Extending the sensing range of Brillouin optical time-domain analysis up to 325 km combining four optical repeaters

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ABSTRACT

A novel scheme is proposed to extend the sensing range of Brillouin optical time-domain analyzers (BOTDA). Specially-designed erbium doped fiber amplifier (EDFA) repeaters are located every 65km fiber along the sensing cable to achieve a total sensing length of 325km, corresponding to a 650km loop. At the end of the sensing fibre, we experimentally demonstrated a measurement repeatability of 2°C (2σ) using a three meters spatial resolution.

Keywords: Brillouin sensor, erbium doped fiber amplifier, distributed strain and temperature measurement, optical repeater, Long distance distributed sensing

1. INTRODUCTION

The continuous demand for energy supplies has led operators to explore and to exploit more remote offshore oil fields characterized by deeper deployments, longer tiebacks and subsea completion. These offshore developments are located either in tropical regions subject to stormy weather or in extreme arctic conditions. Consequently, leak detection and flow assurance are required over distances exceeding hundreds of kilometers. In this context, temperature monitoring has been recently recognized as a method of choice for leak detection [2].

Brillouin optical time-domain analyzers (BOTDA) are excellent candidates to reach such extreme sensing distances based on single topside instrumentation, as they show the longest available sensing distance so far. However, when targeting more than 300 km sensing, corresponding to a fibre loop of more than 600 km, not only creating Brillouin gain is difficult; the probe propagation also becomes a challenge. To solve this challenging sensing scheme, we propose a novel scheme featuring pump amplification based on 65 km long spans using a 2 fibres scheme which manage and prevent the buildup of modulation instability along the sensing sections whilst preserving high pump power and high gain levels. A third fibre is used for probe propagation, with its own 130 km amplified spans. The complete system features 5 sensing spans of 65 km each, reaching a distance of 325 km.

2. PRINCIPLE OF BRILLOUIN OPTICAL TIME DOMAIN ANALYSIS

Let us consider two optical signals, called respectively pump and probe, counterpropagating in an optical fiber and whose frequency difference corresponds to the acoustic frequency of the medium, referred as Brillouin frequency. Their beating enhances the acoustic waves due to the energy density gradient leading to electrostriction. As a result, a net energy transfer takes place from the pump signal to the probe signal. Since the Brillouin frequency shift depends linearly on either temperature or strain, the Stimulated Brillouin Scattering (SBS) interaction can be used to acquire either temperature or strain distribution along a sensing fiber. Such sensors are referred to as Brillouin optical time-domain analyzer (BOTDA). Figure 1 depicts a basic BOTDA optical scheme [1].

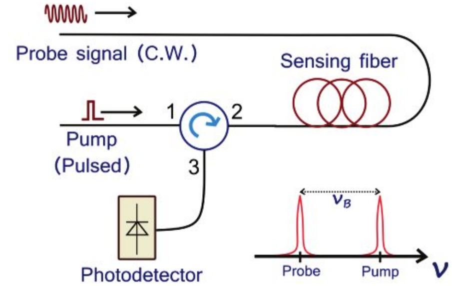

Figure 1: BOTDA schematic

In absence of depletion, the maximum value of the net gain experienced by the probe can be expressed as $G = \frac{G_B}{A_{eff}} L_s P_0 e^{-\alpha d}$ using the small-gain approximation, where G_B is the linear Brillouin gain coefficient, A_{eff} is the effective area, P_0 is the initial pulse power, α is the fiber attenuation, L_S is the spatial resolution and d is the measuring distance. Thus, for a given spatial resolution, the gain is limited by the pump power and decreases over the distance due to the fiber attenuation. At some point along the fibre, the gain becomes smaller than the system acquisition noise, which

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limits the reachable measurable distance. It is not possible to increase the pump power typically above 100 mW without creating modulation instability (MI) or Raman gain, thus limiting the sensing distance to typically 100 km with 5m spatial resolution. In addition, the probe has to travel twice the sensing distance (Figure 1) with an input power limited to around +5dBm due to amplified spontaneous Brillouin scattering (ASBS) threshold and a detection level of around -35dBm when using a preamplifier in front of the photodiode, so that the maximum available optical budget is about 40dB corresponding to a loop of 200 km. Using complex Raman assistance, these limits can be extended slightly, the longest reported sensing distance being around 120 km, resulting in a 240 km long fibre loop [5]. As an alternative to distributed amplification, EDFA repeaters can be regularly inserted along the sensing fibre [3]. The residual pump at the end of the first section is amplified and launched into the next section. However, the MI from the first section is also amplified and is believed to act as seeds and enhances MI in the second section [4]. Hence, the gain cannot be increased as much in the second section as in the first section, as can be seen in [3], leading to a drop of performances in the second section. Therefore, the scheme is of limited interest for cascaded amplification as needed over multiple hundreds of km.

