

Research Progress of Optical H₂O Sensor With a DFB Diode Laser

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Abstract: In the field of near infrared H₂O sensing, the acquisition of the absorption signal usually is from a noisy background, thus it is important to adopt an effective signal demodulation method. This study introduced the research progress in the field of trace water vapor detection, covering different individual gas detection techniques. On the basis of the conventional double-beam differential absorption, the division method in voltage and the dual-peak method based on the differential value of two adjacent absorption lines have been studied. Voltage division has an excellent stability to temperature variation, mechanical extrusion, and fiber bend loss. The dual-peak method proved a linear relation with the water vapor concentration, and this method provided a way to measure the concentration at high pressure. Furthermore, the so called balanced ratiometer detection (BRD) was introduced. It has an outstanding self-adjusting capability, and it can also avoid an excess phase difference caused by the current-to-voltage converting circuit, thus this method has a high sensitivity. In addition, the second harmonic technique applied to gas detection was introduced, and for the high-frequency modulation via driving current, $1/f$ was suppressed apparently; as a result, this technique realized a better sensitive detection by one to two orders of magnitude.

Keywords: Water vapor, gas sensing, DFB diode laser, absorption spectrum

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1. Introduction

Water vapor monitoring is an important task in the high voltage electrical equipment, manufacturing plants, and environment sciences, etc [1]. Common methods usually are the gravimetric method, electrolytic process and dew-point measurement technique [2]. Compared with these methods, the detection based on optical and spectroscopic techniques is attracting more and more attention for fast and selective on-line measurement, especially, the tunable diode laser absorption spectroscopy

(TDLAS), in conjunction with wavelength modulation spectroscopy (WMS), has been developed into a very sensitive and general technique for monitoring trace species [3]. When using the optical measurement based on the absorption spectrum, one has to resolve small changes in a large background. For ppmv level trace water, the absorption is particularly weak; this needs a very effective method to extract the weak signal. In the following, the progress of optical gas sensing in our research group will be introduced to provide reference during the design of the optical gas sensor.

During the demodulation of the absorption signal, the subtraction in voltage has been one of the simplest signal extraction methods. But when compared with the division method, a slight change could cause a more obvious instability of the signal by subtraction. In this paper, a conventional division method in voltage and an approach based on the balanced ratiometer detection (BRD) are introduced. Furthermore, we introduce a new method named as “dual-peak” method, reported in [4], which is aimed at coping with the misreading of the reference value because of the noisy absorption line bottom and the affection of the linewidth broadening at high gas pressure, hence, this method provides a way to measure the concentration at high pressure. In addition, the second harmonic technique is introduced, for the purpose of high sensitive gas detection. Because of the high frequency modulation, the high signal to noise ratio can be obtained.

2. Basic principles

The fundamentals of the molecular absorption spectroscopy have been discussed widely elsewhere [5, 6]. According to the HITRAN2008 database, many gas species exhibit absorption in the ultraviolet (UV), visible, near infrared or mid infrared regions. It is shown in Fig. 1 in which absorption lines in near infrared are typically overtones of fundamental absorption lines in the mid infrared and hence can be significantly weaker. However, the availability of high quality of light sources and detectors, derived from the telecommunications applications, can compensate this disadvantage and reach a high sensitivity.

In the region of near infrared, water vapor has absorption lines at the wavelengths of 1368.579 nm and 1367.862 nm, and there is no absorption of background gases near these wavelengths which guarantees the measurement accuracy. During measuring by the single absorption line, 1368.597 nm

is usually selected for its stronger line strength. A distributed feed-back (DFB) diode laser (WSLS-137010C1424-20) operating at 1370 nm, with a linewidth of 3 MHz, is chosen as the light source. And the output wavelength is tuned by driving current modulation or temperature modulation, and the shifts of the wavelength are 3 pm when the change in the driving current is 1 mA and 90 pm when the change in the LD temperature is 1 °C, respectively.

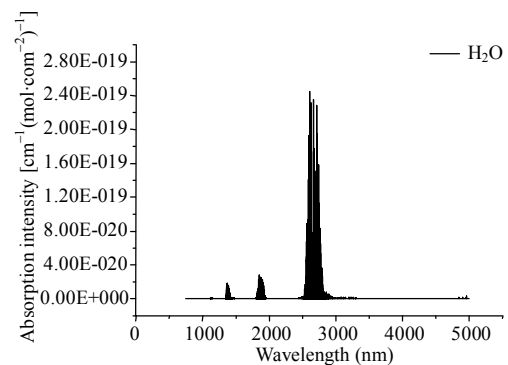


Fig. 1 Absorption spectra for H₂O, taken from HITRAN 2008.

