A Novel Surveillance System for Installed Fiber Optics Cables using Stimulated Brillouin Interaction

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Abstract: A novel surveillance system for installed fiber optic cables is presented. It is based on the analysis of the local stimulated Brillouin scattering interaction. The configuration of the instrument rely on the use of a single laser source and the required light signals are all generated using an electro-optic modulator, resulting in a high stability and an excellent reliability of the setup. Some results of the first field measurements are discussed. They have provided important information on the strain distribution actually experienced by the fibers, fiber uniformity, local birefringence, temperature variations. The system can operate over 100 km and the spatial resolution, which remains sub-metric over the first 10 km, is below 10 m over the full range.

1. Introduction

During the last two decades fiber optics telecommunications have experienced a spectacular progress. Thousands of kilometers of cables are being installed every year to complete an ever growing network. Besides high-speed transmission systems have become more and more sophisticated to achieve higher bit rates for long-haul fiber optic links. At highest bit rates the performances of these systems rely on the quality of the propagation medium. Silica rapidly became the preferred transmission medium because of its low-loss characteristics and the design of single-mode fibers has given to the transmission link a extremely large available bandwidth. However it is known that cable installation procedure and fiber ageing can affect these performances and therefore can impose severe limitations to the whole communication system. Up to date the tests of a fiber link only rely on the traditional OTDR which is suitable for the detection of excess loss and the localization of breaks. It turns out that there is an urgent need for a surveillance equipment for installed fiber optic cables that could diagnose fiber and cable degradation and provide important information such as strain distribution and local birefringence. The instrument should also grant a long-term preventive maintenance and allow to remotely localize possible problems.

The present paper describes the operation and the performances of a new instrument that has been designed for optical fibers surveillance. It is based on the local analysis of stimulated Brillouin inter-action along optical fibers. Brillouin gain spectrum (BGS) measurement has been pointed out several times in the past for its potentiality for strain monitoring in installed telecommunication cables [1]. The purpose of this paper is twofold: to show on one hand that this potentiality has been made effective, since field measurements of installed fiber optics cables currently in operation are demonstrated, and on the other hand that the application of BGS analysis is not limited to strain measurements.

2. Theory *of operation and instrument configuration*

Stimulated Brillouin Scattering (SBS) shows the lowest threshold among all non-linear processes observed in optical fibers. It is also strongly dependent on local physical parameters of the fiber, since the scattered light experiences a frequency downshift ν_B with respect to the incident light proportional to the acoustic velocity within the fiber, this latter being function of temperature and strain. SBS is therefore naturally used to achieve distributed sensors measuring these quantities, and numerous contributions in this field have been presented in the past few years [1, 2, 3, 4].

The basic configuration of a distributed Brillouin sensor is simple: a strong light pulse, hereafter called pump, is launched into the fiber. It crosses a weak CW lightwave, called signal or probe wave, that propagates in the backward direction. SBS occurs when pump and probe overlap, resulting in an amplification of the probe wave provided that the difference between the two frequencies lies within the BGS of the fiber. This BGS shows a Lorentzian distribution centered on the Brillouin shift ν_B that is the quantity to determine. To obtain the BGS and thus determine ν_B, one simply measures the amplification of the Stokes wave while making a frequency scan. The spatial resolution for distributed measurements is directly related to the pulse length. For a given pump power the ultimate spatial resolution is determined by the narrowest pump pulse that leaves a sufficient gain for a BGS measurement to be performed with minimum contrast. Instead of using the now traditional configuration using two laser sources [1, 2, 3], a

