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Dynamic Phase Demodulation Algorithm for Phase-Sensitive OTDR With Direct Detection

YI SHI^D, GUIFANG CHEN, YUANYE WANG, LEI ZHAO, (Member, IEEE),

AND ZHUN FAN^(D), (Senior Member, IEEE) Guangdong Provincial Key Laboratory of Digital Signal and Image Processing, School of Engineering, Shantou University, Shantou 515063, China

Corresponding author: Yi Shi (shy_xflx@163.com)

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ABSTRACT A dynamic phase demodulation algorithm for direct detection Φ -OTDR is proposed and experimentally demonstrated. It offers a way for single channel direct detection Φ -OTDR, which is the simplest and most cost-effective structure, to realize phase demodulation. Through making use of the redundant information between the sensing series from the vibration impacted region, the local extreme points(LEP) of the sensing series can be divided into two types. The second type LEP offers light phase quadrant information, and then the phase can be further reconstructed through anti-trigonometric function. Single frequency and amplitude-modulated waveforms have been correctly demodulated. The demodulated phase amplitude agrees well with theoretical value, which shows a potential application in strain measurement.

INDEX TERMS Optical fiber sensors, demodulation, phase estimation.

I. INTRODUCTION

Phase-sensitive optical time domain reflectometry (Φ-OTDR) was first proposed in 1993 [1]. Compared to conventional OTDR, Φ -OTDR employs highly coherent laser source, which makes the Rayleigh backscattered traces(RBT) coherent and can respond to external vibration. Due to its dynamic vibration detecting ability, Φ -OTDR has been widely investigated and applied in fields, such as monitoring safety and integrity of long pipelines, railway infrastructures and health monitoring of huge structures [2]-[9]. The intensity of backscattered light carries the waveform information of the external vibration. Some technologies have been studied to improve the performance of intensity signal. Alekseev et al. [10] applied a chirp probe pulse under specific law against the self-phase modulation(SPM) effect to improve the contrast of the intensity signal. But this technique can only fully compensate SPM at one certain sensing position. Pastor-Graells et al. [11] applied liner chirp probe pulse in Φ -OTDR and realized temperature and strain measurement through trace to trace comparison. However, the trace to trace comparison reduces the frequency response and a GHz sampling equipment is necessary required in [11],

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which is expensive. Bhatta et al. [12] applied correlation method into chirp-pulse Φ -OTDR and increased the maximum detected strain to about 1000 micro-strain. But the maximum strain is still limited by the frequency band of the chirp pulse, which is 150MHz frequency shift for 1 microstrain. Moreover, due to the nonlinear effect of interference, the intensity signal is distorted. In order to retrieve the external vibration waveform, phase demodulation needs to be applied. Masoudi et al. [13] and Masoudi and Newson [14] proposed a phase demodulation Φ -OTDR structure based on local oscillator and 3×3 coupler. This scheme requires the use of three photo-detectors working in synchronization and an extra interferometry with thermal isolation for stable demodulation. Another way to retrieve the light phase is through I/Q (In phase and Quadrature) demodulation. Wang et al. [15] used a 90° optical hybrid to generate the I/Q components and utilized two detectors and two-channel synchronous acquisition. Pan et al. [16] applied a local oscillator and detected the coherent light with certain beat frequency through a high speed data acquisition equipment, which is costly. The light phase was then obtained through digital I/Q demodulation. Fang et al. [17] applied phase-generated carrier (PGC) modulation in Φ -OTDR, which required an unbalanced Michelson interferometry, and then obtained the light phase through PGC demodulation process. Muanenda et al. [18] applied

homodyne detection to stabilize the demodulation, which requires an extra intererometry and phase modulator at the head end. Liu *et al.* [19] applied heterodyne detection to obtain the I/Q components and demodulated the differential phase, which requires two channel synchronous coherent detection and acquisition. He *et al.* [20] applied self-mixing demodulation with heterodyne detection to stabilize the frequency mixing procedure. Jiang *et al.* [21] applied Kramers-Kronig receiver in Φ -OTDR and realized phase retrieving with one-channel heterodyne detection. Generally, the phase demodulation methods in the literature require coherent detection, extra interferometry or multi-channel synchronous detection and acquisition system, which makes the sensing system more complex and costly.

