# Raman-assisted distributed Brillouin sensor in optical fiber for strain and temperature monitoring in civil engineering applications

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## Abstract

Investigation of a method to extend-range distributed temperature and strain sensor based on detection of the Brillouin frequency shift combined with counter-propagating Raman amplification has been realized. 50-km-range of standard single-mode silica fiber with great results has been sensed. Results of an experimental investigation of Brillouin frequency shift at different fibers.

**Keywords:** Distributed fiber-optic sensor, scattering Brillouin, scattering Raman

## 1.   Introduction

To monitor civil infrastructures in order to evaluate possible damages or complications at themselves is a field in which many efforts have been spent in last years. For this purpose many different kinds of sensors have been used. Among them optical sensors are very promising type since allows to install them in environments where the electric ones are not suitable. Distributed fiber-optic sensors offer unique capabilities for the monitoring of quantities such as temperature and strain over long distances. The term "distributed" refers to the use of an optical fiber as a linear uninterrupted sensor that provides thousands of measurement points continuously distributed over the whole fiber length. In many applications, these sensors avoid the need of a huge number of pin-point sensors (thermocouples, strain gauges, RTDs, Bragg gratins, etc) and complicated multiplexing schemes. Among these, distributed Brillouin sensors have attracted much research interest in the past years [1, 2, 3], and are now widely used for the monitoring of strain and temperature distribution within large structures in civil engineering [2]. Typically, distributed Brillouin sensors can monitor strain and temperature over 20-30 km with 1-2 meter spatial resolution (therefore, over 10'000 measurement points) and an uncertainty in the determination of strain below 5 $\mu\varepsilon$.The measurement range limitation of 20-30 km in the traditional Brillouin setup comes from the fiber attenuation, which is roughly 0.2 dB/km in modern optical fibers at 1.5 $\mu$m transmission window. As the optical signals travelling in the fiber are attenuated, the recovered signal quality is lost and the uncertainty of the measurement grows. This power loss can be compensated by using distributed Raman amplification, which induces a distributed gain along the fiber that compensates for the loss caused by the fiber. To validate this idea, we have experimentally developed a Raman-assisted Brillouin sensor, i.e. a distributed Brillouin sensor that is enhanced by Raman amplification. We show that this setup enables similar performances than the traditional Brillouin setup (in terms of resolution), but over much longer interaction distances. We have experimentally demonstrated the technique in a 50 km fiber. The perspectives of extending the idea to up of 100 km are explored, and seem very feasible in a few months.

## 2. Experimental configuration and results

The measurement of a single parameter like Brillouin frequency shift ($\Delta v_B$) provide information both temperature and strain owing to these two parameters change the value of Brillouin frequency shift. The frequency shift [4] is given by:

$$v_B = \frac{2nV_a}{\lambda_0} \qquad (1)$$

where $V_a$ is the acoustic velocity in silica that depends both temperature and strain; $\lambda_0$ is the pump wave, and $n$ is the refractive index of the fiber. This is because any perturbation that change the acoustic velocity of the fiber will change the parameter $v_B$, and it will be sensed with a standard distributed Brillouin sensor.

The standard distributed Brillouin sensor used has the experimental setup depicted in Fig. 1. We need a pump and a probe signals that are obtained from the same laser diode (LD) with a narrow-linewidth (a few megahertz) at 1556.54 nm and are separated through a 50/50 optical coupler. The output power of the LD is ~2 mW. We adjust the wavelength of the laser through the Current & Temperature control source.
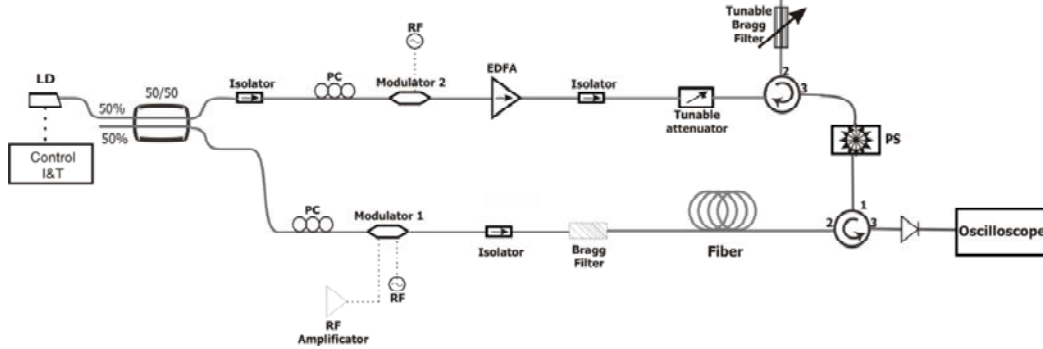


Fig. 1. Experimental setup of the distributed Brillouin sensor. PC: Polarization controller; LD: Laser Diode; EDFA: Erbium Doped Fiber Amplifier. RF: Radio-frequency; PS: Polarization Scrambler.

