A Comprehensive Study of Optical Fiber Acoustic Sensing

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ABSTRACT The optical fiber acoustic sensing system is suitable for long-distance monitoring of the acoustic signals generated by the external disturbances. According to the continuity of sensing units, quasi-distributed and distributed optical fiber acoustic sensing technologies are differentiated to meet different application requirements. On the one hand, the recent progress of Fabry-Perot interferometer (FPI) focusing on the diaphragm material, and the research hotspots in the field of the continuous Fiber Bragg grating (FBG) array are firstly reviewed. On the other hand, Mach-Zehnder interferometry (MZI), Michelson interferometry (MI), and Sagnac interferometry (SI) have rapidly developed in the aspect of the demodulation algorithm optimization with the purpose of the sensing performance improvement. Moreover, the current primary research works of the phase-sensitive optical time-domain reflectometer (φ-OTDR) are the signal-to-noise ratio improvement and the mixed optical structure design. Finally, this paper presents an overview of the recent advances of optical fiber acoustic sensing system in the application domains of military defense, structural health monitoring, petroleum exploration, and development.

INDEX TERMS Acoustic detection, distributed acoustic sensing, optical fiber sensing, φ-OTDR, structural health monitoring.

I. INTRODUCTION

The essence of acoustic wave is a kind of mechanical wave, which is an extremely important information carrier. Its frequency range can reach from infrasound (<20 Hz) to ultrasound (>20 kHz). As a weak vibration signal, acoustic wave plays an extremely important role in human daily life and communication [1]. In practical applications, by detecting acoustic waves in different frequency bands, it can be applied in the fields of ultrasonic medicine, underwater acoustic monitoring, building structure monitoring, and aerospace. In the past few decades, electroacoustic sensors have dominated the field of acoustic detection. However, due to the limited application of electroacoustic sensors in special environments such as strong electromagnetic interference, flammability and

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explosion, electroacoustic sensors are not suitable for long-distance transmission, and it is difficult to perform remote sensing and telemetry. Therefore, the traditional acoustic sensor is difficult to be applied in harsh environments, and the maintenance cost is so high that it cannot meet the actual needs of modern engineering measurement. With the development of the acoustic sensing field, in order to improve cost-effectiveness and anti-electromagnetic interference capability, optical fiber acoustic sensing technology has been extensively studied.

The optical fiber acoustic sensor is similar to other electroacoustic sensors in the aspect of the principle and the structure, but due to the particularity of the measured physical parameters, it has its own characteristics, mainly used in environments where traditional electroacoustic sensors cannot be used. Compared with the traditional electroacoustic sensors, the optical fiber acoustic sensor has a series of

outstanding advantages such as anti-electromagnetic interference, low long-distance transmission loss, convenient installation, good concealment and corrosion resistance [2]. At the same time, due to its high sensitivity, compact structure, simple manufacturing, intrinsic safety and low cost, the utilization of optical fiber acoustic sensors in building structural health monitoring, seismic monitoring, transformer partial discharge diagnosis, underwater acoustic monitoring, aerospace safety, airborne acoustic detection, photoacoustic spectroscopy, photoacoustic imaging and other fields have broad application prospects [3].

According to the structure of the fiber sensor, it can be divided into quasi-distributed fiber sensing technology and distributed fiber sensing technology. Quasi-distributed fiber optic sensors mainly include fiber Bragg grating (FBG), fiber Fabry-Perot (F-P), fiber optic gyroscope (FOG) sensors and fiber surface plasmon sensors. Among them, fiber Bragg grating (FBG) as a new type of optical passive device has attracted the attention of researchers and industrials in recent years. Due to its inherent advantages, such as small size, light weight, and less susceptible to electromagnetic interference, it can be embedded in a variety of composite structures. In addition, from the perspective of hardware production, because of the mature production technology and low production cost of FBG sensors [4], acoustic measurement based on FBG sensing has attracted more and more researchers around the world.

Compared with quasi-distribution technology, distributed optical fiber sensing technology has the advantage of small non-detection zone. In the distributed optical fiber sensing system, each point on the sensing fiber can be used as a sensing unit to achieve continuous detection along the length of the fiber, and there is no blind area. In theory, fully distributed fiber optic sensing technology can achieve infinitely long sensing fiber, infinitely low resolution and unlimited information capacity. In addition, the advantages of the fiber itself have made it a research hotspot. The distributed fiber optic acoustic sensing system continuously monitors the external acoustic or vibration detected by the sensing fiber in real-time using an optical fiber with good sensitivity to the surrounding environment. Distributed acoustic sensing (DAS) systems mainly include interference sensing technology, optical backscattering technology, optical coupling detection technology and optical nonlinear parameter detection technology [5]. Distributed optical fiber acoustic sensing has the characteristics of high sensitivity, large dynamic range and simple structure. It is widely used in oil and gas pipeline monitoring [6], peripheral safety [7], structural health monitoring [8] and other fields, and has broad application prospects and commercial value. In the third chapter, the optical fiber acoustic sensing systems based on interference sensing technology and backscattering technology are introduced. Optical interferometry is to measure the influence of external acoustic disturbance on optical fibers by transforming the phase change of the beam into the intensity change. Then the intensity of light

is detected by photodetector, then demodulated and analyzed by computer software. The interferometry technology has the characteristics of high sensitivity, strong anti-interference ability, high detection accuracy and high spatial resolution. This paper will introduce the related interference techniques, such as Mach-Zehnder Interference (MZI), Michelson Interference (MI) and Sagnac Interference (SI). Backscattering technology refers to the scattering process of laser photons colliding with particles in the optical fiber medium after the light pulse enters into the optical fiber. Scattering in optical fibers includes spontaneous Raman scattering of the same wavelength of the incident light, spontaneous Brillouin scattering and Rayleigh scattering. Rayleigh scattering and spontaneous Brillouin scattering are very sensitive to acoustic vibration. The phase-sensitive optical time domain reflection (Φ-OTDR) technique [9] is used to determine the vibration frequency of the fiber by measuring the parameters of the backscattered light, thereby achieving the purpose of sound detection. Backscattering technology is easy to implement and is relatively mature. However, since the light intensity of the scattered light is relatively weak, the resolution of the system is limited by the shape and width of the emitted light pulse [10]. Therefore, the detection sensitivity of the whole system is low, and the spatial resolution is not high, which cannot fully reflect the advantages of fully distributed sensing technology.

This paper reviews the development of optical fiber acoustic sensors. The advantages, limitations and applications of this technology are introduced. The second chapter introduces the quasi-distributed fiber optic acoustic sensing technology, including fiber Bragg grating (FBG), fiber Fabry-Perot (F-P) sensors. The third chapter introduces in detail the working principle and the latest research results of fiber optic acoustic sensing system based on interference sensing technology and backscattering technology. Finally, the application and advantages of optical fiber sensing system in structural health monitoring, partial discharge diagnosis of transformers, underwater acoustic monitoring, aerospace safety, and airborne acoustic detection are summarized.

II. QUASI-DISTRIBUTED OPTICAL FIBER ACOUSTIC SENSING TECHNOLOGY

Optical fibers, which are columnar, are composed of a core layer, a cladding layer and a coating layer, as shown in Figure 1. The optical fiber sensing system is mainly composed of light source, sensing optical fiber, sensing unit and signal processing system. At present, optical fiber sensors with different modulation types have been gradually developed, including phase type, intensity type, wavelength type and polarization type. By modulating the input optical signal, the measured optical signal carrying the external information can be outputted, which is suitable for the measurement of various physical quantities such as vibration, temperature, strain and so on.
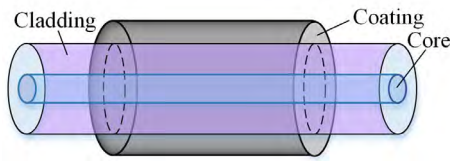
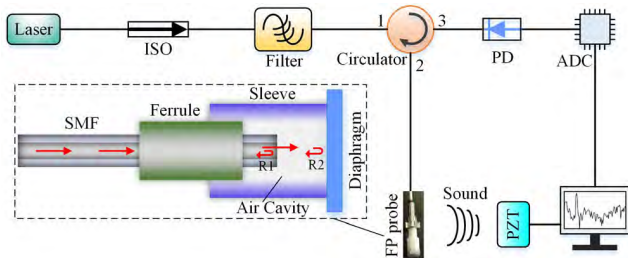**FIGURE 1.** Schematic diagram of optical fiber structure.

