Recent progress in Brillouin distributed fibre sensing

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***Abstract* — This paper will review some recent progresses related to distributed optical fibre sensing using Brillouin Optical Time-Domain Analysis (BOTDA) towards increased performance in range, resolution and acquisition time. Since optical fibre sensing will certainly be a decisive tool for securing dangerous installations and detecting environmental and industrial threats, the comparison of the different techniques and solutions remains however difficult because of the lack of standardized specifications and the difficulty associated to the characterization of such systems. We here present tentative qualification procedures applicable to fiber optic distributed sensing systems**

***Keywords* — fibre optics sensor, Brillouin scattering, distributed temperature sensor, structure monitoring, leakage detection.**

I. Introduction

Fibre distributed sensors are gaining a lot of interests for applications in various fields, such as structure monitoring, pipeline integrity check and geotechnical applications to secure ground stability. This stimulates the development of configuration offering better performance in terms of range, acquisition time and spatial resolution, while keeping the cost of the instrument and the operation simplicity unchanged.

A Brillouin Optical-fibre Time-Domain Analyser, or BOTDA, was initially developed as an instrument enabling non-destructive evaluation of optical fibre attenuation [1], based on the Brillouin interaction between two counter-propagating lightwaves generated by two laser sources placed at the extremities of the fibre under test.

The majority of methods for BOTDA [2,3] has used two distinct lasers for generating pump and probe signals. This requires an excellent frequency locking between the two lasers to secure the 1 MHz stability for accurate measurement. Niklès, Thévenaz and Robert [4-7] proposed a simple way to achieve an ideal stabilization of the frequency difference in a BOTDA. The configuration uses a microwave generator and a LiNbO3 electro-optic modulator (EOM) to generate pump and probe signals from one single laser source.

II. Principle and physical aspects

Developed for telecommunication applications, optical time-domain reflectometers (OTDR) have been the starting point of distributed sensing techniques. They use the Rayleigh scattered light to measure the attenuation profiles of long-haul fibre optic links. In the optical time-domain-coded technique, an optical pulse is launched into the fibre and a photodetector measures the amount of light which is backscattered as the pulse propagates along the fibre. The detected signal, the so-called Rayleigh signature, presents an exponential decay with time which is directly related to the linear attenuation of the fibre. The time information is converted to distance information provided that the speed of light is known, similar to radar or lidar detection techniques

In addition to the information on fibre losses, the OTDR profiles are very useful to localize breaks, to evaluate splices and connectors, and in general to assess the overall quality of a fibre link.

Raman and Brillouin scattering phenomena have been used for distributed sensing applications over the past few years. Raman was first proposed for sensing applications in the 80's [8], whereas Brillouin was introduced later as a way to enhance the range of OTDR [1] and then for strain and/or temperature monitoring applications [9]. Fig. 1 schematically shows the spectrum of the scattered light from a single wavelength λ_o in optical fibres. Both Raman and Brillouin scattering effects are associated with different dynamic non-homogeneities in the silica and therefore have completely different spectral characteristics.

The Raman light scattering is caused by thermally influenced molecular vibrations. Consequently the backscattered light carries the local temperature information at the point where the scattering occurred. The amplitude of the Anti-Stokes component is strongly temperature-dependent whereas the amplitude of the Stokes component is not. Raman

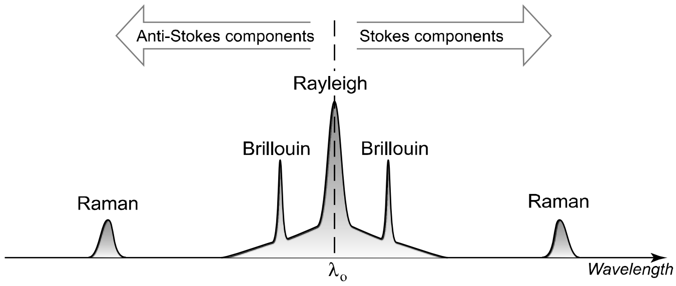

Fig. 1: Schematic representation of the scattered light spectrum from a single wavelength signal propagating in optical fibres. An increase of the fibre temperature has an effect on the Raman and Brillouin components, whereas strain has an effect on Brillouin components only.

sensing requires some filtering to isolate the relevant frequency components and is based on the recording and computation of the ratio between Anti-Stokes amplitude and Stokes amplitude, which contains the temperature information. Since the magnitude of the spontaneous Raman backscattered light is quite low (10 dB below spontaneous Brillouin scattering), high numerical aperture multimode fibres are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation and dispersion characteristics of multimode fibres limit the distance range of Raman-based systems to approximately 10 km, beyond which their decline in usefulness in most practical cases.

