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An all-optical photoacoustic spectrometer for multi-gas analysis

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ABSTRACT

An all-optical photoacoustic spectrometer for multi-gas analysis is reported in this paper. The spectrometer consists of a near-infrared tunable fiber laser connected with an erbium-doped fiber amplifier in series, a fiber acoustic sensor and a first order longitudinal resonant photoacoustic cell. Due to the application of the diaphragm-based Fabry-Perot interferometric fiber acoustic sensor in this system, the all-optical photoacoustic spectrometer has the advantages of immunity to electromagnetic interference, safely in flammable and explosive situations, and long distance sensing. Simultaneous and continuous detection of trace methane, acetylene, carbon dioxide, carbon monoxide and water vapor (CH_4, C_2H_2, CO, CO_2, and H_2O) are implemented. The detection limits (signal-to-noise = 1) of 87 ppm for CH_4, 1.3ppb for C_2H_2, 4.6 ppm for CO, 5.5 ppm for CO_2 and 24 ppm for H_2O are demonstrated at atmospheric pressure and room temperature.

1. Introduction

The interest for compact and reliable multi-gas analysis sensors has been considerably increasing in recent years. Photoacoustic spectroscopy (PAS) is a widely recognized technique for multi-gas analysis, such as dissolved gas analysis for transformers, medical diagnosis, industrial process control and environmental monitoring [1–4]. Near-infrared (NIR) laser PAS technique provides many advantages in terms of sensitivity, selectivity, multi-gas sensing and long life span.

Recently, with the advancement of optical telecommunication, distributed feedback (DFB) laser diodes having fast respond, high power output and wavelength modulation are used in PAS [5,6]. However, a simultaneous monitoring of several species of gases with a single instrument usually requires several lasers, as the typical tuning range of a DFB laser is limited to a few nanometres. The use of multiple lasers makes the PA sensor too complicated and expensive. The NIR tunable erbium-doped fiber laser (TEDFL) is very attractive for spectroscopic gas sensing due to its low cost and unique combination of continuous tunability and broadband wavelength coverage (1520–1610 nm) where overtone vibration bands of many molecules of interest exist (CH_4, CO_2, CO, H_2O, NH_3, C_2H_2, H_2S, HCN, N_2O etc.) [7].

The conventional PA spectrometer usually uses electric acoustic sensor to detect the PA signal, such as piezo-electric microphone and condenser microphone [8,9]. However, the electric acoustic sensor is not competent for operation in some extremely harsh situations, such as in high temperature, high humidity, and strong electromagnetic interference environments. Moreover, the signal generated from the electric microphone is not suitable for long distance transmission. The fiber acoustic sensor has created new opportunity for PA sensing, as it has the advantages of immunity to electromagnetic interference and remote sensing. Comparing with the electric microphone, the use of fiber acoustic sensor also reduces the dimensions of the system, since it does not need preamplifier. As regards Interferometric acoustic sensor for photoacoustic spectroscopy, the earliest reported is the work of Park and Diebold in 1987 [10]. Kauppinen et al. [11] firstly demonstrated a cantilever-based photoacoustic spectrometer, in which an optical acoustic sensor based Michelson interferometer is employed to detect the PA signal and miniature micro-mechanical cantilever is used as the acoustic sensing element.

In this paper, an all-optical photoacoustic spectrometer for multi-gas analysis based on a tunable erbium-doped fiber laser and a fiber acoustic sensor has been implemented. The performance of the spectrometer is demonstrated by the measurements of gas mixture containing trace gases of H_2O, CH_4, C_2H_2, CO and CO_2.

2. Experiment principle and setup

2.1. PA spectrometer

The configuration of all-optical multi-gas PA spectrometer is depicted in Fig. 1. The PA spectrometer is comprised of a TEDFL,

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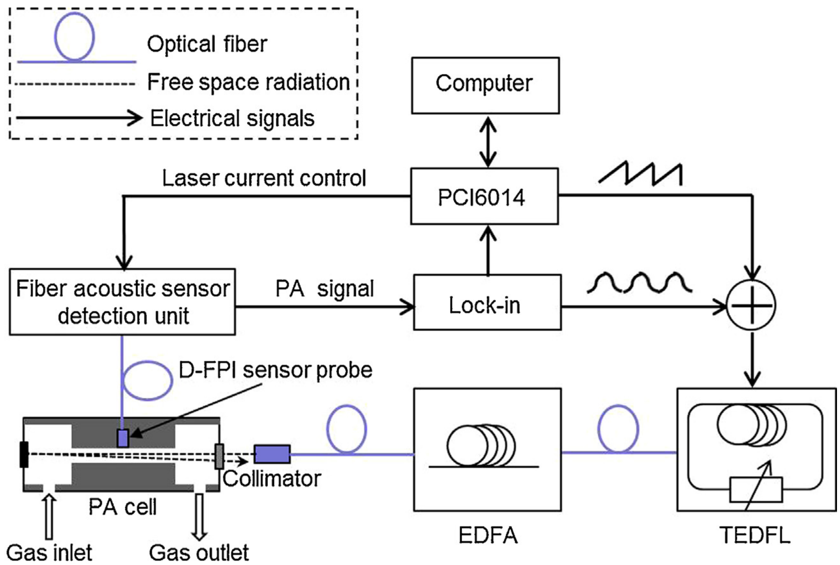

Fig. 1. Configuration of the all-optical PA spectrometer.

