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Research on method for detection of harmful gases in livestock based on open path laser absorption spectrum

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Abstract. The breath and feces of livestock and poultry will produce harmful gases such as ammonia, hydrogen sulfide and carbon dioxide. When the concentration of these gases exceeds the standard, they will seriously harm the health of livestock and poultry and even keepers. Fast and accurate monitoring of these harmful gases is of great significance in improving the health status of animals and keepers. Laser spectroscopy technology is an effective means of gas detection. Because of its high sensitivity and selectivity, it is widely used in gas monitoring. However, the currently adopted method of pumping sample gas detection based on the long optical path gas absorption cell is susceptible to the influence of the high ash and high humidity environment of the livestock and poultry house, causing detection errors. Open path laser absorption spectroscopy technology does not require a gas absorption cell to detect the gas concentration in free space. Based on this principle, this paper develops out the research on the open path laser absorption spectroscopy detection method for harmful gases in livestock and poultry houses, focusing on the design of laser collimation system, laser reflection system, laser focusing system, and laser detection system. The ammonia gas was used as the detection object to verify the feasibility of detecting harmful gas in livestock and poultry houses with open path laser absorption spectroscopy.

1. Introduction

In the process of large-scale livestock and poultry breeding, breathing behavior of livestock and poultry, the fermentation of manure and the decomposition of padding will all produce harmful gases such as ammonia (NH₃)[1,2]. The long-term existence of this harmful gas will damage the health of livestock and poultry and even keepers. Especially in winter, the breeding farms often adopt a sealed method to ensure the temperature of the livestock and poultry houses, which results in the inability to frequently ventilate and cause the concentration of harmful gases to remain high, causing the livestock and poultry to get sick or even die. At the same time, the diffusion of harmful gases in the farm will pollute the atmosphere, affect the air quality near the farm, endanger the health of the surrounding residents, and induce a series of diseases such as the respiratory system[3]. It can be seen that the rapid and accurate



detection of harmful gases in livestock and poultry farms is not only a health security of people and livestock, but also an urgent need for environmental protection and food safety.

As an effective gas detection method, laser spectroscopy has the characteristics of high sensitivity, high selectivity, and remote measurement capability. It widely uses in industrial gas detection[4-6]. At present, laser spectroscopy gas detection often uses a gas absorption cell to pump in gas and then perform detection, this method uses a long optical path gas absorption cell to achieve highly sensitive gas detection. Although this method can stably and accurately measure the gas concentration, it is susceptible to the influence of particles and humidity in the environment when samples are pump into the gas cell. Especially in the face of the complex background environment of high dust particles in livestock and poultry houses, The measurement method of pumping samples into the gas cell does not meet the detection requirements[7,8], which is not conducive to long-term, stable and accurate detection of harmful gases. More importantly, this method can only measure the gas concentration at one point, and cannot reflect the true distribution of harmful gas concentrations in livestock and poultry houses.

Open path laser absorption spectroscopy, without the need for gas absorption cell to pump in the sample gas, which can realize the detection of gas concentration distribution on a line in free space[9]. Compared with the pumped gas into the gas cell, enter the laser absorption spectrum detection, the open path detection method has the characteristics of line measurement, low cost, simple operation, and open measurement[10]. However, this open measurement method has higher requirements for laser spot quality (spot diameter, divergence angle, etc.), and optical devices that reflects or focus the laser beam. In the complex background environment of livestock and poultry houses, how to design the optical path to generate a laser beam with a small diameter and divergence angle and effectively receive the reflected laser beam will directly affect the measurement distance and detection sensitivity of the open path laser absorption spectrum. This article is based on the open path laser absorption spectroscopy, with ammonia as the detection object, development research on the method of open path laser absorption spectroscopy detection of harmful gases in livestock and poultry houses, and provides methods and technical support for the rapid monitoring of gas in portable livestock and poultry houses.

