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Recent advances in laser gas sensors for applications to safety monitoring in intelligent coal mines

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Due to the extremely complex working conditions, various health and safety hazards are present in underground coal mines, which cause economic losses and heavy casualties. Among these hazards, methane gas explosion and coal combustion are recognized as the two major hazards to miners. Traditional electronic sensors in mine safety monitoring systems have problems such as low precision, a large amount of maintenance, and monitoring dead zones. In the past decade, gas sensors based on tunable diode laser absorption spectroscopy (TDLAS) have been extensively studied and tailored for use in the coal mine industry because of their advantages of high sensitivity, high stability, fast response, intrinsic safety, and remote monitoring. This invited paper introduces the recent progress and typical applications of TDLAS-based methane sensors, carbon monoxide sensors, and multi-gas monitoring systems in coal mine gas monitoring, fire prevention, and early warning in intelligent coal mines.

KEYWORDS

coal mine safety, gas sensor, TDLAS, methane, carbon monoxide, multi-gas

Introduction

Currently, coal is one of the primary energy sources, and it will remain so in the near future. In 2021, 81.73 billion tons of coal were produced worldwide, which is 6.0% more than that in 2020. There are more than 5,000 coal mines in China, of which more than 95% are underground coal mines. Coal mine safety is a very serious issue. In the past decade, gas outbursts and explosions and coal combustion have been the two main hazards encountered in underground coal mines, among which gas explosions are the main cause of very serious accidents, where more than 10 people have died. With the rapid development of gas monitoring systems, coal mine safety has been consistently improved, which is signified by the decrease in casualties. In 2002, China produced 1.4 billion tons of coal with 6995 casualties [1]. In 2021, the casualties decreased to 178 and the production increased to 4.13 billion tons, corresponding to an improvement of 111 times in terms of the casualty rate per million tons of coal production (from 4.9 in 2002 to 0.044 in 2021). To further reduce the number of casualties in coal mines and ensure the safety of life and property, all the hazardous gases present in the mines need to be monitored online to prevent the potential accidents. With the rapid development of the Internet of Things (IoT), 5G communication technology, big data, and other new technologies, mine safety IoT and intelligent mines have gradually become a new trend. Different types of mine sensors, especially for methane, carbon monoxide, and other environmental gases, provide the essential environmental information and data basis for constructing mine safety IoT or intelligent mines. Among the requirements of intelligent mines, one of the most important aims is to reduce the workload of miners and realize intelligent sensing, comprehensive monitoring, autonomous analysis, early warning, and effective control. However, the traditional electronic sensors employed in mine safety monitoring systems cannot meet the key requirements of intelligent mines due to problems such as low precision, poor reliability, large amounts of maintenance, and monitoring dead zones.

For methane detection, the main sensors employed in coal mines are catalytic combustion methane sensors [2–4]. However, they have some unavoidable disadvantages, such as easy poisoning, poor selectivity, and regular calibration, which inevitably increase the workload on coal miners and increase the risk of death and injury to workers. Another methane sensor is the infrared gas sensor, which adopts a broadband infrared light source and an optical filter for differential photoelectric detection [5]. However, it is easily affected by humidity and temperature. Therefore, its reliability and stability are poor in the complex environment of underground coal mines. Additionally, electronic sensors are also employed that cannot be used in special hazard areas, such as goaf, which lead to blind areas in monitoring. In the past decades, with the rapid progress in modern optoelectronic technology, the spectral technology has become the focus of research teams at home and abroad [6, 7]. There are many gas detection methods based on spectroscopy, including cavity-enhanced absorption spectroscopy (CEAS) [8], cavity ring-down spectroscopy (CRDS) [9], photoacoustic spectroscopy (PAS) [10], photothermal spectroscopy (PTS) [11], laser Raman spectroscopy (LRS) [12], and tunable diode absorption spectroscopy (TDLAS) [13]. Because of their better environmental adaptability and reliability, gas sensors based on TDLAS are more and more widely used in the field of gas detection [14, 15]. TDLAS-based gas sensors utilize lasers instead of current and voltage to realize information perception and use optical fibers instead of cables as the information transmission medium. Therefore, laser gas sensors are more suitable for flammable, explosive, and humid coal mine environments. TDLAS technology has the great advantage of *in situ* online monitoring, and it has become an irreplaceable detection technology in intelligent mines [16–18]. In 1981, Reid J et al. reported the measurement of gas concentrations based on the second harmonic detection technique, which greatly promoted the development of high-precision TDLAS equipment [19]. Since 2017, laser methane sensors have been gradually employed in coal mines [20]. The maintenance period of methane sensors is extended from 2 weeks for the conventional catalytic combustion methane sensor to 6 months for the laser methane sensor. Consequently, it has significantly reduced the number of underground coal miners and improved the intelligence level of coal mines.

