A Laboratory for an Electronic Systems Design Course

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Abstract

With the help of the Analog Devices company in the form of a number of their integrated circuits donated in the Summer of 2000, a new laboratory for the EE 4330 Electronic Systems Design course has been developed and was taught for the first time in the Fall of 2000. Only a few integrated circuits from other companies are used in this laboratory. One of the main criteria in selecting integrated circuits for this laboratory was that they should be currently widely used by designers of electronic systems. It was also important that laboratory systems with these integrated circuits do not need many external components and may be assembled by the student as a part of the laboratory experiment. Other conditions were that the laboratory experiments had to be inspiring and an excellent laboratory manual would be available. It was possible to achieve these goals because the EE 4330 course had quite a good laboratory prior to the Fall of 2000. The new laboratory was evaluated as superb by the teaching assistant and the students. This paper describes the place and content of the Electronic Systems Design course in the electrical engineering curriculum. The laboratory is a very important part of this course. Lists of laboratory experiments and a set of instruments on every bench are included. Examples of laboratory tasks are also presented.

1. Introduction

As a result of many years of designing analog and digital electronic systems as well as teaching a number of courses at electronics and electrical engineering departments I have a firm opinion about the breadth and depth of teaching electronics at the undergraduate level that is necessary for a student to be competitive in today’s job market. Textbooks by Jaeger [1] and Sedra and Smith [2] are widely used for required electronic courses. These two textbooks are quite different in their coverage of the fundamentals of electronics. However, no matter which textbook would be chosen and what set of topics would be covered, two one semester courses, both with a laboratory, are necessary to establish a decent background in electronics. The number of topics is too large to be squeezed into one course. Also, even if the students have two semesters of circuit analysis prior to the electronics courses, it takes some time before they start to comprehend electronics and work effectively in an electronics laboratory. Assuming that two electronics courses are required, the first electronics course should thoroughly cover an introduction to device physics and simple applications of electronic devices, such as Hall effect current sensors, diodes, and transistors (JFET, BJT, and MOSFET). Also, after the first electronics course, the student must be able to design simple electronic circuits, for example a Zener diode shunt voltage regulator or a single transistor amplifier. It should be remembered that this is the only time when the student will be taught these topics. The second electronics course needs to cover electronic circuits used in analog and digital integrated circuits, including the differential amplifier, current sources, and other multitransistor stages used in analog and digital integrated circuits. In the second course the student also needs to learn about the frequency response of electronic circuits, the feedback concept, stability of electronic systems, power amplifiers, and oscillators. The breadth and depth that must be ensured in these two courses makes them very difficult to teach and is very demanding for the student. Instructors should have vast experience in electronics as well as in teaching. A shortage in instructor's experience may be observed during her/his office hours. A large number of students looking for assistance is not a measure of the popularity of a teacher, but is rather an indication that pieces of information provided in the classroom and the textbook are missing. However, there may not be enough time in lectures for going over a large number of examples and problems that some students would like to see. For one of my office hour, I am available in a classroom for answering students' questions, most frequently on how to solve problems, and I found this practice to be a very effective aid for the student. The number of students that are coming to these "problem solving" sessions varies from 30% to 60% of the class population. Laboratories for these two courses must be carefully designed and taught by experienced instructors. In spite of all the difficulties mentioned above, it is possible to teach these two courses up to the above described standards.

2. Contents of the Electronic Systems Design course

There are some upper level electronics courses, like Electronic Systems Designs, VLSI Design, or Radio Frequency Circuits Design, that are of great importance in the Electrical Engineering education. In the Electronic Systems Design course, finally the hard work in the two required electronic courses is rewarded. The course content is shown in Table 1. The textbook of Sergio Franco [3] that is used for this course covers most of the topics, but still some supplemental materials are necessary for the lectures. Similarly, a good set of homework problems is included in the textbook, but some problems designed by the instructor are a necessity. In lectures, students learn the theory necessary to understand a given electronic circuit. The lecture precedes the laboratory, where the student correlates the theory learned in lectures and from the textbook with the real circuit. The Electronic Systems Design laboratory has been designed in a way that is similar to the work of a design engineer when he or she is not familiar enough with a specific type of integrated circuit. After studying the theory of a given class of IC, a specific circuit from the available set of ICs is selected and the datasheets of this device are studied. Next, it is necessary to verify understanding of this device in the laboratory. This procedure is followed by the student in Electronic Systems Design, with the exception of selecting the ICs. Examples of electronic systems with given ICs are also included in the laboratory work. Almost every laboratory circuit is assembled by the students on a breadboard before coming to the laboratory. Only circuits that do not operate correctly on a breadboard, like switching power supplies for example, are given in the form of ready to use printed board units. Typically two students work on laboratory problems as a team, and the wiring job is equally distributed. In the laboratory,

Table 1

#	Topics	Lab #
1	Instrumentation amplifiers	1
2	High speed operational amplifiers	2
3	Practical operational amplifiers and their applications	3
4	Single supply operational amplifiers	4
5	Isolation amplifiers, Video amplifiers, Logarithmic amplifiers	-
6	Comparators	-
7	Linear voltage regulators	5
8	Voltage reference sources and reference current sources	6
9	Switching voltage regulators	7
10	Analog multipliers	8
11	Precision rectification, absolute value to DC and True-RMS to DC converters	9
12	Analog switches and multiplexers	-
13	Sample and hold circuits	10
14	Digital to analog converters	11
15	Analog to digital converters	12
16	Frequency to voltage and voltage to frequency converters	13
17	Phase detectors	14
18	Phase-locked loops	15
19	Function generators	-

these two students work together on the laboratory assignments, but they write separate laboratory reports. Homework problems are of analytical and design type and are usually assigned after the given device has been examined by the student in the laboratory. In some cases, Spice simulation of designed systems using macro-models of devices is necessary. This organization of the course makes the teaching very efficient. Table 1 shows that almost every type of IC is used in the laboratory. Some of the ICs, such as comparators, analog switches, and multiplexers, are not used as separate laboratory experiments, but are used in some circuits of the 15 laboratory experiments. Three hours are scheduled for every laboratory. To limit the amount of work in the laboratory, it is necessary to use advanced ICs that include auxiliary circuits required for complete operation of the main part of the IC. Most of the ICs used in the Electronic Systems Design Laboratory are of the Analog Devices brand. By donating its ICs, the Analog

Devices Company made it possible to realize this laboratory.
It may look as though this course teaches mostly analog electronic. However, hardware designers of contemporary digital systems use high clock frequencies and need to understand both, digital and analog circuits. Mixed analog and digital circuits are frequently used and designers with a good grasp of analog and digital circuits are in great demand. Designers of ASICs (Application Specific ICs) will find the contents of this course very helpful too.

