

Research Progress of Phase Sensitive Optical Time Domain Vibration Sensing Technology

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ABSTRACT: Phase-sensitive Optical Time Domain Reflectometer (Φ -OTDR) is a kind of distributed type which is developed by the optical time-domain reflection (OTDR) Optical fiber sensing technology. Because of its high sensitivity, fast response, dynamic range and other advantages, and thus get wide attention. In order to learn more about the progress of Φ -OTDR system and carry out new research. On the basis of reading the relevant literature, the Φ -OTDR system is analyzed and summarized, and a series of research methods, system applicable conditions and application environment of Φ -OTDR are summarized. The main parameters of the Φ -OTDR system are discussed in this paper, and the improvement method is proposed to provide the idea for the future system construction.

Keywords: phase sensitive optical time domain reflectometer; fiber interferometer; intrusion detection; pattern recognition; raman zoom

I. INTRODUCTION

Phase-sensitive Optical Time Domain Reflectometer (Φ -OTDR) is also part of the distributed fiber optic sensing technology,^[1] it also uses the backward Rayleigh scattered light to transmit in the fiber. Compared with other optical fiber sensing systems, phase sensitive light time domain reflectometer (Φ -OTDR) has high sensitivity,^[2] fast response speed,^[3] large dynamic range^[4] and high positioning accuracy, which can be applied to the security detection system for large-scale construction facilities, perimeter security, pipeline protection and military base security monitoring. Based on the summary of many research results, this paper further discusses the basic principle, the research status and the related performance parameters of Phase-sensitive Optical Time Domain Reflectometer (Φ -OTDR), and discusses the future development trend of Φ -OTDR and Direction of development.

II. BASIC PRINCIPLES

1.1 Phase-sensitive Optical Time Domain Reflectometer (Φ -OTDR) basic principles

Φ -OTDR is developed on the basis of optical time domain reflectometer (OTDR). The working principle of the two is similar, compared with the broadband light source used by conventional OTDR system, Φ -OTDR system Using ultra-narrow linewidth lasers as light sources. It uses the interference effect between the backward Rayleigh light in the wide pulse, injects the high coherent light into the sensing fiber, and the detector detects the reflected coherent Rayleigh scattered light.^[5] Because the technology combines the OTDR system and interference effects, the system has a high sensitivity and a longer sensing distance. Φ -OTDR mainly includes direct detection and coherent detection of two structures. In the direct detection structure, the backward Rayleigh scattered light is collected by the circulator and captured directly by the photodetector. While in the coherent detection structure, the Rayleigh scattered light needs to be interfered with the local reference light after passing through the circulator, and then the coherent optical signal is transmitted to the photodetector,^[6] This is the main difference between the two systems.

The advantage of direct detection of Φ -OTDR is that the structure is simple, the cost is relatively low, and the data processing is simple. The disadvantage is that the erbium doped fiber amplifier (EDFA) in the system generates spontaneous amplified radiated noise (ASE), the system can not effectively identify the signal when the signal is still noise when the scattered signal, so the signal to noise ratio is poor, the sensing distance is also greatly affected. In contrast to the direct detection structure of the Φ -OTDR, Coherent detection Φ -OTDR most obvious difference is the addition of bandpass filter to filter out ASE noise, and the local reference light signal to noise ratio is also greatly enhanced, so the system Sensing distance is longer. The disadvantage of coherent detection Φ -OTDR is that the system is more complex, and the change of the reference light polarization state has a great influence on the detection result. The Φ -OTDR can be determined according to the actual detection requirements.

Based on Phase-sensitive Optical Time Domain Reflectometer (Φ -OTDR) schematic diagram shown in Figure 1. In the arranged Φ -OTDR system, when the fiber is disturbed at a certain point along the line, the internal refractive index and length of the fiber at that location will change,^[7] resulting in a change in the optical phase of the optical Interference, and then lead to the backward Rayleigh scattering light intensity, that is, backward optical power changes, there will be disturbed when the scattering power curve minus the power curve without disturbance, the disturbance information, according to the light in the fiber speed and disturbance Signal transmission time of the corresponding relationship, the distance of the disturbance signal can be accurately positioned^[9].

