



Low-cost electronic circuitry for photoacoustic gas sensing

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ARTICLE INFO

Article history:

Received 4 October 2021

Received in revised form 9 February 2022

Accepted 14 February 2022

Keywords:

Sine wave generation

Direct digital synthesis

Lock-in detection

Forth

NO₂

ABSTRACT

The circuitry comprises a sine wave generator based on direct digital synthesis, a laser diode driver module, a band-pass frequency filter, a synchronous detector with phase adjustment circuitry and a low pass filter to form an analog lock-in amplifier, and an analog-to-digital converter. A 32-bit ARM microcontroller programmed with the open source Mecrisp dialect of the Forth interpreter language is used to set the frequency, and read the data from the analog-to-digital converter. The circuitry is tethered via a serial interface to a personal computer. A graphical user interface written in Python allows easy interaction with the microcontroller by sending the appropriate Forth commands. The data acquired is visualized and stored on the personal computer for further processing. The circuitry is easy to build as it is based on through-hole devices, except for two necessary surface mount items, which, however, still can be soldered with a fine tipped soldering iron. The performance of the circuitry was demonstrated by the photoacoustic detection of NO₂ using a laser diode with a wavelength of 450 nm.

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Specifications table

Hardware name	Circuitry for photoacoustic gas sensing
Subject area	<ul style="list-style-type: none"> • Chemistry and Biochemistry • Environmental, Planetary and Agricultural Sciences
Hardware type	<ul style="list-style-type: none"> • Measuring physical properties and in-lab sensors • Electrical engineering and computer science
Closest commercial analogue	Lock-in amplifier
Open Source License	CERN OHL v.2.0 (https://ohwr.org/project/licences/wikis/home).
Cost of Hardware	appr. US\$ 380
Source File Repository	https://doi.org/10.5281/zenodo.6024087

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Hardware in context

The photoacoustic effect arises when a light absorbing material is irradiated with an intensity modulated light beam as the absorbed energy gets transformed into heat, and hence into pressure waves. These can be picked up with a microphone. A common use is the quantification of gases, for such applications as industrial hygiene and pollution monitoring or prevention. Recent reviews on photoacoustic gas sensing are available [1,2]. Gases can be detected photoacoustically if the analyte has a strong optical molecular absorbance band which can be matched with a light source. Wavelengths in the UV-range (e.g. ozone at 255 nm), the visible (e.g. NO₂ at 450 nm) or often in the infrared (e.g. methane at 3.3 μm or CO₂ at 4.3 μm) may be employed. In photoacoustic gas sensing usually a laser diode, with an emission wavelength matching the absorbance of the analyte, is employed as light source. The photoacoustic cells are usually fitted with an acoustic resonator, mostly in the form of a tube, and the frequency of the intensity modulation of the light source is matched to its resonance frequency as this yields the highest sensitivity. For a tubular resonator the frequency is not only dependent on its dimensions but also on the speed of sound of the gas mixture, however for the usual determination of minor components in air this can be taken as being constant. The electrical signal obtained with the microphone is processed with a lock-in amplifier in order to suppress ambient noise and hence achieve good limits of detection for the gas to be determined. For the experimenter in the laboratory the electronics for data acquisition usually comprise a series of stand-alone instruments; namely a function generator to create the modulation waveform, a laser diode driver, a microphone preamplifier, a lock-in amplifier, and if the latter is not of the newer digital kind, an analog-to-digital data acquisition unit. For a typical set-up see for example our earlier publication on the sensing of ozone with a red laser diode [3]. The circuitry described herein combines the essential functions required to carry out photoacoustic measurements on a single printed circuit board. The exception is the microphone preamplifier, which needs to be located close to the pick-up microphone in a separate shielded case. The circuitry could be built for approximately 380 US\$ and replaces an assembly of commercial instrument boxes which cost ca. US\$ 7600 to purchase. In particular, commercial lock-in amplifiers cost thousands of US\$. The circuitry presented herein includes all the principal functions of these instruments, specifically, besides the synchronous detector it also features a phase adjustment and a bandpass filter at the signal input. But note, while the circuitry is well suited for quantitative measurements at a fixed frequency, it is not as convenient for doing frequency scans. On the other hand, the circuitry is also considerably more compact than the assembly of commercial instruments, which will be of interest if space is an issue, e.g. for on-site measurements. Modifications of the circuitry, without the laser diode driver, may also be of interest for other applications requiring a lock-in amplifier.