Once the monochromatic radiation of the light source at frequency ν_0 (cm⁻¹) overlaps with a rotation/vibration transition of a gas, the absorption will happen, resulting in the attenuation of the light intensity. The absorption spectroscopy is governed by the Beer-Lambert law, which relates the transmitted intensity I_t to the incident intensity I_0 as

$$I = I_0 \exp(-\alpha CL) \quad (1)$$

where α is the absorption coefficient, C is the concentration of the target gas, L is the length of the absorption path, and I_0 is intensity of the incident light. In the situation of low absorption, $\alpha CL \ll 1$, there can be

$$I = I_0(1 - \alpha CL). \quad (2)$$

Then, the concentration of the gas C can be got by measuring the information corresponding to I or I_0 , or both of them. The detection techniques are most important during the demodulation of concentration C . To provide reference during the design of the gas sensor, different techniques will be introduced in the next section.

3. Introduction of detection techniques

3.1 Division in voltage

Division and subtraction are the most common methods to extract the differential signal. According to (2), division could completely eliminate the influences of the common-mode noise in theory, such as laser power drift, temperature variation, extrusion on optical components, and fiber bend loss before splitting. The division process is shown in Fig. 2. The signal beam transferred through the target gas cell and then was coupled onto an InGaAs photodiode (PD). The reference beam was directly coupled to an identical PD. After the current-to-voltage conversion and amplification, the signals were delivered to a divider to get the ratio of I to I_0 . Processed by the essential circuits above, the final signal was detected to figure out the target gas concentration as the follows:

$$C = \frac{1}{\alpha L} \left(1 - \frac{I}{I_0} \right). \tag{3}$$

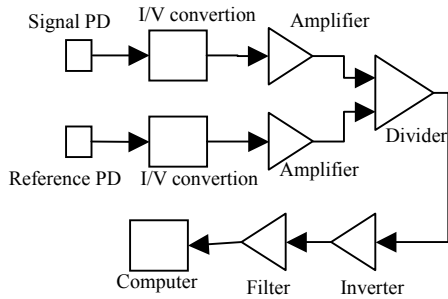


Fig. 2 Schematic diagram of the division method.

Bending loss, mechanical extrusion, and ambient temperature would add differential mode interference to the signal and reference laser beams. In this case, the division performs an excellent stability. Actually, the extrusion and temperature influences are the loss caused by components, thus, all the influences can be roughly regarded as components loss. Taking the fiber for example, the random loss of 0.08 dB was applied to the signal beam channel, and the simulation result is given in Fig. 3. For the division method, the deviation was only 1.36%, which outperformed the BRD method,

3.60%. This indicated that division is more stable.

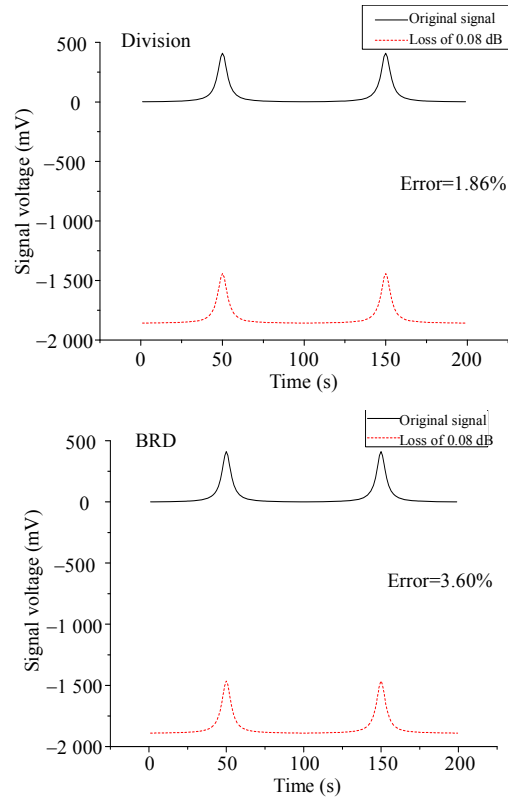


Fig. 3 Suppression to differential mode interference.

