BOTDA sensor with 2-m spatial resolution over 120 km distance using bi-directional distributed Raman amplification

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ABSTRACT

In this paper we propose the use of optimized bi-directional distributed Raman amplification to enhance the operating range of Brillouin optical time-domain analysis (BOTDA) sensors. In particular by combining high-power fiber-Raman lasers and polarization-multiplexed Fabry-Pérot lasers operating at 1450 nm with low relative-intensity-noise (RIN), we demonstrate distributed sensing (using first-order Raman amplification) over 120 km of standard single-mode fiber with 2 meter spatial resolution and with a strain/temperature accuracy of 45με/2.1°C respectively.
Keywords: fiber optic sensors, Brillouin scattering, Raman scattering, temperature sensing, strain sensing.

1. INTRODUCTION

Distributed optical fiber sensors technology is attracting a great interest thanks to its wide range of potential industrial applications in strategic sectors such as energy, security, defense and transportation, among others. In particular, Brillouin optical time-domain analysis (BOTDA) sensors are based on the temperature and strain dependence of the Brillouin frequency shift parameter [1-2], allowing for distributed temperature and strain sensing over tens of km of single-mode optical fibers (SMF). Such distributed measurements are of great interest to monitor civil and industrial infrastructures. One of the main open issues in this technology is related to the possibility of achieving long-range sensing distances [1-2], and several innovative approaches have been recently proposed addressing this matter. In particular the measurement range of the standard BOTDA technique has been sensibly enhanced by the use of pulse coding [1] and the use of distributed Raman amplification [2].

In this paper we focus our attention on distributed Raman amplification, pointing out that a careful optimization is required in order to fully exploit its benefits in terms of sensing range enhancement. In fact, although distributed Raman amplification has already been used also for enhancing the performance of WDM optical communications systems [3] and in distributed fiber sensors based on spontaneous Brillouin scattering [4], we show here that great care must be taken when employing it for BOTDA systems. Three main sources of distortions have been in fact identified in Raman-assisted BOTDA sensors, potentially seriously affecting their performance: RIN transfer from the Raman pumps to the CW Brillouin probe [5], fiber nonlinear effects [6] and nonlocal effects induced by pump depletion [7].

In particular, numerical simulations have been carried out in order to optimize the BOTDA system parameters in terms of optical signal-to-noise ratio (OSNR), minimum power difference between Brillouin pump and probe (to avoid pump depletion), as well as maximum Brillouin pump power along the sensing fiber (to avoid nonlinear effects). We show that when employing Raman pumps in co-propagating direction with respect to the CW probe signal, low relative intensity-noise (RIN) lasers must be used to avoid noise transfer and then fully to exploit the potential of distributed Raman amplifiers. Actually, by combining high-power fiber Raman lasers (FRL) and low-RIN polarization-multiplexed Fabry-Pérot (FP) lasers operating at 1450 nm, we experimentally demonstrate notable distributed measurements over 120 km of SMF using first-order bi-directional Raman amplification, achieving 2-m spatial resolution and a strain/temperature resolution of 45ue / 2.1°C respectively.

2. THEORY AND SYSTEM OPTIMIZATION

In BOTDA schemes, two lightwave signals propagating in opposite directions (a CW probe and a pulsed pump) interact through stimulated Brillouin scattering (SBS), giving rise to optical amplification (or depletion) of the probe intensity. As a result of the interaction, the intensity variations in the probe signal at the photo-receiver can be expressed as:

$$\Delta I_{CW}\left(t,\Delta\nu\right) \propto \int_{v_g t/2}^{v_g t/2+\Delta z} g_B\left(\xi,\Delta\nu\right) Ip\left(\xi,\Delta\nu\right) d\xi \tag{1}$$

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where v_g is the group velocity, Δz is the interaction length (i.e. the spatial resolution), $\Delta\nu$ is the pump-probe optical frequency separation, $g_B\ (\xi,\Delta\nu)$ is the Brillouin gain coefficient and $I_P(\xi,\Delta\nu)$ is the pump intensity [1]. The Brillouin gain spectrum (BGS) is then reconstructed by tuning the pump-probe frequency difference $\Delta\nu$, and the Brillouin frequency shift (BFS) parameter is correspondingly obtained, providing information about the fiber local temperature and/or strain. The maximum usable power levels for pump and probe are limited by the onset of nonlinear effects, such as self phase modulation (SPM) and modulation instability (MI), and of pump depletion, inducing nonlocal probe gain effects. Eq. (1) points out the existing trade-off, at a given spatial resolution, between *i)* a high intensity contrast in the CW probe signal ΔI_{CW}, which is directly linked to the attainable T-ε measurement SNR (and to the measurand resolution), and *ii)* long sensing distances causing low pump-intensity levels $I_P(\xi)$ due to fiber loss. Therefore, distributed Raman amplification can potentially provide an effective technique to overcome such a trade-off, enhancing the attained receiver SNR values.

