

Advances and Application Prospects of Spectrometers and Their Key Technologies

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Abstract:

Spectrometers are key devices for analyzing the structure and properties of substances. They have been widely applied in various fields such as chemistry, physics, biology, environmental monitoring, and astronomy. This article aims to review the classification, core technologies, application areas, and development trends of spectrometers. The article elaborates on the working principles, classification, and key technologies of spectrometers, and discusses their application in different fields and future development directions. In addition, this article also classifies different types of spectrometers, including monochromatic spectrometers, polychromatic spectrometers, infrared spectrometers, etc., and analyzes their respective advantages and disadvantages. The article particularly emphasizes the latest advancements in light source technology, spectrometry, detection technology, and data processing technology. At the same time, this article also outlines the extensive application of spectrometers in various fields.

Keywords: Spectrometers, advances and application prospects, key technologies

1. Introduction

A spectrometer is an instrument that can decompose light into a spectrum according to wavelength. It utilizes the interaction between light and matter to reveal the structure and properties of matter. By analyzing the spectrum, people can understand the composition of atoms and molecules, the type of chemical bonds, and the concentration of substances. Compared to other detection instruments, spectrometers have many advantages, including high precision, high efficiency, and low cost, making them widely used by professionals in various fields.

The development of spectrometers dates back to the seventeenth century when Newton used a prism to disperse sunlight, laying the foundation for the development of spectroscopy [1]. Subsequently, Wollaston discovered dark lines in the solar spectrum in 1802, and Fraunhofer named this phenomenon Fraunhofer lines in 1859. Kirchhoff and Bunsen further discovered that these dark lines were the result of sodium atoms in the sun's outer atmosphere absorbing sodium radiation in the solar spectrum. In 1955, Varshi of Australia turned atomic absorption spectroscopy into a practical analytical method and promoted its commercialization and application [2]. By the mid-

1960s, atomic absorption spectroscopy entered a period of rapid development and was widely applied in scientific research and industrial fields. Today, spectrometers continue to evolve and update, with miniaturized computational spectrometers (MCS) moving towards miniaturization [3]. There are also new types of spectrometers that use solution-processable semiconductors to build on-chip spectral analysis platforms, which are simple, low-cost, and suitable for a variety of spectral analysis needs [4]. Despite significant improvements in the resolution and accuracy of modern spectrometers, challenges still exist when dealing with complex samples.

This article sequentially introduces the principles, classifications and characteristics, key technologies, and application fields of spectrometers, aiming to provide readers with a deeper understanding of spectrometers.

2. The Principle of a Spectrometer

A spectrometer is an analytical instrument that works based on optical phenomena. It analyzes the composition of substances by decomposing light from a light source into a spectrum, which is a band of light of different wavelengths. Specifically, the spectrometer first allows light from the light source to pass through a sample, where the components of the sample absorb light of specific wavelengths, forming a characteristic absorption spectrum. Additionally, the components in the sample may emit or scatter light, forming an emission or scattering spectrum. These spectra are then transmitted to a dispersion system, such as a prism or diffraction grating, which disperses the light by wavelength. Finally, a detector records these dispersed spectra and transmits the data to a processing system for analysis. By comparing the sample spectrum with the spectra of known substances, the components and their

concentrations in the sample can be determined, achieving qualitative and quantitative analysis of the substance.

Traditional spectrometers separate light of different wavelengths through dispersion or diffraction phenomena. Dispersion is the phenomenon where light of different wavelengths has different refractive indices in a medium, thereby decomposing composite light into monochromatic light based on wavelength. The relationship between refractive index and wavelength is as follows:

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^3} + \dots \quad (1)$$

Where: $n(\lambda)$ is the refractive index of light with wavelength λ . A , B , C , etc., are dispersion coefficients, which depend on the properties of the medium.

By utilizing the principle of diffraction, a fine diffraction grating is set up, causing the light passing through a slit to diffract, with different wavelengths of light scattering at different angles, thus serving to separate them.

$$d\theta = \frac{m\lambda}{d} \quad (2)$$

Where: $d\theta$ is the change in the diffraction angle, m is the diffraction order, λ is the wavelength of light, and d is the grating constant. The basic structure of a spectrometer consists of a light source, entrance slit, dispersive element, focusing system, detector, and signal processing unit.

3. Classification and Characteristics of Spectrometers

To better understand the application range and technical characteristics of different spectrometers, this article compiles Table 1, which outlines the seven common types of spectrometers.

Table 1. Comparison of different spectrometers

Spectrometer classification	Advantages	Disadvantage
Monochromatic Spectrometer	Simple structure, easy to operate.	The resolution is low, only capable of analyzing specific wavelengths of light.
Spectrometer for mixed colors	Can analyze multiple wavelengths of light simultaneously.	The device is complex and expensive.
Optical Frequency Comb Spectrometer	Extremely high-frequency stability and accuracy	Technically complex, high maintenance costs.
Infrared Spectrometer	Suitable for analyzing the chemical structures of organic and inorganic compounds.	Requires high environmental conditions, expensive.
Ultraviolet-visible spectrophotometer	Suitable for analyzing substances in solutions, easy to operate.	Limited analytical capabilities for solid samples
Atomic Spectrometer	High sensitivity and high selectivity, suitable for trace element analysis.	The equipment costs are high, and professional operators are required.

