Research on key technology of infrared methane detector based on LED light source

ZHAO Qing-chuan

Chongqing Research Institute Co.Ltd. of China Coal Technology & Engineering Group Corporation, No. 6 Kecheng Road, Jiulongpo District, Chongqing City, 400039, China

e-mail: zhaoqich@163.com

Abstract. According to the characteristics of the infrared absorption spectrum of methane gas mainly distributed in the middle infrared band of 3.2 μm~3.4 μm, an infrared methane sensor and detector based on non-dispersive infrared spectrum technology are developed based on the research of three key technologies of sensor optical path structure design, LED current drive and temperature compensation. The optical path consists of a light emitting diode with a peak wavelength of 3.4 μm, a measuring photodiode with a cutoff wavelength of 3.6 μm and a spherical emitting surface. Through the research of LED current drive control logic, the power consumption of optical measuring device is reduced to 10 mW. The influence of temperature change on the measurement results of methane concentration is studied experimentally. Through data analysis and linear fitting, the temperature compensation algorithm formula is obtained. The experimental results of the compensated sensor and detector platform show that the average power consumption of the sensor is 19.68mW, the influence of temperature change in the temperature range of -20℃~50℃ on the measured value is not more than 3.5% of the true value, the measured concentration value is less affected by water vapor, the response time is less than 20s, and the battery working time is more than 7 days.

1. Introduction

According to statistics from the State Administration of Work Safety on coal mine accidents in China, there were 27 gas accidents in 2019, a year-on-year increase of 68.8%, and 118 deaths, up by 122.6% year on year. Real-time monitoring of gas concentration in coal mines is an important measure to avoid gas accidents and ensure coal mine safety [1-3]. Based on Document 5 (2016) by the State Administration of Work Safety, wireless laser and infrared methane sensor are recommended for the return airway corner, making the development of wireless methane sensor a heated topic of methane detection. Although accurate and free from water vapor interference [4-9], the laser methane detection system is power consuming and not suitable for wireless application. The infrared gas detection system is widely developed and applied due to accuracy and timely response [10-12].

Domestic and foreign researchers have been engaging in the research of non-dispersive infrared gas detection and methane sensor. Zheng Lingjiao et al. [13] developed a differential mid-infrared carbon dioxide detection system, Yu Xin et al. [14] designed a handheld infrared methane detection device featuring low threshold and remarkable performance, Xiong Shifu et al. [15] proposed to apply the "splitting technique" in the structure design of the membrane system of the gas filter, and Ye Weilin et al. [16] reported a high-precision atmospheric methane detection system using continuous-wave interband cascade laser (ICL) based mid-infrared sensor system at room temperature. However, the
above infrared gas detection systems generally use the infrared radiation as the light source, allowing the light to be filtered before taking photoelectric conversion through the pyroelectric detector, thus detecting gas concentration. The result of this structure is highly influenced by water vapor power consuming.

The paper utilized the Non-Dispersive Infrared (NDIR) spectroscopy for the design an IR methane sensor and detection device featuring low power consumption and resistance to water vapor. The IR methane sensor in the detector used a narrow-band infrared light-emitting diode (LED) as the light source, a photodiode (PD) that converted infrared light absorption into current signal, both of which were integrated to constitute a new LED-PD optical gas measurement structure. The studies focused on photoelectric component selection and air chamber design, LED-drive current modulation, and temperature compensation algorithm to avoid impacts of water vapor on IR methane sensor without additional heating devices or other compensation algorithm while greatly lowering the power consumption of the IR methane sensor, thus reducing the impact of temperature variation on the result.

2. System Theory
Analysis of infrared light absorption is based on atom vibration in the molecule. When the infrared rays go through an analyte, it absorbs energy from the analyte ray, with changes in energy corresponding to the analyte's molecule vibration frequency. Therefore, each of the gas molecules has specific absorption spectra, and the variation of absorption intensity before and after the light incident is called the Lambert Beer law. The relationship between the light intensity \( I \) received by the PD detector and the light intensity \( I_0 \) emitted by the LED light source is given by:

\[
I = I_0 \exp(-f(v)KNL)
\]  

In formula (1), \( L \) is the optical path of the sampling gas chamber, and \( K \) is the absorption coefficient related to the measured gas, based on which the gas concentration \( N \) is given by:

\[
N = \frac{\ln(I_0/I)}{f(v)KL}
\]

From Formula (2), when the optical instrument, the sampling chamber's structure, optical path \( L \), and absorption coefficient \( K \) stay fixed, \( f(v) \) is a function of changes in temperature, LED light source intensity and the optical path change. By collecting and receiving current signal from PD detector which is positively correlated with light intensity \( I \), we can detect the concentration of methane.

