Analysis of Optical Fiber Methane Gas Detection System

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Abstract

With the advances in clean energy, natural gas (methane) takes a greater proportion in total energy consumption. Methane gas detection technology has become an important research direction for fire alarm area. Using near-infrared absorption spectroscopy method, this gas detection technology has many unique advantages, such as intrinsic safe, good stability, good selectivity, long working life, etc. In this paper, a gas detection system based on wavelength modulation and second harmonic (2f) signal detection technology is proposed; the process of the first and second harmonic demodulation is simulated; the feasibility of using first harmonic as light intensity reference and the linear relationship between the concentration and second harmonic is analyzed. Finally, a theoretical guidance for product developing with above technology is provided as well.

Keywords: methane; absorption spectrum; second harmonic; lock-in amplifier

1. Introduction

As clean energy, natural gas occupies an increasingly important role in people's lives. Compared with coal, natural gas has several advantages, such as higher calorific value, less toxic and hazardous substances and no waste after combustion. So it is ideal energy in the low-carbon economic category. However, as we all know, the main component of natural gas, methane is a colorless, odorless, flammable, hazardous gas. If the concentration of methane in the air reaches 5%, an explosion may happen, that will endanger people's lives and property.

Currently, methane detection and alarm at home and abroad is mainly using the traditional techniques, include catalytic combustion, metal oxide semiconductor-type, electrochemical sensors. There are some shortcomes of them, for example, easy to drift, poisoning failure, cross-sensitivity and short life, which makes frequent routine maintenance work expensively, and difficult to be kept in good condition is low. Thus, the actual performance has been seriously reduced. In contrast, methane sensors using near-infrared absorption spectroscopy has unique advantages that intrinsically safe, good stability, good selectivity, low maintenance and long service life. Therefore, the research and development of methane gas detectors with near-infrared spectrum absorption has important practical significance for improving the level of gas safety inspection and monitoring.

The research on the infrared methane gas detection technology was carried out in the 1970s abroad \cite{1}. With the development of the optical communication technology and optoelectronic devices in recent years, research in this area shows an accelerated growth trend \cite{2}. The characteristics of methane detection technique using near-infrared absorption spectroscopy are presented. And this article analyzes and simulates the system structure and technique method.

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2. Near-infrared absorption spectroscopy

At present, the near-infrared absorption spectroscopy, based on Lambert-Beer law and the harmonic detection method, is more popular in the international, which is a high-sensitivity, high-resolution, fast response trace gas detection [3, 4]. In particular, using near-infrared distributed feedback (DFB) semiconductor laser as a light source has narrow-linewidth and rapid tuning characteristics. The rapid detection of gas concentration can be achieved by detecting an isolated absorption line of target gas [3-7].

2.1. Lambert-Beer law

Methane and most of other fire gases have good absorption properties in the infrared spectral region. If the light source spectrum covers the wavelength range of one or more of the gas absorption line, when the light passes through the gas, attenuation occurs. According to Lambert-Beer law,

\[ I = I_0 \exp(-\alpha CL) \]  

where \( I \) is the transmission light intensity absorbed by the gas; \( I_0 \) is the incident light intensity; \( \alpha \) is the gas absorption coefficient; \( C \) is the gas concentration; \( L \) is the length of light through the gas.

At atmospheric pressure, the molecular absorption line broadening is mainly pressure broadening. So linear absorption coefficient \( \alpha \) can be approximated by the Lorentz.

\[ \alpha(v) = N_0 \sigma(v) = \frac{N_0 \sigma(v_c)}{1 + \left(\frac{v - v_c}{\gamma}\right)^2} \]  

where \( N_0 \) is the number of molecules per unit volume, at 25 °C under atmospheric pressure, \( N_0=2.6875 \times 10^{19} \); \( \sigma(v) \) is cross section; \( v \) is wave number, \( v_c \) is the wave number at the maximum absorption intensity; \( \gamma \) is half width at half-maximum (HWHM).

