Design and fabrication of a mid-infrared carbon dioxide sensor for the application in greenhouse environment*

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A mid-infrared carbon dioxide (CO_2) sensor is presented for the application in greenhouse environment. An integrated multi-pass gas chamber and a dual-channel differential detection method are adopted to decrease response time and suppress environmental influence, respectively. An optical module is developed using a cost-effective wideband mid-infrared light source, a dual-channel pyre electrical detector and a spherical mirror, and the moisture-proof function is specially designed for enabling the application of this sensor in greenhouse with high humidity. Experiments are carried out to evaluate the sensing performance on CO_2 concentration. According to the experimental results, the limit of detection (*LoD*) is about 3×10^{-5} with an absorption length of 30 cm. The relative detection error is less than 5% within the measurement range of 3×10^{-5}—5×10^{-3}. Based on 10 h long-term stability measurement on 5×10^{-4} and 2×10^{-3} standard CO_2 samples, the maximum fluctuations are 1.08% and 3.6%, respectively. By using a 2.4 GHz wireless network communication system for remote monitoring and data recording, a field measurement of this sensor in a greenhouse is conducted, and good performance is proven in such circumstance.

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Some varying climatic factors, including temperature, humidity, luminance and carbon dioxide (CO_2) concentration in greenhouse, could significantly influence crop yield[1,2]. The combination of automatic monitoring technology and greenhouse farming has been paid more attention in recent years[1-4]. Compared with the general environmental factors in greenhouse, like temperature and humidity, the reasonable CO_2 concentration adjustment is of more potential research value[4-6]. However, the current traditional CO_2 concentration measurement methods[7-9] are limited in some degree, because of the special environmental conditions in greenhouse. For example, the sensitivity of semiconductor-type CO_2 sensors can be reduced by some other mixed gases produced by crops and fertilizers; the large temperature difference in greenhouse may bring negative impact to the stability and repeatability of electrochemical sensors[8,9]. Compared with these techniques, the infrared absorption spectroscopy widely applied in recent years has relatively high accuracy, short response time and good stability. The existing CO_2 sensing techniques include three main types, i.e., photo acoustic spectroscopy (PAS)[10], wavelength modulation spectroscopy (WMS) or tunable diode laser absorption spectroscopy (TDLAS)[11], and direct absorption spectroscopy (DAS)[12]. Even both PAS and TDLAS have better detection performance, the in-situ detection and high temperature difference limit their application in greenhouse environment respectively. Therefore, DAS becomes the most suitable detection technique in the greenhouse environment. Considering the requirements of flexible installation and measurement accuracy in greenhouse, a low-cost mid-infrared CO_2 sensor is designed and implemented in this paper. The application target is the stable and accurate CO_2 concentration measurement in greenhouse for further reasonable CO_2 fertilization on the yield increase. Design, measurement and application of this sensor are performed in detail.

Fig.1 shows the schematic of the developed mid-infrared CO_2 sensor, which includes an optical part and an electrical part. The optical part generally involves a wide-band mid-infrared light source (company, model: IR55), a dual-channel detector with two filter windows at 4.26 μm and 4.00 μm (company, model: LM242), and a spherical reflector for doubling the absorption length. The light source emits wideband infrared light, which

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propagates through the targeted gas and is reflected onto the sensing surface of the dual-channel detector. Those part of light passing through a 4.26 μm filter will be absorbed by CO_2 molecules and generate a detection signal; some part of light passing through a 4.00 μm filter will not be absorbed by CO_2 molecules and generate a reference signal. The electrical part is further divided into three sections. The first section is a light source driver used for modulating the light source. In the second section, i.e., signal processing section, the two signals generated by the detector will be processed by pre-amplification (PA), band-pass filtering (BPF), lock-in amplifying and analog-to-digital conversion (ADC). The last section is a 2.4 GHz wireless communication system, which is used to transmit the concentration data to a laptop for monitoring and data storage.

