



Distributed large-range strain sensing based on birefringence variation in polarization-maintaining fiber using polarization OFDR

LIJIE WANG,^{1,2} HUAJIAN ZHONG,^{1,2} YAQI WANG,³ SHIJIE LI,^{1,2}
GUANFENG CHEN,^{1,2} RONGYI SHAN,^{1,2} CAILING FU,^{1,2}  AND
YIPING WANG^{1,2,*} 

¹Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education/Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

²Shenzhen Key Laboratory of Photonic Devices and Sensing Systems for Internet of Things, Guangdong and Hong Kong Joint Research Centre for Optical Fibre Sensors, Shenzhen University, Shenzhen 518060, China

³Department of Electronic and Computer Engineering, Shenzhen MSU-BIT University, Shenzhen 518172, China

*ypwang@szu.edu.cn

Abstract: A distributed large-range strain sensing method based on birefringence variation in polarization-maintaining fiber (PMF) is proposed and experimentally demonstrated using polarization optical frequency domain reflectometry (P-OFDR). Unlike conventional Rayleigh-based OFDR, which demodulates strain by tracking the spectral shift between reference and strained states, the proposed method reconstructs local birefringence from the relative spectral shift between the Rayleigh spectra of two orthogonal polarization axes in a PANDA fiber. A dual-polarization spatial alignment method is introduced to compensate for the accumulated birefringence-induced delay, while a correlation-quality-constrained strategy is used to suppress unreliable local demodulation results. Axial tensile experiments on an approximately 18 m PANDA fiber demonstrate distributed strain measurement over the experimentally validated range of 0–12000 $\mu\epsilon$ with a nominal spatial resolution of 5 mm. The measured birefringence variation exhibits a linear response to the applied strain, with a coefficient of determination of 0.9997. Repeated measurements yield equivalent strain standard deviations of 3.86–15.23 $\mu\epsilon$ over the tested range. These results demonstrate the potential of birefringence-based P-OFDR for high-spatial-resolution and large-range distributed strain sensing.

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1. Introduction

Distributed optical fiber sensing has been widely used in structural health monitoring, aerospace engineering, geotechnical monitoring, and mechanical deformation measurement because it provides continuous information along the sensing fiber. Among various distributed sensing techniques, optical frequency domain reflectometry (OFDR) is attractive owing to its high spatial resolution and high sensitivity [1–5]. In conventional Rayleigh-based OFDR, strain is generally demodulated by tracking the spectral shift between the reference and strained Rayleigh spectra [4]. However, under large deformation, the Rayleigh spectrum may shift beyond the reliable correlation range or become distorted by nonuniform strain, resulting in correlation degradation and false peak locking.

Several methods have been proposed to extend the measurable strain range of OFDR. Feng et al. exploited the local similar characteristics of Rayleigh scattering spectra to improve the strain range [6]. Wang et al. proposed a phase-accumulation method for wide-range strain sensing [7]. Zou et al. used an adjacent-point-difference spectral-shift method to achieve ultra-large

strain measurement [8], and Bai et al. introduced an optimal spectral similarity pursuit strategy to enhance spectral matching robustness [9]. Although these methods effectively enlarge the measurable strain range, they still mainly rely on spectral correlation or similarity tracking of the same Rayleigh channel. Therefore, high-spatial-resolution large-range strain sensing remains challenging because a short local window contains limited Rayleigh scattering features and is more susceptible to noise, nonuniform strain, and decorrelation.

Polarization-maintaining fiber (PMF) provides an additional sensing parameter through its intrinsic birefringence. In a PANDA PMF, the two orthogonal polarization eigenmodes have different effective refractive indices due to stress-induced refractive-index anisotropy, and the birefringence is sensitive to internal stress and external perturbations [10–12]. Distributed birefringence measurement in PMFs has been demonstrated using OFDR and polarization optical frequency domain reflectometry (P-OFDR). Froggatt et al. characterized PMF using high-sensitivity OFDR [13,14]. Zhou et al. measured distributed group birefringence in PMF using OFDR [15]. In their method, the relative frequency shift was extracted from the frequency separation between the central peak and the side peak of an autocorrelation spectrum. In contrast, the present work directly cross-correlates the spatially aligned local spectra of the separately processed P- and S-axis signals to obtain the local relative frequency shift. The reconstructed birefringence variation is then calibrated to distributed axial strain. Lin et al. demonstrated long-distance distributed birefringence measurement using P-OFDR with birefringence-delay correction [16]. Their work focused on intrinsic birefringence characterization, whereas the present work establishes a birefringence-variation-based method for distributed large-range axial strain sensing. In addition, a correlation-quality-constrained strategy is introduced to improve the reliability of the recursive demodulation.

In this work, a distributed large-range strain sensing method based on birefringence variation in PANDA PMF is proposed and experimentally demonstrated using P-OFDR. The local birefringence is reconstructed from the relative spectral shift between the spatially aligned P- and S-axis Rayleigh spectra, and the strain is obtained from the calibrated birefringence variation. Axial tensile experiments on an 18 m PANDA PMF achieve distributed strain measurement from 0 to 12000 $\mu\epsilon$ with a spatial resolution of 5 mm, demonstrating the potential of birefringence-based P-OFDR for high-spatial-resolution and large-range distributed strain sensing.

2. Principle and signal processing algorithm

2.1. PMF birefringence and P-OFDR interrogation principle

PMF supports two orthogonal polarization eigenmodes, which are usually referred to as the slow axis and the fast axis. In a PANDA PMF, two stress-applying parts are symmetrically introduced beside the fiber core. Owing to the difference in thermal expansion coefficients between the stress-applying parts and the cladding, an anisotropic residual stress field is generated in the fiber core during the fiber drawing and cooling process [17,18]. Through the photoelastic effect, this asymmetric internal stress modifies the refractive-index distribution of the fiber core and causes different effective refractive indices for the two orthogonal polarization axes. Therefore, the intrinsic birefringence of the PMF can be expressed as

$$B = n_s - n_f \quad (1)$$

where n_s and n_f are the effective refractive indices of the slow and fast axes, respectively.

