Wavelength Sweep of Intracavity Fiber Laser for Low Concentration Gas Detection

Author:
Liu, K; Jing, W; Peng, Gang-Ding; Zhang, Jianzhong; Wang, Y; Liu, T; Jia, D; Zhang, H; Zhang, Y

Publication details:
IEEE Photonics Technology Letters
v. 20
Chapter No. 17-20
pp. 1515-1517
1041-1135 (ISSN)

Publication Date:
2008

Publisher DOI:
http://dx.doi.org/10.1109/LPT.2008.928526

Wavelength Sweep of Intracavity Fiber Laser for Low Concentration Gas Detection

Kun Liu, Wencai Jing, Gangding Peng, Jianzhong Zhang, Yan Wang, Tiegen Liu, Dagong Jia, Hongxia Zhang, and Yimo Zhang

***Abstract*—Wavelength sweep technique (WST) is introduced into intracavity 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 200 ppm. With WST, the 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.**

I. Introduction

DETECTION of pollution gas is important in environmental and pollution monitoring [1]–[3]. A 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 intracavity spectroscopy would allow a detection system with very high sensitivity of intracavity detection and the advantages of fiber-optic sensors including remote detection and multiplexing capability [2], [5], [6]. Recently, there has been considerable interest in developing intracavity 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 noise [3], [8].

Manuscript received April 20, 2008; revised June 10, 2008. This work was supported by the National Natural Science Fund of China under Contact 60577013, and by the New Century Support Program for Talented Young Teachers in Universities, MOE (Ministry of Education), China.

K. Liu, T. G. Liu, D. G. Jia, H. X. Zhang, and Y. M. Zhang are with the College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin 300072, China, and also with the Key Laboratory of Opto-Electronics Information and Technical Science (Tianjin University), Ministry of Education, Tianjin 300072, China (e-mail: beiyangkl@tju.edu.cn; tgliu@tju.edu.cn; dagongjia@tju.edu.cn; hxzhang@tju.edu.cn; ymzhang@tju.edu.cn).

W. C. Jing is with the College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin 300072, China, also with the Key Laboratory of Opto-Electronics Information and Technical Science (Tianjin University), Ministry of Education, Tianjin 300072, China, and also with the School of Electrical Engineering and Telecommunications, UNSW, Sydney NSW 2052, Australia (e-mail: wencjing@tju.edu.cn).

G. D. Peng is with the School of Electrical Engineering and Telecommunications, UNSW, Sydney NSW 2052, Australia (e-mail: G.Peng@unsw.edu.au).

J. Z. Zhang is with the Department of Physics, Harbin Engineering University, Harbin 150000, China (e-mail: zhangjianzhong@hrbeu.edu.cn).

Y. Wang is with Tianjin Key Laboratory of Biomedical Detection & Instruments, Tianjin University, Tianjin 300072, China (e-mail: wangyan@tju.edu.cn).

Digital Object Identifier 10.1109/LPT.2008.928526

In this letter, the wavelength sweep technique (WST) is applied to the intracavity 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.

II. 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–Pérot-type tunable optical filter (TOF), a gas cell, a photodetector, and an isolator. The EDFA is pumped by a 980-nm pump laser via a 980/1550 wavelength-division-multiplexing coupler. The bandwidth and the free-spectral range 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 selection by an optical switch. The photodetector 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 favorable performance [10]. Multipoint 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 a highly efficient multipass 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 [2], [3], [5], [7]. The threshold can be approached by adjusting the pump current. When using wavelength sweeping instead of aligning the passband of the TOF to a particular absorption line of the gas, multiabsorption lines with a 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.

Take acetylene for example. When the driver voltage of the TOF is swept from 19.6 to 21.2 V linearly, corresponding to the passband of the TOF scanning around 1530 nm, there are three absorption lines that can be seen clearly, and it takes about 90 s 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 (dotted line), which can be used to realize

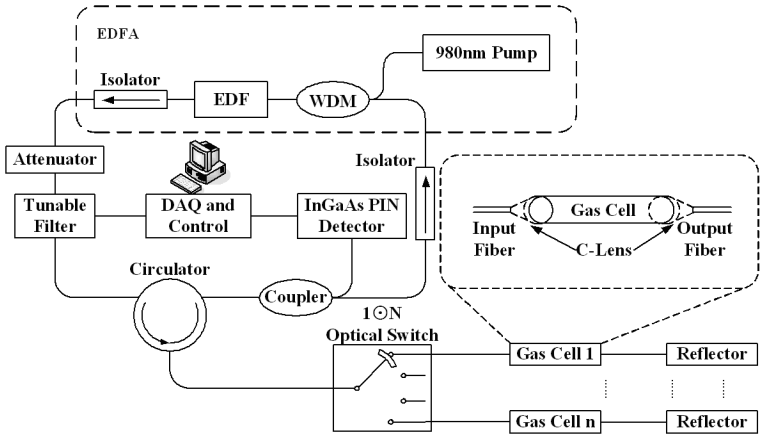

Fig. 1. Experimental setup.

