Advanced embedded control and data acquisition systems for laser-based quartz-enhanced photoacoustic spectroscopy

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***Abstract*— This work describes the development of low-power embedded systems for miniature quartz-enhanced photoacoustic spectroscopy (QEPAS) laser based trace gas sensors. Such sensors must address the following functions simultaneously: 1) laser current control, 2) laser temperature control, 3) multi-harmonic quadrature lock-in amplification, and 4) digital data processing. Currently used methods for control and acquisition result in shoebox sized sensors requiring ~ 3 to 4W of electrical power consumption, which is too high for portable energy harvesting powered monitoring. In order to improve sensors to meet required size and cost demands of portable health monitors and environmental sensor networks, we have consolidated and minimized the necessary processing resources for QEPAS sensors. Our processing system has been reduced to a single 10cm x 6.5cm circuit board constructed entirely from low-cost off-the-shelf components, and achieves power consumption of ~0.2W.**

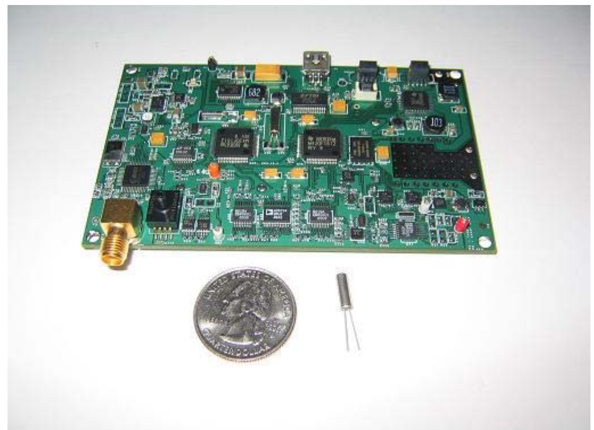

Fig. 1. Top: embedded control system for QEPAS; Bottom left: US quarter; Bottom right: quartz tuning fork

I. Introduction

There is considerable interest in ultra-compact trace gas sensors for applications in medical diagnostics [1], environmental sensor networks for carbon flux and pollution monitoring [2], and explosives, chemical, and biological agent detection [3]. QEPAS [4] provides a low cost, small footprint sensing element capable of quantifying at parts-per-million trace gas concentration levels. By combining QEPAS technology with miniature low power electronics, these demanding research applications can now be addressed with our sensors.

II. Motivation

Laser spectroscopic trace gas sensors provide simultaneously high sensitivity and specificity, necessary in mission critical applications where false positives must be kept to an absolute minimum. Although other techniques (GC-MS, chemiluminescence) can provide these necessary sensing characteristics, factors such as complexity, maintenance (consumables), and power consumption frequently negate the capability for wearable, portable, inconspicuous, and low power monitoring. The foremost applications for compact, low power consumption sensors are a) portable health devices for treatment efficacy, exposure monitors, and patient status, b) sensor networked devices for long-term maintenance-free wide area monitoring of atmospheric chemistry, and c) warfare agent detection in public settings.

A. *Portable Medical Devices*

Health indicators such as blood tests and biopsy are invasive and require costly expert personnel to perform. New methods for disease diagnosis based on breath analysis have recently become feasible with advanced chemical sensors. A chemiluminescence based sensor for breath analysis of nitric oxide (NO) has been US Food and Drug Administration (FDA) approved for asthma diagnosis. However, such a sensor is large and costly, taking up a footprint the size of a table top and continuous maintenance; thus, such sensors are limited to the clinical setting. Furthermore, environmental factors in medicine have become an important research field within public health and medicine. Diseases such as asthma, autism, and cancer may have environmental chemical

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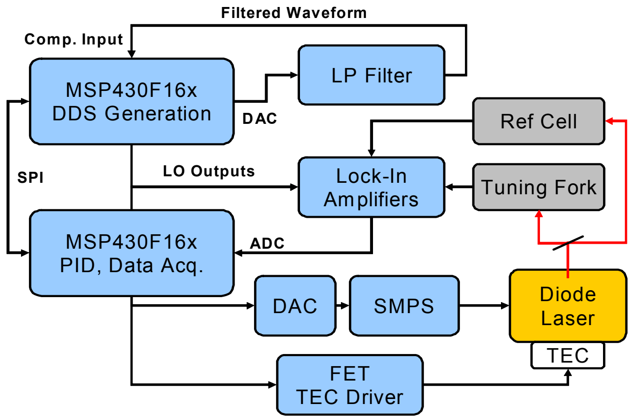

Fig. 2. Simplified block diagram of QEPAS sensor (SMPS – Switch mode power supply, TEC – Thermoelectric Cooler, DDS – Direct Digital Synthesis).

triggers [5]. Portable breath and environmental exposure sensors which may operate with minimal training will provide continuous un-tethered long-term data previously impossible to collect in both disease state monitoring and environmental factor analysis.

