Bipolar optical pulse coding for performance enhancement in BOTDA sensors

Marcelo A. Soto,[1,*] Sébastien Le Floch,[2] and Luc Thévenaz[1]

[1]*EPFL Swiss Federal Institute of Technology, Institute of Electrical Engineering, SCI-STI-LT, Station 11, CH-1015 Lausanne, Switzerland*

[2]*HE-ARC, Rue de la Serre 7, CH-2610 Saint Imier, Switzerland*

[*]*marcelo.soto@epfl.ch*

Abstract: A pump signal based on bipolar pulse coding and single-sideband suppressed-carried (SSB-SC) modulation is proposed for Brillouin optical time-domain analysis (BOTDA) sensors. Making a sequential use of the Brillouin gain and loss spectra, the technique is experimentally validated using bipolar complementary-correlation Golay codes along a 100 km-long fiber and 2 m spatial resolution, fully resolving a 2 m hot-spot at the end of the sensing fiber with no distortion introduced by the decoding algorithm. Experimental results, in good agreement with the theory, indicate that bipolar Golay codes provide a higher signal-to-noise ratio enhancement and stronger robustness to pump depletion in comparison to optimum unipolar pulse codes known for BOTDA sensing.

OCIS codes: (060.2370) Fiber optics sensors; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers.

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1. Introduction

During the last decade Brillouin optical time-domain analysis (BOTDA) [1] has become one of the most active fields of research in optical fiber sensing. The technique is based on stimulated Brillouin scattering (SBS), a nonlinear optical effect occurring in optical fibers and depending on temperature and longitudinal strain. Using a pulsed pump signal and a counter-propagating probe wave, the temperature- and strain-dependent Brillouin gain spectrum

(BGS) can be measured at every fiber location, with a spatial resolution that is given by the pulse width; thus, the shorter is the pulse width, the better the spatial resolution [1].

One of the main limitations in distributed optical fiber sensors is given by the low signal-to-noise ratio (SNR) observed at the far end of the fiber when long sensing distances are concerned, as a simple consequence of the linear loss. Thus, typical performances in BOTDA sensing indicate measurement ranges up to 30-50 km with 1-2 m spatial resolution. In order to extend the sensing range, the pump peak power cannot be increased indefinitely due to the onset of nonlinear effects, which prematurely deplete the pump or broaden its spectrum. During the past few years, methods such as distributed Raman amplification and optical pulse coding have been proposed to increase the sensing distance of BOTDA sensors [2–4], reaching ranges beyond 100 km with metric spatial resolution.

In particular, optical pulse coding increases the SNR of BOTDA measurements by launching several pulse sequences into the fiber, followed by a data processing procedure to retrieve the single-pulse response [3–8]. This way, while keeping the peak pulse power equal to the single pulse case, the total pump energy launched into the fiber is temporally spread and therefore is increased by a factor equal to the number of pulses in each sequence. This leads to measurements with higher SNR but with a spatial resolution equivalent to the single-pulse case. The most efficient codes so far known for long-range sensing employ unipolar (on-off keying) pulse sequences, in which bits '1s' and '0s' represent the ON-OFF status of the light, and can therefore be easily implemented using standard intensity modulation [8].

Other coding methods, such as some of the ones employed in advanced radar systems, make use of bipolar pulse sequences, in which elements '-1s' and '1s' are required. Some of those codes, as for instance bipolar complementary-correlation Golay codes [7], offer even better SNR enhancement than any known coding scheme used in Brillouin sensing. For this reason, it would be of great interest to implement a novel modulation approach for BOTDA in order to overcome the physical constraint imposed by intensity modulation, limited to unipolar pulse sequences, and to achieve the implementation of bipolar pulse sequences realizing the equivalent effect of '*positive*' and '*negative*' pulses.

In this paper a novel technique is indeed proposed and experimentally validated to realize this bipolar effect. The method is based on the combination of return-to-zero (RZ) pulse sequences and single-sideband suppressed-carried (SSB-SC) modulation, following patterns ruled by bipolar coding. The bipolar pulses combine Brillouin gain and loss processes, increasing the intensity contrast of the measured BGS and mitigating the impact of pump depletion with respect to unipolar codes, while optimizing the energy in the sequences since all pulses are ON. Although here the feasibility of the technique is unambiguously demonstrated using bipolar complementary-correlation Golay codes, the method can be perfectly adapted to any other suitable bipolar codes.

