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Different Light Sources and Physical Quantities to Be Monitored in Gas Sensing with Lasers

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Abstract. This article first presents some background and facts about the development of the field of gas sensing with lasers. Subsequently, the relevant content about using lasers for gas sensing was introduced. The introduction starts with the technical system and laser light sources. Laser light sources include several important and widely used lasers. The research directions and content suitable were identified for different lasers based on the existing research progress of different light sources. Starting from the Beer-Lambert law, the derivation process of gas concentration has been restored. Physical quantities detected in application have been classified and introduced, including absorption intensity, absorption line shape, Raman scattering intensity, photoacoustic signal and transmittance, and several physical quantities which are with high relevance to the previous text were derived. At the end of the article, the author summarized the article and provided an outlook on future development of gas sensing with lasers.

Keywords: Gas sensing; lasers; The Beer-Lambert law.

1. Introduction

Laser gas sensing technology has made significant progress in recent years and has shown broad development prospects. As a highly sensitive and selective detection method, laser gas sensors have enormous potential for applications in environmental gas monitoring, industrial safety monitoring, medical care, cutting-edge scientific research, and safety protection. In many fields, such as medicine, industrial production and environmental testing, people need to detect the type or concentration of gases, the use of lasers for gas detection is a very advanced method [1].

Related technologies include different spectroscopies. For example, laser absorption spectroscopy uses a specific wavelength of laser to irradiate a gas sample. When gas molecules absorb a specific wavelength of the laser beam, the intensity of the laser light will decrease. By measuring changes in light intensity, the concentration of gas can be calculated [2,3].

There are some challenges in gas sensing with lasers. The first is laser performance optimization. Improve the tuning range, stability, and output power of the laser. Second, Improved the sensitivity of detection. By increasing the length of optical path and optimizing the detector performance, the detection sensitivity can be further improved. The third is multi component detection. Develop broadband lasers and multi-channel detection systems to achieve simultaneous detection of multi-component gases.

This article introduces the technical system and different laser light sources in Section 2, the cutting-edge progress of different lasers in measuring gases is discussed. The Section 3 introduces the principle of laser gas sensing technology, and in the Section 4, the physical quantities that need to be detected are introduced.

2. Technical System and Light Source

For various complex and different gas situations, people use different light sources to detect gases, but the technical systems often have little difference. This section provides a brief introduction to the technical system and different light sources.

2.1. Technical System

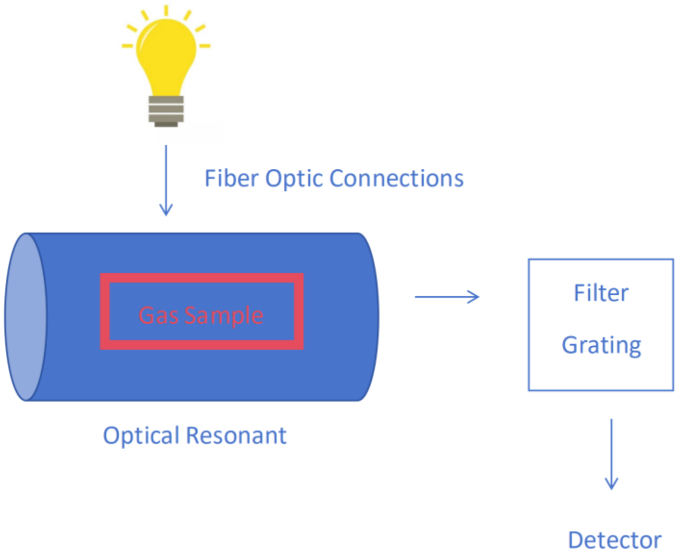

Figure 1. Working principle of laser gas sensing technology system

In Figure 1, fiber optic connectors connect the laser source to the gas sample chamber or optical resonant cavity, ensuring minimal loss of the laser beam during transmission. Optical resonant cavities enhance the interaction between light and gas molecules. Filters and gratings are usually installed at the front end of the detector to adjust the wavelength range of the incident beam. Detectors are usually installed at the end of the beam transmission path, receiving transmitted or reflected laser signals through optical fibers or free space optical paths.