B. *EnvironmentalMonitoring Devices*

Wide area environmental monitoring has been limited to either the use of high resolution sensors mounted on vehicles, or the use of satellite based data. Such techniques require a large investment of resources to provide long-term data. Other maintenance free techniques may be deployed in a sensor network with access to power and space, but may be difficult to deploy in large numbers in remote locations without installing major infrastructure.

Thus, an ultra-compact trace-gas sensor which dissipates relatively low amounts of power is of importance for these applications. As unauthorized industrial emissions detection becomes more important for environmental agencies around the world, higher precision and continuous monitoring will be necessary to confirm such events originated from the suspected source. Energy harvesting sensors with continuous data acquisition will allow for the required interruption-free, high spatio-temporal resolution monitoring.

C. *Warfare Agent Detection*

Deploying sensor networks to monitor chemical warfare agents is also of interest for locating hazardous and explosive materials in public areas. With a network of sensors, a concentration map can be generated to localize emission sources, instead of requiring bomb sniffing dogs or traffic limiting security checkpoints at all entrances. Furthermore, the possibility of directing people to the correct exits to avoid sources will improve evacuation efficiency if necessary.

III. System Architecture

This work represents the latest efforts to simultaneously minimize sensor size, cost, and power consumption while preserving system performance (Fig. 1). The consolidated control functionality was addressed by embedding dual 8 MHz TI MSP430F1611 ultra-low-power processors (Fig. 2).

One processor acts as a low power direct digital synthesis (DDS) waveform source to generate a reference sinusoid waveform. A built-in comparator converted the sinusoid to a digital clock. Build-in timer outputs were used to divide the clock into a laser modulation signal $1f$ (16 kHz), quadrature $2f$ (32kHz) local oscillators, and quadrature $3f$ (49kHz) local oscillators for lock-in amplification. The DDS was implemented with a 31 bit phase tuning word in order to match the high-Q-factor tuning fork resonance (see Fig. 3). A DAC look-up table for the DDS output values was loaded onto the MSP flash memory, and a hardware loop to generate the periodic waveform was programmed in assembly language.

The second processor performs laser control by implementing two digital PID controllers for laser bias current and temperature. The second processor also handles sampling of the lock-in amplified signal and post processing. The PID controller for temperature provided PWM timer outputs to the laser Peltier thermoelectric cooler (see Fig. 4). A method to calculate the current temperature of a thermistor (commonly integrated into telecom lasers) was developed using an INA330. A 16-bit DAC on an SPI bus provides offset bias voltage control signal to a 3MHz switching power regulator for the laser diode, and a high side shunt current monitor provides the feedback signal for the PID compensation, which simultaneously acts as laser line-locking compensation for both wavelength stabilization and a digitally controlled switching current source. The line-locking error signal is generated from a $3f$ lock-in amplifier signal of a reference cell photodiode.

