Mitigation of Polarization Fading in Phase OTDR by Sequential Dual Polarization Reception

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Abstract. *Phase-sensitive Optical Time-Domain Reflectometry (ϕ-OTDR) is inherently limited by polarization-induced fading caused by random state-of-polarization evolution of Rayleigh backscattered fields in optical fibers. These fluctuations lead to deep signal attenuation and degraded phase estimation in coherent detection systems. Conventional mitigation approaches rely on polarization-diversity receivers employing parallel coherent detection channels, which increases system complexity and cost. This paper presents a coherent ϕ-OTDR architecture that suppresses polarization fading using a single coherent receiver. The proposed method is based on the sequential acquisition of orthogonal polarization components of the backscattered field. Identical probe pulses are launched into the sensing fiber, while the returned signal is split into two orthogonal polarization states and time-multiplexed into a single coherent detection chain. The complex responses corresponding to both polarization states are subsequently combined using Maximum-Ratio Combining (MRC), enabling statistically efficient phase reconstruction without parallel receiver hardware. Experimental results demonstrate effective fading suppression and robust vibration detection. Compared to selecting only the stronger polarization channel, the proposed MRC-based approach provides an improvement in the Signal-to-Noise Ratio (SNR) of approximately 3 dB. The architecture preserves polarization diversity gain while significantly reducing receiver complexity, offering a cost-efficient solution for polarization-independent distributed acoustic sensing.*

Keywords

Optical time-domain reflectometry, phase, polarization, unwrap, vibrations, optical fiber

1. Introduction

Optical Time-Domain Reflectometry is a widely adopted technique for distributed fiber sensing, relying on the analysis of Rayleigh backscattered light to detect vibrations and acoustic signals along the fiber with high sensitivity [1]. An advanced variant of this technique, ϕ-OTDR, takes advantage of phase information rather than intensity alone. Phase-based detection provides a direct and deterministic relationship between external perturbations and induced optical phase variations, making ϕ-OTDR particularly well suited for accurate distributed strain and vibration detection. To further enhance sensitivity and phase stability, digital coherent detection schemes are commonly employed [2–4].

Despite its advantages, the performance of ϕ-OTDR systems is limited by several fundamental impairments. Signal fading caused by random interference of Rayleigh backscatter [5] and laser phase noise [6] are among the dominant factors that degrade phase stability and SNR. To address these issues, a variety of mitigation techniques have been proposed [8], [7]. Wavelength diversity has been demonstrated as an effective approach to suppress fading by decorrelating backscattered signals at different optical frequencies [9]. Alternatively, the use of dual-laser configurations with distinct linewidths and phase noise characteristics has been reported to improve robustness against phase noise [10]. The twice-differential phase method has also been introduced to mitigate the influence of laser frequency drift [11]. In addition, polarization-related effects represent a major source of signal degradation in ϕ-OTDR systems. Because of the random birefringence of optical fibers, Rayleigh backscattered light exhibits a strong polarization dependence, which can result in deep polarization fading and spatially varying phase sensitivity. Several polarization mitigation strategies have been investigated [12], [13], including polarization diversity using dual-polarization coherent receivers [14]. Among these approaches, polarization-diverse detection enables the acquisition of multiple statistically independent backscatter responses, thereby significantly reducing the probability of fading while preserving phase information. However, conventional polarization-diverse receivers increase system complexity and cost, which motivates the development of simpler polarization-switching and signal-processing-based solutions.

Accurate phase demodulation is a critical component of ϕ-OTDR signal processing, as it directly determines the fidelity of vibration and strain measurements. To improve

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phase reconstruction accuracy, a recursive branch-cut algorithm has been proposed [15]. A digital demodulation method aimed at reducing hardware-induced noise and system complexity was introduced in [16]. More recently, machine learning techniques have been explored to enhance signal interpretation in ϕ-OTDR systems. For example, the authors in [17] developed a neural-network-based classification framework for identifying different acoustic sources detected by distributed fiber sensors. Owing to these advances, ϕ-OTDR has found widespread application in distributed acoustic sensing. Broadband acoustic signals generated by pencil-break events were detected and localized for the first time using a distributed vibration sensing approach in [18]. Laboratory experiments have demonstrated the capability of fiber-optic cables to monitor railway-induced vibrations [19], while practical deployment scenarios such as high-speed railway intrusion detection have also been reported [20]. Nevertheless, achieving reliable phase recovery in the presence of polarization fading remains a critical challenge, particularly for long-range and dynamic sensing applications.

