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Unexpected non-local effects in dual-probe-sideband BOTDA

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ABSTRACT

Until now, non-local effects in dual-probe-sideband Brillouin Optical Time Domain Analysis (BOTDA) systems have been considered negligible if the probe power is below the Stimulated Brillouin Scattering (SBS) threshold. In this paper, we show the appearance of non-local effects even below the SBS threshold. The pump pulse experiences a frequency-dependent spectral deformation that affects the readout process differently in the gain and loss configurations. The main conclusion of our study is that the measurements in gain configuration are more robust to this non-local effect than the loss configuration. These results are of particular interest for manufacturers of long-range BOTDA systems.
Keywords: Brillouin Scattering, Nonlinear Optics, Fiber Optics Sensors.

1. INTRODUCTION

Non-local effects have been consistently a major limitation for Brillouin Optical Time Domain Analysis (BOTDA) developers. In order to avoid such non-local effects, several strategies have been put forward in the literature in the past few years [1][2]. According to recent models [3], the use of Dual Sideband (DSB) modulation to generate the probe beam effectively turns these non-local effects to be largely negligible whenever the probe wave power does not reach the SBS threshold. While this is a correct assumption in most cases, it might lead to an incomplete description of the non-local effects in this situation. The work presented in this paper shows that to understand non-local effects in this case, a full spectral description of the process is necessary. In addition, a simple analytical model of this phenomenon has been devised and validated against compelling experimental data, showing good agreement.

2. PRINCIPLES

In BOTDA systems, when using DSB modulation on the probe wave, the higher frequency sideband of the probe (which scans the Brillouin Loss process) provides power to the pump pulse, and at the same time, the pump pulse provides power to the lower frequency probe sideband (which scans the Brillouin Gain) [4]. This situation can be analyzed in the analogous way in which the higher and lower frequency sidebands of the probe generate, respectively, a gain and a loss around the pump frequency. Depending on the modulation frequency, the relative position of the gain and loss signatures and the pump pulse can be different, as shown in Fig. 1a.

When the probe wave is modulated to match the Brillouin Frequency Shift (BFS) ($\nu_{mod} = \nu_B$), the amplification and attenuation processes generated, respectively, by the upper and lower frequency sidebands, will occur at the pump frequency, as shown in Fig 1a.ii. This leads to an essentially undistorted pulse spectrum along the distance. However, a modulation of the probe wave at a frequency below the BFS (Fig. 1a.i) ($\nu_{mod} < \nu_B$) implies an amplification curve occurring at a frequency lower than the pump frequency, and simultaneously, an attenuation process happening at a frequency above the pump frequency (note that the amplification and attenuation processes manifest at a frequency shifted $\pm\nu_B$ from the corresponding probe frequency). The overall result is that the pump pulse is spectrally distorted and down-shifted. On the other hand, when the modulation frequency is above the BFS (Fig. 1a.iii) ($\nu_{mod} > \nu_B$), the amplification process generated by the upper frequency sideband occurs at a higher frequency than the pump frequency, and equivalently, the attenuation generated by the lower frequency band occurs at a lower frequency than the pump frequency. This will again lead to a distortion of the pulse spectrum and an up-shifting of its central frequency. Thus, sweeping the modulation frequency around the BFS will modify the pump pulse spectrum, turning it asymmetrical and spectrally shifted upwards or downwards depending on whether the modulation frequency is higher or lower than the BFS. This has a strong impact on how the gain and loss curves are retrieved as we will see next.

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When performing BOTDA measurements, a frequency sweep around the BFS is needed on the probe wave modulation in order to recover a complete BFS profile of the Fiber Under Test (FUT). Therefore, changing the probe wave frequency, the Brillouin Gain and Loss curves interact with a pump pulse spectrum that is spectrally different for each probe frequency, as illustrated in Fig. 1b.i. In particular, when the modulation frequency is below the BFS, the pulse central frequency is down-shifted. This implies that the new frequency difference among pump and upper sideband is closer to the BFS (thus the attenuation is overestimated) and conversely, the frequency difference among pump and lower frequency probe band is lower, which implies an underestimation of the gain curve. A similar situation can be observed in the case in which the modulation frequency is above the BFS (Fig 1b.ii). In this case the pulse central frequency is up-shifted, which implies that the new frequency difference among pump and upper sideband is closer to the BFS. Again, in this situation, the attenuation is overestimated and the gain is underestimated.

