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DISCUSSION

Performance improvement of optical fiber sensor based on phase sensitive optical time domain reflectometry

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Abstract Phase-sensitive optical time-domain reflectometry (Φ-OTDR) has the advantages of high accuracy, large dynamic range and wide measurement range. It is suitable for remote monitoring of signals generated by external interference, and has broad prospects and great application potential. Nowadays, the requirements for its performance are increasing, and more and more scholars start to focus on the specific optimization of Φ-OTDR system for different practical application. The contents of this paper are as follows: (1) The first part introduces the research results of Φ-OTDR system in vibration signals measurement in recent years. Taking the signal-to-noise ratio (SNR) as the index, the solutions to the problems of system noise, laser frequency drift and signal fading are described; (2) The second part introduces the research results of Φ-OTDR system in signal recognition capability in recent years. Taking recognition rate and nuisance alarm rate (NAR) as the indicators, the development of feature extraction and signal classification are described; (3) The third part introduces the research results of Φ-OTDR system on the expansion of the detectable space in recent years. Taking the sensing distance as the index, the study of sensing distance and spatial positioning are described. The traditional Φ-OTDR technology has been mature, and further improvement of performance will pave the way for further expansion and application of Φ-OTDR system for different engineering fields in the future.

Keywords Phase sensitive optical time-domain reflectomety · Vibration signals measurement · Signal-to-noise ratio · Signal recognition · Space detection range

Introduction

Distributed optical fiber sensing (DOFS) technology is a continuous distributed sensing technology that uses optical fiber as both the sensing medium and the transmission medium. In these technologies, Φ-OTDR can detect and locate vibration events at any position along the optical fiber. It is widely used in instrument measurement [1], highway accident monitoring [2], cable leakage detection [3], long-distance pipeline detection [4], perimeter security [5] and so on.

In 1993, Φ-OTDR was first proposed by Taylor et al., which was based on Rayleigh backscattered (RBS) light and ultra-narrow linewidth lasers [6]. In 2003, an all-optical erbium-doped fiber amplifier (EDFA) and an F-P interferometer were mixed to realize laser emission with a line width of less than 3 k Hz. The laser was then modulated by an electro-optical modulator (EOM), achieving a good interference effect [7]. In 2005, vibration sensing on 12 km optical fiber was realized based on Φ-OTDR. Using ultra narrow band width and low-frequency shift laser as the light source, the spatial resolution of the system reached at 100 m [8]. In 2009, an ultra-long distance Φ-OTDR system was mixed with a bidirectional Raman amplifier. The Raman amplifier offsets the scattered light power loss caused by the self-loss of the optical fiber, and the system was finally realized with 74 km sensing distance and 20 m spatial resolution [9]. In 2010, the heterodyne detection was applied in Φ-OTDR, which greatly improved the performance parameters of the system,

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such as spatial resolution and SNR [10]. In 2013, a multi-frequency Φ-OTDR structure using phase modulation to achieve equal intervals of tens of MHz was proposed. Since the frequency of injected detection pulses was independent, the RBS signals at different frequencies were not exactly the same, so fading suppression could be realized [11]. In 2019, the data acquisition card (DAC) whose sampling rate was lower than the frequency of beat signals was applied to collect the signal output of the orthogonal coupler. It demodulated only the data near the vibration position, thereby constructing a new low-cost Φ-OTDR system [12]. In 2022, the phase-locked Φ-OTDR system was designed and instrumented in online status monitoring and surrounding environment perception, achieving good results [13].

At present, the research of Φ-OTDR system has following trends: First, it focuses on solving the problems of Φ-OTDR in measuring low frequency vibration, and extracting useful signals from various mixed signals. This involves improving the SNR, compensating the frequency drift of the laser source, and suppressing fading. Secondly, it focuses on improving the recognition accuracy of Φ-OTDR during signal location and identification to avoid missing alarms and false alarms. This involves improving the accuracy of system feature extraction and reducing the NAR of the system; thirdly, it focuses on broadening the spatial orientation capability of Φ-OTDR in practical applications. This includes expanding the sensing distance, realizing the 2D and 3D space–time positioning. In this paper, the progress of the Φ-OTDR system research in recent years will be briefly reviewed from these three perspectives.

Principles and application challenges of Φ-OTDR systems

Principle of Φ-OTDR system

The principle of the fiber-optic sensing technology based on the Φ-OTDR system is shown in Fig. 1. The ultra-narrow line-width laser generates continuous coherent optical signals, which are modulated into optical pulse signals by an acousto-optic modulator (AOM) and are amplified with an EDFA. After that, the amplified optical pulse signals are injected into the detection cable through the isolator, the circulator port 1 and port 2 in turn. The detection fiber usually chooses ordinary single-mode fiber. In real situations, it is usually laid along the detected objects, such as oil and gas pipelines, submarine optical cables, or simply buried in the land or sea. The optical pulse signal generates Rayleigh scattering during transmission along the optical cable, and the RBS signals return along the optical cable. Then the RBS signals come through the port 2 and port 3, and the noise signals are removed through an optical filter. The phase demodulation of signals after noise filtering is carried out to obtain the vibration signal along the optical fiber. The demodulated optical signals are then converted into an electrical signal by the photoelectric detection (PD). After that, it is collected by the synchronous trigger analog-to-digital (A/D) converter, which is controlled by the waveform generator. Finally the

