Gas leakage monitoring with scanned-wavelength direct absorption spectroscopy

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A natural gas leakage detector based on scanned-wavelength direct absorption spectroscopy is described. The sensor employs a multi-channel scanned-wavelength direct absorption strategy. It has the potential to simultaneously monitor methane and hydrogen sulfide in open path environment. Traditionally, scanned-wavelength direct absorption spectroscopy is the technique choice for natural gas leakage applications because of its simplicity, accuracy, and stability. We perform the gas sensor using direct-absorption wavelength scans with isolated features at 1-kHz repetition rate and the center wavelength is stabilized at the center of the $2\nu_3$ band R(3) line of methane (1.65 μm) and the ($\nu_1 + \nu_2 + \nu_3$) combination band of hydrogen sulfide (1.57 μm), respectively. The influence of light intensity fluctuations can be eliminated by using scanned-wavelength direct absorption spectroscopy. Because of the fast wavelength scanning, the sensor has a response time of less than 0.1 s. The sensor can be configured to sense leakages in path-integrated concentrations of, for example, 100-ppm·m hydrogen sulfide and 10-ppm·m methane.

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Natural gas plays an increasingly important role in improving energy structure and enhancing environmental protection. Natural gas pipeline network has become the indispensable "lifeline" in modern city. It is a very serious issue to predict and prevent natural gas leakage. Therefore, reliable timely detection of failure of any part of the pipeline is critical to ensure the reliability of the natural gas infrastructure. Scanned-wavelength direct absorption spectroscopy is an ideal technology in the natural gas leakage detector, partly because the distributed feedback (DFB) lasers are narrow band, single mode, and relatively powerful (10–30 mW) and may be tuned over several wavenumbers at kilohertz rates by modulating the injection current. The linewidths of methane and hydrogen sulfide absorption features are of order 0.1 cm^{-1} in tunnel. Therefore, wavelength scans across absorption features at kilohertz rates can be easily accomplished with DFB lasers.

Laser sensors have gained popularity in a wide array of practical measurement applications ranging from trace-gas detection[1−5] and leakage diagnostics to numerous industrial applications[6−8]. Most of the laser sensors have used wavelength modulation techniques, such as trace-gas detection[3,6−8]. But scanned-wavelength direct absorption spectroscopy is a low-cost technology and easy to use, and can realize high-sensitivity and high-response gas detection. All currently available natural gas detectors must be positioned within a leakage plume to detect the leakage. In relation to this challenge, the Key Laboratory of Environmental Optics & Technology has developed an optical methane detector, namely the Open Methane Leak Detector (OMLD), which provides stand-off detection of leakages. In this letter, we intro-

duce a new gas sensor for natural gas leakage detection. The scanned-wavelength direct absorption spectroscopy methods are briefly reviewed. The results of experimental simulation of natural gas leakage and field experiment are given.

A linear variation in injection current is used to scan DFB diode lasers simultaneously in intensity and wavelength. Figure 1(a) shows a typical direct-absorption scan using a diode laser, in which the laser intensity changes in response to an injection current ramp. Polynomial fit to two non-absorbing wings of the absorption feature is used to extrapolate a zero-absorption baseline, from which an absorbance plot of the absorption feature may be constructed, as shown in Fig. 1(b). The Beer-Lambert relation:

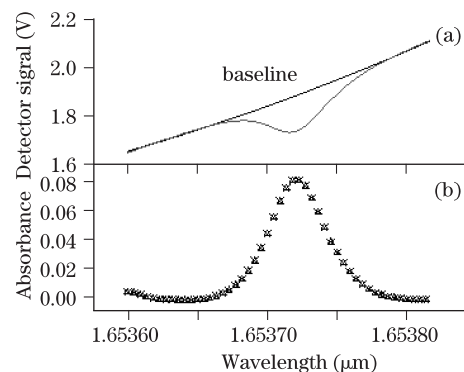$$I(v) = I_0(v) \exp(-\alpha), \tag{1}$$

Fig. 1. (a) Raw detector signal during a single direct absorption laser scan with baseline fit (1653.72 nm feature); (b) absorbance plot resulting from detector signals and baseline.

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can be rearranged to yield

$$\alpha = -\ln\left[\frac{I(\nu)}{I_0(\nu)}\right], \tag{2}$$

which gives the absorbance (α) as a function of the transmitted laser intensity ($I(\nu)$, the detector signal) and the incident laser intensity ($I_0(\nu)$, the baseline fit).

