Development of gas fire detection system using tunable diode laser absorption spectroscopy

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Abstract. The conventional fire detection methods mainly produce an alarm through detecting the changes in smoke concentration, flame radiation, heat and other physical parameters in the environment, but are unable to provide an early warning of a fire emergency. We have designed a gas fire detection system with a high detection sensitivity and high selectivity using the tunable semiconductor diode laser as a light source and combining wavelength modulation and harmonic detection technology. This system can invert the second harmonic signal obtained to obtain the concentration of carbon monoxide gas (a fire characteristic gas) so as to provide an early warning of fire. We reduce the system offset noise and the background noise generated due to the laser interference by deducting the system background spectrum lines from the second harmonic signal. This can also eliminate the interference of other gas spectral lines to a large extent. We detected the concentration of the carbon monoxide gas generated in smoldering sandalwood fire and open beech wood fire with the homemade fire simulator, and tested the lowest detectable limit of system. The test results show that the lowest detectable limit can reach 5×10⁻⁶; the system can maintain stable operation for a long period of time and can automatically trigger a water mist fire extinguishing system, which can fully meet the needs of early fire warning.

1. Introduction
Of all disasters, fire is the most frequent and the most common threat to public safety and social development. It not only causes environmental pollution, destroys ecological balance, but also seriously harms the development of the society. Take America for example, about 1,240,000 fires were reported in 2013. These fires resulted in 3,240 civilian fire fatalities, 15,925 civilian fire injuries and an estimated $11.5 billion in direct property loss [1].Although the cause of fire and combustion processes vary widely, each case of fire has certain physical characteristics, i.e. smoke, flames, and a certain amount of heat generated in the combustion process. By monitoring these physical characteristics we can determine whether a fire is really happening. But traditional physical detection is not always effective in detecting fires. At present, fire detection based on the gas concentrations produced in the combustion process has become an important direction of research. Among the methods for detecting gas concentration, tunable diode laser absorption spectroscopy technology receives increasing attention of the researchers for its characteristics of high selectivity, high sensitivity and high resolution, and has been recognized as a high-sensitivity measurement method with detection limits up to 10⁻⁶ or higher.
TDLAS technology uses the wavelength tuning characteristic of tunable diode laser to obtain the characteristic absorption spectra of the gas to be measured for qualitative or quantitative analysis. Compared with other optical methods, TDLAS exhibits significant advantages in both sensitivity and selectivity. The TDLAS measurement of trace gas concentrations is based on the detection of the absorption lines of the gas molecules, and the frequency and linearity of the absorption lines are the inherent, unique characteristics of gas molecules (just like human fingerprints). This feature can be recorded under high-precision and high-resolution conditions.

The spectral parameters of line positions, integrated line strengths, temperature dependence, and line broadening coefficient needed for quantitation of these molecules can be found in the high resolution transmission (HITRAN) molecular absorption database of spectral lines[10].

2. Determination of characteristic gases associated with fire
TDLAS technology for fire detection detects the concentration of the gas generated in the combustion process. Because the composition of the gas generated in the combustion process is very complicated, it is important to determine which gas should be selected as a characteristic gas for fire detection.

The vast majority of combustible materials that naturally exist contain two elements, C and H, which will generate a considerable amount of CO, CO₂ and H₂O in smoldering or flaming conditions. Given the influence of the humidity in the environment, H₂O is usually not deemed as one of the fire detection parameters. As one of the component gases of the atmosphere, CO₂ exists even in non-fire environments at a certain concentration. Because its content in the air is extremely low under normal circumstances and only appears in a considerable amount when fires occur, CO is usually selected as an indicator gas for fire detection. Figure 1 shows a test done in our laboratory which is used to determine whether carbon monoxide (CO) or carbon dioxide (CO₂) gas is more suitable for detecting a fire. When a tester breathes, the concentration of CO₂ gas near the detection point changes and gradually begins to rise from the normal value of 403 ppm (403 ppm for the current concentration of CO₂ gas in the test room) up to the maximum value of 985 ppm, and then begins to decline, while the concentration of CO gas remains unchanged. Only when there is a fire (simulated through the cotton rope smoldering fire test) does the concentration of CO gas gradually begin to rise...

In order to evaluate the adaptability of carbon monoxide detector to each kind of fire, researchers conducted comparative experiments on carbon monoxide detector, smoke detector and other detectors using six types of experimental fire specified by the European Standard EN54. Only carbon monoxide detector responds to all of the six types of fire, showing the adequacy of using CO as an indicator gas for fire detection.