In Φ -OTDR, the phase change caused by external vibration can be detected in a region around the vibration position due to the width of probe optical pulse. Thus, all the sensing series from that impacted region can be used for retrieving the light phase. The redundancy information between these sensing series gives the possibility for dynamic phase demodulation through only one channel direct detection. Sha *et al.* [22] proposed a demodulation method based on two sensing series from the vibration impacted region with one channel direct detection. Through summation and difference of the sensing series, the IQ component of the extra phase and initial phase can be obtained. However, once the difference component is too small, the phase demodulation will fail. Besides, these two sensing series used for demodulation needs to be carefully chose to avoid coherent fading.

This paper proposes a dynamic phase demodulation algorithm for Φ -OTDR with only one-channel direct detection, which is the simplest and most cost-effective Φ -OTDR structure. Through analyzing and inspecting the redundancy in the sensing series from the vibration impacted region, the phase quadrant information can be retrieved. Combined with the phase quadrant information, light phase could be demodulated through inverse cosine operation of the normalized intensity. As there is no subtraction operation in the algorithm, the small-amplitude problem can be avoided. Experiment results show that the algorithm can correctly extract the dynamic phase waveform for single frequency vibration, amplitude-modulated vibration and chirp vibration. The measured phase amplitude agrees well with the theoretical calculated value, which shows that this algorithm can be further used for strain or temperature detection.

II. PRINCIPLE

In Φ -OTDR structure, the Rayleigh backsacttering light is formed from multiple scatters and can be described as [22],

$$E_M(t) = E_0 \sum_{k=M}^{M+N} e_k \cdot \exp(-2\alpha z_k) \cdot \exp(j \cdot (\omega t - K z_k + \varphi_k))$$
(1)

where z_M represents the spatial distance from the optical detector, the marker M means the M-*th* scatter is at the

position z_M , N is the total number of scatters from z_M to $z_M + SR$, SR is the spatial resolution(SR) of Φ -OTDR, which is half of the probe pulse length in optical fiber, α is the attenuation coefficient of optical fiber, e_k and φ_k are the amplitude and optical phase change caused by the k-th scatter, K and ω are the wavenumber and angular frequency of probe light and E_0 is the initial amplitude of probe pulse. As the addition is within the range of SR, which is half of the pulse width and rather short, the term of attenuation can be ignored. If a perturbation appears at z_{M_1} , the Rayleigh backscattering trace(RBT) in the section ([$z_{M_1}, z_{M_1} + SR$]) can be described as a sum of two terms [22],

$$E_M(t) = E_0 \sum_{k=M}^{M_1} e_k \exp(j \cdot (\omega t - K \cdot z_k + \varphi_k)) + E_0 \sum_{k=M_1+1}^{M+N} e_k \exp(j \cdot (\omega t - K \cdot z_k + \varphi_k + \theta(t)))$$
(2)

where $\theta(t)$ is the optical phase change caused by the perturbation at z_{M_1} .

The light intensity acquired at the head of the fiber can be expressed as [22],

$$I_M(t) = A_{1M}^2 + A_{2M}^2 + 2A_{1M}A_{2M}\cos(\theta(t) + \psi_{2M} - \psi_{1M})$$
(3)

where,

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$$A_{1M} = E_0 (\sum_{k=M}^{M_1} e_k \cos(\varphi_k - Kz_k) + \sum_{k=M}^{M_1} e_k \sin(\varphi_k - Kz_k))^{1/2}$$
(4)

$$A_{2M} = E_0 (\sum_{\substack{k=M_1+1 \\ k=M_1+1}}^{M+N} e_k \cos(\varphi_k - Kz_k) + \sum_{\substack{k=M_1+1 \\ k=M_1+1}}^{M+N} e_k \sin(\varphi_k - Kz_k))^{1/2}$$
(5)

$$\psi_{1M} = \tan^{-1} \left(\frac{\sum_{k=M}^{M_1} e_k \sin(\varphi_k - K z_k)}{\sum_{k=M}^{M_1} e_k \cos(\varphi_k - K z_k)} \right)$$
(6)

$$\psi_{2M} = \tan^{-1}\left(\frac{\sum_{k=M_{1}+1}^{M+N} e_{k} \sin(\varphi_{k} - Kz_{k})}{\sum_{k=M_{1}+1}^{M+N} e_{k} \cos(\varphi_{k} - Kz_{k})}\right)$$
(7)