FIGURE 2. Optical fiber sensing system based on FPI.

A. OPTICAL FIBER ACOUSTIC SENSORS BASED ON FPI

Fabry-Perot interferometer (FPI), also known as etalon, mainly uses Fabry-Perot cavity as optical fiber sensing probe, which enables detection of external variables such as acoustic wave, strain, liquid level, pressure and so on [11]. The Fabry-Perot cavity is composed of two parallel reflectors divided by a certain distance [12], as illuminated in Figure 2. In addition, the air cavity backing the diaphragm plays a critical role in determining the sensor performance, particularly for miniature sensors with small air cavity. In practical applications, without compromising the optical sensitivity, the mechanical sensitivity can be increased by enlarging the air cavity, and then the sensitivity of FP sensor can be improved.

FPI has been widely studied because of its high sensitivity, simple fabrication, small size and low cost. Acoustic and ultrasonic sensors based on FPI configuration have gradually attracted the attention of scholars. Wang et al. has combined micro-electromechanical system (MEMS) with optical fiber sensing technology to produce a small, highly sensitive underwater acoustic probe based on extrinsic Fabry-Perot interferometric (EFPI) [13]. The experimental results show that the signal detected by the sensor in standing wave tube is identical with the acoustic emission signal, and its response sensitivity is about -154.6 dB (re rad/μ Pa) Liu et al. introduced an optical fiber acoustic sensor based on pure silicon micro-cantilever beam [14]. The designed cantilever beam is fabricated by fs laser microfabrication at the end of the optical fiber, which acts as a built-in Fabry-Perot interferometer (FPI). Among them, the thickness and dimension of the micro-cantilever beam can be artificially defined to diversify the response frequency and measurement range, so as to adapt to different applications.

In recent years, extrinsic Fabry-Perot interferometer (EFPI) based on diaphragm, as shown in Figure 2, has become a research hotspot, aiming at increasing the range of acoustic response. More importantly, the EFPI can be used for acoustic detection in air and underwater because of its enclosed air chamber.

Interference occurs due to the multiple superpositions of both reflected and transmitted beams on two parallel surfaces. After light comes through the F-P cavity, photo detector (PD) receives the interference signal and converts it. If the acoustic pressure is applied to the diaphragm, the phase change $\Delta\Phi$ of the optical wave can be simply given as:

$$\Delta\Phi = \frac{4\pi n \Delta L}{\lambda_0} \qquad (1)$$

In Formula (1), n represents the refractive index of the medium filling the cavity. λ_0 refers to the optical wavelength in vacuum. ΔL denotes the deflection of the diaphragm and can be expressed as:

$$\Delta L = \frac{P\partial^4 \left(1 - \upsilon^2\right)}{4.2Eh^3} \qquad (2)$$

where P means the ambient pressure related to the cavity pressure, ∂ represents the half-edge length, υ is the Poisson ratio of the diaphragm material, E refers to the Young modulus and h is the diaphragm thickness.

In an FPI sensor, its sensitivity S at room temperature can be expressed as:

$$S = \frac{3\partial^4 \left(1 - \upsilon^2\right)}{16Eh^3} \qquad (3)$$

According to Formula (3), it can be found that the sensitivity is in direct ratio to the fourth power of half-edge length and inversely proportional to the cube of diaphragm thickness. Therefore, in the FPI-based acoustic sensing system, the detection sensitivity can be improved from two aspects: the diaphragm thickness and the half-edge length. Thus, diaphragm material is crucial to for F-P sensors. Usually, the diaphragm materials of Fabry-Perot cavity mainly include micro-fabricated silicon film, metal film or diaphragm composed of single-mode/multi-mode fiber.

Many researchers use different diaphragm materials for acoustic detection, which has potential application prospects in structural health monitoring and medical ultrasound. Guo et al. introduced an EFPI optical sensor based on ultra-thin silver film for ultrasonic detection in 2012 [15]. Wang et al. demonstrated an infrasound sensor based on polymer diaphragm in 2016 [16]. External infrasound disturbance will cause vibration of the diaphragm, change the length of F-P cavity, and finally lead to the shift of interference spectrum. Through theoretical simulation and experimental verification, the sensor can effectively detect low-frequency infrasound signals of 1-20 Hz. At the same time, an optical fiber infrasound sensor based on ultraviolet adhesive diaphragm is introduced in Wuhan National Laboratory, which shows good acoustic response between 1 Hz and 20 kHz [17]. Subsequently, an acoustic sensor was proposed [18], in which a tapered optical fiber was attached to a nitrile-butadiene diaphragm. Under the action of acoustic pressure, tapered optical fibers bend with the deformation of diaphragm, and finally show a calculable change in transmission power. An ultra-wideband optical fiber acoustic sensor

based on graphene film is proposed [19]. The sensor head assembly is based on EFPI structure of graphene film. The experimental results show that the proposed acoustic sensor can achieve ultra-wideband frequency response from 5 Hz to 0.8 MHz.

However, because it involves micro-fabrication or chemical corrosion, the fabrication process of diaphragms is complex and expensive. In addition, the most critical point is that the air intercepted from outside will enter the Fabry-Perot cavity in an unpredictable way, which will greatly affect the measurement performance of the acoustic sensors based on FPI.

B. OPTICAL FIBER ACOUSTIC SENSORS BASED ON FBG

Fiber Bragg grating (FBG) is an optical passive device, which is a sensor made by periodically modulating the axial refractive index of the fiber core. It has the advantages of good stability, high sensitivity and easy connection with other optical fiber devices, so it obtains extensive application. Hill et al. first involved fiber Bragg grating (FBG) in 1978 [20]. As Meltz et al. [21] developed the method of transverse holographic fabrication, FBG gradually formed. And then ultrasound measurement based on FBG has also developed rapidly [22]. They studied a hydrophone based on FBG, which can detect 950 kHz acoustic signal.

At present, fiber Bragg grating (FBG) has become a research hotspot of underwater acoustic signal detection. When the acoustic signal acts on the optical fiber, the effective refractive index and other parameters of the optical fiber will change, which will cause the reflection wavelength of the FBG to move and realize the sensing of the acoustic signal.

When the incident light enters the fiber Bragg grating (FBG), the relationship between the central wavelength of the reflection λ_B and the effective refractive index n_{eff} and the grating period Λ is as follows [23]:

$$\lambda_B = 2n_{eff}\Lambda \tag{4}$$

When the FBG is acted by acoustic signal, the effective refractive index and grating period will change, which will lead to the shift of the central wavelength of reflected light. The offset changes caused by acoustic signals can be calculated as [24]:

$$\Delta\lambda_B = 2n_{eff}\Delta\Lambda + 2\Lambda\Delta n_{eff} \tag{5}$$

The intensity of the output light, which is theoretically proportional to the acoustic signal, can be obtained by demodulating the Bragg wavelength offset.

FBG has the advantages of short standard distance, versatility and easy of multiplexing. In particular, FBG has the ability to be sensitive to many tested objects while multiplexing [25]. FBG acoustic sensors can also be used in acoustic hydrophones, non-destructive assessment, biomedical sensing and structural health monitoring [26]. Over the past decade, a variety of laser and FBG combination technologies have been studied by academia and industry. Tan et al. designed and validated a sensing system based on

bipolar fiber Bragg grating laser which can simultaneously measure static pressure, temperature and acoustic signals [27]. In 2016, FAZ Technologies Ltd. developed a quasi-distributed optical sensing system [28] for measuring temperature, pressure, acoustic and acceleration by combining fiber Bragg grating (FBG) sensing technology with tunable laser technology. The system has the advantages of high speed and high precision. Siska et al. introduced an acoustic vibration sensing system which combines distributed feedback laser diode and FBG technology [29]. It can be used to detect temperature, strain, vibration or pressure.