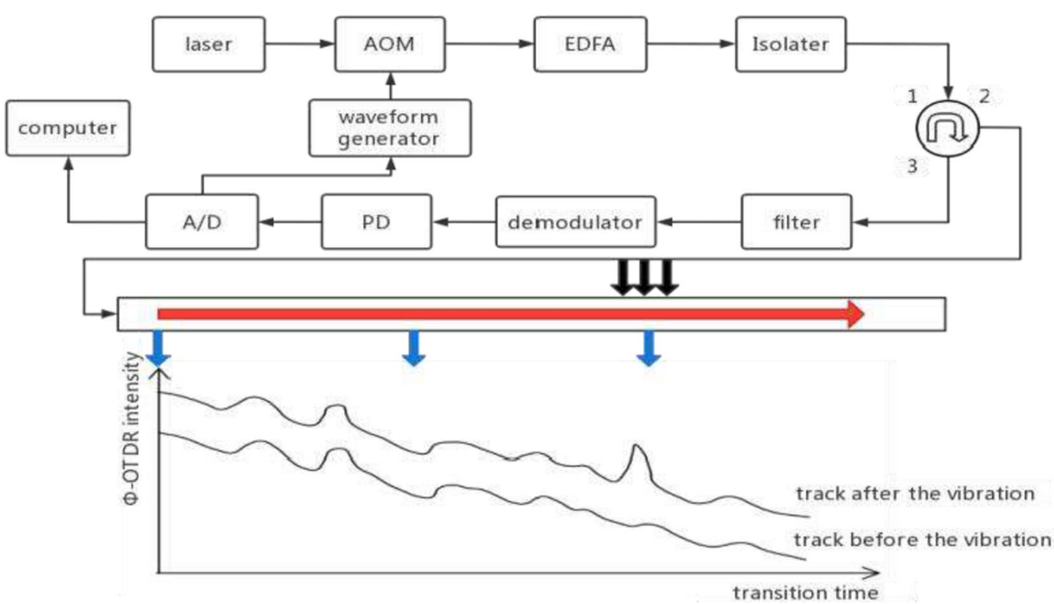

Fig. 1 Schematic diagram of optical fiber sensing technology based on Φ-OTDR system, laser: Ultra-narrow linewidth laser, AOM: acousto-optic modulator, EDFA: erbium-doped fiber amplifier, PD: photo detector, A/D: analog-to-digital conversion

digital electrical signal is transmitted to the signal processing host in real time through the network interface.

Challenges faced in Φ-OTDR system

At present, the Φ-OTDR system mainly faces three challenges in sensing and signal processing:

1. The detection of vibration signals in practical applications is difficult. The frequency drift of the laser source, signal fading and other phenomena in Φ-OTDR system will cause a series of internal noise. The natural environment and human activities will bring a series of external noise. These two types of noises mix with vibration signals, making most of the vibration signals difficult to be measured. With the continuous development of technology and the continuous expansion of application range, it is urgent the Φ-OTDR system to improve the ability to measure weak vibration signals, such as low frequency or small amplitude. Therefore, it is necessary to develop a corresponding technology to improve the capacity of weak vibration signals detection in Φ-OTDR system.
2. The recognition ability of vibration signals in practical applications needs to be improved. Usually, the applications of the Φ-OTDR system have the requirements of long distance and large space. However, with the expansion of distance and space, the influence of the transmission medium(such as water and soil) are also more complex, and the useful information of signals is mostly blocked by the transmission medium. Moreover, the vibration information received at different locations is often inconsistent, resulting in the system having missing alarms and false alarms. Finally, it is impossible to separate the required vibration signals from the aliasing signals, greatly increasing the difficulty of identifying the target vibration source.
3. The detectable space of the Φ-OTDR system in practical applications must be expanded. On the one hand, it is still necessary to continue improving the sensing distance of Φ-OTDR system and expanding the advantages of the Φ-OTDR system in long-distance sensing. On the other hand, since Φ-OTDR is generally 1D positioning along the optical fiber, it is significant to enlarge the positioning dimension, trying to realize 2D and 3D sensing.

Vibration signals measurement based on Φ-OTDR system

In order to describe the accuracy of vibration signals measurement, the concept of signal-to-noise ratio (SNR) is introduced. It is defined as the ratio of the RBS signals to the noises. It can be expressed as:

$$\mathrm{SNR} = 10\lg\left(\frac{P_{\mathrm{S}}}{P_{\mathrm{N}}}\right) = 20\lg\left(\frac{V_{\mathrm{S}}}{V_{\mathrm{N}}}\right) \tag{1}$$

where P_{s} refers to the effective power of the RBS signals, P_{N} refers to the effective power of noise, V_{S} refers to the voltage amplitude of the RBS signals, V_{N} refers to the voltage amplitude of the noise.

The range of vibration signals that can be detected by Φ-OTDR system is gradually expanding years by years. In application areas such as underwater acoustic detection, seismic wave monitoring, and leakage detection, high requirements are put forward for the ability of Φ-OTDR systems to detect weak vibration signals. However, when monitoring these kinds of signals, they are usually submerged in the interference noises, making it difficult to extract and identify, and resulting in a sharp decline in the performance of Φ-OTDR systems. These noises are mainly from three parts: the system noises, noises from laser frequency drift, and noises from fading suppression.

Research on system noises removal

The system noises mainly include the thermal noise, the shot noise, the low-frequency periodic noise, the random noise in the environment and the low-frequency periodic vibration signal noise. The original partial mature denoising methods are only suitable for noise removal in the detection of high frequency vibration, such as average difference method, average differential method or wavelet denoising theory. Due to this fact, many new denoising technologies that are applied to the detection of weak vibration signals with low frequency or small amplitude have been developed in recent years.

Adaptive filtering (AF) is a common signal processing algorithm used to detect specific weak signals under harsh conditions. It has a good noise reduction effect for the non-stationary characteristics of environmental noise, and it has been widely used in fields like radar, sonar and voice processing. The application of AF algorithm in Φ-OTDR was simulated in 2016, and the effect was great [14]. Based on this, a new adaptive time-domain matching filtering (AMF) algorithm was proposed in 2017. This algorithm achieved a significant improvement in SNR without adding any other optical amplification or digital pretreatment of signal data [15]. In 2022, an AF algorithm based on normalized least mean square (NLMS) was proposed, and the filtering curve in the experiment finally obtained the SNR of 22.3 dB at 500.0 Hz [16].

