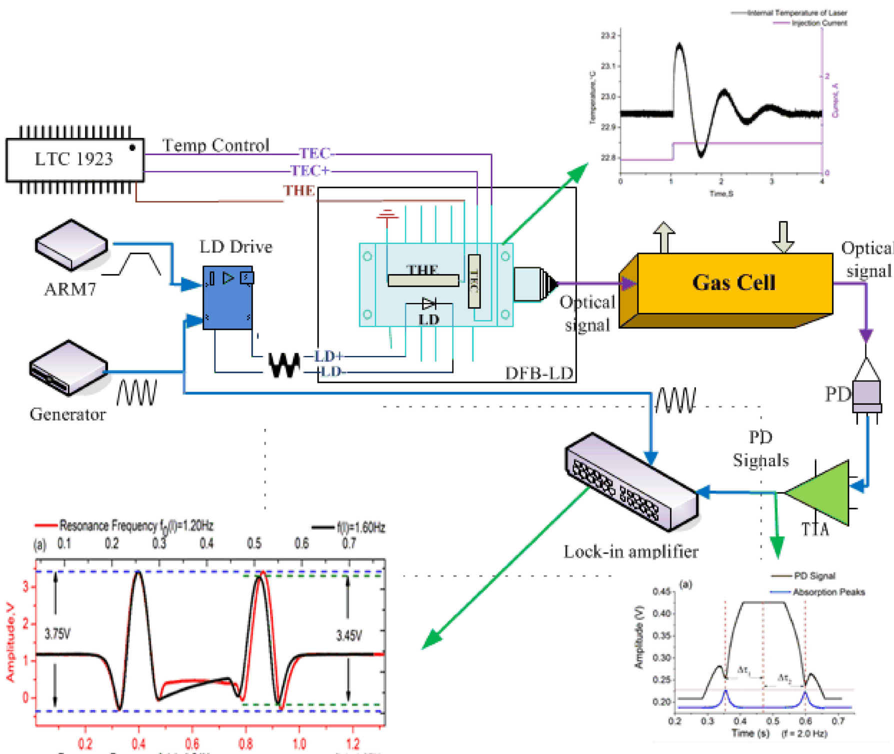
IEEE Photonics Journal
An IEEE Photonics Society Publication

A DFB-LD Internal Temperature Fluctuation Analysis in a TDLAS System for Gas Detection

Volume 11, Number 3, June 2019

Yulei Xie
Jun Chang
Xiaohan Chen
Jiachen Sun
Qinduan Zhang
Fupeng Wang
Zhiwen Zhang
Yiwen Feng



DOI: 10.1109/JPHOT.2019.2916800
1943-0655 © 2019 IEEE

A DFB-LD Internal Temperature Fluctuation Analysis in a TDLAS System for Gas Detection

Yulei Xie, Jun Chang, Xiaohan Chen, Jiachen Sun, Qinduan Zhang, Fupeng Wang, Zhiwen Zhang, and Yiwen Feng

School of Information Science and Engineering, Shandong Provincial Key Laboratory of Laser Technology and Application, Shandong University, Jinan 250100, China

DOI:10.1109/JPHOT.2019.2916800

Manuscript received April 24, 2019; revised May 5, 2019; accepted May 9, 2019. Date of publication May 14, 2019; date of current version May 21, 2019. This work was supported by the National Natural Science Foundation of China under Grant 61475085. Corresponding author: Jun Chang (e-mail: changjun@sdu.edu.cn).

Abstract: The temperature fluctuations inside commercially distributed feedback laser diode were experimentally measured and analyzed in detail in this study. In tunable diode laser absorption spectroscopy based gas sensing systems, the temperature of the laser source is usually fixed and a current signal is used to drive the laser for wavelength scanning or modulation. Even if the laser is controlled by a robust temperature controller, the internal temperature still fluctuates due to the delayed response of the temperature controller when rapidly changing the drive current. These temperature fluctuations result in distortions in the measured absorption signals which can be effectively suppressed by limiting the drive current modulation to the resonance frequency of the temperature control proportional-integral-derivative loop. This study demonstrates a reduction in the temperature dependent absorption distortions and improves the detection uncertainty using this technique.

Index Terms: TDLAS, driving current, temperature fluctuation, resonance frequency.