The absorbance is also a function of line strength $S(T)$, species partial pressure P_i, path length L, and line shape function $\phi(\nu)$:

$$\alpha = S(T)P_iCL\phi(\nu). \tag{3}$$

In open path detection, methane and hydrogen sulfide have been detected under normal temperature and pressure environment. Doppler effect, effect of temperature, and effect of pressure may not be taken into account. The line shape is a normalized function that describes the profile of a spectroscopic transition in frequency space. Absorbance is more in line with the Lorentz line here, so the line shape function is equal to unity and is no longer important. The result from integrating with respect to frequency is called the integrated absorbance area:

$$A = \int_{-\infty}^{\infty} S(T)P_iCL\phi(\nu)\mathrm{d}\nu = S(T)P_iCL. \tag{4}$$

In the detection, the CH_4 and H_2S concentrations in the open path measurements are derived from the measured differential transmittances at 1.65 and 1.57 μm using the calibration values from the reference cell measurements. Calibration, instead of fitting to a HITRAN profile, is preferred for the open path measurements because it allows the calibration of the entire signal processing chain. The gas concentration can be directly calculated using

$$C_1 = \frac{A_1}{A_0} \times C_0 \times \frac{L_0}{L_1}, \tag{5}$$

where A_0 and A_1 are the absorbance cross-sections of standard gas and test gas, respectively, L_0 and L_1 are the optical path of the reference cell and the test optical path, respectively, and C_0 is the standard gas concentration.

As shown in Fig. 2, leakage detection of methane and hydrogen sulfide can be realized by separate scanning technology. Hydrogen sulfide gas, which has weak sorption, can be calibrated by standard methane gas. The H_2S concentration can be obtained by

$$C_{H_2S} = \frac{A_{H_2S}}{A_{CH_4}} \times C_{CH_4} \times \frac{L_{CH_4}}{L_{H_2S}} \times \frac{S_{CH_4}(T)}{S_{H_2S}(T)}, \tag{6}$$

where L_{CH_4} and L_{H_2S} are the optical path of the reference cell and the test optical path respectively, $S_{CH_4}(T)$ and $S_{H_2S}(T)$ are the line strengths of CH_4 and H_2S, respectively.

An OMLD has been installed in the tunnel of Puguang Gas Field in Sichuan Province. It consists of two parts, i.e., the gas analyzer and the optical system, as shown in Fig. 3. The optical system, consisting of the beam expander and the Fresnel telescope, is installed inside the tunnel. The beam expander is installed at one end of the tunnel, and the Fresnel telescope is fixed at the other end. All electric controllers and gas analyzers, linking to the transceiver by fiber and transmission cable, are placed in the control room. A photograph of our developed OMLD is shown in Fig. 4. It consists of the beam expander (Fig. 4(a)), the Fresnel telescope (Fig. 4(b)), and the gas analyzer (Fig. 4(c)).

The detection process is as follows. Firstly, the controllers control the semiconductor laser to emit near-infrared laser with immovable power and certain gas center wavelength. The laser is scanned by the sawtooth of 1 kHz at the vicinity of an absorption line. Secondly, the laser is coupled into the beam expander, passing through the tunnel, and received by the Fresnel telescope. Finally, the detector signals are transmitted by the transmission cable to the control room and analyzed with the gas analyzer. The scanned-wavelength direct absorption spectroscopy method works well in natural gas leakage detection, because the spectrally isolated features of absorbance can be used and noise is eliminated
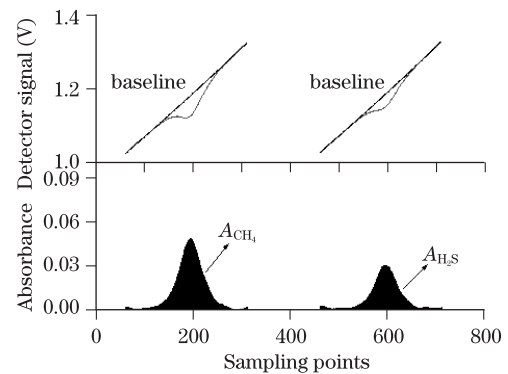

Fig. 2. Scanned-wavelength direct absorption spectroscopy of methane and hydrogen sulfide appears in the system.
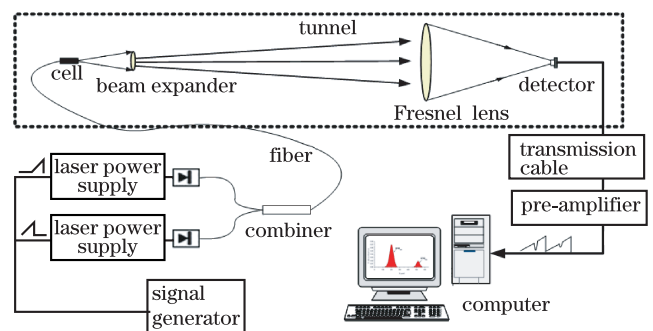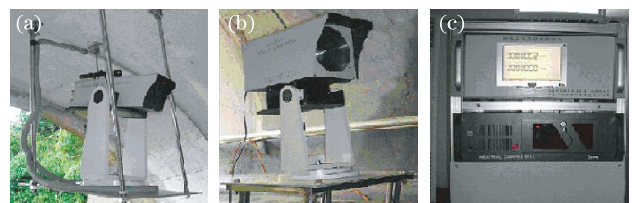

Fig. 3. Diagram of OMLD.

