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# Simple Baseband Method for the Distributed Analysis of Brillouin Phase-Shift Spectra

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*Abstract*— **The phase shift feature of Stimulated Brillouin Scattering is rarely used for the development of sensors based on Brillouin Optical Time-Domain Analysis (BOTDA). However, this feature shows significant interest for sensing thanks to its linear dependence around the Brillouin Frequency Shift. Up to now, distributed Brillouin Phase Shift (BPS) measurements required complex modulations, high-bandwidth detection and sharp filtering. Recently, we introduced the possibility of developing simple distributed measurements of BPS in BOTDA using baseband technology. The basic idea was the use of a Sagnac interferometer coupled to a conventional BOTDA without filtering and incorporating balanced detection. Although the concept was demonstrated, the setup proposed (using a 2x2 optical coupler) had significant shortcomings, the main one being its lack of stability due to the need of setting the interferometer bias through the polarization of the interacting waves. This restricted severely the practicality of the method. In this paper, we propose a setup with enhanced stability thanks to the use of a 3x3 optical coupler. With this configuration, the impact of the drifts along the measurement is strongly reduced, and the quality of the measurements improves substantially. The method is theoretically studied and demonstrated experimentally.**

*Index Terms*—**Brillouin distributed sensors, Brillouin optical time domain analysis, Brillouin scattering, fiber optics sensor, interferometry, nonlinear optics, temperature sensor.**

## I. Introduction

IN the past few decades Brillouin-based distributed temperature/strain sensors have become strong competitors of conventional multipoint sensing systems. In particular, Brillouin Optical Time Domain Analysis (BOTDA) sensors have been lately a trendy study area due to their unique capabilities to monitor large infrastructures.

Brillouin Optical Time Domain Analysis (BOTDA) sensors are based on the optical effect known as Stimulated Brillouin Scattering (SBS) [1]. In this process, two counter propagating signals in the optical fiber (pump and probe) are coupled when a phase matching condition is met ($f_{probe} = f_{pump} - \nu_B$). In these conditions, pump photons are scattered at the same frequency and with the same direction of the probe, leading to an amplification of the probe amplitude. SBS is thus a nonreciprocal effect, as the photons are scattered only in one direction due to the generated acoustic wave nature. SBS manifests as a counter-propagating narrowband gain (in a spectral region around $f_{pump}-\nu_B$) and loss (in a spectral region around $f_{pump}+\nu_B$) when an intense and coherent pump beam ($f_{pump}$) is introduced from one of the ends of an optical fiber. The quantity of interest in BOTDA sensors is the Brillouin Frequency Shift (BFS, $\nu_B$), which is linearly dependent on temperature and strain. At the BFS frequency offset from the pump, the probe amplification/attenuation is maximized.

In addition to the gain and loss feature, the SBS process has an associated Brillouin phase profile, called Brillouin Phase-shift Spectrum (BPS). At the BFS frequency offset from the pump, the phase shift suffered by the probe is zero, while it is rapidly different from zero elsewhere. The BPS therefore exhibits a change of sign around the BFS, and a strong derivative at the BFS position. This strong derivative is responsible of the slow light effects associated to SBS [2].

Conventional BOTDA sensing methods exploit typically the gain/loss of the interaction, but rarely the induced phase shift. Strain or temperature variations in BOTDA systems are typically determined by means of the position of the maximum/minimum of the gain/loss spectra [3]. However the BPS is also a convenient way to determine the BFS, as it exhibits a sharp slope (and hence a large resolution) close to the BFS position. Thus, small BFS changes can be rapidly determined at trace level simply with the BPS. Consequently, several sensing setups have made use of the BPS instead of the BGS to measure temperature/strain with good resolution [4]-[7], and even, to perform vibration measurements [5]. In addition, it has been confirmed that some BPS measurement schemes are immune to non-local effects (depletion) [4].

