Long-range static and dynamic distributed sensing

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***Abstract*— In the past few decades, Brillouin-based distributed temperature and strain sensors have attracted the attention of both the academic and industrial sectors. In particular, B-OTDA systems have been lately a trendy study area due to their numerous and well proofed applications, such as in monitoring large civil structures, energy transportation or environmental applications. One of the main areas of research in B-OTDA sensors focuses on the extension of the measuring range. To do so, it becomes necessary to increase the signal to noise ratio (SNR) of the sensor, in particular considering the reduced signal contrast at the far end of the fiber. Several techniques have been applied in order to achieve this goal, such as Raman amplification and pulse coding. Here, we review some of these techniques (particularly Raman amplification) and their application for range extension of these sensors beyond the 100 km range. In addition, we discuss routes to perform dynamic measurements over such ultra-long spans.**

Keywords—Brillouin Optical Time Domain Analysis, distributed sensing, optical fibers

I. INTRODUCTION

Distributed measurement of temperature and strain along standard optical fibers is possible thanks to several techniques. Among them, Brillouin Optical Time-Domain Analysis (BOTDA) [1,2], has strongly evolved and now is a consolidated fiber sensing technology that is widely used in different application domains (civil engineering, pipelines, fire detection, etc).

The underlying physical phenomenon in this technology is a nonlinear optical effect occurring in the optical fibers and called Stimulated Brillouin Scattering (SBS) [3]. This effect is an acousto-optic process which manifests as a narrowband amplification of a probe beam when an intense coherent pump light beam is introduced through the opposite end of a single-mode fiber. To provide the distributed characteristic to the BOTDA, the pump wave is pulsed and the detected probe signal is analyzed as a function of the time-of-flight of the pump pulse in the fiber. The measurement range and the spatial resolution are two of the most important features of these systems, being generally limited to 20-30 km, with 1-2 meter resolution [4]. The measurement range is limited by the fiber attenuation, which causes an increase in the measurement uncertainty towards the end of the fiber. This is due to the fact that the inevitable fiber attenuation reduces the pump power, hence reducing the gain experienced by the probe and thereby showing a smaller contrast and worse Signal to Noise Ratio (SNR) at the far end of the fiber. At the same time, the resolution is set by the spatial length of the pulses used to produce the distributed interaction. The use of shorter optical pulses increases the resolution, but at the same time the effective distance for amplification is reduced and the measurement uncertainty is increased due to the associated spectral broadening of the interaction. It is necessary then to find a proper balance between the resolution and the measurement range to comply with the required system specifications for each application.

There is an increasing number of large infrastructures requiring intensive monitoring and crossing vast unmanned areas (pipelines crossing desserts, umbilical cables for offshore wind-farms, etc). The robust and continuous monitoring of these structures is critical and economically very demanding using conventional technology. Thus, new approaches are needed to extend the range of conventional distributed sensors for these infrastructures. This paper provides a review of the recent progress towards extending the operating range of distributed Brillouin sensors beyond the frontier of 100 km.

II. BRILLOUIN OPTICAL TIME DOMAIN ANALYSIS ASSISTED BY RAMAN SCATTERING

To improve the dynamic range of BOTDA sensors it becomes necessary to introduce Raman pumping on one or both sides of the sensing fiber, as shown in Fig. 1. Raman amplification induces a distributed gain along the fiber that compensates for the intrinsic fiber loss and thus maintains the pump power to a level to secure a sufficient gain. WDM couplers should allow maximizing the efficiency of the Raman pumping. By means of this amplification we transfer power both to the pump and probe waves, achieving a more homogeneous interaction along the sensing fiber.

