, the gain experienced by the probe due to the pump pulse pedestal is reduced, together with the extra depletion that it induces on the pulses.

3.4. Probe Dithering in Pulse-Coded BOTDA Sensors for Reducing Pump Pulse Depletion

Different pump pulse coding techniques [26] have been used in recent years to improve the SNR of BOTDA sensors so that measurements can be made with longer fiber lengths [4,27]. In a BOTDA sensor with coding, instead of having a pump signal with a single pulse, the pump wave is composed of multiple pulses, with the total number given by the code length. Therefore, the amount of pump pulse depletion suffered by each single-pulse of a sequence, instead of being just related to the power of the probe wave injected into the fiber, also depends on the amplification of the probe wavefronts by previous pulses in the coded sequence. In this way, the successive pulses of a sequence experience an increased depletion factor, since the n-th pulse in the sequence meets a probe wavefront that has previously been amplified by $n-1$ pulses [4]. Hence, non-local effects will appear earlier in BOTDA setups that make use of coding techniques than in conventional single-pulse BOTDA sensors [4].

Furthermore, even for a dual-probe wave BOTDA configuration, which mitigates the appearance of non-local effects, the presence of multiple pulses in the fiber when using coding makes pump pulse depletion become significant at lower input probe wave power than for single-pulse dual-probe systems [4]. Furthermore, pulse-coded BOTDA sensors are less tolerant to a given level of pump depletion with big BFS measurement error even for a pulse depletion factor smaller than $d = 0.2$. This is due to the fact that in coding schemes, it is mandatory to precisely know the power of all the pulses in the sequence in order to properly weigh the decoding matrix. However, the differential depletion of the pulses in the sequence alters those weights and leads to decoding errors [4].

The use of our probe dithering method provides a reduction of pump depletion and enables the use of higher probe powers in pulse-coded BOTDA sensors. For instance, Figure 8 depicts the depletion factor of each pulse in a large code length sequence when a FM modulated dual-probe BOTDA configuration is used. This depletion is significantly smaller than without probe dithering, as we observed experimentally. In fact, we have demonstrated up to 164-km fiber-loop measurement distance, with 1-m spatial resolution and 3-MHz BFS precision using a BOTDA sensor with probe dithering and deploying a sequence length of 79 pulses [4]. To the best of our knowledge, this is the longest sensing distance achieved with a BOTDA sensor using mono-color cyclic coding.

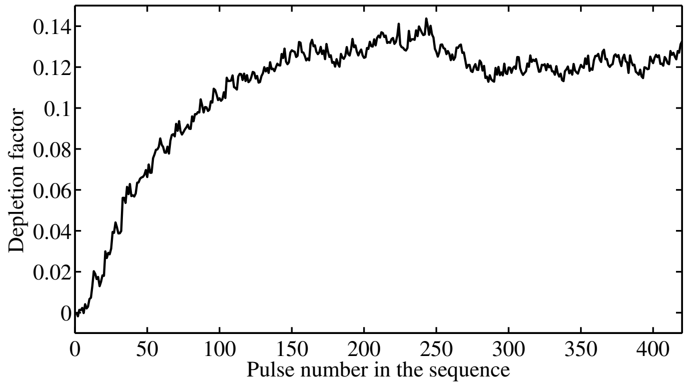


Figure 8. Depletion factor of the pulses of a long code length sequence.

4. Conclusions

Non-local effects are amongst the main constraints on the performance of BOTDA sensors since their onset entails limits to the SNR of the detected probe wave. Conventional pump and probe BOTDA sensors have their probe power severely contained by these effects. Dual-probe setups significantly alleviate the issue, enabling the use of higher probe power. However, they are still prone to second-order non-local effects that distort the pulse spectrum and constrain the probe power to well below the theoretical limit set by the Brillouin threshold of the fiber. This constraint is even more severe when pump pulse coding techniques are deployed. Furthermore, the dual-probe BOTDA sensor performance is still seriously compromised when pump pulses with limited ER are deployed because the pump depletion is increased.

The method for probe optical frequency modulation or dithering provides a comprehensive solution to most of these issues. Its use leads to BOTDA setups that can deploy probe power above the Brillouin threshold of the fiber. Moreover, it can provide side benefits such as amplification of the pump pulses, reduction of ER-related impairments and enhancement of SNR in pulse coding BOTDA. All this with very little complexity added to the conventional dual-probe BOTDA setup.

Acknowledgments: The authors wish to acknowledge the financial support of the Spanish Ministerio de Economía y Competitividad through the projects TEC2013-47264-C2-2-R and TEC2016- 76021-C2-1-R, FEDER funds and the Universidad Pública de Navarra.

Author Contributions: H.I. and A.L. wrote the paper. All the authors reviewed and critiqued the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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