2. SSB-SC modulation based on bipolar codes for BOTDA sensing

The implementation of standard pulse coding in distributed sensing is based on an intensity-modulated pump signal composed of pulse sequences defined by specific unipolar (on-off keying) codes, such as for instance Simplex [3,4] or Golay codes [5]. Pulse coding provides an SNR enhancement (which is quantified by the *coding gain*) with respect to the single-pulse acquisition, assuming the same measurement time, i.e. taking into account the same number of acquired traces. Simplex and complementary-correlation Golay codes are considered to be the optimum coding schemes for sensing application when intensity pulses are used [8], as in the case of Brillouin sensing, both providing practically the same SNR enhancement when long code lengths are used (i.e. for sequences longer than 64 bits). Thus, as reported in the literature, it can be assumed that the coding gain provided by optimum unipolar codes (i.e. for both Simplex and unipolar Golay codes) is equal to $\sqrt{L}/2$, where L is the code length [3,7].

In particular, complementary-correlation Golay codes are pairs of bipolar sequences (i.e. containing elements ' $\pm$ 1') that have non-periodic autocorrelation functions with null sidelobes [7]. In principle, measurements require the use of two coded pulse sequences,

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whose autocorrelations have complementary sidelobes that mutually cancel out when they are summed up. Practical and physical constrains have impeded the direct implementation of bipolar codes (requiring '*positive*' and '*negative*' pulses) in distributed optical fiber sensing based on intensity pulses. To enable the real implementation of Golay codes when employing intensity pulses, pairs of bipolar sequences have been modified into groups of 4 unipolar sequences (i.e. containing elements '0s' and '1s') following the procedure described in [7]. This has enabled the implementation of systems such as Golay-coded optical time-domain reflectometers (OTDR) [7] and Golay-coded BOTDA sensors [5], among others. Unfortunately, under the same code length L condition, the gain provided by unipolar Golay codes is 3 dB lower than the original $\sqrt{L}$ gain offered by bipolar Golay sequences [7], decreasing the potential sensing range enhancement by approximately 7.5 km. This difference in coding gain is a direct consequence of the double intensity contrast provided by bipolar codes, which require at the same time only groups of 2 pulse sequences instead of the 4 needed in the unipolar case, thus reducing the noise impact during the decoding process [7].

Here the original bipolar Golay sequences [7] are implemented for BOTDA sensing by making simultaneous use of the Brillouin gain and loss spectra. The technique can be actually applied to any other suitable bipolar code sequences. Thus, as described in Fig. 1, while the continuous wave (CW) probe signal is maintained at the nominal laser wavelength, a dual-parallel Mach-Zehnder modulator (DP-MZM) can be used to generate a pump signal with SSB-SC modulation [9], so that every bit of the bipolar code is sequentially transmitted in only one of the pump single sidebands, following the patterns defined by bipolar codes. This way bits '1s' of the bipolar sequences are positioned at the upper-frequency sideband inducing Brillouin gain on the probe, while bits '-1s' at the lower-frequency sideband induce Brillouin loss.

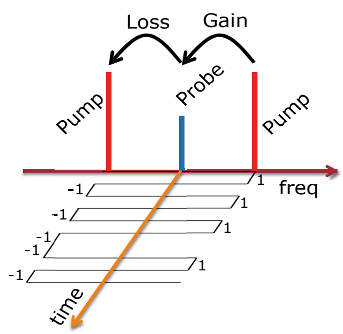

Fig. 1. Principle of the SSB-SC modulation based on bipolar codes for BOTDA sensing.