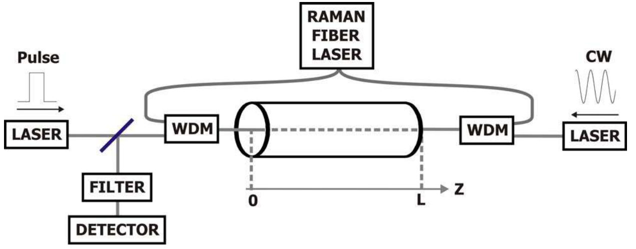
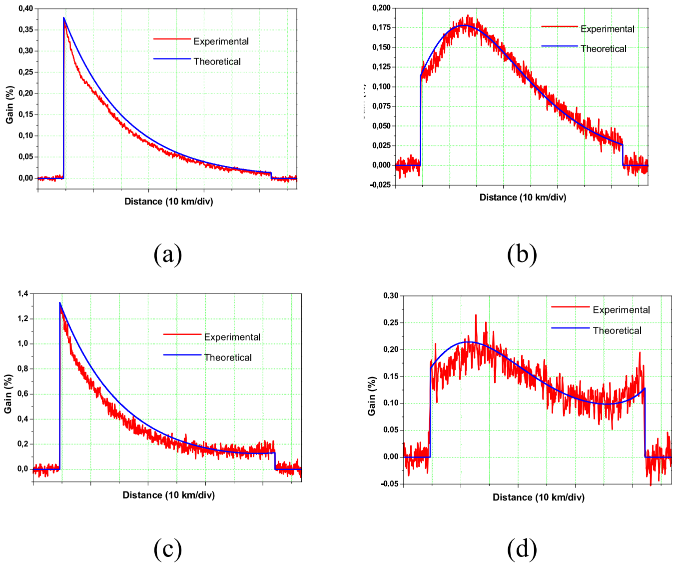


Fig. 1. General configuration of a BOTDA assisted by Raman amplification

Several studies have proven that the fiber losses can be successfully compensated using first or second-order distributed Raman amplification [5], [6], leading to an enhancement of the measurement range without compromising the resolution. In [5], a measurement range of 75 km was demonstrated in a Raman-assisted BOTDA with a resolution of 2 meter.

Fig. 2 shows some traces illustrating the possibilities given by Raman amplification in terms of increasing the signal contrast at the far end of the fiber. In this figure, it can be seen that the side by which we insert the Raman pump implies a complete change in the power distribution of the gain in the sensing fiber, generally having higher contrast close to the side by which the Raman pump is introduced. A relatively good and effective cancellation of the fiber losses can be achieved by pumping bi-directionally in the fiber. As it can be seen the gain remains close to constant all along the fiber. However, as it is visible, Relative Intensity Noise (RIN) transfer from the Raman pumps to the Brillouin probe implies severe degradation of the signal to noise ratio in high-pump power conditions.



(a)

(b)

(c)

(d)

Fig. 2. Sample traces obtained in BOTDA assisted by first-order Raman amplification using (a) no Raman amplification, (b) co-propagating Raman amplification with the Brillouin pump pulse; (c) counter-propagating amplification with the pulse and (d) bi-directional amplification. Theoretical traces are displayed in blue in all cases.

To avoid the effect of RIN transfer and retain the contrast increase benefits of the Raman amplification, an optimization procedure in terms of the pump powers was carried out in [6]. It was achieved a working regime in which the more signal contrast could be achieved without significant RIN transfer impairments. Some sample results are shown in Fig 3, 4 and 5.

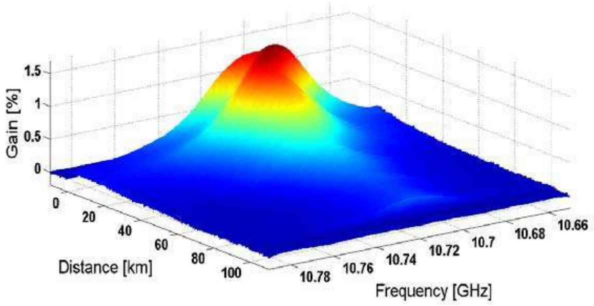


Fig. 3. Brillouin gain spectra (BGS) as a function of distance acquired over 100 km of fiber with bi-directional first-order Raman assistance .

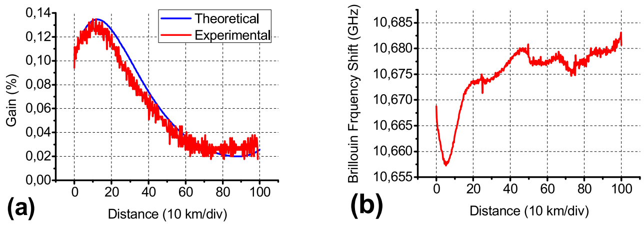


Fig. 4(a) Comparison between the obtained maximum gain trace at each position (red line) and the calculated results using the analytical model of the bidirectional Raman-assisted configuration [5]. (b) Evolution of the Brillouin frequency shift along the 100 km of optical fiber.

