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Reaching the ultimate performance limit given by non-local effects in BOTDA sensors

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ABSTRACT

Non-local effects have been traditionally identified as one of the most limiting factors of the performance of Brillouin optical time-domain analyzers. These phenomena, directly linked with the energy gained/lost by the pump pulse, limit the probe power and ultimately the SNR of the system. Several solutions have been proposed, although none offers the possibility to increase the probe power until its limit, the onset of amplified spontaneous Brillouin scattering. In this work, we propose a technique that avoids non-local effects and permits to set the probe power at its maximum, reaching a 100 km sensing distance with 2 meter resolution.

Keywords: Brillouin distributed sensors, Brillouin scattering, nonlinear optics, fiber optic sensors.

1. INTRODUCTION

Brillouin Optical Time Domain Analysis (BOTDA), a consolidated long-range distributed fiber optic sensing technique, traditionally uses a Dual-Probe-Sideband (DSB) modulation scheme[1], which turns the system to be highly robust against pump depletion and non-local effects compared to a Single Sideband (SSB) probe wave configuration[2]. Even though this procedure works effectively in most of the cases, a recent study[3] has demonstrated that DSB configuration introduces a spectral distortion on the pump pulse that leads to Brillouin Frequency Shift (BFS) determination errors. This phenomenon scales with the probe wave power, which limits the performance of the BOTDA system in terms of signal-to-noise ratio (SNR) and distance. In this work, we propose a novel pump-probe frequency scanning technique that completely eliminates non-local effects[3], up to the ultimate probe power limit given by the onset of amplified spontaneous Brillouin scattering (ASpBS).

2. PRINCIPLE

In principle, by making use of a DSB configuration, the maximum probe power can be significantly raised in the sensing fiber to be ultimately limited to ~6-7 dBm by the onset of ASpBS[2]. This scheme works perfectly when the gain spectrum is exactly located at the median position between the two sidebands, however, it has been recently found[3] that such scheme still suffers from non-local effects when probe and gain spectrum are detuned, even for power in each sideband far below the ASpBS threshold. By sweeping the frequency of the two sidebands in the traditional way[1], as shown in Fig. 1(a), the pump pulse spectrum is subject to an uneven spectral compensation of the gain-loss probe spectra in case of detuning. The pulse spectrum turns out then to be asymmetrically distorted and downshifted or upshifted as the pulse propagates along the sensing fiber, depending on whether the scanned pump-probe frequency offset is higher or lower than the average BFS of the fiber[3]. This detrimental effect comes from the non-zero net gain (indicated by green lines in Fig. 1(a)) that combines Brillouin gain (red curves) and loss (blue curves) spectra generated by the upper and lower probe sidebands, respectively. This pulse distortion actually cumulates along the sensing fiber, inducing a severe distortion in the gain/loss BOTDA traces, thus giving rise to errors in the BFS estimation. The longer the sensing fiber is and the higher the probe power used, the more distorted the pump pulse is.

Instead of sweeping the two probe sidebands symmetrically away and towards the pulse spectrum[1-3], a novel sweeping method is proposed in this paper. This technique keeps a fixed frequency separation between the two probe sidebands while sweeping pump or probe wave frequency to scan the Brillouin Gain or Loss Spectrum (BGS or BLS), as shown in Fig. 1(b). This way, the gain and loss spectra generated by the two probe sidebands exactly cover the same spectral region and mutually cancel out, regardless of the scanned pump-probe frequency offset. Consequently, the pulse

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accomplished. It should be noted that this result has been achieved without using any extra technique, such as Raman assistance[4] or pump pulse coding[5], which implies a brand new measuring performance record. The simplicity of the proposed setup makes these results even more impressive when compared with other studies reaching similar distances.

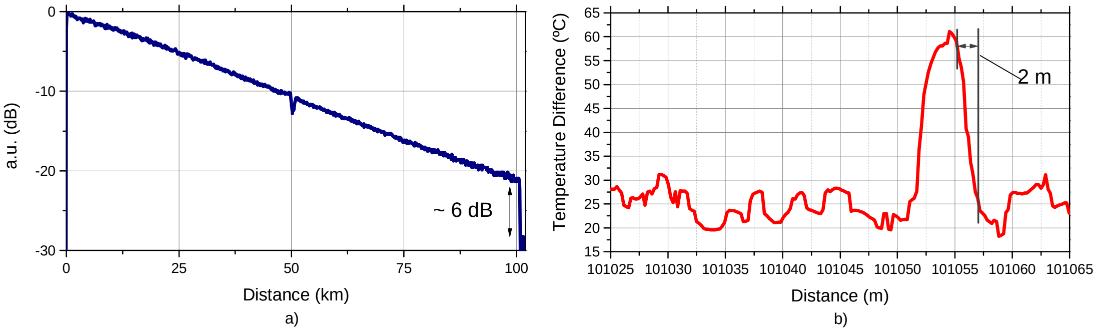

Fig. 4: a) BOTDA trace represented in logarithmic scale of the 100 km FUT for a pump-probe frequency shift of 10.856 GHz, averaged 16000 times. b) BFS translated to temperature difference for a ~ 5-meter hot-spot located around km 100.

4. CONCLUSIONS

In conclusion, we have presented a novel Brillouin optical time-domain analysis technique highly robust against pump depletion and non-local effects. This allows increasing the probe wave power level until the appearance of ASpBS, which is translated into a sensor performance improvement. The measuring methodology is based on varying the pump-probe modulation structure by just fixing the probe sidebands detuning to match the average Brillouin frequency shift of the fiber, and then sweeping the pump pulse frequency. In this case, the recovered Brillouin gain and loss curves are not distorted by non-local effects. Of course, matching the proper pump-probe frequency shift of the fiber is critical to ensure correct measurements. In these conditions, it is possible to increase the probe power up to the ASpBS threshold, allowing us to measure, without any extra assistance, over 100 km with 2 meter resolution (16000 averages) and 2.8 MHz uncertainty. The proposed scheme allows a FoM improvement factor of 10 over the traditional sweeping scheme. This FoM improvement is directly related to the 10 dB SNR improvement accomplished. We believe this technique brings a considerable upgrade for BOTDA systems, giving the possibility of combining it with other additional techniques, such as Raman assistance or pulse coding. We foresee that, combining all these techniques, it might be potentially feasible to measure up to 150 km of fiber with similar resolution values (2 meters).

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