3. Equipment used in the laboratory

A list of instruments used in the Electronic Systems Design Laboratory is shown in Table 2. This set of instruments was not collected specifically for the Electronic Systems Design Laboratory. However, this is an acceptable set of instruments for this laboratory. Some changes in this set would be beneficial, for example the two generators (#5 and #6 in Table 2) can be replaced with one waveform generator with two independent channels. On the other hand, two separate power supplies as well as two digital multimeters are necessary. A digital oscilloscope is essential, primarily for saving files of oscillograms, but also for its measurement and signal analysis features. A frequency counter is not essential, because usually the digital frequency measurement is included in the set of measurements of a digital oscilloscope. However, in some cases this instrument is very handy and students should know how to use it. The gain-phase meter is a necessity in such a laboratory. In many situations measurements of gain and phase at a given frequency are necessary. In addition, use of this instrument shows the student how to measure frequency response parameters, as for example the 3 dB frequency of a filter.

Table 2

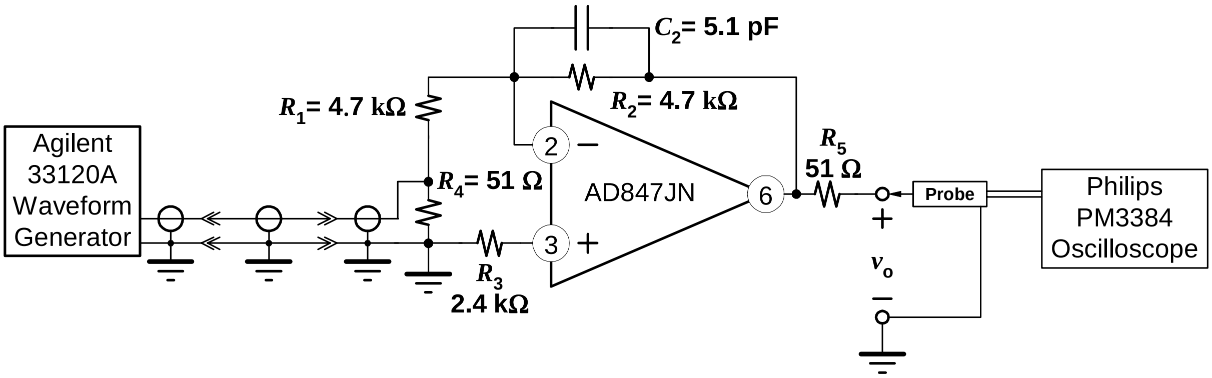
#	Name	Company	Model
1	Power Supply	Tenma	72-2080
2	Power Supply	Tektronix	PS503A
3	Digital Multimeter	Tektronix	DM502A
4	Digital Multimeter	Tektronix	CDM250
5	Waveform Generator	Agilent	33120A
6	Function Generator	Tektronix	FG502
7	Digital Oscilloscope	Fluke/Philips	PM3384B/PM3384
8	Frequency Counter	Fluke	1910A
9	Gain-Phase Meter	Hewlett-Packard	3575A

4. Examples of laboratory assignments

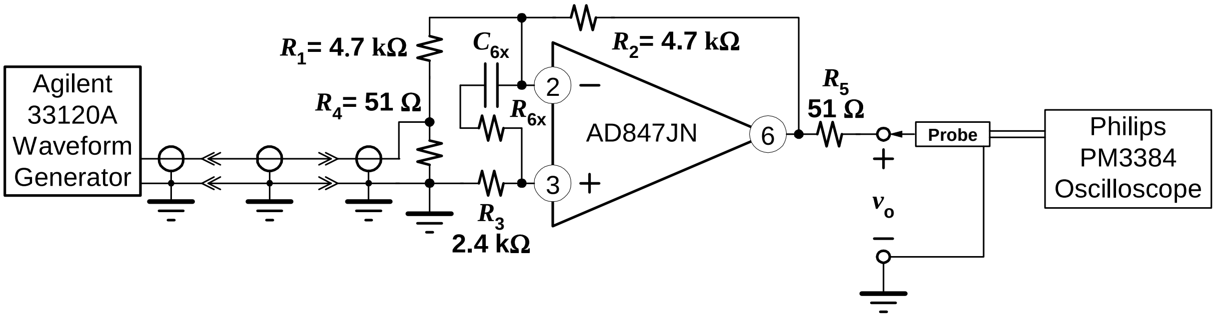
Six examples of laboratory assignments of the Electronic Systems Design Laboratory, each from a different laboratory experiment, are shown below.

4.1 **High Speed Operational Amplifier**

The High Speed Operational Amplifier used in this laboratory is the AD847 from Analog Devices. In the Electronic Systems Design Laboratory, the 3M ACE 118 (or similar) breadboards are used, so amplifiers as the AD847 with unity gain bandwidth of about 50 MHz operate with a sufficient phase margin. The assignments in this laboratory experiment concentrate on stability of the amplifier. One of the assignments is to observe behavior and measure the phase margin of the amplifier with feedback-lead frequency compensation and input-lag frequency compensation. Circuit diagrams of the measurement circuits are shown in Figure 1.



a. feedback-lead frequency compensation



b. input-lag frequency compensation

Figure 1. Wide Bandwidth Amplifier

4.2 **Analog Multipliers**

In this experiment the AD633 analog multiplier from Analog Devices is used. The assignments include measurements of some parameters of the AD633, comparing the results with those given in datasheets, and investigation of its typical applications. One of these applications is an amplitude modulator whose circuit diagram is shown in Figure 2.

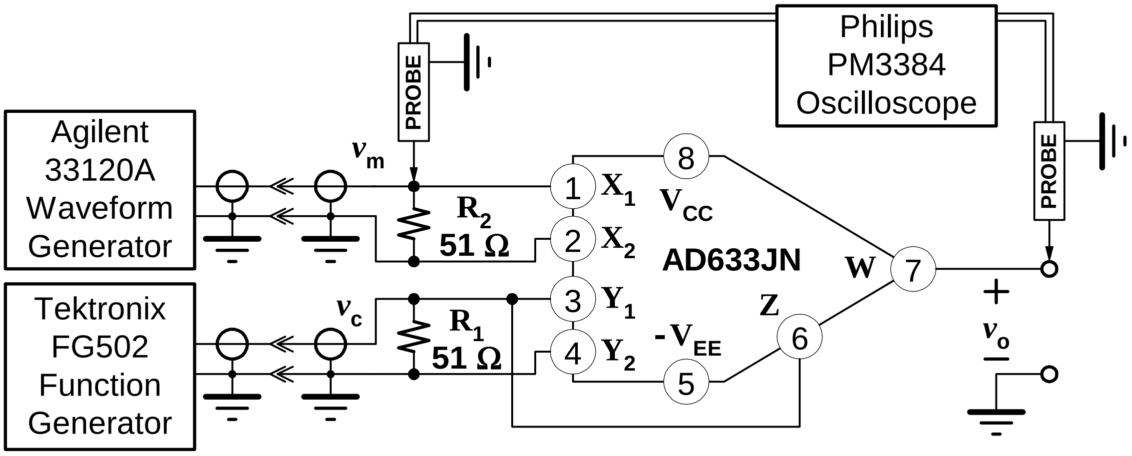


Figure 2. Amplitude Modulator

4.3 **Precise AC to DC Converters**

Two AC to DC converters, the Mean Absolute Deviation to DC converter and the True RMS to DC converter are examined in this laboratory. The AD536 True RMS to DC converter from Analog Devices is employed in this experiment. Shown in Figure 3 is the circuit used to measure the dependence of the output voltage, v_O, on the third harmonic component in the input signal, v_{in}. The same kind of measurement is done for the MAD to DC converter to illustrate the difference in dependence of the v_O on the harmonic content in the v_{in} for these two converters.

