Sensors and Actuators B 190 (2014) 249–258

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Performance improvement of a near-infrared CH_4 detection device using wavelet-denoising-assisted wavelength modulation technique

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ARTICLE INFO

Article history:
Received 27 February 2013
Accepted 18 August 2013
Available online 25 August 2013

Keywords:
Near-infrared (NIR)
Gas detection
Wavelet denoising (WD)
Detection sensitivity
Detection error

ABSTRACT

By introducing wavelet-denoising (WD) in the traditional tunable diode laser absorption spectroscopy (TDLAS), a novel CH_4 detection device based on WD-assisted wavelength modulation technique was experimentally demonstrated. Formulation and detection procedure were presented, and experiments were carried out to prove the normal function on the extraction of 2f signal from severely polluted differential signal with WD algorithm. With the fabricated device, sensing characteristics were measured on CH_4 concentration. The response time is less than 8 s within the whole detection range of 0–50 kppm. By virtue of the suppression on noises with WD, the minimum detection limit (MDL) is dropped from 4 to 1 ppm, the maximum detection error is minimized from 6.2% to 3.8% over the concentration range of 4–50 kppm, and the decreased Allan deviation (per an average observing time of 9 min for 24 h) from 0.13 to 0.08 ppm suggests enhanced stability. The proposed device also exhibits improved performances compared with our previously reported sensors based on simple direct spectroscopy absorption (DSA) technique and wide-band incandescence wire-source.

1. Introduction

For consideration of safe production in coal mine industrial environment, the research in the field of CH_4 detection [1–4] shows the same increasing trend as the detection on other trace gases including NO, CO, SO_2, etc. Owning to the advantages including wide measuring range, high sensitivity, good selectivity, longevity and fast response, spectrum absorption becomes a well-known technique on CH_4 detection, which has been reported elsewhere [5–7]. Besides photoacoustic spectroscopy (PAS) [8,9], direct spectral absorption (DSA) [10,11] is also a preferred method especially used in on-line detection. So far, by adopting mid-infrared (MIR) wideband incandescence source and thermopile detector, two generations of stand-alone CH_4 detection devices have been reported by our group [12,13]. However, the traditional DSA method is easily affected by particles concentration, light intensity fluctuations and baseline-fitting errors. As an improved DSA technique, through tuning the wavelength of distributed feedback (DFB) laser by modulating the driving current and keeping the temperature stabilized, the tunable diode laser absorption spectroscopy (TDLAS) can overcome the above disadvantages and satisfy more difficult measurement requirements, and it is widely used in infrared trace gas detection [14–17].

On the other hand, noises and interferences from electrical components and wires as well as environmental changes are important factors that can deteriorate detection performance. In our previous report [13], by introducing an additional noise-channel besides the traditional detection-channel and reference-channel, noises and interferences were well removed with the least square fast transversal filtering (LS-FTF) denoising algorithm. However, this algorithm is not efficient in TDLAS-based detection system, because (1) the differential signal is not a single-frequency component, and (2) the extraction of second-harmonic (2f) signal is done using software not hardware. As a superior signal processing technique, wavelet denoising (WD) [18–20], which possesses multi-level analytical resolutions both in time- and frequency-domains, is an efficient tool to remove noises from severely polluted signal. Therefore, as a novelty of this paper, a CH_4 detection device based on WD-assisted wavelength modulation technique is experimentally demonstrated. By doing wavelet transformation (WT) on polluted differential signal between detection channel and reference channel, the expansion coefficients under different levels are obtained. The noises, whose expansion coefficients are different from those of the pure signal, can be removed through the use of self-adaptive multi-threshold WD method. Besides, for realizing fast detection,

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http://dx.doi.org/10.1016/j.snb.2013.08.055

