Design rules for Unipolar Unicolor Coded Brillouin Optical Time Domain Analysis

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Abstract: The performance of unipolar unicolor coded Brillouin optical time-domain analysis (BOTDA) is thoroughly studied, providing quantitative guidelines to design a distortion-free coded BOTDA system operating at maximum signal-to-noise ratio.

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1. Introduction

Distributed optical fiber sensing based on Brillouin optical time-domain analysis (BOTDA) has been developed for decades, as it can reliably measure temperature and strain over several tens of kilometers using spatial resolutions of a few meters [1,2]. Through numerous studies on this field, it turns out that the ultimate parameter defining the performance of a BOTDA sensor is the signal-to-noise ratio (SNR) of the measured signals, and therefore any effort to improve the SNR can lead to better performing systems [2]. For a given spatial resolution, the SNR level is proportional to the input pump and probe powers. However, the maximum pump power is limited by modulation instability (MI) to ~100 mW in fibers longer than 20 km [3], while the probe power is limited to about –6 dBm per sideband in a conventional dual sideband configuration to avoid trace distortions [4].

In order to enhance the SNR while keeping the peak pulse power strictly limited, optical pulse coding has been proposed and extensively developed for BOTDA sensing [5-8]. In very early stages of the coding implementation [5,6], the slow gain recovery of erbium-doped fiber amplifiers (EDFAs) was considered as only critical and practical limitation, since it leads to uneven amplification of the code sequences. Therefore, the maximum power of the coded pump was limited by the maximum output power of electro-optic modulators, which is typically ~15 dBm, leading to a sub-optimal use of the coding capabilities. Recently, dedicated efforts have been made in the literature to achieve a flat coded sequence amplification [7,8], enabling optimizing the power of coded sequences. Meanwhile, mature theories have been reported on the optimization of single-pulse BOTDA sensing schemes, especially on the maximization of pump [3] and probe [4] powers. These progresses offer the opportunity to fully evaluate the fundamental limitations and real benefits of pulse coding on the SNR of coded BOTDA schemes with respect to fully optimized standard single-pulse BOTDA schemes. Indeed, it has been recently found out that the high Brillouin amplification resulting from unipolar coding can induce distortions in the decoded traces, while higher-order nonlocal effects can be very detrimental [8]. However, a quantified evaluation of the real impact of the pump and probe powers on the overall performance of the sensor, along with a design tool to fully optimize the performance of unipolar unicolor (= all pulses at the same central frequency) coded BOTDA systems, is still missing in the literature.

In this paper, the impact of the large accumulated Brillouin amplification taking place in unipolar unicolor BOTDA is analyzed, aiming at optimizing the sensing performance. First, we point out that the decoded trace distortion due to the large Brillouin amplification can be overcome by simply using a newly proposed logarithmic normalization during post-processing. This solution is experimentally validated as a robust approach to retrieve the Brillouin gain without any approximation. The limitations imposed by higher-order nonlocal effects are then thoroughly studied, enabling quantifying the trade-off among the pump depletion level, the value of Brillouin amplification and the maximum probe power. The impact of probe power limitation on the overall SNR improvement provided by coding, when compared to a fully optimized single-pulse BOTDA scheme, is modelled and experimentally verified. Although the analysis presented here is carried out using Simplex codes, most conclusions of this work can also be applied to other unipolar coding techniques, such as Golay codes.

2. Logarithmic Normalization

In unipolar unicolor coded BOTDA, the probe interacts with several pump pulses through SBS, experiencing accumulated Brillouin amplification and resulting in a measured probe power at fiber near end given by:

$$P_S^0(z,\nu) = P_{iS}\exp(-\alpha L)\exp\left[G(z,\nu)\right] \quad (1)$$

where L is the fiber length, ν is frequency detuning, P_{is} is the input probe power at fiber far end, and $G(z,\nu)$ is the cumulated linear Brillouin amplification. The measured coded BOTDA trace, as depicted in the left frame of Fig. 1, is composed of the cumulated SBS amplification given by the coded pulse sequence, together with a DC component $P_S^{0-DC} = P_{iS}\exp(-\alpha L)$ representing the CW probe reaching the fiber near end without Brillouin amplification. Assuming that the Brillouin frequency shift (BFS) profile over the fiber section covered by coding sequence is uniform, corresponding to the worst case in term of cumulated amplification, the contribution of each '1' (pulse on) in the coding sequence can be considered identical, so that the cumulated linear Brillouin amplification can be expressed as:

$$G(z,\nu)=\frac{M}{2}g_s(z,\nu)=\frac{M}{2}g_B(z,\nu)P_{iP}\exp(-\alpha z)\Delta z \qquad (2)$$

where M is code length, i.e., the number of the coding bits (number of 1's in the coding sequence is generally $M/2$), P_{iP} is the initial power of each incident pulse, Δz is the spatial resolution, $g_B(z,\nu)$ is the Brillouin gain factor and $g_s(z,\nu)$ is the local single-pulse Brillouin amplification. Since traditional (linear) coding techniques require the linear superposition of the BOTDA traces contributed from all the code pulses, $G(z,\nu)$ must be extracted from the raw measured data through a normalization process, as illustrated by the central frame in Fig. 1. After this stage, $g_s(z,\nu)$ can be retrieved by a dedicated decoding process (see the right frame depicted in Fig. 1).

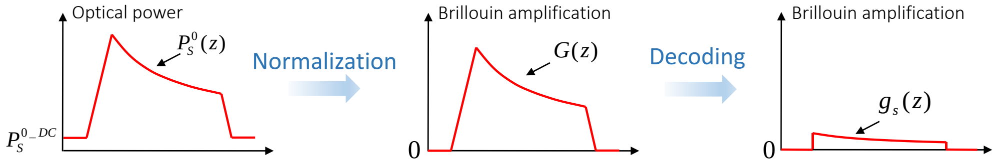

Fig. 1. Schematic illustration of general decoding process for a given ν

The normalization process is usually realized in a linear way and can be mathematically expressed as $G(z,\nu)\approx\left[P_S^0(z,\nu)-P_S^{0-DC}\right]/P_S^{0-DC}=\exp\left[G(z,\nu)\right]-1$, provided that $G(z,\nu)\ll 1$. This small-gain condition can be absolutely secured in a single pump pulse BOTDA scenario, in which the maximum $g_s(z,\nu)$ is in the order of 1% (assuming an optimized peak pump power of ~100 mW). However, when using unipolar unicolor coding, the $G(z,\nu)$ at the fiber entrance, denoted as G_0, can reach up to more than 200% (e.g., 100 mW peak power and 512 bits code length), thereby violating the above mentioned small-gain approximation. The nonlinear contribution of the exponential term becomes this way non-negligible, giving rise to errors on the retrieved $G(z,\nu)$, which further leads to distortions in the decoded Brillouin gain distribution [8]. For demonstration, experiments based on Simplex-coded BOTDA are carried out with a 47 km-long fiber. The pulse peak power is set to ~100 mW and each pulse width is 20 ns (2 m spatial resolution), leading to a $g_s(z,\nu)$ of ~1% at the beginning of the sensing fiber at the peak resonance frequency. The coding length M is adjusted to 127, 255 and 511 bits, resulting in G_0 levels varying as 60%, 120% and 240%, respectively. In order to mitigate the impact of higher-order nonlocal effects, the probe power per sideband is deliberately adjusted to -17 dBm (details will be discussed in Section 3). Fig. 2(a) shows the decoded z-dependent $g_s(z,\nu)$ distributions at the resonance peak frequency when employing traditional linear normalization process. Note that none of them agree with the expected SBS gain value of 1% at the fiber input. Furthermore, clear trace amplitude distortions are observed, while the level of distortion depends on the accumulated (nonlinear) SBS amplification in the coded BOTDA traces. To reduce these SBS-gain-dependent distortions, $G(z,\nu)$ must be restricted if using standard linear normalization, which imposes a fundamental limit to the allowable code length (assuming an optimized pump power limited by MI), consequently impacting on the overall SNR and BOTDA performance.

