Hybrid Coding Scheme for Brillouin Optical Time-domain Analysis Based on Golay and Differential Pulses

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Abstract: A hybrid Golay coding method based on differential pulse-pair sequences is proposed for distributed Brillouin sensing. The method provides 1.5 dB signal-to-noise ratio improvement over unipolar Golay with halved measurement time, securing high spatial resolution.
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1. Introduction

Distributed fiber sensors based on Brillouin optical time domain analysis (BOTDA) have been extensively investigated for decades due to its unique advantage in distributed temperature and strain sensing [1,2]. With progressing studies in this field, today's mature theory points out that all the specifications in BOTDA, such as spatial resolution, sensing range and measurement speed, are ultimately determined by the signal-to-noise ratio (SNR) of the measured signal, the pump-probe frequency offset scanning step and the full-width at half-maximum of the retrieved Brillouin gain spectrum (BGS) [2]. In the case of single-pulse BOTDA, achieving decent performance with sharp (sub-meter) spatial resolution is challenging, since the BGS is broadened and the peak gain is significantly reduced [3]. Aiming at solving this problem, several techniques have been proposed, among them the concept of differential pulse pair (DPP) [4] can realize sharp spatial resolution without BGS degradation, although requiring one more acquisition process with respect to standard single-pulse BOTDA. Since this technique is essentially similar to standard single-pulse BOTDA, the SNR level is limited by nonlinear effect occurring in optical fiber, as the peak power of the pump pulses must be kept below ~100 mW due to modulation instability (MI) [5], and the input probe power must be below -6 dBm to prevent nonlocal effects [6]. To improve the performance of the DPP-BOTDA method, optical pulse coding is a good candidate since it can increase the SNR by a factor $\sqrt{M}/2$ (M is the code length) [7-10], while keeping the pulse peak power below the MI limit. Simplex coding has been successfully demonstrated in DPP-BOTDA [10], by simply subtracting the traces obtained after decoding Simplex-coded traces from the wide and narrow pulses used in DPP.

In this paper, we investigate theoretical and experimental aspects of Golay coding implementation in DPP-BOTDA sensing. A novel hybrid coding method based on Golay sequences and differential pulses is here proposed and experimentally validated. The technique halves the measurement time and increases the SNR coding enhancement by 1.5 dB over the traditional unipolar Golay coding. In addition, a thorough analysis of the coding/decoding process of the proposed and traditional Golay codes is performed, pointing out that the principle and implementation of conventional Golay coding in DPP-BOTDA sensors differs significantly from the approach followed in Simplex-coded DPP-BOTDA systems. The common approach of using *cross-correlation*, initially performed to decode traces associated to wide and narrow pulses of the DPP technique, followed by a *subtraction* operation to obtain the differential gain (approach defined as 'C-S method' in this paper), turns out to severely impair the spatial resolution, being much longer than the expected resolution defined by the differential pulse. On the contrary, the high-resolution differential Brillouin gain can only be achieved by first *subtracting* the Golay-coded traces and then *cross-correlating* the differential coded-traces (this is called "S-C method"). This second approach actually leads to decoded traces with correct high spatial resolution, after measuring 8 coded traces: 4 using unipolar Golay sequences for the wider pulse and 4 for the shorter pulse. This newly proposed hybrid Golay code here eliminates half of the measurements, providing also an additional 1.5 dB coding gain over the traditional S-C method. Sensing over a 10.16 km-long single-mode fiber is demonstrated using the hybrid Golay-DPP coding with a spatial resolution of 50 cm and a frequency uncertainty of 1.4-MHz.