The intrinsic birefringence of the PANDA PMF originates from the stress-induced refractive-index anisotropy in the fiber core [19,20]. When external perturbations, such as axial strain, are applied to the fiber, the stress state of the fiber core changes accordingly. Since the two polarization eigenmodes have different stress-optic responses, their effective refractive indices vary differently, leading to a measurable birefringence variation. Therefore, if the local birefringence distribution

of the PMF can be measured with high spatial resolution, the strain-induced birefringence variation can be further used for distributed strain reconstruction.

P-OFDR provides an effective approach to measure the distributed birefringence of PMF. In P-OFDR, the Rayleigh backscattering signals from the two orthogonal polarization axes are acquired independently. Since the two polarization eigenmodes propagate in the same fiber core, their local Rayleigh backscattering spectra contain similar scattering features. However, due to the different effective refractive indices of the slow and fast axes, a relative spectral shift exists between the local Rayleigh spectra of the two polarization axes. This relative spectral shift carries the local birefringence information of the PMF. According to the PMF birefringence demodulation model, the local birefringence can be expressed as [21]

$$B(z) = \alpha \frac{|\Delta f(z)|}{f_c} \quad (2)$$

where $\Delta f(z)$ is the local frequency shift between the two orthogonal polarization-axis Rayleigh spectra, f_c is the optical center frequency, and α is a calibration coefficient. In this work, $\alpha = 1.05$ is used according to previous P-OFDR birefringence measurement studies [16].

The basic demodulation process of PMF birefringence using P-OFDR is shown in Fig. 1. The auxiliary interferometer is first used to compensate for the nonlinear wavelength sweep of the tunable laser. After optical-frequency resampling and polarization separation, the original P- and S-axis interference signals are obtained in the time domain. Then, the Rayleigh backscattering responses of the two polarization axes are reconstructed, and local Rayleigh backscattering segments are intercepted by a sliding window. The local Rayleigh backscattering (RBS) signals are transformed into local spectra, which are used as the input of the cross-correlation calculation. Finally, the relative frequency shift between the P- and S-axis spectra is extracted from the correlation peak and substituted into Eq. (2) to reconstruct the local birefringence.

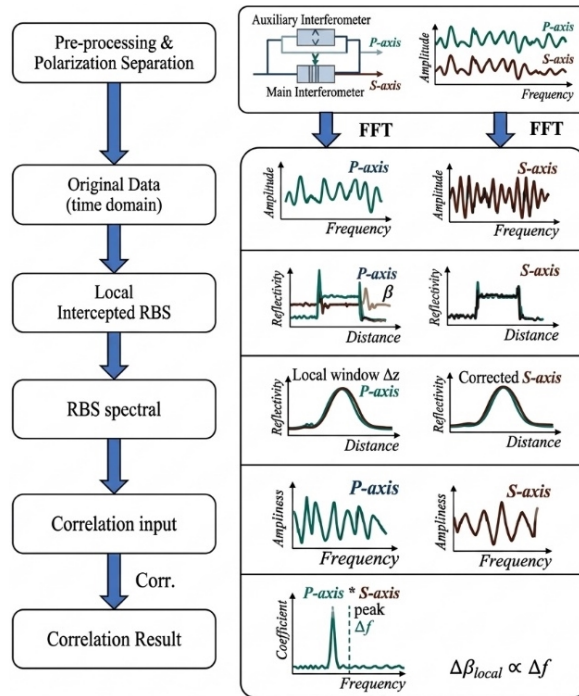


Fig. 1. Basic signal processing flow for P-OFDR birefringence demodulation.

The local frequency shift is obtained by cross-correlating the local P- and S-axis Rayleigh spectra. For the k -th local window, the P-axis complex spectrum $X_P(k)$ and the S-axis complex spectrum $X_S(k)$ are extracted from the distance-domain traces. The local cross-correlation function can be written as

$$R_{PS}(\tau, z) = \int X_P(f, z) X_S^*(f + \tau, z) df \quad (3)$$

and the local frequency shift is determined by

$$\Delta f(z) = \operatorname{argmax}_{\tau} R_{PS}(\tau, z) \quad (4)$$

where $R_{PS}(\tau, z)$ is the local cross-correlation function, τ is the frequency-shift variable, $X_P(f, z)$ and $X_S(f, z)$ are the local Rayleigh spectra of the P and S axes, respectively, and the superscript * denotes complex conjugation. The peak position of the cross-correlation curve gives the local frequency shift $\Delta f(z)$, and the local birefringence is subsequently reconstructed using Eq. (2).

It should be noted that the proposed method is different from conventional Rayleigh-based OFDR strain sensing. In conventional OFDR, strain is usually demodulated by tracking the spectral shift between the reference and strained states of the same Rayleigh channel. Therefore, the demodulation performance strongly depends on the spectral correlation between two different strain states. In contrast, the proposed method first reconstructs the local birefringence from the relative spectral shift between two orthogonal polarization axes in the same measurement state. Then, the strain information is obtained from the strain-induced birefringence variation. This differential-polarization demodulation mechanism provides a potential route for improving the robustness of large-range strain sensing.

