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Modified balanced ratio metric detection system used for high sensitive vapor detection

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ABSTRACT

A modified balanced ratio metric detection (BRD) system was proposed and applied in trace measurement of water vapor. Three features, including proportion of alternating current (AC) and direct current (DC) signals, environment temperature and light intensity ratio have been stated. Their influences on measured result have been analyzed. Meanwhile, techniques including adding filter, using integrated transistor and light intensity ratio adjustment and their effects for measurement improvement have been discussed. The absorption line was chosen at 1368.597 nm and the path length was 10 cm. With application of the above techniques, an accuracy of 5 ppm for water vapor concentration has been achieved.

1. Introduction

Trace measurement of gas is very important in many fields [1]. With the tunable diode laser and signal average method, rapid wavelength changing and high signal-to-noise ratio (SNR) could be realized [2]. So, tunable diode laser absorption spectroscopy (TDLAS) has been widely utilized in detection of gas-phase trace impurities [3,4].

Dual-beam differential absorption, which applies in TDLAS, is commonly utilized in absorption type gas sensor to eliminate external influence [5]. Subtraction and division are common signal processing methods [6]. In a subtractive structure, only when range of signal current and reference current are equal, signal reserves without noise and DC. But the intensity of beam (especially signal beam) varies frequently and common-mode current could not be eliminated all the time because of rigorous adjustment requirement. In addition, signal current and reference current, which are uncorrelated, both contribute to the noise level. Thus the system noise is higher than the noise of the signal beam only.

Division method attracts much attention since it avoids the rigorous adjustment requirement. Division provides compensation for drift and excess noise by dividing out the instantaneous intensity, and it solves the 3 dB additional noise problem of subtraction by making the reference beam stronger than the signal beam [7].

Technique has been developed for the high-sensitivity measurement of water vapor. Balanced ratio metric detection (BRD) system has been utilized to eliminate the common-mode signal and noise. When the original BRD was used for gas sensing, there were many problems such as wave distortion, output instability and poor accuracy. Later, some modified BRD [8] was applied and performance was improved. However, instability still existed and there was promotion space. So we came up with this paper for these problems.

2. Detection theory and experimental system

BRD is an all-electronic scheme which aims to cancel excess noise [7]. The measurement for iodine vapor has been achieved by Haller and Hobbs [5]. Then it has been developed by Mohebati et al. [4]. In this paper, a water-vapor concentration measurement based on near-infrared absorption spectrum is discussed.

BRD system [7] is a fully functional version of the feedback noise canceller. The output is given by the following equation,

$$V = \frac{\kappa T}{q} ln\left(\frac{I_{\text{reference}}}{I_{\text{signal}}} - 1\right) \quad (1)$$

where V is the output voltage, q is the electron charge, T is absolute temperature, k is Boltzmann's constant and $I_{\text{reference}}$ and I_{signal} are currents derived from a reference beam and a signal beam, respectively.

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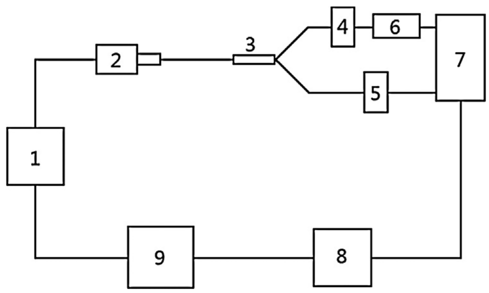


Fig. 1. Schematic of whole experiment apparatus used in our work. (1) Temperature and current controller, (2) tunable diode laser, (3) coupler, (4) fiber of signal beam, (5) fiber of reference beam, (6) gas cell, (7) BRD system, (8) amplifier and filter, (9) data acquisition and processing.

Using the Beer–Lambert law, which states that the transmission of monochromatic light through a gas with a vapor concentration of an absorbing species, C, in the vicinity of a transition with an integrated line strength of $S(T)$, can be written as $\exp[-S(T)g(\nu)pLC]$, where $g(\nu)$ is the line shape function, ν is the frequency of the light, p is the atmospheric pressure, L is the length of the gas medium, and C is the mole fraction of the absorbing species in the gas, the relationship between the signal, V, from the BRD system and the water vapor concentration, C, can be expressed as:

$$V = \frac{kT}{q}\ln[(e^{V_0 q/kT}+1)e^{S(T)g(\nu)pLC}-1] \qquad (2)$$

where V_0 is the output of the BRD system in the absence of absorber.

