Angulo-Vinuesa, X., Martín-López, S., Corredera, P. and González-Herráez, M., "100 km BOTDA temperature sensor with sub-meter resolution", 2012, Proc. SPIE8421, OFS2012 22nd International Conference on Optical Fiber Sensors, 842117

Available at http://dx.doi.org/10.1117/12.974934

100 km BOTDA temperature sensor with sub-meter resolution

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ABSTRACT

Temperature or strain sensing in long-range (> 70 km) Brillouin Optical Time Domain Analysis (BOTDA) below 2 meter resolution cannot be trivially achieved due to numerous matters such as fiber attenuation, self-phase modulation, depletion, resolution-uncertainty trade-offs, etc. In this paper we show that combining Raman assistance and the Differential Pulse-width Pair (DPP) technique sub-metrical resolution is achievable in a BOTDA over 100 km sensing range. We successfully demonstrate the detection of a 0.5 meter hot-spot in the position of worst contrast along the fiber.

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

1. INTRODUCTION

As it is widely known, the spatial resolution of a Brillouin Optical Time Analysis (BOTDA) [1], [2] sensor comes determined by the length of the pulses employed as a pump signal. The ratio between the pulse width and the resolution is roughly 1 meter per every 10 ns, thus pulses shorter than 10 ns should theoretically lead to sub-metrical resolutions; however this approach has an intrinsic limitation in uncertainty. The observed Brillouin gain spectrum is obtained from the convolution between the pulse spectrum and the natural Brillouin gain spectrum. Short pulses show broad spectra, therefore larger uncertainties when determining the Brillouin shift. This natural limit is known as the resolution-uncertainty trade-off [3]. 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 [4]. To avoid the inevitable physical limitations associated to pump pulse shortening in high-resolution setups, the Differential Pulse-width Pair (DPP) technique has been proposed [5]. This technique allows increasing the resolution of BOTDA fiber sensors without broadening the gain spectrum and avoiding self-phase modulation issues. It bases its working principle in the subtraction between gain traces obtained with slightly different pulse widths. The spatial resolution is then given by the differential width between the pulses while the broadening in the gain remains bounded since the pulses used are always much longer than the phonon lifetime (typically 4-8 times larger). The effect of self-phase modulation in these schemes should also be residual for the typical power levels used.

In this work, we employ the DPP technique in a long-range Raman-assisted Brillouin distributed sensor [5], [7]. We demonstrate the possibility of achieving sub-meter resolution in a 100 km range sensor.

2. EXPERIMENTAL SETUP

The experimental setup is depicted in Figure 1. It is very similar to the Raman-assisted BOTDA scheme described in [7], except for a couple of differences. The first difference comes from the fact that the element that makes the pump pulse is a Semiconductor Optical Amplifier (SOA) instead of an Electro-Optic Modulator (EOM) and a Nonlinear Optical Loop Mirror (NOLM). This makes the setup easier to operate while the extinction ratio (ER) remains very high (>50 dB) [8]. It also allows reducing one amplification stage in the pump branch, which improves slightly the signal-to-noise ratio. In addition, the high extinction ratio of these pulses helps to improve the spectral purity in the measurements done with the DPP configuration, as predicted in the numerical results of Minardo et al. [9].

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 [7]). In essence this does not have any impact on the experiment except that the

Updated 1 March 2012

filtering in detection is also shifted and the Brillouin shift curve is up-shifted with respect to the values reported in [7] for the same fiber spools.

