Improved low concentration gas detection system based on intra-cavity fiber laser

Hongxia Zhang,[1,2,a)] Kun Liu,[1,2] Dagong Jia,[1,2] Tianhua Xu,[1,3] Tiegen Liu,[1,2] Gangding Peng,[1,4] Wencai Jing,[4] and Yimo Zhang[1,2]

[1]*College of Precision Instrument and Opto-electronics Engineering, Tianjin University, Tianjin 300072, China*

[2]*Key Laboratory of Opto-electronics Information and Technical Science (Ministry of Education), Tianjin University, Tianjin 300072, China*

[3]*Royal Institute of Technology, Stockholm SE-16440, Sweden*

[4]*School of Electrical Engineering and Telecommunications, UNSW, Sydney, New South Wales 2052, Australia*

ABSTRACT

The improvement of a low concentration gas detection system based on the intra-cavity fiber laser is proposed in this paper. The sensitivity of the system is deduced based on Lambert-Beer law. The optimized system was established with the gas cell made elaborately. In order to apply the wavelength sweeping technique (WST), the FBG grating reflector was substituted by the wavelength independent Faraday rotation reflector. The sensitivity of the system for acetylene detection is reduced to less than 100 ppm by using the average of three absorption spectra. The acetylene detection coefficients of variation with different concentrations are measured. The gas measurement system is validated to detect low concentration gas effectively.

Keywords: Gas sensing; Gas detection; Intra-cavity fiber laser; Wavelength sweeping; optical sensing

1. Introduction

Detection of low concentration poisonous gas is extremely important in environment and pollution monitoring[1][2].Optical fiber sensors based on the absorption spectrum in the low loss window (1~2μm) of silica fiber have been studied extensively for gas detection[3]. It has been found that many important pollutant or inflammable gases such as acetylene (C_2H_2), methane (CH_4) and carbon monoxide (CO) have absorption spectral lines in this wavelength range, which can be detected using the fiber optic sensors. The fiber intra-cavity spectroscopy is a widely used technique due to the high sensitivity of intra-cavity detection and the advantages of fiber optic sensors such as remote detection and multiplexing capability[2][4][5].

Operating in the near infrared region of 1~2μm, we have only access to the overtone absorption spectral lines which are significantly weaker than the fundamental lines[6]. Many methods including wavelength sweeping technique [7], sensitivity enhancement technique [3] and wavelength modulation technique [8] have been applied to improve the detection sensitivity. But the system performance in terms of the minimum detectable gas concentration is not as good as expected due to the limitation of various noise factors, especially the amplified spontaneous emission (ASE) noise.

In this paper, the improvement of a gas sensing system is illustrated in detail. Gas cell and reflector are emphasized as the key factors to improve the system. Wavelength sweeping technique is applied in the fiber intra-cavity gas sensing system using erbium-doped fiber ring lasers, and several absorption spectra of acetylene are obtained. Low concentration detection of gas is realized by averaging these spectra. The experimental setup of gas concentration detection is illustrated in detail. The experimental results are discussed, and the coefficients of variation with different concentrations are measured.

2. Gas detection system

2.1 Principle of gas detection

The structure of the fiber intra-cavity gas detection system (FICGDS) based on erbium-doped fiber ring lasers is shown in Fig.1. The system consists of an erbium-doped fiber (EDF) forward pumped by a 980-nm pump laser, an isolator, a tunable attenuator, a Fabry-Perot (F-P) type tunable optical filter (TOF), and a gas of interest. The detector is used to measure the output optical power spectrum of the FICGDS.

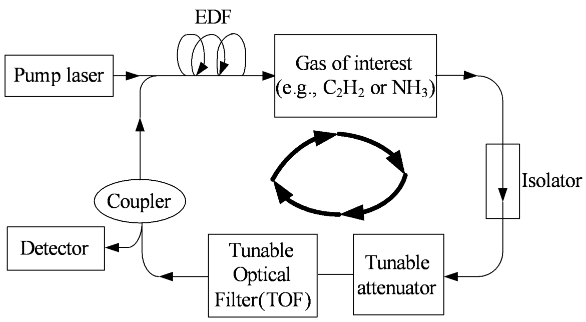

Fig. 1 Structure of fiber intra-cavity gas detection system based on fiber ring lasers.