2. Principle description

Similar to the decoding process followed in Simplex-coded DPP-BOTDA [7,10], the most straightforward way to implement a unipolar Golay-coded DPP-BOTDA traces is to carry out measurements and decoding procedure using first wider pulses (width = T_W in Fig. 1(a)) and then narrower pulses (width = T_N in Fig. 1(b)). By subtracting these two decoded responses, i.e., following the C-S method, a sharp spatial resolution determined by T_W-T_N is expected to be obtained. However, as rectangular pump pulse elements are used (highly recommended for BOTDA), the interrogation functions of the Golay coding technique, given by the cross-correlation functions for the wide and narrow pulses (f_W and f_N), exhibit a triangular shape [9], as shown in Fig. 2 in magenta and blue colors, respectively (the figure shows an example for a 30-25 ns DPP-BOTDA case). This means that after subtracting the two decoded traces, the obtained decoded DPP traces correspond to a spatial resolution determined by an equivalent interrogating function $f_{C-S}^{DPP} = f_W - f_N$, shown by the brown line in Fig. 2. This f_{C-S}^{DPP} function, besides being distorted, carries the information over a fiber section covered by the length of wide pulse, resulting in a spatial resolution equal to the one determined by the wider pulse T_W instead of the differential pulse width T_W-T_N (i.e., 3 m resolution instead of the 50 cm expected, in the example depicted in Fig. 2).

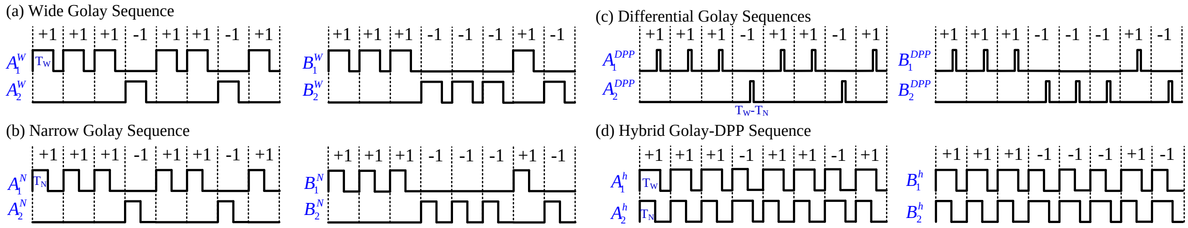

Fig. 1. Temporal shapes of (a) wide-pulse, (b) narrow-pulse, (c) differential-pulse, and (d) hybrid-pulse Golay sequences

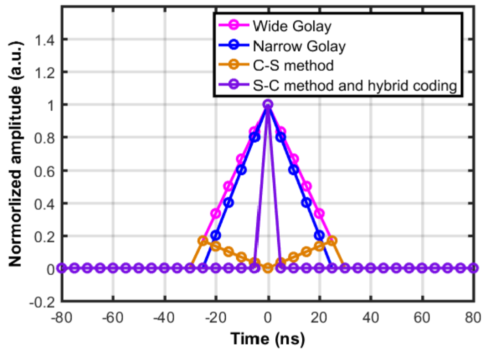

Fig. 2. Simulated Golay coding interrogating functions f_W (wider-pulse Golay sequences), f_N (narrower-pulse Golay sequences), f_{C-S}^{DPP} (C-S method), f_{S-C}^{DPP} (S-C method), and f_{hybrid}^{DPP} (hybrid coding).

Since this degradation of spatial resolution comes from the sequence in which the decoding procedure is carried out (cross-correlation first followed by subtraction), the problem can be readily overcome by re-ordering the post-processing procedure, by firstly carrying out the subtraction of the coded traces with different pulse widths. Defining RA_n^W, RA_n^N, RB_n^W, RB_n^N the BOTDA responses associated to each code sequence A_n^W, A_n^N, B_n^W, B_n^N, the corresponding differential Brillouin responses RA_n^{DPP} and RB_n^{DPP} can be written as:

$$\begin{cases} RA_n^{DPP} = RA_n^W - RA_n^N \\ RB_n^{DPP} = RB_n^W - RB_n^N \end{cases} \text{, which can be further represented as } \begin{cases} RA_n^{DPP} = A_n^{DPP} \otimes h(k) \\ RB_n^{DPP} = B_n^{DPP} \otimes h(k) \end{cases} \quad n = 1,2 \tag{3}$$

where the $\otimes$ sign denotes convolution, $h(k)$ is fiber impulse response, A_n^{DPP} and B_n^{DPP} stand for the differential Golay coded sequences (see Fig. 1(c)), being equivalent to:

$$\begin{cases} A_n^{DPP} = A_n^W - A_n^N \\ B_n^{DPP} = B_n^W - B_n^N \end{cases} \quad n = 1,2 \tag{4}$$