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) has become the primary technology used for trace gas detection due to its unique advantages for real-time analyses and its fast response, high selectivity and high sensitivity without any sample preparation [1]–[5]. It has robust application prospects in atmospheric environmental monitoring, energy saving and emission reduction, early warmings for fires, ecological environmental monitoring, industrial process detection and control and engine detection. In addition, multiple studies have been reported concerning the improvement of its performance for trace gas detection applications.

Compared to the method of short absorption path-length, multi-pass White cells or Herriott cells are widely used to increase the absorption path-length to improve the detection limit [6], [7]. Doussin proposed a multiple-reflection cell for free space detection, and realized an optimal path-length of 672 m [8]. Other methods have been used to improve the accuracy of direct absorption detection. Zhu *et al.* analyzed three extensively used demodulation methods: subtraction, division, and balanced ratiometric detection for dual-beam wavelength-modulation spectroscopy trace gas detection to determine the best strategy [9]. Wang *et al.* proposed a demodulation algorithm, which is immune to fluctuations in the light power, based on the head–tail technique for single-beam water vapor detection under rough environmental conditions [10]. A method of dual-beam, single-detector wavelength-modulation spectroscopy(WMS) originally proposed by Bonfiglioli and Trench has been demonstrated experimentally [11]. In 1980, Bjorklund proposed a method for measuring weak absorption and dispersion called frequency-modulation spectroscopy [12]. TDLAS with WMS enables alternating-current detection at a specific frequency and the use of a lock-in amplifier (LIA) for better signal recovery [13]–[15].

To maintain the stability of the laser output wavelength, temperature controllers are generally employed within the laser to suppress the temperature drift. However, few studies have mentioned the effect of internal temperature fluctuations in laser diodes (LDs), even with a robust temperature controller. Because a distributed feedback laser diode (DFB-LD) is modulated not only by the current but also by the temperature, temperature fluctuations change the relationship between the wavelength and the output power. When the output wavelength of the laser fluctuates, it not only affects the amplitude of the absorption signal, but also causes a distortion in the gas absorption profile. The laser outputs characteristics constitute are the basis of all TDLAS detection techniques, including direct absorption spectroscopy, WMS, and photoacoustic detection. Therefore, it is necessary to determine the level of the temperature fluctuation and its influence in order to improve the detection uncertainty.

In this paper, a DFB-LD internal temperature fluctuation analysis was performed for the first time. Even if the laser is controlled by a robust temperature controller, the inside temperature still fluctuates due to the delay effect of the controller when sharply changing the driving current. By comparing the detection signal and the injection current, we can analyze the internal temperature of the DFB-LD and, at the same time, study the relationship between the detected absorption signal and the internal temperature. In addition, we further explore the influence of different injection waveforms and different driving frequencies on the absorption signal. Finally, we determined the resonance frequency where the resonance is formed by matching the temperature fluctuation curve with the original scanning signal frequency. The TDLAS detection uncertainty can be completely suppressed by using the resonant frequency as proposed in this study.

2. Theory

When the wavelength of the diode laser light overlaps a ro-vibrational transition of a gas, absorption will result in light intensity attenuation. The transmitted intensity $I_{out}(t)$ at the instantaneous time t associated with a gas transition in a gas cell is given by the Beer-Lambert law [16], [17]:

$$I_{out}(t) = I_{in} \cdot exp\left\{-\alpha\left[v(t)\right]CL\right\} \approx I_{in} \cdot \left\{1 - \alpha\left[v(t)\right]CL\right\}, \tag{1}$$

where I_{in} is the incident intensity, $\alpha[v(t)](\text{cm})^{-1}$ is the absorption coefficient at an instantaneous frequency $v(t)$, L (cm) is the optical path length, and C is the concentration of the target gas. An approximation of Equation (1) is valid for low absorbance, i.e., $\alpha[v(t)CL] \ll 1$.

