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RESEARCH ARTICLE

Absorption measurement of methane gas with broadband light source using fiber-optic sensor system

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Abstract The absorption coefficient of methane is very important for measuring the concentration of methane. We theoretically analyzed the general expression of methane absorption coefficient for a given condition, at room temperature of 296 K, and we simulated the relationship between the absorption and the wavelength of the light source. The experimental results we obtained are consistent with the simulation. The discrepancy between the experimental results and the simulation results is also discussed.

Keywords fiber-optic sensor, gas measurement, methane, absorption coefficient

1 Introduction

Explosion of coal mines is a major disaster throughout the human history. To prevent explosion in coal mines, it is extremely important to measure and determine the hazardous gas's concentration in the underground environment for the safety of the mineworkers [1–5]. Methane is the main component of the flammable gas, and the low limit concentration of the methane is 4.9%, and the upper limit concentration is 15.4%. Thus, real-time monitoring and detection of the methane concentration is crucial to the coal mines' safety precautions.

Fiber-optic sensor system was developed in the late 1980s, which exploit methane's light absorption effect to determine the gas concentration. Fiber-optic sensor system has many advantages over other traditional sensors, such as suitable for long-distance and real-time monitoring, immune to electric-magnetic interference (EMI), and easy to form sensor network. To determine the gas concentration, it is extremely important to measure the absorption coefficient of the gas under test.

In this paper, we experimentally demonstrate a fiber-optic sensor system for the detection of methane gas. The absorption coefficient of methane gas was theoretically studied. The experimental data agrees well with the simulation results.

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2 Theoretical principle

For the methane gas, it has typical absorption peaks at the infrared band. When the light goes through the gas under test, the light absorption occurs. According to the Lambert-Beer Law, there is

$$I = I_0 \exp[-\mu(v)PL], \tag{1}$$

where I is the input optical power, I_0 is the output optical power, L is the length of the gas cell, P is the air pressure of the gas under test, and μ is the absorption coefficient of the methane. If P_t is the reference pressure, we have

$$P = P_t C, \tag{2}$$

where C is the concentration of the gas under test. Moreover, the gas absorption coefficient μ can be given as

$$\mu(v) = Sg(v - v_0)N, \tag{3}$$

where S is the absorption lines intensity, g is the normalized linear function, N is the gas particle population per volume per air pressure, v is the wave number of the

optical frequency, and v_0 is the wave number of the central frequency of the gas absorption band.

According to the gas state equation, for the gas particles in unit volume, under unit pressure and temperature T, the particle population N can be expressed as

$$N = \frac{1}{KT}, \tag{4}$$

where K is the Boltzmann constant.

With Eqs. (1)–(4), we can have another expression of the Lambert-Beer Law as

$$I = I_0 \exp[-\alpha(v)CL]. \tag{5}$$

Moreover, the absorption coefficient can be defined as

$$\alpha(v) = Sg(v - v_0)\frac{P_t}{KT}. \tag{6}$$

The linear function g shows that the absorption coefficient varies with optical frequency, e.g., the linewidth broadening. For the gas under test, the linewidth broadening was mainly caused by the homogeneous broadening (Lorenz linetype), and the molecular heat motion induced Doppler inhomogeneous broadening (Gauss linetype). The Lorenz linetype broadening was caused by the collision among the particles, which depends on not only air pressure but also on molecular collision surface; while the Gauss linetype broadening depends only on temperature T.

For our case, the experiment was carried out under standard atmospheric pressure ($P_t = 1$ atm), room temperature of 296 K, and $N = 2.868 \times 10^{19}$ mol·cm^{-3} [6]; thus, linewidth broadening was mainly for the Lorenz linetypes. We have

$$g(v - v_0) = \frac{1}{2\pi} \cdot \frac{\Delta v}{(v - v_0)^2 + (\Delta v/2)^2}, \tag{7}$$

$$\Delta v = 2\gamma \left(\frac{296}{T}\right)^n P_t, \tag{8}$$

where Δv is the half width of the collision broadening, γ is the pressure induced broadening coefficient, and n is the temperature coefficient.

From Eqs. (6)–(8), we can deduce the gas absorption coefficient. As the gas absorption lines were densely spaced, the gas absorption coefficient at the frequency v was superimposed by multiple spectral lines. We simulate the gas absorption with a broadband light source centered at 1650 nm using Matlab. Figure 1 shows that the simulation result of the relationship between the absorption coefficient and the wavelength of the optical source. Note that, here, we only consider the room temperature case. However, the change of the environment temperature could alter the absorption coefficient of the methane gas.

