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Development a low-cost carbon monoxide sensor using homemade CW-DFB QCL and board-level electronics

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ABSTRACT

A mid-infrared sensor was demonstrated for the detection of carbon monoxide (CO) at trace level. In order to reduce cost, a homemade continuous-wave mode distributed feedback quantum cascade laser (CW-DFB QCL), a mini gas cell with 1.6-m optical length, and some self-development electronic modules were adopted as excitation source, absorption pool, and signal controlling and processing tool, respectively. Wavelength modulation spectroscopy (WMS) and phase sensitive detection (PSD) techniques as well as wavelet filtering software algorithm were used to reduce the influence of light source fluctuation and system noise and to improve measurement precision and sensitivity. Under the selected P(11) absorption line located at 2099.083 cm^{-1}, a limit of detection (LoD) of 26 parts per billion by volume (ppbv) at atmospheric pressure was achieved with a 1-s acquisition time. Allan deviation was used to characterize the long-term performance of the CO sensor, and a measurement precision of ~3.4 ppbv was observed with an optimal integration time of ~114 s. As a field measurement, a continuous monitoring on indoor CO concentration for a period of 24 h was conducted, which verified the reliable and robust operation of the developed sensor.

1. Introduction

Carbon monoxide (CO) is an important tracer in atmospheric chemistry, environmental monitoring, industrial process control, and life sciences, etc. [1–4]. In atmosphere, CO, which can be produced by a variety of incomplete combustion activities, including the burning of natural gas, fossil fuel, and other carbon-based fuels, can react with the main tropospheric oxidant, i.e. hydroxyl (OH) radical, and change the lifetime of some greenhouse gases, e.g. methane (CH_4), ozone (O_3). Thus, CO has an indirect influence on global warming and climate change. In addition, CO concentration can be interpreted to indicate combustion efficiency and process, and is also adopted as a physiological messenger for different diseases such as atherosclerosis, Parkinson's and Alzheimer's, etc. Therefore, developing a sensor for monitoring CO concentration in real time is very necessary.

Quantum cascade laser (QCL) is a versatile source for precise measurements in the mid/far-infrared range of 3–24 μm with their room-temperature operation, high power, and narrow linewidth [5]. QCL has the advantages of wider wavelength tunability, smaller size and weight, more compact structure, no cryogenic cooling requirement, compared with lead salt diode lasers, gas lasers (e.g. CO and CO_2) and coherent sources based on difference frequency generation (DFG) and optical parametric oscillators (OPO) [6]. Hence, it is very suitable to use QCL in infrared CO detection. We have so far developed a series of CO detection systems based on pulsed QCLs and direct absorption spectroscopy (DAS) in our laboratory [7–9]. Lei Li, etc. reported the development of a pulsed QCL based CO sensing system, which operating at 2086.21–2086.41 cm^{-1} wavelength range and achieving a limit of detection (LoD) of 2000 ppbv at ambient pressure and temperature of 293 K. C. Chen, etc. reported a mid-infrared CO detection system, which using a pulsed QCL with centre wavelength of 2115.63 cm^{-1} together with a 76 m multi-pass cell and realizing a LoD of 40 ppbv at 100 mbar and temperature of 295 K. Comparing with CO detection systems using pulsed QCLs, the sensors based on continuous wave (CW) QCLs have better characteristics of selectivity, sensitivity and specificity, etc. on account of CW laser's narrower linewidth, better mode structure and lower frequency noise properties, etc. which have an important influence on laser spectroscopy applications. J. Li, etc. reported a Wavelength modulation spectroscopy (WMS) based spectrometer for CO detection, which using

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a CW QCL operating at 2190.018 cm^{-1} and achieving a LoD of 0.4 ppbv at 50 mbar and room temperature (RT) [10]. Recently, Lei Tao, etc. reported the development of a CO sensor based on CW QCL with centre wavelength of 2203.161 cm^{-1}, in conjunction with a multi-pass cell with optical length of 15.8 m and WMS technique, achieving a LoD of 3 ppbv at ambient pressure and RT [11]. Although the performances, such as limit of detection (LoD), sensitivity and precision of the above mentioned sensors are superior, some adverse factors, such as clunky body, high cost and complex operation, prevent them from wide applications.

In this paper, a portable and low-cost CO sensor based on homemade continuous-wave mode distributed feedback QCL (CW-DFB QCL) and some board-level electronics was demonstrated. The main goal of this study was to develop an innovative low-cost product and then to test its performance and the capability of monitoring indoor CO level in situ. The erection of experimental model, the selection of absorption line, the detailed description of the key modules of the sensor, the measurement and characterization of sensing performances, some conclusions and an outlook on the future work will be presented in the following sections.