3.2 Detection based on dual adjacent absorption lines

In direct absorption spectroscopy measurement, generally, the single absorption line is adopted. To calculate the concentration, we should measure the absolute value of the absorption line. As shown in Fig. 4, the existence of the random noise and interferometric noise [7] increases the difficulty and uncertainty of selecting the reference point. Recently, a solution was proposed in [4], using another appropriate absorption peak as the reference point.

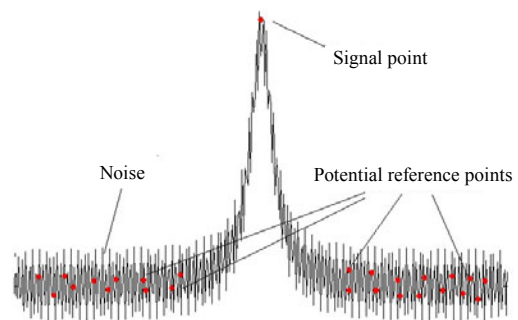


Fig. 4 Schematic diagram of single absorption line, taken from [4].

The experiment has verified that this so-called dual-peak measurement method based on the differential value of two adjacent absorption lines is practical and highly accurate. In the measurement experiment, the temperature modulation was used to tune the DFB diode laser, and the emission wavelength range overlapped the two adjacent absorption lines of water vapor at 1367.862 nm and 1368.597 nm, respectively. The experimental setup was the same as that of the division method introduced in Section 3.1. Figure 5 presents the measuring result. The concentration varied from 100 ppmv to 1200 ppmv. Curve A indicates that there is a well linear relation between the concentration and the measured signal. Curve B shows the measurement error. This error was within 20 ppmv. Meanwhile, the resolution could reach to 10 ppmv when the concentration of water vapor was not higher than 1200 ppmv [4].

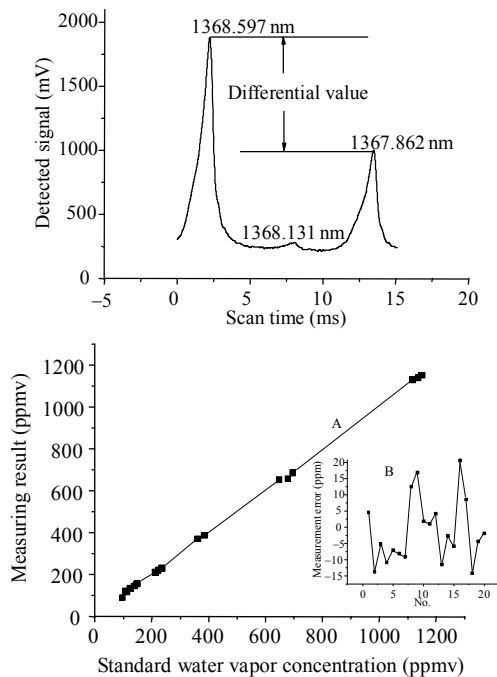
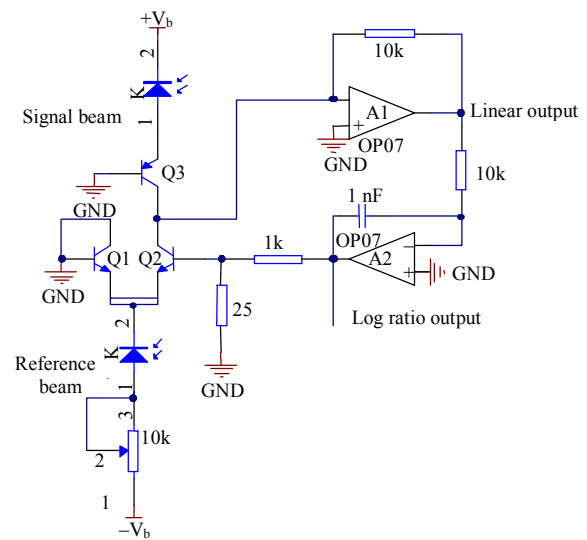
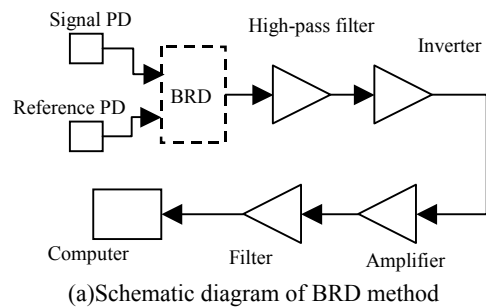


Fig. 5 Measurement result of the water vapor concentration based on the dual-peak method.

