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Procedia Engineering 15 (2011) 5395 – 5399

Procedia Engineering

www.elsevier.com/locate/procedia

Advanced in Control Engineeringand Information Science

A novel photoacoustic spectroscopy system using diphragm based fiber Fabry-Perot sensor

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Abstract

A wavelength modulated photoacoustic spectroscopy system utilizing an optical fiber microphone and a tunable Erbium-doped fiber Ring laser combined with an erbium doped fiber amplifier is first developed. The diaphragm based Fabry-Perot sensor using interferometric/intensity demodulated method is used as high sensitive optical fiber microphone. This system is applied to the detection of acetylene using a resonant photoacoustic cell on its second longitudinal mode. The experimental results demonstrate that the low concentration acetylene flowing measurement can be detected by optical microphone, and the amplitude of second harmonic is proportion to the concentration of acetylene. The linearity is 0.9999. At room temperature and atmospheric pressure, the minimum detectable limit of acetylene is about 1.5 parts-per-billion (ppb) volume (SNR=1), which can be compared with condense microphone.

Keywords: Fiber Fabry-Perot sensor, Acoustic sensor, Photoacoustic spectroscopy, Acetylene, Tunable fiber laser

1. Introduction

Partial discharge (PD) in the transformer is a sign of dielectric defects as well as a caused for further degradation of its insulation system, and may cause a failure of the apparatus. Acetylene (C_2H_2) as the character of gases of PD is a kind of gas with very lively chemical property. Due to inflammable and

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1877-7058 © 2011 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2011.08.1000

explosive property of acetylene, on-line and real-time detection of acetylene concentration is very important in environmental monitoring and safe operation in industry. There are many methods to detect the acetylene concentration. Infrared laser photoacoustic spectroscopy (PAS) is the efficient technique due to its fast response, relative simplicity and compact, overall sensitivity and selectivity. PAS is based on photoacoustic (PA) effect[1], which is the conversion of light to sound. In order to improve the sensitivity of PAS system, many methods have been studied. The wavelength modulation (WM) PAS, which can eliminate background PA signals arising from the windows and wall of PA cell and improve the sensitivity of the PA detection system, is chosen as a popular way[2, 3]. The WM-PAS based on semiconductor laser source [1, 4-7] and tunable erbium doper fiber laser combined with erbium doped fiber amplifier (EDFA)[3] are described in many publications. In PAS system, the microphone response is also an important factor as it is know to work poorly at lower pressure. But the conventional microphone, such a microphone and piezo-transducers, can not survive in the extremely harsh environment, such as high temperature, high humidity, and strong electromagnetic interference. In this paper, an all-fiber PAS for acetylene detection system is described. The wavelength modulated PAS based on a near-infrared tunable Erbium-doped fiber Ring laser (TEDFRL) and a high power erbium doped fiber amplifier (EDFA) is used. And the diaphragm based Extrinsic Fabry-Perot interferometry (EFPI) sensor is used as the high sensitive microphone. The experimental results demonstrate that the low concentration acetylene flowing measurement can be detected by diaphragm based EFPI sensor, and the amplitude of PA signal's second harmonic is proportion to the concentration of acetylene. The linearity is 0.9999. At room temperature and atmospheric pressure, the minimum detectable limit of acetylene is about 1.5 parts-per-billion (ppb) volume (SNR=1), which can be compared with condense microphone. This work demonstrates that the fiber acoustic sensor can be employed as the microphone of PAS and the sensitivity of trace gas detection of optical microphone can be improved in the future.

2. Theory

The detail principles of PAS have been described in many publications [8, 9]. When a wavelength or intensity modulated light goes through the PA cell, the detection gas will absorbed the laser radiation. During the non-radiative relaxation process, the absorbed radiation energy will be converted into periodic local heartily at the modulation frequency. The standing pressure wave will be produced with the PA cell and the PA signal can be produced. The microphone is used to monitor the PA signal. The PA signal, S, in volts, can be given by[3]:

$$S=S_m PCF\alpha+N \tag{1}$$

where S_m in unit of Volt per Pascal (V/Pa) is the sensitivity of microphone, P is the power of incident laser radiation, with unit of Watts (W), C is the concentration (the ratio of volumet) that is being interrogated, F is the PA cell response constant, with the units of Pascal per inverse centimeters per Watt (Pa/ (cm-1W)), α is the absorption coefficient of transition, in inverse centimeters, and N is the system noise in unit of Volt (V). The PA signal is proportional to the concentration of the absorbing gas and the incident laser power. The PA constant is a parameter depending on the PA cell geometry, on the modulation frequency and on measurement conditions. It is determined experimentally from measurements with a gas of known absorption and certified concentration.

