



Sophomore Physics Laboratory (PH005/105)

Analog Electronics

Copyright©Virgínio de Oliveira Sannibale, 2003
(Revision October 2011)

Chapter 5

Basic Op-Amp Applications

5.1 Introduction

In this chapter we will briefly describe some quite useful circuit based on Op-Amp, bipolar junction transistors, and diodes.

5.1.1 Inverting Summing Stage

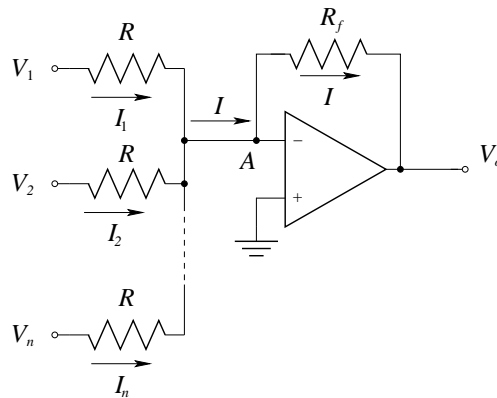


Figure 5.1: Inverting summing stage using an Op-Amp. The analysis of the circuit is quite easy considering that the node A is a virtual ground.

Figure 5.1 shows the typical configuration of an inverting summing stage using an Op-Amp. Using the virtual ground rule for node A and

Ohm's law we have

$$I_n = \frac{V_n}{R}, \quad I = \sum_{n=1}^N I_n.$$

Considering that the output voltage V_o is

$$V_o = -R_f I,$$

we will have

$$V_o = A \sum_{n=1}^N V_n, \quad A = -\frac{R_f}{R}.$$

5.1.2 Basic Instrumentation Amplifier

Instrumentation amplifiers (In-Amp) are designed to have the following characteristics: differential input, very high input impedance, very low output impedance, variable gain, high CMRR, and good thermal stability. Because of those characteristics they are suitable but not restricted to be used as input stages of electronics instruments.

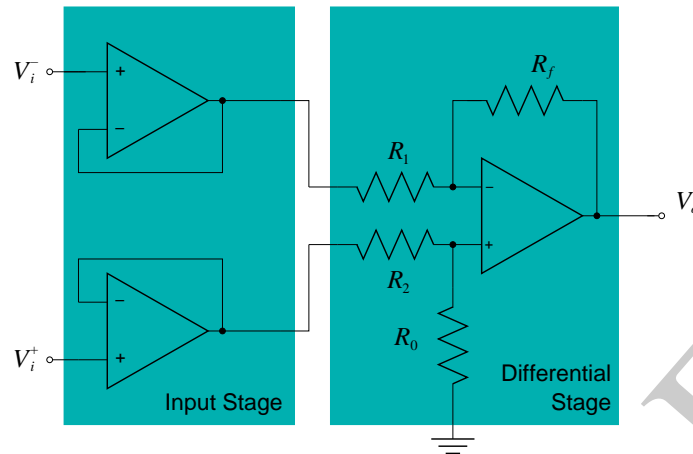


Figure 5.2: Basic instrumentation amplifier circuit.

Figure 5.2 shows a configuration of three operational amplifier necessary to build a basic In-Amps. The two buffers improve the input impedance of this In-Amp, but some of the problems of the differential amplifier are

still present in this circuit, such as common variable gain, and gain thermal stability.

A straightforward improvement is to introduce a variable gain on both amplifiers of the input stage as shown in Figure 5.3(a). Unfortunately, it is quite hard to keep the impedance of the two Op-Amps well matched, and contemporary vary their gain to keep a very high CMRR. A clever solution to this problem is shown in Figure 5.3(b). Because of the virtual ground this configuration is not very different from the previous one but it has the advantage of requiring one resistor to set the gain. In fact, if $R_1 = R_4$ then the gain of the Op-Amps A_1 and A_2 can be set at the same time adjusting just R_G .

For an exhaustive documentation on instrumentation amplifiers consult [2].