For a gas absorption line under atmospheric pressure (0.1 MPa) and normal temperature (298 K), a Lorentzian profile is applicable, where the absorption coefficient $\alpha\,[v(t)](\text{cm})^{-1}$ is defined by:

$$\alpha\left[v(t)\right] = \frac{\alpha_0}{1 + \left[\frac{v(t)-v_0}{\gamma}\right]^2}, \tag{2}$$

where α_0 and v_0 are the absorption coefficient and optical frequency at the absorption line center and γ is the half width at half maximum of the transition lineshape [16]. When the wavelength $v(t)$ changes, the corresponding absorption coefficient $\alpha[v(t)](\text{cm})^{-1}$ also changes, which in turn causes a change in the transmitted intensity $I_{out}(t)$. TDLAS generally uses an InGaAs photodiode (PD) to detect the light output signal; however, such a PD can only respond to the intensity of the light. Therefore, when the DFB-LD output covers one or more absorption lines, it is possible to deduce the change in the wavelength by detecting the relative positions of the absorption peaks in the PDs.

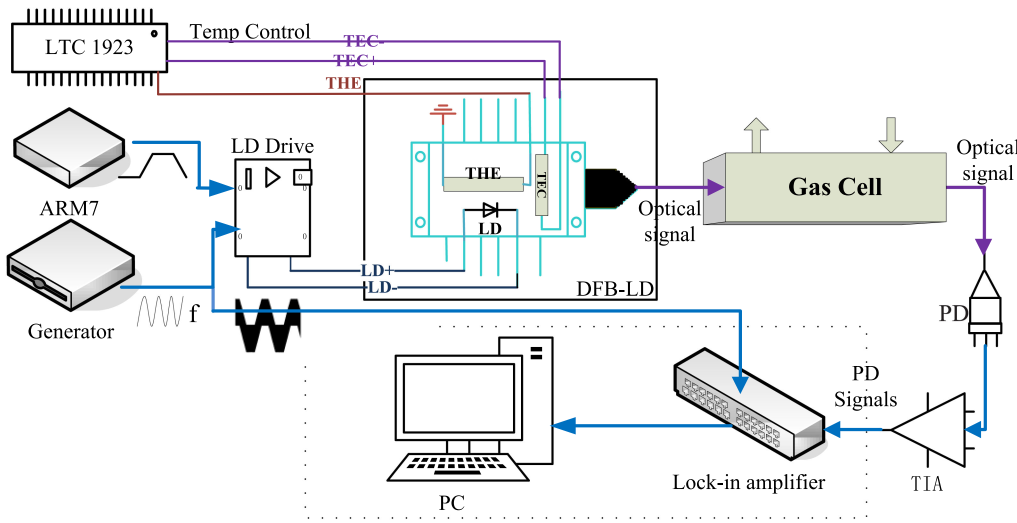


Fig. 1. Schematic of the experimental system (TEC: thermoelectric cooler. THE: thermistor; and TIA: trans-impedance amplifier).

When rapidly changing the injection current to a temperature-controlled LD, the diode internal temperature needs a time t_0 to settle back to the set point. The response time of the temperature controller is determined by multiple factors, including the response time of the control circuit, the response time of the thermistor, and the heating/cooling power of the thermoelectric cooler (TEC). The timescale of the temperature controller loop is on the order of a few hundreds of milliseconds and the optical response has a timescale of nanoseconds, leading to a 100-ms-scale and nominally uncontrolled drift in the DFB-stabilized wavelength of the laser diode output.

As the LD drives the rising/falling current to change the output wavelength, there is a delay between the wavelength and intensity shifts due to the finite TEC temperature controller response time. There is a phase shift between the wavelength and intensity response of the laser due to the influence of the temperature fluctuations. If the wavelength output of the laser covers the characteristic absorption line of a particular gas molecule, the temperature variation inside the laser can be determined judged by monitoring the magnitude and relative position of the absorption peak on the rising and the falling edges of the symmetric waveform.

3. Experiments

3.1 Schematic of the Experimental System

The experimental setup to verify the theory discussed in Section 2 is illustrated in Fig. 1. Water vapor was chosen as the object gas. Water vapor has a strong absorption at 1368.597 nm, where the intensity of the absorption peak is 1.795×10^{-20} $cm^{-1}/(mol^{-1}cm^{-2})$. A DFB-LD (DFB-1370-F-N-I-SM, SN: 15090108) was used as the light source.

The driving current signal of the DFB-LD was generated via an ARM7 (Advanced RISC Machine 7) and a generator. The output of the laser was coupled into a gas cell with an absorption path length of 3 m. The internal temperature of the laser was measured by monitoring the voltage of the thermistor integrated inside the laser source. A commercial chip (LTC-1923, ADI, USA) was employed to control the temperature of the DFB-LD, achieving a temperature stability of ± 0.01 °C.

