Chapter 2

# Amplifiers and Feedback

## 2.1 INTRODUCTION

Practically all circuits using Operational Transconductance Amplifiers are based around one of a few fundamental configurations. In this chapter, you will learn about these building blocks. The basic building blocks [1] are realized using Operational Transconductance Amplifiers (OTA). It is shown that circuits provide improvements in design simplicity and programmability when compared with Op-amp based structures as well as reduced component count.

## 2.2 BASIC INVERTING AMPLIFIER

The basic inverting amplifier is shown in Fig. 2.1. The input voltage $V_i$ is applied to the inverting terminal of OTA and non-inverting terminal is grounded. The load resistance $R_L$ is connected at the output of OTA. Assuming OTA to be ideal, the output current of OTA is

$$I_o = -g_m V_i \tag{2.1}$$

The current flowing through the load $R_L$ is also $I_o$

$$I_o = \frac{V_o}{R_L} \tag{2.2}$$

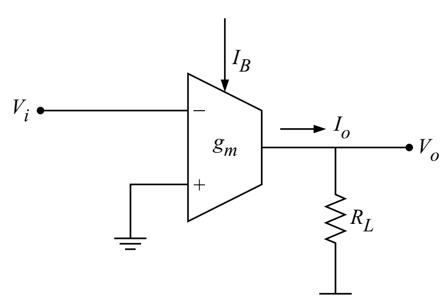



**Fig. 2.1** Inverting amplifier

buffer is used at the output; it is useful for reducing the output impedance ($Z_o$) of the OTA.The analysis of the circuit of Fig. 2.4, gives

$$\frac{V_o}{V_i} = -g_m R_L \tag{2.10}$$

and $$Z_o = 0$$

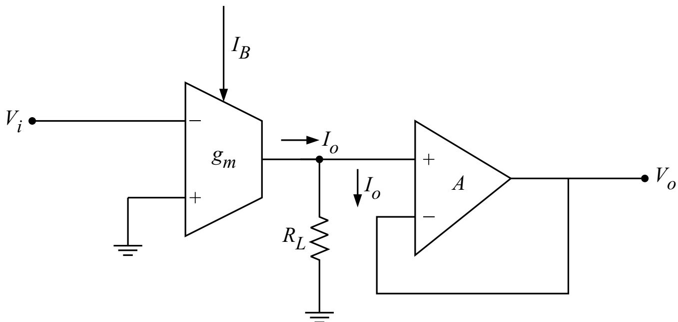



**Fig. 2.4** Inverting feedback amplifier

In the inverting feedback amplifier of Fig. 2.4, the effects of parasitics are due to output parasitic capacitance of the OTA along with instrumentation parasitics, parallel the resistor $R_L$ in discrete component structures, thus causing a roll-off in the frequency response of the circuits.

## 2.6 NON-INVERTING FEEDBACK AMPLIFIER

The circuit for non-inverting feedback amplifier is shown in Fig. 2.5. The input $V_i$ is applied at the non-inverting terminal of OTA and the inverting terminal is grounded. Voltage buffer is connected at the output of OTA. Analysis of the circuit of Fig. 2.5 gives

$$\frac{V_o}{V_i} = g_m R_L \tag{2.11}$$

and $$Z_o = 0$$

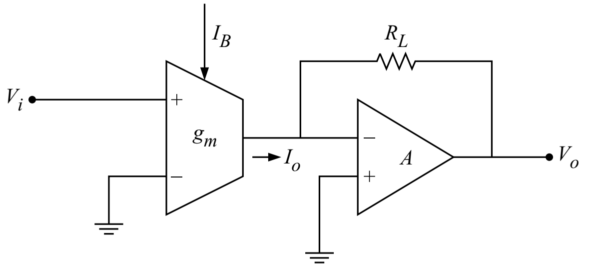



**Fig. 2.5** Non-inverting feedback amplifier

The gain characteristics of the circuit of Fig. 2.4 and Fig. 2.5 are ideally same, but the performance of the two circuits is different due to difference in the effects of parasitics in the circuits. For non-inverting amplifier, the output parasitic capacitance of OTA is connected across the null port of an Op-amp and thus has negligible effects when the Op-amp works properly.

For the inverting and non-inverting feedback amplifiers of Fig. 2.4 and Fig. 2.5, the major factor limiting the bandwidth is generally the finite gain-bandwidth product *GB*, of Op-amp. If the Op-amps are modeled by the single-pole roll-off model, $A(s) = GB/s$, and OTAs are assumed to be ideal, then bandwidth of these circuit is GB, which is independent of the voltage gain of the amplifier, while for single Op-amp base non-inverting and inverting amplifiers of gain $K$ and $-K$, the bandwidth is $GB/K$ and $GB/1+K$, respectively, which depends on gains.

