JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc

Technology Report

Low-Cost, High-Performance Lock-in Amplifier for Pedagogical and Practical Applications

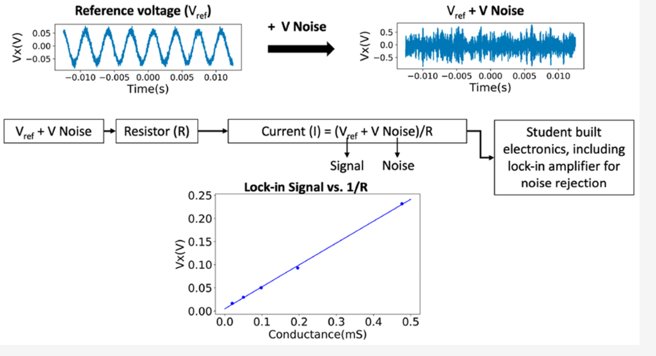
Xicheng Xu, Yoshinori Suganuma, and Al-Amin Dhirani*

Cite This: J. Chem. Educ. 2020, 97, 1167–1171

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Lock-in amplifiers (LIAs) are commonly used in chemistry laboratories to improve noise-to-signal ratios. Constructing and testing a suitably designed LIA provide undergraduate students with an excellent opportunity to learn about theory, construction, and applications of LIA. In particular, students can learn about time-dependent behavior and various components, from resistors (R) and capacitors (C) to packaged microchips such as demodulators and phase shifters. We provide here design and performance characteristics of a two- (Vx, Vy) channel LIA based on balanced modulator/demodulators (AD630). The LIA includes configurable resistor−capacitor (RC) high-pass and low-pass filters, various op-amp circuits, and a phase-shifter. Various configurations of resistors/capacitors, as well as salt solutions and isopropanol/pentane mixtures, are used as samples to measure conductance or capacitance to test both V_x and V_y channels of the LIA. The results are consistent with behaviors expected theoretically. The LIAs yield excellent noise/signal ratios with peak-to-peak values that are <0.2% and that compare favorably with commercial LIA performance.



KEYWORDS: *Upper-Division Undergraduate, Analytical Chemistry, Hands-On Learning/Manipulatives, Conductivity, Laboratory Equipment/Apparatus, Instrumental Methods*

INTRODUCTION

Undergraduate chemistry programs typically include courses on analytical chemistry, chemical instrumentation, and research that teach theory, construction, and applications of various types of basic electric circuits including operational amplifiers circuits.[1] Students with such backgrounds can develop and apply their knowledge to potentiostats for electrochemistry,[2,3] characterization of microelectrodes,[4] measurement of pH,[5] peak resolution,[6] and photometry.[7] Lock-in amplifiers (LIAs) are commonly used in research laboratories to improve signal-to-noise and to analyze time-dependent responses, and their construction provides a particularly good exercise for teaching undergraduate students about circuit principles and applications.[8−13] Previously reported LIA designs use prepackaged LIA integrated circuits such as ADA2200, which enable efficient construction but provide less opportunity for learning, or they use chips such as AD630, which provide a more open architecture but do not provide a means for measuring phase shifts that are critical in understanding time-dependent drive-response behavior (e.g., alternating current or AC circuits).

Here we describe a LIA design that includes the AD630 and an open architecture design as well as some basic, common op-amp circuits such as a summing amplifier and a current (I)-to-voltage (V) converter, which have been taught in chemistry laboratories on their own.[14] The present LIA design affords measurements of both in-phase (V_x) and out-of-phase (V_y) components of a response of a system with respect to a drive. This allows us to describe exercises that students can conduct to learn about fundamental AC circuits by driving resistors (R's) and capacitors (C's) with an AC voltage, using the LIA to measure both the amplitude and phase shift of the response, and comparing with expected R/C behavior. We note that the present LIA design can be used not only for teaching, for example, in a senior analytical chemistry course or a senior instrumental analysis course, but also for research applications.[8,15] It is able to determine the phase shift of the device under test from $\varphi = \tan^{-1}\left(\frac{V_y}{V_x}\right)$. A phase shifter needed to determine V_y is built-in the LIA and need not be added. The LIA's features also include both being inexpensive and having signal/noise ratio that is comparable to that of commercial LIAs (Supporting Information, Figure S3). Three LIAs have