The pump signal travels by the upper branch of the picture and the probe by the bottom one. To get that, these two optical signals were separated by the typical Brillouin frequency shift value, $v_B$ (~10.3-11 GHz) of the fiber under test, and we modulate the probe signal at one of these frequencies by Mach-Zehnder modulator (Modulator 1) and a radiofrequency generator. The output spectrum of this modulation is composed by the carrier frequency and some lateral bands (until second order). The probe signal is the result of filtering one of first order lateral bands (in our case, the lower frequency one). As the separation between the frequencies presented in this spectrum is so small, we use a special fiber Bragg grating, manufactured by Advanced Optical Solutions (AOS), with "W" profile. The spectral transmission of this grating is shown in Fig. 2.

The pump signal is obtained by modulating the LD in the upper branch using a second Mach-Zehnder modulator (Modulator 2). Modulator 2 is pulsed introducing by the bias DC input a pulsed signal of 50 ns (2.3 volts of amplitude and 1 KHz repetition rate) obtained by a function generator. The pulse duration has been chosen to be 5 m of resolution and the repetition rate defined the maximal length of fiber tested. This train of pulsed are amplified using a +23 dBm saturation output power Erbium Doped Fiber Amplified (EDFA) and a tunable attenuator to control the output power. We filter it with a tunable fiber Bragg gratin from AOS which spectral profile is approximately Gaussian and its spectral width is 0.8 nm. The chosen pulse parameters give to the sensor a resolution of 5 m. To control the out power at the EDFA, a tunable attenuator is used. We use a polarization scrambler to eliminate the dependence of de Brillouin gain to the polarization. The pump and the probe signals are

introduce into the fiber under test in counter propagating senses. When the probe frequency let be equal to the characteristic $\nu_B$ of the fiber under test, it will be amplified by the Brillouin gain generated by the pump signal. If any event that changes this parameter occurs, the probe signal will not experiment any amplification. The amplified signal is detected by an InGaAs photodiode. To perform a complete measure, the probe and pump signals must be tuned around the Brillouin gain, and detecting synchrony in order to obtain assigned the position along the fiber. All this sequence is performed with a commercial system manufactured by National Instruments and composed of a PXI rack, with an acquisition card (NI 5122) which maximum velocity is 100 Msamples/s. The control program, which sweeps the frequency of the RF generator and acquires the signal from the NI 5122 has been performed with LabVIEW® 8.6.
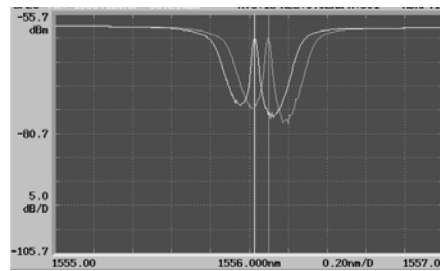


Fig. 2. Spectrum of the special fiber Bragg grating with "W" profile (yellow line), manufactured by AOS, and spectrum of the same grating tune in strain (green line).

