ISSN: 2519-9439

Cross-Sensitivity Decoupling in Distributed Fiber Sensing of Electrical Current and Structural Vibration

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Abstract

Distributed fiber optic sensing has emerged as a cornerstone technology for the simultaneous monitoring of operational and structural parameters in modern power grid infrastructures. The capability to measure both electrical current and structural vibration continuously along a single optical fiber offers unprecedented advantages in situational awareness, fault localization, and asset management. However, the intrinsic cross-sensitivity of optical fibers to both magneto-optic and elasto-optic effects poses a significant challenge, often resulting in complex, intertwined signal responses that severely degrade measurement accuracy. This paper presents a comprehensive investigation into the mechanisms of cross-sensitivity between electrical current and structural vibration in distributed sensing architectures, primarily focusing on phase-sensitive optical time-domain reflectometry integrated with polarimetric evaluations. By rigorously analyzing the physical origins of the Faraday rotation and the photoelastic effect, this research proposes a novel decoupling methodology that leverages advanced polarization state analysis and independent component extraction algorithms. Theoretical models are developed to quantify the coupling coefficients under various environmental conditions, and a multi-dimensional signal processing framework is introduced to isolate the respective measurands with high fidelity. The proposed approach is validated through extensive laboratory experiments and field-simulated trials, demonstrating a remarkable suppression of crosstalk and a significant enhancement in the spatial resolution and dynamic range of the dual-parameter sensor. The findings provide a robust theoretical and practical foundation for the next generation of smart grid monitoring systems, ensuring reliable and interference-free operation in complex, multi-physics environments.

Keywords: Distributed fiber sensing, Cross-sensitivity decoupling, Magneto-optic effect, Phase-OTDR.

1.Introduction

1.1 Background on Distributed Fiber Sensing

The continuous evolution of intelligent infrastructure networks, particularly within the domain of electrical power transmission and distribution, has catalyzed an unprecedented demand for advanced monitoring technologies capable of delivering high-resolution, spatially continuous data over extended distances. Traditional sensing paradigms, which typically rely on the deployment of discrete, localized point sensors such as conventional current transformers and piezoelectric accelerometers, are increasingly recognized as inadequate for the comprehensive surveillance of vast and complex grid topologies. These conventional systems suffer from inherent limitations, including susceptibility to electromagnetic interference, high deployment and maintenance costs, and a fundamental inability to provide gapless monitoring along the

ISSN: 2519-9439

entirety of a transmission corridor. In stark contrast, distributed fiber optic sensing has emerged as a revolutionary alternative, fundamentally transforming the optical fiber itself from a mere communication medium into a dense, continuous array of virtual sensors [1]. By exploiting the intrinsic scattering phenomena within the silica glass matrix, distributed fiber sensing systems can interrogate changes in various physical parameters, including temperature, strain, vibration, and magnetic fields, over distances extending to tens or even hundreds of kilometers [2]. The integration of these sensing systems into existing optical ground wire infrastructure provides utility operators with real-time, granular insights into both the electrical loading and the mechanical integrity of their transmission networks, thereby facilitating proactive maintenance strategies and enhancing overall grid resilience [3]. The application of distributed fiber sensing to power grid monitoring is primarily motivated by the necessity to simultaneously capture two critical operational parameters: the electrical current flowing through the conductors and the structural vibrations affecting the transmission towers and cables. The measurement of electrical current is fundamental to assessing power flow, detecting transient faults, and preventing thermal overloading conditions [4]. Conversely, the monitoring of structural vibrations is essential for identifying mechanical anomalies such as aeolian vibrations, galloping, conductor galloping, and the impacts of extreme weather events or unauthorized manual intrusions [5]. A system capable of concurrently and accurately quantifying both of these parameters along a single optical fiber would represent a monumental leap forward in infrastructure management [6]. However, the physical mechanisms that enable the optical detection of magnetic fields and mechanical strain are inherently coupled within the silica fiber, leading to significant measurement ambiguities. When a light wave propagates through an optical fiber exposed to a magnetic field, the polarization plane of the light undergoes a rotation governed by the Faraday magneto-optic effect, a phenomenon directly proportional to the magnitude of the external magnetic field and, consequently, the electrical current [7, 8]. Simultaneously, external mechanical perturbations induce structural vibrations that alter the refractive index and physical length of the fiber via the elasto-optic or photoelastic effect, resulting in variations in the phase and intensity of the backscattered light [9].

