Study on long distance transmission technique of weak photocurrent signal in laser gas sensor

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The continuous monitoring of H_2S gas concentration is a common problem in natural gas desulfurization process technology. Tunable diode laser absorption spectroscopy (TDLAS) is a preferred technology for continuous monitoring of gas in industrial sites, because of its high selectivity, high sensitivity, and fast response. We discuss the technical solutions of on-line monitoring of H_2S in natural gas desulfurization process technology based on TDLAS, and study the security design of monitoring system in inflammable and explosive areas. We also design a weak photocurrent signal converting circuit and perform experiments on transmission characteristics of different distances. The signal-to-noise ratio (SNR) of laser absorption spectrum does not decrease after the 1 500-m transmission. The detection limit is 300 ppb. The system can be operated stably and reliably, and satisfies the need for continuous monitoring of the H_2S in natural gas desulfurization process.

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The continuous monitoring of H_2S gas concentration is necessary in desulfurization instruments. An intrinsically safe design solution can ensure the long-running reliability of the monitoring system, because natural gas is inflammable and explosive[1].

Tunable diode laser absorption spectroscopy (TDLAS) has characteristics of high selectivity, high sensitivity, fast response, and optical fiber transmission. Therefore, we used single-mode fiber (SMF) to transmit the tuning laser signal to the measurement site for the H_2S monitoring system in natural gas desulfurization process[2]. After being absorbed by gas, the laser signal is converted to current signal at μA-level by a photoelectric detector and transmitted to control room using a long-distance twisted-pair cable[3]. Thus, the intrinsic safety of the on-site sensing part has been ensured. Unfortunately, the experimental results show that the signal-to-noise ratio (SNR) dropped dramatically, thereby greatly affecting the data retrieval of laser absorption spectra when the transmission distance is longer than 50 m. In this letter, we designed a weak photocurrent signal converting circuit and performed experiments on transmission characteristics of different distances. The signal waveform of laser absorption spectrum maintained the original state parameters after the 1 500-m transmission. The detection limit is 300 ppb. The system can be operated stably and reliably, and satisfies the need for continuous monitoring of H_2S in natural gas desulfurization process.

Laser gas sensor is a gas detection apparatus for high-resolution absorption spectrum when laser is used as light source. Based on the Beer-Lambert law, the transmission of laser through gas can be written as[3]

$$T = I_\nu / I_0 = \exp\big[-S(T)g(\nu-\nu_0)NL\big], \qquad (1)$$

where I_ν is the intensity of measured gas after an absorption whose optical path length is L, I_0 is the initial intensity, $S(T)$ is the absorption line strength at central frequency ν_0, $g(\nu-\nu_0)$ is the line shape function, and N is the concentration of absorbing gas molecules. Peak absorption coefficient $\alpha(\nu_0, T)$ is defined as

$$\alpha(\nu_0, T) = S(T)g(\nu-\nu_0)N. \qquad (2)$$

The line shape function $g(\nu-\nu_0)$ is 1, so the integral absorption coefficient is given by

$$\alpha(T) = S(T)N. \qquad (3)$$

The concentration of measured gas is given by

$$N = \frac{-\int \ln\left[\frac{I(\nu)}{I_0(\nu)}\right] \mathrm{d}\nu}{S(T)L}, \qquad (4)$$

where $\mathrm{d}\nu$ is the wavelength point of scanning absorption spectrum.

The minimum of measured gas concentration depends on the gas absorption line strength $S(T)$, the optical path length of absorption, and the resolution of transmission detection generated through Eq. (4). The transmission detection resolution depends on the SNR of absorption spectroscopy and the precision of analog-to-digital (A/D) conversion.