After the distributed birefringence is obtained, strain can be demodulated from the birefringence variation. Under the unloaded state, the local birefringence can be written as

$$B_0(z) = n_s^0(z) - n_f^0(z) \quad (5)$$

where $B_0(z)$ is the initial birefringence distribution, and $n_s^0(z)$ and $n_f^0(z)$ are the effective refractive indices of the slow and fast axes under the unloaded state, respectively. When axial strain is applied, the effective refractive indices of the two polarization eigenmodes vary differently due to their different stress-optic responses, and the birefringence becomes

$$B(z, \varepsilon) = n_s(z, \varepsilon) - n_f(z, \varepsilon) \quad (6)$$

The strain-induced birefringence variation is therefore

$$\Delta B(z) = B(z, \varepsilon) - B_0(z) \quad (7)$$

For a calibrated strain range, the birefringence variation can be approximated by a linear relation

$$\Delta B(z) = K_B \varepsilon(z) \quad (8)$$

where K_B is the birefringence-strain sensitivity coefficient. Thus, the distributed strain can be reconstructed as

$$\varepsilon(z) = \frac{\Delta B(z)}{K_B} \quad (9)$$

This establishes the basic relationship among PMF birefringence, P-OFDR spectral-shift demodulation, and distributed strain reconstruction.

2.2. Dual-polarization spatial alignment

The birefringence demodulation principle described in Section 2.1 requires a high spectral correlation between the local P- and S-axis Rayleigh backscattering spectra used for cross-correlation. However, in an actual PMF, this condition is affected by the birefringence-induced propagation delay between the two orthogonal polarization axes. Since the P and S axes have different effective refractive indices, the same physical position in the fiber corresponds to different optical paths for the two polarization modes. If this effect is ignored and the RBS signals of the P and S axes are intercepted using the same optical-path window, the delay error between the intercepted local RBS signals accumulates with the sensing distance. This accumulated optical-path mismatch introduces decorrelated Rayleigh information into the cross-correlation process, leading to a serious degradation of the correlation coefficient and even false correlation peaks, especially when the sensing distance increases or when a short analysis window is used.

To reduce this effect, a dual-polarization optical-path alignment method is introduced before local spectral correlation. The P-axis trace is used as the reference, and the S-axis window is adaptively adjusted to compensate for the accumulated birefringence-induced optical-path delay. The principle of the optical-path alignment method is shown in Fig. 2. During the demodulation process, the P-axis window moves forward with a fixed step, whereas the S-axis window is updated according to the local birefringence information obtained from the previous demodulation window. In this way, the relative optical-path mismatch between the two polarization axes can be progressively compensated, and the local P- and S-axis RBS spectra used for cross-correlation can maintain a higher degree of spectral similarity along the fiber.

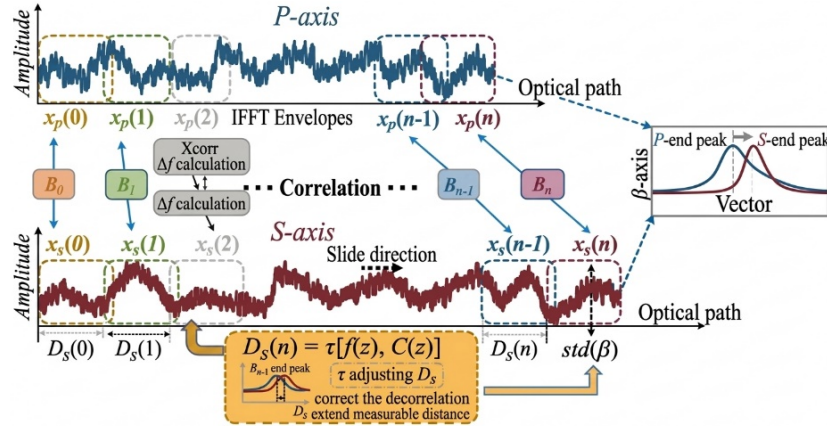


Fig. 2. Signal processing architecture for dual-polarization spatial alignment and local spectral correlation.

Before distributed demodulation, an end-section delay pre-correction is first performed. The P- and S-axis Rayleigh amplitude profiles near the fiber end are normalized and cross-correlated. The accumulated optical-path delay between the two axes is obtained from the peak position of the correlation curve, and quadratic interpolation around the peak is used to improve the delay estimation accuracy. The average birefringence of the PMF is then calculated as

$$\overline{B_0} = \frac{n_g \Delta z}{L} \quad (10)$$

where n_g is the group refractive index used for distance calibration, and L is the PMF length over which the accumulated delay is evaluated. The obtained $\overline{B_0}$ represents the initial average group birefringence of the PMF and is used to remove the dominant accumulated optical-path

mismatch between the two polarization axes, providing an initial reference for the subsequent local delay compensation.

Then, distributed demodulation is performed using a sliding-window method. The analysis-window length determines the nominal spatial resolution, while the sliding step determines the spatial sampling interval. Both parameters are selected by considering the balance among spatial resolution, spectral correlation stability, and signal-to-noise ratio. In the present work, an analysis-window length of 5 mm is used to achieve a nominal spatial resolution of 5 mm. The sliding step is also set to 5 mm, resulting in a spatial sampling interval of 5 mm. For the k -th demodulation position, the P-axis window is moved with a fixed step, while the S-axis step is adaptively updated according to the birefringence demodulated from the previous local window. The adaptive S-axis update can be written as [16]

$$D_s(k) = [1 + B(k-1) - \overline{B_0}]D_s(k-1) \quad (11)$$

where $D_s(k)$ is the adaptive S-axis step of the k -th window, $B(k-1)$ is the birefringence demodulated from the previous window, and $\overline{B_0}$ is the average birefringence obtained from Eq. (10). The updated step is constrained to be positive to avoid invalid window movement. By using this iterative compensation, the P- and S-axis local spectra remain spatially aligned along the fiber.