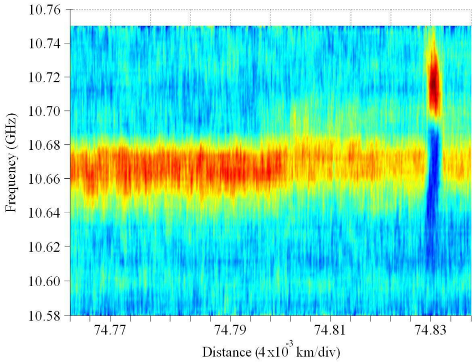


Fig. 5. Hot-sport experiment: the figure shows the Brillouin gain sweep around an induced hot spot (located close to km 75, in the position of worst signal contrast). Frequency is swept between 10.58 GHz and 10.75 GHz. The frequency difference between the hot spot and the rest of the fiber sections is approximately 45 MHz. Considering the sensitivity of 1.3 MHz/ºC in the Brillouin shift, this gives us a temperature variation of 35ºC, which is in good agreement with the expected temperature difference.

III. SECOND-ORDER RAMAN ASSISTANCE

In [7] the measurement distance was increased to 100 km with 2 meter resolution, however using a more complicated second-order setup. Second-order pumping implies the use of a second Raman pump in the scheme of Fig 1 to assist/amplify the first-order Raman pump. If the first-order pump is located at 1455 nm (Stokes order difference), the second Raman pump is located in twice the Stokes difference (1365 nm roughly). This way the evolution of the first-order pump turns out to be very smooth along the fiber and Brillouin interaction is even smoother. As a result, the traces appear as if the fiber behaved in apparent transparency (Fig 6). The system can be tuned to work in apparent transparency also in terms of uncertainty (Fig 7).

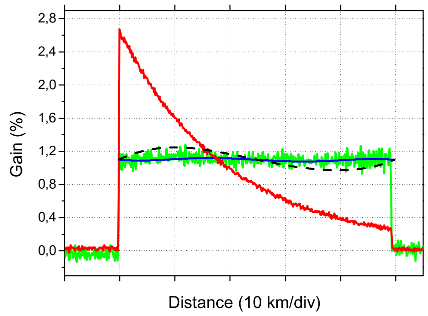


Fig. 6. Experimental gain traces acquired for a 50 km fiber with 40 ns pulses. Red curve shows the conventional BOTDA trace obtained for the maximum gain of the fiber In green, the trace obtained using a cavity-based second-order setup with the same pulse width and probe power. The blue curve shows the simulated gain evolution considering the experimental settings and the dashed curve shows the simulated gain evolution for the first-order amplification configuration considering the same experimental settings and trying to work as close as possible to transparency.

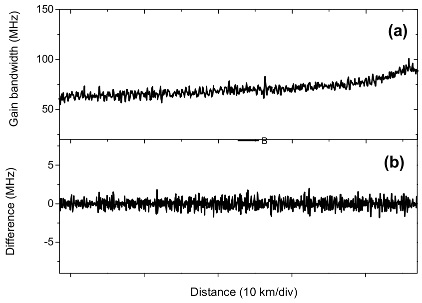


Fig. 7. Experimental gain bandwidth and uncertainty traces obtained in close to transparency conditions. (a) Significant SPM appears towards the end of the fiber, leading to broadening of the gain curve and a potential deterioration of the uncertainty that can be avoided unbalancing the pumps. (b) Conditions of the experimental setup can be found where the uncertainty all along the fiber keeps homogeneous.

The second-order approach was later extended an optimized into a “seeded” configuration (where a small seed at 1455 nm is inserted in the fiber). A careful optimization of the system lead to the achievement of BOTDA measurements over an un-repeatered 240 km fiber loop [8].

IV. BALANCED DETECTION

Stimulated Brillouin Scattering (SBS) features two side bands: the Stokes (gain) and Anti-Stokes (loss) bands. To take advantage of the SBS phenomenon, a single sideband (SSB) modulator can be used at the probe signal to work at Brillouin Gain frequency (Stokes band) or at Brillouin Loss frequency (Anti-Stokes band). However, making use of a dual sideband (DSB) modulator to generate both Stokes and Anti-Stokes bands, the effect of pump depletion can be effectively mitigated [9]. For this reason, DSB modulation turns out to be the preferred option in long-range setups. In conventional BOTDA, one of the two sidebands (Stokes or anti-Stokes) is filtered in detection and fed into a conventional photo-receiver for analysis.

In balanced detection, the receiver features two well matched photodiodes. Two light beams are fed into the corresponding photodiode and the obtained currents are subtracted. Ultimately, the remaining current difference is amplified through a trans-impedance amplifier. This technique allows for the detection of small signal variations over substantial DC levels. It was shown in [10] that this technique could be used advantageously in BOTDA by performing the balanced detection scheme using the Stokes and Anti-Stokes bands in each input diode. In this way, the differential output will be the result of subtracting the negative input signal (Anti-Stokes band) to the positive input signal (Stokes band). Thus, in typical conditions (when an external Mach-Zehnder modulator is employed), the detected signal will be naturally doubled in comparison with a single-detector scheme of equal responsivity.