Received: September 12, 2019
Revised: February 2, 2020
Published: February 17, 2020

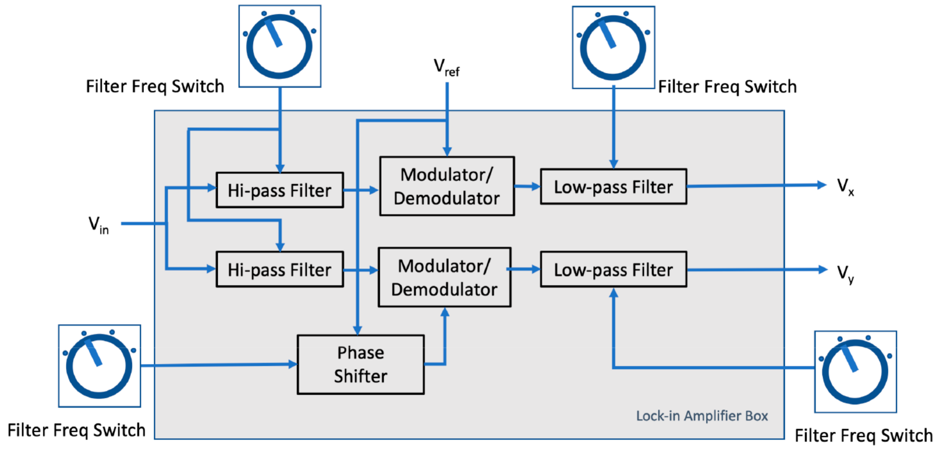


Figure 1. Block diagram of the lock-in amplifier. V_{ref} is the reference signal from a function generator, V_{in} is the input signal, and V_x and V_y are the outputs of the lock-in amplifier.

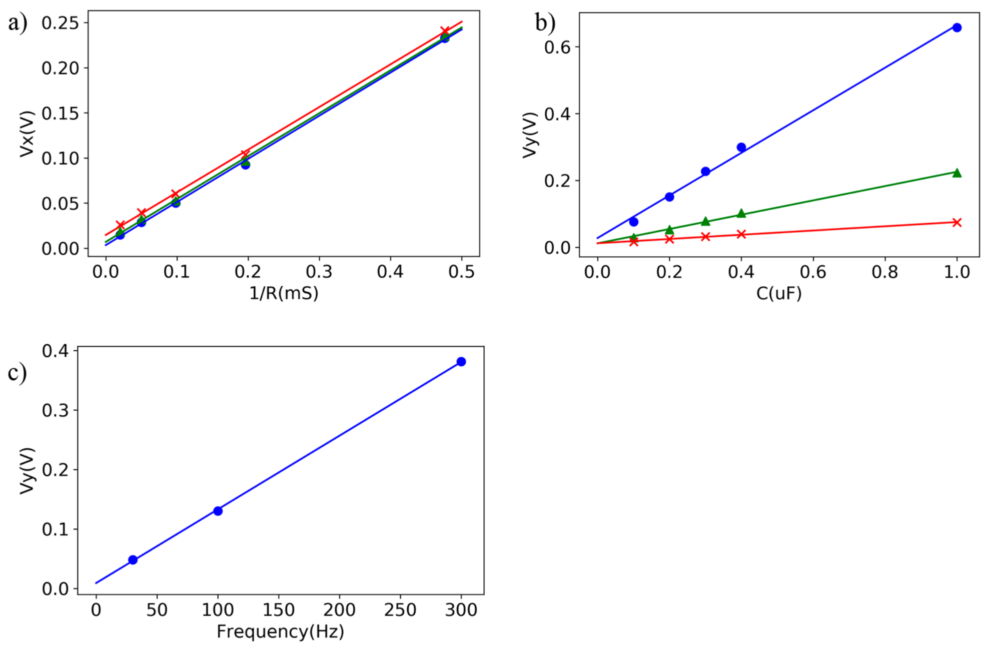


Figure 2. Lock-in amplifier response for a test circuit shown in Figure S2 using (a) various resistances (R) and (b) various capacitances (C), where R and C are the resistance and the capacitance of the test circuit. The points are measured data points and the straight lines are linear fits. The measurements are repeated for different reference frequencies. Blue, green, and red represent 300, 100, and 30 Hz in (a) and (b). (c) V_y versus frequency, where resistance (20 kΩ) and capacitance (0.1 μF) are both fixed.

