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Design and Construction of a System for Trace Toxic Gases in Coal Mines using Mid Infrared Laser

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Abstract: High precision real-time monitoring of coal mine gases is crucial, the toxic and harmful gases such as CH4, CO, CO2, H2S. The mid infrared absorption spectroscopy method has the advantages of safe operation, fast response, high measurement accuracy, long service life, and the ability to detect multiple types, making it the preferred method for the new generation of coal mine gas detection. This paper uses a continuously adjustable mid infrared laser to develop a trace coal mine gas equipment with a detection accuracy of up to 1ppm. The research work includes: theoretical research on gas absorption and content inversion detection based on Beer-Lambert law, development and research of long path and small-sized improved Herriott multi path absorption cells based on spatial light transmission theory, design and integration of photo detectors, and development of online detection equipment for coal mine gas integration. Through the development and promotion of this system, key technologies have been formed in the field of coal mine gas sensing and detection, and application demonstrations have been established.

Keywords: Mid-infrared laser, toxic and harmful gases, Herriott multi path absorption cells, Absorption spectrum, Detection limit.

I. Introduction

The gas environment underground in coal mines is complex, characterized by a wide variety of types and low concentrations. Such places has high demands on trace gas detection systems, such as high sensitivity, integrated detection of multiple gases, and real-time online monitoring for various application scenarios[1]. The existing methods for detecting trace gases include non optical methods and optical methods [2,3]. The former includes chemical titration, electrochemical methods, gas chromatography, etc. These devices have problems such as small detection range, slow reaction time, large volume, and high cost, and are not suitable for the current demand for integrated, miniaturized, and maintenance free gas detection equipment in coal mines[4,5]. The vibrational rotational transition spectral lines in the molecular infrared region of typical gases in coal mines (with mid infrared characteristics such as methane (CH4) at around 3.4 μ m, carbon dioxide (CO2) at around 4.3 μ m, carbon monoxide (CO) at around 4.7 μ m, etc.) are the "fingerprint" information that characterizes their types and contents, and are all located in the mid infrared region (2-12 μ m). The fundamental frequency molecular transition belongs to the strongest vibration region, which is several orders of magnitude stronger than the near-infrared (1-2 μ m) region, making it the best choice for detecting trace gas molecules. Mid infrared laser absorption spectroscopy detection has the advantages of good selectivity and contrast of gas molecules towards spectral lines, strong identification ability, no need for catalytic carriers, fast response speed, and high stability[6,7]. It is the most ideal detection method for gas detection in underground coal mines. This paper is mainly based on a mid infrared laser, which achieves the testing of various harmful gases through wavelength modulation. At the same time, a small multi path absorption cell (length of 48mm) is designed, and the detection system, optical path system, etc. are arranged in an orderly manner to form a new device based on the trace toxic and harmful gas process of mid infrared laser.

II. Experimental System

The experimental design of the wavelength modulated TDLAS system for nonlinear scanning is shown in Figure 1. Among them, the laser output link mainly includes the FY6900 function generator, FBG65/APC DFB semiconductor laser diode and its modulation module; Gas absorption is carried out in a short path Herriot gas absorption cell (total path length: 14.4m, length 48mm)[8,9]; The signal acquisition and demodulation part mainly includes using InGaAs photo detectors (with response wavelengths of 800nm-1700nm) to collect waveform data from the RIGOL DS1102Z-E oscilloscope, and importing it into the SIMULINK data post-processing and demodulation model previously established in MATLAB[10].