Brillouin scattering occurs as a result of an interaction between the propagating optical signal and thermally excited acoustic waves. These hypersound waves present in the silica fibre vibrate in the GHz range, giving rise to frequency shifted components in the scattered light. It can be seen as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fibre. The acoustic velocity is directly related to the medium density which is temperature and strain dependent. As a result the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fibre as shown in Fig. 2 [4].

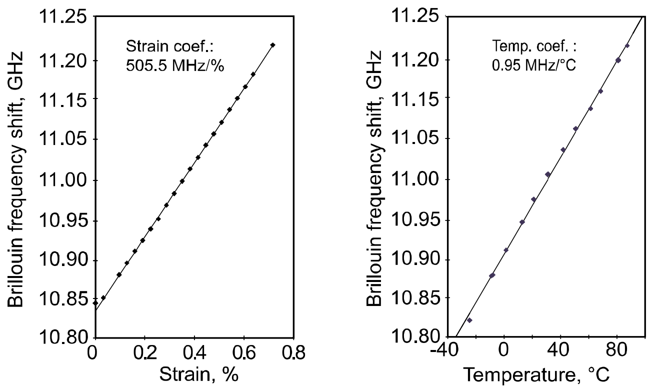

Fig. 2: Strain and temperature dependence of the Brillouin frequency shift of standard telecommunication optical fibres.

Brillouin-based techniques bring the following advantages over other distributed techniques:

1. The technique makes use of standard low-loss single-mode optical fibre offering several tens of kilometres of distance range and a compatibility with telecommunication components.
2. It is a ***frequency-based technique*** as opposed to Raman-based techniques which are intensity based. Brillouin based techniques are consequently inherently more accurate and more stable in the long term, since intensity-based techniques suffer from a higher sensitivity to drifts.
3. Brillouin scattering can be optically ***stimulated*** leading to a much greater intensity of the scattering mechanism and consequently an improved signal-to-noise ratio.
4. The stimulation mechanism involves two counter-propagating lightwaves which can be controlled individually providing a very valuable way to adjust the measurement parameters with respect to the application requirements in terms of resolution, distance range and acquisition time.

The active stimulation of Brillouin scattering can be achieved by using two optical lightwaves. In addition to the optical pulse usually called the pump, a continuous wave (CW) optical signal, the so-called probe signal, is used to probe the Brillouin frequency profile of the fibre. A stimulation of the Brillouin scattering process occurs when the frequency difference (or wavelength separation) of the pulse and the CW signal corresponds to the Brillouin shift (resonance condition) and provided that both optical signals are counter-propagating in the fibre. The interaction leads to a larger scattering efficiency resulting in an energy transfer from the pulse to the probe signal, and an amplification of the probe signal, as can be seen on Fig. 3a. The frequency difference between pulse and probe can be scanned for precise and global mapping of the Brillouin shift along the sensing fibre (Fig. 3b). Lastly at every location, the maximum of the Brillouin gain is calculated (Fig. 3c) and the information translated to temperature or strain using the calibration coefficients in Fig. 2. The probe signal intensity can be adjusted to acceptable levels for low-noise fast acquisition whatever the measurement conditions and fibre layout, thus solving the small signal-to-noise ratio issues which are generally associated with distributed sensing based on spontaneous light scattering.