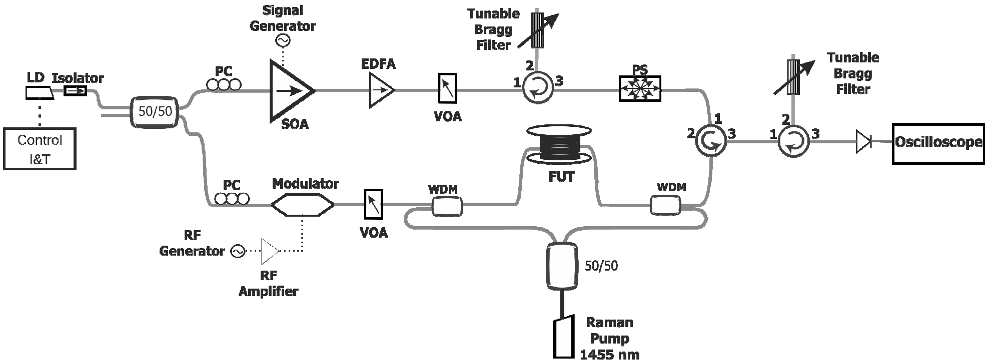


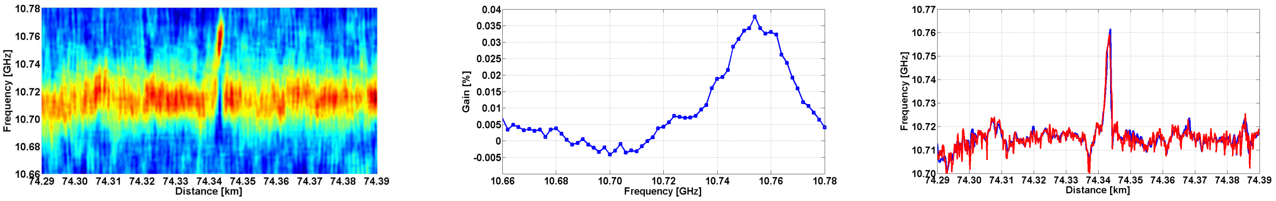
Fig. 1. Experimental setup of the Raman-assisted distributed sub-meter Brillouin sensor. LD: Laser diode; PC: Polarization Controller; SOA: Semiconductor Optical Amplifier; EDFA: Erbium Doped Fiber Amplifier; VOA: Variable Optical Attenuator; WDM: Wavelength Division Multiplexer; FUT: Fiber Under Test;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

Besides these novelties, the setup and the methodology to determine the adequate power settings are exactly the same as the ones employed previously in [7]. Differential measurements with 1 meter spatial resolution are obtained by subtracting the traces obtained with 65 and 55 ns pump pulses and 0.5 meter resolution subtracting 65 and 60 ns traces. A simple normalization procedure ensures that the gain subtraction is robust against small pump power variations. This procedure is correct as long as pump depletion effects can be considered negligible. In our case, the probe power is set below 90 µW, which in the case of symmetric sidebands in the probe, ensures no depletion, even for this very long length [10].

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 (BFS) located at approximately 10.7 GHz for the 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 (~250 mW per each side). In terms of Brillouin pump power, we could raise the power level to a value roughly 3 times higher than the values used in [7] for the 2 meter configuration over the same 100 km range. This is because the effect of self-phase modulation scales with the inverse of the pump pulse width. Since the pulses are 3 times longer, the power can be raised 3 times without adding extra spectral broadening. 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 [7]. The probe power is also increased with respect to the setup described in [7]. 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 SBS threshold without entering into undesired depletion problems. In detection, a procedure is put forward to reduce the relative intensity noise (RIN) transfer problem caused by Raman pumping with a Raman Fiber Laser (RFL) [11]. This procedure is based on the knowledge of the RFL pump spectrum, which conventionally exhibit peaks in the RF spectrum, spaced by the free spectral range of the RFL cavity. These peaks are transferred to the signal and may be strongly present even after the averaging procedure. Peaks in the spectrum at multiples of the Raman cavity FSR are thus eliminated. All these changes lead to a >10 dB increase in trace SNR over the setup described in [7]. To validate the performance of our high-resolution long-range BOTDA, even in the worst conditions, 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. Figure 2(a) shows the gain trace sweep of the subtraction around the hot-spot location (km 74.343) for a probe frequency shift ranging from 10.66 GHz up to 10.78 GHz. As it can be seen, the BFS of the fiber is set at approximately 10.71 GHz all along the 100 meter span analyzed. At the hot spot region, it can be seen that the gain at 10.71 is reduced and a significant part of the gain is recorded at higher offset frequencies. 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], [7], [12].

Therefore, the ~50 MHz frequency difference in the hot spot could be translated as 38ºC difference, which actually matches with the expected temperature change. Figure 2(b) shows 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 good extinction at the position of the maximum of the rest of the fiber (~10.71 GHz), confirming the prediction in [9] of high spectral purity measurements with high ER pulses. Lastly, Fig. 2(c) displays the representation of the BFS (υ_B) with and without the RFL de-noising procedure [11]. The rms frequency difference between consecutive measurements is in the order of 3 MHz, which ensures a maximum uncertainty of ~2.3ºC. As it is visible, the simple de-noising procedure described in [11] eliminates a substantial amount of RIN transfer and helps to reduce ~1.5 ºC in rms uncertainty.