2. Open path laser absorption spectrum gas detection system

The sensitivity of laser absorption spectrum gas detection is closely related to the precise scanning of the laser and the photoelectric detection accuracy, while the measurement distance of the open path measurement method is directly related to the performance of the laser beam collimation system. It can be seen that the open path laser absorption spectrum gas detection system mainly includes laser drive, laser beam collimation, and laser beam signal detection. The principle block diagram of the overall system scheme is illustrated in Fig.1.

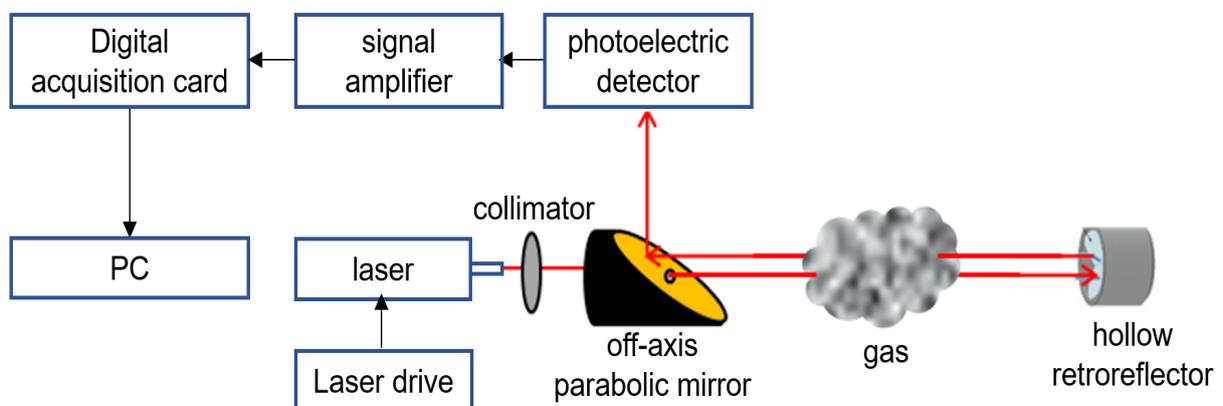


Fig.1 Principle block diagram of open path laser absorption spectroscopy detection method for harmful gases in livestock and poultry houses

2.1. Driver and temperature controller for laser

The laser (Fig.2a) uses a distributed feedback laser with a central wavelength of 1512 nm (Wuhan 69 Technology Co., Ltd., Wuhan, China), adopts a butterfly tail fibre type package, has a power of about 5 mW and a spectral bandwidth of 0.2 nm, and the modulation coefficient of wavelength with current It is 0.01 nm/mA, and the wavelength modulation coefficient with temperature is 0.1 nm/°C. The built-in semiconductor cooler of the laser is controlled by the high-precision temperature control module, which can output high and stable laser power and wavelength. This solution uses a biased low-frequency sawtooth current to drive the DFB laser to achieve laser wavelength scanning under the condition of the laser at a constant temperature. WTC3243 chip (Wavelength Electronics, Inc., Bozeman, United States) as a high-precision temperature control chip, temperature control stability is better than 0.0009 °C, dedicated to applications that require ultra-stable temperature control. The chip can control the internal TEC of the laser by only connecting a DC voltage signal through a temperature setting pin to achieve a constant laser temperature. Therefore, in the design process, the high-precision linear stabilized voltage source AD780 (Analog Devices, Inc., Norwood, United States) is used to generate a 2.5 V reference voltage, and a high-precision potentiometer is used to control the laser at different operating temperatures. According to the laser manual, the working temperature of the laser is placed at 25 °C and the voltage value is 1 V. In terms of laser drive, the WLD3343 (Wavelength Electronics, Inc., Bozeman, United States) high-precision laser driver chip is used, which can provide the laser with a precision current of up to 500 mA without any heat dissipation accessories. During use, a biased low-frequency sawtooth voltage signal is input to its current control pin to make sure that the scanning current of the laser is 60-80 mA to achieve precise wavelength scanning.

