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A Simple Low-Cost Lock-In Amplifier for the Laboratory

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Efforts to modernize physical and analytical chemistry teaching laboratories are often hampered by a lack of funds, but it is possible for students, as part of their laboratory course or for advanced projects, to construct scientific instrumentation that can subsequently be used in experiments. Examples include the construction of a simple spectrophotometer *(1)* or the design and construction of a three-electrode potentiostat *(2)*. For many experiments, it is necessary to measure a weak signal that is mixed with noise. A lock-in amplifier (LIA) accomplishes this by detecting and amplifying only the components of a signal that are in-phase with a reference signal. This instrument is used extensively in chemical research *(3)*, and applications in chemical education have been discussed *(4, 5)*.

In the process of developing low-cost spectroscopy experiments for modernizing the physical chemistry teaching laboratory, we have used commercial LIAs for experiments that include optogalvanic spectroscopy *(6)*, measurement of the photoelectric effect *(6)*, and the detection of gaseous ammonia by absorbance of 2.2 μm light *(7)*. In these experiments, a diode laser or light-emitting diode is pulsed by a function generator, and the signal to be detected is fed to the LIA that uses the function generator as its reference input.

LIAs may be constructed based on either analog or digital techniques *(8)*. Commercial instruments range in price from \$500 to several thousand dollars. While several homemade analog LIAs have been previously described *(9–11)*, some use components that are no longer available *(10)* or require a large number of operational amplifiers *(11)*. An interesting and attractive design for a digital instrument in which the signal processing is implemented largely in software and that is intended for student use has been described *(12)*. However, the commercial data-acquisition hardware and software costs are significant, and a preamplifier still needed to be built. This design is thus most useful for chemistry laboratories that have already made sizable investments in hardware and software.

In this article we describe the construction of a simple, low-cost LIA that is suitable for use in the chemistry teaching laboratory. Our design philosophy is that the instrument should be relatively easy to construct and that the total cost should be under \$100. This is accomplished by using integrated circuits and as few components as necessary to adequately accomplish lock-in amplification. The design is based on the Analog Devices AD630 modulator–demodulator integrated circuit (IC) *(13)*. This IC has been used as a LIA in a number of dedicated applications *(14)*. However, to our knowledge the design and construction of a complete stand-alone instrument based on this device for general student use has not been reported.

Circuit Description

The schematic for the circuit is shown in Figure 1. The circuit can be roughly broken down into three parts: an IC that performs the actual phase-sensitive detection (i.e., lock-in detection), an input amplifier that increases the signal prior to it being sent to this phase-detection circuit, and an output filter–amplifier. The phase-sensitive detection chip belongs to the AD630 family of ICs marketed by Analog Devices. As connected in Figure 1, the device is configured in a gain equal to 2 mode, which eases the drive requirements

