11 Op-Amp Applications

CHAPTER OBJECTIVES

- Learn about constant gain, summing, and buffering amplifiers
- Understand how an active filter works
- Describe different types of controlled sources

11.1 CONSTANT-GAIN MULTIPLIER

One of the most common op-amp circuits is the inverting constant-gain multiplier, which provides a precise gain or amplification. Figure 11.1 shows a standard circuit connection, with the resulting gain being given by

$$A = -\frac{R_f}{R_1} \tag{11.1}$$

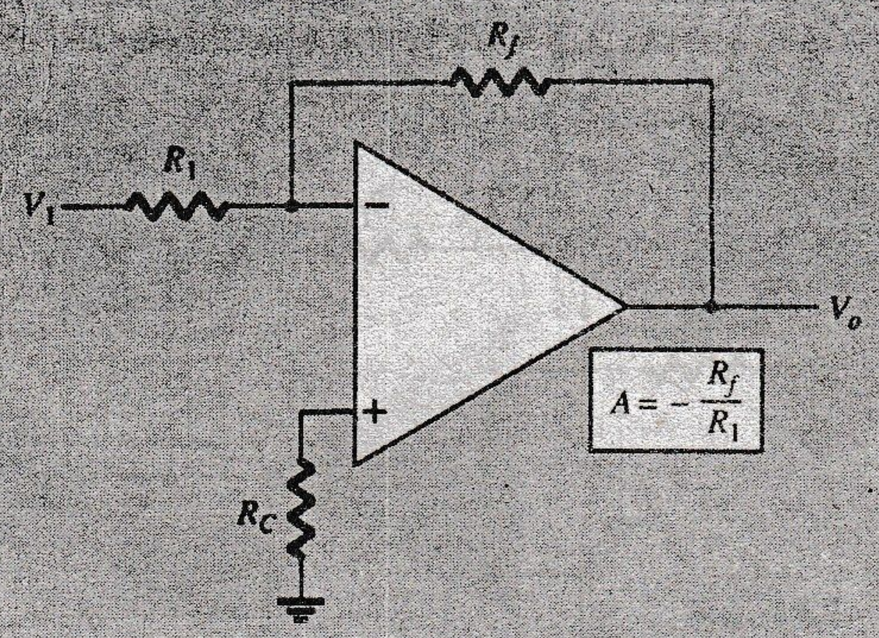


FIG. 11.1
Fixed-gain amplifier.

EXAMPLE 11.1 Determine the output voltage for the circuit of Fig. 11.2 with a sinusoidal input of 2.5 mV.

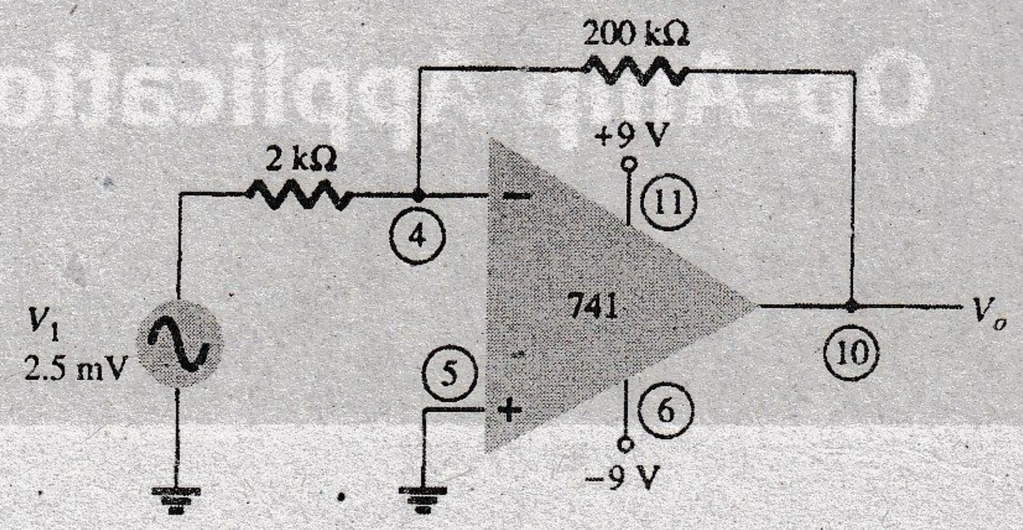


FIG. 11.2
Circuit for Example 11.1.

Solution: The circuit of Fig. 11.2 uses a 741 op-amp to provide a constant or fixed gain. calculated from Eq. (11.1) to be

$$A = -\frac{R_f}{R_1} = -\frac{200\,\text{k}\Omega}{2\,\text{k}\Omega} = -100$$

The output voltage is then

$$V_o = AV_i = -100(2.5\,\text{mV}) = -250\,\text{mV} = \mathbf{-0.25\,V}$$

A noninverting constant-gain multiplier is provided by the circuit of Fig. 11.3, with the gain given by

$$A = 1 + \frac{R_f}{R_1} \tag{11.2}$$

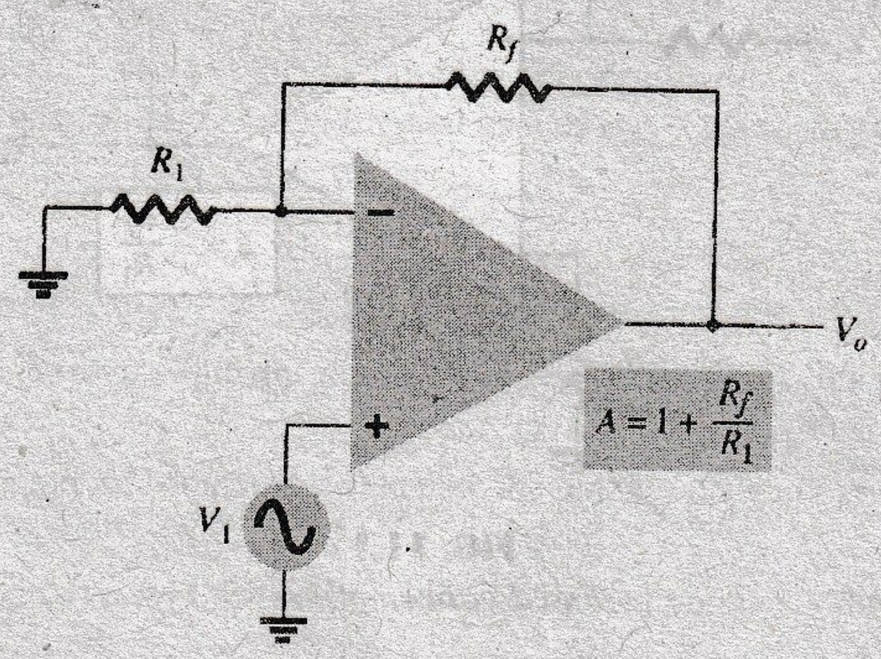


FIG. 11.3
Noninverting fixed-gain amplifier.

EXAMPLE 11.2 Calculate the output voltage from the circuit of Fig. 11.4 for an input of 120 μV.

Solution: The gain of the op-amp circuit is calculated using Eq. (11.2) to be

$$A = 1 + \frac{R_f}{R_1} = 1 + \frac{240\,\text{k}\Omega}{2.4\,\text{k}\Omega} = 1 + 100 = 101$$

The output voltage is then

$$V_o = AV_i = 101(120\,\mu\text{V}) = \mathbf{12.12\,mV}$$

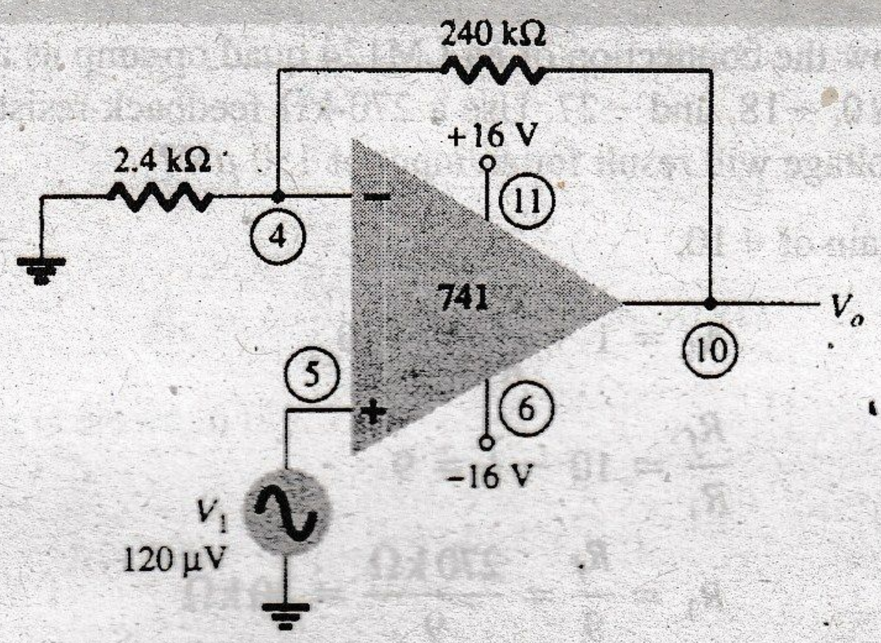


FIG. 11.4
Circuit for Example 11.2.

Multiple-Stage Gains

When a number of stages are connected in series, the overall gain is the product of the individual stage gains. Figure 11.5 shows a connection of three stages. The first stage is connected to provide noninverting gain as given by Eq. (11.1). The next two stages provide an inverting gain given by Eq. (11.1). The overall circuit gain is then noninverting and is calculated by

$$A = A_1A_2A_3$$

where $A_1 = 1 + R_f/R_1$, $A_2 = -R_f/R_2$, and $A_3 = -R_f/R_3$.

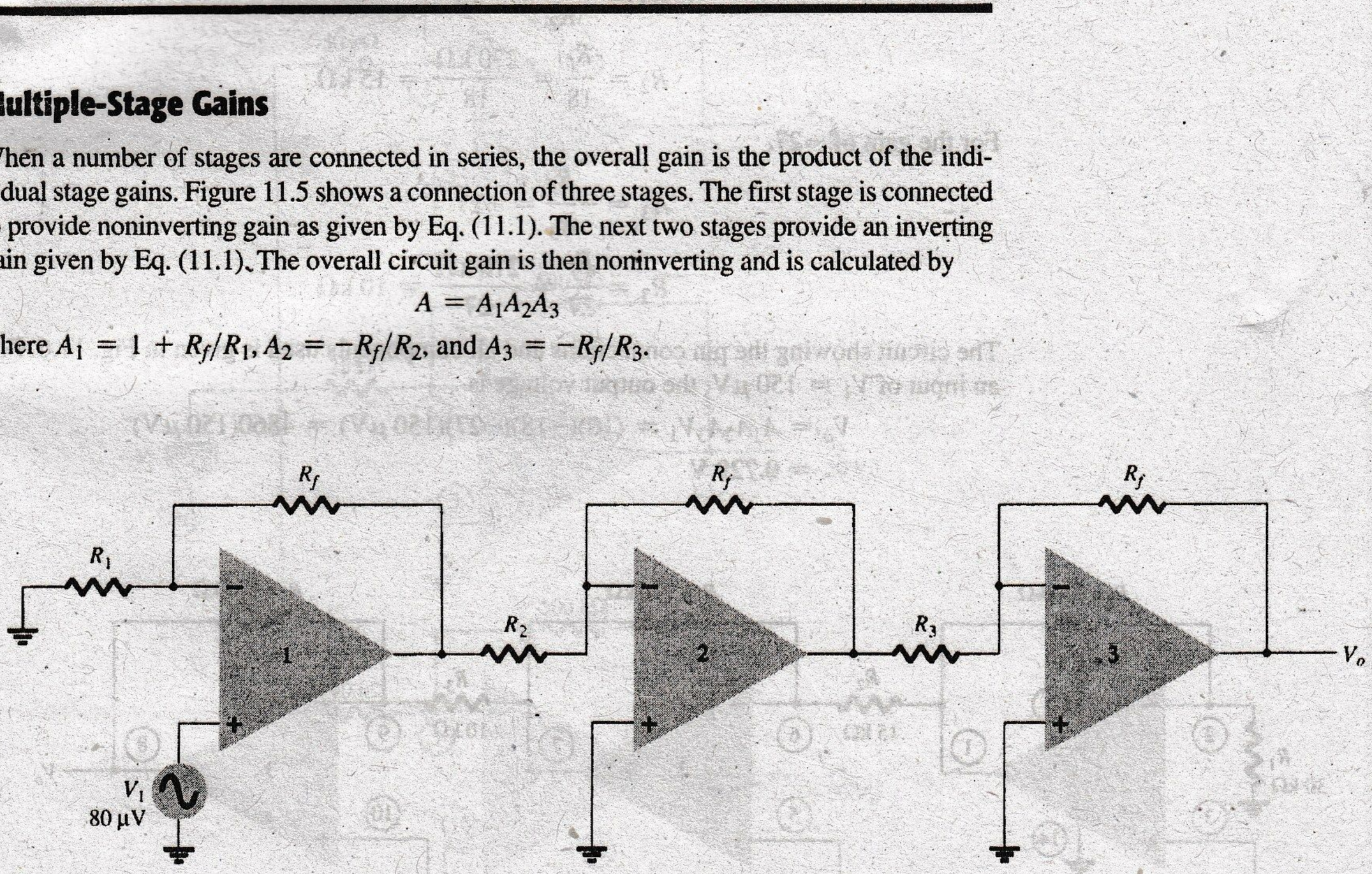


FIG. 11.5
Constant-gain connection with multiple stages.

EXAMPLE 11.3 Calculate the output voltage using the circuit of Fig. 11.5 for resistor components of value $R_f = 470\,\text{k}\Omega$, $R_1 = 4.3\,\text{k}\Omega$, $R_2 = 33\,\text{k}\Omega$, and $R_3 = 33\,\text{k}\Omega$ for an input of 80 μV.

Solution: The amplifier gain is calculated to be

$$A = A_1A_2A_3 = \left(1 + \frac{R_f}{R_1}\right)\left(-\frac{R_f}{R_2}\right)\left(-\frac{R_f}{R_3}\right)$$

$$= \left(1 + \frac{470\,\text{k}\Omega}{4.3\,\text{k}\Omega}\right)\left(-\frac{470\,\text{k}\Omega}{33\,\text{k}\Omega}\right)\left(-\frac{470\,\text{k}\Omega}{33\,\text{k}\Omega}\right)$$

$$= (110.3)(-14.2)(-14.2) = 22.2 \times 10^3$$

so that

$$V_o = AV_i = 22.2 \times 10^3(80\,\mu\text{V}) = \mathbf{1.78\ V}$$

EXAMPLE 11.4 Show the connection of an LM124 quad op-amp as a three-stage amplifier with gains of +10, −18, and −27. Use a 270-kΩ feedback resistor for all three circuits. What output voltage will result for an input of 150 μV?

Solution: For the gain of +10,

$$A_1 = 1 + \frac{R_f}{R_1} = +10$$

$$\frac{R_f}{R_1} = 10 - 1 = 9$$

$$R_1 = \frac{R_f}{9} = \frac{270\,\text{k}\Omega}{9} = 30\,\text{k}\Omega$$

For the gain of −18,

$$A_2 = -\frac{R_f}{R_2} = -18$$

$$R_2 = \frac{R_f}{18} = \frac{270\,\text{k}\Omega}{18} = 15\,\text{k}\Omega$$

For the gain of −27,

$$A_3 = -\frac{R_f}{R_3} = -27$$

$$R_3 = \frac{R_f}{27} = \frac{270\,\text{k}\Omega}{27} = 10\,\text{k}\Omega$$

The circuit showing the pin connections and all components used is given in Fig. 11.6. For an input of $V_1 = 150\,\mu\text{V}$, the output voltage is

$$V_o = A_1A_2A_3V_1 = (10)(-18)(-27)(150\,\mu\text{V}) = 4860(150\,\mu\text{V})$$
$$= \mathbf{0.729\ V}$$

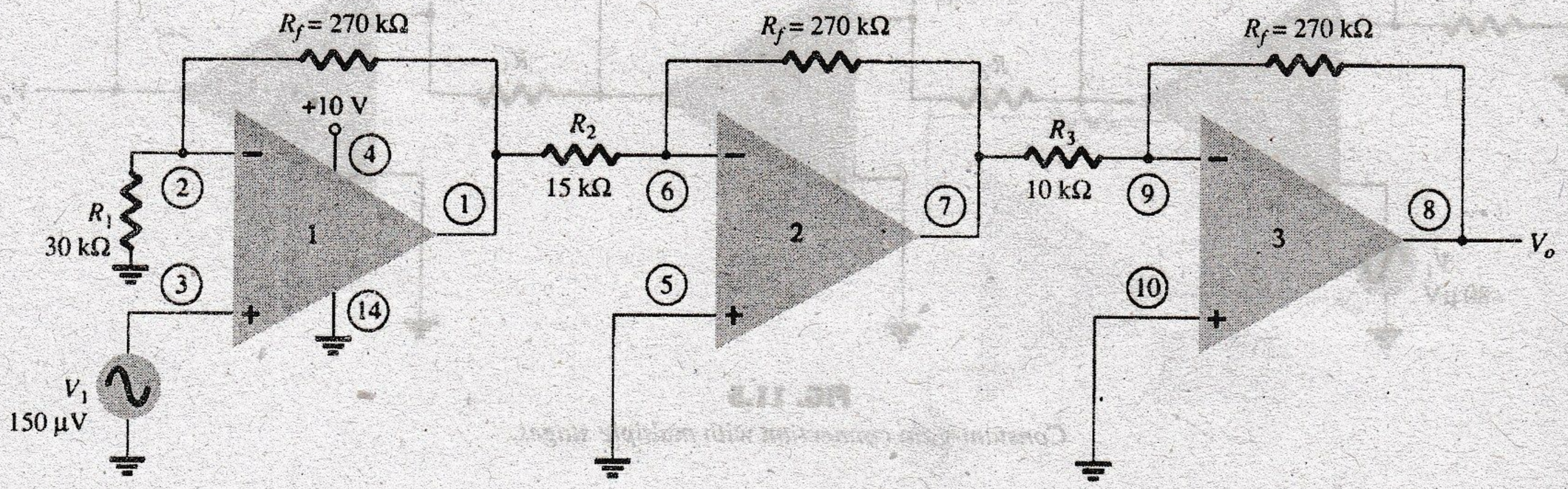


FIG. 11.6
Circuit for Example 11.4 (using LM124).

A number of op-amp stages could also be used to provide separate gains, as demonstrated in the next example.

EXAMPLE 11.5 Show the connection of three op-amp stages using an LM348 IC to provide outputs that are 10, 20, and 50 times larger than the input. Use a feedback resistor of $R_f = 500\,\text{k}\Omega$ in all stages.

Solution: The resistor component for each stage is calculated to be

$$R_1 = -\frac{R_f}{A_1} = -\frac{500\,\text{k}\Omega}{-10} = 50\,\text{k}\Omega$$

$$R_2 = -\frac{R_f}{A_2} = -\frac{500\,\text{k}\Omega}{-20} = 25\,\text{k}\Omega$$

$$R_3 = -\frac{R_f}{A_3} = -\frac{500\,\text{k}\Omega}{-50} = 10\,\text{k}\Omega$$

The resulting circuit is drawn in Fig. 11.7.

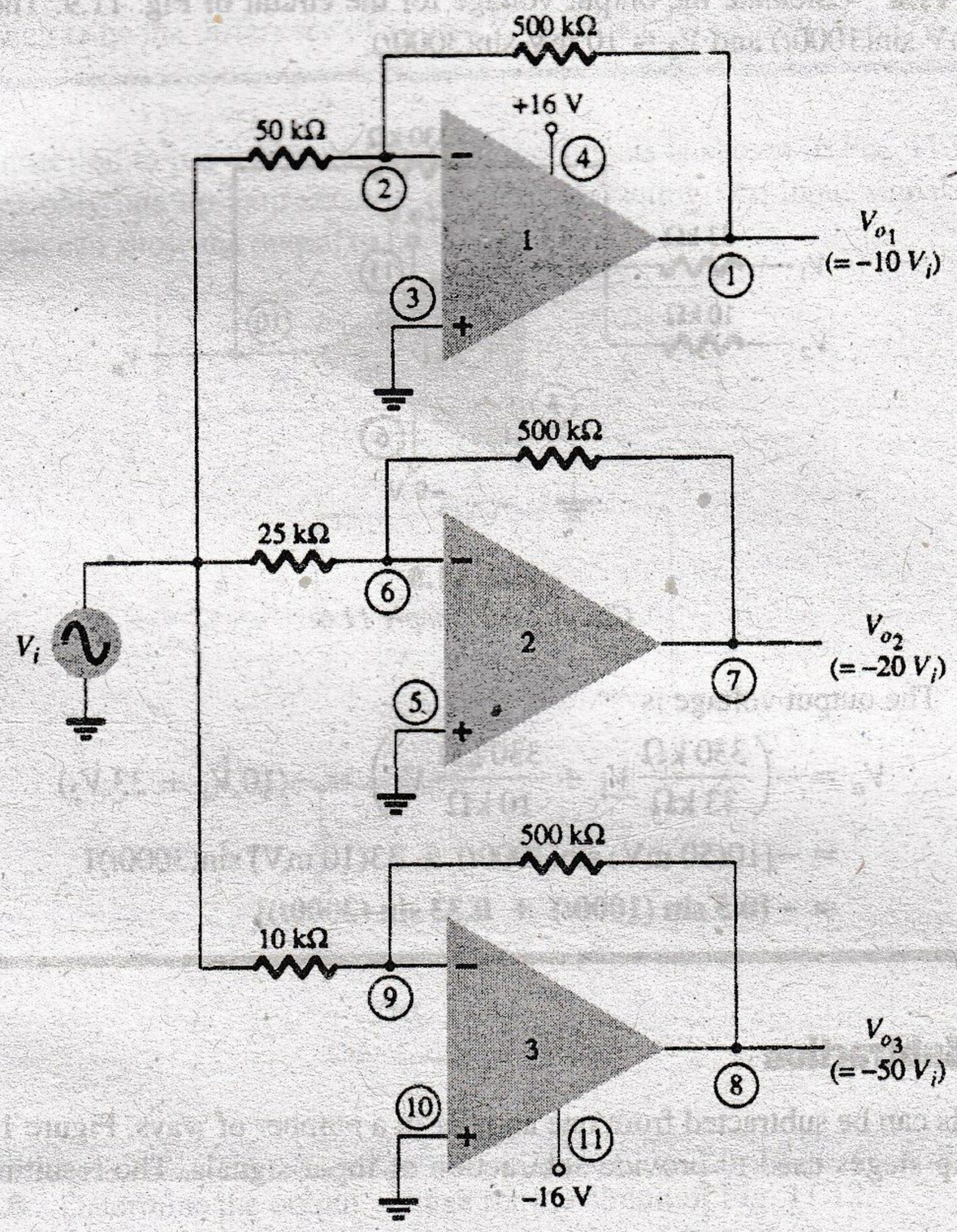


FIG. 11.7
Circuit for Example 11.5 (using LM348).

11.2 VOLTAGE SUMMING

Another popular use of an op-amp is as a summing amplifier. Figure 11.8 shows the connection, with the output being the sum of the three inputs, each multiplied by a different gain. The output voltage is

$$\boxed{V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)} \qquad (11.3)$$

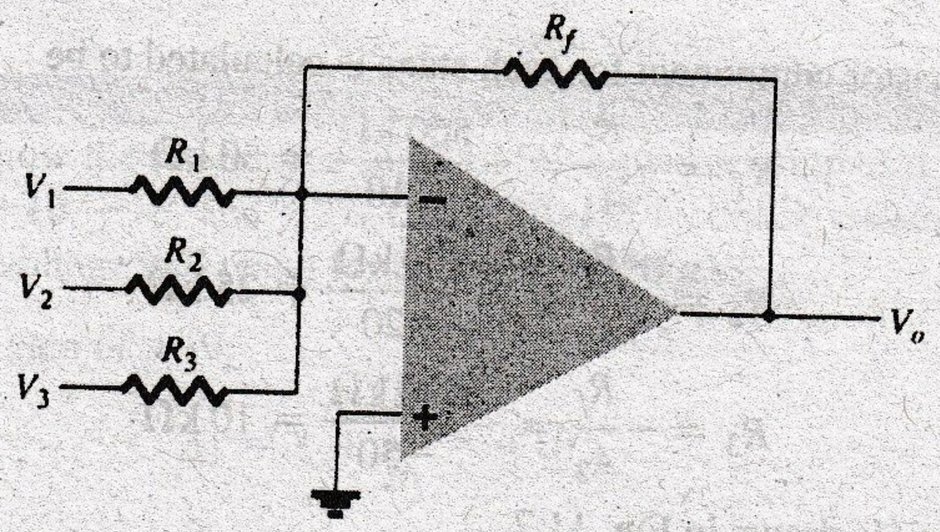


FIG. 11.8
Summing amplifier.

EXAMPLE 11.6 Calculate the output voltage for the circuit of Fig. 11.9. The inputs are $V_1 = 50\text{ mV}\sin(1000t)$ and $V_2 = 10\text{ mV}\sin(3000t)$.