Empirical mode decomposition (EMD) has also been widely used in signal processing. It decomposes the signal into a series of characteristic modal components distributed from high frequency to low frequency without requiring prior information. It has unique advantages in dealing with nonlinear and non-stationary signals. In 2019, EMD was applied to Φ-OTDR, and when the frequencies were 100.0 Hz and 1.2 kHz, the SNR was increased to 42.5 and 39.6 dB, respectively [17]. In 2021, a method based on EMD and Pearson correlation coefficient fusion (EMD-PCC) was proposed. It was more suitable for filtering low-frequency noise components, and the SNR was increased from 7.3 to 13.7 dB [18]. In the same year, a fusion noise reduction method based on EMD and time–frequency peak filtering (EMD-TFPF) algorithm was proposed. It increased the SNR to 37.6 dB with a magnitude down to 4 nε and an acoustic frequency up to 40.0 kHz. The low-frequency response range of system was also expanded to 5.0 Hz [19].

Compressed sensing (CS) is a signal processing algorithm emerging in recent years. It is able to recover vibration signals from fewer measurements, which can reduce data volume and data processing time effectively. Compared with uniform sampling, the number of measurements for reconstructing signals with the random pulse sequence are greatly reduced. CS was imported into Φ-OTDR in 2019, and the SNR was increased to 34.4 dB [20]. In 2022, a further study on CS application in the Φ-OTDR system was processed, increasing the SNR to 40.4 dB at 100.0 Hz and to 30.6 dB at 500.0 Hz. The CS algorithm could not only locate the external intrusion, but also obtain its frequency information [21].

In addition to the above denoising algorithms, there are also some other methods to improve the SNR. In 2020, a cascaded statistics-based signal-processing (CSBSP) framework was proposed for transient weak signal detection. This framework could both capture the target signal and extracts the features. The experiment showed that it was

capable of locating dynamic strain with a magnitude down to $4n\varepsilon$ and an acoustic frequency up to 40.0 kHz, and the SNR reached 5.1 dB [22]. In 2022, a new optimized minima controlled recursive averaging (OMCRA) method was applied to Φ-OTDR. It improved the acoustic detection by especially eliminating the phase noise, and it was helpful to improve the detection sensitivity of the Φ-OTDR system for weak signals. The filtered phase signal could increase the SNR by 11.5 dB on average, and the highest strain resolution is 69.2 $\mathrm{p}\varepsilon/\sqrt{\mathrm{Hz}}$ [23].

Table 1 lists the research results mentioned above.

Table 1 Research on system noise removal in Φ-OTDR

Denoising method	Authors	Year	References
AF	A. Öncü et al	2016	[14]
AMF	A. Öncü et al	2017	[15]
EMD	M. He et al	2019	[17]
CS	S. Qu	2019	[20]
CSBSP	H. Chen et al	2020	[22]
EMD-PCC	Wei Chen et al	2021	[18]
EMD-TFPF	Ting-Tiug Lin et al	2021	[19]
AF + NLMS	Zhihua Yu et al	2022	[16]
CS	Xu Gao	2022	[21]
OMCRA	G. Jia et al	2023	[23]

Research on laser frequency drift compensation

In Φ-OTDR, a local vibration on the optical fiber causes a change in the optical path length of the light, which in turn changes the intensity and phase of the RBS signals. Therefore, by demodulating the intensity change or phase change of the received signals at each position, distributed measurement of the vibration along the optical fiber can be achieved. In general, when there is no vibration on the optical fiber, the RBS signals show a stable speckle pattern at time domain in the figures. However, since the optical phase is related to the frequency of the light wave, a change in the frequency of the laser source will alter the phase difference between the two points, causing a change in the patterns [24]. It has been confirmed that all the current commercial lasers have slow frequency drift, which causes noise in the low-frequency domain, and limits the ability of Φ-OTDR system to measure low-frequency vibrations [25]. The effective means to solve the issue of laser frequency drift are generally ways of system compensation. In this paper, two scheme solutions are listed: the auxiliary Mach-Zender interferometer (MZI) scheme and the optical synchronous heterodyne scheme.

In 2019, an auxiliary MZI was added to the traditional Φ-OTDR system to compensate for the effects of laser frequency drift [26]. As shown in Fig. 2, a coherent detection system was used in the experiment. The auxiliary MZI monitored and tracked the frequency drift of the main signal that occurred in the Φ-OTDR system, and used the results to correct the phase of the main signal. Figure 3 shows the measurement results of the two kinds of vibrations with frequencies of 0.2 and 0.5 Hz, respectively. It could be seen from picture (a) that the demodulation results were in good consistent with the drive signal. It could be seen from picture (b) that the low-frequency noise near the direct current (DC) band was significantly reduced. Finally, the experiment successfully detected the vibration with a frequency of 0.1 Hz, an amplitude of 0.05 V, which corresponded to a strain of 5.9 nε.

In 2021, a Φ-OTDR system based on optical synchronous reference heterodyne scheme was proposed [27]. As shown in Fig. 4, the system used the optical reference detection arm to track the frequency of the vibration signals. The

