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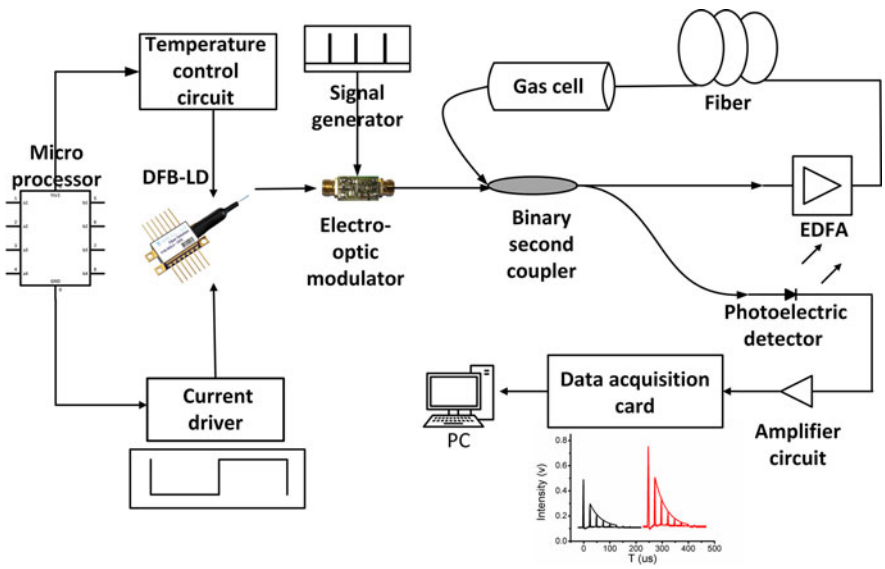

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A Method for Real-Time Monitoring of Inherent System Loss Designed for FLRDS-Based Gas Sensors

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Abstract: An important factor restricting the development of fiber loop ring-down spectroscopy (FLRDS) is that real-time continuous monitoring of the inherent system loss is inconvenient and time-consuming. However, the inherent system loss will vary across environments. To ensure measurement accuracy, real-time monitoring is essential. This paper proposes a method for real-time monitoring of the inherent system loss to improve the accuracy of FLRDS-based gas sensors. A precise dual-wavelength tuning of the laser diode can be achieved by changing the injection current, in which the emission wavelength outside the absorption region can be used to acquire the inherent system loss value fast and conveniently. The advantage of this method has been verified by testing the acetylene concentration of a calibration gas with 1% acetylene. The average measurement error can be decreased from 1.393% to 0.037% through detection and correction the inherent system loss.

Index Terms: Fiber loop ring-down spectroscopy (FLRDS), gas sensors, inherent system loss, dual-wavelength tuning.

1. Introduction

One of the most important actual problems in the gas detection field is that there are strong demands for environmentally hazardous gas detection to prevent explosions or poisoning accidents [1]–[3]. Fiber optic sensors have been playing an increasingly important role in the gas sensing community due to their attractive application features, such as low cost, small footprint, light weight, immunity to electromagnetic interference, and ability to cover long distances and effective multiplexing capability [4]–[7].

Over the last several years, a new kind of fiber optic sensing technique known as fiber loop ring-down spectroscopy (FLRDS) has been developed for gas and other physical quantities sensing [8]–[12]. The FLRDS technique is fundamentally evolved from the well-known cavity ringdown spectroscopy (CRDS) technique [13], [14]. It not only inherits the multi-pass feature from CRDS to obtain a high sensitivity, but also solves the problem in high reflectivity mirror design by using an optical fiber coupler instead of the resonator structure. Therefore, it has good promotion prospects for trace gas detection.

However, an important factor restricting the development of FLRDS is that real-time continuous monitoring of the inherent system loss (broadband optical loss in the loop) is inconvenient and time-consuming [15], [16]. The traditional way to obtain the inherent system loss is to purge the gas cell with a zero gas which is a purge gas distinguished the test-gas (e.g. Nitrogen). Meanwhile, gas absorption losses can be ignored because the concentration of the gas to be measured is reduced to insignificance. In this case, the inherent system loss can be derived from the 1/e ring-down time of the output pulse train. This way is not only a waste of resources and time, but also may interrupt a long-term continuous gas monitoring. Unfortunately, the inherent system loss is sensitive to the surrounding environment and may always vary across environments [17], [18]. The time-varying property can result in a terrible measurement error without monitoring and calibration.