The IR methane detector is powered by a lithium manganese battery and uses a voltage conversion circuit to power the microprocessor, IR methane sensor and other circuits. The microprocessor, as the core chip of operation and control, communicates with the IR methane sensor via the UART interface, and performs sound and light alarm logic control based on the methane concentration in the display circuit and default alarm points. When the detector is out of power, the 5V charger charges the detector through the charging control circuit. The block diagram of the detector is shown in Figure 1.

![Figure 1. System diagram of infrared methane detector](attachment:image.png)
The difficulty in the design of IR methane detector lies in the sensor. How to eliminate the influence of water vapor and temperature variations on the result of detection and reduce the power consumption is the key to the IR methane detector.

3. Design of IR Methane Sensor
The IR methane sensor is composed of optical path, power supply circuit, current-driven LED circuit, photosensitive signal processing circuit, temperature measuring circuit and microprocessor. The block diagram of the sensor is shown in Figure 2. LED light source, PD measurement and sampling air chamber constitute the structure of optical path in the sensor. The power circuit converts the external power supply to rated working voltage of the circuit while LED light source emits infrared light under current-driven circuit. The photodiode absorbs the inlet IR light and outputs current signal, which is converted by the photosensitive signal into voltage signal before being input into the microprocessor for A/D conversion. The microprocessor calculates the concentration of methane based on the formula, enabling communication with the mainboard of the detector via UART interface. In the meantime, the real-time temperature of the circuit is calculated for correction of the methane concentration based on the compensation algorithm.

Figure 2. Principle block diagram of infrared methane sensor system

3.1. LED-PD Measuring structure of optical gas
Recent development of new materials and technologies for optical devices paved way for the high-efficiency LED and PD instruments in the middle infrared spectrum. LED IR light source features spontaneous response and endurance. For IR methane sensor, the LED instrument as the light source provides simple structure and stable performance, which provides a new technical way to improve the performance of IR methane detection.

The IR absorption spectrum of methane gas molecules is mainly distributed in 3.2 μm-3.4 μm mid-wave IR, with another weaker absorption peak at 2.3 μm, while the IR absorption spectra of water molecules is mainly distributed in 2.5 μm-2.8 μm. The main absorption peaks of the two molecules are 0.5μm apart. The traditional incandescent light source features broader spectrum and a proneness to form water spray, so the optical structure of IR methane sensor is likely to be affected by water vapor. To solve the problem, the light source of the IR methane sensor in the paper adopted the narrow-band Lms34LED, with a minimum optocoupler that contains the 3.3 μm main absorption peak of methane. The photodiode of Lms36PD was used as PD measurement, with a cut-off wavelength of 3.6 μm. The spectral correlation between Lms34LED, Lms36PD and the main absorption peak of CH₄ is shown in Figure 3.
Figure 3. Spectra of main absorption peaks of Lms34LED, Lms36PD, and CH₄

From Figure 3, it is known that the spectrum of LED light source has few interactions with the absorption spectrum of water vapor from 2.5 μm to 2.8 μm, a difference of two orders of magnitudes. Therefore, the detection results of the IR methane sensor composed of Lms34LED, Lms36PD and Lms34LED were almost free from the water vapor’s influence.

The sampling chamber is made of stainless steel, and the optical reflector is made of a precision spherical mirror. The IR light from the LED light source in the optical path is transmitted to the spherical mirror at the top of the sampling chamber and reflected to the photodiode for measurement and reference.

3.2. LED current-driven technology

The spontaneous response of LED up to 10 times per nanosecond allows the application of LED-driven logic to run in three different modes, namely the continuous, quasi-continuous and short pulse. The continuous mode is power consuming, while the quasi-continuous mode with a duty ratio of 50% has the maximum average power. The short-pulse mode (less than 10ms) has the maximum peak power on the condition that the LED-driven current exceeds 1A. To reduce the power consumption of the whole sensor and lower the instantaneous impact of LED working current on the power supply, the sensor adopts quasi-continuous mode while maintaining the detection sensitivity of the sensor.