Table 1
Estimated detection limits of the system.

Gas	λ(nm)	PA signal	1σ	SNR	Concentration	Detection limit
CH_4	1529.39	49.6 μV	1.08 μV	46	4000 ppm	87 ppm
C_2H_2	1531.59	83.1 μV	1.08 μV	77	100ppb	1.3ppb
CO	1568.04	94 μV	1.08 μV	87	400 ppm	4.6 ppm
CO_2	1572.34	58 μV	1.08 μV	54	294 ppm	5.5 ppm
H_2O	1527.38	67.8 μV	1.08 μV	63	1500 ppm	24 ppm

an erbium-doped fiber amplifier (EDFA), a fiber acoustic sensor, a Lock-in amplifier, a PA cell, a data acquisition (DAQ) and a computer.

The TEDFL is operated in wavelength modulation mode. The ramp voltage supplied by the DAQ (PCI6014) drives the laser to change the emission wavelength. The sinusoidal waveform voltage sent by the lock-in amplifier (Stanford Research Systems, SR830) dithers the laser's wavelength at half the resonant frequency of the PA cell. The operation wavelength of the TEDFL can be continuously scanned with different scan rate from 1520 nm to 1600 nm. Wavelength modulated light from the TEDFL is amplified to 1W by the EDFA (Amonics Ltd.). The amplified laser is collimated into the PA cell through a fiber collimator. The PA cell consists of a cylindrical acoustic resonator and two buffer volumes, and the cell is sealed with a quartz window and a gold coated mirror. For this cell, the resonant frequency of its first longitude mode is 1600 Hz. A diaphragm based Fabry-Perot interferometric (D-FPI) sensor probe is located at the center of the PA cell to pick up the PA signal. The PA signal is fed into the lock-in amplifier, and then the results are transmitted into the computer. The whole measurement process is controlled by computer program.

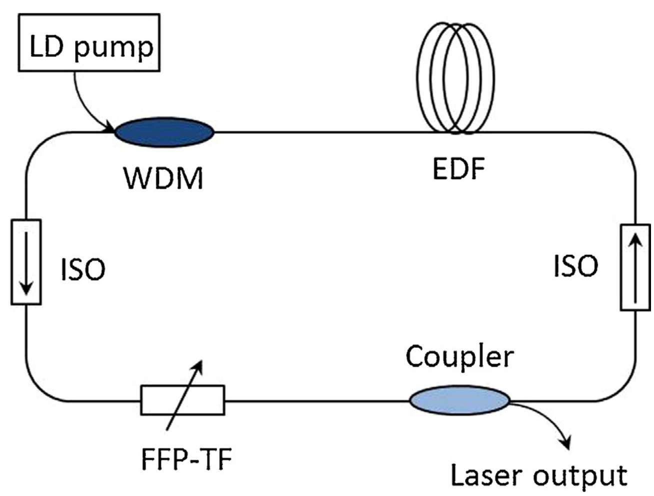

Fig. 2. Schematic diagram of the TEDFL.

2.2. Tunable erbium-doped fiber laser

The configuration of the TEDFL is shown in Fig. 2. A 980 nm pump laser diode (LD) is adopted and a length of 7.3 m erbium-doped fiber (EDF) is used as gain medium. In the fiber laser loop an optical isolator (ISO) is inserted to force the laser to propagate in single direction. The laser operation wavelength can be tuned by changing the voltage loaded on the fiber Fabry-Perot tunable filter (FFP-TF) in the laser loop. The linewidth of the laser output is about 20 pm which is measured by the wavemeter (EXFO WA-7600) with a resolution of 0.2 pm. The output power of the TEDFL is 4.5 mW, and the laser operates in continuous wave.

2.3. Fiber acoustic sensor

The fiber acoustic sensor is shown in Fig. 3. It consists of a D-FPI sensor probe, a fiber acoustic sensor detection unit (within the grey fraction shown in Fig. 3), a data acquisition (PCI6014) and a computer. The structure of the D-FPI sensor probe is illustrated in the inset of Fig. 3. A gold coated polyetherimide (PEI) diaphragm is used as the sensing diaphragm, and a metal base is employed to support the sensing diaphragm. The thickness and effective radius of the PEI diaphragm are 12 μm and 2.5 mm, respectively.