A PD detected the light transmitted through the gas cell (BF14-PD300-F-N; Wuhan 69 Sensor Technology, Wuhan, China) and then convert was the current is converted into a voltage signal via a trans-impedance amplifier (TIA). (An LIA (7230 DSP Lock-in Amplifier; AMETEK, Berwyn, PA, USA) was used for the harmonic detection.

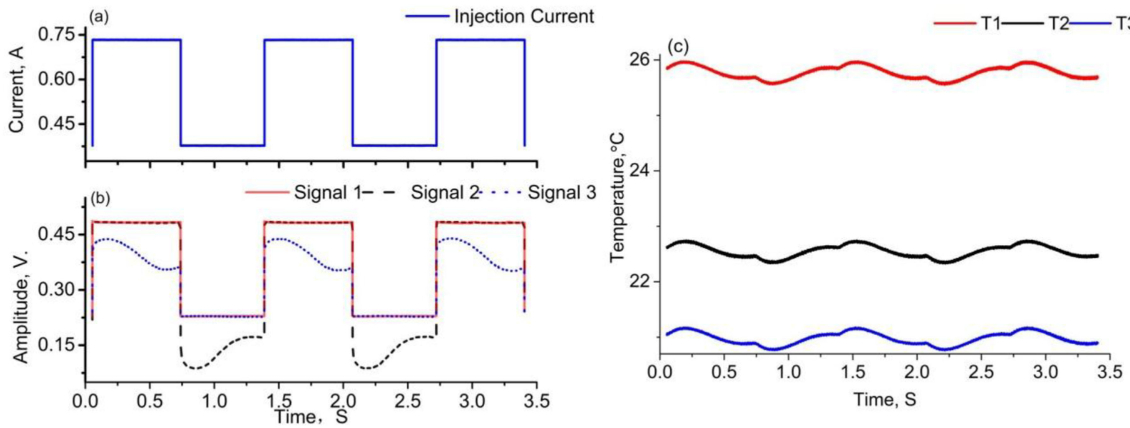


Fig. 2. Comparison of square wave signals at different temperatures. (a)The injection current signal shown is the periodic square wave that was used to modulate the DFB-LD. (b) Signal1, 2 and 3 represent the PD signals of the detected light from the DFB-LD after passing through the gas cell at three different working temperatures. (c) T1, T2 and T3 represent the internal temperature of the LD corresponding to Signals 1, 2 and 3, respectively.

3.2 Experimental Verification and Analysis

3.2.1 Verification of the Internal Temperature Changes of the Laser: To prove that a rapid change in the driving current signal has an effect on the wavelength of the laser, a rapidly changing signal was used to drive the DFB-LD.

As shown in Fig. 2(a), a periodic square wave was used to drive the laser. The light from the laser was detected by the PD after passing through the gas cell and the current signals were then converted by the TIA into a corresponding voltage signal as shown in Fig. 2(b). In these experiments we used the same injection currents and only changed the operating temperatures to three different values, which led to the LD output wavelength covering three different ranges. It is known that this DFB-LD works at 1368.857 nm (T = 25 °C) (the current modulation coefficient was 4.76 pm/mA and the temperature modulation coefficient was 80 $\text{pm} \cdot {}^{\circ}\text{C}^{-1}$) and that water vapor has a strong absorption at 1368.597 nm (7306.752 cm^{-1}), with an absorption line shape width of 35 pm. Therefore, we needed to change the internal temperature of the LD via the temperature controller, LTC-1923, to allow the water vapor absorption to cover the output wavelength.

As shown in Fig. 2(a), the injection current changed from 37.7 mA to 73.3 mA; therefore, output wavelength changed by:

$$\Delta\lambda = (73.3\ \text{mA} - 37.7\ \text{mA}) * 4.76 \left(\frac{\text{pm}}{\text{mA}}\right) = 169.5\ \text{pm}, \tag{3}$$

When the temperature was T1, the DFB-LD output wavelength changed from 1369.019 nm to 1368.816 nm and did not cover the water vapor absorption. Therefore, Signal 1 was the same as the injection current signal: a square wave.

