

Time/frequency coding for Brillouin distributed sensors

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ABSTRACT

In this paper, we propose a novel coding for long range Brillouin Optical Time Analysis (BOTDA) distributed sensors based on a combination of time and frequency pulses, resulting in an additional coding gain of $\sqrt{2}$ with respect to traditional intensity-modulated codes. The generation of frequency-chirped pseudo-arbitrary pulses in return-to-zero (RZ) format with a Direct-Digital Synthesizer (DDS) is presented and the coding gain is experimentally verified, perfectly matching its theoretical value.

Keywords: Stimulated Brillouin scattering, fiber-optics sensors, optical signal processing, distributed fiber sensors.

1. INTRODUCTION

Distributed fiber sensors based on stimulated Brillouin scattering for long distance measurements have been deeply studied for two decades, as they make possible accurate temperature/strain measurements over tens of kilometers with a metric spatial resolution^{1,2}. Research on Brillouin optical time-domain analysis (BOTDA) reached a new level during the past three years thanks to pulse coding techniques. Simplex code was first employed to increase the distance range up to 50 km with a spatial resolution of one meter³. Non return to zero (NRZ) coding causes strong distortions on the local Brillouin gain spectra, due to the pre-excitation of the acoustic wave leading to a distorted response⁴. In this paper, we introduce a unique and original coding scheme named “time/frequency code”, specially configured and optimized for BOTDA sensing. Each pump pulse of the coded sequence has a distinct frequency that is generated at a very fast rate by a direct digital synthesizer (DDS) in the microwave domain. A general principle of the code is presented, and distributed measurements are demonstrated over a distance range of 25 km with a spatial resolution of 2 meter.

2. TIME/FREQUENCY CODE

So far coding schemes in BOTDA are based on the on/off intensity modulation of pump pulses. For example, the second sequence of the Simplex code of length $L=15$ is 011001100110011. Considering globally all sequences, there is on average the same number of “0” and “1” in this code. The decoding process shows no distortion only if all “1” pulses carry the same energy and, since all sequences are distinct, this requires that the boosting amplification on the pump pulses is absolutely temporally flat and invariant from sequence to sequence³. Together with the serious limitation due to the onset of other nonlinear effects⁵ (modulation instability, forward Raman scattering), this practically limits the peak pump power to approximately 15-20 dBm. Actually, since this peak power is strictly limited, a binary intensity coding is not using the full energy potentiality of the sequence, since no energy is transmitted 50% of time - during the “0” bits - and this automatically reduces the gain in signal-to-noise ratio resulting from the coding.

The invented code presented here is filling these energy temporal gaps by realizing coding sequences of frequency modulated pulses having all the same peak power. This way the full energy potentiality of the sequence is exploited and the frequency coding is arranged, so that it corresponds to the frequency grid used for scanning the pump-probe frequency difference. So, instead of sending interacting pump and probe signals with a fixed sequentially incremented frequency difference, a distinct frequency is allocated to each pump pulse forming the code and each sequence presents a different arrangement of these frequency-modulated pulses. Once all traces are recorded, the equivalent traces as those produced by a very intense single frequency pulse can be retrieved via a consequent data processing based on matrix

3. EXPERIMENTAL SET UP

Figure 2 shows a scheme of the experimental set-up. The output of a distributed feedback (DFB) laser source, operating at 1533 nm and delivering a 10 dBm optical power, is split in two arms by an optical coupler. The continuous wave (CW) probe, directly tapped from the laser source, propagates through the lower arm, where the sensing fiber is placed, and is then detected after a circulator. In the upper arm, an intensity modulator (IM), operating in suppressed carrier mode, is driven by a DDS frequency-agile microwave generator: the RF code sequences are uploaded into the DDS, its output is then frequency-doubled and fed to the IM. One of the two generated frequency sidebands is filtered out by a fiber Bragg grating to only leave the upper sideband, which is then amplified by an EDFA. A polarization scrambler is used to suppress the dependence on polarization of the Brillouin response along the fiber.

4. MEASUREMENTS AND RESULTS

In order to evaluate the coding SNR gain, we have performed a distributed measurement over 25 km of a standard G.652 fiber. The spatial resolution was set to 2 m, corresponding to pump pulse duration of 20 ns (the DDS is able to deliver a distinct frequency at a 4 ns rate), in a RZ format: the zero segment duration was set to 60 ns, leaving enough time to the acoustic wave to sufficiently damp⁴. The code length was $L=151$ (prime number), each trace being averaged 4 times, corresponding to a total theoretical SNR enhancement of about 200 (including time-averaging and the coding gain). The 151 distinct frequencies were equally spaced between 10.88 GHz and 11.075 GHz, with a corresponding frequency step of 1.3 MHz. The pump and probe powers were 20 dBm and -10 dBm respectively, this latter being set so that pump depletion is not exceeding 20% at the fiber output⁸. A key point to mention is that the intensity spatial profile of the distributed Brillouin gain appears nearly identical for all traces, since all sequences of pump pulses contain all frequencies, and in particular those that lie in the Brillouin gain spectrum (figure 3).