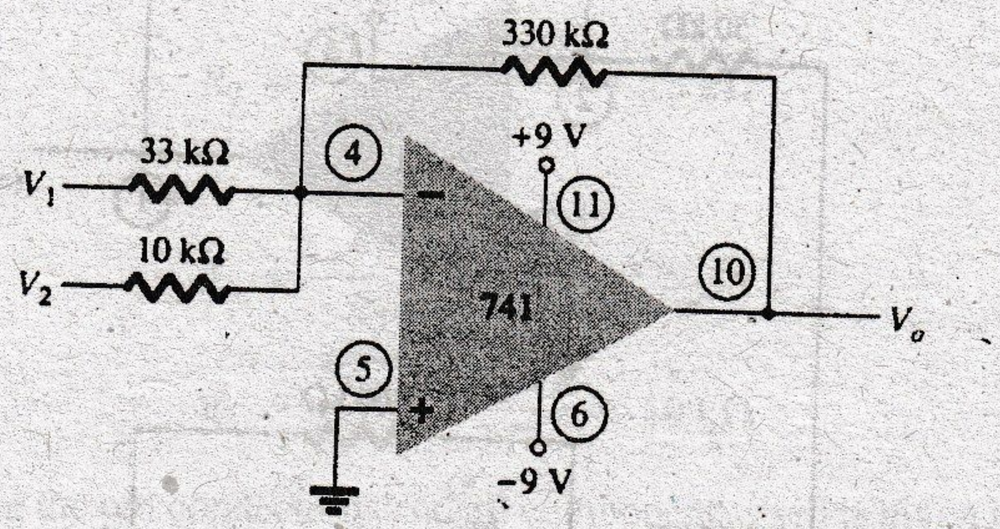


FIG. 11.9
Circuit for Example 11.6.

Solution: The output voltage is

$$V_o = -\left(\frac{330\text{ k}\Omega}{33\text{ k}\Omega}V_1 + \frac{330\text{ k}\Omega}{10\text{ k}\Omega}V_2\right) = -(10\,V_1 + 33\,V_2)$$
$$= -[10(50\text{ mV})\sin(1000t) + 33(10\text{ mV})\sin(3000t)]$$
$$= \mathbf{-[0.5\sin(1000t) + 0.33\sin(3000t)]}$$

Voltage Subtraction

Two signals can be subtracted from one another in a number of ways. Figure 11.10 shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by

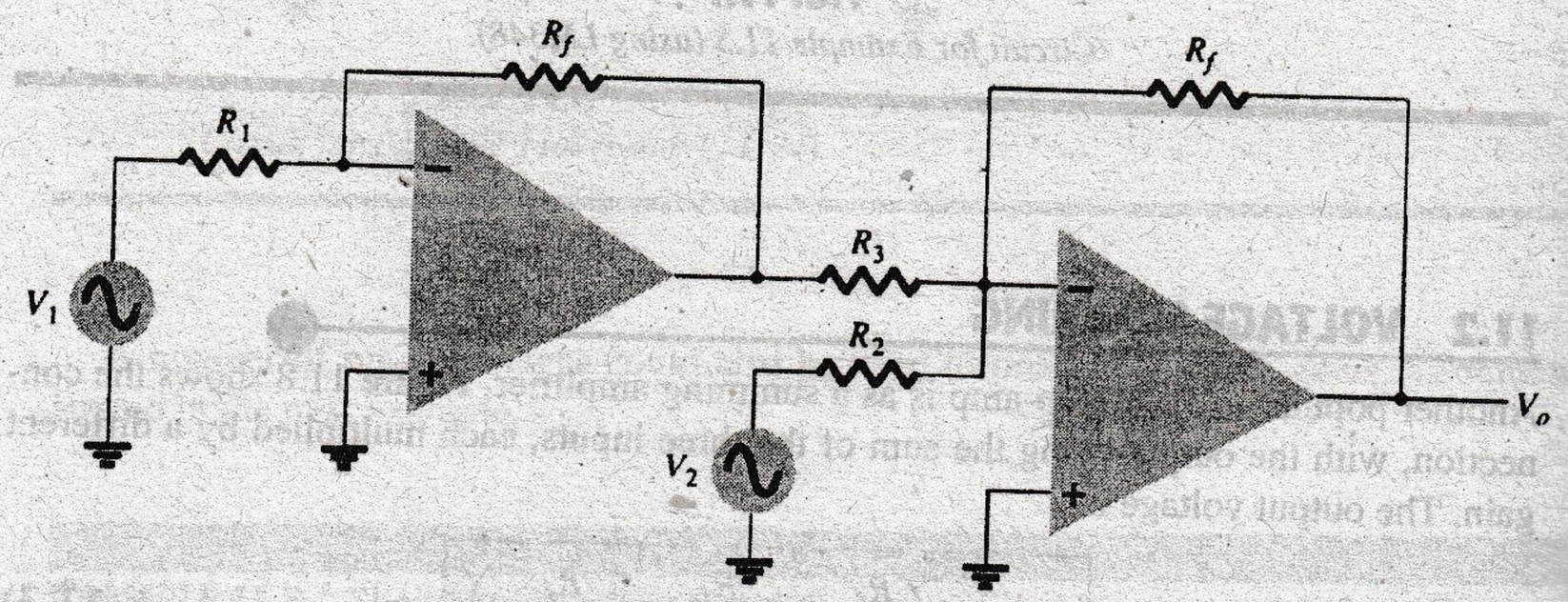


FIG. 11.10
Circuit for subtracting two signals.

$$V_o = -\left[\frac{R_f}{R_3}\left(-\frac{R_f}{R_1}V_1\right) + \frac{R_f}{R_2}V_2\right]$$

$$\boxed{V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)} \qquad (11.4)$$

EXAMPLE 11.7 Determine the output for the circuit of Fig. 11.10 with components $R_f = 1\,\text{M}\Omega$, $R_1 = 100\,\text{k}\Omega$, $R_2 = 50\,\text{k}\Omega$, and $R_3 = 500\,\text{k}\Omega$.

Solution: The output voltage is calculated to be

$$V_o = -\left(\frac{1\,\text{M}\Omega}{50\,\text{k}\Omega}V_2 - \frac{1\,\text{M}\Omega}{500\,\text{k}\Omega}\frac{1\,\text{M}\Omega}{100\,\text{k}\Omega}V_1\right) = -(20\,V_2 - 20\,V_1) = \mathbf{-20(V_2 - V_1)}$$

The output is seen to be the difference of V_2 and V_1 multiplied by a gain factor of -20.

Another connection to provide subtraction of two signals is shown in Fig. 11.11. This connection uses only one op-amp stage to provide subtracting two input signals. Using superposition, we can show the output to be

$$\boxed{V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2} \qquad (11.5)$$

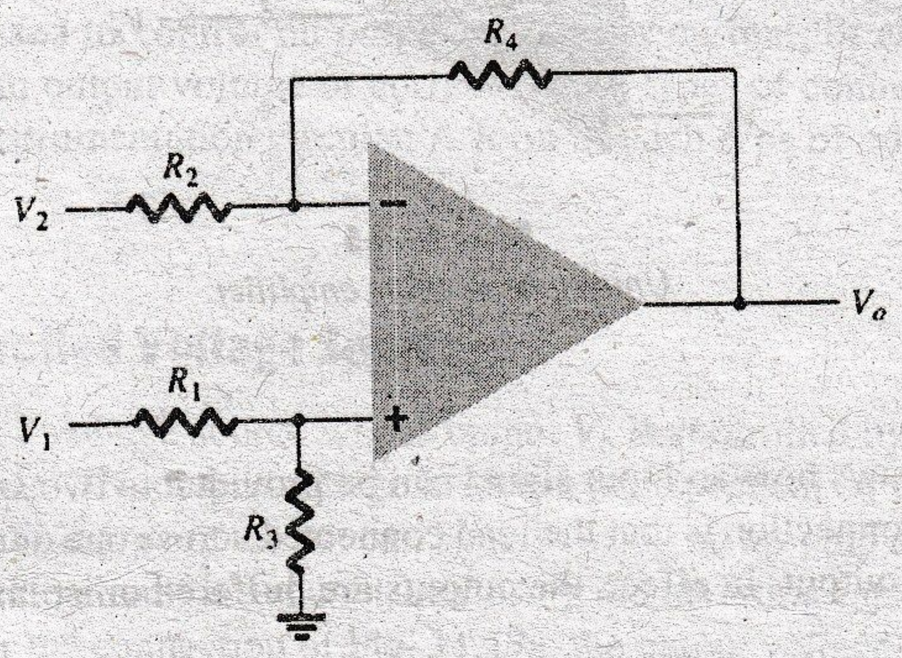


FIG. 11.11
Subtraction circuit.

EXAMPLE 11.8 Determine the output voltage for the circuit of Fig. 11.12.

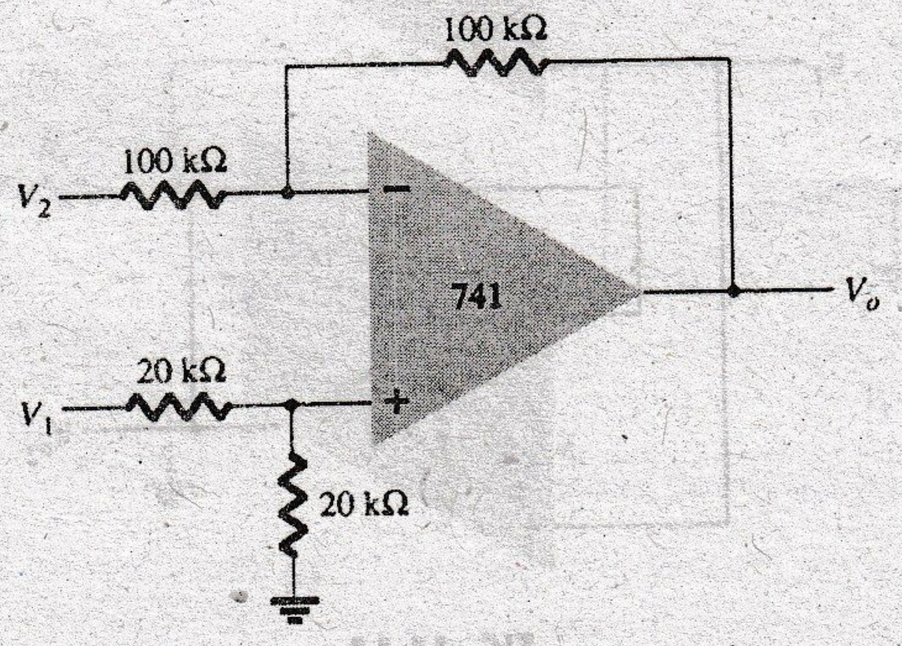


FIG. 11.12
Circuit for Example 11.8.

Solution: The resulting output voltage can be expressed as

$$V_o = \left(\frac{20\,\text{k}\Omega}{20\,\text{k}\Omega + 20\,\text{k}\Omega}\right)\left(\frac{100\,\text{k}\Omega + 100\,\text{k}\Omega}{100\,\text{k}\Omega}\right)V_1 - \frac{100\,\text{k}\Omega}{100\,\text{k}\Omega}V_2$$
$$= V_1 - V_2$$

The resulting output voltage is seen to be the difference of the two input voltages.

11.3 VOLTAGE BUFFER

A voltage buffer circuit provides a means of isolating an input signal from a load by using a stage having unity voltage gain, with no phase or polarity inversion, and acting as an ideal circuit with very high input impedance and low output impedance. Figure 11.13 shows an op-amp connected to provide this buffer amplifier operation. The output voltage is determined by

$$\boxed{V_o = V_1} \tag{11.6}$$

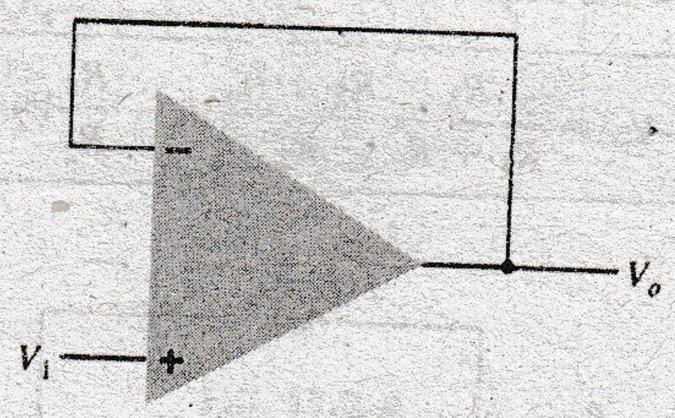


FIG. 11.13
Unity-gain (buffer) amplifier.

Figure 11.14 shows how an input signal can be provided to two separate outputs. The advantage of this connection is that the load connected across one output has no (or little) effect on the other output. In effect, the outputs are buffered or isolated from each other.

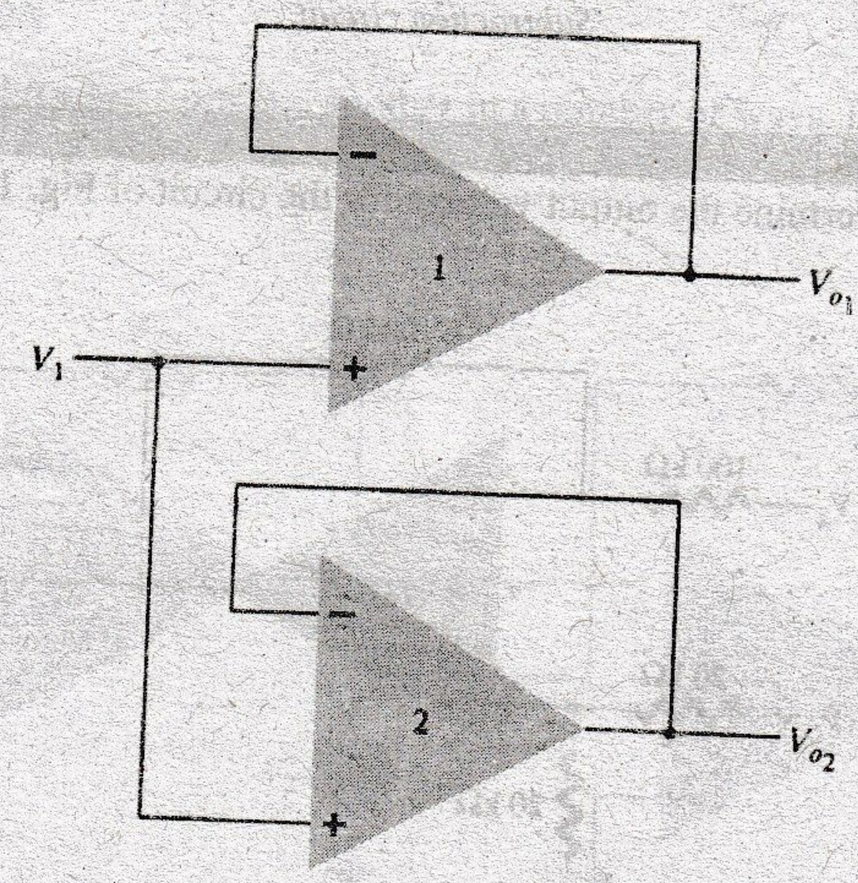


FIG. 11.14
Use of buffer amplifier to provide output signals.

EXAMPLE 11.9 Show the connection of a 741 as a unity-gain circuit.

Solution: The connection is shown in Fig. 11.15.

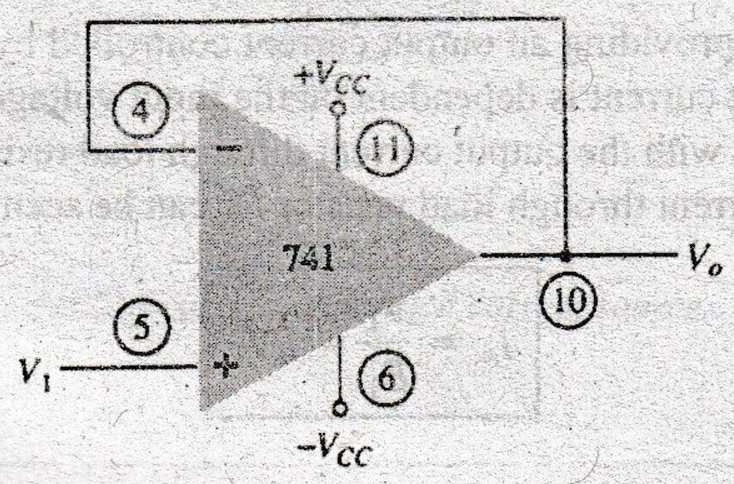


FIG. 11.15
Connection for Example 11.9.

11.4 CONTROLLED SOURCES

Operational amplifiers can be used to form various types of controlled sources. An input voltage can be used to control an output voltage or current, or an input current can be used to control an output voltage or current. These types of connections are suitable for use in various instrumentation circuits. A form of each type of controlled source is provided next.

Voltage-Controlled Voltage Source

An ideal form of a voltage source whose output V_o is controlled by an input voltage V_1 is shown in Fig. 11.16. The output voltage is seen to be dependent on the input voltage (times a scale factor k). This type of circuit can be built using an op-amp as shown in Fig. 11.17. Two versions of the circuit are shown, one using the inverting input, the other the noninverting input. For the connection of Fig. 11.17a, the output voltage is

$$V_o = -\frac{R_f}{R_1}V_1 = kV_1 \tag{11.7}$$

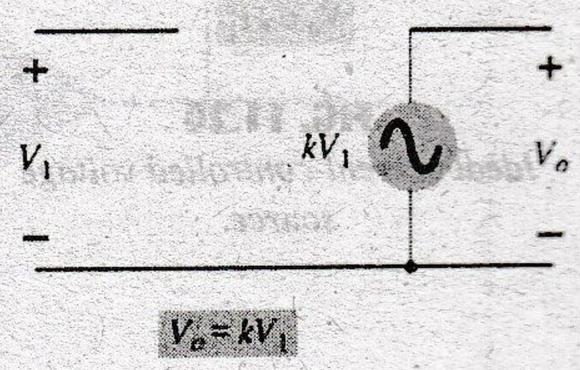


FIG. 11.16
Ideal voltage-controlled voltage source.

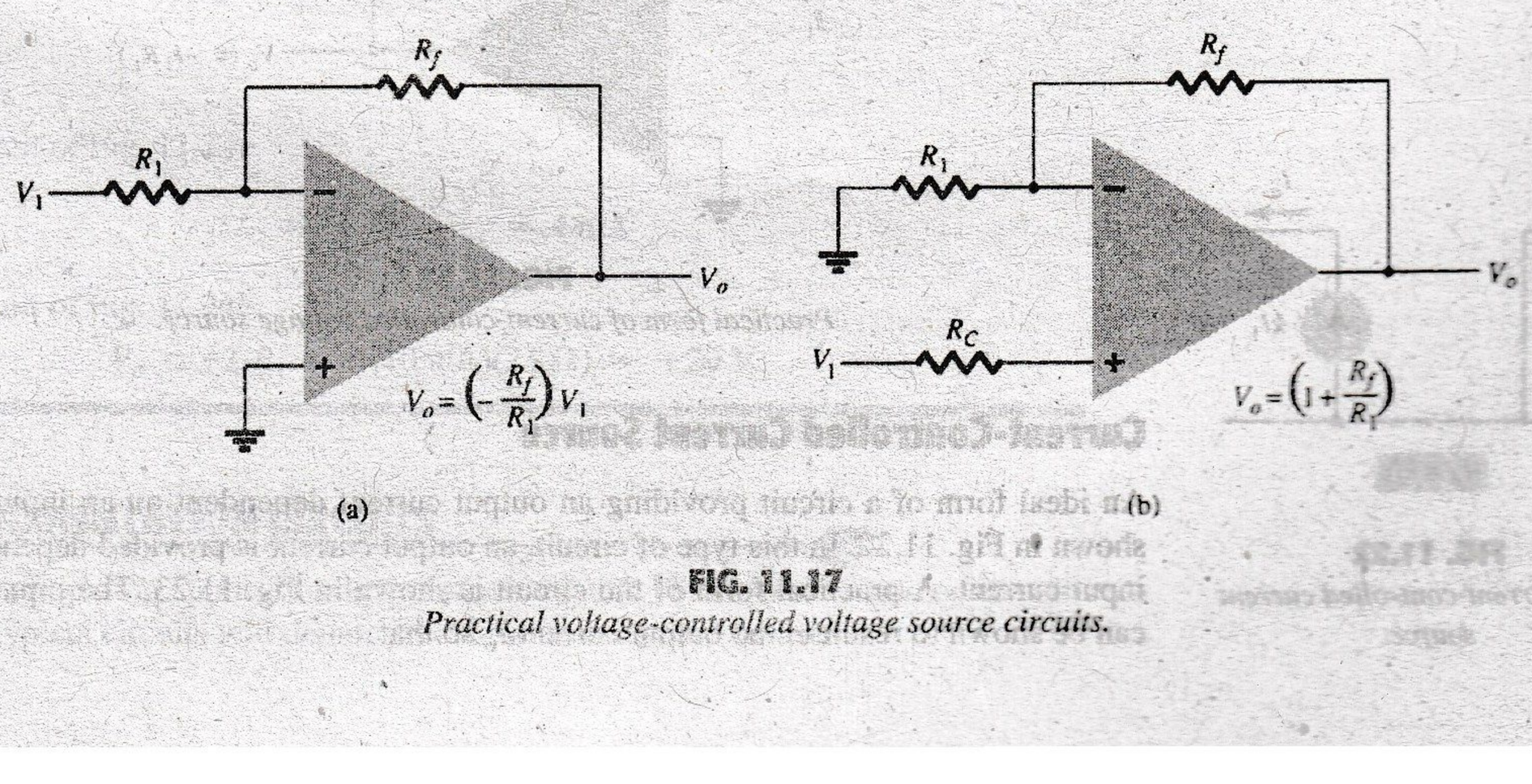


FIG. 11.17
Practical voltage-controlled voltage source circuits.

whereas that of Fig. 11.17b results in

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = kV_1 \tag{11.8}$$

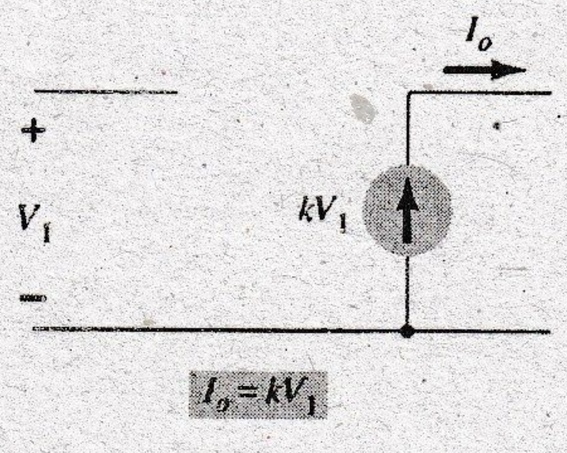


FIG. 11.18
Ideal voltage-controlled current source.

Voltage-Controlled Current Source

An ideal form of circuit providing an output current controlled by an input voltage is that of Fig. 11.18. The output current is dependent on the input voltage. A practical circuit can be built, as in Fig. 11.19, with the output current through load resistor R_L controlled by the input voltage V_1. The current through load resistor R_L can be seen to be

$$I_o = \frac{V_1}{R_1} = kV_1 \tag{11.9}$$

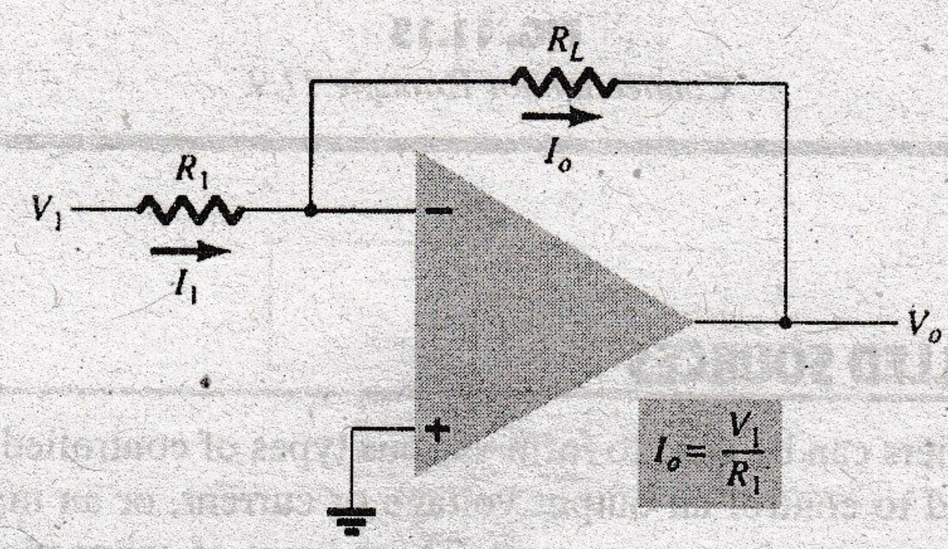


FIG. 11.19
Practical voltage-controlled current source.

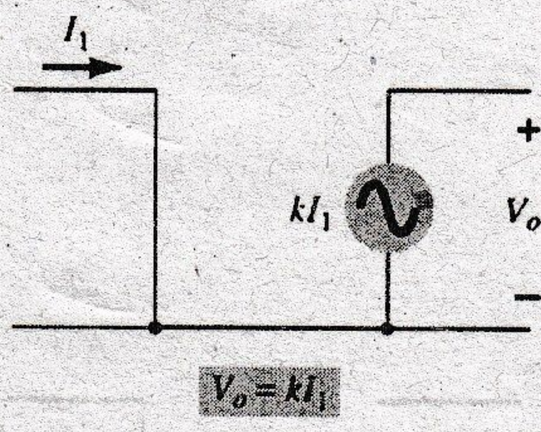


FIG. 11.20
Ideal current-controlled voltage source.