In absorption gas detection, the light transmitted through the absorber together with the spectral extinction. The extinction follows the Lambert-Beer law [9], which can be analyzed as,

$$I(\upsilon) = I_0(\upsilon)\exp[-\alpha(\upsilon)\cdot c\cdot L] \tag{1}$$

Where $I(\upsilon)$ and $I_0(\upsilon)$ are the laser output power with and without the absorber in the cavity, respectively, $\alpha(\upsilon)$ and c are the cross section and the concentration of the absorber respectively, and L is the optical path length of the absorber.

The absorption signal K in the transmitted spectrum is defined as [10]

$$K = \ln\frac{I_0}{I} \tag{2}$$

where $I = I_0 - \Delta I$, ΔI is the reduction of the output power due to the absorption-induced variation in the cavity loss $\Delta\delta$. For a small absorption signal $\Delta I << I_0$, Eq.(2) can be approximated as:

$$K = \frac{\Delta I}{I_0} \tag{3}$$

The sensitivity enhancement factor in terms of $K/\Delta\delta$ can be described as

$$\frac{K}{\Delta\delta} = \frac{\Delta I}{I\Delta\delta} \propto \frac{A}{\delta(A-B\delta)} \tag{4}$$

where A and B are the coefficients dependent on the parameters of the intra-cavity fiber laser (ICFL) [10]. The gas concentration detection precision based on ICFL depends on the signal-to-noise ratio (SNR) of the output laser. The gas concentration with the laser power variation 3dB larger than ASE noise is defined as the detection precision. According to Eq. (1) and Eq. (3), the sensitivity of gas concentration can be expressed as [10]

$$Sen_{in} = \left(\frac{2\times 10^{-SNR/10}}{\alpha L}\right)\bigg/\left(\frac{N_A}{V_m}\right) \tag{5}$$

where N_A and V_m are Avogadro constant and the molar volume respectively. The absorption coefficient and the absorption optical length of the gas are $\alpha = 1.21\times10^{-20}\, cm^{-1}/(molecule \cdot cm^{-3})$ and $l = 10\, cm$ respectively. The sensitivity will reach 62 ppm with SNR equal to 40 dB, while the detectable gas sensitivity will reach 6 ppm with the SNR equal to 50 dB. According to the conclusion from the research of Zhang *et al*, high sensitivity can be obtained when the system works approaching the threshold [11]. However, the SNR will decrease due to the ASE noise at the same time. So the SNR can not be very large. According to the numerical calculation, the system has the sensitivity approaching to magnitude of ppm.

2.2 Improved design of gas sensing system

In Fig.1, the EDF is pumped by a 980-nm pump laser via a 980/1550 WDM coupler. The gas of interest is injected into the gas cell. The gas cell with a reflector is coupled into the main cavity by using a circulator. The output signal can be monitored by the photo-detector after the coupler. The isolator is used to ensure unidirectional operation and prevent spatial hole-burning [12]. When the gas cell is placed in the ICFL, the signal will pass through the cell repeatingly, which can effectively transforms the short gas cell into a highly efficient multi-pass system. This improves the sensitivity of the system [13].

2.3 Improved gas cell

The gas cell is made with aligning a pair of commercial pigtailed C-lens instead of GRIN lenses. The light is collimated by the C-lens, and the radius of facular is directly measured by the infrared CCD. The relationship between the radius of facular and the distance between C-lens and CCD is shown in Fig.2. The nominal working distance of the C-lens is 200mm. From the Fig.2, it can be seen that the beam diverges rapidly and the facular decreases speedily with the distance exceeding 200mm. Therefore, the working distance of the C-lens should be less than 200mm.

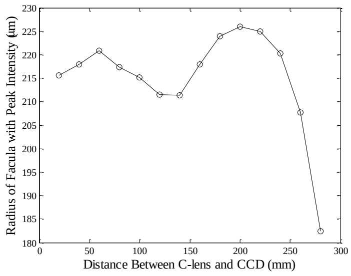

Fig.2 The relationship between radius of facular and distance of the C-lens and CCD

The practical effective length and the cross diameter of gas cell are 10cm and 15mm respectively, with insertion loss of 1.84dB. The gas cell main part is made by cold-rolled steel and the flanges in two sides are corrected with concentric arrangement. Interference fit joint is adopted to guarantee the gas cell obturation between the flange and the main part. There are two thread grooves near the flanges, which is connected with gas tube respectively. One gas tube is responsible for the input gas, while the other is responsible for the output gas. The photograph of the gas cell is shown in Fig.3.

