Research on reduction of long-term distortions and suppression of light intensity fluctuations in a TDLAS system[1]

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ABSTRACT

For any tunable diode laser absorption spectroscopy (TDLAS) system, its performance is often degraded by long-term distortion and fluctuations of light intensity. The source of long-term distortion and the corresponding proposal are discussed at first in this paper. It is proved that the long-term distortion of the system is mainly induced by the change of wavelength dependent transfer function. A balanced optical path can be used to reduce it effectively. In order to decrease the disturbance of intensity fluctuation, a novel method for online correction is presented. It is developed according to the linear relation between the peaks of harmonic power spectra and the incident light intensity. It is demonstrated by the experiments and explained as residual sum frequency and difference frequency power of signal and reference after the lock-in amplifier. This method could achieve real-time light intensity correction with only little calculation. By using a 17.5m multi-pass cell, the experiments show that the system can achieve about 20ppmv stability for long-term continual monitoring. Allan variance indicates that the detection limit for short-term measurement is between 0.3ppmv and 1.5ppmv depending on the response time allowed by the instrument.

Key words: TDLAS**;** long-term distortion; light intensity fluctuation; real-time correction; wavelength modulation spectroscopy.

1. INTRODUCTION

Tunable diode laser absorption spectroscopy (TDLAS) has been widely used for in situ trace gas detection because of its features of high sensitivity, high selectivity and capability of online monitoring [1-3]. However, for any practical TDLAS system installed in the industrial field, its performance is often influenced by long-term distortion and fluctuations of light intensity inevitably existed due to predictable or unpredictable reasons such as background drift, degraded laser source performance as time going and randomly dust scattering. In order to gain better performance of the TDLAS system in the field applications, long-term background drift and light intensity fluctuations must be seriously treated. In this paper the causation of long-term distortion and fluctuations of light intensity will be first briefly discussed, and then some experimental results are demonstrated on removal of long-term distortions and suppression of light intensity fluctuations in a practical TDLAS system. Finally by using Allan variance the detection limit of the system are presented.

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2. DESCRIPTION OF LONG-TERM DISTORTION AND LIGHT INTENSITY FLUCTUATION

The schematic diagram of the TDLAS experimental setup is shown in Fig.1. The diode laser is tuned with the homemade current and temperature controllers to the wavelength of 1.567μm which locates one strong absorption line of the target gas CO. The laser wavelength is scanned through the selected absorption line by a saw-tooth signal at low frequency of 30Hz and simultaneously modulated by a sinusoidal signal at frequency of 10 KHz. The modulated laser beam is divided into two parts with a 1×2 fiber splitter. One arm (80%) is used to measure the gas concentration while the other arm (20%) is used to go through a free space as a reference optical path. Two transmitted laser beams are collimated and then collected by two coincident InGaAs photodiodes, respectively. These two current signals are then transmitted into two-channel LIA to gain the harmonic signals. At last, these signals are sent to computer for processing and harmonic signal detection technique is used for calculation of the target gas concentration.

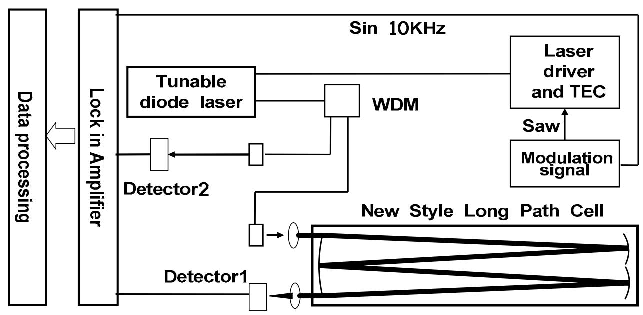

Fig.1. On-line experimental apparatus for TDLAS system. TEC: thermo-electronic cooler.