The greater the working current of LED, the higher the intensity of emission. The sensor’s LED current-driven output is determined based on the light intensity and the capacity of the circuit, where the Lms34LED's working current $I_F$ is 200 mA, working voltage $U_F$ is 0.5 V, the pulse frequency $f$ is 0.5 kHz, the pulse width $τ$ is 1 ms, with 100 pulses per 1000 ms. The average power consumption of LED light source $P_0$ is given by:

$$P_0 = 100τU_FI_F / 1000$$

Insert the values into formula (3), and we have $P_0 = 10mW$, that is, the average power consumption of LED light source is 10mW, while the high-impedance photodiode ranges between 0.15 and 0.6mA in current, with the power consumption to be ignored. Therefore, the power consumption of the IR methane sensor under LED current-driven quasi-continuous mode is far lower than that of the traditional incandescent light source of 100mW. The significant advantage of low power consumption makes it suitable for applications with low power consumption like detectors.

3.3. Photosensitive signal processing circuit

Under certain light and backpressure conditions, Lms36PD can generate a photocurrent with a linear relationship with illumination. The photosensitive signal processing circuit is shown in Figure 4.
Figure 4. Circuit diagram of photosensitive signal processing

As shown in Figure 4, the photocurrent outputs voltage $U_s$ via the photosensitive signal processing circuit, and then goes into the microprocessor for A/D conversion to calculate the voltage value of $U_s$. $U_s$ and the output voltage variation $U_0$ of the photosensitive signal processing circuit in the air and the methane concentration are consistent with calculations of formula (2). The microprocessor calculates the concentration of methane gas based on the function.

4. Temperature compensation and experiment analysis

4.1. Influence of temperature and compensation algorithm

The calculation formula of methane concentration in formula (2) is given in the standard experimental environment. However, in the real scenario, the change of temperature will have an impact on the light intensity of LED and the spectral characteristics of photodiode. For LED, the increase of temperature would lower the emission intensity when factors like temperature and others work together via deep non-radioactive restructuring and depletion of surface restructuring and the carrier heterojunction barrier. In addition, rising temperature would widen peak wavelength. However, the photocurrent of photoelectric receiver Lms36PD shows weaker dark current and stronger photocurrent amid rising temperature. Besides, the photosensitive signal processing circuit and power supply are also affected by temperature. Therefore, it is not suitable to deduce temperature compensation and coefficient through the theoretical formula.

To study the temperature compensation algorithm, we first conducted the temperature influence experiment using the IR methane sensor as a whole to obtain data, based on which the variations were analyzed for temperature compensation on the basis of empirical mathematical formula. To start with, three devices were selected followed by precision calibration of the IR methane sensor using 2.01% VOL standard methane gas at the temperature of 20℃. Then, the calibrated and valid high and low temperature test chamber was used for the temperature experiment within the temperature range of -20℃ and 50℃, with one point selected at each interval of 10℃. Standard methane gas in the concentration of 0.52% VOL, 2.01% VOL and 19.9% was applied in the experiment. The mean of the three sensors was recorded as shown in Table 1.

| Temperature (°C) | Measured value at 0.52(VOL) | Measured value at 2.01(VOL) | Measured value at 19.9(VOL) |
|------------------|-----------------------------|-----------------------------|-----------------------------|
| -20              | 0.61                        | 2.31                        | 22.5                        |
| -10              | 0.58                        | 2.19                        | 21.4                        |
| 0                | 0.56                        | 2.13                        | 20.9                        |
| 10               | 0.55                        | 2.09                        | 20.4                        |
| 20               | 0.53                        | 2.01                        | 19.7                        |
| 30               | 0.52                        | 1.97                        | 19.4                        |
| 40               | 0.51                        | 1.94                        | 19.1                        |
| 50               | 0.5                         | 1.89                        | 18.7                        |

In Table 1, temperature has a great impact on the sensor's measurement results in the range of -20℃ and 50℃, with a maximum deviation of 15% between the measured value and the actual value, far
exceeding the industry standard stipulated in AQ6211-2008 for coal mine non-dispersion-infrared methane sensor, which requires the intrinsic error should not exceed 6% of the actual value. Therefore, temperature compensation is needed.

