High-resolution Raman-assisted Brillouin sensor based on Differential Pulse-width Pair Technique

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ABSTRACT

High sensing resolution in long-distance distributed fiber optic sensors, such as Brillouin Optical Time Domain Analysis (BOTDA), cannot be trivially achieved due to several issues including self-phase modulation, resolution-uncertainty trade-offs and fiber attenuation. These problems could be fixed by the use of differential pulse-pair techniques in combination with Raman amplification. In this work we present a Differential Pulse-width Pair (DPP) Raman-assisted BOTDA sensor, that can achieve 1 meter resolution in a 100 km range.

Keywords: Brillouin scattering, distributed optic fiber sensor, differential pulse-width pair technique, Raman scattering, distributed Raman amplification, temperature sensor.

1. INTRODUCTION

Brillouin Optical Time Domain Analysis (BOTDA) [1], [2] allows temperature and strain detection in a distributed way over standard Single Mode Fibers (SMF). The necessary physical phenomenon to develop a BOTDA is the nonlinear optical effect denominated Stimulated Brillouin Scattering (SBS) [3]. The SBS produces a counter-propagating narrowband amplification of a probe signal within the fiber when an intense coherent pump light is introduced through one of the ends of the SMF. The distributed feature is transmitted to the fiber by pulsing the pump signal and measuring the probe signal as a function of the time-of-flight of the pump pulse within the fiber.

The resolution of the BOTDA, therefore, comes determined by the length of the pulses employed as a pump signal. The pulse-width/resolution relationship is set at 1 meter per every 10 ns. Therefore, pulses shorter than 10 ns will lead to resolutions below 1 meter. Unfortunately, in long range BOTDA systems this pulse width reduction is not effective since an inherent limitation will lie in uncertainty. The detected Brillouin gain spectrum is determined by the convolution between the pulse spectrum (broadened as the pulse is shortened) and the Brillouin gain spectrum (~ 30 MHz in SMFs). The pulse spectrum broadening leads to Brillouin shift determination uncertainties particularly when the pulse width is in the order of twice the phonon life (10 ns in SMFs). This is known as resolution-uncertainty trade-off [4] which states that pulse width reduction does not allow a continuous resolution increase. Moreover, in long-range systems, this trade-off is worsened by the additional detrimental effect of self-phase modulation, which introduces an extra spectral broadening of the pulses as they travel along the fiber [5]. As far as we are concerned, the best resolution demonstrated in sensors with ≥100 km range has been in the order of 2 meters [6], [7]. Differential Pulse-width Pair (DPP) technique [8] allows increasing the resolution of BOTDA fiber sensors without broadening the gain spectrum.

As well as resolution limitations, conventional BOTDA configurations also show restrictions in terms of working range. This restraint is mainly due to the fiber attenuation, which inevitably reduces the gain along the fiber, leading to a contrast loss and an increase in uncertainty in the far end. BOTDA sensors ranging beyond 60 km require support from a distributed amplification all along the sensing fiber. Normally, this amplification is provided through the use of stimulated Raman gain [9]. Raman assistance provides a good way of maintaining the power level of the pump pulse along the fiber, and hence the Brillouin gain contrast achieved. However, it also has inevitable limitations, namely related to the Relative Intensity Noise (RIN) transfer from the Raman pumps to the Brillouin probe [9]. While this performance is enough for most applications, extending the resolution to sub-meter values in Raman-assisted configurations is also desirable.

In this work, we employ the DPP technique [8] in a Raman-assisted BOTDA sensor. The DPP technique bases its working principle in the subtraction between gain traces obtained with slightly different pulse widths. The resolution in this technique is given by the differential width between the pulses while broadening in the gain remains bounded since the pulses used are always much longer than the phonon lifetime. When the two gain signals are subtracted, the remaining gain is theoretically caused by the pulse-width difference. Raman assistance in this case minimizes signal attenuation problems, leading to a good contrast of the measurements over the complete fiber length.