This paper investigates a coherent ϕ-OTDR system employing a polarization diversity reception scheme based on the sequential acquisition of orthogonal polarization components using a single coherent receiver. By utilizing a high-speed RF switch to time-multiplex the backscattered field, the architecture preserves the benefits of polarization diversity while significantly minimizing hardware requirements. The primary contributions of this work are summarized as follows:

- The implementation of a hardware-efficient single-receiver architecture that preserves polarization diversity gain while significantly reducing system complexity and cost compared to conventional dual-channel polarization-diverse systems.

- The development of a signal processing framework that merges phase differences from time-multiplexed polarization components using MRC, thereby effectively mitigating polarization fading and improving phase stability.

- The experimental verification of the system performance, demonstrating reliable phase recovery and accurate frequency estimation in laboratory settings, as well as robust phase retrieval under realistic outdoor deployment conditions.

- A quantifiable performance enhancement, specifically an improvement in the SNR of approximately 2 dB compared to methods that select only the stronger polarization channel.

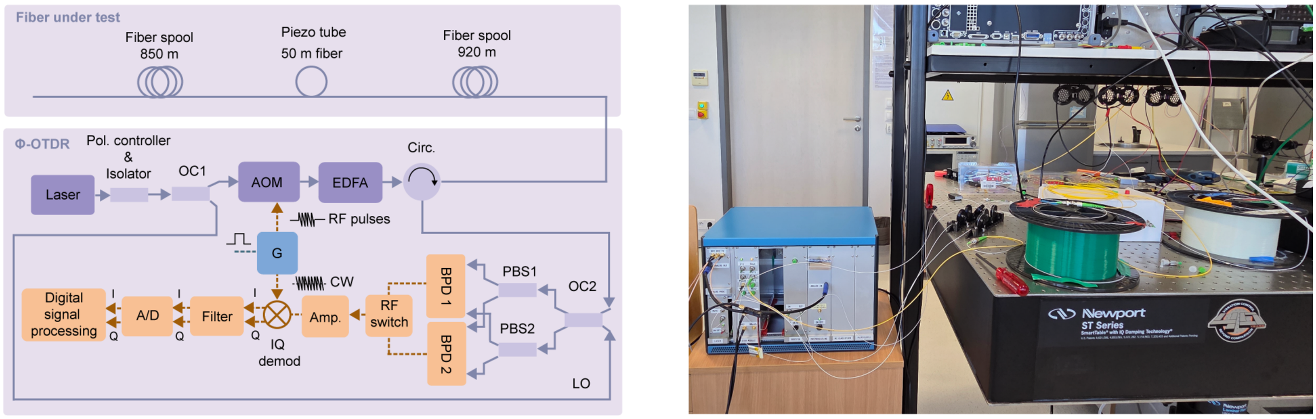
The proposed scheme offers a practical and cost-efficient solution for polarization-independent distributed acoustic sensing, ensuring high phase fidelity without the complexity of parallel receiver hardware.

The paper is structured as follows. Section 2 describes the principle of operation of the coherent ϕ-OTDR system and introduces the proposed sequential polarization reception using a single coherent receiver. Section 3 explains the signal processing procedure, including the separation of the polarization components and their merging. The experimental results and their analysis are given in Sec. 4, where the performance of the proposed approach and its ability to mitigate polarization fading are discussed. Finally, Section 5 concludes the paper and summarizes the main results.