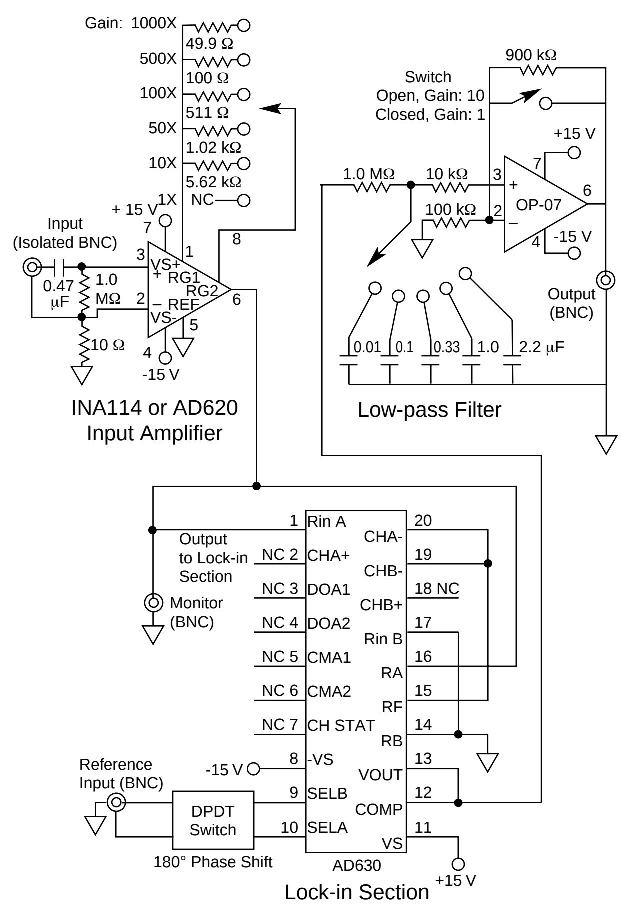

Figure 1. The schematic of the low-cost LIA. Only three integrated circuits are used. The values of the gain resistors shown are for the INA114. Each integrated circuit may be bypassed at its power supply terminals with 0.1 μF capacitors, which are not shown in the schematic. The output can be conveniently read by a digital dc voltmeter.

on the input amplifier. We have tested both the AD630J and the AD630K devices. The less expensive AD630J works adequately in our applications of this circuit and should be suitable for most student laboratory experiments.

It is recommended that a sine wave or square wave be used for the reference signal of the LIA. Tests with the “TTL” output from the types of low-cost function generators commonly found in teaching laboratories have given less than desirable results owing to the poor quality of the “TTL” signal. Inputs 9 and 10 may be connected to the reference signal and ground, respectively, if no phase control is desired. Alternatively, as shown in Figure 1, they may be connected to the reference signal and ground through a polarity reversing double-pole-double-throw (DPDT) switch. This acts as a 180° phase shift control for the reference signal, allowing the output polarity to be selected by the user. For simplicity, the usual precise phase controls found in a research-grade LIA are eliminated. This is also the case in most commercially-available “student grade” LIAs. Similarly, a reference oscillator is not provided since low-cost function generators are readily available and are standard equipment in most teaching labs.

The second part, the input amplifier, is a standard IC instrumentation amplifier, and the gain is set by switching a single resistor. We have used both a Texas Instruments (Burr-Brown) INA114 and an Analog Devices AD620. The former has better input protection (up to 40 V), while the latter has higher bandwidth at high gains (>10 kHz vs 1 kHz for the INA114). Operating the instrumentation amplifier at lower gains and the addition of a second op amp gain stage would increase the bandwidth. An example of such a design is found in the preamplifier for the digital LIA in ref *12.* For the present design, we chose to minimize the chip count instead. Connecting the input in a differential mode would provide better common-mode noise rejection, but all of our student experiments provide single-ended outputs to the LIA. However we do connect the low input of the amplifier to ground through a 10 Ω resistor to reduce the effects of ground loops (pseudo-differential input). Note that instrumentation amplifiers with built-in gain resistors are available at higher cost. However the number of available gains is limited. We have used 1% tolerance metal film resistors that provide adequate accuracy of the gain for most student experiments. If higher accuracy is desired, resistors with tighter tolerances or miniature variable resistors, adjusted for the exact value, may be used. Note that the equation for the value of gain versus the gain resistor is similar but slightly different for the INA114 and the AD620. We show the values for the INA114 in Figure 1.

The input is ac coupled by inserting a capacitor between the input connection and the preamplifier. Alternate current coupling is preferred when the input signal contains a significant dc component that would overload the input amplifier, especially when high gain is needed. Since the input capacitor and resistor form a high-pass filter in ac coupling, dc coupling is preferred when the reference frequency (and hence the desired signal frequency) is low and phase shift and attenuation due to this filter must be avoided. For most of the educational experiments that we have developed *(6, 7),* ac coupling is desirable. Figure 1 contains ac coupling via inclusion of the 0.47 μF capacitor.

The third part of the circuit consists of the output low-pass filter and the output dc amplifier. The filter is a simple single-stage RC filter with a fixed 1-MΩ resistor and switchable capacitors to vary the time constant. Time constants from 0.01 to 2.2 s are available with the components shown; some of these capacitors could be eliminated to simplify construction. Alternatively, inclusion of a two-stage filter would provide better noise rejection at the expense of greater complexity. A Texas Instruments OP-07 device (other manufacturers also market this chip) is used as the output amplifier. It may be operated in either unity or “×10” gain mode. The 10 kΩ resistor at the input limits input transient currents when the time constant is changed.

