Sensors and Actuators B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Developing CH_4 detection limit at $\lambda = 1.654\ \mu m$ by suppressing optical interference fringes in wavelength modulation spectroscopy

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ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 8 September 2017
Accepted 11 September 2017
Available online xxx

Keywords:
CH_4 detection
Wavelength modulation
The minimum detection limit
Interference fringes

ABSTRACT

Optical fringes tend to cause difficulty in gas detection based on wavelength modulation spectroscopy (WMS). In this article, we introduce a convenient fringes suppression method. Through modulation depth optimization and two-frequency modulation technology, we substantially improve the CH_4 detection limit. Our experiment adopts a distributed feedback laser operated at $\lambda = 1.654\ \mu m$ in an open-path environment. The fluctuation of the sensor measurement is dramatically reduced by approximately 10–20 times. The minimum detection limit of the open-path environment improves to 130 ppb m for a 50-min period. Compared with other previously reported near-infrared CH_4 detection systems, our proposed method improves the detection limit further. In contrast to traditional fringe suppressing methods, our method has more advantages in CH_4 detection in open-path environments.

1. Introduction

Methane (CH_4) is a flammable substance that is widely used as a green fuel and is also a main factor in global warming. Measurement sensitivity is significantly important for CH_4 trace gas detection in an open environment [1]. Given its high effectiveness and low cost, wavelength modulation spectroscopy (WMS) [2–13] is widely used to develop portable CH_4 detecting devices [14–18].

In a wavelength modulation (WM) system, detection sensitivity is often limited by optical interference fringes [19–21] rather than the theoretical limit given by other noises [1,22,23]. Interference fringes, which are also called etalon effect, originate from multiple reflections upon surfaces in the optical path. Any change in the cavity length of the etalon will lead to shifts in interference fringes, and the change may be caused by fluctuations in temperature and vibrations of the etalon cell, among others. Therefore, interference fringes cannot be removed by subtracting a zero baseline [24–26]. Various technologies have been introduced to suppress fringe noise. Generally, these methods are used to reduce fringe noise. Anti-reflection coated or wedged optical components are mostly used to alleviate fringe noise [27–29], however, fringes usually still appear. Modulating the fringes with a vibrating cell mirror or a vibrating Brewster angle plate within the cell is often effective [23,29–32], however, this approach increases system complexity or cost synchronously. Filtering the detected signal can effectively reduce the effect of fringes [33–35]. However they have limitations because an unwanted background structure usually includes several fringes that are dependent on temperature, pressure, or other factors [21]. Two-frequency modulation technology, which involves adding a frequency jitter to a diode laser, could be used to suppress fringes [36].

In this paper, we introduce two-frequency modulation into our WM system and present the theoretical deduction of the optimum modulation current by choosing the optimum modulation current through sweeping peak. This method sufficiently reduces fringe noise. Our methods can work quickly without added system complexity. Through our open-path near-infrared (NIR) CH_4 minimum detection system operated at approximately 1.654 μ m, the detection limit of CH_4 can be improved evidently. The rest of this paper is organized as follows: In Section 2, sensor architecture and integration are described, especially the temperature control performance. In in Section 3, we present the main theory deduction. In Section 4, experiment results are shown, and comparisons are made among other reported results. Conclusions are given in Section 5.

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http://dx.doi.org/10.1016/j.snb.2017.09.070
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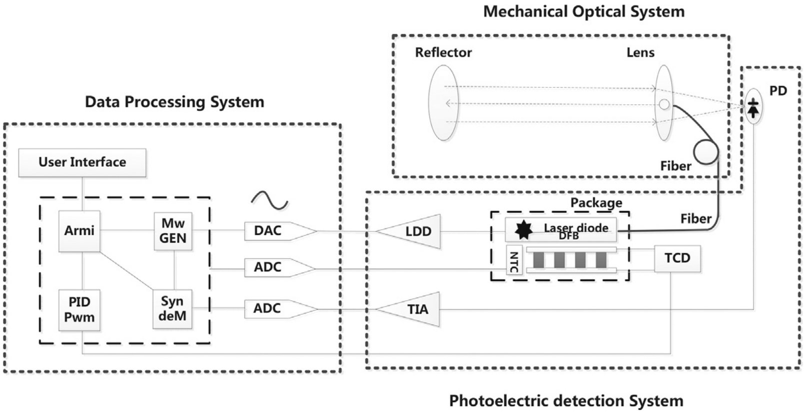

Fig. 1. Frame diagram of the CH_4 detection system.