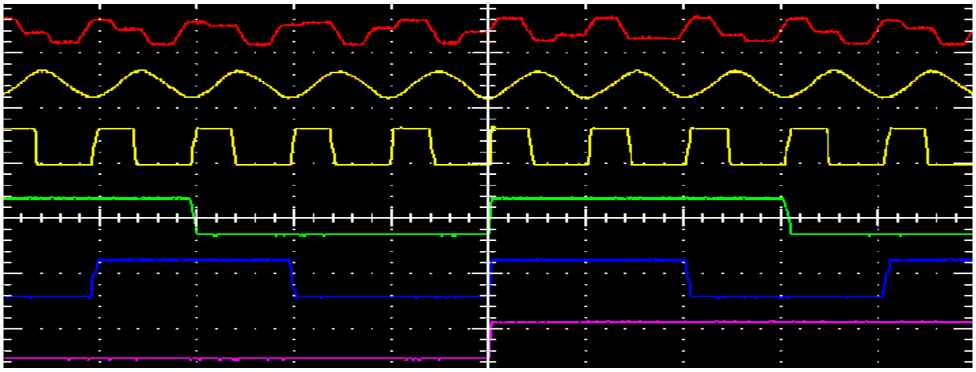

Fig. 3. Oscilloscope trace of harmonic DDS waveforms generated for lock-in amplifier local oscillators (top to bottom: raw DDS DAC output, filtered 196608 Hz, comparator output, 32768 Hz, 49152 Hz, 16384 Hz).

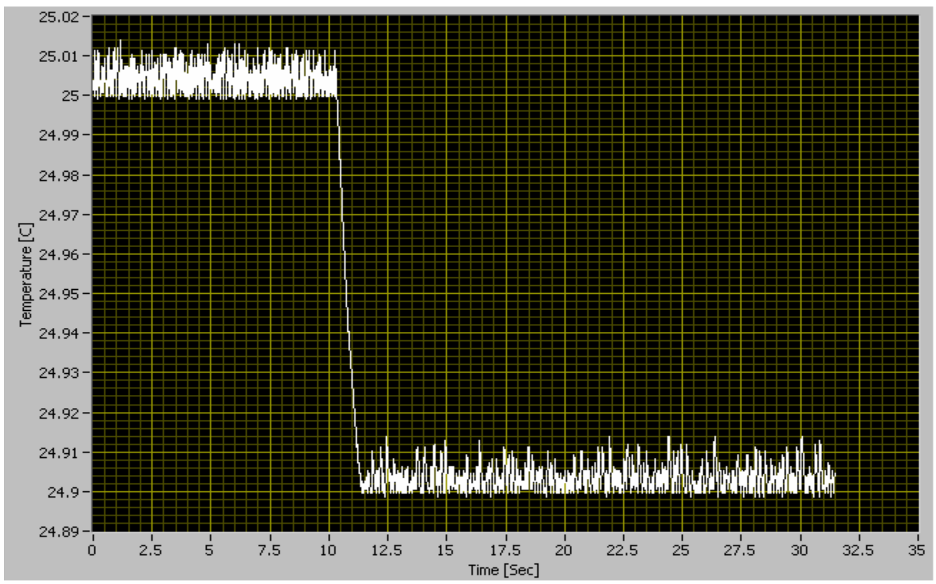

Fig. 4. PWM diode laser Peltier TEC temperature PID regulation, response to 0.1°C set-point change

The digital systems were purposely designed to keep high speed bus lines routed near the analog sections of the board as quiet as possible during measurement mode. This allowed for a dense layout of the ICs. A multiplying DAC was used to provide variable 16-bit attenuation of the laser modulation depth parameter. Thus, each point of the modulation sinusoid did not need to be generated by the DAC, but could be derived directly from the filtered $1f$ clock signal. An external 16-bit ADC (ADS1112) with 240SPS sample rate was used to digitize the lock-in amplifier output over an I^2C interface.

Other peripherals included on the board are a pressure sensor, networking radio, an external flash IC, and battery systems. The MPXM2102 pressure sensor can be used to roughly track ambient (or sealed gas chamber) pressure. An external 8Mbit NAND flash chip provides data storage when communications are unavailable. A TI/Chipcon CC2420 radio was embedded to provide ZigBee IEEE 802.15.4 sensor networking. Additionally, a switching Li-Ion charge system was implemented for 5V AC adaptor and USB charging of the battery during operation of the system.

The circuit board was designed with 4 layers, with all components mounted to the top side except the laser. The laser mounting point on the circuit board was designed with a telecom 14 pin DIL (dual in-line) laser in mind, with a copper landing area and thermal vias for thermal sinking to the board, minimizing the required external heatsinking. The board was also manufactured with 2 oz. copper on the outer layers, and 1 oz. copper on the inner power and ground layers, increasing the thermal mass of the board over standard 1/0.5 oz copper. The laser was mounted on the bottom side to facilitate separation of the high power and sensitive analog sections of the board.

