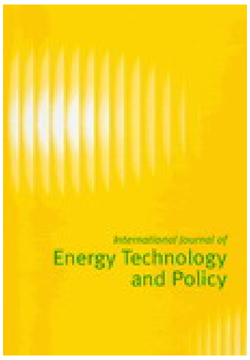

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Abstract: This study aims to explore the fibre distributed sensing system based on high-power ultra-narrow linewidth single-mode fibre lasers to achieve monitoring and protection of important areas such as borders, military restricted areas, power plants, nuclear power plants, prisons, etc. The study uses ultra-narrow linewidth single-mode fibre lasers as light sources, and uses the OTDR interference mechanism to interfere with the Rayleigh scattered light of each part of the optical cable to achieve sensing. The test results show that the maximum deviation between the transmission length and the centre length of the light source in each band does not exceed 0.06 nm, and the centre length offset of the two measurements is less than 0.01 nm. The system has good safety performance, high sensitivity, a wide range of applications and low cost advantages, and can complete precise measurements.

Keywords: optical fibre distributed sensing system; fibre laser; high power; ultra-narrow linewidth.

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1 Introduction

Optical fibre distributed sensing technology is a high-tech technology that integrates optics, mechanics and electronics. It is widely used due to its ultra-high anti-interference ability, excellent thermal insulation and corrosion resistance, excellent sensitivity and large-scale measurement focus on. At border lines, military restricted areas, power plants, nuclear power plants, prisons and other places, the monitoring and protection role of this technology is particularly prominent. Traditional monitoring methods have problems such as being susceptible to interference and complex wiring. Fibre optic distributed sensing technology is not only highly secretive but can also effectively avoid these problems by burying fibre optic lines into the soil. With the rapid development of high-power ultra-narrow linewidth single-mode fibre lasers, the performance of fibre-optic distributed sensing systems has been significantly improved, providing new solutions for safety monitoring in various fields.

Optical fibre distributed sensing technology has shown great application potential in many fields. In power engineering and metallurgical industries, it can monitor equipment status in real time to prevent accidents; in petrochemical plants, it can effectively monitor pipeline leaks to ensure production safety; in road traffic and fire warnings, it can respond quickly to abnormalities situation and reduce accident losses. In addition, this technology can also play an important role in the field of information dissemination and improve the stability and security of data transmission. Therefore, in-depth research on optical fibre distributed sensing technology is of great significance to promote the development of related fields.

This paper proposes a fibre distributed sensing system based on high-power ultra-narrow linewidth single-mode fibre laser and conducts in-depth research on it. The article elaborates on the construction method, working principle and experimental process of the system in detail, and proves the stability and effectiveness of the system in practical applications. In addition, the article also reviews the current research focus of optical fibre distributed sensing systems, including feature extraction technology, event recognition technology, and positioning error reduction methods. These research contents not only enrich the theoretical system of optical fibre distributed sensing technology, but also provide strong support for the practical application of this technology.

2 Related work

The current focus of optical fibre distributed sensing system research is on: For the three most common on-site test signals, Wu compared wavelet packet dissolution and wavelet decomposition as feature extraction techniques. Additionally, he developed a neural network technique for event identification to lower the high false alarm rate in practical applications of the phase-sensitive optical time domain reflectometer technology-based highly sensitive distributed optical fibre vibration sensing system (Wu et al., 2017). The four most common Φ-OTDR oscillation sensing systems were described by Ahmed, along with the distributed optical fibre sensing system based on a phase-sensitive time-domain reflectometer and its operating principles. Additionally, the sensing position and level of precision were detailed together with the development of the system configuration. Their benefits and drawbacks were outlined, which helped determine how to select a workable method in practice (Ahmed and Yu, 2019). Wang proposed a novel approach of multiple zero frequency optimisation to reduce the positioning error of the linear Sagnac distributed optical fibre vibration sensing system. He began it by outlining the conventional positioning strategy. The explanation for the rise in positioning mistake was provided by an analysis of the multiple space-frequency phenomena. He conducted out practical verification after putting up a theoretical strategy for multi-zero frequency optimisation (Wang et al., 2017). Han suggested an ultra-weak fibre Bragg grating (FBG) array-based distributed sensing system with high speed and resolution. In this method, wavelength shift measurements were converted into straightforward intensity measurements using narrow bandwidth filters. By adding a reference channel to the system, the intensity variations of the light source or fibre bending losses were adjusted (Han et al., 2017). These studies have primarily focused on the resolution, accuracy, and error of optical fibre distributed sensing systems. However, there is a relative scarcity of research addressing the stability and sensitivity of these systems. Recent advancements suggest that utilising high-power, narrow linewidth fibre lasers can significantly enhance the stability and sensitivity, reducing noise and improving overall performance. This approach holds great potential for optimising the reliability and precision of fibre-optic distributed sensing technologies.