Fire is one of the major hazards in coal mines. Coal spontaneous combustion stems from coal residues in the goaf being oxidized and heat being accumulated, which consequently accelerates the combustion and causes fire [21, 22]. The presence and increase of CO are typical characteristics during the early stages of oxidation. When the oxidation becomes severe, the temperature starts to increase, and C_2H_4 appears. C_2H_2 is the final warning indicator; its presence signifies that fire is imminent. Therefore, for the early detection of coal combustion, CO is the most important characteristic gas to monitor. Carbon dioxide (CO_2), ethylene (C_2H_4), acetylene (C_2H_2), and other landmark gases are also important for monitoring spontaneous combustion hazards. Typically, the required detection sensitivity for CO is 1 ppm, and for C_2H_4 and C_2H_2, it is 0.1 ppm. Conventional monitoring technology is based on tubing bundle gas sampling systems and chromatography-based gas monitoring instruments [23], which are typically located at the ground monitor center and suffer from long delay times, cumbersome maintenance, and inaccuracy due to possible tubing leakage.

Based on the demands of intelligent coal mines, our group has developed various gas sensors based on TDLAS technology, which have been successfully demonstrated and applied in the construction of mine safety IoT and intelligent coal mines. In this invited paper, the principle, advantages, applications, and recent progress in TDLAS-based gas sensors used for coal mine safety are comprehensively introduced.

Principles of laser absorption spectroscopy

The physical basis of TDLAS technology is the absorption of light energy of a specific frequency by gas molecules. When the frequency of incident light is the same as the vibration frequency inside a molecule, the two resonantly couple, and the molecule absorbs light energy and produces a transition. When the vibration level transits from the ground state to the first excited state, the absorption is the fundamental frequency absorption. When the molecular vibrational level transitions from the ground state to the second excited state and above, the resulting absorption is overtone absorption [24, 25]. The

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absorption peaks have significant characteristics, which can be used as a basis for determining the molecular type or atomic group of gas and can be used for the qualitative and quantitative analyses of gas.

The intensity of infrared light absorbed by gas molecules is related to not only the optical path of light in the material but also the concentration of gas. The Beer–Lambert law of absorption is satisfied between the initial and outgoing light intensities [26]:

$$I_t(v) = I_0(v)\,exp[-\alpha(v)CL], \tag{1}$$

where $I_0(v)$ is the input light power, $I_t(v)$ is the outgoing light intensity, C is the volume concentration of the gas, L is the length of the gas absorption path, and $\alpha(v)$ is the gas absorption coefficient, which is affected by the temperature and pressure as gas is compressible and which satisfies

$$\alpha(v) = S(T)g(v, v_0)P, \tag{2}$$

where $S(T)$ is the temperature dependence of the absorption coefficient, P is the ambient pressure, and $g(v, v_0)$ is the line-shape function. The three commonly used line-shape functions are the Lorentzian function, the Gaussian function, and the Voigt function. In the measurement environment of coal mines, the collision broadening of gas molecules is dominant. Therefore, the Lorentzian function is selected to describe the line-shape function of the absorption spectrum, which satisfies

$$g(v, v_0) = \frac{1}{\pi}\frac{\frac{\Delta v}{2}}{(v - v_0)^2 + \left(\frac{\Delta v}{2}\right)^2}, \tag{3}$$

where v_0 is the central frequency of the absorption spectrum line and Δv is the full width at half height of the spectral line caused by collision widening. The integral value of the line-shape function $g(v, v_0)$ in the full frequency domain is 1 unit. By carrying out logarithm calculations on both sides of Eq. 1 followed by integration, we have

$$S(T)PCL = -\int_{-\infty}^{+\infty}\frac{I_0(v)}{I_t(v)}dv = A. \tag{4}$$

Then, the volume concentration of the gas can be expressed as follows:

$$C = \frac{-\int_{-\infty}^{+\infty}\frac{I_0(v)}{I_t(v)}dv}{S(T)PL} = \frac{A}{S(T)PL}. \tag{5}$$

TDLAS technology mainly uses the narrow line width and tunability of tunable semiconductor lasers to measure one or several close absorption lines of gas molecules. Gas sensors based on TDLAS technology are highly sensitive and stable due to the tunable semiconductor laser's narrow line width, controllable operating temperature, and optical power output, which is the reason for the rapid development of this technology.

