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Self-heterodyne detection for SNR improvement and distributed phase-shift measurements in BOTDA

Ander Zornoza, Mikel Sagues and Alayn Loayssa *Member, IEEE*

Abstract— In this paper we present a Brillouin optical time domain analysis (BOTDA) sensor that takes advantage of the enhanced characteristics obtained employing self-heterodyne optical detection combined with synchronous demodulation. By employing this technique we increase the sensitivity of the sensor and demonstrate experimentally a 12.35-dB enhancement in the SNR compared to conventional direct-detection systems. This detection scheme also enables distributed measurements of the Brillouin phase-shift in an optical fiber, which can lead to enhanced BOTDA schemes.

***Index Terms*— Optical sensing and sensors, Fiber optics sensors, Brillouin Scattering, Coherent systems, Self-heterodyne detection.**

I. Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear effect that originates from the interaction between two counter-propagating signals with an acoustic phonon in an optical fiber. SBS has been widely studied for many applications, and among them sensing is one of the most interesting, because SBS is sensitive to strain and temperature of the fiber. Brillouin time domain analysis (BOTDA) sensors are based on measuring the SBS interaction between a pump pulse and a continuous probe wave that counter-propagate in a fiber [1]. From this characterization of the SBS it is possible to perform distributed measurements of strain and temperature in km-long fibers at meter resolutions [2].

However, the performance of BOTDA sensors is limited by the reduced nature of the SBS interaction, which can be near the noise floor. The natural solution to this problem may seem to enhance the interaction and the detected signal to noise ratio (SNR) by increasing the probe and pump powers. Nevertheless, the maximum usable power of these waves is limited by modulation instability (MI) and spontaneous Raman scattering, in the pump pulse case [3], and by non-local effects, for the probe [4]. These restrict considerably the sensor operation, since using stronger signals deteriorates the overall performance. Different solutions such as Raman amplification [5] or pulsing the probe wave [6, 7] have been proposed, although they can increase the setup cost or increase the measurement time. Other alternative solutions such as coding of the pump signal have been proven as key to improve the sensor performance [8]. In this case there is no need to increase the pump and probe powers and the SNR of the system is improved considerably.

In this paper we demonstrate the benefits of applying coherent detection techniques in BOTDA systems to improve the SNR without the need to increase the pump and probe powers. We also show the possibility to obtain Brillouin phase-shift measurements. Coherent systems have been widely used in fiber optic communication and sensor systems in order to enhance the performance by increasing the sensitivity in detection [9]. We specifically concentrate in the application of self-heterodyne detection in which the detected signal and the local oscillator are generated by the same laser [10]. This way we benefit from a suppression of phase noise and also take advantage from the architecture of BOTDA setups, which facilitates the implementation of self-heterodyne detection [11].

In section II, we start by performing a theoretical analysis of the benefits of using self-heterodyne detection in BOTDA sensors. Then, in section III and IV, we propose and demonstrate a high performance sensor that provides long-range distributed measurements by using self-heterodyne detection. We compare the results achieved with our system to the results achieved with a conventional direct-detection BOTDA under the same conditions to quantify the magnitude of the performance enhancement. Finally, we also show the possibility of measuring the distributed Brillouin phase-shift spectrum along the fiber.

II. Theoretical Background

A. Conventional direct-detection BOTDA.

In fig. 1(a) a conventional BOTDA's detection principle is depicted. The probe wave propagates through the fiber while it is amplified via SBS by a pump pulse travelling in the opposite direction. When the probe wave signal goes out of the fiber a circulator directs it to the detector. The detection is made in base-band converting the signal directly to the electrical domain. Therefore, the received probe wave optical field is given by:

$$E_S\left(t = 2z/V_g, \nu = \nu_s\right) = E_{S0}\exp\left(j2\pi\nu_s t\right)H_{SBS}(\nu_S, z) \quad (1)$$

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Ander Zornoza, Mikel Sagues and Alayn Loayssa are with the Department of Electric and Electronic Engineering, Universidad Pública de Navarra, Campus Arrosadía s/n E-31006 Pamplona, Spain (corresponding author to provide phone: +34948169841; fax: +34948169720; e-mail: ander.zornoza@unavarra.es).