2. Coherent Phase-OTDR System and Polarization Reception Scheme

The experimental setup, shown in Fig. 1, is based on a narrow-linewidth laser (Koheras Basik Mikro). The optical signal is modulated by Radio-Frequency (RF) pulses using an Acousto-Optic Modulator (AOM). The RF pulses are generated by a Field-Programmable Gate Array (FPGA) platform, which produces optical pulses with durations on the order of several hundred nanoseconds by modulating a 200 MHz carrier signal from an RF generator. After modulation, the optical signal is amplified by an Erbium-Doped Fiber Amplifier (EDFA) booster and launched into the sensing fiber through a three-port optical circulator.

The Rayleigh backscattered light returning from the sensing fiber is combined with a reference optical wave using a standard 50 : 50 optical coupler. To reduce polarization fading, two Polarization Beam Splitters (PBS1 and PBS2) are used to separate the combined signal into two orthogonal polarization components. The reference light is aligned at 45° with respect to the PBS axes by adjusting a paddle polarization controller in the reference arm. Each polarization component is detected independently using a balanced photodetector. An RF switch alternately routes the signals from the two polarization channels to the RF receiver stage, where they are amplified, demodulated into In-phase (I) and Quadrature (Q) components, filtered, and subsequently digitized. The custom-made RF switch comprises two ADG919 wideband switches connected in series, with 82 dB isolation and 1.5 dB insertion loss. A high isolation level is required to effectively separate the individual polarization components and prevent any leakage between channels during switching. When polarization channels are not sufficiently isolated, residual signals from one channel can couple into the other, leading to cross-talk, measurement errors, and degradation of overall system performance. High isolation ensures that each polarization state remains independent and that the detected signal accurately represents only the intended channel. The digitization process within the digital signal processing block is performed at a sampling rate of 100 MHz using a 14-bit LTC2155-14 analogue-to-digital converter mounted on a DC1564-A board, which is interfaced via an FMC connector to a Zynq 7000 ZedBoard development platform. The software component of the ϕ-OTDR probe is implemented



(a) (b)

Fig. 1. Phase-sensitive OTDR system: (a) schematic diagram of the proposed system; (b) laboratory setup for testing.

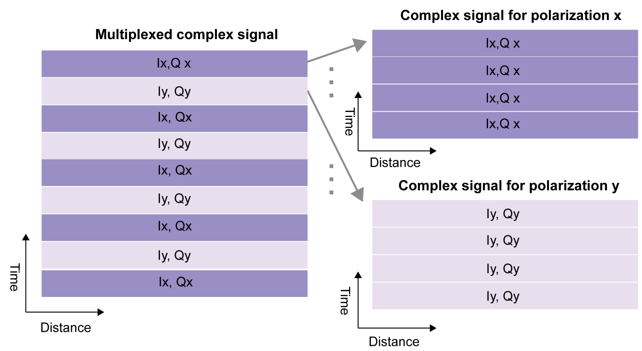


Fig. 2. Multiplexed complex (I/Q) signal and its demultiplexing into two polarization components.

on the Zynq 7000 SoC, acting as an integration element between the programmable logic, the analogue module, and the supervisory control unit to manage the acquisition process and ensure reliable data transfer.

To accommodate the high data volume, deterministic preprocessing, including matched digital filtering and optional signal decimation, is executed directly within the FPGA to eliminate additional latency. Decimation parameters are adjustable via the processor, allowing the system to be flexibly adapted to various scenarios such as laboratory measurements or long-term monitoring. Furthermore, the FPGA logic coordinates the timing of the 200 MHz RF pulses and the 2 kHz sequential switching with the RF switch, followed by matched filtering to maximize the SNR based on the launched pulse duration. Within the next processing procedure, the signal has to be split in order to demodulate the phase difference (see Fig. 2).

