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Distributed strain and temperature sensing over 50 km of SMF with 1 m spatial resolution employing BOTDA and optical pulse coding

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ABSTRACT

In this paper we demonstrate a long-range distributed strain and temperature optical fiber sensor using Brillouin optical time-domain analysis in conjunction with optical pulse coding. Compared to standard BOTDA, pulse coding provides higher signal-to-noise ratio at the same pump peak power, overcoming the limitations induced by pump depletion and modulation instability, and allowing to achieve a record of 1 meter spatial resolution over 50 km of standard single mode fiber with temperature and strain resolution of 2.2 °C and 44 με respectively.

Keywords: Stimulated Brillouin scattering, optical fiber sensors, temperature sensing, strain sensing, Simplex coding.

1. INTRODUCTION

Brillouin-based distributed optical fiber sensors have been a subject of intense research and industrial development, due to their capability of measuring strain and temperature simultaneously over long distances, enabling many practical applications ranging from civil and structural engineering to environmental monitoring and geo-technical engineering. While most recent developments in Brillouin-based techniques have been focused on fiber sensing with a sub-meter spatial resolution [1], distributed sensing with meter-scale resolution over fiber lengths spanning many tens of kilometer [2-4] is still an open issue. Among the different existing techniques for long-range sensing, Brillouin optical time-domain analysis (BOTDA) is the most commonly developed and effective scheme for strain and temperature measurements, enabling high-performance distributed sensing over long fiber ranges [2-4]. In long-range BOTDA-based sensors, the best performance records reported so far [3,4] result in 2 meter / 5 meter spatial resolution over 40 km / 51 km of standard single mode fiber (SMF). The ultimate limits to performance improvement known so far, are related to pump depletion and modulation instability [2,5]; such effects limit the maximum usable power levels, affecting the maximum sensing range and the accuracy in strain-temperature measurements. On the other hand, the Brillouin-scattering response time ultimately limits the BOTDA sensor performance in terms of spatial resolution to a minimum of ~ 1 meter.

In this paper, we propose and implement an optical pulse coding technique [6] in strain and temperature distributed sensors based on BOTDA. We demonstrate that the use of pulse coding effectively overcomes the pump power limitations, thus enabling higher signal-to-noise ratio (SNR) in strain-temperature measurements at the same pump power, allowing up to ~40 km sensing range enhancement. Experimental results demonstrate a record in BOTDA sensing performance of 1 m spatial resolution over 50 km of SMF with 2.2 °C / 44 με temperature / strain resolution.

2. THEORY

Stimulated Brillouin scattering (SBS) is a process in which two counter-propagating lightwaves, at different frequencies, interact with an acoustic wave. The maximum interaction between the two optical signals, so-called pump and probe signals, is reached when the frequency difference between them equals the acoustic wave frequency into the fiber [2]. This frequency difference is called Brillouin frequency shift (BFS) and is proportional to local temperature and strain variations along the sensing fiber (typically with ~1 MHz/°C and ~0.05 MHz/με sensitivities) [6,7], providing an effective mechanism for distributed measurement of these two physical parameters. The spatial information is obtained along the sensing fiber using a pulsed pump signal (launched at the fiber input, z=0) and a CW probe light (launched at the fiber end, z=L, in opposite direction); this technique is the basic of the well-known BOTDA [2,3], and provides a spatial resolution given by the interaction length between pump and probe signals. In order to reconstruct the Brillouin gain spectrum (BGS) along the fiber, the frequency ν of the probe signal is swept around the BFS, and the temporal (t)

variations in the counter-propagating CW probe intensity (ΔI_{CW}), induced by the Brillouin interaction along the fiber, are measured at the fiber input (z=0). This provides an expression for ΔI_{CW} given by [2]:

$$\Delta I_{CW}(t,\nu) = I_{CWL}\exp(-\alpha L)\left\{\exp\left[\int_{t\cdot v_g/2+\Delta z}^{t\cdot v_g/2} -g_B(\xi,\nu)Ip(\xi,\nu)\,d\xi\right]-1\right\} \quad \text{with, } 0<t<2(L-\Delta z)/v_g \tag{1}$$