When the light is passing through a particular path, lots of factors can reduce the light intensity, like dust scattering or absorption in transmission medium. Considering the intensity reduction by gas absorption, Beer-Lambert law is used in general, the response can be described as:

$$\frac{I}{I_0} = \exp(-kL) \quad (1)$$

Where $\boldsymbol{I}$ represents the light intensity after the absorption, and $\boldsymbol{I_0}$ represents the original intensity, $\boldsymbol{k}$ is a reducing coefficient and $\boldsymbol{L}$ denotes the path length. When the gas absorption is very low such as $\boldsymbol{kL \le 0.05}$ [1], equation (1) could be simplified as:

$$\frac{I}{I_0} = 1 - kL = 1 - \sigma(\nu) \quad (2)$$

Where$\sigma(\nu)$ represents the total absorption. There are so many different light loss factors like dust scattering, some of them can be written as a constant number, but generally they are related to the laser wavelength or the intensity. Equation (2) represents the absorption with a function depending on light wavelength to extinguish the gas absorption with some others.

2.1 Signal long-term distortion

In a TDLAS gas detection system, slow signal distortion is the major limit of long-term stability because of its large amplitude. It has been reported that a lot of reasons like wavelength drifts, performance degrade of the laser source or etalon fringe structure change because of thermal effects can result in slow 2f signal distortion [2]. A number of published papers had proposed few methods to reduce those distortions like rapid background subtraction [3] or digital signal processing [4], but there are some limits of those methods when the ambient condition is changed. For instance, it is inconvenient to get the real-time background structure for a TDLAS system installed in an industrial stack for in situ gas monitoring, or when there is an interference or distortion having a very approximate frequency with the absorption signal, in this case the digital method generally could not work very well. In addition, some published papers have proposed double modulation methods [2,5-8] for suppression of signal distortion, two of them are discussed here as examples: (1) addition modulation sine current is added on the diode laser to depress the narrow etalon fringe but it has same drawbacks like digital processing method; (2) additional modulated electric field is added on the gas to produce a modulated Stark-effect, then the background would be distinguished from the useful signal by shifting the absorption line, so slow distortions can be depressed well after the demodulation on a particular frequency, but this method also has drawbacks like expensive cost and it can't be used in some electrostatic prevention conditions.

For the sake of analyzing the slow distortion, all of them could be divided into two types resulting from different origins: one type can lead to signal distortion which is in direct proportion to absorption signal, and the other has no relations to the absorption signal, which were reported as background drifts. In our system, slow signal distortions can be attributed to distortions of wavelength dependent transfer function and intensity dependent reaction function, which is actually RAM here. Fig.2 shows the experimental results of long-term distortions received from the two optical paths described in Fig.1 in the same time.

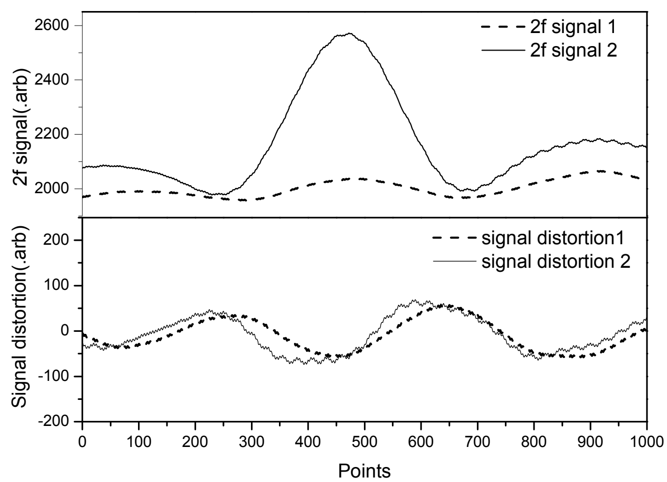

Fig.2. Long-term comparison of the distortions from two different optical paths.

The large signal on the top figure is from the absorption of CO with concentration of 4000ppmv, and the small one is from the free space optical path with no absorption gas of CO. The solid line in the bottom figure is the distortion of the large signal gained after 2 hours in the top figure, while the dashed line in the bottom figure is the distortion of free space signal without absorption gas, which indicates almost no much difference. According to the discussion about the long-term distortion property earlier one can certainly say that it comes from residual amplitude modulation (RAM) or change of wavelength dependent transfer function, and that change may be attributed to the diode laser, the detector or optical path. In additional experiments, the background translates with the wavelength when the laser temperature is changed, so we can safely attribute the long-term distortion to the wavelength dependent transfer function change.