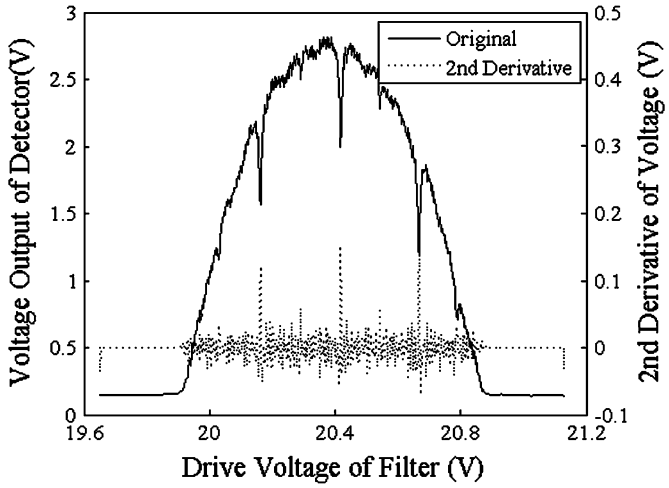

Fig. 2. Absorption spectra of acetylene.

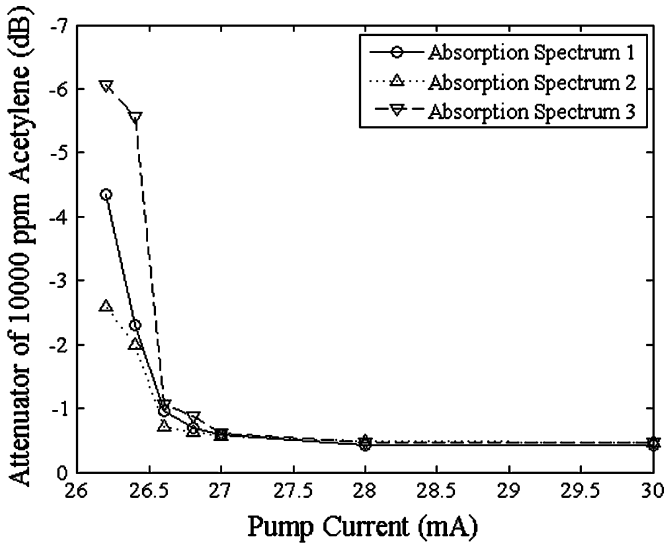

Fig. 3. Absorption intensity versus pump current.

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, 2.60, and 6.06 dB, respectively. The single-pass absorption attenuations tested by tunable laser are 0.12, 0.13, and 0.16 dB, respectively. So the enhancement factors are 35.6, 20.6, and 38.0 times over single-pass, respectively. The absorption cross sections of these absorption lines are 1.17×10^{-20} cm^{-1}/(molecule cm^{-3}), 1.21×10^{-20} cm^{-1}/(molecule cm^{-3}), and 1.14×10^{-20} cm^{-1}/(molecule cm^{-3}), respectively [11]. The absorption spectrum 3 with the smallest absorption cross sections has the largest attenuation enhancement factor, because it runs at the nearest position to the threshold of the laser. When the acetylene concentration in the gas cell is changed from 2000 to 8000 ppm with an 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 the experiment's data.

III. Results and Analysis

The absorption intensities corresponding to 2000, 4000, 6000, and 8000 ppm are used for acetylene concentration calibration. The result is shown in Fig. 4. The markers are the experiment's results, while the lines are the linear fit of the experiment's data. These lines are corresponding to the spectra in Fig. 2 from left to right. It can be seen that the absorption intensities vary approximately linearly with the acetylene concentration inside the gas cell. The slopes of the fit results are -0.157, -0.111, and -0.202 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 the extent of close to the threshold of the system.

When the gas cell is filled with 3000, 5000, and 7000 ppm of acetylene, the absorption spectra are detected and the absorption intensity can be obtained. The acetylene concentration can be also gained by averaging the results calculated using the calibration coefficients and the absorption intensities correspondingly.

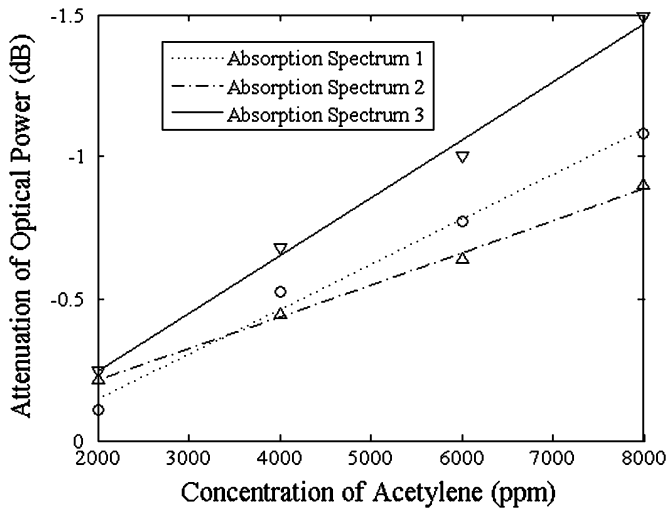

Fig. 4. Calibration of concentration detection.