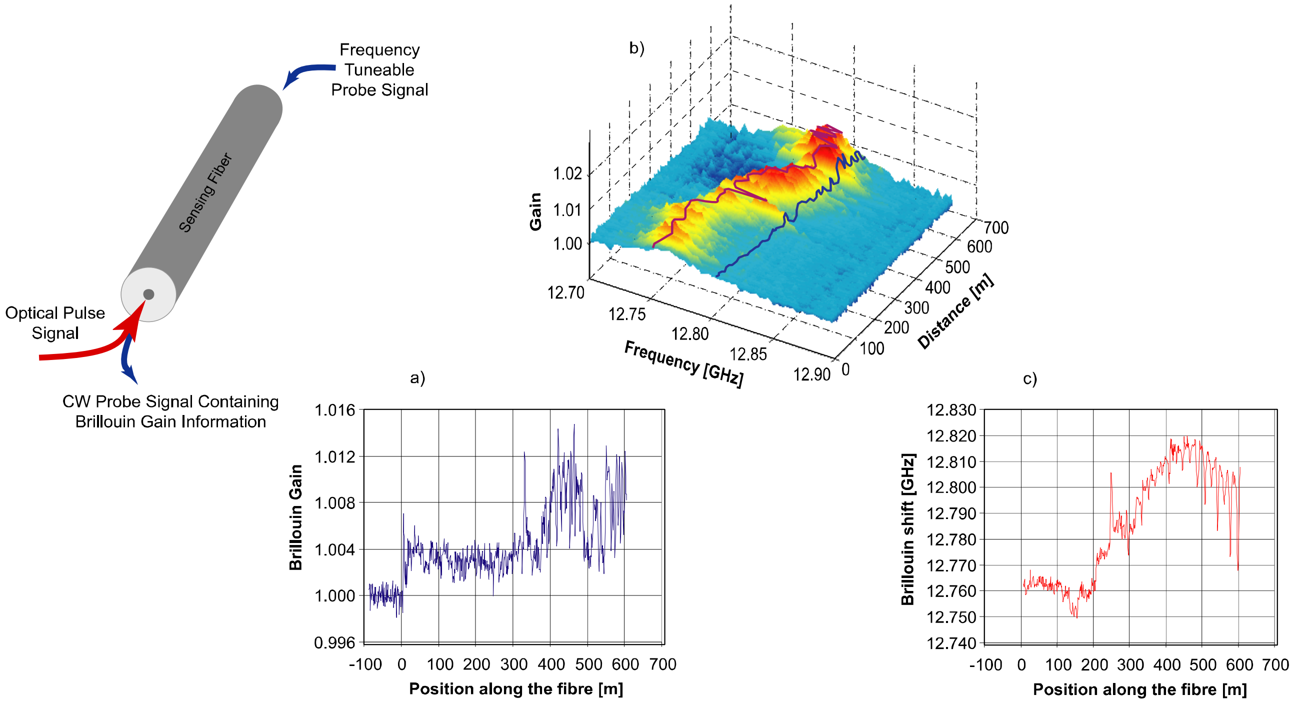

Fig. 3: Schematic representation of the optical signals used to stimulate the Brillouin interaction in optical fibres. a) Amplification profile as function of distance along the test fibre, b) Frequency mapping of the Brillouin gain along the fibre, c) Brillouin shift profile extracted from Fib. 3b).

The localization of the temperature or strain information along the fibre is possible using a pulsed pump signal. The interaction of the probe with the pump is recorded as a function of time and the time information can be converted into distance. An actual temperature profile of the fibre can be computed using calibration curves (Fig. 2). Thanks to the high speed of light, fibre lengths of several kilometres can be scanned within a fraction of second, yielding several thousands of measurement points. The optical configuration of the instrument generating and processing all optical signals is sketched in Fig. 4. For best performance access to both fibre ends is preferred (loop configuration).

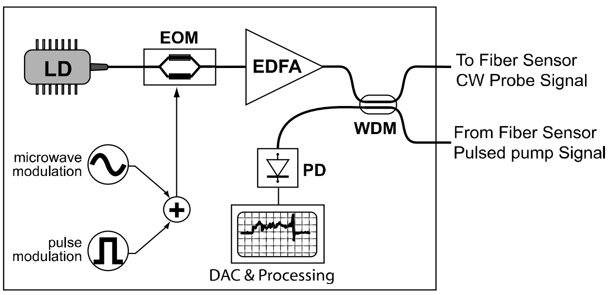

Fig. 4: Schematic setup of the DiTeSt instrument developed for the measurement of Brillouin frequency shift in optical fibres. The monitoring configuration requires a so-called double-ended configuration where both fibre ends are connected to the instrument.

III. QUALIFICATIONS OF DISTRIBUTED SENSING SYSTEMS

The performance of distributed sensing systems depends on the combination of the following parameters: spatial resolution, fibre attenuation and acquisition time (that is a function of the amount of averaging and the number of sampling steps). As a result performance may not be constant over the distance range. It may also depend on the distance location and the effects/interaction prior to the measured location [10]. The measurement accuracy depends on the signal-to-noise ratio (SNR) of the detected optical signals and/or on the measurement contrast in the case of stimulated scattering systems. Both SNR and contrast are related to the spatial resolution, pulse intensity, distance and fibre attenuation. As a result, for a given spatial resolution the accuracy is not constant over the fibre length since the intensity is affected by the fibre attenuation and the noise increases with distance. A proper qualification of a distributed scattering system shall therefore include the quantification of the accuracy vs. distance for the rated fibre attenuation.