The composition principle of laser gas sensor is shown in Fig. 1. We used a distributed-feedback (DFB) laser as light source and measured the single absorption line of H_2S at 1.576 μm. We tuned the laser output wavelength at 1.576 μm using the temperature controller of laser. The laser central current was generated by the current controller, and the wavelength scan current limited the wavelength of the laser output in the range from 1.576 to 1.577 μm. After being split by a 1 : 9 beam splitter, the

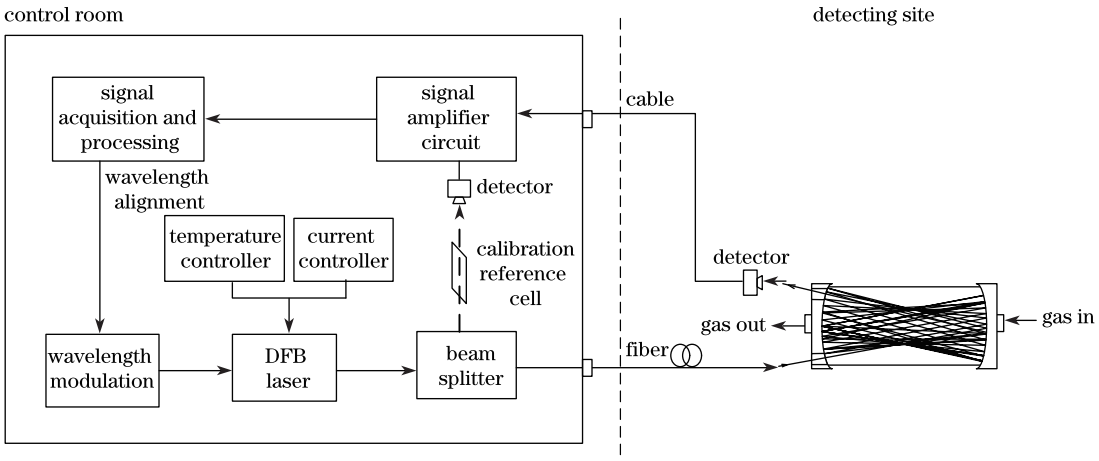

Fig. 1. Schematic diagram of the monitoring H_2S system based on laser absorption spectroscopy.

laser output was made to pass through a Herriot cell, after which a calibration reference cell sealed with calibration H_2S gas was set[4]. Two InGaAs photodiodes were used to convert laser signals to electrical signals that then entered a signal amplifier circuit. We utilized a signal acquisition and processing circuit to collect the signal, through which we calculated the concentration of H_2S gas. The sensor consisted of a host and multipass absorption cell[5]. The host, which included laser, controller circuit, acquisition and processing circuit, was set in the security zone of the control room. The laser signal was transmitted to inflammable and explosive site using SMF and then entered a multipass Herriott cell, which was set in an onsite gas sampling cabinet. After passing through the Herriott cell, the signal was converted to weak current signal by a photoelectric detector and then sent back to the control room, where the current signal was amplified and processed. According to this method, there were only laser and weak photocurrent signals on site. Thus, the need to preserve onsite intrinsic safety was satisfied.

As discussed above, we can obtain the single absorption spectrum line of H_2S gas. The waveform of the signal generated by InGaAs photodiode consisted of the direct current (DC) optical signal given by the laser central working current and sawtooth wave scan signal (Fig. 2). The gas absorption signal is located in the middle of the sawtooth wave. We then calculated the gas concentration after acquiring the absorption spectrum signals of the measuring and reference channels. From Figs. 2(a) and (b), we can see that the SNR of the laser absorption spectra from the measuring channel was higher than that from the reference channel. When the distance between work field and control room was longer than 50 m, the SNR of the transmitted photoelectric signal decreased significantly. In this case, we were unable to calculate the gas concentration correctly. Usually, the distance between work field and control room was longer than 100 m and even over 1 km. Thus, realizing the high fidelity transmission of weak photoelectric signal over long distance is the key to ensure the measuring accuracy of sensor.

From the perspective of analog signal transmission, voltage signal becomes attenuated and deformed after long distance transmission, because transferring cable has resistance and capacitance[6,7]. To some extent, the current signal does not have this problem. Therefore, current is used for analog signal transmission over long distance in industrial detection. Taking this into consideration, we designed a low-noise amplifier circuit for the InGaAs photodiode current. This amplifier circuit linearly amplified μA-level photocurrent signal to mA-level current signal, which was transmitted over long distance using a twisted pair cable. The schematic diagram of the photocurrent conversion was shown in Fig. 3[8].

