Simple method for the elimination of polarization noise in BOTDA using balanced detection of orthogonally-polarized Stokes and anti-Stokes probe sidebands

Alexia Lopez-Gil, Alejandro Dominguez-Lopez, Sonia Martin-Lopez and Miguel Gonzalez-Herraez
Departamento de Electronica, Universidad de Alcala, Escuela Politecnica, 28871, Spain

ABSTRACT

Given the strong polarization sensitivity of Stimulated Brillouin Scattering (SBS), in Brillouin Optical Time Domain Analysis (BOTDA) it turns out to be indispensable to perform some kind of polarization scrambling, either in the pump pulse, or the probe signal (or both). This is usually accomplished using polarization scrambling/switching systems, which, being mechanical, tend to be not as robust as it would be desirable. In this paper we propose a completely passive system, with no moving parts, to perform the polarization scrambling in a BOTDA. It is based on the use of balanced detection among the orthogonally polarized Stokes and anti-Stokes bands of the probe signal. The setup requires no alignment and provides a performance similar to a conventional BOTDA sensor.

Keywords: Brillouin Scattering, distributed optic fiber sensor, balanced detection, polarization noise

1. INTRODUCTION

In recent years Brillouin-based distributed temperature and strain sensors have attracted great interest thanks to their unique properties in the academic and industrial sectors. BOTDA systems have already been applied for real field sensing applications, particularly when infrastructures are located in electrically noisy environments or when the distance to be monitored is long. BOTDA sensors rely on the distributed measurement of SBS gain along an optical fiber. Depending on temperature or strain changes, some of the SBS gain attributes (namely the Brillouin Frequency Shift, BFS) can vary according to well-known sensitivity values.

Stimulated Brillouin Scattering (SBS) is a result of the processes of interference (among the pump and probe waves) and electrostriction[1]. As the process of SBS originates from the interference between two optical waves, its efficiency is inherently dependent on the relative states of polarization (SOPs)[2] of the two interacting waves. SBS gain is maximum when the electric fields of the two waves are aligned, i.e., their vectors trace parallel polarization ellipses and in the same sense of rotation. Conversely, if the two ellipses are again similar, but traced in opposite senses of rotation, with their long axes being orthogonal to each other, then the SBS interaction averages to zero over an optical period[3].

For the SBS gain to take place in a BOTDA, pump and probe waves need to be polarization-aligned, which is generally impossible to guarantee over the full fiber length. In Standard single-mode optical fibers, the SOPs of the optical waves vary randomly as a result of random birefringence along the fiber[4]. Thus, if the BOTDA interaction is performed on a conventional fiber, there appear random positions where the gain is maximized together with positions where the gain is rendered close to zero. To avoid this polarization “noise” in the trace, several passive techniques have been developed. The most used technique is scrambling the polarization state of the pump wave by using a polarization scrambler in order to obtain a pseudo-depolarization of the light; however, the polarization scrambler requires a passive complicated design to ensure that the scrambled polarization states cover all the possible polarization states evenly. In addition, the scrambler has moving parts that make the system less robust than desirable. Some other methods have been developed[5,6], all of them requiring moving parts or sophisticated and unstable polarization alignment.

Lately, the use of balanced detection in BOTDA systems was proposed and demonstrated to increase significantly the SNR[7]. In this work, we propose a simple and novel polarization noise elimination method in BOTDA based on the use of balanced detection and orthogonal polarization states in the Stokes and anti-Stokes sidebands in the probe wave. This method provides comparable results to the method based on polarization scrambler, with the key advantages of being cheaper and more reliable.

