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# Influence of temperature-induced cavity length variation in wavelength modulation spectroscopy

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ABSTRACT

The long-term stability of a given concentration of detected gas in laser spectroscopy is always difficult to achieve. We propose that the optical fringe shift caused by temperature-induced cavity length change is the most important factor that limits long-term stability. A wide range of temperature variation causes a large fluctuation in the detected concentration for a long period, and cavities made of a low-temperature expansion material can effectively inhibit the effects of a large temperature variation and improve the minimum detection limit.

## 1. Introduction

Wavelength modulation spectrometry (WMS) combined with diode-laser absorption is a useful technique in environmental gas monitoring, atmospheric science, spectral measurement, and trace gas concentration detection [1–13]. However, the sensitivity of wavelength modulation (WM) systems is usually severely limited by the presence of Fabry-Perot interference fringes [14], which may originate from laser transmission through individual optical elements, such as windows and lenses, or through air and vacuum paths separated by the surfaces of elements [15,16]. The fringes may obscure weak absorption signals if the free spectral range of the optical fringes is in the same order as the line width of the absorption signal [17].

Several methods have been used to suppress optical fringes on WMS. The first and most obvious method is careful design of the optical system by using antireflection-coated or wedged optical components [18,19]. The second method is to mechanically modulate the system by dithering or rotating various optical components [20–24]. The third method is to modulate the current by adding a jitter current or selecting an appropriate modulation amplitude [25–27]. These measures are usually highly effective in a short period. However, the long-term stability of a concentration of detection system is always difficult to achieve. In the field of trace gas measurement and ambient gas concentration detection, long-term stability is crucial. No systematic analysis has been conducted on the factors that affect the long-term stability of concentration detection.

In this work, we propose that the long-term stability of concentration detection is mainly affected by interference fringe shift, which is due to the effect of temperature on the cavity length change. We present the results of a systematic study and experimental validation and provide suggestions for improving long-term stability.

A $CH_4$ detection system based on the WMS technique was experimentally demonstrated, and transitions at $\lambda = 1.654\,\mu m$ were adopted. The rest of this paper is organized as follows. The design of the detection system and characterization of real diode lasers are presented in Section 2. A systematic theoretical analysis is presented in Section 3. The experimental results are shown in Section 4, and the conclusions are given in Section 5.

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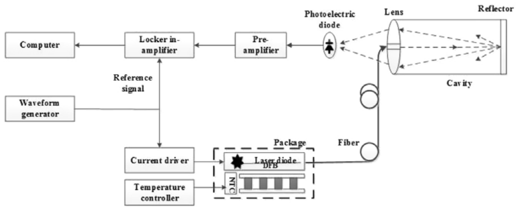


**Fig. 1.** Configuration of the near-infrared $CH_4$ detection system.

## 2. Design of the detection system and characterization of real diode lasers

### 2.1. Design of the detection system

A schematic of the detection system is shown in Fig. 1. A fiber-coupled distributed feedback (DFB) diode laser emitting in the 6047 $cm^{-1}$ region is used as a light source. To suppress interference fringes, the optical components are placed in a special arrangement, and anti-reflective coating is used.

### 2.2. Characterisation of real diode lasers

The laser operation temperature is set to 32.2 °C. The laser temperature stability based on PID control can approach ± 1 mK and even smaller than 1 mK by Kalman filtering (Fig. 2). The temperature (coarse) tuning rate of the laser is approximately 0.033 $cm^{-1}$/K. Thus, the temperature stability is approximately $\pm\ 3 \times 10^{-5} cm^{-1}$.

When the laser temperature is 32.2 °C, the laser center current at the $CH_4$ absorption peak is approximately 61.9 mA. Given that the resistance of the driver circuit changes with temperature as a rate of 20 parts-per-million (ppm) per K. The stability of the laser driver current can be approximately 1.2 μ A/K. The current (fine) tuning rate of the laser is approximately 0.005 $cm^{-1}$/mA, and the current stability is about $6 \times 10^{-6} cm^{-1}$/K.

## 3. Theory

WMS is characterized by the modulation of the wavelength (or the frequency) of light at a frequency $f$ with a frequency-modulation amplitude $\delta\nu$ that exceeds the modulation frequency, i.e., $\delta\nu \gg f$. A lock-in amplifier is used to extract the $n$th harmonic of the detected intensity signal. The frequency of a diode laser can be modulated conveniently through its injection current as follows:

$$\nu = \nu_1 + \delta\nu \cos(2\pi \mathrm{f}\, \mathrm{t}), \tag{1}$$

where $\nu_1$ is the laser center frequency. The laser intensity caused by injection current can be expressed as

$$I = I_1 + \delta \mathrm{I} \cos(2\pi \mathrm{f}\, \mathrm{t} - \psi), \tag{2}$$

where $I_1$ is the laser center intensity and $\psi$ is the phase between frequency modulation and current modulation.

In the absence of any absorption gas, the detected background signal in WMS can be expressed as

$$S_{bg} = \eta\tau I, \tag{3}$$

where $\eta$ is the instrument factor and $\tau$ is the transmission function of the optical system. $\eta$ can be written as

$$\tau = \frac{1}{1 + F\sin^2(2\pi x\nu)}, \tag{4}$$

where $F$ is the finesse coefficient of fringes, the free spectral range is given by $1/2x$, and $x$ is the length of the Fabry-Perot cavity. An etalon created between two surfaces has a small coefficient of finesse $F$. Thus, the transmission function can be approximated as

$$\tau = 1 - F(1 - \cos(4\pi x\nu)/2. \tag{5}$$

When Eq. (3) is expanded, the higher-order term is omitted. Then, the second harmonic term (2$f$) of the background signal can be

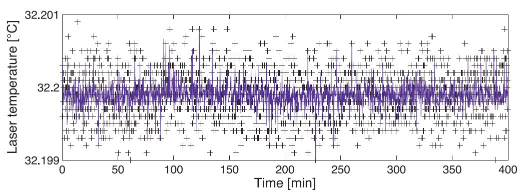


**Fig. 2.** The stability of laser temperature over time. Discrete black plus sign stands for the laser temperature controller, and the blue line shows the Kalman filtering result. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)