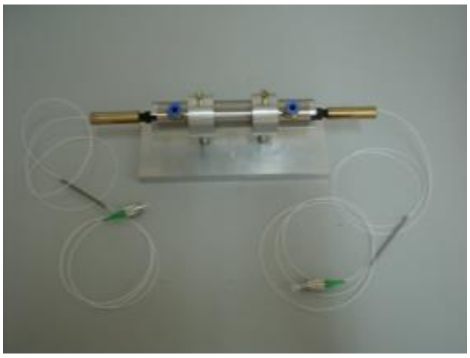

Fig.3 Photograph of gas cell

2.4 Improved reflector

In Zhang's work [5], the fiber Bragg grating (FBG) is acted as wavelength selection device. The gas can be detected by fine tuning the wavelength of the tunable filter to the operation wavelength of FBG with strain, which is aligned to particular absorption lines of the detected gas. But in our system, the FBG is substituted by the Faraday rotation reflector. The Faraday rotation reflector can reflect light with wide wavelength range, and can overcome the fluctuation of signal due to FBG shift. Thus the sensitivity can be improved. The reflector is a wavelength independent device, and so the wavelength sweep technique can be used to detect multi gas absorption lines simultaneously.

2.5 Wavelength sweep technique

In the FICGDS, the F-P type TOF is used as the wavelength sweeping controller. The bandwidth and the free spectral range (FSR) of the TOF are 1.25 GHz and 11.23 THz, respectively. The data acquisition card (DAQ) outputs the sawtooth voltage and drives the TOF after amplification [13]. In one tuning period, all the absorption lines of different gases can be detected.

2.6 Experimental setup

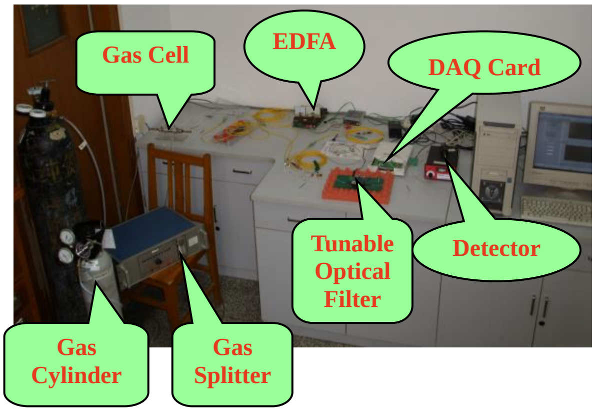

Fig.4 Photograph of gas detection system

The complete photograph of the gas detection system setup used is as shown in Fig.4. The different concentration gas is injected into gas cell from the gas cylinder and gas splitter and after mixture. The input and output gas tubes provide the balanced concentration inside the gas cell. The DAQ card is performed using USB-6251 (NI Corporation), and the TOF is FFP-TF2 (Micro Optics).The gain of EDFA (Erbium-Doped Fiber Amplifier) is about 37 dB. The InGaAs PIN detector detects the light power, which is then input to the computer for data processing.

3. Experimental results and Discussions

Take acetylene as an example for analyzing the experiment results. The driver voltage of the TOF is swept from 5.6 V to 7.2 V, which corresponds to the pass-band of the TOF scanning around 1530 nm. The three absorption spectral lines can be found obviously. The output signal of the detector and its second derivative are shown in Fig.5. It is illustrated that the positions of the absorption spectra (solid line) are accordant with the peaks in the second derivative curve (dot line), which can be used to realize the automatical recognition of the absorption lines.

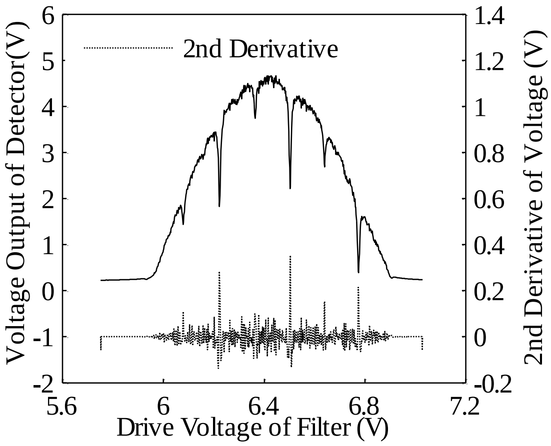

Fig.5 absorption spectra of acetylene

3.1 Gas concentration detection results

The absorption lines intensity will be recorded, and the calibrated gas concentration detection curve can be analyzed correspondingly. The experimental result is shown in Fig.6, where the acetylene concentration in the gas cell changes from 3000ppm to 9000ppm with an interval of 2000ppm. The spectrum 1, spectrum 2 and spectrum 3 correspond to the spectra in Fig.5 from left to right, and the corresponding wavelengths are 1531.588nm, 1530.371nm and 1529.180nm, respectively. The red curve is the ideal value, and the black curve is the average of the three spectral measurement values. The black curve is closer to the ideal value than the individual absorption line measurement value. It can be seen that the absolute error of gas concentration detection is less than 100ppm and the relative error is less than 3％.