2.3. Correlation-quality-constrained demodulation

After the dual-polarization spatial alignment, the local frequency shift between the P- and S-axis spectra is obtained by cross-correlation, and the local birefringence is reconstructed according to the birefringence demodulation model described in Section 2.1. Meanwhile, the maximum value of the normalized cross-correlation curve is recorded as the local correlation coefficient, which is used to evaluate the reliability of the local demodulation result. A higher correlation coefficient indicates stronger similarity between the two local spectra and a more reliable frequency-shift estimation.

In practical demodulation, some local windows may still have low correlation because of weak Rayleigh scattering features, local signal fading, residual spatial mismatch, or noise. These unreliable results may introduce isolated abnormal birefringence values and reduce the stability of strain demodulation. Therefore, a correlation-quality-constrained strategy is introduced. If the local correlation coefficient is lower than a preset threshold, the current demodulation result is regarded as unreliable and replaced by the previous reliable value. This step suppresses isolated false peaks caused by weak spectral similarity, local decorrelation, or imperfect spatial alignment.

For the final birefringence estimation, only the effective sensing region is used. Within this region, high-reliability points are selected according to the correlation coefficient and averaged with correlation weighting:

$$\bar{B} = \frac{\sum_i B_i C_i}{\sum_i C_i} \quad (12)$$

where B_i is the local birefringence value and C_i is the corresponding local cross-correlation coefficient. In this way, high-quality local results contribute more to the final estimation, while unstable regions and low-correlation points are suppressed.

The complete signal processing procedure is summarized as follows. First, the auxiliary interference signal is processed to generate a uniform optical-frequency sampling axis, and the raw P- and S-axis interference signals are resampled to compensate for the nonlinear wavelength sweep of the tunable laser. Then, the corrected P- and S-axis signals are transformed into the distance domain. Next, end-section delay pre-correction and iterative S-axis window adjustment are applied to compensate for the accumulated position mismatch between the two polarization axes. Finally, local P- and S-axis Rayleigh spectra are extracted from spatially matched windows, and the local frequency shift is obtained from the cross-correlation peak for birefringence

reconstruction. The reconstructed birefringence variation is further converted into distributed strain using the calibrated birefringence–strain sensitivity.

The proposed spatial alignment and correlation-quality-constrained strategy are particularly important for high-spatial-resolution distributed strain sensing. When the spatial resolution is set to 5 mm, the local analysis window contains limited Rayleigh scattering information, and the correlation result is more sensitive to spatial mismatch and noise. By ensuring that the P- and S-axis spectra originate from the same physical fiber segment and by suppressing unreliable local correlation results, the proposed method improves the robustness of birefringence demodulation and enables large-range distributed strain measurement with high spatial resolution.

3. Experimental results and discussion

3.1. P-OFDR system

The experimental configuration for distributed large-range strain sensing based on P-OFDR is shown in Fig. 3. The system consisted of a main sensing interferometer and an auxiliary interferometer. The tunable laser was swept from 1545 nm to 1555 nm at a sweep rate of 80 nm/s, and the interference signals were acquired at a sampling rate of 50 MHz. The auxiliary interferometer provided the reference signal for laser-sweep nonlinearity compensation [22].

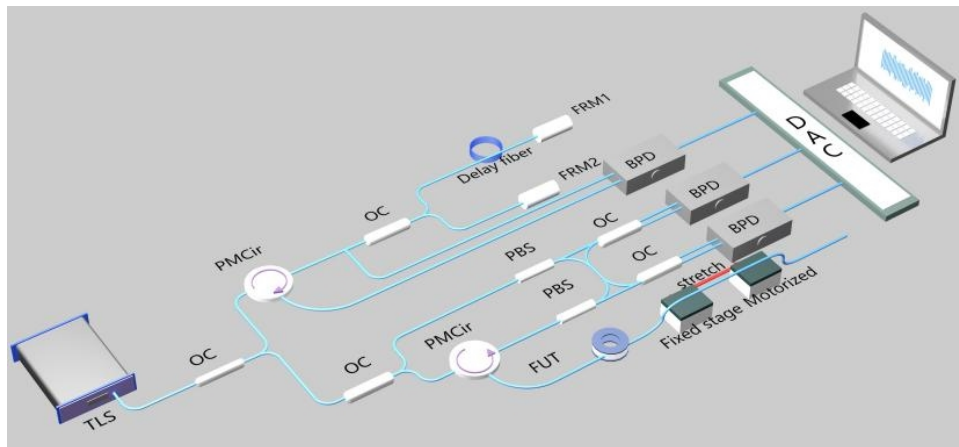


Fig. 3. Experimental setup for distributed large-range strain sensing based on P-OFDR using a PANDA PMF, where the system consists of main and auxiliary interferometers. The auxiliary interferometer was used to compensate the nonlinear wavelength sweep of the tunable laser, and the main interferometer was used to detect the polarization-resolved Rayleigh backscattering signals from the two orthogonal axes of the PMF. Axial strain was applied to the FUT by a translation stage. TLS: tunable laser source; PMCir: polarization-maintaining circulator; OC: optical coupler; FRM: Faraday rotating mirror; PBS: polarization beam splitter; BPD: balanced photodetector; DAC: data acquisition card; FUT: fiber under test.

In the main sensing interferometer, the Rayleigh backscattered signal from the PANDA PMF was resolved into two orthogonal polarization components and detected by balanced photodetectors. The delay fiber and the fiber under test were 40 m and 18 m long, respectively. Axial tensile strain was applied using a motorized translation stage. The fiber used in this experiment was a Nufern PM1550-XP PANDA polarization-maintaining fiber. According to the manufacturer's datasheet, its operating wavelength range is 1440–1625 nm, its core numerical aperture is 0.125, its mode-field diameter is 10.1 μm at 1550 nm, and its cutoff wavelength is 1380 nm. The core, cladding, and coating diameters are 8.5, 125.0, and 245.0 μm , respectively.

