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Intracavity multigas detection based on multiband fiber ring laser

Lin Yu[a,b], Tiegen Liu[a,b], Kun Liu[a,b,*], Junfeng Jiang[a,b], Tao Wang[a,b]

[a] College of Precision Instrument & Opto-electronics Engineering, Tianjin University, Tianjin 300072, China
[b] Key Laboratory of Opto-electronics Information and Technical Science (Tianjin University), Ministry of Education, Tianjin 300072, China

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ABSTRACT

We present a new method for multigas detection based on multiband fiber ring laser. Wavelength division multiplexing is used to realize multiband laser operation. Laser intracavity absorption spectroscopy combined with wavelength modulation technique is used to improve the measurement sensitivity. The second harmonic signal is extracted by the software-based lock-in algorithm for gas concentration retrieval. The relationship between the harmonic amplitudes and gas concentrations is investigated under both weak absorption and strong absorption to improve the accuracy of concentration retrieval. When the system is applied to detect the mixed gases of acetylene, carbon monoxide and carbon dioxide in C + L band, the minimum detectable concentrations are 0.6 ppm, 17.4 ppm and 19.2 ppm respectively.

1. Introduction

Various gases have overtone absorption lines in the near-infrared region. Gas detection based on absorption spectroscopy has been developed in recent decades for applications in industrial process and environmental monitoring [1,2]. If multiple gases are detected, the sensor's spectral range should be wide enough to cover at least one absorption line of each gas. A common method is to multiplex multiple narrowband sources such as distributed feedback diode lasers, each used to detect one specific gas component [3,4]. This way has high sensitivity, but the complexity and cost of the system configuration increase with the number of lasers. Another approach is to employ a single broadband source such as superluminescent diode and supercontinuum source because of its simple system configuration [5,6]. However, the spectral resolution and detection sensitivity are relatively low unless additional enhancement techniques are adopted.

Fiber laser intracavity spectroscopy (FLICS) makes a good compromise between wavelength range, measurement sensitivity and spectral resolution. With a gas cell inserted into the laser cavity, many passes through the absorber can increase the effective absorption length greatly [7–13]. In this way, high sensitivity is obtained. The gain bandwidth of rare-earth doped fiber laser used in FLICS is dozens of nanometers and able to cover the absorption bands of several gases [7]. A fiber grating or a tunable filter is usually used as the tuning component to make the laser wavelength coincide with a specific gas absorption wavelength [8–10]. When multiple gain bands are multiplexed, more gases are detectable. However in previous research more attention was paid on the sensitivity enhancement method, so the detected sample was usually a single gas in a single band for simplicity [7–10]. Investigation of intracavity multigas sensors and extending their detectable absorption bands is of great importance for the development of multigas detection [11,12].

In this paper, we present an intracavity multigas sensor based on multiband wavelength-swept fiber ring laser for the first time. C-band and L-band gain cavities are wavelength division multiplexed in the same erbium doped fiber ring laser. Compared with the previously reported single-band lasers [8–10], this multiband laser achieves a much larger wavelength coverage and hence a larger range of gas species that can be detected. Since multiple absorption lines of multiple gases are obtained in one scan, the measurement accuracy is improved when using multiple absorption lines for gas concentration retrieval. Instead of the traditional intracavity direct absorption technique, wavelength modulation combined with the software-based lock-in technique is adopted for sensitive gas detection. The relationship between the second harmonic amplitudes and gas concentrations is investigated under strong absorption and weak absorption. Finally, three gases of acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2) are detected to demonstrate the sensor's performances.

* Corresponding author. Tel.: +86 22 27409621/27404459.
E-mail address: beiyangkl@tju.edu.cn (K. Liu).

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2. Principle

According to Lambert-Beer law, the laser intensity attenuates exponentially when its frequency coincides with the gas absorption frequency. The absorbance K is given by

$$K(\nu) = \ln\frac{I_0(\nu)}{I(\nu)} = \alpha(\nu)cl \tag{1}$$

where I_0 and I are the incident laser intensity and the transmitted laser intensity respectively, α represents the absorption cross-section at the laser frequency ν, c is the molecule number density and l denotes the effective absorption length. When ν is modulated by a cosine signal as

$$\nu = \nu_0 + \delta\nu\cos(2\pi ft) \tag{2}$$

the transmitted laser intensity I can be expanded by Fourier cosine series as

$$I(\nu) = I(\nu_0, t) = \sum_{n=0}^{\infty} A_n(\nu_0)\cos(2n\pi ft) \tag{3}$$

where $\delta\nu$ and f are the modulation amplitude and modulation frequency respectively, ν_0 is the laser center frequency and A_n is the nth harmonic amplitude. When the laser gain is relatively flat over the narrow frequency range of a modulation period, the incident laser intensity can be regarded as independent of the laser frequency, i.e., $I_0(\nu)$ can be approximated as $I_0(\nu_0)$. Thus the second harmonic amplitude $A_2(\nu_0)$ is expressed as

