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Abstract. We report our research on the development of a gas detection system for environmental application. The CO_2 concentration of a remote site is detected with near-infrared laser spectroscopy. Light from a thermal-tuning DFB laser, whose wavelength is close to 1.57 μm, is delivered to/from the remote gas cell via silica optical fiber. The low transmission attenuation of 0.2 dB/km promises long distance CO_2 sensing in the length of the gas cell in our experiment is 20 cm only, and detection accuracy of CO_2 is 1%. *© 2013 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.OE.52.1.010502]

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1 Introduction

Carbon capture and storage have been identified as effective means to control global warming.[1] CO_2 sequestration is newly developed carbon storage approach, through which CO_2 is pumped into the ground for long-term storage. Real-time large-range CO_2 monitoring on ground and underground helps to estimate the CO_2 movement and leakage, and is essential for CO_2 sequestration.[2]

Traditional electrochemical or semiconductors CO_2 sensors are cross sensitive to other chemical species, and cannot work under high temperature and high humidity, hence are not appropriate for CO_2 sequestration applications.[3,4] Laser spectroscopic sensors measure the gas-specific molecular vibration energy level and are thus crosstalk free. If the laser is delivered via optical fiber, the totally passive configuration of the sensing probe ensures that it can work under critical conductions. CO_2 has a strong absorption at middle infrared range, however, the attenuation of middle infrared light in optical fiber is very high and only be delivered to hundred of meters away.[5] In our system we selected to use 1.57 μm light, at which CO_2 has a weak unique absorption, and the attenuation of such light in silica optical fiber is 0.2 dB/km only. The absorption strength around 1.57 μm is so weak that the interaction length of the light and CO_2 is usually of dozens of meters or even longer, which is not practical for CO_2 sequestration applications. In this letter we use correlation and optimization approaches for data processing, and realize 1% CO_2 accuracy for gas cell as short as 20 cm.

2 Redundant Linear Equations

As shown in Fig. 1, light from a DFB laser passes through a long silica optical single mode fiber (SMF-28), gets modulated by the concentration of CO_2 in the gas cell, passes silica fiber again and is then detected by a photo detector. Under the control of a computer, the wavelength λ of the laser is scanned across an absorption line of CO_2 around 1572 nm by tuning the working temperature of the laser, and according to the Beer's law, the light power received by the photo detector can be expressed as

$$P(\lambda) = P_0 e^{-\sigma(\lambda)L\rho} \approx P_0 - P_0\sigma(\lambda)L\rho, \tag{1}$$

where P_0 is the received power in the absence of gas absorption, L is the optical path length of the gas cell, $\sigma(\lambda)$ is the absorption coefficient of CO_2, and ρ is the concentration of CO_2. For a 20-cm-long gas cell, the absorption is typically less than 10^{-3}, so we apply the first-order Taylor's approximation in Eq. (1) for simplicity. During the scan of wavelength, the ratio of the time-varying component over the DC component can be expressed as a function of ρ:

$$R[\lambda(t)] = \frac{-P_0\sigma(\lambda)L\rho}{P_0} = -\sigma[\lambda(t)]L\rho. \tag{2}$$

In our application, the gas pressure is approximately 1 ATM, thus $\sigma(\lambda)$ can be regarded as a fixed Lorentzian-like curve. We pre-measured the spectral ratio $R_{100}(\lambda)$ for 100% CO_2, and use it as a reference to solve the optimal ρ solution of a redundant linear equations:

$$\begin{bmatrix} R(\lambda_1) \\ R(\lambda_2) \\ \vdots \\ R(\lambda_N) \end{bmatrix} = \rho \begin{bmatrix} R_{100}(\lambda_1) \\ R_{100}(\lambda_2) \\ \vdots \\ R_{100}(\lambda_N) \end{bmatrix} + A. \tag{3}$$

There are only two unknown variables in Eq. (3), but N is usually over 1000. This redundant condition helps to improve the detection accuracy of CO_2 concentration.

3 Spectral Shift Correction

Figure 2(a) shows four typical absorption spectral ratio curves we detected under the same condition. They should be the same in theory, however, due to the hysteresis phenomenon of the temperature control, a spectral error up to 0.1 nm was observed among different scans. As Eq. (3)

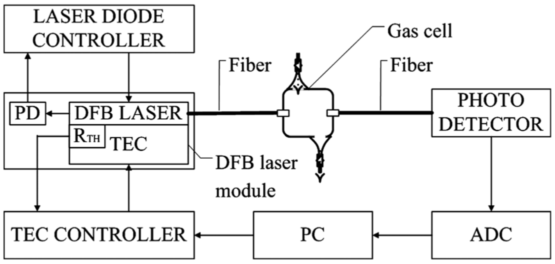

Fig. 1 Laser spectroscopy setup for gas sensing.

