Angulo-Vinuesa, X., Soto, M.A., Martín-López, S., Chin, S., Ania-Castañón, J.D., et al. " Brillouin optical time-domain analysis over a 240 km-long fiber loop with no repeater ", 2012, Proc. SPIE 8421, OFS2012 22nd International Conference on Optical Fiber Sensors, 8421C9.

Available at http://dx.doi.org/10.1117/12.2013201

Brillouin optical time-domain analysis over a 240 km-long fiber loop with no repeater

Xabier Angulo-Vinuesa*[a], Marcelo A. Soto[b], Sonia Martin-Lopez[a], Sang-Hoon Chin[c], Juan Diego Ania-Castañon[a], Pedro Corredera[a], Etienne Rochat[c], Miguel Gonzalez-Herraez[d] and Luc Thévenaz[b]
[a]Instituto de Óptica, CSIC, C/ Serrano 121, 28006, Madrid, Spain;
[b]Inst. of Electrical Engineering, EPFL, SCI STI LT, Station 11, CH-1015 Lausanne, Switzerland;
[c]Omnisens SA, Riond-Bosson 3, CH-1110 Morges, Switzerland;
[d]Dept. de Electrónica, Universidad de Alcalá, C. Universitario, 28871, Alcalá de Henares, Spain.
*E-mail: xabier.angulo@io.cfmac.csic.es; phone +34 915618806 ext.:222

ABSTRACT

In this paper we combine the use of optical pulse coding and seeded second-order Raman amplification to extend the sensing distance of Brillouin optical time-domain analysis (BOTDA) sensors. Using 255-bit Simplex coding, the power levels of the Raman pumps and the Brillouin pump and probe signals were adjusted in order to extend the real physical sensing distance of a BOTDA sensor up to 120 km away from the sensor interrogation unit, employing a 240-km long loop of standard single-mode fiber (SSMF) with no repeater. To the best of our knowledge, this is the first time that distributed measurements are carried out over such a long distance with no active device inserted into the entire sensing loop, constituting a considerable breakthrough in the field.

Keywords: Brillouin scattering, distributed optic fiber sensor, Raman scattering, optical pulse coding, temperature sensing, strain sensing.

1. INTRODUCTION

The demand of distributed fiber optic sensors based on Brillouin optical time-domain analysis (BOTDA) [1] for strain and temperature monitoring in many application fields has been constantly increasing during the last decade due to their unique capability to perform distributed measurements along many tens of km with meter scale spatial resolution. BOTDA sensors are based on the detection of local temperature- and strain-dependent variations of the Brillouin gain spectrum (BGS) [2] along an optical fiber. Measurements are carried out using a pulsed signal (pump wave) which interacts with a counter-propagating signal (probe wave) by means of an acoustic wave generated in the fiber through stimulated Brillouin scattering (SBS) [1], [2]. Since both pump and probe signals must be sent in counter-propagating directions along the optical fiber, the sensor unit requires access to both fiber ends. Thus, BOTDA sensors can exploit the whole sensing fiber whenever the fiber is placed in a bi-dimensional or three-dimensional configuration; however, in some applications in which a linear fiber configuration is required, such as in the case of long pipelines, the useful sensing distance is only half of the fiber length.

During the last years, some techniques have been proposed to extend considerably the sensing distance of BOTDA sensors. In particular, distributed first- and second-order Raman amplification [3], [4] and optical pulse coding [5] have allowed sensing distances beyond 100 km with spatial resolutions of a few meters. The combination of first-order distributed Raman amplification and optical pulse coding for BOTDA sensors has already been proposed by X.-H. Jia *et al.* in Ref. [6], and recently improved in Ref. [7]. Although long sensing distances were reported using the above mentioned methods, in all these cases the full sensing range is determined by the fiber length, and hence only half of this length constitutes the real remoteness from the interrogation unit.

Increasing the sensing range while maintaining a spatial resolution of a few meters (1-5 m) is not trivial due to the weak SBS interaction in BOTDA sensing and due to the limited pump and probe power levels required to avoid nonlinear effects and pump depletion. In this paper we combine seeded 2nd-order Raman amplification with optical pulse coding to extend the range of BOTDA sensors. The power levels of Brillouin probe and pump signals and Raman pumps are adjusted to allow for distributed measurements along a real sensing distance of 120 km, using a 240 km-long standard single-mode fiber (SSMF).