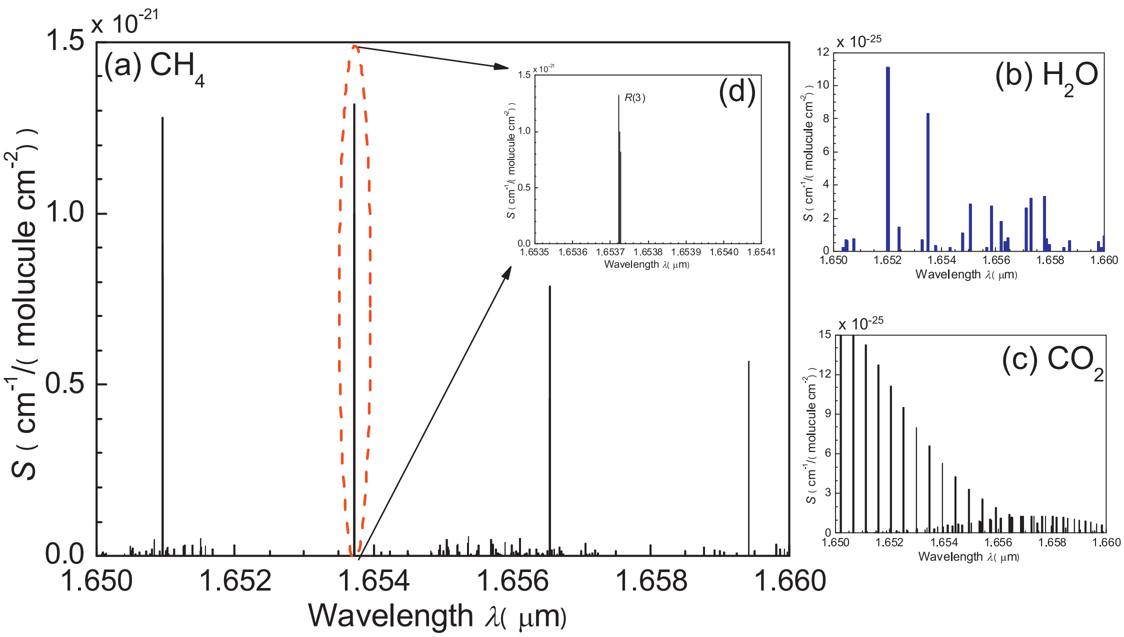

Fig. 1. The absorption spectrum of (a) CH_4, (b) H_2O and (c) CO_2 molecular around 1.654 μm. (d) The detailed illustration of the selected CH_4 absorption band for detection around 1.654 μm.

digital signal processor (DSP), which is capable of high-speed float-data calculation, is utilized instead of other common processors. Comparisons between the sensing performances under the case of using WD and those without using WD indicate that the MDL, accuracy and stability are all improved by virtue of the proposed WD-assisted wavelength modulation technique.

The structure of this paper is organized as follows. First in Section 2, sensor configuration and integration are proposed, and details of optical part and electrical part are described. Then in Section 3, the influence of radon noise on the extracted 2f signal is analyzed. The WD-assisted wavelength modulation technique is demonstrated and verified through experiment. Furthermore in Section 4, measurements on CH_4 concentration are carried out, and detection results are described. In Section 5, comparisons are made among our previously reported sensing devices. Some conclusions are finally reached in Section 6.

2. Sensor configuration and integration

2.1. CH_4 absorption characteristics around 1.654 μm

Though CH_4 has larger absorption intensity at the wavelength of 3.31 μm than that at 1.65 μm, fabrication and development of a 1.65 μm DFB diode laser are generally easier and cheaper than those of a 3.31 μm DFB diode laser. Therefore, near-infrared absorption band around 1.65 μm is selected in CH_4 detection. Fig. 1(a) depicts the absorption spectrum of CH_4 molecular around 1.654 μm, and the intensity is at the level of 10^{-21} cm^{-1}/(molecule cm^{-2}). As can be seen from the comparison among Fig. 1(a)–(c), since the absorption intensities of H_2O and CO_2 are both 4 orders smaller than that of CH_4, H_2O and CO_2 cause slight effect on CH_4 detection. So detection selectivity is assured. The detailed absorption band used in detection is located at the round surrounding area, as shown in Fig. 1(d) for a clearer illustration.

2.2. Device configuration

The configuration of the proposed CH_4 detection device is shown in Fig. 2(a), which generally contains two parts. The optical part is configured with a gas-cell, an NIR TDL source and two NIR detectors. The electrical part is equipped with an electric board for driving, modulating and temperature-controlling of the TDL, dealing with sensing signals, and performing data-processing, calculation and displaying. Details are as follows.

Optical part. A gas-cell (Fig. 2(c)) with a gas injection port and a gas extraction port is used as an absorption pool, and its length is L = 20 cm. A NIR butterfly-packaged TDL (Fig. 2(b)) (available from Chinese Academy of Science) is used as light-source, whose radiation wavelength is around 1.654 μm (25 °C) and threshold current is 20.5 mA. Two high performance InGaAs detectors (J23-18I-R01M-2.2, purchased from Teledyne Judson Technologies), operated over the spectral range from 0.8 to 2.2 μm, are adopted to generate reference signal and detection signal respectively and they have round-type sensing area with a diameter of 1 mm.

Electrical part. The DSP processor (Texas Instrument, TMS320F2812) is used as the primary control and processing component. The laser driver, which is a key module in the proposed device, is composed of four modules, involving temperature sampling module (realized by reading the thermistor inside the laser), temperature control module (realized by driving the thermoelectric cooler (TEC) module equipped inside the laser), laser scanning module using a 25 Hz sawtooth-wave signal (whose maximum peak-to-peak amplitude is 5 V), and laser modulating module using a 5 kHz cosine-wave signal (whose maximum peak-to-peak amplitude is 0.5 V). The sawtooth-wave signal and cosine-wave signal are generated by a digital-to-analog converter (DAC) and a direct digital synthesizing (DDS) component, respectively, then they are superimposed through an adder (ADD) module, and finally the synthesized voltage signal is transformed to current signal via a V/I module to scan and modulate the laser. LCD and keyboard are served as human-computer interaction displaying and configuring components, respectively. The extracted 2f signal output from the digital lock-in amplifier can be either sent to a computer or regenerated via a digital-to-analog converter (DAC) for observation with an oscilloscope.

Working principle. As shown in Fig. 2, the generated laser beam is split into two beams with a fiber optical beam splitter (FOBS). The reference laser beam firstly propagates through an optical attenuator (OA), and then reaches to the reference NIR-detector for