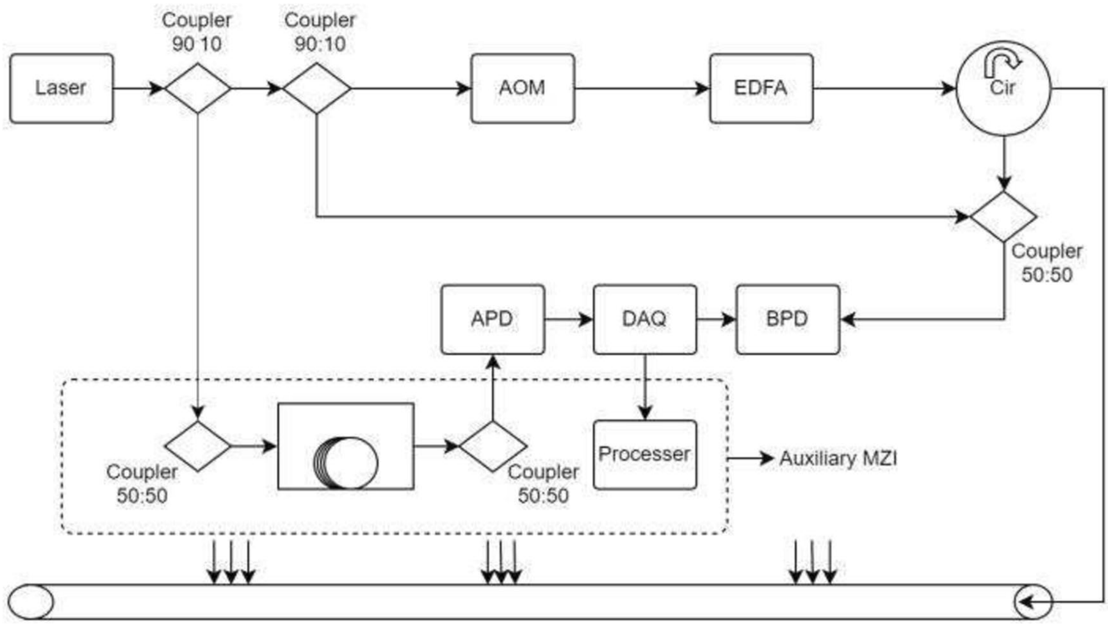

Fig. 2 Schematic diagram of the Φ-OTDR system structure of the auxiliary Mach-Zender interferometer (MZI) [26]

continuous light from the laser is divided into signal light and local oscillator light (OC1). Part of the local oscillator light is mixed with Rayleigh scattering interference light to produce a beat frequency signal (OC3-OC3-BPF-PS2). The other part of the local oscillator light is mixed with the reference light of the actual frequency shift frequency, and used as a quadrature demodulation signal (OC3-EDFA-OC4-BPF-PS1). It effectively solved the frequency drift problem in the traditional heterodyne coherent detection Φ-OTDR system and the stray frequency phenomenon in the demodulation results. As shown in Fig. 5, a detection light pulse with a repetition rate of 5.0 kHz and a pulse width of 100.0 ns was used in the experiment to achieve the SNR of about 31.4 dB on a 10.0 km optical fiber. On the basis of this system, a new recursive least square (RLS) algorithm was also proposed [28]. With a repetition frequency of 5.0 kHz and a pulse width of 100.0 ns, vibration experiments were carried out with different frequencies and amplitudes. The results verified that the RLS algorithm reduced data waveform distortion and improved the demodulation characteristics. In general, the RLS algorithm suppressed the quadrature imbalance phenomenon, which was conducive to the full digital realization of heterodyne detection technology.

Research on fading suppression

Common fading noise consists of two kinds of fading, namely interference fading and polarization fading.

Most Φ-OTDR systems have fading noise caused by interference fading. In heterodyne detection, the RBS signals can be affected by the characteristics of the scattered points in the optical fiber. The statistical characteristics of the scattered point intensity meet the Gaussian distribution and uniform distribution. This results in the intensity characteristics of the RBS signals conforming to the Rayleigh distribution, which looks like a sawtooth profile in figure [29]. Therefore, it has a certain probability of falling into the dead zone and causing interference fading.

Fading noise caused by polarization fading is mainly to be considered when using coherent detection. Because the birefringence causes the random change of the polarization state of light, the polarization state of the intrinsic light and the polarization state of the probe light are basically inconsistent, therefore the polarization fading will inevitably occur.

Both interference fading and polarization fading will reduce the SNR of the corresponding position demodulation results, making it hard to realize the real strain change along the whole optical fiber. This will further cause a series of problems such as phase jump, noise flooding, and even produce false alarms.

Rotation vector synthesis (RVA) is an effective method to suppress fading presented in recent years. Through the rotation synthesis of the decomposed signal vectors, the intensity of the fading points in each group of scattered signals is enhanced by other groups. This will greatly suppress the phase noise, eliminate the pseudo-phase caused by fading, and further realize the suppression of interference fading. In 2021, a pulse-coding Φ-OTDR system was designed, extracting the spectrum using the fast inverse Fourier transform algorithm. Combined with RVA, the