2. PROPOSED BOTDA SYSTEM: THEORY AND EXPERIMENTAL SETUP

The system proposed in this paper makes use of hybrid first- and second-order Raman assistance in combination with 255-bit coding of the Brillouin pump. Seeded second-order Raman assistance [8] is used in the Brillouin pump side to increase the maximum distance reached by the Brillouin pump, without introducing a strong degradation in the signal-to noise ratio (SNR) due to relative intensity noise (RIN) issues. 255-bit Simplex coding of the Brillouin pump is also indispensable to ensure a sufficient SNR over the whole trace. First-order Raman amplification in the probe side is necessary too in order to ensure a minimum detectable power level at the receiver. The Raman assistance in the probe side is performed using a semiconductor laser module featuring low RIN, to minimize the RIN transfer to the probe. In addition, in comparison with previously reported methods, where the sensing fiber length corresponds to the whole optical fiber length, in this case half of the optical fiber length is used for sensing purposes to demonstrate that a real remote position equivalent to the claimed distance range can be actually sensed; while the other half is only used to convey the probe signal and the so-called backward-propagating Raman pump (co-propagating with the probe signal) up to the middle of the fiber (at 120 km distance). The power levels for the backward-propagating Raman pump and the probe signal have to be carefully adjusted to allow enough probe power at the median point of the fiber, maximizing in this way the SBS interaction along the sensing fiber (i.e. along the first half of the full optical fiber span).

The proposed method is based on the experimental setup shown in Fig. 1. The probe signal is generated using a double-sideband technique [2] based on the intensity modulation of the CW laser light by a microwave signal that allows scanning the BGS of the fiber. The amplification of the probe signal is carried out using a Raman pump unit comprising low-RIN semiconductor lasers at 1455 nm, providing a Raman polarization-dependent gain (PDG) lower than 0.5 dB.

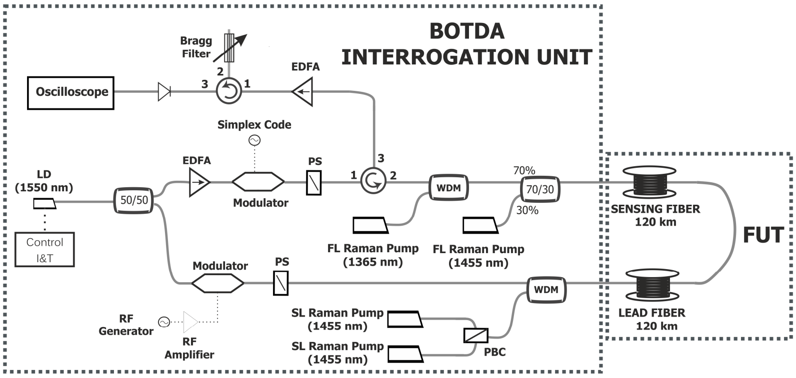

Fig. 1. Experimental setup of the BOTDA system assisted by second-order Raman amplification and optical pulse coding. LD: Laser diode; EDFA: Erbium doped-fiber amplifier; PS: Polarization switch; WDM: Wavelength division multiplexer; FUT: Fiber under test; PBC: Polarization beam combiner; SL: Semiconductor laser; FL: Fiber laser.

On the other hand, an Erbium doped-fiber amplifier (EDFA) followed by an intensity modulator was used to generate a high-power pump signal based on 255-bit Simplex coding and 50 ns pulses, resulting in a spatial resolution of 5 m. The pulse sequences are amplified along the sensing fiber by second-order Raman amplification [4], using two depolarized fiber Raman lasers: a low-power first-order Raman pump at 1455 nm and a second-order Raman pump at 1365 nm. This pumping configuration is known as “seeded Raman amplification” [8] since the low-power first-order Raman pump acts as a “seed” which is amplified by the second-order Raman pump. Although this configuration has widely been used in telecommunication systems [8], as far as we are concerned, it has never been applied in BOTDA sensing.

The optical fiber used in this experiment consists of several drums of standard single-mode fiber, with a total length of 240 km. In particular, the 120 km of sensing section (first fiber half) comprises 3 fiber drums (20 km, 50 km and 50 km) with a similar Brillouin frequency shift (BFS), located between 10.66 GHz and 10.68 GHz for a laser source emitting at 1551 nm. The remaining 120 km that forms the total 240 km loop has a completely different BFS (~ 10.85 GHz) in order to clearly visualize the end of the sensing fiber at 120 km distance. Under this condition, the coded Brillouin pump and probe signal interact along the whole sensing fiber, resulting in the most critical situation to evaluate the impact of pump depletion in the system [9]. In order to avoid polarization-dependent oscillations in the BGS measurements, polarization diversity schemes, based on polarization switches (PS), were placed at the pump and probe branches. At the receiver, a linear-gain EDFA and a tunable fiber Bragg grating were used to select one of the probe sidebands and to filter out other unwanted frequency components (e.g. ASE noise from the EDFA, the Rayleigh signal generated by the coded Brillouin pump, the residual carrier of the probe and the second probe sideband).