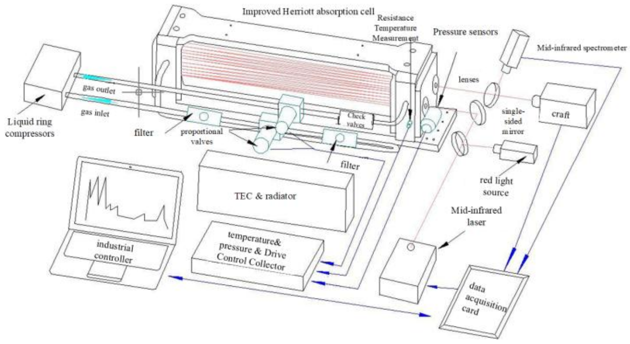


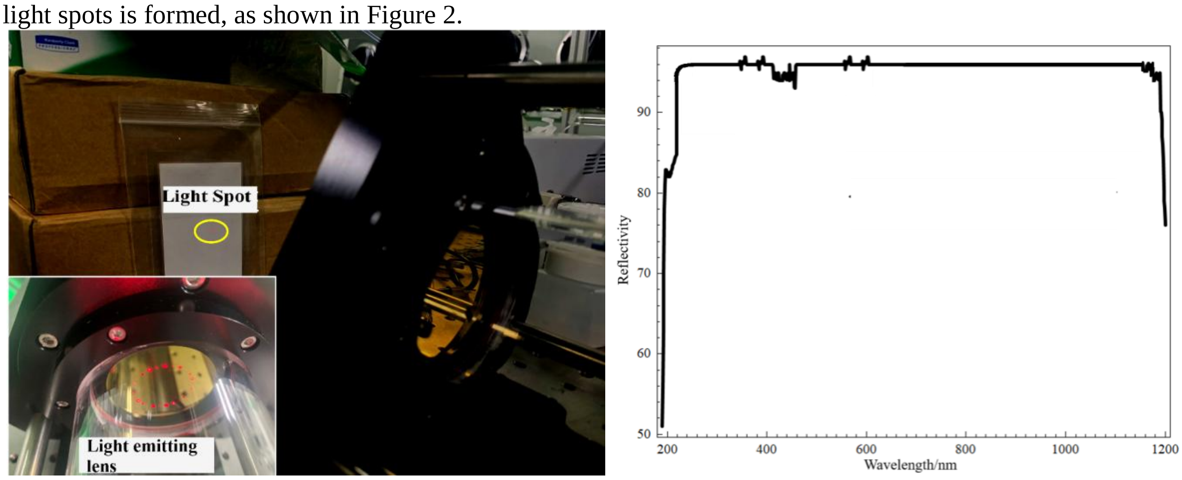
Figure 1: Schematic diagram of equipment structure

2.1 Modulation System

After building the overall framework of the experimental system, DFB-LD modulation, optical path adjustment, gas path connection, and overall system framework construction were carried out in advance. The laser modulation part adopts an analog modulation butterfly shaped DFB-LD laser module [11]. The bias current is adjusted based on an analog input signal with a modulation frequency of 5kHz and an initial amplitude of 2.2V. The average output light intensity is measured using a power meter. After debugging and testing, the optimal modulation parameter combination was obtained.

2.2 Gas Absorption Tank

The gas absorption cell adopts a short path gas absorption cell with an equivalent path length of 14.5m and a peripheral size of 350 x 170 x 48 mm3. The reduction in total length makes the device more compact, and we have designed a length of only 48mm, which is less than 50mm.The working temperature of this chamber is 10-40 ℃, using a metal high reflective film with a working wavelength of 100nm-1200nm, and can operate within a pressure range of ± 200 kPa. The volume is 1.2 L, and there is a Φ 5 quick plug pneumatic connector on each end. The optical path is Herriot configuration, and the incident window is uncoated CaF2. When adjusted to the correct incident angle, the incident light will undergo 300 reflections in the gas absorption cell, forming a total of 300 light spots, which will form 300 light spots on the exit lens (excluding the exit light)[12,13]. Use a 3D adjustment frame to fine tune the angle of the incident fiber until the correct number of light spots is formed, as shown in Figure 2.