In addition, this method provides a feasible way to detect the gas concentration under a high pressure as long as the wavelength tuning range could overlap two appropriate absorption lines of the target gas.

3.3 High sensitive detection using BRD

The BRD is an electric noise cancellation technique, initially innovated by Hobbs [9] based on the Ebers-Moll model. The detailed circuit of the BRD is given in Fig. 6(b). The reference photocurrent was split into two parts across through a differential pair of bipolar junction transistors (BJTs), used as a variable current divider. The split ratio of the reference photocurrent only depended on the difference $\Delta V_{be} = V_{be2} - V_{be1}$, which was independent of the amplitude of the reference photocurrent. Simultaneously, the signal photocurrent was subtracted by the current across Q_2 at the invert junction of the amplifier A1. The output of A1 reflected current subtraction after the feedback resistor. With the integrating amplifier A2, a negative feedback loop was formed to adjust ΔV_{be} automatically by sensing A1's output. Then, A1's output could be forced to be zero, this ensured that



(b) Detailed circuit of BRD, taken from [8]

Fig. 6 Schematic diagram of the BRD method and its detailed circuit.

the signal and divided reference photocurrents were equal, and thus the noise was eliminated identically. The log ratio output, shown in Fig. 6(b) is given in the following equation [8, 9]:

$$V = -\ln\left(\frac{I_{\text{ref}}}{I_{\text{sig}}} - 1\right) \quad (4)$$

where V should be in Volts, and I_{ref} and I_{sig} refer to photocurrents derived from the reference beam and signal beam, respectively. In this method, normalization is processed in current instead of voltage, which fundamentally avoids an excess phase difference caused by the current-to-voltage converting circuit, mainly because of the difference in amplifiers. Figure 7 shows a research test. The demodulated water vapor concentration was well proportional to the water vapor concentration ranging from 56 ppmv to 809 ppmv. The proportional relationship was described by a linear equation with an R-square of 0.99983. This technique can reach to ppbv level; the minimum concentration for water vapor at 1368.597 nm that could be detected by the system has been proven to be 71.8 ppbv with just a 10-cm path length based on the BRD method [8].

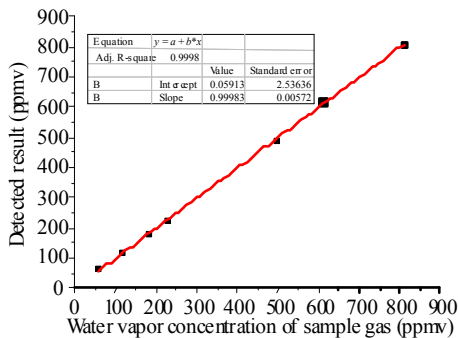
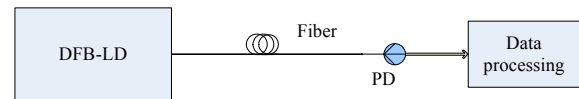


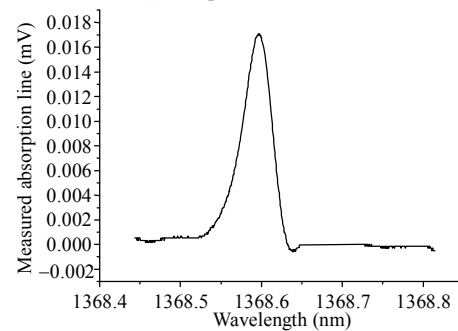
Fig. 7 Measurement result of water vapor concentration based on BRD.

It is important to point out that the intercept in Fig. 7 is small, approximately zero. It is because this experiment was carried out at the situation of two matched PDs. As shown in Fig. 8, the light from the DFB diode laser with an emission wavelength of 1370 nm directly was coupled on a PD. After data processing, the differential signal was obtained, and the absorption line was measured to be 1368.597 nm.

