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Single-beam water vapor detection system with automatic photoelectric conversion gain control

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ABSTRACT

A single-beam optical sensor system with automatic photoelectric conversion gain control is proposed for doing high reliability water vapor detection under relatively rough environmental conditions. Comparing to a dual-beam system, it can distinguish the finer photocurrent variations caused by the optical power drift and provide timely compensation by automatically adjusting the photoelectric conversion gain. This system can be rarely affected by the optical power drift caused by fluctuating ambient temperature or variation of fiber bending loss. The deviation of the single-beam system is below 1.11% when photocurrent decays due to fiber bending loss for bending radius of 5 mm, which is obviously lower than the dual-beam system (8.82%). We also demonstrate the long-term stability of the single-beam system by monitoring a 660 ppm by volume (ppmv) water vapor sample continuously for 24 h. The maximum deviation of the measured concentration during the whole testing period does not exceed 10 ppmv. Experiments have shown that the new system features better reliability and is more apt for remote sensing application which is often subject to light transmission loss.

1. Introduction

A direct absorption spectroscopy (DAS) technique is the simplest laser-based spectroscopic technique for trace gas detection [1–3], which has many advantages, such as excellent insulation property, high sensitivity, wide range, long operating life, and short response time. In DAS, a beam of a tunable laser is sent through the gas chamber to carry gas concentration information and then it is measured with a photo diode (PD). The transmitted intensity will be reduced due to the gas absorption when the frequency of the light is close to an atomic or molecular transition. The concentration of the absorbing gas can be determined by the relative change of the intensity according to Lambert–Beer's law. However, laser amplitude modulation always accompanies with the laser frequency modulation, which results in a strongly sloping background with the absorption signal. To eliminate the background baseline, dual-beam differential optical structure is usually used. The output of the laser is split into two beams (namely reference beam and probe beam). The probe beam is sent through the gas sample and coupled on a photo diode (PD). The reference beam is directly coupled on the other PD. The two optical signals are transformed into the photocurrent signals by PDs and then sent to the differential demodulation circuit. Absorption peak without background baseline can be obtained after amplifying the difference between the two signals.

In the past decades, three all-electronic differential demodulation methods have been common, namely subtraction, division and balanced ratiometric detection (BRD) [4,5]. Especially, BRD is the most common method due to its simplicity and low noise [6,7]. With an electronic balancing technique, a high common-mode laser amplitude noise rejection ratio can be achieved. The final result of the BRD system is immune to power drift of the light source due to the normalization process. However, practical problems with the divider signal arise from the fact that the reference beam and probe beam have to be balanced perfectly. Transmission loss can be determined by many factors, such as the insertion loss of collimator, fiber bending loss and the splitting ratio of the coupler [8–11]. All these factors may destroy the balance between the two beams. In the previous study [12], the variation of background transmission intensity (the probe beam and the reference beam) at different ambient temperatures (and fiber bending loss) has been quantitatively obtained. The experimental results have shown that the transmission loss of two beams can be both changed when ambient temperature or stress changes. And there is a significant difference in the amount of the two changes, which will give an absorbance signal with the baseline tilted. The resulting waveform distortion affects the measuring results seriously [5]. This effect cannot be eliminated through the normalization which can be only worked on

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the common mode power drift between the two beams. In multipoint remote sensing applications, fiber transmission distance is usually very long. Measurement results are often subject to light transmission loss due to external stress. Transmission losses of each monitoring point are not synchronized. This is always the main factor which may deteriorate the sensing system reliability rather than the high frequency noise. Unfortunately, pertaining solutions are rarely brought out. Most current research interests are focused on improving the detection sensitivity.

A single-beam detection system is proposed to solve the above problems. It should be noted that the system is designed to use some industrial applications in which detection sensitivity requirements are relatively low. To overcome the problem that the reference beam is instable in the dual-beam system, designing a high stable reference channel for the difference absorption spectrum is essential. There is now a general consensus that electrical signals emitted by the integrated circuit (IC) perform better reliability than optical signals, because a high common-mode rejection ratio (usually higher than 100 dB) in differential amplifiers of IC could be easily designed [2]. In Fig. 1 we show the deflections of saw-tooth voltage waveform generated by ARM (LTC1758, NXP, Netherlands) that occurs when the surrounding temperature is changed. When the ambient temperature is increased by 10.2 K, the output-signal with a peak-to-peak amplitude fluctuation is below 0.9% (0.452–0.448 V). Compared with the reference beam change of 2.1% in its intensity for one-degree change in temperature [12], the electrical signal is more suitable to serve as a reference. In the single-beam detection system, the photocurrent signal from the reference light path is substituted by a voltage signal. To maintain synchronization with the optical signal of the probe beam, the voltage signal is simultaneously employed to modulate the laser wavelength. In addition, an automatic photoelectric conversion gain control technique is designed with a digital potentiometer to stabilize the differential probe input signal which is converted from the probe beam and carries the water vapor absorption information. Digital potentiometer is used to adjust photoelectric conversion gain continuously according to the change of the transmission loss of the probe beam. The majority of the photocurrent attenuation caused by the optical loss can be effectively compensated by automatically adjusting the photoelectric conversion gain. The amplitudes of the two differential input signals are allowed to vary within a small range, which would barely influence the final results. The reliability of the water vapor detection can be effectively improved.