where V_g is the group velocity in the fiber, E_{S0} is the complex amplitude of the optical field of the probe in the absence of Brillouin interaction, ν_S is its optical frequency and H_{SBS} is the Brillouin gain spectrum. In this expression it has been assumed that the Brillouin interaction of the probe and the pump pulse takes place at a distance z in the fiber and that the pulse was launched t=0 the interaction can be approximated to a Lorentzian profiles such as:

$$H_{SBS}(\nu,z)=\exp\left(\frac{g_{\max}}{1+\dfrac{2j(\nu-\nu_1+\nu_B(z))}{\Delta\nu_B}}\right)=\exp(g_{SBS}(\nu_S,z))\exp(j\phi_{SBS}(\nu_S,z)) \quad (2)$$

where g_{max} is the maximum Brillouin gain, $\Delta\nu_B$ is the Brillouin bandwidth, ν_B is the Brillouin frequency shift, and G_{SBS} and ϕ_{SBS} are the gain and phase-shift generated because of the nonlinear phenomenon. However, with short pulses (~10ns), the interaction spectrum is broader than the Brillouin spectrum described in equation (2) and H_{SBS} is given by the convolution of equation (2) with the actual pulse spectrum. Considering that g_{SBS}<<1 we can approximate:

$$H_{SBS}(\nu,z)\approx(1+g_{SBS}(\nu_S,z))\exp(j\phi_{SBS}(\nu_S,z)) \quad (3)$$

Since the optical power is the square of the optical field, the detected optical power is:

$$P_S(t,\nu)=P_{S0}(1+g_{SBS}(\nu_S,z))^2 \quad (4)$$

Where P_{S0} is the power of the probe power. Then the detected current is:

$$I_S(t,z)=R_D P_S(t,\nu) \quad (5)$$

with R_D the responsivity of the detector, the signal to noise ratio of a conventional BOTDA setup is:

$$SNR_D=\frac{4R_D{}^2P_{S0}^2 g_{SBS}}{\sigma_D^2} \quad (6)$$

where σ^2_D is the total noise of the system that can be expressed as:

$$\sigma_D^2=\sigma_{TD}^2+\sigma_{RD}^2+\sigma_{SD}^2= \quad (7)$$
$$=\frac{4\cdot K_B\cdot T}{R_L}\cdot F_n\cdot\Delta f+RIN\cdot(P_S\cdot R_D)^2\cdot\Delta f+2\cdot q\cdot(R_D\cdot P_S+I_d)\cdot\Delta f$$

Where σ^2_{TD} is the thermal noise contribution, σ^2_{RD} the relative intensity noise (RIN) contribution, σ^2_{SD} the shot noise contribution, K_B the Boltzmann constant, T the photodetector operating temperature, R_L the output resistance, Fn the photodetector noise figure, Δf the photodetector bandwidth, RIN the relative intensity noise of the laser source, q the electron charge and I_d the photodetector dark current. The probe power is usually low (<-15dBm), hence RIN and shot contributions are negligible. Thus, in conventional BOTDA systems where direct detection is employed the noise is predominantly thermal.

As a consequence of the previous analysis we can conclude that in conventional BOTDAs with direct detection the SNR is directly proportional to the detected probe power. Accordingly, with a stronger P_s the SNR is increased. However, this leads to the apparition of non local effects, which can be noticeable with a powers as low as -14dBm in long range measurements [12]. So the maximum probe power launched to the fiber in long range BOTDA measurements must be kept at this level, limiting significantly the systems SNR.