Current-Controlled Voltage Source

An ideal form of a voltage source controlled by an input current is shown in Fig. 11.20. The output voltage is dependent on the input current. A practical form of the circuit is built using an op-amp as shown in Fig. 11.21. The output voltage is seen to be

$$V_o = -I_1 R_L = kI_1 \tag{11.10}$$

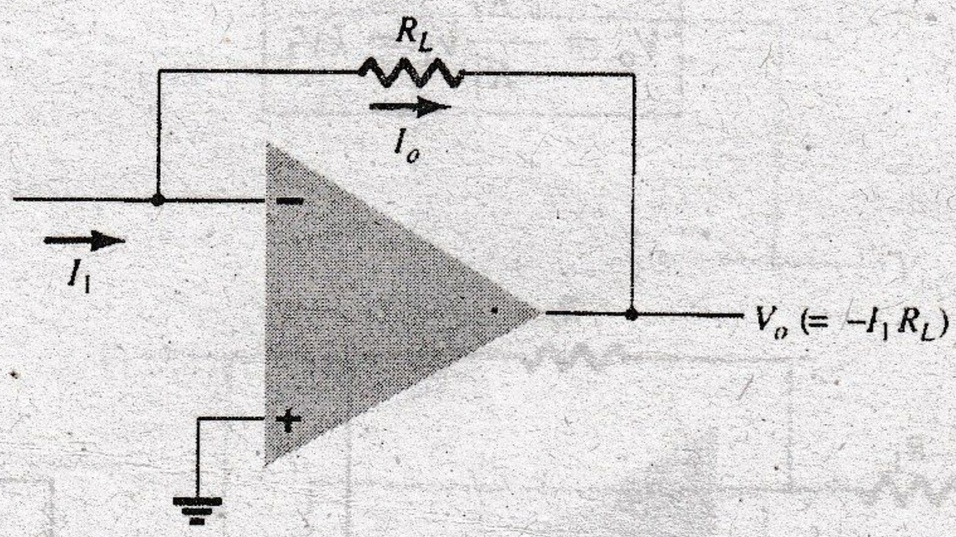


FIG. 11.21
Practical form of current-controlled voltage source.

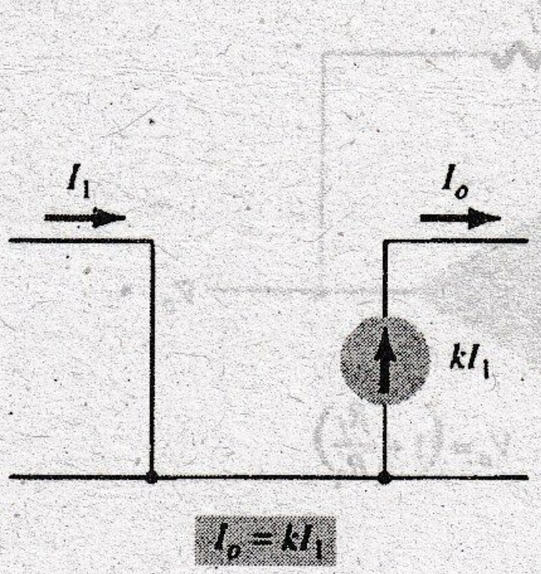


FIG. 11.22
Ideal current-controlled current source.

Current-Controlled Current Source

An ideal form of a circuit providing an output current dependent on an input current is shown in Fig. 11.22. In this type of circuit, an output current is provided dependent on the input current. A practical form of the circuit is shown in Fig. 11.23. The input current I_1 can be shown to result in the output current I_o so that

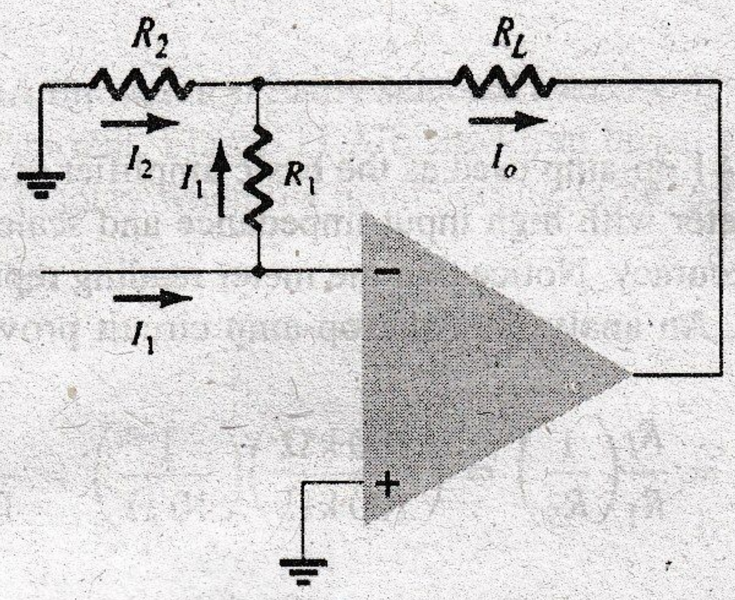
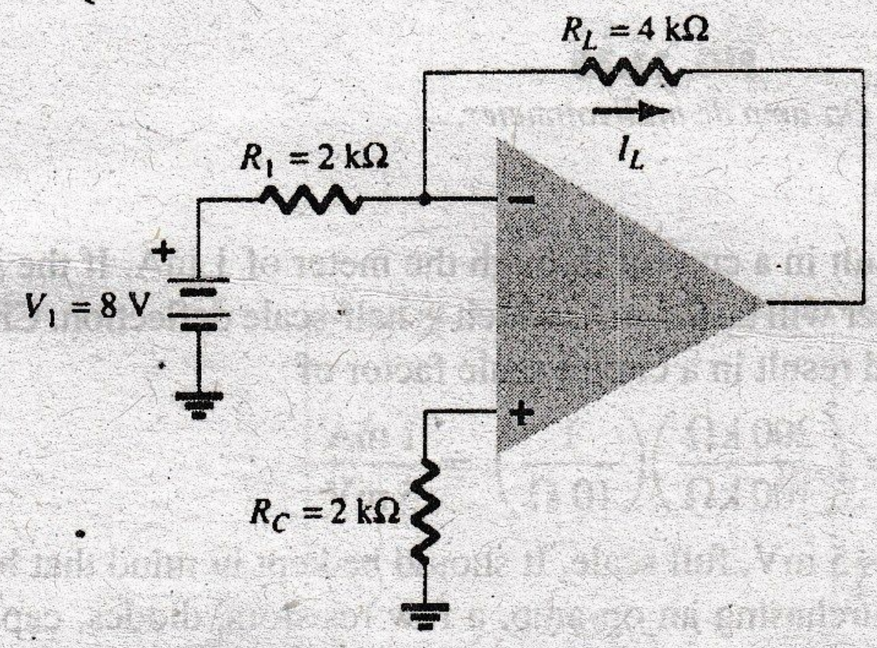


FIG. 11.23
Practical form of current-controlled current source.

$$I_o = I_1 + I_2 = I_1 + \frac{I_1 R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right) I_1 = kI_1 \qquad (11.11)$$

EXAMPLE 11.10

a. For the circuit of Fig. 11.24a, calculate I_L.
b. For the circuit of Fig. 11.24b, calculate V_o.



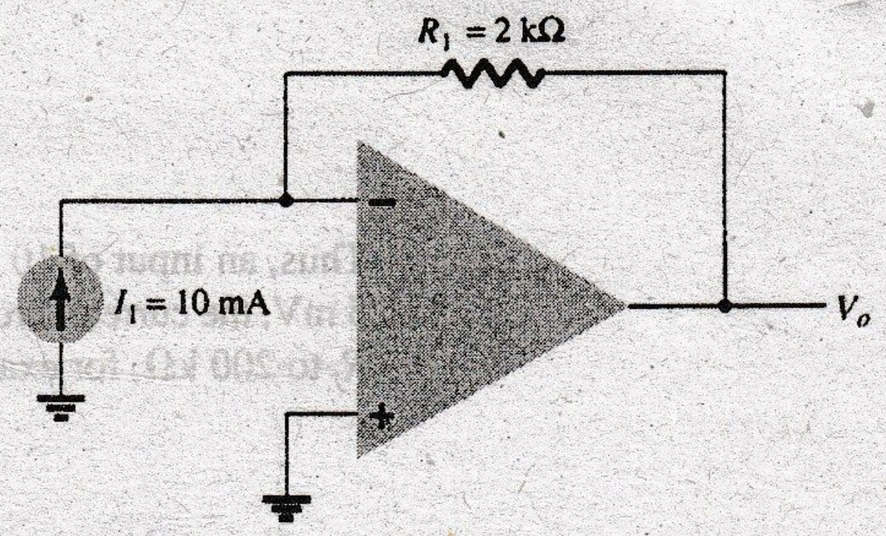


FIG. 11.24
Circuits for Example 11.10.

Solution:

a. For the circuit of Fig. 11.24a,

$$I_L = \frac{V_1}{R_1} = \frac{8\ \text{V}}{2\ \text{k}\Omega} = \mathbf{4\ mA}$$

b. For the circuit of Fig. 11.24b,

$$V_o = -I_1 R_1 = -(10\ \text{mA})(2\ \text{k}\Omega) = \mathbf{-20\ V}$$

11.5 INSTRUMENTATION CIRCUITS

A popular area of op-amp application is in instrumentation circuits such as dc or ac voltmeters. A few typical circuits will demonstrate how op-amps can be used.

dc Millivoltmeter

Figure 11.25 shows a 741 op-amp used as the basic amplifier in a dc millivoltmeter. The amplifier provides a meter with high input impedance and scale factors dependent only on resistor value and accuracy. Notice that the meter reading represents millivolts of signal at the circuit input. An analysis of the op-amp circuit provides the circuit transfer function

$$\left|\frac{I_o}{V_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_S}\right) = \left(\frac{100\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{10\,\text{mV}}$$

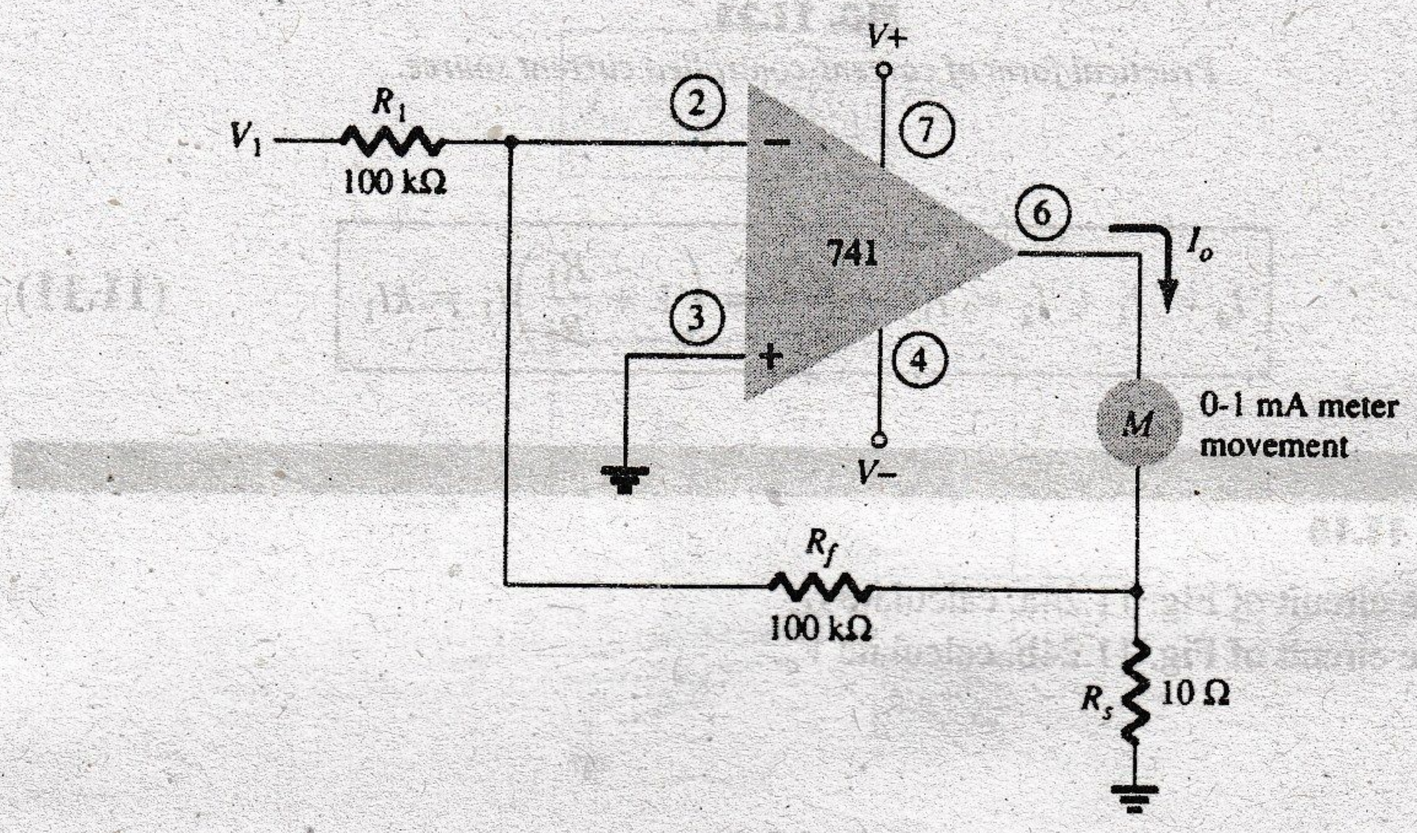


FIG. 11.25
Op-amp dc millivoltmeter.

Thus, an input of 10 mV will result in a current through the meter of 1 mA. If the input is 5 mV, the current through the meter will be 0.5 mA, which is half-scale deflection. Changing R_f to 200 kΩ, for example, would result in a circuit scale factor of

$$\left|\frac{I_o}{V_1}\right| = \left(\frac{200\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{5\,\text{mV}}$$

showing that the meter now reads 5 mV, full scale. It should be kept in mind that building such a millivoltmeter requires purchasing an op-amp, a few resistors, diodes, capacitors, and a meter movement.

ac Millivoltmeter

Another example of an instrumentation circuit is the ac millivoltmeter shown in Fig. 11.26. The circuit transfer function is

$$\left|\frac{I_o}{V_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_S}\right) = \left(\frac{100\,\text{k}\Omega}{100\,\text{k}\Omega}\right)\left(\frac{1}{10\,\Omega}\right) = \frac{1\,\text{mA}}{10\,\text{mV}}$$

which appears the same as the dc millivoltmeter, except that in this case the signal handled is an ac signal. The meter indication provides a full-scale deflection for an ac input voltage of 10 mV, whereas an ac input of 5 mV will result in half-scale deflection with the meter reading interpreted in millivolt units.

Display Driver

Figure 11.27 shows op-amp circuits that can be used to drive a lamp display or LED display. When the noninverting input to the circuit in Fig. 11.27a goes above the inverting input, the output at terminal 1 goes to the positive saturation level (near +5 V in this example) and the lamp is driven "on" when transistor Q_1 conducts. As shown in the circuit, the output of the op-amp provides 30 mA of current to the base of transistor Q_1,

which then drives 600 mA through a suitably selected transistor (with $\beta > 20$) capable of handling that amount of current. Figure 11.27b shows an op-amp circuit that can supply 20 mA to drive an LED display when the noninverting input goes positive compared to the inverting input.

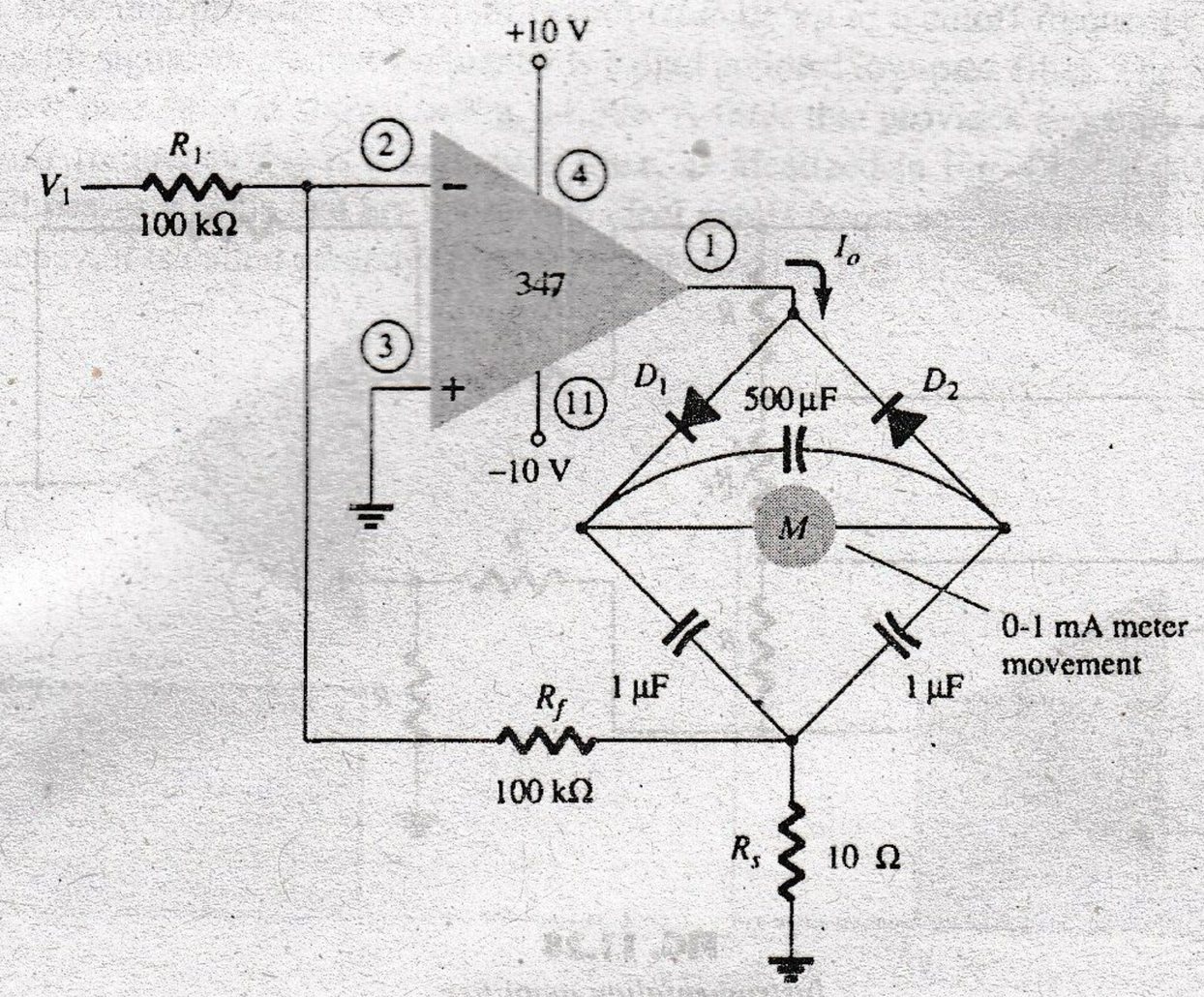


FIG. 11.26
AC millivoltmeter using op-amp.

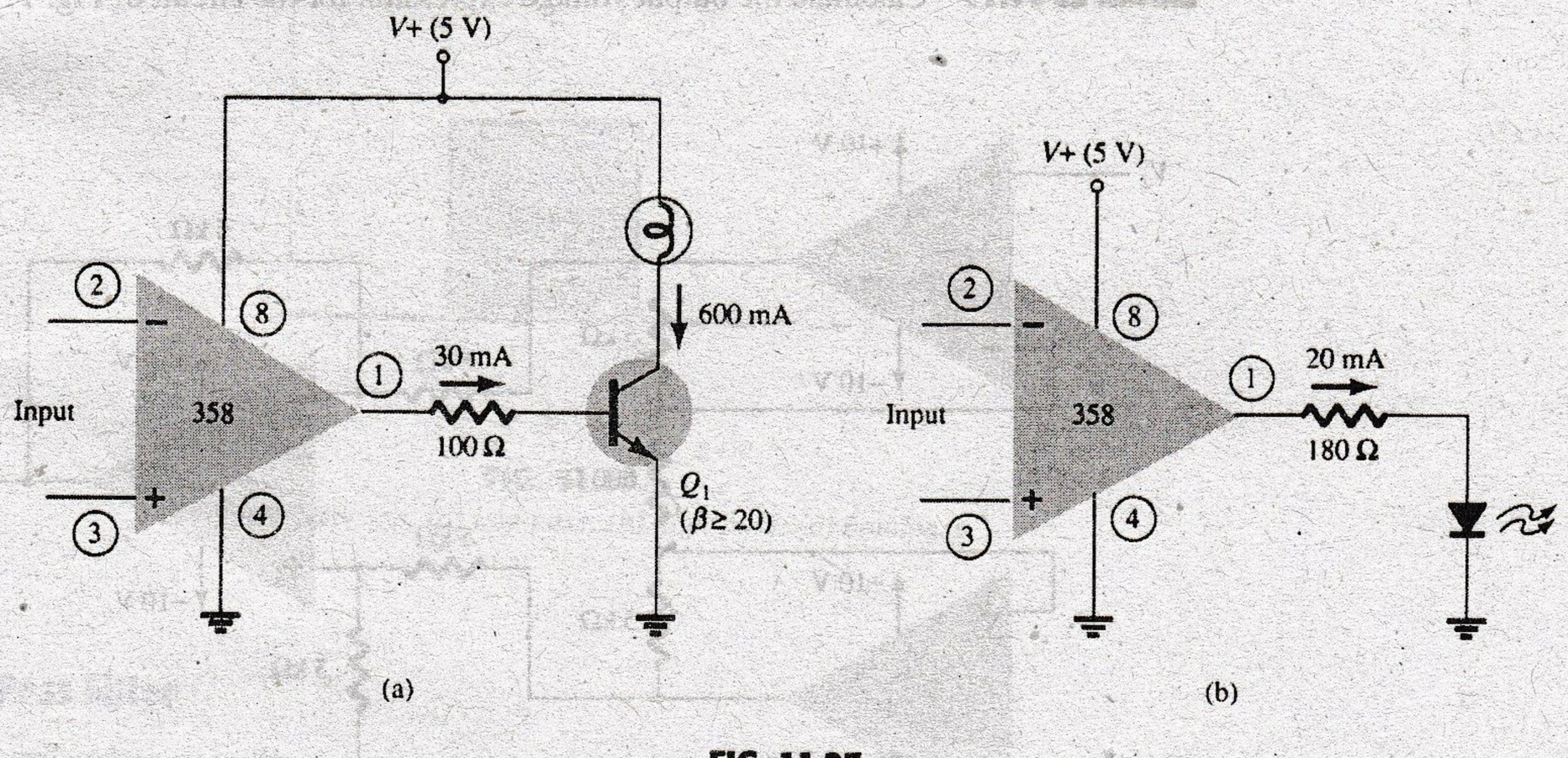


FIG. 11.27
Display driver circuits: (a) lamp driver; (b) LED driver.

Instrumentation Amplifier

A circuit providing an output based on the difference between two inputs (times a scale factor) is shown in Fig. 11.28. A potentiometer is provided to permit adjusting the scale factor of the circuit. Whereas three op-amps are used, a single-quad op-amp IC is all that is necessary (other than the resistor components). The output voltage can be shown to be

$$\frac{V_o}{V_1 - V_2} = 1 + \frac{2R}{R_P}$$

so that the output can be obtained from

$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = k(V_1 - V_2) \tag{11.12}$$

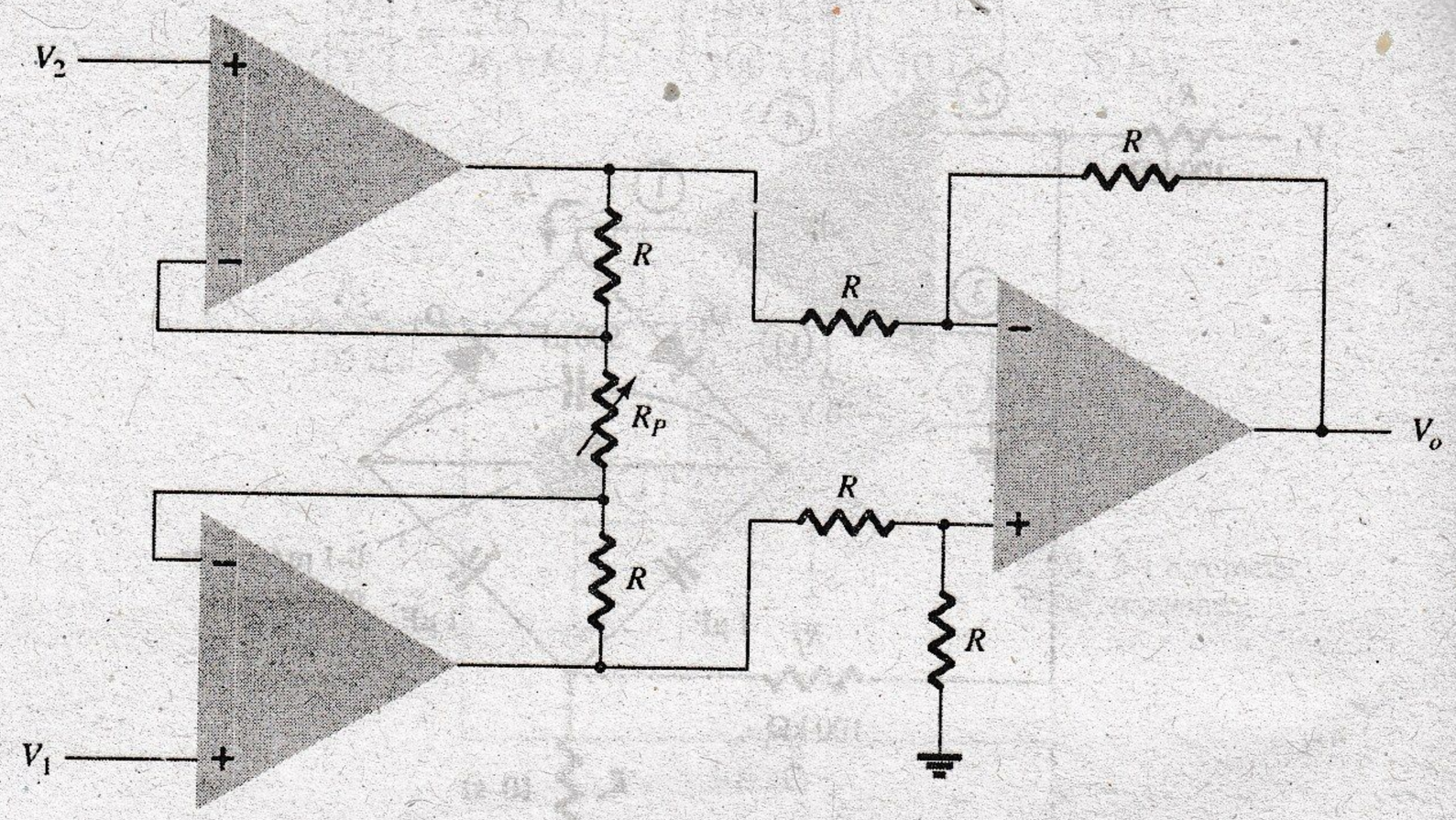


FIG. 11.28
Instrumentation amplifier.