In the subsequent signal processing, a 5 mm local analysis window was used, corresponding to a nominal spatial resolution of 5 mm.

3.2. Birefringence demodulation results

The raw polarization-resolved Rayleigh backscattering signals were acquired using the P-OFDR system shown in Fig. 3. The auxiliary interferometer provided the optical-frequency reference for compensating the nonlinear wavelength sweep, after which the resampled P- and S-axis beat signals detected by the balanced photodetectors were processed for distributed birefringence demodulation.

The signal processing procedure for local birefringence extraction is illustrated in Fig. 4. The beat signals of the P- and S-polarization channels acquired by the P-OFDR system are shown in Fig. 4(a). After optical-frequency resampling using the auxiliary interferometer, the beat signals contain the Rayleigh backscattering information of the two orthogonal polarization axes of the PANDA PMF. The amplitudes of the two channels are not exactly identical, mainly because of the wavelength-dependent polarization response of the optical components, residual polarization crosstalk, and the difference in coupling efficiency between the two polarization channels during the wavelength sweep. Nevertheless, the Rayleigh scattering features in both channels are preserved and can be used for local spectral correlation.

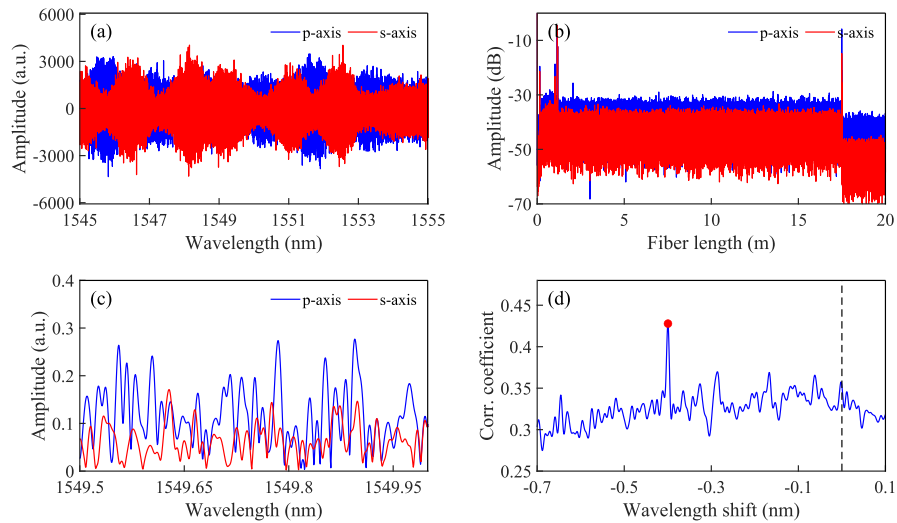


Fig. 4. Signal processing workflow for birefringence extraction: (a) acquired beat frequency interference signals; (b) distance-resolved Rayleigh backscattering profiles for the P and S axes; (c) reconstructed local RBS spectra; (d) cross-correlation coefficient curve of the local spectra indicating the wavelength or frequency shift.

After optical-frequency resampling, FFT is applied to the P- and S-axis beat signals to obtain the distance-domain Rayleigh backscattering profiles, as shown in Fig. 4(b). Because the two polarization eigenmodes have different effective refractive indices, a relative propagation delay is accumulated along the PMF. This delay appears as a spatial offset between the P- and S-axis Rayleigh traces in the distance domain. Therefore, if the two local windows are selected at the same numerical position, they may not correspond to the same physical fiber segment. To avoid this mismatch, the dual-polarization spatial alignment algorithm is applied before local spectral extraction.

A local fiber segment is then selected from the spatially aligned P- and S-axis traces using a sliding window. The local Rayleigh spectra reconstructed from the two axes are shown in

Fig. 4(c). Since the two orthogonal polarization modes are transmitted in the same fiber core, their local Rayleigh spectra have similar scattering characteristics. However, a relative spectral shift is observed between them because of the birefringence of the PMF. After frequency shifting, the main spectral features of the two local spectra are well matched, which confirms the validity of the spatial alignment.

The local frequency shift between the two polarization axes is obtained by cross-correlating the reconstructed spectra. As shown in Fig. 4(d), the peak position of the cross-correlation curve gives the frequency shift Δf , and the peak value is used to evaluate the local demodulation reliability. The local birefringence is then calculated by substituting Δf into Eq. (2). This process establishes the connection between the polarization-resolved P-OFDR signals and the distributed birefringence profile of the PANDA PMF.

To evaluate the effectiveness of the dual-polarization spatial alignment, the local spectral correlation quality before and after correction is compared in Fig. 5. For each demodulation window, the local P- and S-axis Rayleigh spectra are extracted and normalized, and their cross-correlation curve is calculated. The maximum value of the normalized cross-correlation curve is defined as the local correlation coefficient, as shown in Fig. 5(a). A higher correlation coefficient indicates that the two local spectra have stronger similarity and are more likely to originate from the same physical fiber segment.

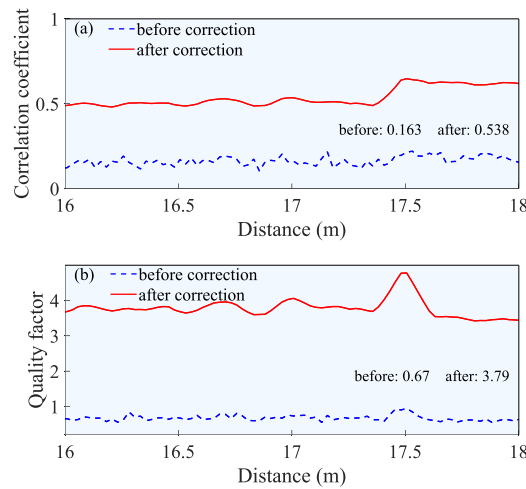


Fig. 5. Comparison of the (a) correlation coefficient and (b) quality factor Q along the fiber distance before and after the proposed correction.