2. EXPERIMENTAL SETUP

The experimental setup is depicted in Figure 1. A similar long-distance BOTDA has already been developed, covering 100 km sensing range with 2 meter resolution [6], although in this case the system is much less complex due to a couple of differences.

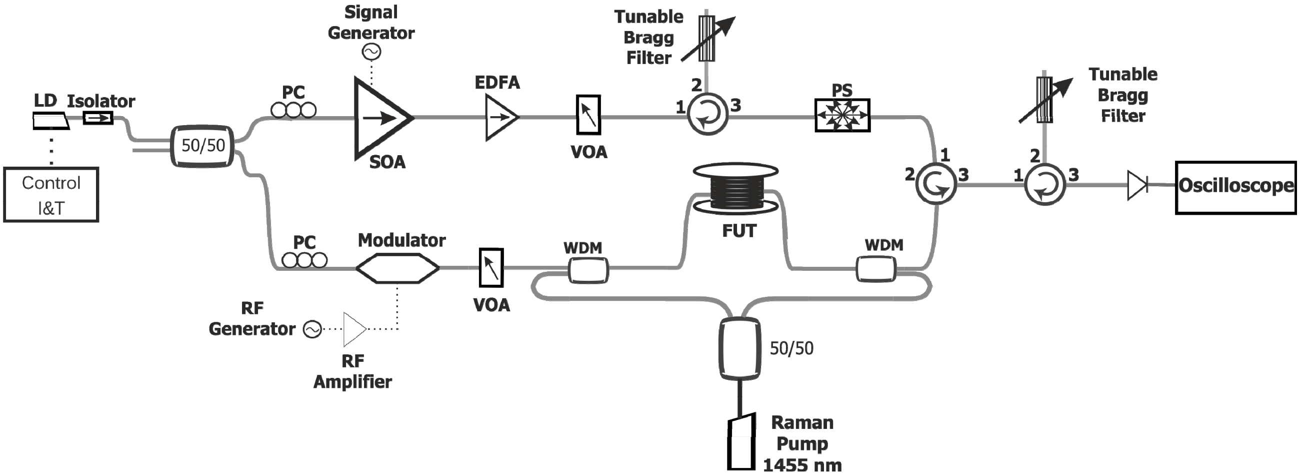

Figure 1. Experimental setup of the Raman-assisted distributed sub-meter Brillouin sensor. LD: Laser diode; PC: Polarization Controller; SOA: Semiconductor Optical Amplifier; EDFA: Erbium Doped Fiber Amplifier; VOA: Variable Optical Attenuator; WDM: Wavelength Division Multiplexer; FUT: Fiber Under Test; PS: Polarization Scrambler.

The first novelty concerns on the substitution of the Electro-Optic Modulator (EOM) that was used to generate the pump pulses with a Semiconductor Optical Amplifier (SOA). This replacement provides a very high extinction ratio to the setup (> 50 dB) [10], which allows the removal of the Nonlinear Optical Loop Mirror (NOLM) and one amplification stage in the pump branch. These changes have helped to slightly improve the signal-to-noise ratio.

The second difference comes from the use of a shorter wavelength laser (the present laser has the central wavelength at 1548.5 nm, shorter than the laser used in [6]). In essence this does not have any impact on the experiment except that the filtering in detection is also shifted and the Brillouin shift curve is up-shifted with respect to the values reported in [6] for the same fiber spools.

Besides the mentioned novelties, the setup is exactly the same as the employed previously in [6]: a Laser Diode (LD) is split and modulated in order to obtain the pump and probe signals without any frequency disturbance between them; the pump pulses are obtained by pulsing through a SOA the 65 and 55 ns pulses supplied by the signal generator which are afterwards amplified within an EDFA; the probe signal is obtained from the lower frequency sideband of an amplitude modulation of the master source around the Brillouin frequency shift (~10.7 GHz) of the Fiber Under Test (FUT); the pump and probe signals are introduced in the fiber in opposite directions to obtain SBS through Wavelength Division Multiplexers (WDM) and all the signals within the FUT are amplified to be able to visualize the 100 km sensing range through a bi-directional Raman amplification [9]; before detection, the final signal is optically filtered to remove the upper sideband.