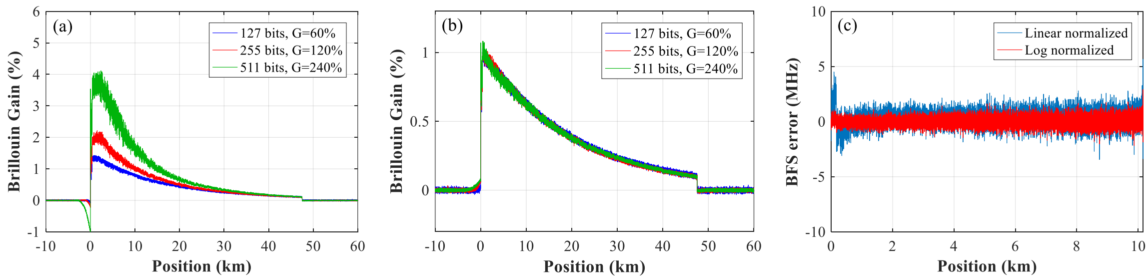

Fig. 2. Decoded Brillouin gain traces for different accumulated Brillouin amplification levels after (a) conventional linear normalization and (b) proposed logarithmic normalization. (c) BFS error profiles over the sensing fiber in case of G_0= 240%.

Indeed, the exponential behavior of the overall Brillouin gain on the probe signal of a BOTDA sensor makes more appropriate the use of a logarithmic normalization for retrieving the linear Brillouin amplification $G(z,\nu)$, which can be expressed as $G(z,\nu)=\ln[P_S^0(z,\nu)/P_S^{0-DC}]$. To demonstrate the feasibility of this newly proposed normalization, the same experimental raw data used for retrieving the curves in Fig. 2(a) under linear normalization are re-used here using the proposed logarithmic normalization. The resulting decoded curves are illustrated in Fig. 2(b), showing a good match with the expected Brillouin gain (1% at the beginning of the fiber) for all curves. Furthermore, these three decoded curves clearly exhibit exactly the same trend regardless of $G(z,\nu)$, demonstrating the beneficial improvement provided by the logarithmic normalization. To further investigate the impact of both normalization methods on the estimated BFS, a measurement with full frequency scan has been performed with a large G_0 of 240%. Since the fiber length is not relevant in this study, and for the sake of visual clarity (i.e., to have a high SNR), a relatively short (10 km-long) standard single-mode fiber with non-uniform BFS distribution (varying over 15 MHz) is used. Utilizing the same raw data, the BFS profiles resulting from linear and logarithmic normalizations are obtained. The BFS errors are illustrated in Fig. 2(c) by subtracting each BFS profile with a reference measurement retrieved by standard single-pulse BOTDA. One can observe that the BFS errors resulting from logarithmic normalization are always below 1 MHz, actually dominated by detection noise. However, the linear normalization results in non-negligible BFS errors all along the fiber, reaching up to 4 MHz nearby the transition regions. These results validate the necessity of using the proposed logarithmic normalization method in high Brillouin gain regime.

3. Higher-order non-local effects

Higher-order non-local effects originate from both large Brillouin amplification and high probe power, restricting the maximum input probe power, therefore limiting the overall SNR performance of the sensor. Although this effect has been previously evaluated [8], the demonstrative experiments were carried out using conventional linear normalization, which eventually biases the pure impact of higher-order nonlocal effects. Thus, the acceptable level of pump depletion still remains unclear, and the required probe power for a given depletion level has not been quantified yet. Here the proposed logarithmic normalization can eliminate the impact of large Brillouin amplification on decoding distortion, allowing for optimizing the probe power. First, the relationship between maximum tolerable depletion level and $G(z,\nu)$ is theoretically investigated, based on the expressions representing the power of lower and upper probe sidebands, i.e., P_{SL} and P_{SU} with no assumptions:

$$P_{SL}(z) = P_{iSL}\, f_{SL}(z) = P_{iSL}\exp\left[-\alpha(L-z)\right]\exp\left[G(z,\nu)\exp(-\alpha z)\right] \quad (3)$$

$$P_{SU}(z) = P_{iSU}\, f_{SU}(z) = P_{iSU}\exp\left[-\alpha(L-z)\right]\exp\left[-G(z,\nu)\exp(-\alpha z)\right] \quad (4)$$

where P_{iSL} and P_{iSU} represent the power of the lower and upper frequency sidebands injected at the far fiber end ($z = L$), and $f_{SL}(z)$ and $f_{SU}(z)$ are functions taking into account the exponential behavior of the accumulated Brillouin amplification and fiber attenuation. From Eqs. (3) and (4) it can be observed that large values of $G(z,\nu)$ can easily unbalance the power of the sidebands. Thus the n^{th} pulse of a coding sequence will interact with probe sidebands that have been considerably amplified/depleted by all previous (from 1 to n-1) coded pulses. Consequently, the last coded pulse would suffer from the highest depletion. To quantitatively analyze this cascaded pump depletion effect, the depletion level of the last coded pulse as a function of probe power per sideband is shown in Fig. 3(a). This figure verifies that the level of pump depletion in coded BOTDA depends not only on the probe power as in the case of single-pulse BOTDA, but also on the level of accumulated Brillouin amplification.

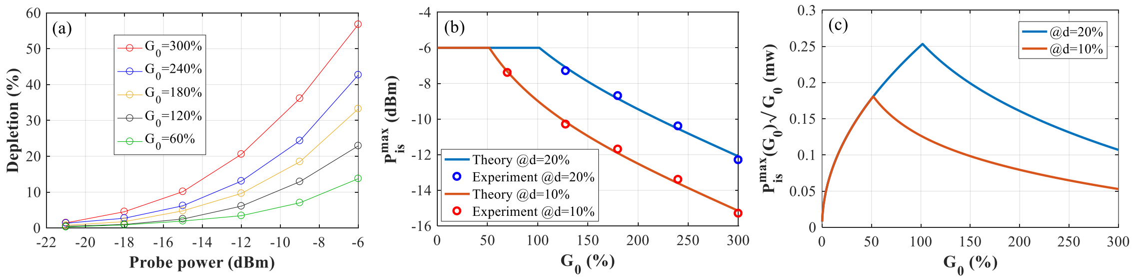

Fig. 3. (a) Depletion level of the last coded pulse as a function of the input probe power in cases of different G_0. (b) Maximum input probe power per sideband and (c) value of $P_{iS}^{max}(G_0)G_0$, both versus the G_0 in the cases of d=20% and d=10% depletion.

For a given G_0 and a depletion factor d of the last coded pulse, and considering $P_{iSL} = P_{iSU} = P_{iS}$, the maximum probe power can be calculated by evaluating the integrated power difference between the two probe sidebands (Eqs. (3) and (4)):

$$P_{iS}^{max}(G_0,d) = \frac{\ln(1-d)}{g_B(\nu)\left[\int_0^L f_{SU}(z)dz - \int_0^L f_{SL}(z)dz\right]} \quad (5)$$

The theoretical $P_{iS}^{max}(G_0,d)$ calculated based on Eq. (5) for the case of 10% (orange curve) and 20% (blue curve) depletion are shown in Fig. 3(b), with an ultimate probe power limit set to -6 dBm [4]. The theoretical curves agree well with the experimental results, validating the presented analysis. Knowing the maximum tolerable probe power for given G_0 and d allows to evaluate the SNR performance of unipolar coded BOTDA. For a given coding length M, the maximum SNR level is proportional to the decoded single-pulse Brillouin amplification $g_s=2G_0/M$ and the SNR improvement from the coding gain $\sqrt{M}/2$:

$$SNR_{coded}^{\max}(G_0,d,M) \propto \frac{\sqrt{M}}{2}\frac{2G_0}{M}P_{iS}^{\max}(G_0,d) = \frac{P_{iS}^{\max}(G_0,d)G_0}{\sqrt{M}} \quad (6)$$