2.2. Photoelectric translating system

The photoelectric detection system is responsible for converting the laser signal after reflection and focusing into a voltage signal of a certain amplitude, and its conversion accuracy directly affects the gas detection sensitivity of the open path laser absorption spectrum. It mainly composes of photodiodes and current-to-voltage circuits. The photodiode is used to output the current signal corresponding to the laser signal. Therefore, it is necessary to select a photodiode with low temperature drift, minimal dark noise, low junction capacitance and high responsivity. G10899-01K (Hamamatsu Corporation, Hamamatsu City, Japan) has a wide spectral response range, low dark noise, junction capacitance and conversion efficiency performance, and is suitable for detecting weak light signals. The current-to-voltage circuit uses a classic transimpedance amplifier [11]. This kind of amplifier can effectively amplify and filter the signal while converting the current into voltage and improve the detection sensitivity. OPA2134 (Texas Instruments, TI., Texas, United States) is an ultra-low distortion and low-noise operational amplifier with excellent bandwidth, common mode rejection ratio and low drift characteristics. It is highly suitable for converting weak current into voltage and amplifying it. In the photoelectric conversion system design process, the compensation capacitance value is chosen according to the junction capacitance of the photodiode and the amplifier chip, and the equivalent input capacitance value, which improves the conversion efficiency and prevents the amplifier from self-oscillation.

2.3. Collimation and collection system for laser beam

In the process of open path laser absorption spectrum detection, the laser spot diameter and divergence angle have a direct impact on the measurement distance and optical signal detection. Considering that the DFB laser adopts the FC-APC fiber interface, the divergence angle is large, which cannot meet the needs of long-distance telemetry. The fiber collimator can focus the laser beam output by the DFB laser tail fibre, control the laser spot diameter and divergence angle, and respond to the needs of long-distance transmission. During the design process, the fiber collimator used THORLABS PAF2-7C-FiberPort model (Fig.2b), with FC/APC fiber interface, which can be directly linked with the FC/APC pigtail of the DFB laser (Fig.2). It's transmittance in the range of 400-1700nm is as high as 98 % or more, has a good collimation effect in the range of 1020-1620 nm, and outputs a laser beam with a small diameter and a small divergence angle (Fig.2).