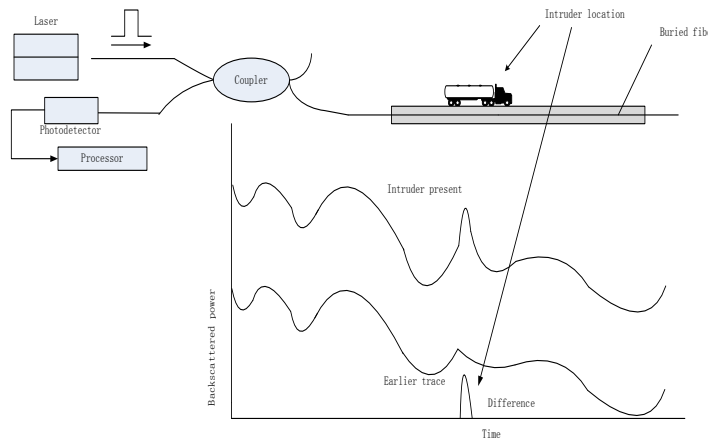


Fig.1 Schematic diagram of distributed fiber-optic perturbation based on Φ -OTDR

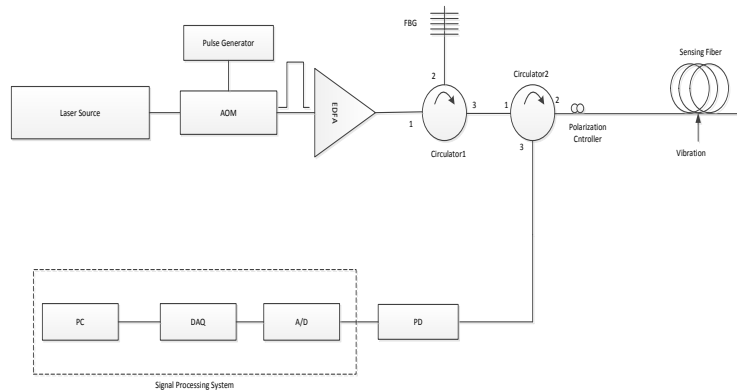


Fig.2 Φ -OTDR system principle structure diagram

Φ -OTDR system block diagram shown in Figure 2, The continuous light generated by the narrow linewidth laser enters the acousto-optic modulator (AOM), and the signal generator is connected to the acousto-optic modulator to modulate the input continuous light into a series of pulsed light. The erbium-doped fiber amplifier (EDFA) amplifies the optical pulse and generates spontaneous emission noise (ASE).^[8] FBG filters out most of the spontaneous emission noise through the circulator 1, and the filtered optical pulse enters the sensing fiber through the circulator 2. In order to maintain the polarization state of the light, a polarization controller (PC) is added to the front of the sensing fiber. Photoelectric detector (PD) is converted into an electrical signal, and finally the data acquisition and processing system demodulates the phase of the optical field, wherein the data acquisition and processing system comprises a digital-to-analog converter (A / D), data acquisition card (DAQ) and PC (PC).

1.2 Distributed Optical Fiber Sensing Technology Based on Interference Principle

Interferometer through the interference of the optical phase changes into light intensity changes, to achieve the detection of external signals. Distributed optical fiber sensing technology based on the principle of interference to determine the optical path difference to determine the relevant physical quantities, also known as phase modulation optical fiber sensing technology,^[9] with a high sensitivity and a wide range of detection frequency. Mainly divided into Mach-Zehnder (Mach-Zehnder) interferometer, Michelson (Michelson)

interferometer and Sagnac (Sagnac) interferometer and so on several.