## 2.7 BUFFERED AMPLIFIERS

The circuit for a feedback amplifier is shown in Fig. 2.6.
Input current ($I_i$) flowing through $R_1$ is

$$I_i = \frac{(V_i - V)}{R_1} \tag{2.12}$$

The output current of OTA, $I_o$ is

$$I_o = -g_m V \tag{2.13}$$

KCL at $V$ gives

$$I_i = -I_o \tag{2.14}$$

The current flowing through $R_2$ is

$$I_o = \frac{(V_0 - V)}{R_2} \tag{2.15}$$

Equating equations (2.13) and (2.15) gives

$$V = \frac{V_o}{1 - g_m R_2} \tag{2.16}$$

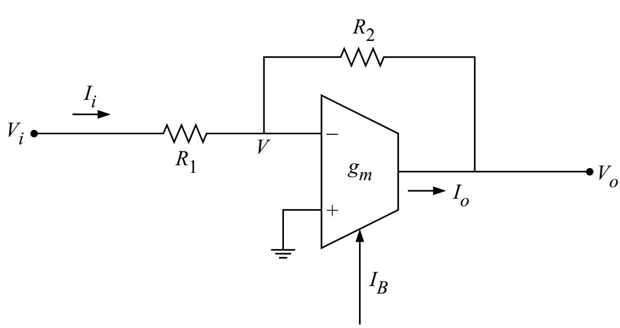



**Fig. 2.6** Buffered amplifier

From equations (2.12), (2.13) and (2.14), we have

$$g_m V = \frac{V_i - V}{R_1}$$

Solving this equation for $V_i$, gives

$$V_i = V(1 + g_m R_1) \tag{2.17}$$

Substituting $V$ from equation (2.16) in equation (2.17) gives

$$V_i = V_o \frac{(1 + g_m R_1)}{(1 - g_m R_2)}$$

or

$$\frac{V_o}{V_i} = \frac{(1 - g_m R_2)}{(1 + g_m R_1)} \tag{2.18}$$

and thus

$$Z_o = \frac{R_1 + R_2}{1 + g_m R_1}$$

From equation (2.18), it is evident that the voltage gain can be continuously adjusted between positive and negative values with the parameter $g_m$.

Consider the circuit of Fig. 2.7. The input signal is applied at the non-inverting terminal. The output current ($I_o$) of OTA is

$$I_o = g_m(V_i - V) \tag{2.19}$$

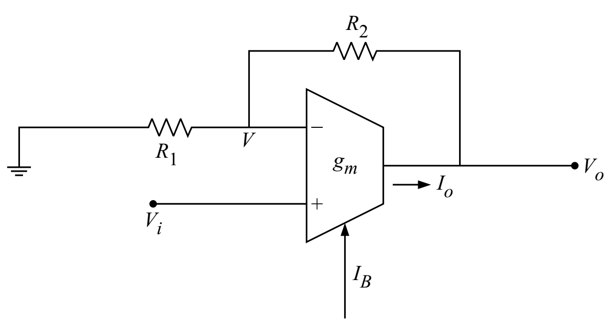



**Fig. 2.7** Buffered amplifier

Also

$$I_o = \frac{V_o - V}{R_2} \tag{2.20}$$

KCL at node $V$ gives

$$\frac{V_o - V}{R_2} = \frac{V}{R_1} \tag{2.21}$$

or

$$V = \frac{V_o R_1}{R_1 + R_2} \tag{2.22}$$

Equating equations (2.19) and (2.20) gives

$$V_o - V = g_m R_2 (V_i - V)$$

or

$$V_o - g_m R_2 V_i = V(1 - g_m R_2) \tag{2.23}$$

Substituting $V$ from equation (2.22) in equation (2.23) gives

$$\frac{V_o}{V_i} = \frac{g_m (R_1 + R_2)}{(1 + g_m R_1)} \tag{2.24}$$

and

$$Z_o = \frac{R_1 + R_2}{1 + g_m R_1}$$

Hence, it is evident that voltage gain can be adjusted with the help of parameter $g_m$.

In the circuit Fig. 2.7, if we interchange the positive and negative terminals of the OTA, then very large gains can be obtained as $g_m R_1$ approaches to unity (as $Z_o$ approaches infinity). In that case voltage gain is given as

$$\frac{V_o}{V_i} = \frac{g_m (R_1 + R_2)}{(1 - g_m R_1)} \tag{2.25}$$

$$Z_o \to \infty$$

## 2.8 SCALE CHANGER

The circuit for scale changer is shown in Fig. 2.8. It consists of two OTAs without any passive components. The input signal $V_i$ is applied at the inverting terminal of $OTA_1$. The output is taken at the output of $OTA_2$.