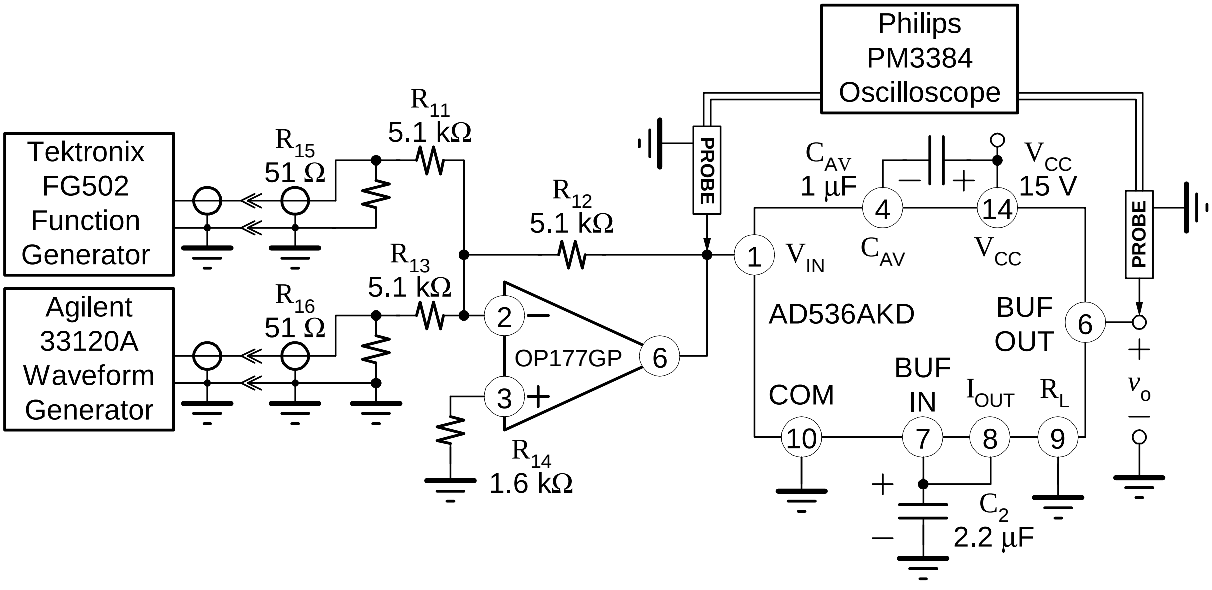


Figure 3 True RMS to DC Converter

4.4 **Sample and Hold Amplifier**

This laboratory experiment has been designed to illustrate operation, measure some parameters and show typical applications of the AD585 Sample and Hold Amplifier. A diagram of the circuit which is used to examine the operation of the AD585 is shown in Figure 4. The AD585 is in the SAMPLE mode for a constant time τ (pulse width of the 74121). The monostable multivibrator 74121 is triggered at the positive zero-crossing of the triangle voltage from the Agilent Waveform Generator, v_{in}. The v_{in} is sampled by the AD585 one time per its period. When the frequency of the v_{in} is being changed, the transition from SAMPLE to HOLD occurs at different phase angles of v_{in}. This relationship is used to examine the operation of the AD585.

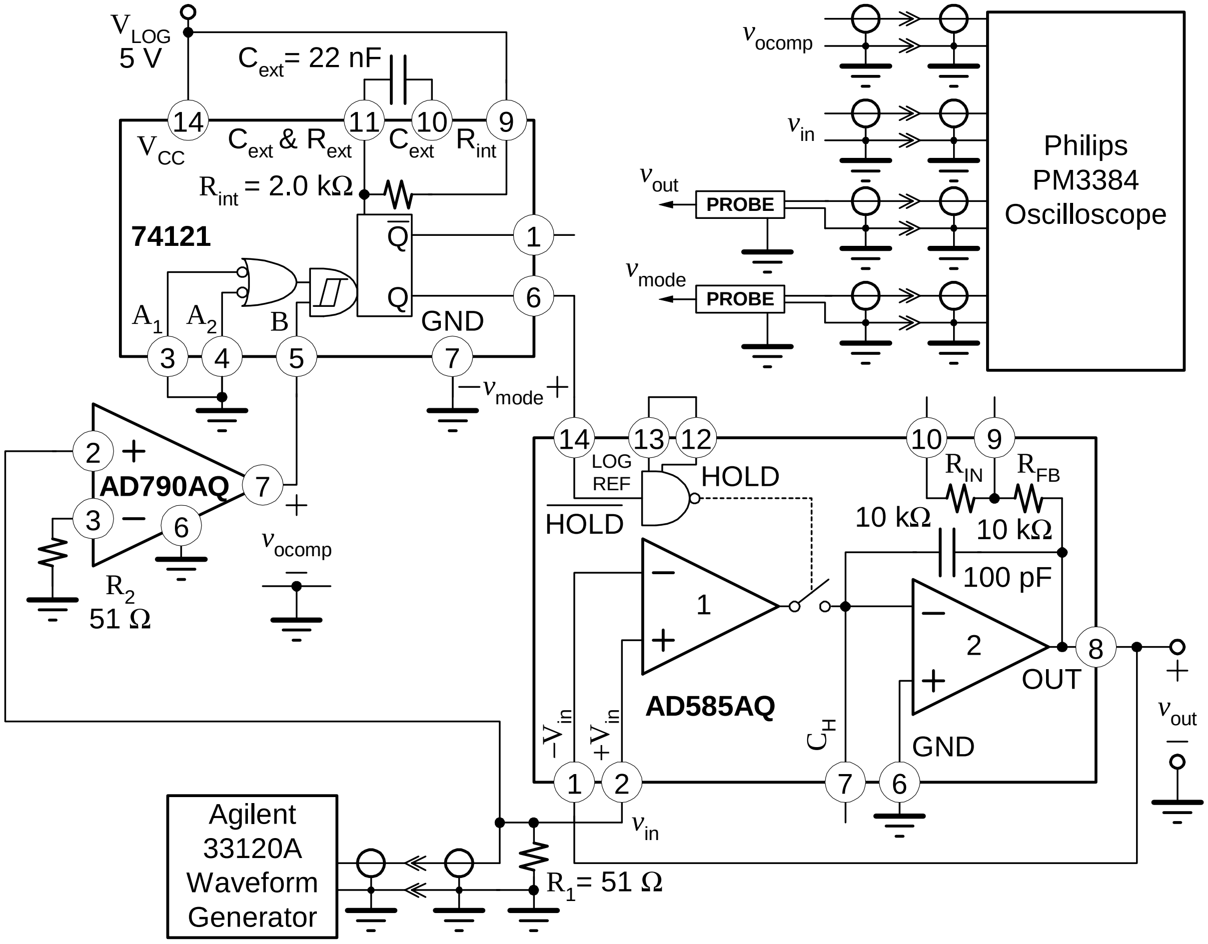


Figure 4. Sample and Hold Amplifier

4.5 **Digital-to-Analog Converter**

The Analog Devices AD7541A Digital-to-Analog Converter (DAC) is used in this laboratory. The AD7541A is a 12-bit multiplying DAC. This laboratory is focused on adjustment procedure, measurements of some parameters, and selected applications of the DAC. Figure 5 shows the circuit diagram of one of the applications of the AD7541A that are examined in this laboratory