The primary areas of study for high-power, extremely-narrow linewidth single-mode fibre lasers are: Feng proposed and verified a single-longitudinal mode fibre laser with ultra-narrow linewidth and high stability in the C-band with excellent performance and wavelength switchable. The high stability was explained by this small change in wavelength of light and laser power detected within 1.5 hours. In practical applications, better temperature compensation and vibration reduction packaging could further improve the performance of fibre lasers (Feng et al., 2019). A high-power, ytterbium-doped fibre laser with LP11 mode laser output was shown by Song. A pair of few-mode FBGs with matching LP11 mode reflection peaks was used to oscillate the LP11 mode. The matching of the reflection peaks of the LP11 mode was optimised using the FBG's temperature sensitivity (Song et al., 2018). Modern high-power fibre lasers with small linewidths, broad linewidths, and 2 m fibre lasers were all assessed by Liu. A approach that showed promise was coherent beam combining. It overcame the limitation of single-channel fibre lasers by achieving higher output power while maintaining outstanding beam quality. High-power coherent beam combining of fibre lasers was made possible thanks to a number of coherent beam combining core technologies, and the beam combining efficiency was high (Liu et al., 2019b). Based on a top-notch high-power amplifier, Wang built an all-fibre laser with a high output power, a low linewidth, and a close proximity to the diffraction limit. The seed was an oscillator with a long fibre optic line and a short cavity. The line width was 0.027 nm when the laser intensity was 7.3 W to prevent the spectrometer's broadening impact. At this point, the seed output power could be increased using a high-power amplifier (Wang et al., 2020). These studies highlight significant advancements in high-power, narrow linewidth fibre lasers, emphasising improved stability, mode control, and output power. However, challenges remain in optimising temperature compensation, vibration reduction, and beam quality in practical applications. While techniques like coherent beam combining and tailored FBGs show promise, further refinement is needed for widespread implementation.

3 Construction method of optical fibre distributed sensing system

Distributed optical fibre sensing systems input light pulses from one side of the cable, just like conventional optical time domain reflectometers. A photodetector examines the Rayleigh light that has been backscattered. The data from the sensing device is produced by coherent interference with the reflected Rayleigh scattered light in the frequency range of the optical pulse, which is different because light flowing through the fibre optic cable is extremely coherent. By measuring the time difference between the optical injection pulse and the received optical signal, the Φ-OTDR may determine the position change of the disturbance. The elastic effect causes the refractive index of the relevant component to change in the case of intrusion on an optical fibre line, changing the optical interference phase there. The intensity of the backscattered illumination changes as a result of the phase change brought on by the light interference effect. The backscattered Rayleigh light is detected with a detector. At the same time, this effect is determined by subtracting the forward and backward Rayleigh scattering curves of Φ-OTDR at different times. The subtracted curve illuminates the temporal distance of the intensity change. If an intrusion is encountered, the post-phase perturbation corresponds to the distance relative to the temporal distance of that end of the injected pulse (Ma et al., 2018; Li et al., 2021).

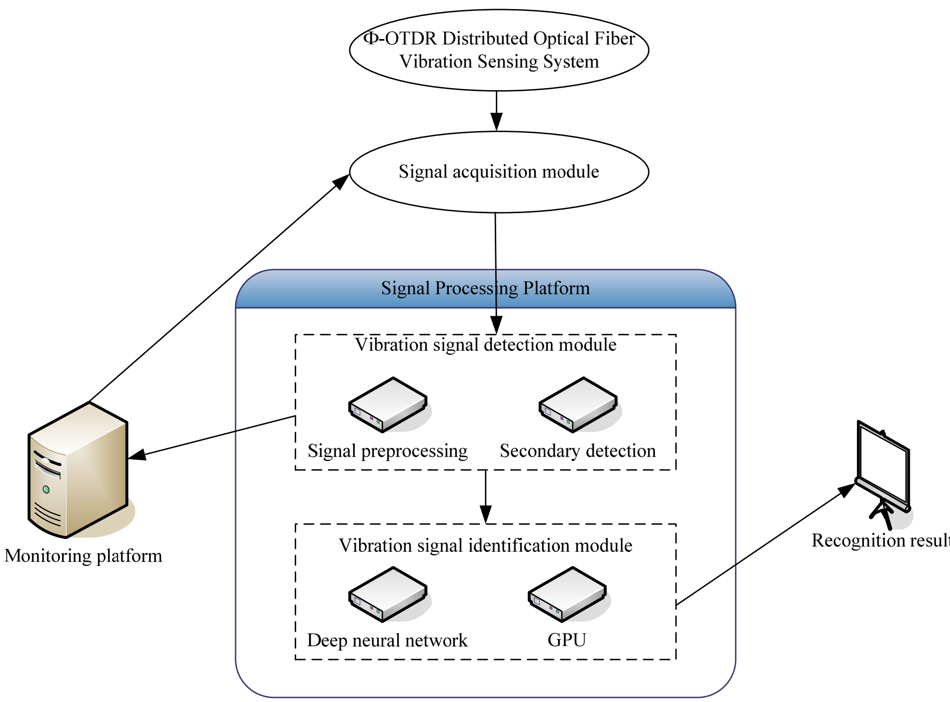
Compared with traditional optical time domain reflectometer, Φ-OTDR needs very narrow line width and small frequency drift. Narrow linewidth is the focus of the Φ-OTDR system, which is the precondition for the system to respond to the electron-optical phase change. The impact on the real effect is more visible and the system is more sensitive the thinner the line width. A particularly small frequency drift is also critical (Abulkasim et al., 2018).