$$A_2(\nu_0) = \frac{2}{\pi}I_0(\nu_0)\int_0^{\pi}\exp[-\alpha(\nu_0 + \delta\nu\cos\theta)cl]\cos 2\theta d\theta \tag{4}$$

where θ=2πft. The exponential term in Eq. (4) is usually further expanded by Taylor series to simplify calculation. In the case of the absorbance less than 0.05, the first order term of the Taylor series can get a good approximation [14]. If we define $H_2(\nu_0)$ as

$$H_2(\nu_0) = -\frac{2}{\pi}\int_0^{\pi}\alpha(\nu_0 + \delta\nu\cos\theta)\cos 2\theta d\theta \tag{5}$$

then $A_2(\nu_0)$ can be given by

$$A_2(\nu_0) = I_0(\nu_0)H_2(\nu_0)cl \tag{6}$$

However, when the absorbance is more than 0.05, the second order term of the Taylor series is included because the first order approximation causes a relatively large error [15]. Similarly, we define $T_2(\nu_0)$ as

$$T_2(\nu_0) = -\frac{1}{\pi}\int_0^{\pi}\alpha^2(\nu_0 + \delta\nu\cos\theta)\cos 2\theta d\theta \tag{7}$$

then $A_2(\nu_0)$ can be written as

$$A_2(\nu_0) = -I_0(\nu_0)T_2(\nu_0)c^2l^2 + I_0(\nu_0)H_2(\nu_0)cl \tag{8}$$

As shown in Eqs. (6) and (8), the relationship between the second harmonic amplitudes and gas molecule number densities is linear under weak absorption, while nonlinear under strong absorption. Thus, when using the second harmonic amplitude to calibrate gas concentration, linear fit or the second order polynomial fit should be selected according to spectral line's absorbance to improve the calibration accuracy.

In experiments, the software-based lock-in technique is adopted to extract and amplify the second harmonic signal because it is compact and economical compared to the traditional lock-in amplifier. The amplitude of the second harmonic signal is calculated using the real part of discrete Fourier transform as follows [16]:

$$A_2(\nu_0) = \frac{1}{N}\sum_{k=0}^{N-1} I(k)\cos\left(\frac{4\pi k}{N}\right) \tag{9}$$

where N denotes the number of sampling points in a modulation period, $I(k)$ is the light intensity corresponding to each point. In order to realize the lock-in detection, the generation of cosine reference signal $\cos(4\pi k/N)$ and the acquisition of laser intensity signal $I(k)$ should be synchronous. This can be achieved by Labview software using the same sampling clock. As a result, the second harmonic amplitude reaches the maximum.

3. System structure

The system setup for multiband intracavity multigas detection is shown in Fig. 1. C-band and L-band erbium-doped fiber amplifiers (EDFA) are wavelength division multiplexed to construct two gain paths. The passbands of wavelength division multiplexer (WDM) coincide with the gain bands. A fiber Fabry-Perot (F-P) tunable filter, whose free spectral range (FSR) is 120 nm and bandwidth is 4.23 GHz, is used for wavelength tuning and modulation. Since the filter's FSR is larger than the bandwidth of C+L band, only one detector PIN 1 is required to detect the gas absorption spectrum without an additional WDM. An isolator is used to ensure unidirectional laser travelling in the ring cavity and eliminate spatial hole-burning. An electronic variable optical attenuator (EVOA) is

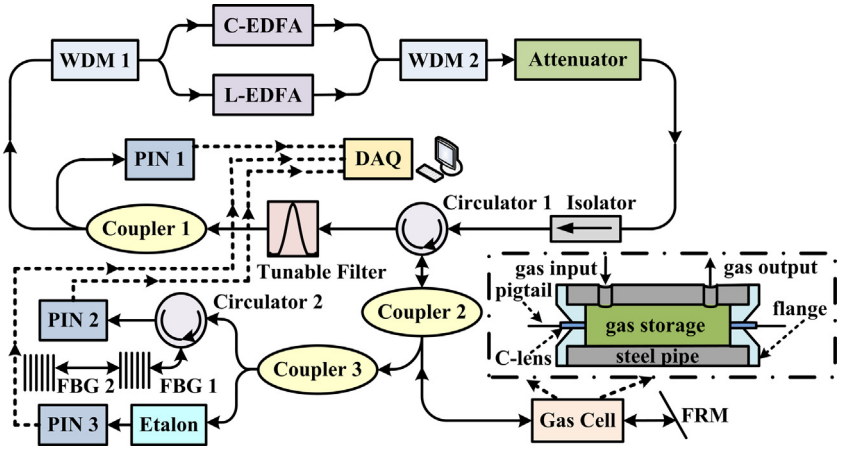

Fig. 1. The configuration of multiband intracavity multigas detection system.