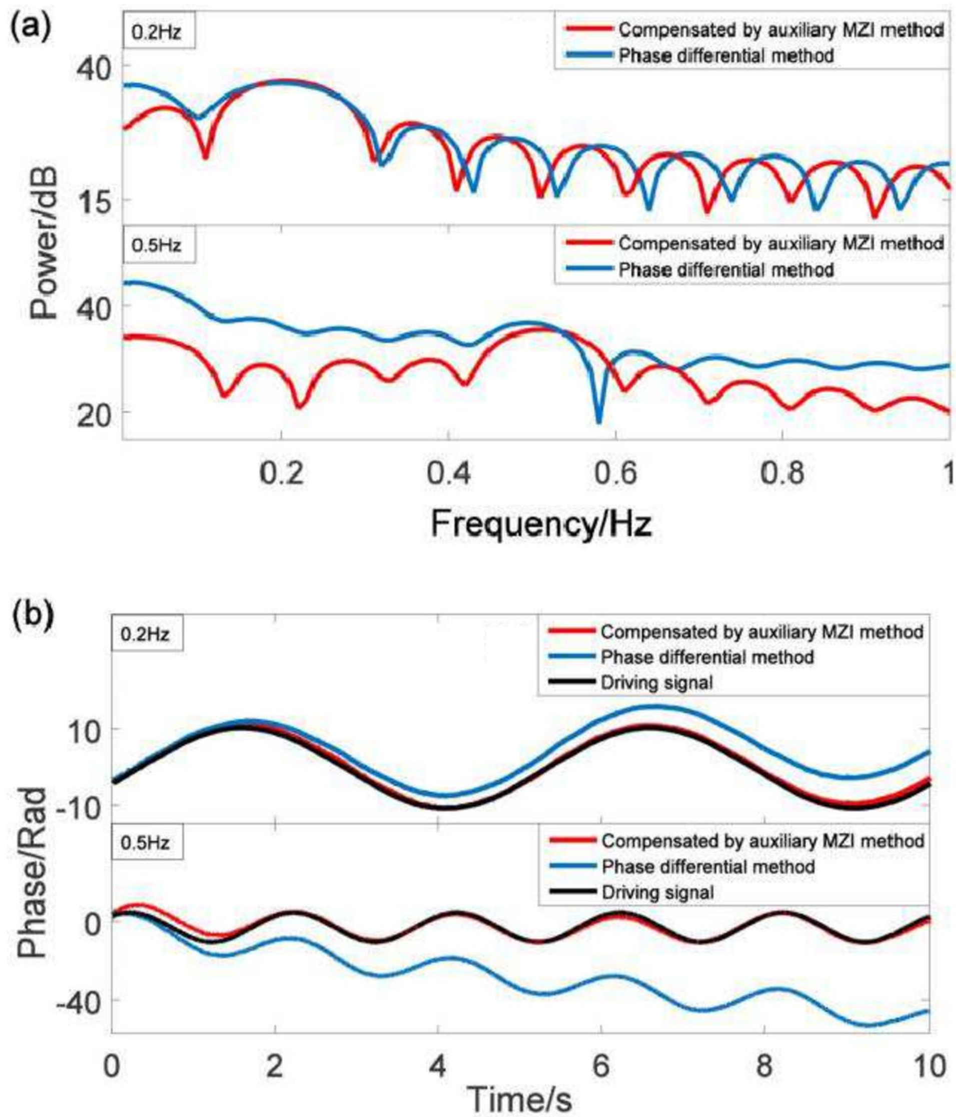

Fig. 3 Schematic diagram of the measurement results of the two vibrations with a frequency of 0.2 and 0.5 Hz, respectively [26]

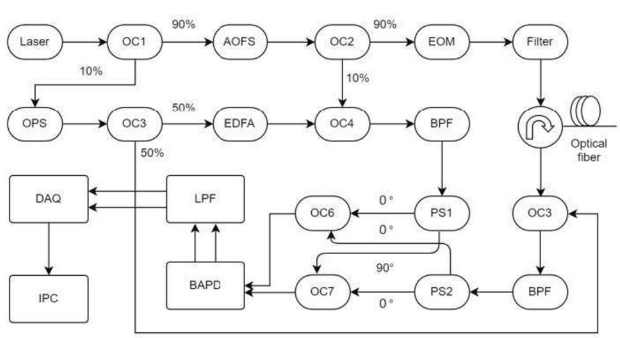

Fig. 4 Schematic diagram of Φ-OTDR based on optical synchronous reference heterodyne scheme [27]

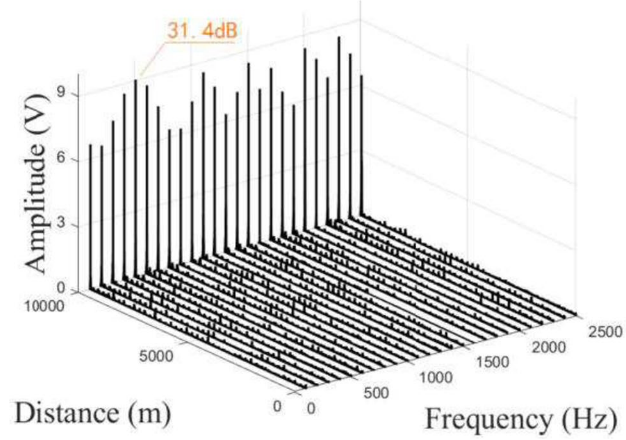

Fig. 5 The SNR of the vibration signal generated by the vibration interference of different frequencies [27]

percentage of interference fading point reduced from 3.0 to 0.3%. Finally the SNR of demodulation phase after interference fading suppression reached to 44.0 dB [30]. In 2022, a multi-frequency decomposition (MFD) method was proposed, which mixed the short-time Fourier transform (STFT) and RVA. Two kinds of vibration were selected, of which the amplitude was 9.2 and 9.4 rad, and the frequency was 500.0 and 800.0 Hz, and these two vibrations were precisely restored [31]. In the same year, the phase jump rate (PHR) was defined to evaluate the degree of signal fading, and a moving rotation vector average (MRVA) method was proposed to suppress fading and eliminate false phase peaks. The result showed that the average SNR was improved by about 11.4 dB compared with the traditional demodulation method [32].

In addition to RVA, there are also many effective methods to suppress fading. In 2016, an analysis was concluded that aggregation of multiple frequencies had benefits in three different ways: reducing the fading probability, decreasing the noise level in the resultant signals, and improving the linearity of the system's response to the perturbation. It was also pointed out that the wavelet decomposition and reconstruction could greatly reduce the influence of coherent fading noise and improve the linearity of the system [33]. In 2020, a statistical method for nearest neighbor analysis was proposed. It could improve the long-term performance of Φ-OTDR system on the basis of numerical calculation without increasing system complexity. The vibration with frequency as low as 0.2 Hz was successfully recovered [34]. In 2022, an active frequency conversion (ATF) method for interference fading suppression in Φ-OTDR system was proposed. The phase modulator was used to achieve multi-frequency detection, and the identification of signal distortion caused by the fading state at demodulation positions was realized by the auxiliary interferometer feedback structure. Through multi-frequency detection, the fading probability was reduced to 1.6% and the correlation coefficient was increased to 0.99 [35]. In 2023, a new Single-Input -Single-Output (SISO) system using few-mode fibers (FMF) was proposed. The FMF had unique advantages, such as high nonlinear threshold and high Rayleigh scattering capture efficiency for sensing, thus suppress fading and achieving a higher SNR. A 4 × 4 MIMO Φ-OTDR system was finally realized, and the average noise floor of the system was − 80.3 dB rad^2/Hz. The lowest noise floor of the system was − 88.0 dB rad^2/Hz, which corresponds to a strain resolution of 0.2 pε/$\sqrt{\text{Hz}}$ [36].

Table 2 lists the research results involved.