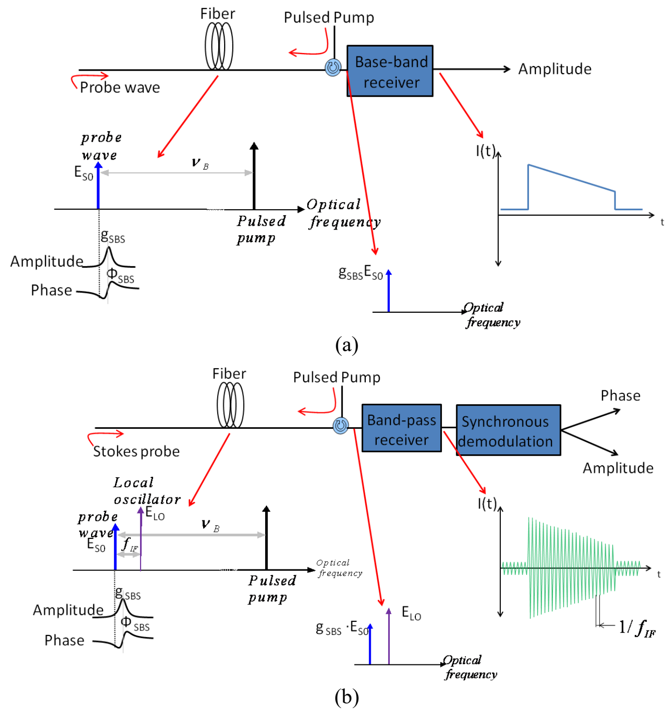


Fig.1: schematic of the BOTDA interaction and detection using direct detection (a) and self-heterodyne detection with synchronous demodulation (b).

B. Self-heterodyne detection BOTDA

In fig. 1(b) we depict the BOTDA scheme using self-heterodyne detection. Instead of a probe signal directly coming from the laser source, we have two signals arriving to the detector: a local oscillator and the probe wave. In the fiber the SBS interaction occurs between the pump pulse and the probe wave. In this case, the total optical field received after Brillouin interaction, operating at an optical frequency of ν_S and ν_{LO} for the probe wave and the local oscillator, is:

$$E_T(t,\nu_s)=E_{S0}g_{SBS}(\nu_S,z)\exp(j(\phi_{SBS}(\nu_S,z)+2\pi\nu_S t))+E_{OL}\exp(j2\pi\nu_{LO}t) \quad (8)$$

where E_{S0} is the complex amplitude of the probe wave, and E_{LO} is the complex amplitude of the local oscillator. Then, the detected optical power at the heterodyne frequency is:

$$P_T(t,\nu)=2R_C\sqrt{P_{S0}(1+g_{SBS}(\nu_S,z))^2P_{LO}}\cos(2\pi f_{IF}t+\phi_0-\phi_{SBS}(\nu_S,z)) \quad (9)$$

where ϕ_0 and f_{IF} are the phase and frequency difference between the probe and the local oscillator, R_C is the responsivity of the detector and the local oscillator and P_{LO} and P_{S0} the optical powers of the local oscillator and the probe wave. The detected current is then:

$$I_C(t)=2R_C\sqrt{P_{S0}(1+g_{SBS}(\nu_S,z))^2P_{LO}}\cos(2\pi f_{IF}t+\phi_0-\phi_{SBS}(\nu_S,z)) \quad (10)$$

The amplitude of this electrical signal is given by the product of the power of both optical signals. This is the reason behind the improvement of the sensitivity of the detector obtained in coherent detection, because the lower power signal is amplified considerably. Furthermore, we do not lose the information of the phase of the signal as we do in a conventional BOTDA (4). I_C is then an amplitude and phase modulated signal that contains not only the conventional information of the Brillouin gain along the fiber, but also information of the Brillouin phase-shift along the fiber. Finally we demodulate this signal so as to obtain the phase and amplitude information in base-band. This last step can be easily performed in the electrical domain through synchronous demodulation, as shown in fig. 1 (b).

Calculating the SNR for the self-heterodyne detection scheme described, we obtain:

$$SNR_C = \frac{8{R_C}^2 P_{S0} g_{SBS} P_{LO}}{\sigma_C^2} \tag{11}$$

Therefore by using self-heterodyne detection, we can maintain the probe wave power to the limit in which non-local effects are negligible, and increase the SNR by using a stronger local oscillator. If the noise in the coherent system is the same as in the conventional system, the theoretical improvement of the SNR is given by $2 \cdot P_C/P_{S0}$. However this is a theoretical limit which is only true if the noise levels in both systems are the same. One thing to take into account is that with a powerful local oscillator the noise of the system is not only given by the thermal noise: relative intensity noise (RIN) and shot noise contributions must be taken into account, which can be negligible in direct detection. Actually, if the local oscillator is powerful enough, we can achieve the shot noise limit. Hence, in the coherent case, the noise is:

