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Resonant photoacoustic gas sensing by PC-based audio detection

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ABSTRACT A new and simple technique for data acquisition and processing in an experiment of resonant photoacoustic detection is presented. It is based on the use of the sound card of a desk or laptop computer for digitizing the signal from a microphone enclosed in an acoustical cavity and further processing by a high-resolution fast Fourier transform. The system is applied to the detection of NO_2 traces in air at atmospheric pressure with an amplitude-modulated visible laser and the results are compared with those obtained by a lock-in amplifier. For the same acquisition time the results for the ultimate measurable concentration were 50 ppbV with this system and 130 ppbV with a lock-in amplifier.

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1 Introduction

The resonant photoacoustic (PA) technique is a very useful tool for trace-gas detection. It is based on the excitation of gaseous samples enclosed in a cell by amplitude-modulated laser radiation at a repetition rate that coincides with an acoustic resonance of the cell–gas system. Currently, the signal from a microphone is synchronously processed by a lock-in amplifier. In this way, a good sensitivity and a high signal-to-noise ratio are achieved when light sources like CW CO, CO_2 and solid lasers [1–3] are used. However, synchronous detection results in expensive equipment and lack of compactness, which are important for field applications.

The purpose of this paper is to present a simple, low-cost and compact signal acquisition and processing system for resonant PA spectroscopy which avoids the use of lock-in amplifiers. It is based on a desk or laptop computer with standard audio input. The performance of the system designed at our laboratory and its limitations are studied for PA detection of NO_2 in air at atmospheric pressure with a chopped multiline argon laser and compared to the conventional system.

2 Experimental

The detection system of a resonant PA experiment for trace-gas measuring is generally based on synchronous detection with a lock-in amplifier in order to obtain a good signal-to-noise ratio. The exciting laser radiation is chopped at different modulation frequencies f_m around an acoustic resonance of the vessel that contains the gas to scan the profile of the resonance peak and precisely determine its maximum. Other detection methods are based on DSP (Digital Signal Processor) and narrow-band filtering.

In our setup the PA signal from a microphone, measured at an arbitrary chopper frequency f_m, is amplified by a factor of 100 before entering into a PC through the sound port and being digitally converted by the sound card (Sound Blaster PCI 128, full-scale sensitivity 200 mV) with a resolution of 16 bits at a sampling rate of 44.1 kHz. The signal is acquired during a time T and analyzed in the frequency domain after transformation by a fast Fourier transform (FFT). The value of the acquisition time must be chosen according to the number of cycles required to obtain a good signal-to-noise ratio, but an upper limit is imposed by the dynamics of the process that will be characterized by this technique and the drift of the resonance frequency due to temperature changes (9 Hz/°C in this case). The Fourier integral of the signal is $\sin[\pi (f - f_m) T] / [\pi (f - f_m)]$ with its maximum at f_m. If f_m is not an integer multiple of the frequency spacing determined by the FFT, which is $1/T$, the profile of the resonance peak is not precisely measured. In order to overcome this difficulty a high-resolution FFT (HRFFT) was applied [4].

The amplitude of the frequency spectrum at the laser-beam chopping frequency f_m is stored and the procedure is repeated for different repetition rates around the cell's resonance with steps adequate for a good definition of the maximum, depending on the cavity Q-factor. The recorded amplitude and the frequency values determine the PA peak, which shows a Lorentzian profile [5].

The first application tests of our acquisition system were carried out for PA detection of NO_2 traces in air (Fig. 1) with visible radiation because of our previous experience in this subject [6–8]. The beam from a cw multiline argon laser (American Laser Corp.) with 100-mW maximum output power was modulated by a chopper (Thor Labs) with variable repetition rate up to 6 kHz. Most measurements were performed at 35-mW mean laser power. Since all laser lines were used in the experiment, we checked the stability of the relative power content of the different lines and found it to be better than 5%. In this way, the average absorption

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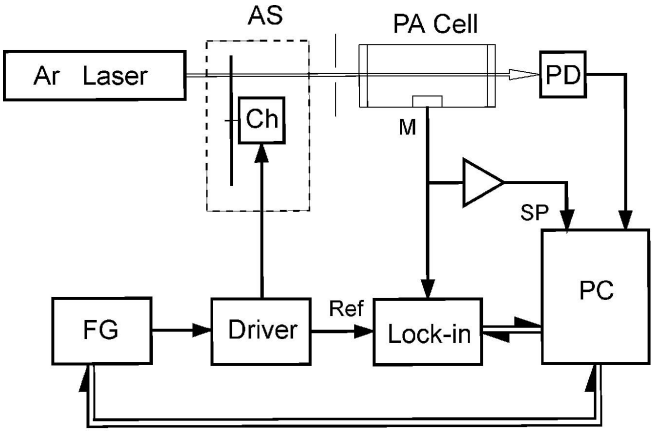

FIGURE 1 Experimental setup for simultaneous measurement of a PA signal with the lock-in and the PC-based systems (PD: power meter, Ch: chopper, FG: function generator, SP: sound port, AS: acoustic shield, M: microphone)

coefficient is constant during the scanning of a resonance peak. The gas samples were prepared in our laboratory using high-purity NO_2 (Liquid Carbonic 99.5%) and chromatographic air (L'Air Liquide 99.5%). The tests to be discussed were performed on samples of NO_2 in air at atmospheric pressure.