3. EXPERIMENTAL SETUP

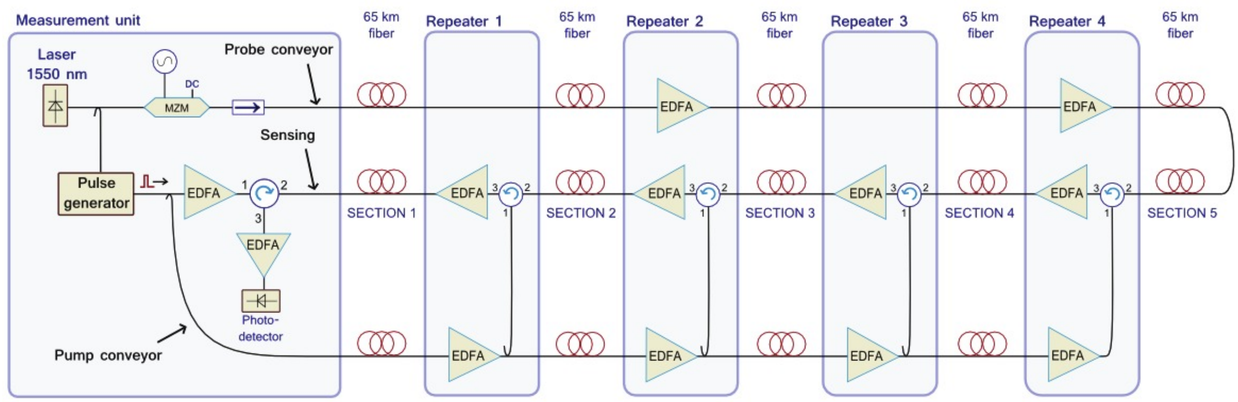
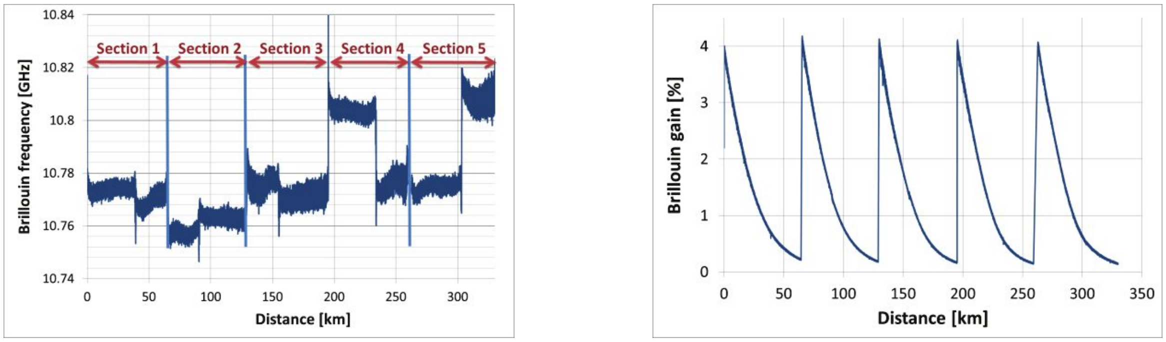


Figure 2 : The experimental setup

In order to avoid those different gain limitations, our setup illustrated in Figure 2 adds a third fiber in parallel to the sensing fibre (the two first being respectively the sensing segment itself and the probe conveyor) whose purpose is to propagate the pump signal at low power in order to avoid any nonlinearity growth during its propagation through the first section (65km). The pulse is then amplified to a high power level right before being injected in the second section whilst a small part of this amplified pump is further transmitted at low power to the next sections. Pump launching into the second section is achieved through a circulator that let the probe, propagating in the other direction, pass from the second to the first section. Such a scheme (patent pending) ensures that each section receives a clean pulse that is spectrally an exact copy of the initial pulse, to the exception of the ASE noise added by the EDFAs. It can be cascaded easily, as shown in Figure 2.

. Both pump and probe are generated from a single laser using a coupler to ensure long term stability. On one side, a semiconductor optical amplifier (SOA) is used to generate 30ns long pulses (3m spatial resolution) which are further amplified before being launched in the first section. Care is taken to generate flat-top pulses to prevent spectral broadening through self-phase modulation [6]. After the amplification, ~1% of the pump signal propagates without any Brillouin interaction to the end of the first section using the 3rd fibre; the rest is used to pump the sensing fibre. On the other side, a carrier suppressed dual side band modulation scheme using an electro-optic Mach-Zehnder modulator creates the probe signal required for the SBS analysis. The probe propagates to the end of the sensing range by placing EDFAs every 2 sections (every 130 km) on the conveyor fiber. Over the sensing distance, the probe counter propagates with respect to the pump through all sections. It was experimentally found that good probe power management over the sensing sections is more critical than on the conveyor fiber. Thus, to maintain high SNR, probe EDFAs were located every 65 km over the sensing distance. Probe level was adjusted so that it never exceeds +5dBm per sideband in the probe conveyor to prevent ASBS and is limited to -7 dBm per sideband in the sensing segment to prevent pump depletion [7].

