



Gas concentration sensor based on fiber loop ring-down spectroscopy



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ABSTRACT

FLRDS technique is popular in recent years. It is an absorption spectroscopic and detection technique. It makes use of an optical cavity, which not only realizes a long effective path-length through a sample, but also eliminates the affection of fluctuations of the light intensity. In this paper, a kind of FLRD gas concentration sensor is presented. We analyze the structural parameters, including the couplers, pulse setting parameters, gas cell, and optimization methods of finding ring-down peak signal, etc. By the experimental data, this system can be reached that gas resolution is up to 1000 ppm, stability is 1.02%, and the repeatability error is 2.37%. Finally, we prove the superiority of the system.

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1. Introduction

Cavity ring-down spectroscopy (CRDS) has been playing an increasingly important role in the sensing community over three decades due to its attractive advantages in many fields, such as technical, environmental, automotive, and medical applications [1–6]. In 21st, Stewart et al. [7] put forward fiber loop ring-down system (FLRDS). FLRDS technique not only has the same advantages as CRDS, but also has its own strong points [8,9]. The FLRDS technique is a transformation of the conventional CRDS [10,11]. It makes use of an optical cavity, which not only realizes a long effective path-length through a sample, but also eliminates the affection of fluctuations of the light intensity.

In 2001, Stewart et al. put forward fiber loop ring-down system (FLRDS) [9]. Later on, simplified versions of fiber loop ring-down devices were introduced by both Lehmann [10] and Look [11,12] groups. The fiber cavity ring-down (FCRD) technique is a transformation of the conventional CRDS in which the cavity constructed by two mirrors with high reflectivity is replaced by a fiber loop, which is shown in Fig. 1.

This paper designs the parameter of FLRDS system, optimizes the method of finding pulse's peak. And finally, based on the system we designed, we did the experiment, which not only proves the superiority of the system, but also has good performance.

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2. Principle and theory

For a fiber loop ring-down system, we can calculate the loss of ring-down cavity and corresponding gas concentration by measuring ring-down time constant. This fiber optical system, which is shown as Fig. 2(a), consists of a fiber loop of length several tens of meters with a sensing unit and two couplers and a high-speed photo-detector, an oscilloscope with highly sampling rate.

Ring-down signal is a series of decaying pulses, which is shown as Fig. 2(b). In the FLRDS, the input light I_0 ratio attenuates as time goes on. Namely, $I = I_0 e^{-\sigma}$. Usually, σ is related to the physical quantity we want. Supposing, δ is the loop loss, and $\delta = 10 \lg(I/I_0)$, we will get Eq. (1).

$$\sigma = \frac{\delta}{4.34} \quad (1)$$

For m travels, the pulse's intensity I^m becomes $I^m = I_0 e^{-m\delta/4.34} = I_0 e^{-\delta t/4.34\tau}$. Here, $t = mt_r$, t_r is the round trip time. Supposing τ is the ring-down time constant at which the intensity decays to $1/e$ of the initial, we can get Eq. (2)

$$\delta = \frac{4.34t_r}{\tau} \quad (2)$$

Here, $\delta = \delta_0 + \delta_s$, where δ_0 is the intrinsic loss, and δ_s is the sensing loss. As we will use this system to measure gas concentration, here δ_s is the gas absorption loss. As according to Lambert–Beer law, $\delta_s = 4.34\alpha Cl$. Here, α is the gas absorption coefficient, C is the gas concentration, l is the length of the gas cell. Therefore, the relationship between gas concentration and ring-down time is that

$$C = \frac{t_r}{4l} \left(\frac{1}{\tau} - \frac{1}{\tau_0} \right) \quad (3)$$

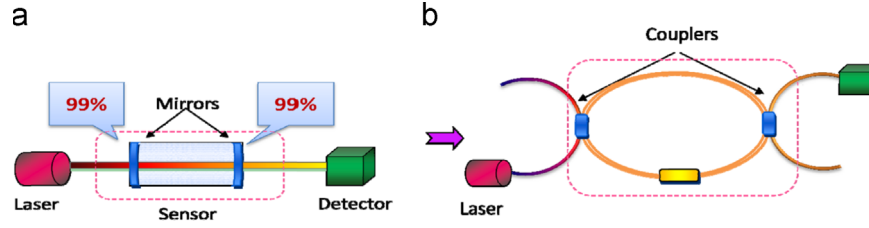


Fig. 1. Comparison of CRDS and FLRDS. (a) Comparison of a conventional CRDS and (b) fiber loop ring-down system (FLRDS).

