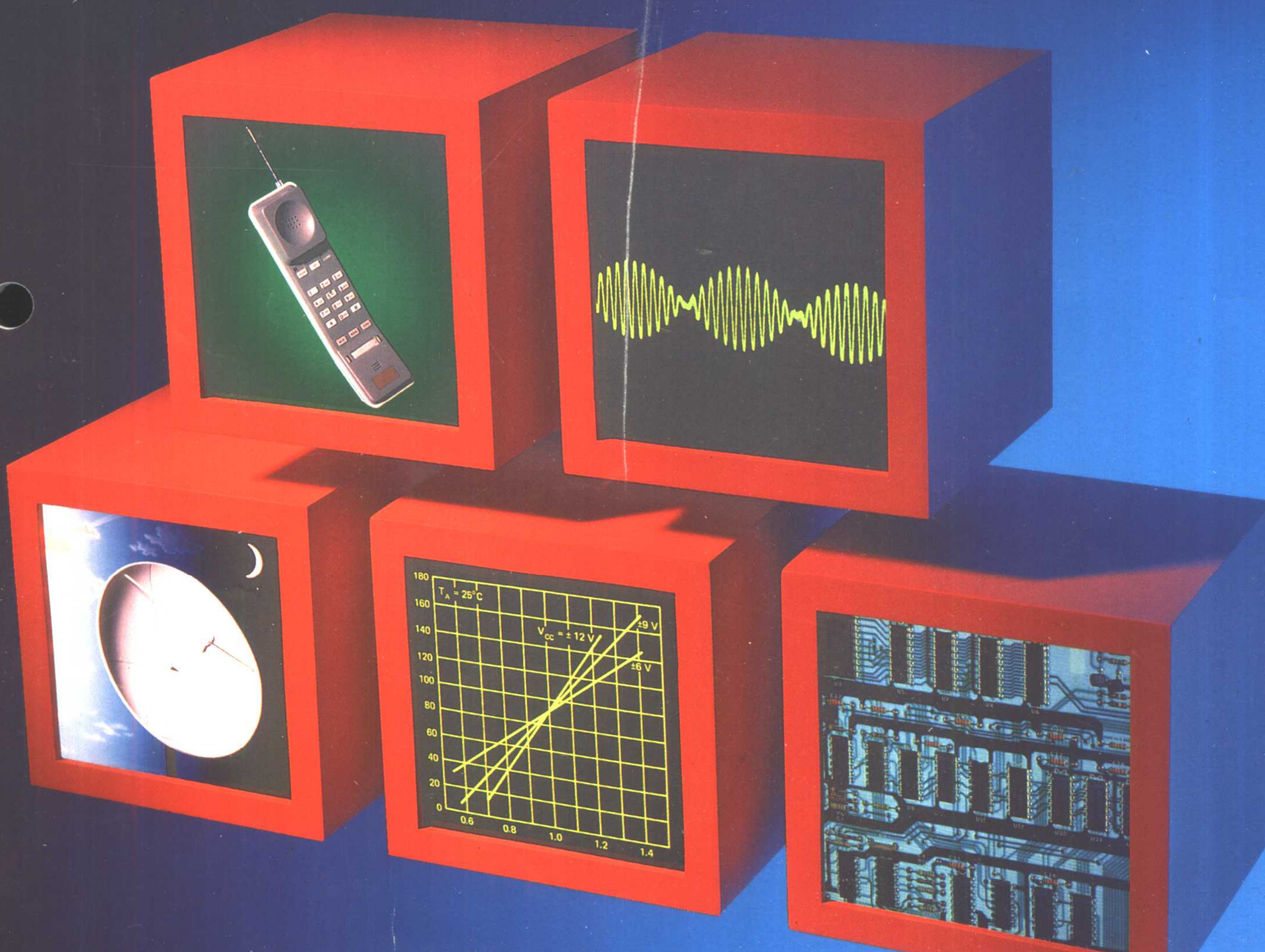
Telecommunications

A TEXT-LAB MANUAL

Second Edition



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TELECOMMUNICATIONS: A Text-Lab Manual, Second Edition

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Preface

In 1912, Lee De Forest, the inventor of the vacuum tube, designed a feedback circuit for his audion amplifier. The amplifier thus became an oscillator and was the first step toward linking the Earth's populations by what is now known as "telecommunications."