Since the carrier of the SSB modulated pump and the probe signal counter-propagate in the sensing fiber at the same frequency, carrier suppression is essential to avoid interference noise in the measurements. This can be realized using a proper DC bias in the DP-MZM [9], similarly to standard MZM. At the same time, the lower- or upper-frequency sideband can be individually selected using another bias port of the modulator [9] on which the electrical waveform containing the bipolar codes is connected. Figure 2(a) shows the optical SSB-SC modulated spectra obtained with a DP-MZM when the intensity level of either the upper or lower sideband is maximized (blue and red lines respectively). Considering that both single sidebands of the pump are symmetrically generated at equal spectral separation from the probe frequency, the pump-probe frequency detuning (given by the frequency of the RF modulating signal) can be set independently of the sign associated to the transmitted pulses, thus ensuring identical Brillouin gain and loss magnitudes.

While non-return-to-zero (NRZ) pulses are obtained using SSB-SC modulation, another intensity modulator can be used after the DP-MZM to generate RZ intensity modulated pulses, then avoiding the detrimental impact of the pre-activated acoustic wave within the codewords [6]. Actually, the duty cycle of the RZ pulses is a critical parameter that has to be properly adjusted to avoid distortions in the decoding process resulting from bit patterning effects. Intensity pulses have to be spaced by more than 40-60 ns for a close-to-complete decay of the acoustic wave amplitude before the next pulse enters the same fiber segment, thus maintaining a linear SBS amplification and avoiding any inter-pulse crosstalk.

Figure 2(b) shows an example of an RZ-pulse sequence corresponding to a 16-bit bipolar Golay codeword. To better highlight the two frequencies contained in the SSB-SC modulated RZ pump signal and assigned to each bit of the bipolar code, pulses at the lower- and upper-frequency sidebands and belonging to the same Golay sequence are separately shown using two distinct curves (red and blue lines) obtained by selective spectral filtering.

It is worth mentioning that although the carrier extinction ratio of SSB modulators is relatively low (less than 30 dB as reported in Fig. 2(a)), the intensity modulator placed after the SSB modulator and used to shape the coded RZ pulses sequence provides additional suppression of the DC carrier component. This way, the residual carrier resulting from the imperfect extinction ratio of the SSB modulator only coexists with the intensity-modulated RZ pulses, and is highly suppressed by the intensity modulator when no pulse is generated. The intensity modulator has an extinction ratio of about 40 dB, so that a real carrier suppression of more than 60 dB can be reasonably expected using the proposed method.

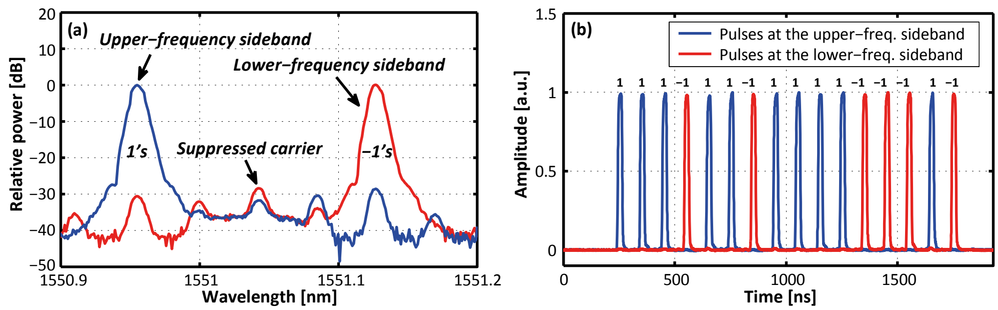

Fig. 2. Principle of the SSB-SC modulation to generate a pump signal based on bipolar codes. (a) Spectra of the SSB-SC modulation obtained using a dual-parallel Mach-Zehnder modulator. (b) Example of a single SSB-SC modulated 16-bit bipolar Golay codeword.