2.2. Harmonic detection technique

Harmonic detection technique uses wavelength modulation and second harmonic (2f) signal detection techniques to achieve highly sensitive detection of target gas. The wavelength modulation of absorption spectra can produce a harmonic signal which is proportional to the concentration of trace gases. In theory, this is a zero-background spectrum detection technique [3, 4].

With wavelength modulation technique, to produce the harmonic signals, a cosine modulation of angular frequency \( \omega \) is superimposed upon the laser. This results in a time variation of the laser frequency given by the following expression

\[ \nu = \nu_c + a \cos(\omega \cdot t) \]  

where \( \nu \) is the instantaneous frequency of the laser wavelength; \( \nu_c \) is the center frequency of the laser modulation; \( a \) is modulation depth. Wavelength of the laser output is modulated cosine. Then the signal generated by the laser passing through gas is a periodic even function, which can be expanded in a cosine Fourier series.

\[ S = \sum_{n=0}^{\infty} H_n(\nu_c) \cos(n\omega \cdot t) \]  

where \( H_n \) is the nth harmonic component of the modulated absorption coefficient. If the absorption coefficient \( \alpha \) is sufficiently small, \( H_n \) can be approximately expressed as
It can be seen from the above equation, that the harmonic components are proportional to the gas concentration. As the theory described above, the harmonic can be used to detect gas concentration. Because the amplitude of each harmonic component decreases with the number of harmonics increasing, low harmonics are often chosen to obtain a higher signal to noise ratio. With the harmonic detection technique, harmonic components can be selected by using a lock-in amplifier. The maximum value of even-order harmonics occurs at the gas absorption line center, and there is a linear relationship between the size of the peak and the detected gas concentration. The peak of the odd harmonics has a shift relative to the center of the absorption line. Among them, the second harmonic amplitude is greatest in all the even harmonics. Based on the above analysis, usually the second harmonic signal is used for gas concentrations inversion. Corresponding to the position of the absorption peak, the first harmonic component is regarded as a reference of light source intensity.

3. Analysis of harmonic detection of methane absorption spectrum

3.1. Detection system constitution

Methane gas detection system block diagram is shown in Fig. 1, which mainly consists of laser light source, drive circuit, temperature control circuit, absorption cell, photovoltaic conversion, lock-in amplifier and signal processing unit.

System uses the sawtooth and cosine signal to modulate laser drive current. The output optical signal modulated by laser drive circuit passes through the fiber into the absorption cell. Absorption cell model is shown in Fig. 2.

Optical signal in the gas cell is modulated by methane gas. Methane concentration information is loaded on the optical signal, and it is converted into electrical signal by photoelectric detector. The detected electrical signal is a weak signal superimposed on a large signal (DC + sawtooth + cosine wave). The signal from detector is high-passed filtered and amplified, then mixed with the cosine signal of angular frequency $\omega$ and the frequency-double cosine signal respectively. The output signals, which are proportional to the Fourier-component at $2\omega$ of the signal from the photodiode respectively, are low-passed filtered, amplified and obtained as the first and second harmonic components. There is a linear relationship between the maximum value of second harmonic and the concentration of the gas. The position of the second harmonic peak is at the center of absorption line. The first harmonic at the absorption line center represents light source intensity.
intensity, which has nothing to do with the gas concentration, and that can be used for reference. Therefore, the ratio of the second and first harmonic component at the absorption line center is independent of the light source intensity, and only related to the value of the gas concentration, which can demodulate the gas concentration information.

3.2. Second harmonic detection

Combination of frequency and the overtone of methane absorption wavelength is in the near infrared wavelength band, right on the 0.8-1.7μm range of optical fiber low-loss transmission window. Communication light source and optical fiber can be conveniently used in the detection system. Methane has a stronger absorption line at 1.66μm, and there is no water vapor and CO₂ absorption. According to PNNL database, as shown in Figure 3, the full width at half-maximum (FWHM) of methane absorption cross section at near 1653.73nm is about 0.06nm, which is the absorption line of the detection system.

