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A mid-infrared carbon monoxide sensor system using wideband absorption spectroscopy and a single-reflection spherical optical chamber



Ming Dong, Chuantao Zheng*, Shuzhuo Miao, Fang Song, Yiding Wang

State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, PR China

HIGHLIGHTS

- Portable mid-infrared CO sensor using wide-band direct absorption spectroscopy.
- Self-developed miniature orthogonal lock-in amplifier for process CO sensing signal.
- Small optimized single-reflection spherical optical cell with a heat-sink.
- The sensor is suitable for the in-suit CO detection in industrial field.

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ABSTRACT

A mid-infrared carbon monoxide (CO) sensor system based on a dual-channel differential detection method was developed using a broadband light source in the 4.60 μm wavelength region and a single-reflection spherical optical chamber with ~ 0.373 m absorption path length. CO detection was realized by targeting the wideband strong absorption lines within 4.55–4.65 μm . A dual-channel pyroelectric detector as well as a self-developed digital signal processor (DSP) based orthogonal lock-in amplifier was employed to process CO sensing signal. A minimum detection limit of ~ 0.5 ppm in volume (ppmv) was achieved with a measurement time of 6 s, based on an Allan deviation analysis of the sensor system. The response time (1000 \rightarrow 0 ppmv) was determined to be ~ 7 s for the CO sensor operation. Due to the characteristics of low detection limit, fast response time and high cost performance, the proposed sensor has relatively good prospect in coal-mining operation.

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1. Introduction

With the rapid development of industry, a large demand for energy leads to a continuous increase in coal mining intensity. China is a world leader in coal output, but China's million-ton coal death rate has been at the top of all coal-producing countries [1–3]. Prevention of coal-mining disasters is a major problem to be solved in the development of Chinese mining industry. According to the latest statistics of the State Administration of Work Safety, coal-mining disasters related to gas explosion account for more than 80% of total disasters in coal mines [4]. Coal mine gases such as methane (CH_4), carbon monoxide (CO) may cause fire or even explosion. Also, CO may cause poisoning suffocation at very low concentration (~ 24 ppm), which is a serious threat to the safety

of coal-mining workers [5,6]. So the design and development of coal mine CO sensors is of great significance.

Generally, gas detection methods can be divided into four types, including semiconductor, electrochemical, catalyst combustion and infrared absorption spectroscopy [7,8]. The selectivity of semiconductor gas sensors is poor, which is a major problem in distinguishing different gases in coal mine [9]. Most electrochemical gas sensors use aqueous solution as an electrolyte, but the evaporation and pollution of electrolyte often weaken gas sensing signal, shorten service life and decrease detection accuracy [10]. The operation temperature of catalytic combustion gas sensors is high, with a surface temperature of up to 200–300 $^\circ\text{C}$ and an internal temperature of up to 700–800 $^\circ\text{C}$ [11]. Such sensors cannot be made into intrinsically-safe sensors for applications in coal-mine environment. Taking into account high humidity and high dust in coal mine, infrared absorption spectroscopy is a suitable choice due to its characteristics of high stability, high sensitivity, good selectivity and wide measuring range [12].

* Corresponding author.

E-mail address: zhengchuantao@jlu.edu.cn (C. Zheng).

Generally, infrared absorption spectroscopy can be divided into three categories, i.e. photo-acoustic spectroscopy (PAS), tunable diode laser absorption spectroscopy (TDLAS) and direct absorption spectroscopy (DAS) [13]. PAS detects gas concentration by acquiring acoustic signals in the gas chamber in terms of photo-acoustic principle [14,15]. Because of special environment in coal mine, sound waves generated by mechanical vibration will severely interfere with normal operation of the sensor. So PAS is unsuitable for coal mine gas detection. Lasers used in TDLAS technique are usually more expensive than infrared thermal source or light emitting diodes (LEDs) [16,17], and some lasers (e.g. lead-salt mid-infrared diode lasers) usually require cryogenic cooling which is not amenable for coal mine operation [18,19].

The main contribution of this work can be summarized as the realization of a portable, low-cost CO sensor system using a simple wideband DAS technique, a self-developed 4-Hz low-frequency lock-in amplifier, and an optical chamber integrated with a light source, a dual-channel detector, an optimized spherical mirror and a heat sink. DAS has advantages of simple optical structure and compact design, and the used broadband thermal source and dual-channel pyroelectric detector in such technique are usually inexpensive compared to mid-infrared lasers and detector [20]. Because of a relatively large divergence angle of a broadband thermal source, a single-reflection optical chamber was designed based on a spherical mirror for increasing light-collection efficiency. A heat sink was also adopted for heat diffusion of the light source to improve sensor thermal stability. Furthermore, a board-level orthogonal 4-Hz low-frequency lock-in amplifier was developed for weak-signal extraction. With the above considerations, a CO sensor by use of DAS technique and wideband absorption spectroscopy was developed aiming targeting the application in coal-mining environment. The structure of this paper is organized as below. Sensor structure will first be described followed by detection principle, optical design and data processing method. Details on the validation of the sensor as well as measurement results of detection limit, response time and stability will be then proposed. Some discussions and conclusions are finally achieved.