In BOTDA sensors assisted by bi-directional Raman amplification, two CW Raman pumps are coupled into both fiber ends, leading to distributed amplification of both Brillouin pump and probe lights. The Raman pump co-propagating with the pulsed Brillouin pump (propagating in $+z$ direction) leads to simultaneous amplification of the BOTDA probe and pump near the fiber input, with a negligible impact of its RIN on the sensor performance [5]. However, the counter-propagating Raman pump (in $-z$ direction), amplifying the BOTDA probe and pump near the far fiber-end, is expected to transfer a large amount of noise to the probe signal due to the propagation of both signals along the same direction. Therefore, a careful optimization of its RIN properties is required to suppress induced penalties.

In order to fully exploit the benefits of the bi-directional optical Raman amplification without incurring in the many sources of inaccuracy potentially related to this technology, the optical power levels for the Brillouin pump, probe signal and both Raman pumps must be suitably optimized in order to minimize penalties originating from the laser RIN, signal double Rayleigh scattering and amplified spontaneous emission (ASE).

Our BOTDA system has been first optimized by numerical simulations based on the integration of partial differential equations describing the coupled pumps and signal evolution taking into account Raman amplification effect [3]. This has allowed us to estimate the optimal power levels to be launched into the sensing fiber in order to maximize the probe OSNR, avoiding at the same time pump depletion and nonlinear effects. In particular, the optimized input power values for the Brillouin pump and co-propagating Raman pump lights have been found to be 10 dBm and 400 mW respectively; such values push the maximum Brillouin pump value well inside the sensing fiber providing several dB of enhancement in probe OSNR, avoiding at the same time nonlinear effects [3]. With such an optimized condition for Brillouin- and co-propagating Raman- pumps at the fiber input, we have then identified the best BOTDA system configuration by further simulation stages encompassing the probe and Raman counter-propagating pump conditions. Fig. 1 reports a bi-dimensional contour plot showing: *i)* the probe OSNR (dotted lines, 125 MHz bandwidth), *ii)* the minimum power difference between Brillouin-pump and probe along the fiber (solid lines); both parameters have been plotted as a function of input probe power (x-axis) and counter-propagating Raman pump power (y-axis). Considering that pump depletion effects are negligible if the minimum power difference between the Brillouin pump and probe signal is greater than ~15 dB, then suitable power levels can be found in Fig. 1 ensuring a sufficiently high OSNR. For instance, in order to have a minimum Brillouin pump-probe power difference of ~17.5 dB, a probe power of ~-20 dBm can be used together with a counter-propagating Raman pump power of ~300 mW, resulting in an OSNR of ~40 dB ensuring high resolution. Note that higher OSNR values could be achieved by decreasing the probe power and increasing the counter-propagating Raman pump power; however, such conditions can easily result in Brillouin-pump power levels well above the nonlinear threshold in proximity of the sensing fiber end.

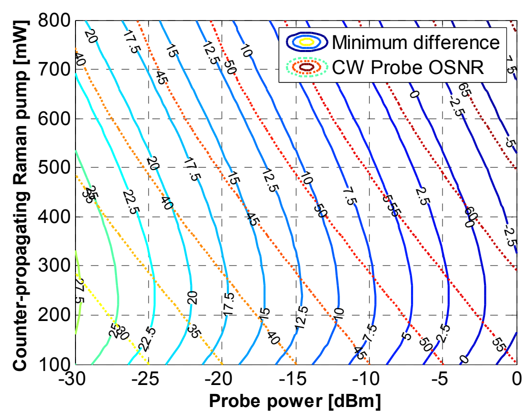

Fig. 1. Simulation results for optimization of power levels for both counter-propagating Raman pump and probe signal