3. Signal Processing and Phase Demodulation

For each polarization channel (x and y), the received complex backscattered signal $E_p(t,z)$, where $p \in \{x,y\}$, is first converted to an instantaneous optical phase

$$\phi_p(t,z) = \arg(E_p(t,z)). \tag{1}$$

Because the phase is wrapped in the interval $[-\pi, \pi]$, unwrapping in the spatial domain (fast-time) is necessary to obtain continuous phase evolution. Spatial unwrapping ensures that phase differences reflect actual fiber strain without artificial discontinuities. Spatial differentiation is then applied with a gauge length Δz, which corresponds to the initial pulse length and determines the spatial resolution of the measurement of the fiber segment over which phase changes are averaged. The spatial phase difference is calculated as

$$\Delta\phi_p^{(z)}(t,z) = \phi_p(t, z+\Delta z) - \phi_p(t,z). \tag{2}$$

As the phase may also wrap in time, temporal unwrapping is subsequently performed, after which temporal differentiation over a time interval Δt is applied to isolate dynamic perturbations,

$$\Delta\phi_p(t,z) = \Delta\phi_p^{(z)}(t+\Delta t, z) - \Delta\phi_p^{(z)}(t,z). \tag{3}$$

This processing chain suppresses common-mode phase noise and slow drifts while preserving vibration-induced phase variations.

In a conventional polarization diversity system, the phase from both complex signals is usually demodulated as follows [14]:

$$\phi(t,z) = \arctan\left(\frac{Q_x(t,z) + Q_y(t,z)}{I_x(t,z) + I_y(t,z)}\right) \tag{4}$$

where x and y correspond to vertical and horizontal polarization planes. In the proposed system, the two polarization channels are time-multiplexed rather than simultaneous. Because of this, the phase of each channel is measured at slightly different times, and the instantaneous phase between channels does not align. As a result, conventional vector summation of the complex signals would cause partial cancellation and distort the reconstructed signal. Therefore, the independently recovered phase-difference signals $\Delta\phi_x(t,z)$ and $\Delta\phi_y(t,z)$ are combined using the MRC method. The MRC is widely used in wireless communication receivers, particularly in multi-antenna systems such as diversity, MIMO, and OFDM systems, where it mitigates fading and interference by maximizing the SNR. In the proposed polarization-diverse ϕ-OTDR system, this principle is adapted to combine the independently recovered phase differences from the two polarization channels. The combining weights $w_x(t,z)$ and $w_y(t,z)$ are derived from the instantaneous signal quality of each polarization channel, typically estimated from the received signal power or an equivalent SNR, and normalized such that $w_x + w_y = 1$. The combined phase-difference signal is then given by

$$\Delta\phi_c(t,z) = w_x(t,z) * \Delta\phi_x(t,z) + w_y(t,z) * \Delta\phi_y(t,z). \quad (5)$$

Finally, the combined phase-difference signal is integrated in space and time to reconstruct the distributed phase response, resulting in improved phase stability and enhanced robustness against polarization-induced fading.

The combining weights are determined from an estimate of the instantaneous signal quality of each polarization channel. For the given x and y polarizations, the received signal power is obtained from the magnitude of the complex backscattered field,

$$P_p(t,z) = \left|E_p(t,z)\right|^2. \quad (6)$$

In addition to power, the local phase variance $\sigma^2_{\phi,p}(t,z)$ is estimated using a sliding window applied to the recovered phase-difference signal. The instantaneous signal quality is then characterized by a combined metric that accounts for both signal strength and phase stability. Based on this metric, the maximum-ratio combining weights are defined as

$$w_p(t,z) = \frac{P_p(t,z)}{\sigma^2_{\phi,p}(t,z)}. \quad (7)$$

The weights are subsequently normalized according to

$$w_x(t,z) = \frac{w_x(t,z)}{w_x(t,z) + w_y(t,z)}, \quad (8)$$

$$w_y(t,z) = \frac{w_y(t,z)}{w_x(t,z) + w_y(t,z)}. \quad (9)$$

This normalization makes the combined phase-difference signal independent of absolute optical power variations and assigns a higher weight to the polarization channel with better instantaneous signal quality. As a result, the weights adapt to polarization fading and improve the robustness of the reconstructed phase signal.