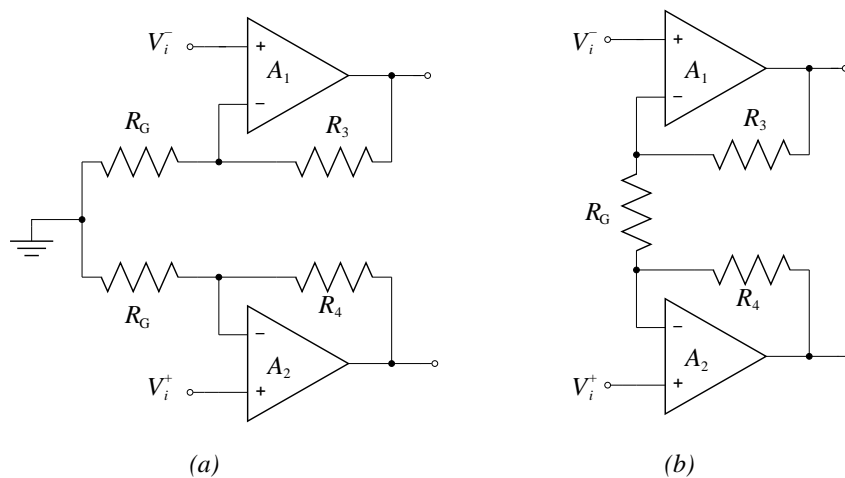


Figure 5.3: Improved input stages of the basic instrumentation amplifier.

5.1.3 Voltage to Current Converter (Transconductance Amplifier)

A voltage to current converter is an amplifier that produces a current proportional to the input voltage. The constant of proportionality is usually called *transconductance*. Figure 5.4 shows a Transconductance Op-Amp, which is nothing but a non inverting Op-Amp scheme.

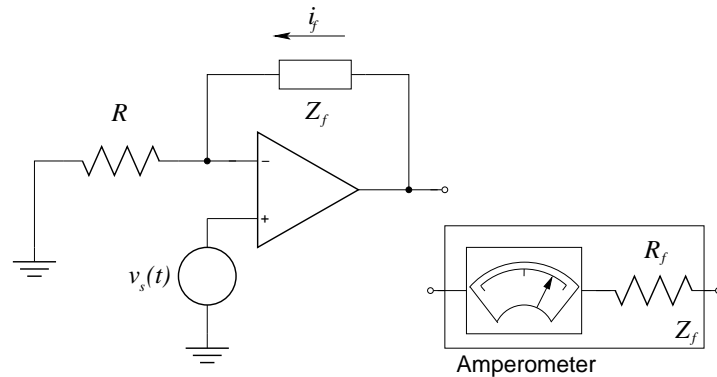


Figure 5.4: Basic transconductance amplifier circuit.

The current flowing through the impedance Z_f is proportional to the voltage v_s . In fact, supposing the infinite input impedance of the Op-Amp, we will have

$$i_f(t) = \frac{v_s(t)}{R}.$$

Placing an amperometer in series with a resistor with large resistance as a feedback impedance, we will have a high resistance voltmeter. In other words, the induced perturbation of such circuit will be very small because of the very high impedance of the operational amplifier.

5.1.4 Current to Voltage Converter (Transresistance Amplifier)

A current to voltage converter is an amplifier that produces a voltage proportional to the input current. The constant of proportionality is called *transimpedance* or *transresistance*, and its units are Ω . Figure 5.5 show a basic configuration for a transimpedance Op-Amp. Due to the virtual ground the current through the shunt resistance is zero, thus the output voltage is the voltage difference across the feedback resistor R_f , i.e.

$$v_o(t) = -R_f i_s(t).$$

Photo-multipliers photo-tubes and photodiodes drivers are a typical application for transresistance Op-amps. In fact, quite often the photo-current produced by those devices need to be amplified and converted into a voltage before being further manipulated.

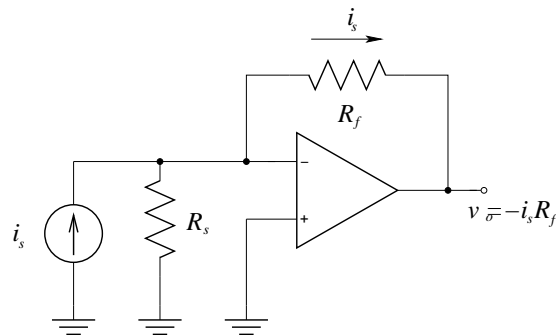


Figure 5.5: Basic transimpedance Op-Amp.