Laser methane sensor and applications to on-line monitoring of coal mine gas

Laser methane sensor

Methane (CH_4) is the most important gas in coal mine safety monitoring. When CH_4 in the concentration range of 5%–16% meets an open flame, it will immediately explode. By pressurizing fresh air flow from the ground to the coal mine, O_2 can be supplied underground, and the CH_4 concentration can be reduced. Methane gas has absorption peaks around the 3.3 μm and 1.65 μm bands. However, the mid-infrared (MIR) laser is very expensive and needs to be cooled. The 1.65 μm band is similar to an optical fiber communication band, and the photoelectric device is mature and cheap. Therefore, laser methane sensors usually choose the absorption peak near 1.65 μm for detection. Direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS) are two signal processing methods widely used in TDLAS [27, 28]. Direct absorption detection can be realized by scanning the gas absorption signal with sawtooth current modulation laser wavelength. When the laser passes through the target gas, a curve rising with the laser wavelength is detected using the photodetector. The curve has a depression at the corresponding absorption peak. The gas absorption characteristic line can be obtained by normalizing the detection curve. The DAS system inverts the gas concentration by directly monitoring the attenuation of light intensity, and its experimental device and scheme are relatively simple. For the WMS system, the high-frequency modulated signal is superimposed on the low-frequency scanning signal as the driving signal of the laser. Then, the harmonic signal of the absorption spectrum is obtained by using the phase-locked amplification technology, and the gas concentration is detected according to the peak value of the harmonic signal. Most of the background noise, especially the 1/f noise, has the characteristics of high intensity in the low-frequency band and is greatly reduced in the high frequency. Therefore, the WMS system can effectively suppress the background noise introduced into the spectrum by circuit systems, optical devices, and optical–mechanical systems. It can effectively extract weak signals from noise and improve the detection sensitivity of spectral signals. Inaba H et al. first used the spectral absorption method to conduct long-distance air pollution monitoring [29]. Uehara K and Tai H used a 1.6-μm single-mode distributed feedback laser (DFB-LD) to detect methane gas concentration at room temperature [30]. The system used the harmonic method with wavelength modulation, and its minimum detectable sensitivity is 20 ppm. The system achieved high detection sensitivity due to the combination of DFB-LD, wavelength modulation harmonic detection technology, and optical fiber technology. Zhang

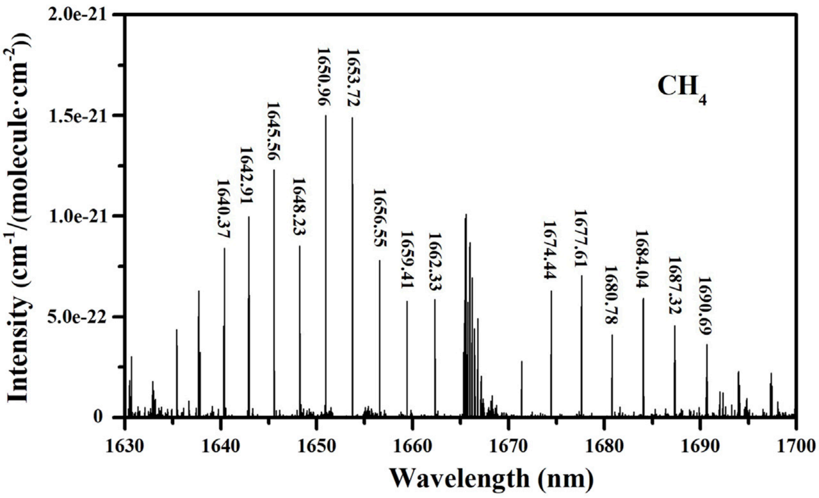

FIGURE 1
Absorption spectra of methane gas in the 1650 nm region.

et al. proposed a single-channel direct absorption methane measurement system with a 1.33-μm DFB-LD and an optical power meter with a response sensitivity of 1 nW [31]. They verified the linear relationship between the output electrical signal and the concentration when the concentration was less than 15%. Iseki et al. designed a portable methane telemetry sensor with a 1.65-μm DFB-LD and a measuring distance of 10 m and a measuring accuracy of 5 ppm [32]. The aforementioned studies greatly promoted the advancement of laser methane sensing technology.

Reducing the overall power consumption of laser methane sensors is important for application in underground coal mines. When the power consumption of a CH_4 sensor is too high, the number of sensors that can be supplied by an intrinsically safe power supply cannot meet the requirements of coal mine gas detection. Additionally, to meet the 6 km transmission distance requirement stipulated by the coal mine safety monitoring system, the sensor current and power consumption need to be reduced as much as possible to increase the detection distance between the sensor probe and the power supply substation. A vertical-cavity surface-emitting laser (VCSEL) has a considerably lower threshold current, operating current, and operating power consumption than the distributed feedback (DFB) laser [33, 34]. Generally, the current modulation regime of the DFB laser is about 10 p.m/mA and that of VCSEL is up to 400 p.m/mA. Thus, VCSEL has higher current-wavelength tuning characteristics than the DFB laser. Moreover, the wavelength modulation coefficient of VCSEL is smaller by temperature modulation and larger by current modulation [35]. With the development of long-wavelength VCSEL technology, the research on gas detection technology based on low-power VCSEL has become very attractive [36, 37].