In 1931, my brother Lou received his amateur radio license and was soon talking to other amateurs throughout the United States and Canada. During this short period of 19 years, thousands of tinkerers had been busy creating electronic circuits by using the diode invented by Thomas A. Edison and the triode invented by Lee De Forest. In August 1989, 77 years (to the month) after the oscillator was designed by De Forest, the Voyager was sending back pictures from the planet Neptune and its moons, billions of miles from Earth. The power of Voyager's transmitter was a mere 20 W. The modern tinkerers had created a superb means of telecommunications.

I often comment while reminiscing about the sound coming from the "cat's whisker" of my crystal detector, that I was fortunate enough to be raised during that wonderful period when many of the great inventors in the fields of electricity and electronics were still living and highly active. De Forest died in 1961 and Guglielmo Marconi, Heinrich Hertz, and Major E. H. Armstrong were all his contemporaries. It is almost incomprehensible to me that within one lifetime, science has taken the quantum leap from the diode to telecommunications between two points separated by billions of miles by means of a 20-W transmitter. This basic course in telecommunications provides a foundation for courses in subjects such as digital communications, fiber optics, and microwave and satellite communications. The emphasis is placed on developing a new tinkerer—you. By this I mean that the course is aimed at training the individual to use electronic components and test instruments. Another important goal of the course is to get the student to experience the excitement that comes when the electronic circuit does what it is expected to do. Emphasis is also placed on the use of components and test instruments and on learning how to develop, wire, and test telecommunication circuits. Some of the circuits that will be evaluated are found in advanced courses. Linear operational amplifiers are used in a variety of amplifiers, oscillators, mixers, and detectors. Amplitude modulation, frequency modulation, pulse width modulator and frequency-shift keying are included in the study. Phase-locked loop circuitry and special tone generators and decoders are also an integral part of this foundation course.

It is estimated that approximately 100 hours will be required for the completion of the text-lab manual. A total list of components needed for the course is provided in Appendix A. Data sheets for all the active components studied are located in Appendix B.

This course in telecommunications is challenging and provides ample opportunity for students to express their creative ability. At the end of the course, students will have a full knowledge of the use, application, and methods of troubleshooting a variety of basic telecommunication circuits.

The author wishes to thank Regan Harycki, for his assistance in revising this manual, and Michael Gandman, for reevaluating each of the experiments. Special thanks go to Lyuda Tulchinskaya and Max Woods for preparation of the artwork. Lana May and Annette Klein are also thanked, for typing and revising the manuscript. All the above-mentioned people are members of the Research & Development department of the Science Instruments Company of Baltimore, Maryland.

The author also wishes to acknowledge with appreciation the manufacturers whose data sheets appear in Appendix B. Thanks also to the instructors and students who reported that they enjoyed the first edition of the manual and offered suggestions for this edition.

Morris Tischler

Introduction

OBJECTIVES

Upon completion of this course of study, and when provided with circuit diagrams using linear integrated circuits as well as laboratory test instruments, you will be able to:

1. Measure circuit voltages and waveshapes and compare them with the data provided in the text and teacher's answer book
2. Troubleshoot electronic circuits and replace defective parts
3. Assemble and test electronic circuits using linear integrated circuits (ICs), and vary component values to derive desired results
4. Develop electronic circuits, within the range of subjects covered by this course, to meet specific requirements
5. Use electronic laboratory test instruments to measure voltages, waveshapes, phase relationships, distortion, and frequencies in order to determine the circuits' operating characteristics
6. Use data sheets for ICs in order to evaluate the proper components to be used in circuit development or the replacement of components during repair
7. Handle sensitive components, such as ICs, during installation and repair without damaging parts
8. Discuss with engineers and other technicians the operation of circuits and subsystems covered in this course
9. Determine the limitations of test instruments used in electronic measurement and troubleshooting
10. Write technical reports relating to circuit development, repair, or maintenance describing the circuit, operating values, malfunction, and repair performed

SCOPE

Electronics is fascinating because there are many opportunities to be creative and to find solutions to electronic problems. Each new piece of equipment, although it appears to be very complex at first, can be divided into a series of basic circuits which use relatively few different types of electronic components. One component, such as a transistor or an IC, can be wired to perform numerous functions. This manual provides experiments to demonstrate the application of linear ICs in an array of electronic circuits.