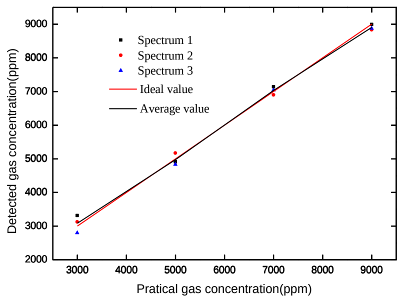

Fig.6 Acetylene concentration detection

3.2 Gas concentration detection repeatability

The repeated experiments of gas concentrations detection are used to evaluate the consistence of absorption intensities measurement with the same gas concentration and test condition. The repeatability is expressed by the coefficient of variation (CV), which is defined as

$$\mathrm{CV} = \frac{\sigma}{\bar{x}} = \sqrt{\frac{\sum_{i=1}^{n}\left(x-\bar{x}\right)^2}{n}} \Bigg/ \bar{x} \quad (5)$$

where σ and $\bar{x}$ are the standard deviation and the mean value in several consecutive measurements. The relationship between CV and the concentration of different acetylene spectra is shown in Fig.7. The CV is less than 0.062 at all concentrations and this means the error of gas detection is no more than 6.2％. Because the absorption spectrum 3, which corresponds to the 1529.180 nm wavelength, is closest to the threshold of the system, it will increase the ASE noise [8]. The CV of spectrum 3 is higher than the other spectra.

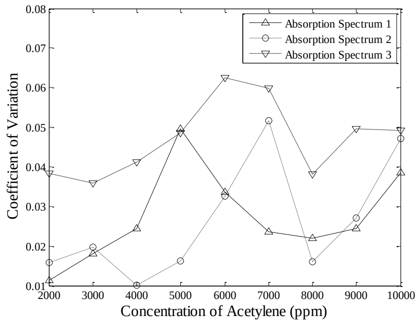

Fig.7 CV vs. concentration of acetylene

3.3 Discussions

Compared with Zhang's work [11], multiple absorption lines can be obtained in one scanning measurement using the WST instead of the fine tuning of the FBG wavelength. Further, the absorption lines with different absorption cross section can also be calibrated separately. One scanning measurement with WST is equal to multiple independent detections. Meanwhile, the creeping of the TOF can also be overcome by using WST [7]. Moreover, the gas cell provides the better performance due to the longer working distance and lower insertion loss of the C-lens [14].So the gas detection system is improved compared to conventional system. The detection sensitivity has be greatly improved compared with the reported minimum detectable concentration of 2253 ppm [11]. However it is beautiful yet incomplete that the CV value of repeatability is still higher than the practical measurement requirement. As the FICGDS works near the threshold of the system, it will induce the fluctuation of the laser output power and the enlargement of the ASE noise. The SNR of the system will be degraded correspondingly. More work is required to suppress or separate the noise, and the detection sensitivity can be further improved.

On the other hand, more gas absorption will improve the detection sensitivity based on Lambert-Beer law. The length of gas cell is limited by the effective working distance of the C-lens. The C-lens with a longer working distance will be chosen later. Furthermore, the gas cell can be cascaded to increase the gas single pass absorption optical path. At the same time, the fiber ring laser can be optimized to increase the laser loop times. Therefore, the gas detection sensitivity can be further improved.

4 Conclusions

In the FICGDS, the multi-pass system leads that we could not obtain the accurate optical path length of the gas absorption, and the experiments need to be worked out to calibrate the gas concentration detection. With WST applied to the system, multiple gas absorption spectral lines with different absorption cross section can be obtained. The sensitivity of gas detection is better than 100ppm and the relative error is less than 3%. The CV of measurement repeatability for gas detection is less than 0.062. The experimental results show that the FICGDS gas sensing system is very effective to detect low concentration gas.

6 Acknowledgments

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