Enhanced-performance BOTDA sensing through optimized pulse coding and low-RIN bidirectional Raman amplification

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Abstract: An enhanced-performance BOTDA sensor is presented combining low-RIN distributed Raman amplification and RZ Simplex-pulse coding. Results demonstrate for first time 1 m spatial resolution over 120 km distance with 1.3°C/26 με resolutions

OCIS codes: (060.2370) Fiber optics sensors; (190.2640) Stimulated scattering; (290.5900) Scattering, stimulated Brillouin

1. Introduction and theoretical background

During the last years there has been an increasing interest in fiber-optic sensor technologies for many industrial applications. In particular, distributed temperature and strain measurements based on Brillouin optical time-domain analysis (BOTDA) sensors [1] have become an attractive solution for many strategic sectors such as security, energy, transportation, among others. The capabilities of BOTDA sensors to measure distributed strain and temperature along several tens of kilometers with meter-scale spatial resolution [2,3] actually provide unique advantages in comparison to standard discrete sensing technologies and also to other distributed sensing methods.

Typically a BOTDA sensor uses a pulsed pump signal and a weak continuous-wave (CW) probe signal (Brillouin gain configuration) interacting with acoustic phonons through stimulated Brillouin scattering (SBS) along the fiber [1]. The probe signal is amplified by SBS throughout the fiber length, depending on the frequency offset between the optical waves and SBS gain spectrum. By sweeping the probe-pump frequency offset, the Brillouin gain spectrum (BGS) can be measured along the whole fiber length with a distance information given by the time-of-flight of the pump pulses within the sensing fiber. The frequency offset showing the maximum SBS gain is named the Brillouin frequency shift (BFS), and exhibits a temperature and strain dependency that allows one to achieve distributed sensing along the optical fiber [1]. The use of BOTDA sensing technology over several tens of km is very attractive for many industrial applications; however, in long-range sensors, when fiber lengths exceeding many tens of km are used, the uniformity of the BFS can likely induce pump depletion and a non-local SBS interactions, thus introducing errors in the measured BFS profile and strongly limiting the attained performance [1].

In this paper, we combine the use of an optimized bidirectional distributed Raman amplifier with an optimized Simplex coding technique in order to extend the sensing distance of BOTDA sensors and to avoid temperature-strain errors due to non-local effects. Employing pulse coding based on return-to-zero (RZ) modulation format with an optimized duty cycle and attaining Raman amplification with low relative-intensity-noise (RIN) transfer, we experimentally demonstrate a significant signal-to-noise ratio (SNR) enhancement in a long-range BOTDA sensor achieving 1 m spatial resolution at 120 km distance with 1.3°C/26 με temperature-strain resolution.

Methods based on distributed Raman amplification [2], time-division multiplexing [3] and optical pulse coding [4] have been recently applied to extend the sensing distance of BOTDA sensors, reaching maximum ranges beyond 100 km, but achieving a limited spatial resolution of 2-3 meters. When smaller spatial resolution values (of the order of 1 m) are sought, significant detrimental issues come into play, since the typical lifetime of the acoustic phonons (~10 ns) results in a considerable broadening of the BGS and a reduction in the peak Brillouin gain levels, thus introducing a significant uncertainty when determining the BFS (and hence the temperature or strain) along the fiber. This issue leads to a significantly worse measurand resolution, up to the extent to hinder reliable measurements. Actually, using some techniques such as pulse coding and frequency-division multiplexing the sensing distance of BOTDA sensors with 1 m spatial resolution has been increased up a maximum of 75 km [7]. A further extension of the sensing range is not straightforward and is not always feasible. Recently, the combined use of distributed Raman amplification and pulse coding has been proposed [8]; however, the high-RIN characteristic of the Raman amplification scheme as well as the non-optimized Raman pump power levels have led to a noisy sensor system and reduced range of 75 km with 2 m spatial resolution only.

As demonstrated in [2], Raman-assisted BOTDA sensors require a careful power optimization for both Raman pumps (in forward and backward directions), the Brillouin pump and the probe signal. In this work aiming at 1 m spatial resolution, the optimization has to take into account a pulsewidth of 10 ns. Under this condition, the assumption of quasi-CW regime for stimulated Raman scattering is valid, and a similar optimization process as in [2] can be also employed in our Raman-assisted Simplex-coded BOTDA scheme. As a result, the optimum power levels at the 120 km-long fiber input are given by -20 dBm for the probe signal, 10 dBm for the Brillouin pump, 24.6 dBm for the backward Raman pump and 25.8 dBm for the forward Raman pump. Such values do not substantially differ from the single-pulse case, under the assumption of non-depleted Raman pumping which is verified with typical probe-pump power difference. From the carried out simulations on the probe-signal RIN-transfer crosstalk, a low-RIN backward Raman pump (co-propagating with the probe signal) has necessarily to be used (RIN < -125 dB/Hz) in order to avoid a significant RIN-transfer penalty to the probe signal, and to achieve an acceptable BOTDA sensor performance at 120 km distance.