$$\sigma_C^2 = \sigma_{TC}^2 + \sigma_{RC}^2 + \sigma_{SC}^2 = \tag{12}$$
$$= \frac{4 \cdot K_B \cdot T}{R_L} \cdot F_n \cdot \Delta f + RIN \cdot (P_{LO} \cdot R_C)^2 \cdot \Delta f + 2 \cdot q \cdot (R_C \cdot P_{LO} + I_d) \cdot \Delta f$$

If we compare the two detection systems, the improvement achieved with self-heterodyne detection is given by:

$$\frac{SNR_C}{SNR_D} = \frac{2{R_C}^2 P_C}{{R_D}^2 P_{S0}} \frac{\sigma_{TD}^2}{\sigma_{TC}^2} \tag{13}$$

So the improvement of $2 \cdot P_C/P_S$ is only true when the increase of the signal due to coherent detection is bigger than the increase of noise due to shot and RIN contributions.

C. Signal generation

As we have seen, the improvement of the system performance is notable using coherent self-heterodyne detection. In conventional self-heterodyne detection, the laser output is divided in two branches. One of the signals, the local oscillator, is delayed, and the other one is modulated. Finally both signals are recombined before the photoreceiver for heterodyne detection [10]. Although this scheme is also possible, we propose a slight modification to apply in BOTDA. It would consist in modulating the laser output and using the sideband as probe and the carrier as LO, without any division and recombination. This scheme is simpler and has the benefit that the LO and the probe wave are coherent, so we avoid phase noise that would appear in the conventional self-heterodyne scheme. For example, we can use optical single-sideband (OSSB) modulation, which would not alter (8) and all the expressions from there on. In this case the sideband will act as probe wave. Note that the modulation frequency, f_{RF}, can be fixed to the desired frequency, and would substitute f_{IF} in (9)-(10).

The self-heterodyne detection we propose is also possible with simpler modulation formats without affecting the system performance, like for example phase modulation. In this case the optical field in detection after Brillouin interaction is:

$$E_T(t,\nu) = E_{S0}(1 + g_{SBS}(\nu_{LO} + f_{RF}, z))\exp(j(\phi_{SBS}(\nu_{LO} + f_{RF}, z) + 2\pi(\nu_{LO} + f_{RF})t)) + E_{OL}\exp(j(\phi_{LO} + 2\pi\nu_{LO}t)) + E_{S0}\exp(-j(2\pi(\nu_{LO} - f_{RF})t)) \tag{14}$$

So the AC component of the photocurrent is:

$$I_{CPM}(t) = 2R_C(1 + g_{SBS}(\nu_{LO} + f_{RF}))\sqrt{P_{S0}P_{LO}} \cdot \cos(2\pi f_{IF}t + \phi_{01} - \phi_{SBS}(\nu_{LO} + f_{RF}, z)) - 2R\sqrt{P_{S0}P_{LO}} \cdot \cos(2\pi f_{RF}t + \phi_{02}) \tag{15}$$

where ϕ_{01} and ϕ_{02} are the phase differences between the carrier and each sideband. Note that although we have another term because of the extra sideband, this does not affect the SNR or the performance.

Moreover, if chromatic dispersion is not significant makes $\phi_{01} \approx \phi_{02}$, what simplifies (15) to:

$$I_{coh\_PM}(t,\nu) = 2RG_{SBS}(\nu_{LO} + f_{RF})\sqrt{P_{S0}P_{LO}}\cos(2\pi f_{IF}t - \phi_{SBS}(\nu_{LO} + f_{RF}, z)) \tag{16}$$

Thus, the signal after detection is only composed by the Brillouin interaction, without a carrier, and the demodulation process is simplified because the RF powers are lower although the SNR is the same.

