Principles and Applications of Optical Temperature Measurement

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Keywords: Fiber Optic Temperature Measurement Technology, Non-Contact Temperature Measurement, Current Status of Fiber Optic Temperature Measurement, Bragg Grating.

Abstract: Temperature measurement is a key link in industry and scientific research. Traditional temperature measurement methods have limitations in complex environments such as high temperature, high pressure, and strong corrosion. Optical temperature measurement has gradually become a research hotspot due to its advantages, such as non-contact measurement, fast response, high precision, and high sensitivity. With the continuous progress of optical technology and material science, the development of new optical temperature measurement methods has important research value. The existing optical temperature measurement methods still face room for technical improvement and optimization in practical applications. This article focuses on the principles and applications of optical temperature measurement methods, and focuses on the fiber optic temperature measurement technology (TMT). By analyzing the basic principles and performance characteristics of point TMT, quasi-distributed TMT, and distributed TMT, we study their principles, their application advantages, and problems in different scenarios. The research results show that fiber optic TMT has significant advantages such as high sensitivity, high precision, corrosion resistance, and distributed measurement, and is especially suitable for complex environments, and can effectively overcome the limitations of traditional TMT. The research conclusions of this paper provide a theoretical basis and practical guidance for the further development and application of fiber optic TMT, and provide new ideas and methods for temperature monitoring in related fields.

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1 INTRODUCTION

Temperature is a basic physical quantity that describes physical states. How to detect temperature quickly and accurately has become an important part of industrial development and scientific research. Optical temperature measurement is used in many fields, such as online detection of power cable line operating temperature, tunnel fire warning and forecasting system, and aircraft engine temperature testing, which require high precision, high sensitivity, high temperature resistance and corrosion resistance (Zeng, Xu & Hou, 2007; Luo et al. 2007; Han et al. 2022). Zeng, Xu & Hou (2007) Based on the temperature measurement principle of distributed fiber, using the same fiber, can realize tunnel fire monitoring and leakage detection. It has the advantages of early warning, setting multiple alarms, finding and positioning disasters (fires and leakages), being accurate, easy to use and maintain, safe and reliable, and long-distance monitoring. The system operates normally and stably, and has strong anti-interference ability. In addition, Yao et al. (2023) applied quasi-distributed fiber grating sensing technology to the measurement system, and after the system design was completed, they verified the anti-interference ability of the designed hydropower plant temperature measurement system, proving that the temperature measurement system can meet the actual temperature measurement needs. In recent years, fiber surface temperature testing technology has made great progress. Hbisreuther et al. (2015) produced a fiber grating high temperature sensor based on multimode single crystal sapphire fiber, and used this sensor to measure the high temperature of 1900°C, and its error is within the range of 2°C (Zhou, 2022).

This paper analyzes the principles and applications of the light temperature measurement

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method. As a new temperature measurement technology (TMT), fiber optic TMT has high sensitivity, accuracy, distributed measurement, and corrosion resistance characteristics. Its application fields and application prospects are broad. This article will analyze the point TMT, quasi-distributed TMT, and distributed TMT of fiber optic TMT, explore the basic principles and performance characteristics of the three fiber optic temperature measurement technologies, and draw their application advantages and problems faced.

2 THE BASIC PRINCIPLE OF LIGHT TMT

The photometric TMT originates from the relationship between the radiated power per unit area and the absolute temperature to the fourth power proposed by Joseph Sterfly (Sun, 1995). This method is a non-contact TMT based on the relationship between the radiation characteristics and temperature of an object. Its principles mainly rely on the law of bold radiation, the law of Wien's displacement, and the law of Planck's bold radiation. In 1884, Austrian physicist Ludwig Boltzmann deduced the same law as the results of the Stefan experiment based on thermodynamic theory and by assuming that light (electromagnetic wave radiation) is used as the working medium of the heat engine, thus providing a theoretical basis for the Stefan law (Huang, 2023). Therefore, this law is also called the Stefan-Boltzmann law. Wien's law of displacement was proposed by German physicist William Wien in 1893(Yang, Li & Ma, 2015). These two studies are also important principles of the photometric temperature method.

3 FIBER OPTIC TEMPERATURE MEASUREMENT

3.1 Point TMT

Point TMT is a technology that measures temperature at specific points and is widely used in industries, power, medical care, environmental monitoring, and other fields. It measures the temperature of the target point directly or non-contactly through a sensor or detector. The fiber temperature sensing device for fluorescent radiation in the dot fiber temperature measurement scheme and the fiber temperature sensing device using semiconductor material crystals are more engineering-friendly.
The measurement system is shown in Figure 1.