Fig. 4. Developed prototype of OMLD consisting of (a) beam expander, (b) Fresnel telescope, and (c) gas analyzer.

by optical engineering and analog signal processing.

Figure 5(a) shows the raw signals recorded inside the 310-m tunnel. 10-cm-long sample cell filled with CH_4 of concentrations from 0.8% to 5.5% and H_2S of concentrations from 6% to 30% was placed inside the tunnel. No change of the position at maximum absorption is well visible in this figure. The most possible reason for this is the laser wavelength stabilities and weak turbulence in the tunnel. The signals for different concentrations were obtained by averaging 100 sawtooth scan during 0.1 s.

Figure 5(b) shows the absorbance at different CH_4 and H_2S concentrations. All absorbances shown in Fig. 5 are compared with measurement results using different gases displaced at the cell. Atmospheric conditions (fog, drizzle, or smog) can be neglected in the tunnel, and signal-to-noise ratio (SNR) can be improved by employing analog signal processing and digital filtering.

Figures 6 and 7 show the linear curve between absorbance and the real gas concentration in the sample cell. The linear fitting coefficient is 99.851% in Fig. 6 and 98.657% in Fig. 7, indicating that the absorbance fits very well with real gas concentration.

The same kind of gas has been tested 8 times by using 10-cm-long sample cell filled with two kinds of gases of concentrations 1.4% and 6%, respectively. The results are shown in Tables 1 and 2. The data illustrate that the system has a good repeatability. The results are obtained by dividing the raw data to the background signal. The system detection limit was not directly measured but extrapolated from the standard deviation of the system. According to the detection limit formula that the detection is approximately equal to 3 times of the standard deviation, the system minimum CH_4 detection limit and H_2S detection limit can be calculated to be 10 and 100 ppm·m, respectively. This sensor can be fully qualified for trace gas leakage detection because of its quantitative and qualitative gas surveying.

The absorbance of different light intensity has been tested. In the experiment, keeping the optical path of 310 m fixed, a 10-cm-long sample cell filled with CH_4 and nitrogen at atmospheric pressure was inserted between the transmitter and the receiver. The concentration of CH_4 was 1.38%, and the laser intensity was changed by the optical attenuator. As shown in Fig. 8, E, H, I, J, and K are different measurements, C, D, E, F, and G are the corresponding absorption signals, where the ratio of light intensity was 2.02:4.27:1.47:1:3.38, whereas the ratio of the absorbance was 0.992 65:0.993 9:0.993 55:1:1.004 99. Figure 9 shows the maximum deviation of 0.73% which can be ignored. From experimental analysis, it is found

that the absorbance is basically unchanged. The influence of the light intensity fluctuations can be eliminated by using scanned-wavelength direct absorption spectroscopy.
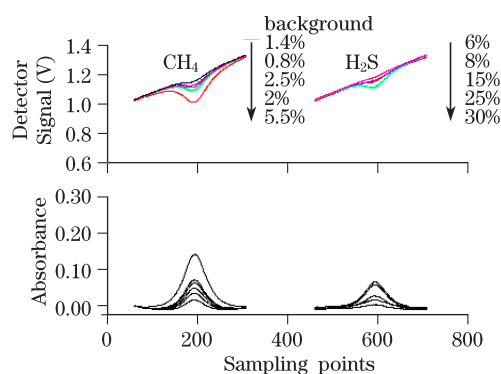

Fig. 5. (a) Raw detector signal at different gas concentrations; (b) absorbance plot obtained from laser scan and baseline.
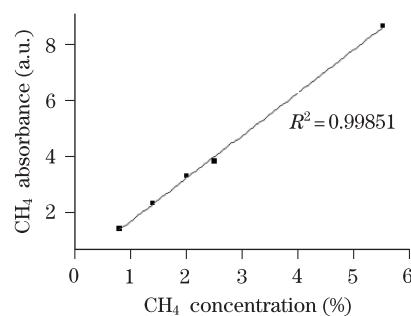

Fig. 6. Linear curve between CH_4 absorbance and the real CH_4 concentration in the sample cell.
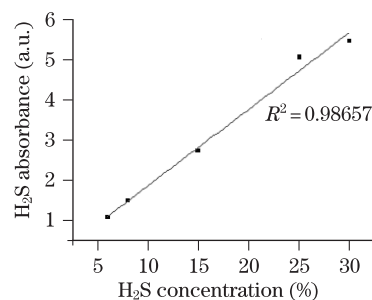

Fig. 7. Linear curve between H_2S absorbance and the real H_2S concentration in the sample cell.