It can be seen in Fig. 1 that the largest absorption peak is at 1645 nm, while the absorption band around 1665 nm has a number of densely spaced absorption peaks. Figure 2 shows the absorption peak around 1645 nm. Figure 3 shows the absorption peaks within the 1665 nm band.

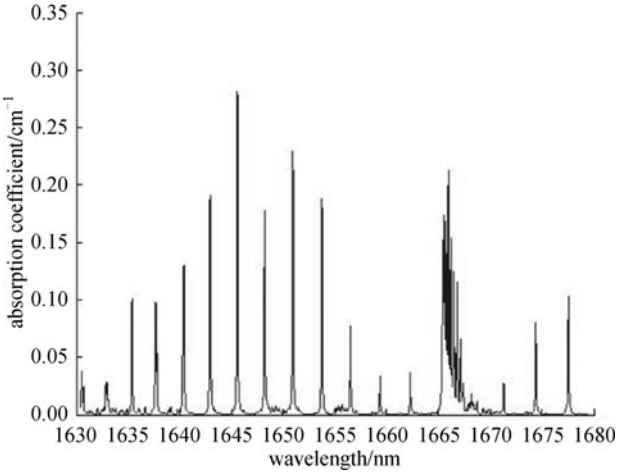

Fig. 1 Simulation result of relationship between methane gas's absorption coefficient and wavelength of light source from 1630 to 1680 nm (under the standard atmospheric pressure $P_t = 1$ atm at room temperature of 296 K)

3 Experimental results

The experimental setup is shown in Fig. 4. An SLD (Denselight SLED DL-CS65M5A) with the center wavelength at 1650 nm and a total output power of 10 mW was used as the light source. Moreover, after the light went through the gas cell to interact with the methane gas, we monitored the output spectrum with an optical spectrum analyzer (Agilent 86140B).

The gas cell was mainly formed by five pairs of collimators, and each pair was separated by 10 cm, as shown in Fig. 5. The collimators was fixed onto a rectangular holder and cascaded together and placed inside the gas cell. When we let the gas under test enter into the gas cell, the light from the SLD broadband source interacted with the gas under test between the collimators.

We pumped 5% methane into the gas cell and monitored the output optical spectrum with the OSA, as shown in Fig. 6. The strong absorption wavelength bands are ~1645 and ~1666 nm. The output spectrum within these two wavelength bands are also measured and shown in Figs. 7 and 8. As seen in Figs. 1 and 6, the absorption wavelengths in the experimental result agree well with those in the simulation result. The peak absorption wavelength of the experimental result in Fig. 7 coincides with the peak absorption wavelength in the simulation result in Fig. 3, which is at 1665.8 nm. Moreover, the peak absorption wavelength, 1645.56 nm, in this wavelength band was