2. System structure and spectroscopic methodology

2.1. Selection of absorption line

In the mid-infrared spectral range, almost all gas molecules have strong fundamental absorption lines. Therefore, it is possible to give a qualitative and quantitative analysis on them sensitively and selectively in this spectral range. Fig. 1(a) shows the absorption spectrum and intensity of four main atmospheric gases, i.e., CH_4, CO, H_2O and CO_2, for a wavelength range from 2.5 to 6.0 μm according to the HITRAN2012 database [12]. The fundamental vibrational band of CO is located in the range of 4.5–4.9 μm with the strongest absorption line at 2172.758 cm^{-1}. However, CO detection is not only depending on its absorption characterization, but also based on the operating wavelength range of the QCL in used. The central wavelength of our CW-DFB QCL is 2099 cm^{-1}, so we employ one of the strongest absorption lines belonging to the CO ν_1 vibrational band, i.e. the P(11) line located at 2099.083 cm^{-1}. Fig. 1(b) shows the simulated detectable absorption lines in the region of 2093–2102 cm^{-1}. It was calculated from the HITRAN database for a 1.6 m path length at atmospheric pressure, room temperature (RT), and typical atmospheric concentrations of the gases in Fig. 1(a). It can be observed that other molecules such as CO_2 and CH_4 have weaker absorption than CO in this region. The absorption of H_2O is very strong, but it is not overlapping with the selected P(11) transition of CO. So interferences from CO_2, CH_4 and H_2O can be negligible.

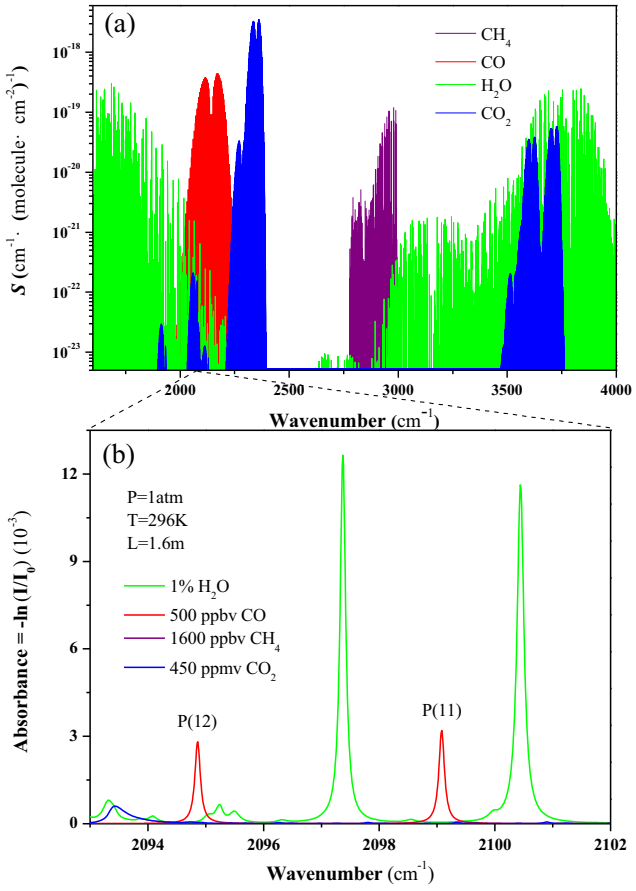

Fig. 1. (a) Absorption lines of CH_4, CO, H_2O and CO_2 for a wide spectral range from 2.5 to 6.0 μm as vertical drop lines; (b) Absorption spectra of H_2O, CO, CH_4, and CO_2 in a narrow range from 2093 cm^{-1} to 2102 cm^{-1} for specific concentrations and a 1.6-m path length at room temperature and atmospheric pressure.

2.2. System structure

The schematic diagram of the sensor system is shown in Fig. 2, which is composed of three sections, including a CW-DFB QCL and associated laser controller, an optical section including a mini gas cell with some reflective optics, and a signal acquisition and processing section.

The homemade thermoelectrically cooled CW-DFB QCL is mounted on a sealed box and integrates with a thermoelectric cooler and a collimating lens, which can work at room temperature. The laser controller designed by ourselves is combined with current drive module and temperature control module. The generated light by the CW-DFB QCL is collimated to make its diameter to be 0.7 mm. The light arrives at the CaF_2 beam splitter (BSW510, Thorlabs, USA) and produces two beams. One beam propagates through the beam splitter and combines with a visible light beam provided by the He-Ne laser using another beam splitter (BSP-DI-25-3, ISP Optics, USA). The new mixed light, i.e. IR-visible light beam, transmits through a mini gas cell and is detected by a Mercury-Cadmium-Telluride (MCT) detector to generate an absorption channel signal ($U_t(t)$). The other beam is firstly reflected by a gold-coating mirror, and then is sensed by another MCT detector to generate an reference channel signal ($U_r(t)$). A subtraction is first performed between the reference channel signal and the absorption channel signal, and then the differential absorption signal is sent to the developed analog orthogonal vector lock-in amplifier to extraction of the second harmonic wavelength modulation spectroscopy signal (WMS-2*f*) in the signal acquisition and processing section. After that, the analog WMS-2*f* is converted to digital signal for further processing and display. In addition, a gas sampling system including mass flow controller, valve, pressurized bottled air (PBA) with standard sample, and pressurized bottled air (PBA) with pure nitrogen, etc. is controlled and monitored by a LabVIEW programme (National Instruments Corp., USA). Via this system, sampling indoor air and reference sample tanks are enabled automatically, as shown in Fig. 2 (upper panel).

2.3. The erection of experimental model

2.3.1. Electro-optical modulation

The WMS and PSD techniques are adopted in our sensor, so the experimental model is mainly based on these two methods. In WMS technique, a mixed signal $f(t)$ composed of sawtooth wave tuning signal and sinusoidal modulation signal is used to drive