5.2 Logarithmic Circuits

By combining summing circuits with logarithmic and anti-logarithmic amplifiers we can build analog multipliers and dividers. The circuits presented here implements those non-linear operations just using the exponential current response of the semiconductor junctions. Because of that, they lack on temperature stability and accuracy. In fact, the diode reverse saturation current introduces an offset at the circuits output producing a systematic error. The temperature dependence of the diode exponential response makes the circuit gain to drift with the temperature. Nevertheless these circuits have a pedagogical interest and are the basis for more sophisticated solutions. For improved logarithmic circuits consult [1] chapter 7, and [1] section 16-13 and[3].

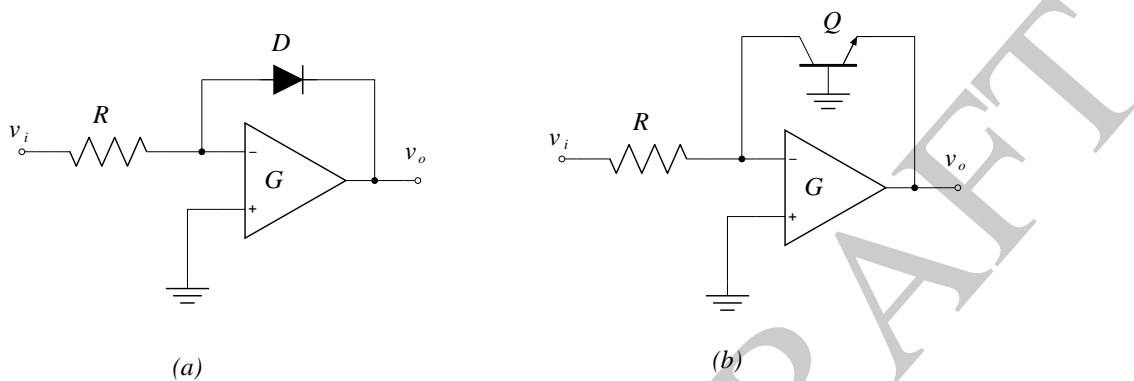


Figure 5.6: Elementary logarithmic amplifiers using a diode or an npn BJT.

5.2.1 Logarithmic Amplifier

Figure 5.6 (a) shows an elementary logarithmic amplifier implementation whose output is proportional to the logarithm of the input. Let's analyze this non-linear amplifier in more detail.

The Op-Amp is mounted as an inverting amplifier, and therefore if v_i is positive, then v_o must be negative and the diode is in conduction. The diode characteristics is

$$i = I_s \left(e^{-qv_o/k_B T} - 1 \right) \simeq I_s e^{-qv_o/k_B T} \quad I_s \ll 1,$$

where $q < 0$ is the electron charge. Considering that

$$i = \frac{v_i}{R},$$

after some algebra we finally get

$$v_o = \frac{k_B T}{-q} [\ln(v_i) - \ln(RI_s)].$$

The constant term $\ln(RI_s)$ is a systematic error that can be measured and subtracted at the output. It is worth to notice that v_i must be positive to have the circuit working properly. An easy way to check the circuit is to send a triangular wave to the input and plot v_o versus v_i . Because the BJT collector current I_c versus V_{BE} is also an exponential curve, we can replace the diode with an npn BJT as shown in Figure 5.6. The advantage of using a transistor as feedback path is that it should provide a larger input dynamic range.

If the circuit with the BJT oscillates at high frequency, a small capacitor in parallel to the transistor should stop the oscillation.

5.2.2 Anti-Logarithmic Amplifier

Figure 5.7 (a) shows an elementary anti-logarithmic amplifier, i.e. the output is proportional to the inverse of logarithm of the input. The current flowing through the diode is