In order to ensure that the laser output wavelength can lock the gas absorption peak stably, the conventional laser gas detection technology usually uses a semiconductor cooler to control the laser temperature within a certain range and uses the method of current trimming to measure the absorption spectrum line. The temperature control system of the laser increases the overall power consumption of the gas detection system. Our group developed a laser methane detection system based on VCSEL without a thermoelectric cooler (TEC). The system realized gas detection without a temperature control system, thus effectively reducing system power consumption. Based on the wide wavelength range of VCSEL, the multi-absorption peak intelligent tracking technology has been successfully developed. Figure 1 shows the absorption spectrum of methane gas in the near-infrared range. The wavelengths we selected to detect the absorption lines are 1642.9 nm, 1645.5 nm, 1650.9 nm, and 1653.7 nm. According to the absorption information of the reference gas chamber, the current feedback technology was used to control the laser to work on one of the aforementioned absorption peaks. According to the wavelength variation law of VCSEL with temperature, a dynamic adjustment relationship had been established between the gas detection absorption peak and temperature. The system realized methane detection by adaptively tracking the methane absorption line. Furthermore, the temperature and pressure characteristics of different absorption peaks have been studied. Subsequently, a laser methane-sensing module has been successfully developed with a power consumption of less than 100 mW at an ambient temperature of −20 to 60°C.

FIGURE 2
The developed laser methane sensor products.

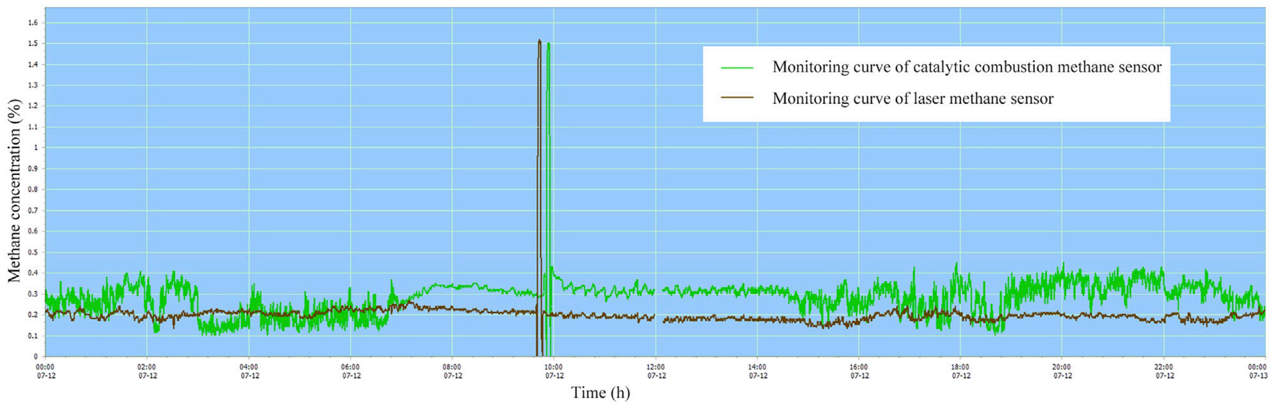

FIGURE 3
The methane monitoring data in 10307 working face.

Applications of the laser methane sensor in coal mine on-line monitoring

According to the safety regulations in coal mines, fixed or mobile methane sensors need to be installed in key areas of the mining face and return air roadways. When the methane concentration reaches 1.0%, a sound and light alarm will be set off, and when the methane concentration reaches 1.5%, power will be cut off for equipment in the related area [38]. Based on the high humidity and dust environment of coal mines, laser methane sensors need to conduct the engineering design of waterproof, dustproof, impact-resistant, anti-electromagnetic interference, and other necessary coal mine electrical equipment. Figure 2 displays the developed laser methane sensor products. These are the optical fiber methane sensor, the second-generation laser methane sensor, the latest miniaturization laser methane sensor, and the portable methane sensor. Currently, laser methane sensors are used in more than 1,000 coal mines in China. This application shows that their advantages, such as stability and moisture resistance, have been recognized by the coal mine industry. Laser methane sensors do not need to be recalibrated, which significantly reduces the workload of equipment maintenance personnel. With its low power consumption characteristics, the module can be used as a wireless sensor for remote detection in the upper corner of coal mines or gas drainage pipelines.