where I_{CWL} is the input probe intensity (at z=L), α is the fiber loss coefficient, L is the fiber length, v_g is the group velocity and Δz is the pump-probe interaction length. $I_P(\xi,\nu)$ is the pump intensity at a given position $z=\xi$ as a function of the frequency. Under the un-depleted pump approximation $I_P(\xi,\nu) = I_{P0}\exp(-\alpha\xi)$, where I_{P0} is the input pump power. Due to the acoustic phonons exponential decay, the BGS ($g_B(\xi,\nu)$) can be well described by a Lorenztian function. Thus, in order to obtain the BFS profile continuously along the sensing fiber, the BGS needs to be measured at every fiber position.

Eq. (1) clearly points out a trade-off between the CW-intensity contrast (ΔI_{CW}) and the spatial resolution (Δz); when high spatial resolution is required (small Δz), the energy transfer (proportional to the integral in Eq. (1)) decreases accordingly, leading to a lower ΔI_{CW}. This effect impacts on the SNR of the measurement, limiting then the maximum reachable sensing distance of the BOTDA sensor. Thus, when long-range sensing is required, long pump pulses should be used in order to increase the SNR and then to extend the sensing range, negatively affecting the spatial resolution. One possibility to extend the sensing range, without affecting the spatial resolution, is to increase either the pump or probe power level (or both of them); however, the maximum usable power is limited by pump depletion [2] and modulation instability effects [5], inducing a distortion in the measured BGS. In such a condition pump depletion would induce non-local effects, so that the measured Brillouin gain at a given fiber position would depend on the Brillouin interaction at every preceding position, producing significant deviation of the measured BGS peak frequency with respect to the real local value [2]. This means that the measured BFS at a particular position in the fiber will be different to the real BFS, leading to systematic errors in the temperature or strain measurements. This effect becomes more and more relevant with the sensing range and optical powers, resulting in the main limitation for long-range BOTDA-based sensors [2,5].

On the other hand, optical pulse coding, as Simplex coding, has been shown to be a practical technique to improve the SNR and increase the sensing range in distributed sensors based on spontaneous Brillouin scattering [6]. The main limitation of Simplex codes stems from their linear property; this implies that their application is assessed with linear systems, while the exponential behavior shown in Eq. (1) for the Brillouin gain indicates a nonlinear process. However, since the interaction length in BOTDA sensors is very short, only a small percentage of the pump power is transferred to the probe signal (assuming no pump depletion). This allows us to consider the SBS gain as a linear process, obtaining:

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

If no pump depletion is induced, the single-pulsed pump can be replaced by a sequence of pulses defined by Simplex codes. Thus, in our proposed BOTDA scheme employing optical pulse coding, the trade-off between spatial resolution and sensing range can be significantly overcome, resulting in an interesting technique to extend the sensing range in BOTDA-based sensors while ensuring high spatial resolution.

3. EXPERIMENTAL SET-UP

Fig. 1 shows the experimental setup of the implemented long-range BOTDA-based sensor. The light source is a standard distributed-feedback (DFB) laser at 1535 nm with ~10 dBm output power. The CW-light is first split into pump and probe branches by using an optical splitter. One of the output of the splitter (70% output) is used as pump signal that is amplified by an Erbium-doped fiber amplifier (EDFA), which is placed before a Mach-Zehnder modulator (MZM) in order to avoid the distortion of the pulses due to Erbium-doped fiber gain depletion. This is basically the main modification of the setup with respect to a conventional BOTDA sensor, where the EDFA is usually situated after the MZM. However, since the maximum pump power level is limited by pump depletion and modulation instability [2,5], this modification does not represent a significant penalty for the system. In the implemented sensor, a computer controlled waveform generator (WFG) is connected to the MZM to generate the different Simplex bit-sequences. To evaluate the performance of coding in BOTDA sensors, the pump signal is shaped by