2.1. Diaphragm based EFPI sensor

A low-finesse F-P interferometer is formed between the end surface of optical fiber and the inner surface of PPESK diaphragm. For a low finesse F-P interferometer, the reflected optical intensity can be expressed by [10, 11]:

$$I_r=2RI_0(1-\cos(4\pi L/\lambda)) \tag{2}$$

where I_0 is the incident optical intensity, R is the reflectivity of the fiber end face and the inner surface of diaphragm whose refractive index is nearly the same as that of the fiber core, λ is the wavelength of the light source, and L is the length of F-P cavity. When the length of F-P cavity changes one half of the light wavelength, the reflected intensity will change a period. For an interferometric/intensity modulated sensor, the initial static operating point of sensor should be set at the quadrature point (shown in Fig.2 as Q points) of the sinusoidal curve.

When a pressure is applied to the diaphragm, the deformation of diaphragm will cause the changes of F-P cavity length and the reflected optical intensity. In our experiment, only the diaphragm center deflection is of interest. For a rigidly clamped round diaphragm, the center deformation is given by[11]:

$$\triangle L=3(1-\mu^2)Pa^4/(16Eh^3) \tag{3}$$

where μ and E are the Poisson's ratio and Young's modulus of diaphragm material respectively, a is the effective radius of the diaphragm defined by the inner radius of the quartz capillary, P is the applied pressure, and h is the diaphragm thickness. This equation is valid only when the deformation is no more than 30% of the thickness of the diaphragm. From Equation (4), we can know that there is a linear relationship between the diaphragm center deflection and the applied pressure. The deflection of the diaphragm is proportional to the fourth power of the diaphragm radius and inversely proportional to the cube of the diaphragm thickness for a certain material.

3. Experiments

3.1. Experimental setup

The PAS experimental setup is shown in Fig.1. Light from tunable Erbium doped fiber laser (TEDFRL) is divided into two branches with a 1 by 99 fiber coupler. 1% of the optical power is transmitted into a hydrogen cyanide (HCN) gas reference cell to calibrate the output wavelength of TEDFRL. 99% branch is amplified by Erbium doped fiber amplifier (EDFA) and launched into the resonant PA cell with a double-pass configuration through a fiber collimator. The excited acoustic wave is detected by the diaphragm based EFPI sensor that located at the center of resonator. The PA signal detected by diaphragm based EFPI sensor is sent to the lock-in amplifier and the second harmonic signal detection technique of lock-in amplifier is also used to eliminate the background noise generated by absorption of the cell windows and the wall of the acoustic resonator. In experiments, the P (9) absorption peak of acetylene at 1530.371nm is chosen and the diaphragm based EFPI sensor is stabilized by an automatic compensation system which will be reported in another paper in detail. The whole experiments were computer program controlled.

3.2. Diaphragm based EFPI sensor

The diaphragm based EFPI sensor is used as microphone, so the sensitivity, linearity, frequency response range, and signal to noise ratio (SNR) of unidirectional diaphragm based EFPI sensor is discussed at firstly. The Diaphragm based EFPI sensor is calibrated by a reference condenser microphone (ME 102, Sennheiser) with sensitivity of 20mv/Pa. The experimental results exhibite that the fiber acoustic sensor has a linear response with correlation coefficient of 0.99998 and the sensitivity of the sensor is 134.7mV/Pa. The diaphragm based EFPI sensor is studied in the frequency range from 0.084 to 20 KHz. The performance is shown in Figure 2. It can be seen that the diaphragm based EFPI sensor has a flat response at least up to 2.5 KHz. And the signal-to-noise (SNR) of diaphragm based EFPI sensor at 1 KHz is 35 dB.