2. Sensor architecture and integration

2.1. Selection of an absorption line

To achieve high sensitivity in gas sensing with tunable diode laser absorption spectroscopy (TDLAS), a strong absorption line needs to be used. Although CH_4 has a strong absorption line in mid-infrared bands, portable CH_4 detection devices usually choose NIR bands because of cost, and they can be more compact and robust in NIR bands. We use DFB laser diodes with wavelength of around 1.65372 μ m (6046.96 cm^{-1}). Around 6046.96 cm^{-1}, the absorption intensity of CH_4 is at least four orders stronger than those of H_2O and CO_2 [37].

2.2. System integration

Our CH_4 detection system consists of a photoelectric detection system, a mechanical optical system, and a data processing system (Fig. 1). The photoelectric detection system is configured with a NIR DFB laser diode, a photoelectric detector (PD), a laser diode driver (LDD), a temperature control driver (TCD), and transimpedance amplifiers (TIA). The mechanical optical system consists of single-mode optical fibres, an open optical cell, an optical convex lens, and a reflection component. The optical path length is adjustable and set as 145 cm in this paper. The optical components are specially placed for suppressing interference fringes. The data processing system is mainly used to realize analog-to-digital conversion, modulation and demodulation calculation, and PID temperature control.

2.3. Temperature control

Temperature control of the DFB laser is significantly important for gas detection, especially if our laser temperature stability based on PID control could approach ±1 mK. Fig. 2 shows the stability of the laser temperature for a period of 400 min, where the laser temperature is 31.9 °C, and the DC current is 1.720 mA.

To further check the temperature stability, we repeatedly sweep the gas absorption spectrum every 15 min. Fig. 3 depicts the result for a period of 2700 min, where the laser temperature is 31.9 °C. To prevent the obstruction of interference fringes on the absorption peak position as much as possible, we suppressed fringes by adopting the proposed method. Fig. 3 shows that the absorption peak shifts to 50 μ A (approximately 2σ), which is equal to 7 mK on the influence of spectrum frequency shift. This finding proves that our system could achieve less than 7 mK temperature accuracy even though frequency shift could be caused by other factors.

3. Theory

3.1. Single-frequency modulation

In TDLAS with WMS, the laser current is typically modulated by a low-frequency ramp and by a cosine wave at a much higher frequency.

The laser total input current i, the laser input DC current i_1, modulation current δi, and the angular frequency ω are shown below,

$$i(i_1, t) = i_1 + \delta i cos(\omega t - \psi) \quad (1)$$

The laser output optical intensity $I(i)$ can be shown as

$$I(i_1, t) = I_{DC}(i_1) + \delta I cos(\omega t - \psi) \quad (2)$$

δI is the intensity amplitude caused by current modulation.

Moreover,

$$I_{DC}(i_1) = \kappa(i_1 - i_{th}) \quad (3)$$

The optical intensity of the DC current is I_{DC}, i_{th} is the threshold current, κ is the current intensity coefficient, and

$$\delta I = \kappa \delta i \quad (4)$$

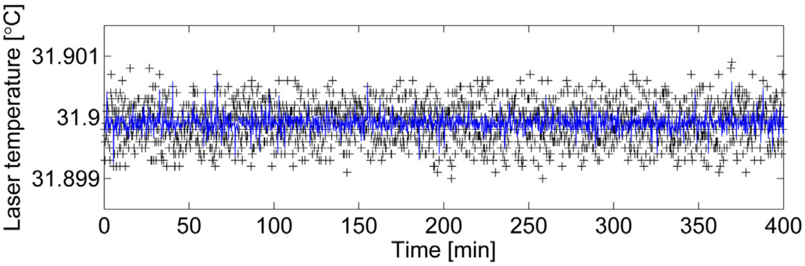

Fig. 2. Discrete black plus sign stands for the laser temperature controller, and the blue line shows the Kalman filtering result. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: W. Liang, et al., Developing CH_4 detection limit at λ = 1.654 μm by suppressing optical interference fringes in wavelength modulation spectroscopy, Sens. Actuators B: Chem. (2017), http://dx.doi.org/10.1016/j.snb.2017.09.070