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Lock-in and Signal Averaging Circuits for an NDIR Gas Spectroscopy Based Carbon Monoxide Detector

By

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SUMMARY

This application note describes two circuits (lock-in and signal averaging) for detection and measurement of low levels of carbon monoxide (CO), using Non-Dispersive Infrared (NDIR) gas spectroscopy. NDIR gas detection and measurement offers reliability, sensitivity, and immunity from false alarms for such applications as CO detectors. The lock-in circuit is analog in nature and enables the measurement of CO levels down to 1 ppm, and meets Canadian Standards Association (CSA) requirements for residential CO detectors; while the signal averaging circuit uses a mixed-signals (analog and digital) approach, inherently capable of much higher resolution than that of the analog circuit.

INTRODUCTION

There are essentially two techniques for extracting faint signals from noise: **Lock-in**, and **Signal Averaging**. In both cases, there are no theoretical limits to the depths from which signals can be extracted, below any given noise floor (e.g., thermal). The practical limits, however, are cost and time required for signal lock-in and signal averaging. An analog circuit is described in some details, then a mixed-signals circuit is described in its block diagram format. The mixed-signals circuit approach turns out to be far superior to the analog circuit approach, be it in terms of performance, cost, and reliability.

ANALOG CIRCUIT

Overview

Reference is being made to Figure 1. The circuit compares the signal amplitudes of two MID-IR photodetectors, each irradiated by a common MID-IR source (which may be thermal or quantum in nature), while each photodetector is tuned to a specific wavelength (3.9 µm, and 4.76 µm), within a relatively narrow IR bandwidth. Tuning is accomplished with the use of optical narrow bandpass filters (NBPF), deposited onto the surface of the photodetectors. The IR absorption spectra of CO peaks at 4.76 µm, while offering no absorption at 3.9 µm (gases commonly encountered in a CO environment present no absorption at 3.9 µm). The 3.9 µm tuned photodetector is utilized as a reference. When CO is present between the MID-IR emitter and detectors, a difference in amplitude (amplitude of the electrical signals generated at the photodetectors) results from the absorption of MID-IR at 4.76 µm, by CO, while no signal absorption occurs at 3.9 µm. This difference is amplified by a high gain (160 dB) instrumentation amplifier. A lock-in technique is then utilized to extract the differential signal (deeply buried into amplified Johnson, shot, 1/f, and other forms of noise). The lock-in stage is then followed by a low-pass filter (which further removes noise components, and switching transients, from the signal output of the lock-in circuit). The filtered differential signal is then sent through a peak detector, which maintains a stable voltage level output for 60 seconds, following power turn OFF to the MID-IR source. That signal is then compared (as a function of its amplitude, and as a function of time) to a voltage reference. If the signal exceeds the reference, it latches in a piezoelectric buzzer, providing audible indication of unacceptably high levels of CO, as a function of time.

NOTE: The block diagram depicted in Figure 1 makes use of switches where transistors are utilized as simple ON/OFF switches in Figure 2. Refer to Figure 3 for the states of the transistors when utilized as simple ON/OFF switches.

Power Supply, Voltage Reference, and Associated Components

Reference is being made to Figure 2. R_1, R_2, and R_{71} provide a virtual ground located half way between +V and $-V_{BATT}$, $+V_{BATT}$ and $-V_{BATT}$, respectively, enabling the use of a single 9 volts dry cell (150 mAh type). $+V_{REF}$ is a precision micropower voltage reference of 2.5 volts. R_{72} is a pull-up resistor. IC_1 is powered directly from the 9 volts battery, whereas the other two time bases (IC_2 and IC_3), and all Op-Amps (except for IC_{10}, $_{11}$, $_{12}$, $_{13}$, and $_{14}$) are powered through the main line switch, Q_1, which latter is turned ON/OFF by IC_1; enabling reduced power consumption for battery powered applications. Note that Q_1 can also be turned ON/OFF by IC_{11}, $_{12}$, $_{13}$, or $_{14}$ (more on this further on). R_{10} and R_{11} are current limiting to the base drives of Q_1 and Q_2, respectively.

Time Bases (Main Time Base, Pulse Generator, and 3.75 kHz Oscillator)

Reference is being made to Figure 3 and Figure 4. IC_1, IC_2, and IC_3 are CMOS 555 timers. The charge/discharge paths of their timing capacitors take place through small signal diodes (e.g., 1N914 type); thereby, avoiding ohmic values that would otherwise be to close to permissible minimums and maximums, for the proper functioning of the 555s and; it enables reduction of all capacitances to a single value (0.33 uF), for cost reduction purposes, while at the same time providing highly reliable and predictable timing accuracies.

MID-IR Emitter, Associated Drive Circuit, and MID-IR Photodetectors

Reference is being made to Figure 2. There are two options for the MID-IR emitter: Thermal (a resistive element), and quantum (MID-IR LED). The MID-IR LED source is utilized for this circuit description. The MID-IR LED source is highly efficient from a quantum point of view, relative to the MID-IR thermal source.