2. Theory

2.1. Infrared Absorption Spectrum Theory

When the light emitted from light source covers a wavelength range of one or more gas absorption line, the transmitted intensity $I(\nu)$ after passed through a uniform absorbing medium follows the law of Beer-Lambert:

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

where $\beta(\nu)\,(\mathrm{cm}^{-1})$ represents the absorption coefficient at the light wave number $\nu\,(\mathrm{cm}^{-1})$, C is the target gas concentration, and L (cm) is the length of the absorption path. The concentration C can be obtained by identifying the emergent light intensity $I(\nu)$ and the incident light intensity $I_0(\nu)$

$$C = \frac{1}{\beta(\nu)L}\ln\left(\frac{I_0(\nu)}{I(\nu)}\right). \tag{2}$$

Once the target gas and the gas cell structure have been identified, the gas absorption coefficient $\beta(\nu)$ and the length of the gas chamber L can be seen as known quantities. $\beta(\nu)$ can be solved using the following formula:

$$\beta(\nu) = 1013250 \times S(T)g(\nu)P/kT \tag{3}$$

where $k = 1.38054 \times 10^{-16}$ $(\mathrm{erg}\cdot\mathrm{K}^{-1})$ is the Boltzmann constant, P (atm) is the total pressure, $S(T)$ (cm/mol) is the line strength at an arbitrary temperature T (K), and $g(\nu)$ (cm) is the line shape function. The line shape function $g(\nu)$ 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. The broadening effect can be described by a Lorentz profile at atmospheric pressure

$$g(\nu) = \frac{1}{2\pi}\frac{\Delta\nu_c}{(\nu-\nu_0)^2 + \left(\frac{\Delta\nu_c}{2}\right)^2} \tag{4}$$

where $\Delta\nu_c\,(\mathrm{cm}^{-1})$ is the full width at half-maximum, and $\nu_0\,(\mathrm{cm}^{-1})$ is the line-center frequency of the transition [19].

2.2. FLRDS Theroy

A FLRDS system can be employed to obtain the ratio between the incident light intensity $I_0(\nu)$ and the emergent light intensity $I(\nu)$ to derive the concentration C further. The schematic diagram of the measurement principle of FLRDS [20] has been shown in Fig. 1. A single-mode distributed feedback laser diode (DFB-LD) with an emission at a gas absorption wavelength is utilized to emit a temporally narrow incident pulse. The input pulses propagate in an optical fiber loop constructed of single-mode fibers, an erbium-doped fiber amplifier (EDFA), optical fiber couplers, and a gas cell. In FLRDS system, input optical pulses are launched into and circulated in the fiber loop many times. A decaying pulse train can be output and gathered by an acquisition system, which can be applied to the derivation of the gas concentration.

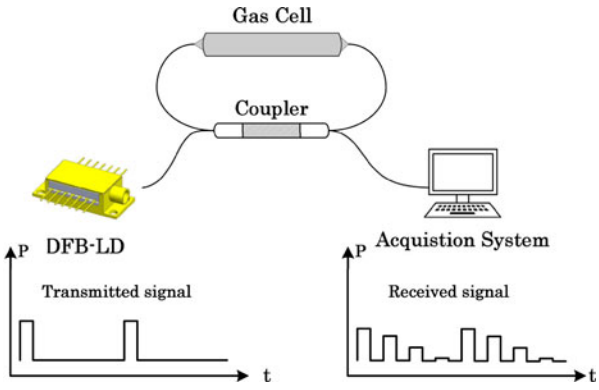

Fig. 1. Schematic diagram of the measurement principle of FLRDS.

The 1/e ring-down time t_e of the output pulse train, which is related to the attenuations of the fiber loop, can be determined directly by exponential fitting algorithms. t_e satisfies the relationship

$$\frac{t_e}{T} = 10\frac{\lg e}{\Gamma} \tag{5}$$

where T represents the round-trip time of the optical pulse signal, and Γ represents the total loss which includes the gas absorption loss α_{gas} and the inherent system loss Γ_0 (a general term for the fiber transmission loss, the coupling loss and the alignment loss), which can be expressed as

$$\Gamma = \alpha_{gas} + \Gamma_0. \tag{6}$$

The gas absorption loss can be defined as

$$\alpha_{gas} = 10\log\left(\frac{I_0(\nu)}{I(\nu)}\right). \tag{7}$$

If the inherent system loss Γ_0 has been known, the concentration can be caculated using (2) and (7).