Table 2 Research on suppression of fading in Φ-OTDR

Methods to suppress fading	Authors	Year	References
Wavelet decomposition and reconstruction	Artog A A et al	2016	[33]
Nearest neighbor analysis	Guojie Tu et al	2020	[34]
SERVS	Kexin Cui et al	2021	[30]
STFT + RVA	Heng Qian et al	2022	[31]
MRVA	Heng Qian et al	2022	[32]
ATF	Yu Wang et al	2022	[35]
MIMO	Bin Lu et al	2023	[36]

Vibration signals recognition based on Φ-OTDR system

In order to improve the recognition ability of vibration signals in practical applications, feature extraction and pattern recognition technology are proposed for Φ-OTDR system. Two concepts are introduced here to describe the ability of signal recognition: recognition rate and nuisance alarm rate (NAR). Recognition rate refers to the number of the input patterns correctly recognized as a percentage of the total number of all the input patterns recognized. The higher the value is, the higher the recognition rate is, and the better the system performance is. NAR describes the frequency of false alarms caused by ground noise, traffic, rain, and wind when using the Φ-OTDR system to detect vibration signals. Its definition is the ratio of the number of false alarms to the total number of alarms, which can be expressed as:

$$\text{NAR} = \frac{n_{\text{N}}}{n_{\text{total}}} \tag{2}$$

where n_{N} is the number of false alarms and n_{total} is the total number of alarms. In general, the smaller the NAR, the better the system performance.

The research of vibration signal recognition methods based on Φ-OTDR system in recent years will be discussed from two aspects: feature extraction and classifiers.

Research on feature extraction

At present, feature extraction can be analyzed from three aspects: time domain feature extraction, frequency domain feature extraction and morphological feature extraction.

Time domain feature extraction is mainly to make statistics of signal changes in time domain. In 2019, a dynamic time series recognition and knowledge mining method based on Hidden Markov Model (HMM) was proposed. The optimal hidden state sequence outputted by signals in HMM library was an important supplement to the information of current physical event signals, and the average recognition rate could reach 98.2% [37]. In 2020, the EMD was used to extract features from normalized signals and normalized differential signals. Finally eleven features were extracted, and each event had a recognition rate of more than 90.0% [38].

When it is impossible to distinguish different vibrations in the time domain, it is also a good choice to start with the frequency domain. In 2020, a fisher scoring extreme learning machine (F-ELM) recognition model was proposed. The experiment extracted 30 time domain features using normalized differential method and 10 frequency domain features using wavelet packet decomposition (WPD) method, and the final average NAR was 4.7% [39]. In 2022, the Meir cepstrum coefficient (MFCC) was used to extract the frequency domain features of stationary signals. Combined with the superposition algorithm and deep learning, the MFCC successfully raised the classification accuracy rate to more than 98.0% [40].

Whether it comes to time domain feature extraction or frequency domain feature extraction, the features are only extracted from the one dimensional space-or-time angle. The morphological feature extraction, however, can extract the signal features from the two dimensional space–time angle. In 2018, the noise from the buried optical cable was collected with dispersion analysis. By comparing the measured data, the model's multi-modal dispersion curve, and the inversion curve of the S-wave velocity profile, the reliability of Φ-OTDR system in monitoring the seismic wave was verified [41]. In 2020, five morphological features were extracted from eight kinds of events, including area, perimeter, density, number of connected domains and Euler number. Then they were mixed with time–frequency domain feature extraction, and the final recognition accuracy reached to more than 97.0% [42].

Research on classifiers

After feature extraction is accomplished, it is still necessary to use classifiers for pattern recognition to further denoise and recognize the data. Generally speaking, classifiers are divided into unsupervised learning and supervised learning.

Unsupervised learning refers to finding patterns in a sample for modeling analysis rather than providing artificial labels. For example, an unsupervised anomaly detection was applied to Φ-OTDR and successfully detect intrusion events within 35.0 km [43]. Supervised learning, on the contrary, refers to obtaining an optimal model by training samples and given labels, and applying it to the unknown samples to achieve the optimal output effect. In practical applications, supervised learning classifiers are generally selected for training to achieve good results.

Support vector machine (SVM) is a traditional classifier based on statistical learning theory. It has the ability to find the classification hyperplane with the largest interval for different types of samples, which make it appropriate for the case of small samples. In 2019, a near class support vector machine (NC-SVM) method based on K-nearest neighbor algorithm was proposed. It extended the application of SVM to multi-class recognition problems, and the real average NAR was 5.6% [44]. In 2021, SVM was mixed with variational mode decomposition (VMD) and multi-scale arrangement entropy (MPE). This achieved good real-time effect and denoising effect, with an average recognition rate of 97.3% [45].

Neural network is a combination of multiple perceptrons to solve classification problems. Common neural network models include convolutional neural network (CNN), probabilistic neural network (PNN), back propagation neural network(BPNN), and so on. Neural network is a method with strong ability of learning and self-adaptation, and it has a good expression when facing many kinds of nonlinear data. In 2019, a partial discharge (PD) recognition based on CNN was proposed. The recognition rates of internal PD, corona PD and surface PD monitoring reached to 98.0%, 96.3%, 91.0% and 100.0% respectively, with a comprehensive recognition rate of 96.3% [46]. In the same year, the BPNN was mixed with wavelet packet transform. This achieved multi-parameter recognition, in which the two-parameter classification recognition rate was 91.4% and the multi-parameter classification recognition rate was 83.2% [47]. In 2021, a time–frequency characteristic (TFC) method was proposed for identifying optical fiber vibration signals, which contained the Hilbert transform, EMD and PNN. The recognition time of the system was 1.4 s and the recognition rate was 99.0% [48].

Table 3 summarizes the above mentioned papers.

