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Simple BOTDA temperature sensor based on distributed Brillouin Phase-Shift measurements within a Sagnac interferometer

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ABSTRACT

In this work we demonstrate an extremely simple BOTDA scheme capable of delivering distributed Brillouin Phase Shift measurements along an optical fiber. It is based on exploiting the non-reciprocity of the Stimulated Brillouin Scattering effect. This non-reciprocity is easily characterized by means of a suitably tuned Sagnac Interferometer. The technique is advantageous as, in comparison with previous methods, no complex modulation, no sharp filtering and no high-bandwidth detection is needed. Theoretical and experimental proofs of the concept are given.

Keywords: Nonlinear optics, Brillouin Scattering, Brillouin optical time domain analysis, temperature sensor.

1. INTRODUCTION

Brillouin Optical Time Domain Analysis (BOTDA) sensors are based on the acusto-optic process denominated Stimulated Brillouin Scattering (SBS)[1]. In this process, two counter propagating waves in the fiber (pump and probe) are coupled when a strict phase matching condition is met ($f_{probe} = f_{pump} - v_B$). In this situation, the pump photons are scattered producing gain at the probe frequency. Symmetrically, a loss is produced in the probe direction at $f_{pump}+v_B$. From a propagation point of view, the SBS is a nonreciprocal process as photons are scattered only in one direction due to the generated acoustic wave nature. The Brillouin Gain Spectrum (BGS), shows a Lorentzian gain distribution centered at the Brillouin Frequency Shift (BFS, v_B) and a Brillouin phase profile, called Brillouin Phase-shift Spectrum (BPS). Generally, BOTDA technology analyzes an amplified/attenuated probe signal as a function of the time-of-flight of a pump pulse in the fiber, based on BGS measurements[2]. By fitting the gain/loss profile in every point, the BFS is obtained in order to retrieve measurements of temperature and strain changes.

There have already been presented some measurement schemes based on BPS[3]-[6], but, unfortunately, all these employ complex phase/frequency modulations to obtain the pump/probe signal and require high–bandwidth photo-detection. Interestingly, the BPS has a linear shape near the BFS and can be also used to measure temperature or strain with good sensitivity. For this reason, the use of BPS has already been demonstrated to perform dynamic strain measurements[5]. Lately, it has been demonstrated that some BPS measurement schemes are immune to non-local effects[4]. This feature can be used to increase the probe power, therefore allowing also a reduction in the measurement time. In this work, we present a novel BOTDA sensor scheme that exploiting the sensitivity of a Sagnac Interferometer (SI)[7] to non-reciprocal effects, retrieves the distributed BPS to measure temperature changes. This proposal simplifies substantially the already existing phase recovery methods since no complex modulation, no high-bandwidth detection and even no narrowband filtering is necessary.

2. THEORETICAL ANALYSIS

As mentioned above, a SI is used in combination with a traditional BOTDA. SI is a widely used interferometer to characterize nonreciprocal effects thanks to its environmental robustness[7]. Fig. 1a shows the schematic representation of this SI and the routes followed by pump and probe waves. As it can be observed, a dual-sideband (DSB) modulated probe is introduced into the Fiber Under Test (FUT) using a 50/50 coupler. The probe signal is divided in two waves, PROBE 1 and PROBE 2, which propagate in opposite directions along the FUT and recombine again at the coupler. Commonly, the states of polarization (SOPs) of these two probes are adjusted (through the PC) to be aligned at the output upon recombination, ensuring that the two waves have followed reciprocal paths. In this case, the SI behaves as a mirror for the probe signal, being the transmitted field zero and the reflected field maximum. Unlike the traditional SI

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case, in our setup, we adjust the PC to have a polarization mismatch at the output (i.e. a phase mismatch among the interfering waves[8] which generate the transmitted and reflected fields) and similar powers in both output ports. This will provide sensitivity to our scheme as we will show in the modelling. The pulsed pump wave is fed into the fiber using another 50/50 coupler in the ring. This ensures that it interacts just with one of the probe waves (PROBE 2 in Fig.1a) while the other (PROBE 1 in Fig.1a) acts as a reference signal. Upon interaction with the pump, the lower frequency sideband of PROBE 2 will be amplified and the higher frequency sideband of PROBE 2 will be attenuated exactly the same amount. Thus, the net power change of PROBE 2 will be zero. However, simultaneously, both sidebands of PROBE 2 will suffer the same nonlinear phase shift (Figure 1b). The output of the SI will then depend on the shape of the phase shift and not on the gain or attenuation.