3. EXPERIMENTAL SET-UP

Fig. 2 reports the experimental setup of the implemented BOTDA sensor based on bi-directional distributed Raman amplification. A distributed-feedback (DFB) laser operating at 1550 nm is split into two branches using a 3-dB optical coupler in order to generate both Brillouin pump and probe signals. In the pump branch, an Erbium-doped fiber amplifier (EDFA), a polarization controller (PC) and a Mach-Zehnder modulator (MZM) with high extinction ratio have been used to generate the pulsed pump wave (with 20-ns pulse width, allowing for 2-m spatial resolution). Note that the location of the MZM after the EDFA allows us to filter out the inter-pulse ASE noise generated in the EDFA. In the probe branch, a PC and an MZM are used to intensity modulate the CW light, generating two sidebands with a frequency separation that is controlled by an RF generator. The optical carrier has been suppressed by properly setting the DC bias of the MZM. A variable optical attenuator (VOA) has been used to properly adjust the probe power that is launched into the fiber. To reduce polarization-dependent gain fluctuations, both sidebands are depolarized using a polarization scrambler (PS). The Brillouin pump and probe signals are launched into 120 km of SMF through two WDM couplers, which are also used to couple both Raman pumps into the fiber. While the co-propagating Raman pump consists in a depolarized FRL at 1450 nm, the counter-propagating pump is implemented by polarization-multiplexing two low-RIN FP lasers (centered at 1450 nm) through a polarization beam-combiner (PBC). In this way, the polarization-dependent gain of the Raman amplifier has been reduced to a negligible level. The optical pump power levels have been adjusted to the values obtained by the numerical optimization reported in Section 2.

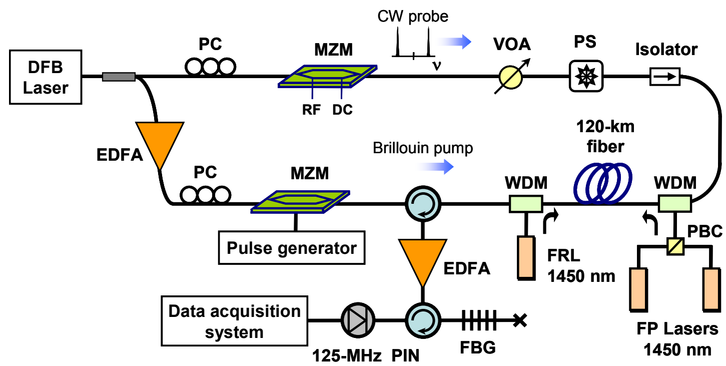

Fig. 2. Experimental setup

At the receiver side, an additional EDFA is used as preamplifier, which is followed by an optical circulator and a 6-GHz fiber Bragg grating (FBG), allowing us to select the Brillouin Stokes component, while filtering out the ASE noise resulting from the EDFA as well as the unwanted Brillouin anti-Stokes, Rayleigh and residual carrier components. A 125-MHz PIN photodiode is then used together with by a transimpedance amplifier (TIA) and a data acquisition system.

4. RESULTS

The BGS of the sensing fiber has been measured as a function of the distance by sweeping the frequency difference between the Brillouin pump and the probe around ~10.87 GHz (using 5k averages per single frequency component), as shown in Fig. 3a; in this figure we can see a top-view the Brillouin gain profile with optimized bi-directional distributed Raman amplification. The Brillouin gain increases along the initial fiber kilometers due to the co-pumping Raman amplification, reaching a maximum value at a distance of ~25 km. The counter-propagating Raman pump then amplifies both the Brillouin pump and probe signals near the far fiber-end, leading to an enhanced Brillouin interaction at very long distances (near ~120 km). By fitting the measured BGS with a Lorentzian curve at every fiber position, the BFS profile along the fiber has been obtained, as reported in Fig. 3b. It is important to mention that the BFS of both fiber spools are slightly different, with a variation of ~10 MHz; however, this value lies within the full-width at half maximum (FWHM) of BGS, allowing for an uninterrupted SBS interaction all along the sensing fiber, representing a realistic situation in terms of pump depletion effects if non-optimized power values are used. The measurand resolution is then obtained by calculating the standard deviation of the measured BFS as a function of the distance. In Fig. 3b we can clearly see that the noisiest BFS trace segment occurs at around ~90-km distance (where the Brillouin gain is minimum), resulting in a resolution better than ~2.1 MHz (equivalent to 45με/2.1°C temperature resolutions) throughout the whole sensing fiber. Considering that the BFS trace (measured at room temperature) does not exhibit any additional deviation,