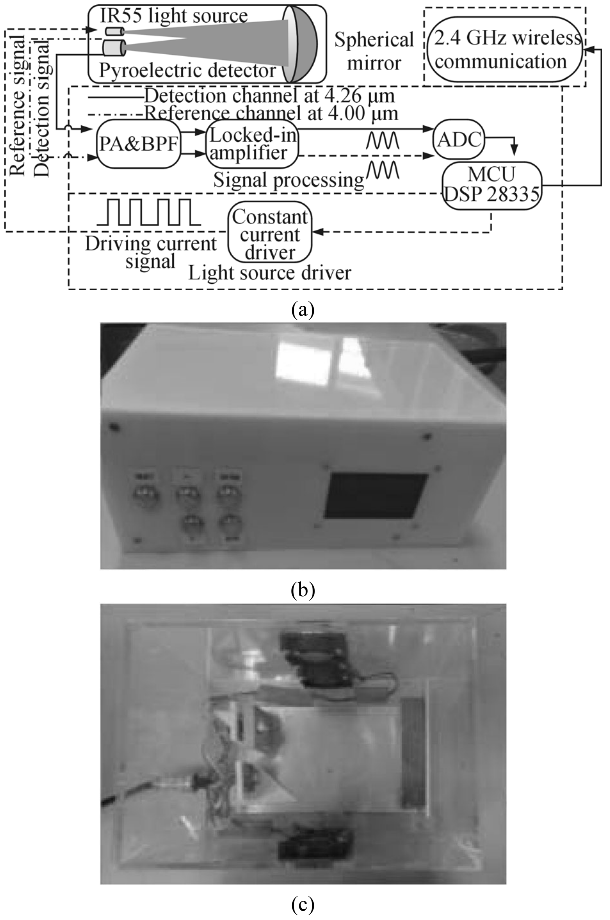
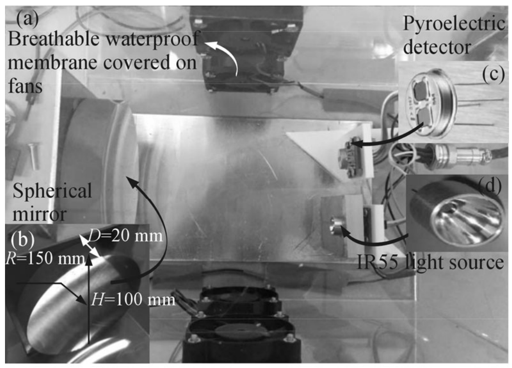


Fig.1 (a) Configuration of the mid-infrared CO_2 detection system including electrical part and optical part; (b) The photo of the electrical part; (c) The photo of the optical part

Equipped with two inherent filters, the PerkinElmer's dual-channel pyroelectric detector (shown in Fig.2(d)) has a detectivity (D^*) of 3.5×10^8 cm·Hz$^{1/2}$/W. The light source IR55 with wide-band radiance (shown in Fig.2(c)) satisfies the absorption wavelength of CO_2 molecule at 4.26 μm. Considering the characteristics of both light source and detector, a 4 Hz square-wave modulation signal with a peak-to-peak current of 148 mA is generated to drive the light source. For the used special spherical mirror, define R, H and D as its radius, height and thickness, respectively, as marked in Fig.2(b). In order to enhance the light collection efficiency under the consideration of both miniature size and easy integration, the relevant parameters of the aluminized spherical reflector are taken as R=200 mm, D=10 mm, and H=125 mm.

In order to enable the application of such a sensor in greenhouse environment, it should be capable of anti-high-humidity and anti-high-temperature. A chamber was intensively designed for this purpose, whose photo is shown in Fig.2(a). There is a compromise selection between waterproof ability and breathability. The selected breathable waterproof membrane is made of expanded polytetrafluoroethylene (ePTFE). The permeability of ePTFE is higher than 4 m/min, which has superior performance than the commonly used material like thermoplastic polyurethanes (TPU). In addition, the high working temperature (up to 250 °C) can withstand the high surface temperature of sensor caused by prolonged direct sunlight. And the excellent chemical stability prevents the sensor from corrosive material from fertilizers. In the greenhouse environment, there is condensation phenomenon caused by the diurnal temperature. The breathable waterproof membrane works as humidity barrier which maintains a constant humidity inside the shell. Four rectangular vents covered by breathable waterproof membrane were symmetrically placed in chamber wall. In order to accelerate the diffusion rate of gas, four fans whose speed can be automatically adjusted were installed close to the vents. To sum up, the sensor has a stable working condition under the protection of breathable waterproof membrane in greenhouse environment.