*alexia.lopez@uah.es

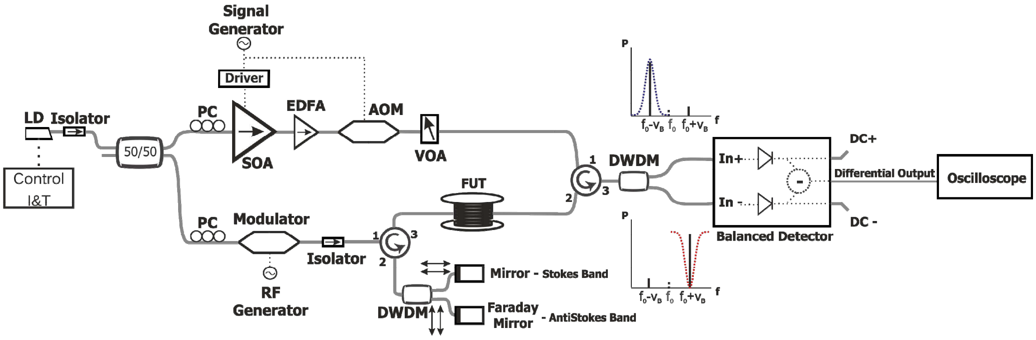


Figure 1. Experimental setup of the BOTDA with Balanced Detection and polarization noise elimination. LD: Laser Diode; PC: Polarization controller; EDFA: Erbium Doped Fiber Amplifier; RF: Radio-frequency generator; AOM: Acousto-Optic Modulator; VOA: Variable Optical Attenuator; DWDM: Dense Wavelength Division Multiplexer.

2. EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the experimental setup proposed in this paper. It is very similar to the BOTDA scheme described in[7] but incorporating a simple set of optical elements to ensure polarization orthogonality of the two probe sidebands. This way, the detected traces in the positive and negative inputs of the balanced detector are obtained with orthogonal SOPs in the probe wave. In this way, when there is gain fading on one channel, the other shows maximum gain, and vice versa.

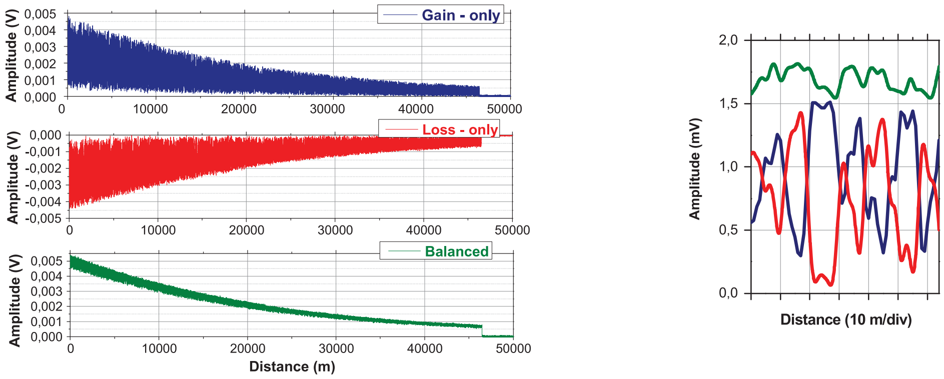
As it is normally done in BOTDA, in this setup the Brillouin pump and probe waves are obtained from the same single distributed feed-back (DFB) laser diode. The laser is split with a 50/50 optical coupler to obtain the pump and probe waves. In this case, we use a conventional electro-optic modulator (EOM) to obtain the probe wave. It is composed of two side bands separated from the pump by a frequency which is controlled by a microwave generator. The generator frequency is chosen to sweep around the Brillouin Frequency shift of the fiber under test. This way, the relative frequency separation of pump and probe waves remains controlled independently of the laser drifts. The carrier signal is suppressed by properly setting the DC bias of the modulator. The probe sidebands will be either amplified (the lower frequency one - Stokes) or attenuated (the higher frequency one, anti-Stokes) by SBS in the fiber under test. To provide orthogonal SOPs to these two sidebands, a simple scheme based on a circulator, a DWDM filter and a couple of mirrors (one conventional, another one a Faraday mirror) is built. The DWDM filter separates the two side bands of the probe signal. In the arm of the lower frequency band, a conventional optical mirror is used to reflect the signal without polarization change. On the other side, in the arm of the higher frequency band a Faraday mirror is used. In this case, the reflected signal polarization is rotated by 90º with respect to the incident signal. In the port 3 of the optical circulator, we obtain the probe signal composed of the two sidebands (recombined by the DWDM) with orthogonal polarizations. This way the polarization scrambler used in[7] is no longer necessary to eliminate the dependence of the Brillouin gain on polarization. The probe power fed into the fiber is ~326 μW on each sideband**.**

To shape the pump pulse, a Semiconductor Optical Amplifier (SOA) is used. The maximum repetition rate is defined by the maximum length of the test fiber, in our case the repetition rate is 1,6 KHz. After pulsing, the optical signal is amplified using an Erbium Doped Fiber Amplifier (EDFA) and the output power is controlled through a Variable Optical Attenuator (VOA). An acousto-optic modulator is inserted in the scheme to improve the extinction ratio of the pulses obtained at the output of the SOA (~40 dB). The pulse peak power fed into the fiber is ~7,56 mW and the pulse duration is 20 ns, so that the sensor resolution is 2 meters.

