Angulo-Vinuesa, X., Dominguez-Lopez, A., Lopez-Gil, A., Ania-Castañon, J. D., Martin-Lopez, S., Gonzalez-Herraez, M., 2015, "Rating the limitations and effectiveness of BOTDA range extension techniques". Proc. SPIE 9634, 24th International Conference on Optical Fibre Sensors, 96346R

Available at http://dx.doi.org/10.1117/12.2194800

Rating the Limitations and Effectiveness of BOTDA Range Extension Techniques

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ABSTRACT

Brillouin Optical Time Domain Analysis (BOTDA) is becoming a consolidated technique in applications requiring high-resolution monitoring over extremely long distances. Extension of the measuring range has therefore become one of the main areas of research around BOTDA technology. To increase the sensing range, it is necessary to increase the Signal to Noise Ratio (SNR) of the retrieved signal. This has been achieved so far by applying techniques like pre-amplification before detection, pulse coding or Raman amplification. Here, we analyze these techniques in terms of their performance limits and provide guidelines that determine which is the best configuration to overcome current range limitations.

Keywords: Brillouin Scattering, distributed optic fiber sensor, pre-amplification, optical pulse coding, distributed Raman amplification, temperature sensor, strain sensor.

1. INTRODUCTION

Standard Brillouin Optical Time Domain Analysis (BOTDA) systems [1] are normally limited in sensing range to 30-40 km due to the intrinsic fiber attenuation (α =0.2 dB/km @ 1550 nm). This phenomenon reduces the intensity of the signals within the fiber, thus decreasing the Signal to Noise Ratio (SNR) as the monitored distance increases. Due to the proliferation of large infrastructures that require intensive monitoring in a distributed way, recently, new approaches have been developed to extend the range of conventional BOTDA systems. These are based on introducing a pre-amplification stage before detection [2], pulse coding [3] or distributed Raman amplification [4,5]. Unfortunately, the application of such technologies does not provide a final solution to fulfill all the required applications, in many cases beyond 100 km fiber length. In this work, we perform an analysis of the different range-extending techniques to evaluate the benefits in terms of SNR enhancement and their effect in the Figure of Merit (FoM) [6] of the BOTDA and its sensing distance. As we will see, the combination among techniques is the path to follow for achieving extremely long sensing ranges, thus, the effect of the different unions is also described.

2. CONVENTIONAL BOTDA RANGE LIMITATIONS

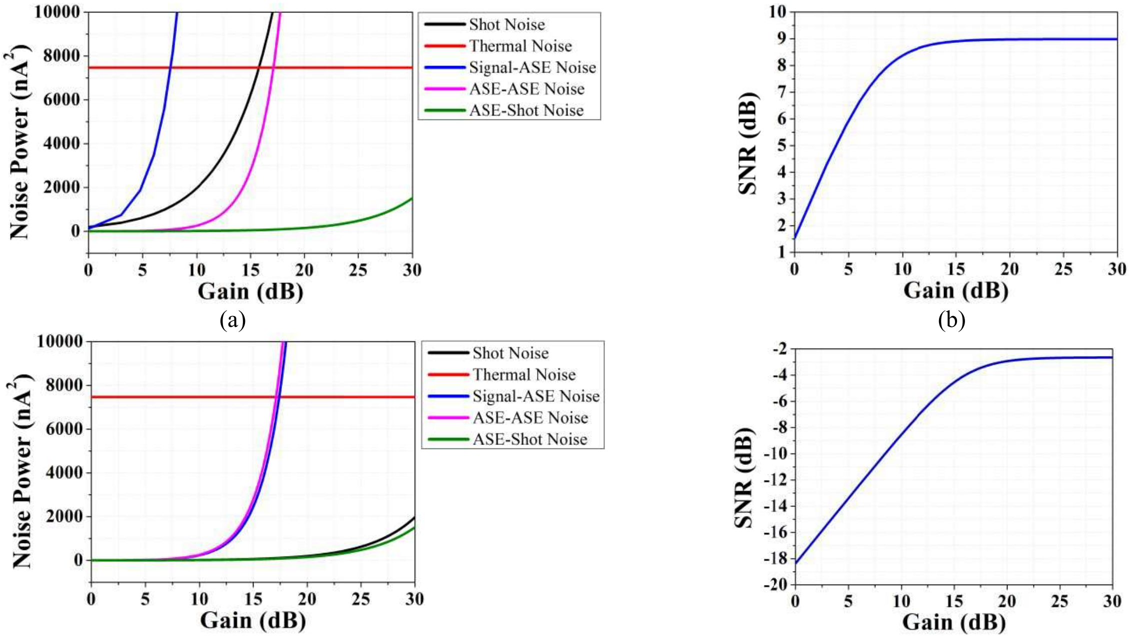
In BOTDA systems, two signals are introduced within the fiber in opposite directions; a pulsed pump wave and a continuous probe wave. The detected probe signal at the far end of the fiber (ΔP_S^0) can be expressed as [6]:

$$\Delta P_S^0 = \frac{g_B}{A_{eff}} P_{Pi} P_{Si} e^{-2\alpha L} \Delta z \tag{1}$$

where g_B is the Brillouin gain coefficient, A_{eff} is the nonlinear effective area, P_{Pi} and P_{Si} are the pump and probe input powers respectively, α is the linear fiber attenuation, L is the fiber length and Δz is the spatial resolution. As it can be seen, fiber attenuation is reflected in a squared exponential decay with distance, which means that the signal ΔP_S^0 is reduced by as much as 10 dB every time the distance is increased in 25 km. Thus, a mild range increase of 25 km implies a signal reduction equivalent to a tenfold improvement in resolution. Besides, it has to be taken into account the distance restriction produced by the BOTDA structure itself when dealing with linear sensing applications. Since the system requires access to both fiber ends, the real measuring distance is half of the employed total fiber length [7]. In terms of power levels, the pump wave is limited by depletion and Modulation Instability (MI) (typ. P_{Pi}<50 mW) and the probe signal (P_{Si}<500 µW) by the appearance of MI [7]. These maximum values are lower for Raman assistance. As stated before, this paper compares several techniques used for range extension by assessing their performance in terms of SNR enhancement.

3. ANALYSIS OF RANGE INCREASE SOLUTIONS IN TERMS OF SNR

A simple way of improving the SNR of the retrieved signal is based on using a pre-amplification stage just before detection, usually by introducing an Erbium Doped Fiber Amplifier (EDFA), which may provide up to 30 dB of gain. As Gain (G) is provided, noise sources materialize [8]. From the photodetector point of view, thermal and shot noises are predominant, with $\langle i_{ther}^2 \rangle \propto T$ and $\langle i_{shot}^2 \rangle \propto G$ respectively. In addition, Amplified Spontaneous Emission (ASE) noises have to be taken into account. ASE introduces noise through different beatings: the beating produced by the ASE noise with the shot noise ($\langle i_{ASE-shot}^2 \rangle \propto G$), the beating with the detected signal ($\langle i_{sig-ASE}^2 \rangle \propto G^2$) and with itself ($\langle i_{ASE-ASE}^2 \rangle \propto G^2$). Based on the proportionalities of each noise source, it can be easily seen that the amplification process is only interesting to overcome the thermal noise contribution in the detector. Beyond this limit, the other noise terms grow at a rate proportional to the gain (G) or gain squared (G^2), therefore the SNR will not improve. In Fig.1 the variation of the different noise sources as a function of the gain in the amplifier and the SNR evolution are represented for a total length of 100 km ((a) - (b)) and 200 km ((c) - (d), 100 km linear sensing range). In both cases, an input probe power of 500 μW is considered and 20 ns pump pulses. The gain in the detector is assumed to be 40 V/mA and the electrical and optical bandwidths are100 MHz and 50 GHz respectively. As we can see, thermal noise is dominant for gain values below 7.5 and 17 dB (100 and 200 km cases respectively) where, from this point onwards the onset of Signal-ASE and the ASE-ASE noise starts to dominate, with its well-known quadratic gain dependence. The optimum gain in terms of SNR appears at roughly 12 dB for 100 km length and 25 dB in the 200 km case, which gives a SNR improvement of roughly 7.5 dB and 15 dB respectively (optical). This SNR improvement is equivalent to a maximum range extension of ~ 19-37.5 km, which is significant but not enough in applications for ranges beyond 100-200 km.