![Figure 1](image-url). The test experiment for determination of fire characteristic gas.
3. Theory

According to the Lambert-Beer's Law, a beam of light will attenuate as it goes through gas. In case of no saturation, the intensity of transmitted light can be described by the following formula:

\[ I(\lambda) = I_0(\lambda)e^{-\sigma(\lambda)\lambda c l} \]  

(1)

Where \( I_0(\lambda) \) and \( I(\lambda) \) represent the input and output light intensities respectively, \( \sigma(\lambda) \) means the absorption cross section of the gas molecules to be measured where the wavelength is \( \lambda \) (which also can be expressed as the product of shape and intensity of the molecular absorption lines), \( c \) is the concentration of the gas to be measured, and \( l \) is the length of absorption path.

In order to reduce the interference of noise signals \[11\] and improve the signal to noise ratio\[12\], the wavelength modulation technology is typically used (modulation frequency <1MHz\[13\]) to modulate the output wavelength of the laser. Assuming the center frequency of the laser light is \( \nu_{cen} \), and the modulation amplitude and modulation frequency are \( \delta m \) and \( \omega_m \), respectively, we get the instantaneous frequency of the laser emission wavelength as follows:

\[ \nu = \nu_{cen} + \delta m \cos(\omega_m l) \]  

(2)

The transmitted light intensity of the laser can be described by the following Fourier series:

\[ I(\nu_{cen}, t) = \sum_{n=0}^{\infty} \Phi_n(\nu_{cen}) \cos(n \omega_m t) \]  

(3)

In Formula (3), \( \Phi_n(\nu_{cen}) \) means n-order harmonic component. When the gas concentration is very low, \( \sigma cl << 1 \). Furthermore, \( I_0 \) can regarded as a constant in an ideal situation, \( \Phi_n(\nu_{cen}) \) can be approximated by the following formula:

\[ \Phi_n(\nu_{cen}) = \frac{2I_0 cl}{\pi} \int_{0}^{\pi} \sigma(\nu_{cen} + \delta m \cos \theta) \cos(n \theta) d\theta \]  

(4)

Where \( \theta = \omega_m t \). When the modulation amplitude is much smaller than the absorption linewidth, the expansion of \( \Phi_n(\nu_{cen}) \) according to the Taylor series can be expressed as follows:

\[ \Phi_n(\nu_{cen}) = \frac{2^{1-n} I_0 cl}{n!} \delta_m \frac{d^n \sigma}{d\nu^n} \bigg|_{\nu=\nu_{cen}} \]  

(5)

As can be seen from Formula (5), the amplitude of the n-order harmonic signal is proportional to the gas concentration. Therefore, in theory, the concentration of the gas can be calculated with any one of the harmonic components. But in practice, as \( n \) increases, the value of \( \Phi_n(\nu_{cen}) \) and the harmonic linewidth will increase as well, which would affect the sensitivity and the resolution of the adjacent interference spectral line. On the other hand, the amplitude of even-order harmonics reaches the maximum at the center of the absorption line, which helps the laser stabilize at the center of the absorption spectra, while the amplitude of the odd harmonics is 0 at the center frequency, which works against the laser stabilizing at the center of the absorption lines. Therefore, when the above-mentioned factors are considered, the second order harmonic signal (\( n=2 \)) is selected in the experiment as a detection signal, i.e.

\[ \Phi_2(\nu_{cen}) = \frac{I_0 cl}{4} \delta_m ^2 \frac{d^2 \sigma}{d\nu^2} \bigg|_{\nu=\nu_{cen}} \]  

(6)

Under atmospheric pressure, the line broadening of the molecules mainly takes the form of pressure broadening, which can be expressed with the Lorenz linetype:
\[ g_N(v, \nu_0) = \frac{\Delta \nu_N / 2\pi}{(v - \nu_0)^2 + (\Delta \nu_N / 2)^2} \]  

(7)

Where \( \Delta \nu_N \) means the half-width of the collision broadening.

4. Experimental setup

The experimental devices are shown in Figure 2. The whole detection system comprises signal generator (TFG3050), laser(NLK1C5EAAA), laser controller (LDC3724B, ILX Lightwave), White absorption cell (homemade), lock-in amplifier (7265, Signal Recovery), fire simulation device (homemade) and data acquisition system (INV303B).