3. RESULTS

In order to avoid pump depletion and nonlinear effects in the fiber, the power of the Raman pumps, Brillouin pump and probe signals were carefully adjusted. In particular, by knowing that the maximum Brillouin pump power occurs at about 30-40 km distance (as a result of the second-order Raman amplification) and by monitoring the power of the coded Brillouin pump at 120 km distance, we can estimate the maximum Brillouin pump power along the fiber. In this way, the power of the first- and second-order forward-propagating Raman pumps were adjusted in order to avoid that the maximum Brillouin pump power exceeds the threshold of nonlinear effects. This condition was reached using a peak Brillouin pump input power of 5.56 mW and forward-propagating Raman pumps of 39.5 mW and 955 mW for the first- and second-order Raman pumps respectively. On the other hand, the backward-propagating Raman pump was adjusted in order to provide the highest possible probe power level at 120 km distance but at the same time to avoid pump depletion within the sensing section. This condition was reached using an input probe signal of 50.69 µW and a backward-propagation Raman pump of 644 mW.

In order to verify the performance of the implemented BOTDA sensor based on the proposed seeded second-order Raman amplification and 255-bit Simplex coding, measurements were acquired with an equivalent of 2040 averaged traces per scanned frequency. After measuring the BOTDA coded traces, a linear decoding process was used to retrieve the single-pulse fiber response at the different scanned frequencies [4].

Fig. 2 shows a top-view of the decoded BGS as a function of the distance, along 120 km sensing range and with 5 m spatial resolution. If we observe at the trace with the maximum Brillouin gain of the last fiber spool (i.e. at 10.66 GHz), depicted in Fig. 3(a), we can clearly see the end of the sensing fiber (~0.03 % gain). It is worth mentioning that the SNR at the end of the fiber (~6.5 dB) is high enough to provide reliable temperature- and strain-dependent variations of the BGS. This can also be verified by fitting the measured BGS at every fiber position, so that the BFS along the whole sensing fiber can be obtained, as shown in Fig. 3(b). In order to evaluate the uncertainty of the measurement (related to the temperature and strain resolution), the standard deviation of the BFS was calculated at the last kilometers of fiber. In this case the calculated standard deviation is 1.9 MHz at around 120 km distance, which is equivalent to a temperature and strain resolution of 1.9ºC and 38 με, respectively. We verified that the pump depletion along the 120 km-long sensing fiber was kept as low as 2.0%, which has a negligible impact on the BGS and BFS measurements [9].

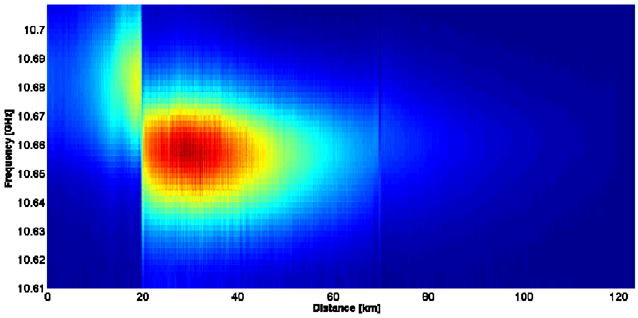

Fig. 2. Decoded BGS as a funtion of distance, along 120 km sensing fiber, using 5 m spatial resolution.

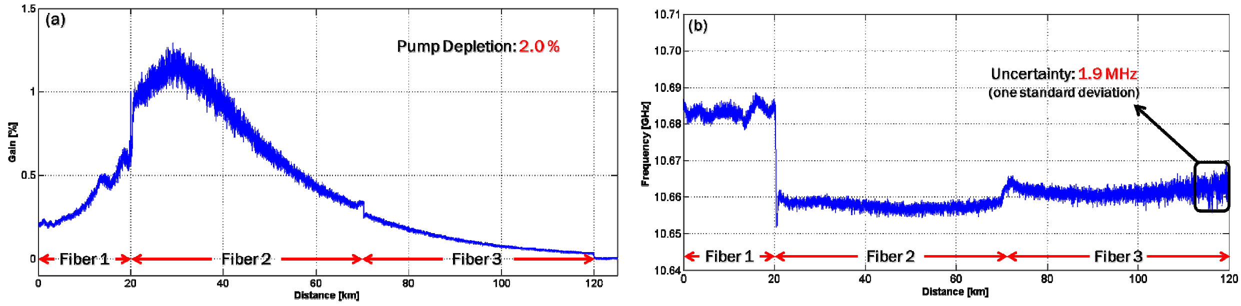

Fig. 3. (a) Brillouin gain profile at 10.66 GHz where we can be perfectly observe the end of the sensing fiber at 120 km distance. (b) BFS profile along the 120 km-long sensing fiber (the uncertainty at the end of the fiber is 1.9 MHz)

Finally, in order to check the operation of the implemented BOTDA sensor in an extreme condition, 5 meters of sensing fiber from the lowest contrast region (i.e. near 120 km distance) were introduced into a hot-water bath at 45ºC, the rest of the fiber being in a controlled room temperature at 25ºC. For clarity reasons Fig. 4 shows only the temperature profile measured in the last meters of fiber; as we can observe the obtained temperature profile perfectly matches with the expected result. This constitutes the first measurement reported at a real 120 km remote distance from the interrogation unit, using a 240 km-long standard single-mode optical fiber with no repeater.