Meanwhile, multiplexing technology and FBG array have also been studied in FBG sensing. In 2007, a fiber optic underwater acoustic sensor was described [30], as depicted in Figure 3. The main innovation is that the sensor probe is composed of two fiber Bragg gratings (FBG). The sensing system can realize self-demodulation through a pair of matched FBGs, which effectively improves the detection sensitivity. In the experimental test, the sensitivity of underwater acoustic pressure measurement can reach 0.78 nm/MPa in the range of 100-200 dB (re rad/μPa).
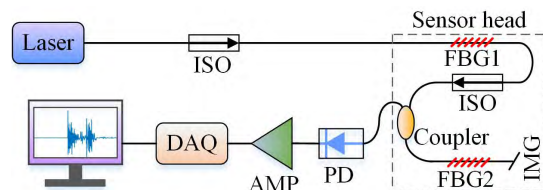

FIGURE 3. Fiber optic underwater acoustic sensor.

In 2015, Wang et al. studied a distributed acoustic sensor with a weak FBG (WFBG) array with an optical erasure interval of 2 m in an Φ-OTDR system with a balanced Michelson interferometer [31]. Subsequently, in order to achieve greater temperature tolerance, they used broadband weak fiber Bragg grating (BWFBG) array instead of ordinary WFBG array to better achieve seismic monitoring [32]. Furthermore, a distributed acoustic sensing system based on weak-FBG array proposed by Sheng Liu [33] was described in Figure 4. The main structure of the system is a balanced Michelson interferometer configuration consisting of a weak FBG array, a 3×3 coupler and two faraday rotator mirrors (FRM). Among them, the weak FBG array is composed of 661 FBGs with a distance of 2.5 m between adjacent FBGs. The spatial resolution of the system is 2.5 m. Acoustic vibration of up to 1000 Hz can be measured accurately in 1.6 km of optical fiber length.
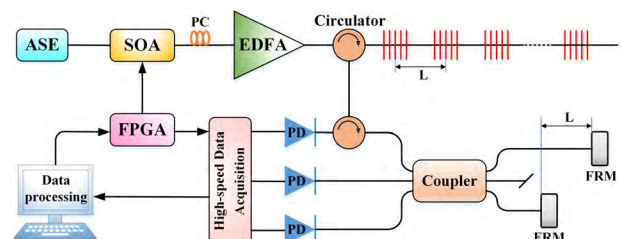

FIGURE 4. A DAS system based on weak-FBG array.

III. DISTRIBUTED OPTICAL FIBER ACOUSTIC SENSING TECHNOLOGY

Distributed optical fiber sensor uses original optical fiber as sensing element, which can measure thousands of points at the same time. It is mainly used for static temperature or strain measurement [34]. Sometimes it can also be used for dynamic monitoring including time-varying signals of pipeline leakage, engine vibration and bridge cracks. In recent decades, it has been widely studied and applied in industrial applications. More and more research institutes use distributed optical fiber sensing systems with composite optical paths to detect and locate sound signals [35], [36].

A. INTERFEROMETRIC OPTICAL FIBER ACOUSTIC SENSORS

Under the action of external sound waves, the refractive index and core diameter of the phase-modulated fiber-optic sensor will change, thereby changing the propagation path of the optical signal in the fiber, and finally the variation of phase occurs. However, because of the high frequency of light, the phase change of light wave cannot be directly detected via the existing detection technology. But in terms of the change in the intensity of light, it can be easily detected. Therefore, the phase change is usually transformed into light intensity change in experiment, and then the acoustic signal is obtained by demodulation technology [37].

It is assumed that the amplitudes of the two beams are E_1 and E_2, respectively. If the phase of one light is modulated by external acoustic disturbances, the other light is isolated from external disturbances so that it is not affected. Then the intensity of interference light can be expressed as:

$$E^2 = E_1 + E_2 + 2E_1E_2 cos(\Delta\phi + \phi_0) \qquad (6)$$

where ϕ_0 is the initial phase difference between two coherent beams. $\Delta\phi$ is the phase difference caused by phase modulation, which directly corresponds to the intensity of interference light. By detecting the intensity of interference signal, the phase change between two beams of light can be determined, and the measured physical parameters can be demodulated. Interferometric sensing technology has attracted extensive attention and research due to its broad application prospects in strain, vibration, magnetic field and acoustic measurement. At present, phase-modulated optical fiber acoustic sensors are mainly based on three interference principles: Mach-Zehnder Interference (MZI), Michelson Interference (MI) and Sagnac Interference (SI) [38].

1) MACH-ZEHNDER INTERFEROMETER

Bucaro et al. firstly proposed the structure of Mach-Zehnder interferometer (MZI) in the field of optical fiber acoustic sensing, as described in Figure 5 [39].

The basic principle of the general Mach-Zehnder fiber-optic interferometer is shown in Figure 5. The coherent light emitted by the laser source is divided into two separate beams by a 1×2 optical coupler. After passing through the coupler, the beams are transmitted in two paths which are named as
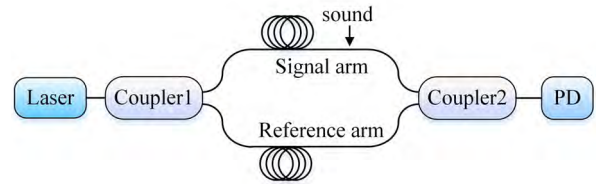

FIGURE 5. Mach-zehnder interference structure.

the signal arm and the reference arm respectively. When the external acoustic pressure exerts on the signal arm, the fiber size of the sensing arm is stretched or contracted, and the refractive index of the sensing arm is changed, causing the phase modulation of optical signal. However, the reference arm is isolated by some substance so that it is not affected by external acoustic pressure. The modulated light and the reference light are coupled by the 2×1 coupler and then they interfere with each other. The interference signal is received by the photodetector, and then the acoustic signal is obtained though the subsequent process of signal demodulation. According to the principle of interference, it suggests that when two beams with the same frequency and the same vibration direction interfere with each other, the interference intensity of the light can be expressed as:

$$I = I_1 + I_2 + 2\sqrt{I_1I_2}cos(\Delta\varphi) \qquad (7)$$

where I_1 and I_2 are the initial intensities of the two beams, and $\Delta\varphi$ is the initial phase difference between the two beams.

At this time, the phase difference $\Delta\varphi$ of the two beams which interfere with each other can be seen as the addition of the following three factors: the initial phase difference φ_0 owing to the asymmetry of the two optical paths themselves, the phase difference φ_s due to the external pressure, and the phase difference φ_ε resulting from the change of fiber length caused by strain, which can be expressed as:

$$\Delta\varphi = \varphi_0 + \varphi_s + \varphi_\varepsilon \qquad (8)$$

The initial phase difference φ_0 is a constant value, so the change in light intensity detected by photodetector is only related to the changes in the phase differences φ_s and φ_ε mentioned above. Thus, it is possible to calculate the corresponding change in the phase difference $\Delta\varphi$ of the two beams after obtaining the intensity change. The acoustic vibration acting on the signal arm can be acquired through the analysis of the phase difference.

This single Mach-Zehnder interferometer can easily detect acoustic signals. Subsequently, in order to locate the acoustic source further, a distributed optical fiber sensing system with dual Mach-Zehnder structure is gradually investigated [40], as illustrated in Figure 6.