Unfortunately, all these schemes are quite complex as they require complex modulations, high-bandwidth detection and sharp filtering in order to measure the probe phase variations. In opposition to these complex methods, we recently proposed [8]-[9] a simple, baseband and filterless measurement scheme to determine the distributed BPS feature in BOTDA systems. The method was based on using a Sagnac Interferometer (SI) as a homodyne interferometer in a conventional BOTDA setup. The use of a dual sideband in this case allowed a convenient measurement of the BPS response by subtracting the transmitted and reflected outputs of the interferometer. The setup presented in [8]-[9] however, showed a significant drawback as a necessary bias of the interferometer was done

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by setting the polarization control (PC) within the SI under conditions of introducing a certain non-reciprocity among the clock-wise and counter-clockwise signals. This biasing of the SI allows performing measurements over short time periods but is quite unstable in periods of minutes as the phase shift and polarization alignment of the two arms drift substantially.

In this paper, an improved configuration over the one shown in [8]-[9] is proposed. This method relies on using a 3x3 optical coupler in the ring. This scheme allows measuring the BPS more robustly and reliably than our former setup.

## II. Theoretical Analysis

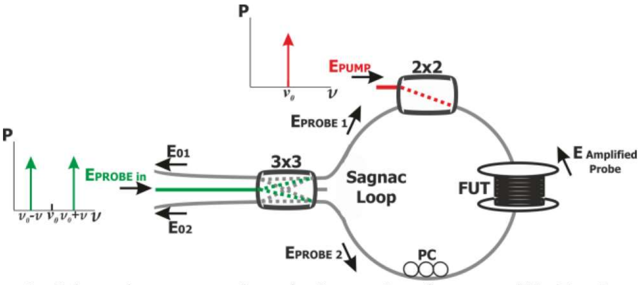



Fig. 1. Schematic representation of a Sagnac Interferometer (SI). $E_{01}$: Output electric field 1; $E_{02}$: Output electric field 2; PC: Polarization Controller; FUT: Fiber Under Test. $\nu_0$: pump frequency.

In Fig. 1 the SI employed in this case is depicted. The probe, a dual-sideband (DSB) modulated signal, is fed into the fiber ring by means of a polarization-independent fiber-optic 3x3 coupler. This coupler divides the probe wave in PROBE 1 and PROBE 2, which travel in opposite directions within the fiber loop and recombine again at the same optical coupler.

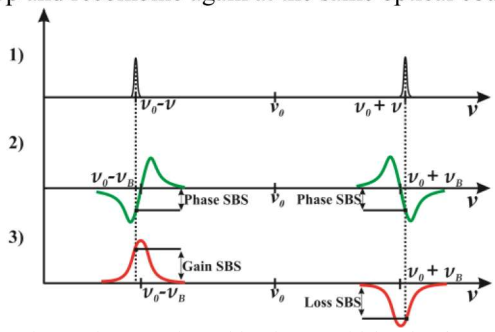



Fig. 2. SBS interaction experienced by the two sidebands of PROBE 2 after travelling along the SI. (a) Probe spectrum (b) Brillouin phase-shift profile for both sidebands and (c) gain and loss curves. $\nu_0$: pump frequency.

In comparison with our previous scheme [8]-[9] instead of a 2x2 coupler, a 3x3 one has been used to provide a higher stability of the SI along the time. In the 2x2 optical coupler case, to provide a certain bias, a polarization misalignment at the output was deliberately produced by means of the PC placed in the Sagnac loop, guaranteeing that there was a phase mismatch among PROBE 1 and PROBE 2 [10], leading to a partial interference between them [8]-[9]. Unfortunately, this phase mismatch was naturally dependent on the birefringence of the fiber under test, which varies randomly over time, and the interferometer was so less stable than desired. In another context, stable operation of SIs has already been demonstrated by using a 3×3 optical coupler [11] as this coupler provides passive biasing (a constant phase shift) in the loop response [12]. This allows obtaining a SI much more robust against slow environmental disturbances.

The SBS pump signal is introduced into the SI through a 2x2 optical coupler. This pump wave will only interact with PROBE 2, and PROBE 1 will act just as a reference signal. Under such conditions, the upper and lower frequency sidebands of PROBE 2 will be amplified/attenuated the same amount, although both will suffer the same nonlinear phase shift (Fig. 2). The outputs of the SI will be dependent on the shape of the phase shift and not on the gain/attenuation curves, as we will show in the modelling. This result will provide us with an extremely simple method to retrieve the whole phase shift map, without the need of any filter or modulation.