2.3 Method for Real-Time Monitoring of Inherent System Loss

The traditional way to obtain the inherent system loss Γ_0 is to blow the zero gas (e.g. Nitrogen) into the gas cell. When the concentration of the gas to be measured is reduced to insignificant, the gas absorption loss can be ignored. In this case, the inherent system loss can be derived from the 1/e ring-down time t_e of the output pulse train. It is doomed to be lack of real-time features due to the tedious operation. However, a real-time monitoring of the inherent system loss is exactly essential because the physical quantity will always change due to the fiber mechanical deformation, the thermal expansion or other factors. In view of this situation, a method for real-time monitoring of the inherent system loss is proposed. The main idea of the method is described as follows: A tunable laser is made to emit beams with two wavelengths of λ_1 and λ_2 by changing the injection current. One (λ_1) is the wavelength of maximum absorption. The other one (λ_2) is not within the range of absorption lines. The loss $\Gamma_{\lambda 1}$ measured by the output pulse train with a wavelength of λ_1 is a sum of the gas absorption loss α_{gas} and the inherent system loss Γ_0. The loss $\Gamma_{\lambda 2}$ measured by the output pulse train with a wavelength of λ_2 includes only the inherent system loss. If the two wavelengths are very close to each other, the difference between the loss $\Gamma_{\lambda 2}$ and the loss Γ_0 can be neglected. The gas absorption loss can be defined as

$$\alpha_{gas} = \Gamma_{\lambda 1} - \Gamma_{\lambda 2} \tag{8}$$

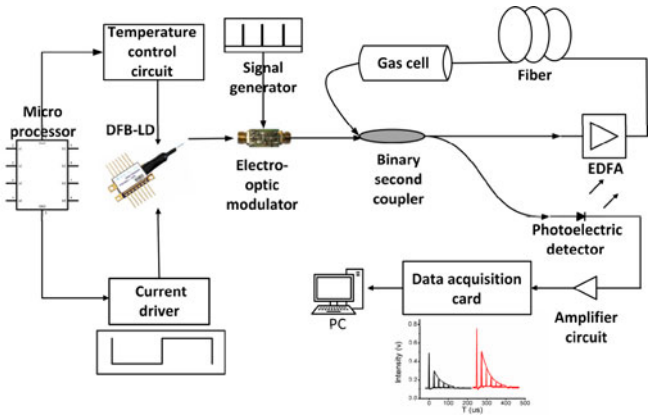

Fig. 2. Schematic diagram of experimental setup for the real-time monitoring method of inherent system loss.

To sum up, adjusting the laser emission wavelength to an appropriate value will be able to get the inherent system loss quickly and easily. The system loss term can be monitored in real-time by using the method to reduce measurement errors.

3. Experiments

As shown in Fig. 2, an experimental platform is set up for acetylene detection to verify the feasibility of the method. A single-mode DFB-LD is used as the light source, in which the output wavelength is modulated by adjusting the laser temperature and the injection current. Laser temperature is fixed to 34.6 degrees Celsius by a micro-temperature controlling chip (LTC1923, Linear Technology, USA). After wavelength calibration, the drive current of λ_1 (1532.83 nm, this is the wavelength of maximum absorption for acetylene) and λ_2 (1532.95 nm, this is not within the range of absorption lines for acetylene) are identified as 51.5 mA and 90.0 mA. And 1532.83 nm is the absorption peak wavelength of acetylene gas. The maximum wavelength drift is less than 3 pm in 24 h. The DFB-LD is connected to a fiber loop system through an electro-optic modulator, as shown in Fig. 2. A square wave current signal with minimum value of 51.5 mA, maximum value of 90.0 mA, duty cycle of 50%, and repetition rate of 1 Hz is used to drive the DFB-LD to realize an alternate wavelength switching. A regular train of voltage pulses with peak value of 3 V, duration of 250 μs, and repetition rate of 4 kHz is utilized to drive the DFB-LD generating light pulses. The round-trip time of the light pulse is 25 μs for a 5 km length of fiber in the loop. Therefore, pulses superposition phenomenon will not be occurred. The light pulses passed through a gas cell consist of a stainless-steel tube. The gas cell is filled with 1% acetylene in which the absorption path is 4 cm. A good air seal structure ensures that we do not need to consider the measurement errors caused by an unstable air concentration. A gain flatness EDFA with embedded automatic gain control (AGC) module is used to compensate for the power loss of the laser in the fiber loop, which will increase the cavity round-trips. The gain variation for signal input level can be decreased significantly by the AGC. In addition, the peak intensities of the ring-down optical signals after amplified by EDFA are still less than 500 μw except the first pulse (the first pulse of the output pulse train does not pass through the gas chamber as it is coupled out directly, and therefore, it gives no information about the gas concentration). The output signal power level is much lower than the output saturation power of the EDFA (15 dBm), which is not enough to lead to a significant gain saturation. The gain flatness of the EDFA is typically $\pm$0.8 dB. Amplified spontaneous emission (ASE) generated by the EDFA is a direct current signal which is superimposed on the pulse signals. The 1/e ring-down time t_e of the output pulse train determined directly by exponential fitting algorithms will be less affected by ASE. Optical

