

Signal to Noise Ratio Performance Analysis for Vibration Detection Using Phase Sensitive OTDR in Distributed Acoustic Sensing

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Abstract

Phase-sensitive optical time-domain reflectometry (Φ -OTDR) has emerged as a powerful technique for distributed acoustic sensing (DAS) in a wide range of applications, including perimeter security. The signal-to-noise ratio (SNR) is a critical parameter in determining the sensitivity and reliability of vibration detection in these systems. In this paper, we present a detailed analysis of SNR performance in Φ -OTDR-based DAS systems. We investigate the influence of key system parameters such as optical pulse width, vibration frequencies and spatial resolution on the SNR value. A DAS setup is developed to evaluate how these parameters affect the backscattered signal and noise characteristics over pulse widths and vibration frequencies. Our results show that SNR increases exponentially with optical pulse widths, but it degrades the spatial resolution value. The findings provide practical insights into the phase information in the development of a more efficient and sensitive DAS system. This work contributes to the growing understanding of SNR limitations and enhancement strategies in distributed fiber optic sensing.

1. Introduction

Fiber optic sensing, especially phase-sensitive optical time-domain reflectometry (Φ -OTDR), is widely used in distributed acoustic sensing (DAS) for applications like structural monitoring, intrusion detection, and seismic sensing [1], [2]. Φ -OTDR detects vibrations by measuring changes in Rayleigh backscattered light along the fiber. Its ability to achieve high spatial and temporal resolution makes it ideal for long-distance sensing [1], [3], [4]. A key factor in DAS performance is the signal-to-noise ratio (SNR), which affects how well vibrations can be detected. Higher SNR leads to more accurate detection, while lower SNR may cause missed or false alarms. Various techniques such as WSVD filtering [4], Golay coding [2], and I/Q demodulation [5] have been used to improve SNR. This paper analyzes how different system parameters like pulse width and averaging impact SNR, using trace differential and I/Q demodulation methods, aiming to optimize DAS performance. However, prior studies mainly focus on coding and signal processing for SNR improvement. Less attention has been given to how optical pulse width impacts both SNR and spatial resolution. This study investigates this trade-off in a practical Φ -OTDR setup.

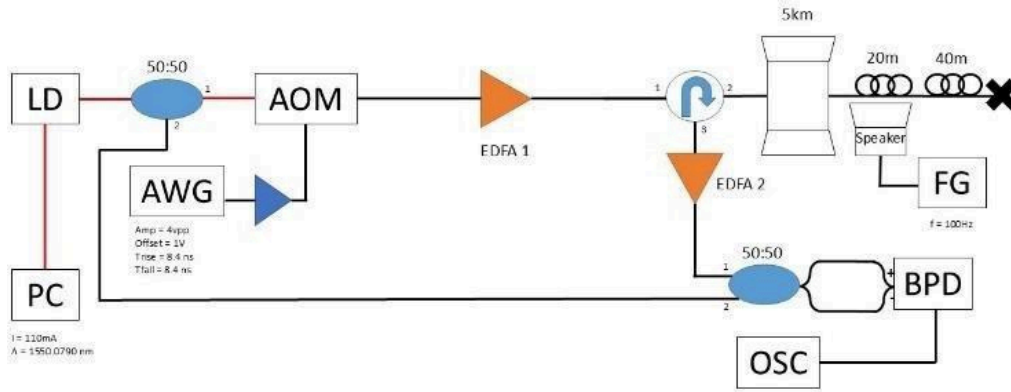


Figure 1: DAS Coherent Detection Setup

2. DAS Setup

The experimental configuration of the Φ -OTDR-based distributed acoustic sensing (DAS) system is illustrated in Figure 1. The system consists of a narrow-linewidth laser diode (LD) operating at a wavelength of 1550.0790 nm and a drive current of 110mA. The laser output is split using a 50:50 coupler, with one branch directed to an acousto-optic modulator (AOM), which is driven by an arbitrary waveform generator (AWG). The AWG generates electrical pulse width (100ns and 200ns) with an 8.4ns rise and fall time.

The modulated optical pulses are amplified by an Erbium-doped fiber amplifier (EDFA 1) before entering the sensing fiber. A 99:1 coupler is used to inject the amplified pulse into a 5 km single-mode sensing fiber. Vibrations are introduced at distance 20 m after 5 km of fiber input, using a speaker driven by a function generator (FG) set to 100Hz. Rayleigh backscattered light is collected and passed through the EDFA 2 for signal amplification, then split by another 50:50 coupler for detection. The signal is demodulated using a balanced photodetector (BPD) and input to an oscilloscope sampled at 100 MSa/s, and 500 traces were averaged. A bandpass filter centered at 100 Hz was applied before SNR calculation.

3. Result Analysis

I/Q demodulation is first applied to the backscattered signal to separate it into in-phase (I) and quadrature (Q) components, enabling precise phase calculation. This allows the system to detect small phase shifts caused by external vibrations. Next, the trace differential method is used, where each trace is subtracted from the next ($T_{\{n+1\}} - T_n$), effectively suppressing static background noise and emphasizing dynamic signal changes. As shown in Figure 2(a), (b), and (c), a distinct peak emerges at the vibration point after differential, while surrounding regions remain relatively low. This confirms successful vibration detection and localization, demonstrating the method's ability to enhance visibility of the vibration. Finally, the signal-to-noise ratio (SNR) is calculated, with the results shown in Table 1. The SNR provides a quantitative measure of detection quality and helps evaluate the system's performance under various parameter settings. The calculated SNR reveals a clear trend with respect to optical pulse width. For a pulse width of 40ns, the SNR was 6.47 dB. Increasing the pulse width to 100ns improved the SNR to 7.65 dB and further increasing it to 200 ns yielded a slightly higher SNR of 7.85 dB. This demonstrates that wider pulse widths enhance SNR by increasing backscattered signal power, although gains become marginal beyond a certain point.

4. Conclusion

This study demonstrates that increasing optical pulse width enhances the SNR in Φ -OTDR-based DAS systems, resulting in improved vibration detection sensitivity. However, this enhancement

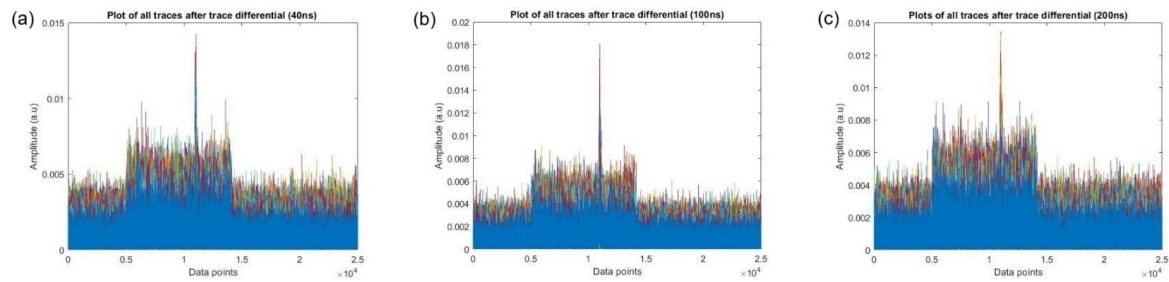


Figure 2: Differential traces for (a) 40 ns, (b) 100 ns, and (c) 200 ns pulse widths. Y- axis scales are unified for comparison.

Table 1: Calculated SNR value.

Pulse Width (ns)	SNR (dB)
40	6.4731
100	7.6522
200	7.8485

comes at the cost of reduced spatial resolution. Therefore, an optimal balance between SNR improvement and spatial resolution must be maintained for effective system performance.

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