Methods of expanding detectable space for Φ-OTDR system

Research on sensing distance

The detection distance mainly refers to the maximum optical fiber sensing distance of RBS signals that can be detected in the Φ-OTDR system. When only one pulse light is transferred inside the optical fiber, the period of this pulse light (T_m) determines the Φ-OTDR sensing distance (L_m). It can be expressed as:

$$L_m = \frac{T_m c}{2n} \tag{3}$$

where c represents the speed of light and n represents the refractive index of the optical fiber. In general, the longer the detection distance is, the larger the monitoring range is,

Table 3 Comparison of feature extraction and pattern recognition methods used in different literatures

Feature extraction method	Extraction feature types	Classifier	Events recognition	Year	References
Filtration	Morphological features		Excavator construction	2019	[43]
Short-time unit multi-domain feature extraction	Time domain features + frequency domain features	HMM	Five kinds of events along the underground pipeline	2019	[41]
Differential method + WPD	Time domain features + frequency domain features	NC-SVM	Watering, climbing, tapping, squeezing, false disturbance	2019	[44]
MFCC	Time domain features + frequency domain features	CNN	Internal PD, Corona PD, Surface PD, Ambient noise	2019	[46]
WPT	Time domain features + frequency domain features	BPXN	Shaking the cage, climbing the fence, knocking the fence, passing the heavy truck, passing the train, blowing the wind, etc	2019	[47]
Hilbert transformation + EMD	Time domain features + frequency domain features	PNN	Strong wind, rain, sunny day, pounding, climbing	2020	[48]
EMD	Time domain features	XGBoost	Watering, climbing, hammering, squeezing and false disturbance	2020	[38]
Normalized differentiation + WPD	Time domain features + frequency domain features	ELM	Watering, knocking, climbing, squeezing and fake disturbance	2020	[39]
Multi-characteristic parameter	Morphological features	SVM	Engineering vehicle driving, rockfall, artificial ramming, Excavating by Excavator	2020	[42]
VMD	Time domain features	SVM	Treadling. Tapping. Sound. Digging	2021	[45]
MFCC	Time domain features + frequency domain features	CNN	Rainy day, sunny day, cycling, jumping, shoveling, digging, walking, watering	2022	[40]

the lower the costs are, and the more timely the ability of controlling the situation is.

In Φ-OTDR system, the intensity of the RBS signals is already very weak, and the strength of the RBS signals also decreases exponentially as the transmission distance increases. What's more, there exists many interference factors, like Fresnel interference, at the end of the fiber, causing the RBS signals to be submerged in the noise and difficult for detection. This will result in the SNR at the end of the fiber very low. The research on sensing distance can not only meet the practical needs of long-distance sensing, but also improve the SNR at the end position of the fiber. Therefore, how to increase the sensing distance in the long-distance Φ-OTDR system on the basis of ensuring the strength of RBS signals has always been a hot topic. The traditional solution was to add EDFA to the Φ-OTDR system to increase the intensity of the RBS signals. But this led to the limitation of the input optical power. Under this circumstance, the extreme distance of the Φ-OTDR system was 25.0 km [49]. Later, the concept of distributed amplification was proposed, and Raman amplification was used to amplify light in both forward and backward directions, which successfully increased the sensing distance. The research and optimization of denoising and fading issues in Φ-OTDR system further promoted the development of long-distance Φ-OTDR system.

In recent years, there are a lot of research results on the improvement of sensing distance in Φ-OTDR system. Some scholars tried to improve the sensing distance without increasing the burden of system hardware, but the distance improvement effect of such methods was limited. For the instance, a global phase demodulation technology was proposed in 2021. It could compensate for the localization defect of the differential cumulative average algorithm, and overcome the limitation of weak RBS signals in the long-distance Φ-OTDR system. Finally it successfully identified the location of the vibration signal on the 90.0 km optical fiber [50]. In 2022, a semantic image segmentation method was proposed, which successfully added the vibration detection distance to 80.8 km without increasing the complexity of the system. It also realized the multi-point vibration measurement with high SNR at 4.00 km, 10.00 km and 20.0 km of optical fiber [51]. Of course, most of the research was based on the improvement of EDFA and distributed amplification system, and the effect was remarkable. In 2021, a Φ-OTDR system using dual coherent light source and bidirectional high-order Raman amplification technology was proposed. It finally achieved a sensing distance of 205.5 km and a spatial resolution of 15.0 m [52]. In 2022, an ultra-long range Φ-OTDR distributed vibration measurement system based on ROPA technology was proposed. It used distributed Raman amplifier and remote gain unit to improve signal

Table 4 Comparison of feature extraction and pattern recognition methods used in different literatures

Methods to increase sensing distance	Distance (km)	Year	References
Global phase demodulation	90.0	2021	[50]
Bidirectional high-order Raman amplification	205 5	2021	[52]
Semantic image segmentation	80.8	2022	[51]
Φ-OTDR + ROPA	175.0	2022	[53]
BOTDR + Φ-OTDR + ROPA	208.0 km	2023	[54]

flatness, and the SNR at the end of 175.0 km optical fiber was 9.8 dB [53]. In 2023, a new system was designed, which included the remote pumped optical amplifier (ROPA) technology, Φ-OTDR system and BOTDR system. By applying thigh order Raman amplifiers, cascaded remote gain units (RGU) and ultralow loss optical fiber, the vibration and temperature information at the distance of 208.0 km was detected [54].

Table 4 summarizes the above-mentioned papers.

Research on spatial positioning

The traditional Φ-OTDR system is mainly used to locate and monitor the vibration along the optical fiber. In recent years, the positioning ability has gradually developed into 2D and 3D space positioning for the needs of practical applications. Seismic wave detection is expected to locate the depth of the earthquake source in the ground and the

transverse distance to the optical fiber. For instance, in 2019 the distributed sound sensing system (DAS) based on the Φ-OTDR system was applied to seabed seismic monitoring. The experiment verified the detection capability of 0.1–0.25 Hz ocean surface gravity waves and secondary microseismic noise. It realized the weak earthquake monitoring of magnitude 1.9 at 100 km away [55].Water depth detection also hopes to have a specific location in the specific events to conduct a 3D position positioning, such as fish swimming, and ships sailing. For instance, in 2021 a distributed fiber optic hydrophone (DOFH) based on Φ-OTDR system was demonstrated and tested. Combined with the new-designed sensitized optical cable, the distributed optical fiber hydrophone (DOFH) can realize the orientation, beamforming and motion tracking of underwater acoustic signals, and has a broad application prospect in Marine acoustic detection [56]. The spatial positioning experiment of Φ-OTDR has wide application prospect and high demand. Here two achievements of spatial positioning are highlighted: vertical offset distance estimation positioning and radial positioning.

