Measurement with 2 m resolution using a Raman-assisted BOTDA sensor featuring 75 km dynamic range

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ABSTRACT

We have used distributed Raman amplification to extend the measurement distance of a Brillouin Optical Time-Domain Analysis (BOTDA) sensor. We successfully demonstrate a dynamic range of 75 km with 2 meter spatial resolution.

Keywords: Stimulated Brillouin scattering, Raman scattering, BOTDA, Raman amplification.

1. INTRODUCTION

Distributed optical fiber Brillouin sensors are attractive solutions for the monitoring of temperature and strain in large structures [1,2]. The operating range of these sensors is typically of the order of 20-30 km (for 1-2 meter resolution), which limits their use in certain applications. This limitation is basically due to fiber attenuation, which reaches a minimum of about 0.2 dB/km in modern optical fibers at a wavelength of 1.5 µm. To achieve longer measurement ranges, previous works [3,4] have used distributed Raman amplification in the sensing fiber. However, relatively low resolution values (20-50 meters) were reported in those works. In many applications it is desirable to keep the resolution in the meter range while extending the working distance. In this work, we have studied different implementations for Raman amplification to extend the measurement distance of a Brillouin Optical Time-Domain Analyzer (BOTDA). We successfully demonstrate a dynamic range of 75 km while keeping the spatial resolution of the sensor at 2 meters. We demonstrate the measurement of a 2m hot-spot close to the end of the fiber.

2. EXPERIMENTAL SETUP

BOTDA systems use two distinct counter-propagating single-frequency light waves in the fiber. One of these light waves (centered at f_0) is pulsed and is meant to generate some amplification on the probe; it is designated as the pump wave. The other one (centered around f_0-υ_B) is a continuous wave, called the probe wave, which will be locally amplified by the pump pulse through stimulated Brillouin scattering (SBS). As the pump pulse travels down the fiber, it will induce a different amplification on the probe depending on the local value of the Brillouin shift. The local amplification of the probe wave will yield a time-dependent variation of the detected probe signal at the pump end. The amplification at each point will be maximized when the pump-probe frequency separation is exactly the Brillouin shift at that point. By scanning for this maximum at all positions, one can obtain a map of the Brillouin shift of the fiber across its whole length [5]. To improve the dynamic range of the BOTDA we propose to introduce Raman pumping from one or both sides of the sensing fiber.

The objective of this study is to determine which pumping configuration provides the largest increase in the dynamic range and enables the longest measurement distance: co-, counter- or bi-directional propagation of the Raman pump with respect to the Brillouin pump wave.

In Fig. 1 we show a schematic diagram of the experimental setup used for this purpose. The setup includes a conventional BOTDA working at 1550 nm. In this experiment, the Brillouin pump and probe waves are obtained from

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he same laser diode (LD) through the sideband modulation technique [5]. The LD (1 MHz linewidth) is split in two arms. One is used to shape the Brillouin pump pulse using an electro-optic modulator (EOM) and a pulse generator. The other arm is modulated with another EOM driven by a RF oscillator tuned close to the Brillouin shift of the fiber under test. The lower frequency sideband generated from the modulation is used as the Brillouin probe in the setup. This way the pump-probe frequency difference remains constant and controlled by the RF oscillator, regardless of the absolute frequency changes of the laser. The Brillouin pump and probe waves are merged with the Raman pumps (by means of suitable WDMs) and introduced into the fiber under test through opposite ends. Before entering the fiber, the Brillouin pump pulse is boosted using an erbium-doped fiber amplifier (EDFA) and its polarization is scrambled to mitigate the polarization sensitivity of the interaction. Before detection, the probe signal is amplified by another EDFA and a grating spectrally selects only the probe wave amplified by SBS. The Raman pump is a Raman Fiber Laser (RFL) emitting at 1455 nm. The power of this laser can be tuned up to 2.4 W. The RFL beam is divided by a calibrated 50/50 coupler in two beams. Each of them will be coupled to the points X and/or Y represented in Fig. 1, depending on the tested experimental configuration for Raman pumping (co-propagating, counterpropagating or bi-directional with respect to the Brillouin pump pulse).