To test our experimental setup we detected variations of $\nu_B$ in different sections of fibers. We have tested two configurations to make the demonstrator. The first one consisted in two long SMF fiber extremes, and a shorter DSF fiber between them. The first 4 km of SMF fiber has the maximum Brillouin gain at 10.83 GHz from the pump; the next 15 m DSF fiber has the maximum Brillouin gain at a 10.5 GHz; and the last 10 km of SMF has the maximum Brillouin gain at 10.82 GHz from the pump. With this configuration of fibers a variation of the acoustic velocity that simulate a variation of temperature or strain is achieve. The results obtained with this group of fibers are represented at Fig. 3. (a), where a frequency sweep between 10.4 GHz and 10.9 GHz has been realized. It's possible to observe that in the approximately 10.8 GHz exists Brillouin amplification in both fibers of the ends (SMFs), but not exist Brillouin gain at the medium fiber (DSF). Changing the RF frequency at 10.5 GHz Brillouin amplification is produced in the medium fiber (DSF), and the rest of the fibers don't experiment Brillouin amplification. This variation of the Brillouin frequency shift is equivalent to a temperature variation of 304.35 ºC or to a longitudinal strain variation of 0.6924%. [5]
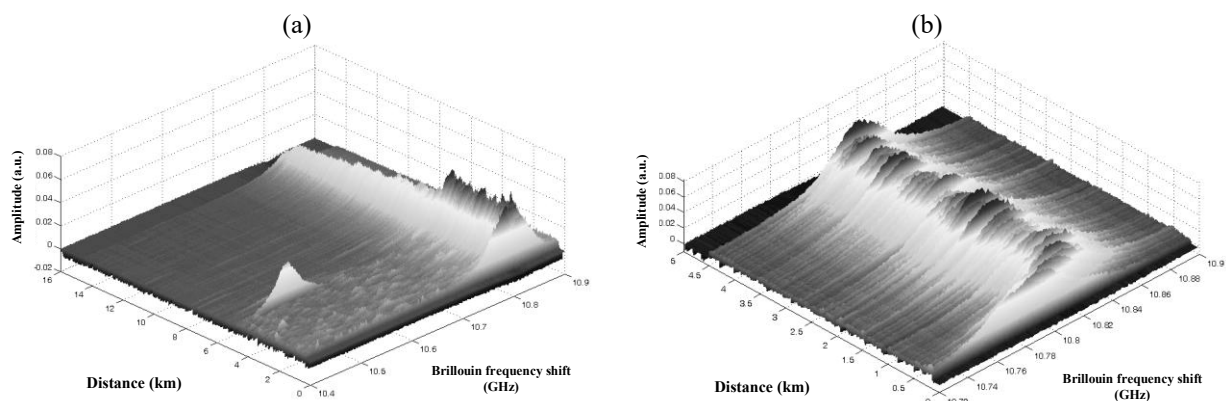


Fig. 3. Experimental results of the distributed Brillouin sensor.

The second configuration consists in a spool of 4 km of SMF fiber. We made a frequency sweep between 10.72 GHz and 10.9 GHz and the results are depicted in Fig. 3 (b). We observe that in one extreme exists a variation in the Brillouin frequency peak gain produced by differences in the stress inside of the fiber spool, due to differences in the stress applied to the fiber in the reeled process. We assign a strain variation of 0.0989% in this reel. All theses measures were made with a sweep frequency step of 1 MHz and 5 meters resolution. It is important to remark that the electric pulses used to generate the optical pulses have a period of 1 ms and a pulse width of 50 ns: the electric signal period is the parameter that regulates the existence of only one pulse in the fiber at one time and not exist aliasing and it must be at least two times the time that the light lasts to travel through all the fiber length; the pulse width is one of the two parameters that regulate the final resolution of the system. The other parameter that regulates the sensor resolution is the data acquisition time, limited by the acquisition speed of the NI 5122 board (100 Msamples/s), that is equivalent to 1 m length optical resolution. In all the acquisitions that have been shown in this paper we have used 20 Msamples/s, that lets a 5 meter resolution, equals the same that the pulse width.

## 3. Raman pump enhance

In a conventional optical fiber the transmitted signals are attenuated typically ~0.2 dB/km, at 1550 nm, so these kind of distributed sensors are limited in length by this parameter. Our purpose is to extend the range of such sensors to make them more versatile in many applications. For that we use a counter-propagating Raman pump that induces a Raman gain inside the fiber under test and works as a distributed Raman amplifier. This configuration allows to sense more kilometers.

Figure 4 depicts the experimental setup of this new sensor configuration. It is essentially the same that the one shown in Fig. 1 but we introduce an aditional counter-propagating beam into the fiber under test. This beam comes from a Raman fiber laser at 1455 nm with a tunable output power (2.4 W maximum). The reflective band arm of a WDM (1470 nm - 1490 nm) is used to introduce the Raman beam into the fiber. By the pass band arm of the WDM (1528 nm - 1563 nm) we insert the pump and the fiber is connected to the common band arm. With the previous configuration (the one described in section 2) we are able to sense along a maximum length of 20 km, with an acceptance signal-noise relation; whereas with this new system we can sense 50 km of a standard optical fiber, but we consider that is possible to sense 100 km of fiber length [6, 7].
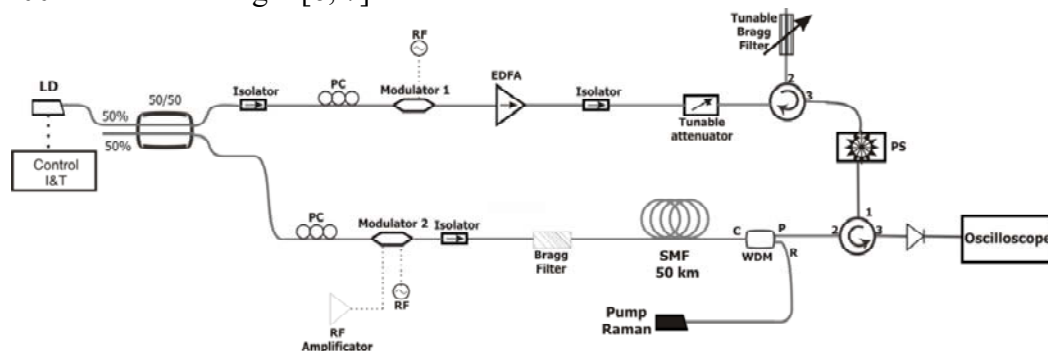