This course does not use a "cookbook" approach, in which you are given very detailed instructions. Instead, you will study each circuit in order to determine how it functions. Indeed, when first connected, the circuit may not perform properly. All the more fun! A circuit that is not working requires more thinking, testing, and changing of component values. A highly qualified technician or engineer needs only the circuit concept and basic information in order to get started. From this starting point, you should be able to make a functional circuit, using the appropriate test instruments.

Some circuits include the equations needed to answer the questions in the manual. Also, these equations can be used to make your own calculations and circuit changes, or those suggested by your instructor. At all times, you should be saying to yourself, "What if I changed the bias, varied the voltage, increased the load? What would happen?" The "what if" provides a greater insight into circuit design.

Several circuits can be combined to form subsystems. You may want to consider the design, assembly, and testing of such configurations and then combine your new subsystems to form larger operating entities.

It is suggested that a brief laboratory report be prepared on each circuit studied. The format of the report is left to the recommendation of your instructor.

LABORATORY EQUIPMENT

The circuits to be studied require certain laboratory test instruments. The following should be available:

Oscilloscope: 5-inch (in), dual-trace, triggered sweep, 20-35 megahertz (MHz)

Function generator: sine, triangle, and square-wave, 1 hertz (Hz) to 2 (MHz)

Digital multimeter and field-effect-transistor volt-ohm milliammeter (FETVOM)

Capacitance or resistance-capacitance-inductance (RCL) bridge, or both

Resistance and capacitance decade substitution boxes

Grid-dip meter, for radio-frequency (RF) circuits only

Distortion meter or analyzer (optional)

Appropriate instrument test leads, probes, and alligator jumpers are also required. An electronic calculator will be a time-saver and should be available for calculations as required in circuit changes. The parts required for each circuit are shown in the circuit diagrams. Resistors are all ¼ watt (W) unless otherwise indicated. Capacitors are rated at 25 or 16 working volts direct current (W V dc). A WORD OF ADVICE: When you design or redesign a circuit, think about how you would change it if the circuit didn't perform as expected. Think about several alternatives. Try your circuit and try it again until your idea is converted into a working circuit or system.

Laboratory Power Supply

For the experiments to be performed properly, well-regulated supplies are required. A well-regulated dual power supply of ± 15 V at 0.5 ampere (A) dc is required. The 15-V sources should be adjustable, and at a full load, the ripple should be less than 10 millivolts (mV). A +5-V dc supply of 1.0 A and a 6-V ac supply is also recommended.

Suggested Laboratory Instruments

Electronic test instruments are available in a variety of types and degrees of quality. Obviously, an oscilloscope that sells for more than $2000 is better and probably more professional than one that sells for $400 to $700. Such expensive instruments can be used but are not required for this course of study.

The following list of suggested instruments that will perform effectively:

Oscilloscope: 5 in., dual-trace, triggered-sweep. Vertical sensitivity, 10 mV/cm each channel frequency response, dc to 35 MHz, with dc and ac input. Horizontal sensitivity, 200 mV/cm; sweep speed, 1 to 0.2 microsecond per centimeter (μs/cm). Magnification, × 10. Two probes, with direct and × 10 attenuation. Test leads may also be helpful.

Function generator: 1 Hz to 2 MHz with less than 0.1 percent distortion for sine, triangle, and square waves. Stepped and variable attenuation, 0 to 60 decibels (dB). 10-V output into 50-ohm (Ω) load.

Voltmeter: Several types of voltmeters can be used. The digital multimeter and FETVOM are typical types. It is suggested that a volt-ohm-milliammeter (VOM) or FETVOM be available along with a digital multimeter, since sometimes two measurements need to be made at the same time. The digital multimeter is most important.

Impedance bridge: A capacitance or RCL bridge (one or two per laboratory) will be useful in checking component values, since, for instance, a capacitor marked 20 microfarads (μF) may actually measure 25 μF or more (20 percent tolerance value). The unit should measure resistance from 0.001 to 11 Ω, capacitance from 1 picofarad (pF) to 11,000 μF, and inductance from 0.1 microhenry (μH) to 1100 μH. It may be battery or alternating current–operated.