After travelling through the fiber and suffering Brillouin Scattering, the light is separated using a DWDM filter, which splits Brillouin Gain band (Stokes) and Brillouin Loss band (Anti-Stokes). The filter used has to be sharp enough to separate both sidebands properly (the rejected band is attenuated in >13 dB). These two different bands are then fed to the positive and negative ports of the balanced detection system. This balanced detector is a receptor which employs two well matched photodiodes. When two light beams are fed into the corresponding photodiode the obtained currents are subtracted and the remaining current difference is amplified through a trans-impedance amplifier. In our case, the differential output will be the result of subtracting the negative input signal (Anti-Stokes band) to the positive input signal (Stokes band). If the power of both bands is the same, the average detected trace is doubled[7]. In terms of the polarization noise, since each trace is measured with an orthogonal SOP, the maxima of polarization noise on one trace match with the minima of the polarization noise of the other one. Overall, the trace obtained in the balanced output shows a polarization noise that is mostly removed. At end, three different output signals are provided by the Balanced Detection System: the Differential Output (with the signal of interest), and two monitoring outputs, where the DC levels of each of the input signals are read. These DC levels are added to normalize the detected trace.

3. RESULTS

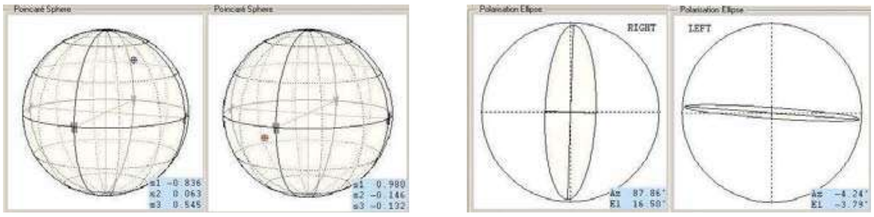
The measurements have been performed using a Brillouin pump pulse-width of 20 ns (2 meter spatial resolution) over ~50 km of single mode fiber (SMF) with an effective area of 70 μm^2 and a Brillouin Frequency Shift (BFS) located at approximately 10.883 GHz for the laser wavelength (~1550 nm). To achieve a clean trace, the traces are averaged 1024 times. In Figure 2 the three traces obtained at 10.883 GHz for the single sideband detection cases (the two on top) and balanced detection (the one on bottom) are depicted. Figure 2b shows a detail of 64 m of the three traces of Figure 2(a) around km 25. It can be observed that the maxima and the minima of the blue (gain) and red (attenuation) traces are located at the same position. Therefore the polarization noise in the balanced channel is mostly removed. Moreover, as is described in[7], when acquiring in balanced mode the trace amplitude of the differential output is twice the trace amplitude of any the single bands and the robustness of the system increases to common-mode noises, which affect both sidebands. For these reasons, the SNR of this scheme is considerably higher than a single-detector system.



(a) (b)

Figure 2. (a) Trace obtained using the single-detector cases (two on top) and balanced detection (one on bottom) for a pump-probe frequency shift of 10.883 GHz. (b) A detail of 64 m of the three traces of Figure (a) around km 25.

Nevertheless, as it is noticeable, a perfect polarization noise cancellation has not been achieved. We measured the polarization states of the two sidebands and they were not perfectly orthogonal, although the disagreement was not excessive (Figure 3). This is probably due to some manufacturing imperfections of the Faraday mirror. In addition, a small mismatch in the optical path lengths of the two sidebands, and any minimal error in the adjustment of the laser could lead to a non-symmetric separation of the two bands, causing an imperfect polarization noise cancellation. However, this setup is as effective removing polarization noise as a commercial polarization scrambler. Having no moving part and being much cheaper, we believe that this solution is certainly advantageous over the traditional polarization scrambler.



(a) (b) (c) (d)

Figure 3. Polarization state displayed in the Poincarè Sphere of Brillouin Stokes band (a) and Brillouin Anti-Stokes band (b), and displayed in the Polarization Ellipse for the Brillouin Stokes band (c) and Brillouin Anti-Stokes band (d).

