Dean&Francis
ISSN 2959-6157

The Principle and Application Prospect of Optical Temperature Measurement

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Abstract:

The principle of optical thermometry not only changes the cognition of deterministic worldview in classical physics but also lays an important foundation for quantum mechanics. The challenge is still to reach places that are difficult to reach or that have an impact on the measurement environment. In this paper, the physical meaning of the principle of optical thermometry and its application and research progress in modern physics are reviewed. The fundamental limitation in quantum measurement is revealed. In this paper, the principle of temperature measurement is based on the characteristic that the emission spectrum of the excited fluorescent material changes with the temperature. The most important characteristic of fluorescence spectrum temperature measurement is that it overcomes the limitations of traditional temperature measurement. In this paper, the basic theory of blackbody radiation, especially Planck's law radiation, is briefly introduced and the close relationship between radiant energy and temperature is emphasized. In the third part, Raman spectroscopy and its basic principle are studied. The last part of this paper focuses on the temperature measurement method's in-depth study of its principle and application. The theoretical basis of the method, including the radiation law and optical properties, is described in detail. The photometric temperature measurement method has a wide application prospect in the fields of industrial production process monitoring, fire early warning, scientific research experiments, and so on. Future research can further optimize the photometric temperature measurement technology, improve its adaptability and reliability, and provide more effective means for temperature measurement.

Keywords: Optical thermometry; principle; application prospect.

ISSN 2959-6157

1. Introduction

Optical Thermometry (OT) is a temperature measurement technique based on the change of Optical properties of materials with temperature. It is widely used in quantum physics, materials science, semiconductor technology, and aerospace. The non-contact characteristic of OT makes it an optimal method for temperature measurement under extreme conditions such as high temperature, high pressure, and strong radiation, it overcomes the measurement error and limitation of the traditional contact sensor caused by environmental restrictions. At present, the research of optical temperature measurement mainly focuses on fluorescence spectroscopy, Raman spectroscopy, photoconductivity, and blackbody radiation. The fluorescence spectroscopy method depends on the fluorescence intensity of a particular material and the temperature dependence of the spectra. Raman spectroscopy is based on the relationship between the peak position of the scattering spectrum and the temperature. The blackbody radiation method determines temperature by analyzing the spectral distribution of thermal radiation. Each method shows unique advantages and limitations in different application scenarios [1].

Since it was put forward in the 20th century, OT has become an important research direction in the interdisciplinary fields of physics and chemistry. Zhang's research shows that OT optimizes temperature sensitivity and stability by combining fluorescent dyes with porous materials, allowing accurate, adjustable temperature measurements at the nanoscale, it provides an effective means for high precision and fast response temperature measurement [2]. The gradient-aided scheme proposed by Li achieves accurate temperature demodulation with centimeter spatial resolution in Raman-distributed optical fiber sensing, which greatly improves the accuracy of temperature monitoring in small areas, it provides a breakthrough for optical temperature measurement in the field of high precision and small-scale measurement [3]. However, traditional OT still has some limitations in high noise environments, fast temperature change detection, and signal attenuation compensation.

This paper discusses in detail the physical principle, technical advantages of optical temperature measurement and its wide applications in different fields. The aim of this paper is to analyze the challenges faced by current technology and look forward to its future development direction.

2. The Principle of OT

2.1 Fluorescence Spectrometry

Such as fluorescence spectroscopy, the phenomenon was first described by the Spanish scientist George. Drew. Georgede Moragas observed from 1575. However, it was not until the late 19th century that scientists began to study the phenomenon systematically. The essence of fluorescence is that after a certain amount of energy is absorbed by a material, the electrons transition from the ground state to the excited state, and then return to the ground state when the release of Lower Energy Light (fluorescence). This process involves a complex energy level conversion mechanism, including vibration relaxation, internal conversion, inter-system spanning, and so on. Photoluminescence, which refers to certain forms of excitation of certain fluorescent materials, will produce beyond the thermal radiation phenomenon.