EXAMPLE 11.11 Calculate the output voltage expression for the circuit of Fig. 11.29.

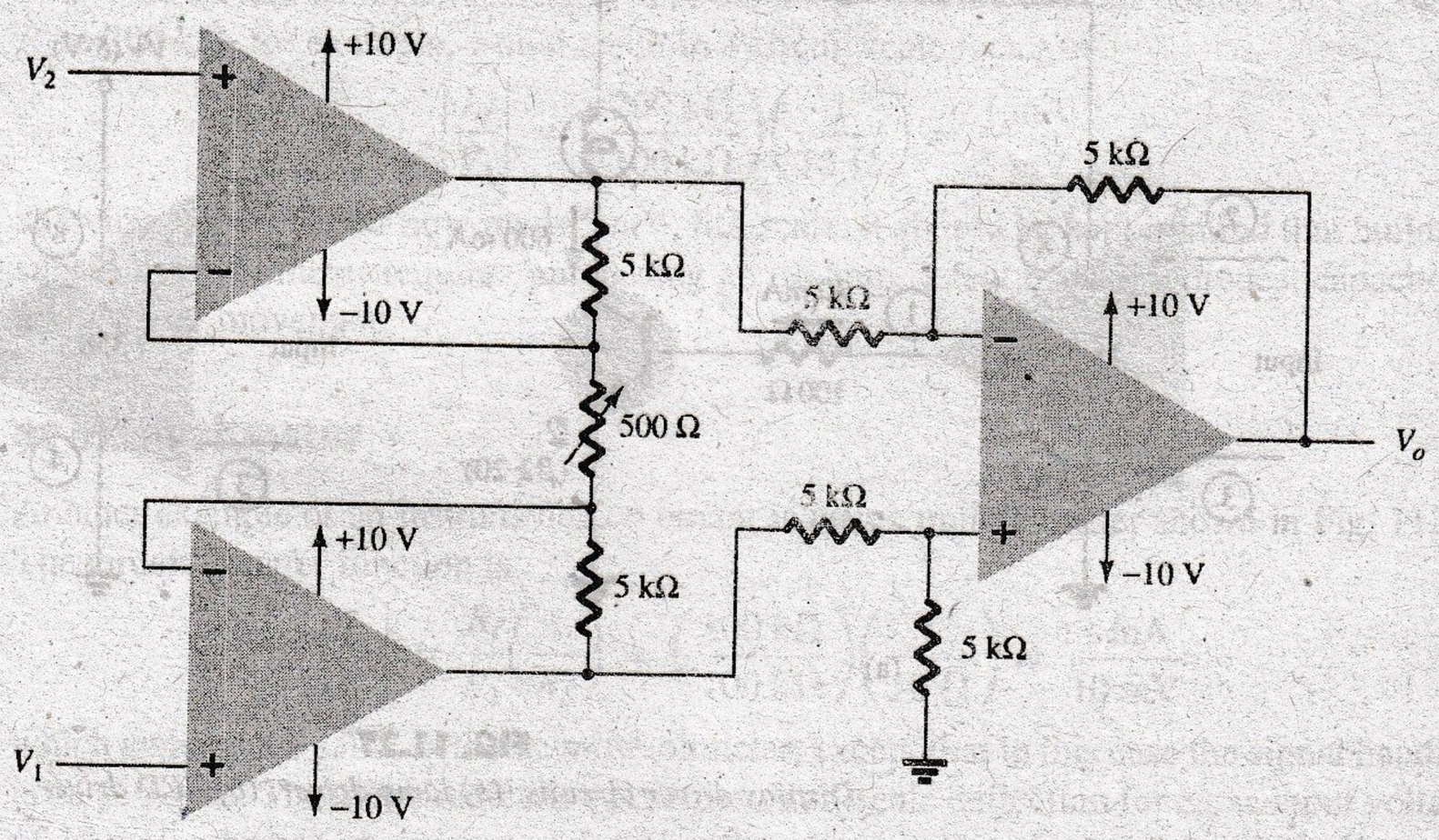


FIG. 11.29
Circuit for Example 11.11.

Solution: The output voltage can then be expressed using Eq. (11.12) as

$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = \left[1 + \frac{2(5000)}{500}\right](V_1 - V_2)$$
$$= \mathbf{21}(V_1 - V_2)$$

11.6 ACTIVE FILTERS

A popular application uses op-amps to build active filter circuits. A filter circuit can be constructed using passive components: resistors and capacitors. An active filter additionally uses an amplifier to provide voltage amplification and signal isolation or buffering.

A filter that provides a constant output from dc up to a cutoff frequency f_{OH} and then passes no signal above that frequency is called an ideal low-pass filter. The ideal response of a low-pass filter is shown in Fig. 11.30a. A filter that provides or passes signals above a cutoff frequency f_{OL} is a high-pass filter, as idealized in Fig. 11.30b. When the filter circuit passes signals that are above one ideal cutoff frequency and below a second cutoff frequency, it is called a bandpass filter, as idealized in Fig. 11.30c.

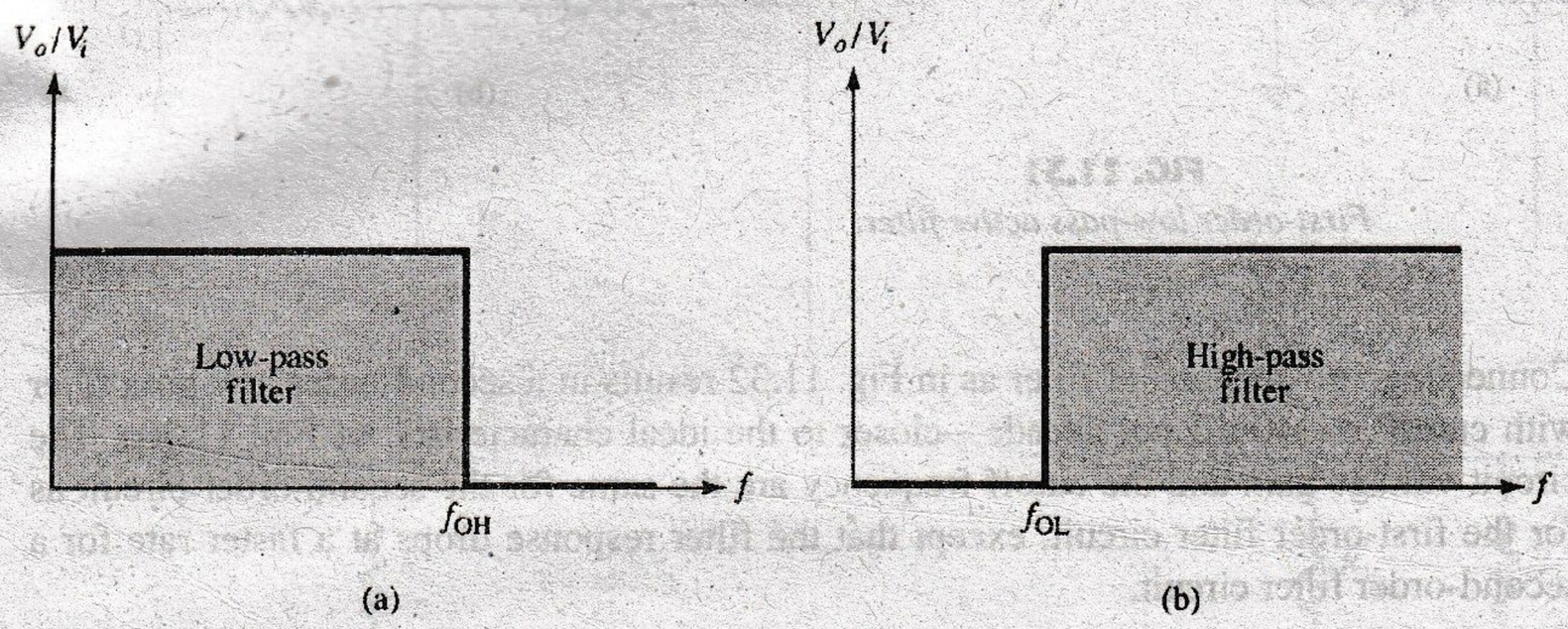


FIG. 11.30
Ideal filter response: (a) low-pass; (b) high-pass; (c) bandpass.

Low-Pass Filter

A first-order, low-pass filter using a single resistor and capacitor as in Fig. 11.31a has a practical slope of −20 dB per decade, as shown in Fig. 11.31b (rather than the ideal response of Fig. 11.30a). The voltage gain below the cutoff frequency is constant at

$$A_v = 1 + \frac{R_F}{R_G} \tag{11.13}$$

at a cutoff frequency of

$$f_{OH} = \frac{1}{2\pi R_1 C_1} \tag{11.14}$$

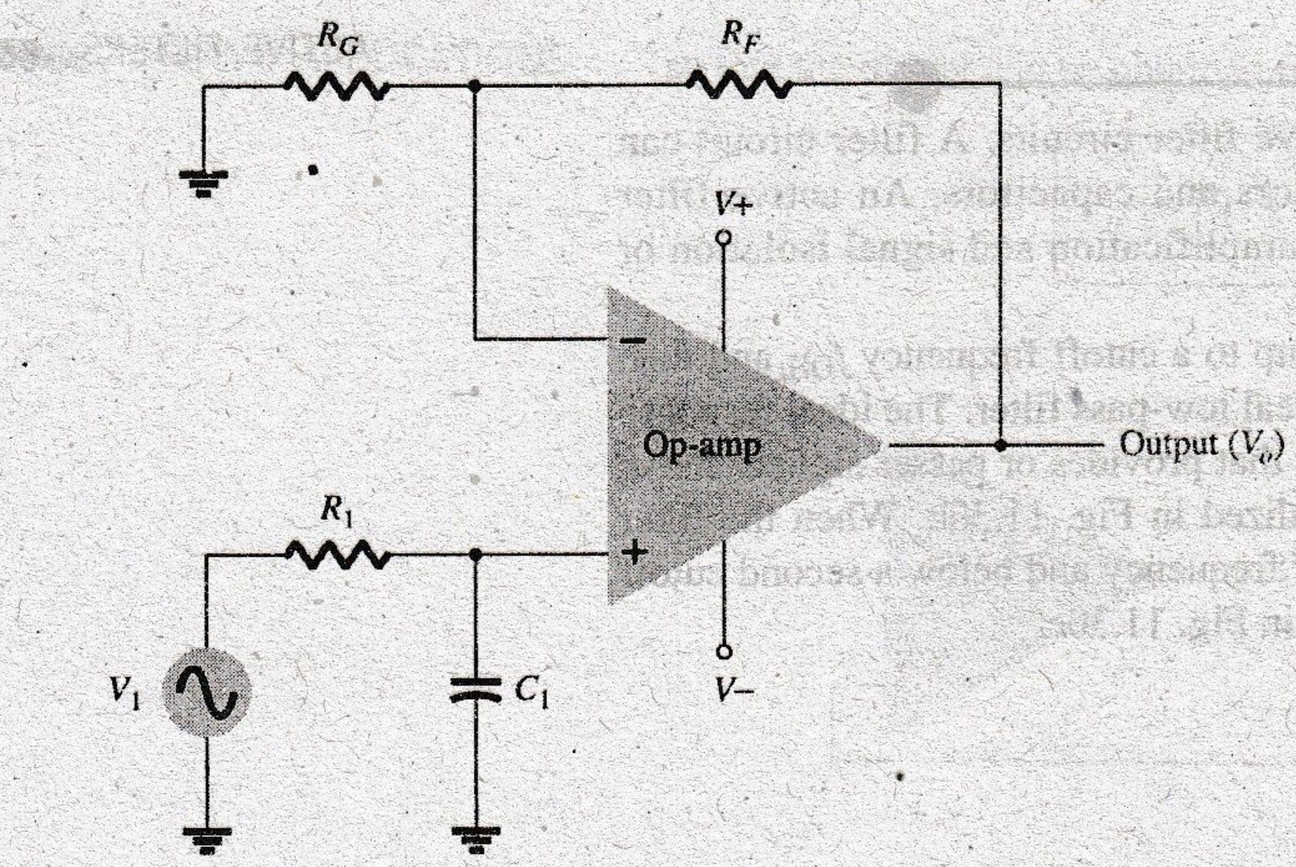


FIG. 11.31
First-order low-pass active filter.

Connecting two sections of filter as in Fig. 11.32 results in a second-order low-pass filter with cutoff at −40 dB per decade—closer to the ideal characteristic of Fig. 11.30a. The circuit voltage gain and the cutoff frequency are the same for the second-order circuit as for the first-order filter circuit, except that the filter response drops at a faster rate for a second-order filter circuit.

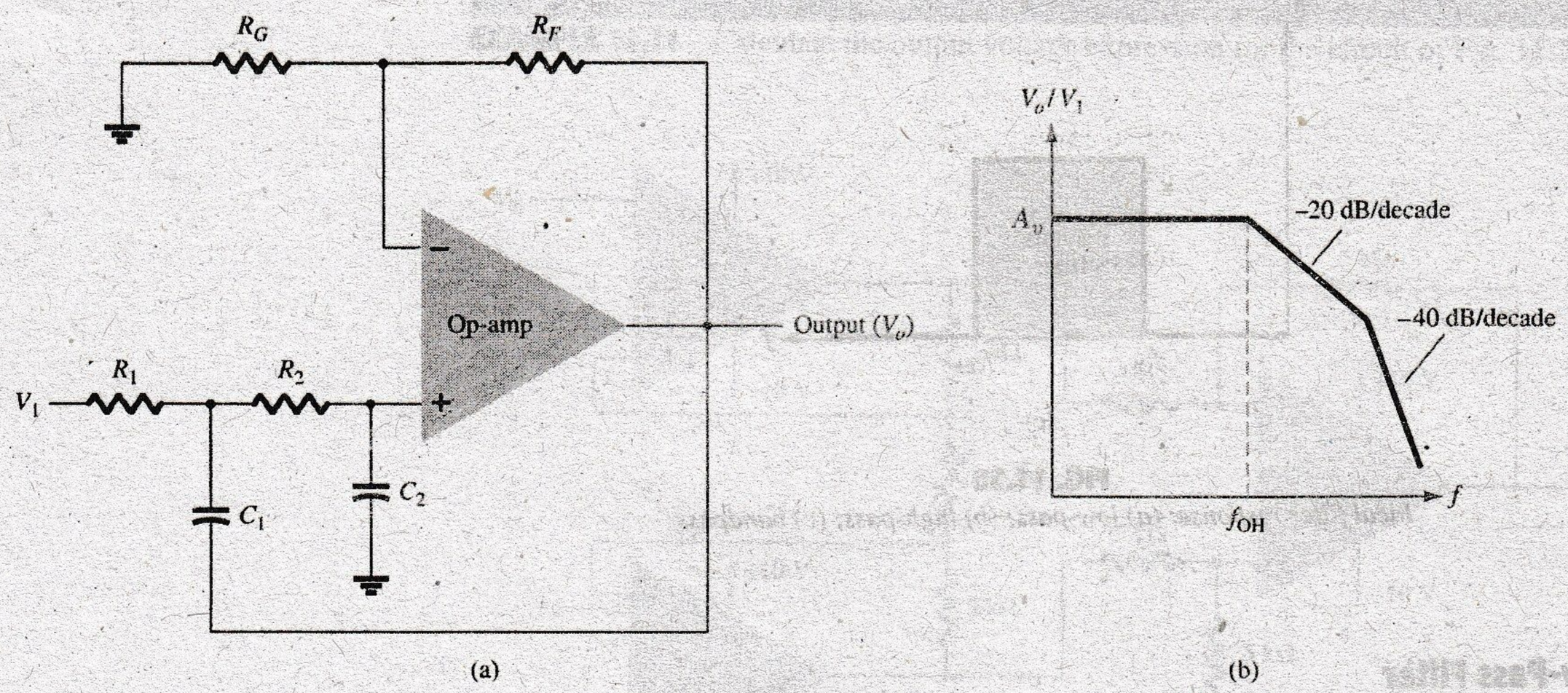


FIG. 11.32
Second-order low-pass active filter.

EXAMPLE 11.12 Calculate the cutoff frequency of a first-order low-pass filter for $R_1 = 1.2\,\text{k}\Omega$ and $C_1 = 0.02\,\mu\text{F}$.

Solution:

$$f_{OH} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(1.2 \times 10^3)(0.02 \times 10^{-6})} = \mathbf{6.63\,kHz}$$

High-Pass Active Filter

First- and second-order high-pass active filters can be built as shown in Fig. 11.33. The amplifier gain is calculated using Eq. (11.13). The amplifier cutoff frequency is

$$\boxed{f_{OL} = \frac{1}{2\pi R_1 C_1}} \tag{11.15}$$

with a second-order filter $R_1 = R_2$, and $C_1 = C_2$ results in the same cutoff frequency as in Eq. (11.15).

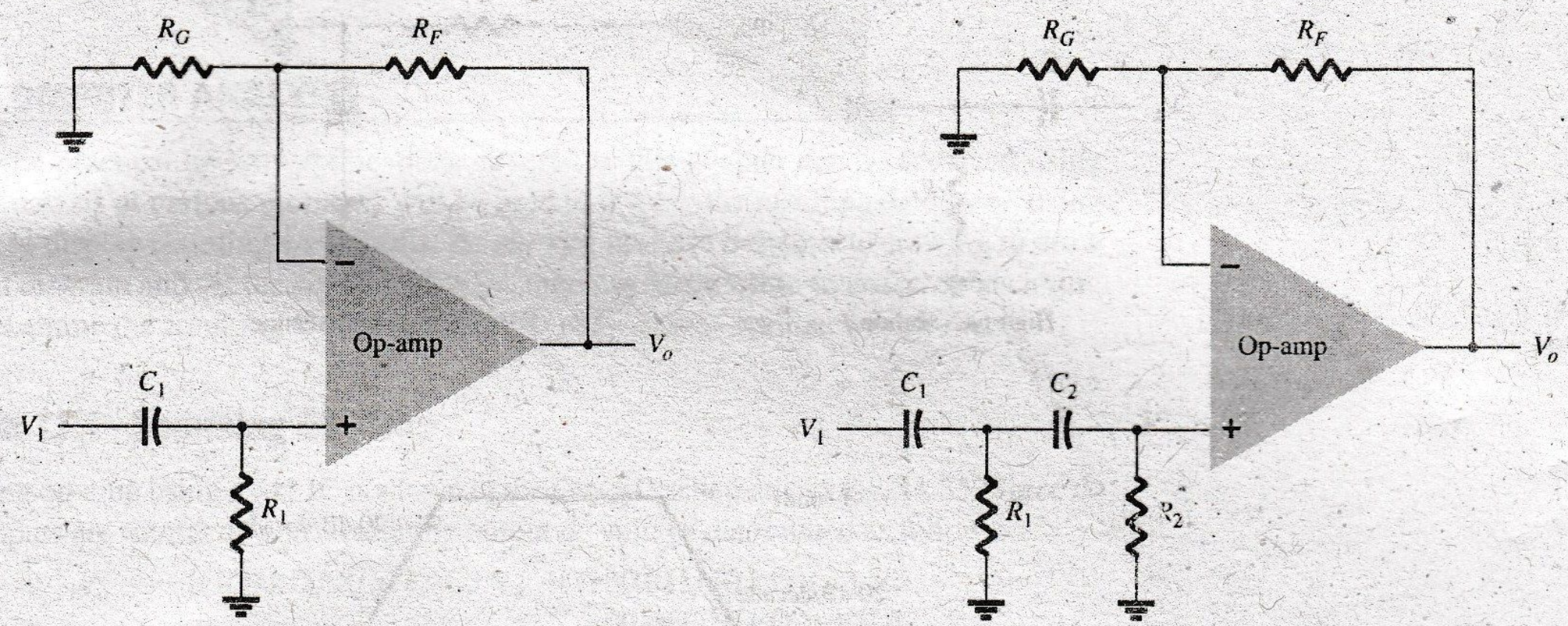


FIG. 11.33
High-pass filter: (a) first order; (b) second order; (c) response plot.

EXAMPLE 11.13 Calculate the cutoff frequency of a second-order high-pass filter as in Fig. 11.33b for $R_1 = R_2 = 2.1\ \text{k}\Omega$, $C_1 = C_2 = 0.05\ \mu\text{F}$, and $R_G = 10\ \text{k}\Omega$, $R_F = 50\ \text{k}\Omega$.

Solution:

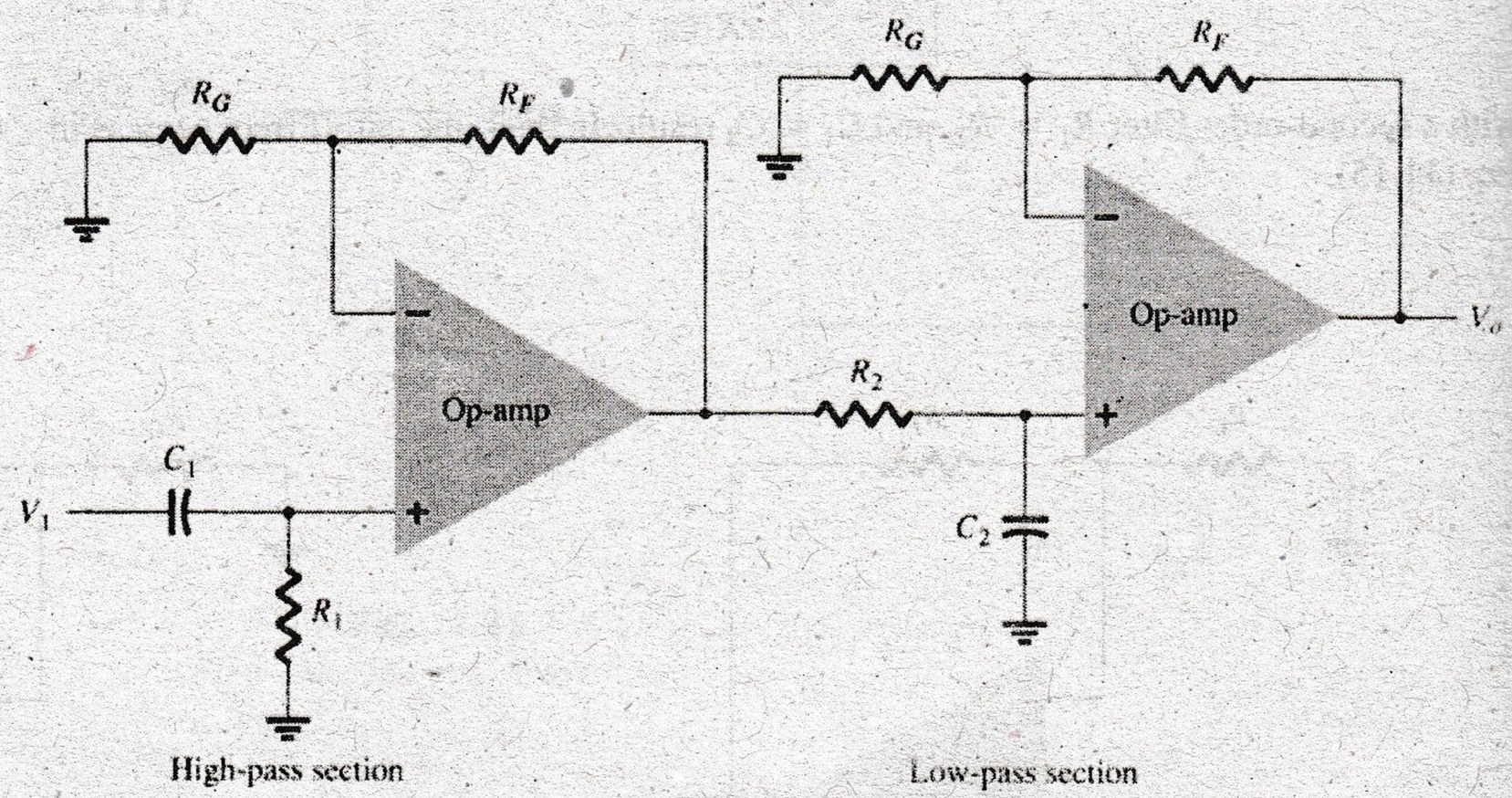
$$\text{Eq. (11.13):} \quad A_v = 1 + \frac{R_F}{R_G} = 1 + \frac{50\ \text{k}\Omega}{10\ \text{k}\Omega} = 6$$

The cutoff frequency is then

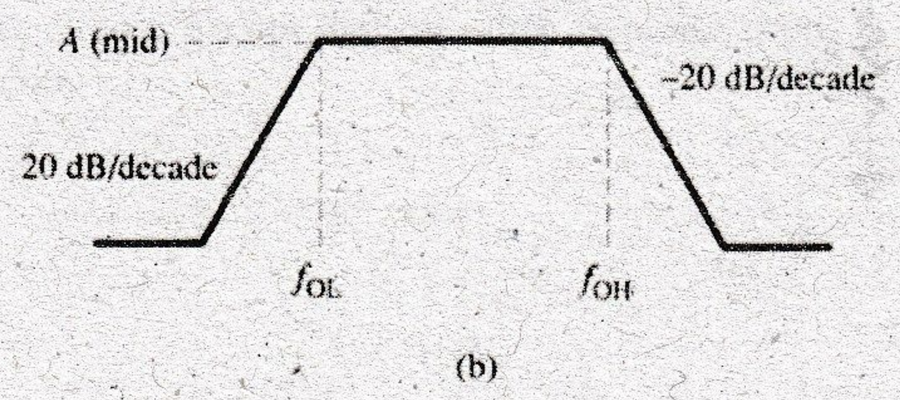
$$\text{Eq. (11.15):} \quad f_{OL} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(2.1 \times 10^3)(0.05 \times 10^{-6})} \approx \mathbf{1.5\ kHz}$$

Bandpass Filter

Figure 11.34 shows a bandpass filter using two stages, the first a high-pass filter and the second a low-pass filter, the combined operation being the desired bandpass response.