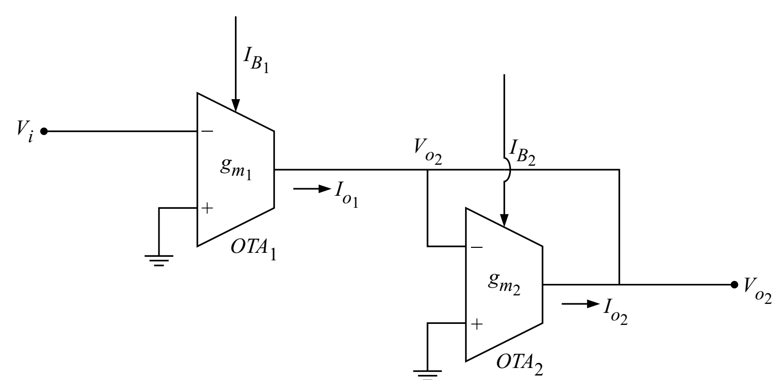



**Fig. 2.8** Scale changer

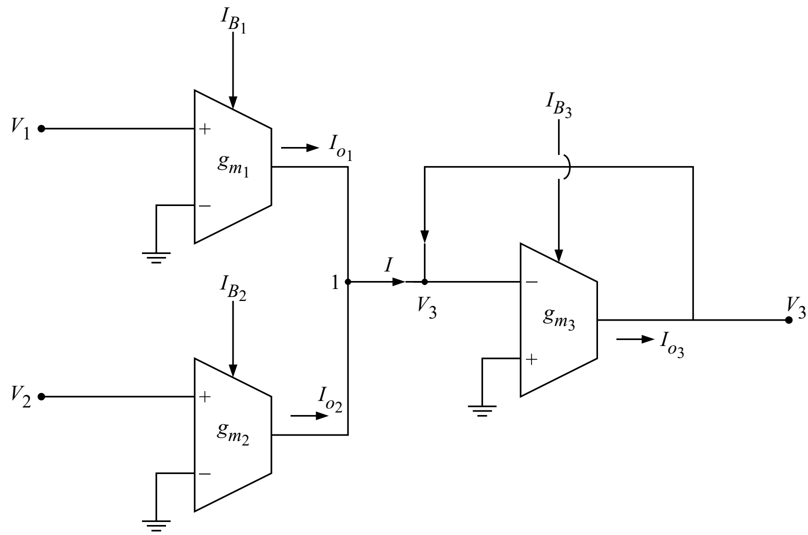



**Fig. 2.9** Summing amplifier

KCL at $V_3$ gives

$$I = -I_{o_3} = -(-g_{m_3}V_3)$$

or

$$I = g_{m_3}V_3 \tag{2.35}$$

From equations (2.31), (2.32) and (2.33), we get

$$I = g_{m_1}V_1 + g_{m_2}V_2 \tag{2.36}$$

Equating equations (2.35) and (2.36) gives

$$g_{m_3}V_3 = g_{m_1}V_1 + g_{m_2}V_2$$

$$V_3 = \frac{g_{m_1}V_1}{g_{m_3}} + \frac{g_{m_2}V_2}{g_{m_3}} \tag{2.37}$$

From equation (2.37), it is evident that the output voltage $V_3$ is the sum of two scaled voltages, and it can be controlled either by $g_{m_1}$, $g_{m_2}$ or $g_{m_3}$. This circuit can also be extended to more than two signals. Interchanging the input terminal of any feed in OTA will change the sign of the corresponding summing coefficient.

## 2.10 DIFFERENTIATOR

The circuit for OTA-based differentiator can be obtained by loading the output of an OTA by an inductor.

### 2.10.1 Two OTA-Based Differentiator

The circuit for differentiator using two OTAs is shown in Fig. 2.10. It consists of two OTAs along with two passive components. The OTA with transconductance gain $g_{m_1}$ is loaded with single OTA-based inductor.[3]

The output current $I_{o_1}$ is

$$I_{o_1} = -g_{m_1} V_1 \tag{2.38}$$

Also

$$I_{o_1} = \frac{(V_o - V_2)}{R} \tag{2.39}$$

The output current $I_{o_2}$ is,

$$I_{o_2} = -g_{m_2} V_o \tag{2.40}$$

Also

$$I_{o_2} = (V_2 - V_o)sC \tag{2.41}$$

Equating equations (2.38) and (2.39) gives

$$-Rg_{m_1} V_i = (V_o - V_2)$$

or

$$V_2 = (V_o + g_{m_1} V_i) \tag{2.42}$$

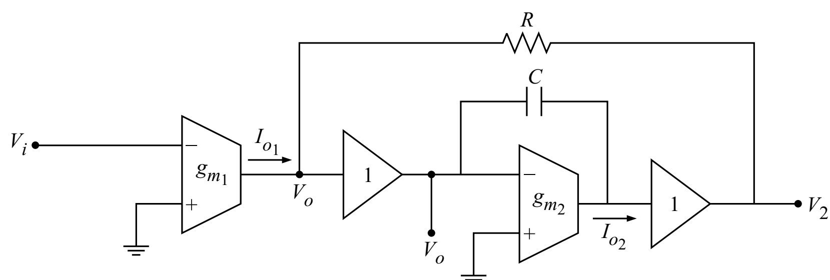



**Fig. 2.10** Two OTA-based differentiator

Equating equations (2.40) and (2.41) gives

$$(V_2 - V_o)sC = -g_{m_2} V_o$$

or

$$V_2 = \frac{V_o sC - g_{m_2} V_o}{sC} \tag{2.43}$$

Equating the equations (2.42) and (2.43) gives voltage gain $\left(\frac{V_o}{V_i}\right)$ of the differentiator as

$$\frac{V_o}{V_i} = \frac{-sg_{m_1} RC}{g_{m_2}} \tag{2.44}$$

From equation (2.44), it is clear that, an ideal inverting differentiator is realized. The voltage gain of the realized differentiator can conveniently be controlled more strongly with the bias current control of the OTAs, i.e., either by $g_{m_1}$ or $g_{m_2}$. Inverting and non-inverting differentiator can be obtained by connecting inverting or non-inverting terminal of $OTA_1$ to ground respectively.