Furthermore, an optimization of RZ Simplex pulse coding is necessary in order to avoid trace distortions due to pattern-dependent acoustic-wave pre-excitation [4]. As resulting from simulations with 10 ns coded pulses, a bit slot equal to 80 ns has to be used (12.5% duty cycle) to enable a significant acoustic wave damping.

2. Experimental Setup

The employed setup is shown in Fig. 1. The optical source is given by a narrowband distributed-feedback (DFB) laser operating at 1550 nm, with an output power which is split into two branches by a 3-dB optical coupler. In the Brillouin-pump branch, the laser light is amplified by an Erbium-doped fiber amplifier (EDFA) and then intensity-modulated by a Mach-Zehnder modulator (MZM) which is driven by a programmable waveform generator (WFG) in order to generate 127-bit Simplex-coded pulses with RZ modulation format.

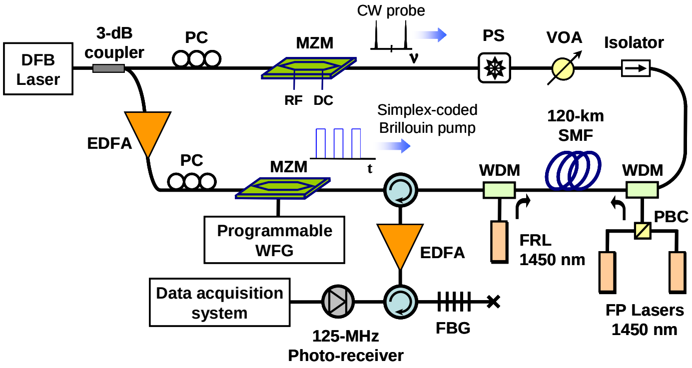

Fig. 1. Experimental set-up

In the probe-signal branch, a second MZM is used to generate two sidebands with a frequency separation that is controlled by an RF generator. A polarization scrambler (PS) is employed to depolarize the probe, thus reducing polarization-dependent SBS gain fluctuations. A variable optical attenuator (VOA) has been used to properly adjust the optical power launched into the sensing fiber.

The sensing fiber is given by 120 km of standard single mode fiber (SMF), composed of two 60 km-long fiber-spools with similar BFS. Two Raman pumps at 1450 nm are coupled into the fiber in forward and backward directions, allowing for bi-directional distributed Raman amplification of both Brillouin pump and probe lights. In order to avoid fluctuation due to polarization-dependent gain, a depolarized fiber Raman laser (FRL) has been used as forward-propagating Raman pump, while the backward-propagating Raman pump has necessarily been implemented in a low-RIN scheme by using 2 polarization-multiplexed Fabry-Perot (FP) lasers (RIN < -130 dB/Hz).

The probe-signal after propagation along the sensing fiber is then coupled into a linear-gain EDFA (used as preamplifier) through a three-port optical circulator. Another optical circulator followed by a 6-GHz fiber Bragg grating (FBG) has been used to filter out the ASE noise of the preamplifier as well as the unwanted Brillouin anti-Stokes and Rayleigh components. Finally, a 125-MHz photo-receiver followed by a data acquisition system connected to a computer has been used for trace processing.

3. Results

Simplex-coded BOTDA traces have been acquired using 127 bit RZ pulse sequences around a frequency span of ~250 MHz (total 8.1k trace time-averaging for the whole span). Figure 2 shows one decoded BOTDA trace at the peak BGS frequency. We can clearly observe the increased SNR obtained from the combination of pulse coding and the optimized distributed bi-directional Raman amplification. Actually, in addition to the SNR enhancement provided by the coding gain and the Raman amplification process, the higher average power of the coded probe signal also allows for a reduction of the ASE noise introduced by the EDFA used as preamplifier at the receiver. The decoded BGS as a function of the distance is shown in Fig. 3. A uniform Brillouin gain linewidth of about ~100 MHz has been obtained along the whole sensing fiber in good agreement with simulations (10 ns pulsewidth), indicating that no broadening of the spectrum has occurred due to acoustic phonon pre-excitation or nonlinear effects, such as modulation instability or self-phase modulation.