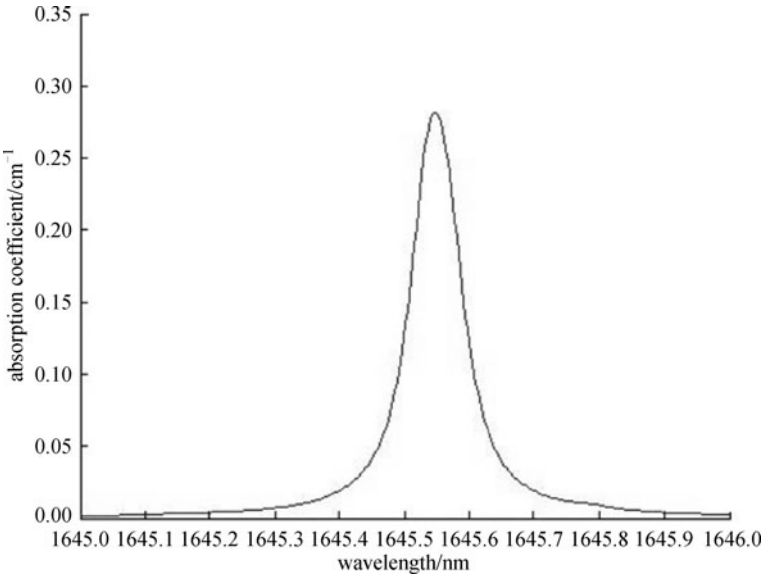

Fig. 2 Simulated methane's absorption coefficient at 1645 nm

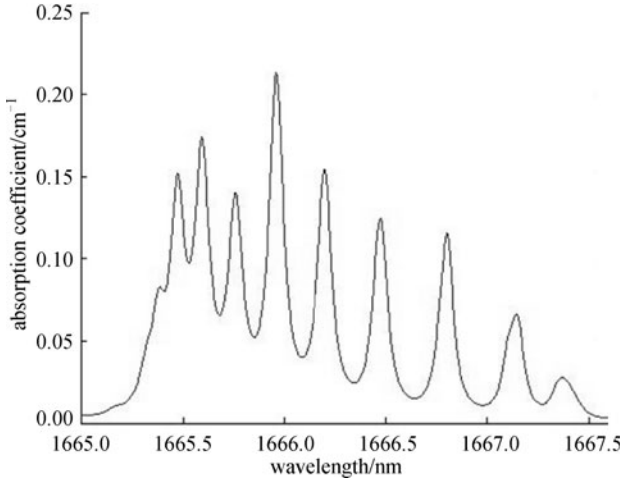

Fig. 3 Simulated methane's absorption coefficient from 1665 to 1668 nm

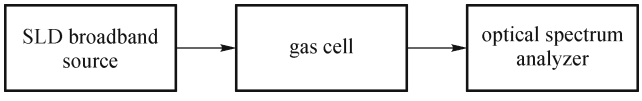

Fig. 4 Schematic diagram of fiber-optic gas sensor system

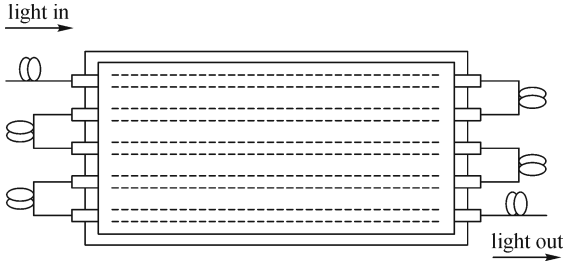

Fig. 5 Schematic diagram of collimators within gas cell where gas under test interacts with light from SLD

almost identical in Figs. 2 and 8, and the bandwidth of the absorption was around 0.1 nm.

In Fig. 3, we can see that the simulation result of the absorption coefficient at the peak absorption wavelength, 1665.8 nm, is 0.28 cm^{-1}. However, the experimental result showed an absorption coefficient of ~0.31 cm^{-1}, which was slightly different from the simulation. This is probably because the actual gas concentration in the gas cell was slightly less than the gas concentration of the gas under test as there was some air in the gas cell before we pumped in the methane gas. In addition, the minimal gas measured concentration is 0.01%.

4 Conclusion

We proposed a fiber-optic sensor system for the detection of the methane gas and demonstrated experimentally. The absorption coefficient of the methane gas was theoretically simulated under standard atmosphere pressure and room temperature conditions. The experimental results confirmed the simulation. The discrepancy between the experimental results and simulation results is due to the inaccurate gas concentration used in the calculation.