III. Experimental setup

In Fig.2 a schematic of the experimental setup is depicted. The scheme is based on the one described in [11]. The output of the laser is divided in two branches employing a 90:10 coupler. The upper branch, with 10 percent of the signal, is directed to a Mach-Zehnder electro-optic modulator (MZ-EOM), where we generate high extinction ratio optical pulses with the RF pulse-shaping technique [13]. For this purpose the MZ-EOM is modulated with RF pulses at near 11GHz so as to obtain a pulsed double-sideband with suppressed carrier modulation of the incident light. The RF pulses are generated in a microwave switch driven by a pulse generator and a microwave synthesizer. After the optical pulses are generated, we amplify them in an erbium doped fiber amplifier (EDFA), to acquire the desired power, and then we filter the ASE noise and the unwanted pulsed sideband in a fiber Bragg grating (FBG). Finally a polarization scrambler is employed to compensate the polarization sensitivity of SBS before the pump pulse is directed to the fiber by a circulator.

The lower branch is used for the probe wave generation. So as to generate the desired signal to perform self-heterodyne detection, we modulate the output of the laser with an electro-optic modulator with an RF signal from a RF synthesizer. Then, the modulated signal goes to the fiber where interacts with the pump pulse. After that, it is directed to a photoreceiver with enough bandwidth to detect the beat of the carrier with the sideband, and perform the self-heterodyne detection. The detected signal is subsequently demodulated in a synchronous demodulator. The same RF synthesizer source is used for the optical modulation and for the RF synchronous demodulation so as to minimize the phase noise that would appear from having different sources [9]. There is a trade-off between using a low or a high frequency in the RF synthesizer. If the frequency is too low, less than 500MHz, the pump pulse also interacts with the carrier, and it must be taken into account. Also, if the frequency is too high, greater than 1.5GHz, the cost of the setup is more expensive.

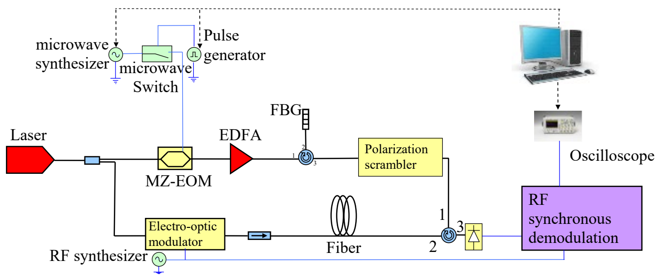


Fig. 2: Scheme of the experimental setup.

Note that in this scheme the frequency sweep between pump and probe waves required to measure the Brillouin spectrum can be made (i) sweeping the microwave signal of the pump pulses (ii) sweeping the RF signal modulating in the probe signal. In case (ii), since the RF signal is one tenth of the microwave signal, the setup cost is reduced considerably. This is because it is much cheaper a RF signal synthesizer (working at frequencies below 1GHz) than a microwave generator (working at frequencies around 11GHz) that can sweep with 1MHz accuracy.

It also should be remarked that since the photocurrent is in AC, the signal amplification is much simpler and cheaper than when it has DC components, like in conventional BOTDAs.

IV. Results

A. Signal to noise ratio improvement

We compared the performance of a conventional BOTDA sensor employing direct detection and our proposal of self-heterodyne detection and RF synchronous demodulation under the same conditions. The experimental setup employing self-heterodyne detection was built following the scheme in fig. 2. The power of the carrier was limited because of spontaneous Brillouin scattering, so we fixed this parameter to the value of 5dBm [14]. The modulation format chosen for self-heterodyne detection was phase modulation at a frequency of 850MHz. This phase modulated signal is shown in fig. 3 measured in an ESA with heterodyne detection. This measurement was used to ensure that the modulation index was the required to have the desired probe wave power.

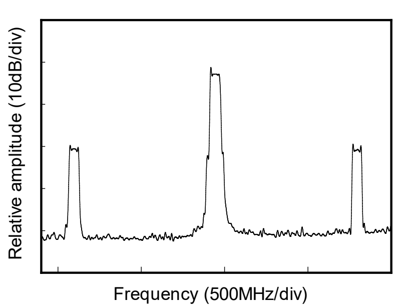


Fig. 3: Phase modulation measured with heterodyne detection, the upper sideband is the probe wave.