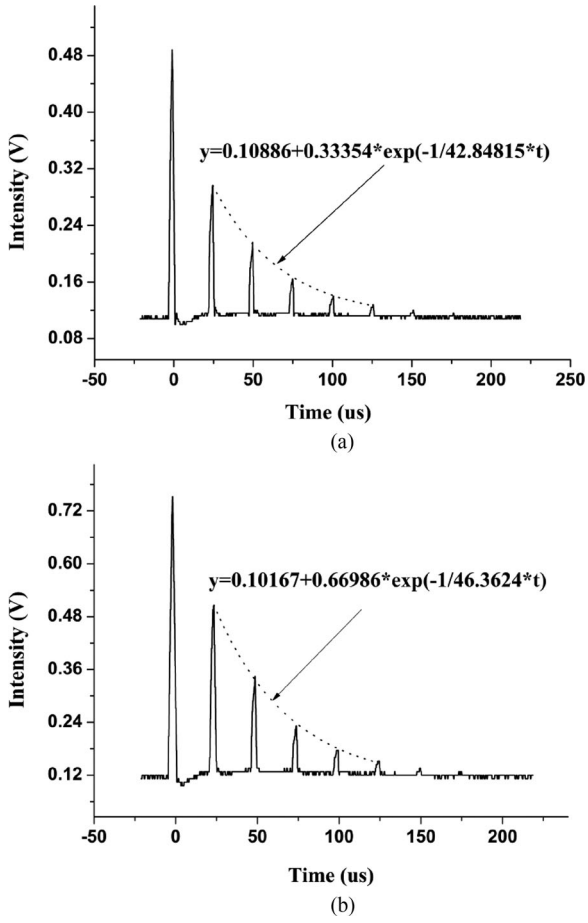

Fig. 3. (a) Ring-down waveforms at a probe wavelength of λ_1. (b) Ring-down waveforms at a probe wavelength of λ_2.

pulses are converted into photocurrent signals by an InGaAs PD with a responsivity of 0.9 A/W, and then, photocurrent signals are converted into voltage signals by a linear current-to-voltage converter and finally acquired by a data-acquisition card (M-DAB-155-12 MAXPHOTONICS China). As the photocurrent is proportional to the light intensity, the voltage signal we measured is also proportional to the light intensity. Signal-to-noise ratio is effectively improved by employing signal averaging technique in the data acquisition card.

The acetylene sample sealed inside the gas cell is monitored continuously for 24 hours. Experimental procedure of a single measurement is described as follows.

As shown in Fig. 3, two pulse sequences with different wavelength are sampled almost simultaneously. $\Gamma_{\lambda 2}$ which is equal to the inherent system loss can be determined from the pulse sequence with wavelength of λ_2 by exponential fitting algorithms. The fitted exponential function is $y = a \times \exp(-b \times t) + c$. As shown in Fig. 3b, the coefficient b is 1/46.362, which means t_e is 46.362 us. The value of $\Gamma_{\lambda 2}$ can be caculated from (5), which is 2.342 dB.

By performing these same steps, we can obtain $\Gamma_{\lambda 1} = 2.534$ dB according to Fig. 3(a).

Using (8), (7), (2), and spectroscopic parameters taken from HITRAN2008 (see Table 1), we can draw a conclusion that the acetylene concentration C is 1.052%, error is 0.052%.

In Fig. 4, we can see that $\Gamma_{\lambda 2}$ fluctuates significantly due to the variation of environmental factors during the 24-hour time period. The maximum fluctuation of inherent system losses can even reach

TABLE 1
Spectroscopic parameters taken from HITRAN2008

Isotopologue	v_0 (cm^{-1})	S(cm × $mol^{\times 1}$)	γ_{air} (cm^{-1})	T (K)	P(atm)
$^{12}C_2H_2$	6523.879242	1.035×10^{-20}	0.0777	296	1

$\Delta v_c = 2 \times \gamma_{air} \times P = 0.1554(cm^{-1})$.