been successfully constructed and tested by an undergraduate student over nine months, and all show similar behavior.

■ DISCUSSION

Figure 1 shows a block diagram of the LIA circuit. Detailed circuit diagrams for V_x and V_y are provided in the Supporting Information (Figure S1). We use AD630 as our modulator/demodulator to perform lockin operation. An explanation of the operation of the AD630 can be found in its datasheet.[16] A mathematical derivation and a simulation (Figure S5) showing how the AD630 modulator/demodulator combined with subsequent low pass filtering isolates the desired frequency response are provided in the Supporting Information. Our design extends a prior report of a 1-channel LIA with an in-phase (V_x) output component[12] by constructing a two-channel LIA with an out-of-phase (V_y) output component as well.[17−20] The input voltage signal (V_{in}) to be analyzed by the LIA first goes through a high pass filter, which also removes any time independent (DC) component. The signal then goes to two modulator/demodulators for processing.

The modulation reference signal (V_{ref}) goes to the V_x modulator/demodulator directly and to the V_y modulator/demodulator after being phase shifted by 90°. The modulation reference signal in our case comes from an inexpensive function generator. As the AD630s operation only depends on V_{ref} zero crossing, most types of waveforms should work. We perform most experiments with a sine wave, but a triangle wave gives good results as well. The outputs of the AD630s are low pass filtered over a much longer time period than the period of the modulation reference signal to obtain nearly DC signals.

All of the filters use switches to change RC filter configurations and, thereby, RC time constants so the LIA can function with different V_{ref} modulation frequencies. For our tests, we used three options: 30, 100, and 300 Hz. We have

https://dx.doi.org/10.1021/acs.jchemed.9b00859
J. Chem. Educ. 2020, 97, 1167−1171

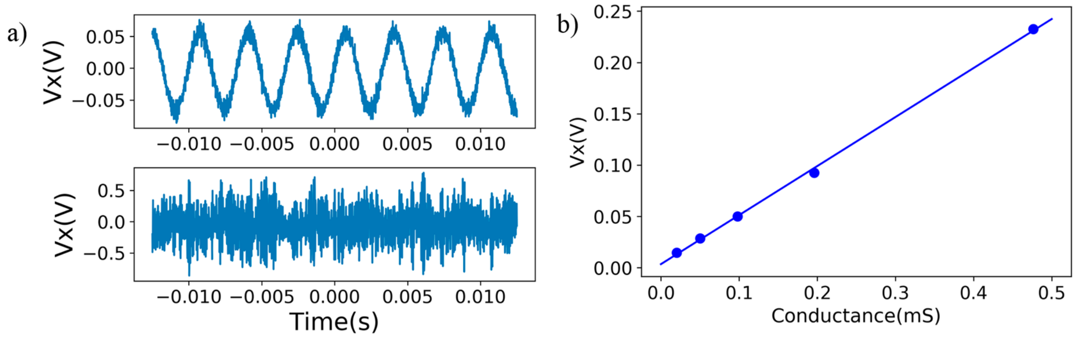


Figure 3. (a) Reference modulation voltage before and after adding noise. The reference voltage plus noise is applied to various test resistors, and the various resulting currents are amplified and analyzed by a lock-in amplifier. (b) The in-phase output of the lock-in amplifier (V_x) versus Conductance (1/Resistance) for various test resistors.