Resistance and capacitance decade boxes: At least one of each of these boxes should be available at each workstation, since it is often more convenient to vary the resistance or capacitance value by turning a knob than by inserting separate components. The suggested resistance box is 15 Ω to 10 MΩ in two ranges.

Distortion meter: This instrument is used to measure the distortion of amplifiers. Usually one or two per laboratory is sufficient. The instrument should be able to measure to within 0.1 percent and should have a frequency range of 20 Hz to 20 kHz and a distortion range of 0.3 to 100 percent of input level from 1 to 300 V.

Grid-dip meter: This instrument is used for measurements of RF circuits. One or two per laboratory are sufficient. Its range should be 1.5 to 250 MHz.

Digital frequency counter (optional): One per laboratory is suggested. Frequency response: 10 Hz to 60 MHz. Sensitivity: 30 mV. Six-digit readout.

LABORATORY EXPERIMENTS

A variety of experiments are presented. The experiments are grouped as circuits relating to linear amplifiers, filters, oscillators, and generators. The circuits selected are typical and simplified. More complex circuits can be developed. For additional information, reference should be made to application notes from such component manufacturers as Motorola, Texas Instruments, and National Semiconductor. Some IC and transistor information is provided in the appendixes.

Each experiment is briefly described, with each circuit, showing component values, and suggested tests are listed. Equations are included as necessary. You will study each circuit, construct the circuit, and make the required tests. A brief report should be written, and it should note what circuit was developed and the circuit parameters should be listed.

There is a wide range of ICs to select from. Some are designed for specific applications. In this course, the ICs suggested to demonstrate circuit operations are chosen for economy, although more specialized IC chips may exist, may be more effective, and may use fewer discrete components.

The experiments call for specific types of measurements, which may require an unusual use of test equipment. You should seek your instructor's assistance when procedures are unfamiliar. As an example, bandwidth (BW) measurements may be required on an audio amplifier. This calls for the function generator source to be held at constant voltage and the amplifier output voltage to be monitored with a meter while the frequency is varied between 10 and 20,000 Hz or higher. The resultant data, visually collected in octaves, should be plotted on semilogarithmic graph paper.

As another example, the input ouput phase relationship of an amplifier can most easily be determined by connecting the input signal to the amplifier into the oscilloscope's horizontal input and the output signal of the amplifier into the oscilloscope's vertical input. A Lissajous pattern will be produced, from which the phase angle can be derived.

Component Tolerances

Generally, resistors of 5 to 10 percent tolerance can be used. Capacitors may be 10 to 20 percent tolerance or more. For circuits in which matched pairs of components are best utilized, the student should check component values and try to match them as closely as possible. Although 1 and 0.1 percent components are available, they are quite costly. Besides, it is good experience to learn when and how to find closely matching components from a low-tolerance batch, since this is often necessary in fieldwork.

Technical Data

Technical data on ICs and circuits are provided in the Appendix. Armed with this information, you will be able not only to better understand the circuits under study but also to design your own circuits.

It should be noted that ICs are constantly in a state of change. In some cases, an IC may become obsolete without an exact replacement. Also, some devices may be encased in either plastic or ceramic. Since changes do occur, always determine whether an alternate device is available.

Laboratory Experimentation Time

Each laboratory assignment will require at least 2 hours to construct, test, and evaluate. It is suggested that only the technical data be gathered in class and that the laboratory report be written outside of class.

CONCLUSION

The course is designed to provide:

1. Broad coverage in the use and application of linear ICs
2. A study of circuits, parameters and subsystems
3. A basic system of study which encourages creativeness and flexibility
4. A selection of topics which can be related to specific fields of interest
5. A coverage of standard types of circuits which can be tailored for special requirements
6. A high degree of learning with minimum investment of time
7. Laboratory work that does not require special assembled parts
8. A text which is not written in "cookbook" fashion but provides an opportunity to troubleshoot circuit problems
9. A course of study which utilizes the latest in IC design
10. Comprehensive training for students of electronics in technical colleges, vocational centers, government, and military training centers.