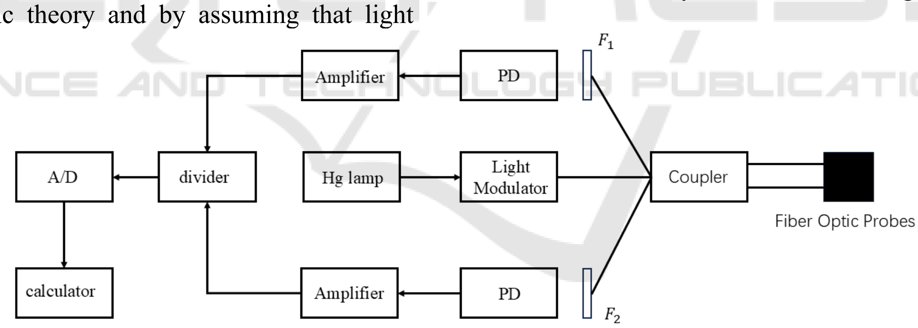

Figure 1: Scheme of the measurement system (Lu, Chen & Yin, 2024).

The system consists of three parts: an optical system, a fiber probe, and a signal processing system. The light source emits ultraviolet light and is tuned into pulse excitation light by the dimmer. It is transmitted to the probe through the optical fiber(TOF) to generate fluorescence. Two silicon photoelectric diodes detect the two fluorescence intensity signals received by TOF. Then it converts the two fluorescence signals into electrical signals. After amplification, it takes the average value and sends it to the divider to obtain the ratio signal, and then converts it into a digital signal through A/D. The ratio of the average value of the two signals is calculated by a computer and used to obtain the measured temperature. Fluorescent fiber temperature measurement has a fast dynamic temperature response, and can achieve accurate temperature measurement under harsh environmental conditions such as high voltage, large current, strong electromagnetic fields, and flammable and explosive environments. Traditional platinum resistors and thermocouples based on thermoelectric effects are prone to inaccuracy due to electromagnetic interference in a strong electromagnetic field environment, and the fluorescent fiber thermometer makes up for this deficiency. Fluorescent fiber TMT

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is currently mainly used in harsh environmental conditions such as strong electromagnetic fields, high voltages, and high currents.

Fluorescent fiber sensors have the advantages of small size, anti-electromagnetic interference, and high temperature resistance. They can be buried in the windings, which can effectively monitor the internal hot spot temperature of the power transformer and accurately understand the location of the hot spot. The application of fluorescent fiber thermometers fundamentally increases the possibility of obtaining the correct thermal model of the power transformer, as well as the online monitoring of the excitation system temperature. According to the survey, the maximum allowable error of fluorescent fiber thermometers currently used in the power industry is ±1.0° C. Due to its good insulation, fluorescent fiber thermometers can be directly attached to the surface of the thyristor component or buried inside it to achieve accurate temperature measurement. (Lu, Chen & Yin. 2024).

3.2 Quasi-Distributed Optical Fiber TMT

Quasi-distributed fiber optic TMT is a technology that uses a fiber grating as a temperature sensor, which can modulate and measure the temperature along TOF. This technology has many advantages, such as high sensitivity, small size, easy integration, and corrosion resistance.

3.2.1 Principles of Quasi-Distributed Fiber TMT

During the specific implementation process, the light emitted by the light source enters TOF through the circulator and is input into the TOF grating along TOF. TOF grating reflects the optical signal 56 back to the circulator, and the final optical signal is analyzed by a spectrometer or a demodulator. The corresponding temperature information is obtained from the wavelength information of the optical signal. The Fiber Bragg Grating(FBG) Temperature Sensor's Operating Principle is to expose and etch the Bragg fiber grating with different center wavelengths along the longitudinal direction of TOF. Each Bragg fiber grating is power-to-reflection for a specific optical wavelength. In the TOF transmission direction, multiple Bragg fiber gratings are connected in series in sequence to form a spatially discrete quasi-spatial distribution temperature measurement system. A beam of wide-spectral light containing multiple wavelengths is injected into TOF, and the beam passes through a series of FBGs, each grating reflecting back a monochromatic light signal corresponding to its central wavelength. (Huang, Xiao, & Li, 2022).

