

# Research on the application of fiber optic sensing technology based on intensity modulation

Kang Yun <sup>1, a</sup>, Jie Hu <sup>1, b</sup>, Baowei Liu <sup>1, c</sup>, Hong Xie <sup>1, d</sup>, Cheng Cheng <sup>1, e</sup>

<sup>1</sup> China Ordnance Industry Test and Research Institute, Xi 'an, Shaanxi, 712000, China

<sup>a</sup> yunkang19940824@163.com, <sup>b</sup> hujie@163.com, <sup>c</sup> lbws2002@163.com,

<sup>d</sup> alice1589@163.com, <sup>e</sup> 1102627027@qq.com

**Abstract.** Today's society has entered the information age with photoelectric technology and sensing technology as the main characteristics, optical fiber sensing technology.

The technology represents the development trend of a new generation of sensors, attracting worldwide attention for its high technical content, good economic benefits, strong penetration capabilities, and broad market prospects. This article delves into the fiber optic sensing technology based on intensity modulation and its applications across various fields. It introduces the basic concepts of fiber optic sensing technology, highlights the central role of intensity modulation in fiber optic sensing, and reviews the development history of intensity-modulated fiber optic sensing technology. The theoretical foundation of intensity-modulated fiber optic sensing technology is thoroughly explained, covering the principles of intensity modulation, the fundamentals of fiber optic sensing technology, and the methods of implementation. The article examines key technologies in intensity-modulated fiber optic sensing technology, including the selection and design of light sources, the design and optimization of fiber optic sensors, and signal demodulation and processing techniques. In terms of application areas, the article explores the specific applications of intensity-modulated fiber optic sensing technology in environmental monitoring, industrial monitoring, and biomedicine, such as air pollution monitoring, water quality monitoring, soil monitoring, temperature monitoring, pressure monitoring, vibration monitoring, physiological parameter monitoring, disease diagnosis and treatment, and biosensors. It also analyzes the challenges currently faced by the technology, including improving sensitivity and resolution, enhancing environmental adaptability and stability, and reducing system integration and costs. Furthermore, it proposes future trends, such as research into new light sources and sensing materials, intelligent and networked systems, multifunctional integration, and miniaturization.

**Keywords:** intensity modulation; optical fiber sensing technology; environmental monitoring; industrial monitoring; biomedical.

## 1. Introduction

Optical fiber sensing technology, a crucial branch of modern sensing, has become one of the key technologies for modern information transmission and measurement due to its unique advantages, such as high sensitivity, resistance to electromagnetic interference, and long-distance transmission. This technology primarily relies on optical fibers as the transmission medium, sensing changes in the external environment by measuring the variations in the transmission characteristics of light signals through the fiber. In optical fiber sensing technology, intensity modulation plays a vital role. Intensity modulation, which involves transmitting information by altering the intensity of light signals, is one of the most fundamental and common modulation methods in optical fiber sensing. It

reflects changes in the physical quantity being measured through changes in the intensity of the light signal, thus enabling precise perception of the external environment. The introduction of intensity modulation technology has not only enhanced the sensitivity and measurement accuracy of optical fiber sensing but also expanded its application scope, making it applicable in various fields such as environmental monitoring, industrial monitoring, and biomedicine. Reviewing the development history of intensity modulation-based optical fiber sensing technology, it is evident that it has achieved many significant results through continuous improvement and refinement. With the rapid advancement of optoelectronic technology, materials science, computer science, and related disciplines, intensity modulation optical fiber sensing technology has also been continuously innovated and improved, significantly enhancing its performance and application scope. This article aims to systematically analyze and reveal the internal mechanisms and development patterns of intensity modulation optical fiber sensing technology, providing valuable references and insights for research and practice in related fields.

## **2. Theoretical basis of intensity modulation optical fiber sensing technology**

### **2.1 Overview of intensity modulation principle**

#### **2.1.1 Definition of intensity modulation**

Intensity modulation, a key technology in optical fiber sensing, involves the laser oscillation [1] where the intensity of the optical carrier (light intensity) changes according to the modulation signal. In other words, intensity modulation is a technique that transmits information by altering the intensity (light intensity) of the optical signal. In an optical fiber sensing system, when external physical quantities such as temperature, pressure, or vibration change, these changes cause alterations in the parameters of the sensor's sensitive elements, such as refractive index and reflectivity, leading to variations in the light intensity within the transmission fiber. This change in light intensity can be detected and converted into an electrical signal, enabling the measurement and perception of external physical quantities.