Note that, distinctively to unipolar pulse coding, bipolar codes require all pulses to be ON, providing an efficient coding method since the full sequence launched into the fiber is densely energized. Any instance of the probe wave will therefore cumulatively experience the interaction with all pulses in the sequence. Since pulses are alternatively generated at two symmetric frequencies around the probe signal, the Brillouin gain induced by bits at the upper frequency ('1s') is compensated by the Brillouin loss produced by pulses at the lower frequency ('-1s'). The Brillouin gain-loss compensation resulting from the bipolar codes leads to a much smaller cumulative Brillouin amplification of the probe wave when compared to the only Brillouin gain generated by unipolar sequences, since there is approximately the same number of pulses generating gain or loss. Under this condition, bipolar sequences ensure that a small cumulative Brillouin gain is maintained all along the fiber, preventing the probe wave to grow substantially like in a unipolar scheme and providing a robust method to limit the amount of pump depletion. It must be pointed out that bipolar codes prevent a double sideband probe compensation from being implemented for cancelling pump depletion. However this efficient tool turns out to be only partially effective even using unipolar coding, since the cumulated gain by all bits in the sequence is so large that the small gain linear approximation is no longer valid and the perfect equalization resulting from the interaction of the two sidebands turns imperfect in this case.

3. Experimental setup

Figure 3 shows the implementation of a BOTDA sensor employing SSB-SC modulation and bipolar coding. The CW light from a distributed feedback laser (DFB) is split into pump and

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probe branches using an optical splitter. The power level of the probe signal (at the nominal laser frequency) is adjusted using a variable optical attenuator (VOA), while its polarization is controlled using a polarization switch (PS) to minimize the impact of the SBS polarization-dependent gain. The pump signal is first SSB-SC modulated using a DP-MZM [9]. While the optical carrier is suppressed by a proper DC bias, an arbitrary waveform generator (AWFG) is connected to another bias port of the modulator to select the proper single-sideband according to the bipolar Golay codes. The two RF ports of the DP-MZM are connected to a microwave generator through a microwave splitter, which enables the injection of the in-phase and in-quadrature signals required for the SSB modulation [9]. A standard MZM is then used to generate synchronized 20 ns RZ intensity pulses with 20% duty cycle, equivalent to 2 m spatial resolution. An Erbium-doped fiber amplifier (EDFA) is placed between the two modulators to increase the pump power launched into the fiber, but at the same time to avoid distortions introduced by the EDFA, since the power at the EDFA input remains constant, and no gain fluctuation is thus expected due to EDFA depletion effects [10]. Coded pulses are sent into 100 km of standard single-mode fiber (SMF), consisting of two spools of 50 km with similar Brillouin frequency shift (BFS). Note that under this condition, energy from the pump is transferred to the probe all along the 100 km sensing fiber, maximizing pump depletion to best validate the proposed method.

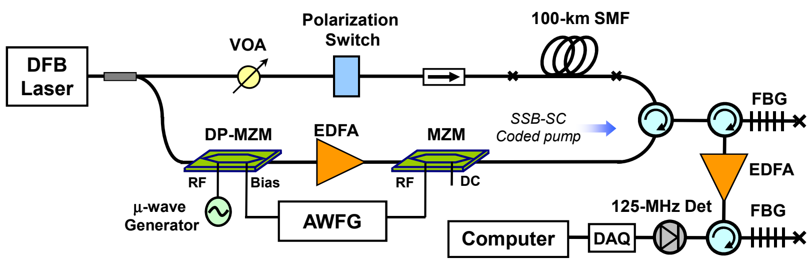


Fig. 3. Experimental setup for BOTDA sensor employing SSB-SC modulation and bipolar codes.

The receiver consists of two tunable narrowband fiber Bragg gratings (FBG) centered at the probe frequency, an EDFA operating as linear-gain pre-amplifier, and a 125 MHz photo-detector connected to a fast data acquisition card (DAQ). Note that the linear operation regime of the EDFA is essential for a decoding process showing no distortion [4]. Comparing to a preliminary implementation [11] where the code length was limited to a maximum of 128 bits (when using 20 ns pulses), pulse sequences up to 2048 bits have been here tested resulting in coded traces with no distortion. This substantial upgrade was possible by filtering out the Rayleigh backscattered light originating from the two pump frequencies before the detection pre-amplification using a first narrowband fiber Bragg grating centered at the probe wavelength. Longer pulse sequences generate stronger Rayleigh backscattered light which could quickly saturate the EDFA used as pre-amplifier before the receiver. This gain saturation would lead to nonlinear amplification of the coded traces, thus inducing potential distortions in the decoding process. Then, the second FBG is used to provide additional Rayleigh-component rejection and to filter out the amplified spontaneous emission (ASE) noise introduced by the pre-amplifier.