2.2. Light Sources

Different light sources can be applied in different situations. Different light sources include Quantum Cascade Lasers, Solid-State Lasers, Fiber Lasers and so on [4].

2.2.1. Quantum Cascade Lasers.

QCL mainly operate in the 3μm-12μm mid infrared band, and QCL are suitable for detecting characteristic absorption lines of many gases [5].

Quantum cascade lasers are suitable for the needs of the mid infrared band, and their widespread application significantly improves the sensitivity of trace gas detection, especially in the mid infrared band. These lasers have achieved the detection of various trace gases and isotopes with concentrations of ppm, ppbv, or even lower, and have been applied in fields such as environmental gas monitoring, industrial safety monitoring, and cutting-edge medicine [6].

2.2.2. Solid-State Lasers.

Solid-state laser is a type of laser with a structure consisting of a main body and active ions. The host may be glass or crystalline. The active ions are typically rare earth or transition metals. Some common solid-state lasers are fixed wavelength lasers, which spectral coverage is 0.81-5.1 μm.

Represented by Cr^{2+}-doped ZnSe and ZnS, broadband mid infrared solid-state lasers have matured and are suitable for practical applications. The detection of trace gases can be achieved through the use of solid-state lasers with extremely high sensitivity and a wide wavelength range.

2.2.3. Fiber Lasers.

Fiber lasers are commonly used for gas detection that requires high precision and sensitivity, such as industrial process control and scientific research. Multiple wavelengths can be achieved through different doping materials and fiber structures.

Erbium-doped fiber lasers can be used in low-pressure stoichiometric methane, nitrogen and oxygen flames doped with NH_3 which concentration is from 0.13% to 1.36%, and in-situ detection of ammonia and hydrogen cyanide can be achieved using fiber laser intracavity spectroscopy technology. When the environment is at a laser pulse duration of 8 μs and room temperature, the minimum detectable concentration of HCN and NH_3 is 1×10^{13} molecules/cm^3, when the environment is at a laser pulse duration of 8 μs and room temperature. This method is suitable for in-situ detection of many other molecules in harsh combustion environments [7].

2.2.4. Diode Lasers.

Diode Lasers are suitable for tuning diode laser absorption spectroscopy, which is a highly sensitive and selective gas detection technology widely used in the fields of environmental gas monitoring, industrial safety supervision, and cutting-edge scientific research.

Using a tunable diode laser, the output wavelength of the laser can be precisely tuned within a narrow wavelength range, usually covering the characteristic absorption spectral lines of gas molecules.

A high-sensitivity carbon monoxide detection system based on near-infrared semiconductor lasers has been developed. The system utilizes a laser with a wavelength of 2.33 microns to achieve rapid detection of carbon monoxide concentration. When evaluating its performance using spectral data processing methods, the minimum detection limit can be reached at ~0.2ppm, with a measurement accuracy of 6.3 ppb [8].

3. Theoretical background

Based on fundamental optical principles, it can be understood why lasers can be used for gas detection. It can infer the composition of gases and the concentration of their components based on the measured optical related physical quantities. Section 3 will introduce the basic principles of optics, while section 4 will introduce the physical quantities to be measured.

3.1. The Beer-Lambert Law

The Beer-Lambert law describes the phenomenon of light absorption in a homogeneous medium, expressed as:

$$I(\nu) = I_0(\nu)e^{-\alpha(\nu)L}. \tag{1}$$

In the equation, $I(\nu)$ refers to transmission intensity, which is the light intensity after passing through the gas sample. Second, $I_0(\nu)$ is the intensity of incident light, which is the light intensity before entering the gas sample. Third, $\alpha(\nu)$ refers to the absorption coefficient, which depends on the type and concentration of the gas as well as the wavelength of the laser. Finally, L refers to the length of the optical path, which is the distance that the laser travels through the gas [9,10].

