Long-Range Distributed Strain and Temperature Sensing with 40-cm Spatial Resolution Based on DPP-BOTDA Employing Optical Pre-Amplification and Simplex Coding

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Abstract: Sub-meter resolution sensing has been achieved employing linear pre-amplification with Simplex-coded pulses employing DPP-BOTDA. Results demonstrate a spatial resolution of ~40 cm over 56km sensing fiber with 1.1°C-22με temperature-strain resolution. .

OCIS codes: (060.2370) Fiber optics sensors; (190.2640) Stimulated scattering.

1. Introduction

Optical fiber sensors for distributed temperature and strain measurements most often employ Brillouin-based optical time-domain analysis (BOTDA) technique, allowing for strain-temperature sensing with spatial resolution values down to about 1 meter scale [1]. For many application domains, however, shorter spatial resolution values are required, most notably in the structural health monitoring (SHM) field, where centimeter-scale detection of cracks in civil engineering structures (within e.g. concrete or steel) could lead to early diagnosis of structural damage and prevention of catastrophic events. In order to achieve sub-meter spatial resolution sensing, complex techniques have to be used, such as those exploiting Brillouin echoes [2] or BOTDA with differential pulsewidth-pair schemes (DPP) [3]. More specifically, DPP-BOTDA constitutes an effective technique to perform distributed sensing with centimeter-scale resolution. Such a technique involves subtraction of two Brillouin signals originating from two light pulses with different pulse-widths; the subtraction process degrades the attained signal-to-noise ratio (SNR) values, thus strongly reducing the final strain-temperature resolutions especially at long sensing ranges. Within such schemes, linear coding techniques could be efficiently used, providing both a sensing range and resolution enhancement factor linked to the coding gain.

In this paper, a long-range DPP-BOTDA sensor based on linear Simplex coding (127 bit) has been implemented with optimized duty cycle and combined to linear optical pre-amplification, allowing for an unprecedented sensing performance, demonstrating a spatial resolution of ~40 cm over 56-km sensing distance with a measured frequency accuracy of ~1.1 MHz (equivalent to ~1.1°C / ~22-με temperature/strain resolution).

2. Theory and limiting conditions

In standard BOTDA sensing, two counter-propagating signals (a pulsed pump and a CW probe wave) interact with acoustic phonons thought stimulated Brillouin scattering (SBS). As a result of the interaction, the intensity variations of the CW probe signal can be expressed as:

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

where v_g is the group velocity, Δz is the interaction length (i.e. the spatial resolution), $I_P(\xi,\Delta\nu)$ is the pump intensity, and $g_B\,(\xi,\Delta\nu)$ is the Brillouin gain coefficient [4]. By tuning the pump-probe frequency difference, $\Delta\nu$, the Brillouin gain spectrum (BGS) is then reconstructed and the Brillouin frequency shift (BFS) is correspondingly obtained, providing information about the fiber temperature and/or strain. Eq. (1) highlights the trade-off between a small spatial resolution (proportional to pulsewidth Δz) and a good intensity contrast in the CW probe signal ΔI_{CW}, which is directly linked to the attainable SNR.

For spatial resolution values below the meter scale, where short pulse-widths have to be used (Δz < 1 m), the pulse duration becomes shorter than the acoustic phonon damping time (10 ns), causing a broadening in BGS in excess of 100 MHz, and leading to a degradation in strain and temperature resolutions [2]. Such an issue, limiting the achievable spatial resolution of standard BOTDA sensors to 1 meter, can be overcome by using DPP-BOTDA schemes. Under such schemes, the high-resolution BGS is obtained by subtracting two Brillouin-induced intensity traces ΔI_{CW} (see Eq. 1) originating from light pulses with different pulse widths (and with suitable frequency separation). Both pulses are longer than the acoustic-phonon lifetime, leading to an effective acoustic-wave pre-excitation and high spatial resolution, avoiding BGS spectral broadening. Unfortunately, the subtraction process of BOTDA traces drastically reduces the SNR, decreasing the temperature-strain resolutions and limiting the maximum achievable sensing distance. Moreover, the pump and probe lights are limited in their maximum usable power value by the onset of pump depletion and nonlinear effects (such as modulation instability) [5], limiting DPP-BOTDA performance in long sensing ranges.

In order to improve the SNR in standard BOTDA sensors, the use of optical pulse coding has been recently proposed [4]. This technique can be also fruitfully applied to enhance the performance in DPP-BOTDA sensors [6]. Actually, different unipolar coding schemes are available for this kind of application; as for instance, complementary-correlation Golay [6] or Simplex codes [7]. Even though both techniques provide similar SNR benefits under similar conditions (e.g. same code length and peak power), the implementation of DPP-BOTDA with Simplex coding can optimize the maximum peak power allowed into the fiber before the onset of nonlinear effects. Actually, in Simplex codes the number of pulses is constant for all code-words; this is not the case in Golay codes, which have a different number of pulses for different code-words [6]; therefore, the codeword containing the largest amount of pulses (leading to a longer SBS interaction length) limits the peak power to lower values with respect to the Simplex coding. For this reason, Simplex codes seem to be particularly efficient in long-sensing ranges. In Simplex coding, however, trace distortions in the decoded BGS can take place, due to the induced bit-dependent pre-excitation of the acoustic wave [8]. In order to avoid such distortions, coded pulses should be used with a return-to-zero (RZ) modulation format using optimized duty cycle values, thus allowing for a linear Brillouin amplification throughout the whole code-word. In such a way, the linear processing required for Simplex decoding can be successfully carried out, resulting in undistorted decoded-trace calculation.