Note that the process is similar to standard unipolar Golay coded BOTDA using a pulse width of T_W-T_N, except that the BGS is not broadened due to the use of long pulses. The decoding process can be represented as:

$$\begin{aligned} &\left[(RA_1^{DPP} - RA_2^{DPP}) * (A_1^{DPP} - A_2^{DPP}) + (RB_1^{DPP} - RB_2^{DPP}) * (B_1^{DPP} - B_2^{DPP})\right] \Big/ \left[2(N_p^W - N_p^N)L\right] \\ &= h(k) \otimes \left[(A_1^{DPP} - A_2^{DPP}) * (A_1^{DPP} - A_2^{DPP}) + (B_1^{DPP} - B_2^{DPP}) * (B_1^{DPP} - B_2^{DPP})\right] \Big/ \left[2(N_p^W - N_p^N)L\right] \\ &= h(k) \otimes f_{S-C}^{DPP} \end{aligned} \tag{5}$$

where the $*$ sign denotes convolution, N_p^W *and* N_p^N are the number of sampled points within the pulse width T_W and T_N, respectively, L is the code length, f_{S-C}^{DPP} is the equivalent interrogating function, which possesses a triangular temporal profile with a width of T_W-T_N, as illustrated in Fig. 2 (see purple curve). This actually represents the expected spatial resolution defined by T_W-T_N. It should be noted that although the sharp spatial resolution can be realized by properly designing the post-processing procedure, 8 Golay sequences have to be sequentially launched into the sensing fiber, being a time-consuming process. Here we propose a novel hybrid Golay coding approach to realize DPP-BOTDA sensing using only 4 coding sequences, as shown in Fig. 1(d). This feature halves the measurement time with respect to S-C method, while still reaching the expected high spatial resolution with no distortion. The coding sequences of this hybrid Golay technique are designed as:

$$A_1^h = A_1^W + A_2^N; \quad A_2^h = A_2^W + A_1^N; \quad B_1^h = B_1^W + B_2^N; \quad B_2^h = B_2^W + B_1^N \tag{6}$$

This way a standard Golay decoding process can be performed based on 4 measurements only:

$$\begin{aligned}&\left[(RA_1^h - RA_2^h)*(A_1^h - A_2^h) + (RB_1^h - RB_2^h)*(B_1^h - B_2^h)\right] / \left[2(N_p^W - N_p^N)L\right] \\ &= h(k) \otimes \left[(A_1^h - A_2^h)*(A_1^h - A_2^h) + (B_1^h - B_2^h)*(B_1^h - B_2^h)\right] / \left[2(N_p^W - N_p^N)L\right] \\ &= h(k) \otimes f_{hybrid}^{DPP}\end{aligned} \quad (7)$$

where f_{hybrid}^{DPP} has exactly the same profile as f_{S-C}^{DPP} in Fig. 2, meaning that the spatial resolution is determined by Tw-T_N. It is important to notice that by using this hybrid Golay coding, the number of coded traces involved in the decoding is halved, resulting in 1.5 dB SNR improvement, even when using half of the acquisition time.