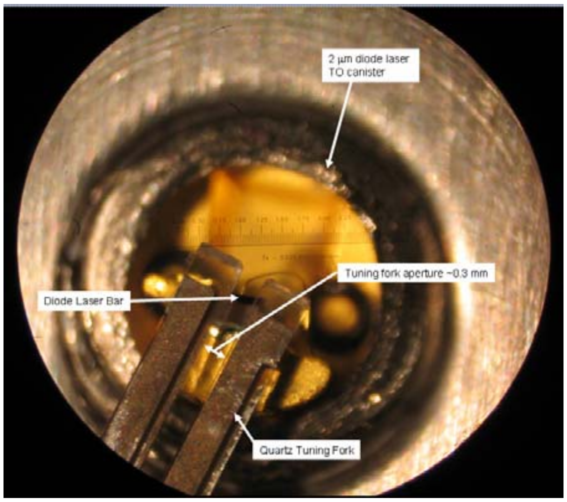

Fig. 5. Photograph of minimal photoacoustic system sensor head. The quartz tuning fork was placed as close as possible to the diode laser bar. The distance between tuning fork prongs was 0.3 mm.

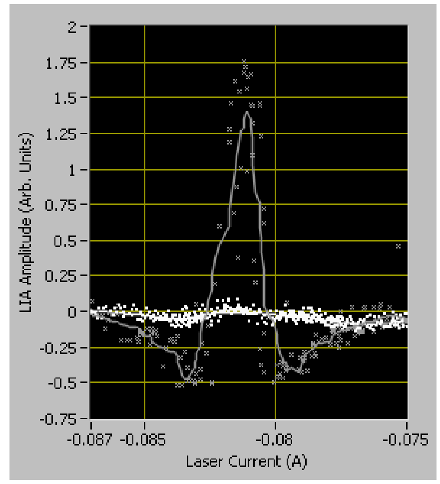

Fig. 6. Example spectra of CO_2. White = Laboratory Air, Grey = 5% CO_2 cylinder source blown into chamber at low flow mixed with laboratory air. Solid lines = smoothed data set. Lock in time constant.= 1 sec.

IV. System Performance

The actual current of the control and acquisition systems measured with an ammeter at the power entry terminals was 56mA (measured with TEC driver and laser driver off), resulting in an electronic power dissipation of 0.201 W at the 3.6V nominal Li-Ion battery voltage.

Although direct absorption spectroscopy with this system controller would allow for lower total power consumption (since such signals are ideally optical power independent), the manufacturability and system cost would be critically affected in sensor network applications. Thus, we have concentrated on QEPAS systems to achieve replicable, autonomous sensors.

The test system implemented a 2 micron DFB laser (NTT Electronics KELD1G5B2TA) to measure CO_2. This laser was mounted within a Thor Labs LDM21 laser mount, which integrated a TEC cooler and thermistor. The LDM21 was plugged into the main board with an adapter board, which converted the DB9 pinouts of the TEC and laser driver to the DIL pinout.

The test system reduced the optical components to the absolute minimum in order to contribute a further cost and size reduction. Thus, the laser TO canister was cut open, and the tuning fork placed directly over the diode output facet as close as possible (Fig. 5). This mounting minimized the amount of power lost due to the divergent beam emitted from the un-collimated laser.

Although there was a strong background signal due to the proximity of the tuning fork to the laser (EM coupling), the CO_2 signal from laboratory air could still be distinguished by current tuning over the line (Fig. 6). A cylinder of 5% CO_2 was blown into the chamber to verify the line position of the signal. Increased concentrations introduced more noise in the signal due to proximity of the excited gas to the opened laser.

The laser voltage was 1.4V, and the laser bias current at line center was 80mA. The TEC power consumption was ~0.4 W to reach 29 °C. Thus, total power consumption to detect ambient CO_2 (300-400 ppm) was ~ 0.75 W.

V. Conclusions and Future Work

An advanced sensor control system has been developed for laser spectroscopic gas sensing applications. Power consumption and total sensor cost has been lowered to allow for high resolution spectroscopic gas sensing in a wider variety of applications.

Further improvements to the system in the near future will include improving the PID loop performance, optimizing amplifier choices for lower power consumption, lowering coupling between the tuning fork, gas sample, and laser, allowing for quantum cascade lasers for high precision applications, and improving temperature regulation using a higher precision PWM control method.

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