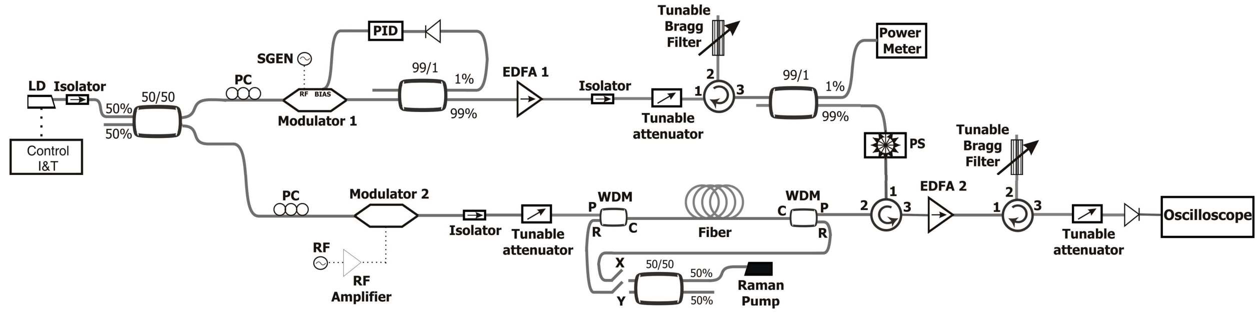

Figure 1. Experimental setup of the Raman-assisted distributed Brillouin sensor. LD: Laser Dide; PC: Polarization controller; SGEN: Signal generator; PID: Proportional-Integral-Derivative electronic circuit; EDFA: Erbium Doped Fiber Amplifier. RF: Radio-frequency generator; PS: Polarization Scrambler; WDM: Wavelength Division Multiplexer.

To verify the correct operation of the setup as a distributed Raman amplifier, we measured the input and output Brillouin pump pulses for all the different configurations that we plan to use for assisting the BOTDA (Raman pump values below 600 mW in all cases, Brillouin pump power adapted to avoid significant depletion). We observe that neither the pulse shape nor its duration suffer any substantial modification.

3. EXPERIMENTAL RESULTS

In this section we present the experimental results obtained with the four different BOTDA configurations (non-assisted by Raman and assisted by Raman co-, contra- and bi-directionally) proposed before. To realize the measures we use a Brillouin pump pulse-width of 20 ns (2 meter spatial resolution) over 75 kilometers of single mode fiber (SMF). The fiber has an effective area of 70 μm^2. The Brillouin frequency shift is approximately 10.65 GHz. To correctly determine the Brillouin frequency shift, depletion of the Brillouin pump due to Brillouin power transfer integrated all over the fiber length must be made negligible, since we would otherwise create a frequency dependent distortion in the trace that would render the measurement incorrect. Therefore, relatively low Brillouin pump powers and gain values (normally 1-2%) must be preferably chosen.

When the BOTDA operates without Raman amplification, the optimum values found are 4.7 mW for the peak power of the Brillouin pump pulse, and 5.2 μW for the probe power. The results obtained at a pump-probe frequency shift of 10.65 GHz are shown in Fig. 2(a), together with the theoretical curve predicted by a simplified mathematical model [6]. We can see that the theoretical result provides a good fit to the experimental one, the disagreement coming mainly from the variation in the Brillouin shift along the fiber (our model assumes the Brillouin gain is constant and maximum all over the fiber). The gain decreases exponentially with the distance as the only consequence of the linear attenuation. This means that, at the far end of the fiber, the gain to be measured is of the order of 0.02%, which is extremely small and gives a large uncertainty in the Brillouin shift determination.