$$i \simeq I_s e^{-qv_i/k_B T} \quad I_s \ll 1.$$

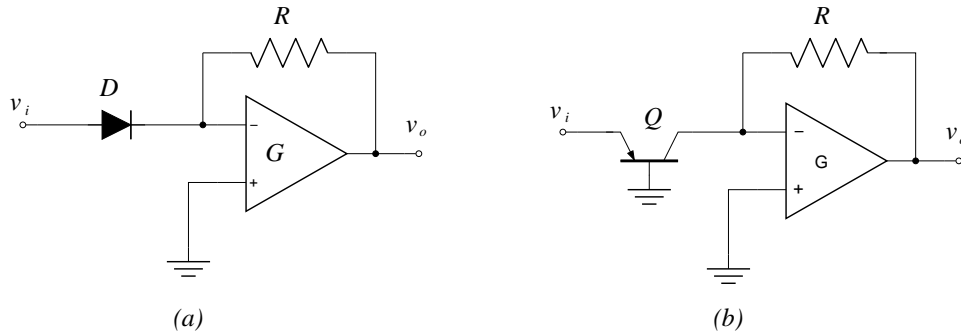


Figure 5.7: Elementary anti-logarithmic amplifiers using a diode or an pnp BJT.

Considering that

$$v_o = -Ri,$$

thus

$$v_o \simeq -RI_s e^{-qv_i/k_B T}.$$

If the input v_i is negative, we have to reverse the diode's connection. In case of the circuit of Figure 5.7 (b) we need to replace the pnp BJT with an npn BJT. Same remarks of the logarithmic amplifier about the BJT, applies to this circuit.

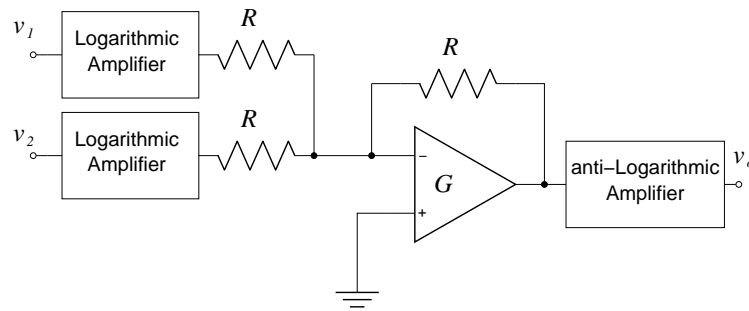


Figure 5.8: Elementary analog multiplier implementation using logarithmic and anti-logarithmic amplifiers

5.2.3 Analog Multiplier

Figure 5.8 shows an elementary analog multiplier based on a two log one anti-log and one adder circuits. For more details about the circuit see [1]

section 7-4 and [1] section 16-13.

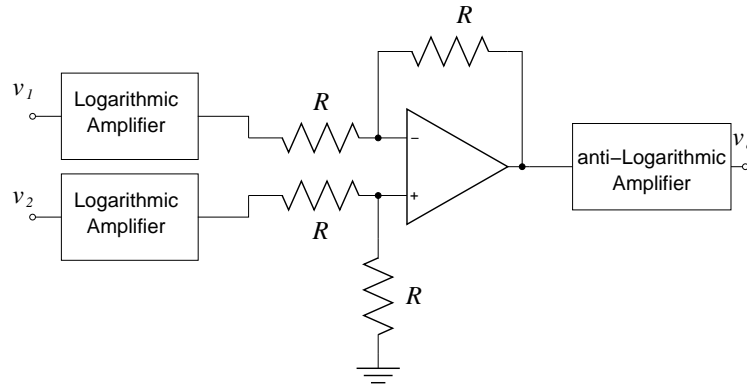


Figure 5.9: Elementary analog divider implementation using logarithmic and anti-logarithmic amplifiers.

5.2.4 Analog Divider

Figure 5.8 shows an elementary logarithmic amplifier based on a two log one anti-log and one adder circuits. Fore more details about the circuit see [1] section 7-5 and [1] section 16-13.

5.3 Multiple-Feedback Band-Pass Filter

Figure 5.10 shows the so called multiple-feedback bandpass, a quite good scheme for large pass-band filters, i.e. moderate quality factors around 10.