two high-pass filters, two low-pass (two-stage) filters, and one phase shifter, and the choices of modulation frequencies and corresponding filter frequencies can be switched depending on the application. We used one 2-pole switch for high-pass filters, two 2-pole switches for low-pass filters, and one 1-pole switch for the phase shifter. Note that the high pass filters, while filtering out the DC signal, also introduce a phase shift. This phase shift can be observed by using a resistor as a sample test circuit (see Figure S2). Such a purely resistive test circuit should not generate a V_y component, but one is observed corresponding to approximately a 7° phase shift in our circuit. We take this into account in the final values of V_x and V_y recorded. That is, viewing the output of the LIA system as a vector (V_x, V_y), we correct for this 7° phase shift by rotating (V_x, V_y) counterclockwise by 7° about the origin using a rotational matrix. The matrix and the resulting formulas are provided in the Supporting Information.

The RC high-pass filters can have three different configurations. Using a 1 μF capacitor and 5.3k, 15k, and 53k resistors gives cutoff frequencies of 30, 10, and 3 Hz, which correspond to our choices of V_{ref} modulation frequencies of 300, 100, and 30 Hz, respectively. The low-pass filters have similar configurations, but they filter out frequencies above 30, 10, and 3 Hz. Note that we use two-stage low-pass filters to filter more effectively and improve our signal-to-noise ratio (Figure S4).

The circuit for V_y is similar to that for V_x but includes a phase shifter. The phase shifter inputs V_{ref} (also used by the LIA channel measuring V_x) and shifts it by 90°. Depending on the V_{ref} modulation frequency, one of the resistor options is chosen by a 3-position-1-pole switch, where the 5.3k, 15k, and 53k resistors correspond to 300, 100, and 30 Hz, modulation frequency, respectively. The output of the phase shifter then goes through a buffer before fed to the modulator/demodulator as its reference signal. It is worth noting that the modulator/demodulator is sensitive to the offsets in the phase of the reference signal, which is related to the resistor−capacitor configuration. If the reference signal processed by the phase shifter is not centered around 0 V or the phase shifter did not shift by exactly 90°, errors are introduced. Therefore, we choose a low-offset op-amp for the phase shifter (OPA177) and use a trim potentiometer in series with the resistors of the phase shifter to ensure a phase as close to 90° as possible. Once the values of the trim resistances are known, fixed resistors may be used in place of the trim potentiometers. It is recommended to remind students to check the phase shifter output with an oscilloscope or other instruments before moving further.

The LIA design has been implemented by a third-year undergraduate student, and Figure 2 shows the results with a sample test circuit consisting of a resistor (R) in parallel with a capacitor (C) (Figure S2). We expect that V_{in} of the LIA system proportional to conductance of the test circuit, $1/R + j2\pi\nu C$, where ν is frequency. V_x is expected to be proportional to 1/R and V_y to νC. Figure 2a shows V_x versus 1/R for various R's, keeping C and ν fixed. The measurements are repeated at the three frequency choices, 300, 100, and 30 Hz. V_x is proportional to 1/R with slope that is independent of frequency as expected. Figure 2b shows V_y versus C keeping R and ν fixed. The measurements are repeated at the three frequency choices. V_y is proportional to C as expected, with slopes that change with frequency. To test whether the slopes are proportional with frequency, Figure 2c shows V_y versus the frequencies of the reference signal while keeping R and C fixed and confirms that V_y is proportional with the frequency as expected.

Figure 3 provides a vivid demonstration conducted by the undergraduate student showing the ability of a LIA to recover signals from a noisy environment. White noise generated by a python program and outputted from an audio port of a personal computer is summed with V_{ref} using a summing amplifier. The sum is applied to a sample test circuit that consists of a resistor, and the resulting current is amplified by an IV convertor to generate V_{in} (see Figure S2 with V_DC replaced by a headphone output from a personal computer). Figure 3a shows V_{in} with and without noise. It is difficult to see the modulation signal in the presence of the noise. Figure 3b shows the V_x versus the conductance (1/R) of the sample circuit when there is noise. Despite the noise, we still observed an excellent straight line, just like the one in Figure 2a, indicating a remarkable ability of the LIA to reject noise.