As a new generation of lasers, fibre lasers should form their own safety specifications on the premise of inheriting laser safety protection measures such as solid-state lasers and vapour lasers. An excellent fibre laser that meets the requirements should be equipped with a complete safety support system, which consists of active control and automatic control systems (Shi et al., 2021). In the active automatic control system, the laser operators turn off the laser kinetic energy supply or press the 'emergency protection switch' to turn off the laser export according to the specific situation at the time, thereby reducing the probability of adverse events. This part of the automatic control system consists of three parts: intelligent monitoring system, alarm equipment, and mandatory power-off system software. First of all, the real-time monitoring system software takes the power of the laser as the basic monitoring object, which combines the operating temperature, the return laser power and the communication environment as the basic monitoring objects. When the monitoring objects such as power and ambient temperature exceed the preset value range, the operation alarm device alarm is activated to urge the control panel to terminate the inspection. According to the corresponding lights of the alarm object flashing, the relevant person in charge is helped to check. When the detector detects that the control board ignores the alarm or generates a more serious common fault in an instant. When the indicator enters the preset risk category, the machine is forcibly turned off and the laser is locked to prevent the laser or damage from causing other negative effects (Chu et al., 2020; Zhang et al., 2021).

The fibre laser control system is based on the analysis and judgment of the operating state of the laser. The key basis for the judgment is the stability of the laser derived power. Therefore, an excellent fibre laser power monitoring system would become the mainstay of fibre laser application security, which is also the future development trend of fibre lasers (Xue et al., 2020).

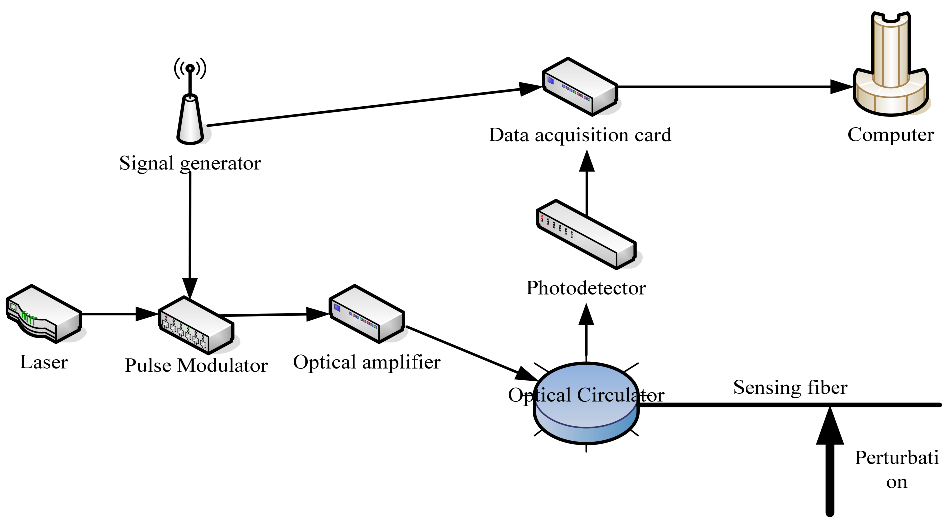
This work develops an integrated optical fibre vibration signal detection system to detect the external optical fibre's vibration signal in real time and enable system continuous monitoring (Gao et al., 2019). Figure 1 shows the architecture of the Φ-OTDR distributed optical fibre vibration signal monitoring system. Φ-OTDR distributed optical fibre vibration signal detection system is mainly composed of Φ-OTDR distributed optical fibre vibration monitoring system, signal collection module, signal preparation processing and inspection module, vibration signal identification module and monitoring platform. Among them, the sensing signal is the light intensity signal of the reverse direction Rayleigh scattering of the optical fibre. The signal collection module mainly collects the optical fibre vibration signal from the optical fibre sensing software, which transmits it to the subsequent modules for analysis and processing. The signal solution service platform includes signal preparation processing, inspection module and vibration signal identification module. Among them, the identification module can quickly operate the GPU through the independent graphics card, which can quickly obtain the identification conclusion. The monitoring management platform is an interactive service platform with services such as storing data, querying early warning reminders, and changing parameter configuration (Liu et al., 2019a).

