Brillouin Frequency Shift estimation in BOTDA via subpixel processing

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ABSTRACT

In this paper we propose the employment of sub-pixel algorithms for the estimation of the central frequency of the Brillouin Gain Spectrum in a Brillouin Optical Time Domain Analyzer. The experimental results will show that the proposed solution shows a good performance when the chosen frequency step for the required frequency sweep is high. If the improved computational efficiency in comparison to the traditional Lorentzian fitting is also considered, it can be concluded that this approach may be of great interest for dynamic measurement scenarios.

Keywords: stimulated Brillouin scattering, distributed sensing, BOTDA, Brillouin frequency shift, sub-pixel algorithm, Lorentzian fitting

1. INTRODUCTION

Distributed sensing based on the stimulated Brillouin scattering (SBS) has been an intensive area of research during the last years with applications from the energy to the civil engineering sectors, just to mention some examples. SBS is based on the employment of two counter-propagating waves, the so-called pump and probe that interact via acoustic phonons within the optical fiber to give rise to an amplified probe signal. Its frequency is directly related to the strain and temperature at each point of the optical fiber, provided that the pump wave is pulsed.

Although there are different schemes based on the frequency [1] and correlation [2] domains, the most common implementation of SBS-based distributed sensing is the Brillouin Optical Time Domain Analysis (BOTDA), usually by means of the sideband technique [3]. In this configuration the frequency of the pulsed pump is normally kept constant, while the probe signal, obtained via an electro-optical modulator (EOM) and a RF generator, is swept in frequency to allow a reconstruction of the Brillouin Gain Spectrum (BGS) at the detector. Afterwards, the Brillouin Frequency Shift (BFS) is estimated as the central frequency of the BGS by using a Lorentzian fitting process.

It is worth mentioning that this frequency sweep, in addition to the required averaging of the acquired traces, implies a significant increase in the measurement time over the whole fiber under test (FUT), thus avoiding dynamic measurements in the so-called standard BOTDA implementations. Different variations have been proposed in this regard to allow fast measurements, as the slope-assisted BOTDA [4], the employment of multiple pump and probe waves to avoid the frequency sweep [5] or the use of the Brillouin phase-shift and RF demodulation [6].

Although there are other factors limiting the measurement time, as the time of flight of the pump pulses, the frequency scanning is probably the most relevant. In addition, the above mentioned fitting process used for the BFS estimation is also time consuming, as it involves an iterative stage. In this paper we explore the employment of subpixel algorithms instead of the Lorentzian fitting. These algorithms have been extensively used for image processing [7], but they have been also applied in fiber Bragg grating (FBG) applications [8] or plasma optical spectroscopy for welding diagnostics [9]. Their computational performance as well as the resulting accuracy for different scanning granularities will be analyzed for distributed BOTDA measurements over 50km.

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2. EXPERIMENTAL ISSUES

The conventional BOTDA scheme depicted in Fig. 1 was used to perform the required experimental tests. A single laser source (λ = 1550.92 nm) generates the light required for both pump and probe waves. The optical coupler located at the output of the laser source divides the light (10% to the pump wave, 90% to the probe wave) into two branches. The upper one generates the pump pulses via a semiconductor optical amplifier (SOA). The pump pulse is amplified via an erbium doped fiber amplifier (EDFA) and then a polarization scrambler is employed to avoid the polarization dependence of the SBS gain along the fiber. The probe wave is generated by an EOM and RF generator, thus giving rise to two sidebands and a carrier that is suppressed by adjusting the bias voltage of the EOM. Both sidebands are transmitted via an optical isolator to the FUT, where they will interact with the pump pulse. The detection stage is formed by two optical circulators, which allow to select the lower frequency sideband with a FBG, and a high-transimpedance gain 125 MHz photodetector and acquisition card (ACQ) integrated in a PC.