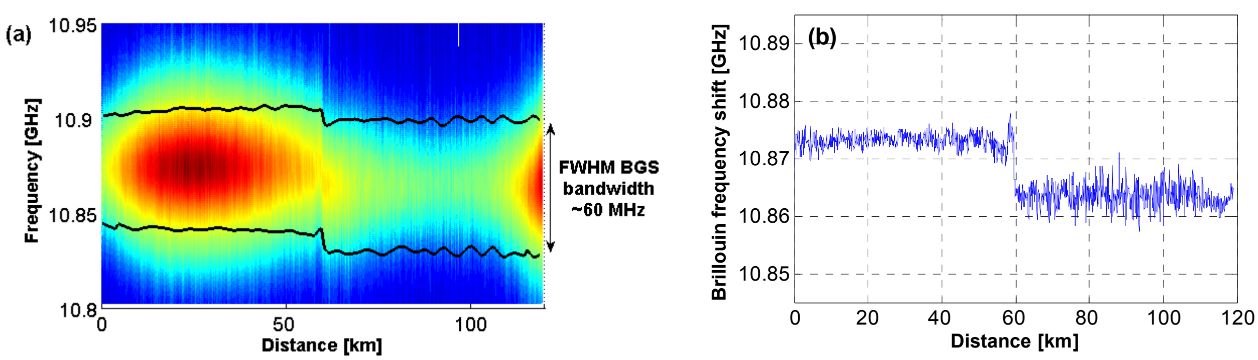

Fig. 3. (a) Top-view of the measured BGS, and (b) BFS of the sensing fiber versus distance.

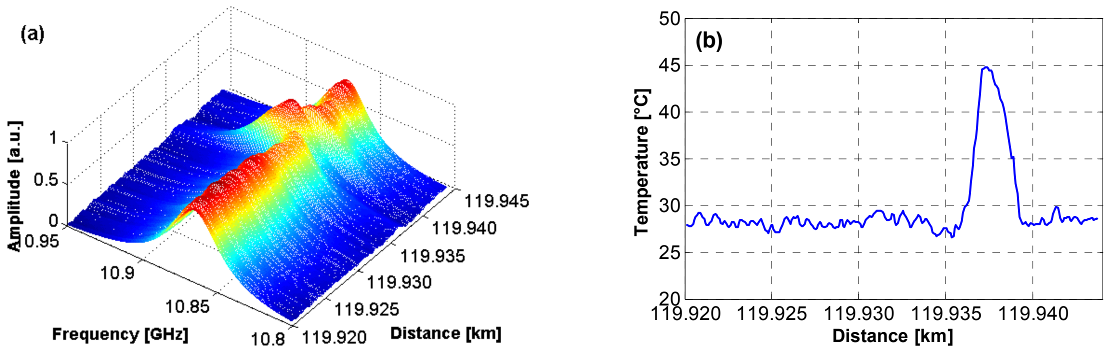

Fig. 4. (a) Brillouin gain spectrum and (b) temperature profile in the last 25 meters of fiber (the initial part is omitted for clarity).

we can assume that pump depletion as well as nonlocal effects are negligible in our experiment (this is also evident from the measured BGS reported in Fig. 3a). Furthermore, the BGS FWHM has also been analyzed as a function of the distance (reported in Fig. 3a), exhibiting a non-broadened, constant value of ~60 MHz along the 120 km fiber, and confirming that our measurements are not affected by nonlinearities, such as MI and SPM.

In order to assess the spatial resolution of the sensor, detection of a short hot-spot has been verified by heating 2 m of fiber up to 45°C near the far fiber-end (119.337 km), while keeping the rest of the fiber at room temperature (28°C). The measured BGS is reported in Fig. 4a, where we can observe a frequency shift of ~17 MHz at the hot-spot position. The temperature profile at ~120-km distance (obtained from the BFS parameter) is reporting in Fig. 4b, showing the ability to detect a temperature change of ~17°C within ~2 m of fiber (spatial resolution measured as 10%-90% response).

Note that BGS measurements were also carried out using a second FRL at 1450 nm as counter-propagating Raman pump (with the same power as the polarization-multiplexed FP lasers). In such a condition the higher RIN of FRL (~-105 dB/Hz compared to -135 dB/Hz of FP lasers) induces ~6 dB reduction in the acquired SNR traces with a significant reduction of the BOTDA sensor performance in terms of sensing range, confirming the observed degradation in [2] when using high laser RIN values.

5. CONCLUSIONS

In conclusion we have shown that an optimized first-order bi-directional distributed Raman amplifier can effectively enhance the range of BOTDA sensors. By optimizing the experimental conditions through numerical simulations and using low RIN pump lasers we have demonstrated record distributed measurements over 120 km of standard single-mode fiber with a spatial resolution of 2 m and a strain/temperature resolution of 45με/2.1°C respectively.

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