Figure 1 Φ-OTDR distributed optical fibre vibration signal monitoring system frame diagram (see online version for colours)



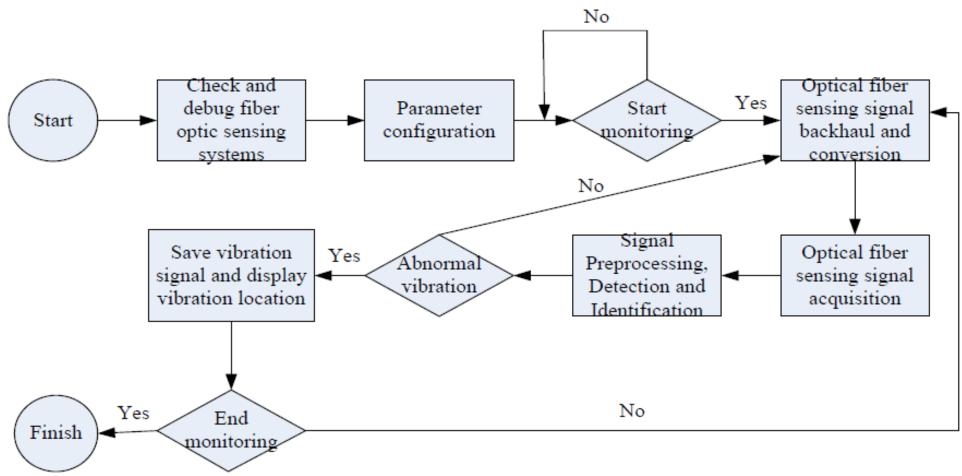
The Φ-OTDR distributed optical fibre sensing system is one of them that use a direct detection optical path construction. The frame diagram of the distributed optical fibre sensing system with Φ-OTDR is shown in Figure 2. The continuous light sensed by the laser is modulated into a pulsed laser by a pulse modulator and a fibre amplifier. It then becomes larger and enters the sensor fibre according to the optical circulator. The post-Rayleigh scattered light generated in the process of optical pulse spreading returns to the optical circulator and is received by the photodetector to generate an electrical signal. The data acquisition card collects the electrical signal and converts it into an analogue signal, which is sent to the electronic computer for resolution. The main parameters of the optical pulse generated by the pulse modulator and the timing control obtained by the data acquisition card are controlled by the signal generator. The Φ-OTDR system configuration requires the use of a narrow line-spacing laser generator as the light source. The continuous light from the laser generator is modulated into a pulsed laser by a pulse modulator, which is generally modulated by a photoelectric or light-controlled modulator. However, after the incoming light passes through the modulator, there is a certain amount of loss due to insertion loss. In order to prevent the backward Rayleigh's diffuse light data signal from being too weak to cause difficulty in detection, optical pulse amplification is also required (Dwivedi et al., 2022). The Φ-OTDR system software targets the post-Rayleigh scattered light in the fibre, which requires the use of a low-noise, power-amplified photodetector. The data acquisition card is used to convert the simulated analogue electrical signal output by the photodetector into a digital data signal. The information in the main control board is then resolved or transmitted to the electronic computer. The sampling frequency of the data acquisition card affects the overall spatial resolution of the sensor. The type of system bus also affects the information transmission rate between the data acquisition card and the computer.

Figure 2 Structure of the Φ-OTDR distributed optical fibre sensing system (see online version for colours)



The monitoring procedure for the entire system is depicted in Figure 3. The parameter setup of the real-time monitoring system is altered once the detection and adjustment of the Φ-OTDR distributed optical fibre vibration sensing system is finished. The Rayleigh scattered light travels through the photoelectric converter in the sensor fibre sequentially from close to distant at various distances after the monitoring command is sent. The intensity signal is converted into an electronic signal, and then passed through the signal acquisition card. The signal acquisition module reads the data of the acquisition card into the buffer through the high-speed serial computer expansion bus interface. The monitoring platform controls the size of the cache capacity, whether the acquisition and processing has been implemented, whether the data is saved and parameter settings. The collected signals are submitted to the signal analysis platform for resolution. When abnormal vibration occurs, the vibration signals are stored and displayed on the monitoring console (Zhu et al., 2021).