4. Experimental results

The first set of measurements aims at verifying experimentally the SNR enhancement capabilities of the proposed technique employing SSB-SC modulation and bipolar codes. The experimental coding gain provided by bipolar Golay codes as a function of the code length has been compared with the theoretical values, as well as with the SNR enhancement achieved by unipolar Golay codes. Results shown in Fig. 4 indicate that the measured SNR enhancement provided by bipolar Golay codes is 3 dB higher than the obtained by unipolar Golay sequences, in perfect agreement with the theory [7]. This additional coding gain makes bipolar Golay codes the best coding method achieved so far in BOTDA sensors, allowing for a sensing range extension of 7.5 km or a four-fold measurement time reduction, when compared to previously reported optimum coding schemes of the same length (i.e. unipolar Golay and Simplex codes [3–6]).

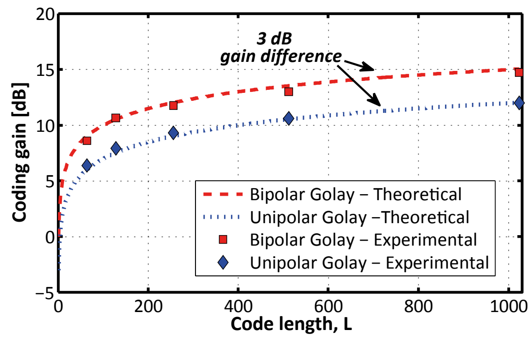
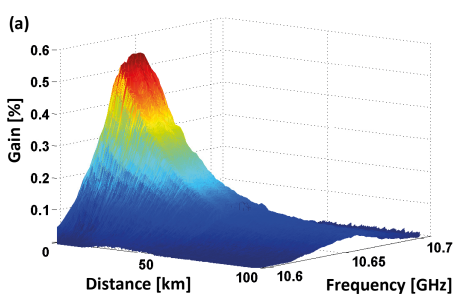


Fig. 4. Coding gain for both unipolar and bipolar Golay codes in BOTDA sensing.

Figure 5(a) shows the decoded BGS as a function of distance obtained with 512 bit bipolar Golay codes and 2k time-averaged traces. Figure 5(b) shows the BFS obtained by fitting the decoded BGS at every position along the 100 km-long fiber. Calculating the standard deviation of the BFS, the frequency uncertainty has been found to be 0.8 MHz, which corresponds to a temperature and strain resolution of 0.8°C and 16με, respectively.



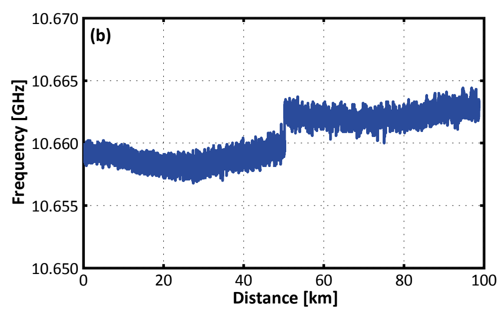


Fig. 5. Measurements along 100 km sensing distance using 512-bit bipolar Golay codes and SSB-SC modulation. (a) Decoded BGS vs distance. (b) Respective BFS profile.

In order to verify the real spatial resolution of the implemented system, 2 m of fiber at the end of the 100 km sensing range have been heated up to 55°C, while the rest of the sensing fiber has been maintained at ambient temperature (25°C). Figure 6 shows the measured hot-spot, revealed by a Brillouin frequency variation of 31 MHz along 2 m of fiber. This result, in good agreement with prediction, demonstrates that the proposed method does not induce distortions as a result of potential errors during the Golay decoding process.