#### **2.1.2 Basic principle of intensity modulation**

The fundamental principle of intensity modulation is to reflect changes in the physical quantity being measured by altering the intensity of the optical signal. Specifically, when the sensitive element in an optical fiber sensor interacts with external physical quantities, its parameters (such as refractive index and reflectivity) change, which in turn affects the intensity of the optical signal transmitted through the fiber[2]. This altered optical signal is then received by a receiver (such as an optical detector) and converted into an electrical signal. After demodulation, the information about the physical quantity being measured is obtained.

In the process of intensity modulation, there is a specific correlation between the changes in the intensity of the optical signal and the changes in the physical quantity being measured. Therefore, by measuring the changes in the intensity of the optical signal, precise measurement and perception of the physical quantity can be achieved. This technology offers high sensitivity, rapid response, and resistance to electromagnetic interference, making it widely used in fiber optic sensing. However, in practical applications, intensity modulation technology may face challenges from factors such as light source stability, fiber loss, and environmental noise. To address these issues, researchers typically implement various technical measures, including using highly stable light

sources, optimizing fiber structure, and incorporating noise suppression algorithms, to enhance the performance and reliability of the intensity modulation fiber optic sensing system.

## **2.2 Basic of optical fiber sensing technology**

### **2.2.1 Basic structure and characteristics of optical fiber**

Optical fibers, or optical conductive fibers, are media that use the principle of total internal reflection to transmit information. They consist of three main layers: the core, the cladding, and the coating. The core, located at the center of the fiber, serves as the primary channel for light wave transmission. To enhance the efficiency of light transmission, the core is typically doped with impurities to increase its refractive index [3]. The cladding, which surrounds the core, has a slightly lower refractive index than the core. This design ensures total internal reflection at the interface between the core and the cladding, enabling long-distance transmission of light through the fiber. The coating, the outermost layer of the fiber, protects it from environmental contamination and mechanical damage.

The primary characteristics of optical fibers include low transmission loss. Due to the principle of total internal reflection, optical fibers transmit information with much lower loss compared to traditional electrical signal lines. They also offer a wide bandwidth, capable of supporting high-speed data transmission with a bandwidth of tens of GHz or more. Optical fibers are highly resistant to electromagnetic interference because they use light signals for transmission, which are unaffected by electromagnetic fields. Additionally, optical fibers are lightweight and flexible, with diameters ranging from a few micrometers to several hundred micrometers, making them easy to install and lay.

### **2.2.2 Working principle of optical fiber sensing**

Fiber optic sensing technology works by converting the state of the object being measured into a measurable optical signal, which is then transmitted and detected using optical fibers. Specifically, when external conditions such as temperature, pressure, or displacement change, these changes can alter certain characteristics of the optical signal, such as its intensity, phase, or polarization state[4]. The altered optical signal is then transmitted through the fiber to an optoelectronic device, where it is demodulated to reveal information about the physical quantity being measured. Fiber optic sensing technology is known for its high sensitivity, fast response time, and strong resistance to electromagnetic interference, making it widely used in various fields.

## **2.3 The realization of intensity modulated optical fiber sensing technology**

In the process of realizing intensity modulation optical fiber sensing technology, it involves many aspects such as light source and modulation technology, optical fiber sensor design and signal demodulation and processing technology.

### **2.3.1 Light source and modulation technology**

The light source is a key component in intensity-modulated fiber optic sensing technology, and its performance directly impacts the system's measurement accuracy and stability. Typically, such systems use stable and reliable light sources, including semiconductor lasers and fiber lasers. These light sources offer advantages like stable output power, narrow spectral width, and small linewidth, which meet the system's requirements for light source performance. The modulation technique is crucial for achieving intensity modulation. In an intensity-modulated fiber optic sensing system, this modulation is primarily achieved by adjusting the light source's output power or the intensity of the

optical signal transmitted through the fiber. Specifically, the output power can be adjusted by controlling the light source's drive current or voltage with electrical signals; alternatively, a modulator (such as an electro-optic modulator or an acousto-optic modulator) can be introduced into the fiber to alter the intensity of the optical signal using electrical or acoustic signals.