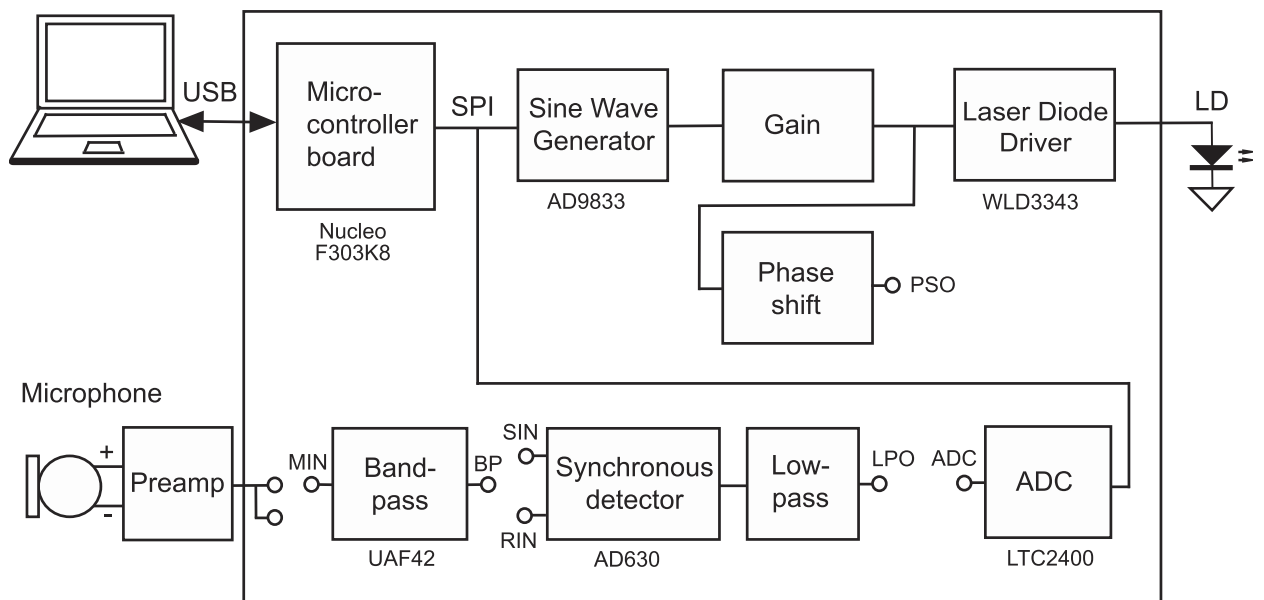


Fig. 1. Block diagram of the electronic set-up. The parts within the frame are contained on the single printed circuit board. The circles represent connecting pins to allow different configurations by placing jumper wires between the functional blocks.

Hardware description

A block diagram of the circuitry contained on a single printed circuit board (PCB) of the Eurocard size (100 × 160 mm) is shown in Fig. 1 and the circuit diagram in Fig. 2. The modulation sine wave is created with a function generator IC and then fed to a laser diode driver module. The same signal is also passed through a phase adjustment circuitry to the reference input of the synchronous detector. This allows for compensation of the phase shift arising in the photoacoustic cell due to the relatively slow propagation of the sound wave. The photoacoustic signal is picked up with a microphone and boosted with a preamplifier, located next to the microphone. Its output signal is passed to the main circuitry with a coax cable. It is normally bandpass filtered to reduce noise before the synchronous detector, and low pass filtered after it. The thus obtained DC signal is then digitized with an analog-to-digital converter (ADC). Note, that some of the connections between the functional blocks are not hardwired. This enables a reconfiguration of the set-up to determine the operating frequency for the photoacoustic cell. A microcontroller serves for setting the frequency of the function generator and for operating the ADC and transferring the data via USB to a PC for visualization and further processing. The system is controlled with a graphical user interface (GUI) program running on the PC.

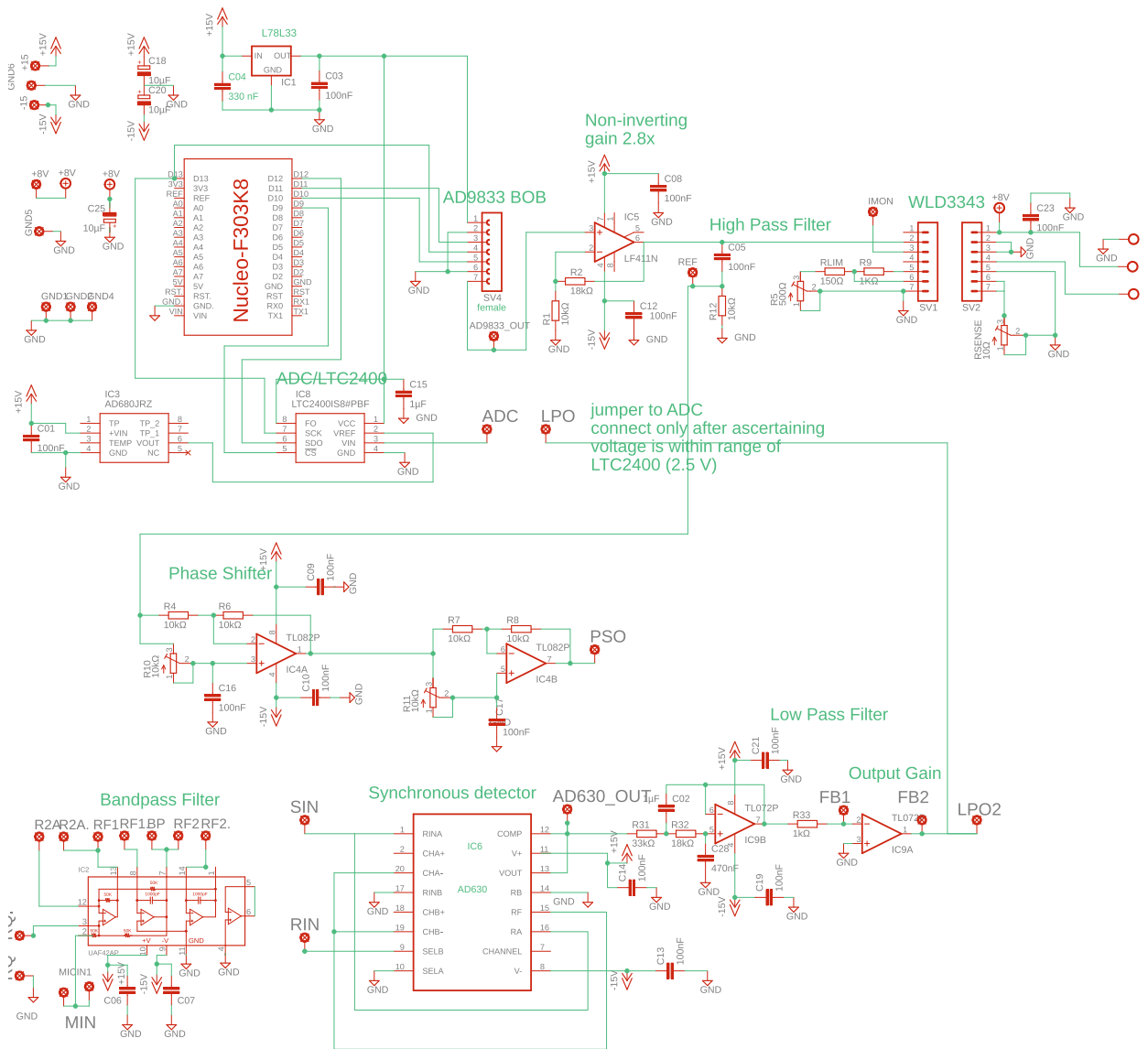


Fig. 2. Circuit diagram.