4. Experimental Results and Discussion

This section presents the experimental validation of the proposed polarization-diverse ϕ-OTDR signal processing framework. Laboratory measurements were conducted using a controlled test setup to evaluate the performance of the phase recovery and polarization combining method. The sensing fiber consists of two fiber spools with lengths of 920 m and 850 m, respectively (see Fig. 1), with a piezo-electric transducer positioned between them. A 50 m section of the fiber is wound around the transducer to allow controlled excitation of the fiber by applied vibrations. The piezo (PI PT120) was driven by a harmonic signal with frequency 71 Hz and amplitude 200 mV from an arbitrary generator. Before the measurement, the polarization was carefully aligned between the horizontal and vertical planes using the polarization controller behind the laser. In the experiment, a laser pulse with a duration of 310 ns was launched into the sensing fiber. The main system parameters used during the test measurements are presented in Tab. 1.

The backscattered signal was recorded as a complex waveform and subsequently processed within the FPGA-based acquisition system, where it underwent digital decimation and matched filtering with parameters specifically tailored to the duration of the launched probe pulse. The digitized complex data was subsequently transferred to a workstation for offline signal processing and phase reconstruction performed within MATLAB.

To demonstrate the relevance of the proposed MRC technique, the combined phase-difference signal $\Delta\phi_c(t,z)$ is compared with the individual polarization components $\Delta\phi_x(t,z)$ and $\Delta\phi_y(t,z)$ over 2000 realizations, as shown in Fig. 3. The polarization-induced fades, manifested as spikes in the individual signals, are significantly suppressed in the combined response.

Laser linewidth	< 1 kHz
Wavelength range	1535–580 nm
Pulse width	310 ns
Peak launch power	23 dBm
Sampling	100 MHz
Sensing fiber length (Lab)	1800 m
Sensing fiber length (Outdoor)	3520 m
Spatial resolution	31 m
Pulse repetition rate	2 kHz

Tab. 1. The main parameters of the system during the test measurements.

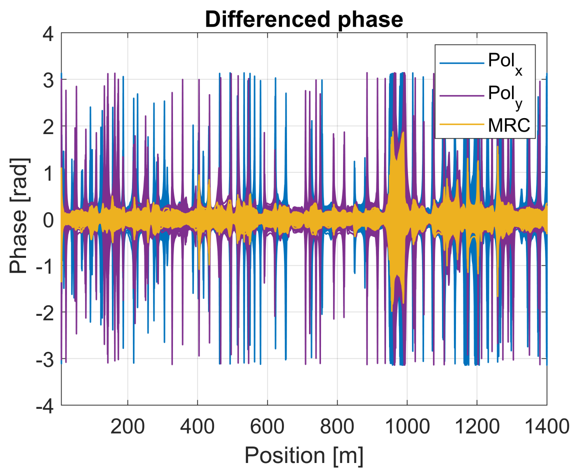


Fig. 3. Combined differenced phase $\Delta\phi_c(t,z)$ obtained using MRC, compared with $\Delta\phi_x(t,z)$ and $\Delta\phi_y(t,z)$.

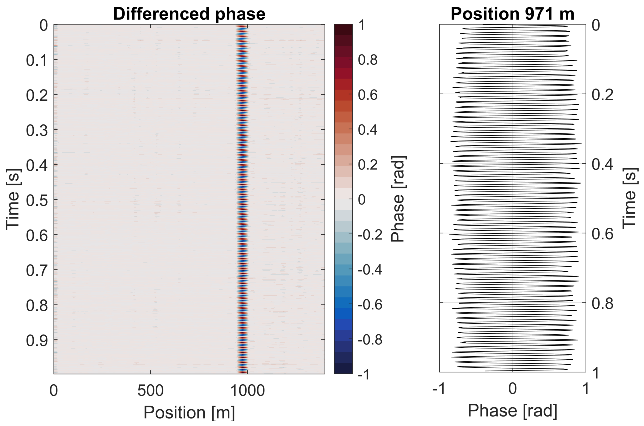


Fig. 4. Waterfall of the phase-difference signal after integration and the reconstructed phase at a fiber position of 971 m obtained using MRC.