For CO detection, the best light source is lasers with wavelength of 4.65 microns. But in fact, the far-infrared laser is expensive to buy and inconvenient to maintain. CO also has absorption line of wavelength 1579.737 nm in its absorption spectrum, which, although has lower absorption intensity than 4.65 microns wavelength, can still be used for fire detection depending on the strong radiation of the laser. Therefore, we choose the continuously tunable DFB diode laser which is relatively affordable. The laser can work at room temperature, with output power of 10 mW, emission wavelength of 1579 nm (the CO characteristic absorption peak) and output frequency coinciding with the absorption lines of carbon monoxide.

The temperature and current of the laser are controlled by a semiconductor laser controller (LDC3724B, ILX LightWave). Controller has a variety of built-in temperature sensors. The change rate of wavelengths with the temperature is 0.1 nm / K.

In order to reduce the interference of the noise spectrum, we superimpose a 5 kHz high-frequency sine wave signal on the 50 Hz low frequency sawtooth signal to modulate the emission wavelength.
The sawtooth wave is generated by the signal generator and the high-frequency sine wave is generated by the lock-in amplifier. These two waveforms, after superimposed by the adder, are injected into the laser controller for laser modulation and scanning.

The beam emitted from the laser enters the absorption cell through the lens after being led out by the optical fiber. The optical fiber is 9/125 μm (1km) single-mode corresponding to the wavelength of about 1579 nm whose transmission loss is below 1dB/km. The White absorption cell is an very important part of the measurement system which based on multiple reflection. The optical path is increased in the cell through the increase of the number of reflections. The total optical path is approximately 100 m, and the temperature uniformity of the cell body is better than ± 0.5 ℃, and a high vacuum of more than $1.33 \times 10^{-5}$ Pa can be maintained within the cell. The White multiple reflection cell consists of a spherical mirror, a corner reflector and a field lens. The number of reflections can be adjusted with the spherical mirror in order to change the optical path in the multiple reflection cell. The absorption cell is open, and when fire breaks out, the fire products enter the absorption cell through the opening. Some of the incident laser beam is absorbed by CO that is part of the products, while some is emitted through the exit end after multiple reflections before received by the PIN photodiode on the optical path, which converts the optical signals into electrical signals. The wavelength response range of the photodiode is 1000-1700 nm, characterized by low noise and high sensitivity.

As the useful signals are relatively weak and submerged in the noise signals, the output signals from the photodetector are input to a lock-in amplifier, where a second harmonic detection is used to return second harmonic signals of the gas absorption lines. These signals are collected by the data acquisition card and fed into the computer for processing. The TDLAS, by combining wavelength modulation spectroscopy and second harmonic detection, can suppress noise to a large extent and improve the sensitivity of the system [14-16].

In order to simulate fire, a homemade fire simulation device is used. The device is an iron container whose bottom is a hollow cuboid 50 cm by 50 cm and 80 cm in height. The top of the device is a cone with 45 degrees angle, and the tip is connected with a cylindrical pipe with inner diameter of 2.5 cm for installing PVC pipes. Fire products can hardly enter the White cell depending on its natural buoyancy, so a suction device is installed in the fire simulation device, which can efficiently transfer the combustion products produced in the experiment into the absorption cell.

5. Experiment

5.1. Second harmonic detection

A homemade gas distribution system is used to prepare CO gases of various concentrations required for the experiment. The mass flow ratio method is adopted in the preparation and 99.999% industrial carbon monoxide and 99.999% nitrogen of high purity are used. The gas distribution system is based on accurate mass flowmeter SFC4000 (Sensirion), and produces the mixed gas with a pressure of 1 atm. To avoid interference from other gases, the White cell is vacuumed ($2.6 \times 10^{-4}$ Pa or less) many times prior to the experiment, and then rinsed with 99.999% pure N2 before vacuumed again. This is to rule out the possibility of spectral absorption caused by the presence of other interference gases.

The method where the system background spectra are deducted from the second harmonic signal obtained from the experiment is used to reduce the offset noise caused by modulation and the background noise formed by the optical streaks as a result of laser interference. This not only effectively suppresses the background interference, but also largely eliminates the effects of the spectra of other interference gases.

Figure 3 shows the second harmonic signals of CO at different concentrations. It can be found that the signal is substantially symmetrical on both sides, indicating that the impact of the residual amplitude modulation of the laser is relatively small.

Figure 4 shows the linear relationship between the configured concentration and the measured concentration of the CO gas. As can be seen from Figure 4, the concentration measured by the system
has a good linear relationship with the configured concentration, where the linear correlation is 0.99. Under the same conditions, its good reproducibility is proven by a number of tests, with the maximum deviation between the signals controlled within a small range.