3.2. The Absorption Coefficient

The absorption coefficient is

$$\alpha(\nu) = S(T)PX\phi(\nu - \nu_0). \tag{2}$$

$S(T)$refers to line strength, which is the absorption line strength dependent on temperature. P is the total pressure of the gas. X is the gas concentration. $\phi(\nu - \nu_0)$ refers to a linear function, describing the shape of the absorption line near the central wavelength ν_0.

3.3. The Gas Concentration

The absorption can be calculated by measuring the transmitted light intensity $I(\nu)$ and incident light intensity $I_0(\nu)$, leading to the determination of gas concentration X.

The absorbance $A(\nu)$ can be expressed as

$$A(\nu) = \ln\frac{I_0(\nu)}{I(\nu)}. \tag{3}$$

To solve for the gas concentration X, substituting the absorption $A(\nu)$ into the Beer-Lambert law,

$$A(\nu) = \alpha(\nu)L, \tag{4}$$

$$\ln\frac{I_0(\nu)}{I(\nu)} = S(T)PX\phi(\nu - \nu_0)L, \tag{5}$$

then it can obtain the gas concentration X,

$$X = \frac{[\ln\frac{I_0(\nu)}{I(\nu)}]}{S(T)P\phi(\nu-\nu_0)L}. \tag{6}$$

It shows that the concentration of the target gas can be determined by measuring the incident and transmitted light intensities and knowing the system parameters, such as the optical path length and line strength.

4. Physical quantities detected in applications

In gas sensing with lasers, the physical quantities detected are mainly related to the characteristics of gas molecules. The absorption, divergence, and scattering characteristics of gas molecules towards lasers are related to the properties of the gas molecules themselves. These characteristics can reflect information such as the type and concentration of gas.

4.1. Absorption Intensity

The reduction in the intensity of transmitted light by gas molecules after absorbing the energy of laser is absorption intensity.

According to the Beer-Lambert law, absorption intensity can be represented as

$$I(\nu) = I_0(\nu)e^{-\alpha(\nu)L}. \tag{7}$$

According to the Beer-Lambert law and tunable diode laser absorption spectroscopy, the concentration of gas can be calculated based on the intensity of absorbed light.

4.2. Absorption Line Shape

Absorption line shape describes the frequency distribution of light absorption by gas molecules. By analyzing the shape of absorption spectral lines, it can be obtained by some information such as gas temperature and pressure, which is affected by the Doppler effect and collision broadening effect.

4.3. Raman Scattering Intensity

Raman scattering intensity refers to the intensity of scattered light resulting from interactions between gas molecules and incident laser photons.

Raman scattering intensity $I_R(\nu)$ is directly proportional to the concentration of gas molecules N and the incident light intensity $I_0(\nu)$, $I_R(\nu)$ can be represented as

$$I_R(\nu) = kNI_0(\nu). \quad (8)$$

4.4. Photoacoustic Signal

Photoacoustic signal refers to the sound wave signal generated by non-radioactive transitions of gas molecules after absorbing laser energy.

When the laser is modulated and irradiated onto a gas sample, the absorbed light energy is converted into thermal energy, causing local expansion and contraction of the gas, thereby generating sound waves, which is a type of sound wave that can be detected by a microphone or other acoustic detector.

4.5. Transmittance

Transmittance refers to the ratio of that transmission intensity ratio to incident light intensity, it can be represented as

$$T = \frac{I(\nu)}{I_0(\nu)}. \quad (9)$$

The measurement of transmittance can directly reflect the absorption characteristics of gases, thereby deriving the concentration of gases.

5. Summary

The author has introduced laser gas sensing from the perspectives of optical systems, principles, and measured physical quantities. Related technologies will be applied in many fields and make certain contributions to human development, but there are also many areas that need to be improved. In the future, by optimizing the performance of lasers and improving spectral analysis algorithms, the detection sensitivity and selectivity of laser gas sensors will be further improved, enabling more accurate detection and differentiation of trace gases. With the advancement of spectroscopic analysis technology, future laser gas sensors will be able to simultaneously detect multiple gas components, greatly improving detection efficiency and suitable for more complex gas environment monitoring.

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