

Enhancement of signal-to-noise ratio in Brillouin optical time domain analyzers by dual-probe detection

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ABSTRACT

We demonstrate a simple technique to enhance the signal-to-noise ratio (SNR) in Brillouin optical time-domain analysis sensors by the addition of gain and loss processes. The technique is based on the shift of the pump pulse optical frequency in a double-sideband probe system, so that the gain and loss processes take place at different frequencies. In this manner, the loss and the gain do not cancel each other out, and it makes possible to take advantage of both informations at the same time, obtaining an improvement of 3 dB on the SNR. Furthermore, the technique does not need an optical filtering, so that larger improvement on SNR and a simplification of the setup are obtained. The method is experimentally demonstrated in a 101 km fiber spool, obtaining a measurement uncertainty of 2.6 MHz (2σ) at the worst-contrast position for 2 m spatial resolution. This leads, to the best of our knowledge, to the highest figure-of-merit in a BOTDA without using coding or raman amplification.

Keywords: Brillouin distributed sensors, Brillouin optical time domain analysis, Signal-to-noise ratio improvement

1. INTRODUCTION

Distributed optical fiber sensors based on Brillouin optical time-domain analysis (BOTDA) are attracting a great deal of attention due to their ability to perform distributed measurements of temperature and strain over large structures. In such a way, they can be applied in civil and geotechnical engineering, in the monitoring of oil or gas pipelines, railway inspection and many other structural health monitoring applications.

All these structures require a large sensing range. However, the sensing range of BOTDA sensors is limited, among other things, by the maximum probe and pump powers that can be brought in the fiber before the appearance of nonlinear effects or the so-called non-local effects.^{1,2} To solve these limitations and achieve an improvement of the signal-to-noise ratio (SNR) of BOTDA sensors, several research works have been presented over the last few years. Examples of contributions intended to alleviate these limitations include the use of balanced detection,³ time and frequency pump-probe multiplexing,⁴ distributed Raman amplification,⁵ coding⁶ or distributed pump amplification.⁷

In this work, we present a simple modification to conventional BOTDA sensors that simultaneously provides gain and loss spectral information, so that an improvement on the SNR as well as a simplification of the setup by removing the optical filters are obtained. The technique is based on shifting the pump frequency in a dual-probe BOTDA configuration, so that the information of loss and gain processes are simultaneously present in a frequency scan, thus allowing to receive both data at the same time (i.e. in the same interaction zone).

2. FUNDAMENTALS OF THE TECHNIQUE

The fundamentals of the proposed analyzer are explained in Fig. 1 by depicting the spectra of the various optical waves involved in the technique. In a conventional dual-probe BOTDA sensor, as it is highlighted in Fig. 1a, despite holding Brillouin loss and gain information, both informations overlap exactly at the same frequency of the spectral scan. For that reason, only one sideband in frequency is usually selected by optical filtering in detection. Depending on the selected sideband, Brillouin gain or loss spectrum is measured.

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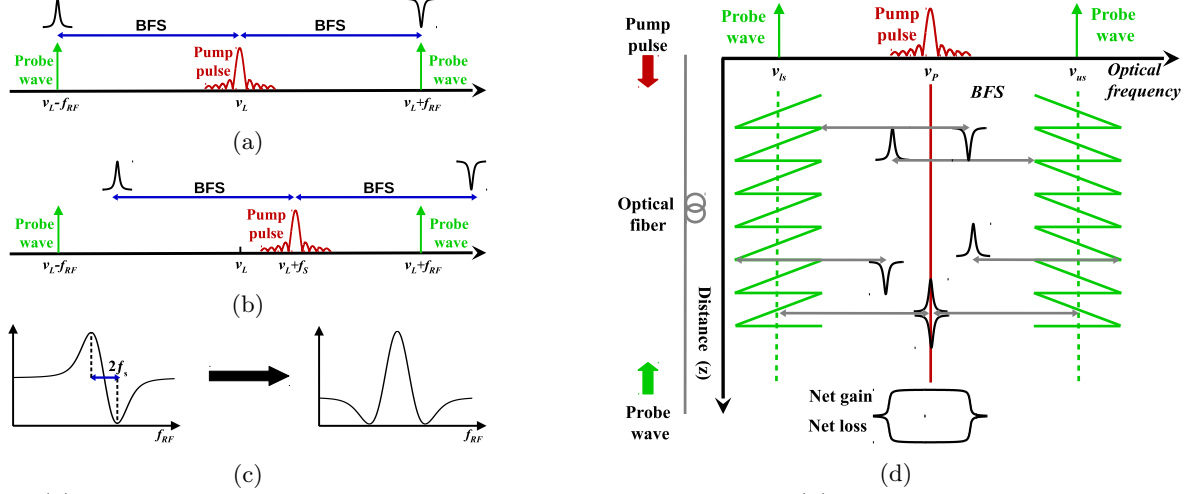


Figure 1: (a) Brillouin interaction of the conventional dual-probe BOTDA (b) Brillouin interaction of the dual-probe BOTDA with the pump shifted in frequency (c) obtained Brillouin spectral scan for the proposed technique (d) Brillouin interaction of the optical waves in a frequency modulated dual-probe BOTDA.