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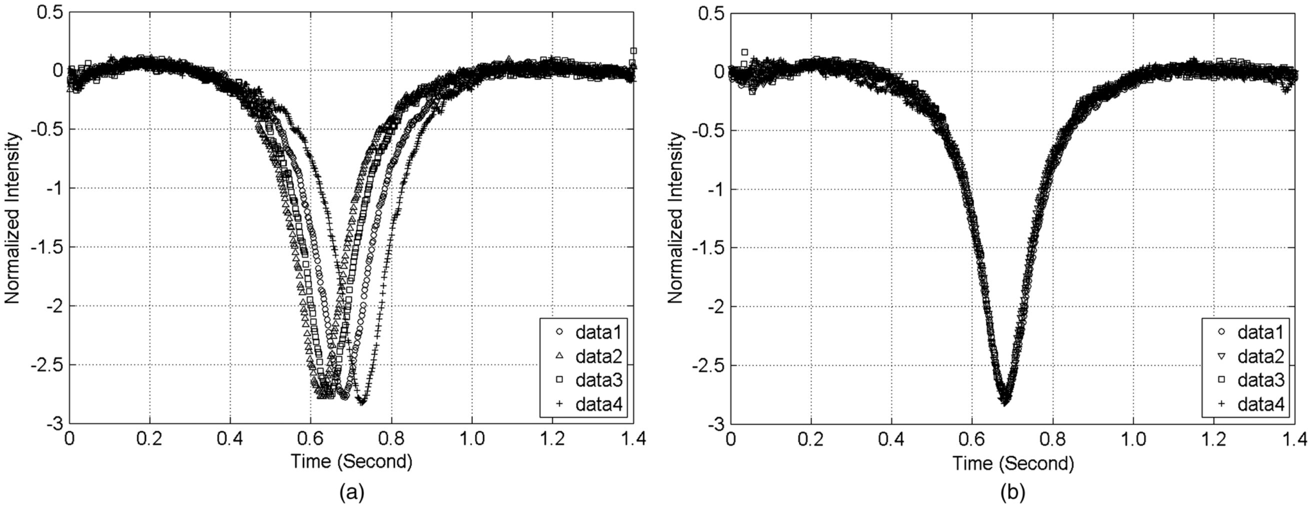

Fig. 2 Compensate the instability of thermal tuning. (a) original collected spectra for pure CO_2 whose absorption lines shift randomly; (b) the shift was compensated by correlation algorithm.

depends not only on the absorption amplitude but also on the spectral information, such wavelength instability will degrade the demodulation accuracy of CO_2concentration significantly. A spectrum correlation approach[6] is used to solve the problem:

1. For each spectral ratio $R_m(\lambda_n)$, $m = 1, 2 \ldots M$, $n = 1, 2, \ldots N$, its effective center q_m is estimated as

$$q_m = \frac{1}{N} \sum_{n=1}^{N} n * R_m(\lambda_n). \tag{4}$$

2. For $m = 2, 3, \ldots M$, calculate the cross correlation of R_m and R_1 for delay values in the vicinity of $q_m - q_1$, and find the optical delay τ_m where the correlation is maximum.
3. Shift $R_m(\lambda_n)$ by τ_m, the spectral instability is then solved.

Figure 2(b) shows the correction results for spectra given in Fig. 2(a).

4 Experimental Results

By changing the operation temperature, the wavelength of the DFB laser was scanned from 1571.0 nm to 1572.5 nm, covering one of the CO_2's absorption lines at 1572.23 nm. CO_2 samples whose concentration ranged from 0% to 90%, were tested, and the data were analyzed with correlation and optimization approaches as described in Secs. 2 and 3. Measurement is repeated 10 times to estimate the test stability. Figure 3 shows typical absorption spectra obtained for eight different CO_2 concentrations, and the estimated concentration values are given in Fig. 4, where error bars are used to show the repeatability of the results under same test conditions. The error bar demonstrates that the standard deviation is ~1%. We hence conclude that the system detection accuracy is 1% and the resolution is higher than 1%.

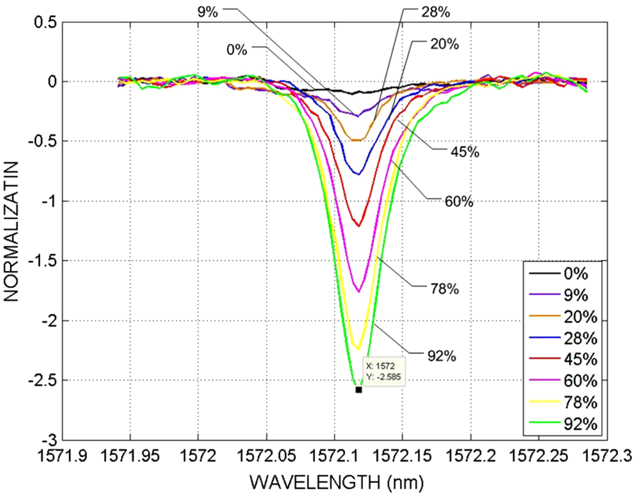

Fig. 3 Typical measured spectra at different CO_2 concentrations.

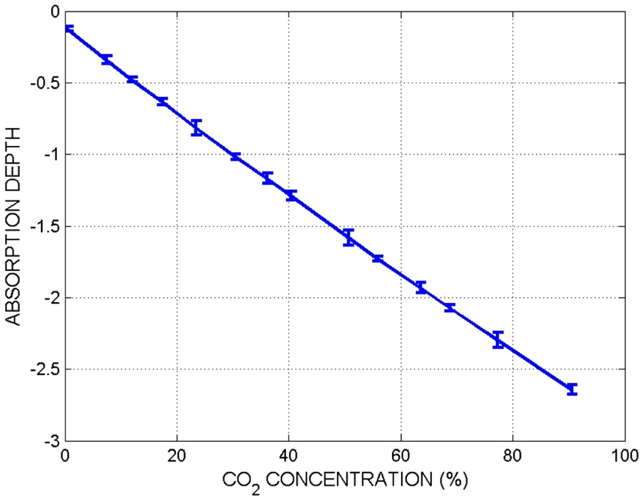

Fig. 4 Estimated concentrations with error bar.

5 Conclusion

For CO_2 sequestration application, the background (concentration of CO_2 in normal air) is around 0.03%, while the signal level (leakage concentration) usually ranges from 1% to 100%. The 1% detection accuracy we have obtained is sufficient for CO_2 sequestration monitoring. Moreover, the system is based on near-infrared, the low attenuation and reliable performance of silica fiber ensures the long distance and large range remote sensing.

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Biographies and photographs of the authors are not available.