In Eq.(3), the four quantities A_{1M} , A_{2M} , ψ_{1M} and ψ_{2M} are a result of the scattering profile, which determined by the sensing fiber. Their values are stochastic and unable to be obtained. However, once the sensing fiber and the source laser is assigned, those four quantities are determined. They are supposed to be constant if the whole sensing system is in an



FIGURE 1. The occurrence moment of LEP-I and LEP-II in different sensing positions.

ideal condition. However, in the practical situation, those four quantities will be affected by the environmental temperature fluctuation, laser frequency drift, and laser power fluctuation, which leads to a slowly drift of those four quantities. But they can still be treated as a constant parameter in a short time range, for example, in 0.1 second. In order to simplify the analysis, the intensity in Eq.(3) can be rewritten to be,

$$I_M(t) = D_M + A_M \cos(\theta(t) + \psi_M)$$
(8)

where, D_M is the direct current(DC) component, A_M is the amplitude of the alternating current(AC) component, ψ_M is the initial phase and t stands for the count number of the probe pulse. All of them are determined by the position mark M and can be regarded as constant in a short time range. The derivative of $I_M(t)$ is,

$$\frac{dI_M(t)}{dt} = -A_M \sin(\theta(t) + \psi_M) \cdot \theta'(t)$$
(9)

where $\theta'(t)$ is the derivative of $\theta(t)$.

Let Eq.(9) to be zero, the local extreme points(LEP) of $I_M(t)$ can be obtained. These LEPs can be expressed as,

$$\begin{cases} \theta'(t) = 0, & t \in \{LEP - I\} \\ \theta(t) = n\pi - \psi_M, & n \text{ is integer}, \ t \in \{LEP - II\} \end{cases}$$
(10)

Eq.(10) shows that there are two types of LEP. The first type of LEP (LEP-I) is inherited from the phase change caused by the perturbation. These LEPs have has nothing to do with the distance mark M, which means they appear at the same moment for different sensing positions, which is in the range of $[z_{M_1}, z_{M_1} + SR]$. The second type of LEP (LEP-II) is determined by both the phase change $\theta(t)$ and the initial phase ψ_M . For different sensing positions, their initial phases ψ_M are different. Thus, the occurrence moments of LEP-II are different for different sensing positions. Fig.1 gives an example shows the difference between LEP-I and LEP-II. LEP-Is always occur at the same time and LEP-IIs occur at different time.

As LEP-I and LEP-II have different origins, they can be separated through inspecting multiple sensing series in

the range of $[Z_{M1}, Z_{M1} + SR]$, which is denoted as $I_{M_1}(t), I_{M_1+1}(t), \ldots, I_{M_1+N}(t)$. Through inspecting the differential of each sensing series, all the LEPs can be obtained, denoted as sets T_{M_1} , T_{M_1+1} , ..., T_{M_1+N} . Through searching for the same elements in every LEP set, the LEP-I can be obtained. For each sensing series, the LEP-Is are the same, denoted as $T^{\text{LEP-II}}$. And the rest of LEPs belong to LEP-II, denoted as $T_{M_1}^{\text{LEP-II}}$, $T_{M_1+1}^{\text{LEP-II}}$, \dots , $T_{M_1+N}^{\text{LEP-II}}$. Substituting LEP-II into Eq.(8), the local maximum and

local minimum of $I_M(t)$ can be obtained,

$$I_M(t) = \mathcal{D}_M \pm A_M, \ t \in T_M^{LEP-II}$$
(11)