(a)



(b)

FIG. 11.34
Bandpass active filter.

EXAMPLE 11.14 Calculate the cutoff frequencies of the bandpass filter circuit of Fig. 11.34 with $R_1 = R_2 = 10\,\text{k}\Omega$, $C_1 = 0.1\,\mu\text{F}$, and $C_2 = 0.002\,\mu\text{F}$.

Solution:

$$f_{OL} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(10 \times 10^3)(0.1 \times 10^{-6})} = \mathbf{159.15\ Hz}$$

$$f_{OH} = \frac{1}{2\pi R_2 C_2} = \frac{1}{2\pi(10 \times 10^3)(0.002 \times 10^{-6})} = \mathbf{7.96\ kHz}$$

11.7 SUMMARY

Equations

Constant-gain multiplier:

$$A = -\frac{R_f}{R_1}$$

Noninverting constant-gain multiplier:

$$A = 1 + \frac{R_f}{R_1}$$

Voltage-summing amplifier:

$$A = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

Voltage buffer:

$$V_o = V_1$$

Low-pass active filter cutoff frequency:

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

High-pass active filter cutoff frequency:

$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

11.8 COMPUTER ANALYSIS

Many of the practical op-amp applications covered in this chapter can be analyzed using PSpice. Analysis of various problems will be used to display the resulting dc bias or, using **PROBE**, to display resulting waveforms. As always, first use **Schematic** drawing to draw the circuit diagram and set the desired analysis, then use **Simulation** to analyze the circuit. Finally, examine the resulting **Output** or use **PROBE** to view various waveforms.

Program 11.1—Summing Op-Amp

A summing op-amp using a 741 IC is shown in the OrCAD schematic in Fig. 11.35. Three dc voltage inputs are summed, with a resulting output dc voltage determined as follows:

$$\begin{aligned} V_o &= -[(100\,\text{k}\Omega/20\,\text{k}\Omega)(+2\,\text{V}) + (100\,\text{k}\Omega/50\,\text{k}\Omega)(-3\,\text{V}) \\ &\qquad + (100\,\text{k}\Omega/10\,\text{k}\Omega(+1\,\text{V})] \\ &= -[(10\,\text{V}) + (-6\,\text{V}) + (10\,\text{V})] = -[20\,\text{V} - 6\,\text{V}] = -14\,\text{V} \end{aligned}$$

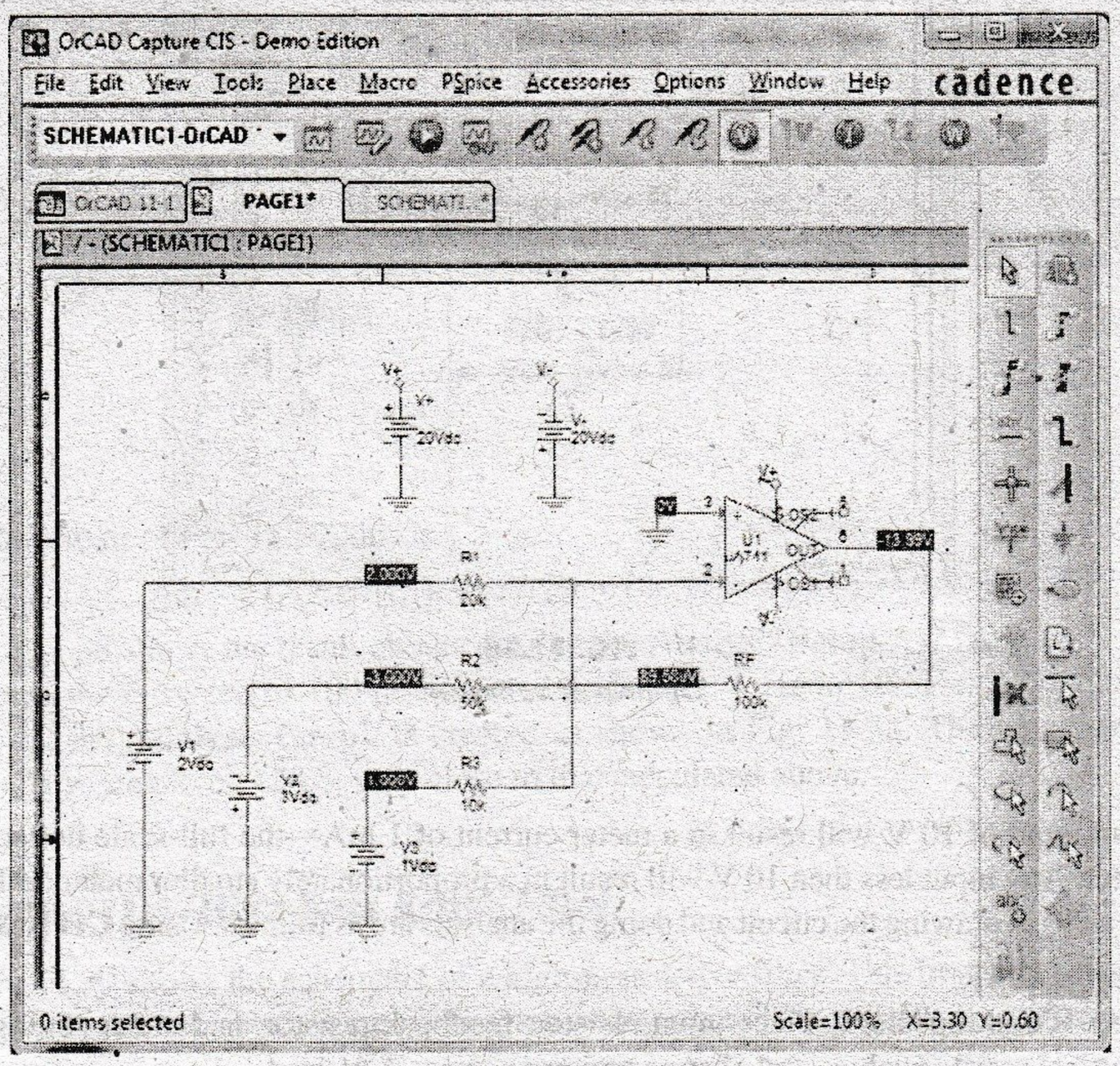


FIG. 11.35
Summing amplifier using a μA741 op-amp.

The steps in drawing the circuit and doing the analysis are as follows. Using **Get New Part**:

Select **μA741**.
Select **R** and repeatedly place three input resistors and one feedback resistor; set resistor values and change resistor names, if desired.
Select **VDC** and place three input voltages and two supply voltages; set voltage values and change voltage names, if desired.
Select **GLOBAL** (global connector) and use to identify supply voltages and make connection to op-amp power input terminals (4 and 7).

Now that the circuit is drawn and all part names and values set as in Fig. 11.35, press the **Simulation** (Run PSpice) button to have PSpice analyze the circuit. Since no specific analysis has been chosen, only the dc bias will be carried out.

Press the **Enable Bias Voltage Display** button to see the dc voltages at various points in the circuit. The bias voltages displayed in Fig. 11.35 show the output to be -13.99 V (compared to the calculated value of -14 V above).

Program 11.2–Op-Amp DC Voltmeter

A dc voltmeter built using a μA741 op-amp is provided by the OrCAD schematic of Fig. 11.36. From the material presented in Section 11.5, the transfer function of the circuit is

$$I_o/V_1 = (R_F/R_1)(1/R_S) = (1\ \text{M}\Omega/1\ \text{M}\Omega)(1/10\ \text{k}\Omega)$$

The full-scale setting of this voltmeter (for I_o full scale at 1 mA) is then

$$V_1(\text{full scale}) = (10\ \text{k}\Omega)(1\ \text{mA}) = 10\ \text{V}$$

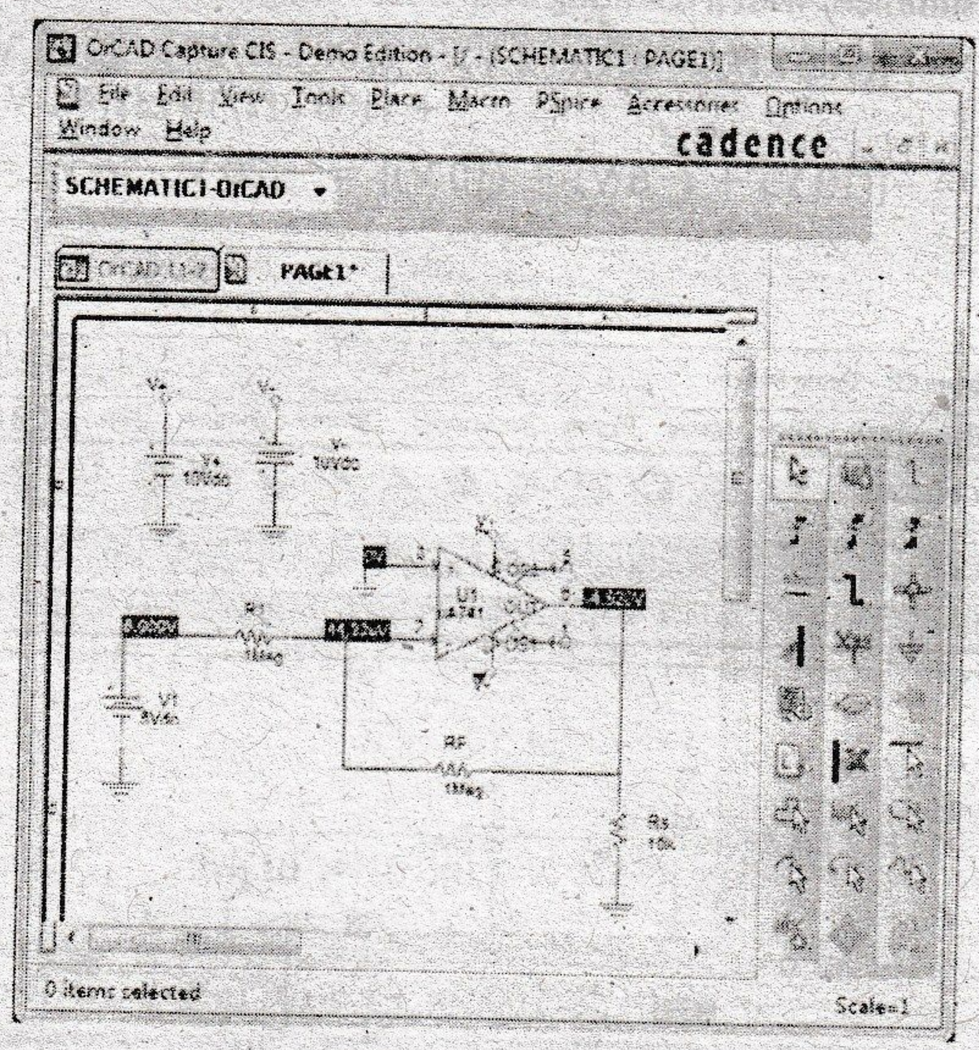


FIG. 11.36
Op-amp dc voltmeter.

Thus, an input of 10 V will result in a meter current of 1 mA—the full-scale deflection of the meter. Any input less then 10 V will result in a proportionately smaller meter deflection.

The steps in drawing the circuit and doing the analysis are as follows. Using **Get New Part**:

Select **μA741**.
Select **R** and repeatedly place input resistor, feedback resistor, and meter setting resistor; set resistor values and change resistor names, if desired.
Select **VDC** and place input voltage and two supply voltages; set voltage values and change voltage names, if desired.

Select **GLOBAL** (global connector) and use to identify supply voltages and make connection to op-amp power input terminals (4 and 7).
Select **IPROBE** and use as meter movement.

Now that the circuit is drawn and all part names and values set as in Fig. 11.36, press the **Simulation** button (Run PSpice) to have PSpice analyze the circuit. Since no specific analysis has been chosen, only the dc bias will be carried out.

Figure 11.36 shows that an input of 5 V will result in a current of 0.5 mA, with the meter reading of 0.5 being read as 5 V (since 1 mA full scale will occur for 10 V input).

Program 11.3–Low-Pass Active Filter

Figure 11.37 shows the schematic of a low-pass active filter. This first-order filter circuit passes frequencies from dc up to the cutoff frequency determined by resistor R_1 and capacitor C_1 using

$$f_{OH} = 1/(2\pi R_1 C_1)$$

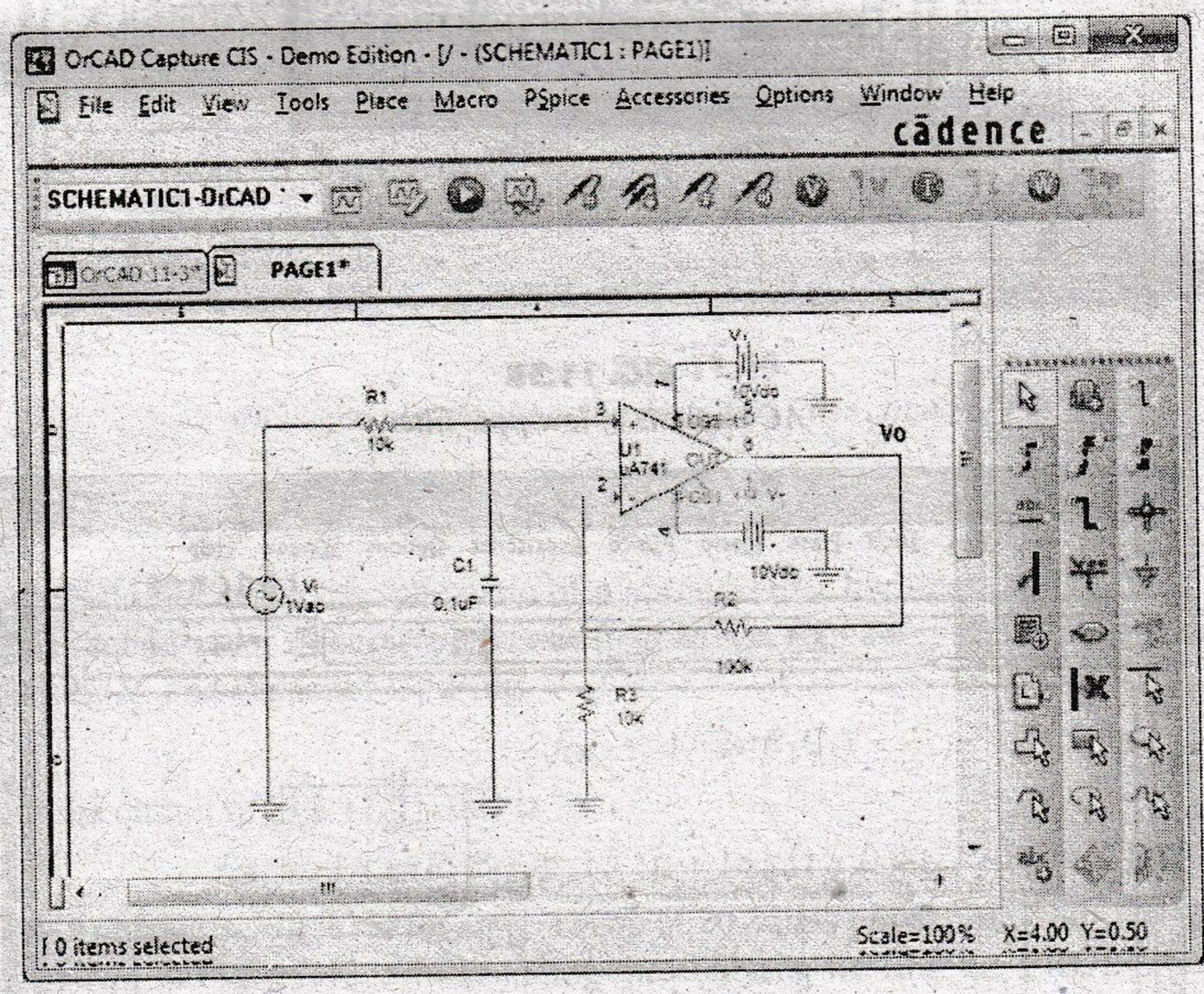


FIG. 11.37
Low-pass active filter.

For the circuit of Fig. 11.37, this is

$$f_{OH} = 1/(2\pi R_1 C_1) = 1/(2\pi \cdot 10\,\text{k}\Omega \cdot 0.1\,\mu\text{F}) = 159\,\text{Hz}$$

Figure 11.38 shows the result obtained using the **Analysis Setup-AC frequency** and then choosing an ac sweep of 100 points per decade from 1 Hz to 10 kHz. After running the analysis, the **Analysis Graph** is created as shown in Fig. 11.38. The cutoff frequency obtained is seen to be 158.8, very close to that calculated above.

Program 11.4–High-Pass Active Filter

Figure 11.39 shows the schematic of a high-pass active filter. This first-order filter circuit passes frequencies above a cutoff frequency determined by resistor R_1 and capacitor C_1 using

$$f_{OL} = 1/(2\pi R_1 C_1)$$

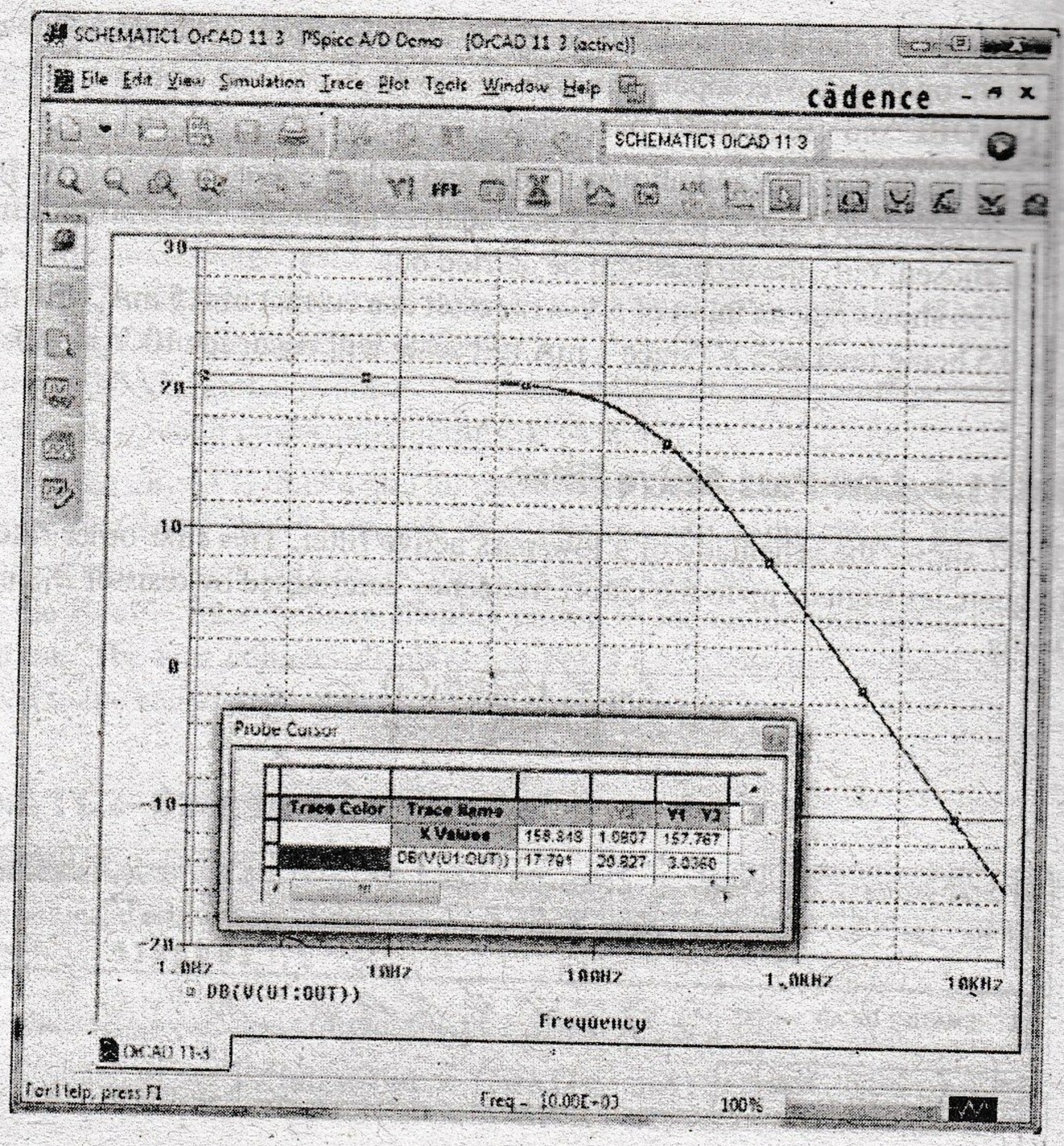


FIG. 11.38

AC analysis of low-pass filter.

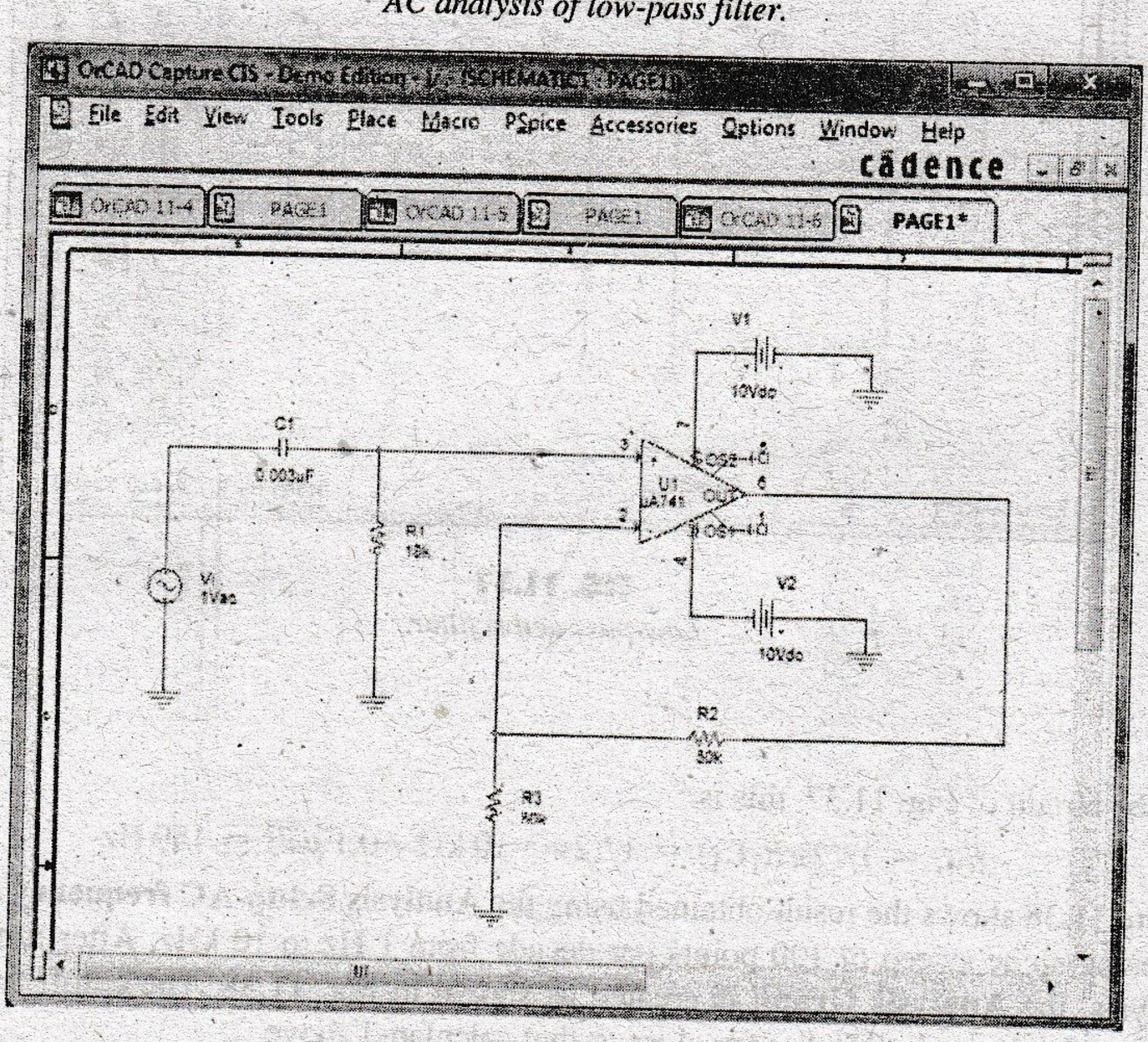


FIG. 11.39

High-pass active filter.