The course is challenging, interesting, and, what is most important, fun. Have a good time and enjoy it!

PART 1

Amplifier Circuits

Contents

EXPERIMENT

1 Noninverting Follower Amplifiers

OBJECTIVES

Upon completion of this experiment, construction of circuitry, testing, and evaluation of data, you will be able to:

1. Use IC operational amplifiers as noninverting, high-gain amplifiers and as unity amplifiers
2. Calculate circuit component values
3. Compute and measure stage gain and the high-frequency roll-off points on the frequency response curve
4. Design operational amplifier circuits to meet specific requirements

DISCUSSION

The follower amplifier preserves the sign of the input signal. Essentially, the output V_{out} is equal to twice the input V_{in}. The output signal feedback to the negative input acts as degenerative feedback over a wide frequency range. The circuit shown in Fig. 1-1 can be used to isolate a signal source from the circuit being driven without changing the sign, phase, or amplitude of the signal.

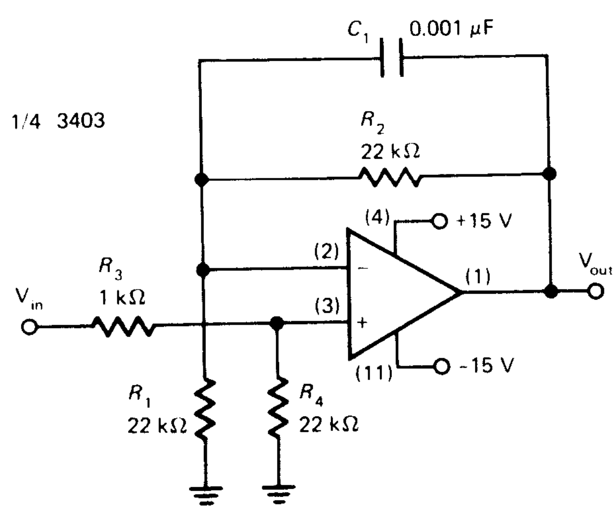

FIG. 1-1 Noninverting amplifier.

If the feedback resistor R_2 were connected to the inverting (−) input and the signal fed to the inverting (−) input through R_1, the amplifier would invert the signal. The ratio of R_2/R_1 determines the voltage gain of the amplifier. If they are equal, the gain is essentially 2. If they are equal and R_4 is changed to equal R_1, the gain of the amplifier is unity. This type of amplifier might be called a *unity-gain* amplifier or follower.

EQUATIONS

$$\text{Gain } G = \frac{V_{out}}{V_{in}}$$

$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_1}\right)$$

where

$$R_2 = R_1 \quad \text{and} \quad V_{out} = 2\,V_{in}$$

$$\text{Gain (dB)} = 20 \log \frac{V_{out}}{V_{in}}$$

MATERIALS REQUIRED

ACTIVE DEVICES:
- [1] MC3403

RESISTORS (5 percent, ¼ W):
- [1] 1 kΩ
- [3] 22 kΩ
- [2] 100 kΩ

CAPACITORS (disc, 20 percent, 25 V):
- [1] 0.001 μF

MISCELLANEOUS:
- [1] IC socket, 14-pin

TEST INSTRUMENTS:
- Oscilloscope, dual-trace, 5-in
- Function generator, 10 Hz to 1 MHz
- Digital multimeter
- Power supply, ±15 V, 50 mA

EXPERIMENT 1 Name ______________________ Date ____________

Experimental Procedures

Answers

1. Construct the circuit shown in Fig. 1-1. Apply a small sine-wave signal at the input [about 5 $mV_{p\text{-}p}$ (peak-to-peak)]. Record the gain of the amplifier circuit. 1. ____________
2. Connect the amplifier output to the horizontal input of the oscilloscope. (See Fig. 1-2 for method of measurement.) Change R_1 and R_2 to 100 kΩ each.
   a. Does this affect the gain? 2a. ____________
   b. Does this affect the phase? 2b. ____________
3. By changing the value of C_1, set the amplifier's high-frequency roll-off to 3 dB down at 12 kHz; that is, make V_{out} at 12 kHz equal to 0.7 times V_{out} at the midrange. Record the new value of C_1. 3. ____________
4. Rearrange the circuit components to make the design a follower with signal inversion.
   a. Determine the phase shift of the amplifier. 4a. ____________
   b. Measure the gain of the circuit. 4b. ____________

For Further Research

Design a two-amplifier system in which both amplifiers have the same input signal but the outputs are out of phase 180° and the output signal voltages are of equal amplitude. The high-frequency roll-off point of both amplifiers should be 3 dB down at 3 kHz. Compute the gain in decibels of each amplifier.