The MID-IR LED is driven with a constant current of 50 mA, with the use of IC_{16} (configured as a constant current source). IC_{16} is powered ON for 2 seconds by Q_1, once every 60 seconds. Laser trimming of R_{13} is utilized for setting the voltage, at the non-inverting input of IC_5, equal to that of IC_4. R_{83} is current limiting to the base drive of Q_{21}.

High Gain Instrumentation Amplifier

Reference is being made to Figure 2. The circuit topology is that of a high gain instrumentation amplifier, and conservative. A differential voltage gain of 10,000 for the input stage (IC_4 and IC_5) is definable through R_{15}; while the output stage, IC_6, also provides a differential voltage gain of 10,000. These two stages can provide a total gain of 100,000,000 (160 dB). IC_7 provides common mode rejection and offset compensation. Three laser trimmed resistors, R_{15}, R_{21}, and R_{28}, allow fine adjustment of the amplifier's gain, CMRR, and offset, respectively; while R_{16} provides scaling of the 3.9 µm MID-IR photodetector's signal. C_{10} is a DC blocking capacitor, converting the output DC signal of the high gain instrumentation amplifier into an AC signal, as seen by the Op-Amp of the Lock-in Demodulator, IC_8. D_{23} and D_{24} clip the output voltage of IC_6 to 6 volts peak-to-peak, thereby, preventing the Op-Amp from saturating, which would otherwise limit its gain to less than 80 dB at < 5 kHz. Strings of small signal diodes with fast recovery times (e.g., 1N914) are required instead of 3.0 V zeners (e.g., MMBZ5225BLT1), due to the latter's high leakage current and soft knee in the < 6.2 volts region.

Lock-in Demodulator

Reference is being made to Figure 4. The lock-in demodulator (also called: Balanced Demodulator, Synchronous Demodulator, Phase Sensitive Detector, or Phase Sensitive Rectifier) rectifies the signal present at its input, as a function of the 3.75 kHz oscillator's signal (IC_3), which drives Q_3 and Q_4, providing the net effective equivalent of a narrow (1 Hz) bandpass filter tuned to 3.75 kHz. The output of the lock-in demodulator (Q_3 and Q_4 circuit node) is sent through a low-pass filter (R_{34} and C_4), of which the corner frequency is set to 1.34 Hz, which removes carrier components (3.75 kHz) of the rectified signal, along with any other type of amplified noise (Johnson, shot, 1/f, etc.). The corner frequency of 1.34 Hz enables to charge/discharge C_4 to 7 time constants, within less than 0.831 second (the peak detector is reset following 0.990 second, each time Q_1 turns ON). Reference is being made to Figure 3. IC_8 is configured as a unity gain inverting buffer. Q_3 and Q_4 are utilized as line switches for the rectification of the input signal (C_{10}-R_{23} node). R_{77} is a pull-up resistor, while R_{78} is current limiting to the base drive of Q_5.

Peak Detector

Reference is being made to Figure 2. The output of the lock-in demodulator is sent to IC_9, configured as a non-inverting unity gain buffer, and driving the input of the peak detector. D_{11} prevents C_5 from discharging. R_{40} prevents oscillation of IC_9, which latter would otherwise be looking straight into a purely capacitive load, while R_{39} limits the discharge current of C_5 through Q_{10}, and Q_{11}. Reference is being made to Figure 3. Q_9 turns OFF once every 60 seconds, turning Q_{10} and Q_{11} ON, which discharges C_5 during the LOW portion of the pulse generator's output (IC_2). IC_{10} is chosen for its high input impedance, providing less than 0.1% droop of C_5's voltage during 60 seconds. R_{36}, R_{37}, and R_{38} are current limiting to the base drives of Q_9, Q_{10}, and Q_{11}, respectively, while R_{35} is a pull-up resistor.

PPM Level Comparators

Reference is being made to Figure 2. The signal's level at each comparator's inverting input is compared to the reference at their respective non-inverting inputs. Their rate of rise is also set by an RC time constant ($R_{41}C_6$, $R_{48}C_7$, $R_{51}C_8$, $R_{56}C_9$), so that the comparators' outputs will change state (from HIGH to LOW), according to the levels of CO detected, and as a function of time, meeting CSA standard (CAN/CGA-6.19-M93) for Residential Carbon Monoxide Detectors (see Table 1). Q_{12} through Q_{19} are turned ON by the Reset Switch, thereby discharging (resetting) the capacitors that make up the RC time constants ($R_{41}C_6$, $R_{48}C_7$, $R_{51}C_8$, $R_{56}C_9$), following an abnormally high level of CO, indicated by the audible alarm triggered by the detection circuit. R_{44}, R_{45}, R_{49}, R_{50}, R_{54}, R_{55}, R_{59}, and R_{60} provide a small hysteresis to the comparators; thereby, avoiding audible alarms that would otherwise occur in an intermittent fashion at the onset of detection of an abnormally high level of CO. D_{12} through D_{15} prevent the outputs of each comparator from sourcing into the other comparators' outputs, should one of the comparators' outputs go LOW. R_{42}, R_{43}, R_{47}, R_{48}, R_{52}, R_{53}, R_{57}, and R_{58} are current limiting to the base drive of Q_{12} to Q_{19}, respectively, while R_{73} is a pull-down resistor.