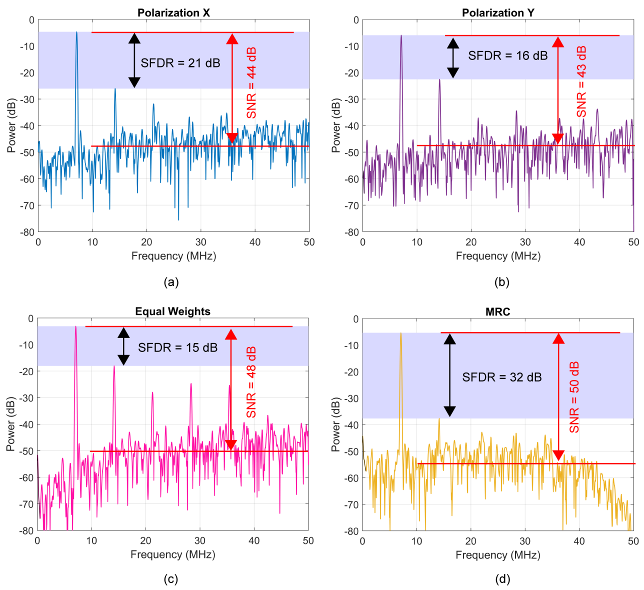


Fig. 5. Spectrum of the reconstructed phase signal at the position 971 m for: (a) $\Delta\phi_x(t,z)$; (b) $\Delta\phi_y(t,z)$; (c) $\Delta\phi_e(t,z)$ for equal weights; (d) $\Delta\phi_c(t,z)$ obtained using MRC.

It is clearly visible in Fig. 4 that the vibrations induced by the transducer are located at a fiber position of 971 m. The reconstructed phase signal shows significantly reduced polarization-induced fading over the entire sensing range.

In Fig. 5, the spectrum of the reconstructed phase signal $\Delta\phi_c(t,z)$ is compared against the individual polarization components ($\Delta\phi_x(t,z)$ and $\Delta\phi_y(t,z)$) and a baseline merging approach using equal weights $\Delta\phi_e(t,z)$ ($w_x = 0.5, w_y = 0.5$). The spectrum reveals that individual polarization channels are highly susceptible to polarization-induced fading, which manifests as an elevated noise floor and the presence of unwanted higher harmonics. While the equal weights approach provides a basic combination of the two orthogonal states, it lacks the ability to adapt to the fluctuating signal quality of each channel. In contrast, the MRC method adaptively assigns weights based on the instantaneous power and phase stability of each component. This adaptive weighting leads to a significant reduction in the noise floor, particularly at frequencies above 100 Hz, and the effective suppression of parasitic harmonics that are visible in the individual x and y planes. As a result, the MRC-based approach provides a quantifiable improvement of approximately 3 dB in SNR and 10 dB in SFDR compared to selecting only the stronger polarization channel $\Delta\phi_x(t,z)$. Furthermore, it yields an improvement of 2 dB in SNR and 17 dB in SFDR when compared to an equal weights strategy, ensuring robust and high-fidelity phase reconstruction even in fiber segments with weak optical signals.

Outdoor measurements were performed on a 440 m perimeter where a single-mode fiber was buried about 0.5 m underground to secure the area. Various intrusion events were simulated, including a person hammering an iron rod into the ground, opening the gate, walking, and running along the perimeter. Each activity produced distinct mechanical vibrations, showing that the system can detect and localize different types of disturbances. The measurement setup is shown in Fig. 6. The sensing fiber was connected to the ϕ-OTDR system and arranged in 8 loops, giving a total fiber length of approximately 3520 m.