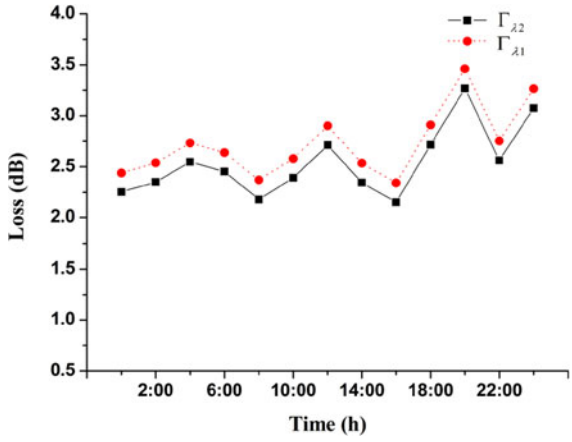

Fig. 4. Loss changes during the whole experimental period.

up to 1.091 dB. Variation of inherent system losses may be caused by a variety of environmental factors (such as external forces, temperature, pressure), and large temperature fluctuations are the most significant factors in this experiment. For example, thermal expansion and contraction due to temperature change will be led to a collimation mismatch problem, which can be occurred in the laser or the gas cell, and cause an additional loss in light intensity. Although the concentration of the acetylene trapped in the gas cell remains basically unchanged, the $\Gamma_{\lambda 1}$ trend changes must be similar with the $\Gamma_{\lambda 2}$ trend changes. If we do not implement a real-time monitoring of the inherent system loss for calibration, the change will be incorrectly attributed to gas concentration changes, resulting in huge error.

Due to the limitations of the traditional method for monitoring the system loss, the variable has often been seen as a fixed value. Of course, the traditional approach will take some measures to suppress the change of system loss, such as temperature control, etc. Under these measures, the fluctuation of the system loss may not be apparent as that in this experiment. Here the mean value (2.538 dB) of $\Gamma_{\lambda 2}$ throughout the experimental period is used to instead of the inherent system loss in real time for simulating a measurement process by using the traditional method. As shown in Fig. 5, the dotted line representing the calculated concentration of acetylene has a peak at 5.044%. Minimum value is negative, which does not have a physical meaning (the main reason is that the system loss fluctuation is too much, which causes the mean value of $\Gamma_{\lambda 2}$ even more than the total loss $\Gamma_{\lambda 1}$). The mean absolute error in estimating concentrations is 1.393%. An obvious comparison is the solid line in Fig. 5, which records the calculated concentration after real-time monitoring and calibrating the inherent system loss. The mean absolute error has decreased to 0.037%. It looks promising for adopting our proposed method. Optimizations of the gain-clamping and gain flatness of the EDFA are key measures to further enhance the accuracy of the FLRDS system. Compensation for laser wavelength drift also matters.

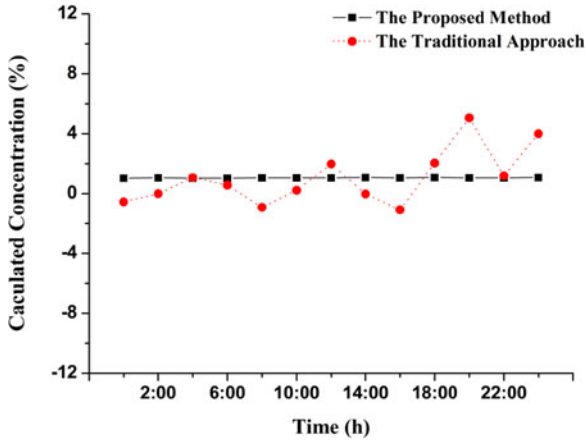

Fig. 5. Accuracy improvement by real-time monitoring the inherent system loss.

4. Conclusion

A main drawback of FLRDS-based gas sensors is the lack of a real-time monitoring regimen for the inherent system loss. The traditional way of obtaining the system loss is to purge the gas cell with a zero gas until the gas absorption effect can be ignored. It is inefficient in operation and may interrupt a long-term continuous gas monitoring. Unfortunately, the inherent system loss is sensitive to the surrounding environment and may always vary across environments. We have proven that through a 24-hours monitoring experiment. Experimental data have indicated that the maximum fluctuation of inherent system losses can even reach up to 1.091 dB. It also explains the importance of real-time monitoring of the inherent system loss for calibration. In view of this situation, we propose a real-time monitoring method to improve the accuracy of FLRDS-based gas sensors. A precise dual-wavelength tuning of the laser diode can be achieved by changing the injection current in which the emission wavelength outside the absorption region can be used to acquire the inherent system loss value fast and conveniently. The advantage of this method has been verified by testing the acetylene concentration of a calibration gas with 1% acetylene. The average measurement error can be decreased from 1.393% to 0.037% through detection and correcting the inherent system loss. It looks promising for adopting our proposed method.

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