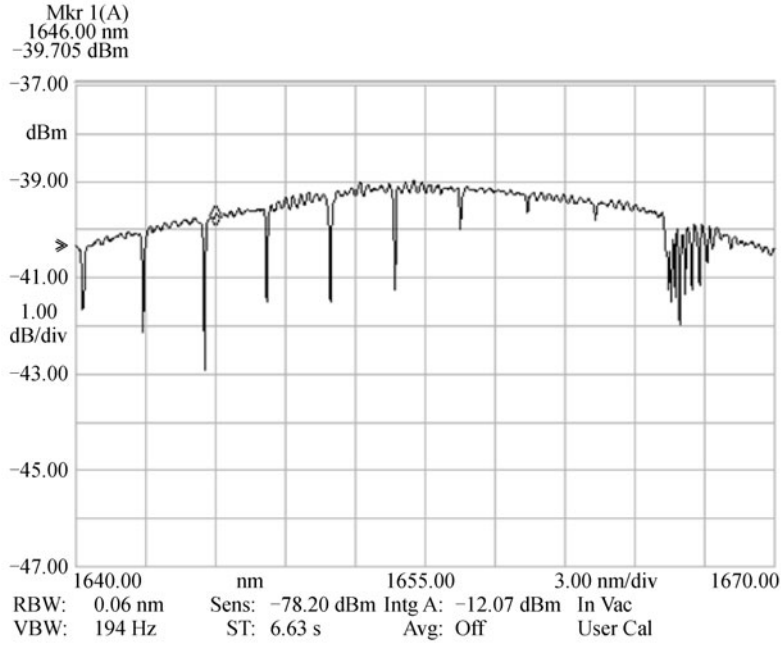

Fig. 6 Measured output spectrum (from 1640 to 1670 nm) of light source after 5% methane gas pumped into gas cell

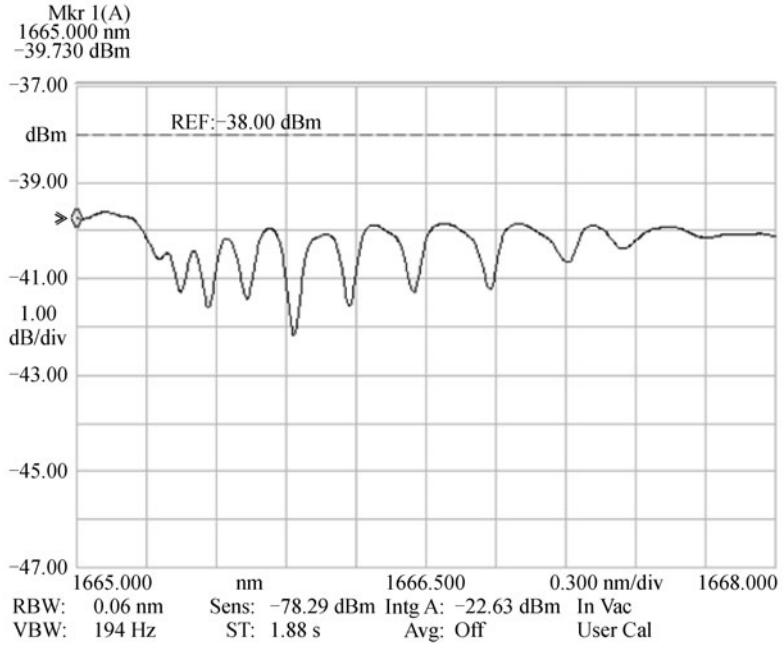

Fig. 7 Measured output spectrum from 1665 to 1668 nm when 5% methane was pumped into gas cell

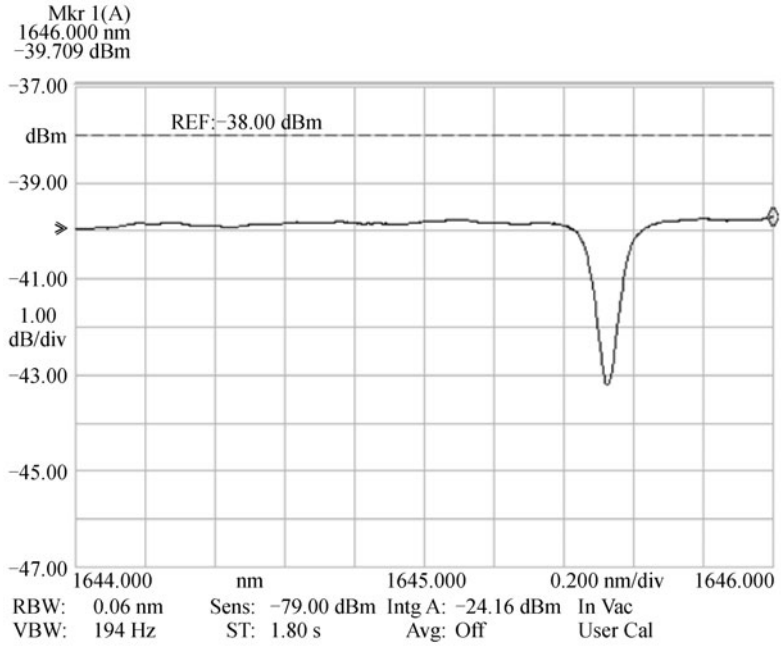

Fig. 8 Measured output spectrum from 1644 to 1646 nm when 5% methane was pumped into gas cell

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