The circuitry was kept simple to construct by relying on commercially available modules where possible (function generator, laser diode driver, microcontroller). It is based on through-hole components for easy solderability, except for two integrated circuits (ICs) which are not available in the DIP (dual in-line package) format. However, these are of the SOIC (small outline IC) size, the largest SMD (surface mount device) IC package available, which can be soldered with a conventional soldering iron.

Waveform generator and amplifier

The modulation sine wave is produced with a DDS (direct digital synthesis) IC (AD9833). This replaces a function generator, which is a stand alone instrument costing several hundred US\$. As the IC is only available in a tiny MSOP (mini small outline package) format, and therefore requires special soldering techniques, a ready made module on a small PCB, which is available inexpensively, was employed. This contains the complete circuitry necessary for its operation. The signal was high pass filtered (for removal of a DC (direct current) bias) and amplified by a factor of 2.8 with an operational amplifier (LF411) to condition it for the laser diode driver module.

Laser diode driver

Laser diodes in photoacoustics require a driver circuitry which modulates the current in proportion to a control signal. As laser diodes are very sensitive to current spikes (e.g. on turning on) such drivers also include special protection measures. Therefore a commercially available module (WLD3343) was also employed for this task, which is still considerably less expensive than commonly employed stand alone laser diode driver instruments. This module is capable of a maximum current of 2.2 A, and for cooling requires a heat sink fitted with an active fan.

Bandpass filter

A bandpass filter was added in front of the input of the synchronous detector in order to improve the signal-to-noise ratio for quantitative measurements. The design of such frequency filters is not trivial and thus for simplification a universal filter IC (UAF42) available from Texas Instruments was employed. The filter was configured as a 2nd order active bandpass filter. The centre frequency, bandwidth and Q-factor are simply set by external resistors of appropriate values. The easiest way to determine these values is by using the software program FILTER42, which can be downloaded from the web-site of Texas Instruments. But please note, that a MS DOS emulator or a version of MS Windows with a DOS prompt is required to run the program. The program will calculate resistor values which are actually available for purchase and give a centre frequency as close as possible to the value specified by the user. In order to allow modifications, the resistors were also not hand-soldered onto the board.

Phase shifter

The synchronous detector requires the modulation signal at its reference input. As the photoacoustic signal is delayed due to the relatively slow propagation of the acoustic wave in the gas, the phase of the reference signal also needs to be adjusted. Otherwise the signal at the output of the synchronous detector is reduced. The adjustable delay was implemented with a dual stage phase shifter circuitry (known as an all-pass filter) based on a dual operational amplifier IC. The trimmer resistors of the two stages allow a wide adjustment range.

Synchronous detector, low pass filter and output amplifier

The synchronous detector is based on a dedicated IC, the AD630 from Analog Devices. This device effectively rectifies the part of the signal which corresponds to the frequency at the reference input. The resulting pulsed DC signal then needs smoothing by low pass filtering. This was implemented with a double pole active low pass filter based on an operational amplifier. Subsequently it is amplified to match the signal to the input range of the analog-to-digital converter (ADC).

Analog to digital converter

The analog to digital conversion (ADC) is performed with a 24-bit delta-sigma converter IC from Analog Devices (LTC2400), which requires a 2.5 V bandgap voltage reference (AD680) for precise results.

Microcontroller

Two of the components of the circuitry, namely the DDS function generator (AD9833) and the ADC (LTC2400) need to be connected via SPI (serial peripheral interface) bus to a microcontroller for their operation. Furthermore, the microcontroller needs to be connected via USB (universal serial bus) to a PC (personal computer) for user interaction as well as visualization and storage of data. As for the calculation of the frequency setting of the DDS and for the processing of the conversion results

of the ADC a microcontroller with a wide data bus is preferable, a 32 bit M4 Cortex ARM microcontroller (STM32F303K8) from STMicroelectronics was employed. As a simple solution, a ready made evaluation board (Nucleo F303K8) available from STMicroelectronics was employed, which includes all auxiliary parts, in particular the USB bridge IC required for the communication with the PC. The software routines for setting the frequency of the AD9833 and for reading the conversions results of the LTC2400 were written in a version of the programming language Forth, which is available as open source software for the STM32F303K8 microcontroller under the name Mecrisp-Stellaris (<http://mecrisp.sourceforge.net>). Forth is an interpreter language which is compact (ca. 16 kByte) and can therefore be installed on a small microcontroller. Its interactive nature facilitates the software development and the use of a tethered approach, in which a microcontroller based instrument is supervised by software running on a PC. For more information on this versatile approach, which was found to be highly useful in our research laboratory, please consult our tutorial [4]. The graphical user interface (GUI) on the PC was written in Python 3.

Power supplies

The main circuitry requires a ± 15 V split power supply. The laser diode driver needs a separate unipolar supply with a voltage and current capability according to the requirement of the laser diode employed (8 V in our case) and a power supply for the fan mounted on its heat sink. The microcontroller board is powered via the USB of the PC.