Gas chamber integrated in detector

Fig.2 (a) Photo of the gas chamber equipped with an optical part inside and a breathable waterproof membrane; (b) Photo of the aluminized spherical reflector mirror; (c) Spectral curve of light source IR55; (d) Photo of PerkinElmer's dual-channel pyroelectric detector

The noise characteristics of the sensor were measured using a radio-frequency spectrum analyzer. When the light source was modulated by a square-wave signal with a frequency of 4 Hz, the measured frequency responses of the two output signals from detection channel and reference channel are shown in Fig.3(a) and (b), respectively, where the tested signals are directly obtained from the pre-amplifier. The main noise is white noise, which can decrease the detection sensitivity on CO_2 concentration. From Fig.3, both of the two signals have a satisfactory signal-to-noise ratio (*SNR*) at the modulated signal frequency of 4 Hz. The 10-dB bandwidth is ~ 2 Hz at 4 Hz frequency, implying good performance of this sensor.

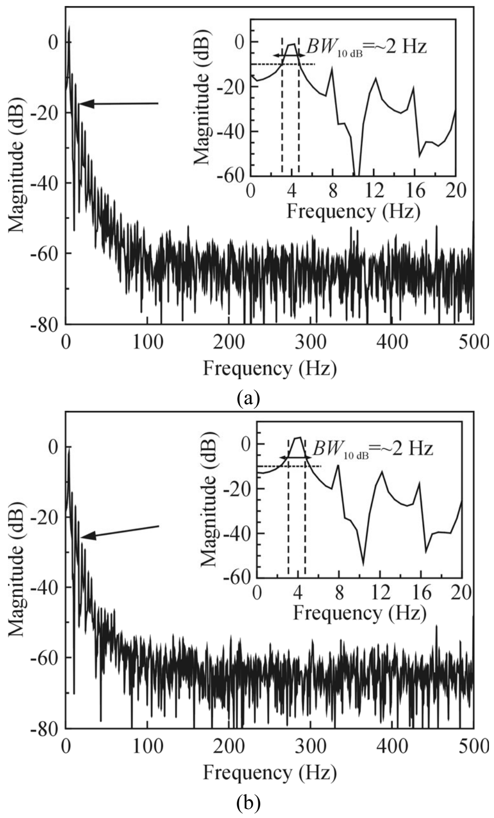


Fig.3 When the infrared light source is set to be modulation state, the measured spectra of the two output signals from (a) detection channel and (b) reference channel, where the two signals are obtained from the pre-amplifier

During the calibration of the sensor system, a standard CO_2 sample was kept flushing the chamber and the continuous data were recorded for more than 10 min until the display measured value was stable. According to the actual situation in greenhouse, the measurement calibration range is 0—5×10^{-3}. The relationship between the measured CO_2 concentration (C) and the differential-ratio value between the two amplitudes of the output voltage signals (defined as U_1 and U_2) is

$$C = 598.692 - 1\,635.07 \times \ln(\Delta U + 0.200\,8)\ , \qquad (1)$$

where $\Delta U = (U_2 - U_1)/U_1$.

In order to measure the limit of detection (*LoD*), the gas chamber was flushed by N_2 firstly. Then, the CO_2 mass flow was increased slowly until a minimum peak-to-peak output voltage ratio increase can be observed steadily. This CO_2 concentration is defined as the *LoD*. The whole process can be seen in Fig.4(c). The *LoD* of this sensor system is estimated to be 3×10^{-5}.

Under each measurement point, data were kept being recorded for 10 min. The relative errors were calculated, plotted and shown in Fig.4(b). When the measured CO_2 concentration is lower than 5×10^{-5}, the relative error reaches the peak value up to 7.6%. By contrast, the error fluctuation is less than 3% when the measured CO_2 concentration is larger than 10^{-4}. This performance is acceptable because of the relatively high concentration of atmospheric carbon dioxide in a greenhouse.