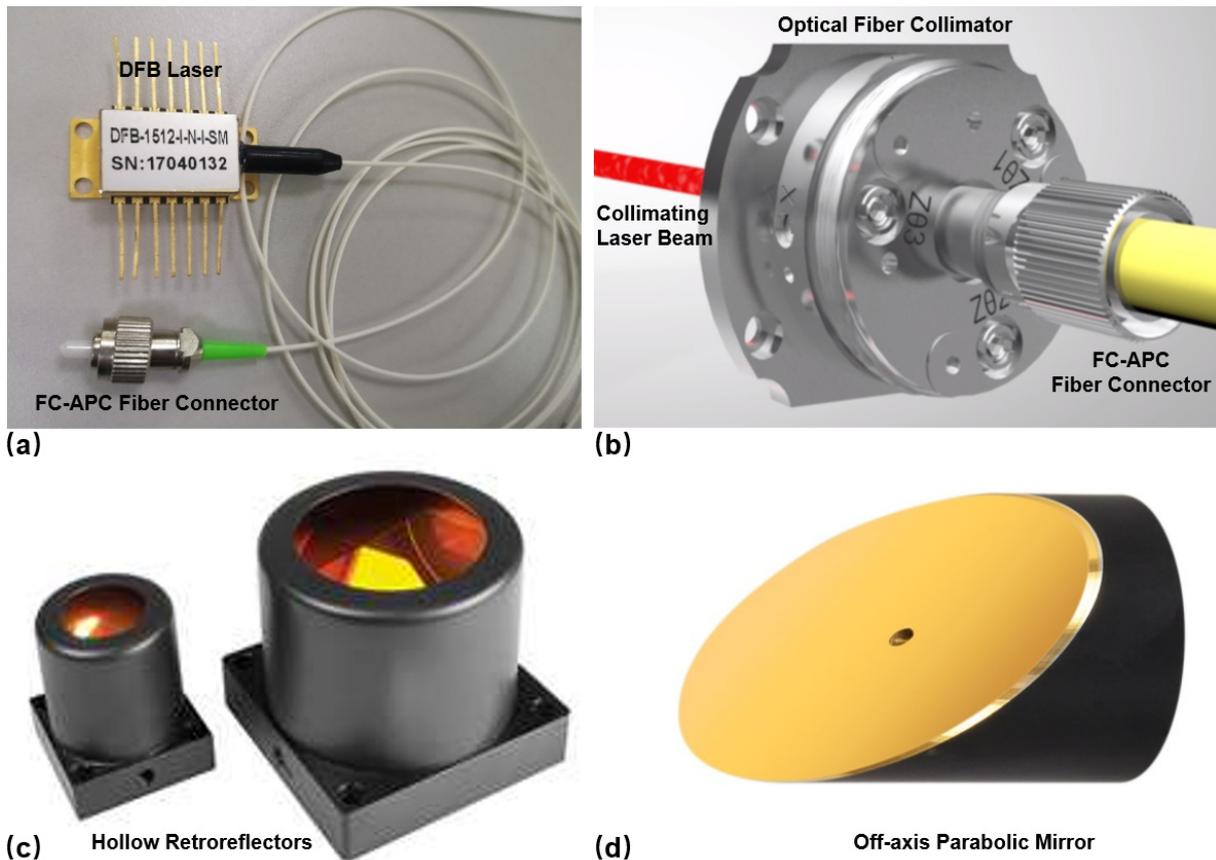


Fig.2 Optical elements: (a) DFB Laser; (b) Optical Fiber Collimator; (c) Hollow Retroreflectors; (d) Off-axis Parabolic Mirror

During the measurement of open path laser absorption spectroscopy, the long-distance laser beam needs to return through the reflector. The hollow retroreflectors is composed of three coated mirrors to form a corner prism. It adopts a hollow structure to reduce the influence of position deviation and vibration on the reflection effect. It can reflect the laser beam incident at any angle within 180° , which is very suitable for reflection and long-distance transmission laser. During the design process, the hollow retroreflectors (Fig.2c) was modeled as #49-675 (Edmund, city, country), with an effective aperture of 50.8 mm, a beam shift of 2 arc seconds and 3 gold-plated mirrors, which can be effective Reflects laser beams with a wavelength range of 700-16000 nm.

The off-axis parabolic mirror (Fig.2) is used to focus the laser signal reflected by the hollow retroreflector. Make a photodetector at its focal length to achieve maximum optical signal detection. During the design process, the off-axis parabolic mirror selected THORLABS MPD249V-M01-90 model (Fig.2d). The diameter of the center hole is 3.2 mm, which is used to transmit the collimated laser beam output by the fiber collimator. It has an average reflectivity of $> 96\%$ in the range of 800 nm - 20 μm , and the focal length is 4 inches. The mounting hole can match the fiber collimator, which is convenient for installation and fixation.

2.4. Data collection

In the design process, a data acquisition card is utilized to collect the voltage signal output by the photoelectric conversion system. The acquisition card model is USB6005, with 8 bipolar synchronous analog input, and can collect voltage signals within the range of $0 \sim \pm 5\text{ V}$ or $0 \sim \pm 10\text{ V}$. 16-bit input accuracy guarantees the linearity error is less than 0.01 %. The sampling frequency of the acquisition card is 100 kHz, which can respond meet as to the request of sampling rate.