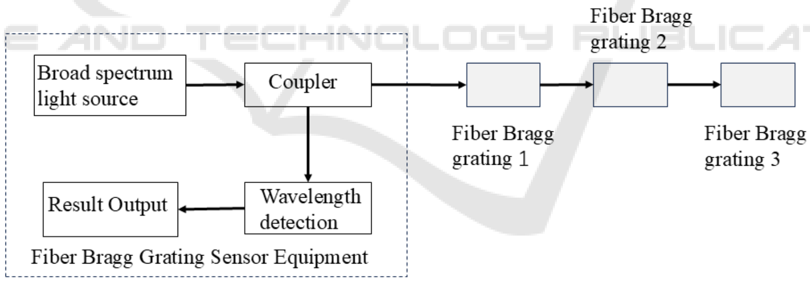

Figure 2: Fiber grating sensor equipment (Huang, Xiao, & Li, 2022).

The principle is shown in Figure 2. The FBG sensor device has a built-in wide-spectrum light source, which is coupled to the on-site FBG sensor through a coupler. The sensing part of the FBG sensor is distributed in different spatial positions in the temperature measurement area.

3.3.2 Distributed Fiber TMT

While the light waves are conducted in TOF, the specific wavelengths of light generated by different physical processes are different in TOF, and the signal light carrying temperature characteristics is demodulated at one end of TOF to achieve fully distributed temperature measurement. As shown in Figure 3, when light waves are transmitted in optical fibers, backscattered light is generated, including Rayleigh scattering, Raman scattering, and Brillouin scattering. When light irradiates matter, the photon interacts with molecules or atoms in matter, causing the energy of the photon to change, thereby producing scattered light. Raman scattering is one of the inelastic scattering phenomena, and the frequency of the scattered light is different from the frequency of the incident light.

Detecting the backscattering generated by various points along TOF, through the relationship between these backscattered light and the measured (such as temperature, stress, vibration, etc.), a distributed fiber sensing distributed fiber TMT can be realized, which is to use the temperature modulation characteristics of a certain specific light propagating in TOF to demodulate this temperature-carrying signal light at one end of TOF, thereby realizing distributed TMT (Liu & Sun, 2009).

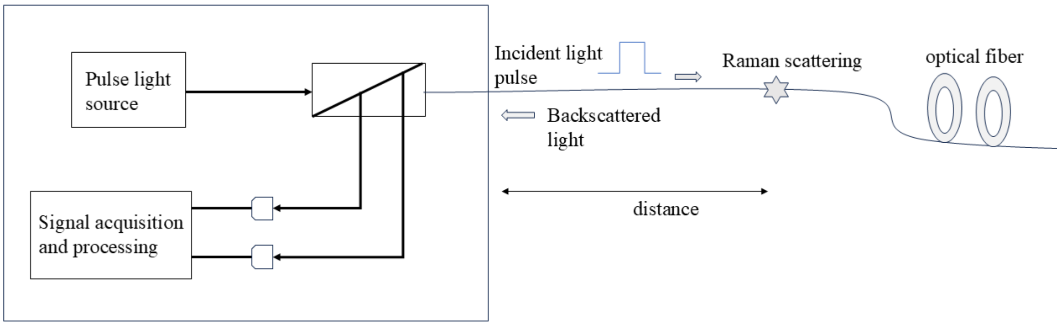

Figure 3: Principle diagram of optical fiber temperature measurement (Bo, 2024)

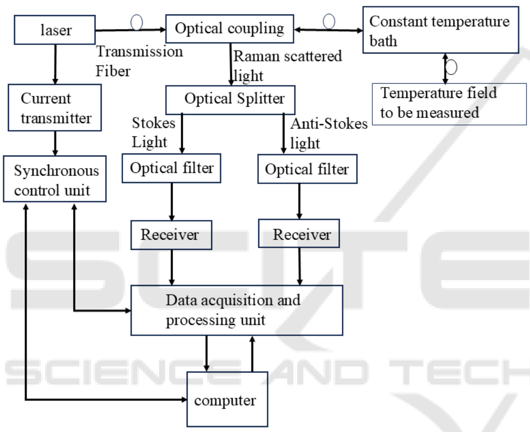

Figure 4: Principle of Distributed Fiber Optic High Temperature Sensor (Tong & Song, 2014).

During the transmission of a pulsed laser, the backscattered light signal of the sensing optical fiber will return to the optical coupler along the original transmission path and be coupled into the optical processing subsystem (Figure 4). Through the spectrometer, Stokes light and anti-Stokes light of different frequencies in the Raman scattered light are separated and entered into different optical paths for processing. The bandpass light filter filters out other scattered light and interfering light, allowing only Stokes and anti-Stokes Raman scattered light with temperature information to pass through. These two scattered lights are photoelectrically converted through their respective avalanche photodiodes (APDs), and the electrical signal is amplified, sent to the data acquisition and processing module, and the temperature is demodulated at different time positions, and then the spatial distribution information of the temperature is reconstructed through the OTDR principle, and displayed in a table or graphical format. Since the entire system has certain noise and losses, multiple measurements are required during operation. The data is then accumulated and averaged to eliminate adverse effects and obtain more accurate temperature distribution data. Finally, the data is stored in a computer database for the next step of application analysis (Al-Harb, 1998).