- The circuitry replaces several commercial instruments at significantly lower cost.
- The performance is comparable to that achieved with commercial instruments.
- The circuitry can be used as a prototype for further development in portable photoacoustic gas sensing.
- With small modifications the circuitry will be useful for other applications where lock-in detection is required.

Design files

Design files summary

Design file name	File type	Open source license	Location of the file
PCB.sch	EAGLE schematic	CERN OHL v.2.0	https://doi.org/10.5281/zenodo.6024087
PCB.brd	EAGLE layout	CERN OHL v.2.0	https://doi.org/10.5281/zenodo.6024087
Forth-Words.fth	Mecrisp Forth program	CERN OHL v.2.0	https://doi.org/10.5281/zenodo.6024087
GUI.py	Python PC program	CERN OHL v.2.0	https://doi.org/10.5281/zenodo.6024087

PCB.sch and PCB.brd are the design files in the pcb layout program EAGLE for the circuitry. Forth-Words.fth is the Forth program to be installed on the STM32F303K8 microcontroller. GUI.py is the Python GUI program to be installed on the PC.

Bill of materials

Designator	Component	Number	Cost per unit - US\$	Total cost - US\$	Source of materials	Material type
Nucleo F303K8	Micro-controller board	1	11.00	11.00	Mouser.com	Semiconductor module
AD9833 BOB	AD9833 breakout board	1	3.00	3.00	Aliexpress.com	Semiconductor module
WLD3343	Laser diode driver	1	99.00	99.00	Teamwavelength.com	Semiconductor module
IC1	L78L33ACZ	1	0.50	0.50	Mouser.com	Semiconductor
IC2	UAF42	1	22.00	22.00	Mouser.com	Semiconductor
IC3	AD680	1	15.00	15.00	Mouser.com	Semiconductor
IC4	TL082	1	1.00	1.00	Mouser.com	Semiconductor
IC5	LF411	1	2.40	2.40	Mouser.com	Semiconductor
IC6	AD630JNZ	1	43.00	43.00	Mouser.com	Semiconductor
IC8	LTC2400	1	15.00	15.00	Mouser.com	Semiconductor

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Designator	Component	Number	Cost per unit - US\$	Total cost - US\$	Source of materials	Material type
IC9	TL072	1	1.00	1.00	Mouser.com	Semiconductor
R5	Bourns 3296Y-1-501LF	1	2.30	2.30	Mouser.com	Trimmer resistor 500 Ω
RSense	Bourns 3296Y-1-100LF	1	2.70	2.70	Mouser.com	Trimmer resistor 10 Ω
R10, R11	Bourns 3296Y-1-103LF	2	2.90	5.80	Mouser.com	Trimmer resistors 10 k
C20, C18, C25	10 μ F, 5 mm AVX TAP106M035CCS	3	1.20	3.60	Mouser.com	Tantalum capacitor
C01, C03, C05, C06, C07, C08, C09, C10, C12, C13, C14, C16, C17, C19, C21, C23	100 nF, 2.5 mm Wima MKS0C031000C00MSSD	16	0.80	12.80	Mouser.com	Foil capacitor
C04	330 nF, 5 mm Wima MKS2C033301C00KSSD	1	0.65	0.65	Mouser.com	Foil capacitor
C28	470 nF, 5 mm Wima MKS2C034701C00KSSD	1	0.75	0.75	Mouser.com	Foil capacitor
C02, C15	1 μ F, 2.5 mm Wima MKS0B041000F00KSSD	2	1.60	3.20	Mouser.com	Foil capacitor
RLIM	150 Ω 250 mW, 1%	1	0.25	0.25	Mouser.com	Resistor
R9, R33	1 k Ω 250 mW, 1%	2	0.25	0.50	Mouser.com	Resistor
R1, R4, R6, R7, R8, R12, Feedback1	10 k Ω 250 mW, 1%	6	0.25	1.50	Mouser.com	Resistor
R32	10 k Ω 250 mW, 1%	1	0.25	0.25	Mouser.com	Resistor
R31	10 k Ω 250 mW, 1%	1	0.25	0.25	Mouser.com	Resistor
R2	18 k Ω 250 mW, 1%	1	0.25	0.25	Mouser.com	Resistor
Wire to board terminal block	Phoenix Contact 1,888,690	1	1.90	1.90	Mouser.com	Connector
15 pin female header	Gravitech 15Fx1-254 mm	2	1.20	2.40	Mouser.com	Sockets for the Nucleo board
7 pin female header	3 M 929850-01-07-RA	3	1.80	5.40	Mouser.com	Sockets for AD9833 BOB and WLD3343
Pins	Vogt 1365a.61	Pack of 100	5.00	5.00	Conrad.ch	Contact pins
Lugs	Vogt 1360.28	Pack of 100	7.70	7.70	Conrad.ch	Cable lugs for external connections and plugged resistors

In addition to the parts listed in the table, resistors are needed for the bandpass filter according to the required frequency, as well as a case for housing and connectors of your preference to make the external connections for signal and power.