Eq. (6) points out that in order to optimize the SNR performance of unipolar coded BOTDA sensors, the coding length M must be minimized for a given value of G_0. This means that g_s must be maximized, thus leading to $M_{\min} = 2G_0 / g_s^{\max}$, where $g_s^{\max}$ is the maximum single-pulse Brillouin gain, which is determined by the spatial resolution and the maximum allowable pulse peak power (~100 mW in long fibers). Under this condition, the maximum SNR can be represented as:

$$SNR_{coded}^{\max}(G_0,d) \propto P_{iS}^{\max}(G_0,d)G_0 / \sqrt{M_{\min}} = P_{iS}^{\max}(G_0,d)\sqrt{G_0 g_s^{\max}/2} \quad (7)$$

The ultimate SNR improvement $\Delta SNR^{\max}$ brought by unipolar codes over an optimized single-pulse BOTDA can then be calculated. Knowing that the optimal single-pulse SNR, $SNR_{pulse}^{\max}$, is proportional to $P_{iS-pulse}^{\max}g_s^{\max}$ (where $P_{iS-pulse}^{\max}$ is the maximum allowed probe power in standard BOTDA: -6 dBm), $\Delta SNR^{\max}$ can be obtained:

$$\Delta SNR^{\max}(G_0,d) = \frac{SNR_{coded}^{\max}}{SNR_{pulse}^{\max}} = \frac{P_{iS}^{\max}(G_0,d)\sqrt{G_0}}{P_{iS-pulse}^{\max}\sqrt{2g_s^{\max}}} \quad (8)$$

Since in the optimized single-pulse case, the denominator of Eq. (8) is constant, the SNR improvement basically depends on the term $P_{iS}^{\max}(G_0,d)\sqrt{G_0}$. The behavior of this term as a function of G_0 is illustrated in Fig. 3(c), for different d, which clearly indicates that the maximum SNR of coded BOTDA can be achieved at very specific values of G_0. For example, a depletion level of 20% corresponds to an the optimal G_0 equal to 1, as illustrated in Fig. 3(c). In this optimal condition, Eq. (8) can be written as:

$$\Delta SNR^{\max} = 1/\sqrt{2g_s^{\max}} \quad (9)$$

with an optimized M equal to $2/g_s^{\max}$. Note that Eq. (9) emphasizes that the optimal SNR improvement given by unipolar codes solely depends on $g_s^{\max}$, which is ultimately determined by the spatial resolution since the pulse peak power must always be kept at its maximum level. To verify Eq. (9), experiments using Simplex-coded BOTDA are carried out at 2 m spatial resolution, corresponding to a $g_s^{\max}$ equal to 1.2%. The experimentally obtained $\Delta SNR^{\max}$ is found to be 7.5 dB, in good agreement with Eq. (9). Indeed, Eq. (9) also indicates that the broader the spatial resolution, the larger $g_s^{\max}$, leading to the lower SNR improvement brought by coding. Therefore, when Eq. (9) is equal to or smaller than 1, corresponding to the case of $g_s^{\max} \geq 50\%$ (spatial resolution ≥ 30 m), the unipolar coding technique has no benefit with respect to an ultimately optimized single-pulse BOTDA system. This means that the maximum capabilities of the code can only be exploited when the spatial resolution is much shorter (e.g., 1-2 meters), for which the SNR enhancement provided by the coding gain can be obtained with moderate code lengths (e.g., 127 bits).

4. Conclusion

Optimization on the performance of unicolor unipolar coded BOTDA sensors has been carried out. Logarithmic normalization has been proposed and demonstrated to be capable of extracting precisely the linear Brillouin gain G profile along the fiber without any approximation. Thorough analysis of higher-order non-local effects points out that a high code gain obtained from long coded sequences is not always beneficial and the code gain has to be optimized in a given situation. It brings on the essential novel result that the best advantage from coding is obtained in situations when the single pulse gain is small, i.e. for short spatial resolutions (2 meter and less).

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4. References

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