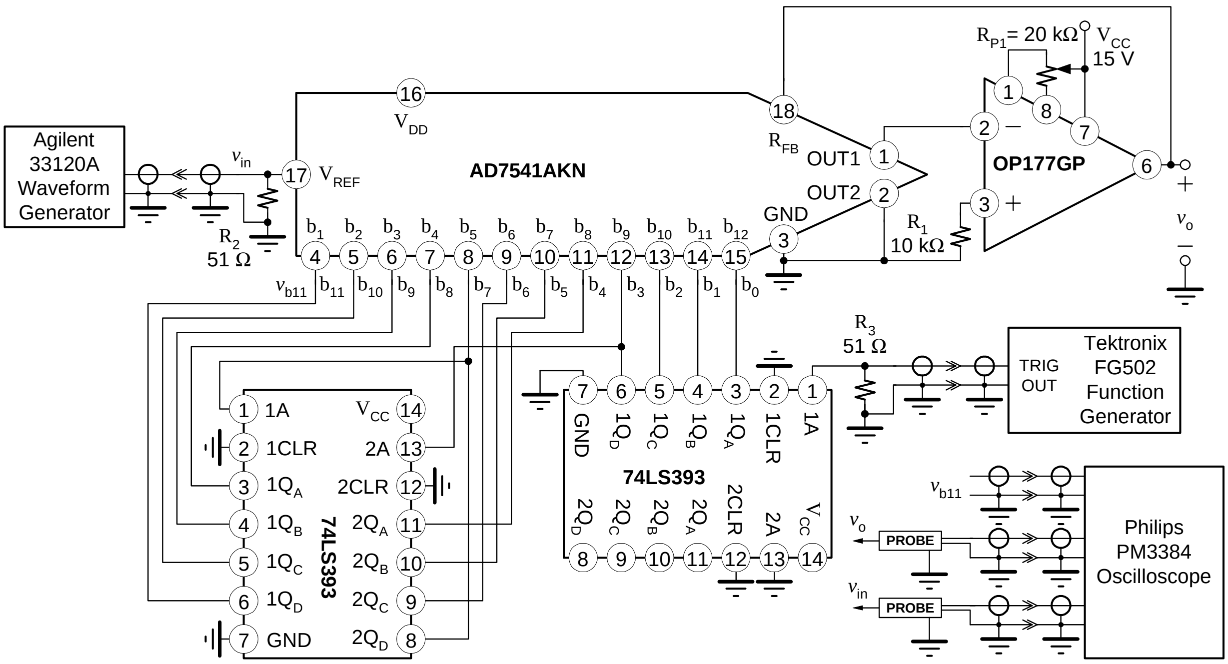


Figure 5. Digital-to-Analog Converter

experiment. The input voltage to the DAC, v_{in}, is a sinusoidal signal obtained from the Agilent Waveform Generator. The digital input for the DAC is produced by a 12 bit binary counter driven by a signal from the Tektronix Function Generator at frequency f_{CLK} = 1 MHz. The output voltage from the DAC, v_o, is observed with the oscilloscope for three frequencies of the Agilent Waveform Generator, $2^{-13}f_{CLK}$, $2^{-13}10f_{CLK}$, and $2^{-13}100f_{CLK}$.

4.6 **Successive Approximation Analog-to-Digital Converter**

The core of the circuit for this laboratory experiment is the Analog Devices AD774B 12 bit successive approximation Analog-to-Digital Converter (ADC). This ADC requires minimal external circuitry for its full operation. The program of this laboratory experiment includes adjustment procedure and measurements that show the operation of the ADC. These tasks are performed in the circuit with the circuit diagram as shown in Figures 6 and 7. The conversion rate is determined by the frequency of the Agilent Waveform Generator. Because of the high resolution of the AD774B, it is necessary to have a source of the v_{IN} that has a fine adjustment of its voltage. The Tektronix Digital Multimeter used in this laboratory has too low of an accuracy as compared with the AD774B and only the operation of the ADC may be examined in this circuit. The digital display for this circuit is shown in Figure 7. Use of typical bar graph display modules in this circuit is very convenient.

5. Conclusion

The strategy used in designing the Electronic Systems Design course was centered on effectiveness of teaching. Because in such a course the laboratory is a fundamental component to achieve maximum effectiveness of teaching, effort has been made to design an excellent laboratory. Many factors were considered to accomplish this goal. A laboratory must be properly equipped with instruments that ensure accurate measurements and effective data collection. Integrated circuits used to build electronic systems have to be currently and widely used by design engineers. In addition, they must work without limitations with a minimum number of external components. For example, the sample and hold amplifier used in this laboratory has the internal holding capacitor, the ADC includes the digital circuit necessary for its full operation. Thus, the electronic systems used in the laboratory may be assembled by students. If assembling of the electronic system is one task in the program of a laboratory experiment, then one important educational element is added, that is learning skills of debugging hardware. In this laboratory students learn not only functions of a given IC, but also measurement techniques, how to collect data, how to write technical reports, and how to work in a team. They also learn the importance of understanding how the IC is built, how it operates, and how to make analysis of an electronic system with this IC. The Electronic Systems Design Laboratory has been tested in the Fall of 2000 and needs only minor corrections related to results of measurements of many electronic systems of the same kind. These details became apparent when students worked in the laboratory.

6. Acknowledgment

The author would like to thank the Analog Devices Company for their generous donation. Without their help it would be impossible for the author to realize this project.