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4 CURRENT STATUS OF OPTICAL FIBER TMT

TOF temperature measurement is the preferred solution for temperature measurement in the power industry due to its excellent characteristics, such as moisture resistance, corrosion resistance, electromagnetic interference resistance, insulation, small size, and high sensitivity. In particular, point optical fiber temperature measurement and fully distributed optical fiber temperature measurement have been widely used in different application scenarios (Huang, Xiao, & Li, 2022)

4.1 Application of Fiber Point Temperature Measurement in Power Systems

For various reasons, the connecting parts of electrical equipment, such as isolating switches, switch cabinet dynamic and static contacts, cable heads, etc., when the current passes, the temperature rises, causing the equipment to age and the insulation to drop. In severe cases, it will cause short circuits, damage the equipment, and interrupt the power supply. During the operation of the transformer, the overtemperature of the winding will cause insulation aging, burning, breakdown, and other accidents. Other physical and chemical changes inside the transformer (such as local discharge and local overheating, etc.) will also cause changes in the transformer temperature, making the transformer perform differently from the temperature rise trajectory of normal operation. Previously, the on-duty personnel regularly used infrared cameras, thermometers, or temperature indicators to monitor the equipment offline. This method can only measure the temperature of the contact point exposed outside, while there is no effective monitoring method for the contact point temperature in the metal-enclosed switch cabinet. The fluorescent fiber temperature measurement solution has been used in power systems due to its small size, convenient integration, safe and reliable performance, anti-electromagnetic interference, good insulation performance, convenient installation, and flexible networking. The fluorescent fiber probe has a small size and can be measured deeply in the internal heat generation point to achieve real and effective monitoring of the heat generation point; it can be easily integrated into the intelligent switch cabinet and passed the type test; it can realize on-site display, which is convenient to integrate into the control system (Huang, Xiao, & Li, 2022).

4.2 Application of Fully Distributed Fiber Temperature Measurement in Power Systems

In recent years, distributed fiber temperature measurement systems based on Raman scattering and Brillouin scattering have been vigorously developed and promoted. Taking advantage of the inherent advantages of fiber sensing and combining the characteristics of fiber transmission and sensing, an optical fiber temperature measurement system with a monitoring distance of more than 30 km, continuous space monitoring, high monitoring sensitivity, corrosion resistance, and anti-interference is realized. It only requires the deployment of monitoring equipment at one end of the optical cable, and no additional sensing units are needed along the way. While achieving long-distance monitoring, it reduces the difficulty of deployment and maintenance. Raman distributed fiber TMT based on single-mode communication optical cables Because common communication optical cables are used as temperature measurement sensors, no additional equipment is required, and the temperature measurement sensitivity is high and the performance is stable, it is very suitable for temperature monitoring applications in business scenarios such as power pipeline corridors and overhead lines (Huang, Xiao, & Li, 2022).

5 CONCLUSION

This article discusses the principles and applications of the optical temperature measurement method in depth, focusing on optical fiber TMT. As a non-contact TMT, photothermal measurement has gradually become an important means in industrial and scientific research, with its advantages such as high accuracy, rapid response, and suitability for complex environments. Its principle is mainly based on the law of bold radiation, Wien's displacement law, and Planck's bold radiation law, and the temperature is calculated by measuring the radiation characteristics of an object. In terms of fiber optic TMT, this paper analyzes point TMT, quasi-distributed TMT, and distributed TMT in detail. Point TMT uses the fluorescent radiation phenomenon to determine temperature by measuring changes in fluorescence intensity or lifetime. It has high sensitivity and rapid response and is suitable for local temperature monitoring. Quasi-distributed TMT is based on the characteristics of TFG. It has the advantages of high precision and corrosion resistance, and is suitable for multi-point temperature monitoring. Distributed TMT uses backscattered light (such as Raman scattering) in optical fibers to achieve continuous temperature monitoring, which can provide temperature distribution information along TOFs and is suitable for long-distance and large-area temperature monitoring.

This article provides the theoretical basis and practical guidance for the further development and application of fiber optic TMT, and provides new ideas and methods for temperature monitoring in related fields. With the continuous advancement of technology, fiber optic TMT is expected to be widely used in more fields, providing more reliable temperature monitoring solutions for industrial production and scientific research.

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