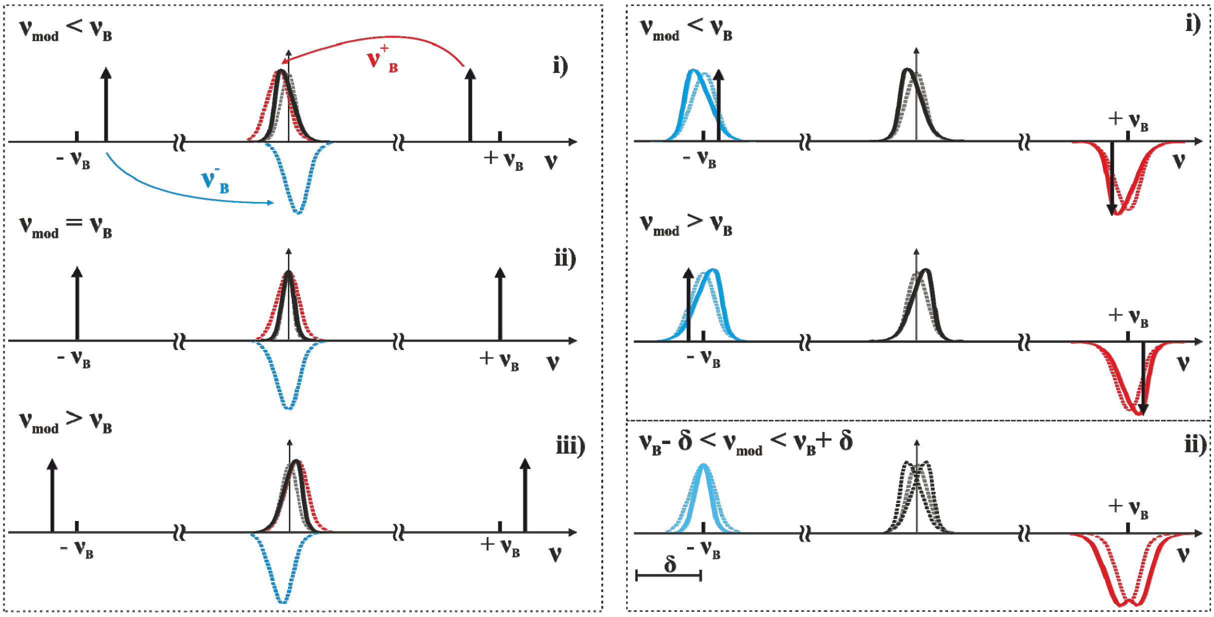

Fig. 1: a) Illustration of the SBS-induced distortion in the pump pulse when using DSB-SC modulation on the probe wave. The pump pulse suffers a spectral deformation with several consequences, including a spectral deformation and a shifting of the central frequency. The dashed-line curves correspond to the gain/attenuation processes generated by the Stokes and anti-Stokes probe beam components. b): i) Illustration of the SBS interaction between a non-uniform pulse spectrum and the Brillouin Gain and Loss curves while sweeping the probe wave modulation frequency; ii) Resulting spectra after a complete sweep of the probe wave modulation frequency, varying such frequency over a certain amount (± δ) around the BFS of the FUT. The gain process shows an apparent narrowing while the attenuation process appears to be broader.

This particular phenomenon leads to one remarkable result: as the pump pulse advances towards the end of the fiber, the "observed" Brillouin Gain Spectrum (BGS) progressively narrows while the observed Brillouin Loss Spectrum (BLS) broadens. Such important outcome will imply a better determination of the BFS in the Brillouin Gain case and a worse determination in the Brillouin Loss one. Moveover, it can be shown that the energy content of the pulse grows slightly when the modulation frequency is slightly detuned from the BFS. This behavior is responsible for the appearance of two side lobes in the Brillouin Loss curve, situation that worsens when increasing the probe wave power provided at the fiber end. There is an additional point of concern for BOTDA developers in this case, which has to do with the fact that the Brillouin gain and loss processes on the pump induced by, respectively, the upper and lower frequency sidebands of the probe are not exactly located at the same frequency offset from their corresponding sideband.

3. RESULTS

In order to analyze in detail the above model of non-local effects in BOTDA systems, we developed the BOTDA scheme represented in Fig. 2. It is a variation of the classical BOTDA system prepared by this group [5], in this case generating the pump pulse using an Electro-Optical Modulator (EOM) and using a conventional single-sideband detection scheme. In addition, an extra scheme has been used, in order to visualize the evolution of the spectrum of the pump pulse after going through the FUT. The measurements have been performed over ~50 km of single-mode fiber (SMF) with an essentially homogeneous BFS located at 10.865 GHz at the pump wavelength (~1550 nm). The pulse width used is 50 ns, and the pulse peak power provided is ~50mW. The acquired traces have always been averaged 1024 times. These results are validated against an analytical model to be presented at the conference.