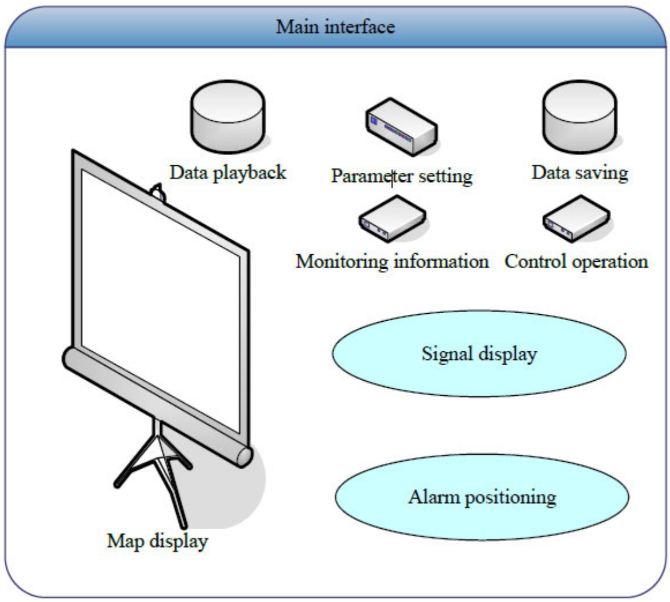
Figure 3 Process of system monitoring (see online version for colours)



The monitoring platform realises the interaction between human and machine. Using this system, users can control all system software and observe the corresponding alarm information. Figure 4 shows some important functions of the monitoring system. The monitoring platform is written in C# language. The signal acquisition and processing optimisation algorithm is written in C++ language. In the design, C++ is used to write signal preparation processing and identification algorithm program flow to form a dynamic link library. The DLL generated by the monitoring platform is called to complete the real-time monitoring system function. The identification function uses TensorFlow to call the GPU to perform fast calculation (Yu et al., 2021).

The monitoring management platform mainly includes functional areas such as real-time monitoring, data information review, parameter setting and data collection. The main page is used to display the real-time monitoring screen. In the main page, the execution or completion of the monitoring can be monitored by operating the keys in the control circuit box. The right of the control circuit switch is a record of supervisory information such as collection rate, information volume, field sampling and alarm frequency. Below the control circuit switch is the real-time monitoring curve, which indicates the change of the indoor space signal at that time (Liaw et al., 2021; Rivet et al., 2021). There is an alarm record in the lower right corner of the main page. It indicates the alarm site, the alarm site energy and the occurrence time while storing the alarm signal. On the left side of the main page is the monitoring graph. The red circle line represents the monitored boundary position. When an alarm occurs in a certain place, an alarm sign appears on the system map where the alarm occurs, that is, the position where the exclamation mark is issued at the upper left of the monitoring line. The data information review is to retrieve and display the real-time monitoring and alarm files saved before on the main page, which is conducive to repeated query and analysis. Parameter settings include optimisation algorithm parameter settings and data acquisition card parameter settings. The parameter setting of the algorithm includes the main parameters that need to be manually set in the process of identifying the algorithm. The parameter setting of the data acquisition card depends on the collection method of the vibration signal of the optical fibre line. Data collection is mainly to save the optical fibre vibration sensing signal, which is convenient for offline analysis. In general, the monitoring management platform customised in this paper is an interactive operation platform that integrates video monitoring system operation control, manual parameter setting, accurate alarm positioning, supervision information recording, vibration signal and map display, data storage and data information review (Wei and Kehtarnavaz, 2019).