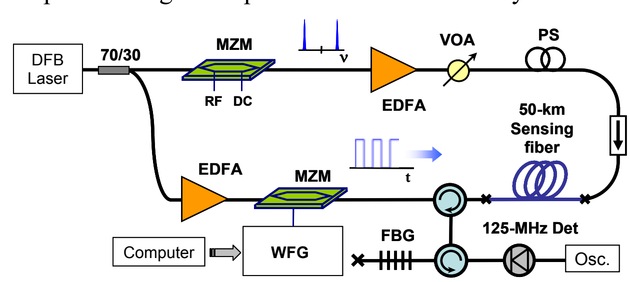

Fig. 1. Experimental setup for the Simplex-coded BOTDA-based sensor.

intensity modulating the CW-light using the MZM, producing either a single pulse or a 511-bit Simplex-coded sequence, with an individual pulse duration of 10 ns, providing an attainable spatial resolution of 1 m. The other output port of the splitter (30% output) is used to generate the probe signal; a MZM, controlled by a microwave (RF) generator and a DC voltage supplier, is used to generate two sidebands around the laser frequency with high carrier suppression [3]. Since the two sidebands will interact with the counter-propagating pump signal through the SBS process, by tuning the frequency of the microwave signal at around the BFS, it is possible to measure the BGS profile along the fiber. These two sidebands are first amplified by an EDFA, followed by a variable optical attenuator (VOA) to control the probe power level sent into the fiber. Note that the propagation of both sidebands along the fiber reduces pump depletion and non-local effects [7], alleviating the possible additional pump depletion introduced by Simplex coding in long sensing-range BOTDA-based sensors. On the other hand, since the efficiency of SBS is polarization dependent, a polarization scrambler (PS) has been used to depolarize the probe light, so that fluctuation of the Brillouin gain due to polarization changes along the fiber are highly suppressed. Probe and pump signals are then launched in counter-propagating directions into a 50 km standard single mode fiber. Although both sidebands of the probe are extracted at one of the fiber-ends using an optical circulator, only the Stokes component is selected by a narrowband fiber Bragg grating (FBG, < 0.1 nm), and then detected by a 125-MHz photodiode, connected to an oscilloscope controlled by a computer.

4. RESULTS

In order to estimate the real benefits resulting from pulse coding in BOTDA sensors, we have carried out a comparison between a 511-bit Simplex-coded sensor and a conventional sensor under the condition of equivalent measurement time and number of acquired traces. Every codeword has been averaged 4 times, equivalent to ~2K averages in the single-pulse case, corresponding to a measurement time of ~1 s per frequency step of the reconstructed BGS, excluding processing overhead. Fig. 2a shows a comparison of normalized BOTDA traces measured at the maximum Brillouin gain frequency shift (~10.986 GHz) with the 511-bit Simplex codes and the single-pulse case. We can clearly observe the SNR improvement obtained when optical pulse coding is used. The experimentally measured coding gain is actually ~10.3 dB, well in agreement with the expected theoretical value (10.5 dB). Considering the large amount of noise in the conventional BOTDA sensor, it is evident that no sensible measurement can be performed over the full 50-km range using 1 m spatial resolution. However, the coding gain in this case allows us to effectively extend the sensing range by ~40km; actually, the end of the fiber, in Fig. 2a, is clearly visible when using coding, obtaining ~5dB of SNR at 50-km distance, while, with single pulse, a SNR ~5dB is only obtained at 10 km distance. The ~40-km distance enhancement is also expected from theory, considering the improved SNR (~10.3 dB) and the typical fiber loss values (~0.25 dB/km). The BGS measured along the fiber when using Simplex coding is actually shown in Fig. 2b; the BFS parameter has then been obtained from the measured BGS along the fiber and is shown in Fig. 2b inset, for both conventional and Simplex-coded BOTDA sensors. By calculating the standard deviation of the BFS trace, we can obtain the frequency accuracy of the measurement which is ~2.2 MHz at 50-km distance in the case of coding. This corresponds to a temperature and strain resolution of ~2.2 °C and ~44 με, respectively. It is important to mention that the BFS obtained after 30 km-distance in the single-pulse case is meaningless since it corresponds to the peak value of a completely noisy spectrum, as reported in Figs. 2a and 3. Fig. 3 actually shows the normalized BGS measured at 45 km-distance for both Simplex-coded (upper trace) and single-pulsed cases (lower trace). This comparison clearly points out how a completely buried spectrum (as the one obtained by the conventional sensor) can be effectively measured and reconstructed using Simplex coding.