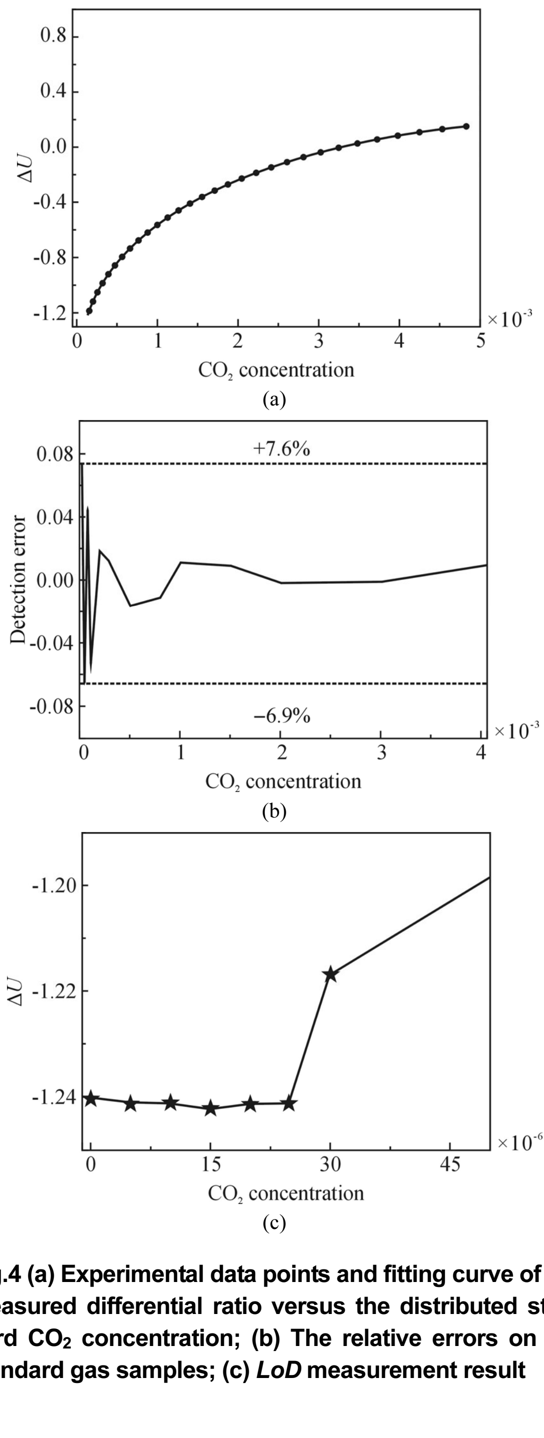


Fig.4 (a) Experimental data points and fitting curve of the measured differential ratio versus the distributed standard CO_2 concentration; (b) The relative errors on the standard gas samples; (c) *LoD* measurement result

To assess the stability of the sensor, two gas samples with the concentrations of 5×10^{-4} and 2×10^{-3} were prepared, which can be regarded as the normal CO_2 concentration and the desired CO_2 concentration in greenhouse. These samples were kept flushing the chamber during the measurement process, and they were measured for 10 h, respectively. Because of the noise and interferences, after 10 h detection, the absolute errors implied from Fig.5 are less than 1.08% and 3.6% for the 5×10^{-4} and 2×10^{-3} gas samples, respectively.