Figure 4 The monitoring system's primary purposes (see online version for colours)



In this paper, the relevant formulas involved in the optical fibre distributed sensing system are mainly as follows:

$$E_{cl}^{x} = E_0 e^{-2dN_l} \sum_{a=1}^{Q} h_a^x e^{b\theta_a} \tag{1}$$

E_0 – input electric field energy. d – fibre attenuation coefficient. N_l – the length of the first l segment of the fibre.

$$I_{cl}^{x} = \left|E_{cl}^{x}\right|^2 = \sum_{a=1}^{Q-1} \sum_{a'=a+1}^{Q} E_0^2 h e^{-4dN_l} + 2E_0^2 a^2 \sum_{a=1}^{Q-1} \sum_{a'=a+1}^{Q} \cos\theta_a' - \theta_a \tag{2}$$

$\left|E_{cl}^{x}\right|^2$ – sum of scattered signal strengths.

$$K(s) = \sum_{i=0}^{D} f(i) s^{-i} \tag{3}$$

D – FIR filter order.

$$y(d) = -\sum_{i=0}^{D} f(i) y(d-i) \tag{4}$$

$y(d)$ – split the equation.

$$K_P(s) = 1 - s^{-i} \tag{5}$$

$K_P(s)$ – pre-emphasis processing.

$$h_p(a) = x((p-1)\times G + 1 + a)\times u(a) \tag{6}$$

P – current frame index, a – element index in frame, G – window length.

$$u(a) = \begin{cases} 1 & 1 \le a \le G \\ & 0 \end{cases} \tag{7}$$

$u(a)$ – fibre window function.

$$u(a) = \begin{cases} 0.5\{1-\cos[2\pi a/(G-1)]\} & 1 \le a \le G \\ 0 & \end{cases} \tag{8}$$

$$u(a) = \begin{cases} 0.51\{1-0.43\cos[2\pi a/(G-1)]\} & 1 \le a \le G \\ 0 & \end{cases} \tag{9}$$

$$T(d) = \frac{1}{G}\sum_{a=1}^{G} \left|h_p(a)\right| \tag{10}$$

$T(d)$ – short-term average level of the d^{th} frame.

$$E(d) = \frac{1}{G}\sum_{a=1}^{G} h_p(a)^2 \tag{11}$$

$T(d)$ – the short-term average energy of the optical fibre sensing signal $h_p(a)$ in the d^{th} frame.

4 Optical fibre distributed sensing system experiment

To evaluate the system's performance after each component is built, a simulation system has been developed. Figure 5 shows the structure of this simulation, which is intended to assess the performance of the sensing system across different real-world environments. The simulation includes four distinct placement scenarios for the sensing units, each representing a different environmental condition: grass, windowsill, artificial hedge, and artificial fence. The grass environment is simulated by burying the sensors underground to replicate conditions where the sensor is embedded in soil. The artificial hedge and fence environments are simulated by positioning the sensors beneath hanging nets, mimicking outdoor conditions where the sensors are sheltered or covered by materials such as hedges or fences. Lastly, the windowsill environment is simulated by placing the sensors under a cover, representing a typical indoor setting where the sensors are exposed to external temperature or light changes.

In the signal reception module, a dense wavelength division multiplexing (DWDM) system is employed to transmit signals according to their wavelengths to the corresponding photoelectric conversion modules. The resulting electrical signals are then captured by a multi-channel data acquisition card connected to the user's PC, which sends the data to the client management software for further analysis. The software interface displays the sensor data in real-time and triggers an alarm if any abnormal sensor readings are detected, ensuring prompt response and continuous system monitoring.

Figure 5 Simulation experiment structure diagram (see online version for colours)

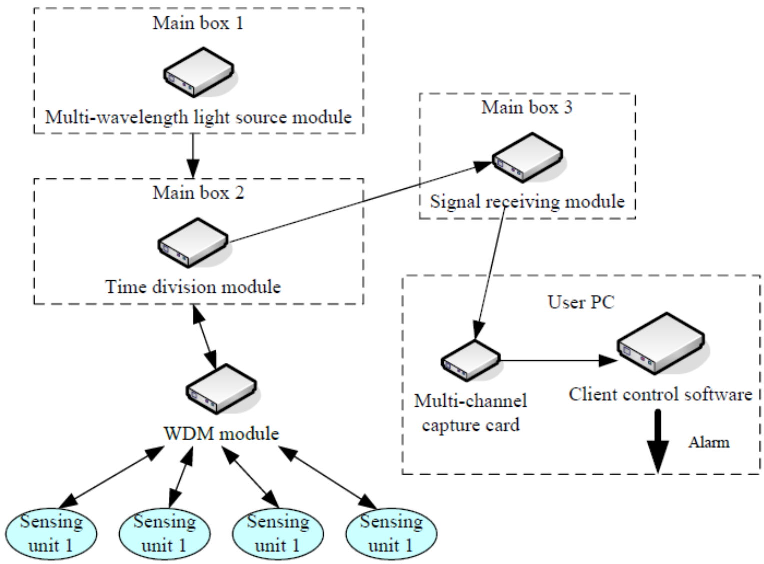
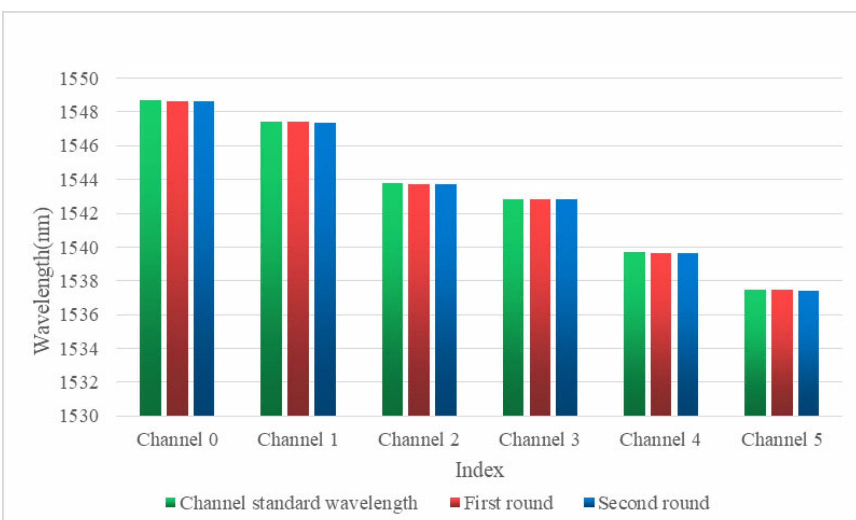