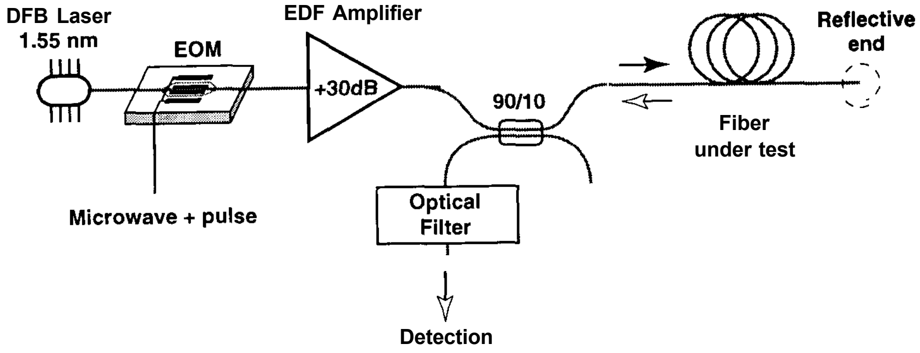

Fig. 1: Experimental configuration of the Brillouin scattering based system.

novel experimental setup has been developed in our laboratory[5]. Its main original feature is the presence of a single laser source that is modulated through an Mach-Zehnder electro-optic modulator (EOM) to generate both pump and probe lightwaves. This gives to the system an inherent stability, as far as frequency drifts of the laser are concerned. In addition, access to a single fiber end is required to perform the measurements, what is an obvious advantage in the field. On-site measurements have been so far performed using a 150 mW Nd:YAG laser at 1319 nm, leading to a 3 m best resolution [6]. To improve this figure, it was necessary to boost the intensity of the pump wave, what can be ideally performed using an optical amplifier at 1550nm. The experimental setup is schematically shown in Fig. 1. In proper working conditions of the EDFA peak pump powers in the Watt range can thus be obtained and sub-meter spatial resolution can be reached. Minimal absorption loss is a further advantage of the 1550 nm transmission window, making a 100 km sensing range possible.

3. *Applications*

The first field measurements using the local analysis of stimulated Brillouin interaction (LASBI) have provided essential information on: fiber identification, local strain, fiber uniformity, fiber local birefringence, temperature distribution.

3.1 *Fiber identification (manufacturing process, profile)*

The LASBI investigation gives access to the value of the local Brillouin frequency shift, which depends on fiber parameters such as dopant concentration and refractive index profile. The Brillouin frequency shift can in fact

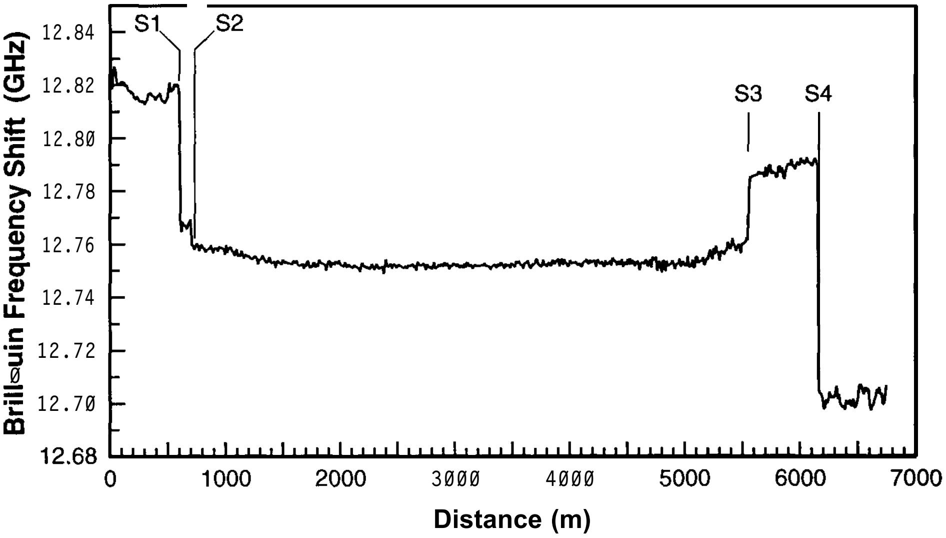

Fig. 2: *Identification of different sections of a fiber optic cable installed under the lake of Geneva. The five segments of fiber are identified by their different Brillouin frequency shift. The splices are indicated S1 to S4 on the graphic.*

be considered as a sort of fingerprint of a specific fiber, and can be used to identify different fibers. Fig. 2 presents the result of a measurement carried out on a 6.8 km-fiber optic cable of the Swiss Telecom PTT network. The Brilloum shift profile shows that this link has been made of 5 fiber segments coming from different preforms spliced together (the splices are indicated S1 through S4). The third segment (from S2 to S3) corresponds to an underwater section of the link. The Brillouin shift of the last segment, by far under the value of standard telecom fibers, indicates that the geometry of the refractive index profile is different for that fiber.