The InGaAs photodiode, operational amplifier U1A, and resistor radio frequency (RF) comprised a conversion circuit converting photocurrent to voltage (Fig. 3). The value of the resistor was fixed, so that the voltage responding to the maximal unsaturated photocurrent was 2 V, making the output voltage of U1A was 0–2 V. The level-shifting circuit constructed on the base of the operational amplifier U1B converted the output voltage of U1A from the range of 0–2 V to 0.2–1 V[9]. The voltage-current conversion circuit consisting of U2B and Q1 converted the output voltage signal from 0.2 to 1 V of U1A to current signal transmitted over long distance using twisted pair cable from 4 to 20 mA. In order to lower

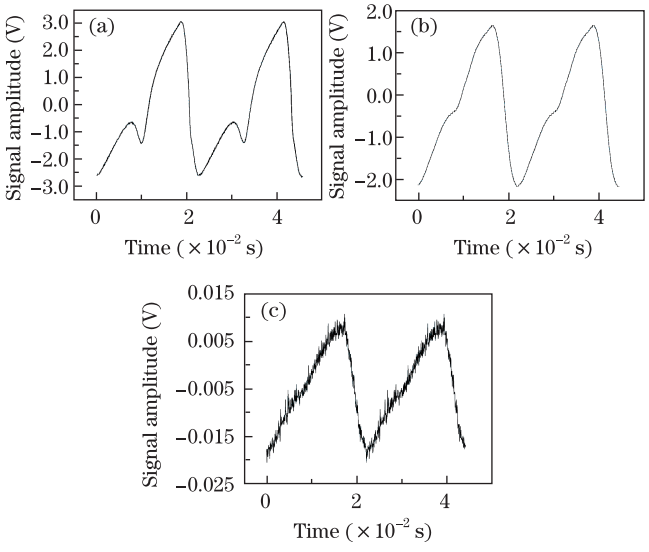

Fig. 2. Waveforms of the laser absorption spectrum. (a) Reference channel signal; (b) measuring channel signal (5 m); (c) measuring channel signal (50 m).

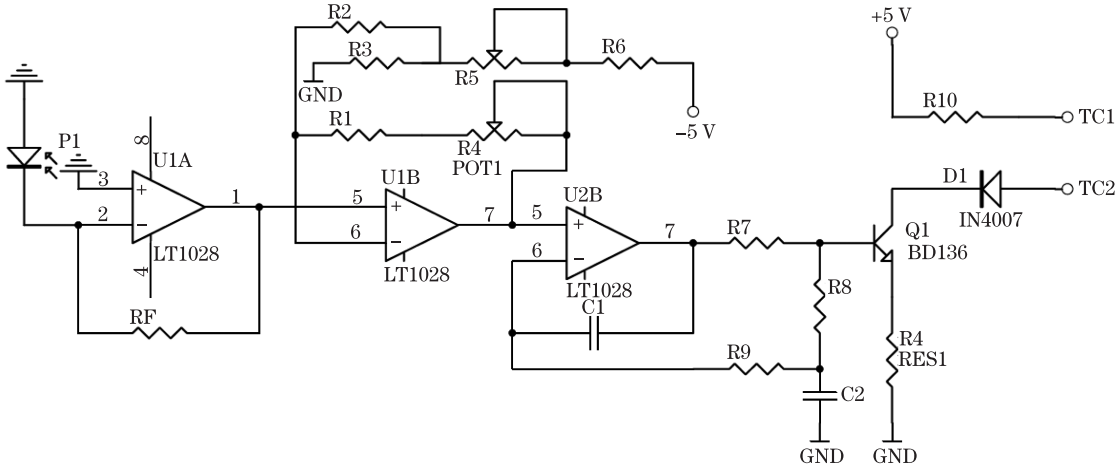

Fig. 3. Schematic diagram of the μA photocurrent to mA converter.

the SNR of the circuit, we chose a low-noise operational amplifier LT1 028, whose typical voltage noise value was 0.85 nV/$\sqrt{\text{Hz}}$[10]. We also chose a voltage-current conversion resistor, R4, whose temperature coefficient was 5 ppm/°C. The temperature shift of output current was controlled within 1 μA/°C.