Figure 1 shows the use of a ±15 V dual-polarity power supply, but a ±12 V supply could be substituted with only a slight loss in performance. Alternatively, the entire unit could be operated with ±9 V by simply hooking two 9-V alkaline batteries in series and using their point of contact as the common of the circuit. Of course, lower power-supply voltages will limit the dynamic range of the instrument. Each chip may be bypassed at its power-supply terminals with 0.1-μF capacitors (between the chip and ground) as a good design practice to minimize noise in the supply voltages to the ICs. However, in instruments that we have built using two 9-V batteries, the 0.1-μF bypass capacitors were found not to be necessary. The total current drawn by the components is less than 50 mA.

Testing of the Instrument

To demonstrate and test the homemade LIA, an experiment has been performed in which a 2.2-μm infrared light-emitting diode (LED) is modulated by the square wave output of a function generator. The square wave is also used as the reference input of the LIA through the use of a BNC “tee” (splitter) on the output of the function generator. The infrared light passes through ammonia gas contained in a 15.2-cm long stainless-steel sample cell and is detected by a 2.2-μm photodiode, whose output is amplified and sent to the input of the LIA instrument. This absorbance experiment has been described in detail in ref *7.* Note that the experiment is carried out in the presence of ambient room light.

The absorbance data obtained by varying the pressure of ammonia in the sample cell are shown in Figure 2. The absorbance at a particular pressure is calculated from the measured LIA output voltage (V) according to the following equation

$$\text{Absorbance} = -\log\,(V/V_o) \qquad (1)$$

where V_o is the output voltage for the evacuated cell. As shown in Figure 2, the plot of absorbance versus ammonia pressure is linear over the pressure range studied. Also included in Figure 2 are data taken simultaneously using a commercial low-cost LIA (ThorLabs LIA100). The commercial instrument is fed the same input signal (again through the use of a BNC tee) as the homemade instrument, and its reference signal consists of the TTL output of the function generator. The only notable difference in performance between the commercial and homemade instruments is that the LIA100 seems to function properly with the TTL reference signal from low-cost function generators. As discussed earlier, the poor qual-

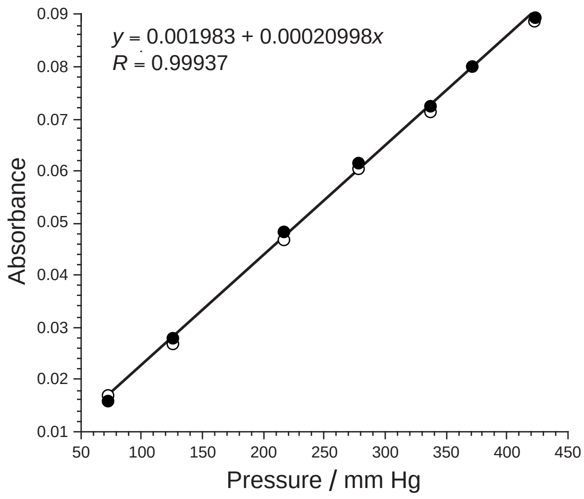

Figure 2. Plot of absorbance versus ammonia pressure for 2.2-μm radiation from an infrared light-emitting diode. The light source is pulsed at 100 Hz by a 50% duty-cycle square wave from a function generator, and the transmitted light is detected by a 2.2-μm photodiode, whose output is fed to the LIAs. The solid circles represent data from the output of the homemade LIA (2.2-s time constant, x50 gain), and the hollow circles represent data from the output of a commercial LIA (ThorLabs LIA100, 3-s time constant, 60 db gain). The linear fit is for the homemade LIA data set.

ity of such a reference signal is problematic for the homemade instrument.

The output voltages of the commercial and homemade LIAs differ less than 0.5% for all pressures, indicating proper performance of the homemade instrument. Figure 2 also includes the equation of the linear fit to the homemade LIA data. The slope of this line is in excellent agreement with the results reported in ref *7* and yields an extinction coefficient of 1.38×10^{-5} Torr^{-1} cm^{-1} (1.03×10^{-7} Pa^{-1} cm^{-1}).

Conclusions

This LIA may be assembled for less than \$100 and is ideal for use in the student laboratory. The total cost of the integrated circuits is less than \$30, and its construction and use may serve as a component of a course in scientific instrumentation or a physical chemistry laboratory course. Alternatively, it may be constructed by the instructor for student use.

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[W]Supplemental Material

A detailed parts list is available in this issue of *JCE Online*.

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