3.2 *Local strain detection;*

Localization of excessive strain was the first foreseen application of LASBI systems [1]. The strain dependence of the Brillouin frequency shift is approximately 60 MHz/με (50 MHz/με) for standard fibers at 1.3 μm (at 1.55 μm)[7, 8]. The spatial resolution achieved by our instrument actually reaches the physical limits. A 80 cm fiber segment experiencing a 1.5 ‰ elongation can be clearly identified, as shown in Fig. 3. A fiber optic link can thus be checked for the absence of strain, which is the key information for a long-term reliability.

3.3 *Fiber uniformity evaluation;*

The dependence of the Brillouin frequency shift on the dopant concentration can be used to check the fiber uniformity, which is an important condition for a constant cut-off wavelength all along an optical fiber. An ideal fiber placed with no strain in a temperature controlled environment should show a constant value of Brillouin frequency shift throughout the length. Any deviation from this value can be attributed to non-uniformity in the fiber constitutive parameters. In practice another fiber can be used to monitor the environmental conditions, as can be seen in Fig. 4.

3.4 *Determination of local birefringence;*

It has been demonstrated over the past few years that polarization mode dispersion (PMD) may limit the ultimate data rate through an optical fiber. The basic reason for PMD is the

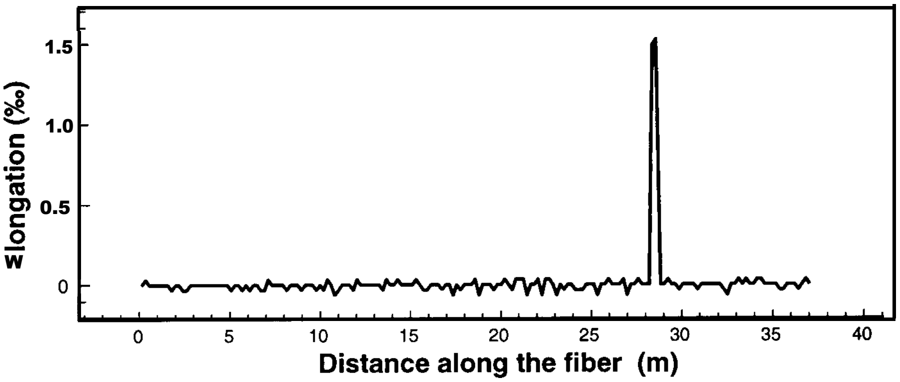

Fig. 3: Defection and localization of the presence of local strain. Here a 80cm fiber segment stretched by a 155g weight is clearly identified, resulting in a 1.52‰ elongation.