For the circuit of Fig. 11.39, this is

$$f_{OH} = 1/(2\pi R_1 C_1) = 1/(2\pi \cdot 18\,\text{k}\Omega \cdot 0.003\,\mu\text{F}) = 2.95\,\text{kHz}$$

The **Analysis** is set for an ac sweep of 100 points per decade from 10 Hz to 100 kHz. After running the analysis, the output showing the output voltage in dB units is that shown in Fig. 11.40. The cutoff frequency obtained is seen to be 2.9 kHz, very close to that calculated above.

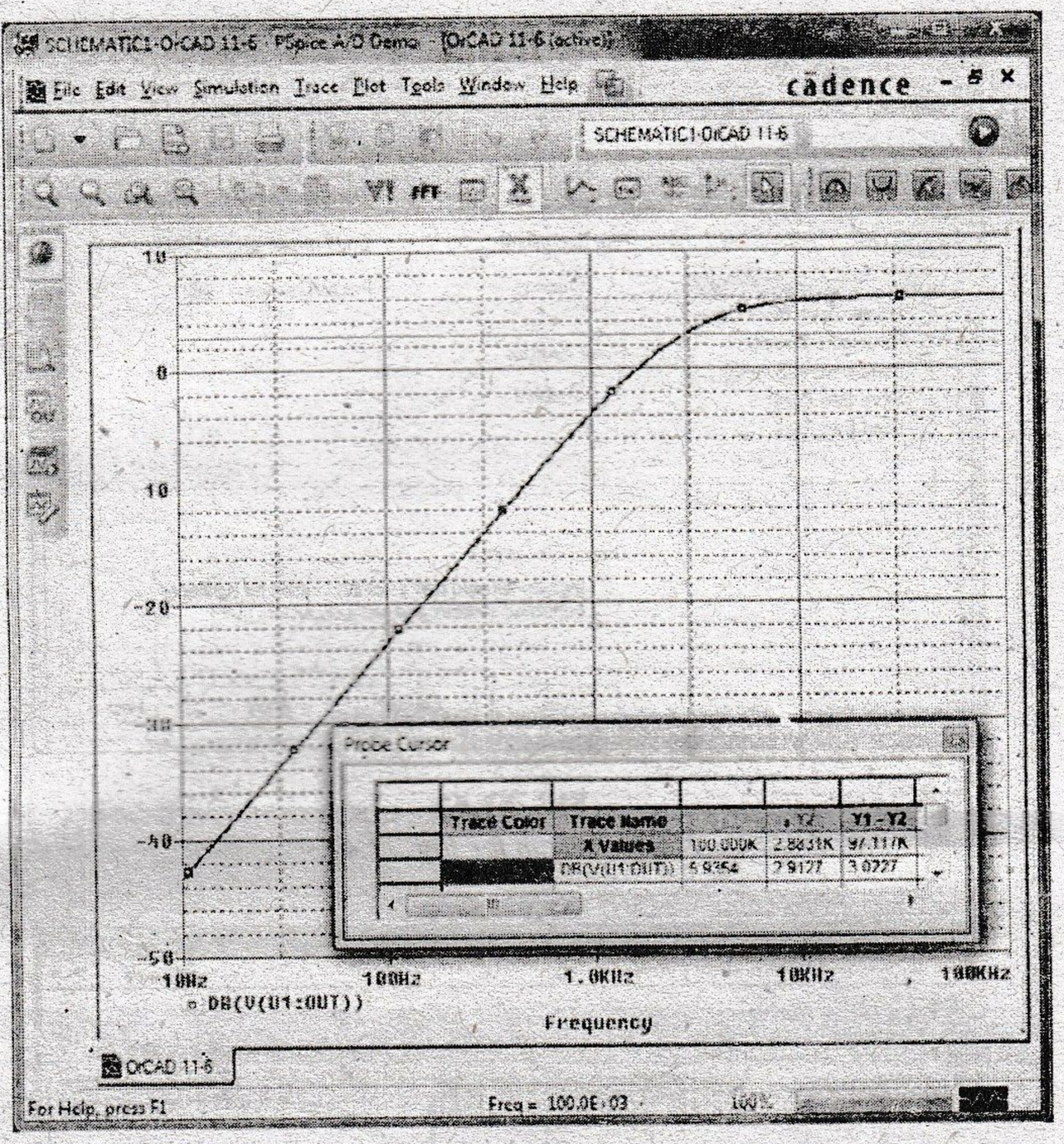


FIG. 11.40

dB output plot for the active high-pass filter circuit of Fig. 11.39.

Program 11.5—Second-Order High-Pass Active Filter

Figure 11.41 shows the schematic of a second-order high-pass active filter using Orcad. This second-order filter circuit passes frequencies above a cutoff frequency determined by resistor R_1 and capacitor C_1 using

$$f_{OL} = 1/(2\pi R_1 C_1)$$

For the circuit of Fig. 11.41, this is

$$f_{OL} = 1/(2\pi R_1 C_1) = 1/(2\pi \cdot 18\,\text{k}\Omega \cdot 0.0022\,\mu\text{F}) = 4\,\text{kHz}$$

The **Analysis Setup** is set for an ac sweep of 20 points per decade from 100 Hz to 100 kHz, as shown in Fig. 11.42. After running the analysis, we find the **PROBE** output showing

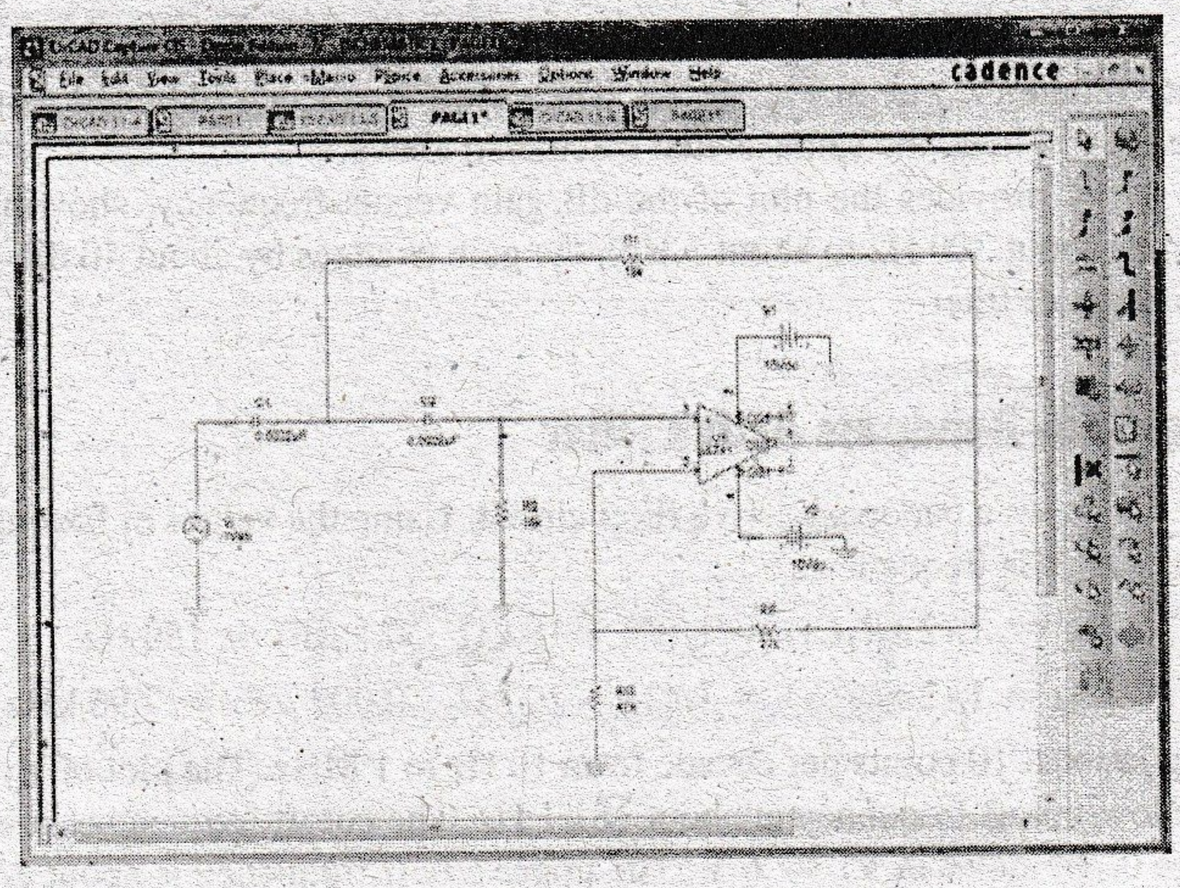


FIG. 11.41

Second-order high-pass filter.

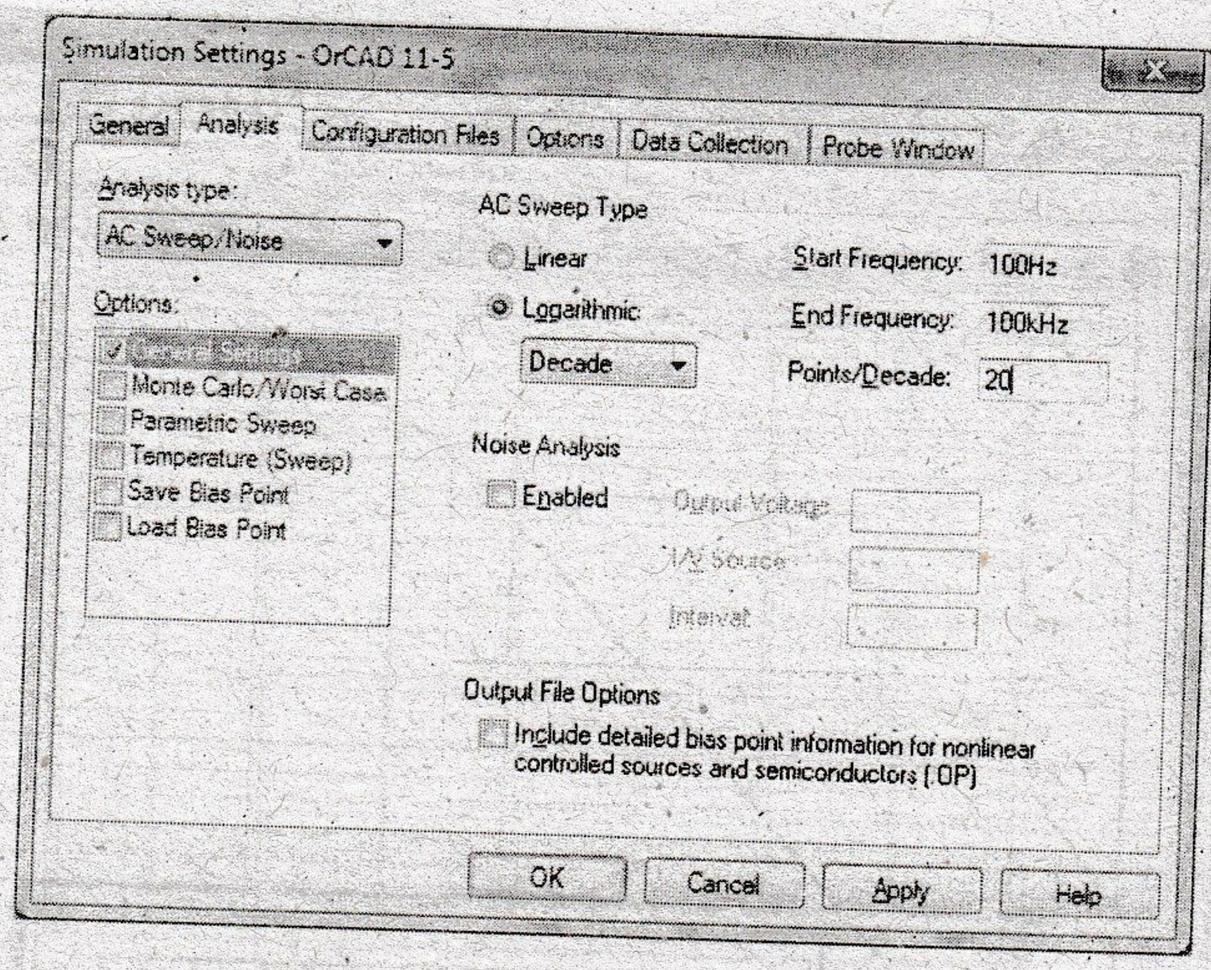


FIG. 11.42
Analysis setup for Fig. 11.41.

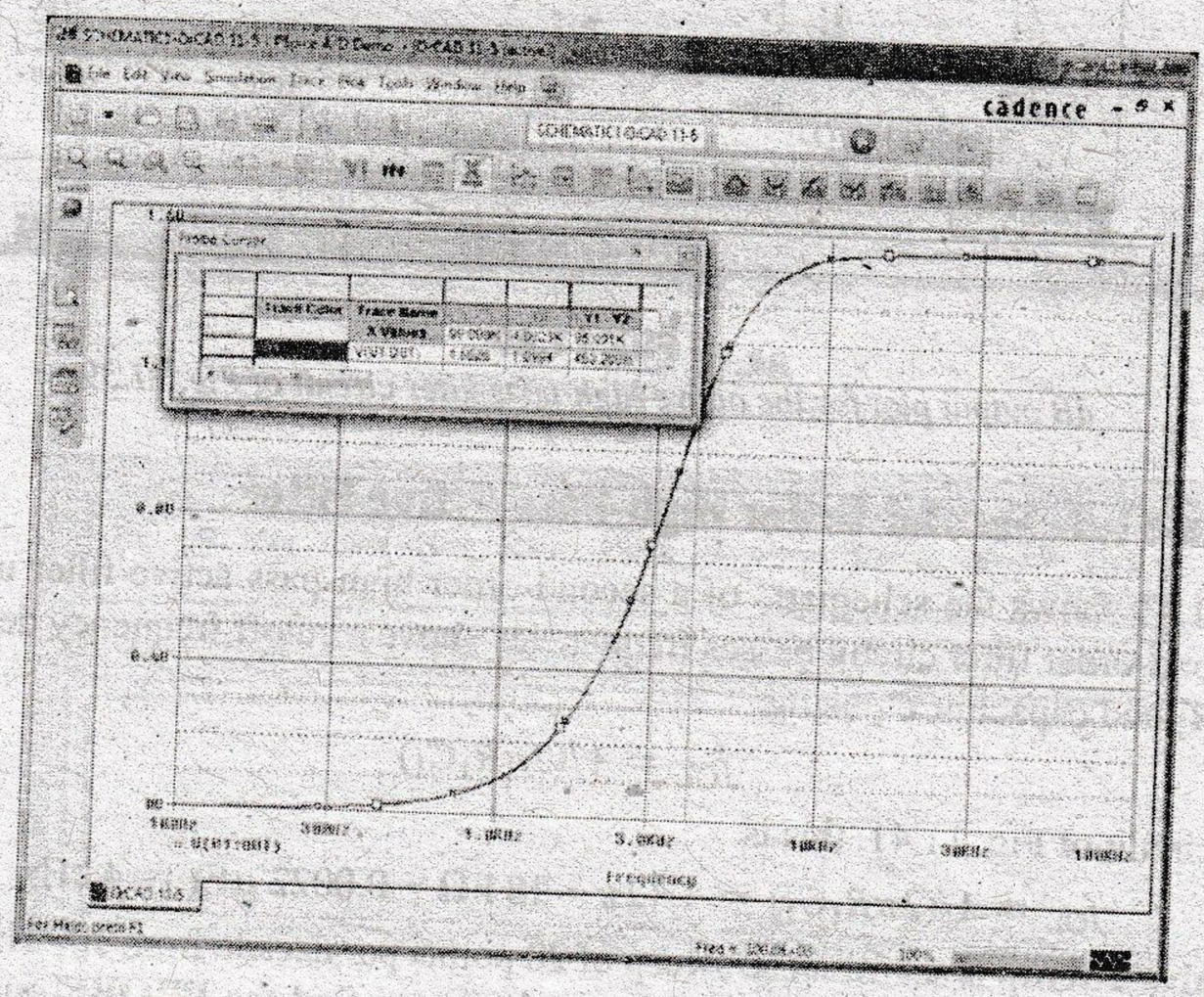


FIG. 11.43
Probe plot of V_o for second-order high-pass active filter.

the output voltage (V_o) as in Fig. 11.43. The cutoff frequency obtained using **Cursor** is seen to be **fL** = 4 kHz, the same as that calculated above.

Figure 11.44 provides the plot of the dB gain versus frequency, showing that over a decade (from about 300 Hz to about 3 Hz), the gain changes by about 40 dB—as expected for a second-order filter.

Program 11.6–Bandpass Active Filter

Figure 11.45 shows a bandpass active filter circuit. Using the values of Example 11.14, we obtain the bandpass frequencies

$$f_{OL} = 1/(2\pi R_1 C_1) = 1/(2\pi \cdot 10\,\text{k}\Omega \cdot 0.1\,\mu\text{F}) = 159\,\text{Hz}$$
$$f_{OH} = 1/(2\pi R_2 C_2) = 1/(2\pi \cdot 10\,\text{k}\Omega \cdot 0.002\,\mu\text{F}) = 7.96\,\text{kHz}$$

The sweep is set at 10 points per decade from 10 Hz to 1 MHz. The plot of V_o in Fig. 11.46 shows the low-cutoff frequency at about 181.1 Hz. The cutoff frequencies are measured at the voltage 0.707 (7.8423 V) $\cong$ 6 V. The upper cutoff frequency is about 8.2 kHz, using the cursor on the upper 0.707 voltage point. These values match those calculated above quite well.

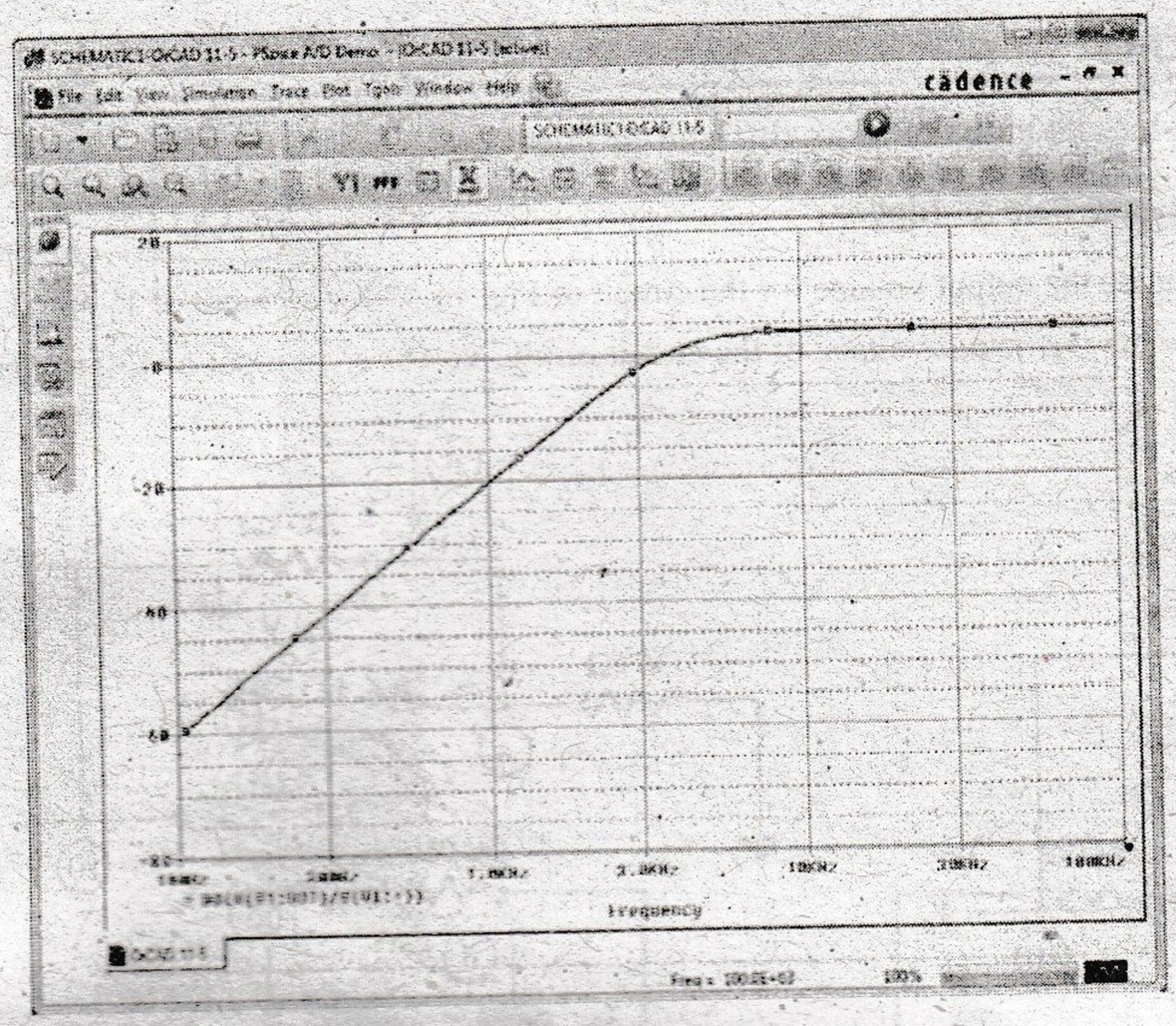


FIG. 11.44

Plot of dB (V_o/V_i) for a second-order high-pass active filter.

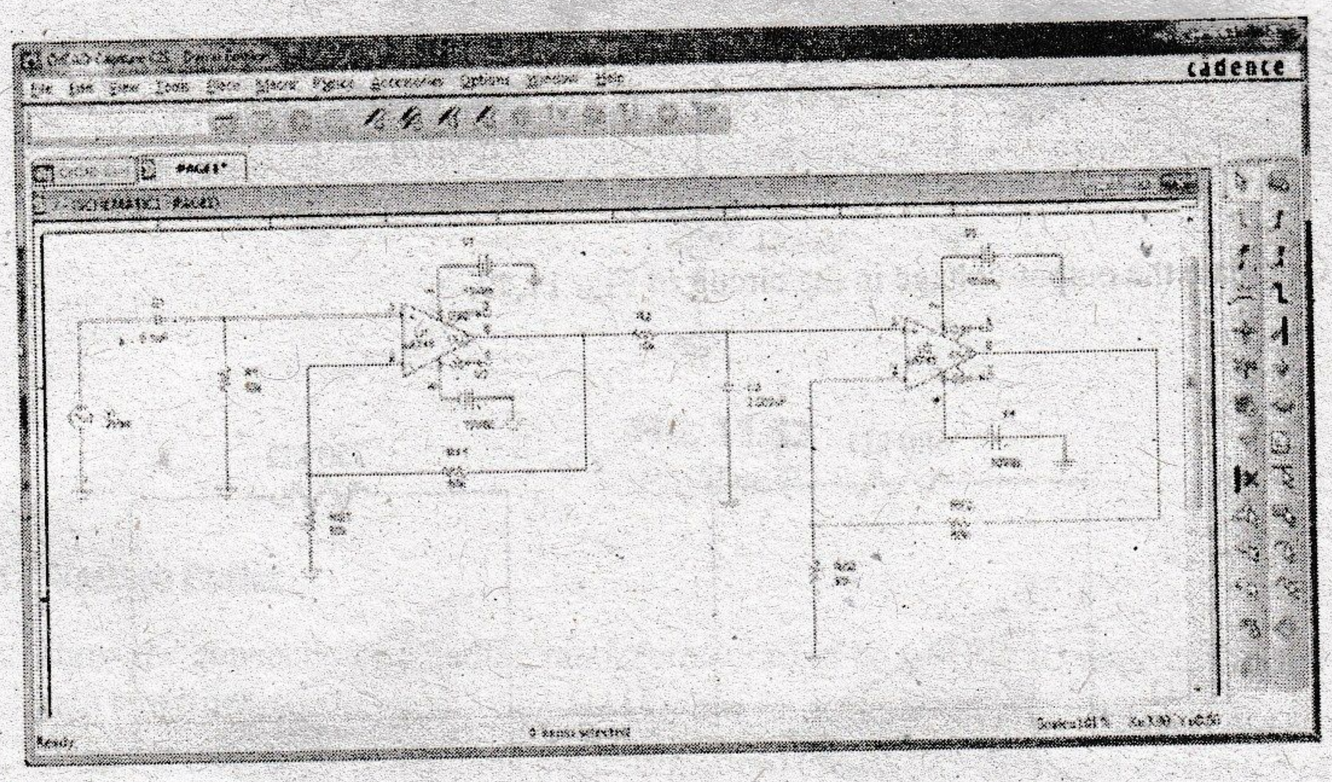


FIG. 11.45

Bandpass active filter.