Build instructions

Printed circuit board fabrication and assembly

The layout for the printed circuit board was created with the CAD program EAGLE (from www.autodesk.com). We manufactured the board ourselves from photoresist coated base material in our chemistry laboratory, a photograph is shown in [Fig. 3](#). The reader most likely will prefer to order it from a commercial board manufacturer. We have had good experience with Beta Layout (<https://de.beta-layout.com>), who accept the EAGLE CAD files. Other board houses may require Gerber files, which, however, can also be created with the EAGLE application from the native EAGLE files. The board was populated by hand soldering. It is recommended to use sockets for the electronic modules mounted on the board, and for the more expen-

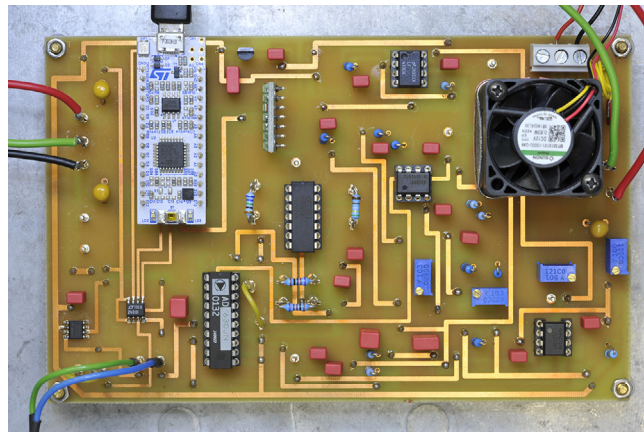


Fig. 3. The printed circuit board.

sive ICs. Good quality gold plated sockets should be employed, at least for the parts in the signal amplification path. The connections between the modules which need to be jumpered were made with the help of silver coated pins of 1.3 mm diameter and matching wire lugs. These were also used for mounting the resistors which needed to be exchangeable and as test points, and give a more solid contact than the usual 1/10th inch headers. A 10 k Ω resistor is placed in the feedback path of the output amplifier. The board should be housed in a grounded metallic box fitted with sockets of the preferred format to enable the power and external signal connections.

Programming of the microcontroller

The open source Mecrisp-Stellaris Forth interpreter is available for download from <https://sourceforge.net/projects/mecrisp/files/>. (Make sure to download Mecrisp-Stellaris, not any of the other Mecrisp variants available from the same repository. The Mecrisp-Stellaris version employed by us was 2.5.3, but you might want to use the latest update.) After expanding the package locate the file “mecrisp-stellaris-stm32f303k8.bin” and copy it to the home directory of your computer. The Nucleo board includes a programmer/debugger so that no separate programming hardware is necessary. Simply connect the Nucleo board to the computer via a USB cable (USB 2.0 with Micro B plug). One of the possible methods for the installation of the Forth software package on the microcontroller is based on a utility program called ST-Link running on a PC. For Windows this can be downloaded from the web-site of STMicroelectronics (www.st.com), for a Macintosh (and Linux) it may be installed easiest using the package manager Homebrew. Flashing Mecrisp-Stellaris on the Nucleo board with the ST-Link utility then requires two steps (type on the command line or in the terminal):

1. Erasure of the flash memory: `st-flash erase`
2. Flashing the binary: `st-flash write mecrisp-stellaris-stm32f303k8.bin 0x08000000`

Following the successful installation of Mecrisp-Stellaris a fully operational Forth system is now present on the microcontroller and it is possible to communicate with it by using a serial terminal emulator program on the PC. We have been using CoolTerm (<https://freeware.the-meiers.org>). You will need to identify the port to which the microcontroller is connected (with CoolTerm the menu item *Re-Scan Serial Ports* will bring up a list of the available ports, which under Windows will be 'COM6' or similar). Make a note of the name of the port. Establish a connection with a baudrate of 115200, 8 data bits 8, no parity and 1 stop bit. In the *Transmit* menu set the transmit character delay to 3 ms and the transmit line delay to 100 ms in order to allow the microcontroller to process the data sent to it without overrun and then click *Connect*. The routines for setting the frequency by programming the DDS IC (AD9833) and for reading the conversion results of the ADC (LTC2400) are compiled on the microcontroller by sending the source file *Forth-Words.fth* (from the supplemental material) to the microcontroller by choosing *Send Text/Binary File* under the *Connection* tab. To check that all the Forth code has been embedded in the library on the microcontroller you can type 'words' followed by a carriage return, and all the compiled sub-routines (called words in Forth) will be shown line by line. The last entry should be 'LTC2400AVERAGEDREAD'. The Forth system will indicate that it is ready by issuing an 'ok'. All the words shown are available for interactive execution and testing via the serial terminal. If you are interested in exploring Forth, our earlier article can serve as an entry point [4].

Setting up the graphical user interface on the PC

The graphical user interface, shown in Fig. 4, to carry out a frequency scan and to acquire signal vs. time data, has been programmed in Python 3 and should run under Windows, macOS and Linux. The script can be found in the supplemental material under the name of *GUI.py*. It is not necessary to be fluent in Python programming in order to use it, but some basic knowledge on