After amplification and modulation, the light emitted by the laser is divided into clockwise and counterclockwise beams by a 1×2 coupler. The two light signals pass through coupler 2 and coupler 3, interfere at the end of the paths, and then are received by photodetectors respectively. In Figure 6, if the length of the reference arm is set to l and
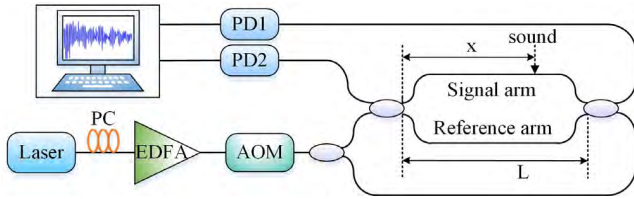
FIGURE 6. A DAS system with dual mach-zehnder structure.

the distance between the coupler 2 and the acoustic source is set to x, the time delay of the two light paths can be expressed as [41], [42]:

$$d = \frac{2l - x}{c/n} - \frac{x}{c/n} = \frac{2n}{c} (l - x) \qquad (9)$$

where c represents the speed of light in vacuum and n represents the refractive index of the fiber core. By estimating the time delay, the location of acoustic source can be realized.

Distributed acoustic sensors based on Mach-Zehnder interferometer have the characteristics of low cost, simple structure and long sensing range. It can be used for distributed acoustic sensing and positioning of large-scale structural health monitoring. At present, the research based on optimized demodulation algorithm has been widely concerned by academia. Sun et al. introduced the algorithm of time delay estimation in the experiment of Mach Zehnder interferometric sensing [43], and realized signal homodyne demodulation by using 3×3 optical fiber coupler. The resolution of the system is less than 100 m on a 6.8 km long optical fiber. Zhan Chun et al. validated the working principle of distributed optical fiber sensing system based on Mach-Zehnder interferometer on the testing optical fiber of 8 km [44]. Vibration detection at frequencies of 100 Hz-20 kHz was realized. The spatial resolution of 100 m was obtained by combining optical delay effect with cross-correlation algorithm. Then, they proposed a phase demodulation algorithm of 3×3 coupler for vibration and acoustic detection [45]. Experiments show that the sensitivity and resolution of the system are improved. The optical fiber perturbation positioning sensor developed by Zhang Chunxi's research group [40] has been tested on 18.46 km long-distance optical fiber cable, which can display the perturbation position in real time. However, the average positioning error is about 390 m. They deduced a multi-disturbances localization algorithm based on correlation theory and frequency-domain analysis [46]. The theory proves the feasibility of the algorithm in distributed sensing system based on Mach-Zehnder interferometer, and it is suitable for structural health monitoring, intrusion detection and oil and gas leakage detection. Subsequently, they designed an intrinsically distributed acoustic emission sensor based on the system [47]. By measuring the time delay of two optical signals, the position of acoustic emission can be deduced. It is found that the average positioning error is about 206 m in the range of 20 km. In 2014, Chen et al. validated a distributed optical fiber vibration sensing configuration based on Mach-Zehnder interferometer [48]. The vibration source

was located by the dispersion effect between the sensing signal and the reference signal, and the delay error was estimated by a cross-correlator. The pencil break signal with a frequency of 9 MHz can be detected on the sensing fiber of 320 km, and the spatial resolution of 31 m can be achieved. In 2016, Zboril et al. used Mach-Zehnder optical fiber sensing system to detect acoustic vibrations caused by touching on the window panes [49]. Finally, the results have shown that the system can measure the very weak acoustic vibration generated on the surface of plastic windows, and has high sensitivity, which can be applied to the field of safety protection. Yang et al. used the quadratic cross-correlation algorithm to estimate the time delay based on the dual Mach-Zehnder interferometric distributed optical fiber sensing system [50], which effectively reduced the noise error and improved the location accuracy of the disturbance signal.

In recent years, acoustic sensing technology has been gradually applied in partial discharge detection. Because partial discharge cannot be measured directly, it is usually monitored by optical fiber ultrasonic detection because of its strong anti-electromagnetic interference ability and insulation performance [51]–[53]. Posada Roman et al. [54] used a multi-channel Mach-Sender interferometer system to detect the acoustic emission signal caused by partial discharge in the transformer model, and tested it at 150 kHz, and obtained a higher resolution than 10 Pa.

2) MICHELSON INTERFEROMETER
The sensing optical path diagram based on Michelson optical fiber interferometer is shown in Figure 7.
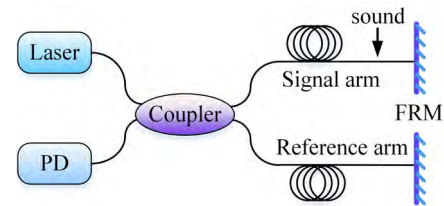

FIGURE 7. The structural chart of michelson interferometer.

Among them, the reflective end of the reference and sensing fibers is an important component of the optical fiber interferometer. After passing through the coupler, the light signal emitted by the light source is divided into two channels, one through the reference fiber arm, the other through the signal arm, which is disturbed by external sound. When reaching the mirror, the two beams of light are reflected back to the coupler and interfere with each other. The interference light carries sound information. After being detected by photoelectric detectors, it assumes the change of light intensity, and eventually converts it into electrical signal. Then it can demodulate the sound signal through signal processing. The intensity of light received by the photodetector can be expressed as:

$$P = P_0 (1 + cos(\Delta\phi)) \qquad (10)$$

where $\Delta\phi$ is the phase difference caused by the acoustic pressure between the reference light and the signal light. Compared with Mach-Zehnder interferometer, the structure of Michelson interferometer uses less fiber couplers and reduces the optical loss. But its main disadvantage is that the interference signal reflected to the photodetector will also be reflected to the laser source, which will have a negative impact on the normal operation of the laser and form the noise. Therefore, in order to eliminate this kind of noise, it is necessary to increase the application of optical isolator.

Michelson optical fiber sensing system has clear principle, simple structure and high theoretical value. Many researchers try different demodulation algorithms to further optimize the performance of the system. Chojnack proposed a distributed sensing system based on unbalanced Michelson interferometer in 2002 [55], and used digital processing technology and 3×3 coupler for signal processing and phase demodulation respectively. Dual-Michelson interferometer systems are used to locate the acoustic disturbance in 4012 m sensing optical fiber in Beijing University of Posts and Telecommunications [56]. The location accuracy is 51 m, which can be used for perimeter safety detection. Wang et al. obtained a sensitivity of about -150 dB (re rad/μPa) by 3×3 coupler demodulation in a sensing system combined with a Φ-OTDR and a Michelson interferometer [57]. Experiments show that the system can simultaneously locate and restore external acoustic disturbances. Liu et al. used the system to detect external acoustic disturbances [58]. The sensitivity of -148 dB (re rad/μPa) is successfully obtained by using the phase carrier demodulation algorithm on the system.

3) SAGNAC INTERFEROMETER
Angeline et al. [59] have further developed Sagnac technology in the field of distributed optical fiber sensing based on fiber optic gyroscope (FOG) technology. Figure 8 describes the principle of distributed acoustic sensing based on Sagnac interference. The incident light is divided into two clockwise (CW) and counterclockwise (CCW) pulses propagating along the optical fiber loop by a 50:50 coupler. After a week of cycle, they interfere at the coupler. When the external sound acts on the optical fiber, the refractive index of the core changes, and finally the phase changes. After demodulation by the photodetector (PD), it transforms into the change of light intensity.

When a beam of light passes through an optical fiber of length l, the phase delay $\Delta\Phi$ produced by the acoustic signal

is as follows:

$$\Delta\Phi = \beta(\Delta l) + l(\Delta\beta)$$
$$= \beta(\Delta l) + l\frac{\partial\beta}{\partial n}(\Delta n) + l\frac{\partial\beta}{\partial d}(\Delta d) \quad (11)$$

In Formula (11), d denotes the diameter of the sensing fiber core and β is the propagation constant of light wave in optical fibers, $\beta = nk_0$. Where n is the refractive index of the core, k_0 is the wave number of light in vacuum, $k_0 = 2\pi/\lambda_0$, and λ_0 is the wavelength of light in vacuum.