Carbon Monoxide Concentration Versus Time For 10 Per Cent Carboxyhaemoglobin (Cohb)	
A. Carbon monoxide concentration and response time:	
Concentration (ppm)	Maximum response time (minutes)
100	90
200	35
400	15
B. False alarm resistance specification:	
Concentration (ppm)	Exposure time (minutes) (no alarm)
100 ± 5	5
9 + 3 minus 5	480

Table 1

NOTE: The 9 ppm detection level is not required for CSA approval. However, it was designed into the circuit, for the purpose of exploring and evaluating the limits of what can be accomplished with an analog approach to measuring CO to 1 ppm. If the 9 ppm detection level (as a function of time; e.g., > 480 minutes) would be required, say for purposes of sensitivity as a function of time (480 minutes), then 100 megaohms shunt resistors would have to be introduced into the circuit (in parallel with C_6 through C_9), in order to reduce the error that would otherwise result from the leakage of the capacitors utilized for the RC time constants, given the extremely high ohmic values (e.g., 12.5 gigaohms) required of their associated resistors (R_{41}, R_{48}, R_{51}, R_{56}). These shunt resistors are illustrated as R_{66} through R_{69}. In other words, the circuit is shown with RC time constants that are equal to just below the maximum permissible time limits set by CSA, including the 9 ppm level, for the purpose of illustrating the limits of what can be accomplished with the analog approach taken for the design of this circuit; while in fact the circuit can meet CSA requirements with much smaller time constants (e.g., 30 seconds), than the ones illustrated by the time constant values set by the circuit's components (e.g., 90, 35, and 15 minutes, for the 100, 200, and 400 ppm levels, respectively). An abnormally high level of CO sends the output of one of the comparators LOW, turning Q_1 and Q_{20} ON, via R_{79}, and D_{17} and R_{65}, respectively. Q_1 and Q_{20} remain ON, until the Reset Switch is manually actuated. When Q_{20} turns ON, it enables IC_3 to drive the piezoelectric buzzer.

Low Battery Voltage Detector and Indicator

Reference is being made to Figure 2. If the battery voltage falls below that stipulated in the CSA Standard (CAN/CGA-6.19-M93) for Residential Carbon Monoxide Detectors, then the piezoelectric buzzer is turned ON (via Q_{20} and IC_{15}) thereby allowing IC_3 to drive it for 10 milliseconds (enabled by the 10 milliseconds pulse of IC_2 at the non-inverting input of IC_{15} (Refer to Figure 3). IC_{15} is configured as a summing comparator (through R_{61}, R_{64}, and R_{76}). The latter compares the battery voltage to the reference voltage $+V_{REF}$. If the battery voltage falls below the preset minimum, the output of IC_{15} goes LOW, enabling a 10 milliseconds beep once every 60 seconds. R_{62} and R_{63} form a voltage divider for the input signal received from the output of IC_2 (leaving $-V_{BATT}$ compared to $+V_{REF}$ when the output of IC_2 goes LOW). D_{17} prevents the output of IC_{15} from latching Q_1 ON, while D_{16} prevents the outputs of the PPM comparators from sourcing into the output of IC_{15}, should one of the comparators' outputs go LOW. R_{65} is current limiting to the base drive of Q_{20}, while R_{74} is a pull-up resistor. D_1 provides a "Status OK" indication for 10 milliseconds, once every 60 seconds, driven by the LOW of IC_2's output pulse. R_3 is current limiting to D_1.

Analog Circuit - Parts list

- MID-IR LED : 4600-4800 nm, Ioffe Physico-Technical Institute, 26, Polytechnicheskaya, 194021, St-
- Petersburg, Russia - **http://www.ioffe.rssi.ru**
- MID-IR Photodetectors : Philips RPY77 (InSb). NOTE : Philips Electronics no longer manufactures IR detectors of the InSb or MCT types; however, equivalent detectors can be obtained from Judson (EG&G) - **http://www.judsontechnologies.com**
- Voltage Reference : REF192 Analog Devices; or equivalent - **http://www.analog.com**
- IC_1, IC_2, IC_3 : LMC555 National Semiconductor, or equivalent; CMOS 555 timer - **http://www.national.com**
- IC_4, IC_5, IC_6 : LMH6632 National Semiconductor; high open loop gain Op-Amp - **http://www.national.com**
- IC_7, IC_8, IC_9, IC_{10}, IC_{11} through IC_{16} : LMC6442 National Semiconductor; low voltage Op-Amp - **http://www.national.com**
- Q_1, Q_{20} : 2N2907 Motorola; general purpose small signal - **http://www.onsemi.com**
- Q_2, Q_5 through Q_{19}, Q_{21} : 2N2222 Motorola; general purpose small signal - **http://www.onsemi.com**
- Q_3 and Q_4 : MMBFJ177LT1 Motorola; P Channel FETs , low $V_{GS(off)}$ - **http://www.onsemi.com**
- All Diodes : 1N914, or equivalent
- D_{23}, D_{24} : 1N914 X 6, or equivalent
- D_1 : 10 mA LED
- All Capacitors : 0.33 uF polypropylene; low leakage
- All Resistors : 0.25 W metal film
- Piezoelectric buzzer. NOTE : the frequency of oscillator IC_3 should be selected to match the peak frequency response of the selected buzzer. In other words, the frequency of oscillation can be anywhere between 1 and 5 kHz; it will not affect the performance of the lock-in circuit.