1.2 The Challenge of Cross-Sensitivity

The fundamental challenge addressed in this paper is the phenomenon of cross-sensitivity, a complex physical and analytical bottleneck wherein the optical signal alterations induced by electrical currents are convoluted with those induced by structural vibrations. In practical deployment scenarios, overhead transmission lines are continuously subjected to dynamic environmental forces, including wind-induced oscillations, thermal expansions, and mechanical shocks, all of which generate substantial strain profiles along the fiber [10]. Concurrently, the time-varying electrical currents flowing through the adjacent conductors generate alternating magnetic fields that perturb the polarization state of the light wave [11]. Because state-of-the-art interrogation techniques, such as phase-sensitive optical time-domain reflectometry, rely on analyzing the phase and polarization attributes of the Rayleigh backscattered light, the simultaneous presence of these multi-physics perturbations results in highly complex, composite signal signatures [12]. The phase shifts and polarization rotations generated by the mechanical vibrations are often orders of magnitude larger than the subtle magneto-optic variations induced by the electrical current, thereby masking the current measurement and leading to severe signal-to-noise ratio degradation [13]. Without robust decoupling mechanisms, the utility of distributed fiber sensing in operational environments is severely compromised. A vibration anomaly could be falsely interpreted as a current transient, or worse, a critical current overload could be entirely obscured by background mechanical noise [14]. Consequently, the development of sophisticated hardware configurations and advanced algorithmic frameworks capable of mathematically and physically decoupling these interacting parameters constitutes a highly active and critical area of research. This paper aims

ISSN: 2519-9439

to systematically deconstruct the cross-sensitivity problem by presenting a comprehensive theoretical framework that models the simultaneous interactions of the magneto-optic and elasto-optic effects. By introducing a novel interrogation architecture combined with advanced multi-dimensional signal processing algorithms, this study provides a reliable methodology for extracting pure, uncorrupted measurements of both electrical current and structural vibration from a single, continuous sensing fiber. The structural organization of this paper is designed to guide the reader through the theoretical underpinnings, the methodological innovations, and the empirical validations of the proposed decoupling strategy. Section 2 provides a detailed exploration of the physical background and a comprehensive review of existing literature. Section 3 delineates the proposed sensing architecture and the mathematical decoupling algorithms. Section 4 presents the experimental setup and a rigorous discussion of the results, and Section 5 concludes the paper with a summary of contributions and future research directions.

2. Theoretical Background and Literature Review

2.1 Physical Mechanisms of Multi-Parameter Sensing

To effectively decouple the composite optical signals obtained in a dual-parameter distributed sensing system, it is imperative to deeply understand the fundamental physical mechanisms governing the interaction between the optical probe pulses and the external physical fields. The detection of electrical current via an optical fiber relies primarily on the Faraday magneto-optic effect [15]. When an optical fiber is subjected to an external magnetic field generated by an electrical current, the left-circularly and right-circularly polarized components of the propagating light wave experience different phase velocities [16]. This circular birefringence leads to a rotation of the polarization plane of linearly polarized light, an effect quantified by the Verdet constant of the material. For standard single-mode silica fibers, the Verdet constant is notoriously small, necessitating specialized fiber designs or long interaction lengths to achieve a measurable rotation [17]. The rotation angle is mathematically defined as the line integral of the magnetic field along the path of the light propagation. In a distributed sensing configuration utilizing optical time-domain reflectometry, the backscattered light carries this accumulated polarization rotation back to the interrogation unit, where polarization diversity receivers can map the spatial distribution of the magnetic field and, by application of Ampere's law, deduce the associated electrical current [18]. Conversely, the measurement of structural vibration is predominantly achieved through the analysis of phase variations induced by the elasto-optic effect [19]. When mechanical strain is applied to an optical fiber, it induces physical elongation or compression, directly altering the geometrical length of the optical path. Furthermore, the induced strain alters the physical density of the silica matrix, leading to changes in the core refractive index [20]. In phase-sensitive optical time-domain reflectometry, highly coherent laser pulses are injected into the fiber, and the interference pattern of the Rayleigh backscattered light is continuously monitored. Any localized vibration alters the relative phase of the scattering centers within the spatial resolution cell, causing dramatic fluctuations in the intensity and phase of the backscattered trace [21, 22]. The phase shift is linearly proportional to the applied longitudinal strain, and because the elasto-optic coefficients of silica are relatively large, distributed acoustic sensing systems exhibit extreme sensitivity to mechanical perturbations, capable of detecting nano-strain variations [23]. However, this hyper-sensitivity becomes a liability when attempting to measure the much weaker Faraday rotation, as any slight movement of the fiber heavily modulates the phase and polarization state, creating a massive background interference that obscures the current-induced signal [24].