Through an appropriate interpolation method, such as linear interpolation, the upper and lower envelops can be obtained. Here, D_M can be estimated by the average of upper envelop and lower envelop. A_M can be estimated by half of the difference between upper envelop and lower envelop. As a result, D_M becomes 0 and A_M becomes 1. The intensity signal can be expressed as,

$$I_M(t) = 1 \cdot \cos(\theta(t) + \psi_M) \tag{12}$$

Through inverse cosine, the phase in Eq.(12) can be expressed as,

$$\theta(t) + \psi_M = (-1)^l \cdot \arccos(I_M(t)) + 2n\pi,$$

$$i = 1 \text{ or } 2, \text{ n is integer}$$
(13)

In order to gain $\theta(t)$, *i* and *n* are still needed to be determined. Considering $\theta(t)$ is the phase change caused by extra perturbation, it can be regarded as a continuous function. Firstly, the parameter i is determined. Assume the set of LEP-II is $\{t_1, t_2, t_3, \ldots\}$. These LEP-IIs divide the whole time into several subsections. In each subsection, for example $[t_1, t_2]$, the parameter *i* keeps the same. And for every adjacent subsections, for example $[t_1, t_2]$ and $[t_2, t_3]$, their parameter *i* are different. Assuming the parameter *i* is 1 in the first subsection $[0, t_1]$, the parameter *i* in the rest subsections can be determined one by one. After the parameter *i* is obtained, the parameter n can be determined by a traditional phase unwrapping operation, such as the unwrap function in Mat-*Lab.* Considering the initial phase ψ_M is a slow varying drift and the perturbation phase change $\theta(t)$ is an fast oscillation, they can be further separated by a high pass or low pass filter.

The algorithm flow is shown in Fig.2. It should notice that this algorithm using the sensing series within the SR of Φ -OTDR. Thus the SR of this algorithm is the same as the SR of Φ -OTDR. And the vibration is located by the intensity trace before phase demodulation.

III. EXPERIMENT AND RESULTS

A. EXPERIMENT SETUP

The experiment system setup is shown in Fig.3. An ultra narrow line width laser with 3kHz line width is used as the light source. The continuous probe light is then modulated into pulses by an AOM and boosted by an Erbium doped fiber amplifier (EDFA). The repetition rate of the probe pulse



FIGURE 2. Flow of the proposed demodulation algorithm.



FIGURE 3. Experimental setup.

is set to be 20kHz, with 200ns pulse width, corresponding to 20m SR. A fiber Bragg grating (FBG) is employed to remove the amplifier spontaneous emission (ASE) noise from EDFA. The probe pulse light is then injected into a 1km long sensing fiber through an optical circulator(Cir.2) and the RBT is detected by a photo detector with 400MHz bandwidth. The detector's signal is sampled by a 100MS/s data acquisition card (DAQ), corresponding to about 1m per sampling point. One piezoelectric transducer cylinder (PZT) with 1.25cm radius and 1.05m optical fiber glued on its outside is placed at 200m away from Cir.2 and is applied as a perturbation source. The attached fiber is pre-tensioned when we glue it. The PZT is then driven by a signal generator. The vibration amplitude of the PZT under different driving voltages and frequencies have been measured by a laser displacement sensor (Made by Keyence) and is shown in Fig.4. From Fig.4, the vibration amplitude is tens of nanometer. In the experiment, the driving voltage is set to be 6Vp-p. In order to demonstrate the performance of this phase extraction method, different driving signals are applied to PZT to generate different kinds of vibration waveforms.

B. SINGLE FREQUENCY WAVEFORM EXPERIMENT

The sinusoidal driving signal with 100Hz frequency and 6Vpp amplitude is applied. As the spatial sampling distance is



FIGURE 4. Vibration amplitude of PZT under different driving frequencies and voltages.



FIGURE 5. Sensing series from 203m and 206m(a) and their details(b).

