Novel method for correcting light intensity fluctuation in the TDLAS system

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A novel method for online correction of light intensity fluctuation in a practical tunable diode laser absorption spectroscopy (TDLAS) system with wavelength modulation is presented. The proposed method is developed according to the linear relation between peaks at multiple frequencies of sine modulation in the power spectral density of the demodulated second-harmonic (2f) signal and the incident light intensity. Those peaks are demonstrated experimentally and explained as residual power at the first-harmonic and third-harmonic frequencies after 2f demodulation of the residual amplitude modulation signal due to the limited integrating time constant of the lock-in-amplifier. This method can achieve real-time correction of light intensity fluctuations with only little calculation. It can work well in a very large range of light intensity and has great potential applications in the wavelength modulation spectroscopy system.

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Tunable diode laser absorption spectroscopy (TDLAS) has been widely used for *in situ* trace gas detection and temperature measurements because of its high sensitivity, high selectivity, and quick response[1−5]. However, the performance of any practical system installed in the industrial field is often degraded by the inevitable occurrence of light intensity fluctuations due to predictable or unpredictable sources such as laser intensity fluctuation or dust scattering. To gain better performance of the TDLAS system in field application, the correction of light intensity fluctuations must be improved. Traditional light intensity correction methods need additional electronic circuits and data sampling channels which depress the system's efficiency and result in added cost. A new kind of low-cost light intensity correction method based on the original system is reported in this letter. In any practical wavelength modulation TDLAS system, the power spectrum of the demodulated second-harmonic (2f) signal has residual power signals leaked at the first-harmonic (1f) and third-harmonic (3f) frequencies because of the limited integrating time constant of the lock-in-amplifier (LIA). The correction is achieved according to the linear relation between amplitudes of those residual signals and the incident light intensity. The method has been experimentally demonstrated to work well in a very large range of light intensity, with high signal-to-noise ratio (SNR), and has great potential applications in a similar fast response wavelength modulation spectroscopy (WMS) system.

The basic principle of TDLAS can be written as

$$\frac{I}{I_0} = C\exp(-kL), \tag{1}$$

where I_0 is the incident light intensity, I is the transmitted light intensity, k is the absorption coefficient, C is the intensity coefficient induced by loss of generality[6] such as dust scattering, and L is the optical path length. When the absorption is weak enough, Eq. (1) can be simplified to

$$\frac{I}{I_0} = C(1-kL) = C[1-\sigma(\lambda)], \tag{2}$$

where λ is the laser wavelength and $\sigma(\lambda)$ is the absorption factor[7].

Depending on the required sensitivity and measurement accuracy, direct absorption and WMS technologies are often employed for trace gas monitoring in a TDLAS system. Compared with the WMS technique, direct absorption is simpler and cheaper, but its measurement accuracy and sensitivity frequently suffer from serious noise such as excess noise from the diode laser[8−10] or photon detector. In a 2f-detection TDLAS system, additional high-frequency sine injection current is added to the laser. This addition brings the signal to a high-frequency region and eliminates low-frequency noise, then the absorption signal can be recovered by a LIA. At the same time, this method can improve the resolution by eliminating the large base signal in direct absorption. The diagram of the typical wavelength modulation TDLAS system is shown in Fig. 1. The frequencies of sawtooth and sine waves are 30 and 10 kHz, respectively. A signal from the photon detector is sent into a LIA to get the demodulated 2f signal of the absorption. Lastly, gas concentration can be extracted from the demodulated 2f signals.

In the 2f-detection TDLAS system, the demodulated 2f signal is proportional to the absorption, light intensity, and gain constant of the circuit, so light intensity fluctuations should be normalized first. Traditional light intensity normalization methods include normalizations of sawtooth wave, sine wave, and offset of the demodulated 1f signal[11,12]. However, those methods all have weak points such as the need for additional circuit and sample channels which depress the system's efficiency and result in added cost. As an alternative scheme, a new method for light intensity correction will be introduced.