The first item in Formula (11) represents the phase difference $\Delta\phi_1$ (Strain effect) caused by the change of the length of the sensing fiber; the second item is the phase difference $\Delta\phi_n$ (Elastic light effect) caused by the change of the refractive index of the sensing fiber; and the third item is the phase difference (Poisson effect) caused by the change of the diameter of the sensing fiber core, which can be generally neglected because of its relatively small value.

$$\Delta\phi = \beta(\Delta l) + l\frac{\partial\beta}{\partial n}(\Delta n) = \Delta\phi_1 + \Delta\phi_n \quad (12)$$

Clockwise and counterclockwise light interfere at the coupler, and the output interference signal carries the phase difference caused by the acoustic signal. The relationship between the external acoustic signal and the output light intensity can be expressed as follows:

$$I = I_0(1 + cos(\Delta\phi)) = 4I_0\, cos^2\left(\frac{\Delta\phi}{2}\right) \quad (13)$$

After photoelectric conversion, acoustic signal can be restored by audio processing system.

The sensing system based on Sagnac interferometer has the advantages of small size, light weight, easy laying, high sensitivity, anti-electromagnetic interference, intrinsic safety, etc. It has been widely used in offshore oil exploration, intelligent oil wells, anti-submarine warfare, port traffic monitoring, seismic monitoring, aging monitoring of civil buildings and other practical scenarios [60]. In practical applications, there is often a need to monitor multiple pipelines at the same time, so distributed optical fiber sensor array based on Sagnac interferometer comes into being. It can not only detect the occurrence of disturbance events, but also determine the location of sound source in real time. At present, many scholars are studying optical fiber acoustic sensor array. In a 2002's report, the experimenter installed a triaxial hydrophone array 145 m off the coast of South Florida [61].

A two-sensors fold Sagnac sensing array (FSSA) was proposed by Vakoc [62], as illustrated in Figure 9. The light pulses are split into clockwise pulses (CW) through port a of the 3×3 coupler and counterclockwise pulses (CCW) through port e of the 3×3 coupler, one port of which is unused. The CW pulses are transmitted from port a to port b of the 2×2 coupler 2 and are reflected to port c of the coupler1 by the reflector after traveling up the delay coil. A part of the CW pulses enters each sensing rung through the 2×2 coupler 3, and the resulting pulse sequence returns to the port d of the 3×3 coupler. The PZT wrapped around the optical fiber is
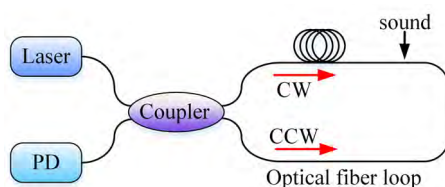

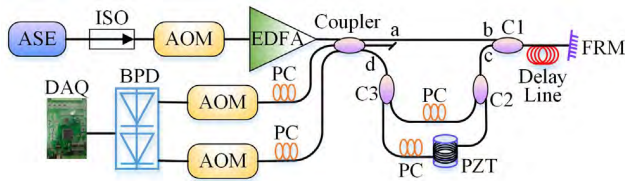**FIGURE 8.** Principle diagram of sagnac interferometer.

FIGURE 9. Acoustic sensing system based on folded sagnac array.

placed in the second sensing fiber, which allows us to modulate the phase by applying a voltage to simulate the acoustic signal. The CCW pulses travel the same path in the opposite direction, and the interference between the CW pulses and the CCW pulses occurs in the 3 × 3 coupler. The FSSA showed a phase sensitivity of approximately 0.8 $\mu rad/\sqrt{Hz}$ when a balanced detector was used, and the desensitization of the delay coil, which was detected in the system, was agree with the theory.

Figure 9 illustrates the working principle of the optical fiber sensor. The incident light is divided into two light paths along clockwise (CW) direction and counterclockwise (CCW) direction by coupler 1. When clockwise pulses pass through the sensing arm and counterclockwise pulses pass through the reference arm, they will firstly meet at 2 × 2 coupler 2. Some of them continue to move in the direction opposite to the original propagation direction, and interfere in coupler 1. The other part of the light passes through coupler 3 and interferes. The interference signals are received by photodetectors respectively.

In the aspect of optimizing demodulation algorithm, many research works have also been done. In 2008, Hang et al. proposed a distributed optical fiber acoustic sensor based on Sagnac array [63], which can be used for real-time monitoring and location of multiple pipeline leakage incidents at the same time. Experiments show that the location error is less than 0.54%. Qian et al. [64] introduced a kind of optical fiber acoustic sensor based on Sagnac ring. It uses four sensing coils on the sensing arm to restore and locate the acoustic signal. Researchers at Fudan University have innovatively proposed a cepstrum method for long-distance time-domain positioning in a sensing system combined with Mach-Zehnder and Sagnac interferometers, and achieved better location accuracy [65]. In the research of distributed optical fiber vibration sensor system based on dual-interference, Wang et al. preprocessed the dual-interference signal by combining the minimum control recursive averaging algorithm with generalized cross-correlation algorithm, so as to reduce the error of time delay estimation and locate and restore the disturbance signal more accurately [66].

B. OPTICAL FIBER ACOUSTIC SENSORS BASED ON BACKSCATTERING

For a sensor based on interference technology, only a single vibration can be located at the same time, that is to say, multiple sound disturbances cannot simultaneously be located independently. Another technology under study is

based on optical backscattering sensors, mainly referred to the phase-sensitive optical time-domain reflectometer (Φ-OTDR). At present, distributed optical fiber acoustic sensor based on Φ-OTDR primarily is composed of optical fiber interferometer and sensor based on optical fiber backscattering. Φ-OTDR is caused by the interference of backscattered light from different parts of the optical fiber. Phase change is perceived by subtracting the output time-varying light power trajectory from the previously stored reference light power trajectory, and the position of the disturbance is proportional to the time when the trajectory changes. Φ-OTDR system is fundamentally based on the interference of reference light and Rayleigh scattering light coming back from the inside of the optical fiber. The phase of Rayleigh scattering light is disturbed by perturbation events, which makes the amplitude of Rayleigh scattering light change. Distributed acoustic sensors based on Φ-OTDR provide information of position, frequency or amplitude of sound disturbance by measuring intensity changes.

In recent years, the technology of combining other interferometer with Φ-OTDR system has been formed and popularized. Researchers at Chongqing University have successively studied a distributed optical fiber sensing system which combines Mach-Zehnder interferometer (MZI) with phase-sensitive optical time-domain reflector (Φ-OTDR) [67], [68]. The system is used to measure the acoustic perturbation caused by the abrupt break of pencil near the optical fiber ring. The spatial resolution of 5 m and the frequency response of 6.3 MHz are obtained under the 1150 m sensing optical fiber [69]. Then Shandong Key Laboratory of Optical Fiber Sensing Technology combined Michelson interferometer (MI) with Φ-OTDR in distributed optical fiber acoustic measurement, and innovatively adopted 3 × 3 coupler demodulation technology [70]. The basic principle diagram is shown in Figure 10. A Michelson interferometer structure consisting of a coupler and two Faraday rotating mirrors with half arm length z is added to the output of the conventional Φ-OTDR configuration.

The Rayleigh scattering signal is injected into the Michelson interferometer. Suppose that the incident coherent optical signal is a rectangular monochrome pulse with frequency f and pulse width ω. When $t = 0$, the optical pulse is emitted into the optical fiber, and the backward Rayleigh scattering light propagates in the optical fiber. The backward Rayleigh
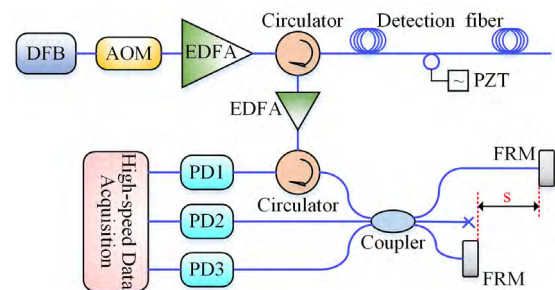

FIGURE 10. Configuration of interferometer based on Φ-OTDR.

scattering light obtained is as follows:

$$e_r(t) = \sum_{i=1}^{N} A_i cos\left[2\pi f\left(t - \tau_i\right)\right]$$

$$exp\left(-\alpha\frac{C\tau_i}{n_f}\right) rect\left(\frac{t - \tau_i}{\omega}\right) \quad (14)$$

where A_i is the amplitude of the *i*-th scattered wave, τ_i is the time delay of the scattered wave and N is the total number of scattered waves, and α stands for the attenuation constant. When the value of $(t - \tau_i/\omega)$ is between 0 and 1, the rectangular function $rect(t - \tau_i/\omega)$ has a value of 1, otherwise the value is zero. Among them, $\tau_i = ((2n_f l_i)/C)$, l_i represents the distance between the input end and the *i*-th scatterer, C is the speed of light in vacuum, n_f is the refractive index of the core.