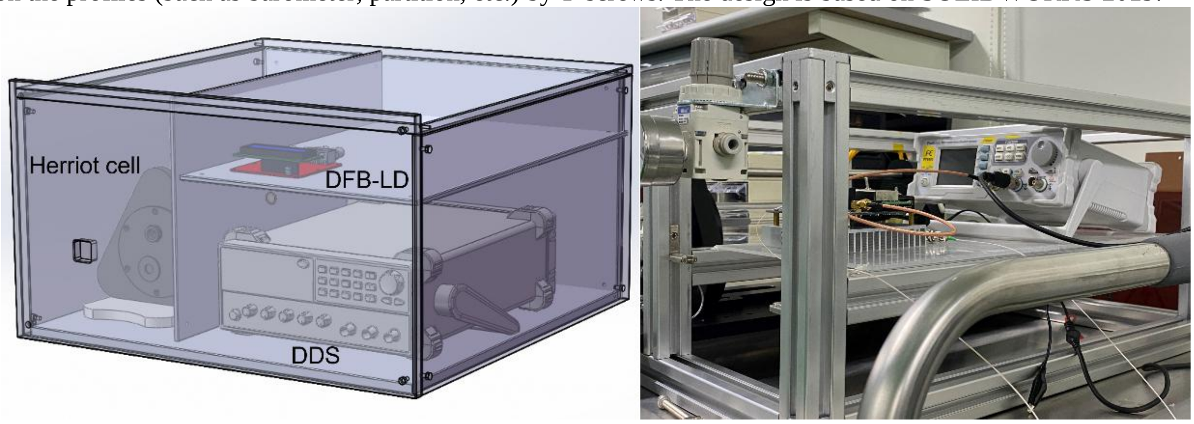
(a) Physical image (b) spectral range of reflectance (200-1200nm)

Figure 2: Herriot gas absorption cell

Based on MATLAB SIMULINK data demodulation, the transmitted light intensity data collected by the display is used to establish a phase-locked amplifier module in SIMULINK for post-processing of harmonic demodulation.

2.3 Integrated Structural Design and Integration

Based on the existing experimental conditions, the overall framework of the TDLAS system used in the experiment was designed and constructed. The design structure and physical diagram are shown in Figure 3. In consideration of the subsequent addition of demodulation circuit, as well as the addition of multi-sensor cooperative sensing and other functional expansion, instead of using a panel to seal the system, aluminum profiles are used to build the system framework, and the system components (laser modulation module, gas absorption cell, quadrature demodulation module, signal detection data upload module, etc.) are placed or fixed on the profiles (such as barometer, partition, etc.) by T-screws. The design is based on SOLIDWORKS 2019.

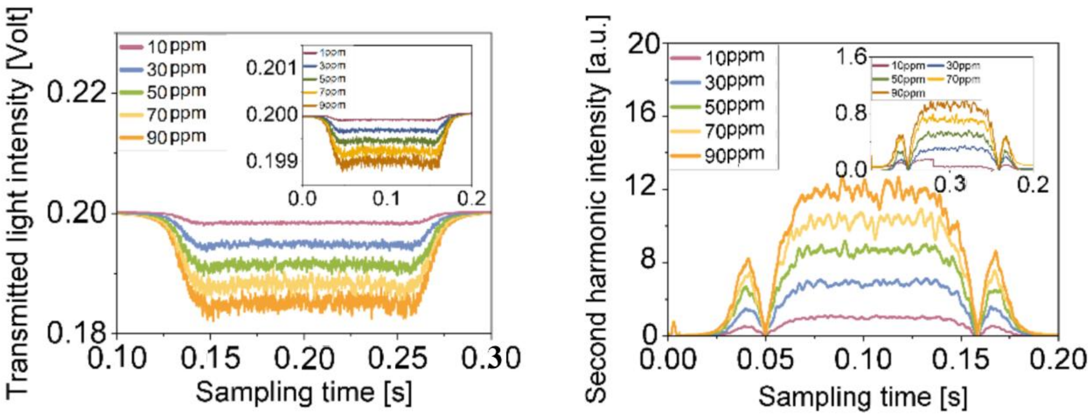


(a) Design Drawing (b) Physical Image

Figure 3: Overall framework of integrated system for infrared laser trace toxic and harmful gas equipment

III. Experimental testing

Using the lock-in amplifier module established in SIMULINK numerical simulation, post-processing was performed on the transmitted light intensity data collected by the oscilloscope in the experiment [14]. When the methane gas concentration is between 10 ppm and 1000 ppm, the transmitted light intensity signal corresponding to the scanning bias voltage process under the nonlinear scanning scheme [15,16]. In the nonlinear scanning experiment, samples with the same concentration as linear scanning were used, and a bias voltage scanning process was employed. This process aims to capture the ideal absorption signal, determined by the duration of the absorption peak. Selecting the modulation parameter with the longest absorption peak duration as the optimal wavelength modulation parameter, subsequent analysis is based on these optimal parameters. The amplitude of the second harmonic signal obtained by the nonlinear scanning method based on the optimal absorption signal is shown in Figure 4.