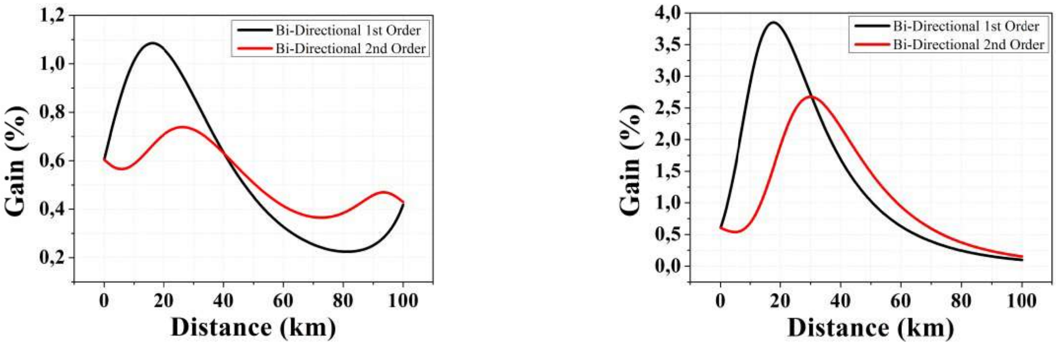


(a)
(b)
(c)
(d)

Figure 1. Noise power (a)-(c) and SNR evolution (b)-(d) for 100 and 200 km respectively for 1024 averaged traces.

Another technique to increase the SNR bases its principle on coding the pump wave with a known pulse sequence. The amplified probe wave is recovered as a linear superposition of all the traces produced by each independent pulse. As a result of the superposition, there is an increase in the received energy level, thus increasing the SNR. Through simple algebraic operations, it is possible to de-convolve the measured traces to obtain the equivalent of a single pulse trace. The gain in SNR produced by the code scales with the square root of the code-length ($\sqrt{L_C}$) [3], thus the longer the code, the higher the measured energy with the consequent SNR improvement. Nonetheless, pulse coding bases its principle on ensuring the linearity of the detection stage, where a 1 bit change in the code has to be reliably measured. This means that the non-linearity of the detector at the probe power level has to be better than $1/Lc$, which turns out to be extremely challenging in conventional InGaAs photodiodes for $Lc > 1000$. Besides, signal processing time also has to be taken into consideration. In conclusion, we can say that, for affordable pulse code lengths (~ 511 bits), the SNR enhancement is approximately 10 dB, which implies a range increase of roughly 25 km.

The last technique is based on introducing a fully distributed gain along the sensing fiber through stimulated Raman scattering, in order to partially or totally compensate the intrinsic fiber loss. This reduces the limitation of the double attenuation suffered by the detected probe wave (Eq. 1). The configurations incorporated to the standard BOTDA scheme can be based on First-order Raman amplification [4] or Second-order Raman amplification [5]. To provide considerable gain levels to long range systems, Raman assistance requires relatively high powers, normally achieved through Raman fiber lasers. These lasers introduce Relative Intensity Noise (RIN) transfer, although it cannot be considered as a fundamental limitation since several techniques have been shown to strongly reduce it, such as the balanced detection proposed by Dominguez-Lopez *et al.* in [9]. Fig.2 shows a representation of the theoretical gain traces achieved in a bi-directional First- and Second-order Raman-assisted configuration for 100 km (a) and 200 km (100 km linear) (b) (pump wave: 20 ns and 10 mW peak power - probe wave: 50 μW). Perfect end-to-end transparency has been considered for the probe wave in these calculations. Based on the models developed in [4,5] and neglecting RIN transfer, the ASE noise power in detection can be evaluated; -41.47 dBm and -35.48 dBm in the First-order configuration for 100 and 200 km respectively and -41.77 dBm and -36.69 dBm in the Second-order one (in all cases for a 50 GHz optical filter). This sets the SNR in the worst contrast position to be roughly 14 dB in the First-order case and 19 dB in the Second-order scheme for 100 km, and 1.5 dB and 6.5 dB for the 200 km case (in all cases, with 1024 averages). In this last case, the SNR enhancement given by Raman is ~ 20 and ~ 25 dB, largely surpassing all the previous techniques.