Figure 3 shows the continuous monitoring data of methane gas in 10,307 working faces of the Xinlongzhuang coal mine from 12 July to 13 July 2018. The results show that the monitoring curve of the laser methane sensor has a smaller fluctuation and a faster response than that of the traditional catalytic combustion methane sensor. Moreover, it verifies that the laser methane sensor is not easily affected by moisture, in contrast to the traditional catalytic element and infrared methane sensor, which are easily affected by moisture. Thus, laser methane sensors provide an effective way for methane monitoring in intelligent coal mines.

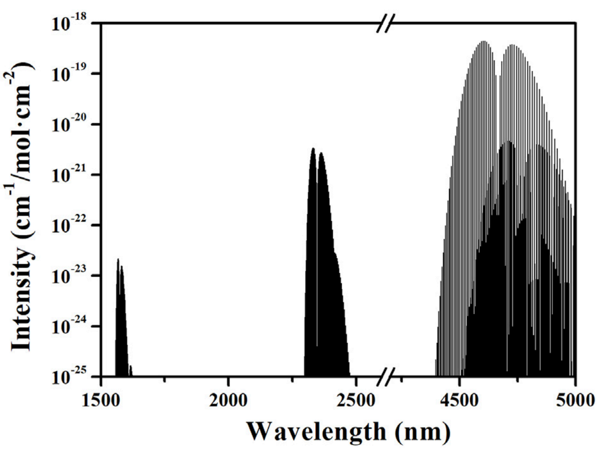

FIGURE 4
Absorption lines of CO from 1.5 μm to 5 μm.

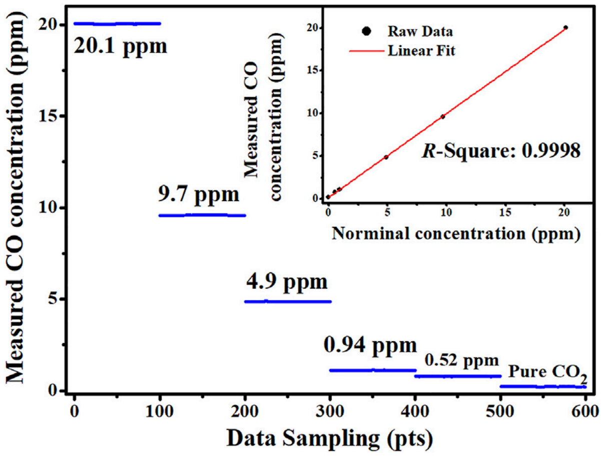

FIGURE 5
The typical measurement data of CO monitoring system.

Coal mine fire monitoring and early warning

In China, 95% of the coal mines are well coal mines, and more than 60% have a spontaneous combustion tendency. In goaf, coal can easily oxidize spontaneously and even develop into fire. In the early stage, the oxidation reaction mainly produces CO, and as the temperature increases, the oxidation reaction becomes violent and yields C_2H_4 and C_2H_2. Therefore, the presence of CO, C_2H_4, and C_2H_2 can be used for fire warning. Additionally, O_2, CH_4, and CO_2 are important gases that need to be monitored for the spontaneous combustion control of coal.

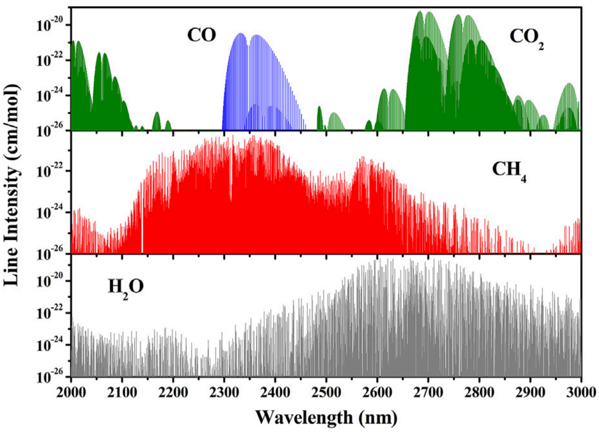

FIGURE 6
Absorption lines of CH_4, CO, CO_2, and H_2O at 2-3 μm.