(a) Nonlinear Scanning (b) The Demodulated Second Harmonic

Figure 4: The transmitted light intensity signal

Based on the fitting curve obtained from 0-1000ppm data, repeated concentration inversion experiments were conducted on methane at a concentration of 100 ppm, and the frequency distribution obtained is shown in Figure 5.

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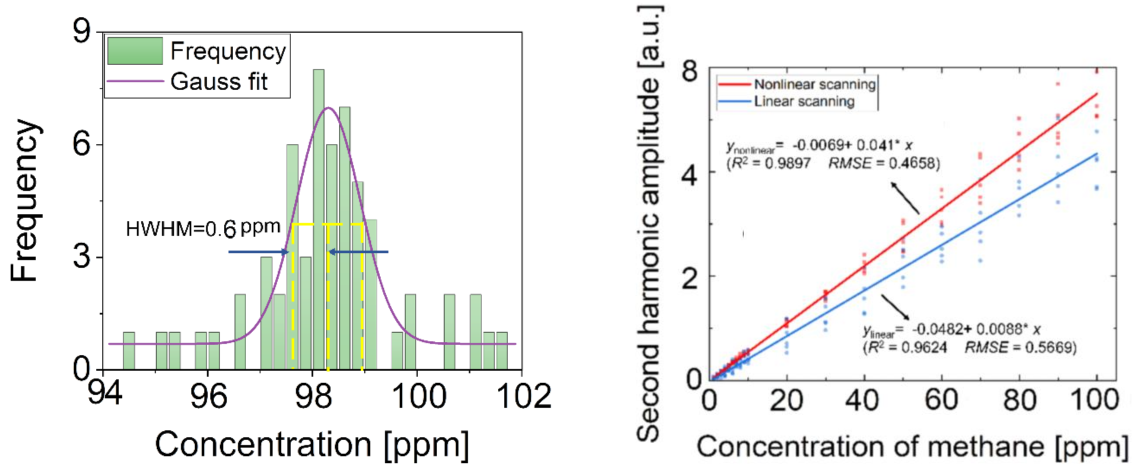

(a) Gaussian Fitting (b) Nonlinear Modulation Method

Figure 5: Data fitting curve

Taking a Gaussian fitting curve, the half height and half width value of the curve is the system resolution, which means that the measurement resolution of CH_4 by the system is 0.719 ppm, and the ratio of resolution to frequency center is equal to a relative accuracy of 0.72%. The volume fraction of methane gas measured during this period is 100.31±0.719ppm. Similar to the detection of other gases, the accuracy has also reached below 1ppm, such as CO^2 at 0.91ppm, CO at 0.85ppm, and H_2S at 0.78ppm.

IV. Conclusion

This article mainly focuses on the detection of toxic and harmful gases in the coal environment. The main work carried out includes theoretical analysis, system design and experimental verification, and equipment construction. In terms of theoretical analysis, the effectiveness of wavelength modulation spectroscopy (WMS-TDLAS) in gas detection was verified. Based on the Beer Lambert gas absorption law, a mathematical model for molecular absorption spectroscopy was derived, and a model and mathematical expression method for inverting gas content were established, providing theoretical support for high-precision gas detection; System optimization and experimental verification: Verify the effectiveness of wavelength modulation spectroscopy (WMS-TDLAS) in gas detection, use MATLAB/SIMULINK for numerical simulation and experimental data processing, and require the optimal integration time and detection accuracy for precise detection. A nonlinear scanning signal loading method is proposed, and experiments show that the method can achieve the following effects: standard deviation (RMSE) is reduced by 60%, detection limit is reduced by 70%, system detection limit (LOD) reaches 0.719 ppm, and the optimal integration time is 50 seconds, significantly improving system performance. Equipment construction: Integration of laser system, weak gas absorption cell (length of 48mm), photo detector, etc. By using orthogonal phase-locked amplification and demodulation circuits, the response speed and integration of the system can be improved. Use MULTISIM software for circuit simulation, complete schematic drawing and production; Conduct research on calibrating methane inversion models using TDLAS with orthogonal demodulation hardware circuits to achieve rapid and accurate detection of toxic and harmful gases.

Acknowledgments

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