Enhanced long-range distributed strain and temperature sensing using BOTDA and optical pulse coding

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Abstract *Optical pulse coding is successfully applied to long-range sensors based on Brillouin optical time domain analysis, achieving a record of 1 meter spatial resolution over 50 km of SMF with 2.2°C / 44με temperature/strain resolutions.*

Introduction

Distributed optical fibre sensors based on Brillouin scattering are attracting a great interest [1], thanks to their unique simultaneous strain and temperature measurement capabilities. Among the different existing techniques, distributed sensing exploiting Brillouin optical time domain analysis (BOTDA) provides one of the most attractive schemes, allowing for high-performance sensing over long fibre ranges [2-4]. The best performance reported so far for long-range BOTDA sensors results in 2 m / 5 m spatial resolution over 40 km / 51 km single mode fibre [3,4]. The main factors limiting the sensing-range are given by pump depletion effects and modulation instability when large peak power levels are used [2,3].

In this paper, we propose and implement for the first time an optical pulse coding for distributed strain and temperature sensing using BOTDA. We demonstrate that the use of pulse coding effectively enhances the sensing range of BOTDA-based systems, providing the best performance reported so far, to our knowledge: strain and temperature sensing with 1m spatial resolution over 50 km of SM fibre with an accuracy of 2.2 °C / 44 με at the fibre-end.

Theory

Stimulated Brillouin scattering (SBS) is a process in which an acoustic wave interacts with two counter-propagating optical signals at different frequencies [2-4], the so-called pump and probe signals. The maximum SBS interaction occurs when the frequency difference between the two optical waves equals the acoustic wave frequency into the fibre, called Brillouin frequency shift (BFS). Since the BFS is temperature and strain dependent, we can measure both physical parameters by reconstructing the Brillouin gain spectrum (BGS) along the fibre [2,3]. This can be obtained by measuring the temporal changes in the CW probe intensity after the SBS interaction. Assuming no pump depletion, the energy transfer from the pump to the CW probe signal can be considered as a linear process, so that the temporal (t) changes in the CW probe intensity (ΔI_{CW}) as a function of the frequency, ν, can then be written as:

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

where v_g is the group velocity, Δz is the pump-probe interaction length, which defines the spatial resolution, $g_B(\xi,\nu)$ is the frequency dependent Brillouin gain at position $z=\xi$, and $I_P(\xi,\nu)$ is the pump intensity, given by $I_{P0}exp(-\alpha\xi)$ under the assumption of un-depleted pump (I_{P0} is the input pump power, α is the fibre loss). Eq. (1) clearly points out a trade-off between the CW probe signal variation ΔI_{CW} and the spatial resolution (Δz); in fact when high spatial resolution is required (small Δz), the integral in Eq. (1) decreases accordingly, leading to a lower ΔI_{CW}. This feature impacts on the measured SNR and limits the maximum sensing range [2,3]. Moreover, the peak power (of both pump and probe) cannot be too much increased because modulation instability or pump depletion would take place leading to distortions in the measured BGS [2]. These effects increase with the sensing range [2] and represent the main limitation in long-range BOTDA-based sensors, leading to errors in temperature/strain estimation.

On the other hand, we have recently demonstrated that the use of optical pulse coding [5], as for instance Simplex codes, allows for an effective sensing range enhancement in case of spontaneous Brillouin-based sensors. In this paper we propose and demonstrate the use of pulse coding in BOTDA-based sensors. Assuming no pump depletion and considering then the linear behaviour described by Eq. (1), we expect that Simplex codes can be effectively used to generate the pump signal, alleviating the trade-off between spatial resolution and sensing range. We show that the proposed coded BOTDA scheme allows for a significant sensing range enhancement while ensuring a high spatial resolution.

Experimental set-up

Fig. 1 shows the experimental set-up used to implement the Simplex coded-BOTDA system. The light source is a DFB laser operating at 1535 nm with ~10 dBm optical power. The CW-light is split into pump and probe branches; the pump power is amplified using an Erbium-doped fibre amplifier (EDFA), from which pulses are shaped by a Mach-Zehnder modulator (MZM), which is controlled by a waveform generator in order to obtain either a single pulse or a 511-bit Simplex-coded sequence with an