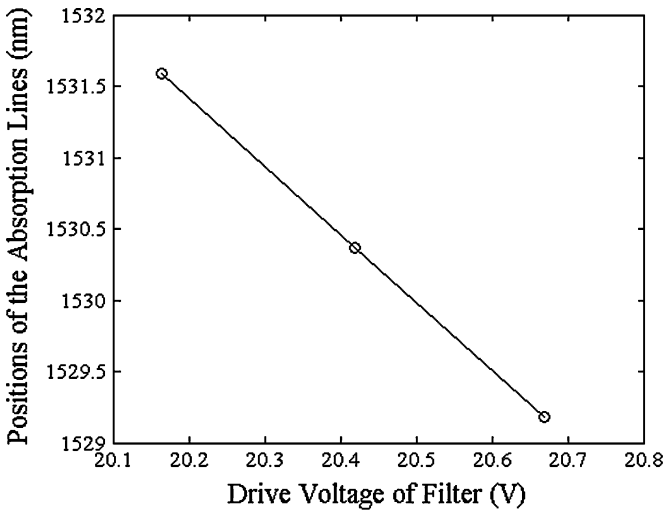

Fig. 5. Relationship between the positions of the absorption lines and the drive voltage of the filter.

It is shown that the absolute errors are 190, 73, and 54 ppm for the concentrations mentioned above, respectively. So the sensitivity can be limited less than 200 ppm when the system is used for acetylene detection, which is much more sensitive compared with a minimum detectable concentration of 2253 ppm without WST [3]. The performance of the system is improved remarkably when using WST.

On the other hand, the positions of the spectra can be used to reflect the sweeping characteristic of the ICFL. The practical wavelengths of acetylene absorption spectra near 1530 nm are 1531.588, 1530.371, and 1529.180 nm. The positions of the absorption lines in the detected spectrum are corresponding to them, so the relationship between them must be linear. The linear fit between the positions of the absorption lines and the drive voltage of the filter corresponding to the absorption lines is shown in Fig. 5. The deviation is under 5 pm when the concentration of acetylene in the gas cell is varied. So the wavelength sweeping of the ICFL has the linearity higher than 99.79% for about 2.4 nm around 1530 nm.

IV. Conclusion

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 200 ppm by averaging the results for each absorption line. It is also demonstrated that the linearity of the ICFL is higher than 99.79% for about 2.4 nm around 1530 nm.

References

[1] G. Stewart, *Optical Fiber Sensor*. Dordrecht: Kluwer, 1999, ch. 5.
[2] G. Stewart, K. Antherton, H. Yu, and B. Culshaw, "An investigation of an optical fibre amplifier loop for intra-cavity and ring-down cavity loss measurements," *Meas. Sci. Technol.*, vol. 12, pp. 843–849, Jul. 2001.
[3] Y. Zhang *et al.*, "Investigation of erbium-doped fiber laser intracavity absorption sensor for gas detection," *Opt. Commun.*, vol. 234, pp. 435–441, Apr. 2004.
[4] J. Cousin *et al.*, "Application of a continuous-wave tunable erbium-doped finer laser to molecular spectroscopy in the near infrared," *Appl. Phys. B*, vol. 83, pp. 261–266, May 2006.
[5] Y. Zhang, W. Jin, H. B. Yu, M. Zhang, Y. B. Liao, H. L. Ho, M. S. Demokan, G. Stewart, B. Culshaw, and Y. H. Li, "Novel intracavity sensing network based on mode-locked fiber laser," *IEEE Photon. Technol. Lett.*, vol. 14, no. 9, pp. 1336–1338, Sep. 2002.
[6] Y. Zhang, M. Zhang, and W. Jin, "Multi-point, fiber-optic gas detection with intra-cavity spectroscopy," *Opt. Commun.*, vol. 220, pp. 361–364, May 2003.
[7] Y. Zhang, M. Zhang, and W. Jin, "Sensitivity enhancement in erbium-doped fiber laser intra-cavity absorption sensor," *Sens. Actuators A, Phys.*, vol. 104, pp. 183–187, Apr. 2003.
[8] M. Zhang, D. N. Wang, W. Jin, and Y. B. Liao, "Wavelength modulation technique for intra-cavity absorption gas sensor," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 1, pp. 136–139, Feb. 2004.
[9] A. Gusarov and F. Liegeois, "Experimental study of a tunable fiber ring laser stability," *Opt. Commun.*, vol. 234, pp. 391–397, Apr. 2004.
[10] W. C. Jing *et al.*, "Design and implementation of a broadband optical rotary joint using C-lenses," *Opt. Express*, vol. 12, pp. 4088–4093, Aug. 2004.
[11] HITRAN Molecular Spectroscopic Database 2004.