Simulation Analysis on the Simultaneous Deployment of Brillouin Gain and Loss in Coded Brillouin Optical Time Domain Analysis (BOTDA) Fiber Sensor

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Abstract. We report in this paper the simulation analysis on the simultaneous deployment of Brillouin gain and Brillouin loss in the Golay coded phase-shift pulse Brillouin optical time domain analysis (PSP-BOTDA) fiber optic sensor for improving the sensing distance and at the same time obtaining high spatial resolution measurement. In this technique, the Golay coded pump pulse is alternately frequency modulated for the purpose of generating Stokes and Anti-Stokes scattering. The technique also modulates the coded pump with the return-to-zero (RZ) formats. Simulation analysis has revealed that the simultaneous use of Brillouin gain- and loss and the pulse coding technique in the PSP-BOTDA has improved the dynamic sensing range and the signal-to-noise improvement ratio (SNIR) of the sensor. By performing simulation over 500 m of fiber, we have also successfully demonstrated 10-cm of high spatial resolution measurement with the use of 1ns of coded pulse duration.

1. Introduction

Brillouin optical time domain analysis (BOTDA) is a well-known technique for measuring distributed strain over a long range of fiber optic cable [1]. BOTDA utilizes the occurrence of stimulated Brillouin scattering (SBS) due to the interaction of pump light (pump), Stokes light (cw) and acoustic wave to measure strain and temperature changes across fiber optic cable. The frequency of the SBS generated from this interaction is either down- or upshifted, depending on the Brillouin scattering interaction that takes place. In the case of obtaining Brillouin gain process, Stokes scattering is utilized, in which the frequency of the Brillouin backscattered light is reduced (downshifted). In contrast, for Brillouin loss process, anti-Stokes scattering takes place, causing the increase (upshifted) in frequency of the Brillouin backscattered light. In both cases, this shift in this frequency is called Brillouin frequency shift (BFS). The linear increase in the BFS with strain and temperature makes the BOTDA system beneficial to measure local changes in the strain and temperature along the fiber cable. Structural health monitoring for buildings, bridges, dams, etc. for the purpose of disaster prevention is an example of the BOTDA application.

High-spatial resolution measurement is necessary in BOTDA for an efficient use in the above applications. Sub-meter spatial resolution measurement is required especially in order to detect early defect in a concrete structure. In early stage of BOTDA development, 1 m spatial resolution was demonstrated, which corresponds to the use of 10 ns pump pulse duration [2]. One way to further

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improve the spatial resolution is narrowing the pump pulse duration. However, narrowing the pulse duration to a value of shorter than the phonon lifetime can cause an inefficient acoustic wave excitation. This effect leads to a significant decrease in the measured Brillouin gain and also increase in the Brillouin gain spectrum width, because the acoustic wave that plays role in generating the SBS cannot be efficiently excited.

 Previously, a technique called phase-shift pulse BOTDA (PSP-BOTDA) for the purpose of improving the spatial resolution [3]. In the PSP-BOTDA, two kinds of pump pulses are used. One pump contains a preceding pulse with long duration (1st pulse) followed by a pulse with short duration (2nd pulse); the phase difference between these two pulses is zero. The configuration of another pump is the same, but the 2nd pulse has π-phase difference compared to the 1st pulse. The 1st pulse is used to effectively excite acoustic wave while the 2nd pulse will interact with this acoustic wave to generate SBS wave which is then used for the strain measurement. The subtraction of the Brillouin signals obtained by the two pumps yields differential Brillouin gain; the duration of the 2nd pulse determines the spatial resolution.

 Signal-to-noise ratio (SNR) is another necessary parameter in characterizing a BOTDA sensor. There are some reports on the use of code system in modulating the pump light for the purpose of SNR improvement. They are for examples simplex coded BOTDA [4] and coded DPP-BOTDA [5]. The techniques of modulating the pump light of the PSP-BOTDA with Golay complementary sequences (Golay codes); coded continuous-PSP-BOTDA, coded discrete PSP-BOTDA and dual Golay codes PSP-BOTDA were also proposed [6].

 To enable long distance measurement, the optical pulse coding techniques described above are also applicable. However, in this paper, we propose a novel method of simultaneously deploying both Brillouin gain and Brillouin loss interaction in the previously proposed coded PSP-BOTDA technique. In details, the downshifted and upshifted frequency modulation techniques for simultaneously generating Stokes and anti-Stokes scatterings were deployed. By simultaneously exploiting both Brillouin gain- and loss interactions, one can obtain a balanced energy transfer between the pump and the probe, mitigating the optical power depletion problem.