The spatial resolution may also be affected by dispersion, which introduces pulse broadening with distance, especially when multimode fibres are to be used (Raman-based systems). Moreover the acquisition time should also be taken into account since the SNR is affected by the acquisition (integration, averaging) time. Attempts to increase the SNR by increasing the optical pulse intensity are limited by non-linear effects (both Raman and Modulation Instabilities in single-mode fibre based systems), which affect the distance range [11] and the accuracy [12]. As a result, both dynamic range and distance range are acquisition time dependent. Moreover for a given spatial resolution the distance range is limited, which means that the measurements cannot be performed with the specified accuracy beyond a certain distance. One has to accept either a lower measurand accuracy to reach farther distances or use a lower spatial resolution.

The ultimate answer to the specifications of the performance of a distributed sensing system lies in the clear description of how the specification parameters are inter-related, i.e. information about the measurement accuracy shall always be given for given distance (including fibre losses) in conjunction with a given spatial resolution and a specified acquisition time.

This section provides information about a tentative qualification of a stimulated Brillouin scattering distributed sensing system aiming at validating its performance.

Spatial resolution:

A simple method to verify the spatial resolution of Brillouin-based system is to use fibre segments of different lengths (0.5, 1.0, 1.5 and 2 m in Fig. 5) spliced to fixed length of a different type of fibre. This creates abrupt Brillouin frequency shift steps as shown in Fig. 5 because of the difference in core composition [4], from roughly 10.85 GHz (standard ITU-T-G652 fibre) to 11 GHz (pure silica core fibre) (equivalent to 3000 microstrains). Although the above test efficiently confirms the system's spatial resolution (sections of at least equal or longer distance than the spatial resolution should be resolved), it provides little information about the ability to meet the measurement accuracy on the given spatial resolution. It can also be seen from Fig. 5 that the transition depends on the distance resolution (sampling interval) and it occurs over 0.1 m whatever the spatial resolution was. As a result the spatial resolution definition based on the distance over which a 10% to 90% step change occurs is not applicable.

Actual temperature and/or strain steps should be used to fully qualify the system performance. Fig. 6 shows the result obtained using a temperature controlled bath and sections of different fibre lengths (10 m, 5 m, 2 m, 1 m and 0.5 m)

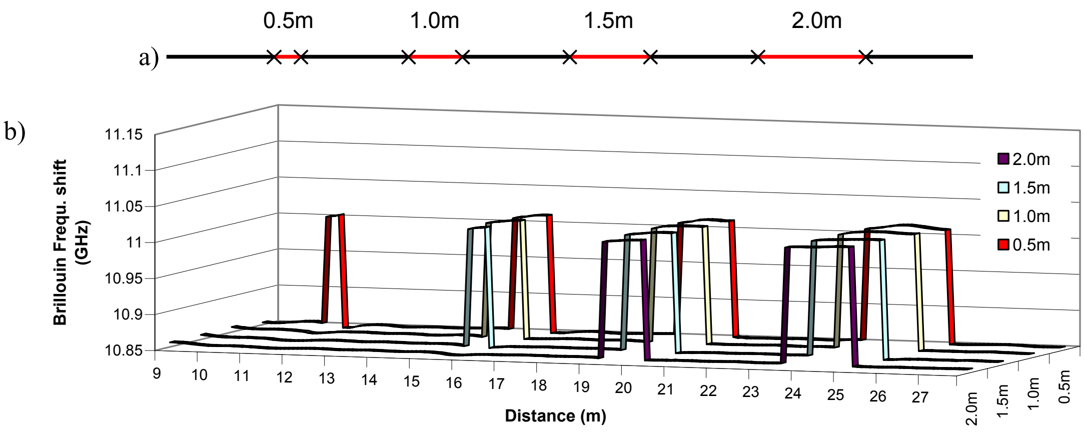

Fig.5: (a) Test setup of the spatial resolution using sections of two different fibre types; (b) test results for different spatial resolution settings ranging from 0.5 m to 2 m.

exposed to the water temperature whereas 5m sections remain at room temperature in between the sections placed in the bath. The measurement performed with a 1 meter spatial resolution shows that the 10 m, 5 m, 2 m and 1 m sections are measured with the full accuracy whereas the 0.5 m section is not measured with the full accuracy although the section is clearly detected. The test confirms the 1 m spatial resolution characteristic of the system.

A similar test could be performed using an elongated fibre section of known length using a micro-positioning unit. The temperature test of Fig. 6 is easier to perform since strain tests require reliable and good fixing points. Fig. 7 shows the results obtained with a 2 m fibre section gradually stretched by 0.2 mm steps (corresponding to 100 microstrains additional strain per step). The measurement was performed with a 1 m spatial resolution.

