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

M. A. Soto,1,2 G. Bolognini,2 F. Di Pasquale,2 L. Thévenaz1
1 EPFL Swiss Federal Institute of Technology, Institute of Electrical Engineering, Group for Fibre Optics, STI IEL GR-SCI Station 11, CH-1015 Lausanne, Switzerland, email: m.soto@sssup.it
2 Scuola Superiore Sant’ Anna, via G. Moruzzi 1, 56124, Pisa, Italy

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 / 44 μC 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 μC 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 \( I(t) \) changes in the CW probe intensity \( \Delta I_{cw}(t) \) as a function of the frequency, \( \nu \), can then be written as:

\[
\Delta I_{cw}(t, \nu) \propto \int \frac{v}{\nu^2} - g_B(\xi, \nu) I_p(\xi, \nu) d\xi \tag{1}
\]

where \( v \) is the group velocity, \( \Delta \) 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 \( I_p \exp(-\alpha \xi) \) under the assumption of un-depleted pump \( (I_p) \) is the input pump power, \( \alpha \) is the fibre loss).

Eq. (1) clearly points out a trade-off between the CW probe signal variation \( \Delta I_{cw} \) and the spatial resolution \( \Delta \nu \). If \( \Delta I_{cw} \) is the integral in Eq. (1) decreases accordingly, leading to a lower \( \Delta I_{cw} \). 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
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