Raman Spectrometer	No sample preparation is required, can perform non-invasive analysis.	The analysis of fluorescent substances is limited, with relatively low sensitivity.
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Table 1 shows the comparison of advantages and disadvantages among different spectrometers. Overall, choosing the appropriate spectrometer requires a comprehensive consideration of its application scenarios and specific needs, weighing the pros and cons to achieve the best analytical results.

4. Key Technologies of Spectrometers

4.1 Light Source Technology

The light source is a core component of a spectrometer, and its performance directly affects the overall performance and application range of the spectrometer. In the design of spectrometers, the selection and optimization of the light source are crucial. In recent years, with the development of micro-nano technology, spectrometers are evolving towards smaller and more refined directions, but this often means limitations in resolution and operating range. The innovative work of researcher Ma Yaoguang's team has brought breakthrough progress to this field.

The team has developed a micro-nano fiber cone spectrometer, which adopts the unique structure of micro-nano fiber cones. This structure can efficiently encode the spectral information that passes through it. Micro-nano fiber cones are components designed based on the principles of light transmission and manipulation at the micro-nano scale. Their working principle is mainly based on the following aspects:

Firstly, the tip diameter of the micro-nano fiber optic taper is extremely small, allowing for high focusing of light. When light passes through this tapered structure, there is a strong interaction between light and matter, which helps to improve the resolution of the spectrum. Secondly, the shape and size of the micro-nano fiber optic taper can be precisely controlled, enabling efficient encoding and decoding of spectral information for specific wavelength ranges. This structure also effectively reduces stray light and background noise, further enhancing the clarity and signal-to-noise ratio of the spectrum.

The spectrometer developed by Ma Yaoguang's team operates in the wavelength range of 450nm to 1100nm, covering a wide area from blue light to near-infrared light, which gives it potential application value in multiple fields. Most notably, the resolution of the spectrometer for input light can reach a level of 1.5pm (picometers), an extremely high resolution that gives it a significant advantage in fine analysis fields.

Furthermore, the core component cost of this spectrometer is controlled within a hundred yuan, greatly reducing the threshold for high-end spectral analysis technology, and is expected to promote the widespread application of spectral technology in environmental monitoring, biomedicine, chemical analysis, and other fields. The successful development of this technology not only demonstrates the tremendous potential of micro-nano fibers in spectrometer design but also provides new ideas and directions for the further development of spectral analysis technology. [5]

4.2 Spectroscopy Technology

The use of two optical frequency combs with different repetition rates, combined with a time lens to achieve an optical Fourier transform, is an innovative spectral analysis technology. This technology was developed by Professor Zhang Xinliang's team at Huazhong University of Science and Technology. It combines hybrid optical comb asynchronous optical sampling technology, achieving a spectral resolution of 1 pm at a measurement frame rate of 1MHz, significantly improving the measurement speed and accuracy of the spectrometer.

An optical frequency comb is a light source composed of a series of equally spaced frequencies, possessing very high-frequency stability and precision. In Professor Zhang's research, they employed two optical frequency combs with different repetition rates, which are offset in time, forming an asynchronous sampling system. With the time lens, this system can perform optical Fourier transform, converting signals from the time domain to the frequency domain, thereby obtaining spectral information. The key to this hybrid optical comb asynchronous optical sampling technology lies in its ability to sample the emitted spectrum at different time points and then combine these sampling points to form a complete spectral map. Since the sampling interval is very short, measurements can be made at an extremely high frame rate while maintaining a very high spectral resolution. The advantages of this technology include:

1. High-speed measurement: A measurement frame rate of 1MHz means that a million independent spectral measurements can be made per second, which is crucial for rapidly changing systems or applications that require real-time monitoring.
2. High resolution: A spectral resolution of 1 pm is sufficient to distinguish very fine spectral features, which is significant for fields such as chemical analysis and biological detection.

This new type of spectral measurement technology can not only measure emission spectra at very high resolution and speed but also has the potential for further integration. Through integration, the spectrometer can become more compact and portable, thereby expanding its application range in fields such as environmental monitoring, industrial inspection, and medical diagnosis. In addition, the development of this technology also provides a new direction for the application of optical frequency combs and is expected to drive a revolutionary advancement in spectral analysis technology [6].