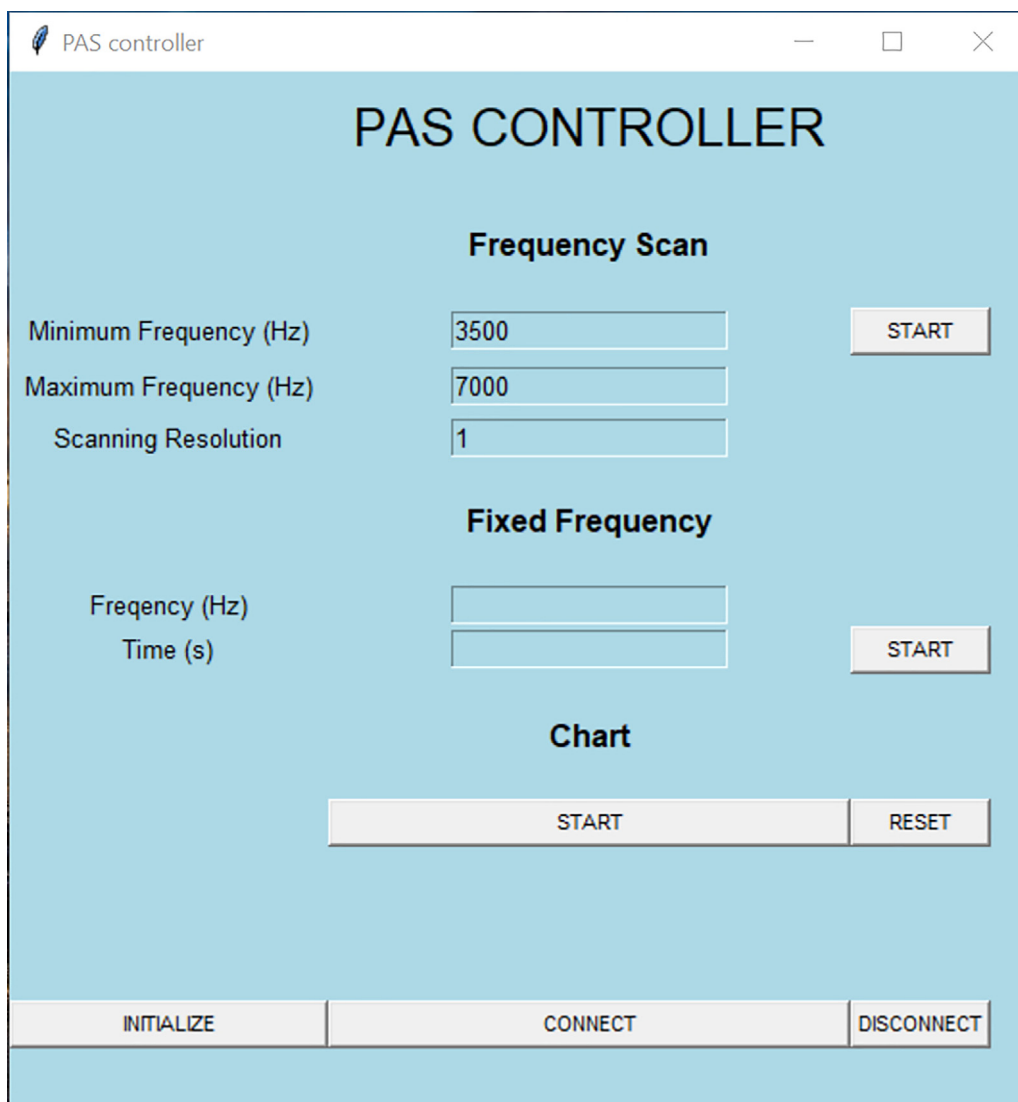


Fig. 4. A screenshot image of graphical user interface (GUI).

how to work with Python under the PC operating system of your choice is necessary. You should know how to install Python 3, if it is not already present, and execute a Python 3 script. Before the script can be run, it also has to be assured that the packages listed at the beginning of the script are installed on the computer (using the package manager pip3 for checking what is present and for installing missing packages). Consult www.python.org on how to carry out these tasks if you are new to Python.

Operation instructions

Basic setup

Make sure that the Nucleo board is not connected software-wise to your computer via the terminal emulator program (use the *Disconnect* menu item in CoolTerm or close the program). Open the Python 3 script (*GUI.py*) with a plain text editor and change the name of the port according to the one of your set-up (see section 5.2) in the line “ser = serial.Serial(‘COM6’, 115200, timeout = 1)” near the end, and save the modified file. Run the script. In the GUI click the *CONNECT* button to connect the system. Then click *INITIALIZE* to set up the AD9833 and the LTC2400.

Determination of the resonance frequency

A photoacoustic cell should be operated at its resonance frequency for highest sensitivity and if not known it must be determined before quantitative measurements are carried out. For this either the cell is filled with the gas to be sensed at

the highest possible concentration, or a small loudspeaker driven by the sine wave is placed into the cell to excite its resonance. The frequency for the maximum signal strength can then be found by carrying out a frequency sweep set up with the GUI. The maximum may be determined by simply monitoring the amplitude of the signal from the microphone amplifier with an oscilloscope. It is also possible to record the intensity vs. frequency by temporarily feeding the output of the microphone amplifier directly (*i.e.* bypassing the bandpass filter) to the signal input of the synchronous detector (AD630)(via the pin labelled SIN). The reference input (RIN) should be connected to the same signal. This configuration does not make optimal use of the circuitry for noise suppression but avoids a bias due to the phase shift of the acoustic signal. The data can be visualized after the frequency sweep is finished by clicking the START button under the Chart header. The data will also be saved in a text file for further processing if desired. It is essential that the signal from the output amplifier which is passed to the ADC does not exceed + 2.5 V as this is the top of the input range of the latter, but it should also not be too small. Check with a multimeter before connecting the ADC pin to LPO, and if necessary change the feedback resistor fitted to the output amplifier (between FB1 and FB2) to adjust its gain.

Quantitative measurements at the resonance frequency

Calculate the values of the four resistors, R_{F1} , R_{F2} , R_Q , and R_{2A} , for the bandpass filter using the FILTER42 program and fit the resistors to the pins on the board labelled accordingly using the solder lugs. Reconfigure the connections on the board so that the bandpass filter is in the signal path from the microphone amplifier to the synchronous detector by connecting the microphone amplifier to MIN and BP to SIN. Connect the reference input of the synchronous detector (RIN) to the output of

