Advanced Pulse Coding Techniques for Distributed Optical Fiber Sensors

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Abstract: Advanced optical pulse coding methods to enhance the performance of distributed optical fiber sensors are reviewed. In particular, the latest implementations dedicated to high-performance long-range Raman and Brillouin based distributed sensing are described.
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1. Introduction

Increasing the number of resolved points in distributed optical fiber sensors, by either improving the spatial resolution or extending the fiber length, is one of the main challenges that new techniques have been facing during the last years [1]. Considering that the sensor response is proportional to the optical energy contained in the pulse propagating along the fiber, the signal-to-noise ratio (SNR) of the measurements results to be reduced whenever the spatial resolution is improved (i.e. shorter pulses are used) or the sensing distance is extended, leading to poorer sensing performance. In order to increase the dynamic range of acquired temporal traces, longer pulses and/or higher peak power could be used. However, the pulse peak power launched into the fiber cannot be increased indefinitely as a consequence of the onset of nonlinear effects, while on the other hand longer pulses lead to an unavoidable degradation of the spatial resolution. The onset of the nonlinear effects is essentially determined by the peak power launched into the fiber, and hence, an alternative to increase the optical energy propagating in the fiber without increasing the peak pump power is to spread the energy in the time domain by using suitable coded pulse sequences [2,3], thus avoiding nonlinearities and maintaining the spatial resolution given by the single-pulse duration.

In this paper, a review of the theory of optical pulse coding is first addressed. The specific constraints to real implementations of pulse coding are then described for high-performance sensing schemes based on Raman and Brillouin scattering. Recent novel methods, including bipolar and time-frequency domain coding, are also discussed.

2. Optical pulse coding – Principle of operation

Optical pulse coding use sequences of short pulses (see Fig. 1a) which are launched into the fiber in bursts at a low repetition rate fixed by the fiber length, as in a standard single-pulse scheme. The method requires a suitable decoding process based on a *linear* transformation to retrieve the single-pulse fiber response, which is obtained with an improved SNR. Measurements with higher SNR offer the possibility to improve the spatial resolution, extend the sensing range, reduce the measurement time and/or reduce the measurand uncertainty along the entire sensing fiber.

Conventional distributed optical fiber methods use intensity-modulated pulses, which unfortunately limit the implementation of optical pulse coding only to *unipolar codes* containing 0's and 1's [2,3]. As shown in Fig. 1a, the codes define sequences of 0's and 1's, which represent the OFF and ON state of the light, respectively. Among the existing types of codes, two of them have offered significant benefits for sensing; they are: *i)* Simplex codes [2], and *ii)* Golay codes [3]. Both unipolar codes provide similar *coding gain*, which is defined as the SNR enhancement with respect to the single-pulse acquisition. To reach substantial performance improvement, the code length L, i.e. the number of pulses per sequence, is typically greater than 63 bits, which leads in both cases to a coding gain equal to $\sqrt{L}/2$, as shown in Fig. 1b. This way, more than 10 dB SNR enhancement can be achieved using 512 bits/sequence. It is important to mention that the SNR enhancement provided by pulse coding is calculated assuming the same number of acquired traces, i.e. same measurement time, as required by the single-pulse case [2,3]. Thus, besides the overhead required for data storage and decoding process, the method does not increase the measurement time.

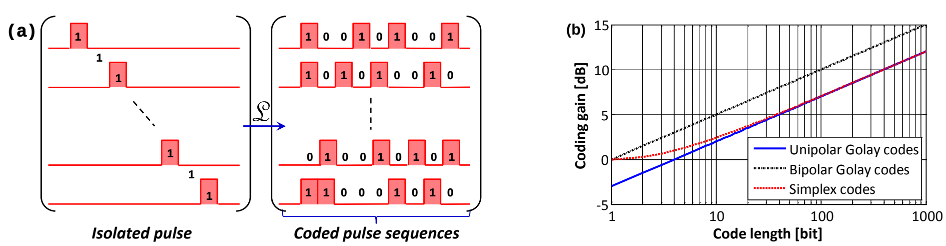

Fig. 1. Principle of optical pulse coding for distributed optical fiber sensing. (a) Specific codes define the distribution of pulses within several sequences. (b) Coding gain (SNR enhancement) obtained by known optimum codes, such as Simplex and Golay codes

3. Implementation of pulse coding in Raman-based distributed temperature sensors

The first implementations of pulse coding in distributed fiber sensing were carried out in Raman-based sensors based on semiconductor lasers and operating over either single-mode [4] or multimode [5] fibers. Significant SNR enhancement has been demonstrated using standard coding methods; however, the potential of pulse coding in terms of absolute performance has been limited to some extent by the maximum power offered by semiconductor lasers.