In addition to the correlation coefficient, a peak-quality factor Q is used to further evaluate the reliability of the correlation peak. As shown in Fig. 5(b), the Q factor is also improved after correction, indicating that the main correlation peak becomes more distinguishable from the background fluctuation and sidelobes. Before correction, the accumulated birefringence-induced spatial delay causes the local P- and S-axis windows to gradually deviate from one another with increasing distance, which reduces spectral similarity and may introduce false correlation peaks. After correction, the adaptive S-axis window update effectively compensates for the accumulated mismatch, leading to higher local spectral consistency and more reliable frequency-shift extraction. These results confirm that the proposed spatial alignment method is necessary for distributed birefringence demodulation in long PMF. Quantitatively, the average correlation coefficient increased from 0.163 before correction to 0.538 after correction, while the average quality factor Q increased from 0.67 to 3.79. These results confirm the improvement in local P/S-axis spectral matching and correlation-peak reliability after spatial alignment.

After the effectiveness of the dual-polarization spatial alignment was verified, distributed birefringence demodulation was performed along the PMF using the sliding-window method. Based on the polarization-resolved P-OFDR signals, the P- and S-axis beat signals were first resampled and transformed into distance-domain Rayleigh backscattering profiles. For each local window, the spatially aligned P- and S-axis Rayleigh spectra were reconstructed from the same physical fiber segment. According to the local spectral correlation model described in Section 2.1, the frequency shift Δf between the two polarization axes was obtained from the peak position of the cross-correlation curve. The corresponding local birefringence B_i was then calculated from Δf using Eq. (2). Meanwhile, the maximum value of the normalized cross-correlation curve was recorded as the local correlation coefficient, which was used to evaluate the reliability of the demodulated result. Therefore, the distributed profiles of the correlation coefficient, frequency shift, and birefringence can be obtained simultaneously by moving the analysis window along the fiber.

The distributed demodulation results are shown in Fig. 6. Figure 6(a) presents the local correlation coefficient distribution along the fiber. Most regions within the effective sensing length exhibit relatively high correlation coefficients, indicating that reliable local spectral matching is achieved after delay correction and adaptive window locking. A small number of low-correlation points are still observed, which may be attributed to local signal fading, weak Rayleigh features, residual spatial mismatch, or noise. These points are subsequently suppressed by the correlation-quality-constrained strategy described in Section 2.2. Figure 6(b) shows the local frequency shift between the two orthogonal polarization axes extracted from the correlation peak positions. Since this frequency shift originates from the differential propagation of the two polarization eigenmodes in the PANDA PMF, it directly reflects the local birefringence information. By substituting the demodulated frequency shift into Eq. (2), the distributed birefringence profile is reconstructed, as shown in Fig. 6(c). The birefringence remains relatively stable along the effective sensing length, which agrees with the expected intrinsic birefringence distribution of the PMF under the unloaded state. The dashed line in Fig. 6(c) represents the correlation-coefficient-weighted mean birefringence calculated using Eq. (12). By assigning larger weights to high-correlation points and suppressing unreliable local results, the weighted averaging strategy provides a more robust estimation of the mean birefringence. These results demonstrate that the proposed processing method can reliably extract the distributed birefringence of the PANDA PMF from the polarization-resolved P-OFDR signals.

3.3. Distributed large-range strain sensing results

To evaluate the distributed strain sensing performance of the proposed birefringence-based P-OFDR method, axial tensile tests were carried out on a PANDA PMF. The fiber under test was approximately 18 m long, while only a 100 cm section was selected as the tensile gauge section. As shown in Fig. 7, this 100 cm section was clamped between a fixed displacement platform (FDP) and a moving displacement platform (MDP), and the remaining fiber length was kept unstrained. During the experiment, the FDP was fixed, while the MDP was translated along the fiber axis to apply controlled tensile strain to the gauge section. The applied strain was calculated as $\varepsilon_{\text{app}} = \Delta L / L_g$, where ΔL is the displacement of the MDP and $L_g = 100$ cm is the gauge length. Therefore, displacement of 1 mm corresponds to an axial strain of 1000 $\mu\epsilon$.

To identify the loaded fiber section, the cumulative phase change induced by the reconstructed strain distribution was calculated as an auxiliary spatial indicator. Based on the previously reported relationship between axial strain and accumulated optical phase [7], the cumulative phase was obtained by integrating the birefringence-derived strain along the fiber using the strain-induced optical phase response coefficient. It should be emphasized that this cumulative phase is calculated from the reconstructed strain distribution and is therefore used only as an auxiliary spatial indicator of the loaded section, rather than as an independent measurement for

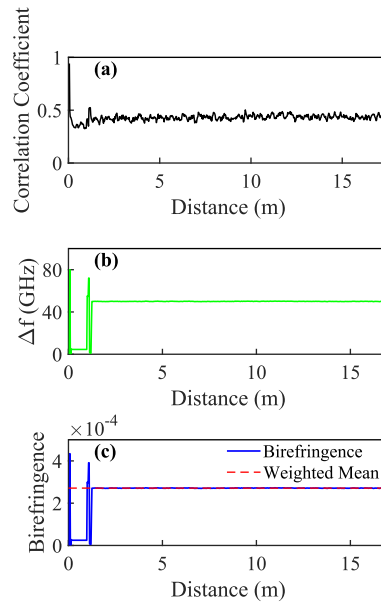


Fig. 6. Distributed measurement results along the fiber: (a) the cross-correlation coefficient profile; (b) the local frequency shift Δf between the orthogonal polarization modes; (c) the demodulated distributed birefringence and its weighted mean over the effective sensing length.