According to Planck's law, when matter is excited by some form of energy, an electron transitions between energy levels E1 and E2(e1 < E2) and emits light waves of λ wavelength [3]. The fluorescence temperature measuring device made of the function relation between the fluorescence afterglow life and temperature has a superiority that the traditional temperature measuring method can not compare with [4]. Then focus on the Förster resonance energy transfer (FRET) if two fluorophores are separated by 1-10 nm and the emission spectra of one fluorophore (donor) overlap the absorption spectra of the other fluorophores (receptor), when the donor is excited by the incident light, its energy can be transferred to the receptor molecule in a non-radiative way through the dipole-dipole coupling, and the donor molecule decays to the ground state without emitting fluorescence, the receptor molecule transitions from the ground state to the excited state, then decays to the ground state and simultaneously emits fluorescence. This process is called fluorescence resonance energy transfer (FRET), and it is Förster resonance energy transfer [5].

2.2 Blackbody Radiation Method

The concept of blackbody radiation was first proposed by German physicist Gustav. In the 19th century, Gustav Kirchhoff proposed that he define an ideal object -- a blackbody -- that would absorb electromagnetic radiation of all frequencies without reflecting or transmitting it. In 1900, Max. Plonk's quantum theory, which explains the spectral distribution of blackbody radiation and derives Planck's law from it, was the beginning of quantum mechanics.

2.3 Raman Spectroscopy

Raman spectroscopy is a method of analysis by scattering effect. In 1928, Indian physicist C. V. Raman and his colleagues in his experiments, Krishnan observed a new kind of scattering, now known as Raman scattering. They found that when monochromatic light passes through a transparent material, there is a small change in the frequency of the scattered light in addition to the main Rayleigh scattering. Scattering of light usually refers to the process by which some of the light energy is absorbed, emitted, converted, and propagated in different directions, after light interacts with particles in matter, such as molecules, particles, or lattices. Its core is that after the incident light of a certain frequency interacts with matter, the molecule or atom absorbs the energy of the incident light, enters the excited state and radiates, and releases the energy of the excited state as photons.

Elastic scattering refers to the collision of light with particles or molecules in the medium, there is no energy transfer, and scattering light and incident light frequency are the same, that is, Rayleigh scattering. Tunku Abdul Rahman scattering is a type of inelastic scattering that occurs when light collides with particles or molecules in the medium, causing the frequency of the scattered light to change relative to the frequency of the incident light. In Sir George Stokes, 1st Baronet scattering, the sample absorbs the energy of the excitation light, which is scattered at a lower frequency than the incident light. Anti-stokes scattering is the opposite, the frequency of scattered light is higher than the frequency of incident light [6]. In addition to temperature measurement, Raman scattering is widely used in materials research, semiconductor industry, and other fields.

2.4 Principle of OT

OT is a technique for measuring temperature by optical means. It is mainly based on the close relationship between the optical properties of blackbody radiation and temperature. When the temperature of the object changes, the optical performance of blackbody radiation, such as radiation intensity, spectral distribution, and so on, will change accordingly. OT uses specialized blackbody and other specialized equipment to detect and analyze the thermal radiation emitted by objects. By comparing the thermal radiation characteristic of the measured object with the known temperature standard, or by using the special Stepan Boltzmann law, Weiss displacement law, and optical formula and model, the temperature value of the object can be calculated.

Non-contact measurement, that is, no interference to the object to be measured, is suitable for small objects, moving objects, or high temperature, high pressure, and other special environment temperature measurements. Fast response, that is, real-time monitoring of temperature changes. The measurement range is wide, from low temperature to high temperature has the corresponding optical temperature measurement method. However, the method is greatly influenced by environmental factors, such as the absorption and scattering of light, etc. At the same time, the optical characteristics of the measured objects have higher requirements, some methods need specific fluorescent materials or objects with a certain emissivity. In some cases, the precision of optical temperature measurement may be lower than that of traditional contact temperature measurement.

3. Applications and Contributions

With the rapid development of modern science and technology, OT, as a new temperature measurement technology, has been widely used in many fields for its high precision, non-contact measurement, and wide temperature range. Optical temperature measurement not only improves the accuracy and efficiency of temperature measurement but also brings revolutionary changes to scientific research, industrial production, and medical diagnosis.