The delayed wave generated by optical signal passing through Michelson interferometer can be expressed as:

$$e_d(t) = \sum_{j=1}^{N} A_j cos\left[2\pi f\left(t - \tau_j - \tau_z\right)\right]$$

$$exp\left(-\alpha\frac{C\tau_j}{n_f}\right) rect\left(\frac{t - \tau_j - \tau_z}{\omega}\right) \quad (15)$$

where z is the half arm length of the MI, and $\tau_z = ((2n_f z)/C)$ represents the time delay caused by the MI.

After the interference of two beams of light, the optical power of the interference signal is as follows:

$$I(t) = \left[e_r(t) + e_d(t)\right] \times \left[e_r(t) + e_d(t)\right]^*$$

$$= \sum_{i=1}^{N} A_i^2 exp\left(-2\alpha\frac{C\tau_i}{n_f}\right) rect\left(\frac{t - \tau_i}{\omega}\right)$$

$$+ \sum_{j=1}^{N} A_j^2 exp\left(-2\alpha\frac{C\tau_j}{n_f}\right) rect\left(\frac{t - \tau_j - \tau_z}{\omega}\right)$$

$$+ 2\sum_{i=1}^{N} A_i \sum_{j=1}^{N} A_j cos\left(\Delta\varphi\right) \times exp\left[-\alpha\frac{C\left(\tau_i + \tau_j\right)}{n_f}\right]$$

$$\times rect\left(\frac{t - \tau_i}{\omega}\right) rect\left(\frac{t - \tau_j - \tau_z}{\omega}\right) \quad (16)$$

The parameter $\Delta\varphi = (4\pi f n_f z/C) + \left(4\pi f n_f\left(l_j - l_i\right)/C\right)$ represents the phase difference engendered by the half arm length and the distance between the *j*-th and the *i*-th scatterers.

The interferometric signal includes not only the location information of the sound source, but also the phase change after demodulation. Finally, the distributed acoustic response can be measured by analyzing the backscattering power displayed. Experiments show that different acoustic sources with different intensity can be demodulated, and phase, amplitude, frequency response and location information can be obtained simultaneously.

Subsequently, on the basis of this system, they added a sensing network with 500 ultra-weak fiber Bragg gratings (UWFBG) with the same spacing of 2 m as Figure 11 [31], and carried out the experimental study of
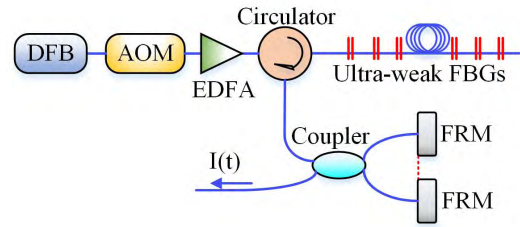

FIGURE 11. The Φ-OTDR-interferometer system with uwFBGs.

acoustic detection in water tank. The results show that when the pressure detection limit is 0.122 Pa and the frequency response is 450-600 Hz, the system successfully demodulates distributed acoustic signals with the sensitivity of −158 dB (re rad/μPa).

In Φ-OTDR system, the location of sound source is an urgent concern. In order to solve this problem, many research institutes have carried out a lot of experiments, including noise elimination, signal-to-noise ratio (SNR) improvement and system performance optimization.

For example, Lu et al. weakened the noise power by moving differential method and average method, and at the same time, the frequency response range was expanded [71]. Under different polarization conditions, Qin et al. recommended a wavelet denoising method to eliminate random noise caused by different vibration sources and detectors [72]. Muanenda et al. used the method of cyclic pulse coding to improve the SNR of backscattered signals by 9 dB in Φ-OTDR system [73]. The main method of operation is to realize cyclic coding by modulating inter-pulse coherence and intra-pulse incoherence. Subsequently, they applied cyclic pulse coding to a distributed sensing system for simultaneous measurement of acoustic and temperature [74], which can detect acoustical vibration at 500 Hz at 5 km, and the temperature resolution is less than 0.5°. Then in order to improve the SNR of Φ-OTDR acoustic sensing system, a combination of phase difference average estimation, infinite impulse response filtering and piecewise unwrapping algorithm is expounded [75]. Moreover, a narrow linewidth light source is used to improve the system performance. Rao et.al. used the DAS system based on Φ-OTDR to measure dynamic strain, and achieved 12.6 km of sensing range and 10 m of spatial resolution [76]. They combine the I/Q demodulation and the homodyne detection of 90 mixed mode to demodulate the phase information of optical signal successfully without interferometer configuration in the experimental optical path. The experimental schematic diagram is elucidated in Figure 12.

Ölçer et al. no longer use the traditional method to average the detected signal trajectory, but introduce an adaptive algorithm to improve the signal-to-noise ratio (SNR) by detecting a set of noise parameters, so as to improve the detection performance [77]. Then a curve denoising method is also put forward to improve the performance of Φ-OTDR system by weakening the time-domain noise [78]. Subsequently, the empirical mode decomposition (EMD) method
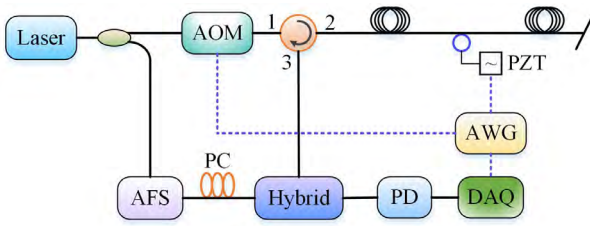
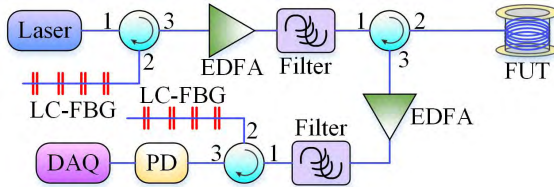**FIGURE 12. Optical fiber sensing system diagram based on COTDR.**

FIGURE 13. Sensor system based on Φ-OTDR and FBG.

is described to improve the SNR of location information [79], [80]. Since then, adaptive temporal matched filtering method [81], two-dimensional edge detection method [82], adaptive image processing method [83] and correlation dimension method [84] have gradually been proposed, which have achieved the purpose of reducing noise and improving the location SNR. In the distributed optical fiber sensing system based on Φ-OTDR, Wang et al. proposed a heterodyne demodulation method based on heat treatment and cross-correlation principle [85]. The SNR can be increased by 6.22 dB by characterizing the time-skew and phase-mismatch of the in-phase and quadrature (I/Q) signals and compensating them in real time. At the same time, they applied the concepts of heterodyne Φ-OTDR linearization and Golay pulse coding to DAS system for the first time [86], and tested them on 10 km sensing fiber. The results show that the SNR of sensing signal has been further improved. Subsequently, they proposed a method of M-degree summation of incoherent scattered light-waves to suppress the noise caused by Rayleigh fading [87]. The combination of Φ-OTDR sensor and chirped pulse amplification configuration can further enhance the SNR by 20 dB with a spatial resolution of 1.8 cm [88]. The basic experimental schematic diagram is shown in Figure 13.