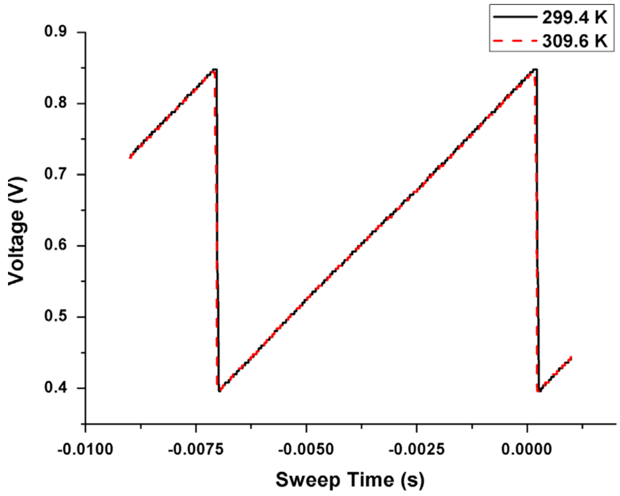

Fig. 1. Thermal reliability of the saw-tooth voltage waveform generated from ARM. The saw-tooth voltage waveform at 299.4 K is shown as the solid line. And the waveform at 309.6 K is provided as the dash line for comparison.

2. Theory

2.1. Beer–Lambert law

The TDLAS technique is based on the absorption of monochromatic near-IR radiation. The transmission of a probe beam through a uniform absorbing medium follows the Beer–Lambert law.

$$I = I_0 \exp(-\beta(\nu)CL) \tag{1}$$

where $\beta(\nu)$ represents the absorption coefficient; C is the concentration of gas to be measured; L is the length of the absorption path. The concentration C could be obtained by identifying the emergent light intensity I and the incident light intensity I_0.

$$\beta(\nu) = 0.101325 \times S(T)g(\nu)P/kT \tag{2}$$

where k (J K^{-1}) is Boltzmann's constant. $S(T)$ (cm mol^{-1}) is the line strength at an arbitrary temperature, which could be found in HITRAN 2008 [13]; the line shape function $g(\nu)$ (cm) is determined by the physical mechanisms that perturb the energy levels of the transition or the way in which the absorbing molecules interact with the laser beam [14]. When $\beta(\nu)CL$ is much less than 1, there is

$$\exp(-\beta(\nu)CL) \approx 1 - \beta(\nu)CL \tag{3}$$

$$C \approx (I_0 - I)/(I_0\beta(\nu)L) \tag{4}$$

where I_0 is constant,

$$C \propto I_0 - I \tag{5}$$

In the single-beam detection system, I is the intensity of the probe beam, the reference electrical signal is served as I_0. The light intensity is converted into a voltage signal to be demodulated by the demodulation circuit.

2.2. Single-beam detection system

A block diagram of the single-beam water vapor detection experimental system with automatic photoelectric conversion gain control is shown in Fig. 2. The system uses a distributed feedback laser diode (DFB-LD), emitting at ~1368 nm. A temperature control circuit is used to control the DFB-LD operating at a fixed temperature. A saw-tooth voltage waveform generated by ARM is divided into two channels. One is converted into current and thereby provides a suitable driving current for the DFB-LD to realize a wavelength scanning. An optical power modulation, known as residual amplitude modulation (RAM), is always companied with the wavelength modulation by the injection current [15]. The power modulation will lead to an absorbance signal with baseline titled in the direct absorption spectrum. The other channel is amplified by the amplifier A1 and connected to the non-inverting input of the differential amplifier to serve as the differential reference input. The beam emitted from the DFB-LD passes through the gas cell to carry water vapor concentration information and then it is received by the photoelectric converter with automatic gain control.

2.3. Automatic photoelectric conversion gain control

The schematic diagram of the photoelectric converter is shown in dashed box at the bottom of Fig. 2. The output of the photoelectric converter V_{out} can be described by Eq. (6), which is served as the differential probe input after the inverter.

$$V_{out} = I_{pho} \times R_{gain} \tag{6}$$

where R_{gain} is the effective resistance of the digital potentiometer, which is controlled by ARM via serial peripheral interface (SPI).