■ APPLICATION EXAMPLE

The ability of the LIA to measure both V_x and V_y enables scientifically interesting and technologically important electrical characterization of solvents and solutions. As shown above, V_x can probe 1/Resistance. This can be used to test water quality, an important application used in pharmaceutical manufacturing, environmental monitoring, drinking water testing, etc. To demonstrate that V_x increases with increasing concentration of ionic contaminants in water, we constructed a cell with interdigitated electrodes and used it to measure V_x for aqueous solutions with various KCl concentrations. In

https://dx.doi.org/10.1021/acs.jchemed.9b00859
J. Chem. Educ. 2020, 97, 1167−1171

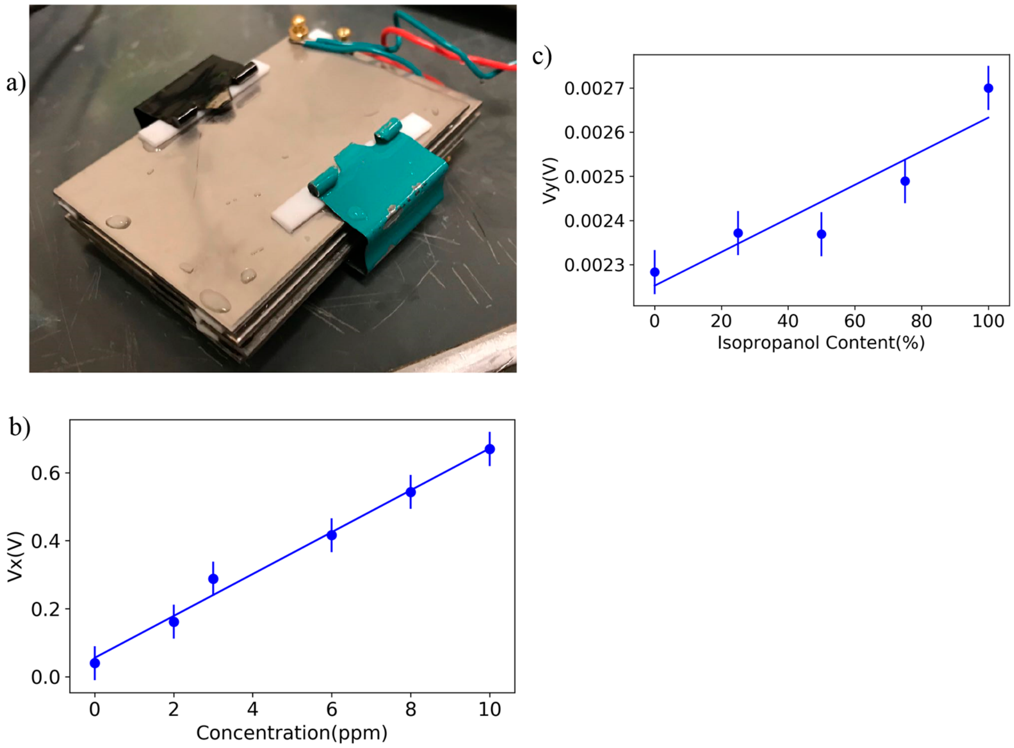


Figure 4. (a) Homemade stainless-steel interdigitated electrode with four-layers. (b) V_x versus KCl (aqueous) concentration. (c) V_y versus isopropanol content by volume in isopropanol + pentane mixtures. In (b) and (c), both data (points) and linear fits are shown. The V_{ref} was set to 300 mV (RMS) at 300 Hz, and the filter frequencies were set to 300 Hz accordingly.

addition, as shown above, the LIA provides V_y, which can probe capacitance. Capacitance depends on dielectric constant and is a measure of the polarizability of a material (i.e., its dipole moment per unit volume). The polar versus nonpolar nature of solvents is an important concept in chemistry, and physical chemistry laboratory experiments measuring the dielectric constant of solvents and solvents mixtures using various electrode configurations and electronics have been reported in textbooks and the literature.[21−24] To demonstrate the ability of the LIA to probe dielectric constant, we measured V_y using the interdigitated electrodes and various mixtures of *n*-pentane and isopropanol.