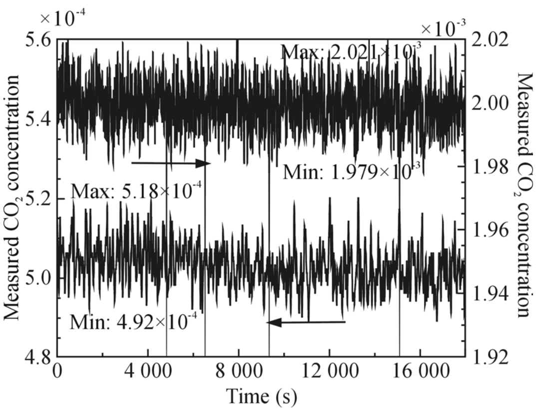
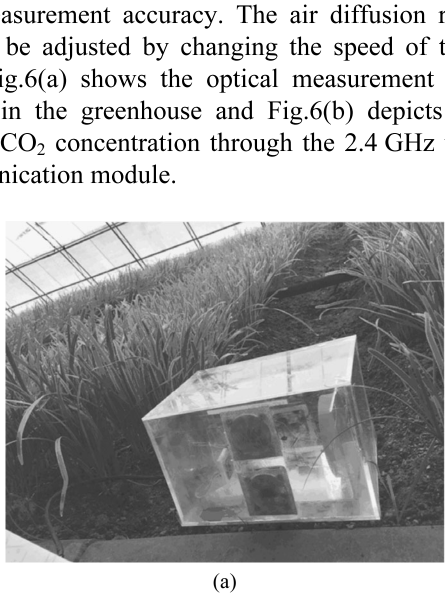
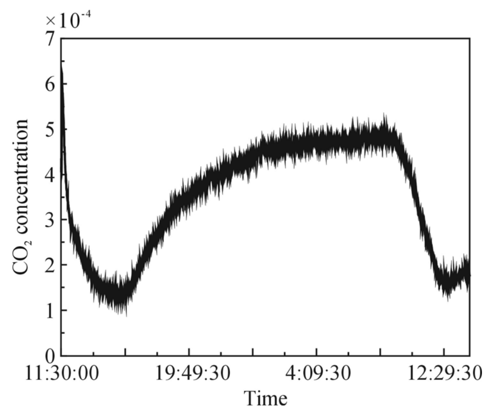


Fig.5 The long-term measurement results of the concentration on two CO_2 samples with concentrations of 5×10^{-4} and 2×10^{-3}, respectively

As an application of this sensor in greenhouse environment, some filed experiments were carried out in Town She Lin in Jilin Province. It is found that good performance of the breathable waterproof membrane prevented the influence from high environmental humidity in greenhouse to the sensor. The isolation design of the electrical and optical parts was proven to be efficient in preventing the influence on the electrical circuit resulting from the greenhouse environment and also in CO_2 sensing in such an environment. The CO_2 concentration sensor has good performance in terms of stability and measurement accuracy. The air diffusion rate was able to be adjusted by changing the speed of the used fans. Fig.6(a) shows the optical measurement part installed in the greenhouse and Fig.6(b) depicts the recorded CO_2 concentration through the 2.4 GHz wireless communication module.



(a)



(b)

Fig.6 (a) Photo of field test of the sensor in a greenhouse; (b) Measured CO_2 concentration for more than 24 h

The variation trend of CO_2 concentration in greenhouse has a sharp decline around 13:00 o'clock in line with the law of plants' photosynthesis. After 15:30, the rolling machine was driven to cover the straws on the greenhouse to prevent the temperature loss. Consequently, the luminance decreases to zero and the respiration of plants replaces the photosynthesis. The CO_2 concentration accumulates to more than 5×10^{-4} slowly. The good performance of this detection system reveals a potential application for the further developed control system in greenhouse environment.

Comparing the ever reported CO_2 detection devices or sensors, the CO_2 detection performance like *LoD* based on distributed feedback laser (DFBL) technology is not significantly reduced because of the small absorption at 1.5 μm, 2.0 μm or 2.7 μm[13]. In addition, the widely used tunable diode laser absorption spectroscopy (TDLAS) sensors are highly sensitive to monitor gas concentration in combustion environment[13]. In the other hand, the CO_2 detection systems based on quantum cascade laser (QCL) technology have outstanding performance in *LoD* in the price of very high cost[14]. The detection device in this paper has advantages of low cost and good humidity resistance. Furthermore, the flexible, high integration structure and additional wireless communication ability simplify the installation in greenhouse. After field test, the good performance indicates a further potential combination between this real-time concentration monitor and a reasonable CO_2 fertilizer.

In summary, a differential mid-infrared CO_2 concentration detection device is designed and implemented. The spherical mirror based multi-pass chamber and breathable waterproof membrane supply a flexible and reasonable structure for greenhouse application. The *LoD* of this CO_2 sensor is about 3×10^{-5}, and the relative error is lower than 3% when the measured CO_2 concentration is higher than 10^{-4}. Based on the 10 h long-term measurement on the 5×10^{-4} and 2×10^{-3} CO_2 samples, the maximum detection errors are about 1.08% and 3.6%, respectively. Through a field experiment in a greenhouse, this sensor exhibits good performance and therefore shows a potential application in monitoring and controlling CO_2 concentration in greenhouse.

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