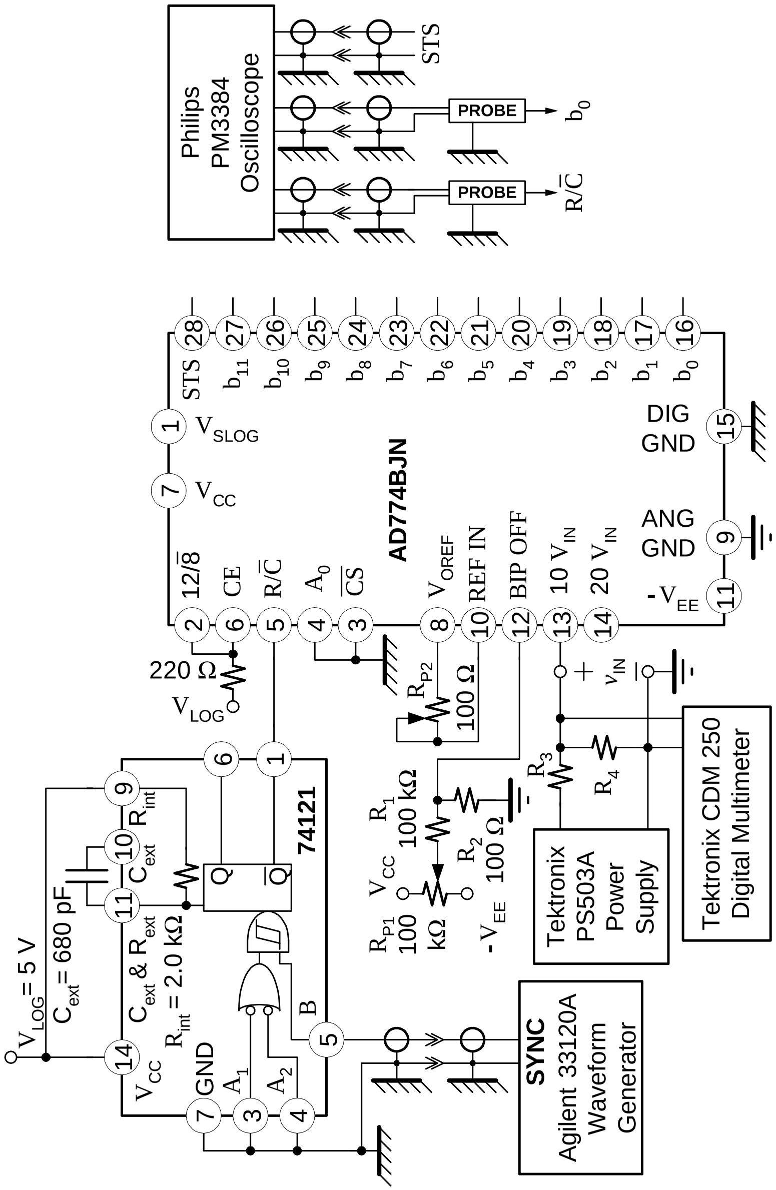
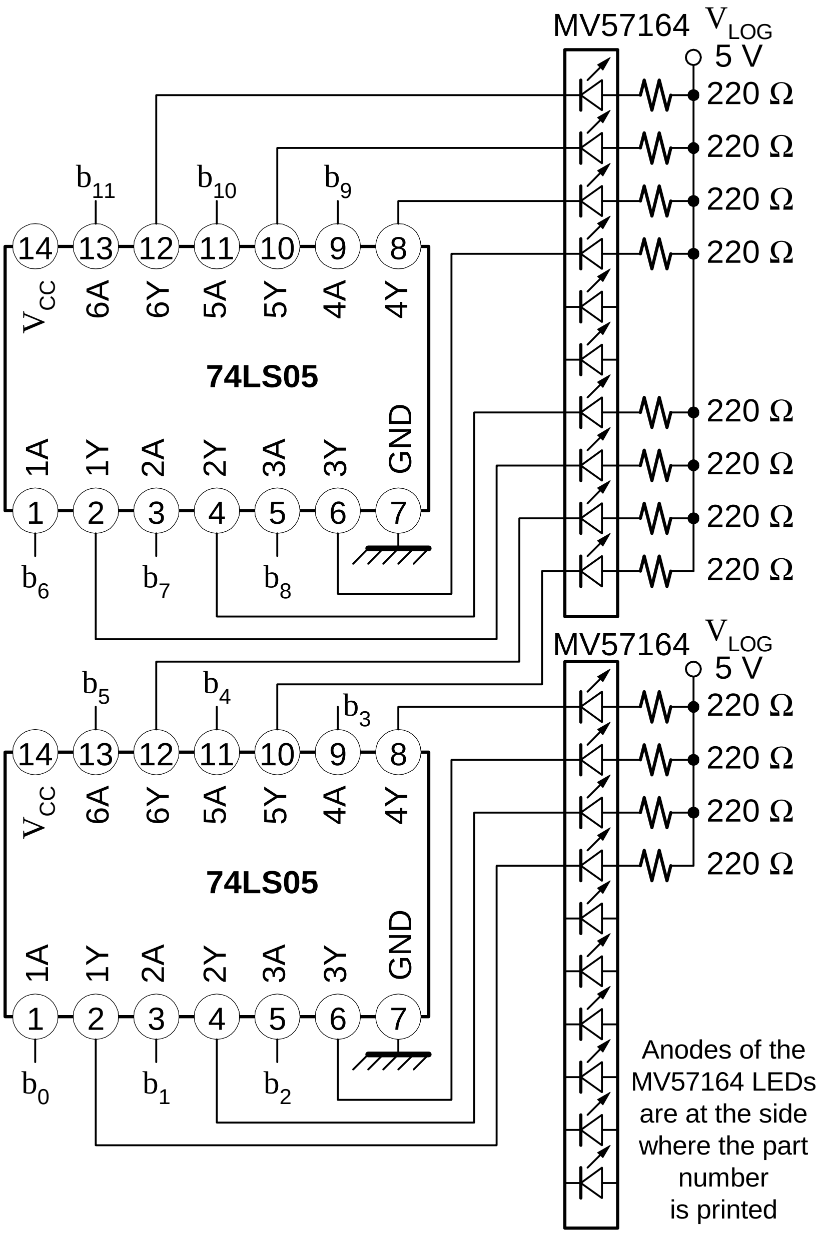


Figure 6. Analog-to-Digital Converter



Anodes of the MV57164 LEDs are at the side where the part number is printed

Figure 7. Digital Display for the ADC

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Stanislaw F. Legowski received M.S. and Ph.D. degrees in electronics engineering from the Technical University of Gdansk, Poland. From 1958 to 1962 he was a Research Assistant at the Oceanographic Institute of the Polish Academy of Sciences in Sopot, Poland, where his research was primarily in instrumentation and measurement methods used in oceanography. From 1962 to 1983 he was consecutively a Teaching Assistant, Lecturer, and Assistant Professor at the Technical University of Gdansk. His main research areas were electronic measurement systems, electrical measurements of nonelectrical quantities, and automatic measurement methods of analog integrated circuits. In 1983 he joined the faculty of the Electrical Engineering Department at the University of Wyoming, where he is currently a Professor. His research interests are electronics, analog and digital systems analysis and design, and power electronics. Dr. Legowski was awarded The Best Teacher of the Academic Year 1979/80 in the Electronics Department at the Technical University of Gdansk and the Outstanding Faculty Member of the College of Engineering at the University of Wyoming for the 1983/84 academic year.