Figure 6 Multi-wavelength light source wavelength stability test (see online version for colours)



The main box 1 is placed to operate indoors. The broadband light source should always be kept working at room temperature. Cooling equipment such as a fan in the main box 1 also ensures the operating temperature of other working components. Therefore, it must be measured at room temperature. Figure 6 shows the statistical graph of the wavelength stability test of the multi-wavelength light source. As can be seen in Figure 6, the difference between the derived wavelength of the multi-wavelength light source and the wavelength under test is less than 0.06 nm. The wavelength difference between two precise measurements is less than 0.01 nm, which can meet the requirements of system operation.

Due to the high link loss of the system, in order to prevent the power of the sensor-induced signal from being completely lost, each channel requires a relatively large power. Higher power derivation can also lower the performance requirements for the photodetector, which leaves room for overall expansion. In addition, in the processing of the system software, the power ratio rather than the absolute power is used for the pulse change amplitude. That is to say, the signal power of the system software has been normalised. However, if the power of the signal source varies widely, it still has a significant impact on data processing. It can be seen that maintaining the stable operation of the system requires stable multi-wavelength light source power.

Figure 7 The output power performance test of each channel after amplification (see online version for colours)

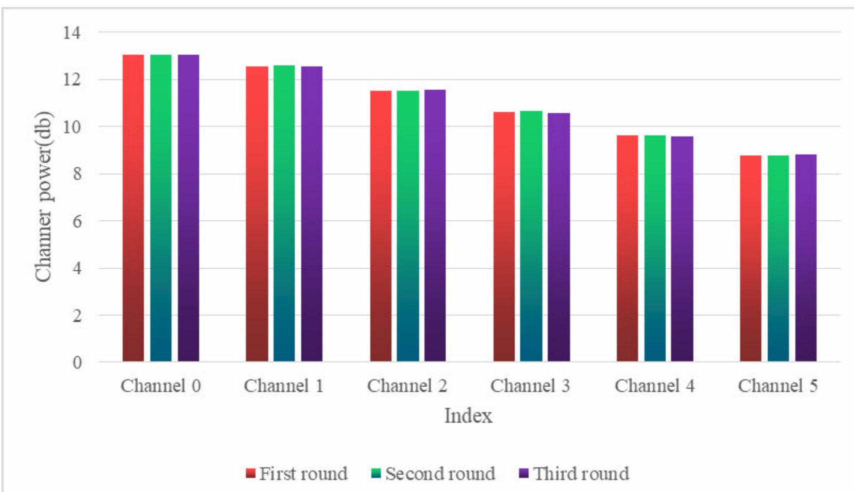


Figure 7 shows the output power performance test results of each channel after amplification. It can be seen that the situation occurs despite the large power difference of the channels. However, the operation of the system is relatively stable. The maximum value of fluctuation is less than 0.05 db, and the reliability is guaranteed. The power levelling slot can solve the problem that the power difference between channels is relatively large. However, in order not to reduce the total power, the test uses a method of rationally arranging the sensor cells. The high-consumption sensor units are placed on high-power channels, and the low-loss sensor units are placed on low-power channels. According to the reasonable layout, the column number and DWDM series number can ensure the actual effect of the whole system.

