Brillouin optical time-domain reflectometry (BOTDR) has the advantage of requiring access to only one end of the sensing fibre, which is an important property for some applications. The coherent detection of spontaneous Brillouin scattering allows high sensitivity of temperature/strain measurements, close to one of the well-known Brillouin optical time-domain analyser-based solutions. In-line amplification based on bidirectional erbium-doped fibre amplification (EDFA) modules can improve sensing distance and temperature accuracy. This study demonstrates a distributed sensing over 150 km with 5-m spatial resolution and a temperature error of less than 2°C in 10 min without requiring specific BOTDR adaptation. A record performance of 0.7°C in 60 min has been also obtained, which corresponds to the best performance obtained in reflectometer configuration at this distance.

Introduction: Brillouin sensing systems are of great interest for the monitoring of infrastructures in many areas, such as civil engineering or oil and gas industries and geophysical sciences. Indeed, the Brillouin frequency shift has the property of being linearly dependent on temperature and strain [1]. Most of the methods reported so far either have used the Brillouin optical time-domain analyser configuration as the signal-to-noise ratio is better thanks to stimulated Brillouin gain [2]. Brillouin optical time-domain reflectometer (BOTDR) interrogators measure the Brillouin spontaneous backscatter signal [2, 3]. They are usually preferable for applications as access to only one fibre end is required. Extending the sensing range of BOTDR has become a major challenge today, for example, in the field of offshore wind turbines where the export cable can frequently reach a length of above 200 km. Different techniques have been investigated as pulse coding [4] or distributed Raman amplification [5, 6]. It is well-known that the last solution presents better performances than erbium-doped fibre amplification (EDFA) solutions but needs high-power pump (i.e. lower reliability for offshore context) and is polarisation-dependent gain. In-line EDFA technique is a simple solution to extend sensing distance using standard BOTDR solution [7]. In this study, we demonstrate an extended 150-km sensing distance with 5-m spatial resolution using in-line bidirectional EDFA architecture.

A BOTDR is based on a heterodyne detection scheme allowing analysis of very low amplitude Brillouin backscatter. Classical BOTDR requires high-bandwidth photodiode as the Brillouin frequency $\nu_B$ is $\sim$11 GHz. So, the electrical signal should be downshifted using microwave mixer before low-pass filtering and digital acquisition. Our interrogator can detect the backscatter signal directly at low frequency (LF) $< 1$ GHz, allowing lower noise photodetector. The frequency of the reference wave, also called local oscillator (LO) results from a Brillouin wave in a specifically selected optical fibre. So, no electrical frequency down-shifter is required before analog-to-digital conversion.

A schematic diagram of the BOTDR is presented in Figure 1 [8]. The Continuous Wave (CW) laser output at $\nu_{O}$ is divided into two paths. A fraction of the laser power is amplified, cut into pulses by an acousto-optical modulator (AOM) and then injected into the sensing fibre through a three-port circulator. The EDFA output power is adjusted to control the peak pulse power. The return port of the circulator collects the Stokes backscattered component at frequency $\nu_{AO} = (\nu_{O} - \nu_{BS})$ where $\nu_{AO}$ is the upshift AOM frequency (+200 MHz) and $\nu_{BS}$ is the spontaneous Brillouin Stokes frequency shift in the sensing fibre. To generate the LO, the rest of the CW laser, amplified beyond the Brillouin power threshold (i.e. $\sim$7 dBm), is injected into a carefully chosen reference fibre, a SMF28-ULL fibre of $\sim$10-km length in this case, in order to generate stimulated Brillouin backscattered component at frequency $\nu_{Bref}$ such that the difference $(\nu_{Bref} - \nu_{BS})$ is in the range 100–600 MHz. A $\pm$20 dBm pump power injection allows $>20$ dB rejection between pump Rayleigh backscattering and Brillouin intensity. The Brillouin-based LO is scrambled in polarization. A balanced photodetector detects the optical beat at the frequency $\nu_{AO} + (\nu_{Bref} - \nu_{BS})$. The LO detected signal is digitalised using a 2 G/s Data AcQuisition (DAQ) system. Then, a digital signal processing consists to apply the fast Fourier transform algorithm and averaged over many acquisitions. Figure 2 shows a typical spatial map of the backscatter signal spectra obtained for a 100-km SMF28 fibre in ambient temperature, centred around 10.75 GHz and which decrease in function of distance due to fibre attenuation. A typical parabolic fitting is applied to the Brillouin frequency spectrum to determine the Brillouin frequency shift as a function of the distance.