Laser CO sensor

Accurate measurement of CO, the signature gas of early fire, is of decisive significance for the early diagnosis of fire and for providing sufficient time for prevention and control. The real-time monitoring of the CO concentration should be performed in coal seams that are prone to spontaneous combustion, such as return air lanes in mining areas, firewalls in closed fire areas, and spontaneous combustion observation points. The alarm trigger of the CO sensor is the CO concentration of 24 ppm. As depicted in Figure 4, CO affords absorption lines in the infrared region: the weak second overtone band (~1.56 μm), the first overtone band (~2.3 μm), and the strongest fundamental vibration band (~4.6 μm) [39]. According to the Beer–Lambert law, the performance of the laser CO sensors is closely related to the strength of the absorption lines. The figure shows that the near-infrared (NIR) absorption is about four magnitudes weaker than that around 4.6 μm. However, to use telecommunication laser devices and standard single-mode optical fibers, the harmonic absorption spectra in the NIR region are of interest. Xia et al. realized a detection sensitivity of 0.25 ppm in the 1566.6 nm band using the 56 m optical path and second harmonic technique [40]. Owing to the advantage of intrinsic safety, this sensor scheme can be successfully applied in coal mines. However, a long-path-length multi-pass gas cell must be employed in the developed NIR CO sensors. Therefore, complex structures and large volumes may be unavoidable for the NIR CO sensors.

As shown in Figure 4, the absorption lines of CO have coefficients of 3.47×10^{-21} (cm^{-1}/mol cm^{-2}) at 2.3 μm, which is about two magnitudes stronger than NIR absorption. Therefore, a highly sensitive CO sensor can be realized using a 2.3-μm laser. CO sensors with increasing sensitivity have been

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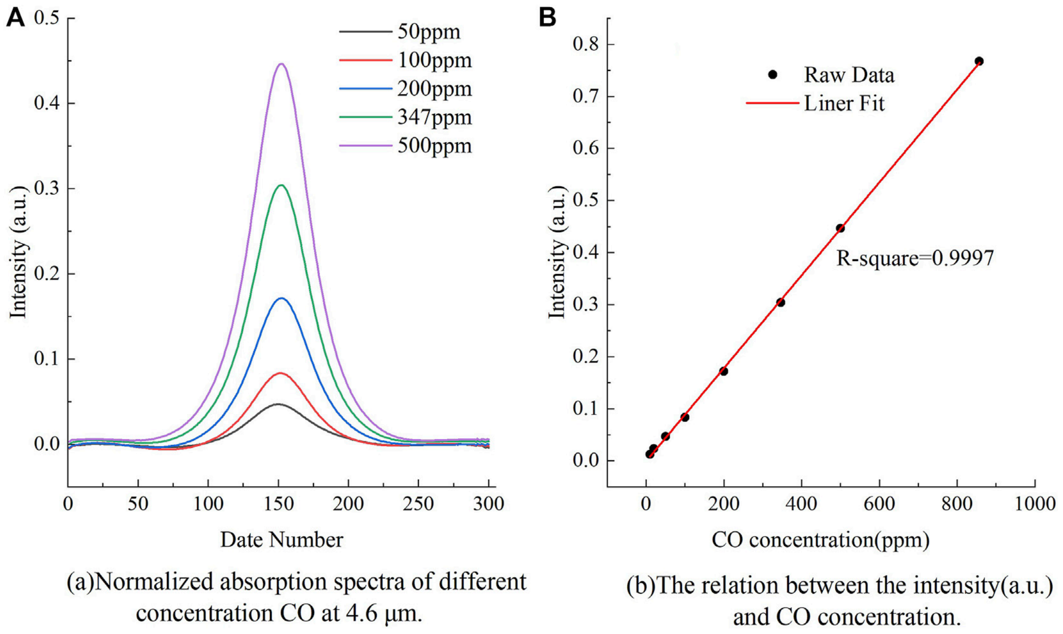

FIGURE 7
The typical measurement data.

reported using a 2.3-μm laser diode. Dang et al. achieved a detection sensitivity of 0.06 ppm for CO monitoring with a 2334 nm absorption peak, which is therefore attractive for coal mining applications [41]. Chen et al. adopted a 2.3-μm VCSEL as the light source and realized the detection of trace CO using wavelength modulation and by introducing a reference chamber [42]. Wang et al. presented a stable and reliable CO monitoring system with high sensitivity for use in the mining industry in particular, tailoring the design specifically for forecasting spontaneous combustion [43]. Their results are shown in Figure 5.

The main difficulty in CO detection in underground coal mines is the elimination of the influence of CH_4, CO_2, and humidity on the measurement. The absorption lines of CH_4, CO, CO_2, and H_2O at 2–3 μm are shown in Figure 6. Therefore, the problem of multi-gas cross-interference in the practical application of sensors in underground coal mines needs to be analyzed and solved. In the 2.33 μm band, CH_4 has a serious effect on CO. Although it can be compensated by measuring the methane concentration, the compensation effect is limited due to the limitations of the methane measurement accuracy.

In the MIR band of 4.6 μm, several strong CO absorption peaks are present, which are not interfered by CH_4 and CO_2. With the rapid development of MIR laser technology, the TDLAS-based CO sensor has made a new breakthrough [44–46]. In recent years, compact CO sensors with ultra-high

TABLE 1 Measurement requirements of multi-gas monitoring.