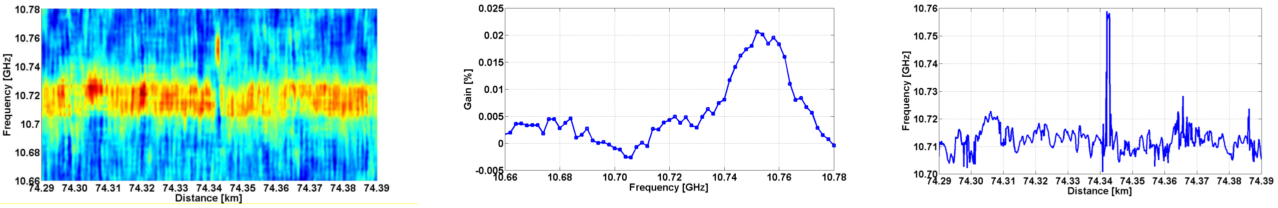
(a) (b) (c)

Fig. 2. (a) Result of the subtraction between the 65 ns and 55 ns Brillouin gain traces for the 1 meter hot-spot (100 meter span); (b) gain profile obtained at the position of the hot-spot; (c) BFS vs distance around the hot-spot.

With RFL pumping, the RIN transfer problem becomes too large to make useful measurements with sub-meter resolution. To push further down the resolution, we decided to use Semiconductor Laser (SL) pumping on the probe side of our BOTDA. This type of lasers have much lower RIN values than RFLs (typically -105 dBc/Hz for RFLs and -140 dBc/Hz for SLs), and their advantageous use in Raman-assisted BOTDA has already been successfully confirmed by Soto et al. in previous works [13]. SL pumping in the probe end minimizes the RIN transfer issues in detection, as justified in previous analysis [7],[13].

4. IMPROVED PERFORMANCE USING A SEMICONDUCTOR PUMP.

In this case 0.5 meter fiber length was introduced in the hot bath and differential measurements were developed with 65 and 60 ns pulse widths. The pumping in the probe end is done at similar power levels than in the previous case, except for the fact that a SL is providing the pump entering through the probe end. The Raman pump on the other side is left unaltered (conventional RFL). In Figure 3(a) (100 m span measurement) it can be seen the subtraction between the obtained traces and once the de-noising procedure is applied. It is noticeable that the detection of the hot-spot is performed properly and that in this position (~74.34 km) the gain completely switches from 10.71 GHz to 10.76 GHz. The measurement quality is comparable to the case of 1 meter resolution with RFLs [11]. Figure 3(b) shows the gain sweep at the exact position of the hot-spot, again showing spectrally pure measurements in the hot-spot. In Figure 3(c) we depict the obtained BFS curve as a function of distance around the hot-spot. By subtracting consecutive measurements we could determine that the rms uncertainty of the measurement is close to 2.9ºC (3.8 MHz).



(a) (b) (c)

Fig. 3. (a) Result of the subtraction between the 65 ns and 60 ns Brillouin gain traces for the 0.5 meter hot-spot (100 meter span); (b) gain profile obtained at the position of the hot-spot; (c) BFS vs distance, measured around the hot-spot.

5. CONCLUSIONS

In this work we have presented a high resolution long-range Raman-assisted BOTDA temperature sensor based on the DPP technique that resolves in a distributed way sub-meter hot-spots all along 100 km. This has been achieved by a careful engineering of the sensing setup and a simple de-noising procedure that reduces the RIN transfer issue in Raman-assisted configurations, in the usual case of pumping with a fiber laser.

1 and 0.5 meter hot-spots are clearly detected with good contrast, the latter using semiconductor laser-based Raman pumping in the probe end. In this case, the estimated rms uncertainty in the measurements is in the order of 2.9ºC. The results achieved illustrate that this technique has potential to provide good results in the sub-meter range, especially when the Raman assistance in the setup is done with semiconductor lasers.

ACKOWLEDGMENTS

This work was supported in part by the Spanish Ministry of Science and Innovation through projects TEC2009-14423-C02-01 and TEC2009-14423-C02-02 and the Comunidad de Madrid through project FACTOTEM-2. Sonia Martin-Lopez acknowledges funding from the Spanish Ministry of Science and Innovation through a "Juan de la Cierva" contract. We also acknowledge discussions with Dr. Juan Diego Ania-Castañon (CSIC) and Prof. Luc Thévenaz (EPFL, Switzerland).

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