The Pyrex acoustical cavity was cylindrical with 70-mm internal diameter and 100-mm length; two optical glass windows enclosed the cell. The microphone (ear-aid, Knowles EM-4447) was attached to the walls at the middle point of the cell's length. This shape defined the first radial mode at around 5700 Hz and an experimental Q-factor of 380 for air at room temperature.

The microphone signal for each frequency was processed by a DSP lock-in amplifier (Stanford Research, model SR830) synchronized with the chopper and fed in parallel into the PC through the sound port, after amplification by a Tektronix AM502 module. The PC system was previously calibrated with a sinusoidal signal.

The chopper was acoustically shielded in order to minimize the noise coming from the rotating wheel. The tests, carried out simultaneously with the sound-card-based system and the synchronous detection, gave an attenuation of the chopper-blade whistle of 15 dB in both cases.

3 Results

An example of a typical PA signal at a fixed chopping frequency near resonance acquired with the system described above is shown in Fig. 2a. It corresponds to a sample of 630 ppmV NO_2 in pure air, excited at a frequency $f_m = 5691$ Hz and an acquisition time window T of 0.5 s (22 050 samples). The high signal-to-noise ratio is evident and the signal period is defined by eight samples. The high-resolution Fourier spectrum of this signal, obtained by calculation of the FFT for different amounts of samples down to 21 950 in steps of 10 samples, appears in Fig. 2b. The maximum amplitude is determined with high precision and the effect of the square time window in the side lobes of the peak is evident. On the other hand, direct application of the FFT gives a much lower value for the maximum. This is due to

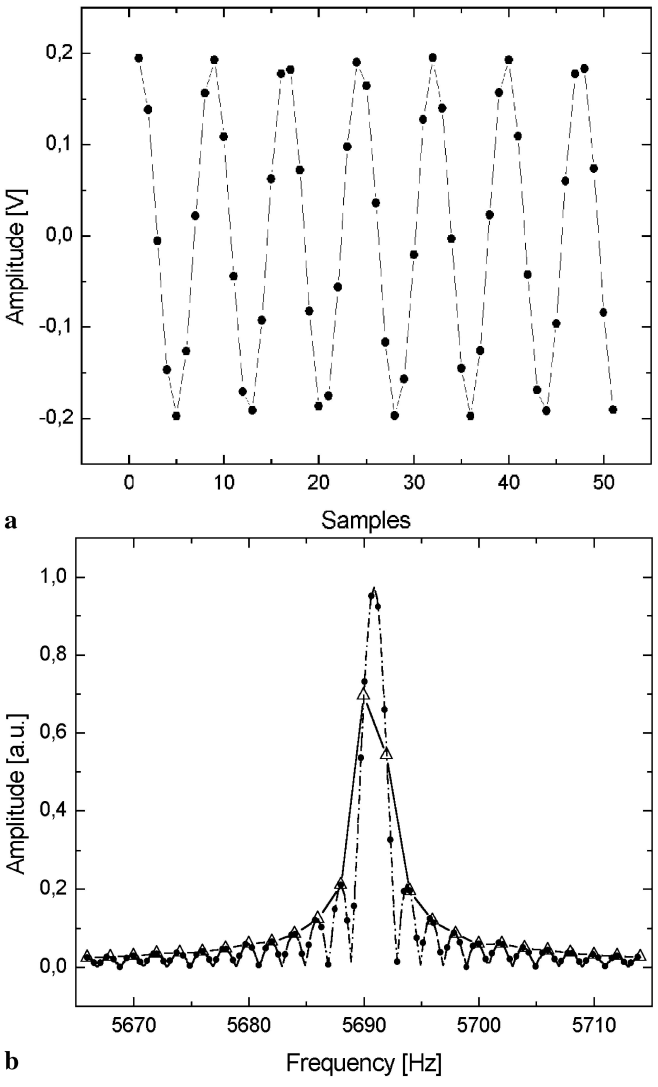

FIGURE 2 **a** Part of the PA signal obtained by the PC-based system for 630 ppmV of NO_2 in air. **b** Comparison of the spectrum of the PA signal of Fig. 2a obtained by the FFT (*triangle*) with the results by the HRFFT (*circle*)

the lack of coincidence of the chopping frequency and the value of the frequency scale resulting from the FFT applied to the signal in a 0.5-s window. As shown, the application of the HRFFT allows us to choose the most convenient window size and scanning step for the conditions of the experiment, independently of the frequency spacing obtained by the FFT.

The whole resonance peak, simultaneously registered at a temperature of 28.6 °C with both systems with a frequency resolution of 1 Hz, is shown in Fig. 3 for the same sample as above. The temperature did not drift more than 0.1 °C during the whole scanning; thus the resonance frequency shift (~ 1 Hz) is not important. In order to compare the performance of the systems for application in pollution measurements, they were used with similar integration times. The time constant of the lock-in system was set at 1 s, as well as the acquisition window T in the PC sound-card-based system. The results show a perfect coincidence between both acquisitions.