3. Results and Discussion

In response to the demand for open path laser absorption spectrum gas detection, comprehensively considering the parameters and performance of each component in the system, the system optical path structure is comprehensively designed (Fig.3a). The assembly of the open path laser absorption spectrum gas detection system is shown in Fig.3b. The laser, laser temperature control and drive chip, and power supply system are integrated on the PCB circuit board. The off-axis parabolic mirror, fiber collimator and photoelectric conversion system are fixed on a metal panel. The sensing surface of the photodetector is placed at the focal point of the off-axis parabolic mirror. The laser tail fibre is connected to the fiber collimator interface.

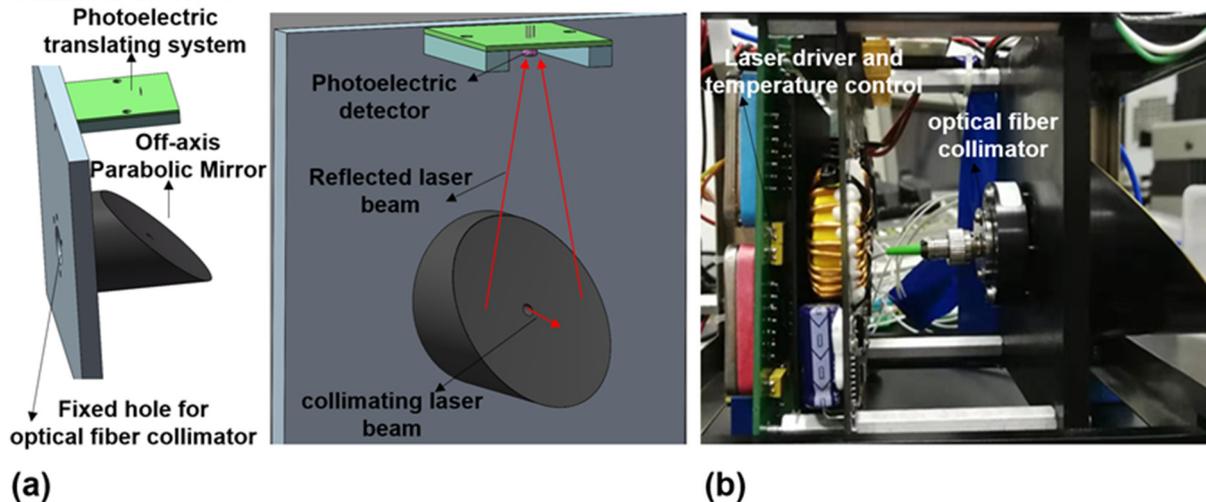


Fig.3 Open path laser absorption spectroscopy gas detection system: (a) optical path and mechanical design; (b) system assembly physical diagram

The physical picture of the open path laser absorption spectrum gas detection is illustrated in Fig.4. The laser works at a constant temperature of 25 °C, and uses a 5 Hz low-frequency sawtooth wave to form a scanning current between 55 and 85 mA of the laser to scan the laser wavelength. Use of data acquisition card and supporting host computer software to collect the voltage signal corresponding to the laser beam output by the photoelectric conversion system. The distance between the off-axis parabolic mirror and the hollow reflector is 2 m. After the light is reflected once, the effective length of the open path is 4 m. A PPMA plastic box is placed in the path of the open path. When there is no ammonia gas in the box, the collected voltage signal (Original signal) has no absorption peak. When the ammonia water with the cap opened is sealed in the PMMA plastic box, because the inside of the box is filled with a certain concentration of ammonia gas, the collected voltage signal (absorption signal) has an obvious absorption peak, indicating the designed open path laser absorption spectrum. It can detect the concentration of ammonia in open spaces. This structure does not need to pump the sample into the gas cell, and has unique advantages in the face of high dust, high temperature and high humidity livestock and poultry houses. The research results laid a theoretical and technical foundation for the development of open path laser absorption spectroscopy detection equipment for harmful gases in livestock and poultry houses.