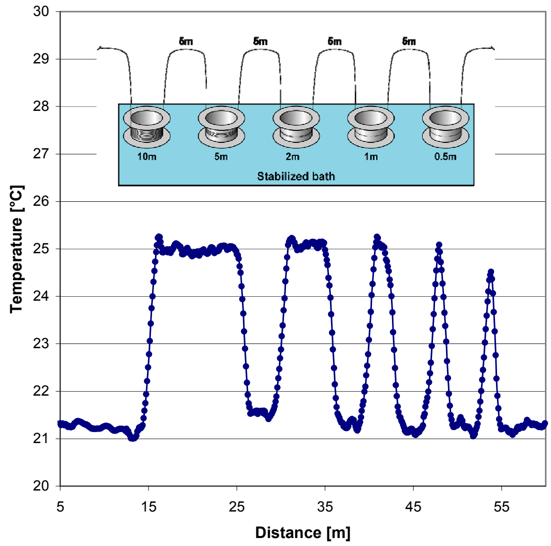

Fig.6: Sections of different lengths placed in a temperature controlled bath set to 25°C. Measurement performed with a 1m spatial resolution.

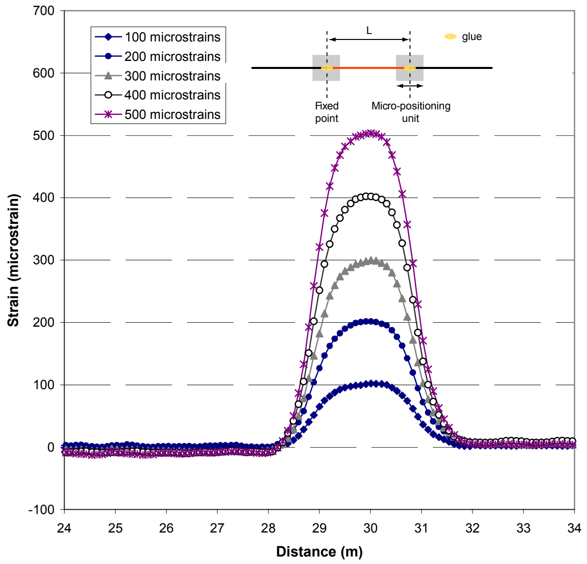

Fig.7: Strain test results performed on a fibre section L=2m submitted to given strain by means of a micro-positioning unit.

The measurement precision can be quantified by the repeatability, i.e. the difference between measurements performed in identical conditions. It can be measured locally and evaluated as a function of the distance for a given spatial resolution and acquisition time, as well as specified fibre attenuation. Fig. 8 shows the result of typical repeatability tests obtained in a 20 km fibre (ITU-T-G652 fiber 0.2 dB/km) with a 1 m spatial resolution and a 2 minute acquisition time. It is represented as the standard deviation of the measured local values, evaluated over 100 m sections in the same fibre.

In order to fully assess the measurement precision for a given spatial resolution and fiber losses but taking into account different acquisition times the procedure described in Fig. 8 needs to be repeated for different acquisition times. The overall measurement precision figures in terms of temperature and strain accuracies is then fully characterized as in Fig. 9, which shows typical repeatability features which can be obtained in a 30 km fibre (ITU-T-G652, 0.2 dB/km) obtained with a 1.5 m spatial resolution and different acquisition times. The representation in Fig. 9 is the most appropriate way to fully and accurately describe the performance of a distributed scattering sensing system. The calculated precision is given in temperature and strain units using the calibration shown in Fig. 2.

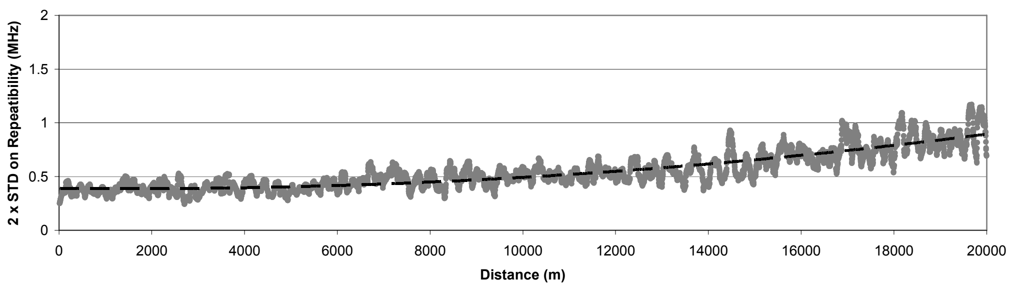

Fig. 8: Difference between the measurements of the Brillouin frequency shift repeated in identical conditions over 20 km, using a 1 m spatial resolution and 2 minute acquisition time. Evolution of the precision (twice the standard deviation of the noise computed over 100m section) as a function of distance and quadratic fit.