High-performance Raman distributed sensors typically operate over multimode fibers (MMF) and make use of high-power pulsed lasers, such as Q-switched or rare-earth-doped fiber lasers, which are characterized by peak powers of tens of Watt, repetition rates of up to a few hundreds kHz and very low duty cycles. Unfortunately, this type of pulsed-laser technology is not compatible with the pulse modulation frequencies (up to 100 MHz for 1 m spatial resolution) required to implement standard pulse coding. Thus, recently a new method based on cyclic Simplex codes has been proposed to overcome this limitation [6]. Contrarily to standard coding methods, cyclic codes are based on a single quasi-periodic bit sequence [6]; and owning to its particular properties, bits do not need to be sent along the fiber in bursts, so that they can be individually launched into the fiber at a low repetition rate in order to fill the entire sensing length with many bits. Cyclic codes enable the use of high peak power lasers not only in MMF but most noticeable also in single-mode fibers [7], thus overcoming the limitations imposed by modal dispersion in MMF as well as the low SNR characterizing time-domain Raman traces in single-mode fibers.

3. Implementation of pulse coding in Brillouin distributed fiber sensors

Optical pulse coding in Brillouin optical time-domain reflectometry (BOTDR) [8] or analysis (BOTDA) [9] was firstly implemented using non-return-to-zero (NRZ) intensity-modulated pulses. However, it was quickly proved that the pre-excitation of the acoustic wave resulting from sequences of NRZ pulses leads to a nonlinear Brillouin interaction that breaks the linearity required by pulse coding techniques [10], resulting in distortions of the measured Brillouin gain spectrum due to bit patterning effects. In order to overcome this problem, pulses with return-to-zero format have to be used whenever coding is implemented in Brillouin sensors with metric spatial resolution [10].

In BOTDA schemes, the pump-probe interaction, requiring the scan of the Brillouin gain/loss spectrum, has also enabled the implementation of novel pulse coding methods with larger coding gain. In this regard, two different approaches have been recently proposed: *i)* time-frequency codes, also called colored codes [11,12], and *ii)* bipolar codes [13]. In the first case, coding methods based on pseudo-random pulse sequences [11] or on a modified version of Simplex codes [12] have been proposed. In such schemes, sequences are coded in the time domain with pulses at different frequencies, taking full advantage of the double scanning (position and pump-probe detuning) acquisition in BOTDA schemes. In the second case, a novel implementation for pulse sequences containing -1's and 1's (*bipolar codes*) has been recently proposed making consecutive use of Brillouin gain and loss processes [13]. The technique requires pump pulses at two different frequencies, symmetrically generated at equal spectral separation from a single-frequency probe, showing stronger robustness to pump depletion due to gain/loss compensation. Owning to its perfect symmetric operation in gain and loss modes, BOTDA offers the unique possibility to implement bipolar codes in distributed sensing. This method has opened the possibility to use new types of coding in BOTDA sensing, such as bipolar Golay codes [3], which, as shown in Fig. 1b, offer a larger SNR enhancement than any optimal unipolar code used for distributed fiber sensing.

In conclusion, optical coding has shown to be a cost-effective solution to improve the SNR of time-domain measurements in distributed optical fiber sensors without major modifications of the standard schemes. Although the operating principle of the method is the same for Raman and Brillouin distributed sensors, specific implementations are required to overcome practical and physical limitations and to take advantage of the specificities of each scattering process. This has enabled Raman and Brillouin distributed sensing along 58 km and 120 km of single-mode fibers, respectively, using a spatial resolution of few meters.

4. References

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