NDIR CO Detector (MID-IR LED Option) - Block Diagram

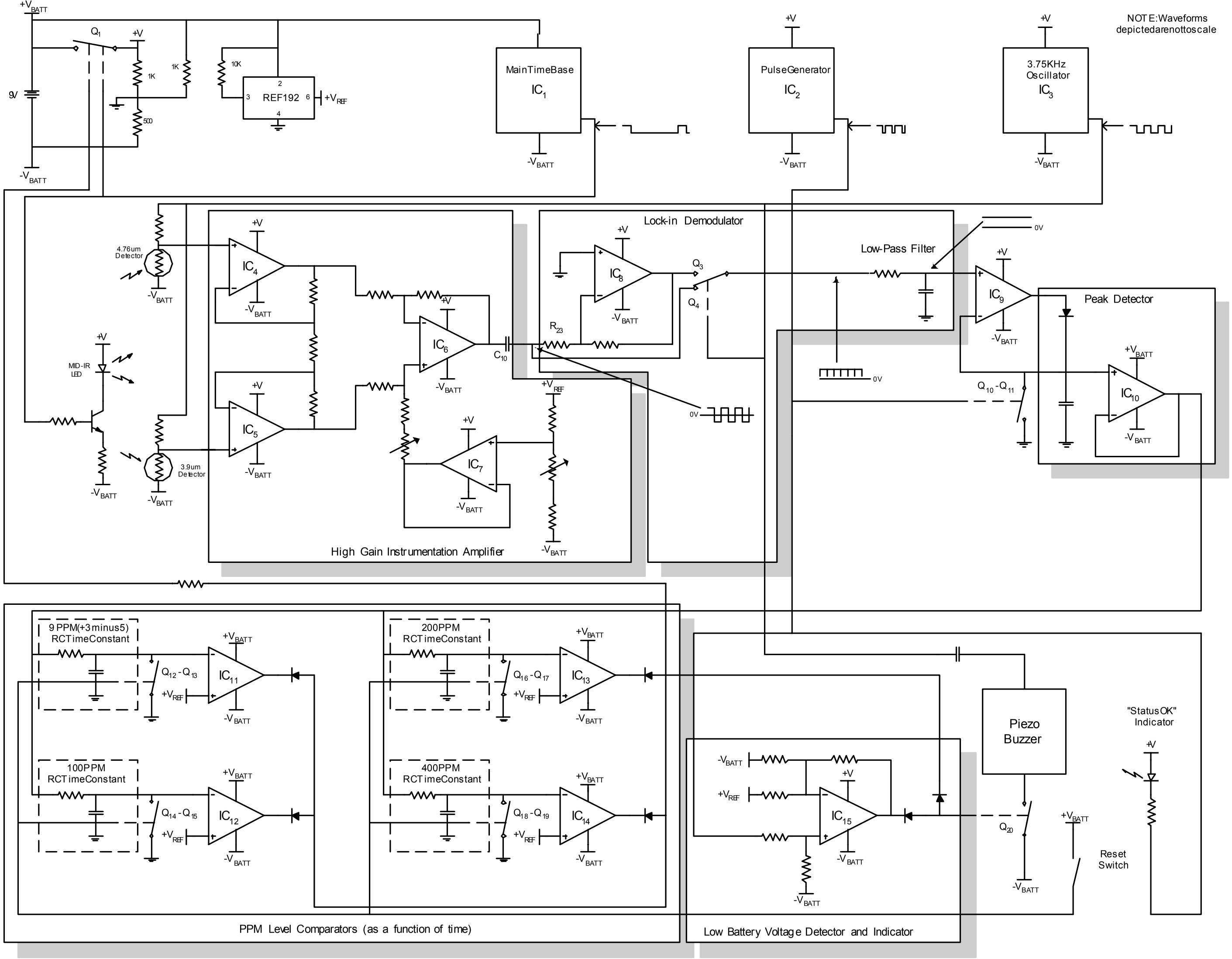


Figure 1