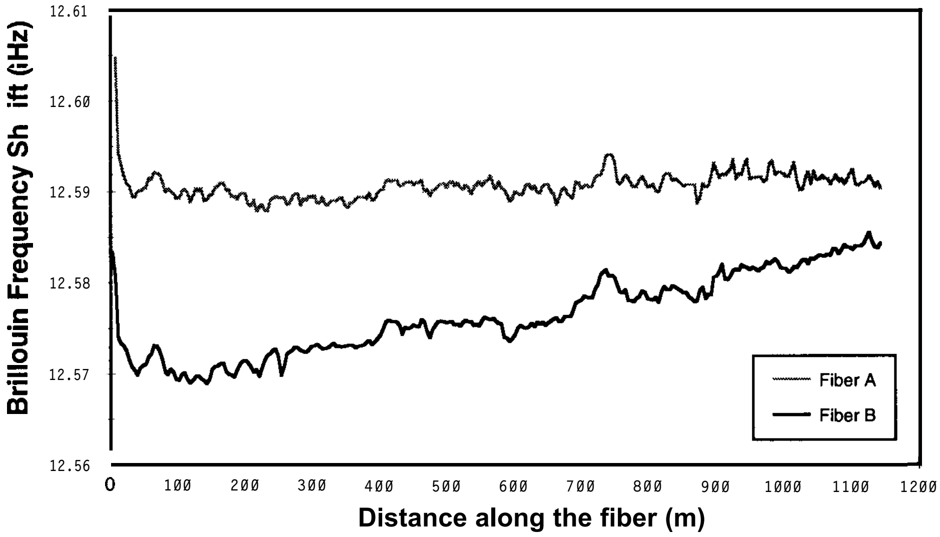

Fig. 4: *Two different fibers out of the same tube in the same cable present different Brillouin characteristics. They both experience to the same temperature fluctuations but Fiber B presents a non-homogenous dopanf concentration, resulting in a variation of the Brillouin frequency shift, corresponding to a 2.3 ‰ wt. mol. decrease of the* GeO_2 *concentration over 1 km.*

presence of intrinsic or induced birefringence within the fiber. Measuring the local birefringence would thus provide key information to localize the fiber segments mainly contributing to PMD, so that an efficient action could be undertaken for cable upgrade.

The amplification rate at any location depends on local features of the fiber, such as temperature and strain, but also on the relative polarizations of the waves crossing at this point. The time recording of the intensity of the reflected light gives the spatial distribution of the Brillouin gain along the fiber, that is directly related to the polarization variations experienced by light during its propagation. The local gain is actually polarization-dependent, being maximal for aligned fields and zero for crossed fields. The gain varies along the fiber as the relative polarizations of pump and probe are changed by birefringence, as shown in the measured gain profile in Fig. 5. The information about the birefringence beat length can be extracted from such a gain profile, provided that the beat length is larger than the spatial resolution of the system. The distance between a maximum and the next minimum of the gain corresponds to a quarter of the local beat length. Fig. 5 shows the local beat length obtained from a typical gain profile, as well as the gain profile itself.

3.5 *Other applications*

Distributed Brillouin scattering based systems have been first proposed to analyze the attenuation characteristics of optical fibers [9]. The use of Brillouin scattering instead of Rayleigh scattering brings a 10 dB improvement in the dynamic range, but

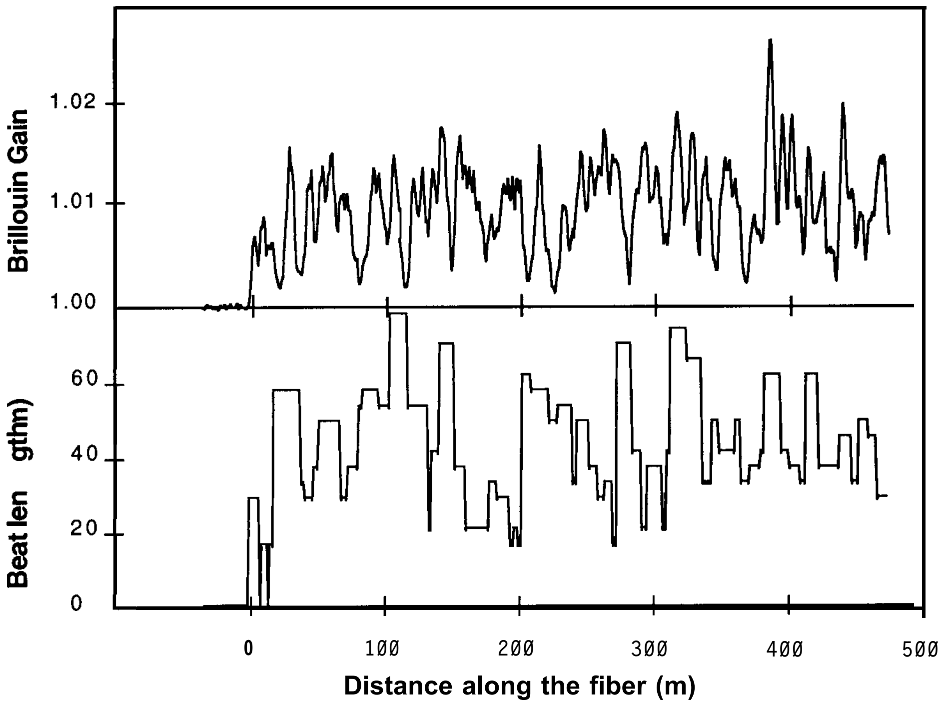

Fig. 5: Brillouin gain distribution along a segment of fiber (fop) and calculated corresponding local beat length (bottom).

require some complicated processing to get rid of fluctuations due to polarization variations (see Fig. 5).