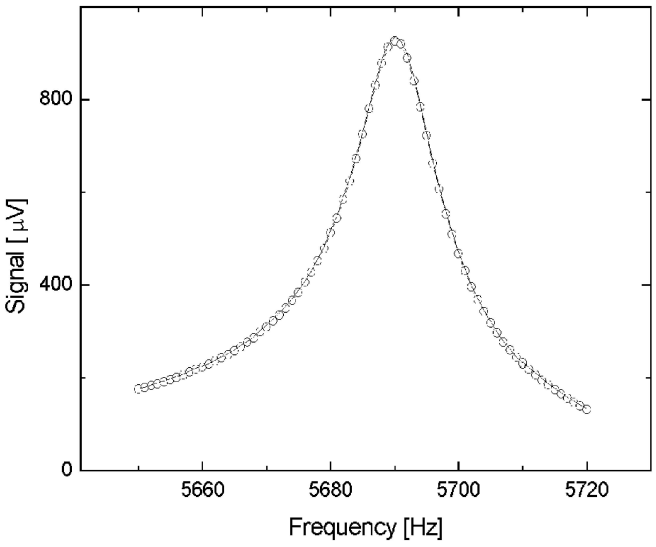

FIGURE 3 Comparison of the resonance profile acquired by the lock-in amplifier (o) with the scan by the sound-card-based system (*solid line*)

We also determined the ultimate sensitivity for NO_2 concentration measurement for both systems. For this purpose, the calibration was performed by measuring the resonance-peak amplitude for samples of different compositions NO_2–air at atmospheric pressure, between 2.7 and 630 ppmV. The PA signal around resonance was registered by our PC-based system within a window of 1 s and the laser power was monitored at the same time. The maximum amplitude in the Fourier spectrum for each laser repetition rate was averaged over three consecutive measurements. The results of amplitude vs concentration at constant laser power (35 mW) are shown in Fig. 4; linear regression applied to this set of points gives a correlation coefficient of 0.999.

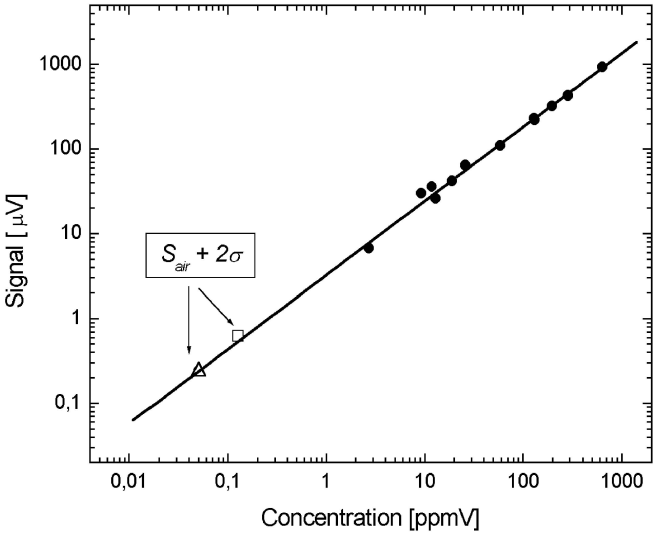

FIGURE 4 Calibration curve for NO_2 in air at atmospheric pressure and linear fit. The background corresponding to pure air, obtained by both systems, is shown

The ultimate sensitivity was obtained by determining the mean value of the signal amplitude (S_{air}) around the resonance plus twice the standard deviation σ, with the laser beam passing through the cell containing pure air at atmospheric pressure. Formerly, we had tested that acoustic shielding of the PA cell does not further lower the background signal, with respect to the signal already attenuated after shielding the chopper. We also proved, by blocking the laser radiation, that there is no measurable signal coming from the windows. Thus, after discarding these possible unwanted signal sources, the background may be ascribed to electronic noise or mechanical vibrations.

In Fig. 4 the measurements obtained for pure air at atmospheric pressure are indicated; they correspond to 50 ppbV for the sound-card-based system (circle) and 130 ppbV for synchronous detection (square). With a random noise, we made certain that this difference is due to the different bandwidths of the instruments for our acquisition conditions.

The input noise of the sound card was also registered by our system; it is consistent with the signal-to-noise ratio specified by the manufacturer (90 dB) and comparable to the PA background signal for pure air. Therefore, we consider that we reached the ultimate sensitivity attainable with this PA setup and the sound-card-based acquisition system.

4 Conclusions

The system for PA detection based on signal acquisition by a PC sound card is an interesting alternative to synchronous detection. It is of very low cost and allows us to develop compact and portable equipment for field applications, as the whole acquisition and processing system can be included in a laptop computer.

In the specific case of PA detection of NO_2 traces [7, 8], based on solid-state lasers, this system may be included with no harm to the performance already obtained with a lock-in amplifier. In consequence, making use of this simple device would be adequate for NO_2 trace quantification in car exhausts, control of automobile catalytic converters' efficiency and measurements in moderately contaminated urban areas.

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