1m, the 1.05m fiber attached on the PZT can be regarded as one point. The sensing series obtained between 200m and 220m are extracted for phase demodulation. Before sending these sensing series into phase demodulation process, a signal prepossessing based on moving average method [23] is applied to eliminate the high frequency random noise. Through moving average method, the signal to noise ratio (SNR) of the sensing series are improved from \sim 0.46dB to \sim 15.61dB (SNR is calculated through power spectrum density). Fig.5 shows two sensing series extracted from 203m and 206m positions and their details. In the detailed figure, the LEP-I and LEP-II can be separated through inspecting their occurrence moment in two sensing series. In fact, multiple sensing series are applied to figure out whether one LEP belongs to LEP-I or LEP-II. With the help of applying more sensing series, LEP-I extraction process become more reliable. Even one or two sensing series have similar initial phase and similar appearance, the LEP-I can still be recognized through inspecting other sensing series. Fig.6(a) shows the demodulated phase of sensing series at 203m using the proposed method. The SNR of the demodulated phase is ~ 16.82 dB, which is ~ 1.31 dB improved compared with the intensity sensing series. And Fig.6(b) shows the Fast Fourier Transform(FFT) results of the original sensing series and its demodulated phase. In time domain, the amplitude of the demodulated phase can be read, which is about 3.48 rad. In frequency domain, the original sensing series shows a similar amplitude (0.95 and 0.88) for 100Hz and



FIGURE 6. Demodulated phase(a) and its FFT result compared with original intensity series(b).



FIGURE 7. Amplitude of demodulated phase with respect to different driving voltages and frequencies.

200Hz, which indicates a strong second harmonic generation. In the FFT result of demodulated phase, the 100Hz frequency component (1.47) is more than 8 times larger than the 200 Hz frequency component (0.17), which indicates a strong suppression of nonlinear. Considering that the vibration amplitude of PZT is 9.01nm and the radius is 1.25cm, the strain on fiber is $0.7208n\varepsilon$. The phase change can be determined by the strain of fiber through the following equation [18],

$$\Delta \phi = \varepsilon \Delta L (2\pi n/\lambda) \times 0.78 \tag{14}$$

where, ε is the strain on fiber, ΔL is the fiber length under strain, n is the refractive index and λ is the wavelength. Note that ΔL is 1.05m, n is 1.47 and λ is 1550nm. The phase change calculated through Eq.(14) is 3.51 rad. The demodulated result (3.48 rad) agrees well with the theoretical calculated value (3.51rad). Fig.7 shows more demodulated phase amplitude under 6~10Vp-p PZT driving voltages with different frequencies. The amplitude of demodulated phase shows a linearity with respect to voltage and basically agrees with the vibration amplitude of PZT, which shows the effectiveness of the proposed algorithm and its potential used in strain measurement.

C. AMPLITUDE-MODULATED WAVEFORM EXPERIMENT

The driving signal with 200Hz carrier frequency, 10Hz modulation frequency and 100% modulation depth is then applied.



FIGURE 8. Sensing series from 208m and 212m (a) and their details (b).

The driving voltage is still set to be 6Vp-p and other parameters also keep the same. The sensing series obtained between 200m and 220m are extracted for phase demodulation and a denoised procedure based on moving averaging is applied (with SNR improved from \sim 1.40dB to \sim 15.80dB). Fig.8 shows the sensing series and their details in the dashed box the from 208m and 212m positions. The details show the LEP-Is and LEP-IIs. In fact, multiple sensing series are applied to help determine the type belonging of each LEP. Fig.9 shows the demodulated phase and its FFT from the sensing series from 212m. The SNR of the demodulated phase is \sim 17.11dB, which is ~ 1.31 dB improved compared with the intensity signal. The waveform of the demodulated phase shows an amplitude-modulated appearance, which shows a 3.73 rad maximum amplitude. The FFT result shows that the demodulated phase has three main frequencies, 200.0Hz, 190.2Hz and 209.9Hz. The 200.0Hz frequency equals to the carrier frequency of the PZT driving signal. The 190.2Hz and 209.9Hz frequencies with similar amplitude are the side bands due to modulation, which indicates the modulation frequency is 9.85Hz, corresponding to the 10Hz modulation frequency of PZT driving signal. The error is mainly due to the analysis precision of FFT. Once a longer data is applied, the frequency precision can be improved.