3. RESULTS

In this section we will show the high-resolution results that we could obtain with the DPP Raman-assisted BOTDA. The 100 km fiber is composed by four SMF spools of 25 km with an effective area of 70 μm^2 and a similar Brillouin frequency shift located at approximately 10.7 GHz for the employed laser wavelength (~1548.5 nm). The peak power of pump and probe were 6 mW and 81 μW respectively, with 500 mW of total Raman pump power.

The control of the pump power is extremely important in this kind of sensors since the signal can easily generate self-phase modulation as well as be depleted. The effect of the self-phase modulation is scaled with the inverse of the pump pulse width, thus higher pulses allow proportional higher pump power signals. In this work 65 and 55 ns pulses were employed which are roughly 3 times longer than the ones used in [6] to sense 2 meters (20 ns) over 100 km. Consequently, in this work we could employ a pump power signal 3 times higher than the one employed in [6] without adding extra spectral broadening or depletion. Combining the peak power increase and the pulse width increase, the gain values recorded in the experiments of this work are roughly 10 times larger than the ones recorded in [6]. The probe power is also increased with respect to the setup described in [6]. This obeys to a careful setting of the modulator working point to minimize the power imbalance between the two side-bands. With perfectly symmetric sidebands, the probe power can be theoretically raised up to a value close to the stimulated Brillouin scattering threshold without entering into undesired depletion problems. The Raman pump power used is slightly below the value necessary for a good compensation of the losses. However, this ensures a good behavior of the setup in terms of Relative Intensity Noise (RIN). Figure 2 shows a gain trace recorded for the complete fiber length with a pulse width of 65 ns.

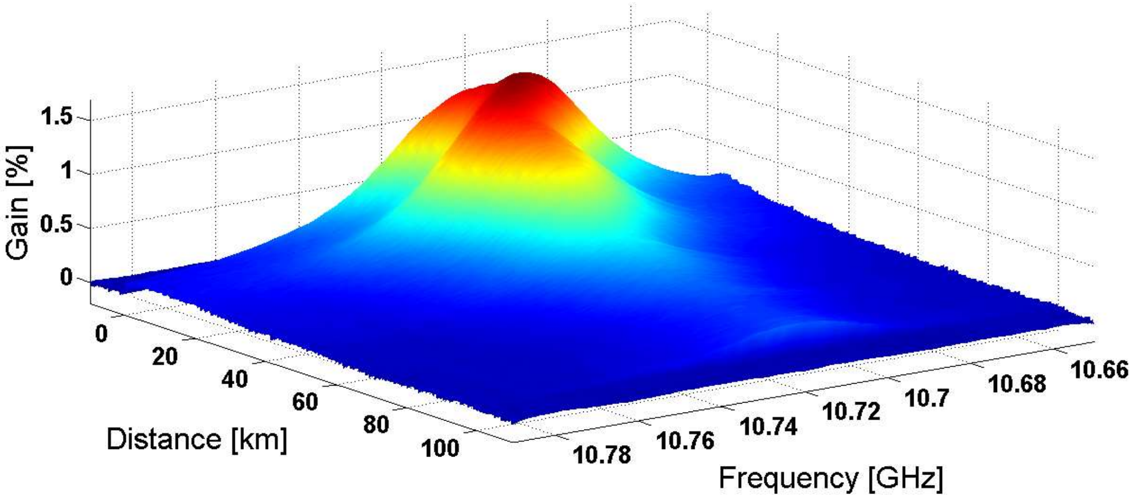

Figure 2. Brillouin gain sweep for the complete fiber length. The probe signal frequency is swept from 10.66 GHz until 10.78 GHz. The traces are acquired with 65 ns pulses.