(a) (b)

Figure 2. Theoretical Brillouin gain traces for bi-directional 1st or 2nd order pumping on 100 (a) and 200 km (100 linear) (b).

By making a comparison among the evaluated techniques, in terms of SNR it is evident that Raman amplification provides the best option when range is the parameter to be enhanced. Still, even though it can display remarkable distance extension, the approach is obviously limited and the complexity of the technique is considerable. Moreover, it should be noted that the SNR estimated in the Raman-assisted case is still too low for real application in the 200 km scenario. Pulse coding has to be used for reaching a sufficient SNR. It is important to realize that the SNR in the Raman assisted cases in transparency is limited by signal-ASE beating in the detector. It is therefore clear that EDFA pre-amplification makes little sense in this case, as more amplification would in no way lead to a better SNR. When working below transparency, there is a chance that EDFA and Raman may be used together advantageously. As none of the proposed three techniques provides an ultimate solution to extend the sensing range of BOTDAs it is evident then, that the combination among techniques can provide the key.

4. EFFECT OF COMBINATION OF TECHNIQUES

By employing the Figure of Merit (FoM) [6] reported by Soto *et al.* it is possible to evaluate the effect of the combination among the aforementioned techniques on the performance of BOTDA sensors. The first “long range” BOTDA [10] showed a FoM of 2 (mainly due to the low resolution of 10 m). With the introduction of pre-amplification [2], the FoM was increased up to 6.8. With the application of pulse coding [3] a performance improvement was obtained of almost a factor of 10 in comparison to the previous results. As expected, Raman amplification (First- [4] and Second-order [5]) implies a considerable breakthrough. The sensing range is increased until 100 km maintaining a 2 meter resolution. In spite of the acquired range extension, the FoM is only improved ~ 7 times, mainly due to the elevated number of averages performed due to the detrimental effect of RIN transfer. When RIN noise is removed, e.g. by applying the balanced detection technique [9], the FoM upgrades up to 500, as expected from our models. The combination of coding with pre-amplification [11] and Raman [12], can provide 120 km sensing ranges with resolutions of few meters, but the number of averages is still elevated. The unification of all three techniques [13] is the one that provides a sensing range greater than 100 km with a 4 meter resolution and an averaging of 500, improving enormously the performance of the BOTDA until 13,000. In all the proposed systems, the sensing range equals the total fiber length employed; therefore, if a linear measuring application is required, the maximum sensing distance is of “just” ~ 60 km. By combining all three techniques in a linear sensing configuration [7], it is possible to reach 120 km of sensing fiber (240 km of fiber loop) with 5 meter resolution and the equivalent of 2048 averages. Evidently, the FoM is quickly increased up to 300,000.

5. CONCLUSIONS

In this work, we have presented a measure of the limits of the available techniques to obtain extremely long sensing ranges on BOTDA systems. After a detailed revision of the available techniques (pre-amplification, pulse coding and Raman assistance) and the application of the FoM, it is concluded that the combination among techniques is the most effective way to break the limiting barrier of 100 km. This has been demonstrated in recent literature results, which might be improved in the future. It is evident that the combination of all the proposed techniques is the path to follow when extremely long distances are required. Obviously, the complexity of such systems is considerable too, but the performance enhancement is so obvious, that is completely worth it. The range achieved so far provides an efficient sensing solution for most applications so far, but still some demanding applications may require larger sensing ranges. There are already some research groups and companies that are introducing balanced detection in their long-range BOTDA systems, probably the final improvement on the proposed schemes to break the 150 km sensing distance barrier.

ACKNOWLEDGEMENTS

This work was supported by the ERC through Starting Grant U-FINE (Grant no. 307441), the Spanish “Plan Nacional de I+D+i” through projects TEC2012-37958-C02-01/02, TEC2013-45265-R and TEC2011-27314, the INTERREG SUDOE program ECOAL-MGT, and the Comunidad de Madrid under projects EDISON and SINFOTON. S. Martin-Lopez acknowledges support by the Spanish MINECO through a “Ramón y Cajal” contract.

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