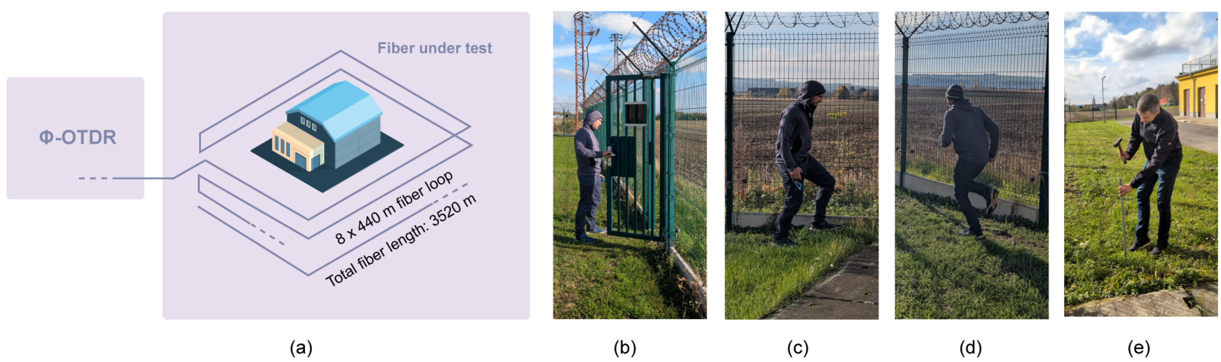


Fig. 6. Outdoor experimental setup and representative intrusion scenarios: (a) schematic diagram of the measurement configuration; (b) opening of a small gate; (c) walking along the secured fence; (d) running along the fence; (e) hammering an iron rod into the ground near the buried sensing fiber.

In analogy with the laboratory measurements, the effectiveness of the proposed MRC technique is demonstrated using real outdoor experimental data. The combined phase-difference signal for a hammering event is compared with the individual polarization components as shown in Fig. 7. The polarization-induced fades, which appear as strong phase fluctuations in the individual channels, are significantly suppressed in the combined response.

Figures 8, 9, 10, and 11 present the waterfall plots of the reconstructed phase for different simulated intrusion events, where the disturbances appear eight times along the fiber due to the looped configuration. As expected, events with strong physical impacts create clear and highly visible phase changes. For example, opening a small gate (see Fig. 8) and hammering an iron rod into the ground near the buried fiber (see Fig. 9) produce strong, localized vibrations that appear as sharp signals. Running along the fence (see Fig. 11) also shakes the structure and the ground, creating an easily detectable pattern. In contrast, walking along the fence (see Fig. 10) transfers much less energy to the sensing fiber. Because of this, the signal for walking is very weak and barely visible above the system's background noise.

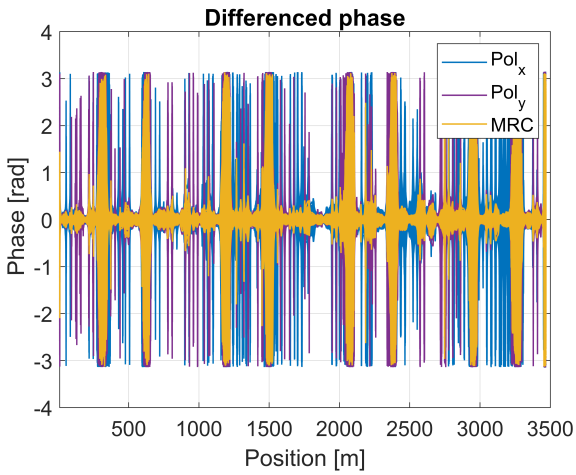


Fig. 7. Combined differenced phase $\Delta\phi_c(t, z)$ obtained using MRC, compared with $\Delta\phi_x(t, z)$ and $\Delta\phi_y(t, z)$ for a hammering event.

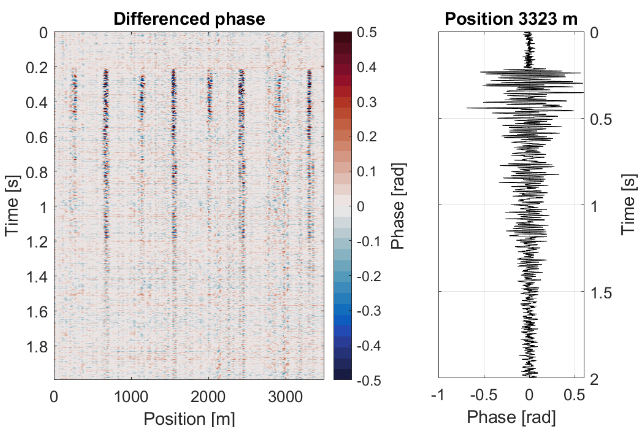


Fig. 8. Reconstructed phase waterfall plot along the sensing fiber during a small gate opening event.