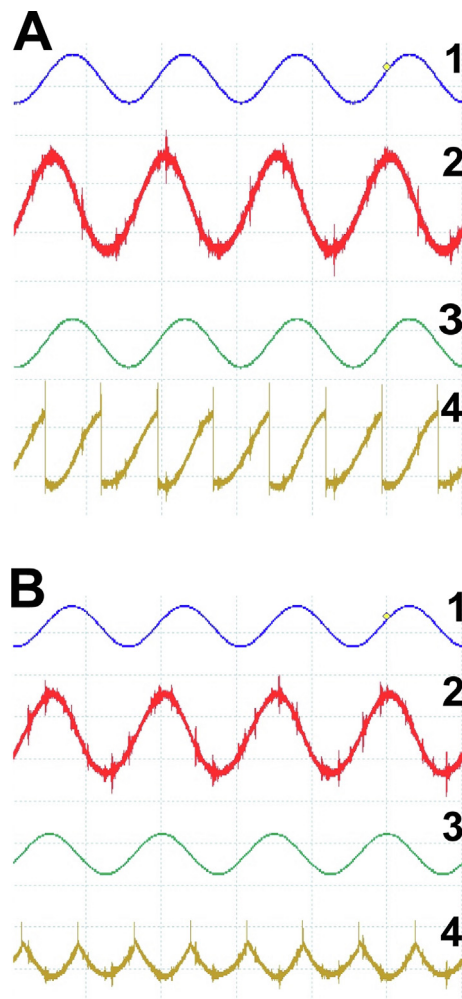


Fig. 5. Images of oscilloscope output obtained with the help of a loudspeaker to illustrate the phase adjustment process. A) before adjustment, B) after adjustment, 1) original excitation signal, 2) signal picked up with the microphone, 3) reference signal, 4) output of the synchronous detector before low pass filtering.

the phase shifter (PSO). Now the phase shift is adjusted with the help of an oscilloscope. Preferably a 4-channel model is employed but at a pinch it is also possible to do this with a 2-channel model. This needs to be done while the cell is filled with the gas to be determined at the highest possible concentration. The process is illustrated in Fig. 5. Note, that for the sake of clarity these images were obtained by using a small loudspeaker to create a strong acoustic signal, rather than the photoacoustic cell. The real photoacoustic signal will be weaker and more strongly overlapped with electronic noise. Panel A shows the screen as it might appear before adjustment. The top trace shows the sine wave excitation signal from the function generator. The second trace is the signal obtained from the microphone, which shows a significant phase shift compared to the excitation signal. The reference signal, which is fed to the reference input of the synchronous detector is shown in the third trace. In this case it is exactly in phase with the excitation signal. The output of the synchronous detector before low pass filtering is shown in trace 4. As this shows positive as well as negative going components, after low pass filtering the signal will be attenuated. For optimization the phase of the reference has to be adjusted. Use one or both of the trimmer resistors until it is in phase with the signal from the microphone as illustrated in panel B of Fig. 5. The output at the synchronous detector should correspond to trace 4 of the right hand panel of Fig. 5, being symmetrical and entirely in

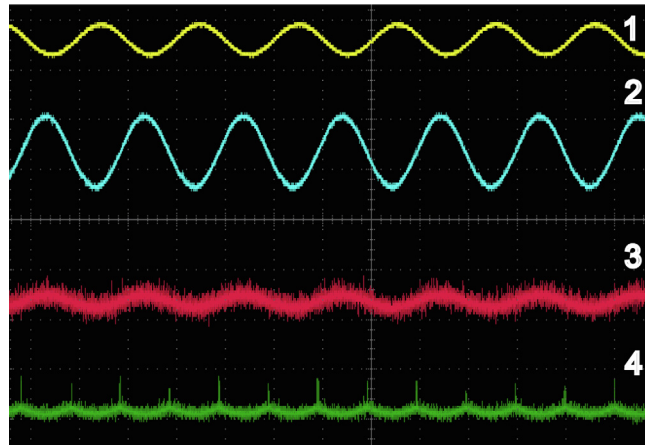


Fig. 6. Image of an oscilloscope output for the signals for the photoacoustic cell used for validation after phase adjustment. 1) original excitation signal, 2) phase adjusted reference signal, 3) signal picked up with the microphone 4) output of the synchronous detector before low pass filtering.

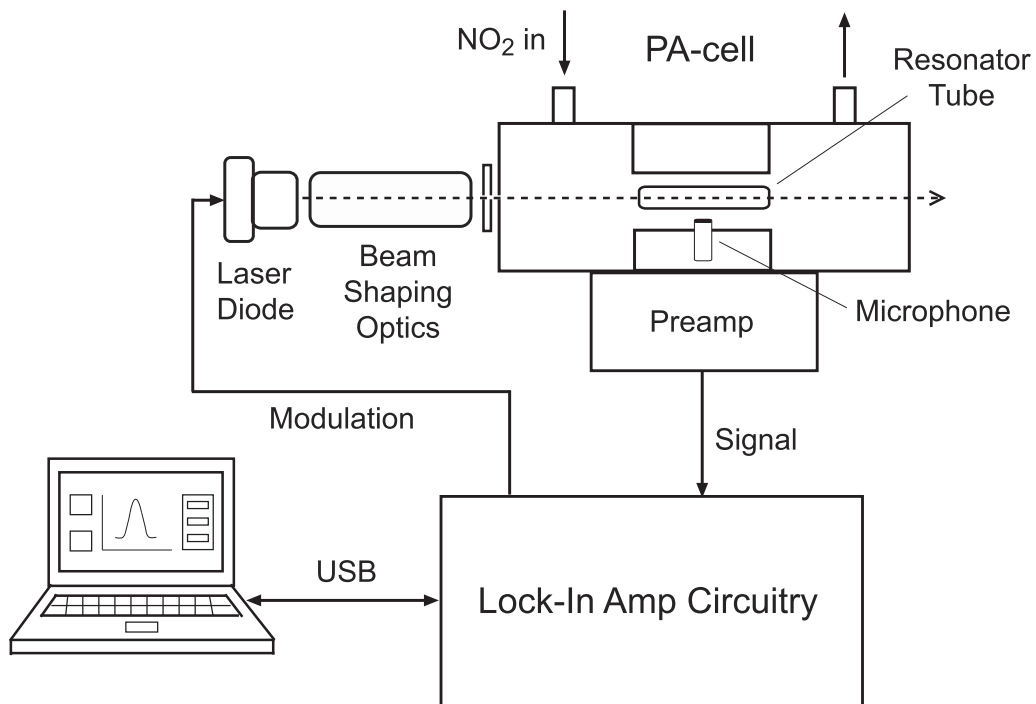


Fig. 7. Schematic drawing of the photoacoustic set-up (not to scale).

the negative voltage range. On close examination it becomes apparent that the positive going part of the sine wave of the raw signal is made negative by the synchronous detector, while the negative going part is left as is, leading to the pulsating negative voltage of trace 4. The output of the AD630 should then be symmetrical and in the negative voltage range. An illustration of the appearance of the weaker signals obtained for a photoacoustic cell is shown in Fig. 6. Quantitative measurements may now be carried out using the controls in the Fixed Frequency section of the GUI.