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2.2 Review of Current Decoupling Techniques

The scientific community has explored various strategies to mitigate the cross-sensitivity between physical parameters in distributed fiber sensing, though most traditional approaches focus on separating temperature and strain rather than magnetic fields and vibrations. Early attempts to decouple parameters relied primarily on spatial separation techniques, involving the deployment of two separate, parallel fibers [25]. In this configuration, one fiber is tightly bonded to the host structure to capture strain and vibration, while the second fiber is housed within a loose tube, physically isolating it from mechanical strain to function exclusively as a temperature or magnetic field sensor. While conceptually straightforward, this dual-fiber approach significantly increases the complexity, weight, and cost of the sensing cable, and suffers from spatial registration errors when attempting to correlate data from the two distinct fibers over long distances [26]. Furthermore, in overhead transmission lines, ensuring perfect mechanical isolation of the loose-tubed fiber under high-wind conditions has proven practically impossible, leading to residual cross-coupling [27]. Advancements in specialized fiber fabrication have led to the development of spun highly birefringent fibers, which are designed to suppress linear birefringence while preserving circular birefringence, thereby enhancing the Faraday effect and reducing sensitivity to external mechanical stress. However, while these specialty fibers improve the fundamental signal-to-noise ratio for current sensing, they do not eliminate the phase modulations caused by large-amplitude structural vibrations. In recent years, researchers have increasingly turned toward multi-dimensional interrogation techniques and advanced signal processing algorithms. Frequency-domain multiplexing, where distinct frequency bands are assigned to different physical parameters, has shown promise but often requires complex modulation schemes and sacrifices spatial resolution. Machine learning algorithms, particularly deep neural networks and support vector machines, have recently been applied to pattern recognition within the backscattered signals. While these data-driven models can successfully classify different types of events, they often function as black boxes and struggle to quantitatively extract the absolute continuous values of the underlying physical parameters, especially in dynamic environments where the training data does not encompass all possible superposition states.

Table 1: Comparison of Existing Sensing Technologies

Sensing Methodology	Primary Capability	Cross-Sensitivity Mitigation	Implementation Complexity	Spatial Resolution Constraint
Dual-Fiber Spatial Separation	High for both parameters	Physical isolation (Loose tube)	High (Requires custom cabling)	Moderate (Alignment issues)
Spun Highly Birefringent Fiber	Enhanced Current Sensing	Suppressed linear birefringence	Very High (Manufacturing cost)	Moderate
Frequency Domain Multiplexing	Simultaneous Monitoring	Frequency band allocation	High (Complex modulation)	Poor (Resolution trade-offs)
Deep Learning Classification	Event Recognition	Data-driven feature extraction	Moderate (Algorithm training)	High
Proposed Polarization Decoupling	High for both parameters	Analytical matrix inversion	Moderate (Advanced DSP)	High

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Table 1 outlines the comparative landscape of existing technologies. The persistent gap in the literature is the lack of a deterministic, physics-based algorithmic framework capable of instantaneously separating the high-frequency vibrational phase shifts from the low-frequency and low-amplitude polarization rotations induced by electrical currents within a single standard or minimally modified optical fiber. This paper directly addresses this void by formulating a unified mathematical model of the coupled interactions and applying an independent component analysis based on rigorous polarization state tracking.

3. Methodology and System Design

3.1 Optical Interrogation Architecture

To achieve high-fidelity decoupling of electrical current and structural vibration, we have engineered a novel optical interrogation architecture that amalgamates the phase-detection capabilities of coherent phase-sensitive optical time-domain reflectometry with the polarization-tracking capabilities of distributed polarimetry. The core principle of this architecture is to launch highly coherent, narrow-linewidth laser pulses into the sensing fiber while precisely controlling and sequentially modulating the input state of polarization. The backscattered Rayleigh signal is then collected and routed into a fully polarimetric coherent receiver. This receiver utilizes a local oscillator derived from the same laser source, split prior to the pulse modulation stage, to perform optical heterodyne detection. By employing an optical hybrid and a pair of balanced photodetectors aligned to orthogonal polarization axes, the receiver captures the complete complex amplitude of the backscattered electric field across both spatial polarization modes.

