

Temperature Dependence of the Brillouin Frequency Shift (BFS) using Independent Real Spectral Analysis in DCS-BOTDR Fiber Sensor

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Abstract

We propose an independent real spectral analysis method to improve the Brillouin frequency shift (BFS) resolution using the differential cross-spectrum technique (DCS-BOTDR). The proposed method only considers the real components to extract BGS. For a 1.2 km test fiber length, we have achieved 0.4 m spatial resolution, 1.98 MHz Brillouin frequency accuracy, and 1.025 MHz/°C temperature sensitivity using the proposed method.

1. Introduction

Brillouin optical time domain reflectometry (BOTDR) is a widely used technique for distributed fiber sensing to monitor temperature and strain along optical fibers. The BOTDR fiber sensor relies on the spontaneous Brillouin scattering (SpBS), where light interacts with acoustic phonons, producing a frequency-shifted backscattered signal known as the Brillouin frequency shift (BFS) caused by the strain and temperature variations along the fibers. The frequency shift was calculated from Brillouin gain spectrum (BGS), i.e., a relationship between the amplitude and the frequency of the backscattered signal, computed using a fast Fourier Transform (FFT) algorithm. Time-domain signals are converted to the frequency domain using this algorithm, with conventional approaches analyzing the power spectral density (PSD).

Previously, some studies have been conducted to improve BOTDR system performance using the FFT-based approach. According to Wang et al. (2017), their study improved signal-to-noise ratio (SNR), reduced measurement time, and frequency uncertainty of 0.37 MHz by using complementary coding and FFT [1]. Tu et al. (2014) proposed a short-time Fourier transform (STFT) BOTDR for dynamic strain measurement that continuously reconstructs the BFS from time-domain data and achieved a 16.7 Hz strain variation over 270 m of sensing fiber [2]. Even though FFT-based BOTDR has made significant progress towards improving SNR and reducing measurement time, there is limited research that focuses on using the real spectrum to extract BGS. Additionally, most existing approaches are based on complex computations or PSD techniques, resulting in larger processing overhead and a wider spectral linewidth. Hence, this study aims to evaluate the improvement in the BFS resolution and temperature sensing accuracy by applying the independent FFT-based real spectral analysis in a differential cross-spectrum (DCS-BOTDR) fiber sensor. As a proof-of-concept, a temperature dependence analysis was conducted at different temperatures to assess the effectiveness of the proposed method.

2. Independent Real Spectral Analysis in DCS-BOTDR

The DCS-BOTDR is a method to improve the performance of the conventional BOTDR system by generating a probe pulse pair consisting of a long (T_L) and short (T_S) pulse, separated with a short interval (T_i) using an

intensity modulation scheme. This technique successfully achieved an accurate BFS result with high spatial resolution measurement [3]. The experimental setup, illustrated in Figure 1(a), employed a 1550 nm continuous-wave laser (12 dBm) modulated via a Mach-Zehnder modulator (MZM) driven by a 10 GHz signal from a synthesized signal generator (SSG). An acousto-optic modulator (AOM) was used to generate the optical pulses, and then modulated by an arbitrary waveform generator (AWG) to produce a probe pulse pair of $T_L = 10$ ns, $T_S = 4$ ns, and $T_i = 2$ ns. Two Erbium-doped fiber amplifiers (EDFAs) produced an output power of approximately 600 mW to compensate for insertion losses. This study employed a total of 1.2 km fiber length, with an 8 m heated section at the fiber end was immersed in a 70 °C water bath for temperature sensing. Finally, the SpBS trace was collected via an oscilloscope (OSC) with a sampling rate of 5 Gbps, then BFS estimation with an averaging of 20,000 will be computed using signal processing.

To extract the BGS, the FFT algorithm of the DCS-BOTDR uses conventional spectral analysis by considering both spectral components; real and imaginary – to compute PSD, as expressed in the following equation:

$$PSD(f) = \sqrt{Re(f)^2 - Im(f)^2} \quad (1)$$

where the spectrum is converted to the frequency domain. Meanwhile, the independent real spectral analysis simplifies the process by considering only the real component, hence reducing the processing time to extract the BGS. In terms of the BFS resolution, the real spectrum can achieve higher spatial resolution compared to the PSD spectrum. From Figure 1(b), the spectrum width (full-width at half-maximum – FWHM) yielded by the PSD and real spectral analysis is 130.77 MHz and 39.44 MHz respectively. The linewidth derived from the PSD method aligns with the FWHM reported by Zan et al. (2022) for $T_L = 10$ ns, approximately 130 MHz, hence proving the validity of the comparison [4]. Narrow linewidth with sharper spectral peak in the real spectrum allows more precise localization, hence enhances the BFS resolution in the DCS-BOTDR system.