A typical demodulated 2f signal in a TDLAS system is shown in Fig. 2. Figure 2(a) shows the time-domain demodulated 2f signal. Figure 2(b) presents the corresponding power spectral density (PSD). The figures show that, besides the low-frequency signal containing the absorption signal, there are two large PSD peaks at 10 and 30 kHz, and a tiny peak at 20 kHz. These peaks are the residual power signals leaked through LIA at multiple frequencies of sine modulation in the demodulated 2f signal due to the limited integrating time constant of the LIA. The peaks could also be simply explained in theory as residual sum frequency or difference frequency power of the residual amplitude modulation (RAM) signal and the reference.

To better describe the results above, the operational principle diagram of the LIA is shown in Fig. 3. The original signal from the photon detector is preprocessed at first, and then passes through a band-pass to filter out most of the low-frequency component. For 2f-detection, the LIA should be set working at the 2f mode; in this case, the 10-kHz sine-wave frequency will be first doubled to 20 kHz and converted to square wave for reference, and then calculated by the phase-sensitive detector together with the signal from the photon detector. Finally, the integration calculation is done to eliminate high-frequency signal and then the concentration can be extracted from the low-frequency signal.

In a TDLAS system, the diode laser wavelength is modulated by the sawtooth and high-frequency sine injection current, as well as wavelength modulation. There is also the modulation of light intensity, which is called RAM[7] and can be expressed as

$$I_0(t) = I_c + I_a \cos \omega t, \tag{3}$$

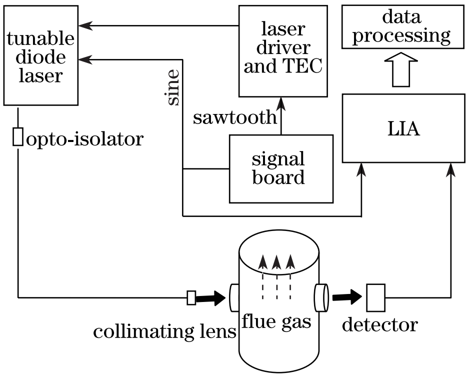

Fig. 1. Schematic diagram of the wavelength modulation TDLAS gas detection system. TEC: thermoelectric cooler.

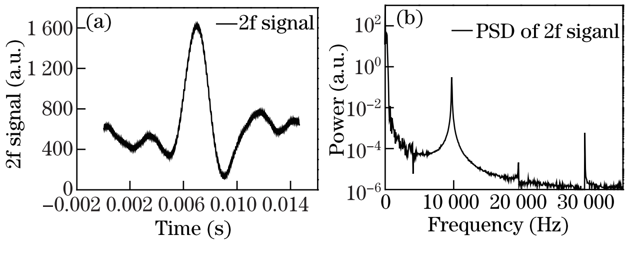

Fig. 2. Typical 2f output of the LIA. (a) Time-domain figure and (b) corresponding PSD.

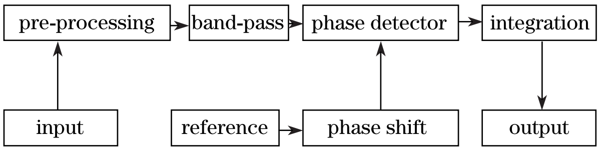

Fig. 3. Schematic diagram of the LIA.

where I_c is the centered light intensity drived by DC and sawtooth currents, and I_a is the amplitude of intensity modulation drived by sine-wave current.

To summarize Eqs. (2) and (3), the current signal from the detector i_{det} can be assumed as

$$\begin{aligned} i_{det} &= \Re I(t) = \Re C I_0(t)[1-\sigma(\lambda(t))] \\ &= \Re C(I_c + I_a \cos \omega t)[1-\sigma(\lambda(t))], \end{aligned} \tag{4}$$

where $\Re$ represents the photoelectric conversion efficiency. Most of the low-frequency signal, which is actually I_c in Eq. (4), would be filtered out. Hence, the phase-sensitive detection can be described as