### 2.10.2 Three OTA-Based Differentiator

The circuit for differentiator using three OTAs is shown in Fig. 2.11. It consists of three OTAs along with a capacitor. The OTA with $g_{m1}$ is loaded by two OTA-based inductors [2].

The output current $I_{o_1}$ is

$$I_{o_1} = -g_{m_1} V_i \tag{2.45}$$

KCL at $V_o$ gives

$$I_{o_1} = -I_{o_3} \tag{2.46}$$

$$I_{o_2} = g_{m_2} V_o \tag{2.47a}$$

Also

$$I_{o_2} = sV_2C \tag{2.47b}$$

$$I_{o_3} = -g_{m_3} V_2 \tag{2.48}$$

From equations (2.45), (2.46) and (2.48), we get

$$-g_{m_1} V_i = -(-g_{m_3} V_2)$$

or

$$V_2 = -\frac{g_{m_1}}{g_{m_3}} V_i \tag{2.49}$$

Equating the equations (2.47a) and (2.47b) gives

$$g_{m_2} V_o = sV_2C$$

or

$$V_2 = \frac{g_{m_2} V_o}{sC} \tag{2.50}$$

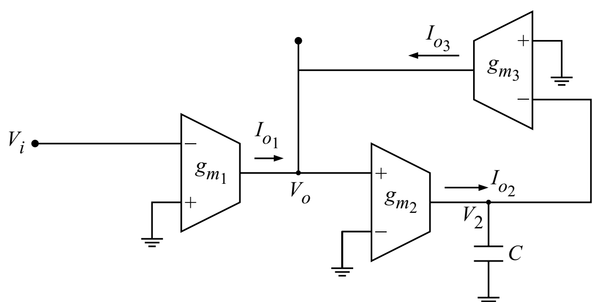



**Fig. 2.11** Three OTA-based differentiator

The realized current mode differentiator is composed of only active devices; hence, the circuit is suitable for monolithic implementation either with CMOS or bipolar technologies. In addition to this no realizability conditions are imposed for the circuit and all the active sensitivities are found to be low.

## 2.11 INTEGRATOR

Integrators serves as the basic building block in many filter structures. The circuit for OTA based integrator can be obtained by loading the output of OTA by a capacitor.

### 2.11.1 Ideal Integrator

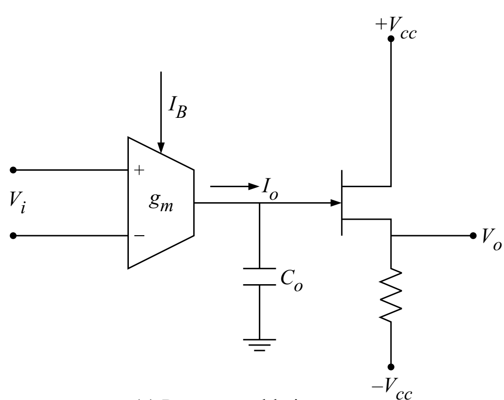
The voltage variable integrator with a differential input is shown in Fig. 2.13(a). It is also known as programmable integrator (PI). Its symbolic representation is shown in Fig. 2.13(b). In the circuit of Fig. 2.13(a), the OTA is loaded by a capacitor. Since the output impedance of OTA is ideally infinite, a very high input impedance buffer is used to avoid undesirable loading.