Furthermore, when aiming at long sensing distances, the use of low pump power (to avoid nonlinear effects) and low probe power (to avoid the pump depletion) also limits the SNR at the receiver due to low Brillouin gain and high fiber loss. Hence optical pre-amplification could be used to enhance the probe-signal intensity contrast, enabling high-resolution long-range measurements. However, the use of optical pre-amplification in coded-BOTDA sensors is not straightforward, since this can easily induce distortions in the coded traces due to gain saturation, hindering the subsequent decoding process which requires high linearity for all codeword-related traces, and its use and conditions must be suitably optimized.

3. Experimental set-up

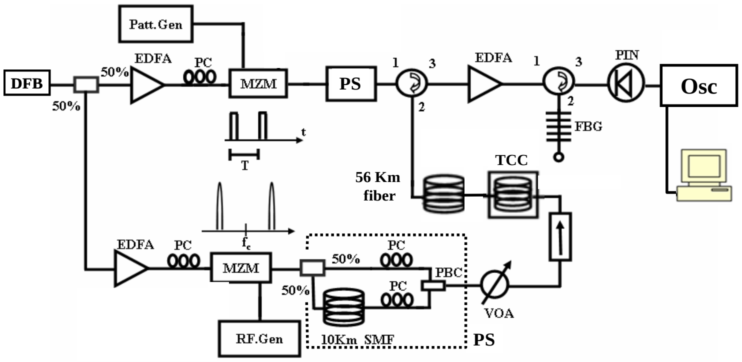

Fig. 1. Experimental set-up

The experimental set-up shown in Fig. 1 has been used to implement Simplex coding techniques in a DPP-BOTDA sensor. A DFB laser operating at 1550 nm has been used (P_{IN} ~13 dBm). The laser light is split into two branches to generate the probe and pump beams. In the probe beam, an erbium-doped fiber amplifier (EDFA) followed by a polarization controller and a Mach-Zehnder modulator (MZM), driven by a microwave generator, are used to modulate the intensity of the CW-light and to generate two sidebands around the laser frequency. A polarization scrambler (PS) and a variable optical attenuator (VOA) are used to launch into the fiber a depolarized probe beam with a suitable optical power, avoiding polarization-induced noise, pump depletion and distortion in the measured BGS due to nonlocal effects. In the pump branch, an EDFA, a polarization controller and a MZM are used to generate 127-bit Simplex-coded pulses with high peak power. Simplex coding with RZ pulses have been used with a bit slot of 120 ns and a pulse-width pair of 60 ns and 56 ns (with a rise/fall time shorter than 1 ns), allowing for a spatial resolution of 40 cm. Another PS is used to depolarize the pump beam, avoiding polarization-dependent oscillations in the Brillouin gain.

4. Results

In DPP-BOTDA experiments, Simplex-coded pump and CW probe lights are launched in counter-propagating directions into ~56 km of large effective-area single-mode fiber (LEAF). At the receiver, the relevant Stokes signal is extracted using optical circulators and a narrowband fiber Bragg grating (FBG) with 6-GHz bandwidth. The propagation of both sidebands actually reduces pump depletion [5], which constitutes one of the main factors limiting the sensing distance in long-range BOTDA sensors. The selected Brillouin component is then amplified by an EDFA operating as a linear pre-amplifier, avoiding trace distortion at the receiver. A 400-MHz photodiode has then been used together with a computer-controlled oscilloscope (Osc) to perform the measurements. In order to estimate the experimental spatial resolution, ~4 m of fiber at ~56-km distance have been placed inside a temperature