Furthermore, in engineering, because the density of Rayleigh backscattering signal returned from the end of the optical fiber is very weak, the backscattering signal needs to be further amplified to increase the sensing range. The application of time-varying gain amplification method in vibration sensing system of Φ-OTDR is demonstrated for the first time by Zhou et.al [89]. The system has a spatial resolution of 5 m and a sensing range of up to 44 km with a pulse width of 50 ns. Recently, a highly sensitive quasi-distributed optical fiber acoustic sensing system based on Φ-OTDR has been reported, which probes a weak reflector array by coherent detection [90], as demonstrated in Figure 14. It is found that the phase noise dominated in low frequency range severely limits the operation of coherent detection in
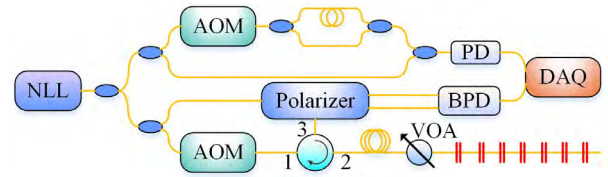

FIGURE 14. High-sensitivity quasi-distributed optical fiber acoustic sensing system.

Φ-OTDR system. Therefore, a phase-noise-compensated configuration, an auxiliary interferometer, is adopted to improve the system performance. In the proposed Φ-OTDR system, a weak reflector array, as the sensing element, is used to replace a single mode fiber (SMF), which can reflect probe pulse with a low reflectivity without augmenting prominently the transmission loss of optical fiber. The weak reflectors that can be UWFBG or other structures are written along the fiber at a changeless spacing L, which determines the spatial resolution of the system. Then a cylindrical piezoelectric transducer (PZT) wrapped with optical fiber is utilized to generate a 100 Hz driving signal to simulate the external acoustic signal. An acoustic signal sensitivity of 3.84 $p\varepsilon/\sqrt{Hz}$ can be acquired in the simulated scene with 20 km fiber length and 10 m spatial resolution.

Frequency shift measurement based on backscattering signal can measure external acoustic interference more accurately and quantitatively. Chen et al. realized frequency division multiplexing (FDM) and reduced sampling rate by using matched filtering algorithm and under-sampling method in a time-gated digital optical frequency domain reflectometer (TGD-OFDR) based distributed acoustic sensor system [91]. Setting the length of the optical fiber under test as 24.7 km, the system can detect the acoustic disturbance with a frequency of 9 kHz, in which the spatial resolution is 10 m and the signal-to-noise ratio is 30 dB. In recent years, Φ-OTDR-based distributed optical fiber acoustic system has also been applied to practical projects. For example, Sifta et al. realized the long-distance laying of Φ-OTDR optical fiber sensing system in 2015 [92]. They laid buried optical cables up to 4 km and tested them at different frequencies from 100 Hz to 1 kHz, resulting in a high sensitivity. Experiments show that Φ-OTDR system can be used to detect, locate and classify the sound vibration caused by moving people, trains or other objects, as well as to monitor pipeline damage and seismicity areas.

IV. APPLICATION

Since the 1970s, optical fiber sensors have acquired widespread research of academia for their superior performance. Among them, optical fiber acoustic sensing technology as a hot spot of concern, for different environments and different measured parameters, a variety of optical fiber acoustic sensors also emerge, and have immense application prospects, such as structural health monitoring [93], [94], underwater combat [95], pipeline early warning [96], [97], seismic monitoring [98], optical imaging [99] and many

other fields. In recent years, distributed acoustic sensing (DAS) has become a mainstream technology. By measuring the acoustic turbulence in the extended area of optical fibers, then demodulating and processing optical signal, the location and restoration of turbulence can be achieved [100]. Recent investigations testify that DAS is extensively used in many security and integrity monitoring systems. Over the past few years, the DAS market has been growing continuously and steadily, and the expectation of outnumbering $2 billion will be met by 2025. The DAS system is mainly used in military defense, building structure monitoring, and oil and gas detection, and can be extended to perimeter security, rail transit, large-scale acoustic positioning and many other fields. This paper mainly summarizes the application of DAS system in military defense, building structure monitoring, and oil and gas detection.

A. MILITARY DEFENSE

Because of its large area and abundant resources, the ocean occupies a strategic position in the territorial expansion of various countries. With the increasing awareness of marine protection around the world, in order to weaken the enemy submarine force, anti-submarine warfare has become the focus of military attention of all countries. In recent decades, due to the continuous improvement of submarine performance and the emergence of silent submarines [101], the optimization of sensor-based underwater anti-submarine is also facing severe challenges. As one of the simplest acoustic detectors, optical hydrophones can receive underwater acoustic in different directions when used in anti-submarine. Compared with the traditional piezoelectric acoustic sensors, the size, detection distance and anti-interference ability of the optical fiber underwater acoustic sensors have been greatly improved [99]. Acoustic wave can transmit energy over a long distance in the sea. Whereas other energy fields, such as electromagnetic fields, will decay rapidly in water [102]. Therefore, no technology can threaten the dominance of acoustic field underwater. In the complex ocean, optical fiber acoustic sensor has its unique advantages, such as good stability and high sensitivity. At the same time, the key is that hydrophone detection is not affected by hydrostatic pressure and acoustic frequency [103]. But ordinary optical hydrophones cannot distinguish and accurately locate acoustic sources from all directions. If multiple hydrophones are arranged into linear, cylindrical or other shape arrays, the direction of acoustic source can be judged according to the time difference produced by different hydrophones when receiving the same sound. Therefore, the application of large-scale optical fiber hydrophone array has important military value [104]. In recent ten years, optical fiber acoustic sensor has been widely and deeply studied in underwater acoustic detection field. While conducting a lot of academic research, the United States has implemented an anti-submarine military team based on hydrophone array, but it is still in its infancy.

The physical characteristics of the optical fiber and the interference principle of the optical fiber acoustic sensor determine that it has some excellent features that traditional piezoelectric sensors do not have. Compared to traditional piezoelectric hydrophones, fiber optic hydrophones are based on multiplexing technology and have many advantages such as high sensitivity, wide frequency response range, compact structure, easy mass array formation, strong electromagnetic interference resistance, and harsh environment resistance [105]. Among these, the optical fiber hydrophone based on the principle of interference has high detection sensitivity and large dynamic range, so it has been widely studied and applied. It is the most mature technology at present and its detection sensitivity is three orders of magnitude higher than that of piezoelectric hydrophone [106].

In order to meet the practical application and cost control requirements of large-scale fiber-optic hydrophone arrays, the reuse technology of fiber-optic hydrophone arrays has become the focus of research since the mid-1980s. Fiber-optic hydrophone array multiplexing is a technology that can transmit multi-element channel signals simultaneously in a single fiber. Combining with demodulation algorithm, the array multiplexing technology enables the system to have the ability of multi-channel synchronous demodulation [107], thus improving the detection performance of the whole hydrophone array. Typical multiplexing technologies include time division multiplexing [108], frequency division multiplexing [109], dense wavelength division multiplexing [110], and polarization multiplexing [111], among which dense wavelength division multiplexing technology evolved in the development of optical fiber communication technology. Comparing these reuse technologies, the degree of reuse is different, and the technical difficulty of implementation is also different.

B. STRUCTURAL HEALTH MONNITORING

In recent years, a large number of infrastructures such as highways, railways and high-speed railways have been built. With the extension of service time, due to the unpredictable weather environment and the impact of human accidents, these infrastructures will be damaged to varying degrees, thus affecting the safety of infrastructure and pedestrians. Therefore, the security inspection of infrastructure is particularly important. Traditional facilities monitoring methods mainly include piezoelectric detection technology [112], but it cannot monitor the safety of buildings in real time. As a new non-destructive detection method, optical fiber acoustic sensor has the advantages of high sensitivity, strong anti-interference ability, real-time continuous monitoring and so on, which has attracted wide attention [9]. By attaching optical fiber sensors to metal or concrete surfaces or burying them in buildings or soils, real-time and continuous monitoring of stress, strain and crack generation and propagation in engineering buildings can be achieved [113]. For example, Nanyang University of Technology has studied the problem of crack monitoring of fixed beams by using fiber Bragg grating (FBG) and fiber optic polarization sensor (FOPS) [114]. Optical fiber acoustic sensor head can also be integrated

on a single optical fiber to form a distributed large-scale monitoring and detection system, which greatly improves the detection efficiency, saves detection costs, saves time and human resources, and can use wireless transmission network for remote monitoring [115]. At the same time, it also provides great convenience for real-time detection in special environment.