D. CHIRP WAVEFORM EXPERIMENT

The PZT driving signal is set to be a chirp waveform. The chirp range is from 50Hz to 200Hz and the repetition time is 500ms. The driving voltage is 6Vp-p. The sensing series obtained between 200m and 220m are extracted for phase demodulation and a denoised procedure based on moving averaging is applied (with SNR improved from \sim 3.24dB to \sim 17.20dB). Fig.10(a) shows the intensity sensing series from 203m position. The insert figure illustrates the its details, which shows a sinusoidal form. However, with the help of other sensing series, it can be found that the some of the LEPs in 203m sensing series belong to LEP-II, which are showed in Fig.10(b). In this case, the intensity sensing series shows a sinusoidal form, but its frequency is twice as much as the frequency of PZT driving signal.



FIGURE 9. Demodulated phase(a) and its FFT result(b).



FIGURE 10. Sensing series from 203m(a) and its LEPs(b).

Fig.11 shows the demodulated phase and its short time Fourier transformation(STFT) result. The demodulated phase shows a chirp appearance, with 3.66 rad amplitude in average and 501.1ms repetition time, which agrees well with the driving signal. The SNR of demodulated phase is \sim 18.75dB, which is \sim 1.55dB improved compared with the intensity signal. The lower frequency part shows a higher amplitude and the higher frequency part shows a lower amplitude. This amplitude fluctuation maybe due to the frequencies response difference of PZT. Fig.11(b) shows the frequency repeatedly sweeps from 50Hz to 200Hz, which agrees well with the chirp PZT driving signal.

IV. DISCUSSION

The SNR of the sensing series send to phase demodulate is important to ensure the LEPs can be found accurately. Usually, these sensing series contain high frequency noise and need to be smoothed through denoise method, such as moving average to remove the out-band noise and wavelet denoising to remove the in-band noise. Based on experience, these denoised signals should reach at least \sim 15dB SNR



FIGURE 11. Demodulated chirp phase(a) and its short time Fourier transformation(STFT) result(b).

before sending to demodulation. The low SNR may cause demodulation failure. As the LEPs need to be find one by one, the length of sensing series should longer than one period of the vibration.

Another concern is about the coherent fading problem in Φ -OTDR. When the sensing series face a full coherent fading, little information can be delivered to the intensity series. Thus, the demonstration will fail. For those cases with a certain extent of coherent fading, which means some vibration information can still be delivered to the sensing seires, the phase demodulation could work if the SNR requirement is satisfied.

V. CONCLUSION

This paper proposed a dynamic phase demodulating algorithm for Φ -OTDR system with direct detection, which is basically the simplest Φ -OTDR structure. Without additional detectors, interferometry, optical hybrid or super-high speed acquisition card, the proposed demodulating algorithm can help reduce the cost of the sensing system. Taking advantage of the redundant information between each sensing series, two types of LEP can be distinguished. LEP-II will help to find the envelop of the sensing series and offer the quadrant information in inverse cosine processing. Besides, the algorithm avoids subtractions between each RBT, which gets rid of the demodulating failure caused by small subtraction result during the demodulation. The algorithm was applied to measure sinusoidal dynamic phase change, amplitude-modulated phase change and chirp phase change, demonstrating its capability in dynamic phase measurement.

REFERENCES

 H. F. Taylor and C. E. Lee, "Apparatus and method for fiber optic intrusion sensing," U.S. Patent 5 194 847, Mar. 16, 1993.