### 2.3.2 Design of optical fiber sensor

In sensor design, key factors to consider include the sensor's sensitivity, measurement range, response time, and stability. To enhance performance, high-sensitivity optical fiber materials and structures, such as fiber Bragg gratings (FBGs) and fiber interferometers, are commonly used. Additionally, the sensor's structure should be optimized to minimize environmental interference and noise affecting the measurement results. In sensor design, the coupling between the light source and the optical fiber must also be considered. To improve coupling efficiency, optical components like optical couplers or lenses are typically employed to achieve precise coupling between the light source and the optical fiber. Furthermore, a thorough study of the optical fiber's transmission characteristics is essential to understand the transmission patterns and loss mechanisms of optical signals, providing theoretical support for sensor design.

### 2.3.3 Signal demodulation and processing technology

In the signal demodulation process, the received optical signals are converted into electrical signals, and the information about the physical quantity being measured is extracted. Typically, this process involves steps such as photoelectric conversion, amplification, and filtering. During photoelectric conversion, photodiodes or photomultiplier tubes are commonly used to convert optical signals into electrical signals. In the amplification and filtering stages, the electrical signals are amplified and filtered to enhance their signal-to-noise ratio and resistance to interference. In signal processing technology, digital signal processing techniques are often employed to further process and analyze the demodulated electrical signals. These techniques, including signal filtering, feature extraction, and pattern recognition, enable precise analysis and processing of measurement results. Through digital signal processing, the measurement accuracy and stability of intensity-modulated fiber optic sensing systems can be significantly improved.

## **3. Second, research on key technologies of optical fiber sensing technology based on intensity modulation**

### **3.1 Light source selection and design**

In the optical fiber sensing technology based on intensity modulation, the selection and design of light source are very important. The light source not only determines the measurement range and accuracy of the sensing system, but also affects the stability and reliability of the system.

#### 3.1.1 Type and characteristics of light source

There are various types of light sources, including semiconductor lasers, fiber lasers, and superluminescent diodes (SLDs). Each type has its own characteristics and is suitable for different applications. For example, semiconductor lasers are known for their compact size, high efficiency, and long lifespan, making them ideal for sensing systems that require high precision and stability. Fiber lasers, with their tunable wavelengths and narrow linewidths, are ideal for sensing systems that need multi-wavelength or multi-parameter measurements. SLDs, with their broad spectral output and high power output, are widely used in fluorescence spectroscopy and biological imaging [5]. When selecting a light source, it is important to consider factors such as output power, spectral

characteristics, modulation bandwidth, and noise level. For example, sensing systems requiring high-precision measurements should use light sources with stable output power, narrow spectral linewidths, and large modulation bandwidths. Sensing systems requiring high-sensitivity detection should use light sources with low noise levels and a wide spectral range.

### 3.1.2 Light source stability and modulation performance

The stability of the light source is a critical factor affecting the performance of a sensing system. A poorly stable light source can lead to increased fluctuations and uncertainty in measurement results, thereby impacting the system's accuracy and reliability. Therefore, when designing a sensing system, it is essential to select a light source with good stability and implement effective measures to minimize the impact of light source fluctuations on system performance. Additionally, the modulation performance of the light source is also a crucial consideration. A light source with excellent modulation performance can quickly respond to changes in the modulation signal, enabling rapid and accurate measurements. To enhance the modulation performance of the light source, methods such as using high-speed modulators and optimizing the light source drive circuit can be employed.

## 3.2 Design and optimization of optical fiber sensor

### 3.2.1 Sensor structure design

The design of optical fiber sensors should take into account the characteristics and requirements of the measurement object to achieve high sensitivity, precision, and stability. In designing the sensor structure, it is essential to select core and cladding materials with appropriate refractive indices, thermal stability, and chemical stability based on the physical and chemical properties of the measurement object. The length and diameter of the optical fiber should be determined according to the measurement range and accuracy requirements. Longer fibers can provide a wider measurement range but may also increase signal attenuation and noise interference; thinner fibers can enhance sensitivity but may reduce mechanical strength and stability[6]. The sensitive element, which interacts directly with the measured object in optical fiber sensors, should be designed to effectively convert the measured physical quantity into changes in light signals. The design of the sensitive element should consider factors such as sensitivity, linearity, stability, and reliability.