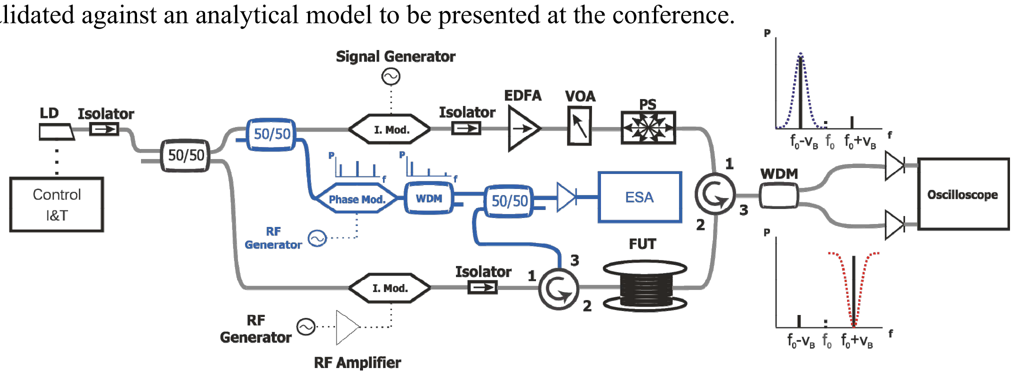

Fig. 2: BOTDA experimental setup. LD: Laser Diode; I. Mod.: Intensity Modulator; EDFA: Erbium Doped Fiber Amplifier; RF: Radio-frequency generator; VOA: Variable Optical Attenuator; PS: Polarization Scrambler; FUT: Fiber Under Test; WDM: Wavelength Division Multiplexer; ESA: Electrical Spectrum Analyzer.

The first remarkable result is the observation of an asymmetric spectral shift of the pump pulse dependent on the probe frequency. In Fig. 3a we can see the evolution of the electrical spectrum of the pump pulse after experiencing SBS through the fiber. As it can be seen, the interaction of both the attenuation and amplification processes caused by the probe sidebands with the pulse modifies its spectral shape, leading to a frequency upshifting of the pulse when the modulation frequency is above ν_B and a down shifting when it is below, as expected from the previous section. When augmenting the probe wave power, the resulting spectra present a higher unevenness in their power distribution. Moreover, when scanning close to the BFS frequency it is visible an increase in the pulse energy content. The slight detuning of the BFS for the lower and upper frequency sidebands causes this increase in pulse energy content to be larger when the modulation frequency is above the BFS.