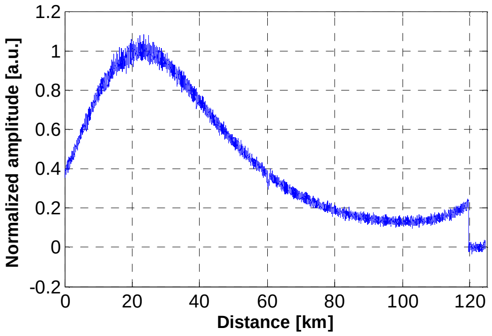

Fig. 2. BOTDA trace vs distance at the peak BGS frequency

The inset in Fig. 3 shows an example of measurement of the residual Brillouin pump (for one specific Simplex-codeword modulation) after propagation and amplification along 120 km; the measured waveform also confirms that bi-directional Raman amplification does not distort the coded pulse sequence thanks to the fast response time of the Raman effect. This is an important feature of our setup, since distortions can be other types of optical amplifiers are employed to amplify coded sequences, such as for EDFAs, which have been demonstrated to significantly impact on the performance of the BOTDA pulse coding technique.

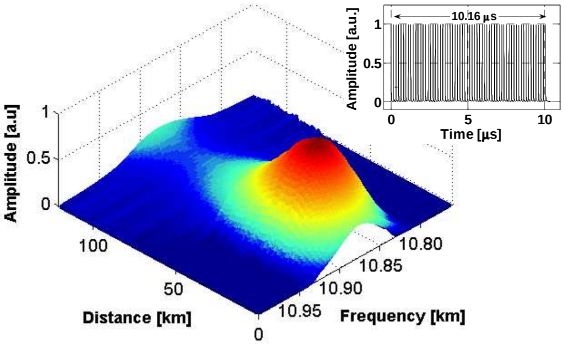

Fig. 3. Decoded BGS as a function of the distance. Inset: Residual Simplex-coded Brillouin pump after Raman amplification.

A Lorentzian curve has been fitted to the decoded BGS throughout the fiber, allowing us to obtain the BFS as a function of the distance. The BFS vs fiber length is reported in Fig. 4, showing a slight difference in BFS (~5 MHz) within the two different spools at room temperature (27.5°C). Since the BFS difference is small compared to the Brillouin gain linewidth (~100 MHz), the SBS interaction takes place continuously along the 120 km-long fiber, corresponding to the worst case condition in terms of pump depletion effects. Thanks to the use of a double-sideband probe-signal and an optimized bi-directional Raman amplification scheme, the level of pump depletion was kept as low as 0.8% (measured as the residual Brillouin pump variation with and without SBS interaction).

The worst-case temperature and strain resolutions have been evaluated as the standard deviation of the measured BFS. As shown in Fig. 2, the lowest SNR is observed at ~100 km distance, and the corresponding worst-case temperature and strain resolutions have been estimated as 1.3°C and 26 με, respectively.

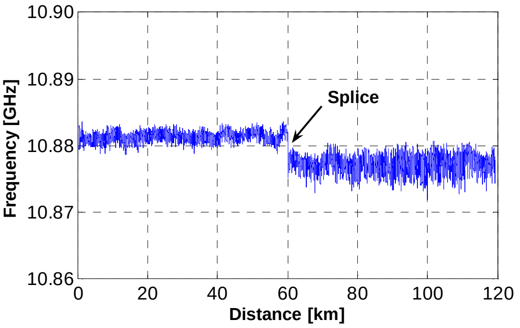

Fig. 4. BFS vs distance along 120 km-long fiber

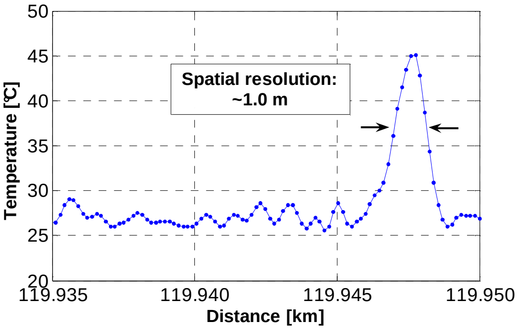

Fig. 5. Measured temperature vs distance near the fiber-end

In order to verify the real spatial-resolution capabilities of the implemented BOTDA sensor, *one meter* of fiber near a 120 km distance has been placed inside a temperature-controlled chamber at 45°C. The measured temperature profile for the last meters of fiber is shown in Fig. 5, where we can clearly observe an accurate measure temperature step (17.5 °C step) along a fiber section of ~1.0 m (calculated as the full-width at half maximum of the *T* change). This is the first demonstration of a BOTDA sensor over 120 km fiber with 1 m spatial resolution, also resulting in a significantly enhanced temperature resolution with respect to previously reported long-range BOTDA sensors.

In conclusion, we have sensibly enhanced the performance of long-range BOTDA sensors using an optimized bi-directional distributed Raman amplification scheme employing low-RIN backward-propagating pumps in combination with pulse coding techniques, based on RZ modulation format and optimized duty cycle. We have experimentally demonstrated, for first time to our knowledge, distributed sensing over 120 km distance with 1 m spatial resolution and temperature/strain resolutions of 1.3°C/26 με.

4. References

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