The system conducts artificially set intrusion tests on four sensor units arranged in various environments: lawns, windows, artificial fences and artificial fences to observe the actual effect of comprehensive monitoring. In the same wavelength division module, the lawn corresponds to channel 3. The window corresponds to channel 2. The simulated fence corresponds to channel 1. The simulated fence corresponds to channel 0. The platform's alarm communication is crucial. The system software should prevent one sensor unit from being invaded and the sensing data signal of the other sensor unit from abnormal conditions. When testing the actual implementation scheme, an intrusion test is carried out on a sensor unit in the simulation system to observe whether there is a change in the corresponding sensor data signal, whether there is an alarm, and whether the sensor data signal of other sensor units changes abnormally.

Table 1 System alarm correspondence test

Test round	*Hacked unit*	*Alarm unit*	*Other units*
1	Lawn	Lawn	No abnormality
2	Simulation fence	Simulation fence	No abnormality
3	Artificial fence	Artificial fence	No abnormality
4	Lawn	Lawn	No abnormality
5	Window	Window	No abnormality

As shown in Table 1, it is the system alarm correspondence test. As a result, it can be seen that the intruded unit corresponds to the final alarm unit. The correspondence between the system alarms is no problem. If an area is invaded, the corresponding signal can immediately alarm, other areas would not be affected, resulting in random reports.

When multiple protected areas of the system are simultaneously invaded by the outside world, the system must display all the alarm information content and no false alarms can occur. To determine the true impact of the system's alarm, a simultaneous incursion of the sensing unit experiment is run. As shown in Table 2, the results of the alarm integrity test of the system that invaded several protection areas at the same time. It can be seen that when multiple protected areas of the system are simultaneously invaded by the outside world, the system would issue an alarm to several protection areas that have been invaded. This shows that there are no omissions or misstatements.

Table 2 Integrity test of multi-zone intrusion system alarm at the same time

Test round	*Hacked unit*	*Alarm unit*	*Other units*
1	Lawn, simulation fence, window	Lawn, simulation fence, window	No abnormality
2	Artificial fence, lawn	Artificial fence, lawn	No abnormality
3	Simulation fence, artificial fence, window	Simulation fence, artificial fence, window	No abnormality
4	Lawn, window	Lawn, window	No abnormality
5	Lawn, artificial fence	Lawn, artificial fence	No abnormality

Because the sensor unit is placed outdoors, it is made of light-weight cables, and the DWDM control module and the tail waveguide are also packaged in the form of moisture-proof optical fibre fusion splicing. However, it may still be damaged by external forces. Therefore, if the differential signals strength of the sensor unit changes, an alarm should be issued. If the sensor data signal suddenly disappears, it should also sound an alarm. The alert must be different from other alerts. Therefore, this function is enacted in the system settings. If the system software sensor unit is damaged and the data signal subsides, the system would issue a warning in voice mode, which reminds the relevant staff to maintain the equipment in time. After testing, the alarm function is normal. When one of the sensing units is pulled out, the system immediately sends out an alarm signal of ‘cable wire disconnection alarm’.

The system features three alarm methods and a connected video surveillance function to improve real-time monitoring and response. When an intrusion or abnormal condition is detected, the relevant sensor unit triggers a bright red flashing signal on the client control program interface, instantly notifying the operator. At the same time, an audible alarm sounds at the alarm site to alert nearby personnel. To facilitate swift action, the system also sends e-mail notifications to the managers’ mobile phones, enabling remote monitoring.

Moreover, the system is integrated with a video surveillance network. When an alarm is triggered, the camera near the sensor unit activates to monitor the affected area, providing real-time video feedback. Unlike traditional video surveillance systems that continuously monitor areas, this setup only turns on cameras when an alarm occurs, reducing operational time. The same camera can be linked to multiple sensor units, optimising resource use and significantly lowering operational costs. This integrated alarm method not only boosts efficiency but also enhances the system’s cost-effectiveness, offering a more sustainable approach to continuous monitoring and rapid response.

5 Conclusions

This paper elaborates on the design of the distributed fibre optic sensing system, the design of the monitoring platform software, and the working content of the system, and completes the specific design and construction of the Φ-OTDR distributed fibre optic line vibration signal detection system. Through system experiments, the stability of the system and the actual monitoring effect are verified. Although this study has achieved certain results, there are still some shortcomings. There is relatively little research on the stability of the system, and in practical applications, fibre optic sensors may be affected by environmental factors, resulting in measurement errors. Future research will further improve the system stability analysis, optimise the algorithm to improve measurement accuracy, and explore more application scenarios to give full play to the potential of fibre optic distributed sensing technology.

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