- [2] X. Bao and L. Chen, "Recent progress in distributed fiber optic sensors," Sensors, vol. 12, no. 7, pp. 8601–8639, 2012.
- [3] G.-M. Ma, C. Shi, W.-Q. Qin, Y.-B. Li, H.-Y. Zhou, and C.-R. Li, "A non-intrusive electrical discharge localization method for gas insulated line based on phase-sensitive OTDR and Michelson interferometer," *IEEE Trans. Power Del.*, vol. 34, no. 4, pp. 1324–1331, Aug. 2019.
- [4] J. C. Juarez, E. W. Maier, K. Nam Choi, and H. F. Taylor, "Distributed fiber-optic intrusion sensor system," *J. Lightw. Technol.*, vol. 23, no. 6, pp. 2081–2087, Jun. 2005.
- [5] W. Pan, K. Zhao, C. Xie, X. Li, J. Chen, and L. Hu, "Distributed online monitoring method and application of cable partial discharge based on φ -OTDR," *IEEE Access*, vol. 7, pp. 144444–144450, 2019.
- [6] S. Mikhailov, L. Zhang, T. Geernaert, F. Berghmans, and L. Thevenaz, "Distributed hydrostatic pressure measurement using phase-OTDR in a highly birefringent photonic crystal fiber," *J. Lightw. Technol.*, vol. 37, no. 18, pp. 4496–4500, Sep. 15, 2019.
- [7] F. Peng, H. Wu, X.-H. Jia, Y.-J. Rao, Z.-N. Wang, and Z.-P. Peng, "Ultra-long high-sensitivity *φ*-OTDR for high spatial resolution intrusion detection of pipelines," *Opt. Express*, vol. 22, no. 11, pp. 13804–13810, Jun. 2014.
- [8] H. Wu, X. Liu, Y. Xiao, and Y. Rao, "A dynamic time sequence recognition and knowledge mining method based on the hidden Markov models (HMMs) for pipeline safety monitoring with *φ*-OTDR," *J. Lightw. Technol.*, vol. 37, no. 19, pp. 4991–5000, Oct. 1, 2019.
- [9] C. Du, S. Dutta, P. Kurup, T. Yu, and X. Wang, "A review of railway infrastructure monitoring using fiber optic sensors," *Sens. Actuators A*, *Phys.*, vol. 303, Mar. 2020, Art. no. 111728.
- [10] A. E. Alekseev, V. S. Vdovenko, B. G. Gorshkov, V. T. Potapov, and D. E. Simikin, "Contrast enhancement in an optical time-domain reflectometer via self-phase modulation compensation by chirped probe pulses," *Laser Phys.*, vol. 26, no. 3, Mar. 2016, Art. no. 035101.
- [11] J. Pastor-Graells, H. F. Martins, A. Garcia-Ruiz, S. Martin-Lopez, and M. Gonzalez-Herraez, "Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses," *Opt. Express*, vol. 24, no. 12, p. 13121, Jun. 2016.
- [12] H. D. Bhatta, L. Costa, A. Garcia-Ruiz, M. R. Fernandez-Ruiz, H. F. Martins, M. Tur, and M. Gonzalez-Herraez, "Dynamic measurements of 1000 microstrains using chirped-pulse phase-sensitive optical timedomain reflectometry," *J. Lightw. Technol.*, vol. 37, no. 18, pp. 4888–4895, Sep. 15, 2019.
- [13] A. Masoudi, M. Belal, and T. P. Newson, "A distributed optical fibre dynamic strain sensor based on phase-OTDR," *Meas. Sci. Technol.*, vol. 24, no. 8, Aug. 2013, Art. no. 085204.
- [14] A. Masoudi and T. P. Newson, "High spatial resolution distributed optical fiber dynamic strain sensor with enhanced frequency and strain resolution," *Opt. Lett.*, vol. 42, no. 2, pp. 290–293, Jan. 2017.
- [15] Z. Wang, L. Zhang, S. Wang, N. Xue, F. Peng, M. Fan, W. X. S. Qian, J. Rao, and Y. Rao, "Coherent φ-OTDR based on I/Q demodulation and homodyne detection," *Opt. Express*, vol. 24, no. 2, pp. 853–858, 2016.
- [16] Z. Pan, K. Liang, Q. Ye, H. Cai, R. Qu, and Z. Fang, "Phase-sensitive OTDR system based on digital coherent detection," in *Proc. Opt. Sensors Biophoton.*, Shanghai, China, 2011, p. 83110.
- [17] G. Fang, T. Xu, S. Feng, and F. Li, "Phase-sensitive optical time domain reflectometer based on phase-generated carrier algorithm," *J. Lightw. Technol.*, vol. 33, no. 13, pp. 2811–2816, Jul. 1, 2015.
- [18] Y. Muanenda, S. Faralli, C. J. Oton, and F. Di Pasquale, "Dynamic phase extraction in a modulated double-pulse φ-OTDR sensor using a stable homodyne demodulation in direct detection," *Opt. Express*, vol. 26, no. 2, pp. 687–701, Jan. 2018.
- [19] H. Liu, F. Pang, L. Lv, X. Mei, Y. Song, J. Chen, and T. Wang, "True phase measurement of distributed vibration sensors based on heterodyne φ -OTDR," *IEEE Photon. J.*, vol. 10, no. 1, pp. 1–9, Feb. 2018.
- [20] H. He, L.-Y. Shao, Z. Li, Z. Zhang, X. Zou, B. Luo, W. Pan, and L. Yan, "Self-mixing demodulation for coherent phase-sensitive OTDR system," *Sensors*, vol. 16, no. 5, pp. 681–691, 2016.
- [21] J. Jiang, Z. Wang, Z. Wang, Y. Wu, S. Lin, J. Xiong, Y. Chen, and Y. Rao, "Coherent Kramers-Kronig receiver for Φ-OTDR," *J. Lightw. Technol.*, vol. 37, no. 18, pp. 4799–4807, Sep. 15, 2019.
- [22] Z. Sha, H. Feng, and Z. Zeng, "Phase demodulation method in phasesensitive OTDR without coherent detection," *Opt. Express*, vol. 25, no. 5, pp. 4831–4844, Mar. 2017.
- [23] Y. Lu, T. Zhu, L. Chen, and X. Bao, "Distributed vibration sensor based on coherent detection of phase-OTDR," *J. Lightw. Technol.*, vol. 28, no. 22, pp. 3243–3249, Nov. 15, 2010.