3. Experimental setup and results

The experimental configuration for demonstrating hybrid Golay-DPP coded BOTDA is shown in Fig. 3, which can also be used to validate the spatial resolution features of the S-C and C-S methods, by loading different types of Golay sequences into an arbitrary waveform generator (AWG). The light from a narrow linewidth (~1 MHz) distributed feedback laser (DFB1) at the wavelength of 1549.6 nm is split by a 90:10 optical coupler. In the upper (probe) branch, an intensity modulator (IM1) biased at V_π performs a carrier-suppressed dual sideband (CS-DSB) modulation, which is driven by an RF signal generated from a microwave generator (MG). The scanning of the pump-probe frequency offset is carried out by tuning the RF signal frequency. After passing through a polarization scrambler to minimize the impact of polarization fading, the modulated probe light is launched with a peak power of ~60µW per sideband into a 10.164 km-long sensing fiber through an optical isolator.

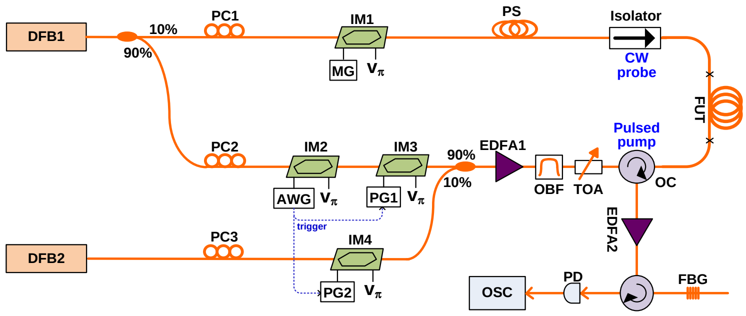

Fig. 3. Experimental configuration for hybrid Golay-DPP coded BOTDA.

In the lower branch, the optical Golay coded pulse sequence is generated using an intensity modulator (IM2) biased at V_π, which is driven by an electrical pulse sequence generated by an AWG. The length of the coded sequences is 61.44 µs in time scale, and their period is set to 300 µs. To increase the pulse extinction ratio, a 61.54 µs optical pulse with a period of 300 µs is applied to gate the coded optical pulse sequence, securing a high extinction ratio of the optical signal at the output of IM3. In order to avoid distortions caused by the slow transients of the EDFA, another optical pulse from DFB2 at a different wavelength (1552 nm) and a width of 1 us is launched into the EDFA1 slightly before the optical Golay sequences. This way, flat amplified Golay coding sequences are obtained, which are then launched into the sensing fiber as pump light through an optical circulator. At the detection stage, the lower-frequency probe sideband is selected (i.e., measuring the Brillouin gain) by a fiber Bragg grating (FBG) with a 3-dB linewidth of 6 GHz after being amplified by EDFA2. The selected sideband is then sent to a 350-MHz photo-detector (PD) connected to an electrical oscilloscope (OSC) for data acquisition.

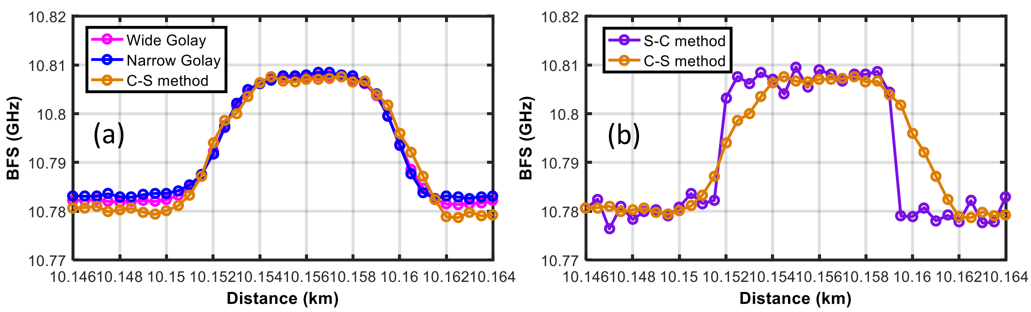

Fig. 4. Decoded BFS at the far fiber end by using (a) wide-pulse Golay sequences (magenta), narrow-pulse Golay sequences (blue), and DPP-pulses resulting after decoding with the C-S method (brown); and (b) DPP-pulses resulting from decoding employing C-S (brown) and S-C (purple) methods.