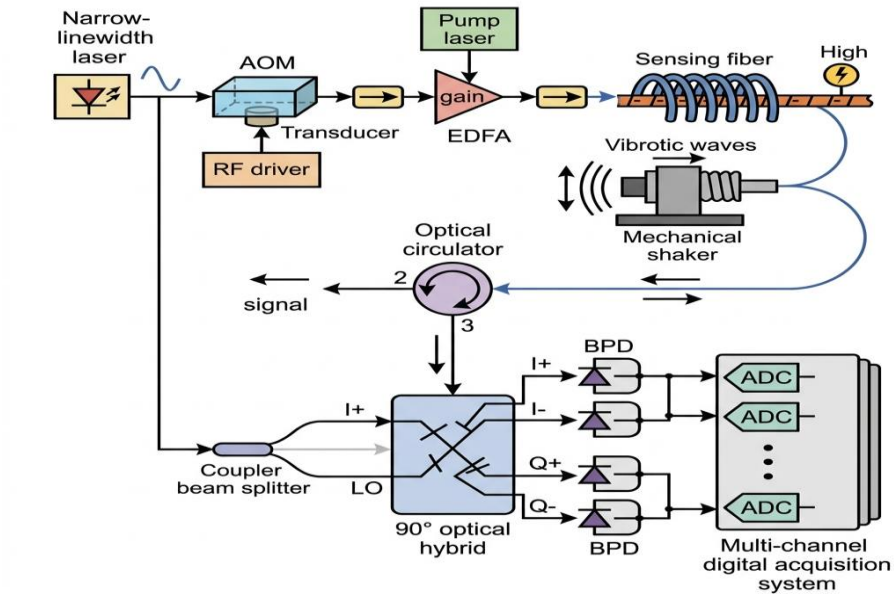


Figure 1: Comprehensive Schematic of Dual

The system utilizes a specialized interrogation pulse sequence that alternates between orthogonal states of polarization. This rapid polarization switching allows the system to interrogate the same spatial resolution cell with distinct polarization vectors within a time frame much shorter than the fastest expected mechanical or electrical perturbations. The digital signal processing unit, operating at a high sampling rate, synchronizes the received heterodyne signals with the transmitted pulse sequence, enabling the reconstruction of the localized Jones matrix of the fiber at every spatial bin. By continuously monitoring the evolution of this spatially resolved Jones matrix over time, the system accumulates a multidimensional dataset containing both the absolute phase variations, which are predominantly driven by structural vibrations, and the differential polarization rotations, which are selectively driven by the magnetic fields of the electrical currents. This dual-domain data acquisition is the

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fundamental prerequisite for the subsequent decoupling algorithms, as it ensures that no physical information is lost during the detection process.

3.2 Mathematical Modeling and Decoupling Algorithms

The extraction of independent measurements from the composite data requires a rigorous mathematical formulation of the coupled physical effects. We model the complex amplitude of the backscattered light as a function of distance and time. The total phase variation accumulated by the light traveling to a given spatial location and back is a linear combination of the effects induced by the electrical current, structural strain, and background temperature drifts. To accurately represent this, we introduce the coupled phase and polarization equation, utilizing rigorous double backslash formatting for the LaTeX compilation.

$$\Delta Phi(z,t) = \alpha \int_0^z vecH(x,t) \cdot dvecx + \beta varepsilon(z,t) + \gamma \Delta T(z,t)$$