The output current ($I_o$) of OTA is given as

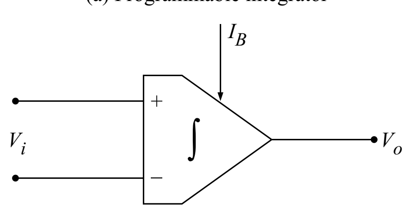
$$I_o = g_m V_i \tag{2.62}$$

Also

$$I_o = sV_o C_o \tag{2.63}$$




(a) Programmable integrator




(b) The symbol for programmable integrator

**Fig. 2.13**

Equating equations (2.62) and (2.63) gives

$$g_m V_i = sV_o C_o$$

$$T_{P1} = \frac{V_o}{V_i} = \frac{g_m}{sC_o} = \frac{K}{s} \tag{2.64}$$

and

$$K = \frac{g_m}{C_o} = \frac{I_B}{2V_T C_o} \tag{2.65}$$

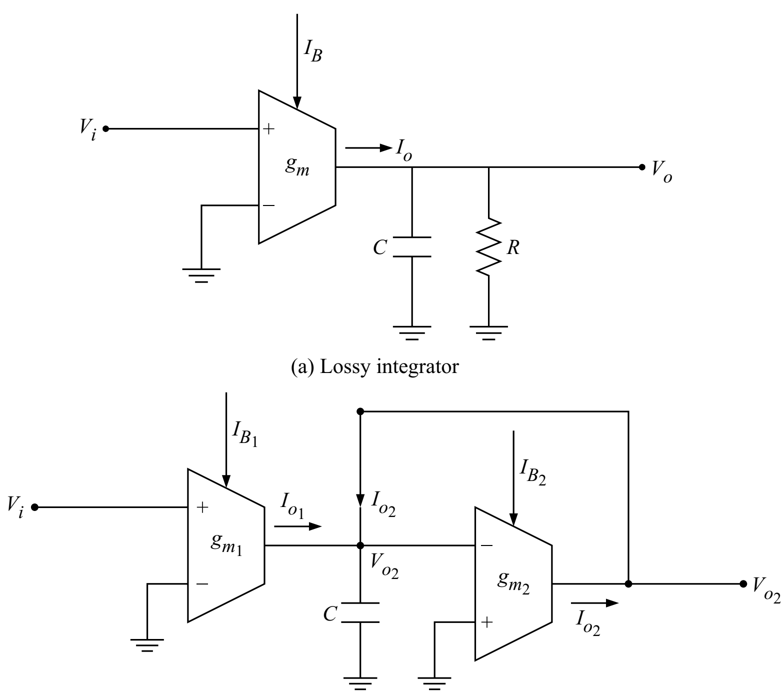
where

$K$ = integration constant

From equation (2.64), it is clear that the circuit realizes an ideal integrator and its gain is directly proportional to OTA's bias current $I_B$. Hence, gain can be controlled by varying the bias current $I_B$. Inverting and non-inverting integrators can be obtained by connecting inverting or non-inverting terminal of OTA to ground respectively.

## 2.11.2 Lossy Integrators

The circuit for lossy integrator is shown in Fig. 2.14(a). The input is applied at non-inverting terminal of OTA. The output current, $I_o$ is given as




(a) Lossy integrator

(b) OTA-C lossy integrator

**Fig. 2.14**

$$I_o = g_m V_i \tag{2.66}$$

Also

$$I_o = V_o(G + sC) \tag{2.67}$$

Equating equations (2.66) and (2.67) gives

$$g_m V_i = V_o(G + sC)$$

or

$$\frac{V_o}{V_i} = \frac{g_m R}{1 + sCR} \tag{2.68}$$

Equation (2.68) shows that the circuit of Fig. 2.14(a) has a loss that is fixed by the RC product and the gain is adjusted by $g_m$. This circuit also works as first order low-pass filter.

Another circuit for lossy integrator is shown in Fig. 2.14(b). It consists of two OTAs along with a capacitor. This circuit can be obtained by replacing the resistor $R$ of circuit in Fig. 2.14(a) by an OTA-based simulated resistor.

Consider the analysis of circuit of Fig. 2.14(b), the output current $I_{o_1}$ of first OTA is

$$I_{o_1} = g_{m_1} V_i \tag{2.69}$$

KCL at $V_{o_2}$ gives

$$I_{o_1} = -I_{o_2} \tag{2.70}$$

The current flowing through capacitor is $I_{o_1} + I_{o_2}$ is given as

$$I_{o_1} + I_{o_2} = sCV_{o_2} \tag{2.71}$$

or

$$V_{o_2} = \frac{I_{o_1} + I_{o_2}}{sC} \tag{2.72}$$

$$I_{o_2} = -g_{m_2} V_{o_2} \tag{2.73}$$

Substituting the expressions of current $I_{o_1}$ from equation (2.69) and $I_{o_2}$ from (2.73) in equation (2.72), we get

$$V_{o_2} = \frac{g_{m_1} V_i - g_{m_2} V_{o_2}}{sC}$$

After simplification, the voltage gain of the integrator is given by

$$\frac{V_{o_2}}{V_i} = \frac{g_{m_1}}{sC + g_{m_2}} \tag{2.74}$$

Equation (2.74) shows that the pole frequency can be controlled by $g_{m_2}$ and dc gain by $g_{m_1}$.

### 2.11.3 Active only Integrator

The active only integrator with electronically tunable time constants is described, which consists of two OTAs and one Op-amp, without using any passive component. The resulting current mode active only integrator is shown in Fig. 2.15.

The routine analysis of the circuit yields

$$H_{\text{int}}(s) = \frac{I_{o_2}}{I_{in}} = \frac{g_{m_4}B}{sg_{m_3}} = \frac{1}{s\tau} \tag{2.75}$$

where $$\tau = g_{m3}/Bg_{m4} \tag{2.76}$$

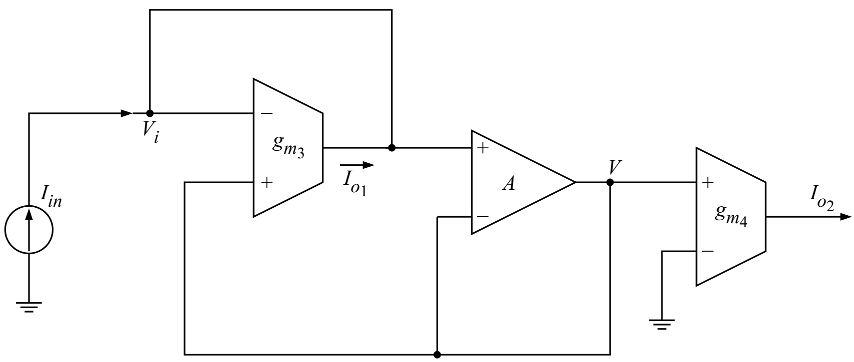



**Fig. 2.15** Active only integrator

It can be seen that the time constant of the integrator of Fig. 2.15 can be tuned electronically by changing $g_{m3}$ and or $g_{m4}$. The active sensitivities of the circuit are expresses as