When the temperature was T2, the wavelength changed from 1368.563 nm to 1368.599 nm and just covered the absorption at 1368.597 nm. The waveform of Signal 2, shown in Fig. 2(b) indicates that the upper side of the square wave remained unchanged while the lower side became a wavy curve in which the laser output had its minimum wavelength.

When the temperature was T3, the wavelength changed from 1368.606 nm to 1368.630 nm and overlapped the absorption with a width of 35 pm at 1368.597 nm. The waveform of Signal 3, shown in Fig. 2(b), in which the laser output had its maximum wavelength, indicates that the lower side of the square wave remained unchanged while the upper side became a wavy curve.

It is known that the injection current and the internal temperature determine the DFB-LD output wavelength. If the temperature remains at a signal point, the absorption coefficient will remain the same. The signal will remain a straight line unless the amplitude is decreased. In fact, we can see

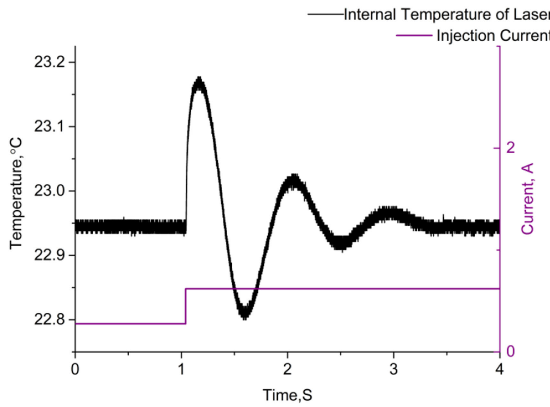


Fig. 3. The internal temperature fluctuation of the laser when the injection current changed sharply.

that the temperature change led to the change in the transmitted intensity I_{out}(t); this was verified in Signals 2 and 3.

As shown in Fig. 3, at the beginning of the experiment the injection current maintained a stable value; however, at T = 1 s, the injection current rapidly increased, which led to a sudden increase in the laser output power. Correspondingly, the temperature of the laser immediately increased. Therefore, the thermal balance inside the laser, as controlled by the robust temperature controller, was broken and the internal temperature of the laser increased rapidly. The temperature control system needed some time to respond to the temperature, change and then the TEC quickly worked to reduce the temperature inside the laser. We saw that a temperature fluctuation of $\Delta T = 0.44\ ^{\circ}C$ corresponded to a laser output wavelength fluctuation of $\Delta\lambda_T = 35.2$ pm. After repeated heating and cooling, which was clearly due to the poorly-tuned proportional-integral-derivative (PID) parameters involved in LTC-1923 or LDC-501, the temperature changed to form a relaxation oscillation, and finally stabilized at the initial temperature as shown in Fig. 3. By changing the PID parameters, it should be possible to critically reduce the temperature response, leading to a much more rapid convergence to the set-point temperature.

3.2.2 Effect of Changes in the Injection Current on the Temperature and Absorption Signals: As mentioned above, the temperature changes affect the output wavelength of the laser. This is very well understood, however, its influence on the absorption signals in TDLAS systems has not been addressed in detail before. When the output wavelength of the laser overlaps the water vapor absorption line, we can determine the output wavelength drift due to the temperature changes by comparing the relative positions of the absorption peaks on the rising and falling edges. As shown in Fig. 4(a), when the scanning trapezoidal wave frequency $f_1 = 2.0$ Hz, it is clear that the relative positions of the absorption peaks are significantly different at the rising and falling edges. Here we used $\Delta\tau_1$ and $\Delta\tau_2$ as shown in Fig. 4(a), which were defined as the distance (the proportion of a cycle) from the center of the trapezoidal wave to the respective absorption peaks, to reflect the phase shift between the wavelength and the intensity of the laser output.

When the scanning frequency was 2.0 Hz, and the measured $\Delta\tau_1$ and $\Delta\tau_2$ were 0.24 and 0.26, respectively. In addition, the amplitude of the first absorption peak was 5% higher than the amplitude of the second peak.