It is interesting now to think what happens in terms of the noise. Considering equal noise characteristics for the two input photodiodes, the use of balanced detection will lead to an increase of the noise of only $\sqrt{2}$ (sum of two independent equally-distributed random variables). Thus, an overall improvement of $\sqrt{2}$ in SNR should be expected in this configuration over a conventional single-detector option.

In addition to the previous discussion, this detection technique has an additional number of advantages: in the first place, it makes the system strongly robust to common-mode noise sources (noise sources affecting equally both bands). Common noise sources may include: master laser intensity noise, modulator drifts, varying coupling losses in the fiber, etc. This also includes Relative Intensity Noise induced by raman RIN transfer. However, effective common-mode intensity noise cancellation will occur solely when optical lengths for both sidebands are equal before reaching the detector [10].

In a recent paper [11], this salient feature of balanced detection was exploited to improve the figure of merit of a Raman-assisted BOTDA by a factor of 5. Some results are shown in Figs 8 and 9.

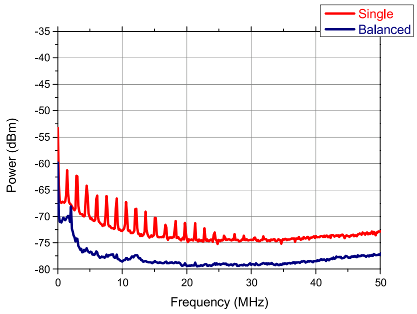


Fig 8. RIN transfer suppression in the detected probe wave using balanced detection. The electrical spectra of the detected probe wave is shown using conventional (single detector - red) and balanced detection (blue). The peaks corresponding to the RIN noise transfer are completely eliminated in the balanced case as it is visible.

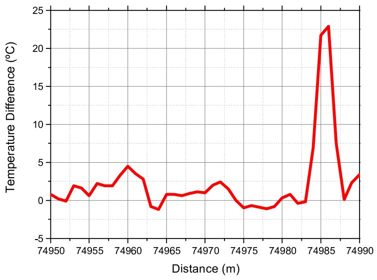


Fig. 9. Brillouin frequency shift translated to temperature difference around a ~2-meter hot-spot (located around km 75).

V. LONG RANGE DYNAMIC MEASUREMENTS

Raman assistance technology has been also used in combination with phase-OTDR techniques to produce long-range and dynamic measurements of fiber perturbations. In [12], a first-order Raman-assisted phase-OTDR setup was developed and optimized, allowing the distributed monitoring of vibrations over a length of more than 100 km. In particular, the RIN noise in this case was minimized along the setup by using a careful power optimization and balanced detection. In addition, a semiconductor optical amplifier (SOA) and an optical switch were used to greatly decrease the intra-band coherent noise of the setup. The sensor was able to measure vibrations of up to 250 Hz (close to the limits set by the time of flight of light pulses) with a resolution of 10 m in a range of 125 km (see Fig. 10).

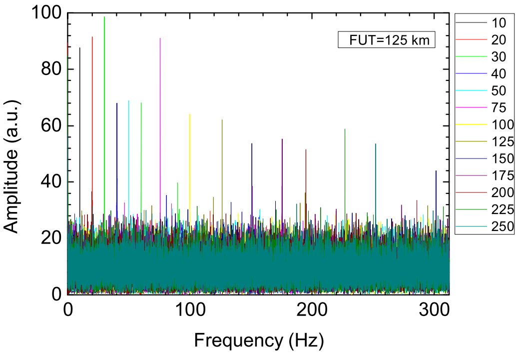


Fig 10. Dynamic response of the phase-OTDR sensor assisted by Raman over 125 km. The measurements are recorded in the position of worse contrast (around km 98).

It is interesting to mention that, to achieve the above performance, no post-processing was required in the signal.

VI. CONCLUSIONS

We have presented a review of the recent progress towards the achievement of long-range static Brillouin sensing using Raman assistance. Prospects to extend these results to dynamic measurements have also been presented.

ACKNOWLEDGMENTS

The authors 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. HFM acknowledges funding from the Portuguese Fundação para a Ciência e Tecnologia (FCT) for providing his PhD Scholarship, SFRH / BD / 76991 / 2011.

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