Besides its application in civil infrastructure, fiber-optic acoustic sensing technology can also be applied to structural health monitoring of aircrafts and large cranes. For example, Harbin University of Technology has carried out the research of FBG sensor [116], EFPI strain sensor and acoustic emission sensor based on fused tapered fiber coupler. The application of optical fiber sensor to monitor the curing process of composite structure [117], damage identification of composite structure and structural health monitoring of composite pressure vessel have been carried out. Liang Dakai and others of Nanjing University of Aeronautics and Astronautics have developed a strain monitoring system for distributed fiber Bragg grating sensing network based on wavelength division multiplexing structure [118], [119], as shown in Figure.15. They used the FBG network monitoring structure to successfully detect the shock response signal generated by the impact hammer. At the same time, in the research of smart materials and structures, Sierra-Pérez et al. built a prototype of 13.5m wind turbine blade in Pamplona, Spain [120]. The embedded optical fiber sensors are used to detect damage by measuring strain. It provides theoretical basis and practical reference values such as the layout and multiplexing technologies of sensor, for the application of optical fiber acoustic sensor in structural health monitoring.
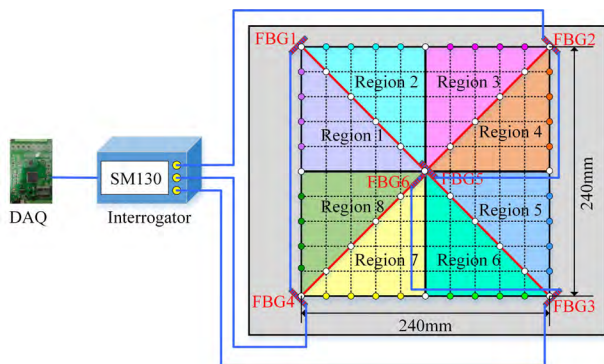
Compared with the traditional logging technology, the monitoring technology based on optical fiber sensor can build a complete real-time data set from the top to the bottom of the well, which greatly reduces the time of detecting limited intervals and improves the efficiency of the whole system. In addition, the advantages of non-contact measurement make the DAS system not destroy the original temperature and pressure field in the well, and can truly reflect the actual test situation. Because of its high spatial resolution, the DAS system can detect hundreds of signals per kilometer, which is much higher than the detection efficiency of traditional sensors. The routing of DAS system is simple, and only one sensing fiber is needed to realize distributed measurement.

The DAS system has made significant progress in petroleum exploration, oil spill monitoring, hydraulic fracturing (HF) operation monitoring, vertical seismic profile (VSP) measurement, downhole monitoring, micro-seismic acquisition, intelligent well and gas lift well monitoring [122]. For example, Ni et al. [123] used the DAS system to measure oscillating pressure signals along optical fibers. It has wide application prospects in geological fluids, geomechanics, earthquake and temperature monitoring. Carpenter [124] proposed a detection system combining single-phase flow profiling and DAS to replace the traditional production logging tool (PLT). By deploying the system on the whole wellbore, the downhole production and injection performance are measured. By installing optical fibers to oil wells and monitoring fluid and pressure changes in oil and gas production reservoirs, vertical seismic profile (VSP) imaging with high vertical and lateral resolution were obtained [125], as described in Figure 16.
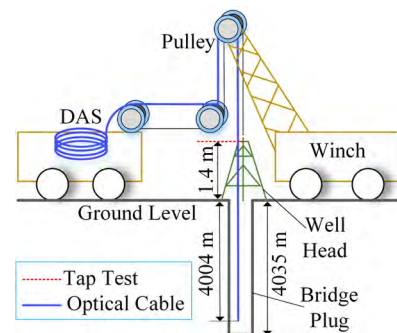

FIGURE 15. The diagram of impact monitoring system.

FIGURE 16. Configuration of vertical seismic profile survey by DAS.

C. PETROLEUM EXPLORATION AND DEVELOPMENT

At present, many oilfields have encountered bottlenecks in their development, because the original development logging technology cannot fully meet the needs of oilfield development [121].

Real-time and reliable monitoring technology is the basis to ensure efficient production of oil and gas wells. In the past decades, the DAS system has developed rapidly in oil and gas monitoring due to its ability to withstand harsh environment.

Furthermore, the DAS system based on surface plasmon resonance (SPR) are very sensitive to small changes in refractive index of external media [126]. Therefore, oil spill alarm products based on SPR sensing technology can realize real-time detection of oil spill process [127], and the cost is low [128]. Therefore, SPR sensing technology has been widely used in the measurement and detection of related physical quantities, which will cause the change of refractive index [129]. For example, in 2015, Verma et al. proposed that the refractive index detection accuracy of SPR sensor can reach 0.01 [130]. At the same time, Crescitelli and others

TABLE 1. Comparisons and challenges.

Classification		Advantage	Disadvantage	Challenge	Application
Quasi-Distributed Optical Fiber Sensing Technology	FP	Small size	Complex production	Manufacturing technology	Pipeline inspection, Biomedicine
	FBG	High transmission efficiency, and multiplexing	High cost and complex packaging process	Multiplexing technology	Oil and gas exploration
Distributed Optical Fiber Sensing Technology	MZI	Wide sensing range	Low positioning accuracy	Time delay estimation	Pipeline leak detection
	MI	Simple structure	Low sensitivity	System stability	Building safety
	Sagnac	Low requirement for laser source	Low positioning accuracy	Demodulation technology	Earthquake monitoring
	Φ-OTDR	High positioning accuracy	Low SNR and spatial resolution	Mixed optical structure	Intrusion location

demonstrated the technology platform based on localized surface plasmon resonance (LSPR) integration [131]. They successfully applied the device to optical probe and acoustic detection without labeling chemical and biological sensors.

The practical application of DAS system includes optical fiber acoustic monitoring for military defense, battlefield event location and monitoring, distributed passive sonar in ocean field, underground oil and gas exploration, event flow monitoring for railway and traffic, perimeter security and so on. The DAS system has introduced advanced sensing technology for many industries, which has huge application potential and utility value.

D. COMPARISONS and CHALLENGES

In summary, we compare the advantages and disadvantages of different optical fiber acoustic sensing technologies, and also summarize the challenges and opportunities of optical fiber acoustic sensing technology in Table 1.

V. CONCLUSION

Optical fiber acoustic sensing technology has the advantages of large-scale monitoring, good concealment, good flexibility, anti-electromagnetic interference, and has great social benefits. When the acoustic disturbance acts on the sensing fiber, the optical parameters such as the intensity, phase, polarization state and optical frequency of the fiber will change. This paper summarizes the various technologies of optical fiber acoustic sensing from the quasi-distributed and distributed aspects, including FBG, FPI point sensing technology, Michelson, Mach-Zehnder, Sagnac interference technology, and Φ-OTDR sensing technology based on backscattering. Each technology has its own advantages in cost, complexity and performance, but the sensing system based on Φ-OTDR is currently the most widely studied, because it can achieve multi-source monitoring in a relatively economical and effective way within a larger monitoring distance.

At the end, the application of optical fiber acoustic sensing system in military defense, structure health monitoring, and oil and gas detection is summarized. In the future, the DAS system can not only be used to guard important sites such as cultural relics and historical sites, border towns and military bases. It can also be used for safety monitoring of underground pipelines such as theft damage, pipeline leakage and construction damage. In addition, it has a bright future in underwater pipeline safety monitoring such as bio-gnawing, fishing boat towing, communication eavesdropping and so on.

VI. CONFLICT OF INTERESTS
The authors declare no conflict of interest.

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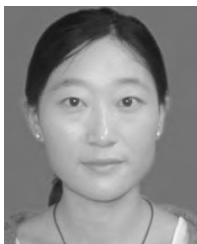
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