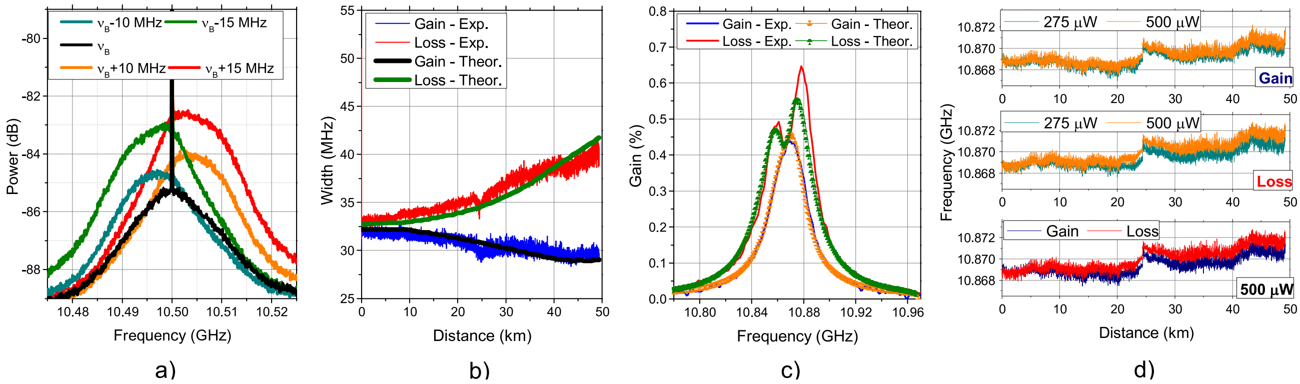

Fig. 3: BOTDA outcomes for a ~50 km SMF. a) Electrical spectra (75 kHz of resolution bandwidth) of the detected pump pulse recorded after going through the FUT and experiencing SBS for a fixed probe wave power of ~500 µW (on each sideband), sweeping the probe modulation frequency around the BFS of the FUT. b) Experimental and theoretical evolution of the FWHM for the Brillouin Gain and Brillouin Loss spectra. c) Experimental and theoretical representation of the BGS and BLS at 49.768 km for a frequency sweep between 10.78 GHz and 10.98 GHz. d) Brillouin frequency shift profiles obtained for different probe wave powers on a ~50 km SMF. BFS profiles obtained from the measured Brillouin Gain band for two values of probe power (Top); BFS profiles obtained from the measured Brillouin Loss band for two values of probe power (Middle); BFS profiles of the Brilluoin Gain and Loss bands for a fixed probe wave power of ~500 µW (on each sideband) (Bottom).

When performing comprehensive BOTDA measurements, the disproportion and shifting of the pump pulse spectrum grows to become an undesired phenomenon, especially when measuring at the far end of the fiber. This phenomenon leads us to a major outcome: it broadens and distorts the BLS profile meanwhile narrows the BGS, as discussed in the previous section. Fig. 3b illustrates the evolution of the Full Width at Half Maximum (FWHM) of the BGS and BLS profiles along the distance. As it can be seen, the FWHM of the experimental BLS broadens ~7.5 MHz, meanwhile the simulated results show a broadening of ~8.5 MHz. Conversely, the FWHM of the BGS narrows ~3 MHz, confirming the decrease of ~3 MHz observed at the simulated results. In Fig. 3c, we can see the Gain and Loss spectra for a probe power of ~500 µW (on each sideband) at the very end of the FUT (point 49.768 km). The spurious new lobes retrieved on the BLS are, in fact, as predicted, slightly unbalanced among each other due to the small BFS offset generated by the Brillouin Gain and Loss bands. In this case, the theoretical model adjusts correctly to the experimental result, following reliably the profile shape.

On top of the above results, we have taken a deeper look at the consequences of these non-local effects in terms of the BFS determination. As we have already seen, the BLS at the very end of the fiber presents two asymmetric side lobes (see Fig. 3c). Indeed, due to the small mismatch of the BFS generated by the Brillouin Gain and Loss bands, such spurious peaks are unequal, and the higher frequency lobe always prevails over the lower frequency one. The appearance of these lobes can lead to a distorted determination of the maximum of the retrieved curves, which should be consistently overestimated. In Fig. 3d we analyze the mismatch in the determination of the BFS along the fiber when increasing the probe power (hence increasing the asymmetry in the side lobes). Increasing the probe wave power leads to a BFS displaced an average of ~1 MHz to higher frequencies at the very end of the fiber in the Brillouin Loss spectrum, meanwhile the BFS obtained retrieved from the Brillouin Gain spectrum shifts ~0.6 MHz at the same position. Furthermore, we have also observed the behavior of the BFS obtained for both the BGS and BLS for a fixed probe wave power (Fig. 3d, bottom). The displacement of the BFS extracted from the measured loss curve at the very end of the fiber is again ~1 MHz above the BFS obtained in the gain case, whereas the BFS measured for both cases at the beginning of the FUT remains equal. These results clearly confirm the slight up-shifting phenomenon of the BFS predicted by the qualitative models, which is stronger in the attenuation case.

4. CONCLUSIONS

In conclusion, we have presented a series of non-local effects of dual-probe-sideband BOTDA systems. It has been shown that the pump pulse spectrum suffers a distortion and frequency shifting while sweeping the probe wave modulation frequency. The most remarkable consequence of this phenomenon is that the Full Width at Half Maximum (FWHM) of the Brillouin Gain Spectrum (BGS) narrows towards the end of the fiber, whereas the FWHM of the Brillouin Loss Spectrum (BLS) considerably broadens. Besides, the BLS is affected by the appearance of spurious side lobes meanwhile the BGS remains roughly well-proportioned.

In addition, the slight offset among the gain and loss processes generated by the upper and lower frequency components of the probe creates an asymmetry in the retrieved BGS and BLS curves that yields in an error in the determination of the BFS. In both cases, the BFS tends to shift to higher frequencies towards the end of the fiber, being larger the error in the attenuation case. All these undesired effects mainly prevail in the Brillouin Loss case over the Gain one. All these results have been demonstrated both theoretically and experimentally. Furthermore, we foresee this effect might affect the spatial resolution of the system. Hence, we believe all these results may have important implications for developers of long-range BOTDA systems.

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