Fig. 4. Experimental setup of the distributed Brillouin sensor Raman-assisted. PC: Polarization controller; LD: Laser Diode; EDFA: Erbium Doped Fiber Amplifier. RF: Radio-frequency; PS: Polarization Scrambler; WDM: Wavelenght Division Multiplexer.

In Fig. 5 we show two oscilloscope traces, in which the horizontal scale has been converted to length units, to compare our setup with and without Raman amplification. To make this test we use 50 km of standard optical fiber and we Raman output power was 550 mW. The blue trace is a representation of the Brillouin maximum amplification of the probe

signal along the 50 km of fiber (it occurs at 10.68 GHz from the pump), using Raman enhancement. The red line represents the same measure without Raman. It is possible to observe with this trace that the pump wave is attenuated and it is impossible to sense a so long fiber length.
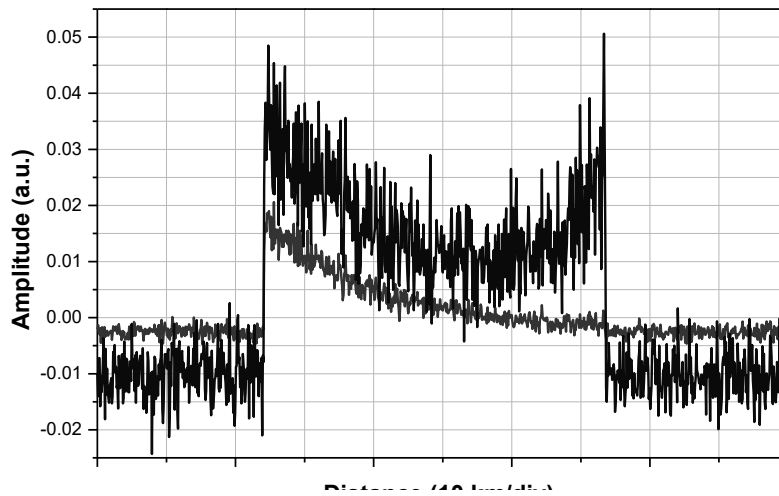


Fig. 5. Representation of the difference between using Raman (blue trace) and not using Raman (red trace) enhancement in a distributed Brillouin sensor. The measures has been performed for 50 km of standard optical fiber and 550 mW of Raman pump.

## 4. Conclusion

We have presented two experimental setups for developing a distributed Brillouin sensor for sensing temperature and strain. The first one lets us to monitor until 20 km of optical fiber with a resolution of 5 m. To improve the fiber length limitation we introduce Raman amplification into the fiber under test. With this new configuration we obtain a sensor demonstrator that presents the same resolution (5 m) but that can sense more than 50 km with a very acceptable signal-noise relation and perspectives of extending to 100 km seem very feasible in a few months.

## 5. Acknowledgements

## References

1. T. Horigushi, M. Tateda. *Optics Lett.* 1989, vol. 14, p. 408.
2. L. Thévenaz, M. Facchini, A. Fellay and P. Robert. *13th International Conference on Optical Fiber Sensors.* B. Y. Kim and K. Hotate, eds. Proc. SPIE. 1999, vol. 3746, p. 343.
3. M. Niklés. *Proc. Third European Workshop on Optical Fiber Sensors.* Italy. 2007, 66190D.
4. G.P. Agrawal. *Nonlinear Fiber Optics.* In: Quantum Electronics Principles and Applications. New York: Academic. 2001.
5. M. Niklès. *PhD Thesis Nº 1674.* EPFL, Switzerland. 1997.
6. M.N. Alahbabi, Y.T. Cho and T.P. Newson. *J. Opt. Soc. Am. B.* 2005, 22, pp. 1321-1324.
7. M.N. Alahbabi, Y.T. Cho, and T.P. Newson. *Opt. Lett.* 2005, 30, p. 11.