The conventional BOTDA built for the comparison followed the scheme in [13], and also takes advantage of the RF-pulse shaping technique.

We set all the operational parameters such as probe power, pump power, number of averages and spatial resolution to the same values in both systems. The probe power, i.e. the side band of the modulation in the self-heterodyne setup and the unaltered laser output in the conventional setup, was set to -13dBm so as to avoid non local effects. The pump pulse power was limited because of modulation instability, and fixed to a value of 21.5dBm. The photoreceivers employed in the two cases where different to fit the required bandwidth, power and coupling characteristics of the two systems. Nevertheless, the thermal noise level in the two cases where similar. The spatial resolution was fixed to 1m and the averaging to 1024 acquisitions. We performed BOTDA measurements in a 20.6-km SMF fiber. In fig. 4 the distributed Brillouin gain trace near a ν_B frequency difference between pump and probe is shown. The trace using self-heterodyne detection is much cleaner than the trace using conventional direct detection. In order to quantify the improvement achieved we calculated the SNR of each trace as:

$$SNR = \frac{V^2_{BOTDA}}{\sigma_v^2} \tag{17}$$

with V_{BOTDA} the amplitude of the BOTDA signal when the Brillouin gain is minimum (at the end of the fiber) and σ_v^2 the variance of the noise floor in the BOTDA trace. The improvement obtained using self-heterodyne detection is measured to be of 12.35dB, which matches the theoretical value calculated with (13), 13.1dB.

By sweeping the frequency of the pump wave in a span of 400MHz with steps of 4MHz we can reconstruct the whole Brillouin spectra for each point of the fiber and measure the ν_B along the fiber. This measurement for both cases is represented in fig. 5, and the measurement employing self-heterodyne detection is clearly cleaner. In order to approximate the accuracy of the sensors we calculated the standard deviation of the measured ν_B along the fiber. We performed 5 consecutive measurements with the fiber under the same conditions, and we depict the obtained standard deviation distribution in fig. 6. Once again the measurements performed with coherent detection show to be better than the measurements performed with conventional BOTDA. Using the values from figure 6 we can also quantify the SNR in BOTDA sensors by the expression [1]:

$$SNR = \frac{\Delta \nu^4_B}{4 \cdot \delta \nu_B{}^4} \tag{18}$$

where $\delta\nu_B$ is the resolution of the measurement. The improvement of SNR is of 14.3dB. However, we are using 10ns pulses for our measurements and (18) was defined taking into account the Lorentzian shape of the Brillouin spectrum. As in our case the profile of the Brillouin gain spectrum is no more Lorentzian, it comes from the convolution between a Lorentzian and the pulse spectrum, we doubt of the validity of equation (18) in this case.

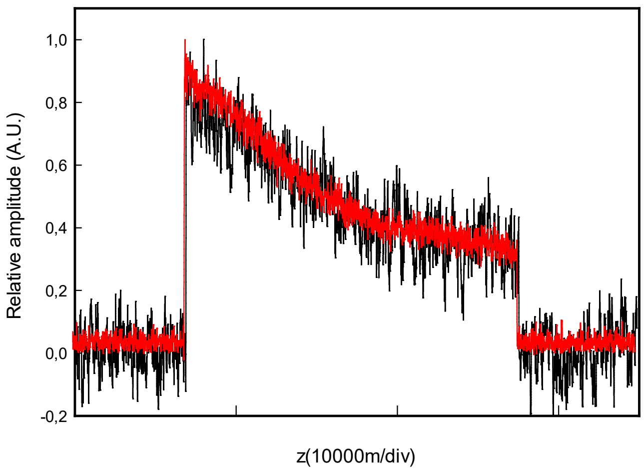


Fig. 4: BOTDA traces of both systems in 20km fiber at 1m resolution, where the red trace was measured employing the coherent BOTDA and the black trace with conventional BOTDA.