2. Sensor structure and design

2.1. Sensor structure

Fig. 1 shows the structure of the mid-infrared CO sensor system. A digital signal processor (TI, TMS28335, USA) generates a 4 Hz square-wave signal through an enhanced capture module (eCAP) inside. The square-wave signal modulates a wideband light source (Boston Electronics, IR-55, USA) through a constant current circuit. The IR-55 series is a micro-electro-mechanical system (MEMS) technology electrically modulated infrared emitter built into a HawkEye parabolic optic. The series uses a thin film of diamond-like carbon as the active element for faster electric modulation. The light emitted by the light source with a certain divergence angle is reflected by a spherical mirror with a focal length of 100 mm, and converges at a focal point where a pyroelectric detector (PerkinElmer, LM244, USA) is located. The detector has two photo-electric conversion channels. Each channel has an optical filter before the entrance window. The channel with a filter centered at 4.6 μm is used as a detection channel and the channel with a filter centered at 3.93 μm is used as a reference channel. So the detector generates a detection signal $u_1(\lambda)$ and a reference signal $u_2(\lambda)$. These two signals are first subjected to impedance matching by a preamplifier (PA), then a differential operation between them is made for generating a differential signal, i.e. $\Delta u(t) = u_2(t) - u_1(t)$. The amplitudes of $u_2(t)$ and $\Delta u(t)$ are extracted by a self-developed lock-in amplifier. After passing

through a sampling/holding circuit (SH), the output from the lock-in amplifier is sampled by an analogue-to-digital (ADC) module. The sampled data is processed with a sliding average filtering algorithm, and finally the results are transmitted to a laptop for observation in real time.

The Beer-Lambert law in Eq. (1) shows the relationship between CO concentration and received light intensity, as

$$I(\lambda) = I_0(\lambda) \exp[-K(\lambda)CL] \quad (1)$$

where I is received light intensity by the detector, I_0 is the emitting intensity, K is a molecule absorption coefficient, and L is optical path length. Under modulation, the time-dependent light intensity at $\lambda_1 = 4.6 \mu\text{m}$ and $\lambda_2 = 3.93 \mu\text{m}$ will be converted to $u_1(\lambda)$ and $u_2(\lambda)$. Define their amplitude as U_1 and U_2 , respectively. The final CO concentration could be expressed as a function of ΔU as

$$C = -\frac{1}{KL} \ln \left(1 - \frac{\Delta U}{U_2} \right) \quad (2)$$

where ΔU is the amplitude of the differential signal i.e. $\Delta U = \text{Amp}[u_2(\lambda) - u_1(\lambda)]$. Through the differential method, the signal to noise ratio (SNR) of the sensor system can be improved. Moreover, light intensity change caused by some interference factors, such as interference of dust on optical mirrors, light intensity change caused by source current variation, will make the change of ΔU and U_2 in a similar way, so the ratio of $\Delta U/U_2$ can be helpful in reducing the impact of interferences.

The lifetime of IR-55 was tested under a driving current of 135 mA in the datasheet, which is ~ 3 years. In the design of our sensor system, the driving current the light source was set to 100 mA to extend the lifetime of the CO sensor. Also, the infrared radiation of the light source will change as the using time increases. However, this change was compensated using a dual-channel differential detection method. The change in infrared light intensity will cause the output signals from the two channels to change in synchronization. So the decrease of light power will not obviously affect the sensor performance.

2.2. Emission characteristics of infrared source

Fig. 2 shows the infrared spectrum of the broadband light source, a micro-electro-mechanical systems based infrared emitter with a thin film of diamond inside for fast electric modulation. The spectrum was obtained using a Fourier transform infrared spectrometer (Thermo Fisher Scientific, model Nicolet Is50FT-IR, USA) at the unmodulated driving current of 110 mA. The infrared spectrum of the light source covers the entire mid-infrared region (2–20 μm), and the relative intensity is comparatively strong at 4.6 μm .

2.3. Absorption spectrum of CO within the detector's sensing windows

The primary criteria for wavelength selection includes strong absorbance and minimum spectral interference from other gases. Fig. 3(a) shows the CO absorption band as well as the response of the detector from 3.8 to 5.0 μm . The red¹ line is the response of the detection channel. The central wavelength is 4.6 μm with a half bandwidth of 0.1 μm ranging from 4.55 to 4.65 μm , which covers the fundamental CO absorption band. The blue line is the response of the reference channel. The central wavelength is 3.93 μm with a half bandwidth of 0.1 μm ranging from 3.88 to 3.98 μm , where almost no CO absorption is found.

¹ For interpretation of color in Figs. 3 and 4, the reader is referred to the web version of this article.

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