In 2020, a method for estimating vertical offset distance and judging threat level was proposed [57]. As shown in Fig. 6, when the vibration source was at different vertical offset distances, the energy attenuation mode of the vibration signal would also change. Therefore, the signal power could be calculated after the fast Fourier transform and narrowband filtering to obtain the energy attenuation characteristics. Then, the spatial energy laws under different vertical distances could be identified by combining the integrated learning model, in which four SVM and one RF were used. Two kinds of mechanical tapping and mechanical digging events were studied in the experiment, and three threat levels were divided according to the vertical distance, which were I (0–4 m), II (5–10 m) and III (11–15 m). For the mechanical knock events, the classification accuracy within ± 1 and ± 2 m positioning errors was 92.3 and 100.0%, respectively, and the average accuracy of threat level prediction is 99.1%. For the mechanical mining events, the accuracy of prediction within ± 1 and ± 2 m positioning errors was 83.5 and 86.7% respectively, and the accuracy of threat level prediction was 82.0%.

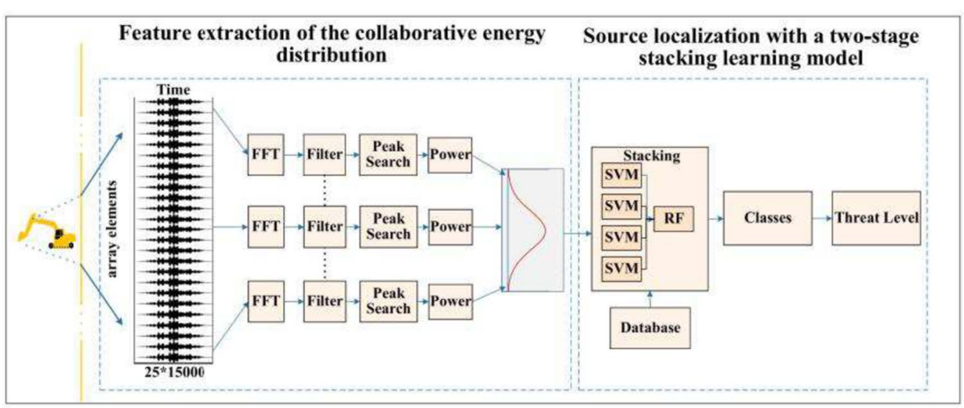

Fig. 6 Vertical distance estimation method based on spatial energy distribution and ensemble learning model [57]

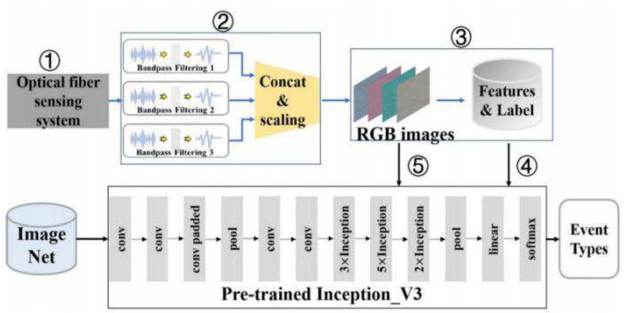

Fig. 7 Schematic diagram of multi-radial distance event recognition method [58]

In 2021, a multi-radial distance event recognition method applicable to Φ-OTDR system based on CNN system was proposed [58]. As shown in Fig. 7, the RBS signals returned by the optical fiber was first formed into a spatio-temporal data matrix. Then it was filtered to obtain an RGB image. The Inception-V3 network was trained using the ImageNet dataset with RGB images as input to the network. Three bandpass filters were used for filtering, and the simulated annealing (SA) algorithm was used to search the maximum Euclidean distance to select the passband of the three filters in the frequency domain. This helped to highlight the differences between subclasses at different radial distances, and finally facilitate network identification. In addition, the experiment also defined the internal general class error (IGE) and the crossed general class error (CGE) to show the classification capability of the event type and radial distance. IGE referred to the error probability of radial distance identification, and CGE referred to the error probability of event type identification. In the experiment, five kinds of events including background sound, jumping, digging, walking and brick throwing were studied, and the IGE value and CGE value were finally obtained as 4.9 and 8.8%. The classification accuracy was improved from 33.6 to 86.8%, realizing the simultaneous judgment of event type and radial distance.

Summary and prospect

The DOFS technology can measure the physical parameters around the optical fiber in a fully distributed way, which is the advantage that traditional electrical sensors and point optical fiber sensors cannot reach. In particular, Φ-OTDR system has great advantages, such as long sensing distance and high SNR. At present, there are three breakthrough points in the Φ-OTDR system. The first is to further improve its ability to measure vibration signals in a strong noise background, involving the common problems that many traditional Φ-OTDR systems face, such as system noise removal, compensation of laser frequency drift, suppression of fading. With the continuous improvement of system performance, the amplitude of weak signals detected by Φ-OTDR can reach tens of millivoltampere (mV) at least, and the corresponding strain can reach the $n\varepsilon$ level. The second is to further increase its ability of recognition and forewarning at early times, and reduce missing alarms and false alarms. In this aspect, efforts are mainly made in feature extraction and classifier. The method of feature extraction is mainly multi-time–frequency domain hybriding extraction. Classifiers are also developing in the direction of multiple classifiers combination. At present, most of the average recognition rate in Φ-OTDR system can be maintained above 90%, and the average NAR can be no higher than 10%. The third is to further broaden its measurement range, including the sensing distance and the spatial positioning. Due to the application in the frontier field, this part is the current frontier field of Φ-OTDR system exploration, and has great potential. At present, the furthest detection distance of Φ-OTDR system has exceeded 200.0 km. The signal-to-noise ratio at the end of the fiber can be maintained above 5.0 dB. The research of Φ-OTDR system from a single plane to 3D space positioning also has good progress. In general, combined with the key performances of Φ-OTDR system, this paper summarizes and discusses the frontier scientific achievements in the field of Φ-OTDR in recent years according to the three breakthrough points. In future, the Φ-OTDR system will further develop on the basis of performance improvement, and the value played in more complex use scenarios and monitoring tasks will be further improved, especially the combination of machine learning and pattern recognition will make it become a hot spot in the field of security monitoring, acoustic sensing and other fields to promote its further development.

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