Appendix An Example of a Laboratory Experiment Guide

EE 4330 Electronic Systems Design Fall 2000

Laboratory #3

Parameters of Practical Operational Amplifiers

The purpose of this laboratory is to measure some of the parameters of operational amplifiers. Three µA741 operational amplifiers will be used as the Device Under Test (DUT) and the following parameters will be measured: input offset voltage, input bias current, input offset current, open loop dc voltage amplification, and slew rate. Before coming to the laboratory, read sections 5.1, 5.2, 5.4, 5.6, 6.1, 6.2, and 6.4 in the textbook, sections Description in the Texas Instruments datasheets of the µA741 and General Description in the National Semiconductor datasheets of the LM741, as well as the following description of this laboratory experiment.

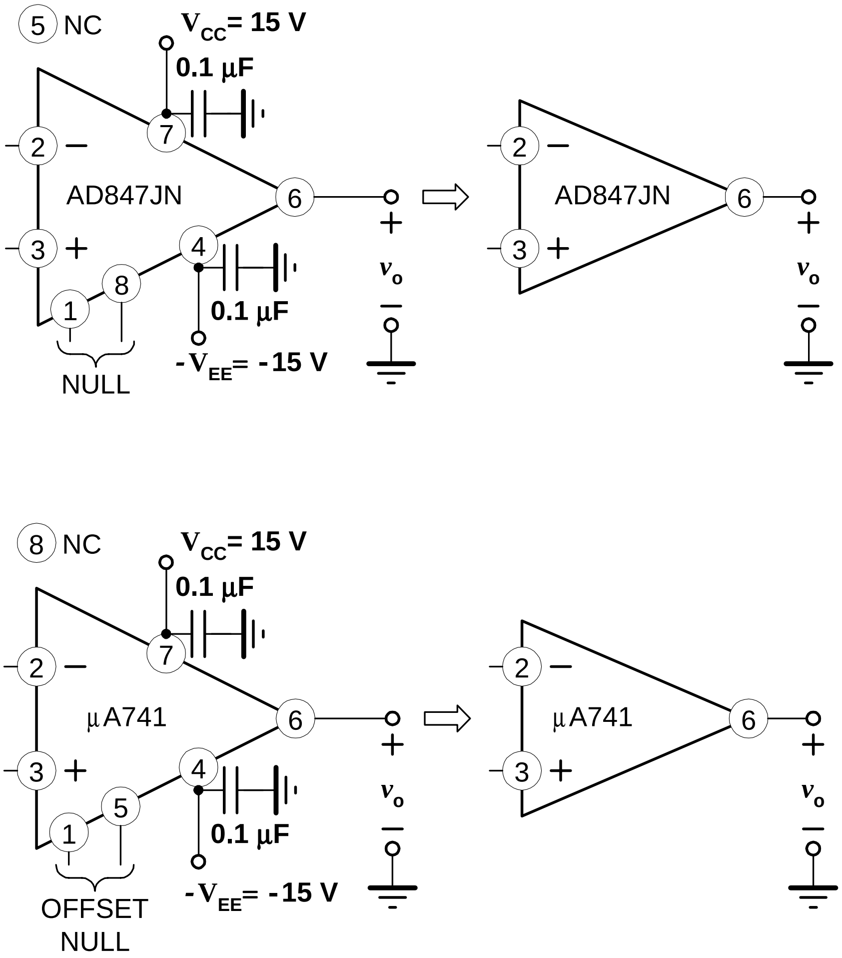

Figure 1

Laboratory

Every integrated circuit on the breadboard needs to have the 0.1 μF bypass capacitors, as it is shown in Figure 1. Only one pair of the 100 μF bypass capacitors needs to be used for the entire circuit assembled on the breadboard. In Figures 2 to 8 power supply pins and the bypass capacitors are not shown. In this laboratory, the offset null of the ICs will not be used.

Input offset voltage, V_{OS}

Measurement circuit for the V_{OS} is shown in Figure 2. In the circuit diagram, the op amp #1 is the DUT and op amps #2 and #3 belong to the measurement circuit. The V_{OS} is computed as

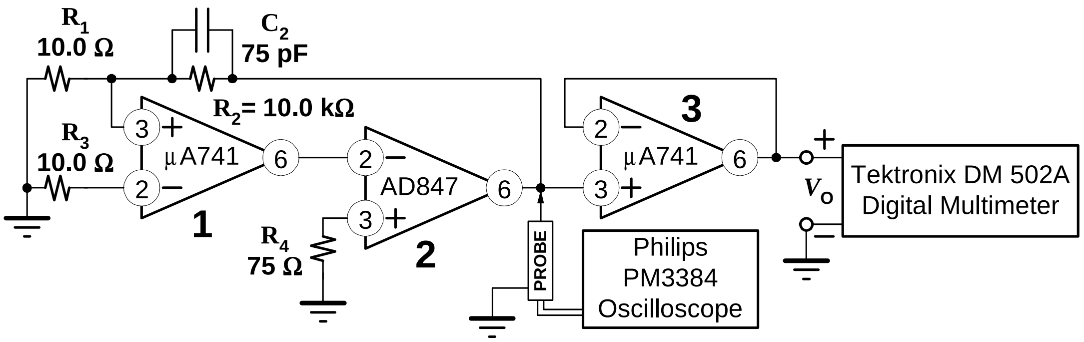

Figure 2

$$\mathbf{V_{OS}} = -\frac{\mathbf{R_1}}{\mathbf{R_1} + \mathbf{R_2}} \mathbf{V_O} \, . \tag{1}$$

In the circuit, the oscilloscope is used to monitor whether the circuit behaves normally (for example, that there are no oscillations, that the op amps are in the linear region). The op amp #2 is used to force the output of the DUT to have a desired output voltage, that for this circuit is 0 V. Amplifiers #1 and #2 form a compound operational amplifier with gain equal

$$\mathbf{A}(\mathbf{s}) = \mathbf{A_1}(\mathbf{s})\mathbf{A_2}(\mathbf{s}) \, , \tag{2}$$

where A_1(s) is the open loop gain of op amp #1, and A_2(s) is the open loop gain of op amp #2. The feedback network of the amplifier includes resistors R_2 and R_1, and frequency compensation capacitor C_2. In order to obtain a desired phase margin of the amplifier, the op amp #2 must be a wide bandwidth one, hence the AD847 is used in the circuit. For this circuit, to obtain a close to optimal frequency response, the compensation capacitance C_2 from the range 68 pF to 82 pF is required. Phase margin of the circuit shown in Figure 2 was measured in the circuit shown in Figure 3 as PhM = 57^o. The optimal phase margin equals 60^o, when the magnitude response is maximally flat. The peaking of the magnitude response of the amplifier occurred at 154 kHz. The bandwidth of the amplifier with the compound op amp has been measured as f_{3dB}= 330 kHz. All measured values are close to those obtained from computations.