As shown in Fig. 4(b), $\Delta\tau_1$ and $\Delta\tau_1$ fluctuated with changing scanning frequencies, which means that using different scanning frequencies changed the phase shift between the wavelength output and the intensity response. The reason for this change may be that different driving frequencies affect the temperature recovery differently due to the delay of the TEC controller, therefore affecting the phase delay between the wavelength and the intensity. By fitting the data points of $\Delta\tau_1$ and $\Delta\tau_1$ along with the frequency, an intersection was observed as shown in Fig. 4(b); this was the resonance frequency location that we had aimed to find. To clearly show the difference between working in the

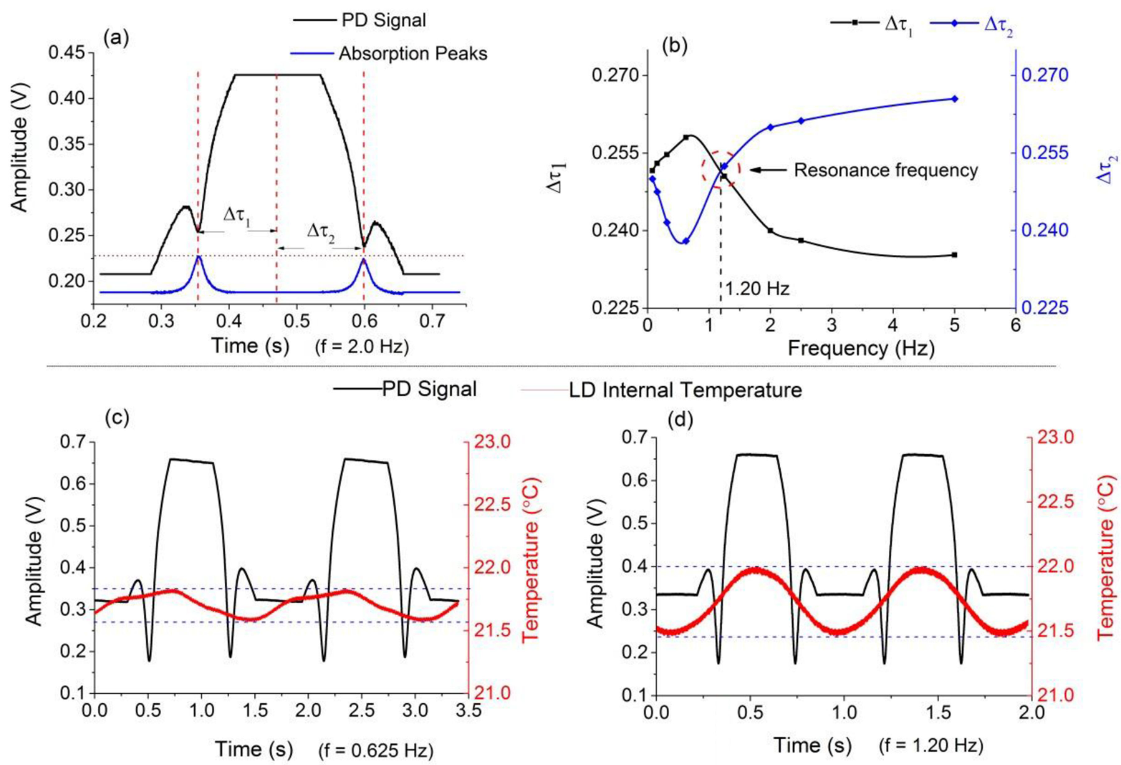


Fig. 4. The influence of different scanning frequencies on absorption signals. (a) The detected absorption signal and the definition of $\Delta\tau_1$ and $\Delta\tau_2$, when the scanning frequency $f_1 = 2.0$ Hz. (b) The changes in $\Delta\tau_1$ and $\Delta\tau_2$ corresponding to different scanning frequencies. The point marked with the dashed circle is the resonance frequency. (c) The detected absorption signal and temperature fluctuation in the scanning frequency of 0.625 Hz. (d) The detected absorption signal and temperature fluctuation for a resonance frequency of 1.20 Hz.

resonance frequency and in other frequencies, the absorption signals and temperatures measured in frequencies of 0.625 Hz and 1.20 Hz (the resonance frequency) were compared as shown in Figs. 4(c) and 4(d). The temperature fluctuations were differed between the rising and falling edges as shown in Fig. 4(c). That is why the locations of the corresponding absorption peaks were different. However, the absorption peaks located on the two sides were absolutely symmetric when working at the resonance frequency, as shown in Fig. 4(d).