In the bi-directional Raman pumping configuration (Fig. 2(b)), the optimal pump peak power is 3.2 mW and the probe wave power is adjusted to 0.4 µW. Note that both pump and probe powers have been significantly reduced so as to avoid Brillouin gain saturation. This measurement has been made using a Raman pump power of 610 mW (305 mW on each side) which is basically enough to ensure transparency of the fiber from an end-to-end perspective. As shown, in this configuration the gain distribution is quite flat, since the dynamic range of the measurement system does not need to accommodate large variations (this is not the case of the previous configuration, for instance). All over the fiber, the gain is well over 0.1%, which is still comfortable to perform a measurement. The biggest disadvantage is that this configuration also exhibits larger noise than the previous one, as it can be seen in the figure. This noise is caused by Relative Intensity Noise (RIN) transfer from the Raman pumps (the RIN of the RFL is -110 dBc/Hz). We believe that this RIN issue can be much improved with semiconductor pumps, which usually exhibit much better RIN values. For the co-propagating Raman pump configuration (Fig. 2(c)), the best results are obtained with the following settings: peak Brillouin pump power set to 1.9 mW, probe power set to 1.7 µW, and a Raman pump power of 355 mW. Again, it must be stressed that the Brillouin pump power has been significantly reduced to avoid gain saturation. In this case the noise is smaller than in the previous case, but at the far end of the fiber the gain values to be measured are only slightly larger than in the case of no Raman pumping. Again, this is a strong drawback in this configuration, although the Brillouin shift determination is still better than without the Raman pumping.

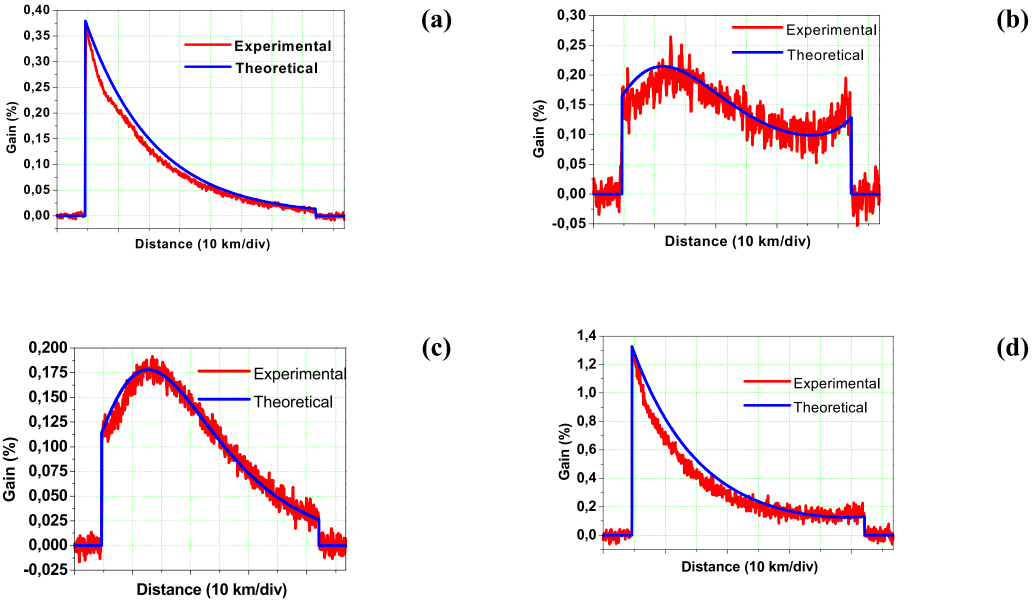

Fig.2. Theoretical and experimental gain traces obtained with the BOTDA without Raman amplification (a), with bi-directional Raman amplification (b), with co-propagating Raman amplification (c) and with counter-propagating Raman amplification (d).

For the counter-propagating configuration (Fig. 2(d)), the optimum performance is found when the peak Brillouin pump power is set to 18.8 mW and the probe wave power has been adjusted to 0.25 µW. The Raman pump power is 302 mW. Note that in this case the Brillouin pump power has been increased very significantly while the probe wave has been strongly reduced. This means that the gain contrast that we can obtain at the beginning of the fiber is much larger even than the one obtained in the non-pumped case while the contrast in the far end of the fiber is in the order of 0.1%, which is still comfortable to measure. Still, the noise increase is evident but, there is also a good improvement in Brillouin shift determination.