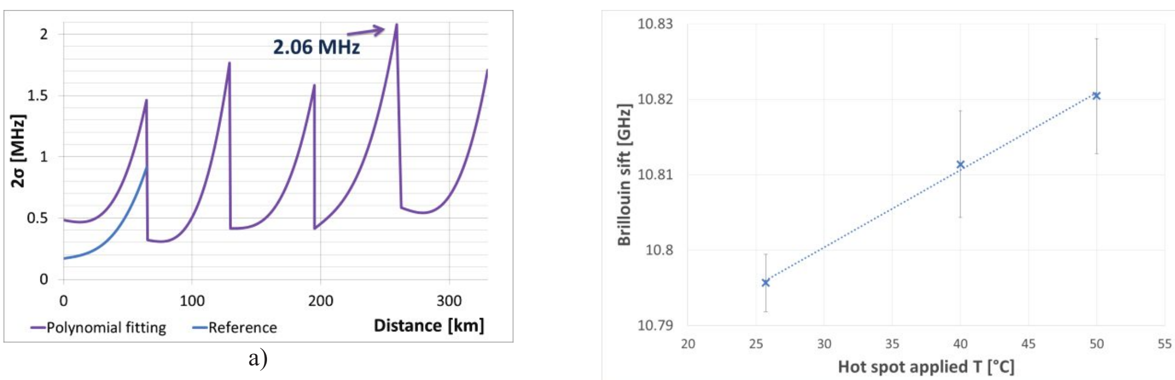
4. RESULTS



a) b)

Figure 3: Evolution over the measuring distance of a) the Brillouin gain and b) the Brillouin frequency

Figure 3 a shows the evolution of the measured Brillouin frequency over the whole distance. Each section consists in two fiber spools spliced together resulting in about 65 km fiber. All the spools were from the same manufacturer. The total variation of the Brillouin gain is about 60 MHz is but it is only spread over 20 MHz for the majority of the sensing length, which is within the FWHM of the gain spectrum (about 30 MHz). As a result, there is an overlap of the different Brillouin spectra and interaction over the whole sensing length, which would correspond to the worst case in a practical application [7]. The evolution of the Brillouin gain over the measurement distance is shown in figure 3b. Four replicas of the initial gain section are observed, proving the complete restoration of the pump pulse by the smart repeater, with slight gain differences occurring from section to section due to the varying fiber's Brillouin frequencies and different fiber distances. In addition, there is no drastic gain drop that could have been caused by MI and pure spatial exponential decays of the gain over the five sections validated the absence of nonlinearities.



a) b)

Figure 4 : a) Evolution of the 2-standard deviation (2σ) over the measuring distance and b) Brillouin shift as a function of temperature (hotspot) at the end of the measuring distance.

Figure 4a shows measurement repeatability as a 3rd order polynomial fitting of the 2-standard deviation (2σ) over four consecutive measurements (upper trace). Spatial resolution is 3m and the measurement time is 104 minutes. For reference purposes, the lower trace (first section only) shows the same measurement repeatability with similar conditions on one single 65 km sensing section (130 km loop). It turns out that the standard deviation is about twice larger than for a single loop. In addition, the repeatability significantly fluctuates over the different sections, revealing pump signal differences probably caused by disparities among repeaters (slightly different signal powers, fiber lengths variations, ASE noise level differences, etc). However, an amazing 2 MHz (2σ) repeatability with 3m spatial resolution is maintained over a linear sensing distance of 325 km. Figure 4b shows the Brillouin frequency shift as a function of temperature averaged over a 10-meters long hotspot located at the far end of the measurement range (330.68 km away from the instrument). In order to reduce the measurement time down to 45 minutes, averaging was reduced and frequency steps were increased, corresponding to a 2.5 penalty with respect to the previous settings, hence leading to an equivalent end-of-fiber 2σ repeatability 4.5 MHz. When computing the repeatability over the 10m long hotspot, a value of 5 MHz is obtained, which is in good agreement with the prediction. In addition, the linearity of the frequency shift versus temperature (1 MHz/°C) confirms that the system is correctly operating.

5. CONCLUSION

A BOTDA measurement over a linear distance of 325 km (650 km loop) with a precision of 2 degrees has been experimentally demonstrated using a proprietary repeater scheme for both pump regeneration and probe propagation. This repeater is designed to minimize the impact of spurious nonlinearities, by blocking the spontaneous noise cumulating over the distance and seeding the distant segments. This is possible at the expense of an additional fibre to independently propagate out of the sensing segment the pump pulse to the different sections. This implementation is, to our knowledge, the longest sensing distance ever achieved using a BOTDA. The measurement repeatability computed as twice the standard deviation over four consecutive measurements is constantly below 2 MHz with 3m spatial resolution and a measurement time of 104 minutes. The response at the end of the sensing fibre is still very good, despite some penalty when comparing to a single sensing section of 65 km. This is mainly due to ASE noise and power level fluctuations cumulated over the probe signal by the amplifying scheme as well as ASE noise added to the pump. In addition, the sensing fibre being not temperature stabilized, part of the degradation is likely due to the long acquisition time.

6. ACKNOWLEDGMENT

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