3.2.3 Resonance Frequency Correction for a Waveform: Previous experiments have studied the effect of temperature changes on direct absorption signals. In the WMS method, the DFB-DL is driven by the combination of a low frequency scanning ramp and a high frequency sinusoidal signal. As shown in Fig. 5(a), the commercial chip (LTC-1923) can be employed to control the temperature of the laser. Comparing the second harmonic signal at the resonant frequency of 1.20 Hz to the signal at the non-resonant frequency of 1.60 Hz, it was found that the amplitude of the second harmonic signal on the right was 8% smaller than the one on the left when the system did not operate at the resonance frequency. Under the condition of the resonance frequency, the two second harmonic signals showed good symmetry, with the same amplitudes and relative positions. In addition, the profile of second harmonic signal improved. In another experiment, a more robust temperature controller, LDC-501, was used to control the laser temperature to determine if the unexpected temperature drifts were a specific to the LTC1923. As a result, the same phenomenon was observed, and the resonant frequency was measured to be 1.24 Hz, giving a better result compared to the signal at the non-resonant frequency of 1.07 Hz.

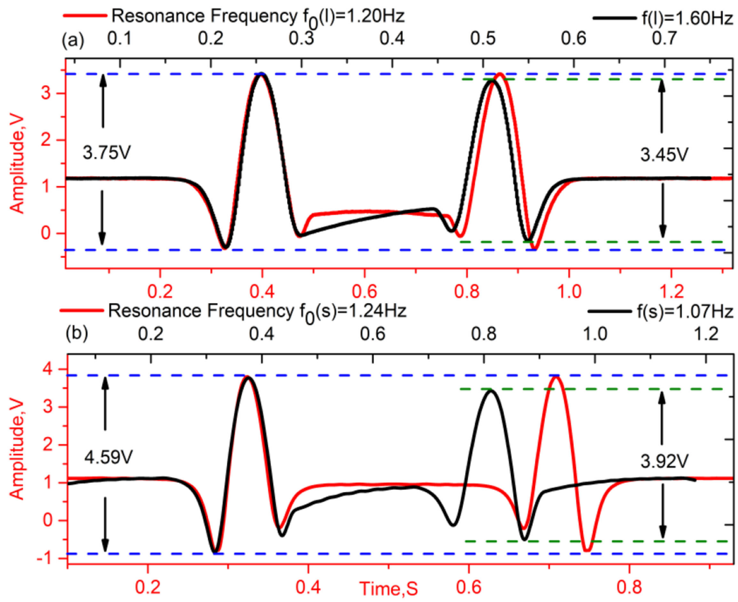


Fig. 5. The second harmonic signals measured at different scanning frequencies. (a) With LTC-1923 employed to control the temperature of the DFB-LD, the black line represents the second harmonic signal measured at a scanning frequency of 1.60 Hz, and the red line represents the second harmonic signal measured at a scanning frequency of 1.20 Hz. (b) With the laser diode controller(LDC-501, Stanford Research Systems, USA) employed to control the temperature of the DFB-LD, the black line represents the second harmonic signal measured at a scanning frequency of 1.07 Hz and the red line represents the second harmonic signal measured at a scanning frequency of 1.24 Hz.

4. Conclusions

This is the first time the influence of the internal temperature fluctuation of a DFB-LD on a gas sensing system has been discussed in details, even though the DFB-LD was controlled by using a robust commercial temperature controller. The main reason for the fluctuation of the temperature was that the thermal equilibrium state, maintained by the internal temperature controller of the laser, is broken because the driving signal changed too rapidly.

We changed the frequency of the driving signal to study its effects on the internal temperature of the DFB-LD. Lowering the temperature fluctuation by reducing the frequency of the injection current is a very effective technique.

Furthermore, we explored the so-called resonance frequency using experiments in which the influence of the temperature could be efficiently, eliminated; this frequency can be chosen as the modulation frequency in WMS systems for laser driving to provide a better absorption signal. Previously, the absorption signals on the rising and falling edges were both used to calculate the water vapor concentrations and the results had an 8% uncertainty. However, this uncertainty can be completely suppressed by virtue of the proposed resonant frequency in this study. Nevertheless, more robust temperature controllers and techniques to suppress such effects should be developed in the future.