We filled the Herriot cell with 10-ppm calibration H_2S gas to test the performance of the system. We performed the experiment in two steps. First, the photoelectric detector signal was transmitted to the signal acquirasion and processing circuit using different lengths of transmission cables. The signal waveforms were recorded. The waveforms were obtained through different transmission cables with different lengths L (L = 5, 20, 100, and 200 m) without current conversion circuit. These are shown in Fig. 4.

As shown in Fig. 4(b), the noise level increased when the transmission distance was longer than 50 m. When the transmission distances were 100 and 200 m, the noise level increased dramatically, so that the absorption signal could not be distinguished. The SNRs of different transmission distances are listed in Table 1. The SNR was –5.95 dB when the transmission distance was 200 m.

Second, we used the current conversion circuit shown in Fig. 3 to convert the photocurrent signal of the photoelectric detector to the mA-level current. This was transmitted to the signal acquirasion and processing circuit using different lengths of transmission cables, after which we recorded the signal waveform. The waveforms obtained using different lengths L (L = 500, 700, 1 000, 1 200, 1 500, and 1 700 m) of transmission cables are shown in Fig. 5.

As shown in Fig. 5, the signal waveform was still in good shape when the transmission distance was 1 500 m. Table 2 showed the SNR at different transmissions. The SNR was 2.91 dB when transmission was 1 500 m.

Table 1. SNR of Different Transmission Distances without Current Conversion

Distance (m)	5	50	100	200
SNR (dB)	40.61	15.90	1.77	–5.95

Table 2. SNR of Different Transmission Distances with Current Conversion

Distance (m)	500	700	1 000	1 200	1 500	1 700
SNR (dB)	39.21	15.90	11.21	5.28	2.91	2.02

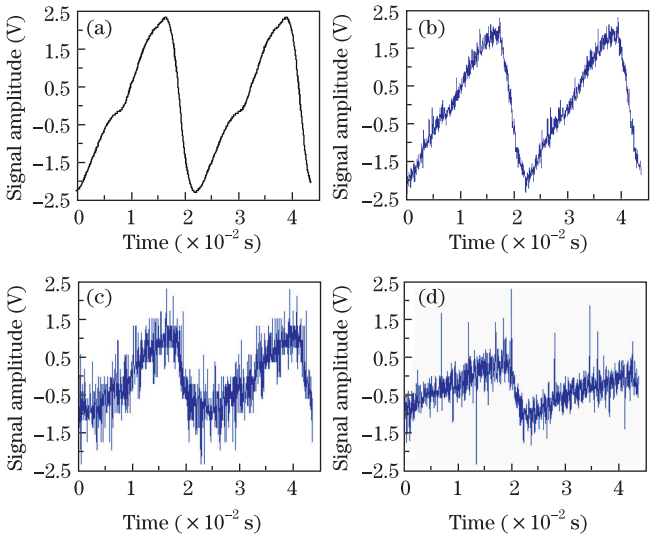

Fig. 4. Signal waveforms obtained from different transmission cables without the current conversion circuit. (a) L= 5, (b) 50, (c) 100, and (d) 200 m.

We measured calibration H_2S at 7 concentrations: 500, 300, 100, 50, 20, 10, and 2 ppm. The fit curves of the measuring results are shown in Fig. 6. We found that the linear correlation coefficient measured by the system was 0.9964. We measured the 2-ppm calibration gas continuously and illustrated the results in Fig. 7. Measuring the results indicated that the measuring result repetitiveness (3σ) of H_2S monitoring system was 300 ppb.