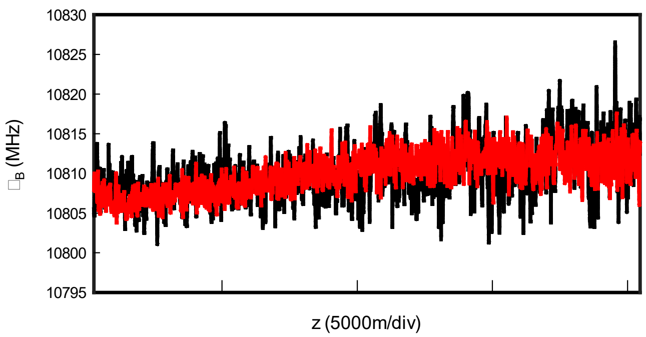


Fig. 5: ν_B measured in a 20km fiber at 1m resolution, where the red trace was obtained employing the coherent BOTDA and the black trace with conventional BOTDA.

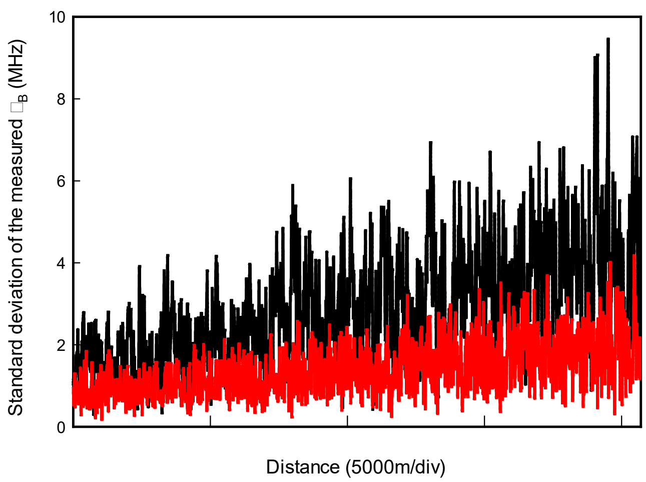


Fig. 6: standard deviation of 5 consecutive distributed measurement of the Brillouin frequency shift in black with self heterodyne detection and in black with conventional BOTDA

In fig. 7 we depict the ν_B measured between two sections of a fiber at different temperature. Here we can measure the spatial resolution, which is below 1m. This measurement was taken in a 25km fiber with 10ns pump pulses so as to ensure the systems capability, and it was the last 36m section of the fiber the one introduced in a thermal bath at a temperature of 50ºC.

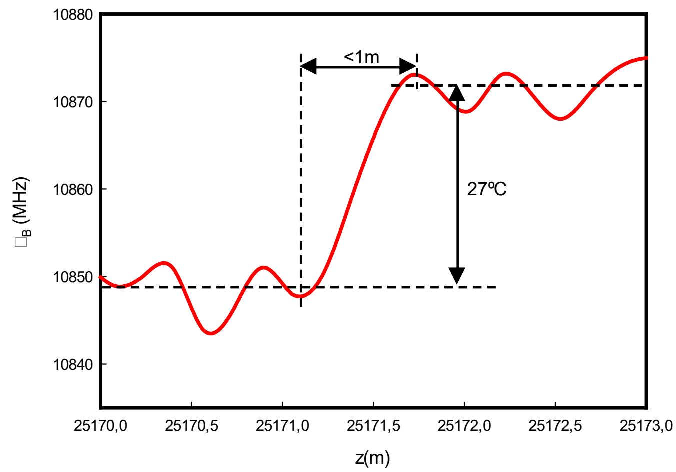


Fig. 7: Zoom of the ν_B in the transition between the room temperature fiber section and the 36m section at the end of a25.2km fiber that has been heated to 50ºC in a thermal bath.

B. *Distributed phase measurements*

We measured the distributed Brillouin phase-shift and Brillouin gain simultaneously, but this time using an OSSB modulator. The modulating frequency was chosen to operate at 500MHz to generate the desired modulation format for self-heterodyne detection, which is illustrated in fig. 8. The probe wave was measured to be -22dBm, and with pump pulses of 21dBm we performed measurements in a 25km fiber with 6m resolution. In fig. 9 we show the results of the measurements, in which we depict the distributed measurements of the gain and phase-shift. In the last section of the fiber, where the fiber is heated up to 50ºC, the Brillouin phase and gain are shifted in frequency according to the temperature change.