Pump depletion and nonlocal effects have been carefully investigated in our measurements, since they represent the main limitation of long-range BOTDA sensors [2,5]. If pump depletion occurs, the BGS should exhibit a hole "burned" around

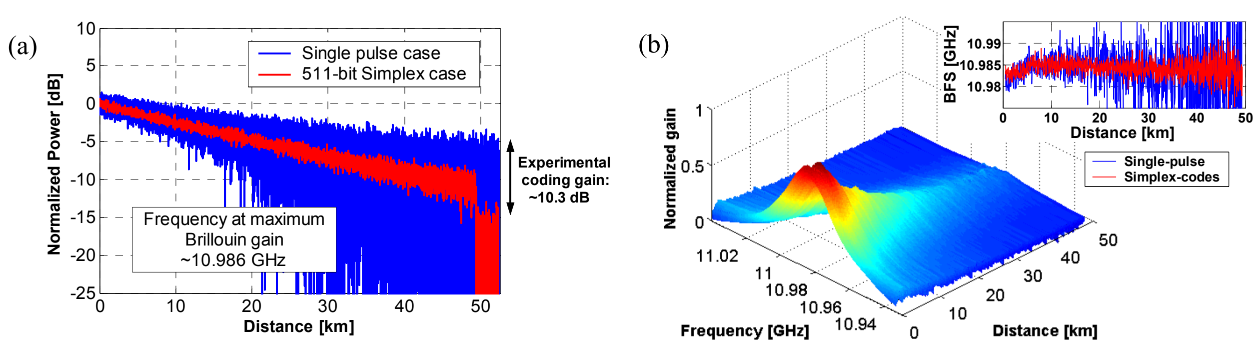

Fig. 2. (a) BOTDA-traces with both single-pulse and Simplex coding case, (b) BGS as a function of the distance, using 511-bit Simplex coding. Inset: BFS parameter measured along the 50 km fiber, with the conventional and Simplex-coded BOTDA-based sensor.

the BFS [7], which is not present in the spectra shown in Figs. 2b and 3. The residual pump variation, measured as the relative change of pump power after propagation along the fiber, with and without SBS interaction, is actually less than 0.7 %, indicating negligible pump depletion; this feature is also confirmed by the linear behavior (in dB scale) of the traces in Fig. 2a. Moreover, when pump depletion takes place, it should induce nonlocal effects, resulting in a deviation of the BFS profile along the fiber, which accumulates and increases with the distance [2]; however this effect has not been observed in our measurements, as shown in Fig. 2b inset.

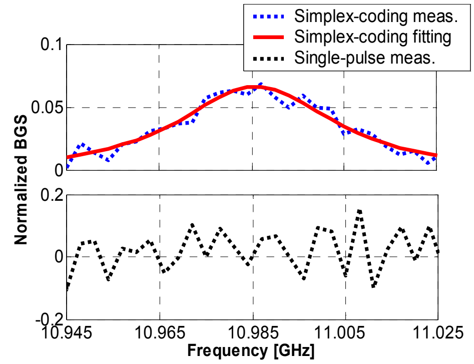

Fig. 3. Measured BGS at 45 km-distance, when using Simplex-coded and conventional BOTDA sensors.