Because the fiber interference interferometer has the advantages of simple structure and high sensitivity, it is widely used in practice. However, due to the limitations of a single system, many researchers put the interference sensor into the Φ -OTDR system, the result is greatly improved the frequency response of the hybrid system. Yi Shi^[10] designed a new system by combining the Mach-Zehnder interferometer and the phase-sensitive light time-domain reflectometer. The heterodyne detection is used to maintain the signal-to-noise ratio of the positioning signal, achieving a wide frequency resolution of 1 Hz to 50 MHz and a high spatial resolution of 20 m. This system is important in applications where measurement requirements require wideband and high positioning accuracy. Yixin Zhang^[11] designed a new single-end-access system, which incorporates MZ interferometer and Φ -OTDR vibration sensing system, so that the system positioning information and high frequency response can be obtained at the same time. The system achieves a spatial resolution of 10 m and a frequency response of 1.2 MHz on a 6.35 km fiber. In order to reduce the fluctuations caused by light and the outside world and the existence of high hazard alarm rate (NAR), Sheng Liang^[12] constructed a hybrid system of Mach-Zehnder interferometer and phase-sensitive optical time domain (Φ -OTDR). The NAR in the single-phase sensitive time-domain reflection technique (Φ -OTDR) drops from 15% to 1%. Where NAR is a harmful alarm rate. MZ interferometer combination Φ -OTDR system has a unique advantage. Φ -OTDR is used to detect and locate the interference, and then the interference detected by Φ -OTDR is confirmed by the MZ interferometer to eliminate the disturbance alarm caused by high noise in the Φ -OTDR system. In addition, the detection frequency range of these interferometers is limited by the detection bandwidth and the sampling frequency of the data acquisition card.^[13] In doing research, we should also think of ways to improve the detection bandwidth and data acquisition card frequency in order to improve system performance.

1.3 Φ -Otdr sensing system related performance parameters

1.3.1 Φ -Otdr main noise

Any kind of sensing technique always has noise. The noise is generally not a single case, it is a variety of noise superimposed together, deteriorating the performance of the system. Φ -OTDR system noise can be divided into two major categories of electrical noise and optical noise.

Electrical noise mainly refers to thermal noise. Due to thermal vibration to produce thermal noise, Electronic components is affected by temperature changes. Due to the widespread presence of thermal noise in electronic devices and electronic transmission media, thermal noise is difficult to eliminate. There are kinds of optical noise. Coherent Rayleigh noise is Rayleigh coherent fading noise, generally not considered in the Φ -OTDR system. The relative intensity noise is due to changes in the intensity of the output light source. The spontaneous amplification of the radiated noise is due to the broad-spectrum noise of the electron-hole pair of spontaneous emission in the optical amplifier medium, which is amplified with the signal. Phase noise is more complex. As the system is subject to a variety of noise within the impact of the output signal phase changes, resulting in phase noise. For example, when the sideband signal deviates from its own center frequency and goes to the nearest frequency, the sideband signal is phase noise. Phase noise can be used as a measure of the advantages and disadvantages of the performance of the laser, so Φ -OTDR system laser selection should also pay attention to the phase noise suppression. Researchers have improved the phase noise by using Wiener filtering.^[14] Polarization-related noise is a problem caused by the manufacturing process of optical fibers. Due to the limitation of the process level, the polarization state changes when the light is transmitted in the optical fiber, resulting in polarization-related noise. In practical applications, the external disturbance event may also change the birefringence characteristics of light. Light in the disturbance position and after the optical fiber transmission in the polarization state changes, will produce polarization-related noise. For the polarization noise, we can use the polarization-maintaining fiber in the system to improve, but also can use the tail polarization polarization method to reduce the polarization noise. Generally, electrical noise can be improved by means of averaging. The relative intensity noise in the optical noise can be improved by means of the phase-generated carrier signal (PGC), and the averaging method has also improved its effect. For spontaneous amplification noise can be eliminated using a filter.

Improve the system's signal to noise ratio, the most important means is to use noise reduction method. In the Φ -OTDR system commonly used in the signal denoising methods are cumulative average denoising, moving average denoising, wavelet denoising and so on. In addition, the application of Sobel algorithm to Φ -OTDR system can also effectively improve the signal to noise ratio.

1.3.2 Spatial resolution and detectable frequency

Spatial resolution is a measure of the system's ability to distinguish the shortest detection distance of two adjacent events. The spatial resolution of the system can be improved by inputting a narrow laser pulse, and increasing the sampling frequency of the data acquisition card can greatly improve the spatial resolution of the

system. Researchers have proposed the following improvements in spatial resolution: two-dimensional edge detection, heterodyne detection, wavelet denoising and suppression caused by the fading caused by modulation and so on. The maximum detectable frequency of the Φ -OTDR system depends on the repetition frequency of the laser. The higher the detection frequency, the better the performance of the system. At present, the international Φ -OTDR maximum detection frequency has increased to 5Hz, the next stage, the researchers strive to increase the maximum detection frequency to 1Hz.