In order to test the performance of our high-resolution long range BOTDA, we introduce a hot spot between the last two fiber spools (around km 75), where the gain contrast is minimal. 1 meter of fiber was introduced in a water bath at 60ºC (± 5ºC), with a room temperature of 22ºC. In Figure 3 it can be seen the gain trace sweep around the hot-spot for 65 and 55 ns pump pulses (pictures (a) and (b)respectively) for a probe frequency shift ranging from 10.66 GHz up to 10.78 GHz. It is noticeable that the Brillouin Frequency Shift (BFS) of the fiber is set at approximately 10.71 GHz all along the 100 meter span analyzed. At the hot spot region (74.34 km) the gain at 10.71 is reduced and a significant part of the gain is recorded at higher offset frequencies. The distance over which this change in gain behavior is recorded spans over the pulse length in both cases, being therefore longer for the gain sweep acquired with longer pulse length.

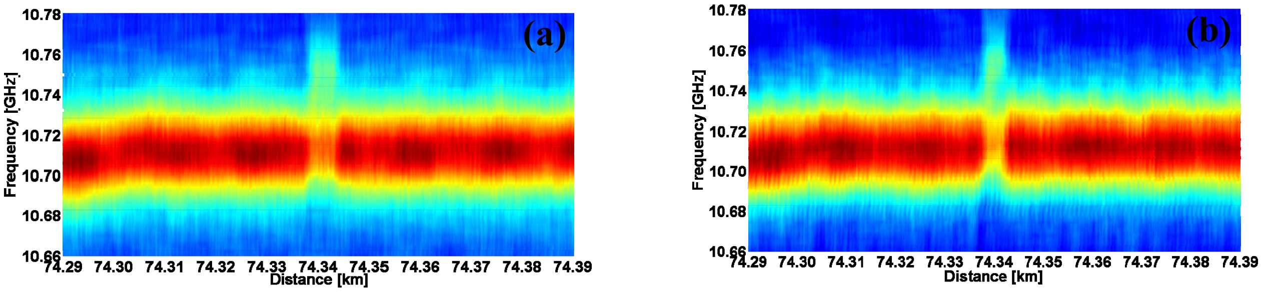

Figure 3. Brillouin gain sweep around the hot spot (located close to 74.34 km). The probe signal frequency is swept from 10.66 GHz until 10.78 GHz for (a) 65 ns pump pulses and (b) 55 ns pump pulses. It is noticeable the width difference between both hot-spots due to the pulse signal width difference.

As stated before, the subtraction between the hot-spot traces will exhibit a final resolution equal to the width difference of the original pulses in the measured hot-spot traces. The employed pulse lengths were 65 and 55 ns, which should give 1 meter resolution after subtraction (10 ns). The final result of the subtraction of these two traces is shown in Figure 4(a). The 1 meter hot-spot (the real fiber size introduced in the hot bath) is clearly visible, in km 74.343. The gain maximum visibly switches from the value of 10.71 to 10.76. This frequency difference can be easily translated to temperature by using the sensitivity of the BFS to temperature, which is 1.3 MHz/ºC in our particular case [6], [11]. Therefore, the 50 MHz frequency difference in the hot spot could be translated as 38 ºC difference, which actually matches with the expected temperature change. Figure 4(b) shows the Brillouin Frequency Shift (BFS) of the subtracted trace. The maximum rms difference between consecutive traces is ~ 4 MHz which ensures an uncertainty of ~3 ºC. In Figure 4(c) it is shown the gain sweep at the exact position of the hot-spot. It is noticeable a gain increase at the hot-spot frequency (~ 10.76 GHz) and a complete absence of gain at the un-shifted position (~ 10.71 GHz).