![Fig. 3. Methane absorption cross section at 1653.7nm.](image)

Considering the actual characteristics of DFB lasers, at a steady temperature, there is an approximately linear relationship between the light intensity and the current, the light intensity increases with the current; there is also an approximately linear relationship between wavelength and current, the wavelength increases with the current too. Therefore, there is an approximately linear relationship between the light intensity and wavelength. According to the formula (1,2), methane absorption line spectra scanned by DFB laser is simulated, the gas concentration of 1%, the absorption path length 25cm, as shown in Fig. 4

![Fig. 4. Methane absorption spectrum](image)
The light source is modulated as formula (3). The center frequency $\nu_c$ is slowly tuned by ramping the diode current, and a cosine oscillation is mixed. At sawtooth frequency of 50Hz, cosine modulation frequency of 8kHz, modulation of 2.2, the sampling rate of 800k/s, the sampling results in one period of sawtooth is shown in Fig. 5.

![Fig. 5. Light signal with methane gas concentration](image1)

It can be seen that second harmonic signal is generated near the methane absorption line center. Through the lock-in amplifier, the first and second harmonic signal can be obtained. Details are demonstrated below. First, filtering out the impact of sawtooth wave with high-pass filter, the signal is shown in Fig. 6.

![Fig. 6. Modulated signal without sawtooth](image2)

Second, the filtered signal is multiplied by the 8kHz and 16kHz cosine respectively. The first and second harmonic components can be obtained with low-pass filter, as shown in Fig. 7.

![Fig. 7. Modulated signal with harmonic components](image3)
In theory the even harmonic signal is even symmetric about the absorption line center. However, due to the residue of other odd harmonic components and remainder of amplitude modulation, as the Figure 7 shows, the second harmonic signal is not completely symmetrical on both sides. According to the formula (5), there is a linear relationship between the maximum value of second harmonic and gas concentration, as well as the maximum value of second harmonic and light source intensity, as shown in Fig.7. Therefore, in order to avoid the impact of light intensity fluctuation, introducing light intensity reference is needed. Theoretically, the first harmonic value at absorption line center should be chosen as light source reference. But in fact, taking into account that the maximum slope of first harmonic is also at the absorption line center, any tiny deviation in horizontal position will lead to large errors. Thus, the flat on both sides of first harmonic is usually used as the light source reference.

When the gas concentration changes from 0 to 5%, the peak of second harmonic versus gas concentration and first harmonic light reference change versus the gas concentration are shown in Fig. 8.

It can be seen from Fig. 8, that using the flat on both sides of the first harmonic as light source reference makes no changes with the concentration basically, which can accurately reflect the information of incident light intensity. There is an approximately linear relationship with second harmonic and gas concentration. In the derivation of the formula (5), some higher order small items are ignored, which caused some non-linear. But on the whole, as shown in Fig. 9, under the lower explosion limit of methane, the linearity of the peak of second harmonic and the concentration can still reach 0.9978, in theory.
4. Conclusion

As clean energy, natural gas which’s main component is methane, occupies an increasingly important role in people's lives. Methane gas detection technology has become an important research direction for alarm fire detection area, which is an effective method for early detection of natural gas leakage. Methane gas detection system based on near-infrared tunable diode laser absorption spectroscopy is analyzed; a wavelength modulation spectroscopy and harmonic detection technique for the detection of low concentrations of methane is simulated, which linearity can reach 0.9978 in theory; and the feasibility of using first harmonic as light source reference is analyzed. System uses light as transmission carrier and sensing media. The probe doesn’t need power. With the ordinary communication fiber, sensors can be installed in 5 km away. That is an intrinsically safe, high stability, long working life methane gas detection system. And the system can be achieved for other fire gas detection only by increasing or replacing the semiconductor laser light source, that provides a good research platform for early fire detection technology.

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