### 3.2.2 Sensor sensitivity and dynamic range

The sensitivity and dynamic range of optical fiber sensors are crucial indicators of their performance. Sensitivity reflects the sensor's ability to respond to changes in the physical quantity being measured, while dynamic range determines the range of physical quantities that can be measured. To enhance the sensitivity and dynamic range of optical fiber sensors, gain mechanisms such as optical amplifiers or gain fibers can be introduced into the sensor to boost the intensity of the optical signal, thereby improving the sensor's sensitivity. Advanced modulation and demodulation techniques, such as frequency modulation and phase modulation, can improve the signal-to-noise ratio and interference resistance of the optical signal, thus expanding the sensor's dynamic range. By integrating optical fiber sensors with other types of sensors, such as electrical and chemical sensors, multi-parameter measurements and cross-verification can be achieved, further enhancing the sensor's sensitivity and reliability.

### 3.2.3 Sensor environmental adaptability

Fiber optic sensors should have excellent environmental adaptability to accommodate changes in the environment under various application scenarios. To enhance the sensor's environmental adaptability, materials with good weather resistance, corrosion resistance, and oxidation resistance should be selected during the design phase to ensure the sensor's stability and reliability in harsh environments. Introducing a temperature compensation mechanism into the sensor can reduce the impact of temperature changes on measurement results, thereby improving the sensor's temperature stability. By optimizing the packaging and protective measures, the external environment's impact on the sensor can be minimized, enhancing its interference resistance and reliability. For example, waterproof, dustproof, and shockproof packaging technologies can be used to protect the sensor from external environmental factors.

### **3.3 Signal demodulation and processing technology**

#### **3.3.1 Signal demodulation method**

Signal demodulation involves converting the optical signals from sensors into electrical signals and extracting information related to the physical quantity being measured. In fiber optic sensing technology, common methods of signal demodulation include intensity demodulation, phase demodulation, and frequency demodulation. Intensity demodulation works by interpreting changes in the intensity of the optical signal. When the physical quantity being measured changes, the intensity of the optical signal in the fiber changes, and this change can be used to extract relevant information. Phase demodulation uses the phase changes in the optical signal to interpret information. This method offers higher sensitivity and precision but requires more complex demodulation techniques and equipment. Frequency demodulation interprets information based on changes in the frequency of the optical signal. In applications such as vibration measurement, where there is a direct relationship between the frequency changes of the optical signal and the physical quantity being measured, the frequency changes can be used to extract relevant information.

#### **3.3.2 Signal processing algorithm**

In fiber optic sensing technology, signal processing algorithms are used to further process and analyze the demodulated electrical signals, extracting more precise and useful information. Commonly used signal processing algorithms include filtering, fitting, and spectral analysis. Filtering algorithms remove noise and interference from the signal, improving its signal-to-noise ratio. Common filtering methods include low-pass, high-pass, and band-pass filters. Fitting algorithms are used to fit and interpolate the signal, resulting in a smoother and more continuous curve. These algorithms help accurately describe the trends and characteristics of the signal. Spectral analysis examines the frequency distribution of the signal to understand the magnitude and distribution of different frequency components. This analysis helps identify useful and interfering components, guiding subsequent signal processing.

#### **3.3.3 Noise suppression and signal enhancement**

In optical fiber sensing systems, noise is inevitable. Noise can interfere with signal transmission and processing, reducing the system's measurement accuracy and stability. Therefore, noise suppression and signal enhancement technologies are crucial for improving system performance. Noise suppression techniques reduce the impact of noise on signals through hardware or software methods. Hardware suppression methods include using low-noise optoelectronic devices and optimizing optical path design; software suppression methods include digital filtering, noise prediction, and compensation. Signal enhancement techniques improve the system's measurement

accuracy and sensitivity by amplifying and enhancing the signal. Common signal enhancement techniques include optical amplification and electrical amplification. Optical amplification can be achieved using optical amplifiers, while electrical amplification can be achieved by adjusting the amplifier's gain and bandwidth. In practical applications, multiple signal demodulation methods, signal processing algorithms, and noise suppression and signal enhancement technologies are typically combined to achieve optimal system performance.