Our proposal is to preserve the information of both probe waves, by simply shifting the frequency of the pump, as it is portrayed in Fig. 1b. Thus, the gain and loss processes are unbalanced due to the fact that they occur at different frequencies with respect to the pump, so that both Brillouin gain and loss spectra are simultaneously presented in a spectral scan, separated by twice the frequency shift (f_S) of the pump. As a result (left spectra of Fig. 1c), the information of gain and loss processes is measured, the frequency difference between them being $2f_S$.⁶ Therefore, selecting f_S , the maximum contrast between the gain and loss spectra takes place when f_S is larger than the half width at half maximum of the Brillouin spectrum, $2f_S > \Delta\nu_B$. Thus, the resultant Brillouin spectrum is obtained by just adding gain and loss spectra, as it is portrayed in the right spectrum of Fig. 1c. In such a way, for a given position z in the fiber the obtained gain is proportional to $g_B P_P(z) P_{P_{r1}}(z) \Delta z$ while the loss is given by $-g_B P_P(z) P_{P_{r2}}(z) \Delta z$, where g_B is the Brillouin gain coefficient, P_P is the pump pulse power, $P_{P_{r1}}$ and $P_{P_{r2}}$ are both probe wave power and Δz is the pulse length. After the superposition of both spectra, the overall signal gain will be proportional to $g_B P_P(z) (P_{P_{r1}}(z) + P_{P_{r2}}(z)) \Delta z$. Typically $P_{P_{r1}} = P_{P_{r2}}$, so that the detected signal will be doubled (3 dB) in comparison with a conventional dual-probe scheme. Furthermore, as no optical filtering is necessary, a larger enhancement in the SNR is obtained, as well as a simplification of the setup. However, it should be noted that in this technique a larger frequency scan is needed, with an increase of $2f_S$ MHz, which leads to a slightly increased measurement time. Therefore, the total SNR enhancement can be quantified by the relation:

$$SNR_{enh} = 2 \frac{\Delta f_{RF}}{\Delta f_{RF} + 2f_S} L_{OF}^2, \quad (1)$$

where Δf_{RF} is the frequency scan in a conventional dual-probe BOTDA setup and L_{OF} is the insertion loss of the optical filtering process. Note that this expression assumes that the setup is limited by the receiver noise.

However, it is important to point out that with the method described above, the gain and loss induced by the probes upon the carrier are not compensated. As a consequence, the technique would lose the advantage provided by dual-probe BOTDA configuration, so that the pump would experience the same depletion as for a conventional single probe BOTDA.¹ Nevertheless, it is possible to solve this limitation by just modulating in frequency the probes,⁸ as it is depicted in Fig. 1d. The optical frequency of the probe waves is modulated following a saw-tooth shape and synchronized to the pump pulses so that a sequence of pulses experiences the same wavelength of the probe waves along the fiber. Hence, avoiding the non-local effects and also the Brillouin threshold limit, this allows a maximum injected probe power in the fiber.⁸

3. EXPERIMENTAL RESULTS

In order to study the capabilities of the proposed technique, the experimental setup which is depicted in Fig. 2 was assembled. The optical source was a DFB laser at 1530nm whose output was divided by a coupler into two branches. In the upper branch, to generate the pump, an acousto-optic modulator (AOM) was used to shift the optical frequency of the laser by 30 MHz, and then pulsed using a semiconductor optical amplifier (SOA). Then, so as to smooth polarization effects, the polarization state of the pulsed pump was randomized with a polarization scrambler, and amplified to a peak power of 100 mW in an erbium doped amplifier (EDFA) before launching into the sensing fiber.

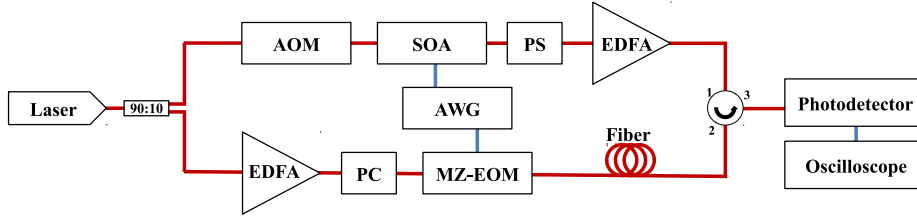


Figure 2: Experimental setup for the BOTDA sensor.