Overall, these results demonstrate that the ϕ-OTDR system easily detects high-impact intrusions, but also show the challenge of capturing very light, low-energy movements along the perimeter.

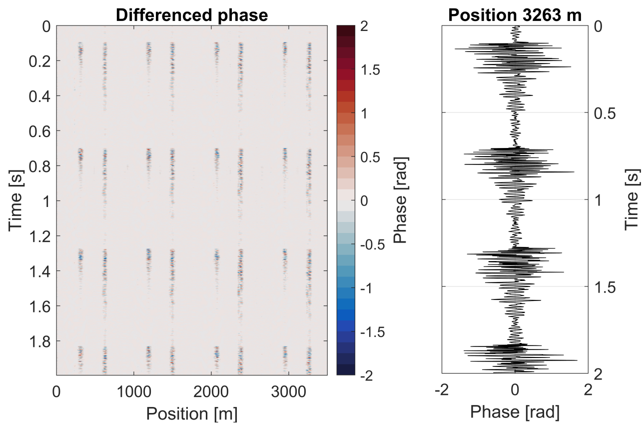


Fig. 9. Reconstructed phase waterfall plot along the sensing fiber during a nearby hammering event.

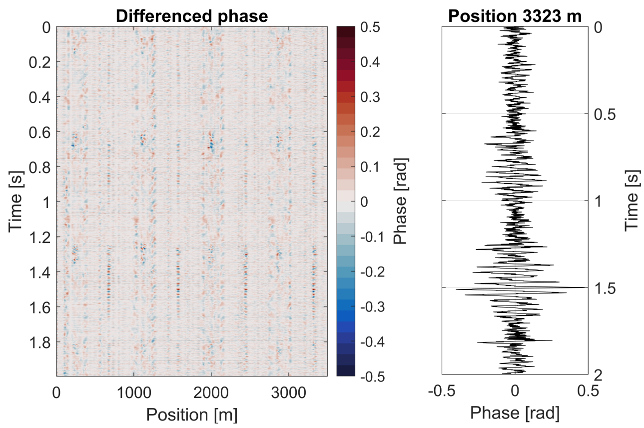


Fig. 10. Reconstructed phase waterfall plot along the sensing fiber during a fence walking event.

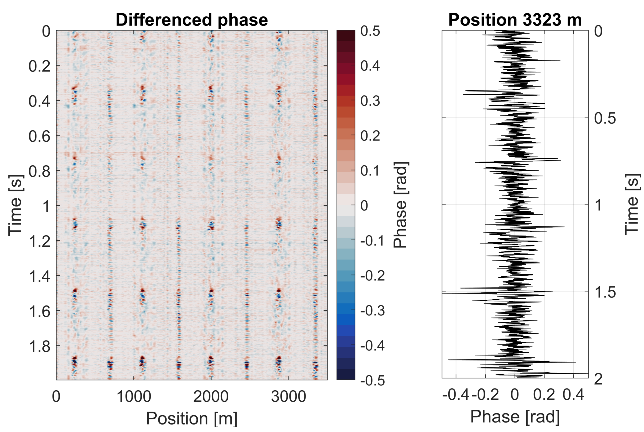


Fig. 11. Reconstructed phase waterfall plot during a running event along the protected fence.

5. Conclusion

This paper presented a polarization-diverse ϕ-OTDR sensing system combined with a dedicated signal-processing framework for robust phase recovery under polarization fading conditions. Owing to the time-multiplexed acquisition of the polarization channels, phase differences were independently reconstructed and subsequently merged using a maximum-ratio combining approach based on instantaneous signal quality metrics. Experimental results obtained in both laboratory and outdoor environments demonstrate that the proposed method significantly suppresses polarization-induced fading while preserving the integrity of vibration-induced phase signals. Controlled laboratory tests using a piezoelectric transducer, as well as field measurements involving various intrusion scenarios, confirm reliable event detection and localization along the sensing fiber. The proposed approach improves phase stability without increasing optical hardware complexity, making it a practical solution for distributed vibration sensing and perimeter security applications based on ϕ-OTDR systems.

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