NDIR CO Detector (MID-IR LED Option) - Circuit Schematic

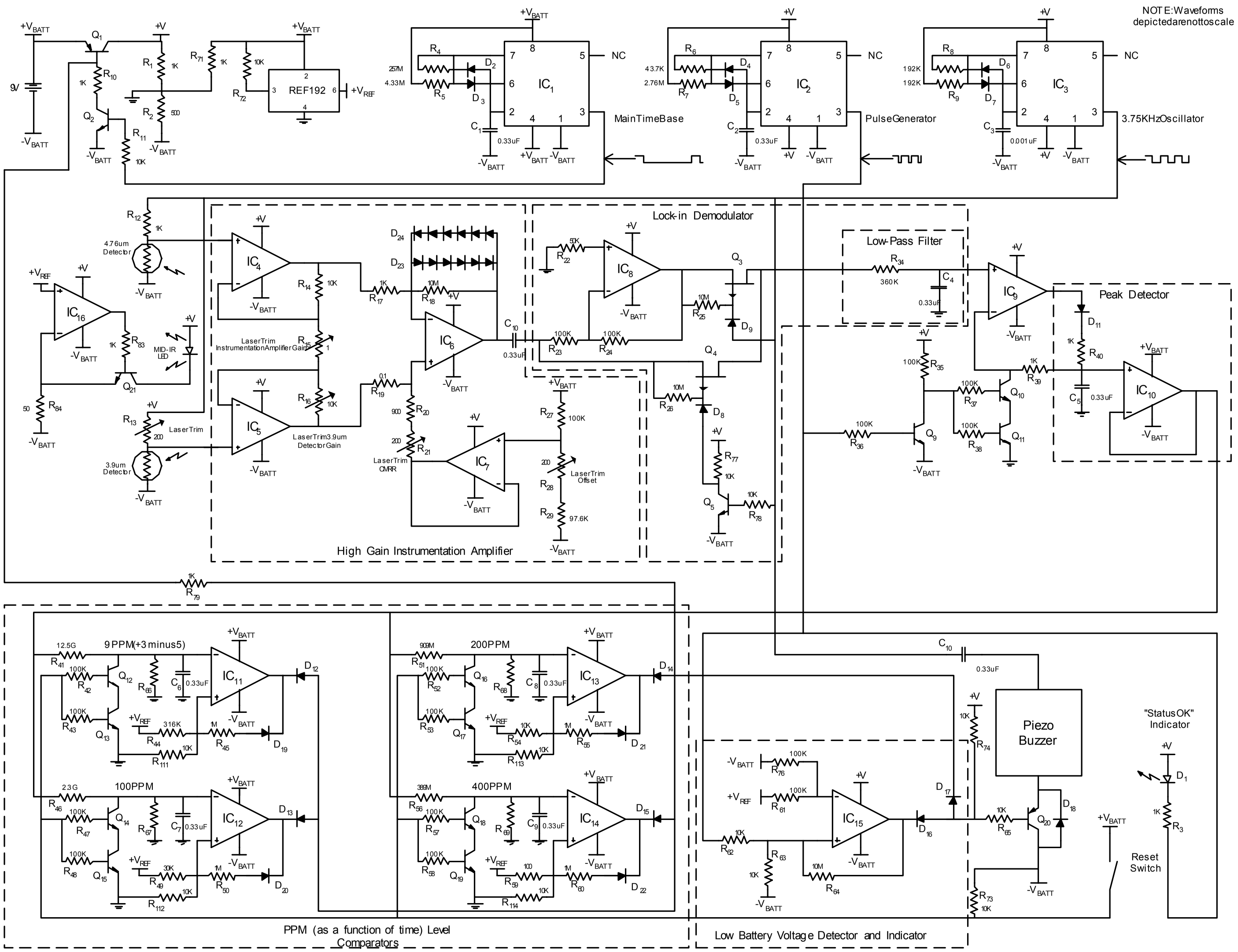
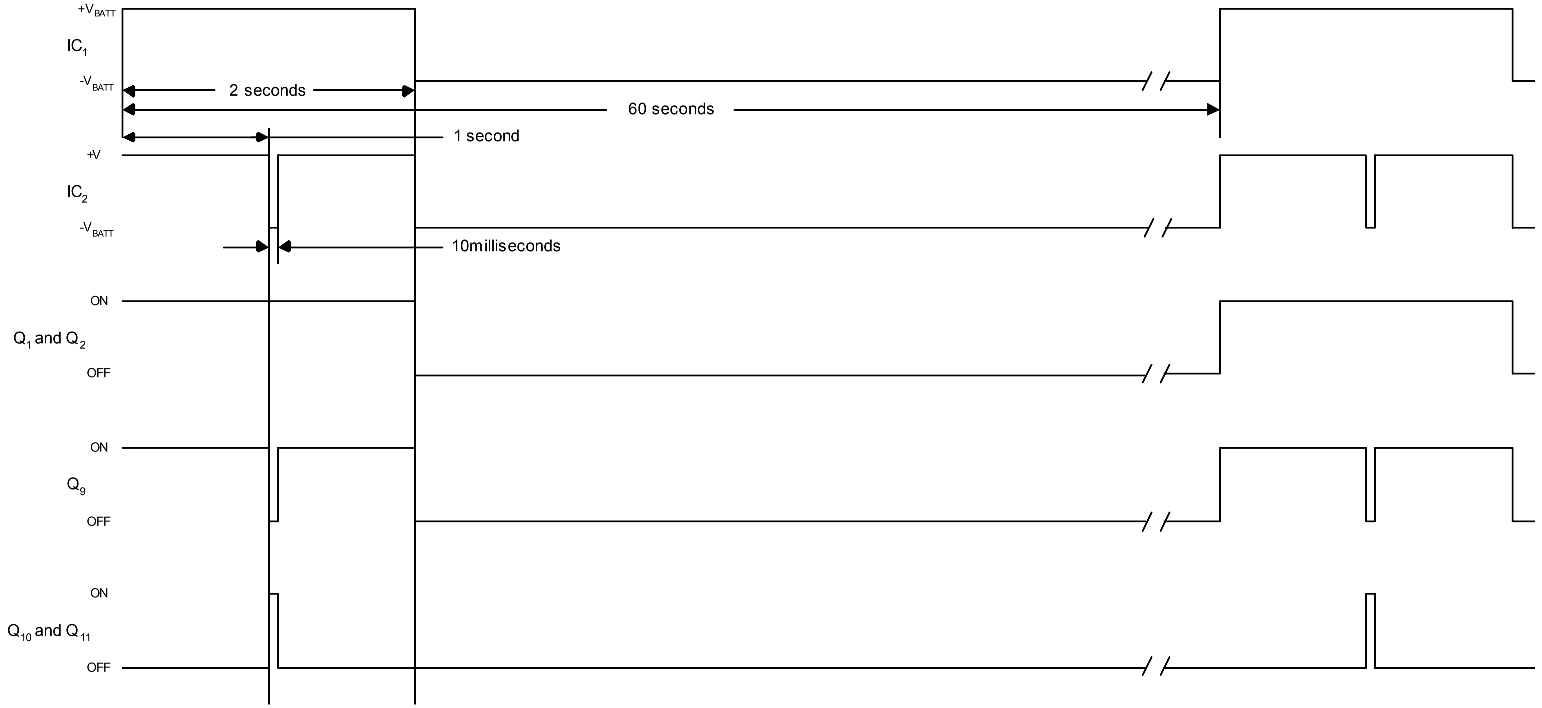