In the lower branch of the setup, the optical source was amplified by another EDFA and went through a polarization controller (PC) to a Mach-Zehnder electrooptic modulator (MZ-EOM). This modulator was driven by an arbitrary waveform generator (AWG), and biased for minimum transmission so as to generate a modulation, with 5 mW per sideband. For this purpose, the AWG provides a microwave signal with an instantaneous frequency varying around the Brillouin frequency shift (BFS) of the fiber following a saw-tooth shape with a cycle of $2,5 \mu\text{s}$ and a peak-to-peak frequency deviation of 310 MHz, inducing an identical modulation of the optical frequency of the probe waves. After Brillouin interaction of these probe signals with the pump pulse, they both were simultaneously detected and captured in a digital oscilloscope.

To analyze the performance of the system, distributed temperature measurements were performed over a 101.6 km length of standard single-mode fiber, with a total attenuation of 21 dB. The pulse duration was set to 20 ns, corresponding to approximately 2 m spatial resolution. The final 5 m of the fiber was placed loose in a climatic chamber, while the rest was held at room temperature in a spool. The frequency step of the spectral scan was 2.5 MHz and 1000 averages were used to obtain the final traces.

The temperature of the climatic chamber (hot spot) was modified in steps of 10°C with the purpose of evaluating the precision of the system. Fig. 3a depicts the evolution of the measured BFS at the end of the fiber

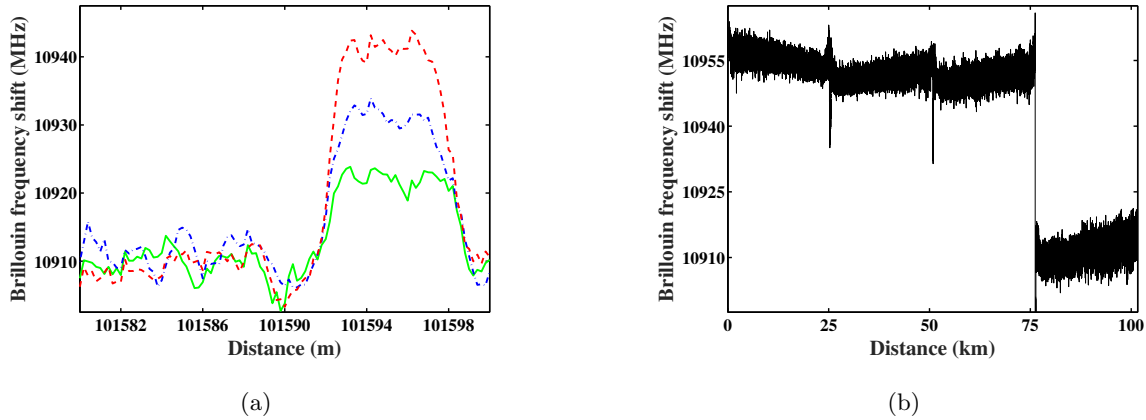


Figure 3: (a) Calculated BFS as a function of distance at the final locations of the fiber, as the temperature is risen in the climatic chamber in 10°C steps (b) Distribution of the BFS profile of the fiber.

for different temperatures. The 5 m section corresponding to the hot spot is clearly visible and a fast transition between the heated section and the rest of the fiber is also observed. The spatial resolution was confirmed to be 2 m by measuring the rise time between two adjacent sections of the fiber at different temperature. Fig. 3b portrays the BFS along the whole sensing fiber, where four fiber spools (25.4 km per each ones) are clearly distinguishable, with a fairly uniform BFS of the first three and a slightly different one for the last spool. The BFS along the fiber was calculated by performing a quadratic fit on the Brillouin gain spectrum (BGS).

Also, we analyzed the performance of the sensor in terms of measurement accuracy. For this purpose, a series of 10 consecutive measurements for stable temperature conditions were carried out. From these measurements, the 2-sigma BFS measurement precision was found to be 2.6 MHz. Furthermore, based on the obtained results, the figure of merit (FoM) of this BOTDA setup was calculated,⁹ obtaining a value of 2325. To the best of our knowledge, these are the best results obtained without coding and/or Raman amplification.

4. CONCLUSIONS

In this paper, we have introduced a new technique for dual-probe BOTDA sensors to obtain gain and loss spectra at the same time, based on the shift in frequency of the pump signal. Thus, the trace amplitude at the end of the fiber is doubled, so that the SNR in the detectors is enhanced. Furthermore, a simplification of the sensor and a larger improvement of the SNR is obtained as no optical filtering is necessary. Which, in turn, leads to enhanced sensor performance in terms of precision or measurement time. The capabilities of the technique have been demonstrated, performing distributed temperature measurements over a 101 km length of fiber with high accuracy and spatial resolution.

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.

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