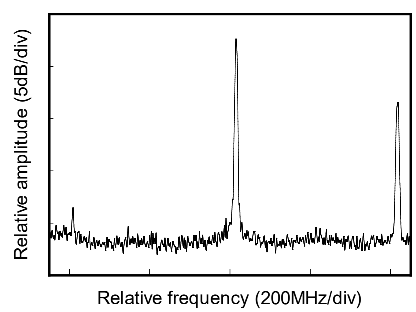
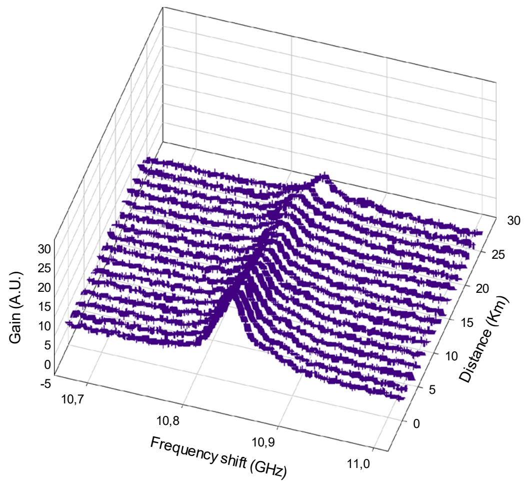
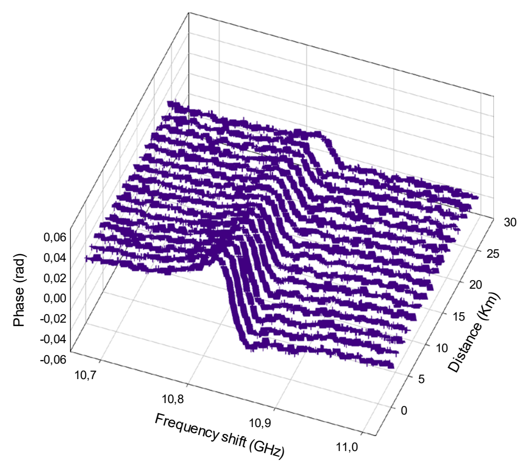


Fig. 8: OSSB modulation measured with heterodyne detection, the upper sideband is the probe wave.



(a)



(b)

Fig. 9: Distributed measurements of the Brillouin gain spectra (a) and phase-shift spectra (b) performed with OSSB modulation and self-heterodyne detection.

Distributed phase measurements open a window to new applications of BOTDA sensors. For example since we have information of amplitude and the phase, fitting to these measurands simultaneously we can improve the sensor accuracy. Also, the phase profile, which has a linear shape near the Brillouin frequency, could be exploited for dynamic measurements, where usually the Brillouin gain spectra is used [15], incrementing the measuring dynamic range. Detailed results of the applications of phase measurements will be published elsewhere.

V. Conclusion

In this paper we have presented a BOTDA sensor employing coherent detection techniques to improve the sensor performance by incrementing the SNR. In a conventional system the SNR is limited by the maximum pump pulse and probe powers, which cannot be incremented above a threshold value because of non local effects, MI or spontaneous Raman scattering. Using coherent self-heterodyne detection we do not raise the pump and probe powers, and we have experimentally demonstrated an increase of 12.35dB in the SNR in long range measurements. We also show that we are able to carry out distributed measurements of the Brillouin phase-shift, which leads to new applications and enhanced sensors.

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Biography

Alayn Loayssa was born in San Sebastian, Spain, in 1973. He holds a M.Sc. in Telecommunication Engineering (1997) and Ph.D. in optical communications (2001), both from the Public University of Navarre, Spain. In 2001 he was visiting Research Fellow at the University of Melbourne, Australia. Currently, he is an Associate Professor at the Electrical and

Electronic Engineering Department of the Public University of Navarre and a member of the Optical Communications Research group, where he leads research on microwave photonics, optical measurements applications and Brillouin distributed sensing. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and has also served as member of the Technical Program Committee of the IEEE International Microwave Photonics Conference (MWP). In addition, he is a member of the editorial board of the International Journal of Microwave Science and Technology.