In order to fully demonstrate a spatial resolution of 1 m over 50 km, we have increased the temperature of one meter of fiber, near 50-km distance, up to 50°C, while keeping the rest of the fiber at room temperature (25°C). Fig. 4a shows the measured spectrum at the end of the fiber, while Fig. 4b reports the BFS parameter in that region. We can clearly see a variation of ~25 MHz in the spectrum, corresponding to a ~25°C temperature change. The full-width at half maximum (FWHM) of the BFS change is ~1.0 m, demonstrating the potentiality of using optical pulse coding to achieve high spatial resolution (of the order of one meter) in long-range BOTDA sensors spanning several tens of kilometers.

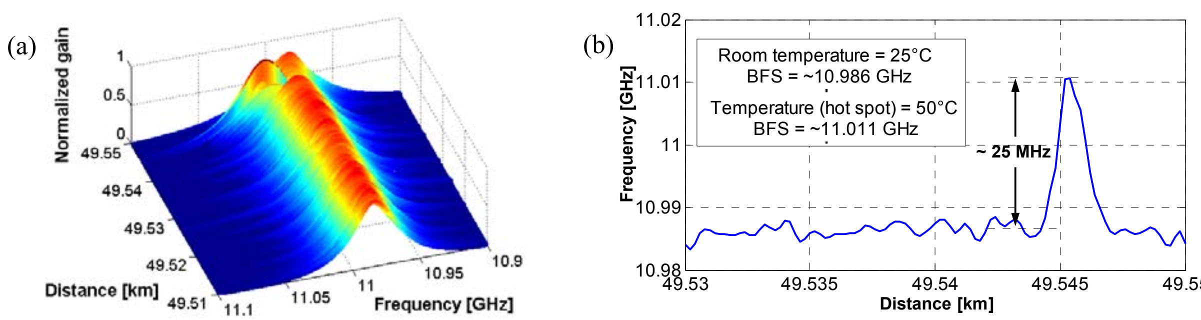

Fig. 4. Experimental demonstration of 1 m spatial resolution at 50-km distance. (a) BGS and, (b) BFS as a function of the distance.

5. CONCLUSIONS

In conclusion we have successfully applied optical pulse Simplex coding for distributed temperature and strain measurements in BOTDA-based sensors. Optical coding has been shown to be a cost-effective solution to overcome the pump peak power limitations which affect conventional BOTDA systems, allowing us to extend the sensing range by ~40 km, without major modifications of the setup. This feature allows us to reach a record in long-range BOTDA sensors of 1 meter spatial resolution over 50 km single mode optical fiber with strain and temperature resolution of 44 με and 2.2 °C respectively.

6. REFERENCES

[1] L. Thévenaz et al., "Distributed fiber sensing using Brillouin echoes," Proc. of SPIE 7004, 19th International Conference on Optical Fibre Sensors, 70043N, (2008).
[2] A. Minardo et al., "A reconstruction technique for long-range stimulated Brillouin scattering distributed fibre-optic sensors: experimental results," Meas. Sci. Technol., vol 16, pp. 900-908, 2005.
[3] S. Diaz et al., "A High-performance Optical Time-Domain Brillouin Distributed Fiber Sensor," IEEE Sensors J., vol. 8, no. 7, pp. 1268-1272, 2008.
[4] X. Bao et al., "Experimental and Theoretical Studies on a Distributed Temperature Sensor Based on Brillouin Scattering," J. Lightw. Technol., vol. 13, no. 7, pp. 1340-1348, 1995.
[5] D. Alasia et al., "Detrimental effect of modulation instability on distributed optical fiber sensors using stimulated Brillouin scattering," Proc. of SPIE 5855, 17th International Conference on Optical Fibre Sensors, 587-590 (2005).
[6] M. A. Soto et al., "Enhanced Simultaneous Distributed Strain and Temperature Fiber Sensor Employing Spontaneous Brillouin Scattering and Optical Pulse Coding," IEEE Photon. Technol. Lett., vol. 21, no. 7, pp. 450-452, 2009.
[7] A. Minardo et al., "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.