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Embedded system based data acquisition and control system for photoacoustic spectroscopic applications

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ABSTRACT

Laser absorption spectroscopy by photoacoustic (PA) detection technique is increasingly used in trace gas analysis. Our research group focuses on related instrument and application development. In this paper the design and test results of a newly developed field programmable gate array based data acquisition and control system (DACS), are introduced. It became necessary to develop this new system since the limits of the old one had been reached; furthermore, it was challenging to implement new advanced measuring protocols. The system was designed to be scalable in order to be able to implement further ideas or measurement protocols without significant hardware or software modifications. In the current configuration, approximately 60% of the resources of the system are used. A complete PA measuring system was built around the new DACS to determine the analytical properties: the normalized noise equivalent absorption is $7.5 \times 10^{-10}\,cm^{-1}\,W\,Hz^{-1/2}$, while the estimated dynamic range for measuring optical absorption is 7.5 orders of magnitude.

1. Introduction

1.1. Motivation

In recent years the number of reported photoacoustic (PA) instruments to prove their applicability in various areas has been steadily increasing [1–4]. Amongst these instruments are those which were developed by our research group for various applications, including in the natural gas industry [5–7], airborne hygrometry [8–9], source apportionment of urban light-absorbing aerosols [10–11], measurements of gas permeability [12], and clinical research [13]. The main components of our instruments are basically always the same: a data acquisition and control system (DACS), one or more longitudinal differential detection cells [14], (a) modulated light source(s) which is/are either telecommunication-type diode lasers [15] or frequency converted Nd:YAG lasers [10] and gas handling units in various configurations.

The DACS has a fundamental role in a PA system. It drives the laser: tunes and stabilizes its wavelength and modulates its emitted light. It amplifies the microphone signal(s) and calculates the PA signal (which is usually defined as the amplitude of the microphone signal at the

Abbreviations: AC, Alternating Current; CH, Channel; DACS, Data acquisition and control system; DC, Direct current; FPGA, Field Programmable Gate Array; IC, Integrated Circuit; IO, Input–output; PA, Photoacoustic; PCB, Printed Circuit Board; PI, Proportional–integral; PID, Proportional–integral-derivative; PLL, Phase locked loop; PWM, Pulse-width modulation; RT, Real Time; SPI, Serial peripheral interface; TDL, Tunable diode laser.

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laser modulation frequency). It also calculates either the optical absorption coefficient or the concentration of light-absorbing components from the PA signal based on pre-programmed calibration factors. In most cases, the DACS has various additional functions such as controlling the gas handling system and communicating with other instruments. Our recently developed systems [5–13] were based on a highly integrated target DACS. This system turned out to be one of the bottlenecks during the application developments due to its limited capabilities; therefore, a fundamental redesign of our DACS became essential.

It was decided that the new DACS would be based on a general purpose industry standard, commercial off-the-shelf development platform, which has to be supplemented with additional units only for those functions, which cannot be performed by the platform itself. The new system, its development, and the most important test results are presented in this paper. This paper is organized as follows: First, the salient points about PA spectroscopy are introduced in Section 1.2, focusing on the hardware and software necessities. The materials and methods section (Section 2.) contains the descriptions of the new DACS (hardware and software), the PA system into which it was implemented, and experiments aimed at verifying the performance of the new DACS. In the Results and Discussion section (Section 3.), the most important test results, such as dynamic range and detection limits, are introduced and discussed. In Appendix A, the supplementary home-made peripherals are introduced.

1.2. Basics of PA spectroscopy

1.2.1. The PA effect

The PA effect is the conversion of electromagnetic radiation to acoustic waves through modulated absorption, non-radiative molecular relaxation, local heating, thermal expansion, and sound wave generation [16–18]. If a gas sample is illuminated by a train of light pulses or by intensity or wavelength-modulated light, which are at least partially absorbed by the sample, the absorbed light energy generates acoustic waves. In most of the PA experimental arrangements, the gas sample being analyzed is introduced into an acoustic resonator [14], which amplifies the acoustic signal (AS) that has been generated, which in turn is measured by a sensitive microphone or by a quartz tuning fork [19]. The amplitude of the signal generated is usually determined by lock-in technique. The amplitude thus determined is usually called as PA signal and will be referred to as such in the followings. In most cases, the PA signal is proportional to the power of the applied light beam, the molar absorption coefficient, and the partial pressure of the absorbing molecules. One multiplicative parameter describes the measurement cell, and another defines the sensitivity of the microphones [20].

$$PA = MCP\alpha c \tag{1}$$

where M is the sensitivity of the microphone, C is the so-called cell constant, P is the power of the light beam, α is the molar absorption coefficient, and c is the concentration of the absorbing molecules.

1.2.2. Tunable diode laser (TDL)-based PA spectroscopy

In selective and compact PA instruments nowadays, mostly TDL-s are used as light sources especially the narrow linewidth fiber coupled distributed feedback (DFB) [15] types. DFB diode lasers can be wavelength-tuned by their temperature and by the applied current. Above the operational threshold current, the wavelength and the power of the lasers as the function of temperature and current can be given as:

$$\lambda(I,T) = \lambda_0 + aT + bI \tag{2}$$

$$P_{laser}(I) = P_0 + fI \tag{3}$$

where λ_0 is a virtual wavelength for 0 K temperature and 0 mA current, a is the temperature tuning coefficient (typical value: 100 pm/K), T is the temperature in K, b is the current tuning coefficient (typical value: 5 pm/mA), I is the applied laser diode current; P_0 is the negative virtual power at 0 mA current, and f is the slope of the power–current curve above the threshold limit (typical value: 0.10–0.30 mW/mA).

The temperature of these lasers is used to stabilize their wavelength, while current is used to fine-tune it [21]. These lasers have an integrated Peltier element and a negative temperature coefficient (NTC) thermistor, which can be used for temperature stabilization through proportional-integral (PI) or proportional-integral-derivative (PID) control methods. The desired stability of the temperature is 0.01 K or better. For highly accurate and precise temperature and therefore central wavelength stabilization, the temperature of the laser housing also has to be stabilized. For this purpose, an externally placed Peltier element, and an NTC thermistor should be used with PI or PID control.

DFB lasers can be modulated with the modulation of the driving current; such a modulation results in the modulation of both the wavelength and the power. Both of them can generate AS, and their mechanisms have previously been discussed in detail [22–24].

1.2.3. PA cell

The PA cell [14] has three major functions: it isolates the gas sample being analyzed, it amplifies the AS that has been generated, and it detects it with the integrated microphones. To do this effectively, the modulation frequency of the laser has to be the same as one of the resonance frequencies of the PA cell itself. During the measurements, a single longitudinal mode differential type was used. The pathlength in such a PA cell is around 10 cm, so the light attenuation is hardly ever more than 10%; therefore, the rest of the light beam can be introduced into a second and maybe third or fourth measuring cell thus making it possible to analyze the same gas multiple times to increase the precision of the measurement by averaging, or to analyze different gas streams simultaneously (Fig. 1).

The resonance frequency of the PA cell depends on its geometry and on the sound velocity within the gas inside. Besides the composition, the sound velocity also depends on the temperature of the gas; therefore, the temperature of the cell has to be stabilized and the sampling line also has to be tempered. These types of PA cells require 0.5 K