$$S^{\tau}_{g_{m3}} = -S^{\tau}_{g_{m4}} = -S^{\tau}_{B} = 1 \tag{2.77}$$

These sensitivities are all small. It can be noted that $\tau$ can be made large simply by changing the ratio $g_{m_3}/g_{m_4}$ without an increase in the active sensitivities. In addition to this the current mode integrator can be converted to a transimpedance type by removing the output OTA and taking signal from the Op-amp output.

#### *Effects of non-idealities of the integrator*

The effects of the non-idealities of Op-amp and OTAs on the integrator transfer function are investigated. Considering the non-ideal models of the Op-amp and OTA given by equations (2.58) and (2.59), the transfer function of differentiator is given by

$$H_{\text{int}}(s) = \frac{g_{m_{04}}B\omega_{pb}\omega_{p4}(s+\omega_{p_3})}{g_{m_{03}}\omega_{p_3}s(s^2+(\omega_{pb}+\omega_{p_4})s+\omega_{pb}\omega_{p_4}} \tag{2.78}$$

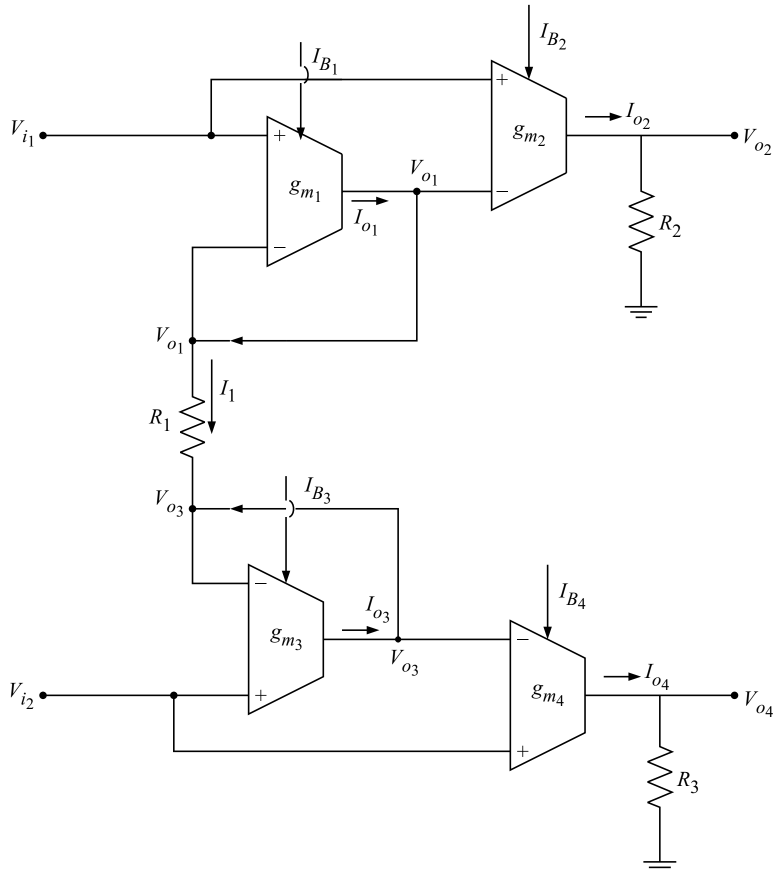



**Fig. 2.17** OTA-based temperature-insensitive instrumentation amplifier

with $g_{m_1}$ and $g_{m_3}$, such as the commercially available dual variable OTAs CA3280 or LM13600.

If the circuit is designed such that $g_{m_1}R_1 >> 1$, $I_{B_1} = I_{B_3}$ or $g_{m_1} = g_{m_3}$, then the analysis of the circuit gives

$$V_{o_2} = \frac{g_{m_2}}{g_{m_1}}\frac{R_2}{R_1}(V_{i_1} - V_{i_2}) = \frac{I_{B_2}}{I_{B_1}}\frac{R_2}{R_1}(V_{i_1} - V_{i_2}) \tag{2.87}$$

$$V_{o_4} = \frac{g_{m_4}}{g_{m_3}}\frac{R_3}{R_1}(V_{i_2} - V_{i_1}) = \frac{I_{B_4}}{I_{B_3}}\frac{R_3}{R_1}(V_{i_2} - V_{i_1}) \tag{2.88}$$

It can be seen from equations (2.87) and (2.88) that the voltage gains of instrumentation amplifier are electronically tunable by the bias control currents $I_{B_1}$ and $I_{B_4}$ without disturbing the balance of the circuit. In addition to this the circuit obtains a common-mode gain of zero without the need of any resistor matching.

## 2.14 COMPARATOR

For an OTA to function as a comparator, it has to be worked in the non-linear region of its characteristic. The OTA will basically act as a comparator with current output. The circuit for OTA-based comparator [5] is shown in Fig. 2.18.