Gas	Full-scale	Resolution		Unit
CO	0–1000	0–100	±4	10^{-6}
		100–500	±5% true value	
		500–1000	±6% true value	
CO_2	0–5	0–0.5	±0.1	%
		0.5–5	±(0.08 + 5% true value)	
C_2H_2	0–100	0–2	±0.5	10^{-6}
		2–5	±1	
		5–10	±2	
		10–20	±3	
		20–100	±(1 + 10% true value)	
C_2H_4	0–100	0–2	±0.5	
		2–5	±1	10^{-6}
		5–10	±2	
		10–20	±3	
		20–100	±(1 + 10% true value)	
CH_4	0–100	0–1	±0.1	%
		1–40	±10% true value	
		40–100	±10	

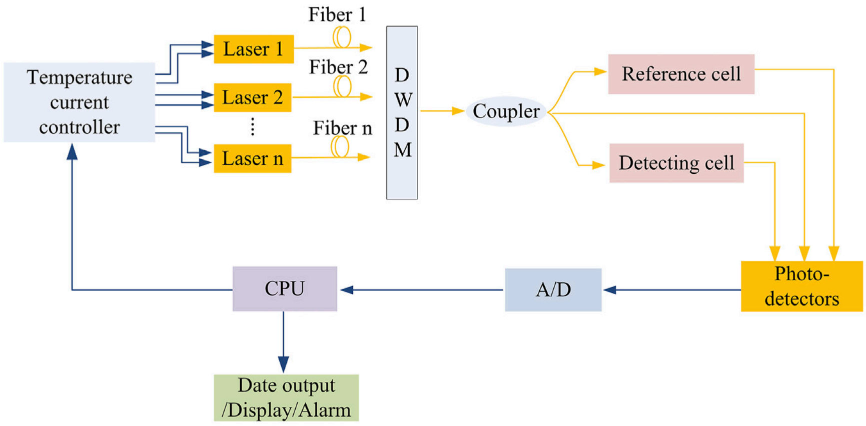

FIGURE 8
Block diagram of TDLAS-based multi-gas sensor system.