Mathematically, we have developed a scalar model of its performance. We have analyzed, in both outputs of the SI, the upper and lower frequency sidebands of the probe signal. If normalized fields are assumed for simplicity purposes, the light intensity for the lower and the upper frequency sidebands in one of the output ports will have the following form:

$$|E_{01}|^2_{\nu_0-\nu} \propto \left|e^{+j60^\circ}+(1+G)e^{-j60^\circ}\right|^2 \quad (1)$$

$$|E_{01}|^2_{\nu_0+\nu} \propto \left|e^{+j60^\circ}+(1+A)e^{-j60^\circ}\right|^2 \quad (2)$$

Where $\nu_0$ is the frequency of the pump wave employed.

The light intensity equations for both frequency bands in the other port ($E_{02}$) are similar to equations (1) and (2) but changing the signs of the phase delay corresponding to the 3x3 coupler [13]. For small gains, G (Brillouin gain) can be approximated by:

$$G=e^{(g_B\cdot P_P\cdot\Delta z)} \approx 1+g_B(\nu)\cdot P_P\cdot\Delta z \quad (3)$$

being Pp the pump power, $\Delta z$ the spatial resolution and $g_B(\nu)$ the complex Brillouin gain/loss coefficient, defined as:

$$g_B(\nu)=g(\nu)+j\sigma(\nu)=\frac{g_P/A_{eff}}{1+j\left(\frac{\nu-\nu_B}{\Delta\nu_B}\right)} \quad (4)$$

where $g_p$ is the Brillouin gain factor ($5\cdot10^{-11}$ m/W), $A_{eff}$ the effective area, $\nu$ the optical frequency shift, $\nu_B$ the BFS and $\Delta\nu_B$ the Brillouin gain bandwidth.

The AC part of the output power in the $E_{01}$ port is:

$$|E_{01}|^2 \propto 2\left[\sqrt{3}\,\sigma(\nu)\right] \quad (5)$$

and the AC part in $E_{02}$ turns out to have the same amplitude with reverse sign. As it is visible, a signal proportional to the SBS phase shift can be extracted from either light channel, without the need of a non-reciprocal phase delay between the two propagation directions, as in the 2x2 scheme. This renders the 3x3 configuration much more stable than the 2x2 one.

Subtracting the light intensities in both output channels, the result is obviously twice the amplitude of any single channel. From a practical point of view, this can be obtained with a balanced detector. Besides the increased amplitude in the Brillouin phase signal, the balanced detection system makes the system more robust to common-mode intensity noise [14].

## III. EXPERIMENTAL SETUP

To verify the previous analysis, the experimental setup shown in Fig. 4 has been developed. This scheme is similar to the setup used in [8]-[9] except for the replacement of the input 2x2 optical coupler by a 3x3 one, as aforementioned. Due to this change the optical circulator is no longer required in the probe branch and, so, removed from the setup.

As in most BOTDA setups, in this scheme both pump and probe waves are created from a single Distributed Feedback (DFB) laser diode [3]. The laser has a linewidth of 1.6 MHz. The probe wave is obtained by means a Mach-Zehnder Electro-Optic Modulator (EOM) (Modulator 2 in Fig. 3) yielding a dual-sideband (DSB) signal with no carrier. The output probe power launched into the SI is in the order of tens/hundreds of microwatts on each sideband.

The pump wave is shaped though another EOM, obtaining 25 ns pulses (2.5 meter spatial resolution). A high-speed switch with a transparent window of 190 ns is placed in the scheme to achieve high extinction ratio (~40 dB) pulses. The optical power is amplified employing an Erbium Doper Fiber Amplifier (EDFA). A band-pass optical filter (BPOF) with a 30-dB bandwidth of 1 nm is used to eliminate most of the amplified spontaneous emission (ASE) noise introduced by the EDFA. Upon entrance into the ring through the 2x2 optical coupler, the pump pulses have a peak power of ~60 mW. Moreover, we set a polarization scrambler to reduce the polarization sensitivity of the SBS interaction.