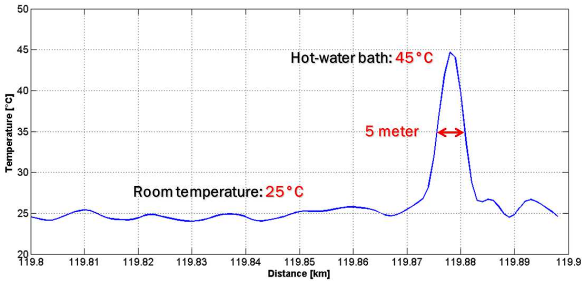

Fig. 4. Detection of a 5 m hot-spot near 120 km sensing distance

4. CONCLUSION

In this work we have implemented a long-range BOTDA sensor assisted by seeded second-order Raman amplification and optical pulse coding. A proper power adjustment has allowed distributed measurements along a real physical distance of 120 km away from the sensor unit, using a 240 km fiber loop configuration and 5 m spatial resolution. As far as we are concerned this is the first time that such a sensing distance is reached with a BOTDA sensor, which we consider is a considerable breakthrough in the distributed fiber sensors field. We believe that further extension of the sensing range needs deeper investigation since the implemented system has very little margin to increase power levels (including the Raman pump power).

ACKNOWLEDGMENTS

This work was supported in part by the Spanish Ministry of Science and Innovation through projects TEC2009-14423-C02-01 and TEC2009-14423-C02-02 and the Comunidad de Madrid through project FACTOTEM-2. Sonia Martin-Lopez acknowledges funding from the Spanish Ministry of Science and Innovation through a “Juan de la Cierva” contract. The authors would also like to acknowledge the Swiss Commission for Technology and Innovation (Project 13122.1) for their support. Miguel Gonzalez-Herraez acknowledges funding from the European Research Council through Starting Grant U-FINE (Grant no. 307441).

REFERENCES

[1] Horiguchi, T., Shimizu, K., Kurashima, T., Tateda, M. and Koyamada, Y., “Development of a distributed sensing technique using Brillouin scattering,” IEEE J. of Lightwave Technol. 13(7), 1296-1302 (1995)

[2] Niklès, M., Thévenaz, L., Robert, P. A., “Simple distributed fiber sensor based on Brillouin gain spectrum analysis,” J. of Lightwave Technol. 15(10), 1842-1851 (1997).

[3] Angulo-Vinuesa, X., *et al.*, “Raman Assisted Brillouin Distributed Temperature Sensor Over 100 km Featuring 2 m Resolution and 1.2 ºC Uncertainty,” IEEE J. Lightwave Technol. 30(8), 1060-1065 (2012).

[4] Martin-Lopez, S., *et al.*, “Brillouin optical time-domain analysis assisted by second-order Raman amplification,” Opt. Exp. 18(18), 18769-18778 (2010).

[5] Soto, M. A., Bolognini, G., and Di Pasquale, F., “Long-range simplex-coded BOTDA sensor over 120 km distance employing optical preamplification,” Opt. Lett. 36(2), 232-234 (2011).

[6] Jia, X.-H., *et al.*, “Experimental demonstration on 2.5-m spatial resolution and 1°C temperature uncertainty over long-distance BOTDA with combined Raman amplification and optical pulse coding,” IEEE Photon. Technol. Lett. 23(7), 435-437 (2011).

[7] Soto, M. A., Bolognini, G., and Di Pasquale, F., “Simplex-Coded BOTDA Sensor Over 120 km SMF with 1 m Spatial Resolution Assisted by Optimized Bidirectional Raman Amplification,” IEEE Photon. Technol. Lett., in press (2012).

[8] Faralli, S., *et al.*, “Bidirectional Higher Order Cascaded Raman Amplification Benefits for 10-Gb/s WDM Unrepeated Transmission Systems,” IEEE J. Lightwave Technol. 23(8), 2427-2433 (2005).

[9] Thévenaz, L., Mafang, S. F., and Lin, J., “Impact of pump depletion on the determination of the Brillouin gain frequency in distributed fiber sensors,” Proc. SPIE 7753, 21st International Conference on Optical Fiber Sensors, 775322 (2011).