YI SHI received the B.S. degree in engineering and the Ph.D. degree in instrument science and technology from Tianjin University, Tianjin, China, in 2012 and 2018, respectively.

He has been an Assistant Professor with the Department of Engineering, Shantou University, Shantou, Guangdong, China, since 2018. His research interests include the distributed optical fiber sensor, mode recognition, and smart instrument.

GUIFANG CHEN received the B.E. degree in information engineering from Hunan Agricultural University, China, in 2019. She is currently pursuing the M.E. degree in information and communication engineering with the School of Engineering, Shantou University.

Her recent research direction is signal processing based on deep learning. Her research interests include signal processing, deep learning, and image processing.

YUANYE WANG received the B.Eng. degree in electronics and information engineering from Northeast Agricultural University, China, in 2018. He is currently pursuing the M.E. degree in electronics and communication engineering with the School of Engineering, Shantou University.

His recent research direction is intelligent event recognition of sensing fiber. His research interests include image processing, deep learning, and optical fiber sensor.

LEI ZHAO (Member, IEEE) was born in Anhui, China, in 1988. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2011, 2013, and 2018, respectively.

He is currently an Associate Professor with the College of Engineering, Shantou University, Shantou, China. His research interests include power conversion and control technology.

ZHUN FAN (Senior Member, IEEE) received the B.S. and M.S. degrees in control engineering from the Huazhong University of Science and Technology, Wuhan, China, in 1995 and 2000, respectively, and the Ph.D. degree in electrical and computer engineering from Michigan State University, Lansing, MI, USA, in 2004.

He is currently a Full Professor with Shantou University (STU), Shantou, China. He also serves as the Head of the Department of Electrical Engi-

neering and the Director of the Guangdong Provincial Key Laboratory of Digital Signal and Image Processing. Before joining STU, he was an Associate Professor with the Technical University of Denmark (DTU), from 2007 to 2011, first with the Department of Mechanical Engineering, then with the Department of Management Engineering, and as an Assistant Professor with the Department of Mechanical Engineering, Shantou University, from 2004 to 2007. He has been a Principle Investigator of a number of projects from Danish Research Agency of Science Technology and Innovation, and National Natural Science Foundation of China. His research interests include intelligent control and robotic systems, robot vision and cognition, MEMS, computational intelligence, design automation, optimization of mechanical systems, machine learning and image processing.