For low concentrations, i.e. for cases when $S(T)g(\nu)pLC \ll 1$, the expression above can be series expanded yielding,

$$V = V_0 + S(T)g(\nu)pLC\cdot\frac{kT}{q}(1-e^{-V_0 q/kT}) \qquad (3)$$

which shows that the signal is linearly dependent on the concentration of analyte.

The initial system uses a ladder-shaped current, which drives the laser and makes wavelength cover the gas absorption peak [8]. The schematic of experiment apparatus is shown in Fig. 1. Ideally, the absorption peak of water vapor will be obtained without any other noise. We detect the bottom and peak point to get the absorption intensity. Concentration of water vapor could be obtained through calibration and linear approximation. However, waveform distortion happens in practice. Besides, the change of environment temperature and light intensity ratio would also affect system measured results. And these features will be discussed.

2.1. Proportion of AC and DC signals

BRD is initially proposed to extract differential-mode signal and eliminate the common-mode signal and noise. However, even through calculation, BRD system could not eliminate common-mode signal all the time.

In BRD system, reference-beam intensity should be larger than the signal beam. But there is no definite requirement for their ratio. The currents derived from reference beam can be described as:

$$I_{\text{reference}} = A + B\cdot f(t) \qquad (4)$$

where B is the intensity of AC, and $f(t)$ is the normalized function of AC signal. The waveform of $f(t)$ is the same as ladder-shaped drive current. The output voltage switched from photoelectric detector (PD) current is shown by Fig. 2. The currents derived from signal beam can be described as

$$I_{\text{signal}} = C + D\cdot g(t) \qquad (5)$$

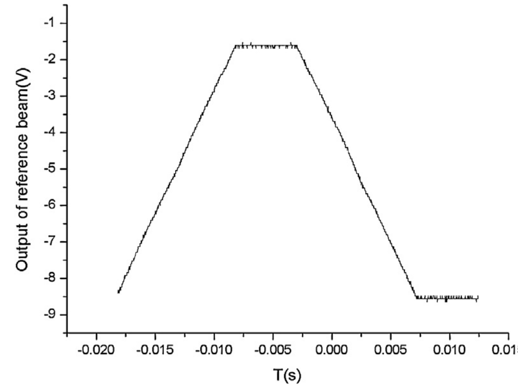


Fig. 2. Output of reference beam.

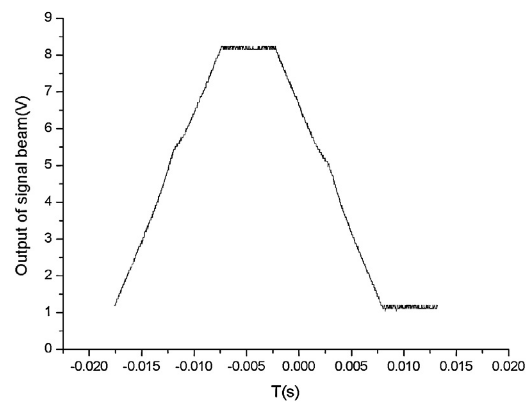
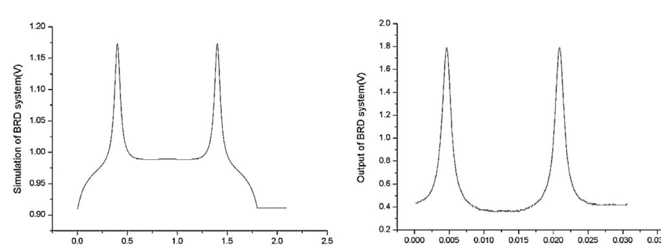


Fig. 3. Output of signal beam.

where C is intensity of DC and D is intensity of AC. As the signal beam is absorbed by water in the gas cell, the function $g(t)$ has not only the ladder-shaped part but also the water absorption line part, which is shown in Fig. 3. Owing to the randomicity of $I_{\text{reference}}$ and I_{signal}, the ratio of A and C is likely different from that of B and D. Through calculation and simulation, we can find other low-frequency noise except the absorption peaks. Fig. 4 shows the calculated and measured results respectively. Fig. 5 shows the relationship between measured results and the calibration of the trace water meter when there is low-frequency noise. In this situation, it is difficult to find the real bottom. As a result, measurement error of absorption intensity will increase and the accuracy of BRD system will be deteriorated. In other words, linearity of system would get worse when the condition, which is the ratio of A and C is equals the ratio of B and D, is not met. In order to overcome this problem, variable resistor or frequency selection is used. Low frequency noise would be eliminated and the real bottom would be detected more easily as shown in Fig. 6.



(a) Simulation result (b) Measured result

Fig. 4. Output of BRD system affected by the generation of low-frequency signal by simulation and measurement, respectively.