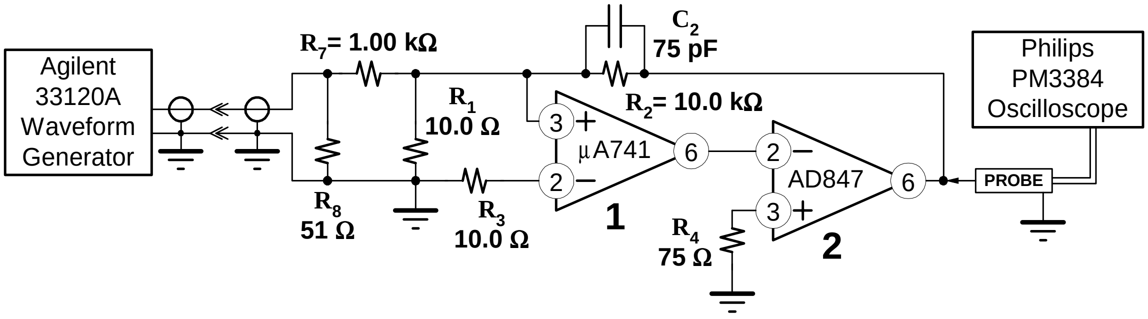

Figure 3

In Figure 2, the op amp 3 is used as a buffer between the output op amp #2 and loads it with a capacitance that may cause stability problems of the measurement circuit. It is safe to attach an oscilloscope probe to the output of op amp #2, but a voltmeter may have an input capacitance that is too large for the output of the measurement circuit.

It may be proved, that the offset voltage of the op amp #2, which has not been nulled, has a negligible effect on measurement error in the measurement circuits shown in Figures 2, 4, 5, 6, and 7. Similarly, op amp #3 has not been nulled, but the effect of that is negligible. For example, if the offset voltage of op amp #3 is 1 mV, its contribution to the total error of offset voltage measurement equals 1 μV, which is computed using equation (1). Notice, that the value of resistance R_4 equals the typical output resistance of the μA741 (op amp #1 has no feedback).

Table 1

	R_1	R_2	R_3, Fig 4 & 6	R_5
Nominal value	10.0 Ω	10.0 kΩ	100 kΩ	100 kΩ
Measured value				

Table 2

DUT #	V_O	V_{OS}
1		
2		
3		

Input bias currents and input offset current

The circuit used to measure the bias current of the inverting input, I^-_B, is shown in Figure 4. The value of I^-_B is computed from the equation

$$\mathbf{I_B^-} = -\left(\frac{\mathbf{R_1}}{\mathbf{R_1} + \mathbf{R_2}}\mathbf{V_O} + \mathbf{V_{OS}}\right)\frac{\mathbf{1}}{\mathbf{R_3}}\,. \tag{3}$$

The circuit used to measure the bias current of the noninverting input, I^+_B, is shown in Figure 5.

The value of I^+_B is computed from the equation

$$\mathbf{I_B^+} = \left(\frac{\mathbf{R_1}}{\mathbf{R_1}+\mathbf{R_2}}\mathbf{V_O} + \mathbf{V_{OS}}\right)\frac{\mathbf{1}}{\mathbf{R_5}}. \tag{4}$$

The input bias current is defined as

$$\mathbf{I_B} = \frac{\mathbf{I_B^+} + \mathbf{I_B^-}}{\mathbf{2}}. \tag{5}$$

The circuit used to measure the input offset current, I_{OS}, is shown in Figure 6. The I_{OS} is defined as

$$\mathbf{I_{OS}} = \mathbf{I_B^+} - \mathbf{I_B^-} \tag{6}$$

and from measurements made in the circuit shown in Figure 6, I_{OS} is computed from the equation

$$\mathbf{I_{OS}} = \left(\frac{\mathbf{R_1}}{\mathbf{R_1}+\mathbf{R_2}}\mathbf{V_O} + \mathbf{V_{OS}}\right)\left(\frac{\mathbf{1}}{\mathbf{R_3}} - \frac{\mathbf{1}}{\mathbf{R_5}}\right). \tag{7}$$