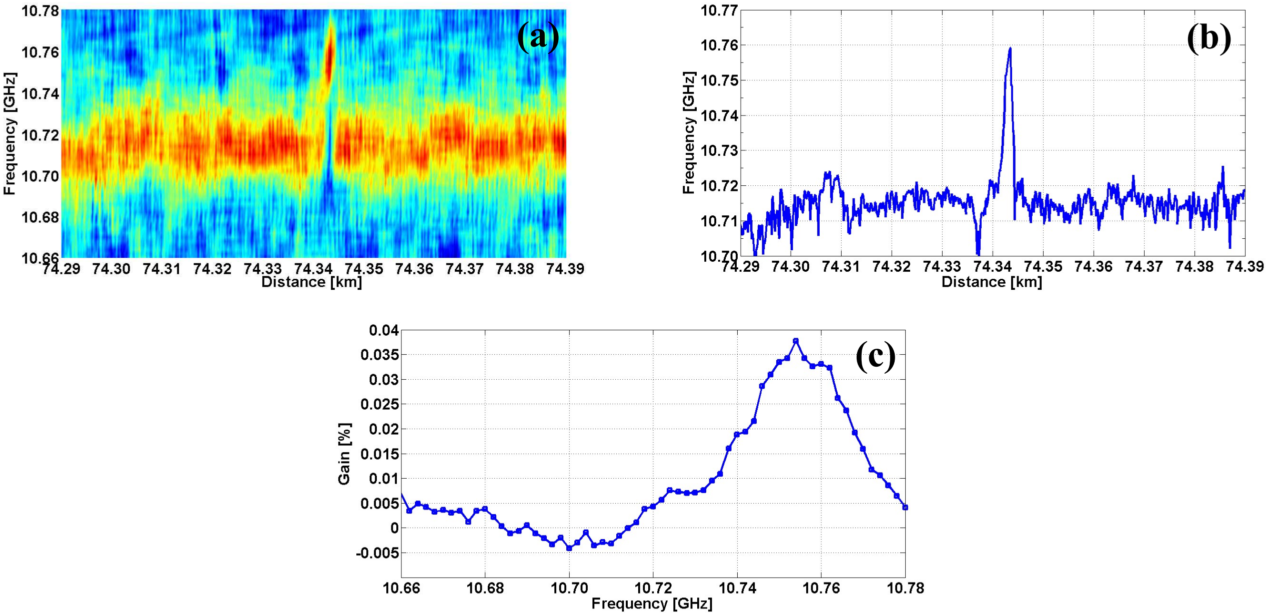

Figure 4. (a) Result of the subtraction between the 65 ns and 55 ns Brillouin gain traces for the 1 meter hot-spot; (b) Representation of the BFS of the subtraction which determines the uncertainty of the measurement (3 ºC); (c) Gain profile obtained at the position of the hot-spot.

By having a careful look to the subtraction trace (Figure 4(a)) it is noticeable some quasi-periodic noise contributions all over the trace. This is due to the RIN introduced by the Raman fiber laser employed to deliver bi-directional amplification to the pump and probe signals within the fiber. From the experimental point of view, we think that the most proper solution for this matter is to substitute the RFL with a Semiconductor Laser (SL) [7], since these lasers have a smaller RIN figures. The employed RFL has a RIN value of -110 dBc/Hz while a standard SL will show approximately -140 dBc/Hz. Unfortunately, SLs do not reach the same power levels as RFLs, and hence it will be necessary to modify the employed setup in order to attain the same sensing length.

4. CONCLUSIONS

In this work we have presented a high resolution long-range BOTDA temperature sensor based on a DPP technique that resolves in a distributed way 1 meter all along 100 km. The DPP technique in our Raman-assisted sensor allows an increase in resolution avoiding all the problems derived from pulse width reduction in the conventional setup. This technique is based in the subtraction between gain traces obtained with slightly different pulse widths, where the final resolution is set by the differential width of the employed pulses. In our experiment 65 and 55 ns pulses were employed, which sets a final resolution of 1 meter. The use of such long pulses simultaneously allows an increase of the pump signal power as well as avoiding all the issues derived from the use of 10 ns pump pulses shorter (self-phase modulation, resolution uncertainty trade-off, etc.).

We consider that further fine-tuning of the setup could lead us to achieve higher sensing resolutions, entering the sub-meter range. As indicated, the elimination of the RIN transfer introduced by the RFL could be very helpful in order to attain less noisy subtraction figures. This could be obtained by the use of a semiconductor laser as Raman pump.

ACKOWLEDGMENTS

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