#### **4. Fourth, research on the application of fiber optic sensing technology based on intensity modulation in different fields**

##### **4.1 Application in environmental monitoring**

In the field of environmental monitoring, intensity-modulated fiber optic sensing technology has shown broad application prospects, particularly in atmospheric pollution, water quality, and soil monitoring. For atmospheric pollution monitoring, this technology can monitor the content of gaseous pollutants in real time and perform precise quantitative analysis. Fiber optic sensors can quickly detect key pollutants such as carbon dioxide, sulfur dioxide, nitrogen oxides, microplastic particles, and heavy metals in the air, providing timely warnings about air quality deterioration [7]. This technology not only enhances the real-time and accuracy of monitoring but also helps reduce the impact of air pollution on human health. In water quality monitoring, intensity-modulated fiber optic sensing technology plays a crucial role. Traditional methods often require sampling and laboratory analysis, which are time-consuming and costly. Fiber optic sensing technology, however, can monitor water quality indicators like dissolved oxygen, pH, and water temperature in real time and remotely, with high automation and accuracy. For example, fiber Bragg grating sensing technology can monitor pH levels and concentrations, while fiber Bragg grating sensing technology can monitor dissolved oxygen and temperature. These technologies provide more timely and accurate water quality monitoring data, offering scientific evidence for water protection and pollution control. Fiber optic sensing technology also has unique advantages in soil monitoring. Traditional methods for monitoring soil moisture and temperature often use discrete sensors, which cannot provide real-time data on the overall changes in soil moisture and temperature. Fiber optic sensing technology, by embedding optical fibers in the soil, can continuously and in real-time monitor changes in humidity and temperature across the entire soil profile. By measuring the light attenuation and scattering characteristics within the fibers, it can accurately determine the distribution of moisture and temperature in the soil. This comprehensive monitoring method provides a powerful tool for studying and managing soil moisture and temperature. Fiber optic sensing technology based on intensity modulation has broad application prospects in environmental monitoring. By continuously monitoring environmental parameters such as air quality, water quality, and soil conditions, it can provide robust technical support for environmental protection and sustainable development.

##### **4.2 Application in the field of industrial monitoring**

In the field of industrial monitoring, fiber optic sensing technology based on intensity modulation also shows a wide range of application potential, especially in temperature monitoring, pressure monitoring and vibration monitoring.

In industrial settings, precise temperature monitoring is essential for ensuring the normal operation of equipment and production safety. Fiber optic sensing technology based on intensity

modulation offers significant advantages in temperature monitoring. One commonly used method is fluorescence radiation fiber optic temperature sensing. By coating the end of the optical fiber with a fluorescent material, the intrinsic residual luminescence time of the material can be utilized to accurately measure the temperature at the measurement point. This technology is characterized by its compact size, ease of integration, reliable performance, resistance to electromagnetic interference, and excellent insulation properties, making it particularly suitable for internal temperature measurements in electrical equipment. In industrial processes, pressure monitoring is crucial for ensuring equipment safety, preventing accidents, and enhancing product quality. Fiber optic sensing technology provides high measurement accuracy and rapid response capabilities in pressure monitoring. Using fiber optic pressure sensors allows for real-time monitoring of pressure changes in pipelines, storage tanks, and other equipment, enabling adjustments as needed. Additionally, fiber optic sensing technology excels in its strong resistance to interference, long-distance transmission, and simultaneous multi-point monitoring, making it an ideal choice for industrial pressure monitoring. In the industrial sector, the vibration status of machinery is a critical indicator for assessing its health and predicting potential failures. Fiber optic vibration sensors convert mechanical vibrations into electrical signals for monitoring and recording, offering high precision, reliability, and strong resistance to electromagnetic interference. Installing fiber optic vibration sensors enables real-time monitoring of the vibration status of machinery, identifying abnormal vibrations, and promptly detecting fault points, thereby reducing equipment damage and downtime. Fiber optic vibration sensors can also be used in material testing, structural analysis and other fields to provide strong support for production and research.