There existed water vapor inside some optical components of the optical fiber gas sensor, which has been proven in [10]. During the above experiment, the water vapor inside the DFB diode laser has been eliminated by applying the differential processing (BRD technique), and the water vapor inside the two PDs has been suppressed by matching processing. Besides the water vapor, other gases like N₂, O₂, and CO₂ potentially existing in the components, based on our research, have to be taken into consideration during the design of the corresponding high sensitive and high precision gas sensing system.



(a) Simple schematic



(b) Detected absorption spectrum

Fig. 8 Observation of water vapor inside the DFB diode laser and PD at 1368.597 nm, taken from [10].

3.4 High sensitive detection based on the second harmonic signal

Compared to the direct detection mentioned above, the harmonic signal technique enables the alternating current (AC) detection at some frequency chosen and the use of a lock-in amplifier for the better signal recovery. The chosen modulation and detected signal frequency is sufficiently high to eliminate laser and $1/f$ noise. Besides, the lock-in amplifier allows the narrower signal bandwidth and, hence, noise is minimized. As a result, the technique is more sensitive by one to two orders of magnitude relative to the direct detection.

A general schematic that introduces this detection technique based on harmonic signals is

shown in Fig. 9. In the design of the detection system, a low-frequency, the 4-Hz sawtooth current combined with a high-frequency, 1k-Hz sinusoidal current was applied to drive the DFB diode laser. With the dither over absorption features and wavelength scan by the sawtooth current, the second harmonic signal profile could be recovered by a lock-in amplifier at the receiver. The detected result is shown in Fig. 10.

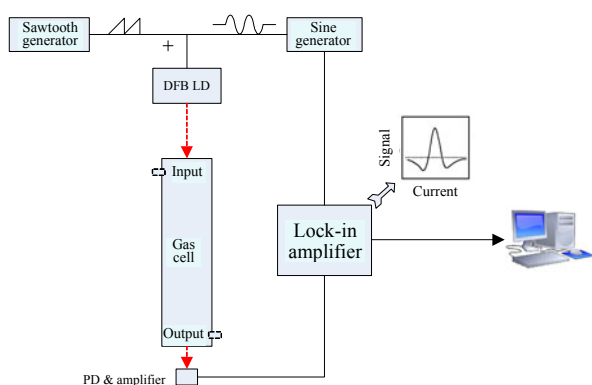


Fig. 9 Schematic for the harmonic detection technique for gas measurement.

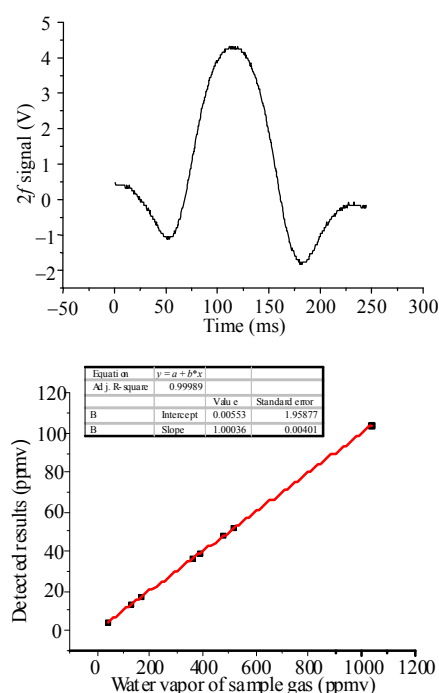


Fig. 10 Measurement result of the water vapor concentration based on the second harmonic signal.

In general, this method confers one apparent advantage: improved detection sensitivity resulting from a decrease in $1/f$ noise because of high

frequency sinusoidal modulation and from the narrow bandwidth of the lock-in amplifier.

4. Conclusions

In this paper, the progress of the DFB diode laser based water vapor sensor is reported, and different techniques used for gas sensing are introduced above. Division in voltage has a more excellent stability than BRD in suppressing ambient temperature variation, mechanical extrusion, and fiber bend loss, while the BRD outperforms in self-adjusting capability by using a differential pair of BJTs as a variable current divider, this method performs well in term of sensitivity. As to the dual-peak method, it provides a method for accuracy improvement and a feasible way to high pressure condition. In addition, a technique based on the harmonic signal is introduced. The detection sensitivity has been further improved for the high-frequency modulation via the driving current and narrow bandwidth of the lock-in amplifier.

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