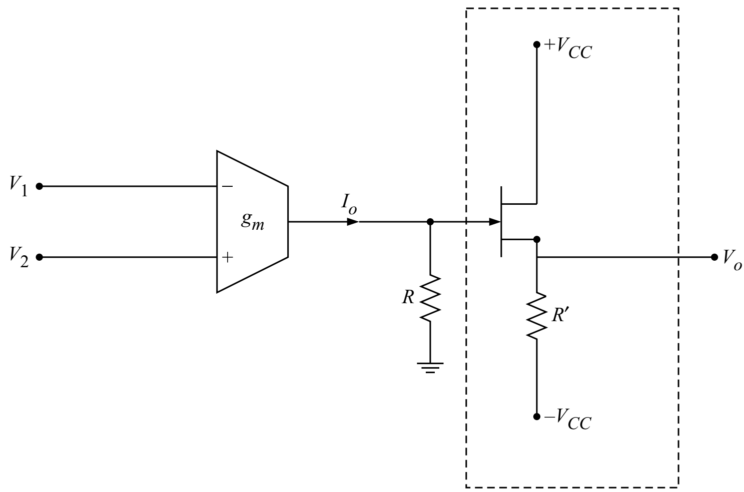



**Fig. 2.18** OTA-based comparator

A comparator is a circuit, which compares input signal $V_i$ with a reference voltage $V_R$. Usually, the reference voltage $V_R$ is applied to non-inverting terminal with a proper load and buffer connected at the output, the OTA behaves like a DVCVS. With the buffered OTA, the output voltage will switch from a positive $V(1)$ level to a negative $V(0)$ level, as the inverting signal is less than or greater than the reference level.

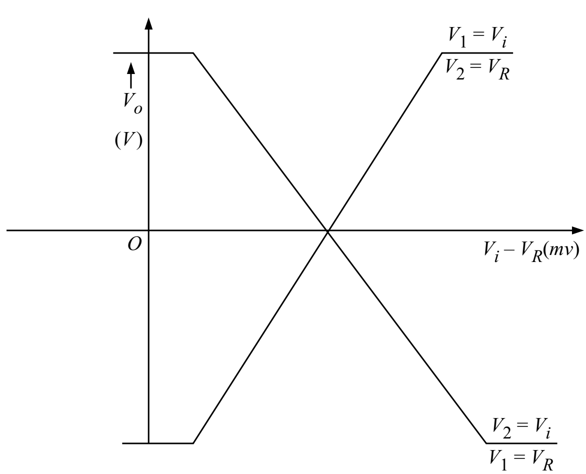



**Fig. 2.19** Transfer characteristic

For the proper operation, the output current (or voltage across load) should be of constant value $I(1)$ or $V(1)$ for $V_i > V_R$ and another constant value $I(0)$ or $V(0)$ for $V_i < V_R$. The transfer characteristic is shown in Fig. 2.19. The special features of an OTA-based comparator of Fig. 2.19 is that the voltages $V(0)$ and $V(1)$ may be varied simply by varying the bias current $I_B$ or the voltage $V_B$. Because $I_o$ is directly proportional to $I_B$, the change in $I_B$ causes the OTA to saturate at different levels of voltages. Thus, different levels of output voltages may be obtained through bias current control. The bias current limits are set by manufacturer's specifications.

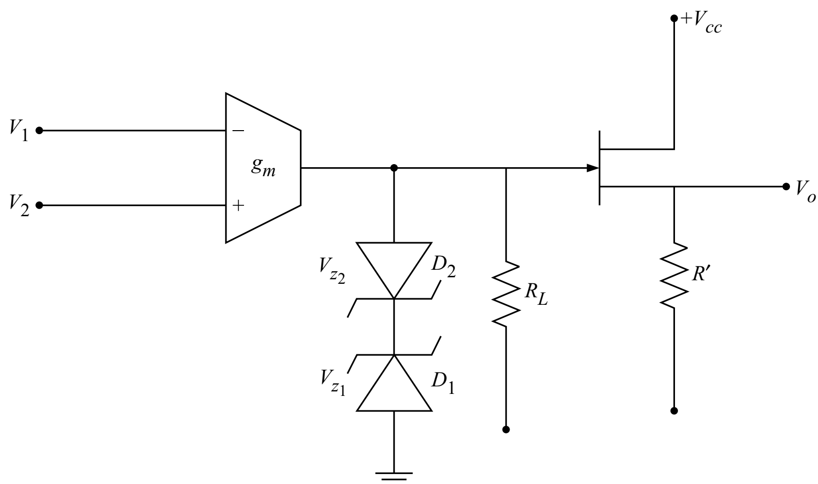



**Fig. 2.20** OTA-based comparator using clamping diodes

The zener diodes $D_1$ and $D_2$ are used to clamp the output of the comparator as shown in Fig. 2.20. As the Zener diodes reduce the switching speed, the technique of bias current control seems to be more attractive from the considerations of speed. Also it provides convenient and continuous control of output levels.