### **4.3 Application in the biomedical field**

In the biomedical field, intensity-modulated fiber optic sensing technology has achieved significant application results, particularly in physiological parameter monitoring, disease diagnosis and treatment, and biosensors. Physiological parameter monitoring is a critical aspect of healthcare, involving the real-time monitoring of vital indicators such as heart rate, blood pressure, respiration, and body temperature. Fiber optic sensing technology achieves precise measurement of these parameters through optical sensors. For instance, a fiber optic blood pressure sensor can detect the flow rate and volume of blood by fixing a fiber optic cable to the patient's veins, thereby estimating the blood pressure. This sensor offers high precision, rapid response, and resistance to electromagnetic interference, providing doctors with accurate diagnostic information. Fiber optic sensing technology also plays a crucial role in disease diagnosis and treatment. In disease diagnosis, it can be used for biomed imaging, such as optical coherence tomography (OCT), which achieves high-resolution 3D imaging by measuring the interference of reflected light, aiding doctors in non-invasive observation and diagnosis of biological tissues like the eyes, skin, and blood vessels. Fiber optic sensing technology can also be used for spectral analysis, helping diagnose by analyzing the chemical composition and drug concentration within organisms. In treatment, fiber optic sensing technology has significant advantages. For example, fiber optic sensors can guide laser surgery operations by delivering laser energy to the target area through fiber optics and monitoring the laser's position and intensity with sensors, ensuring the accuracy and safety of the treatment. Fiber optic sensing technology can also be utilized in endoscopies and minimally invasive surgeries, assisting doctors with real-time image transmission and system monitoring. Bio-sensors represent another significant application of fiber optic sensing technology in the biomedical field. Biomedical fiber optic sensors, which utilize fiber optic technology, are widely used in drug screening,

biomolecular measurement, and disease diagnosis due to their superior sensing and contact characteristics. These sensors typically consist of components such as optical fibers, light sources, detectors, and signal processing systems, enabling real-time monitoring of various physical, chemical, and biological parameters within the body. For example, fiber optic biosensors can detect biomolecules like blood glucose and uric acid, providing convenient monitoring options for diabetic patients and others.

## Conclusion

In summary, fiber optic sensing technology based on intensity modulation has demonstrated broad application prospects in various fields, including environmental monitoring, industrial monitoring, and biomedicine, thanks to its unique advantages. Through in-depth research and continuous innovation, this technology has made significant progress in sensitivity, resolution, and environmental adaptability. However, facing increasingly complex application environments and diverse needs, the technology still faces numerous challenges, such as further improving sensitivity and resolution, enhancing environmental adaptability and stability, and reducing system integration costs. Looking ahead, with the development of new materials, processes, and technologies, we have every reason to believe that fiber optic sensing technology based on intensity modulation will become more mature and complete, providing strong support for achieving higher levels of measurement and control. At the same time, interdisciplinary integration and innovative development will also be key drivers for the continuous advancement of this technology.

## References

- [1] Jia Zhenan, Li Yagang, Yao Jian. Research on the Application of Engineering Monitoring Based on Fiber Optic Sensing Technology [J]. *Infrared*, 2024,45(04):39-45.
- [2] Song Xiuguang, Zhao Tao, Bi Yanmei, et al. Application of optical fiber sensing technology in road traffic [J]. *Journal of Shandong University (Engineering Edition)*, 2024,54(02):13-26+35.
- [3] Chufeng Hong, Bian Zhenglan, Xue Liang, et al. Exploration of Online and Offline Hybrid Course Construction for Fiber Optic Sensing Technology [J]. *Higher Education Journal*, 2024,10(07):106-109.
- [4] Guo Longjian. Application of optical fiber sensing technology in bridge detection [J]. *Transportation Construction and Management*, 2024, (01):77-79.
- [5] An Ning, Yin Baojun, Chen Shuhan, et al. Research Progress on Optical Fiber Sensing Technology [J]. *Journal of Yanshan University*, 2023,47(05):441-457.
- [6] Cao Zhongwei. Research on Interference-type Optical Fiber Ultrasonic Sensor and Its Demodulation Technology [D]. Xi'an Petroleum University, 2023.
- [7] Yin Haisong. Application of Distributed Optical Fiber Sensing Technology in Pile Foundation Testing [J]. *Intelligent Building and Smart City*, 2022, (11):176-178.