4.3 Detection Technology

With the development of nanotechnology, high-resolution spectrometers have become an important tool for studying the structure and properties of nanomaterials. The advancement of this technology has led to more precise analysis of substances in the fields of materials science and chemistry. A research team led by Professor Wu Hanchun from the School of Physics at the Beijing Institute of Technology has developed a new type of van der Waals heterojunction spectrometer. This miniature spectrometer not only features a small size (19 micrometers), high spectral resolution (5nm), wide spectral response range (400nm-nm), and high response speed, but also has imaging, storage, and neuromorphic computing capabilities [7].

4.4 Signal Processing and Analysis Technology

Signal processing and analysis techniques are key to transforming spectral data into useful information. By integrating artificial intelligence algorithms and big data analytics, spectrometers can more accurately interpret complex spectral signals, achieving deeper insights into sample information. The application of this technology significantly enhances the analytical efficiency and accuracy of spectrometers. Professor Mei Yongfeng's research group has proposed a novel design for a miniaturized reconfigurable spectrometer that combines the advantages of traditional spectrometers with those of computational reconfigurable spectrometers. Through integrated self-referenced narrowband filtering channels, artificial intelligence algorithms can perform simultaneous searches for spectral and algorithm parameters in a higher-dimensional parameter space [8].

5. Examples of Spectrometer Applications in Various Fields

Spectrometers, as an advanced detection technology, demonstrate their unique technical advantages in applications across various fields. In the field of geological explo-

ration, spectrometers are used to identify specific minerals and types of rocks. Researchers use imaging spectrometers to discover minerals rich in various elements, and this data helps mining companies to more accurately locate areas for extraction. NASA's Mars rovers "Curiosity" and "Perseverance" are equipped with a ChemCam instrument, an advanced laser-induced breakdown spectrometer (LIBS). These rovers analyze the chemical composition of Martian rocks and soil, aiding researchers in understanding the geological history of Mars.

In the field of environmental protection, imaging spectrometers are used to monitor and assess environmental pollution. For example, researchers in Europe use imaging spectrometers to monitor algae growth in the Danube River, enabling timely detection and management of algal blooms. During the Deepwater Horizon oil spill in the Gulf of Mexico, the National Oceanic and Atmospheric Administration (NOAA) used aircraft and satellites equipped with spectrometers to monitor the extent and thickness of the oil slick on the sea. These spectrometers can identify the unique spectral signatures of oil slicks, thereby helping to determine the level of pollution and its spread.

In medicine, the application of imaging spectrometers is gradually developing. For instance, in drug development and quality control, FTIR spectrometers are used to analyze the structure and composition of drug molecules, ensuring the safety and efficacy of drugs. Many hospitals use Raman spectroscopic imaging technology to analyze tumor tissues; this technique can help doctors distinguish between normal and cancerous tissues, allowing for more precise tumor removal during surgery.

6. Spectrometer Deficiencies and Directions for Improvement

Although spectrometers play an important role in various fields, they still have certain limitations. Firstly, traditional spectrometers are large in size and heavy in weight, which limits their application in portable devices. Spectrometers developed using semiconductor nanomaterials can be reduced to a thousandth of the size of the smallest spectrometers available on the market. Such spectrometers can be applied to devices like smartphones and watches. While maintaining functionality, even smaller and more portable spectrometers are a direction for future development.

Secondly, the resolution and accuracy need improvement, especially when dealing with complex samples. Moreover, the stability and anti-interference capabilities of spectrometers also need to be enhanced. Early spectrometers, especially the large ones used in laboratories, were

typically highly sensitive to environmental changes and prone to external interference. These interferences could come from factors such as light, heat, and vibration in the laboratory environment. With technological advancements, modern spectrometers, especially portable and on-line spectrometers, have significantly improved in terms of anti-interference capabilities. For example, fiber optic spectrometers use optical fibers to introduce the sample's spectrum into the instrument, effectively isolating the impact of the external environment. Additionally, some modern spectrometers employ advanced signal processing techniques that can effectively filter out noise and interference, improving data quality.

Future development of spectrometers will focus more on technological innovation, such as adopting more advanced signal processing technologies and higher precision sensors to enhance their anti-interference capabilities. Alternatively, through system integration and optimized design, the impact of external factors on spectrometers can be reduced. For instance, using vibration isolation materials and devices to reduce the impact of mechanical vibrations, and employing temperature control and stabilization technologies to minimize the effects of environmental temperature changes.

7. Conclusion

This article systematically analyzes the principles, classifications, and technologies of spectrometers, and their applications in various fields. Spectrometers use the principle of light dispersion to detect information from samples. There are many types of spectrometers, each with its advantages and disadvantages, and different types are used in various application scenarios. The key technologies of spectrometers affect their accuracy, efficiency, and application costs, among other factors. New types of

spectrometers are constantly being developed, providing more convenient conditions for scientific research. By sorting out existing technologies, this article reveals the shortcomings of spectrometers in terms of portability, resolution, and accuracy, and proposes corresponding directions for improvement. Overall, the potential for the development of spectrometers is enormous. With continuous technological advancements, they will undoubtedly serve scientific research, industrial production, and daily life in various fields better in the future.

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