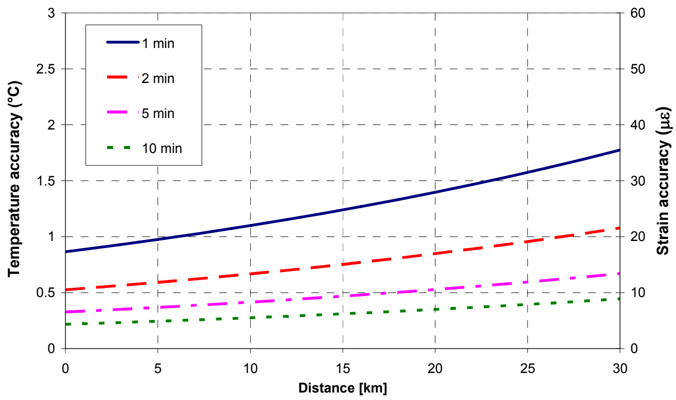

Fig. 9: Measurement precision in terms of temperature and strain as a function of distance for a 1.5 m spatial resolution and different acquisition times; measurements performed on a 30 km fibre spool (ITU-T G652 0.2 dB/km attenuation).

Attenuation [dB]	Measurement time [min.]	Instrument settings
0	1	Standard optical settings (standard instrument HW settings)
-2	1	
-3	1	
-4.5	2	
-5	2	
-6	4	
-7.5	4	
-9	4	
-10.5	6.5	
-12	7	
-13.5	7	
-15	10	Customized setting (optical signal intensity increased)
-16.5	18	
-18	18	
-19.5	32	
-21	45	

Table 1: Dynamic range test results; instrument settings (acquisition time and optical levels) changed to maintain 20 microstrain resolution as the attenuation was increased.

Dynamic range

The dynamic range can be tested using a manual optical attenuator inserted before a fibre test sample. In Table 1, a 10 km fibre (ITU-T-G652) was measured using the DiTeSt stimulated Brillouin scattering sensing system while a manual attenuator was used to simulate high fibre loss. The attenuator affects both pump and probe signal only once, in the sense that the attenuation is located in one branch of the loop near the zero meter position and before the 10 km fibre. The measurement parameters were changed in order to maintain a 20 microstrain resolution (i.e. repeatability between measurements better than 20 microstrains). From 0 dB to 15 dB attenuations, the acquisition time had to be increased to maintain the specified 20 microstrain resolution.

Beyond 15 dB of attenuation, the optical intensity settings had to be changed and the acquisition time further increased in order to compensate for the high attenuation of the sensing fibre. Beyond 21 dB, the measurements performance could not be maintained anymore and hardware modification would be required to further increase the measurement dynamic range. The increased measurement time is due to the fact that longer averaging times and smaller frequency steps were required to maintain the 20 microstrain resolution.

A clear advantage of stimulated Brillouin-based systems can be seen giving the flexibility to adjust pump and probe intensities can be used to compensate for high fibre losses.

IV. Recent Progresses

The recent developments on stimulated Brillouin-based systems were manifolds and mainly focussed on substantial improvements of the performances in terms of spatial resolution, length range (dynamic range) and acquisition time. This was made possible through a redesign of the optical configuration minimizing the occurrence of optical noise [14]. Thanks to this novel set-up measurements could be performed over 20 km with a 1 m spatial resolution and even over 50 km with a 7 m spatial resolution. But the most significant progresses were obtained for the acquisition time that shows a ten-fold reduction and for the spatial resolution that could be improved down to 20 cm over a short range (< 1 km), as illustrated in the measurement shown in Fig. 10. The 20 cm spatial resolution is obtained at the expense of a worse frequency resolution, but 1 MHz frequency resolution (equiv. to 1 degC or 20 µstrain) is already reached with a 32 cm spatial resolution.

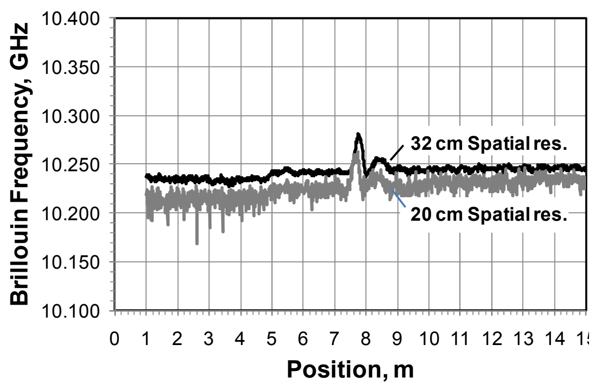

Fig.10 High spatial resolution measurements along a short fibre obtained with only a 256 times trace averaging, clearly fully resolving a 20 cm hot spot.