Researchers have made efforts to improve the spatial resolution and detectable frequencies. University of Ottawa, Canada Bao Xiaoyi proposed a Φ -OTDR vibration system. As shown in Figure 3, the system's wideband audio components are generated by Pencil Break vibration, and for the first time, Pencil break is used for positioning recognition and measurement of distributed vibration sensors. Among them, Pencil break is a method used to identify cracks in concrete or steel bridge detection technology. The system is divided into measuring light and reference light through the coupler 1, the measuring light passes through a series of devices after entering the sensing fiber, the backward scattered light through the circulator in the coupler 2 with the reference light coherent, the balance detector will coherent signal Signal to noise ratio increased by 3dB. In the system, the heterogeneous detection method of moving average and moving difference is introduced to increase the frequency response range of the system. When the pulse width is 50ns, the system has a spatial resolution of 5m and a SNR of 6.5dB. If the data acquisition card trigger response frequency of 10kHz, after 10 times the average, Pencil break detection frequency response range up to 1kHz. The system can be used as a dynamic detection of any structure.^[15]

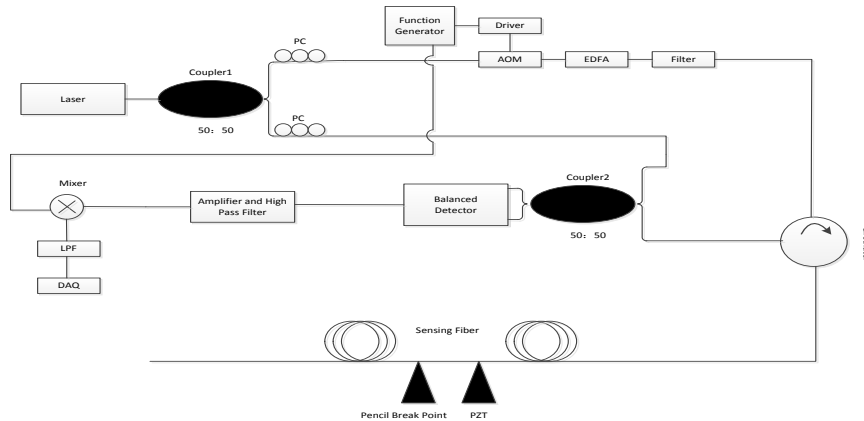


Fig.3 Φ -OTDR based on heterodyne detection

However, since the system uses a fiber loop with a length of 0.25m as the sensing part, the vibration time is in the middle of the closed loop, so it is not applicable in practice. Therefore, Bao Xiaoyi proposed a distributed vibration sensing system based on polarization-maintaining fiber configuration. The polarization and noise caused by polarization are improved by the polarization maintaining element, and the detection frequency is increased to 2.25 kHz. The system uses the linearly sensitive polarization-maintaining fiber instead of the original single-mode fiber loop to reduce the average number of times to 4 times, the spatial resolution of 1m, SNR greater than 2dB, the system is expected to be applied to the actual construction, civil and other structural health monitoring. The system structure is shown in Figure 4,