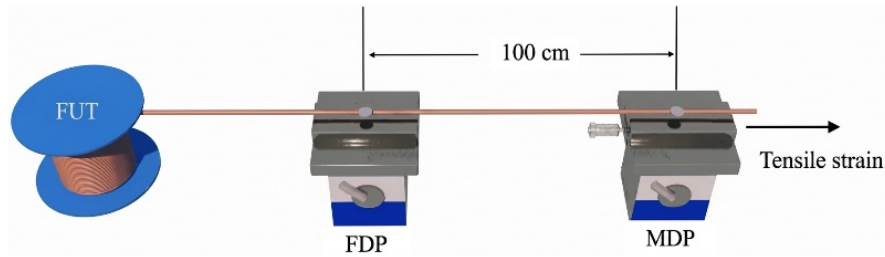


Fig. 7. Experimental setup for axial tensile strain loading of the PANDA PMF, where the PMF was mounted between a fixed displacement platform and a moving displacement platform with a 100 cm gauge length. The FDP was kept stationary, while the MDP was translated along the fiber axis to apply controlled tensile strain to the sensing fiber. FDP: fixed displacement platform; MDP: moving displacement platform.

validating the strain results. The localized phase variation in Fig. 8(a) is consistent with the known loading configuration and indicates that the applied deformation is mainly concentrated within the clamped gauge section, while the remaining fiber sections are not intentionally stretched.

After the strained region is identified, the distributed birefringence profiles under different applied strain levels are reconstructed from the relative spectral shift between the P- and S-axis Rayleigh spectra, as presented in Fig. 8(b). For each spatial position, the local frequency shift is first obtained by cross-correlating the spatially aligned P- and S-axis spectra according to Eqs. (3) and (4), and then converted into birefringence according to Eq. (2). As the applied tensile strain increases, the birefringence in the loaded region changes progressively, whereas the birefringence in the unloaded region remains nearly unchanged. This spatial contrast is consistent with the known 100 cm gauge-section loading configuration and with the auxiliary cumulative-phase

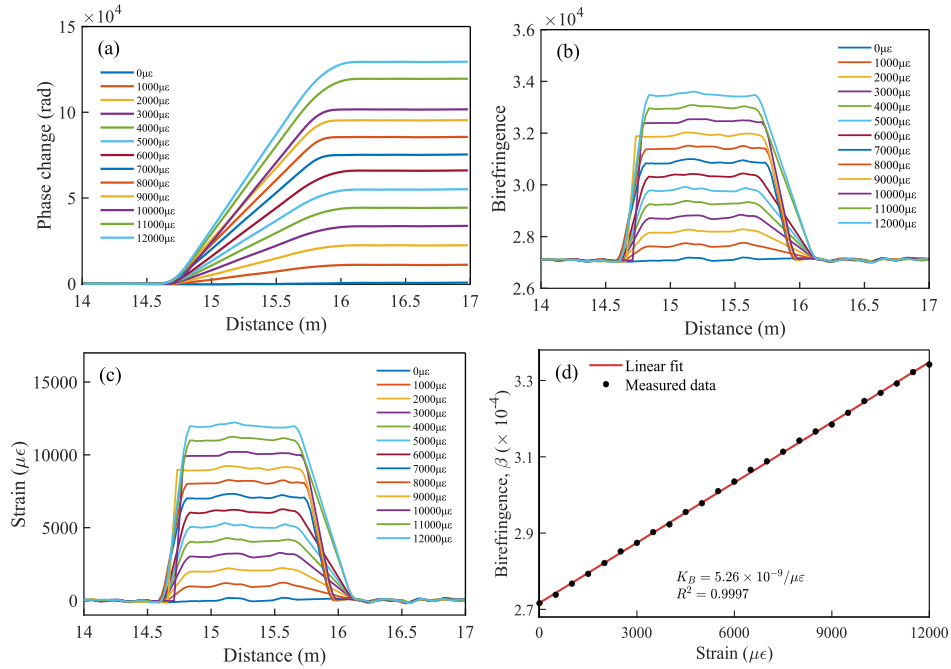


Fig. 8. Experimental results of distributed strain measurement and sensitivity analysis: (a) distributed phase change along the fiber; (b) distributed birefringence profiles under various strain levels; (c) recovered distributed strain profiles; (d) linear fitting between the measured birefringence and applied strain.

distribution in Fig. 8(a). Because the cumulative phase is derived from the reconstructed strain, it is used here only to indicate the spatial location of the applied deformation; the strain response itself is evaluated from the birefringence variation and the corresponding calibration. In addition, the continuous evolution of the birefringence profile with increasing strain demonstrates that the proposed method can track large strain-induced birefringence changes without relying on reference-to-measurement spectral matching of a single Rayleigh channel.

The strain-induced birefringence variation is then obtained by subtracting the initial birefringence profile measured under the unloaded state from the birefringence profile measured under each loaded state. According to Eq. (9), the distributed birefringence variation is converted into strain using the calibrated birefringence–strain sensitivity coefficient. The reconstructed strain profiles in Fig. 8(c) are mainly concentrated within the loaded gauge section, in agreement with the actual loading configuration and consistent with the auxiliary cumulative-phase distribution shown in Fig. 8(a). Outside the strained region, the reconstructed strain remains close to zero, indicating good spatial selectivity of the proposed method. These results demonstrate that the proposed birefringence-based P-OFDR scheme can not only identify the location of the strained region but also quantitatively reconstruct the distributed axial strain with a spatial resolution of 5 mm.