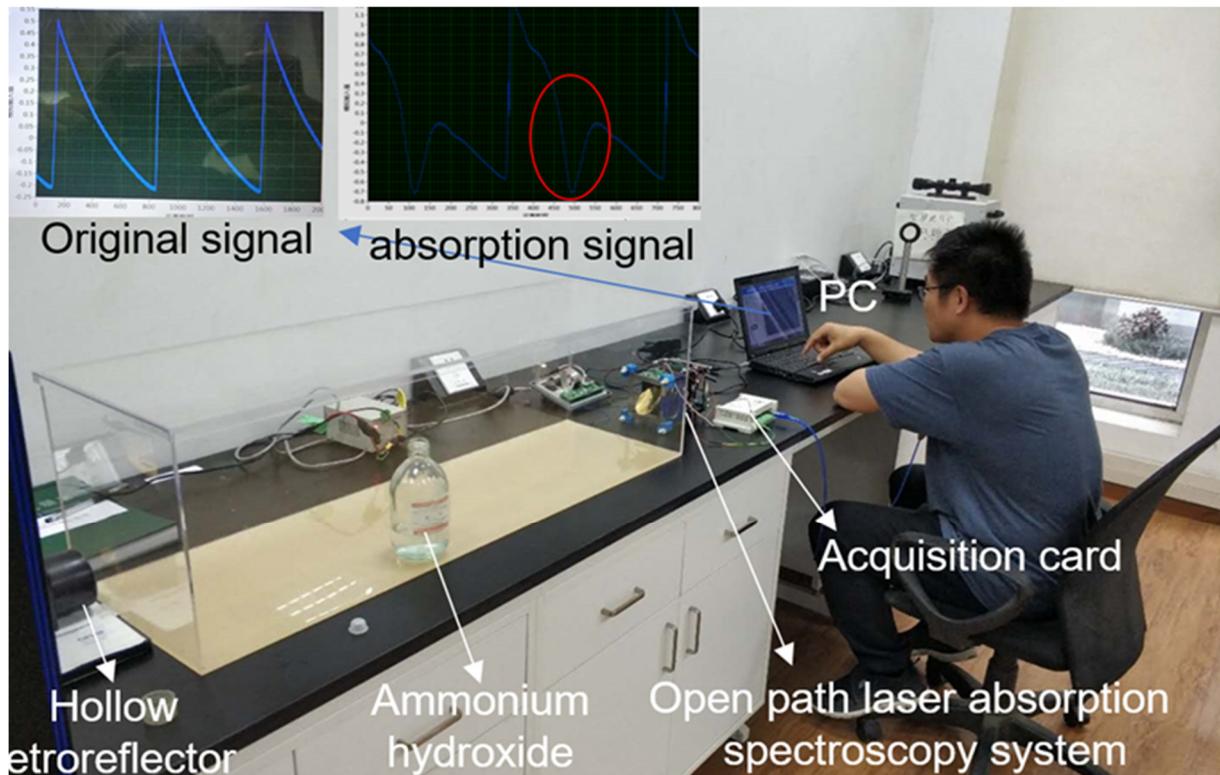


Fig.4 Open path laser absorption spectroscopy system for detecting ammonia

4. Conclusion

Based on the principle of laser absorption spectroscopy, this paper designs a high-precision laser drive and temperature control module, photoelectric conversion system, laser collimation and collection system, and develops the research on the open path laser absorption spectroscopy detection method of harmful gases in livestock and poultry houses. Tests have shown that the open path laser absorption spectroscopy detection system provided in this article can detect the voltage absorption peak caused by the ammonia absorption of laser beam in the 4m open path, with extremely high sensitivity. It can be seen that the system can detect the concentration of harmful gases in the open space environment of livestock and poultry houses without taking samples into the gas cell, providing theoretical foundation and technical support for intelligent monitoring of air quality in livestock and poultry houses.

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