Figure 4a shows a photograph of the interdigitated electrodes. The electrodes are constructed using 4 × 1/16″ thick stainless-steel plates, separated by polytetrafluoroethylene pads and held together by paper clips. The first and third plates are connected, as are the second and fourth. Connections between plates and between the plates and the electronics are made using tapped holes in the stainless-steel plates and screws and nuts to clamp wires. Figure 4b shows V_x versus KCl concentration ranging from 0 to 10 ppm (ppm), as well as a linear fit to the data. The data exhibit a reasonably linear behavior, confirming that 1/Resistance (i.e., conductance) increases linearly with KCl concentration in this concentration range. Figure 4c shows V_y for various mixtures of pentane (dielectric constant 1.8[25]) and isopropanol (dielectric constant 17.9[25]). We chose these two solvents because they are miscible and quite insulating, and therefore, they highlight the V_y capability of the LIA. Using V_y to characterize the dielectric constant of more polar or conducting solvents requires care to avoid impurities, which can significantly modify the dielectric constant. We prepared 150 mL mixtures of isopropanol + pentane, varying the isopropanol content from 0 to 100% in 25% increments. Figure 4c shows V_y measured for the various mixtures as well as a linear fit to the data. The data exhibit a reasonably linear behavior.

■ CONCLUSION

Using op-amps, a modulator/demodulator and basic resistors and capacitors, we show how to build an inexpensive 2-channel (V_x, V_y) LIA. Three such LIAs have been constructed by an undergraduate student working part time during an academic year (i.e., over 9 months). The performance of the LIA is tested using simple R/C sample test circuits, KCl salt solutions, and isopropanol/pentane mixtures. Also, the LIA's ability to recover a signal from a noisy environment is confirmed. This experiment provides a number of pedagogical features. By building the LIA system, along with a summing amplifier, a phase shifter, and an IV converter, students gain knowledge about electronic circuits, including op-amps. The sample R/C circuits and the filters teach students about AC circuits. Overall, constructing and testing the LIA can also train students in aspects of signal processing and troubleshooting apparatus.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00859.

Detailed circuit diagrams, test circuit, noise characterization, mathematical simulation and formulas for LIA operation, formulas for phase shift (PDF, DOCX)

https://dx.doi.org/10.1021/acs.jchemed.9b00859
J. Chem. Educ. 2020, 97, 1167−1171

AUTHOR INFORMATION

Corresponding Author

Al-Amin Dhirani − *Department of Chemistry, University of Toronto, Toronto, Ontario M5S 3H6, Canada;* orcid.org/0000-0003-3257-4327; Email: a.dhirani@utoronto.ca

Authors

Xicheng Xu − *Department of Chemistry, University of Toronto, Toronto, Ontario M5S 3H6, Canada*

Yoshinori Suganuma − *Department of Chemistry, University of Toronto, Toronto, Ontario M5S 3H6, Canada*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.jchemed.9b00859

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors acknowledge support from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