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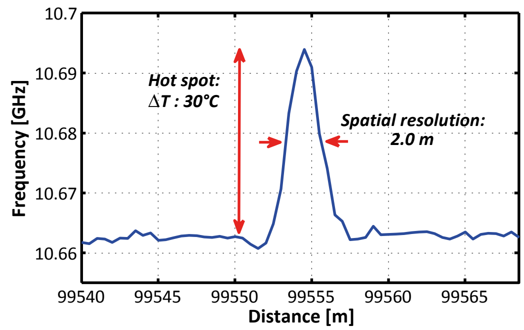

Fig. 6. Measurement of a 2 m-long hot-spot at a sensing distance of ~100 km. The induced temperature variation was 30°C, while the measurement indicates a Brillouin frequency variation of about 31 MHz.

In addition, unipolar and bipolar coding schemes have been compared in terms of pump depletion robustness. The residual coded pump power (after propagating along the 100 km sensing fiber) is shown in Fig. 7 with (solid red line) and without (dashed blue line) Brillouin interaction, for the bipolar (Fig. 7(a)) and unipolar (Fig. 7(b)) coding schemes. It can be noticed that in the case of bipolar codes, pump pulses at the lower-frequency sideband are amplified along the fiber, while pulses at the upper-frequency sideband turn out to be depleted. This power unbalance occurs after the pump propagates along the whole sensing fiber and in this case it is limited to about only 5% of the pulse power measured with no Brillouin interaction. On the other hand, as reported in Fig. 7(b), when unipolar Golay codes are used (with identical optical power levels and code length), the residual pump is clearly depleted by ~16% after propagating along the 100 km-long fiber. This can be explained by the uniform BFS along the sensing fiber, which induces a continuous power transfer from the pump to the probe (i.e. strong pump depletion) when unipolar Golay codes are used. However, when using the proposed method based on SSB-SC pulses and bipolar codes, much lower levels of depletion occur since the power transferred from the upper-frequency pulses (Brillouin gain process) is on average compensated by the power transferred from the probe to the lower-frequency pulses (Brillouin loss process). Therefore, as a result of this SBS gain-loss compensation associated to bipolar coding, the probe power does not experience a significant total Brillouin gain during propagation along the fiber, as it cumulatively occurs when unipolar coding is used (where only Brillouin gain takes place). As a consequence, reduced levels of pump depletion or excess amplification occur with the proposed coding scheme.

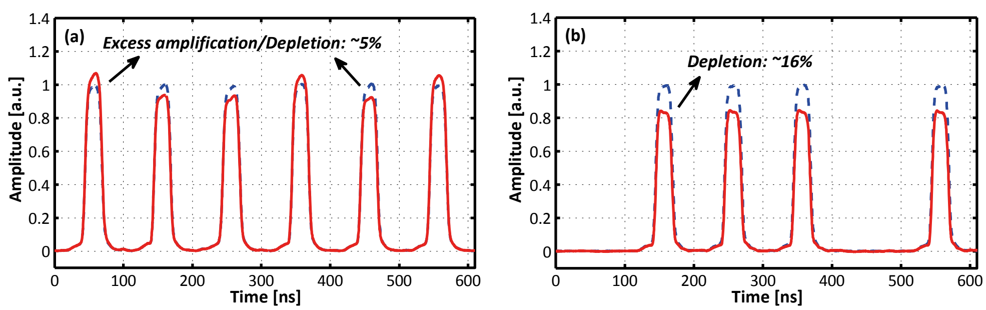

Fig. 7. Residual pump after propagating along 100 km of fiber, when using (a) bipolar and (b) unipolar Golay codes. The dashed blue lines represent the reference residual power with no SBS interaction, while the solid red lines correspond to the case of maximum SBS gain/loss.

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7. Conclusion

In this work we have proposed and demonstrated the implementation of bipolar pulse coding in BOTDA sensors. Thanks to its perfectly symmetric operation in gain and loss modes, stimulated Brillouin scattering offers the unique possibility to implement bipolar coding in distributed optical sensing. In particular, the technique has been validated using bipolar Golay codes, which have demonstrated to provide a higher SNR enhancement in comparison to any other known coding method for Brillouin-based sensing. The proposed method opens the possibility to use any other type of bipolar codes in BOTDA sensing and to gain a significant step in performance without increasing the power levels in the system.

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