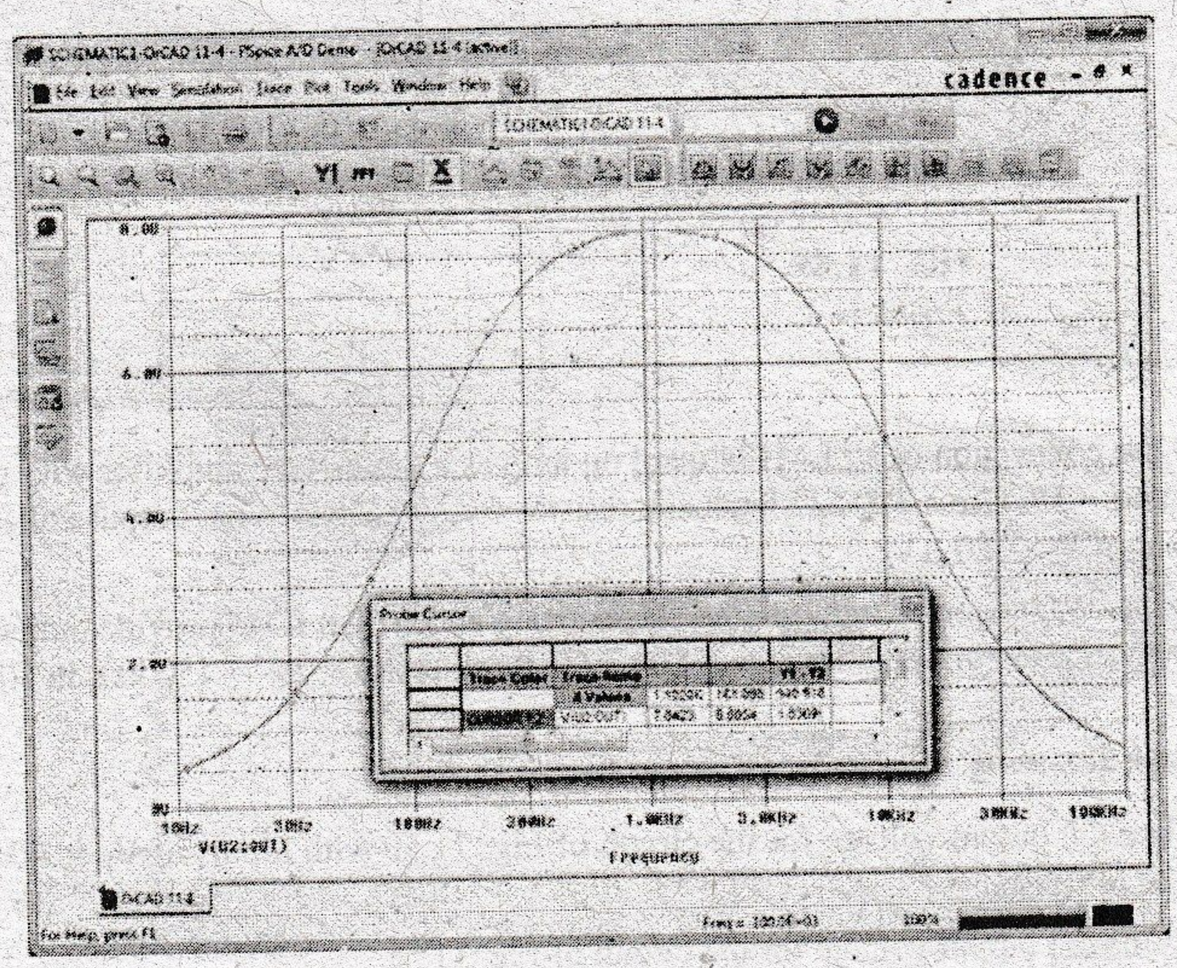


FIG. 11.46

Probe plot of bandpass active filter.

PROBLEMS

*Note: Asterisks indicate more difficult problems.

11.1 Constant-Gain Multiplier

1. Calculate the output voltage for the circuit of Fig. 11.47 for an input of $V_i = 3.5$ mV rms.
2. Calculate the output voltage of the circuit of Fig. 11.48 for an input of 150 mV rms.

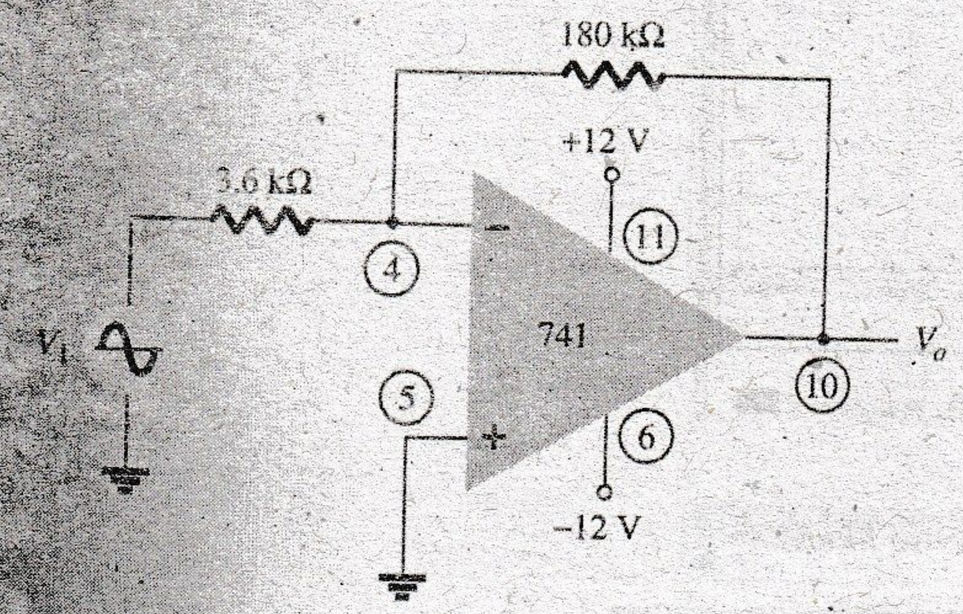


FIG. 11.47
Problem 1.

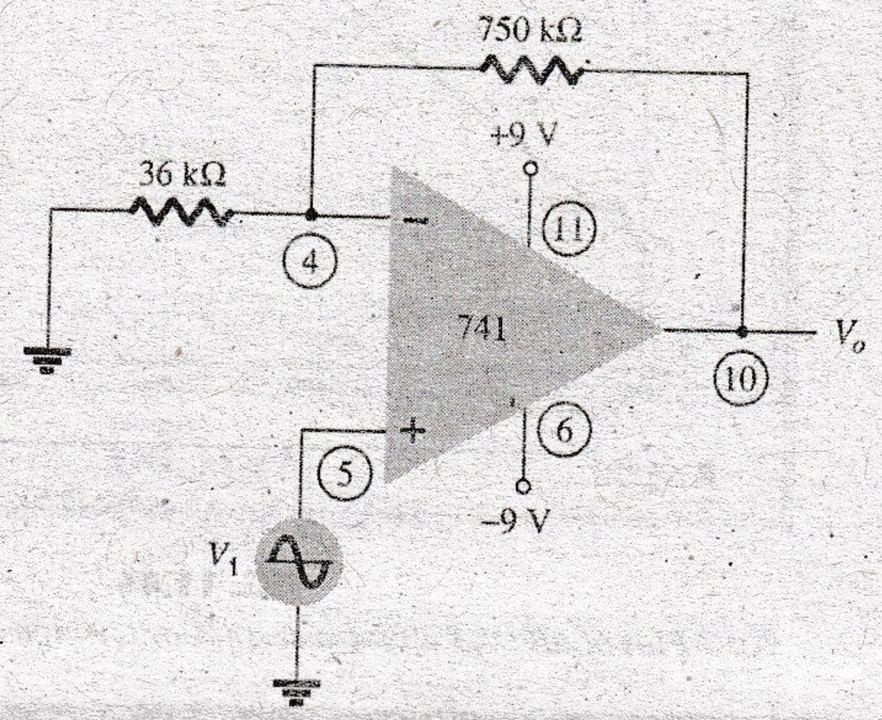


FIG. 11.48
Problem 2.

*3. Calculate the output voltage in the circuit of Fig. 11.49.

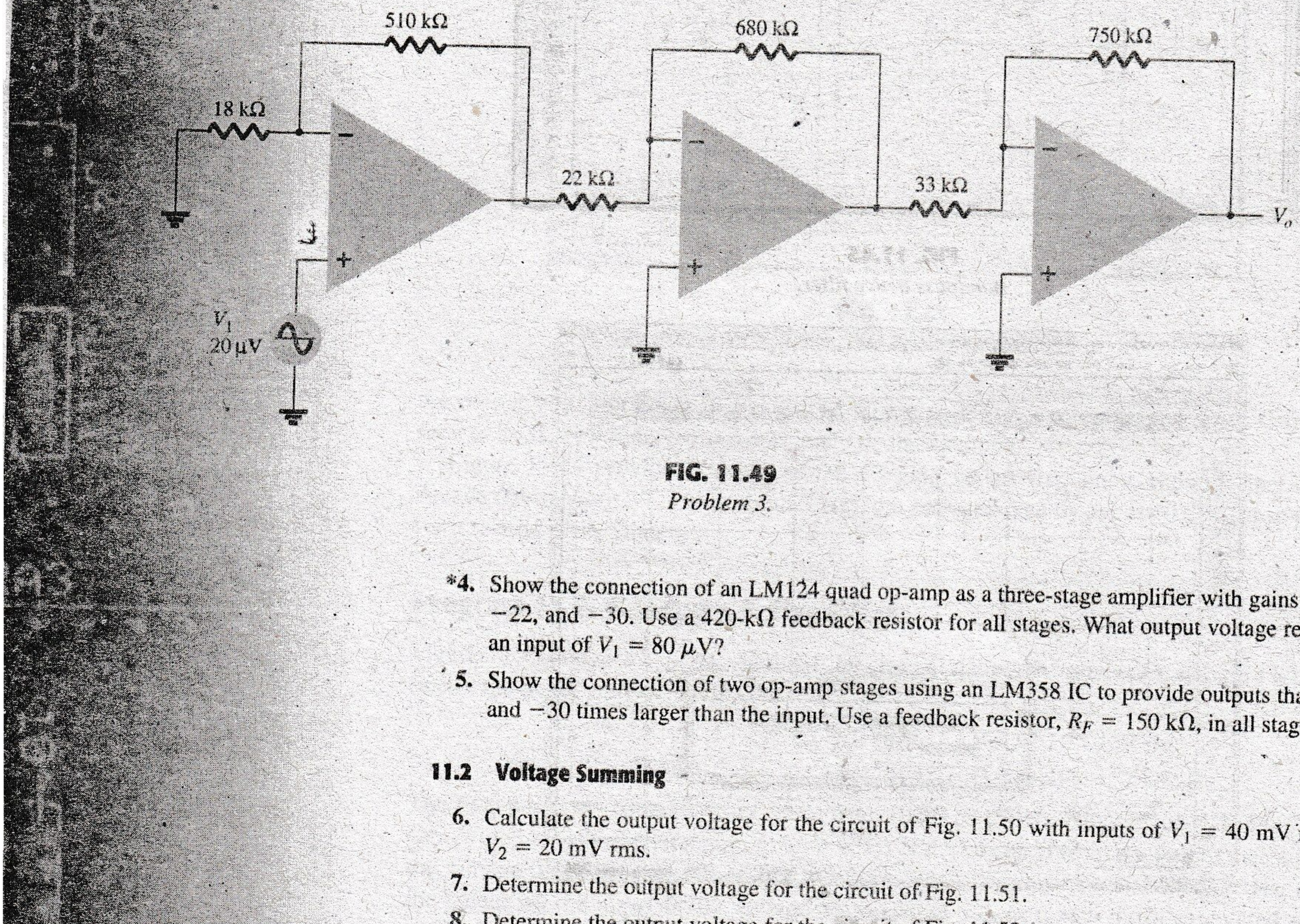


FIG. 11.49
Problem 3.

*4. Show the connection of an LM124 quad op-amp as a three-stage amplifier with gains of +15, −22, and −30. Use a 420-kΩ feedback resistor for all stages. What output voltage results for an input of $V_1 = 80\ \mu$V?

5. Show the connection of two op-amp stages using an LM358 IC to provide outputs that are 15 and −30 times larger than the input. Use a feedback resistor, $R_F = 150$ kΩ, in all stages.

11.2 Voltage Summing

6. Calculate the output voltage for the circuit of Fig. 11.50 with inputs of $V_1 = 40$ mV rms and $V_2 = 20$ mV rms.
7. Determine the output voltage for the circuit of Fig. 11.51.
8. Determine the output voltage for the circuit of Fig. 11.52.

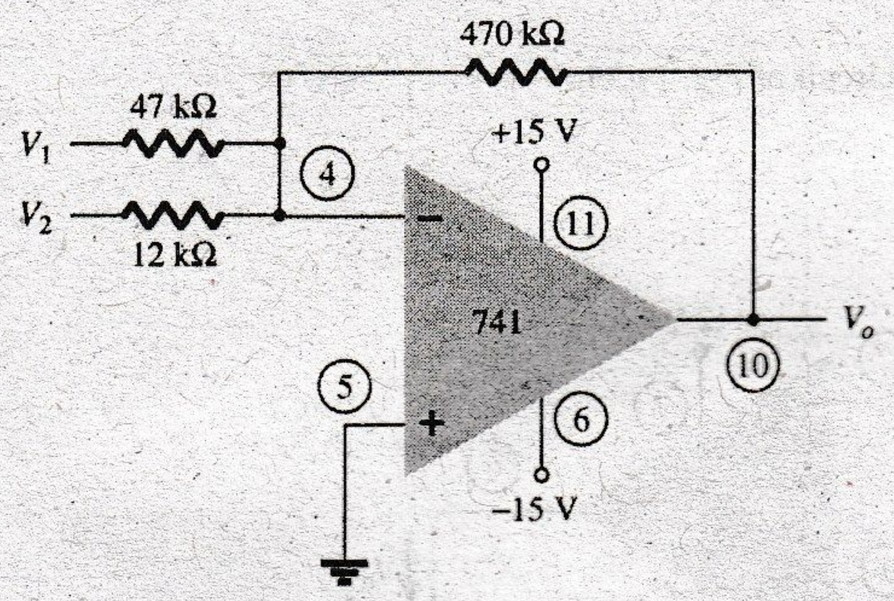


FIG. 11.50
Problem 6.

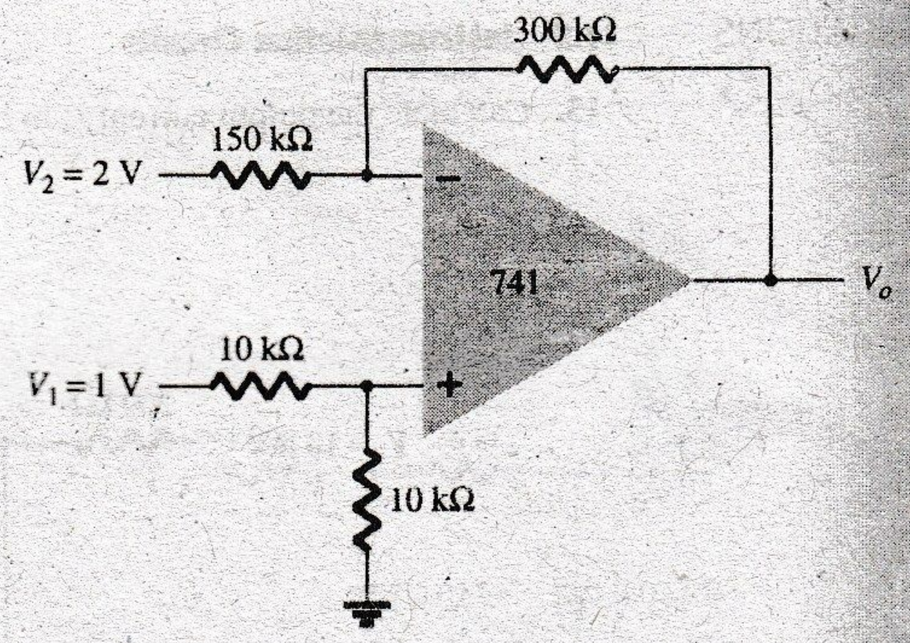


FIG. 11.51
Problem 7.

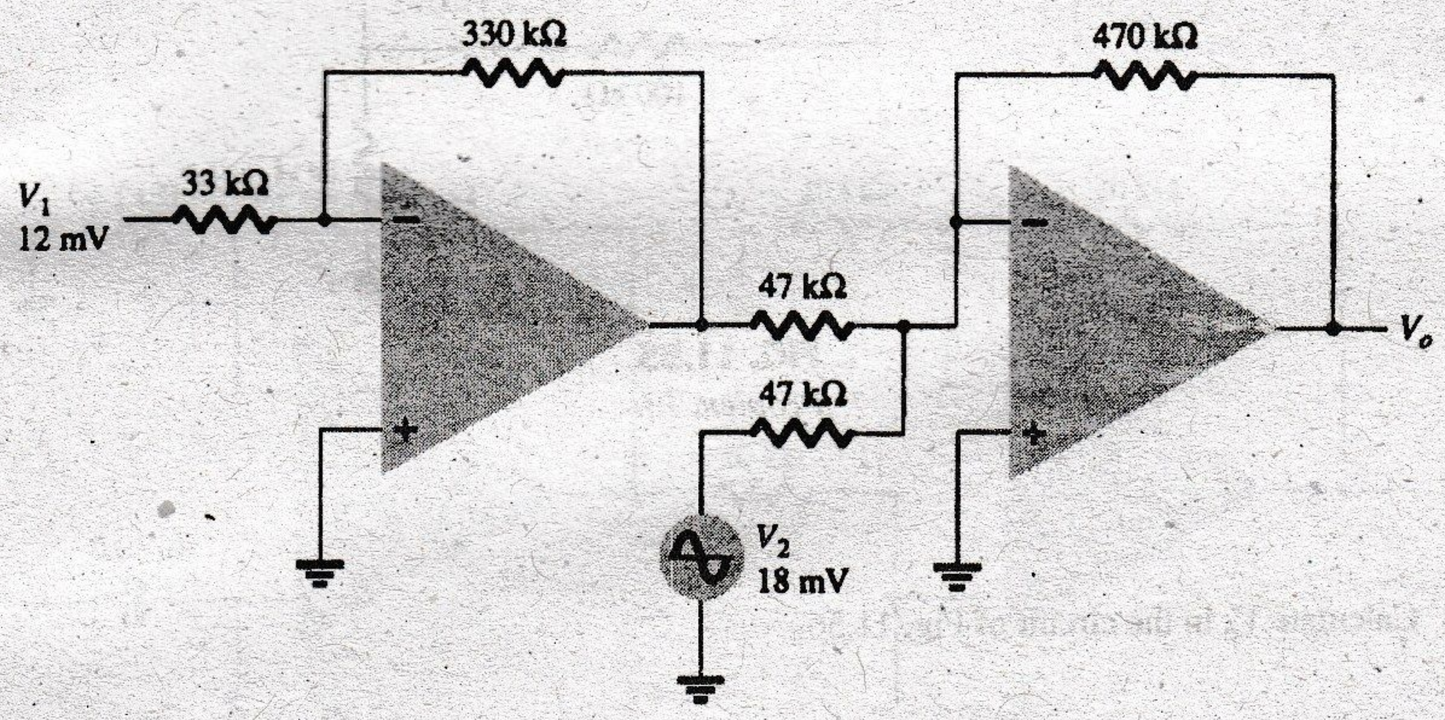


FIG. 11.52
Problem 8.

11.3 Voltage Buffer

9. Show the connection (including pin information) of an LM124 IC stage connected as a unity-gain amplifier.
10. Show the connection (including pin information) of two LM358 stages connected as unity-gain amplifiers to provide the same output.

11.4 Controlled Sources

11. For the circuit of Fig. 11.53, calculate I_L.
12. Calculate V_o for the circuit of Fig. 11.54.

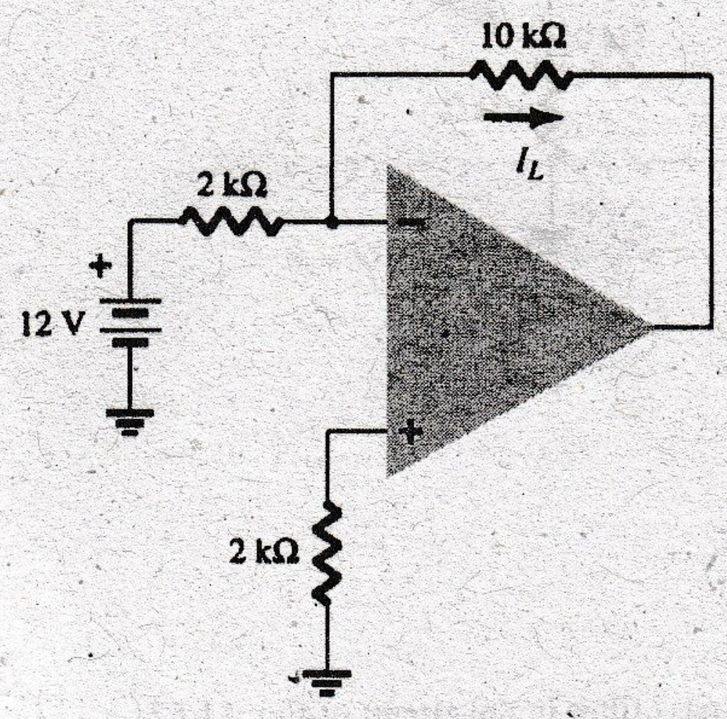


FIG. 11.53
Problem 11.

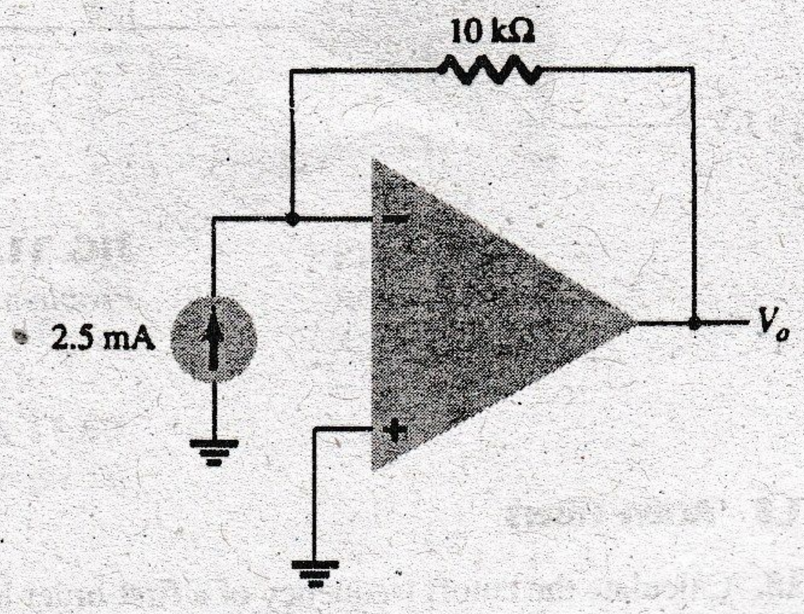


FIG. 11.54
Problem 12.

11.5 Instrumentation Circuits

13. Calculate the output current I_o in the circuit of Fig. 11.55.

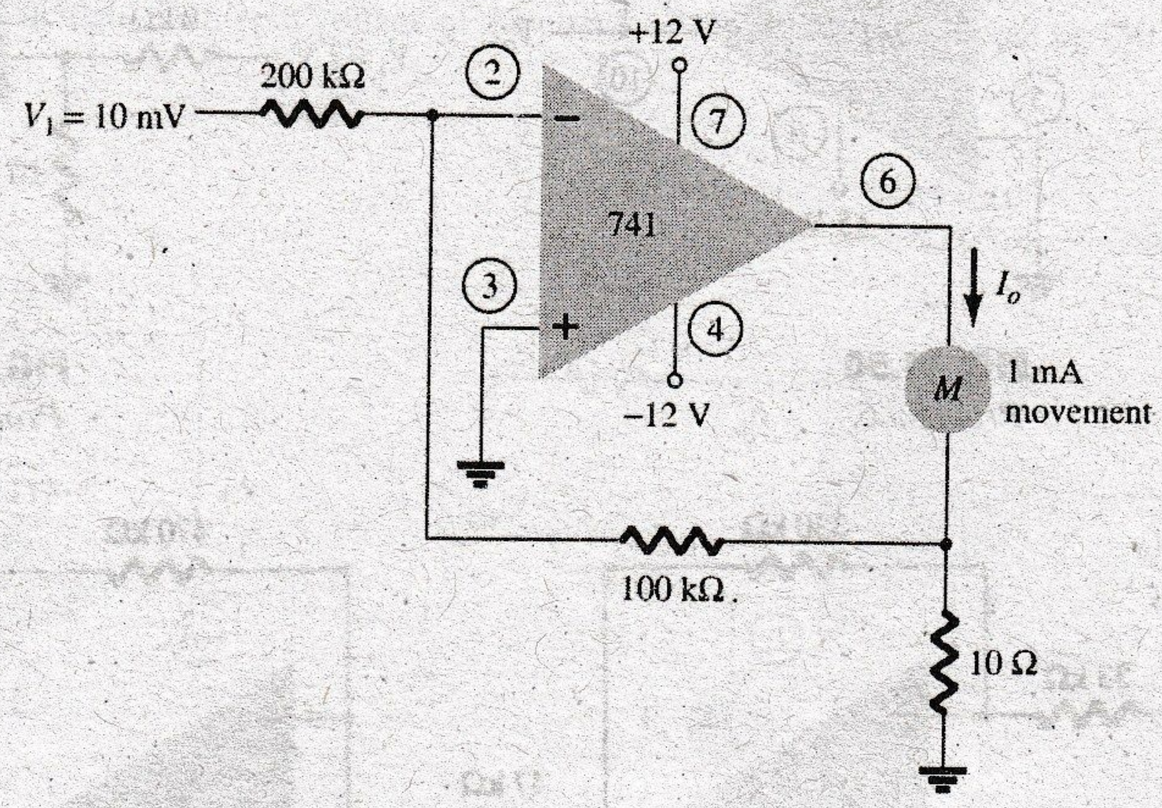


FIG. 11.55
Problem 13.