Table 3

DUT #	V_O	I^-_B
1		
2		
3		

Table 4

DUT #	V_O	I^+_B	I_B
1			
2			
3			

Table 5

DUT #	V_O	I_{OS} measured, Fig. 6	I_{OS} computed, Figs. 4 & 5
1			
2			
3			

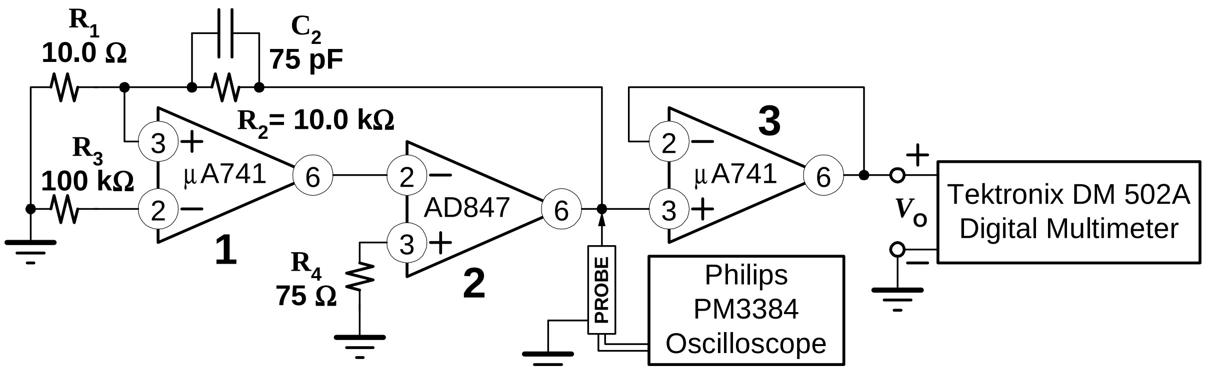

Figure 4

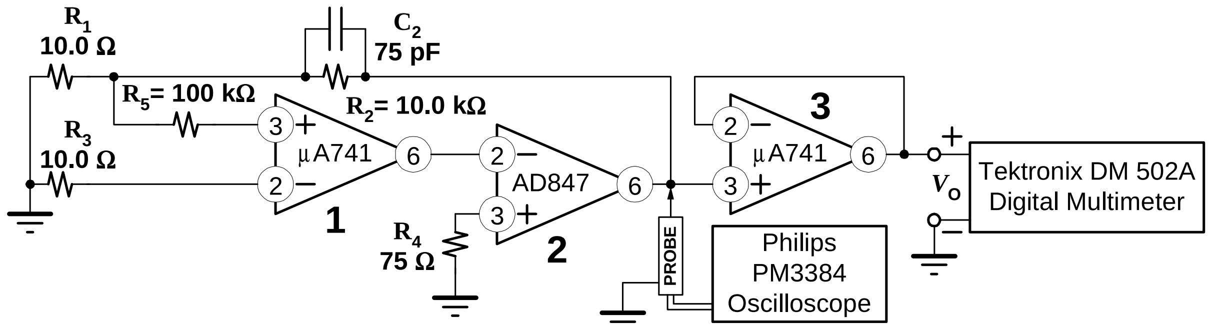

Figure 5

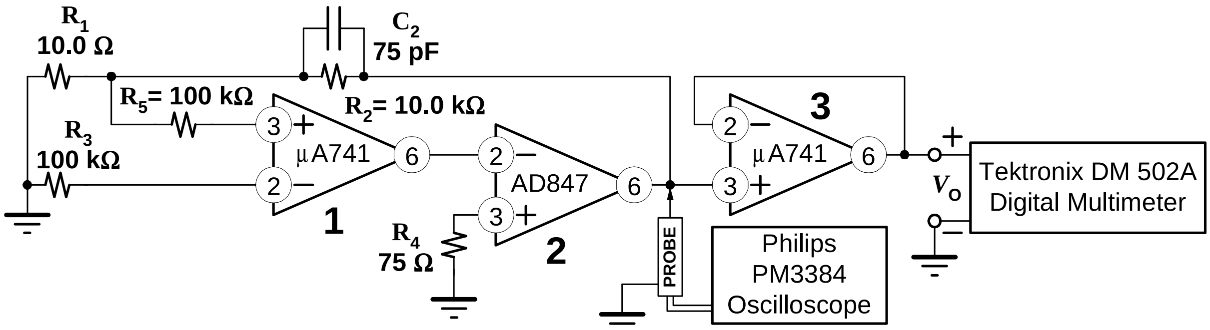

Figure 6

Open loop DC gain, A_0

Open loop DC amplification is measured in the circuit shown in Figure 7. In this circuit, voltage of the noninverting input of op amp #2 is forced by the power supply and measured by the digital multimeter. The voltage of the noninverting input of op amp #2 is reflected to the output of the DUT by the action of op amp #2, that produces such an output voltage V_O for which this condition is satisfied. Because in the circuits shown in Figures 2 to 7 the output voltage of the DUT equals the voltage at the noninverting input of op amp #2, in the circuit of Figure 7 it is possible to force the output of the DUT to have any voltage from the linear range of its operation. Hence, A_0 is computed as

$$\mathbf{A_0} = \frac{\Delta \mathbf{V_2^+}}{\Delta \mathbf{V_{ID,DUT}}} = \frac{\mathbf{R_1} + \mathbf{R_2}}{\mathbf{R_1}} \frac{\Delta \mathbf{V_{O,DUT}}}{\Delta \mathbf{V_O}} , \qquad (8)$$

where V^{+}_{2} is the voltage at the noninverting input of the op amp #2 and $V_{O,DUT} = V^{+}_{2}$, and $V_{ID,DUT}$ is the differential input voltage of op amp #1. Notice that if a constant $\Delta V_{O,DUT}$ is used, then the larger A_0 is, the smaller the ΔV_O.

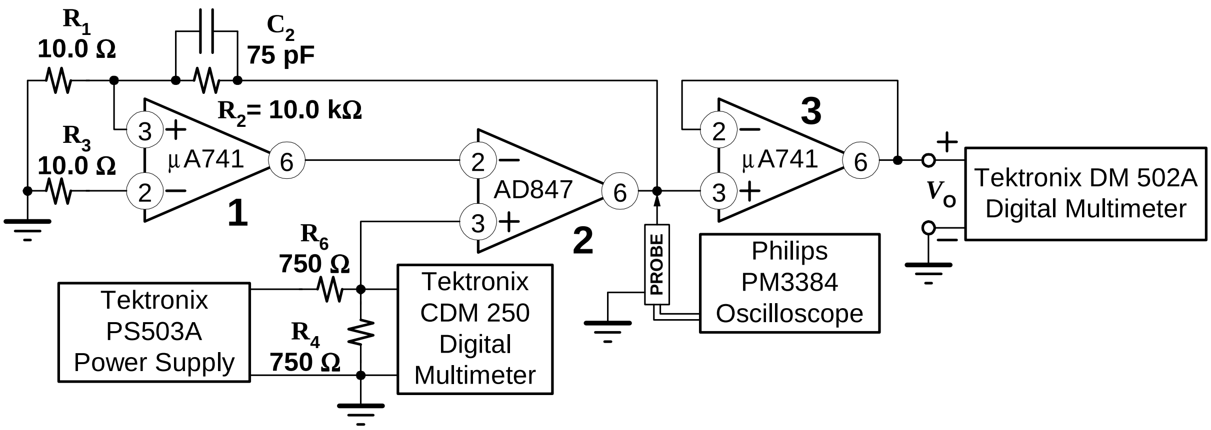

Figure 7

Table 6

DUT #	$V^{+}_{2,1}$	$V^{+}_{2,2}$	ΔV^{+}_{2}	$V_{O,1}$	$V_{O,2}$	ΔV_O	A_0
1							
2							
3							

where $\Delta V^{+}_{2} = V^{+}_{2,2} - V^{+}_{2,1}$ and $\Delta V_O = V_{O,2} - V_{O,1}$.

Slew Rate, SR

Measure the slew rate of the three DUTs in the circuit shown in Figure 8. The rise time, τ_r , as well as the fall time, τ_f , are defined as time increments of the output voltage of the circuit excited by an ideal square wave, and corresponding to instantaneous voltage values of 10% and 90% of the output voltage peak-to-peak value for the τ_r , and voltage values of 90% and 10% of the output voltage peak-to-peak value for the τ_f . To compute the slew rate, use the larger of these two values (worst case). Set the square wave on the input to the voltage follower to 20 V_{pp} . Save files of oscillograms of the input and output voltage to the voltage follower for one of the three DUTs.

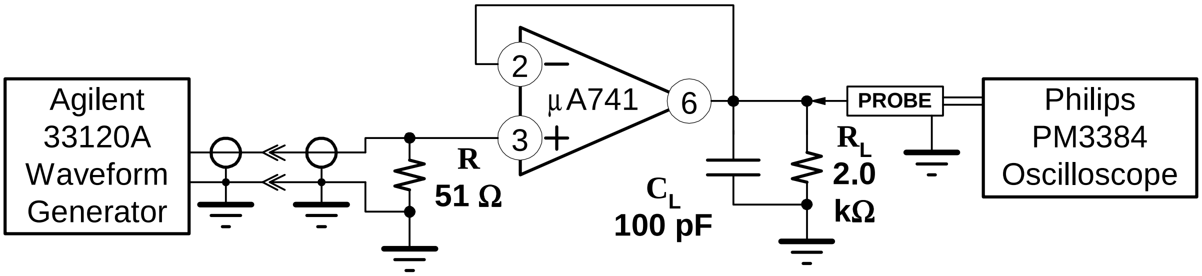

Figure 8

Table 7

DUT #	τ_r	τ_f	SR
1			
2			
3			

Report

1. Describe how you made the measurements of each parameter measured in this laboratory.
2. Compare measured parameter values with those specified in datasheets.
3. Explain why the phase margin of the circuit shown in Figure 2 may be measured in the circuit shown in Figure 3.
4. Prove equations (3) and (5).