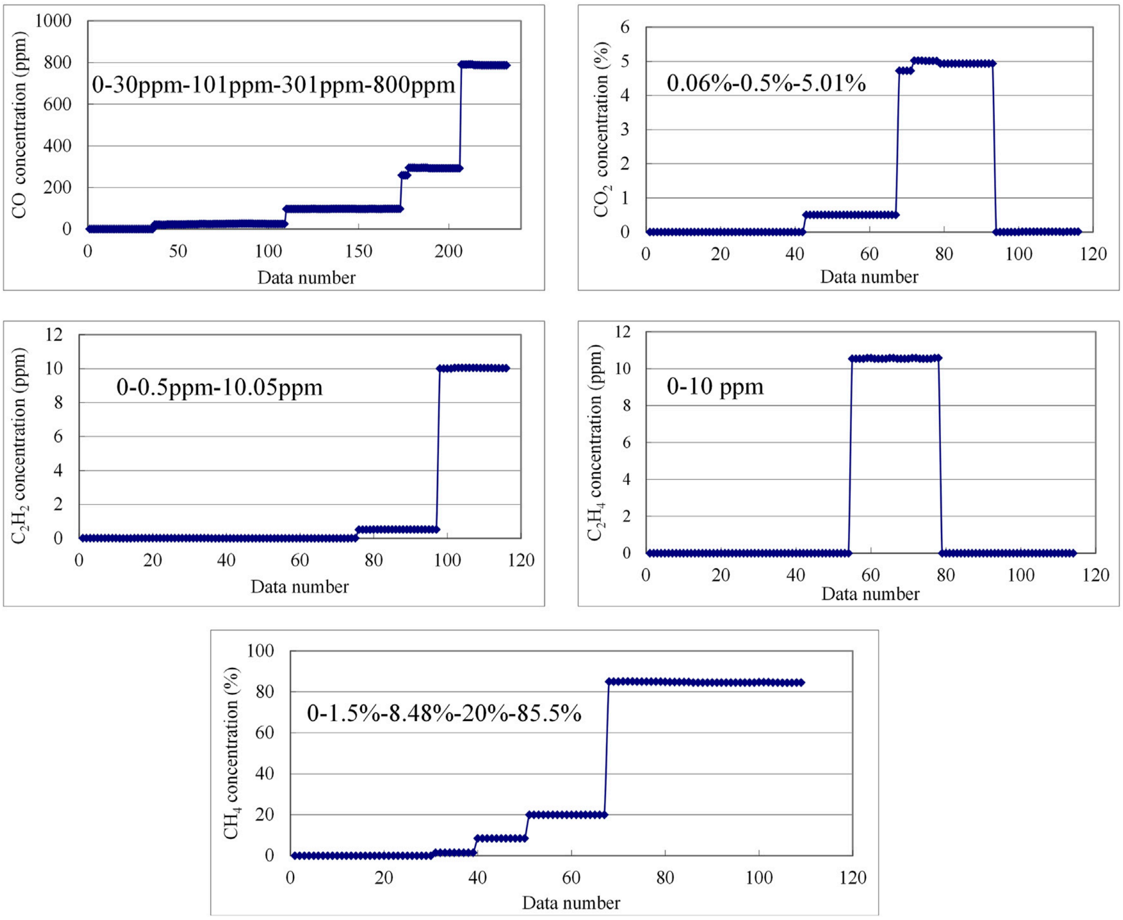

FIGURE 9
The test data of laser multi-gas monitoring system.

sensitivity have been reported using a room-temperature interband cascade laser or a quantum cascade laser (QCL) around 4.6 μm [47–49]. Our team developed a laser CO gas sensor with an optical path of 20 cm using a 4.6-μm QCL, and the measured results are shown in Figure 7. As shown in the figure, the detection sensitivity is greatly improved, even with short optical paths.

Multi-gas monitoring system

For early warning of coal spontaneous combustion, high precision and a wide dynamic detection range for the gas concentrations of CH_4, CO, CO_2, C_2H_4, and C_2H_2 as well as other markers are required. The typical measurement requirements for multi-gas monitoring are shown in Table 1.

In the recent years, considerable studies have been conducted on multi-gas monitoring [50–52]. Zhao et al. designed a detection system that can simultaneously detect CH_4, CO, and C_2H_2 by multiplexing 1653.72 nm, 2326.82 nm, and 1531.59 nm light sources [53]. However, the field application environment of coal mines has not been well studied. Based on the typical demand for coal mine fire monitoring and early warning, our group developed a laser multi-gas sensing system based on a multi-band semiconductor laser array. The schematic of the multi-gas sensing device is shown in Figure 8. The monitoring system solves the problem of the measurement error caused by the spectral overlap in a multi-component gas environment and realizes the simultaneous high-precision detection of trace gases and high-concentration gases. The test data on the laser multi-gas sensing device are shown in Figure 9. As an effective technical solution, the combination of the TDLAS-based multi-gas monitoring system and the fiber optic Raman-scattering-based distributed temperature sensor (DTS) provides early warning information about both the oxidation status and the hot zone location, which are increasingly used for goaf combustion monitoring in coal mines.

Conclusion

In the next few decades, coal will still occupy an important position in the energy structure. Therefore, the study on coal mine safety is of great significance. Multi-parameter monitoring in coal mines is challenging as the monitoring area is large, the environment is complex and harsh, and the number of objects to monitor is vast. With the advances in laser absorption spectroscopy, an increasing number of TDLAS-based gas sensors are being developed and applied in coal mines because of their unique advantages, including intrinsic safety, online detection, high precision, and reliability.

Coal mines have many hidden dangers, such as gas explosions and coal spontaneous ignition. Based on the monitoring needs of coal mine safety hazards, this invited paper focused on the research on laser methane sensors, CO sensors, multi-gas sensors and the application progress in gas monitoring and fire prevention. The laser methane sensor has realized full-range measurements with high precision, and field applications have shown that it has a significantly higher moisture resistance than infrared sensors. Since they do not require calibration, laser gas sensors can greatly reduce the maintenance workload, false alarm, and human fault. Aiming at the typical demand for multi-gas monitoring for coal mine fire monitoring and early warning, laser CO sensors and laser multi-gas sensing systems were demonstrated herein. With the rapid development of MIR laser technology, miniaturized laser trace gas sensors are gradually expected to be widely used in the coal mining industry.

With increasing coal mine safety, the emphasis has shifted toward mine safety IoT. For the monitoring and prevention of all hazards, mine safety IoT will be realized through the development of IoT and intelligent big data analysis. It is hoped that this invited paper can promote the application and technical progress of laser sensing technologies for mine safety and advance the rapid development of intelligent mines.

Author contributions

WG: methodology and writing—original draft. JH: methodology and writing—original draft. WG, JU, and ZW: writing—reviewing and editing. YW: validation. QZ: formal analysis. TZ: project administration and supervision. KG: conceptualization. YL: discussion and suggestions. TL: discussion and suggestions. WZ: proofreading. YN: resources.

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Conflict of interest

JH, TL, and YN were employed by the company Shandong Micro-Sensor Photonics Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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