In order to reduce the influence of transfer function changes, a balanced or reference optical path is used to measure the long-term distortion for 8 hours. Assumed that A1, B1 are original signals from two optical paths as described in Fig.1, respectively, and A2, B2 represent those signals received 8 hours later, then the distortion in single optical path is A2-A1 or B2-B1, and (B2-B1)-(A2-A1) represents the subtracted distortions in balanced optical path scheme. The result is shown in Fig. 3. The solid line in left figure shows the distortion of B2-B1 while the dashed line in left figure shows the distortions (B2-B1)-(A2-A1) in balanced optical path scheme. There are signal distortions with amplitude equal to absorbance of 1.18×10^{-3} or corresponding absorption by CO with concentration of 268ppm in a multi-pass cell with total optical path of 17.5m and 2.1×10^{-4} in the balance optical path, indicate 6 times suppression of long-term signal distortion in balance optical path. In the right figure there are variance in those two optical paths, the variance in the balanced optical path scheme (solid square points) shows 34 times suppression comparing to the single one (triangle points) for 8 hours, also indicates about 6 times suppression of distortion amplitude.

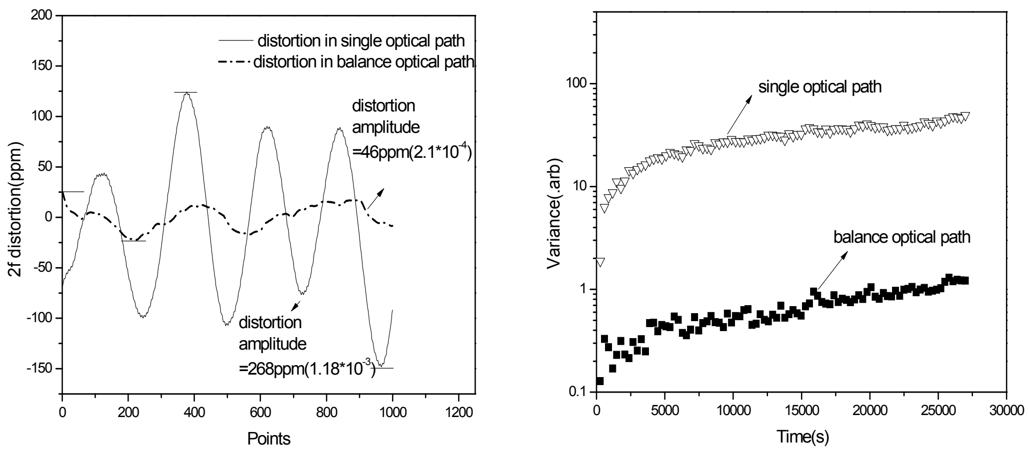

Fig.3. Long-term distortion measurements of two optical schemes for 8 hours. The left figure shows distortions in balanced optical paths and single optical path, respectively; the right figure shows variance in those two schemes.

2.2 Light intensity fluctuation

In a TDLAS system, 2f signal is proportional to the absorption, the light intensity and gain constant of the circuit, so light intensity fluctuations induced by dust should be normalized firstly. Traditional light intensity normalization methods are raw signal, sine signal and 1f signal normalization [9]. But those methods need additional circuit and sample channel, which depress the system's efficiency and result to more cost. Light intensity can be simplified as equation (4) with absorption and non-linear intensity reaction ignored:

$$i = i_0 + \Delta i_1 \cos \omega t \qquad (4)$$

Where i_0 is the light intensity determined by DC and saw current, $\Delta i_1 cos \omega t$ represents modulation intensity.