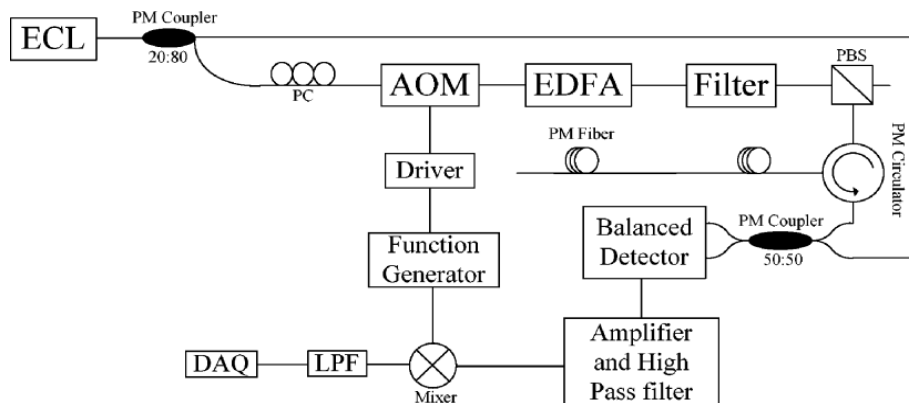


Fig.4 Φ -OTDR fiber vibration sensing system based on full polarization control

1.3.3 Sensitivity

Sensitivity refers to the system's ability to respond to external disturbance events. The higher the sensitivity, the higher the responsiveness of the system to small signals. Detecting the line width of the light source has an important effect on the sensitivity of the Φ -OTDR system. OTDR system can not respond to optical phase modulation, because it uses a wide range of semiconductor lasers, up to several GHz or even several THz, resulting in reflected light signal in different parts of the interference caused by light fluctuations, can not be detected in the detector Light intensity signal reflected.^[16] The Φ -OTDR system is different, because the system line width is very narrow, can respond to changes in optical phase. When the Φ -OTDR system, the narrower the line width, the more obvious the interference effect, the higher the sensitivity of the system at this time. And the repetition frequency of the pulse modulation also has an important influence on the sensitivity. The repetition frequency of the optical pulse affects the sensitivity of the system by affecting the system to detect the maximum frequency of the external disturbance signal,^[17] The higher the repetition frequency of the pulse modulation, the higher the maximum frequency of the signal that can be detected, and the more responsive to the high frequency disturbance signal. The use of high-performance detectors also increases the sensitivity of the system.

1.3.4 Dynamic range

The dynamic range determines the maximum detectable range of the Φ -OTDR system, that is, the maximum distance that the sensor fiber can be laid in the system. It is also an important indicator of system performance. If the dynamic range is small, the far-end scattered signal will be submerged in the noise. As the light in the optical fiber transmission loss, so Φ -OTDR sensing distance is limited. In addition, the fiber is also affected by the nonlinear effect, so, can not blindly improve the power of the probe light pulse to increase the sensing distance. The sensing distance of the Φ -OTDR is also affected by the performance of the photodetector and the noise of the system. Improving the dynamic range of the system, can take the following methods: increase the power of the incoming fiber pulse, improve the signal to noise ratio of the system and improve the sensitivity of the receiver.

To enhance the dynamic range of Φ -OTDR system, the researchers mainly through the input signal amplification method to achieve. Since the phase-sensitive optical time-domain reflectometer (Φ -OTDR) was proposed by H.F. Taylor in 1993,^[18] the erbium-doped fiber amplifier was added to the system for centralized amplification of the optical pulse in order to transmit and compensate the AOM insertion loss in the system. The sensing distance of the system has been greatly improved. However, the centralized amplification allows the system to have large spontaneous emission noise (ASE), and the extension of the sensing distance is affected by the nonlinear effect of the system. Therefore, the distributed amplification technology has unique advantages. At present, the improvement of the range of sensing methods are mainly Raman amplification, Brillouin amplification and mixed amplification. Hugo F. Martins uses a first-order Raman amplification to improve the performance of the Φ -OTDR over long distances. The structure is shown in Figure 5. The novelty of this system lies in the use of Raman amplification and balanced detection of two noise reduction methods combined to improve the system's signal to noise ratio. In addition, the system also uses semiconductor optical amplifiers (SOA) and optical switches to limit Φ -OTDR pulses, resulting in a significant reduction in noise in the coherent band. The sensing system is capable of detecting vibrations up to 250kHz in the 125km range with a spatial resolution of 10m.