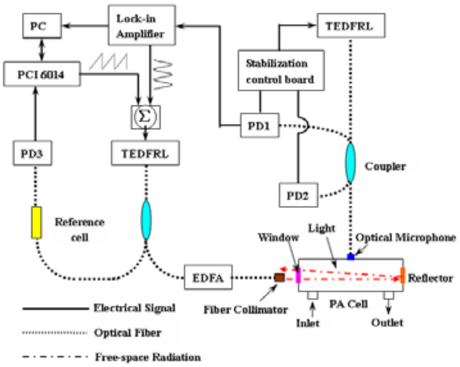


Fig.1. Experimental schematic of PAS based o TEDFL-EDFA n

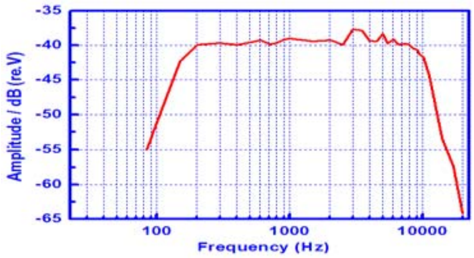


Fig.2. Frequency response of diaphragm based EFPI sensor

3.3. System optimization and tests

All experiments are operated at room temperature and standard atmospheric pressure. The method to determine the optimum modulation depth is described in the reference[12]. The optimum modulation depth is obtained when the ratio of PA signal and linewidth is the highest. The spectra were recorded when modulation depth is increased from 4mV to 26mV peak to peak (mVp-p) for flowed acetylene with 1 ppm concentration. The results are shown in Figure 3. The optimum modulation depth of PA cell is 20mV. The optimum parameters of wavelength modulation were used to measure the acetylene with different concentrations which were obtained by diluting 9.9ppm acetylene gas with synthetic air. At room temperature and atmosphere pressure, the absorption spectrum of 50ppb acetylene in synthetic air obtained by tuning TEDFRL across the acetylene transition (P9) near 1530.371nm at optimum conditions is shown in Figure 4. From the measured result, a signal-to-noise ratio (SNR) of 31.7 is obtained. In our experiments, the noise estimated to be the standard deviation of the PA signal at an off-resonant wavelength is shown on the graph. The SNR indicates that the noise-limited detection limit is about 1.56ppb of acetylene.

4. Conclusion

In this paper, we have described in detail the all-fiber PAS system. The diaphragm based EFPI sensor with sensitivity of 137mV/Pa and flat frequency response range from 84Hz to 2.5 KHz is used as the microphone of PAS. Based on the wavelength modulation, the PAS system is tested to detect the acetylene at room temperature and atmospheric pressure. The second harmonic amplitude of PA signal is proportion to the concentration of acetylene and the correlation coefficient for a linear fit is 0.99985. The minimum detectable limit of acetylene is about 1.5 parts-per-billion (ppb) volume (SNR=1), which is lower than the demands of acetylene detection of 5 parts-per-million (ppm) volume in industry and can be compared with condense microphone. This all-fiber PAS system can be used in harsh environment, such as high temperature, high humidity, and strong electromagnetic interference.

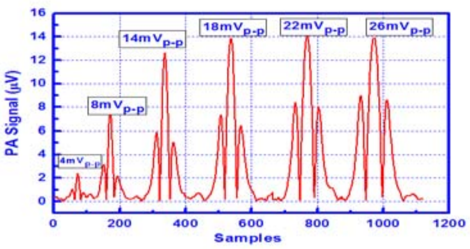
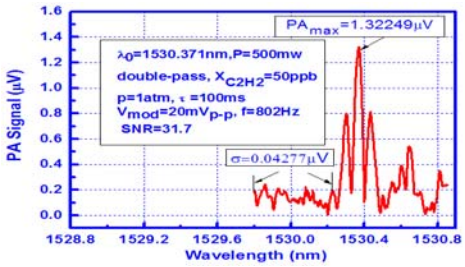


Fig.3. C_2H_2 transitions near 1530.371 with modulation depths varying from 4mVp-p to 26mVp-p



F ig.48. Measured 2f spectra of 50ppb flowing C2H2in synthetic air at optimum conditions

Acknowledgement

This work was supported by "the Fundamental Research Funds for the Central Universities", N100423005.

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