Here is the recipe to get it working. Select the following parameter which define the filter characteristics, i.e the center angular frequency ω_0 the quality factor Q or the the pass-band interval (ω_1, ω_2) , and the pass-band gain A_{pb}

$$\begin{aligned}\omega_0 &= \sqrt{\omega_2 \omega_1} \\ Q &= \frac{\omega_0}{\omega_2 - \omega_1} \\ A_{pb} &< 2Q^2\end{aligned}$$

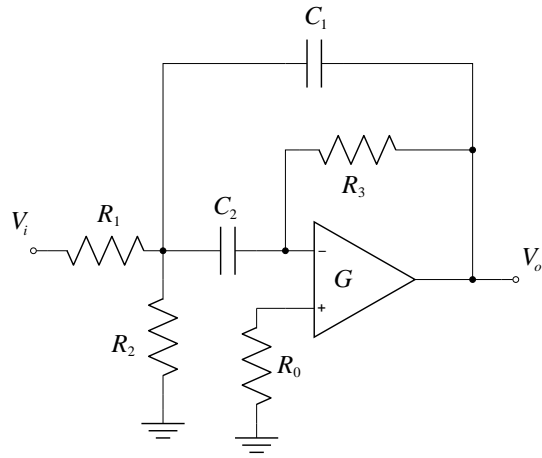


Figure 5.10: Multiple-feedback band-pass filter.

Set the same value C for the two capacitors and compute the resistance values

$$R_1 = \frac{Q}{\omega_0 C A_{pb}}$$

$$R_2 = \frac{Q}{\omega_0 C (2Q^2 - A_{pb})}$$

$$R_3 = \frac{2Q}{\omega_0 C}$$

Verify that

$$A_{pb} = \frac{R_3}{2R_1} < 2Q^2$$

See [1] sections 8-4.2, and 8-5.3 for more details.

5.4 Peak and Peak-to-Peak Detectors

The peak detector circuit is shown in Figure 5.11. The basic ideal is to implement an integrator circuit with a memory.

To understand the circuit let's first short circuit D_o and remove R . Then the Op-amp A_0 is just a unitary gain voltage follower that charges

the capacitor C up to the peak voltage. The function of D_0 and of A_1 (high input impedance) is to prevent the fast discharge of the capacitor.

Because of D_0 the voltage across the capacitor is not the max voltage at the input, and this will create a systematic error at the output v_o . Placing a feedback from v_o to v_i will fix the problem. In fact, because v_+ must be equal to v_- , A_0 will compensate for the difference.

Introducing the resistance ($R \simeq 100\text{k}\Omega$) in the feedback will provide some isolation for v_o when v_i is lower than v_C .

The Op-Amp A_0 should have a high slew rate ($\sim 20 \text{ V}/\mu\text{s}$) to avoid the maximum voltage being limited by the Op-Amp slew rate.

The capacitor doesn't have to limit the Op-Amp A_0 slew rate S , i. e.

$$\frac{i_C}{C} \ll \frac{dv}{dt} = S$$

It is worthwhile to notice that if D_0 and D_1 are reversed the circuit becomes a negative peak detector.

The technology of the hold capacitor C is important in this application. The best choice to reduce leakage is probably polypropylene, and after that polystyrene or Mylar.

Using a positive and a negative peak detector as the input of a differential amplifier stage we can build a peak-to-peak detector (for more details see [1] section 9-1). Some things to check: holding time (a given % drop from the maximum) versus capacitor technology, systematic errors, settling time required for the output to stabilize.

5.5 Zero Crossing Detector

When v_i is positive and because it is connected to the negative input then v_o becomes negative and the diode D_1 is forward biased and conducting.

5.6 Analog Comparator

An *analog comparator* or simply *comparator* is a circuit with two inputs v_i , v_{ref} and one output v_o which fulfills the following characteristic:

$$v_o = \begin{cases} V_1 & , v_i > v_{ref} \\ V_2, & v_i \leq v_{ref} \end{cases}$$

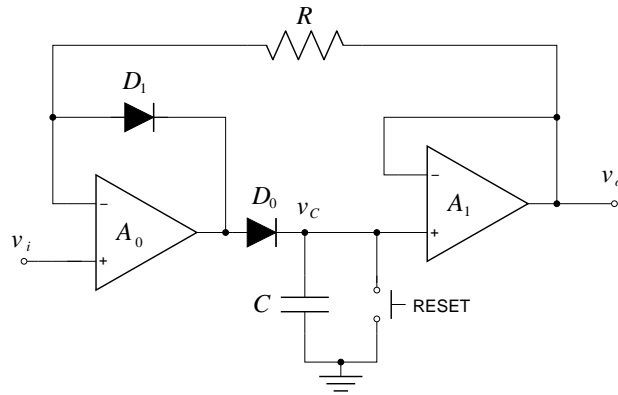


Figure 5.11: Peak detector circuit.