Table 1. Measurement Reproducibility of CH_4 with Concentration of 1.4%

Result (%)	1.404	1.397	1.395	1.403	1.396	1.402	1.404	1.397
Relative Error	0.0028	0.0021	0.0036	0.0021	0.0029	0.0014	0.0029	0.0021
Standard Deviation 3.8 ppm·m								

Table 2. Measurement Reproducibility of H_2S with Concentration of 6%

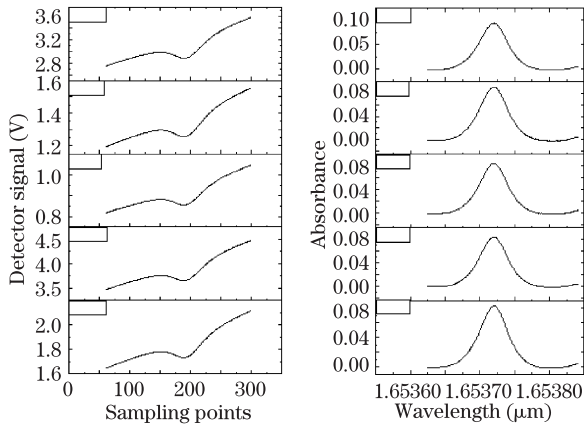| Result (%)	6.033	5.978	6.059	5.985	5.962	6.044	6.029	6.045
Relative Error	0.0055	0.0037	0.0098	0.0025	0.0063	0.0073	0.0048	0.0075
Standard Deviation 36.3 ppm·m								

Fig. 8. Absorbance of different light intensity (the left is the detection signals and the right is the absorption signals).
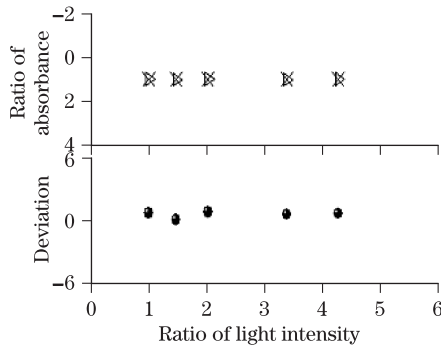

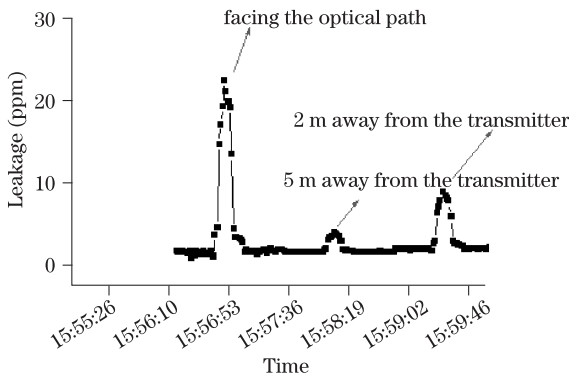Fig. 9. Ratio of the absorbance among different light intensity.

Fig. 10. Common leakage detection scenario.

Although the original project plan envisioned a leakage detection of the system, we were unable to find an acceptable leakage test. Instead, we performed leakage simulations of the natural gas leakage detection scenario inside the tunnel. In these simulations, we demonstrated the ability to measure methane leakages within the laser beam path when it passed through the tunnel. Figure 10 shows a time-trace of the sensor's output in a common leakage detection scenario. CH_4 with the concentration of 1% was used to simulate gas leakage experiments. Gas flow rate was controlled at 20 kg/h. The optical path direction was north-south. Considering the wind speed of 3 m/s in the optical path direction, we simulated the natural gas leakage detection scenario in different places. For 5 m away from the transmitter, the presence of methane diffusion from the cylinders was clearly indicated as a distinct rise above the background. With the gas nozzle closer to the optical path direction, methane absorption signals became larger. When it faced the optical path, the highest reading was obtained. The sensor had a response time of less than 0.1 s. The data of Fig. 10 illustrate that it is easy to establish a threshold value above which an alarm will be activated, because methane in the ambient air contributes a background signal that may be as small as a leakage signal. So this sensor can survey natural gas leakage accurately and quickly.

In conclusion, the results from the experiment of our system show the feasibility of using scanned-wavelength direct absorption spectroscopy to detect natural gas leakage. OMLD can be particularly valuable when natural gas leakage needs to be monitored. The system can be used in worse environment because of eliminating the influence of laser power fluctuations and high sensitivity. The sensor has a response time of less than 0.1 s, which can fully meet the desire of early warning.

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