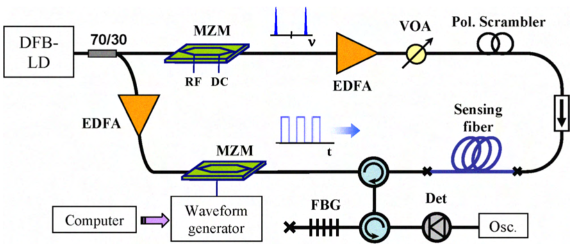

Fig. 1: Simplex-coded BOTDA-based sensor

individual pulse duration of 10 ns, allowing for 1 m spatial resolution. In the probe branch, the frequency shift of the laser light is realized by using a MZM controlled by a microwave (RF) generator and a DC voltage. Two modulation sidebands are produced in the probe laser spectrum, with a highly suppressed carrier [3]. The optical frequency of the probe can be easily controlled by adjusting the frequency of the microwave signal. The probe signal is then amplified by an EDFA, followed by a variable optical attenuator (VOA) to control the probe power level launched into the fibre. In order to reduce polarization-induced fading, a polarization scrambler is used to depolarize the probe light. Both probe and pump signals are launched in counter-propagating directions into a 50km standard single mode fibre (SMF). The probe signal components are extracted at the fibre end using an optical circulator and a narrowband fibre Bragg grating (FBG, < 0.1 nm); only one sideband is detected by a 125-MHz photodiode, which is connected to an oscilloscope controlled by a computer.

Results

In order to estimate the benefit resulting from Simplex coding under the condition of an identical measurement time, every codeword has been averaged 4 times, equivalent to ~2K averages in the single-pulse case. Fig. 2 compares the traces obtained with the single-pulse case and the Simplex-coding, at the maximum Brillouin gain frequency shift (~10.986 GHz). We can clearly see that no sensible measurement can be performed over the full 50-km range using 1m spatial resolution and conventional BOTDA. On the other hand, the fibre far end is clearly observed when using Simplex coding, obtaining ~ 5dB of SNR at 50-km distance. By comparing the SNR of both traces, the experimental coding gain reaches ~10.3 dB, which is in agreement with the expected theoretical value (10.5 dB). Fig. 3 shows the BGS measured along the fibre, when using Simplex coding, by sweeping the

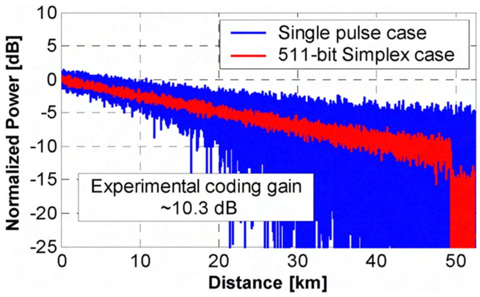

Fig. 2: BOTDA-traces with single pulse vs Simplex coding

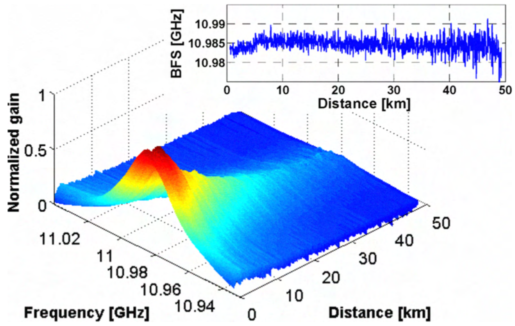

Fig. 3: Measured BGS vs distance, when using coding. Inset: BFS parameter measured along the 50 km of fibre

modulation frequency of the probe signal. It is important to point out that there is no distortion of the trace due to the use of this coding technique. Pump depletion and nonlocal effects [2] have not been observed in the measurements, as confirmed by the linear behaviour (in dB scale) of the traces shown in Fig. 2. Moreover, the measured residual pump variation when using pulse coding is less than 0.7% (measured as the relative variation of the residual pump power after propagation into the fibre, with and without Brillouin interaction), indicating a negligible pump depletion along the sensing fibre. The frequency accuracy obtained when using coding (calculated as the standard deviation of the BFS, shown in Fig. 3 inset) is ~2.2 MHz at 50-km distance, representing a resolution in temperature and strain equivalent to ~2.2 °C and ~**44** $\mu\varepsilon$, respectively.

In order to fully demonstrate the long-range performance of the proposed scheme, 1m of fibre has been heated up to 50°C near the far fibre-end, corresponding to a temperature variation of 25°C with respect to the room temperature. Fig. 4 shows the BFS obtained at 50-km distance, where we can clearly see a variation of ~25 MHz over a fibre length of 1m (calculated as the full-width at half maximum, FWHM, of the BFS change), demonstrating the enhanced performance of the proposed technique.

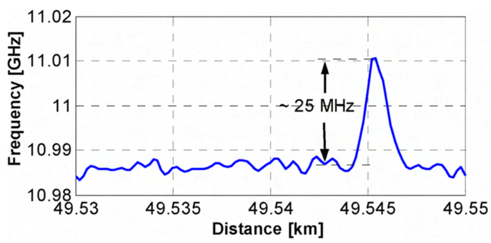

Fig. 4: BFS when heating 1m of fibre near 50-km distance

In conclusion, we have demonstrated that pulse coding can successfully extend the range of BOTDA sensors by at least 20 km, with no modification of the setup, resulting in a cost-effective solution.

References

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