An Op-Amp with no feedback behaves like a comparator. In fact, if we apply a voltage $v_i > v_{ref}$, then $V_+ - V_- = v_i - v_{ref} > 0$. Because of the high gain, the Op-Amp will set v_o to its maximum value $+V_{sat}$ which is a value close to the positive voltage of the power supply. If $v_i < v_{ref}$, then $v_o = -V_{sat}$. The magnitude of the saturation voltage are typically about 1V less than the supplies voltages.

Depending on which input we use as voltage reference v_{ref} , the Op-amp can be an inverting or a non inverting analog comparator.

5.7 Regenerative Comparator (The Schmitt Trigger)

The *Regenerative comparator* or *Schmitt Trigger*¹ shown in Figure 5.12 is a comparator circuit with hysteresis.

It is important to notice that the circuit has a positive feedback. With positive feedback, the gain becomes larger than the open loop gain making the comparator to swing faster to one of the saturation levels.

Considering the current flowing through R_1 and R_2 , we have

¹Otto Herbert Schmitt (1913-1998) American scientist considered the inventor of this device, that appeared in an article in 1938 with the name of "thermionic trigger"[?].

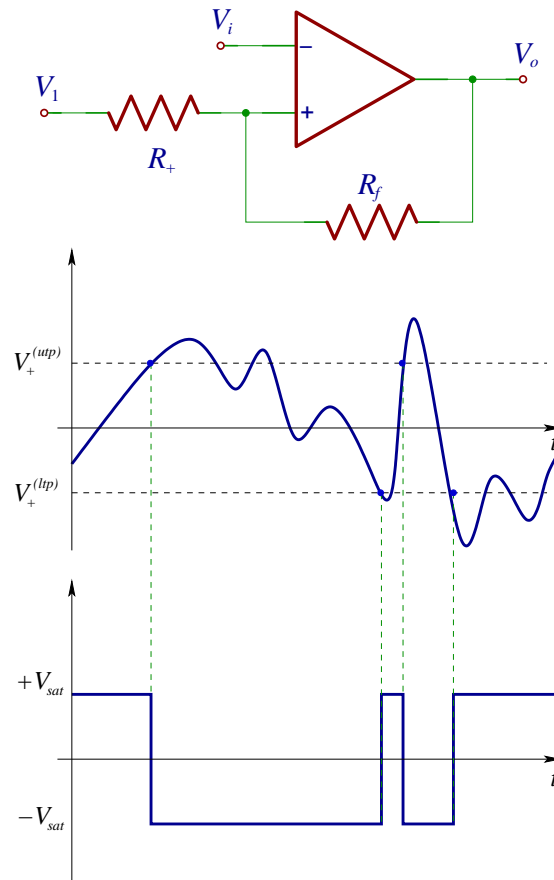


Figure 5.12: Schmitt Trigger and its qualitative response to a signal that swings up and down between and through the saturation voltages $\pm V_{sat}$.

$$I = \frac{V_1 - V_+}{R_+} = \frac{V_+ - V_o}{R_f}, \quad \Rightarrow \quad V_+ = \frac{V_1 R_f + V_o R_+}{R_f + R_+}.$$

The output V_o can have two values, $\pm V_{sat}$. Consequently, V_+ will assume just two trip points values

$$V_+^{(utp)} = \frac{V_1 R_f + V_{sat} R_+}{R_f + R_+} \quad V_+^{(ltp)} = \frac{V_1 R_f - V_{sat} R_+}{R_f + R_+}$$

When $V_i < V_+^{(utp)}$, V_o is high, and when $V_i < V_+^{(ltp)}$, V_o is low.

To set $V_+ = 0$ it requires that

$$V_1 = -\frac{R_+}{R_f}V_o$$

This circuit is usually used to drive an analog to digital converter (ADC). In fact, jittering of the input signal due to noise which prevents from keeping the output constant, will be eliminated by the hysteresis of the Schmitt trigger (values between the trip points will not affect the output).

See [1] section 11 for more detailed explanations.

Example1: ($V_{sat} = 15V$)

Supposing we want to have the trip points to be $V_+ = \pm 1.5V$, if we set $V_1 = 0$ then $R_f = 9R_+$.