To obtain accurate temperature measurements, the optical gas chamber was equipped with an interior NTC thermistor with a standard resistance of 5 kΩ. The microprocessor sampled and processed the signals with A/D conversion to get the exact temperature values. The data in Table 1 was normalized based on data obtained at 20℃ to generate three standard gas-temperature compensation coefficient \( \varepsilon \) curves in the concentration of 0.52%VOL, 2.01%VOL and 19.9%VOL.

![Figure 5. Curve of Temperature compensation coefficient](image)

To eliminate the impact of temperature variation on the sensor, we introduced the temperature compensation formula given by:

\[
C = C' / \varepsilon
\]  \( (4) \)

In formula (4), \( C \) is the concentration of methane after temperature compensation, and \( C' \) is the concentration without temperature compensation, and \( \varepsilon \) is a linear function of temperature \( T_s \). The curve shown in Figure 5 is linearly fitted as shown in formula (5).

\[
\varepsilon = -0.0027T_s + 1.0682
\]  \( (5) \)

Based on formula (4) and (5), the algorithm was programmed for temperature compensation of methane measurement results to improve the accuracy of the sensor under different environmental conditions.

### 4.2. Experiment analysis

To verify the feasibility of IR methane sensor based on LED light source and the accuracy with temperature compensation, the sample of IR methane sensor was made as a component of the IR methane detector. The photo of the detector is shown in Figure 6.

![Figure 6. Physical figure of the IR methane detector](image)
The present sensitive components integrating carrier catalysis, thermal conductivity and laser methane detection have a minimum power consumption of at least 100mW on average. The IR methane sensor and detector shown in Figure 8 have an average current of 5.18mA when the voltage of the detector's battery hits 3.8V, while the LED-based IR methane detector has an average power consumption of 19.68mW, a significant advantage in terms of power consumption.

The impact of humidity on the detector was tested in a range of 25%RH and 95%RH. The maximum value of zero drift of the detector was 0.02%VOL, basically free from water vapor interference.

The impact of temperature on the detector was tested in the range of -20℃ and 50℃. The experimental analysis revealed a maximum temperature-compensated error of no more than 3.5% of the actual value, proving the temperature compensation algorithm was effective.

The working voltage, working current, intrinsic error, time of response and performance of the detector were tested in accordance with the instruction, with the parameters of the detector's performance shown in Table 2.

| Parameters               | Value                           |
|--------------------------|---------------------------------|
| Working voltage/ V DC    | 3.0~4.3                         |
| Average current/ mA      | <8                              |
| Measuring range/%VOL     | 0~100                           |
| Indication Error         | ±0.06/ ( 0~1.00% ) ; ±6% / ( 1.00~100% ) |
| Response time/s          | <20                             |
| Battery working time/day | >7                              |

From Table 2, the performances of the portable IR methane instrument equipped with the IR methane sensor as the sensitive component have all met or exceeded the industry standards of AQ6211-2008 for coal mine non-dispersive infrared methane sensor.

5. Conclusion
The new LED component with a peak wavelength of 3.3um which is the same as the main absorption peak of methane gas molecules is combined with the PD instrument with a wavelength of 3.6um to create a photoelectric detector in the paper, which developed the non-dispersive IR spectrum based IR methane sensor integrating the LED current-driven circuit and photosensitive signal processing circuit. The IR methane detector was equipped with the IR sensor along with tests of temperature, humidity and other influential factors, based on which the compensation formula of temperature and humidity as well as performance indicators were given in the paper. The IR methane detector developed in the paper has low power consumption and simple structure in addition to water vapor proof, making it worthy of promotion in methane detection at coal mines.

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Author
The first author: ZHAO Qing-chuan (1984 -), male, Han nationality, Jining City, Shandong Province, associate researcher, engaging in coal mine safety equipment research and development work in China Coal Technology Engineering Group Chongqing Research Institute, the main research direction for
the gas sensor design and electrical control technology. E-mail: zhaqich@163.com; Tel./Mobile Phone: 023-68683335/19923878608.

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