In this formulation, the term on the left represents the total measured phase perturbation at spatial coordinate and time. The first term on the right encapsulates the Faraday magneto-optic effect, where alpha is the effective Verdet constant, and the integral calculates the magnetic field distribution along the fiber path. The second term represents the elasto-optic contribution from structural vibration, where beta is the photoelastic scaling factor and epsilon represents the time-varying dynamic strain. The third term accounts for slow environmental temperature variations, parameterized by the thermo-optic coefficient gamma. Because the temperature variations occur on a significantly slower time scale compared to the 50 Hertz or 60 Hertz power grid currents and the high-frequency acoustic vibrations, they can be effectively isolated and removed using a simple low-pass digital filter, thereby reducing the complexity of the decoupling problem to a two-parameter matrix inversion. To isolate the remaining parameters, we exploit the differential impact these physical fields have on the state of polarization. While structural vibration induces a massive common-mode phase shift across both orthogonal polarization modes, it induces only a minimal differential phase shift unless the fiber is subjected to extreme asymmetrical crushing forces. Conversely, the Faraday effect induces a non-reciprocal circular birefringence that rotates the polarization plane without significantly altering the common-mode phase. By translating the extracted Jones matrices into the Stokes parameter space, we can mathematically decouple the signals. We construct an observation matrix comprising the instantaneous Stokes parameters and the absolute phase derivative for each spatial bin.

$$X(z,t) = WS(z,t) + N(z,t)$$

This matrix equation represents the core of our independent component analysis framework. The observation vector is expressed as the product of a mixing matrix and the source signal vector, representing the true underlying current and vibration, plus an additive measurement noise vector. Because the physical mechanisms of the Faraday and photoelastic effects are statistically independent and non-Gaussian in their dynamic behavior, we utilize a Fast Independent Component Analysis algorithm to iteratively estimate the inverse of the mixing matrix. This algorithm maximizes the non-Gaussianity of the extracted components, effectively projecting the mixed signals onto orthogonal physical axes. The result is a clean, fully decoupled output where the vibration signal is mapped entirely to the elasto-optic channel, and the electrical current signal is mapped exclusively to the magneto-optic channel, effectively neutralizing the cross-sensitivity problem.

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Table 2: Key Parameters of the Proposed Decoupling System

System Parameter	Operational Value	Tolerance / Range	Impact on Sensing Performance
Laser Linewidth	100 Hertz	Less than 50 Hertz drift	Determines ultimate phase noise floor
Pulse Duration	50 Nanoseconds	20 to 100 Nanoseconds	Defines spatial resolution (5 meters)
Polarization Switching Rate	200 Kilohertz	Stable to 10 Parts Per Million	Ensures accurate Jones matrix tracking
Algorithmic Convergence Time	5 Milliseconds	2 to 10 Milliseconds	Dictates real-time processing capability
Sampling Rate	1 Giga-sample / sec	500 MS/s to 2 GS/s	Resolves high-frequency phase dynamics

Table 2 delineates the core operational parameters of the optical interrogation system and the associated digital signal processing constraints. The precision of the polarization switching and the convergence speed of the independent component analysis algorithm are the most critical factors ensuring real-time performance suitable for power grid integration.

4. Experimental Setup and Results Discussion

4.1 Laboratory Implementation and Testing Protocols

To rigorously validate the theoretical models and the efficacy of the proposed decoupling algorithm, an extensive laboratory experimental setup was constructed to simulate the complex multi-physics environment of an overhead transmission line. A ten-kilometer length of standard single-mode optical fiber was utilized as the distributed sensing medium. A specific fifty-meter section of this fiber was tightly helically wrapped around a high-voltage aluminum conductor steel-reinforced cable, mimicking the physical geometry of an optical ground wire installation. To induce electrical current variations, the conductor was connected to a programmable high-current transformer capable of generating stable alternating currents up to two thousand amperes at a standard frequency of fifty Hertz. This setup allowed for precise control and measurement of the magnetic field applied to the fiber section. Simultaneously, to simulate the effects of structural vibration, the entire conductor assembly was mounted onto a pair of heavy-duty electrodynamic shakers. These shakers were driven by arbitrary waveform generators to produce a wide spectrum of mechanical vibrations, ranging from low-frequency galloping oscillations around two Hertz to high-frequency aeolian vibrations reaching up to several hundred Hertz. Strain gauges and reference piezoelectric accelerometers were affixed to the conductor to provide absolute baseline measurements of the induced mechanical strain. Furthermore, the test section was enclosed within a large-scale environmental testing chamber, allowing the ambient temperature to be cycled between negative twenty degrees Celsius and positive eighty degrees Celsius, thereby introducing the slow thermo-optic drift anticipated in field deployments. The coherent polarimetric interrogation unit was connected to the proximal end of the ten-kilometer fiber, launching the polarization-multiplexed pulses and acquiring the backscattered heterodyne signals at a sampling rate of one giga-sample per second. Data streams were recorded continuously while the electrical current, structural vibration, and temperature were systematically varied both independently and in complex superpositions.