![Figure 3](image_url)  
**Figure 3.** The second harmonic signals of CO at different concentrations.

![Figure 4](image_url)  
**Figure 4.** The linear relationship between the measured and the true values of CO concentration.

5.2. Fire simulation

After the system is commissioned, sandalwood and beech wood are lit in the combustion chamber to simulate smoldering fires and open fires. At the same time, the fan is started and experimental data are collected. The combustion products emitted from the smoke vent in the combustion chamber are transferred to the entrance to the White cell through the PVC pipe. While the data is being collected, the fixed window smoothing function and frequency-domain averaging function are usable to eliminate the impact of random noise.

During the smoldering fire simulation test, the ignited and then put out sandalwood with a diameter of 2.5 mm is placed on the center bottom of the combustion chamber, so as to generate continuous smoke. The change in CO gas concentration is as shown in Figure 5. As can be seen from the figure, the concentration of CO gas continues to increase from the beginning of the test; it reaches 5 ppm at t=21s and then continues to increase, and reaches the maximum value of 79 ppm at t=119s. Later, it starts to decline (The decline curve is not shown in Fig.5).

In the simulation of open flames, pieces of beech wood with dimension of 1cm × 2cm × 2.5 cm (moisture content lower than 3%) are stacked in three tiers and placed in the combustion chamber. On the center bottom of the combustion chamber is a 5cm-diameter dish filled with 5 ml of industrial alcohol which is ignited. The change in the CO concentration generated from the beech burn is shown in Figure 6. As can be seen from the figure, the CO concentration reaches 5 ppm at t=29s. Although it dips briefly at the first peak, the CO concentration maintains a growing trend in general, and reaches a maximum value of 34 ppm at t=120s before starting to decrease. As the data in Figure 6 only represents a capture of 120 seconds, the downward curve is not shown in the Figure.

Figures 5 and 6 show that both smoldering fires and open flames can lead to continuous rise of CO concentration in air. Whereas the CO content in normal air is typically very low, it is feasible to determine the occurrence of fire depending on the concentration of CO gas. Generally, smoldering generates higher concentrations of CO than open flames. The maximum CO concentration shown in Figure 5 is approximately 2.32 times that in the Figure 6.
5.3. Coordinated fire suppression

A gas fire detection system that works well should be able to sound the alarm and act in conjunction with fire extinguishing systems, in addition to the ability to detect fire. The signals of the CO concentration are judged using the self-made program. When the concentration exceeds the set threshold value, the microcontroller (AT89S51) on the control circuit board issues a command that enables the relay control circuit to connect, which triggers the sound and light alarm (P2475) and starts the water mist fire extinguishing system to put out the fire. The water mist is driven by high-pressure nitrogen, and the 30 L water tank is connected with the pipeline made of stainless steel equipped with a filter. The high-pressure air reaches the required pressure through the relief valve and pressurizes the water in the tank, which flows through the shut-off valve before sprayed through the spray nozzle in the form of fine mist. The alarm threshold usually varies with the importance of places and can be set as required. We set 5 ppm as the threshold value of the alarm signal, meaning any signal showing a concentration greater than or equal to 5 ppm is considered a fire alarm. The experiments show that the alarm works once the experiment starts, and the water mist fire extinguishing system begins to function as well.

6. Conclusion

Tunable diode laser absorption spectroscopy (TDLAS) uses the wavelength tuning characteristic of diode laser for qualitative or quantitative analysis of the target gas. This approach not only has the feature of high precision and good selectivity, but also fast response and has been applied in the monitoring of atmospheric trace gas, gas leaks and other fields.

In the paper, the concentrations of CO generated by the smoldering sandalwood and the open beech wood fire are measured by the least-squares data processing method using narrow linewidth tunable semiconductor laser as a light source in combination with a long optical path White cell, wavelength modulation and the harmonic detection technology. The research results show that the system works well in online measuring the CO concentrations in the environment with real-time displays. The lowest detectable limit is 5×10⁻⁶, and the system runs with stability on long-term basis and can meet the requirements of early fire warning. In the experiment, background subtraction is used to effectively reduce the impact of the residual amplitude modulation and the background noised formed by the optical streaks resulted from laser interference. This improves the signal-to-noise ratio and guarantees that the CO concentration in the environment is measured online and accurately obtained through inversion. With a different wavelength diode laser as a light source, the TDLAS technology can also
be used for the detection of other gases, and therefore holds great promise for further applications in areas such as environmental protection, industrial control, chemical reaction dynamics and other fields.

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