A substantial effort has also been carried out to multiply the range covered by the sensor, in order to satisfy the most demanding applications, such as pipeline monitoring, river banks control and the possibility to remotely interrogate a sensor placed at a long distance from the control station. Although low loss optical fibres are available (propagation loss < 0.25 dB/km), the attenuation of the fibre still sets limits to the BOTDA measurement range. Furthermore the performances in terms of spatial resolution and temperature/strain accuracy are also related to the distance range, since the optical waves are being affected by the fibre attenuation. On one hand the decreasing pulse intensity generates a smaller interaction and on the other hand a weaker signal on the photo-detector is associated to a lower signal-to-noise ratio that requires longer averaging times. Furthermore optical fibre non-linearities set the limits of pump pulse intensities [12, 13]. The distance range of this technique is therefore limited to some 30 km, with the possibility through the recent progresses presented above to extend it to 50 km with a spatial resolution extended to 7 m. However the pump-and-probe technique offers flexibility that makes possible the development of regeneration or repeater modules that provide either an extension of the distance range or remote sensing capabilities.

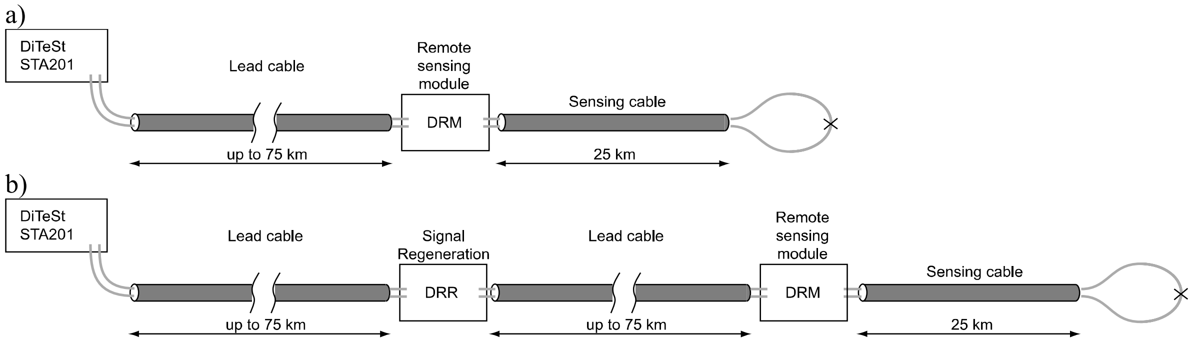

Fig 11: Schematic representation of remote monitoring using repeaters and remote regeneration for optical signal regeneration and processing.

To efficiently extend the range the concept is shown in Fig. 11a. A standard fibre optic telecommunication cable is used to bring the pump and probe signals to a remote module (DRM) that includes optical signal processing for optical power control and signal routing.

The setup depicted in Fig. 11 is especially suitable for remote sensing applications where the instrumentation has to be installed remotely from the sensing area. In addition to a robust design the remote modules require power consumption (as little as 20W) that makes them suitable for very remote installation and sub-sea applications.

A dedicated “distance extension” module (DRR), was developed for applications where the sensing area is located more than 75 km away from the instrument (Fig. 11b). The module performs active signal regeneration by using optical amplification techniques similar to those extensively used in optical telecommunications. The modules can be cascaded leading to remote distances in excess of hundreds of kilometres.

The performance obtained with the remote sensing modules is very similar to that available directly from of the instrument in terms of repeatability and temperature/strain accuracy. The measurement time is slightly longer since the pulse repetition rate has to be decreased in order to allow sufficient time for the lightwaves to travel back and forth in the fibres. The test bench depicted in Fig. 12 was used for the evaluation of the performance of the remote measurement system. Two 50 km sections of lead multi-fibre optics cable and one DRR repeater module were used to bring the lightwave signals to the DRM remote sensing module standing 100km away from the measuring unit. A test rig comprising 5 sections of different fibre lengths (ranging from 0.5 m to 10 m sections) was connected to the DRM through a 16'375 m fibre spool. The five different test sections were placed in a temperature controlled bath so that their temperature could be varied. Temperature measurements with a 1.5 m spatial resolution were repeated for different bath temperatures (from 15°C to 45°C). The measured profiles are shown in Fig. 12. The average measurement time was about 5 minutes per profile. Although the spatial resolution was set to 1.5 m, the 0.5 m section was clearly identified as a consequence of spatial over-sampling (interleaving). Full measurement accuracy was obtained only for sections greater or equal to the spatial resolution (2 m, 5 m and 10 m) demonstrating a true 1.5 m meter spatial resolution.