$$\begin{aligned} S &= k_1 \cdot i_{det} \cos(2\omega t + \Delta\theta) \\ &= k_1 \cdot \Re C \cdot I_a \cos \omega t[1-\sigma(\lambda(t))] \cdot \cos(2\omega t + \Delta\theta) \\ &= k_1 \cdot \Re C \cdot I_a \cos \omega t \cos(2\omega t + \Delta\theta) - k_1 \cdot \Re C \cdot I_a \\ &\quad \cdot \sigma(\lambda(t)) \cdot \cos \omega t \cos(2\omega t + \Delta\theta) \\ &= S_1 - S_2, \end{aligned} \tag{5}$$

where S is the total signal after the phase-sensitive detection, k_1 is the system constant related to LIA, and $\Delta\theta$ is the phase delay between the signal and the reference. It has to state that one uses $\cos(2\omega t + \Delta\theta)$ to represent the reference instead of the square wave for simple. In a traditional TDLAS system, only the second term S_2 in Eq. (5), which is proportional to gas absorption and general loss C of light intensity, is used in the abstraction of gas concentration. However, the first term S_1 is also meaningful in this letter and can be expressed as

$$\begin{aligned} S_1 &= k_1 \Re C \cdot I_a \cos \omega t \cdot \cos(2\omega t + \Delta\theta) \\ &= k_2 \cdot C \cdot [\cos(3wt + \Delta\theta) + \cos(wt + \Delta\theta)], \end{aligned} \tag{6}$$

where k_2 is a constant. In Eq. (6), there are 10 and 30 kHz signals after the phase-sensitive detection whose amplitude are also proportional to C. Therefore, if those 10- and 30-kHz signals can be extracted, they can be used to correct the fluctuating light intensity.

The 20-kHz peak can also be explained as the sum frequency power of reference and residual low-frequency signal after the band-pass filter. As a result of the explanation, there would be a 20-kHz peak and a tiny 10-kHz peak in PSD of the demodulated 1f signal, results which are quite coincident with those of the experiment (Fig. 4).

For a common LIA, its so-called narrow bandwidth is valid only when the time constant is long enough compared with the period of modulation wave. However, in the practical wavelength modulation system presented here, the LIA board is mainly used to gain the demodulated 2f signal, which has the period of wavelength scanning time. The scanning time is determined by the sawtooth frequency, which is usually less than 100 Hz. Moreover, in order to overcome possible intensity fluctuation with high frequency, the sawtooth frequency should not be too low. In the current system, the sawtooth frequency is set at 30 Hz. Therefore, the integrating time constant of the LIA could not be too long; otherwise, the LIA would also filter out the absorption signal in 30 Hz. The integrator is actually a low-pass filter in the analog LIA board. The base time constant of the LIA is set to 2 ms; with this limited time constant, it is impossible for a LIA to filter out all harmonic components clearly and other harmonic components will always leak through the LIA (Fig. 2). This is the reason that the 10- and 30-kHz signals appear in the result.

As mentioned above, Eq. (6) shows that the amplitude of the 10- and 30-kHz signals are both proportional to C and that they can survive from the low-pass filter in the LIA, which indicate that they can be used to correct the light intensity. Since all those signals come from a demodulated 2f signal, there is no additional circuit or sample channel needed and the method can achieve absolute real-time correction. Thus, the proposed method can be simply used in the wavelength modulation TDLAS system without any structural change. To obtain the amplitude, a fast Fourier transform (FFT) process is performed, which makes this method quite simple and low cost. The 10-kHz signal is chosen to correct the light intensity fluctuations because of its larger amplitude.

The proposed method is used in a practical instrument for CO measurement. First, the corrected demodulated 2f signal is obtained when the light intensity is changed. In a real gas detection system, part of the demodulated 2f signals is chosen to extract the amplitude of 10-kHz signal in a period state, which is decided by the intensity fluctuation frequency. The FFT calculation would be done to get the amplitude. The test result is shown in Fig. 5. Figure 5(a) shows the original signals at different light intensities, and Fig. 5(b) shows the normalized signals. The figures show good result when the light intensity is reduced to 200/1168 = 17%, which indicated a large dynamic range of the method.

