Intra-Cavity Absorption Sensors for Gas Detection Using Wavelength Sweep Technique

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Abstract—Wavelength sweep technique (WST) is introduced into intra-cavity fiber laser (ICFL) for low concentration gas detection. The limitation induced by noise can be eliminated using this method, and the performance of the system is improved. The sensitivity of the system is reduced to less than 300 ppm. With WST, sweeping characteristic of the ICFL can be described according to known gas absorption spectra.

Index Terms—Gas detection, optical fiber laser, spectrum analysis, wavelength measurement.

1. Introduction

Detection of pollution gas is important in environmental and pollution monitoring [1]-[3]. Widely tunable laser operating in the near infrared is the best option due to the economical components provided by telecommunication industry and low cost [2][4]. The implementation of intra-cavity spectroscopy would allow a detection system with very high sensitivity of intra-cavity detection and the advantages of fiber-optic sensors including remote detection and multiplexing capability [2][5]-[8]. Recently, there have been considerable interests in developing intra-cavity spectroscopy [2][5]-[8], including sensitivity enhancement and wavelength modulation. 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 [3][8].

In this paper, wavelength sweep technique (WST) is applied to intra-cavity fiber laser (ICFL), and several absorption spectra can be obtained. Low concentration detection of gas is realized by analyzing these spectra. And the sweeping characteristic of the ICFL can also be illuminated by these spectra.

2. System and Experiments

The experimental setup of the ICFL used for low concentration gas detection is shown in Fig. 1. The system contains an Erbium-doped fiber amplifier (EDFA), a Fabry-Perot type tunable optical filter (TOF), a gas cell, a photo-detector, and an isolator. The EDFA is pumped by a 980 nm pump laser via a 980/1550 WDM coupler. The bandwidth and the free spectral range (FSR) of the TOF are 1.25 GHz and 11.23 THz, respectively. The gas cell with a reflector is coupled into the main cavity by a circulator after selected by an optical switch. The photo-detector after a 50:50 coupler can monitor the output signal. The isolator is used to ensure unidirectional operation and prevent spatial hole-burning [9]. The gas cell is made by aligning a pair of commercial pigtailed C-lens, and the interaction length is about 50 mm. The longer working distance and the lower insertion loss of C-lens enable the gas cell with more favourable performance [10]. Multi-point gas detection can be realized in this system via the optical switch.

With the gas cell placed within the ICFL, the very large number of passes through the cell can effectively transform a short gas cell into highly efficient multi-pass system, and thus improve the sensitivity. According to rate equations, high sensitivity of gas detection can only be achieved when the ICFL is running close to the threshold [4][1][5][7]. The threshold can be approached by adjusting the pump current. When using wavelength sweeping instead of aligning the pass-band of the TOF to a particular absorption line of the gas, multi absorption lines with different absorption cross-section can be obtained. The concentration of the gas can be calculated using each spectrum in one scan. The average of all the results in the same scan is treated as the practical concentration, and thus the detection limitation is reduced sharply. At the same time, the creeping of the TOF can also be overcome.
Taking acetylene for example, when the driver voltage of the TOF is swept from 19.6 V to 21.2 V linearly, corresponding to the pass-band of the TOF scanning around 1530 nm, there are three absorption lines that can be seen obviously. And it takes about 90 seconds for one scan across these absorption lines. The output signal of the detector and its second derivative are shown in Fig. 2. 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 absorption lines recognition automatically. The concentration of the gas is proportional to the amplitude of the Gaussian fit spectrum. The relationship between the absorption intensities and the pump current is shown in Fig. 3. These lines are corresponding to the spectra in Fig. 2 from left to right. When the pump current is closed to 26 mA, the attenuations of the absorption lines increase sharply. When the pump current is set to 26.2 mA, the attenuations of the absorption lines are 4.35 dB, 2.60 dB, and 6.06 dB, respectively. The single-pass absorption attenuations tested by tunable laser are 0.12 dB, 0.13 dB, and 0.16 dB, respectively. So the enhancement factors are 35.6, 20.6, and 38.0 times over single-pass, respectively. When the acetylene concentration in the gas cell is changed from 2000 ppm to 9000 ppm with interval of 1000 ppm, the absorption spectra are collected through sweeping the drive voltage. The positions of the absorption lines and the absorption intensities can be calculated using experiments data.

3. Results and Analysis

The absorption intensities of different concentration are used for acetylene concentration calibration. The result is shown in Fig. 4. The markers are the experiments results, while the lines are the linear fit of the experiments data. These lines are corresponding to the spectra in Fig. 2 from left to right. It can be seen that the attenuations of the absorption intensities in logarithm unit vary approximately linearly with the acetylene concentration inside the gas cell. The slopes of the fit results are $-0.157 \text{dB/ppm}$, $-0.120 \times 10^{-3} \text{dB/ppm}$, and $-0.208 \times 10^{-3} \text{dB/ppm}$, respectively. Spectrum 2 has the largest absorption cross-section but its pump current is the farthest to the threshold, and it has the lowest sensitivity. Spectrum 3 has the smallest absorption cross-section but its pump current is the nearest to the threshold, and it has the largest sensitivity. So the primary influent factor of gas detection is in the extent close to the threshold of the system.
The concentration sensitivity of the system can be evaluated according to the slopes and the errors of linear fit. The errors of linear fit for these spectra are 0.0354 dB, 0.0311 dB, and 0.0286 dB, respectively. So the concentration errors are 226 ppm, 259 ppm, and 137 ppm, respectively. So the sensitivity can be limited less than 300 ppm when the system is used for acetylene detection, which is much more sensitive compared with minimum detectable concentration of 2253 ppm without WST. The sensitivity can be further reduced when using average algorithm. The performance of the system is improved remarkably when using WST.

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4. Conclusions

WST is applied to ICFL, which makes the low concentration gas detection possible. Combining with wavelength sweep and sensitivity enhancement, three spectra can be detected and used to calibrate the concentration of acetylene as validation. The automatic absorption recognition is realized through peak detection in the second derivative curve. The sensitivity of gas detection is higher than 300 ppm. It is also demonstrated that the linearity of the ICFL is higher than 99.79% for about 2.4 nm around 1530 nm.

References


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