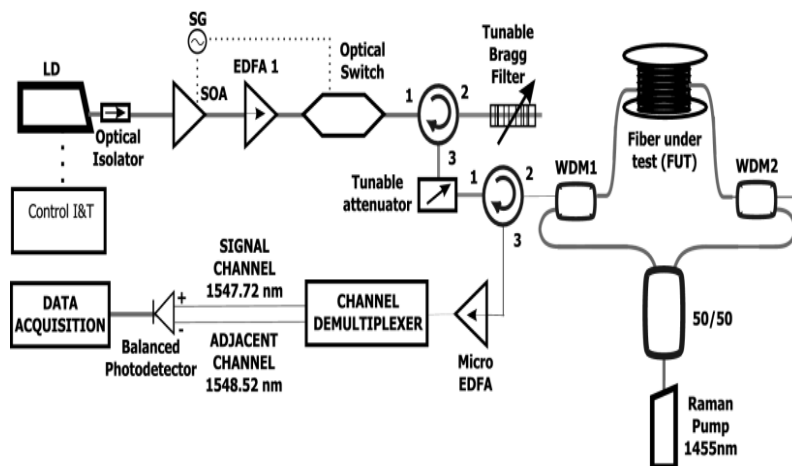


Fig.5 Φ -OTDR fiber vibration sensing system based on bidirectional first-order raman amplification technology

After that, Hugo F.Martins changed the system to combine the super-long Raman fiber laser (URFL) cavity with the phase-sensitive optical time-domain reflectometer (Φ -OTDR) to replace the first order in the original Φ -OTDR system Raman magnifies, as shown in Figure 6. Compared with the previous system, the scheme significantly enhanced the signal to noise ratio (SNR). Since the relative intensity noise (RIN) introduced by Raman amplification is mainly transmitted in the low frequency range below 5MHz, the balanced detection can better suppress common mode noise. In the absence of any follow-up processing, the system can be 125km within the detection range to achieve 10m of spatial resolution and 380Hz vibration.^{[19][20]}

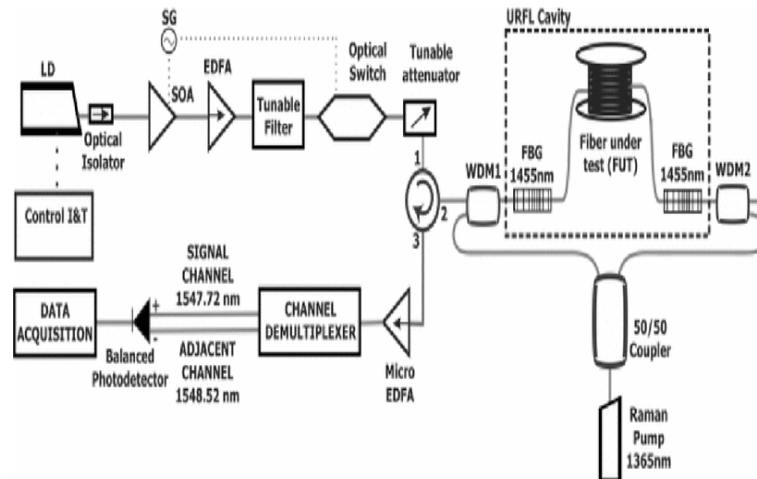


Fig.6 Φ -OTDR fiber vibration sensing system based on super long raman fiber laser cavity

In 2014, the University of Electronic Science and Technology Rao Yunjiang, who also proposed a long distance Φ -OTDR system to achieve real-time detection of external disturbances, the system has a high sensitivity. As shown in Fig. 7, this system adopts bidirectional Raman amplification, combined with heterodyne detection and wavelet denoising to improve the dynamic range and signal-to-noise ratio of the system. The detection distance of the system is 128km, the spatial resolution is 15m, and the signal to noise ratio is 14dB.^[21]