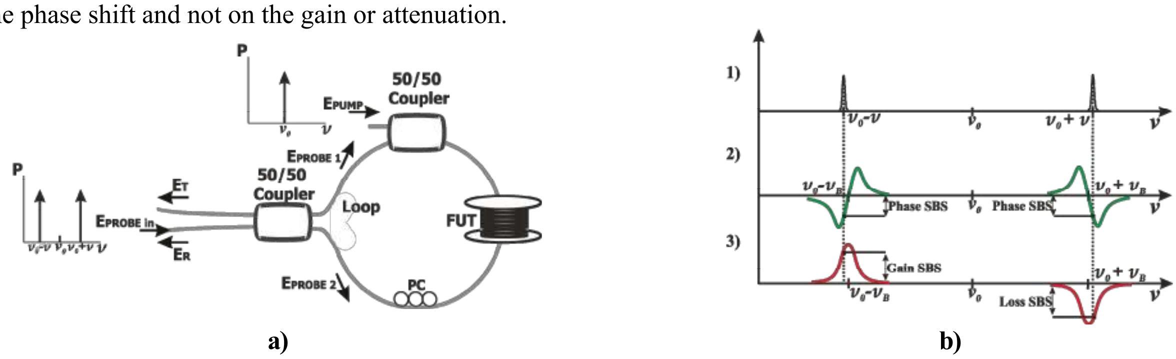


Figure 1. (a) Schematic representation of a Sagnac Interferometer (SI). E_T: Transmitted electric field; E_R: Reflected electric field; PC: Polarization Controller; FUT: Fiber Under Test. (b) SBS interaction experienced by the two sidebands of PROBE 2 after travelling along the SI. (1) Probe spectrum (2) Brillouin phase-shift profile for both sidebands, showing that the two sidebands experience the same phase shift and (3) gain and loss curves showing that both sidebands suffer complementary amplitude responses.

A simple, scalar mathematical model has been developed in order to illustrate the behavior of the proposed system. It assumes that the interfering part of the counter-propagating beams shows a relative phase delay of 2ϕ. The output signal obtained for the gain and attenuation sidebands of the probe, both in transmission and in reflection have been analyzed. Assuming normalized fields, the transmitted light intensity can be written as:

$$\left|E_T\right|^2 = \left|E_T\right|^2_{f_0-\nu_B} + \left|E_T\right|^2_{f_0+\nu_B} = \left|e^{-j\phi} - Ge^{+j\phi}\right|^2 + \left|e^{-j\phi} - Ae^{+j\phi}\right|^2 \tag{1}$$

Similarly, the reflected light intensity has the following form (detector bandwidth is assumed $<<\nu_B$):

$$\left|E_R\right|^2 = \left|E_R\right|^2_{f_0-\nu_B} + \left|E_R\right|^2_{f_0+\nu_B} = \left|e^{-j\phi} + Ge^{+j\phi}\right|^2 + \left|e^{-j\phi} + Ae^{+j\phi}\right|^2 \tag{2}$$

where G and A are considered small enough to be linearized and approximated by:

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

$$A = e^{(-g_B(\nu)\cdot P_P \cdot \Delta_z)} \approx 1 - g_B(\nu)\cdot P_P \cdot \Delta z \tag{4}$$

where P_P is the peak pump power, Δz the pump pulse width and $g_B(\nu)$ is the complex Brillouin gain coefficient, defined as:

$$g_B(\nu) = g(\nu) + j\sigma(\nu) = \frac{g_P / A_{eff}}{1 + j\left(\frac{\nu - \nu_B}{\Delta \nu_B}\right)} \tag{5}$$

where g_p is the Brillouin gain coefficient ($5\cdot 10^{-11}$ m/W), A_{eff} the effective area, ν is the optical frequency shift, ν_B is the BFS and $\Delta\nu_B$ is the Brillouin gain bandwidth. The AC part of the transmitted power results to be:

$$\left|E_T\right|^2 \approx 16\sigma(\nu)\sin(2\phi) - 8\sigma(\nu)\sin(4\phi) \tag{6}$$

and the AC part of the reflected power can be expressed as:

$$\left|E_R\right|^2 \approx -16\sigma(\nu)\sin(2\phi) - 8\sigma(\nu)\sin(4\phi) \tag{7}$$