Figure 2

NDIR CO Detector - Timing Waveforms and Pulse Widths Diagram



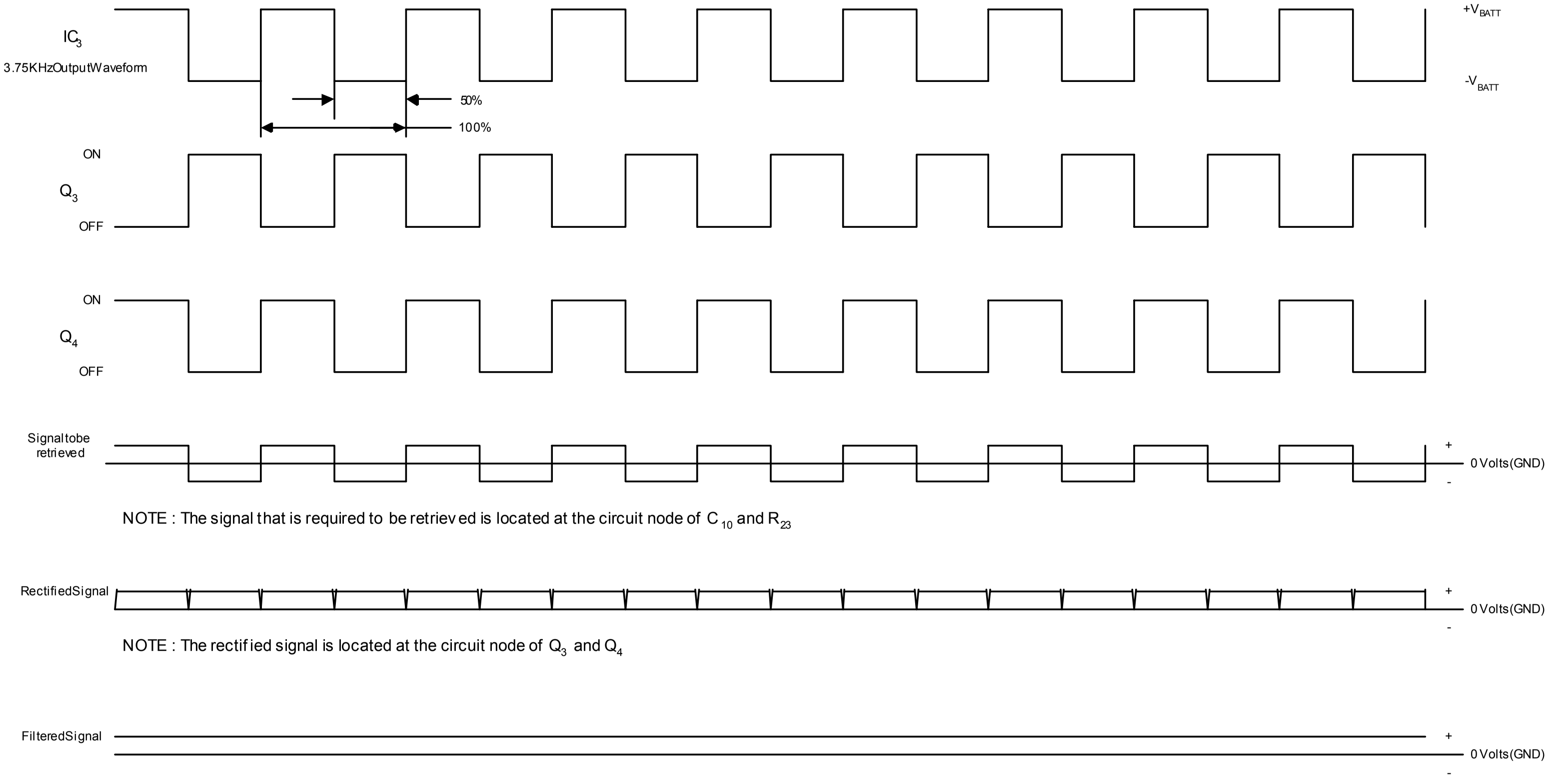
NOTES:

1- A time delay of one second is introduced for the components and waveforms to reach a state of equilibrium.

2- The pulse of 10 milliseconds enables discharge of C_5; in other words, it clears the peak level recorded during the previous pulse of 2 seconds of the main timebase, IC_1, so that a valid CO level measurement may occur during the period that follows the pulse of 10 milliseconds

Figure 3

NDIR CO Detector - Lock-in Demodulator Waveforms Diagram



NOTE : The signal that is required to be retrieved is located at the circuit node of C_{10} and R_{23}

NOTE : The rectified signal is located at the circuit node of Q_3 and Q_4

NOTE : The filtered signal is located at the non-inverting input of IC_9

NOTES:

1- Given that the amplitude of the noise component is 10^6 greater than the signal that is required to be retrieved, the noise component is not shown for clarity of illustration

2- The amplitude of the waveforms is not to scale

Figure 4

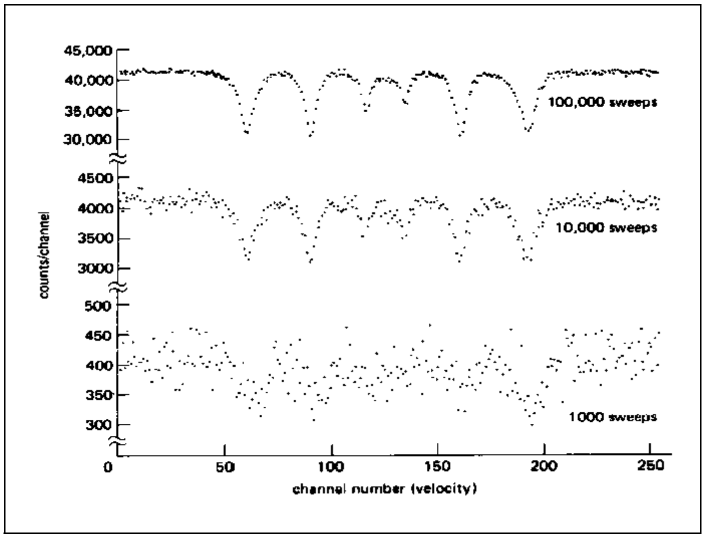
MIXED-SIGNALS CIRCUIT

Reference is being made to Figure 6. The differential signal and its noise components are amplified by the high gain instrumentation amplifier, of which the output is sent to an A/D converter (The Cypress MicroSystems' Programmable System-on-Chip (PSoC) harbors a software definable A/D converter, with up to 11 bits of resolution at this point in time). The output of the A/D is then processed by software internal to the PSoC, using signal averaging techniques to extract the desired information (the signal sought). Figure 1 illustrates signal averaging. The cost of the components is, approximately, $1.00 for the high gain instrumentation amplifier, and $2.80 (in quantities > 100) for the Cypress MicroSystems' CY8C25122 PSoC FLASH based microcontroller (4K FLASH, 128B RAM. 8 PIN DIP).

The mixed-signals approach has significant advantages over the analog circuit approach from an electronics point of view. A few of these are that laser trims would likely not be required, nor the use of auto-zeroing techniques (which latter may turn out necessary for the analog circuit, in order to counteract components' drifts as a function of time, given that, for the analog circuit, the latter is pushed to the limits of stability in terms of long term drifts that may affect the circuit's reliability, given the magnitudes of the circuit's voltage gains). Additionally, even if going to an ASIC for the analog circuit, the components' cost, for the digital circuit, would be approximately 5 or more times cheaper than for the analog circuit. Moreover, digital information can be obtained at its output (e.g., numerical values concerning the level of gas measured, fluctuations measured as a function of time, etc., and serial data that can be sent directly to, say an LCD display, the latter equipped with a serial to parallel converter).

It is of note that, although the block diagram shows tuned emitters and detectors, only the emitters or detectors may be tuned. Moreover, the circuit can be made to work equally well by pulsing the detectors instead of the emitters.