Figure 3 represents the evolution of frequency error with distance, which corresponds of the standard deviation from the experimental mean Brillouin frequency shift. It can be converted into temperature variation thanks to temperature coefficient of Brillouin frequency shift $C_T = 1$ MHz/°C. For a 10-min-long measurement, 10-m spatial resolution (blue line), frequency (temperature) error vary from 0.1 MHz (0.1°C) at 0 km to 1 MHz (1°C) at 60 km and then become catastrophic after 80 km beyond 6 MHz (i.e. 6°C). For a 5-m spatial resolution (red line), more spatial details can be provided but at the expense of temperature error.
about more than 1.5°C at 50 km due to the increased noise level. Dashed plots correspond to an exponential fitting according to power attenuation with distance [9], with an exponential parameter in accordance with the attenuation coefficient ($\alpha \approx 0.2$ dB/km).

To further extend the sensor range, unfortunately, increasing the injected optical pulses power is impossible because of many non-linear phenomena (phase self-modulation or stimulated Brillouin scattering [10]). We opted for the installation of in-line bidirectional EDFA amplification modules (Figure 4). The co-propagating EDFAs are designed for pulsed amplification and the counter-propagating EDFAs for CW amplification at low power. Moreover, separate amplification for the pulse and Brillouin backscattering allows mitigation of counter-propagation amplified spontaneous emission (ASE). Range spacing between repeaters is $L = 50$ km, chosen in order to limit the accumulation of ASE. Indeed, Optical Signal to Noise Ratio (OSNR) degradation between 0 km and just after the first EDFA (A and B points in Figure 4), for two operating points of output power of the latter (12.2 and 9.2 dBm), is only about few tenths of dB for sections of 50 and 60 km (Table 1). Beyond this, the degradation increases to a few dB. In addition, these 50–60 km distances correspond to the temperature error range of our systems (Figure 3) that are starting to exceed acceptable thresholds for applications. It therefore seems advisable to re-amplify the optical signal at this distance so as to return to error values close to what we have at the start of the previous fibre span. The co-propagating EDFAs are designed for 10-dB gain and 10-dBm output power in order to compensate optical losses after propagation in the previous 50-km fibre section. The counter-propagating EDFA are designed for 0-dBm output power in order to amplify the continuous low Brillouin backscattering signal created in the following 50-km section. Optical filters after each EDFA, with a bandwidth of 1 nm, limit ASE accumulation with a good tolerance to filters concatenation effect.

Over 100 km (resolution of 5 m), with a single amplification module placed in the middle, we see on the spectral mapping (Figure 5(b)) that the signal is correctly restored without adding visible noise compared to the case without amplification (Figure 5(a)). Even if error deviation in 10 min is slightly degraded over the first 50 km, it is almost restored as at the start of the second span of fibre line (Figure 5(d), blue solid) and is around 1.7°C at 100 km, very clearly improving the detection performance of a BOTDR at 100 km with a 5-m spatial resolution to reach temperature error of 1.7°C in a short time of 10 min, suitable for structure monitoring industry needs in terms. At 150 km, with a second repeater, ~2°C error is obtained in the same time. Improve temperature error performance of 0.7°C at 150 km can be obtained by increasing the acquisition time to 60 min and the resolution to 10 m, which constitutes a record performance on this type of interrogator. In the near future, it will be possible to reduce measurement time around 20 min by tripling interrogator’s parallel computing resources and thus meet the most demanding industry requirements.

**Conclusion:** Finally, the use of a bidirectional amplification module based on EDFA clearly improved temperature measurement performance of a BOTDR at 100 km with a 5-m spatial resolution to reach temperature error of 1.7°C in a short time of 10 min, suitable for structure monitoring industry needs in terms. At 150 km, with a second repeater, ~2°C error is obtained in the same time. Improve temperature error performance of 0.7°C at 150 km can be obtained by increasing the acquisition time to 60 min and the resolution to 10 m, which constitutes a record performance on this type of interrogator. In the near future, it will be possible to reduce measurement time around 20 min by tripling interrogator’s parallel computing resources and thus meet the most demanding industry requirements.

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