The performance of Golay-coded DPP-BOTDA is evaluated for the different described approaches. The width of the wide and narrow pulses are set to 30 ns and 25 ns, corresponding to spatial resolutions of 3 m and 2.5 m, respectively, and a differential spatial resolution of 50 cm. The coded BOTDA traces are acquired with 256 times averaging. A ~10-m hotspot is placed near the fiber end in a water bath at temperature of 50°C, while the rest of the sensing fiber is at room temperature (25 °C). The BFS profiles, around the applied hotspot, processed using the two traditional Golay schemes (i.e. the S-C and C-S methods) are shown in Fig. 4. In particular, Fig. 4(a) shows that the C-S method leads to a spatial resolution equivalent to the one obtained with the long (non differential) pulses. This demonstrates the poor spatial resolution resulting from the C-S method. Using the same experimental data, Golay traces are decoded by the S-C method and the retrieved BFS profile is illustrated in Fig. 4(b), and compared with the C-S method. Results clearly indicate that a sharper BFS transition is obtained by the S-C method (corresponding to a 50-cm spatial resolution), thus demonstrating that the only way to achieve the DPP spatial resolution is to use the S-C decoding, and not the C-S method.

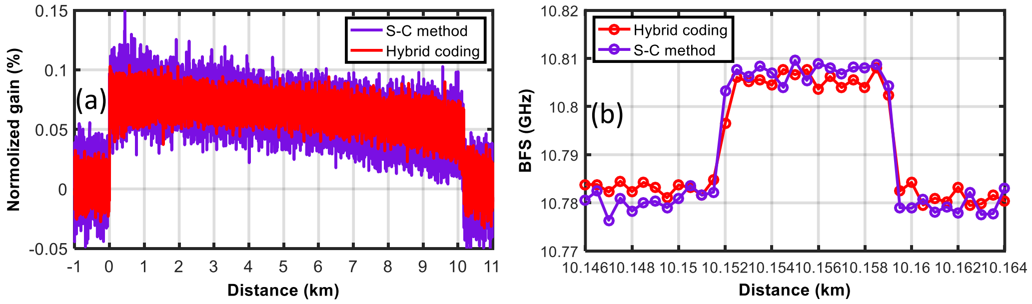

Fig. 5. (a) Decoded Brillouin gain traces obtained at 10.78GHz by using S-C method (purple) and hybrid coding method (red). (b) Decoded BFS at the far fiber end (around the hot-spot section) when using hybrid coding method (red) and S-C method (blue).

Finally, by uploading the hybrid Golay sequences to the AWG while keeping the same measurement condition, the performance of the hybrid Golay coded BOTDA is evaluated. First, the decoded Brillouin gain traces along the sensing fiber at the resonance peak frequency are shown in Fig. 5(a), for the S-C method and the proposed hybrid Golay scheme. About 1.5-dB SNR difference can be observed, which is in good agreement with the theoretical analysis in section 2 (due to the lower noise resulting from the reduced number of acquired traces). The retrieved BFS profile around the hotspot (red curve) is shown in Fig. 5(b), demonstrating the high spatial resolution (50 cm) achieved by the hybrid DPP-Golay coding (being similar to the S-C method, as expected).

4. Conclusion

Theoretical and experimental analyses of Golay coding in DPP-BOTDA sensors have been reported, proposing different approaches for coding/decoding. In particular a novel hybrid coding method combining unipolar Golay with differential pulses has been proposed and experimentally demonstrated, verifying that the hybrid coding method can secure sharp (sub-meter) spatial resolution, while providing an enhanced SNR and lower measurement time than conventional unipolar Golay coding. It is expected that this technique can also be combined with bipolar Golay sequences [8,9] in order to further improve the performance of coded DPP-BOTDA sensors.

5. Acknowledgments

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6. References

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