Self-Test

Test your knowledge of the subject by answering the following questions.

1. When you use a linear IC as a noninverting amplifier, the signal is fed into the ____________ input.
2. In a noninverting amplifier, if the feedback resistor R_2 equals 100 kΩ and the resistance from the inverting input (−) to ground R_1 equals 1 kΩ, the stage gain is ____________ .

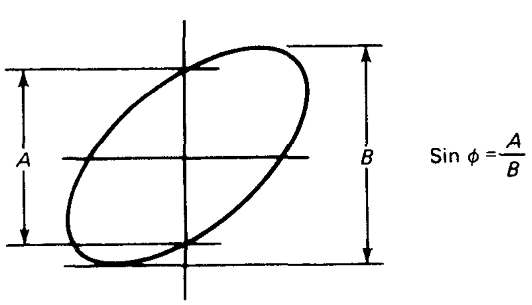

FIG. 1-2 Measuring the phase-shift of an amplifier.

3. If $R_2 = R_1 = 10\ k\Omega$ and $V_{in} = 1$ V, V_{out} = ______________________________ .
4. If $R_2 = R_1 = 100\ k\Omega$ and $R_3 = R_4 = 10\ k\Omega$, the voltage gain of the amplifier is

______________________________ .

5. If a positive-going pulse is fed into the noninverting input of the circuit in Fig. 1-1, the output pulse will be ______________________________ -going.

EXPERIMENT

2 High-Gain Inverting Voltage Amplifiers

OBJECTIVES

Upon completion of this experiment, construction of circuitry, testing, and evaluation of data, you will be able to:

1. Use IC operational amplifiers as high-gain inverting amplifiers
2. Compute and measure stage gain and input resistance R_{in}
3. Determine an amplifier's bandwidth
4. Design voltage amplifiers to meet specific requirements

EQUATIONS

$$R_3 = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{out} \approx V_{in}\frac{R_2}{R_1}$$

$$\text{Gain (dB)} = 20 \log \frac{V_{out}}{V_{in}}$$

DISCUSSION

The operational amplifier, when connected into the circuit arrangement shown in Fig. 2-1, performs as an inverting amplifier whose gain is determined by the ratio of R_2 to R_1 (provided the gain of the IC amplifier is high). A small capacitor, its value depending on the frequency of operation desired, is placed across the feedback resistor R_2 to improve the amplifier's stability and to prevent oscillation. Capacitor C_2 may be required at low input signal levels to remove input noise; it is used also to limit the high-frequency response. Without this capacitor the frequency response will depend on the bandwidth of the chips amplifier and C_1. If the audio generator used for performing the tests has a dc component in its output, a large isolating capacitor, C_3, should be inserted at the amplifier input.

MATERIALS REQUIRED

ACTIVE DEVICES:
- [1] MC3403

RESISTORS (5 percent, ¼ W):
- Assortment of resistors, 100 Ω to 1 MΩ

CAPACITORS (disc, Mylar, electrolytic, 25 V):
- Assortment of capacitors, 100 pF to 0.1 μF, 10 percent

MISCELLANEOUS COMPONENTS:
- [1] IC socket, 14-pin

TEST INSTRUMENTS:
- Oscilloscope, dual-trace, 5-in
- Function generator, 10 Hz to 1 MHz
- Digital multimeter
- Power supply, ±15 V, 50 mA