Typical 2f signal and the corresponding power spectral density (PSD) of the system are shown in Fig 4. It can be seen that, when the modulation signal frequency is 10 KHz, besides of low frequency signal which contains the absorption signal, there are two large PSD peaks at 10 KHz, and 30 KHz, and tiny peak at 20 KHz. These peaks can be assumed as residual sum frequency or difference frequency power of signal and reference after the limit integration in the lock-in amplifier.

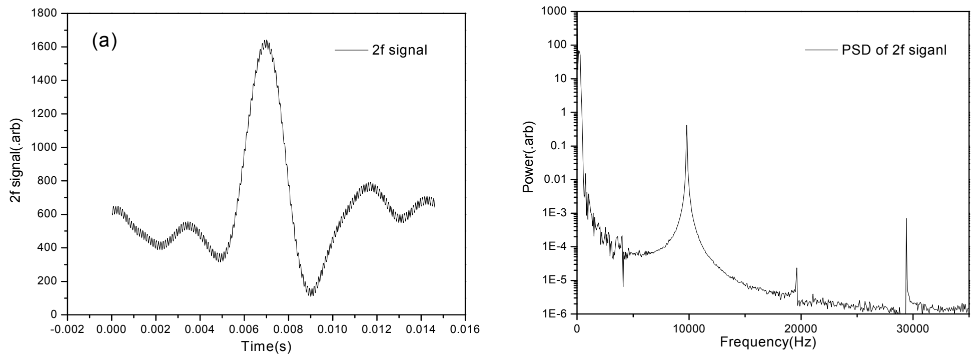

Fig.4. Typical 2f output of the LIA (left figure) and the corresponding power spectral density (PSD) (right figure).

The phase detection in a lock-in amplifier (LIA) can be described as:

$$\begin{aligned} S &= K_1 \cdot \Delta i_1 \cos \omega t \cos(2\omega t + \Delta\theta) \\ &= \frac{K_1}{2} \cdot \Delta i_1 [\cos(3\omega t + \Delta\theta) + \cos(\omega t + \Delta\theta)] \end{aligned} \qquad (5)$$

Where $\boldsymbol{K_1}$ represents system index which is proportional to light intensity and $\Delta\theta$ is the phase delay between the signal and reference. It can be seen in equation (5) that there are 10 KHz and 30 KHz signals after the phase detection.

The integrator is a low-pass filter in our analog LIA board, and the time-constant is set to about 2ms. So there will be some residual of high frequency signal leaked through after the integration, as shown in Fig.4. In addition, the 20 KHz peak can be explained as the sum frequency power of reference and residual DC signal after the DC-block. Apparently, equation (5) indicates that the amplitude of those signals of 10KHz and 30KHz are both proportional to $\boldsymbol{K_1}$, which indicates that they can be used to correct the light intensity. Because all those peaks come from 2f signal, there is no additional circuit or sample channel needed, so this method can be simply used in the WMS system without any structure change. Considering about larger amplitude of the 10 KHz peak, it is chosen to correct the fluctuating light intensity.

The experiment result of intensity correction is shown in Fig.5. The left figure shows normalized 2f signals at different light intensity, and the right one is the original 2f signals. Those figures show good result when the light intensity has been reduced to 200/1168=17%, which indicates large working range of the method.