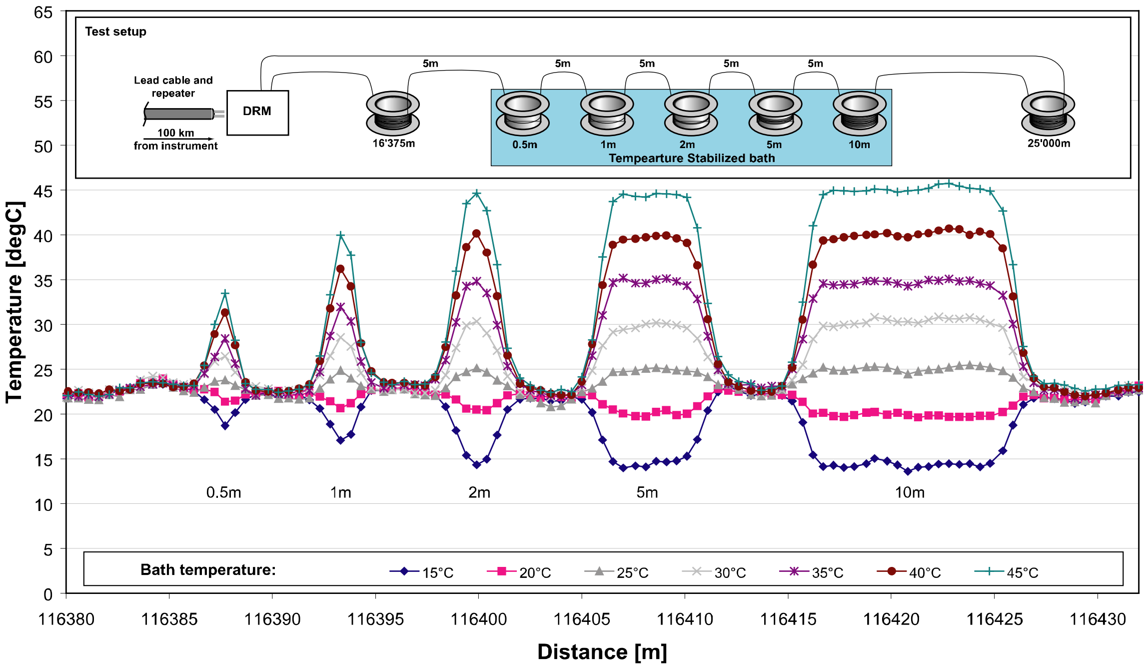

Fig. 8: Temperature measurements performed 116,400m away from the measuring unit using dedicated repeaters and signals regenerators (DRR and DRM). The test setup is composed of different fibre sections (0.5, 1, 2, 5, and 10m respectively) placed in a temperature controlled bath.

V. Conclusions

The ability to meet the requirements of demanding applications such as structural monitoring (high dynamic range, high spatial resolution, high sensitivity), pipeline monitoring (high sensitivity, medium to high spatial resolution, long distance), oil wells monitoring (high dynamic range, high precision) or else fire detection (short acquisition time) with a Brillouin-based distributed fibre optic sensing system has been demonstrated.

The need to qualify the system performance according to established extensive standards was emphasized and some guidelines for test procedures were described. It is of prime importance to have agreed standardized definitions about how to describe system performance under given operational conditions in order to deliver a clear message to the users and to provide possibilities to enable comparison of various systems.

On the other hand the sustained demand from potential users for even better performance stimulates the development of novel approaches. For this purpose we have developed a novel BOTDA configuration designed to minimize all sources of intensity noise, resulting in extreme performances in terms of range, spatial resolution and acquisition time. These novel approaches will certainly boost even more the performance in the coming years.

This demonstrates that fibre distributed sensors offer a powerful tool and a response to the demand of developed societies for a more secure environment.

Acknoledgements

The authors are grateful to their co-workers F.Briffod (Omnisens), S.Foaleng Mafang (EPFL) and S.Diaz Lucas (University of Pamplona-Spain), who developed the different techniques and performed most of the measurements. They would also like to acknowledge the technical and financial support from Omnisens and the Swiss State Secretariat for Education and Research Project COST 06.0015. Some of this research has been also carried out in the framework of the European COST Action 299 FIDES.

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