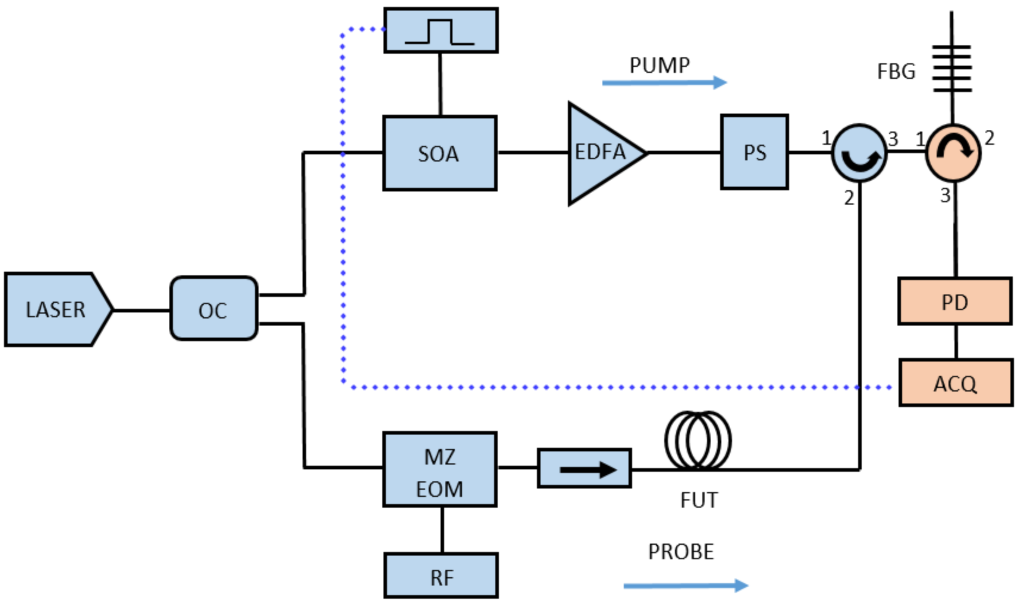

Figure 1. Schematic setup of the BOTDA system used in the experimental tests: Optical Coupler (OC), Semiconductor Optical Amplifier (SOA), Erbium Doped Fiber Amplifier (EDFA), Polarization Scrambler (PS), Match-Zender Electro-Optical Modulator (MZ-EOM), RF Generator (RF), Fiber Under Test (FUT), Fiber Bragg Grating (FBG), Photodetector (PD) and Acquisition Card (ACQ).

To explore the proposed solution the centroid subpixel algorithm CDA was selected. It is based on the estimation of the mass centre of the peak under analysis:

$$f_{sub} = \frac{\sum_j f_j i_j}{\sum_j i_j}, \tag{1}$$

where f_{sub} is the subpixel estimation of the peak frequency and f_j and i_j the frequency and intensity associated with the pixel j. The code to perform the BFS estimation was implemented in Matlab, and compared to the conventional Lorentzian fitting.

To evaluate their corresponding performances a 50km standard monomode fiber was deployed with an estimated BFS of approximately 10.70 GHz. Several measurements were performed considering a frequency range between 10.59 and 10.79 GHz, and scanning granularities of 2, 4, 6, 8, 10 and 20 MHz. A 4096 averaging of the acquired BOTDA traces was performed to improve the signal-to-noise ratio (SNR).

Figure 2 (a) depicts BFS profiles derived of employing Lorentzian fitting and different scanning granularities: 2MHz (black), 10 MHz (red) and 20 MHz (blue). As expected, the use of a smaller granularity gives rise to a less noisy profile, although the differences between the 2 and 10 MHz profiles are subtle. The BFS curve obtained with the 20 MHz granularity exhibits a clearly degraded SNR, as well as an error in the BFS estimation that increases with distance. For example, the standard deviation of the 2 MHz granularity BFS profile between 30 and 40km is 1.33 MHz, while the one associated with the 20 MHz granularity is 1.69 MHz. The corresponding mean BFS values are 10.691 and 10.693 GHz.

Figure 2(b) presents the comparison of the worst case BFS profile (for a 20MHz granularity) obtained via Lorentzian fitting and the result of substituting it with the CDA subpixel processing. It can be observed how the SNR clearly improves with the proposed solution, with a standard deviation, again evaluated within the 30 to 40 km section, of 0.86 MHz. The root mean square error over the whole FUT, computed using the 2 MHz granularity profile as a reference, is 2.68 MHz for the Lorentzian fitting and 1.80 MHz using CDA. It should be mentioned that the saturated profile obtained for the 20 MHz granularity (between x ≈ 10 and 20 km) and Lorentzian fitting is precisely due to the chosen granularity and not to other effects to be found in BOTDA traces such as modulation instability.

