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Original research article

A dual-tone modulation method to reduce the background fluctuation in tunable diode laser absorption spectroscopy

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ABSTRACT

Optical interference fringe, known as etalon effect, is the main factor which causes background fluctuation in trace gas concentration detection based on tunable diode laser absorption spectroscopy(TDLAS). The fringes make the background signal present a sinusoidal oscillation, which reduces the system's detection ability on the gas of more low concentration. To reduce the background fluctuations, a dual-tone modulation (DTM) method is introduced to the model based on Beer-Lambert law and etalon effects. According to the results of simulation and actual experiments, the DTM method can significantly reduce the background fluctuations. More specifically, the standard deviation (STD) value of background fluctuations decreased from 2.6239 parts-per-million (ppm) to 0.19 ppm in our experiments, where the STD of 0.19 ppm is corresponding to absorption of $6.224*10^{-6}$ $Hz^{-1/2}$ with effective optical path length of 2.8 m and integral time of 0.1 s. The results of long-term detection experiment further demonstrated the stability of DTM in reducing the background fluctuations and the reliability of trace gas concentration detection.

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) is a widely used technique in environmental gas monitoring, atmospheric science, and spectral measurement areas, especially in trace gas concentration detection due to its many merits such as no-contact, high-sensitivity, high-precision, good-selectivity and fast-response time [1,2]. TDLAS measures the gas concentration by studying the laser intensity variation when laser pass through the target gas. However, almost all TDLAS system suffer from background fluctuation which significantly hinder the system's ability on low-concentration gas detection. Therefore it is important to find an approach to reduce the background fluctuation in trace gas detection.

The main factor causing background fluctuations in the detection of trace gas concentration is optical interference fringe. The fringes, also called etalon effects, are caused by multiple reflections upon surfaces in the optical path. The fringes can obscure the weak absorption signals especially when the free spectral range (FSR) of the optical fringes is in the same order as the line width of the absorption signal. These fringes cause an oscillation of the photo current during wavelength scanning, which may be regarded as an absorption signal incorrectly in the absence of absorbers.

In the past decades, several techniques have been introduced to reduce the influence of optical interference fringes [3]. Besides using anti-reflection coating and wedged optical components in optical system [4], frequency modulation(FM)

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manipulation, improvements in device and post-detection filtering also have been used [5]. Among them, FM methods are complicated and highly dependent on the performances of the laser diode (LD) applied. Improvements in device include mechanical vibration modulation, dithering or rotating various optical components [6–8] and double-beam techniques[3,9]. Most of these device improvements are effective, but they add the complexity and the cost of the detection system, and some types of optical fringes still exist (for example, the fringes coming from beam steering optics and LD inside). Post-detection filtering often use high-pass filters or low-pass filters [10], but this technique affects the response time of system and is not effective when the free spectral range (FSR) of fringes is comparable to the gas absorption line-width. In addition, for the measurement of lower absorption, these methods mentioned above are limited in the ability on reducing interference fringes, because such fringes can arise in various parts of the optical apparatus.

In this paper, a dual-tone modulation (DTM) method is proposed to reduce the background fluctuation, which can be applied to any analytical absorption system. The main feature of the method is to combine wavelength modulation spectroscopy (WMS) with harmonic detection and to put dual sinusoidal injection currents in the LD to modulate the center frequency. The DTM method can reduce the influence of fringes on the output signal at the detection frequency.

2. Theory and method

2.1. TDLAS

According to the Beer-Lambert law, when a narrow-band light with a frequency of ν passes through a gas cell filled with an absorbing gas [11], the transmitted intensity $I(\nu)$ is given by:

$$I(\nu) = I_0(\nu)\exp[-a(\nu)CL] \tag{1}$$

where $I_0(\nu)$ is the incident intensity of the narrow-band light, C is the gas concentration, L is the path length through the gas, and $a(\nu)$ is the absorption coefficient of the gas at frequency ν. When the sample has a small optical thickness, i.e. $a(\nu)CL \ll 1$, the transmitted intensity can be approximated as follows [12–14].

$$I(\nu) \approx I_0(\nu)[1 - a(\nu)CL] \tag{2}$$

When the experiment environment is 1 atm at room temperature, the collision broadening dominates. Then $a(\nu)$ can be described by normalized Lorentz function [14,15], that is,

$$a(\nu) = \frac{a_0}{1 + (\frac{\nu - \nu_c}{\gamma})^2} \tag{3}$$

where α_0 is the absorption coefficient at center absorption frequency ν_c, and γ is the half width at the half maximum of the absorption line.

In real-time gas measurements, the laser frequency is usually kept near the center of the molecular transition of interest by adjusting the laser temperature. The frequency of the LD is then tuned by injecting current. Different types of current modulation define different methods of absorption spectroscopy. Among them, the technique usually used is WMS. The laser injection current is swept over a transition of interest at a low frequency. Meanwhile, a high frequency sinusoidal modulation signal is superimposed. When the LD is modulated by a sinusoidal injection current of frequency w, the instantaneous frequency can be defined as

$$\nu(t) = \nu_c + \nu_a \cos(wt) \tag{4}$$

where ν_c is the center laser frequency and ν_a is the modulation amplitude of the laser.

When the LD is modulated through injection current, the transmitted intensity and absorption line shape profile are modulated at the same time [12]. Hence the transmitted intensity can be revised as

$$I = (I_0 + \Delta I_0 \cos wt)\exp[-a(\nu_c + \nu_a \cos wt)CL] \tag{5}$$

where ΔI_0 is the modulation amplitude of intensity. Then the transmitted intensity at the center frequency can be further expressed in terms of cosine Fourier series. It is an even function and can be written as

$$I(\nu_c, t) = \sum_{n=0}^{\infty} A_n(\nu_c)\cos(nwt) \tag{6}$$

where $A_n(\nu_c)$ is the nth Fourier component of the modulated absorption coefficient at the center frequency.

2.2. Etalon effects

The trace gas measurement system based on TDLAS usually includes two parts: detection circuit and optical system. In the optical system, the surfaces of optical component reflect the light when the laser passes through the gas cell. The reflected lights are generally weak in light intensity [16], but they are mutual superposition and make the light's transmissivity be