(1) Bauer, S. H. Scientific Literacy Vs Black-Boxes - with Reference to the Design of Student Laboratory Experiments. *J. Chem. Educ.* **1990**, *67*, 692−693.
(2) Bottei, R. S.; Boczkowski, R. J. Amplifier Voltage Boosters for High Resistance Electrochemical Cells. *J. Chem. Educ.* **1970**, *47* (4), 312−315.
(3) Li, Y. C.; Melenbrink, E. L.; Cordonier, G. J.; Boggs, C.; Khan, A.; Isaac, M. K.; Nkhonjera, L. K.; Bahati, D.; Billinge, S. J.; Haile, S. M.; Kreuter, R. A.; Crable, R. M.; Mallouk, T. E. An Easily Fabricated Low-Cost Potentiostat Coupled with User-Friendly Software for Introducing Students to Electrochemical Reactions and Electroanalytical Techniques. *J. Chem. Educ.* **2018**, *95*, 1658−1661.
(4) Sur, U. K.; Dhason, A.; Lakshminarayanan, V. A Simple and Low-Cost Ultramicroelectrode Fabrication and Characterization Method for Undergraduate Students. *J. Chem. Educ.* **2012**, *89*, 168−172.
(5) Papadopoulos, N. J.; Jannakoudakis, A. A Chemical Instrumentation Course on Microcontrollers and Op Amps. Construction of a pH Meter. *J. Chem. Educ.* **2016**, *93*, 1323−1325.
(6) Gilmartin, G.; Chang, S. K.; Harrington, G. W. A Laboratory Experiment in Peak Resolution using Operational-Amplifiers. *J. Chem. Educ.* **1986**, *63*, 276−277.
(7) McClain, R. L. Construction of a Photometer as an Instructional Tool for Electronics and Instrumentation. *J. Chem. Educ.* **2014**, *91*, 747−750.
(8) Ortega-Robles, E.; Cruz-Orea, A.; Elias-Vinas, D. Simple and portable low frequency lock-in amplifier designed for photoacoustic measurements and its application to thermal effusivity determination in liquids. *Rev. Sci. Instrum.* **2018**, *89*, 034904.
(9) Wolfson, R. The Lock-in Amplifier - a Student Experiment. *Am. J. Phys.* **1991**, *59*, 569−572.
(10) Scofield, J. H. Frequency-Domain Description of a Lock-in Amplifier. *Am. J. Phys.* **1994**, *62*, 129−133.
(11) Temple, P. A. Introduction to Phase-Sensitive Amplifiers - Inexpensive Student Instrument. *Am. J. Phys.* **1975**, *43*, 801−807.
(12) Sengupta, S. K.; Farnham, J. M.; Whitten, J. E. A simple low-cost lock-in amplifier for the laboratory. *J. Chem. Educ.* **2005**, *82*, 1399−1401.
(13) DeVore, S.; Gauthier, A.; Levy, J.; Singh, C. Improving student understanding of lock-in amplifiers. *Am. J. Phys.* **2016**, *83*, 52.
(14) Braun, R. D. Operational amplifier experiments for the chemistry laboratory. *J. Chem. Educ.* **1996**, *73*, 858−861.
(15) LeBoulluec, P.; Liu, H.; Yuan, B. A cost-efficient frequency-domain photoacoustic imaging system. *Am. J. Phys.* **2013**, *81*, 712−717.
(16) Data Sheet for AD630 Balanced Modulator-Demodulator. *Rev. G.*, 2020. https://www.analog.com/en/products/ad630.html# (accessed Jan 25, 2020).
(17) O'Haver, T. C. Lock-in Amplifiers—Part I. *J. Chem. Educ.* **1972**, *49* (3), A131.
(18) O'Haver, T. C. Lock-in Amplifiers—Part II. *J. Chem. Educ.* **1972**, *49* (4), A211.
(19) Wang, G.; Reboul, S.; Choquel, J.; Fertein, E.; Chen, W. Circular Regression in a Dual-Phase Lock-In Amplifier for Coherent Detection of Weak Signal. *Sensors* **2017**, *17*, 2615.
(20) Schultz, K. D. Phase-sensitive detection in the undergraduate lab using a low-cost microcontroller. *Am. J. Phys.* **2016**, *84*, 557−561.
(21) Aguilar, H. M.; Maldonado, R. F. Capacitive Cells for Dielectric Constant Measurement. *Physics Education* **2015**, *50*, 662−666.
(22) Chao, T. H. A Modified Resonance Apparatus for the Determination of Dielectric Constants. *J. Chem. Educ.* **1988**, *65*, 837−838.
(23) Bonilla, A.; Vassos, B. A Novel Approach for Dipole Moment Laboratory Experiments. *J. Chem. Educ.* **1977**, *54*, 130−131.
(24) Shoemaker, D. P.; Garland, C. W.; Nibler, J. W. *Experiments in Physical Chemistry*, 6th ed.; McGraw-Hill: New York, 1996.
(25) *Dielectric Constants of Common Materials*; KAB USA. https://www.kabusa.com/Dilectric-Constants.pdf (accessed Jan 25, 2020).

https://dx.doi.org/10.1021/acs.jchemed.9b00859
J. Chem. Educ. 2020, 97, 1167−1171