To obtain actual BFS measurements, the Brillouin gain was swept over the range of interest and the resulting curve was fitted using the standard procedures. In Figure 4, the Brillouin Frequency shift with the distance is depicted. The standard deviation of the obtained BFS among five consecutive traces at the beginning of the fiber (first 5000 points window) is ~1.49 MHz. At the end of the fiber under test (last 5000 points window), the standard deviation is ~1.51 MHz.

In terms of the figure-of-merit discussed by[8], the FOM calculated at the end of the fiber is 43.03, taking into account that the number of averaged traces is 1024, the sensing fiber length is 50 km, the spatial resolution is 2 meters, the frequency sampling step is 1 MHz in a standard fiber with 27 MHz Brillouin full-width at half maximum and 0.2 dB/Km attenuation.

It is interesting to make a comparison with a BOTDA system incorporating balanced detection but using a conventional polarization scrambler[7]. In comparison to this system, our system seems to be only slightly less accurate for the same resolution (1.39 MHz compared to 1.51 MHz). Considering the increase in robustness and the reduced price, our option looks appealing for integration in field systems.

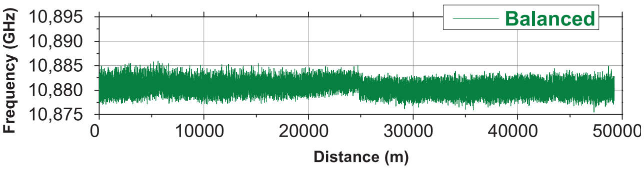


Figure 4. Brillouin frequency shift of the balanced detection acquisition for ~50 km of SMF and 2 m resolution.

4. CONCLUSION

In this work we have presented a method to avoid the polarization noise in BOTDA systems. Our method is based on the balanced detection of traces obtained with orthogonally polarized Stokes and anti-Stokes sidebands. Our scheme has no moving parts and provides clear improvements in terms of cost. In terms of performance, the results obtained are comparable to the conventional systems employing scramblers. Improved Faraday mirrors would ensure lower polarization noise and therefore better results. As all the systems based on balanced detection, our system is also robust to common-mode noises.

ACKNOWLEDGMENTS

We acknowledge funding from the European Research Council through Starting Grant U-FINE (Grant no. 307441), the Spanish “Plan Nacional de I+D+i” through projects TEC2012-37958-C02-01 and TEC2012-37958-C02-02, the regional program FACTOTEM2 funded by the Comunidad de Madrid and the INTERREG SUDOE program ECOAL-MGT. S. Martin-Lopez acknowledges funding from the Spanish Ministry of Science and Innovation through a “Ramón y Cajal” contract.

REFERENCES

[1] Agrawal, G. P., [NonLinear Fiber Optics], CA:Academic, San Diego, 9 (2001)
[2] Stolen, R.H.,“Polarization effects in fiber Raman and Brillouin Lasers,” IEEE J. Quant. Electron. 15, 1157-1160 (1979)
[3] Tur, M., Zadok, A., Zilka,Eyal, E.A., and Thevenaz, L. “Polarization Properties of Stimulated Brillouin Scattering and their Implications on Slow and Fast Light,” paper SMC2 in Slow Light OSA topical meeting Honolulu Hawaii, (2009)
[4] Van Deventer, M.O. and Boot, A. J., “Polarization properties of stimulated Brillouin scattering in single-mode fibers,” J. Lightw. Technol., 12 (4), 585590 (1994)
[5] Yang, J., Yu, C., Chen, Z., Ng, J., and Yang, X., “Suppression of polarization sensitivity in BOTDA fiber distributed sensing system,” Proc. SPIE 7004 (700421), (2008)
[6] Diaz, S., Mafang, S. F., Lopez-Amo, M., and Thevenaz, L., “A High-Performance Optical Time-Domain Brillouin Distributed Fiber Sensor,” IEE Sens Journal 8 (7), (2008)
[7] Domínguez-López, A., López-Gil, A., Martín-López and S., González-Herráez, M., “Signal-to-noise ratio improvement in BOTDA using balanced detection,” IEEE Photonic. Tech. Lett. Accepted (2013)
[8] Thévenaz, L., and Soto, M. A., “Rating the performance of a Brillouin distributed fiber sensor,” Proc. SPIE 8421 (8421A7), (2012)