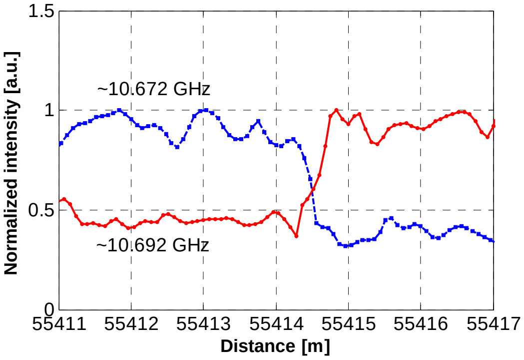

Fig. 2. Intensity traces at BGS peak frequencies near far fiber-end

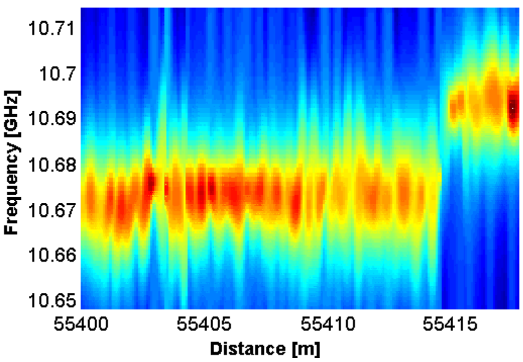

Fig. 3. Top view of decoded BGS near the far fiber-end

controlled chamber (TCC), where the fiber temperature has been increased to 45°C (the room temperature was 25°C). Considering that the BFS at 25°C is ~10.672 GHz, the induced temperature change shifts the BFS up to ~10.692 GHz (~20 MHz difference). Fig. 2 shows DPP-BOTDA traces obtained at both frequencies (10.672 GHz and 10.692 GHz). We can clearly see how the intensity of the trace at ~10.672 GHz decreases while the intensity of the other trace increases due to the higher temperature. The measurement of the whole BGS as a function of the distance is reported in Fig. 3, where we can observe the induced shift in the BGS. It is important to mention that the use of RZ modulation format with 50% duty cycle provides a uniform Brillouin amplification, avoiding nonlinear SBS amplification that could lead to distortion in the decoded BGS due to acoustic-wave pre-excitation [8].

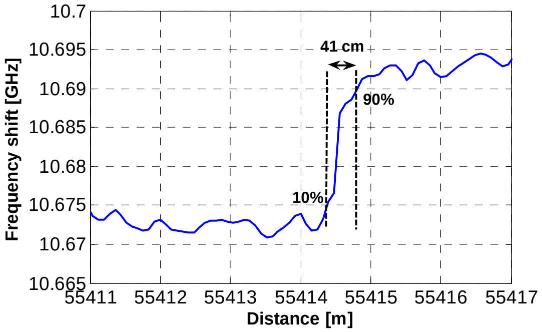

Fig. 4. Brillouin frequency shift versus distance, near fiber-end (56-km distance) around the heated fiber spool.

Note that thanks to a much higher intensity contrast occurring in the probe signal due to pulse coding, the use of an EDFA as a preamplifier turns out to be highly effective due to the significantly lower introduced noise, with respect to pre-amplification in single-pulse DPP-BOTDA experiments. The EDFA has been used under optimized gain and saturation power conditions to avoid trace distortions due to non-linear amplification with saturating gain. Despite such possible issues, the use of optical pre-amplification is possible for long sensing ranges, under suitable optimization, thanks to lower probe power at receiver side, allowing for linear preamplifier operation without EDFA-linked trace distortions. By fitting the measured BGS with a Lorentzian curve, the temperature profile of the last meters of fiber can be obtained from the BFS shown in Fig. 4. In order to estimate the experimental spatial resolution, the 10% to 90% of the frequency variation is analyzed. Fig. 4 clearly shows the obtained spatial resolution, which resulted to be ~41 cm near the fiber end. The achieved frequency accuracy has been then calculated as the standard deviation of the BFS profile, resulting in ~1.1 MHz at ~56-km distance (equivalent to ~1.1°C / ~22-με temperature/strain resolution).

In conclusion, we have demonstrated sub-meter spatial resolution (< 41 cm) in long-range sensing using DPP-BOTDA combined with 127-bit linear Simplex coding and linear-regime pre-amplification of coded sequences, which have enabled BFS measurement accuracy better than 1.1 MHz throughout 56-km fiber distance.

6. References

[1] T. Horiguchi, K. Shimizu, T. Kurashima, M. Tateda and Y. Koyamada, "Development of a distributed sensing technique using Brillouin scattering," *J. Lightwave Technol.*, vol. 13, no. 7, pp. 1296-1301, 1995.

[2] L. Thévenaz and S. F. Mafang, "Distributed fiber sensing using Brillouin echoes," *Proc. SPIE*, vol. 7004, pp. 1–4, 2008.

[3] W. Li, X. Bao, Y. Li and L. Chen, "Differential pulse-width pair BOTDA for high spatial resolution sensing," *Opt. Express*, vol. 16, no. 26, pp. 21616-21625, 2008.

[4] M. A. Soto, G. Bolognini, F. Di Pasquale and L. Thévenaz, "Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range," *Opt. Lett.*, vol. 35, no. 2, pp. 259-261, 2010.

[5] A. Minardo, R. Bernini and L. Zeni, "A Simple Technique for Reducing Pump Depletion in Long-Range Distributed Brillouin Fiber Sensors," *IEEE Sensors J.*, vol. 9, no. 6, pp. 633-634, 2009.

[6] H. Liang, W. Li, N. Linze, L. Chen and X. Bao, "High-resolution DPP-BOTDA over 50 km LEAF using return-to-zero coded pulses," *Opt. Lett.*, vol. 35, no. 10, pp. 1503-1505, 2010.

[7] M. D. Jones, "Using Simplex Codes to Improve OTDR Sensitivity", *IEEE Photonics Technol. Lett.*, vol, 15, no.7, pp. 822 - 824, 1993.

[8] M. A. Soto, G. Bolognini and F. Di Pasquale, "Analysis of pulse modulation format in coded BOTDA sensors," *Opt. Express*, vol. 18, no. 14, pp. 14878-14892, 2010.