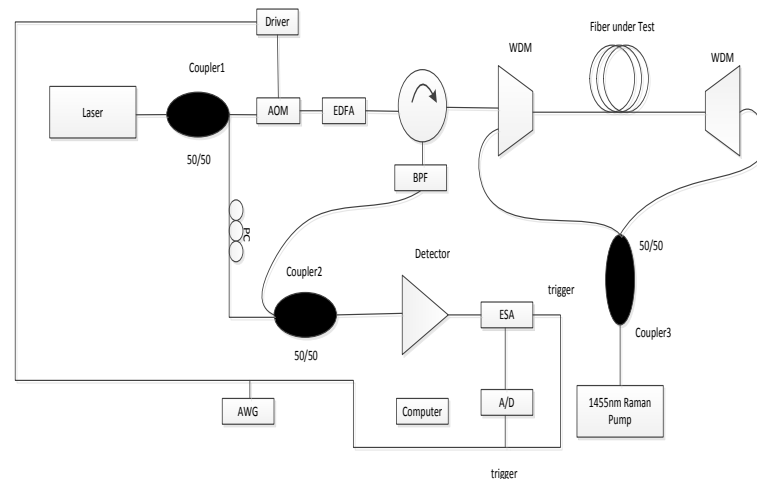


Fig.7 A long distance Φ -OTDR fiber vibration sensing system

And Zinan Wang and others to build Φ -OTDR fiber vibration sensing system to achieve a 175km distance sensor, and further increase the system's sensing distance.^[22] As shown in Figure 8, the system uses three different pumping schemes to extend the sensing range of the Φ -OTDR. Common-pumped second-order Raman amplifiers based on random fiber lasers provide gain primarily in the first half of the overall system; And then the reverse propagation of the Brillouin pump in the next 50km segment dominated amplification, the last step Raman amplification in the last 37km of the system for signal enhancement. The system's light source is 100Hz and the pulse width is 250ns.

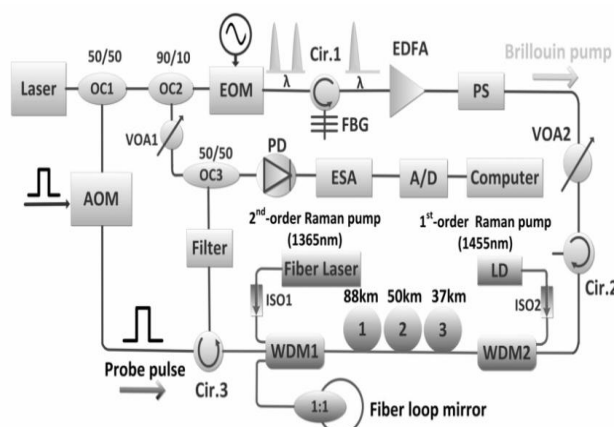


Fig.8 Ultra - long distance Φ -OTDR optical fiber vibration sensing system based on hybrid distributed amplifier

The advantages of distributed amplification are further seen from the experimental results. The future Φ -OTDR dynamic range is still the focus of the study. In addition to the already applied Raman amplification, Brillouin amplification also has research value. Compared to the Raman gain, Brillouin's gain is much greater than the Raman gain, up to three orders of magnitude. In addition, at the same time the introduction of distributed amplification technology, the use of heterodyne detection and other methods also with the system's sensing distance has a positive effect.

1.3.5 Phase blur problem

The strain measurement range of the system is also limited due to the phase blur, which can cause the misjudgment of the vibration frequency and the error measurement of the vibration amplitude, and even the omission of the large strain information.^[2,3] The backscattered light power in the fiber is periodically fluctuating with the increase of the stress. If the phase difference of the interference light field caused by the strain of the sensing fiber exceeds the monotonic range of the trigonometric function, the backscattered light power has a periodic multi-value phenomenon, that is, the phase is blurred. In order to avoid phase blur, Φ -OTDR system and the system parameters should be reasonable. The above mentioned Liang Kezhen and others in 2012 proposed a digital coherent detection and Wiener filtering technology combined phase-sensitive optical time domain reflection technology (Φ -OTDR). The application of Wiener filtering effectively reduces the phase noise caused by the phase noise of the laser and the additive noise caused by the additive noise of the detector, effectively avoiding the problem of phase blur.

IV. CONCLUSION

This paper mainly deals with the comprehensive discussion of Φ -OTDR system. The basic principle of Φ -OTDR system is introduced, and the related structure of Φ -OTDR system is discussed. The related parameters of the system are briefly summarized, and the improvement of the relevant parameters is analyzed. Among them, the Raman amplification technology and Φ -OTDR system will be more combined with the structure of the study. Since the gain of the stimulated Brillouin is much greater than the Raman gain, the combination of Brillouin and Φ -OTDR system is also a direction for future development. The author will be based on this research ideas, put forward a new hybrid Φ -OTDR system, continue to improve the sensing distance. In addition, the Φ -OTDR signal from the spatial domain and frequency domain analysis, respectively, to distinguish the specific mode of intrusion signal will also be the focus of future research direction.

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