To verify the correct operation of the setup as a sensor we made some hot spot detection experiments. We inserted ~2 meters of the sensing fiber just before the far end (74.82 km) in a water bath with controlled temperature (around 50ºC, with 5ºC hysteresis). This acts as a hot spot with respect to the lab temperature, which is kept around 20ºC. The frequency sweep was done in the same conditions as the previous measurements for all the Raman-assisted configurations. Results of a sample sweep (counter-propagating configuration) are shown in Figure 3(a) (traces are averaged 16000 times per frequency). Figure 3(b) shows the measured Brillouin shift as a function of the position around the hot spot for all the Raman-assisted configurations. We can see that all the configurations correctly determine the location of the hot spot and also give a good estimation of the Brillouin shift change in that location. All the configurations give a Brillouin shift change in the hot-spot location of approximately 40 MHz. Considering the sensitivity of the Brillouin shift to temperature (1.3 MHz/ºC), this gives a temperature change of roughly 30ºC, which agrees well with the expected temperature change. Out of the hot spot, the co- and counter-propagating Raman configurations agree very well, while in the hot-spot they seem to show a small disagreement of 7 MHz (slightly more than 5ºC). We believe that this is probably more due to the hysteresis in the temperature controller of the bath rather than the performance of the actual measurement setup. The bi-directional configuration, however, shows a much larger noise all over the trace, which is caused by the RIN transfer from the Raman pump. This is an issue that may be solved using Raman pumps with lower RIN values.

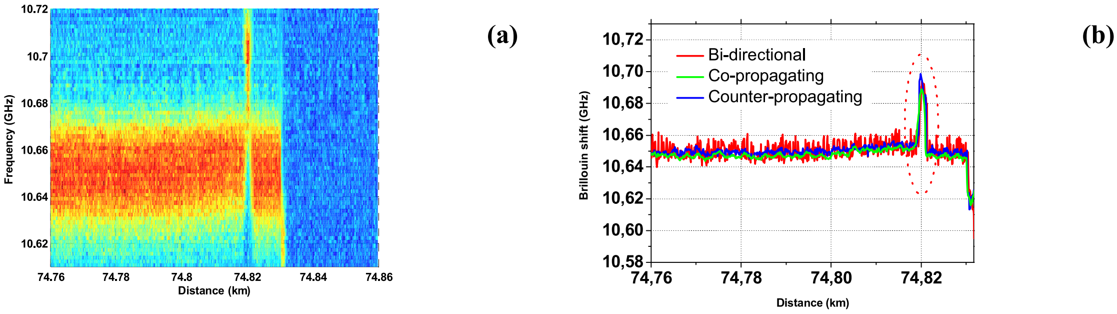

Fig.3. (a)Traces obtained close to the hot-spot location (74.82 km) for a pump-probe frequency sweep between 10.61 GHz and 10.72 GHz. (b) Brillouin shift determination around the hot-spot location (74.82 km). Measurement conditions are the following: Brillouin pump power is 18.8 mW, probe wave power is 0.25 µW, Raman pump power is 302 mW..

4. CONCLUSIONS

We have presented a Raman-assisted distributed sensor based on stimulated Brillouin scattering for sensing temperature and strain. This experimental setup allows us to monitor up to 75 km of optical fiber with a resolution of 2 meters, with marked contrast improvement at long distances due to the effect of distributed amplification. We have tested three different Raman pumping configurations: co-propagating, counter-propagating and bi-directional propagation. The best results in terms of contrast are obtained for the counter-propagating and bi-directional schemes (specially the first one). The bi-directional configuration allows achieving a quasi-constant gain distribution, which is interesting because the dynamic range in detection does not need to be very broad (unlike the other configurations). The results also highlight the importance of the RIN in the Raman pump (the contra-propagating configuration gives the best result because of RIN, but the bi-directional case would be the best if this problem is fixed). We have also demonstrated the viability of detection of 2 m hot-spot in the worst of the cases (at the end of the sensing fiber). We believe that it is feasible to reach 100 km of monitored distance with minor improvements in the experimental setup.

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