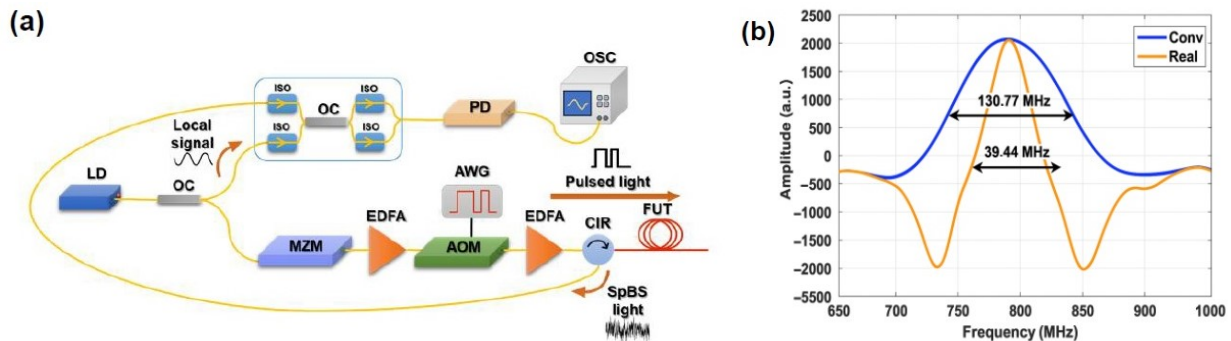


Figure 1. (a) Schematic diagram of the DCS-BOTDR experimental. (b) The FWHM comparison of BGS between conventional (PSD) and real spectrum.

3. Experimental Results

The length of fiber-under-test (FUT) is 1.2 km, where an 8 m segment at the fiber end was heated in the water bath at different temperatures, from 30°C to 70°C with an interval of 10°C. The BFS result is shown in Figure 2(a), and the distribution is accurately plotted the 8 m heated section. Spatial resolution of the edge detection is 0.4 m, which agrees with the previous study [5]. Figure 2(b) shows the linear relation between the BFS distribution and the temperature of the heated section. The BFS accuracy was determined by calculating the standard deviation of the BFS, and an average of 1.98 MHz was obtained at five different temperatures.

This result demonstrates an improvement over previous works. Earlier study on the DCS- BOTDR was performed by Zan et al. (2018) analyzed the BGS using the PSD method and obtained a BFS accuracy of 3 MHz [3]. To enhance the BFS resolution, Almoosa et al. (2022) implemented an artificial neural network (ANN) in their recent research on the DCS-BOTDR, reporting an improvement of 2.88 MHz [6]. Instead of using ANN models, which are complex and require training overhead, the independent FFT-based real spectral analysis is a straightforward approach with simplified computations to extract the BGS with greater fidelity, achieving a resolution of 1.98 MHz while also reducing spectral distortion. A linear relationship between the BFS over different temperatures was illustrated in Figure 2(b). A slope analysis to determine the temperature sensitivity was computed and yielded a value of 1.025 MHz/°C. This result proved the reliability of the proposed method.



A coefficient of $R^2 = 0.9934$ signifies the potential of the independent real spectral analysis to obtain precise temperature sensing analysis for the BOTDR system.

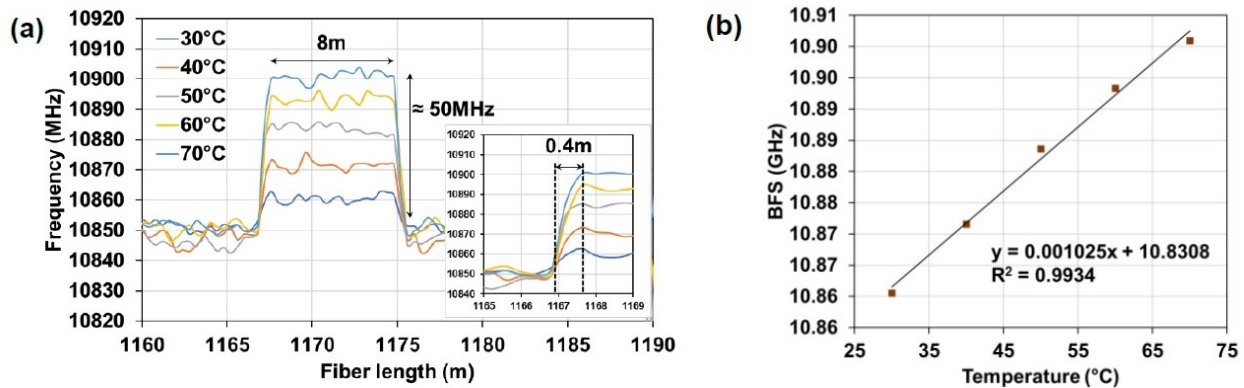


Figure 2. (a) BFS distribution at five different temperatures and (b) linear relationship between BFS and temperatures.

4. Conclusion

We have proposed a simplified spectral analysis technique by independently analyzing the real component of the FFT analysis. This technique effectively improves the BFS resolution from 2.88 MHz compared to the prior study to 1.98 MHz, which enhances the DCS- BOTDR signal performance. The temperature sensitivity of 1.025 MHz/°C and the R^2 coefficient of 0.9934 highlights the reliability of the proposed method for the temperature sensing of the distributed fiber optic sensor.

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