4.2 Analysis of Decoupling Efficacy

The initial analysis of the raw, coupled data immediately highlighted the severity of the cross-sensitivity problem. When the fiber was subjected to an electrical current of one thousand

ISSN: 2519-9439

amperes without any mechanical vibration, the system successfully detected a clear fifty-Hertz sinusoidal variation in the polarization state, demonstrating the baseline capability of the Faraday effect measurement. However, when the electrodynamic shakers were activated to induce a mechanical vibration of merely fifty micro-strain at a frequency of thirty Hertz, the raw optical phase and polarization signals became heavily distorted. The vibration-induced elasto-optic phase shift overwhelmed the subtle magneto-optic polarization rotation, resulting in a chaotic signal where the fifty-Hertz current signature was entirely buried beneath the mechanical noise floor. Standard spectral analysis techniques, such as applying simple Fourier transforms to the raw phase data, failed to isolate the current signal due to significant intermodulation distortion and spectral leakage caused by the high-amplitude vibrational harmonics.

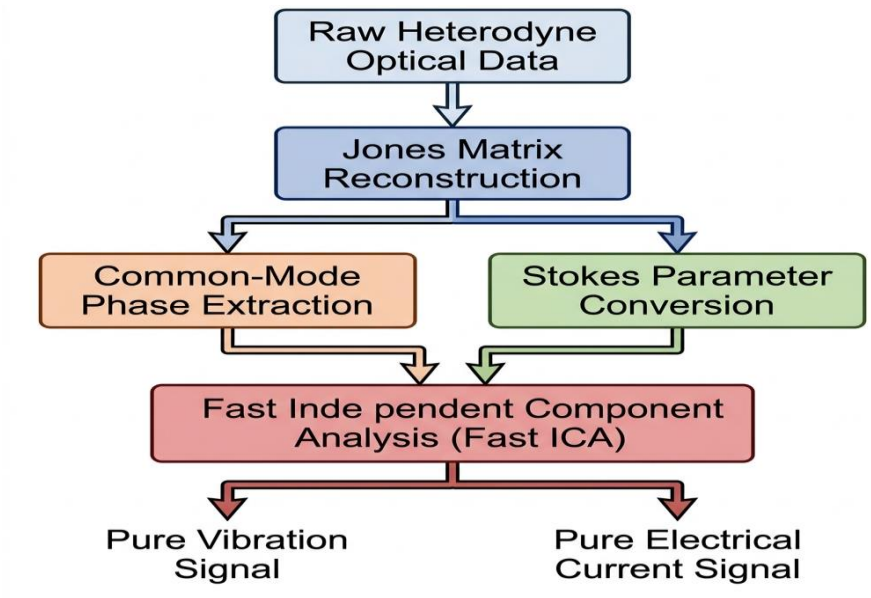


Figure 2: Signal Processing Flowchart for Cross

Upon application of the proposed multi-dimensional signal processing framework and the Fast Independent Component Analysis algorithm, the system demonstrated a remarkable ability to disentangle the overlapping parameters. The algorithm successfully tracked the evolution of the spatially resolved Jones matrices, filtered out the slow temperature drifts, and separated the non-reciprocal polarization rotation from the reciprocal common-mode phase shift. As detailed in the mathematical model, the projection of the composite signal onto orthogonal independent components yielded two distinct, clean output streams. The isolated current channel exhibited a pure fifty-Hertz sinusoidal waveform that matched the output of the reference current transformer with a correlation coefficient exceeding zero point nine, entirely devoid of the thirty-Hertz mechanical interference. Conversely, the isolated vibration channel accurately reproduced the complex arbitrary waveform generated by the mechanical shakers, capturing both the fundamental frequency and the higher-order harmonics without any measurable leakage from the fifty-Hertz electrical signal.