In terms of integration time (the time required for signal averaging), less than one minute worst case seems a reasonable estimate for producing reliable and meaningful information at the output of the PSoC (e.g., detection and measurement of CO down to <1 ppm).



Mössbauer absorption spectrum showing effect of signal averaging.

(Reproduced from ***The Art of Electronics***, by Dr. P. Horowitz, and Dr. W. Hill)

Figure 5

Mixed-Signals NDIR CO Detector - Block Diagram

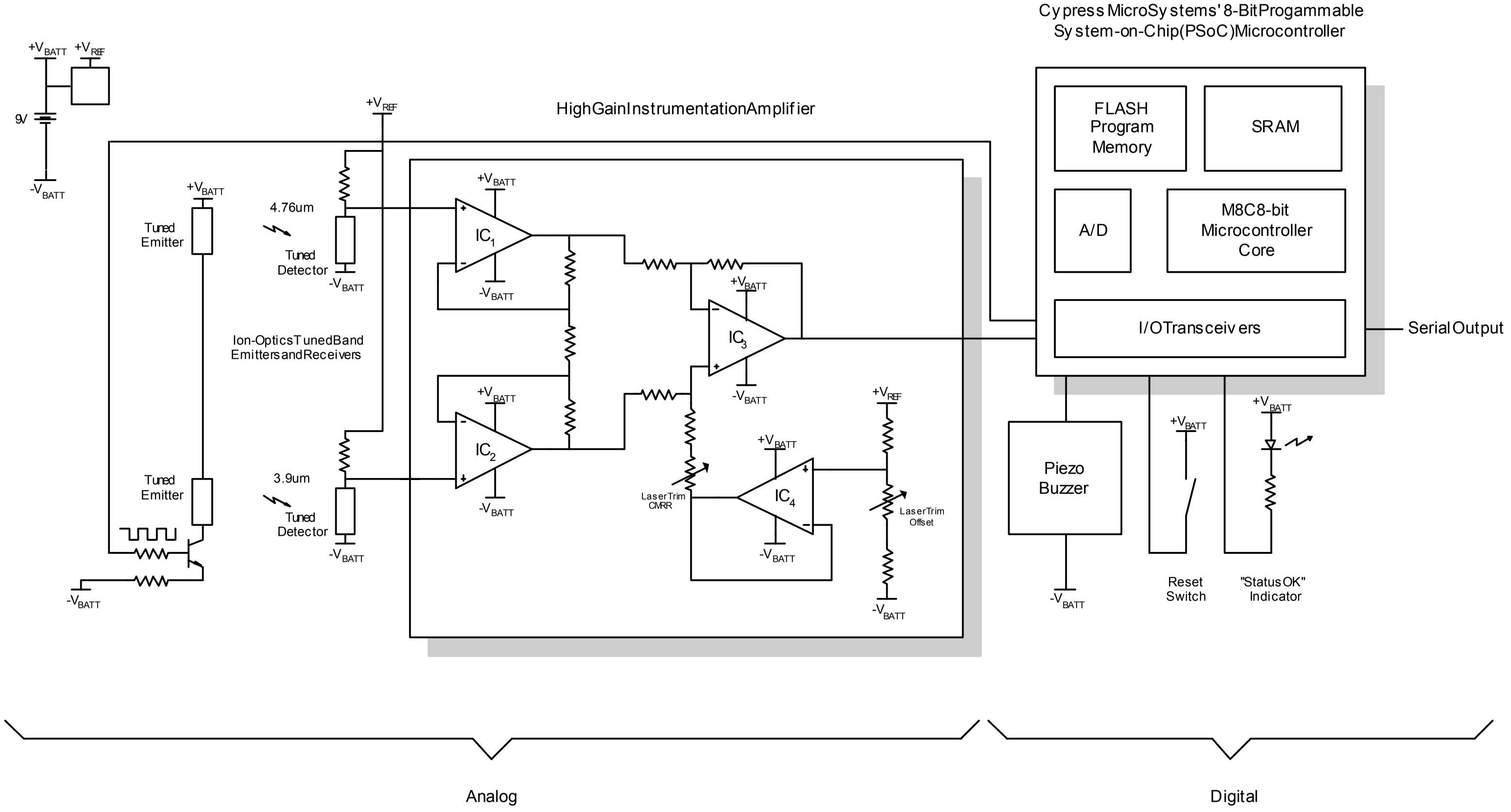


Figure 5

Mixed-Signals Circuit - Parts List

- IC_1, IC_2 IC_3 IC_4: LMH6632 National Semiconductor; high open loop gain Op-Amp - **http://www.national.com**
- Cypress MicroSystems' Programmable System-on-Chip (PSoC): CY8C25122 PSoC FLASH based microcontroller (4K FLASH, 128B RAM. 8 PIN DIP) - **http://www.cypressmicro.com**

CONCLUSION

State of the art technology (such as the Cypress MicroSystems' Programmable System-on-Chip (PSoC)), applied to NDIR gas spectroscopy, coupled to signal averaging techniques, can enable low cost ultra-high resolution gas detection and measurement.