Apart from these results, the main motivation of avoiding the conventional fitting process might lie in its high computational cost. The average processing time (over 10 tests) of the CDA processing was 0.241s for the whole BFS of 2MHz granularity, considering a data matrix of 101 (frequency) x 12000 (spatial) samples. In the same scenario, the Lorentzian fitting gave rise to a processing time in the order of several minutes. These performance tests were carried out using MATLAB in a conventional laptop (i5-2410M (2.30 GHz) processor with 4 GB RAM).

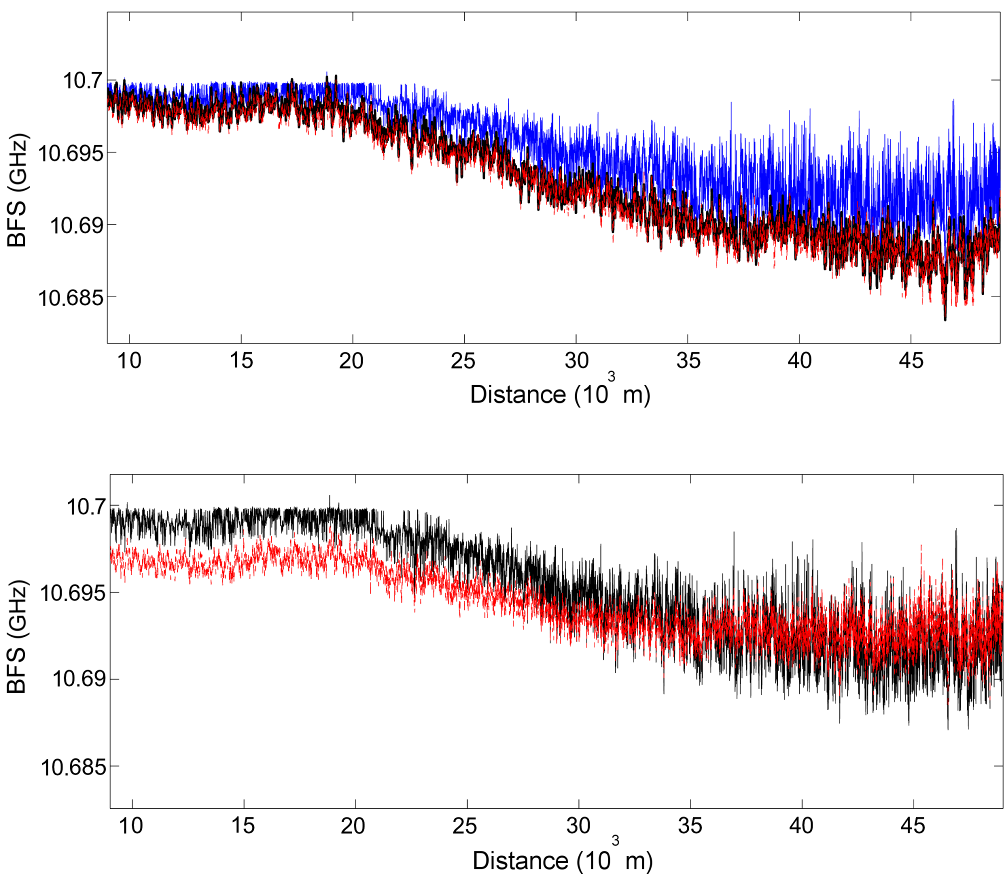

Figure 2. (a) Comparison of the BFS profiles obtained with Lorentzian fitting for the deployed fiber (9 to 49km) for different scanning granularities (2 MHz: black line; 10 MHz: red line; 20 MHz: blue line); (b) Comparison of the BFS profiles for the deployed fiber (9 to 49km) for a scanning granularity of 20 MHz with Lorentzian fitting (black) and subpixel CDA processing (red).

3. CONCLUSIONS

In this paper we have proposed the employment of subpixel algorithms to substitute the standard fitting process performed to obtain the Brillouin frequency shift in distributed BOTDA systems. The results obtained with tests developed with a conventional BOTDA system and a 50km length sensing fiber show the improved performance of this approach in some specific scenarios. BFS profiles have been obtained for different scanning granularities, giving rise to the expected degradation in the BFS estimation. For the worst case scenario, considering a 20 MHz scenario, the CDA subpixel algorithm has exhibited a clearly improved performance in terms of signal-to-noise ratio, frequency accuracy and computational times in comparison to the Lorentzian fitting. These results suggest that the proposed solution may be of special interest for distributed dynamic measurements, where fast acquisition and processing is required. In this regard, further studies will be performed to extend this analysis to a more complete set of BOTDA scenarios.

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