*14. Calculate V_o in the circuit of Fig. 11.56.

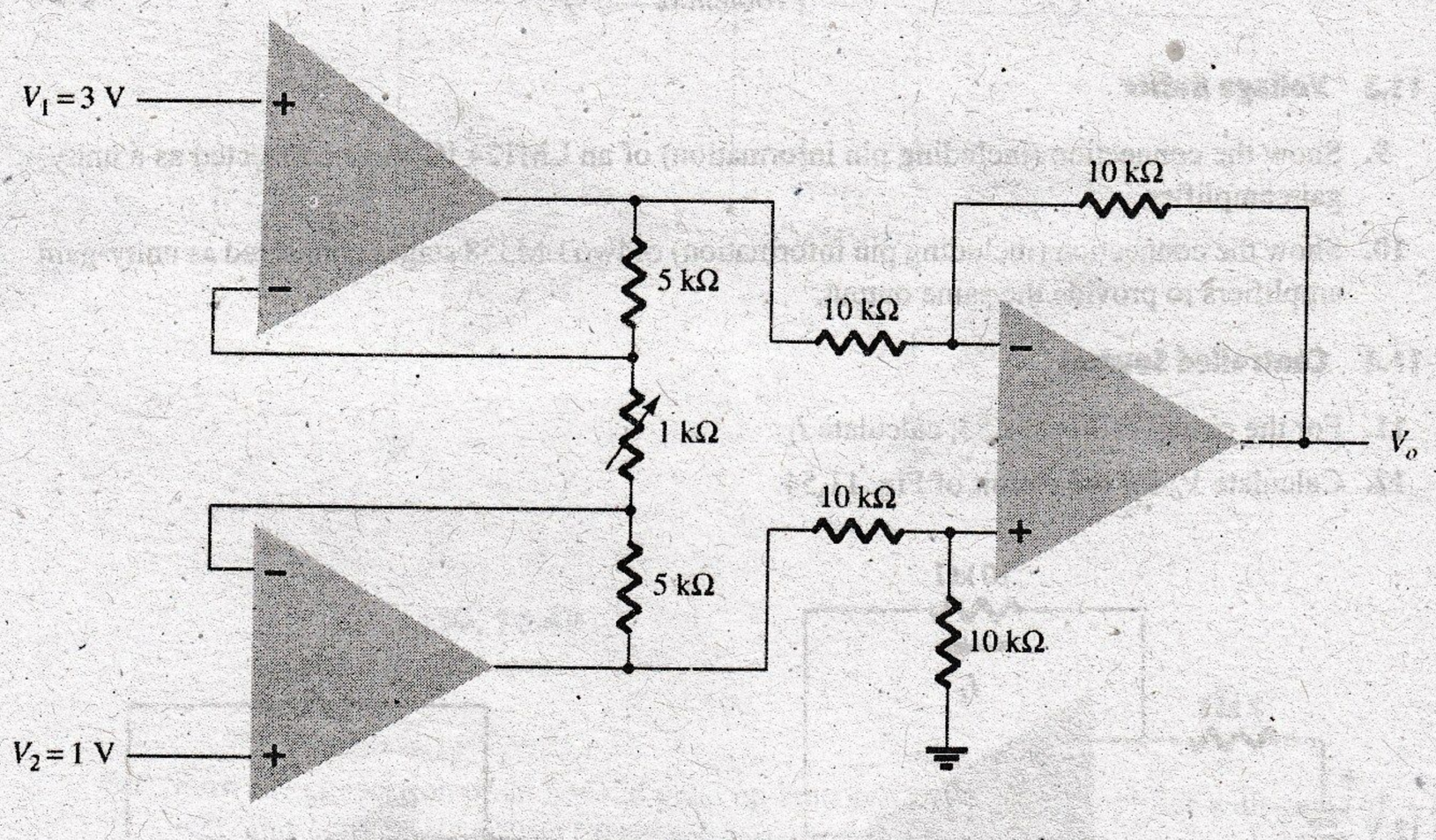


FIG. 11.56
Problem 14.

11.6 Active Filters

15. Calculate the cutoff frequency of a first-order low-pass filter in the circuit of Fig. 11.57.
16. Calculate the cutoff frequency of the high-pass filter circuit in Fig. 11.58.
17. Calculate the lower and upper cutoff frequencies of the bandpass filter circuit in Fig. 11.59.

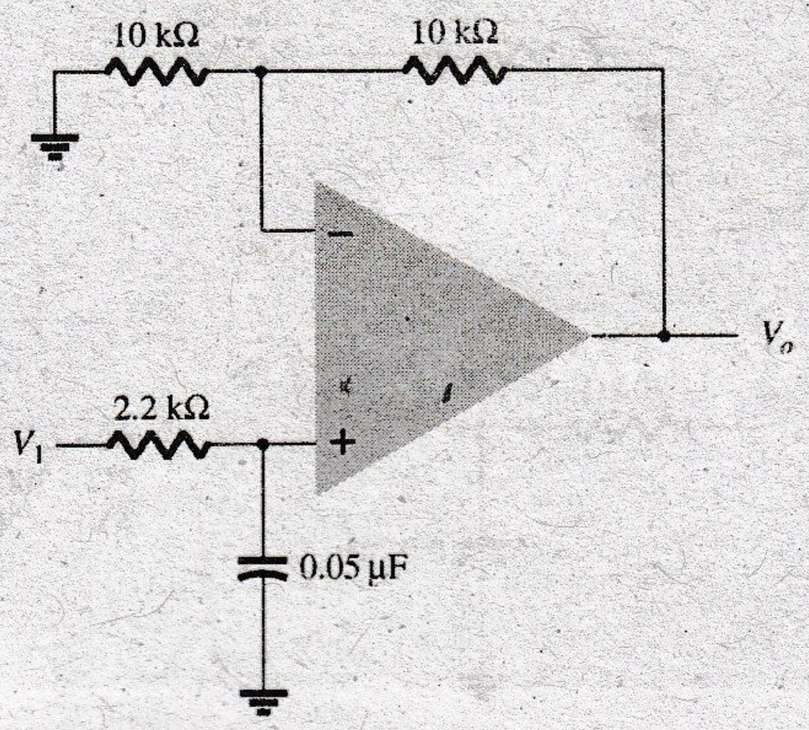


FIG. 11.57
Problem 15.

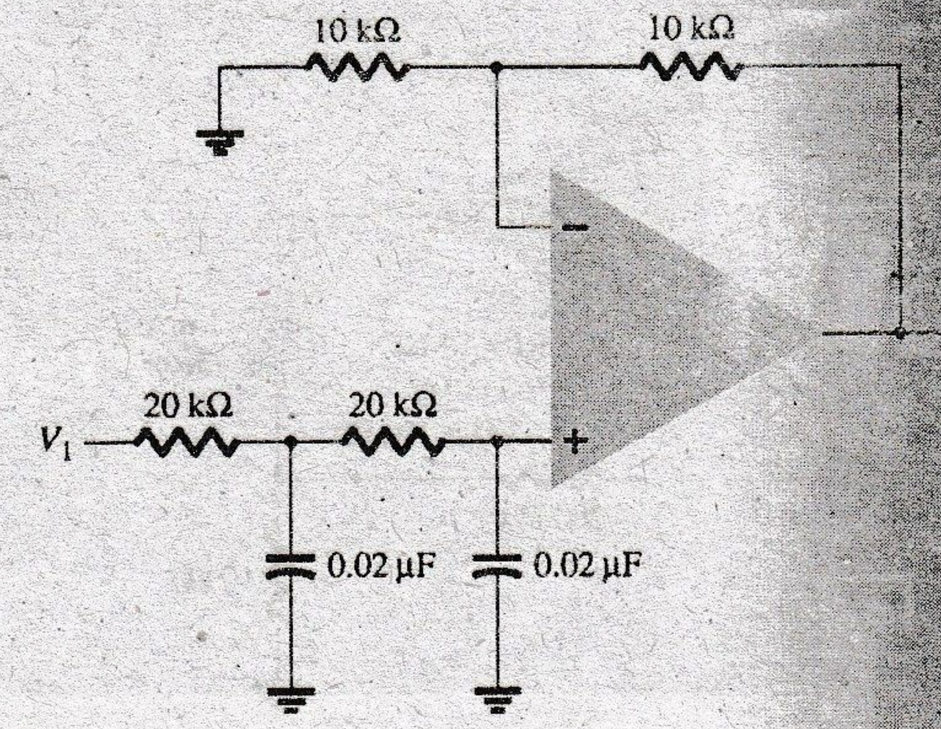


FIG. 11.58
Problem 16.

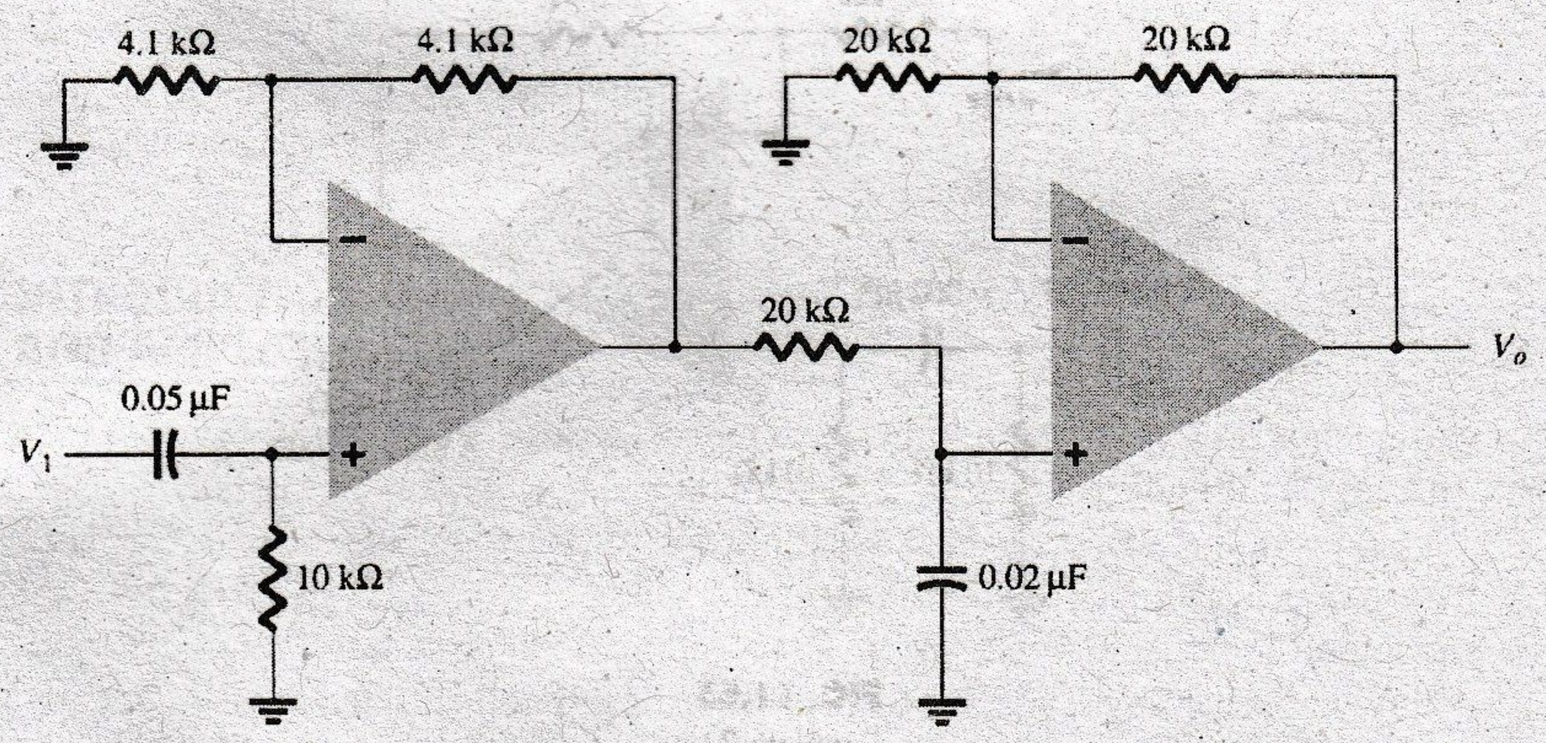


FIG. 11.59
Problem 17.

11.8 Computer Analysis

***18.** Use Design Center to draw the schematic of Fig. 11.60 and determine V_o.

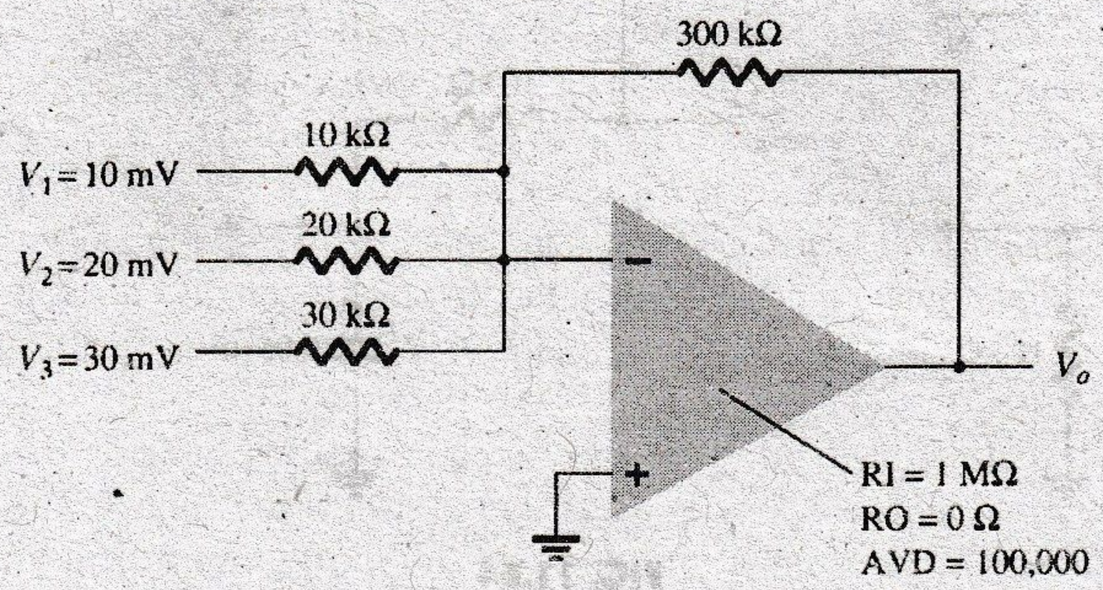


FIG. 11.60
Problem 18.

***19.** Use Design Center to calculate I(VSENSE) in the circuit of Fig. 11.61.

***20.** Use Multisim to plot the response of the low-pass filter circuit in Fig. 11.62.

***21.** Use Multisim to plot the [illegible] of the high-pass filter circuit in Fig. 11.63.

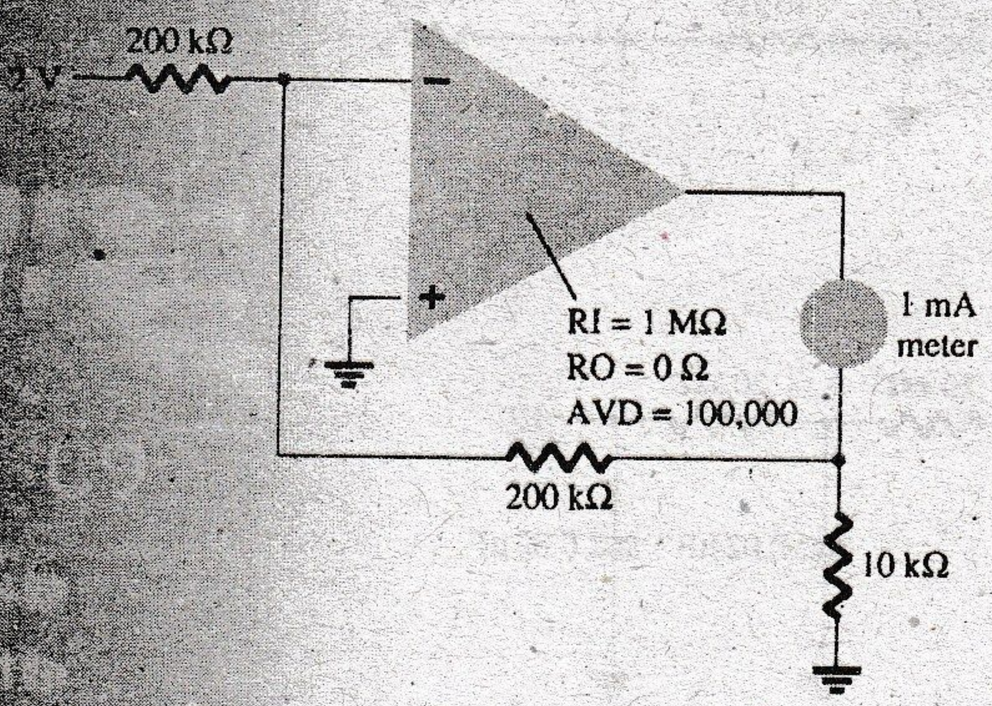


FIG. 11.61
Problem 19.

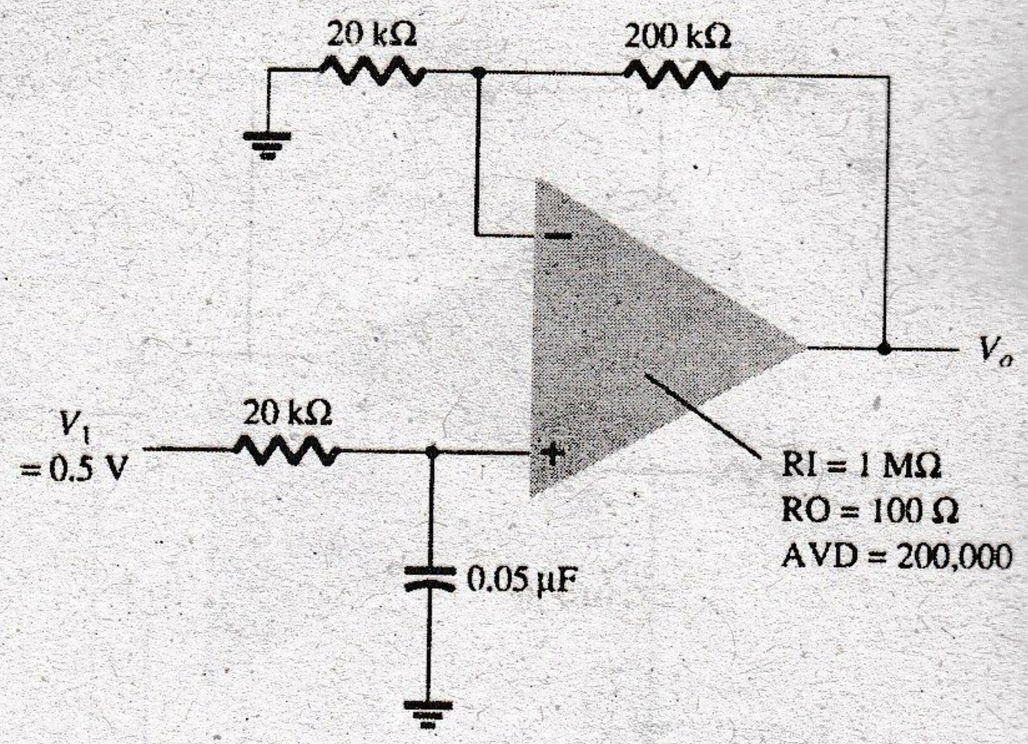


FIG. 11.62
Problem 20.

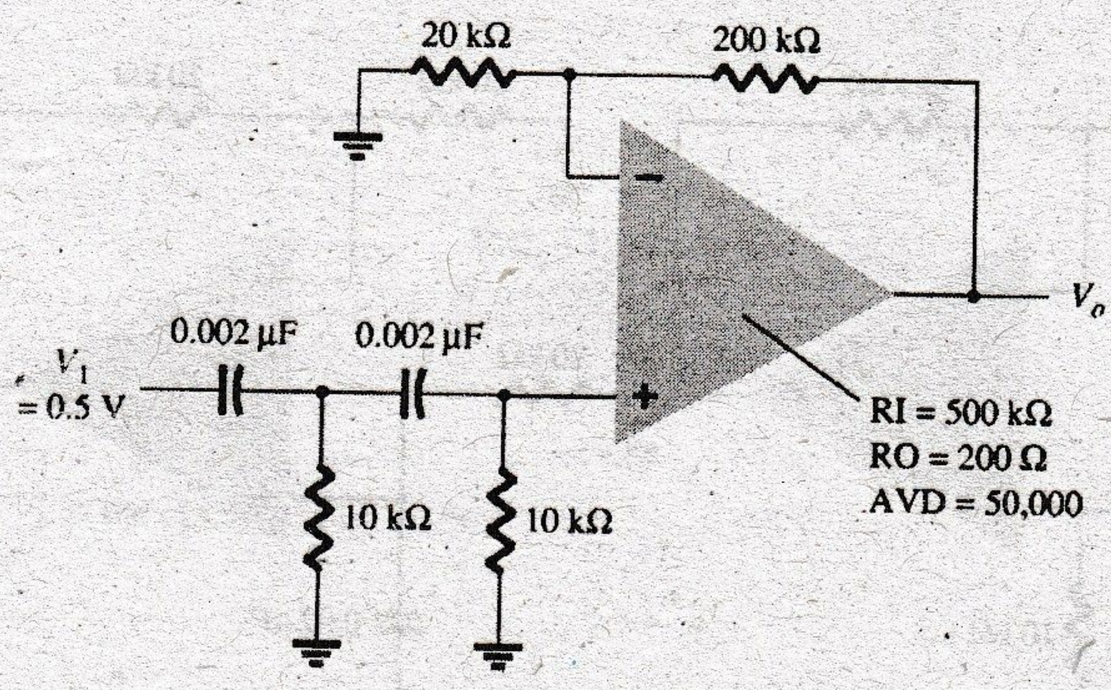


FIG. 11.63
Problem 21.

***22.** Use Design Center to plot the response of the bandpass filter circuit in Fig. 11.64.

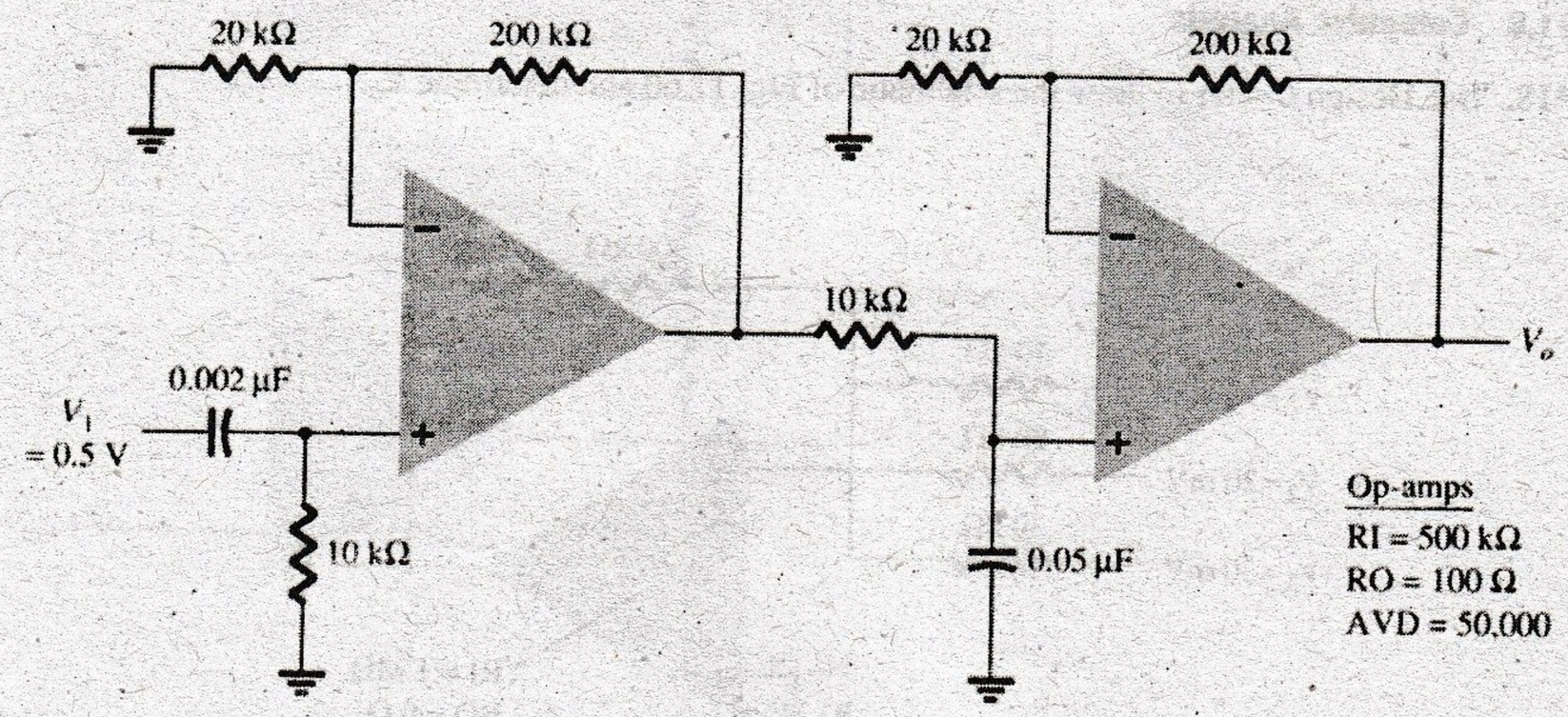


FIG. 11.64
Problem 22.