Validation and characterization

The complete circuitry was tested with a photoacoustic cell set-up for the determination of NO_2 employing a blue laser diode (450 nm, L450P1600MM from Thorlabs, Bergkirchen, Germany). The arrangement is illustrated in Fig. 7. The cell had been adapted from an original design reported by Rück et al. [5]. Details on its construction, including information on the optical parts employed, can be found in our previous publication on its use for the determination of ozone with a red laser diode cell [3]. The filter was configured with a centre frequency of 4908 kHz, a bandwidth of 200 Hz and a Q factor of 24.38. The resistors, R_{F1} , R_{F2} , R_Q , and R_{2A} were calculated as 10.2 k Ω , 10.2 k Ω , 665 Ω , and 5.49 k Ω respectively. A frequency scan for 10 ppmV NO_2 with the bandpass filter in place is shown in Fig. 8. The response of the system to various concentrations of NO_2 is illustrated in Fig. 9. A calibration curve was acquired by measuring 6 concentrations of NO_2 varied from 1 to 10 ppmV. A linear response was obtained with a coefficient of determination (r^2) of 0.9999. The limit of detection (LOD) was determined as 100 ppbV (3σ), by the repeated measurement of 1 ppmV NO_2 against the baseline signal, which compares favourably with many reported LODs for photoacoustic gas sensing [1,2].

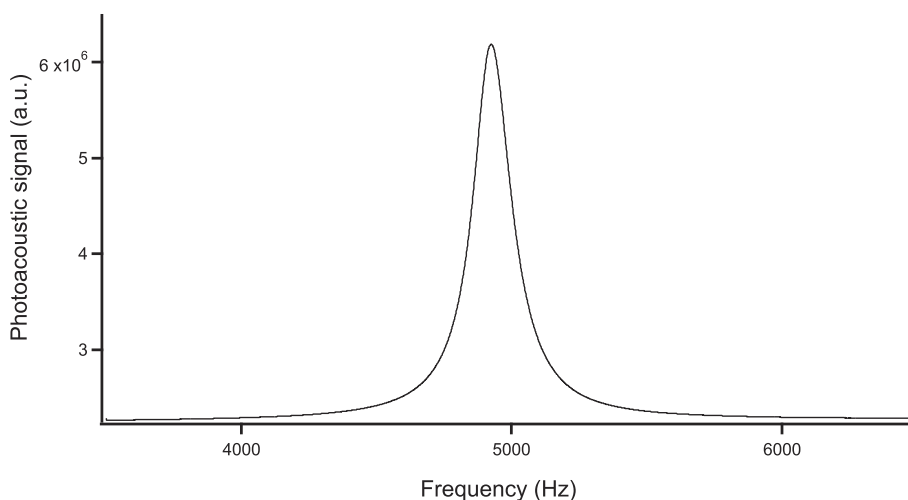


Fig. 8. Frequency scan for 10 ppmV NO_2 and a bandpass filter with a centre frequency of 4908 kHz and a bandwidth of 200 Hz in place.

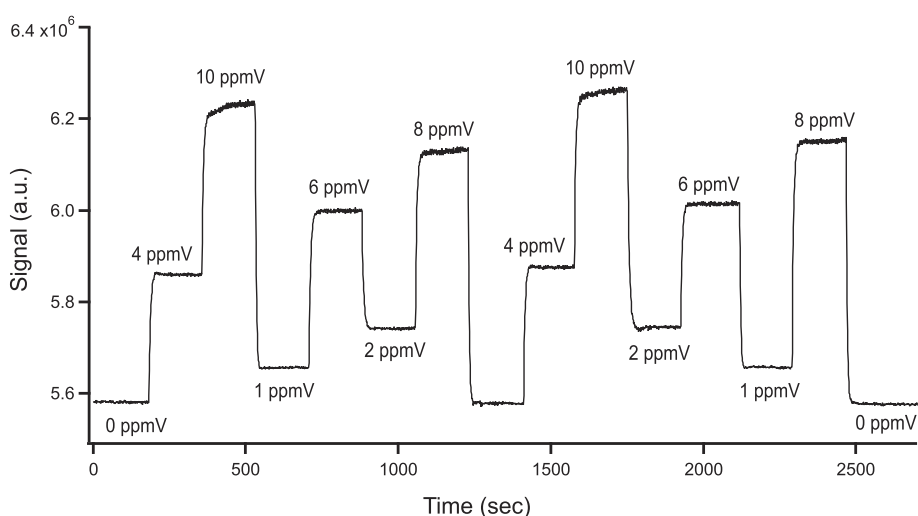


Fig. 9. Photoacoustic signal for various NO_2 concentrations from 0 to 10 ppmV obtained with a fixed frequency run.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge King Mongkut's Institute of Technology Ladkrabang (KMITL) for the financial support through a fellowship to Kanchalar Keeratirawee. The authors also thank Anatoly Johnson and Georg Holderied for help with setting up the optics and electronics.

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