As it can be seen, as long as there is a phase delay between the two propagation directions in the SI ($\phi \neq 0$), a signal proportional to the Brillouin phase shift can be extracted from either the transmitted or reflected light channels. Therefore, the BPS can be recovered inverted or non-inverted depending on the specific settings of the PC.

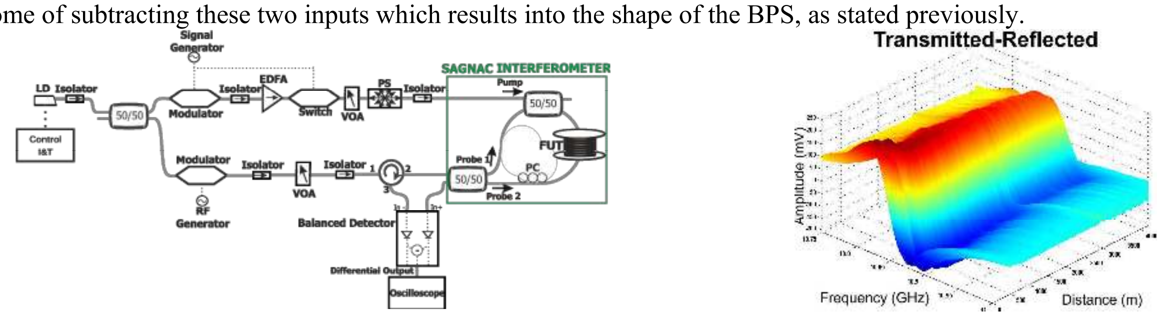
If we subtract the AC part of the reflected light intensity to the AC part of the transmitted light intensity, the result is computed to be:

$$\left|E_T\right|^2 - \left|E_R\right|^2 \approx 32\sigma(\nu)\sin(2\phi) \quad (8)$$

As it is visible, when subtracting the two light intensities, employing in our scheme a balanced detection system[9], the trace amplitude of the differential output is twice the amplitude of a single channel (assuming $\phi \approx \pi/4$) and the robustness of the system increases to common mode noises.

3. EXPERIMENTAL SETUP

To prove the above analysis, we developed the BOTDA scheme represented in Fig. 2a. It is based on a previously developed BOTDA setup[9] although, as aforementioned, it incorporates a SI. As in most BOTDA schemes, pump and probe waves are developed from a single Distributed Feedback (DFB) laser diode[2]. At the probe side, a Mach-Zehnder Electro-Optic Modulator (EOM) is used to make a dual sideband with suppressed carrier modulation. The probe power fed into the SI is ~1 mW on each sideband. The modulating frequency of the EOM is chosen to sweep around the BFS of the FUT. The output probe power is controlled using a Variable Optical Attenuator (VOA) and is divided by the 50/50 coupler included in the SI. The pump wave is pulsed using another EOM. A switch is inserted to improve the extinction ratio of the pulses obtained at the output of the EOM (~40 dB). After pulsing, the optical power is amplified using an Erbium Doper Fiber Amplifier (EDFA) and is also controlled using a VOA. The pulse peak power provided to the SI is ~60 mW. The pump polarization is scrambled by a polarization scrambler. The pump pulses are introduced into the ring using another 50/50 coupler, as mentioned above. The transmitted and reflected fields of the SI (E_T and E_R respectively) are then introduced into the positive and negative ports of a balanced detection system. The differential output will be the outcome of subtracting these two inputs which results into the shape of the BPS, as stated previously.



a) b)

Figure 2. (a) Experimental setup of the BOTDA with a Sagnac Interferometer (SI). LD: Laser Diode; EDFA: Erbium Doped Fiber Amplifier; VOA: Variable Optical Attenuator; PS: Polarization Scrambler; RF: Radio-Frequency; PC: Polarization Controller; FUT: Fiber Under Test. (b) BPS sweep for the complete fiber length. The probe signal frequency is swept from 10.75 GHz until 11 GHz and the traces are acquired with 25 ns pulses. Number of averages is 1024