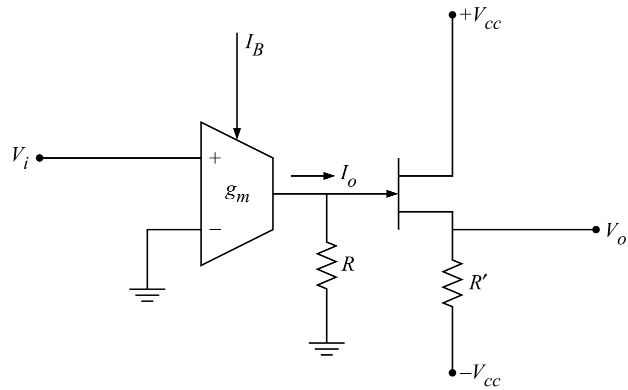
## 2.15 ZERO-CROSSING DETECTORS

In the circuit of OTA-based comparator of Fig. 2.18, if $V_R$ is equal to zero, then the output will change from one state to another very rapidly, every time the input passes through zero. Such a configuration is called a zero-crossing detector. In the OTA-based zero-crossing detector, the two extreme levels of output can be controlled through the bias current. Some of the applications of zero-crossing detectors are given below.

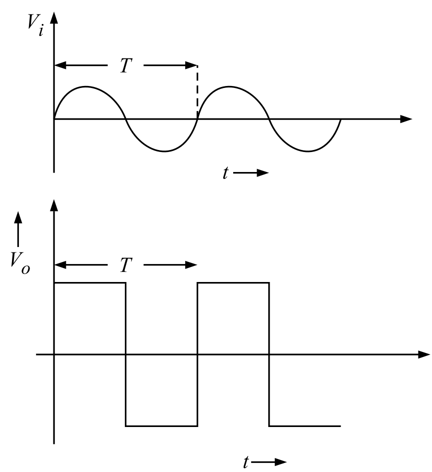
### 2.15.1 Square Wave from a Sine Wave

If the input to a comparator is a sine wave, then the output is a square wave. In case of a zero-crossing detector a symmetrical square wave results. The circuit for square wave from sine wave is shown in Fig. 2.21(a).

At higher frequencies, the rising and falling edges of the square wave become slanted, as with the case of an Op-amp comparator, due to slew rate limitation. In the OTA-based circuit of square wave from sine wave, the amplitude of square wave can be adjusted through bias control current of OTA.




(a) Square wave from sine wave generator




(b)

**Fig. 2.21**

### 2.15.2 Timing Marker from A Sine Wave

The square wave output $V_o$ of circuit of Fig. 2.21(b) is applied to the input of an R-C circuit, as shown in Fig. 2.22. If the time constant RC is very small as

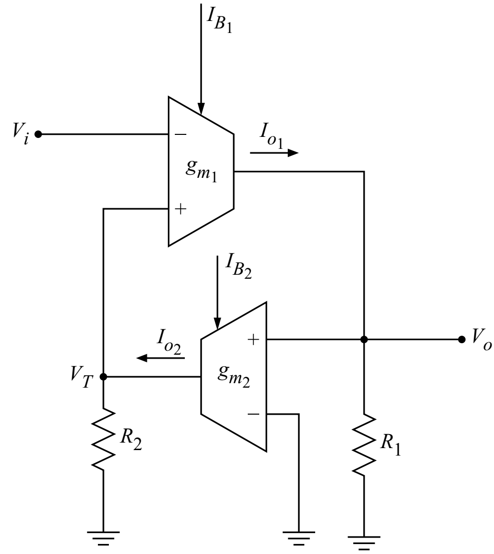



**Fig. 2.23** New current controlled OTA-R Schmitt trigger

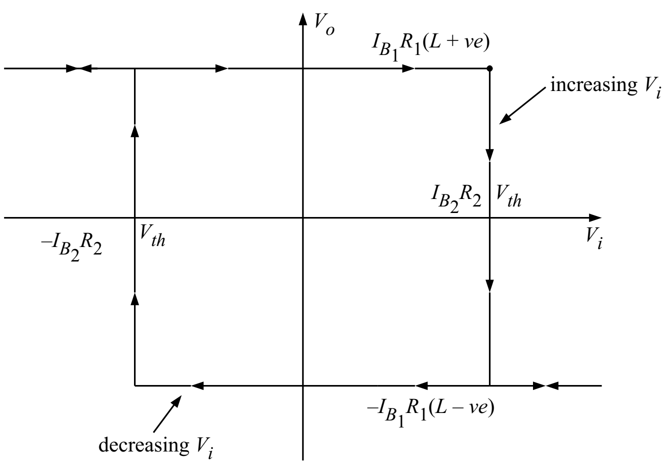



**Fig. 2.24** Transfer characteristic of Schmitt trigger

can note from the circuit that there is no change until $V_i$ reaches a value equal to $V_T$. As $V_i$ begins to exceed this value, a negative voltage appears between the input terminals of first OTA. This voltage is amplified by the first amplifier, which is formed by first OTA and resistor $R_1$, and thus, output $V_o$ goes negative. The second voltage amplifier, formed by second OTA and resistor $R_2$, in turn causes $V_T$ to negative thereby increasing the negative input to first OTA and keeping the

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