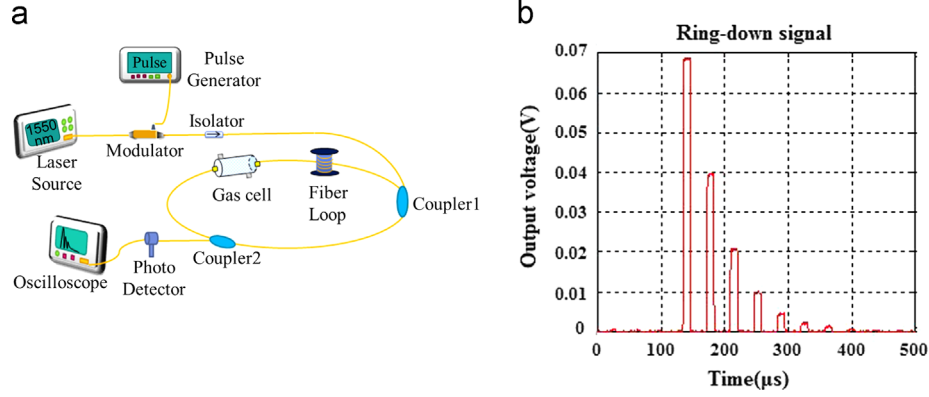


Fig. 2. Fiber loop ring-down system. (a) Schematic diagram and (b) ring-down signal.

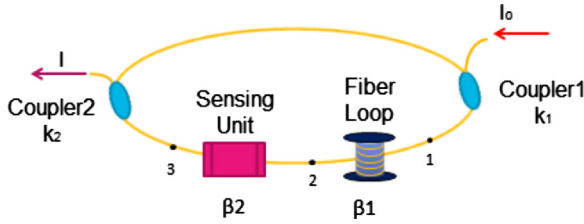


Fig. 3. The schematic diagram of analyzing splitting ratio.

3. Method and analyzing

3.1. Effect of splitting ratio of couplers

In the FLRDS, there are two couplers, the splitting ratio of coupler1 is k_1 ($0 < k_1 < 1$), and the other is k_2 ($0 < k_2 < 1$). The loss of the fiber loop is β_1 , the sensing loss is β_2 . The schematic diagram of analyzing splitting ratio is shown as Fig. 3.

For the first loop, after the input light I_0 travels through coupler1, fiber loop, sensing unit, and coupler2, some of the light proceed to loop, whereas, the others I_1 is detected by the detector. And I_1 is

$$I_1 = I_0(1-k_1)(1-k_2) \cdot 10^{-(\beta_1+\beta_2)/10} \quad (4)$$

According to the same derivation, I_2 which is detected by the detector is

$$I_2 = I_0(1-k_1)(1-k_2) \cdot k_1 k_2 \cdot 10^{-2(\beta_1+\beta_2)/10} \quad (5)$$

For the third loop, I_3 which is detected by the detector is

$$I_3 = I_0(1-k_1)(1-k_2) \cdot (k_1 k_2)^2 \cdot 10^{-3(\beta_1+\beta_2)/10} \quad (6)$$

By using mathematics inductive method, we demonstrate and conclude that for the n th loop, I_n is

$$I_n = I_0(1-k_1)(1-k_2) \cdot (k_1 k_2)^{n-1} \cdot 10^{-n(\beta_1+\beta_2)/10} \quad (7)$$

As oscilloscope shows the voltage values, we use voltage instead of light intensity. Here, we get formula (12)

$$U_n = U_0(1-k_1)(1-k_2) \cdot (k_1 k_2)^{n-1} \cdot 10^{-n(\beta_1+\beta_2)/10} \quad (8)$$

Here, we use a combination of three kinds of couplers with different splitting ratio, that is, 0.50:0.50, 0.01:0.99 and 0.10:0.90 to get ring-down signals by both simulation and experiment, which is shown as Fig. 4.

Experimental results are in good agreement with theory. In order to improve the accuracy of the fitted equation, we should considerate both the number of pulse's peak and pulse's peak intensity. Therefore, we choose the couplers with splitting ratio 0.10:0.90 which is more superior than others.

3.2. Methods for finding ring-down peak signal

Data processing is necessary to get information from ring-down signal including finding peaks and curve fitting exponential decay equation. Here, we find the peak value based on the method of five-point sliding average method. Fig. 5 shows work flow of peak finding.

First, we use the method of five-point sliding average method to filter the noise from the original signal. However, the ring-down waveform becomes distorted, which is shown as Fig. 5(b).

Here, we just get the abscissa values of each peak, and then, we use these abscissa values to find and average the area of ordinate values of the original curve points, which is shown as Fig. 5(c), and these average values are used as ordinate values of these peaks. Because the period between the two peaks is a fixed value, we use these fixed points as the abscissa values of these peaks. Finally, we use abscissa and ordinate values to fit the ring-down curve by exponential equation ($y = a \cdot \exp(-b \cdot x)$) and obtain the ring-down time by the decay rate, b .

4. Experimental result

4.1. Source fluctuations influence on the system

From formula (3), we know that the fluctuations of the source cannot influence gas concentration. Here, we just adjust the intensity of the input light to prove it. Fig. 6 shows the ring-down curves change by adjusting the input light intensity.

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