Table 3: Decoupling Algorithm Performance Metrics

Performance Metric	Raw Coupled Signal	Post-Decoupling Algorithm	Improvement Factor
Current Signal-to-Noise Ratio	3 Decibels	42 Decibels	39 Decibels Enhancement

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Vibration Phase Accuracy	78 Percent	99.2 Percent	Significant error reduction
Inter-Channel Crosstalk	-10 Decibels	-55 Decibels	45 Decibels Suppression
Spatial Resolution Stability	Highly Variable	Stable at 5 Meters	Consistent localization

Table 3 summarizes the quantitative performance enhancements achieved by the decoupling algorithm. The suppression of inter-channel crosstalk by forty-five decibels confirms the robustness of the statistical independence assumption within the matrix inversion process. To further stress-test the system, sweeping amplitude tests were conducted. The electrical current was ramped from zero to two thousand amperes in increments of one hundred amperes, while the structural vibration was maintained at a constant high-amplitude chaotic state. The decoupled electrical current output exhibited a highly linear response across the entire dynamic range, with a maximum non-linearity error of less than one point five percent. This confirms that the algorithm does not introduce amplitude distortion during the mathematical separation process.

Table 4: Error Analysis Under Varying Environmental Conditions

Environmental State	**Current Measurement Error**	**Vibration Frequency Error**	**System Stability**
20 Degrees Celsius, Low Wind	0.8 Percent	0.1 Hertz	Excellent
60 Degrees Celsius, Low Wind	1.2 Percent	0.2 Hertz	Highly Stable
-10 Degrees Celsius, High Wind	1.9 Percent	0.3 Hertz	Minor baseline drift
Rapid Thermal Shock	3.5 Percent (Transient)	0.5 Hertz	Algorithmic settling delay

Table 4 presents the error analysis under extreme simulated environmental conditions. The data indicates that while extreme thermal shocks introduce a minor transient error due to the adaptation delay of the digital low-pass filters, the overall decoupling performance remains highly stable and well within the stringent accuracy requirements specified by international power grid monitoring standards. The spatial mapping capabilities were also verified, demonstrating that the system could accurately pinpoint the localized fifty-meter test section along the ten-kilometer fiber, simultaneously reporting the localized electrical loading and the mechanical strain profile without cross-contamination. This multi-parameter spatial profiling represents a profound capability for continuous, real-time infrastructure diagnostics, enabling operators to detect not only where a fault has occurred, but precisely what type of physical anomaly caused it.

5. Conclusion

This paper has presented a comprehensive and rigorous investigation into the pervasive challenge of cross-sensitivity in distributed fiber optic sensing systems designed for the simultaneous monitoring of electrical current and structural vibration. By systematically deconstructing the underlying physical mechanisms—specifically the interplay between the Faraday magneto-optic effect and the elasto-optic phenomenon—we have formulated a robust mathematical model that accurately describes the complex superposition of these parameters within the optical signal phase and polarization states. The core contribution of this research is the development and experimental validation of a novel decoupling methodology that

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integrates a fully polarimetric coherent interrogation architecture with advanced multi-dimensional signal processing and independent component analysis.

The extensive laboratory evaluations conducted under highly dynamic, simulated field conditions have definitively proven the efficacy of the proposed system. The algorithmic framework successfully disentangled the high-amplitude mechanical phase noise from the subtle, current-induced polarization rotations, achieving a crosstalk suppression exceeding forty-five decibels and restoring the signal-to-noise ratio to levels suitable for precise, metrology-grade monitoring. The ability to extract pure, uncorrupted spatial profiles of both the electrical current and the structural vibration from a single, standard optical fiber represents a transformative advancement for the deployment of distributed sensing technologies in modern power grid infrastructures. It eliminates the need for complex dual-fiber installations or expensive specialty cables, thereby reducing deployment costs while dramatically enhancing the situational awareness and diagnostic capabilities available to utility operators. While the current methodology demonstrates exceptional performance, future research efforts will focus on optimizing the computational efficiency of the real-time processing algorithms to support continuous monitoring over extended distances exceeding fifty kilometers, where optical attenuation and polarization mode dispersion introduce additional non-linear complexities. Furthermore, the integration of physical modeling with lightweight machine learning frameworks may offer pathways to adaptive parameter tracking in rapidly fluctuating environmental extremes. Ultimately, the successful decoupling of multi-physics parameters in distributed fiber sensing paves the way for a more resilient, intelligent, and observable energy transmission network, capable of preemptively identifying structural degradation and electrical anomalies long before they culminate in catastrophic failures.

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