5.8 Phase Shifter

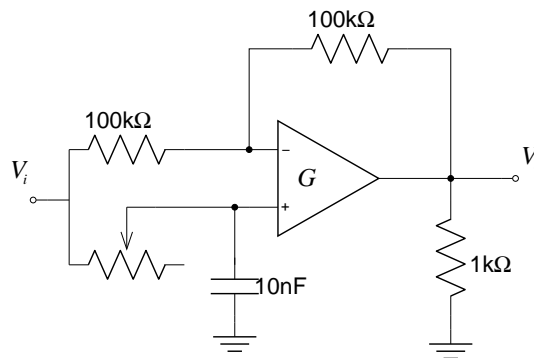


Figure 5.13: Phase shifter circuit.

A phase shifter circuit shown in Figure 5.13, produces a signal at the output V_o which is equal to the input V_i with a phase shift φ given by the following formula

$$\tan\left(\frac{|\varphi|}{2}\right) = \frac{1}{RC\omega}$$

Supposing that we want a phase shift of 90° for a 1kHz sinusoid , then

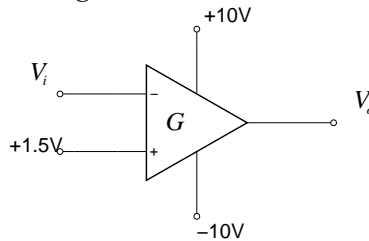
$$R = \frac{1}{\tan\left(\frac{\phi}{2}\right) C\omega} = \frac{1}{1 \cdot 10^{-8} \cdot 2\pi \cdot 10^3} = 15.915\text{k}\Omega.$$

Exchanging the potentiometer and the capacitor changes lead to lag.

DRAFT

5.9 Problems Preparatory to the Laboratory

1. Considering the following circuit, determine the voltage output V_o for the following input voltages $V_i = -2V, 1V, 1.5V, 3V$



2. Consider the Schmitt trigger of Figure 5.12.
 - (a) If $V_o = -15V$ and $V_+ = 0V$, compute V_1 .
 - (b) If $V_o = +15V$, and $V_1 = 15V$, compute V_+ .
3. Design a Schmitt trigger with two diode clamps and one resistor connected to the output.
 - (a) Limit the output V_o from 0 to 5V.
 - (b) Compute the resistance value R necessary to limit the diode current to 10mA.
4. What is the practical maximum and minimum output voltage of the logarithmic amplifier in Figure 5.6?
5. Chose and study at least two circuit to study and design. New circuits different than those ones proposed in this chapter are also welcome. For a good source of new circuits based on Op-Amps see [1], [4], and [2].

5.10 Laboratory Procedure

No special procedure is required for this laboratory week. The student is encouraged to study, build and test more than one circuit (two at least) from this chapter and the next chapter on active filters. It is important also to try to find out circuit limitations, and to measure their performance.

Students are also encouraged to try basic Op-Amp applications different from the ones suggested in this notes.

Depending on the type of circuit the usual following measurements can be done to characterize the circuit

- Frequency response
- transient response
- Circuit output variation versus circuit parameter variation (voltage, resistance capacitance, etc..)

As usual, a report of the work done during the laboratory hours is required.

- Consult the data-sheets to properly connect the devices pin-out.
- Before powering your circuit up, always cross-check the power supply connections.
- It is always a good practice to turn on the dual power supply at the same time to avoid potential damages of electronic components.

DRAFT

Bibliography

- [1] Luces M. Faulkenberry. An introduction to Operational Amplifiers with Linear IC Applications, Second Edition.
- [2] Charles Kitchin and Lew Counts, A Designer's Guide to Instrumentation Amplifiers (2nd Edition), Analog Devices (<http://www.analog.com/en/DCcList/0,3090,759%255F%255F42,00.html>)
- [3] Theory and Applications of Logarithmic Amplifiers, National Semiconductors, AN-311 (<http://www.national.com/an/AN/AN-311.pdf>).
- [4] Horowitz and Hill, The Art of Electronics, Second Edition
- [5] Microelectronics Jacob Millman & Arvin Grabel, McGraw-Hill Electrical Engineering Series
- [6] A thermionic trigger, Otto H Schmitt 1938 J. Sci. Instrum. 15 24-26.

DRAFT

DRAFT