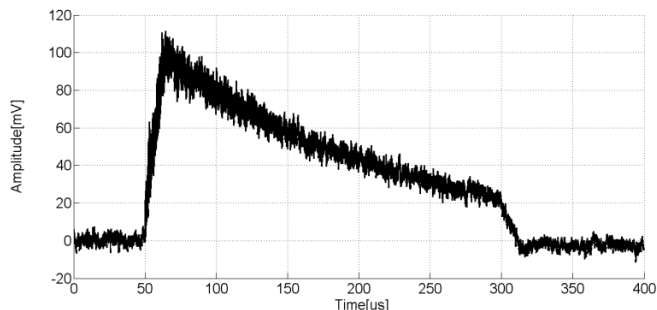


Figure 3: BOTDA intensity temporal profile obtained using a typical coded pulse sequence ($L=151$).

The variation in intensity between all the L^2 traces was $\pm 20\%$ for this measurement. Figure 4 shows the measurement of the Brillouin gain spectrum at the output of the fiber. The obtained residual standard deviation after a quadratic fitting, results in an experimental coding gain of 9.7 dB, which is in agreement with the theoretical value (9.4 dB).

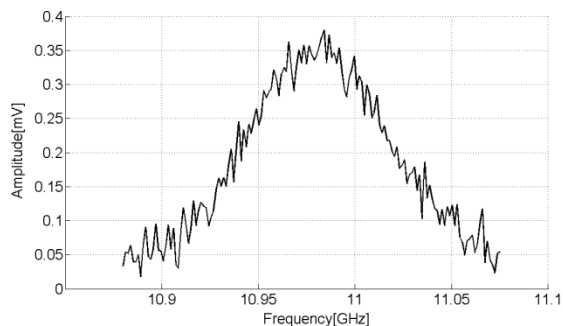


Figure 4: Brillouin gain spectrum at a distance of 24.5km, obtained after processing using the complex decoding procedure.

Finally, figure 5 shows the measured Brillouin frequency shift (BFS) along the fiber, with an accuracy of ± 1.5 MHz at the end of the fiber. These results are of course still below the state-of-the-art, but the purpose of the experimental test

was to demonstrate that the information can be securely retrieved, in spite of a complex decoding, and the coding brings the SNR enhancement that is anticipated. In addition this clearly proves that the coded frequencies are correctly generated in the DDS, with excellent accuracy (in fact better than 0.1 MHz). The next step will be the implementation of this code in a top performing BOTDA set-up.

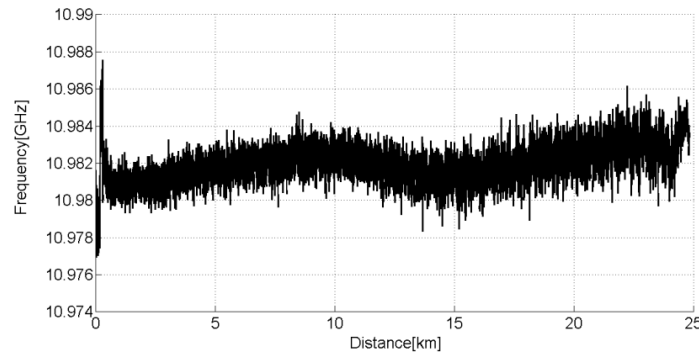


Figure 5: BFS in the fiber using time/frequency coding ($L=151$) with RZ pulses.

5. CONCLUSION

In conclusion, we have successfully shown that a specific dedicated coding - the time/frequency code - can be implemented in BOTDA sensors, taking fully advantage of the double scanning (position and pump-probe detuning) acquisition required for such sensors. The position and frequency scans are both rearranged by the coding, leading to a beneficial gain in SNR and the information can be reliably retrieved despite the complex array governing the rearrangement of the launched sequences. The direct digital synthesizer is a crucial element since its recent availability in the microwave domain makes possible the fast generation of short pulses, at distinct frequencies and at a rate in the nanosecond range to build the coded sequences. Measurements have proved that the coding gain follows the theoretical relation $(L/2)^{1/2}$, which is larger than conventional binary intensity-based codes.

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REFERENCES

- [1] Horiguchi, T., and Tateda, M., "BOTDA—non-destructive measurement of single-mode optical fibre attenuation characteristics using Brillouin interaction: theory", *J. Lightwave Technol.* 7, 1170-6 (1989).
- [2] Horiguchi, T., Kurashima, T., and Tateda, M., "A technique to measure distributed strain in optical fibers", *IEEE Photon. Technol. Lett.* 2, 352 (1990).
- [3] Soto, M. A., Bolognini, G., Di Pasquale, F. and Thévenaz, L., "50 km Simplex-coded BOTDA sensor for distributed strain and temperature measurements with 1 m spatial resolution", *Optics Letters* 35(2), 259-261 (2010).
- [4] Soto, M. A., Bolognini, G. and Di Pasquale, F., "Analysis of pulse modulation format in coded BOTDA sensors", *Optics Express* 18(14), 14878-14892 (2010).
- [5] Foaleng, S. M. and Thévenaz, L., "Impact of Raman scattering and modulation instability on the performances of Brillouin sensors", *Proc. SPIE* 7753, 77539V-1 (2011).
- [6] Jiang, Z, Xu, Z. and Gao, S., "Algorithms for finding the inverses of factor block circulant matrices", *Numerical Mathematics* 15(1), 1-11 (2006).
- [7] Vogel, C. R., "Computational methods for inverse problems", *Frontiers in Applied Mathematics* (2002).
- [8] Thévenaz, L., Foaleng, M. F. and Lin, J., "Impact of pump depletion on the determination of the Brillouin gain frequency in distributed fiber sensors", *Proc. SPIE* 7753, 775322 (2011).