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4. RESULTS

The measurements have been performed using a Brillouin pump pulse-width of 25 ns (2.5 meter spatial resolution) over ~4.3 km of single-mode fiber (composed of two different fiber spools of 4 km and 300 m) with an essentially homogeneous BFS located at 10.88 GHz at the pump wavelength (~1550 nm). To achieve a clean trace, the traces are averaged 1024 times.

In Fig. 2b we depict the measurements of the phase-shift for the complete fiber length. Such outcome confirms the possibility of using this scheme to perform distributed BPS measurements. The phase profile at the midpoint of the FUT length presents residual pump power, which is mostly removed using the balanced detector.

Fig. 3a shows the detected signal in transmission and reflection from the SI at a given spatial location (a given point of the fiber). As it can be inferred, the transmitted and reflected intensities follow the phase profile of the SBS interaction, as predicted in Equations (6) and (7), while the balanced channel shows the phase contribution with double sensitivity, as expected. This figure is also consistent with the simulation results obtained using the model described above (Fig. 3b).

As it happens with the BGS, the BPS maintains the shape but its position in frequency with respect to the pump varies in response to changing strain or temperature conditions. In this technique, it is possible work with the center frequency of the phase shift profile, which is coincident with the BFS of the FUT (~10.88 GHz). In case an inhomogeneity is produced (temperature or strain event), the phase curve will be displaced exactly in the same amount as the gain curve would shift. The performance of the setup as a sensor was verified by locating a hot spot at the end of the optical fiber (km. 4.3). This is done by introducing ~2.5 meters in a temperature-controlled oven at 85ºC. Fig. 3c shows the results of temperature change around the hot-spot (orange) in comparison with the same location in a room with a temperature of 25 ºC (blue). The frequency difference between these two profiles is approximately 80 MHz. Considering a sensitivity of 1.33 MHz/ºC in the Brillouin shift, this gives us a temperature variation of ~60 ºC, which is a good agreement with the expected temperature difference. The hot spot is also correctly identified as being ~2.5 meters wide.

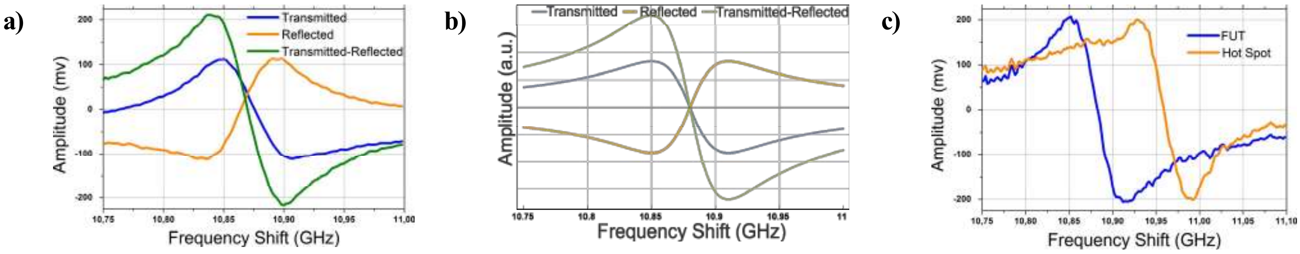

Figure 3. (a) Experimental transmitted light intensity (blue) and reflected light intensity (orange) together with the BPS profile recovered in the balanced detector for a given position (green). (b) Simulated results of the previous configuration. (c) BPS around a ~ 2.5-meter hot-spot (located around km 4.3).

5. CONCLUSIONS

In conclusion, we have presented a simple technique to measure the distributed BPS profile incorporating a SI in a BOTDA. The resulting system has been demonstrated as a sensor for distributed temperature measurements. This novel method reduces the complexity of the existing techniques to retrieve the BPS since no phase modulation, no high-bandwidth detectors and no filters are needed. The technique has been theoretically studied and proof-of-concept experiments have been performed to demonstrate its feasibility.

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