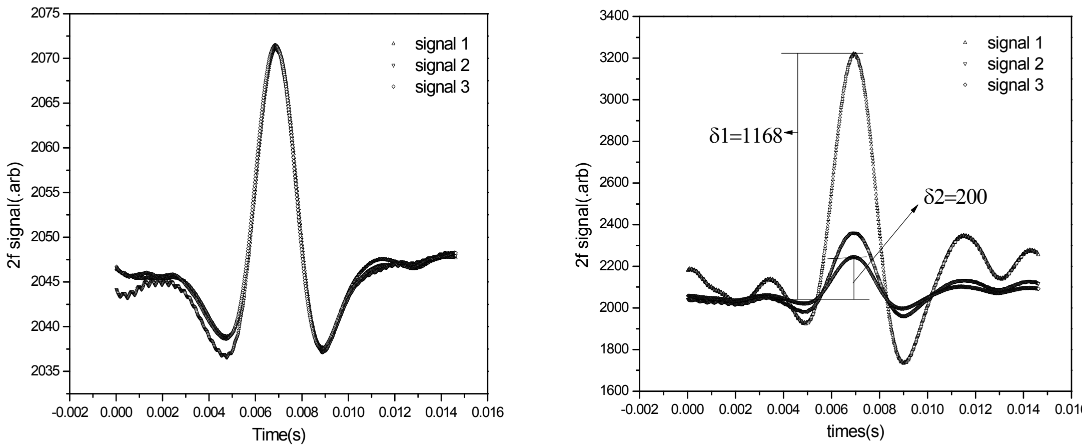

Fig.5. Result of the light intensity normalization of the 2f signal. The left figure shows normalized 2f signals at different light intensity and the right one is the original 2f signals.

3. EXPERIMENTAL RESULT ON LONG-TERM STABILITY AND DETECTION LIMIT

In order to check the long-term stability and short-term detection limit of the TDLAS system, Allan variance analysis is carried out and the experimental results are shown in Fig.6. In a balanced optical path scheme, measurement of CO concentration is taken for 8 hours. The left figure shows concentration results in the experiment, the data shows 20ppmv long-term concentration drifts. The Allan variance is shown in the right figure, the marked point shows the detection limit, which is about 0.3ppmv with 31 seconds integration time, it can also be considered as the ultimate limit of measurement when the response time is not required so strictly, and short-term detection limit is between 0.3ppmv and 1.5ppmv depending on the response time of the instrument allowed.

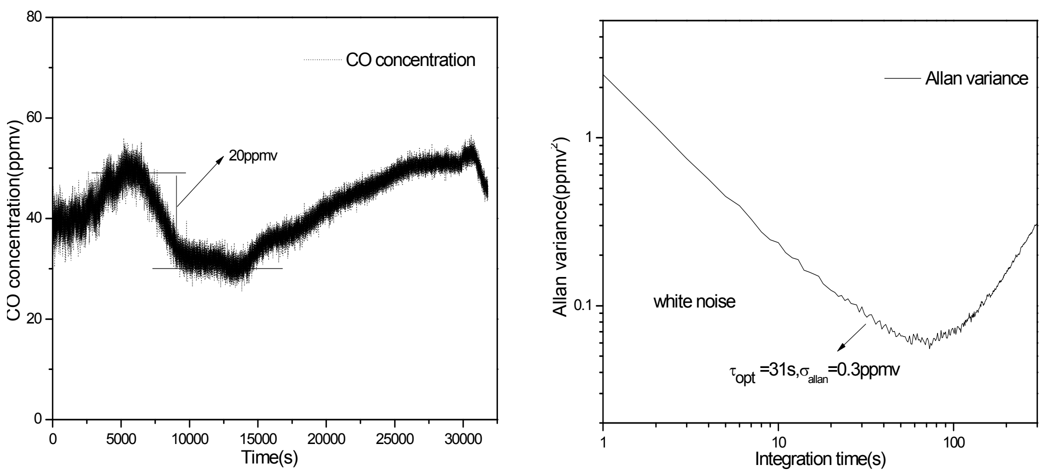

Fig.6. Comparison of long term measurement of CO concentration. The left figure shows the concentration and the right figure shows the Allan variance.

4. CONCLUSION

In order to reduce the measurement fluctuations and gain high reliability, the source of long-term distortion and the corresponding proposal are discussed in the paper, it is proved that the long-term distortion of this system is mainly induced by wavelength dependent transfer function change, and a balanced optical path can be used to reduce it effectively. A novel method for online correction of light intensity fluctuations is developed according to the linear relation between the peaks of harmonic power spectra and the incident light intensity. By using a 17.5m multi-pass cell, CO detection experiment shows that the system can achieve long-term stability of 20ppmv. The detection limit is about 0.3ppmv with 31 seconds integration time, and the short-term detection limit is between 0.3ppmv and 1.5ppmv with respect to the response time required.

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