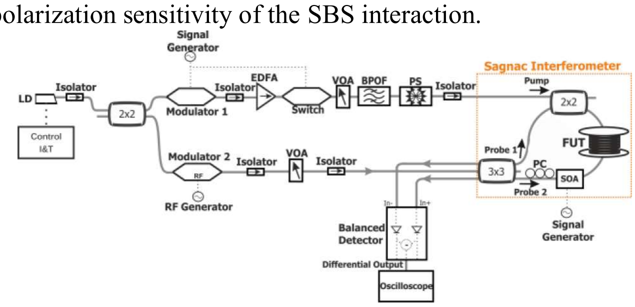



Fig. 3. Scheme of the BOTDA using a Sagnac Interferometer (SI). LD: Laser Diode; EDFA: Erbium Doped Fiber Amplifier; VOA: Variable Optical Attenuator; BPOF: Band-Pass Optical Filter; PS: Polarization Scrambler; RF: Radio-Frequency; PC: Polarization Controller; FUT: Fiber Under Test.

The input signal is split into PROBE 1 and PROBE 2 by a 3x3 optical coupler (one port of this coupler will be unused), as discussed previously, and fed in opposite directions into the fiber loop according to the schematic representation in Fig.1.

In this scheme, the states of polarization of these two waves are initially aligned adjusting the polarization controller so they interfere completely. The possible temporal evolution of the states of polarization of these two waves is not as critical as in the setup with the 2x2 coupler [8]-[9], particularly because of the different phase shift induced by the 3x3 coupler.

The fields obtained at the output of the SI ($E_{O1}$ and $E_{O2}$) are then fed into the positive and negative ports of a balanced detection system. The differential output will be the outcome of subtracting the negative input signal ($E_{O2}$) to the positive one ($E_{O1}$). The AC part of this signal as a function of the RF frequency will give us the local reading of the BPS profile.

Unfortunately, the phase profile at the midpoint of the FUT length presents residual pump power, which would be completely eliminated employing the balanced detection system if the coupling ratio of the input optical coupler was perfect. As the couplers are never completely perfect, a Semiconductor Optical Amplifier (SOA) acting as a switch is placed within the SI. The SOA is gated so as to block the pump light pulse (which appears in the middle of the FUT trace). This makes the software removal process used in the previous schemes [8]-[9] not so indispensable. It can be inferred from Fig. 4 that the unwanted pump pulse at the midpoint of the temporal trace in the case of placing a SOA in the loop is considerably shorter than in the other case.

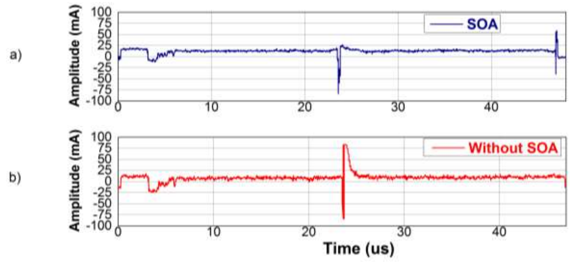
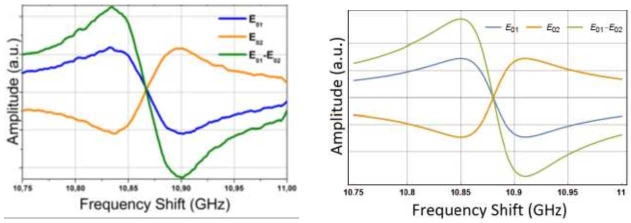



Fig. 4. (a) Temporal output trace obtained with a SOA within the SI for a pump-probe frequency shift of 10.87 GHz. (b) Temporal output trace obtained without incorporating a SOA under the same conditions.

## IV. RESULTS

In this section, the results, obtained with the presented BOTDA experimental setup, will be shown. In order to confirm the performance of the system, different measurements have been performed over ~4.3 km of single-mode fiber (composed of two fiber spools of 4 km and 300 m) with an essentially homogeneous BFS located at 10.87 GHz (at ~1550 nm and 25ºC). The probe wave was swept from 10.75 GHz until 11 GHz and signals were averaged 1024 times to clean the BOTDA traces.




(a) (b)

Fig. 5. (a) Experimental output light intensity 1 (blue) and output light intensity 2 (orange) together with the Brillouin Phase-Shift profile recovered in the balanced detector (green). (b) Simulated results from the analytical model under the same conditions.

In Fig. 5(a), the two AC signals obtained at the output of the SI at a given point of the loop are depicted. As it can be observed, both intensities follow the phase profile of the SBS effect while the balanced channel shows the phase contribution with double amplitude, as expected. This graph is consistent with the simulations obtained utilizing the scalar model given in the previous section (Fig. 5(b)).