In conclusion, in order to ensure the intrinsic safety of a site sensor, we transmit weak photocurrent signals of an H_2S monitoring system to a control room over a long distance in natural gas desulfurization process. We discuss the technical approach for long distance transmission of weak photocurrent signals and designed a weak photocurrent

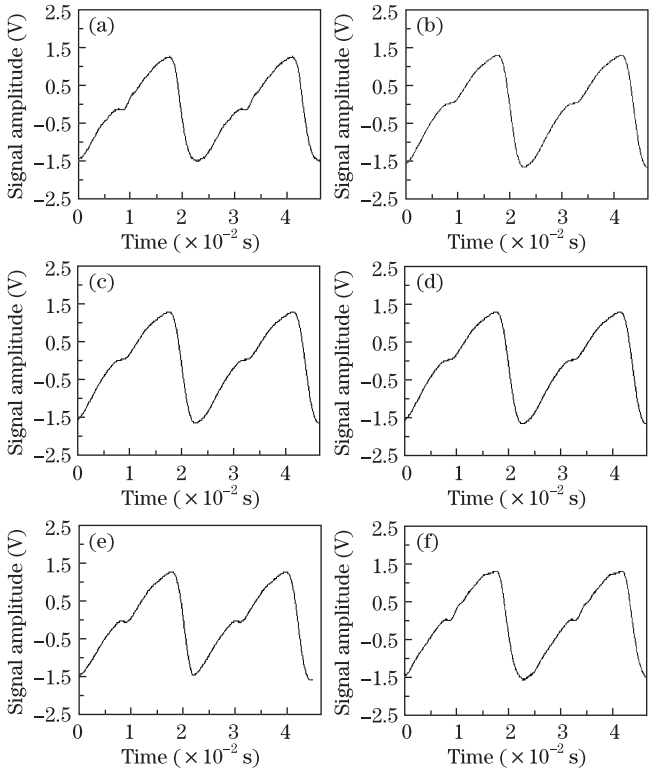

Fig. 5. Signal waveforms obtained from different lengths of transmission cables with the current conversion circuit. (a) L=500, (b) 700, (c) 1 000, (d) 1 200, (e) 1 500, and (f) 1 700 m.

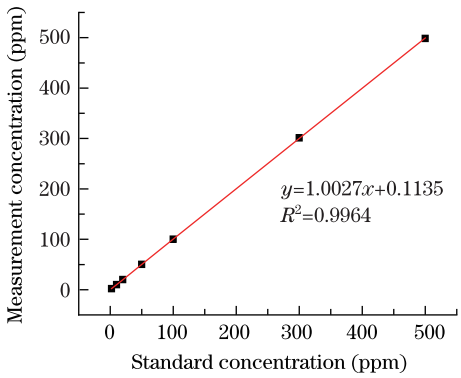

Fig. 6. Measuring results of H_2S at different concentrations.

signal converting circuit, which could convert weak photoelectric current signal to current signal at the range of 4–20 mA. We also perform experiments on the transmission characteristics of different distances using twisted-pair cable. The signal waveform of the laser

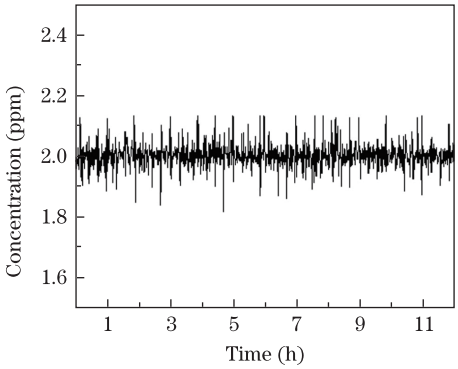

Fig. 7. Continuously measuring result of 2-ppm H_2S.

absorption spectrum maintain the original state parameters after the 1 500-m transmission. The detection limit is 300 ppb. The system can be operated stably and reliably, and satisfies the need for continuous monitoring of H_2S in natural gas desulfurization process.

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