The temperature dependence of the Brillouin frequency shift (approximately 1.3 MHz/°C at 1.3 µm for standard fibers) can be used to perform distributed temperature measurements [2, 3, 4]. Again the temperature and strain cross-sensitivity of the Brillouin frequency shift must be taken into account. However it can be compensated by calibration measurements in temperature controlled environment.

4. Conclusions

A novel surveillance system for fiber optic cable has been developed. The high stability and reliability of the experimental configuration of the instrument is very promising for the further development of an industrial prototype. The system specifications are illustrated by the figure of merit shown in Fig. 6. The most remarkable feature shown on this graph is the maintained resolution over a long distance: it remains below 3 meters over 50 km, as a consequence of the low loss at 1550 nm. On the other hand, the optimal resolution for very short fibers is slightly less than 1 m. This kind of sensors is thus definitely dedicated for long range measurements with meter resolution and is not suitable for a centimeter resolution.

Local analysis of stimulated Brillouin interaction measurements have been carried out on different installations of the Swiss Telecom MT

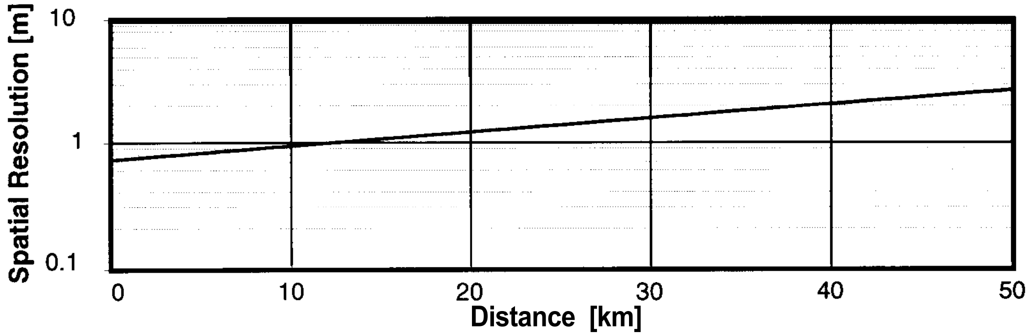

Fig. 6 *Spatial resolution as afuncfion of the distance along the fiber at a wave length of 1.55 μm.*

currently in operation. Important information was collected for the first time on the actual strain experienced by the fiber, fiber non-uniformity, local fiber birefringence, leaving demonstrative charts. Measurements have been repeated over a one year period to check the long term stability of the fiber links in different seasonal conditions.

In spite of the metric limitation of the spatial resolution, the applications of Brillouin sensing technique remain numerous: the figure of merit shown in Fig. 6 indicates in particular that the LASBI instrument is very competitive when a resolution in the meter range is needed over a considerable distance. Some typical applications are the detection of defects in telecom fibers, the monitoring of deformations in large-sized concrete structures like tunnels or dams, and the centralized temperature survey of building at a city scale.

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Marc Niklès received the Dipl.-Ing. degree in Microtechnology from the Swiss Federal Institute of Technology of Lausanne (EPFL) in 1989. He recieved the Ph.D. degree from the Electrical Engineering Department of the Swiss Federal Institute of Technology of Lausanne in 1997. In 1990 he joined the Metrology Laboratory of the Swiss Federal Institute of Technology of Lausanne, Switzerland, where he developed metrological facilities for characterizing integrated optical devices and applications using optical signal processing. For his doctoral research he investigated stimulated Brillouin scattering in optical fibers and developped a new fiber optic distributed temperature sensor

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