2. Simulation Setup and Results

2.1. Assignment of Brillouin gain- and loss process to the coded pump pulse

 Figure 1 illustrates an example of the 4 bits Golay coded pump pulse utilized in the PSP-BOTDA technique. The Golay coded pump pulse contains of two types of pulses, the long 1st pulse of duration $T_1$ and the narrow pulse of duration $T_2$ (2nd pulse). The 1st pulse is set so long, usually longer than 10 ns for an efficient SBS generation. The 2nd pulse is coded according to the Golay code element for the strain measurement at high spatial resolution. In the previously proposed coded PSP-BOTDA technique, a set of coded pulses are frequency modulated for generating either Brillouin gain or Brillouin loss interaction. This method will allow only one-way energy transfer during the scattering process, causing depletion of energy. However, in the proposed technique, as can be seen from Fig. 1, each pulse group that contains both 1st and 2nd pulses is alternately frequency modulated for the purpose of generating Brillouin gain- and loss. Thus, by performing this method, it would allow mutual and balanced energy transfer between the pump pulse and the probe. This will mitigate the pump depletion effect and hence allow for longer distance measurement. It should be noted that similar to the conventional coded PSP-BOTDA, phase-inverted codeword was also necessary for subtracting the PSP-BOTDA signals and then auto-correlation for decoding the Golay codes; these processes result into high spatial resolution and high signal-to-noise ratio measurements, as described in the Introduction section.
2.2. Simulation Setup

The simulations on the simultaneous deployment of Brillouin gain and loss in the Golay coded PSP-BOTDA was performed based on the method introduced in [7]. In our mathematical analysis, the effect of fiber loss was ignored. The simulation arrangement is shown in Fig. 2. Figure 2 also shows an example of a pump light that has been coded with a codeword produced by Golay code. As an example, 2-bit Golay code with codewords \{1, -1\} was assigned to RZ pulses. The durations of the 1st pulse T₁, 2nd pulse T₂, and interval T_i were set to 30 ns, 1 ns and 100 ns, respectively; the use of 1 ns of coded pulse is expected to produce 10 cm spatial resolution measurement. It should be noted that duration T_i was set much longer than the acoustic wave time constant to avoid SBS interaction between the preceding and succeeding pulse groups. To demonstrate the effectiveness of the simultaneous deployment of Brillouin gain and loss, the length of the test fibers was set to 500 m. Reference fiber of 10 m in length was spliced alternately. The BFS difference between the test and reference fibers was set to 50 MHz. The pump and probe powers were set to 60 mW and 2 mW, respectively. In the simulations, the Brillouin gain spectrum width ∆ν_b was set to 35 MHz, which estimates the acoustic wave time constant to about 10 ns. In this simulation, Golay code length was set to 8 bits. The Brillouin signals obtained were decoded via correlation calculations for Golay codes.

2.3. Simulation Results and Analysis

Figure 3 shows the results of Brillouin signal along the 500 m of fiber, measured with 8 bits of Golay code. For comparison, the simulation result for conventional coded PSP-BOTDA that used only Brillouin gain was also performed and depicted in Fig. 3. It is clearly seen from the figure that for conventional coded PSP-BOTDA, the Brillouin signal has decreased towards the end of the fiber, as expected. This is because for the Brillouin gain process, the energy transfer occurs from the pump light to the probe light, causing the attenuation of the pump light energy when propagating towards the end of the fiber. In contrast, for the proposed technique, one can clearly observe that the SBS signal amplitude is almost maintained until the end of the 500 m test fiber. This is because of the mutual energy transfer between the pump and the probe light during the alternate Brillouin gain and loss interactions. Thus, we have successfully confirmed the effective of simultaneously deploying both Brillouin gain and loss in coded PSP-BOTDA for improving the dynamic range of signal measurement along a 500 m fiber. We have also analyzed the spatial resolution and confirmed 10 cm spatial resolution. We then analyze the spectrum of the Brillouin gain/loss signal, which is depicted in Fig. 4.
was extracted from the signal simulated at the 10 m location. From the figure, it is observed that there almost no distortion in the spectral shape. We have also confirmed a narrow spectrum width of around 40 MHz by calculating the full width at half maximum (FWHM) of the spectrum.

Figure 3. SBS signal along a 500 m test fiber. The graph in grey colour is the result for conventional Golay coded PSP-BOTDA utilizing only Brillouin gain, while the graph in black colour is the result for the proposed Brillouin gain/loss in Golay coded PSP-BOTDA technique.

Figure 4. Brillouin gain/loss spectrum (BGLS) simulated at location 10 m.

3. Conclusion
We proposed a novel technique to simultaneously utilize both Brillouin gain and Brillouin loss in the Golay coded PSP-BOTDA sensing technique for improving its sensing range performance. In details, the coded pump pulse is alternately frequency modulated for the purpose of generating Stokes and anti-Stokes scattering. The alternately Stokes and anti-Stokes interactions respectively have resulted in mutual optical energy transfer between the pump and the probe during the stimulated Brillouin scattering (SBS) process. From the simulation results, a uniform Brillouin signal amplitude along a 500 m test fiber was observed, confirming the successful of the proposed technique. Furthermore, by using 1 ns duration of Golay coded pulse, 10 cm spatial resolution was obtained, confirming a high spatial resolution measurement. From the spectral analysis at a distance along the test fiber, a narrow Brillouin gain/loss spectrum (BGLS) spectrum width of around 40 MHz was obtained; this confirmed that the characteristics of the measured spectrum are very similar to the spectrum of steady state condition.

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