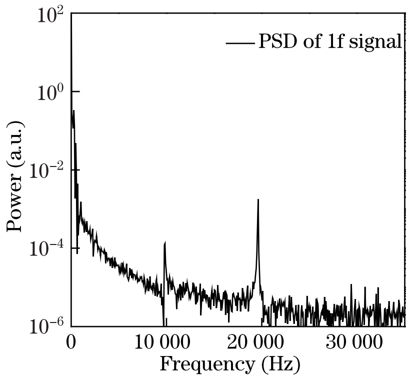

Fig. 4. Typical PSD figure of the 1f output of the LIA.

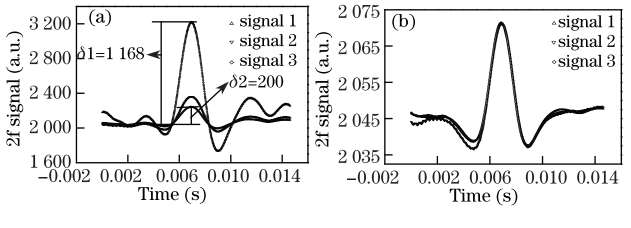

Fig. 5. Result of the light intensity normalization of the demodulated 2f signal. (a) Original demodulated 2f signals at different light intensities and (b) corrected signals.

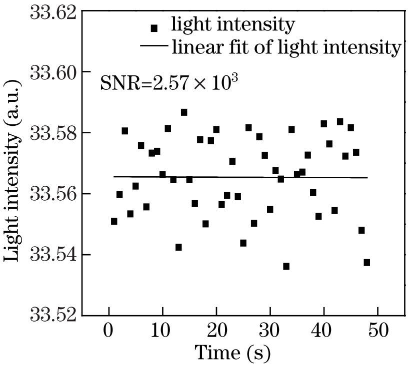

Fig. 6. SNR of the light intensity extraction test.

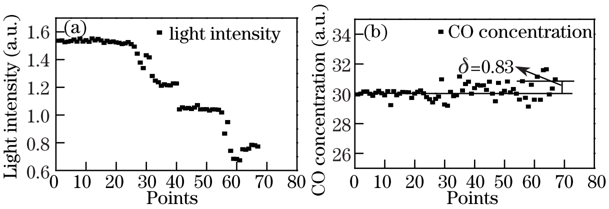

Fig. 7. Demonstration of the accuracy of light intensity fluctuation correction method. (a) Artificial change of light intensity in a large range and (b) corresponding measurement results of CO concentration with the correction method of light intensity fluctuation.

To test the limit of the light intensity abstraction, the SNR of the intensity is obtained by testing the 10-kHz signal amplitude at stable light condition (Fig. 6). The mean of those intensities is about 36.57, while the standard deviation is 1.42×10^{-2} and SNR = $36.57/(1.42 \times 10^{-2})=2.57\times10^3$. This high SNR can ensure the intensity correction will not bring additional noise in and decrease the system's sensitivity.

The experimental result of concentration measurement after correction of light intensity fluctuation is shown in Fig. 7. In the experiment, the light intensity is factitiously changed as shown in Fig. 7(a) to verify the accuracy of the correction method of light intensity fluctuations. Figure 7(b) shows only 0.83/30=2.8% change of concentration while the change of light intensity is about 0.8/1.5=53%, which indicates adequate reliability of the method. The tiny concentration change can be assumed as the nonlinear reaction of the system. Figure 7(b) also shows that the SNR of the measurement runs down with the decline of light intensity.

In conclusion, the multi-peaks in PSD of the demodulated 2f signal in a wavelength modulation TDLAS system are analyzed. A new correction method of light intensity fluctuation is developed according to the linear relation between the peak's amplitude and the incident light intensity. This kind of method can achieve real-time light intensity correction with no additional change in hardware besides little calculation. The SNR is up to 2.57×10^3 in the test, which indicates the great reliability of this method. The proposed method is demonstrated to work well in a very large range of light intensity fluctuations. Note that the time constant should be carefully selected for a particular system to use the online correction of light intensity fluctuation with the method reported in this letter. A compromise must be reached in choosing the time constant of the LIA; a long time constant will reduce the high-frequency interference noise, but it will also reduce the performance of intensity calculation.

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