To confirm the performance of the system as a sensor, a hot spot was located in the FUT. At the end of the fiber, ~2.5 meters were heated in a temperature-controlled oven at 70 ºC.

In Fig. 6, we show the results of the BPS change in the hot-spot position (grey) in comparison with a non-heated region (green). It is visible the frequency increment of 60 MHz, which perfectly agrees with the expected temperature difference considering a sensitivity of 1.33 MHz/ºC.

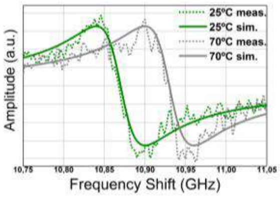



Fig. 6. BPS around a ~2.5-meter hot-spot (located around km 4.3).

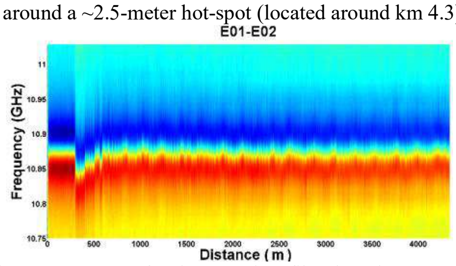



Fig. 7. Full frequency sweep for the complete fiber length.

Fig. 7 shows the full 3D Brillouin map of the obtained phase shape for the 4.3 km of FUT, after removal of the small midpoint residual pump. This confirms the possibility of using this method to perform distributed BPS measurements with reasonably high quality.

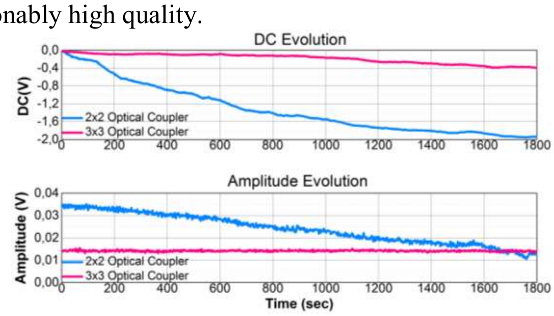



Fig. 8. DC and amplitude (difference between the trace levels at maximum and minimum BPS shift) evolution over a 30 minutes period from a measured temporal output trace for the case of using a 2x2 optical coupler in the loop [8]-[9] and a 3x3 coupler in the loop.

The performance of this setup in terms of stability was tested by measuring the variation of the DC and the amplitude (difference between the trace values at maximum and minimum BPS shift) over time from a measured temporal output trace of the experimental setup presented in this paper and of the previous schemes [8]-[9]. In Fig. 8 it is shown a comparison of the DC evolution in both cases over a 30 minutes period for the same input powers. As it can be inferred from Fig. 8, the drift in the case of using the 2x2 optical coupler is much higher than in the 3x3 case, which demonstrates that this scheme has greater bias point and scale factor stability than the previous one. The DC level in the 3x3 coupler scheme shows a very slight drift that can be due to thermal-induced polarization misalignment over time.

## V. Conclusion

To sum up, we have demonstrated a novel setup to perform robust, baseband and filter-less distributed measurements of BPS along single-mode fibers. Compared to our previous method [8]-[9], this one shows an increased robustness against drifts. This increased robustness stems from the use of a 3x3 optical coupler in the SI developed. The capability of the developed system as a temperature sensor has been proved and its stability in comparison with previous methods (based on a 2x2 coupler) assessed. Through this method, it is possible to retrieve the BPS in a far less complex way in comparison with the existing phase modulation schemes. The fundamentals of the technique have been described theoretically and validated through simulations and experimental measurements.

The leading advantage of this system is its simplicity in terms of adjustment, as only a polarization control has to be roughly set and no filtering has to be adjusted. However, the system also presents drawbacks as its moderate drift with ambient conditions and the presence of additional Rayleigh noise in comparison with the standard BOTDA scheme (a detailed discussion of Rayleigh noise in SI is developed in [11]). The latter turns out to be the inevitable price to pay for the surprising simplicity of this setup. Thus, this system should be considered for use in specific applications with simple operation, short scanning ranges, small distance ranges and high resolution to small BFS variations.

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