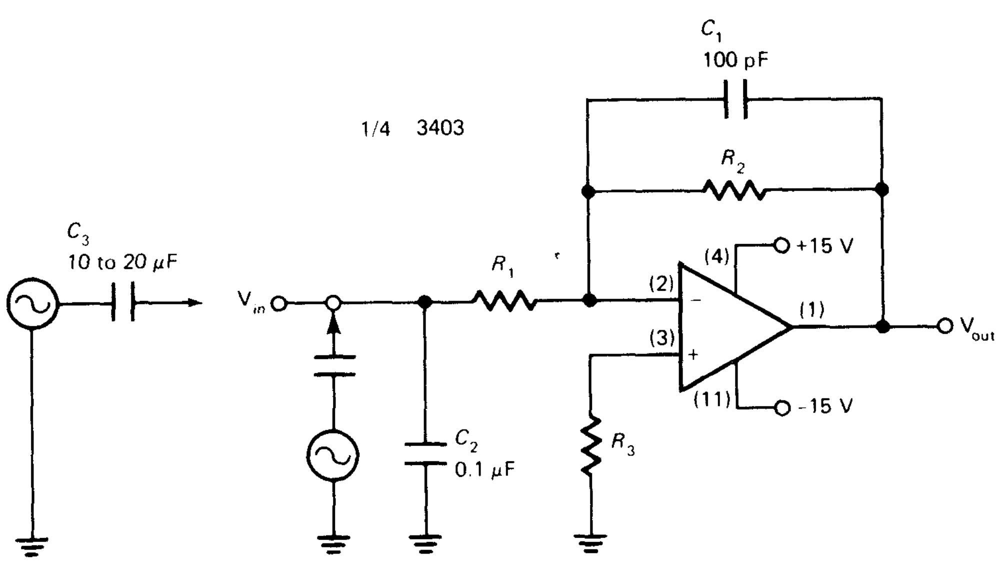

FIG. 2-1 Phase-inverting voltage amplifier.

EXPERIMENT 2 Name ______________________________ Date ______________

Experimental Procedures

Answers

1. Referring to Table 2-1:
   a. Calculate R_3 for gains of 1 to 5000. — 1a. ______________
   b. Validate the gains of 1 to 1000 for the resistor values listed. — 1b. ______________
   c. Compute the gain in decibels for the validated gain measurements. — 1c. ______________
2. Construct the circuit shown in Fig. 2-1. Confirm the upper bandwidth (BW) for the gain of 1000. Measure and record the 3-dB point of the high-frequency roll-off. — 2. ______________
3. Confirm R_{in} for the gain of 100 by connecting in series a variable or decade resistor between the generator and the amplifier circuit. Measure the voltage across the resistor and make it equal to the amplifier input-signal voltage. The series resistor then equals the amplifier input R_{in}. An alternative method is to measure the output voltage V_{out} with 0-Ω series resistance and then increase the value of the series resistor until V_{out} is one-half its original value. Record the value of R_{in}. — 3. ______________
4. Change the value of C_3 so that the low-frequency 3-dB roll-off point is 10 Hz.
   a. Has your high-frequency roll-off changed? — 4a. ______________
   b. What is the bandwidth of this circuit? — 4b. ______________
5. Determine the values of R_1 and R_2 for a voltage gain of 5000 at 1 kHz.
   a. R_1 = ______________ Hz — 5a. ______________
   b. R_2 = ______________ Hz — 5b. ______________

For Further Research

Design a two-amplifier system in which both amplifiers have the same input signal but the outputs are out of phase 180° and the output signal voltages are of equal amplitude. The high-frequency roll-off point of both amplifiers should be 3 dB down at 3 kHz. Compute the gain in decibels of each amplifier.

TABLE 2-1

Gain R_{in}	R_1, kΩ	R_2, kΩ	BW	R_3	Gain, Measured	Gain, dB
1	10	10	1 MHz			
10	1	10	100 kHz			
100	1	100	10 kHz			
1000	1	1000	1 kHz			
5000						

Self-Test

Test your knowledge of the subject by answering the following questions.

1. When you use a linear IC as an inverter, the signal is fed into the ______________________________ input.
2. Refer to Fig. 2-1. If $R_3 \approx 1\ \text{k}\Omega$, $R_2 = 20\ \text{k}\Omega$, and $R_1 = 1\ \text{k}\Omega$, the stage gain is ______________________________ .
3. From the data provided in the Appendix, determine the typical input impedance for an MC3403. ______________________________ .
4. Making the input coupling capacitor smaller will limit the ______________________________ -frequency roll-off.
5. The feedback capacitor limits the ______________________________ -frequency roll-off.