References

[1] S. Hunsmann, K. Wunderle, S. Wagner, U. Rascher, U. Schurr, and V. Ebert, “Absolute, high resolution water transpiration rate measurements on single plant leaves via tunable diode laser absorption spectroscopy (TDLAS) at 1.37 μm,” *Appl. Phys. B, Lasers Opt.*, vol. 92, pp. 393–401, 2006.

[2] Q. Wang *et al.*, “Detection of water vapor concentration based on differential value of two adjacent absorption peaks,” *Laser Phys. Lett.*, vol. 9, pp. 421–425, 2012.

[3] G. Durry *et al.*, "Near infrared diode laser spectroscopy of C_2H_2, H_2O, CO_2 and their isotopologues and the application to TDLAS, a tunable diode laser spectrometer for the martian PHOBOS-GRUNT space mission," *Appl. Phys. B Lasers Opt.*, vol. 99, pp. 339–351, 2010.

[4] F. Wang, J. Chang, Q. Wang, W. Wei, and Z. Qin, "TDLAS gas sensing system utilizing fiber reflector based round-trip structure: Double absorption path-length, residual amplitude modulation removal," *Sensors Actuators, A Phys.*, vol. 259, pp. 152–159, 2017.

[5] M. A. Bolshov, Y. A. Kuritsyn, V. V. Liger, V. R. Mironenko, S. B. Leonov, and D. A. Yarantsev, "Measurements of the temperature and water vapor concentration in a hot zone by tunable diode laser absorption spectrometry," *Appl. Phys. B, Lasers Opt.*, vol. 100, pp. 397–407, 2010.

[6] J. U. White, "Long optical paths of large aperture," *J. Opt. Soc. America*, vol. 32, pp. 285–288, 1942.

[7] W. R. Trutna and R. L. Byer, "Multiple-pass raman gain cell," *Appl. Opt.*, vol. 19, pp. 301–312, 1980.

[8] J.-F. Doussin, R. Dominique, and C. Patrick, "Multiple-pass cell for very-long-path infrared spectrometry," *Appl. Opt.*, vol. 38, pp. 4145–4150, 1999.

[9] C. Zhu *et al.*, "Reliability analysis and comparison of demodulation methods for dual-beam wavelength-modulation spectroscopy water vapor detection," *Appl. Opt.*, vol. 52, pp. 4171–4178, 2013.

[10] F. Wang *et al.*, "Demodulation algorithm used in single-beam system immune to light power drift," *Appl. Opt.*, vol. 54, pp. 2032–2038, 2015.

[11] E. I. Moses and C. L. Tang, "High-sensitivity laser wavelength-modulation spectroscopy," *Opt. Lett.*, vol. 1, pp. 115–117, 1977.

[12] G. C. Bjorklund, "Frequency-modulation spectroscopy: A new method for measuring weak absorptions and dispersions," *Opt. Lett.*, vol. 5, pp. 15–17, 1980.

[13] F. Wang *et al.*, "Simultaneous measurement on gas concentration and particle mass concentration by tunable diode laser," *Flow Meas. Instrum.*, vol. 21, pp. 382–387, 2010.

[14] X. M. Wang, "Measurement of CO_2 concentration in flame based on tunable diode laser absorption spectroscopy," *J. Atmospheric Environ. Opt.*, vol. 2, no. 4, pp. 290–295, 2007.

[15] K. Duffin, A. J. McGettrick, W. Johnstone, G. Stewart, and D. G. Moodie, "Tunable diode-laser spectroscopy with wavelength modulation: A calibration-free approach to the recovery of absolute gas absorption line shapes," *J. Lightw. Technol.*, vol. 25, no. 10, pp. 3114–3125, Oct. 2007.

[16] W. Wei, J. Chang, Q. Wang, and Z. Qin, "Modulation index adjustment for recovery of pure wavelength modulation spectroscopy second harmonic signal waveforms," *Sensors (Switzerland)*, vol. 17, 2017, Art. no. 163.

[17] K. Ruxton, A. L. Chakraborty, W. Johnstone, M. Lengden, G. Stewart, and K. Duffin, "Tunable diode laser spectroscopy with wavelength modulation: Elimination of residual amplitude modulation in a phasor decomposition approach," *Sensors Actuators, B Chem.*, vol. 150, no. 1, pp. 367–375, 2010.