To further quantify the strain response, the average birefringence variation in the loaded region was calculated at each applied strain level and compared with the nominal strain applied by the displacement stage. The corresponding linear fitting result is summarized in Fig. 8(d). A clear linear relationship is obtained over the entire tested range from 0 to 12000 $\mu\epsilon$. The fitted birefringence–strain sensitivity is $K_B = 5.26 \times 10^{-9} / \mu\epsilon$, and the coefficient of determination is $R^2 = 0.9997$. The high linearity indicates that the strain-induced birefringence variation in the

PMF can be used as a reliable parameter for quantitative strain demodulation. More importantly, the proposed method maintains a spatial resolution of 5 mm over the large strain range, which is difficult for conventional Rayleigh-based OFDR because the local reference-to-measurement spectral correlation usually degrades significantly under large deformation.

The repeatability of the proposed method was evaluated by performing repeated tensile loading tests over the same strain range. At each strain plateau, the birefringence was demodulated using the same spatial alignment and correlation-quality-constrained processing procedure. The deviations of the demodulated birefringence from the fitted value are summarized in Fig. 9. The scatter points represent the birefringence deviations obtained from repeated measurements, and the error bars indicate the corresponding $\pm 1\sigma$ standard deviation at each strain level. The standard deviations remain within the range of 2.03×10^{-8} to 8.01×10^{-8} over the entire 0–12000 $\mu\epsilon$ strain range, corresponding to equivalent strain standard deviations of 3.86 to 15.23 $\mu\epsilon$ based on the calibrated birefringence–strain sensitivity (K_B) coefficient of $5.26 \times 10^{-9}/\mu\epsilon$. No obvious increase in fluctuation is observed at high strain levels, indicating that the proposed demodulation method does not suffer from severe decorrelation even under large axial deformation.

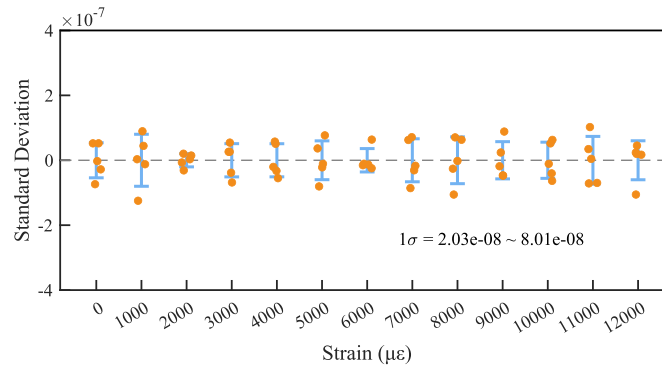


Fig. 9. Measurement stability and repeatability evaluation across the extensive 0–12000 $\mu\epsilon$ strain range. The scatter points represent the deviations of the demodulated birefringence for repeated tests at each applied strain plateau, and the error bars indicate the corresponding $\pm 1\sigma$ standard deviation range from 2.03×10^{-8} to 8.01×10^{-8} , corresponding to equivalent strain standard deviations of 3.86 to 15.23 $\mu\epsilon$.

In addition to the repeated measurements at each strain plateau, a supplementary stability test was conducted at the maximum applied strain of 12000 $\mu\epsilon$. The fiber was maintained at this strain level for nearly 1 h, after which an additional birefringence measurement was performed using the same P-OFDR processing procedure. The birefringence obtained after the holding period remained consistent with the value measured immediately after strain application. This result provides supplementary evidence that the birefringence response remains stable during sustained loading at the maximum experimentally tested strain.

The repeatability results confirm that the combination of birefringence demodulation, dual-polarization spatial alignment, and correlation-quality constraint provides stable strain estimation. The spatial alignment reduces the accumulated mismatch between the two polarization axes, while the correlation-quality constraint suppresses unreliable local spectral matching results. Therefore, the proposed P-OFDR scheme provides an effective approach for distributed large-range strain sensing with high spatial resolution.

3.4. Discussion

The results in Figs. 8 and 9 show that the proposed birefringence-based P-OFDR method can maintain a 5 mm nominal spatial resolution while providing approximately linear and repeatable

strain measurements over the experimentally validated range of 0–12000 $\mu\epsilon$. This performance is attributed to the differential-polarization demodulation scheme, in which the strain-induced birefringence variation is extracted from the relative spectral shift between the two orthogonal polarization axes, together with the dual-polarization spatial alignment and correlation-quality constraint. Unlike conventional Rayleigh-based OFDR, the proposed method does not directly rely on reference-to-measurement spectral matching in a single polarization channel, which helps reduce the influence of large spectral shifts under high strain. The range of 0–12000 $\mu\epsilon$ should nevertheless be regarded as the experimentally validated range rather than the theoretical limit, since the applicable range depends on the linearity of the birefringence–strain response, the signal-to-noise ratio, the measurable spectral-shift range, and the mechanical tolerance of the PMF. For applications involving other fiber types or significant temperature variations, independent calibration and temperature compensation would be required.

4. Conclusion

A distributed large-range strain sensing method based on birefringence variation in PANDA PMF was experimentally demonstrated using P-OFDR. The local birefringence was reconstructed from the relative spectral shift between the P- and S-axis Rayleigh backscattering spectra, reducing the dependence on conventional single-channel reference-to-measurement spectral matching. Dual-polarization spatial alignment was used to compensate for the accumulated delay between the two polarization axes, and a correlation-quality-constrained strategy, including low-correlation-point compensation, valid-distance screening, and correlation-coefficient-weighted averaging, was introduced to improve demodulation robustness. Axial tensile experiments on an approximately 18 m PMF achieved distributed strain measurement from 0 to 12000 $\mu\epsilon$ with a spatial resolution of 5 mm. The birefringence variation showed good linearity with the applied strain, and the repeatability tests yielded equivalent strain standard deviations of 3.86–15.23 $\mu\epsilon$ over the tested strain range. These results confirm that PMF birefringence variation interrogated by P-OFDR provides an effective approach for high-spatial-resolution distributed large-range strain sensing.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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