In the field of industrial production, the optical temperature measurement method is particularly widely used. Take metal manufacturing and semiconductor manufacturing as an example, these industries have very high requirements for temperature control. By measuring the spectral changes of the reflection and transmission of the material surface, the laser temperature measurement technology can monitor the temperature change of the material in the high-temperature environment in real-time, to ensure product quality and production efficiency. In addition, the application of optical thermometers in the oil and gas industry, particularly in pipeline leakage and deformation monitoring, through the Brillouin optical fiber distributed sensing system (DTSS) real-time monitoring of temperature and strain, effectively identifies corrosion, environmental hazards, and potential damage to improve pipeline safety and maintenance efficiency [7].

In the field of scientific research, OT provides a new means for exploring the behavior of matter under extreme conditions. For example, in the study of high-temperature Superconductor classification, laser interferometry can accurately measure the phase transition of materials at different temperatures, providing important data to understand the superconducting mechanism. In addition, optical fiber temperature sensors have shown great potential in areas such as Environmental monitoring and geological exploration. The distributed optical fiber temperature sensor can be used for real-time monitoring of large-scale environmental temperature, which provides a scientific basis for climate change research and geological disaster warning.

In the field of medical diagnosis, OT also shows unique advantages. The fluorescence fiber temperature sensor can accurately measure the temperature of the human body by

ISSN 2959-6157

measuring the temperature change of the fluorescence material in human tissue, which provides new technical support for tumor hyperthermia and other treatment methods. The practical application of optical temperature measurement technology in medicine has significantly improved the accuracy and flexibility of temperature monitoring. For example, Luxtron M3300 system can provide real-time temperature measurement of ± 0.2 ° C in the range of 0 ° C to 120 ° C, the non-metallic probe can be used in MRI, RF, and microwave environments, which overcomes the inapplicability of the traditional temperature sensor in the high-frequency environment [8]. In addition, fiber optic temperature sensors have been widely used in minimally invasive surgery. By combining fiber-optic sensors with surgical instruments, doctors can monitor tissue temperature in the surgical area in real-time, thereby reducing surgical risks and improving the success rate of surgery.

OT has not only been widely used in industrial production, scientific research, and medical diagnosis but has also made an important contribution to social progress and economic development. However, the future development of optical temperature measurement technology faces multiple challenges. First, multi-parameter measurement capabilities need to be expanded from two-parameter to three-parameter or more to cope with cross-effects [8]. At the same time, improves the sensitivity and accuracy of the sensor to adapt to high pressure, strong radiation extreme temperature, and other harsh environments. In addition, the design of more intelligent and adjustable sensors to respond to different samples and conditions is also a key goal. Simplifying the manufacturing process will reduce costs and improve usability. In the medical field, the development of small devices that can monitor patients' temperatures in real-time will enhance rapid response to infection and improve the quality of care. In general, these efforts aim at improving the effectiveness and reliability of optical temperature measurement technology in various fields. Finally, the OT provides a new means for scientific research and promotes a deeper understanding of the natural world and the material world.

4. Conclusion

As an important breakthrough in modern temperature measurement technology, OT has shown great potential in scientific research and industrial application due to its high precision, non-contact, and extreme environmental adaptability. Different optical temperature measurement methods, such as fluorescence spectroscopy, Raman spectroscopy, photoconductivity, and blackbody radiation, provide accurate temperature measurement methods in their respective application fields, quantum mechanics, materials science, biomedicine, and so on. In the future, with advances in materials science and optoelectronic technology, OT is expected to be further improved based on technological innovation and optimization, such as higher measurement sensitivity, the ability to adapt to complex environments, and the wide application of real-time monitoring.

In addition, the optical temperature measurement method provides a new prospect for the deep mining of material microstructure characteristics and expands the application range of non-contact temperature measurement methods. Through further technical breakthroughs, the method will be more applicable to a variety of application scenarios, and provide support for scientific exploration in fields ranging from extreme environmental physics research to microscale biomedicine, thus for the promotion of social and technological progress and economic development to make a sustained contribution.

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