APPLICATIONS OF OPERATIONAL TRANSCONDUCTANCE AMPLIFIER (OTA)

by

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THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING

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Purusottam Maity

ABSTRACT

In this thesis operational transconductance amplifier has been used as a fundamental building block for many types of electronic systems. They are very useful in low voltage high speed wide bandwidth systems & applications with increased slew rate and high CMRR. Voltage controlled amplifier, voltage controlled resistor, Schmitt trigger, comparator, multiplexer, sample and hold circuit, voltage controlled filters, voltage controlled oscillators, rectifier, optical receiver, driving circuits, etc. have been implemented, characteristics of which are dependent on controllable transconductance. The circuits implemented are simple in design and the mathematical formulas derived are very interesting. These circuits can work well in many types of signal processing applications where opamp or any other circuit element has limitations.

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CHAPTER 1

BACKGROUND AND OVERVIEW OF THE THESIS

1.1 Technology Background

Most of the modern devices demand building blocks that can operate on low voltage supply and less power consumption and features of these devices restrict on the programmability of the circuits. The operational transconductance amplifier (OTA) is used as a fundamental building block in many analog signal processing systems because of its simple design, low cost and less power consumption. Like a traditional op amp it has two differential high input impedance terminals and can work in feedback configuration in the frequency range of several megahertz. However op amp has limitations in slew rate and bandwidth which makes the OTA as a replacement for an active component in filter, oscillator, VCA, S/H, comparator, restoration, driving circuits etc. As a current mode device it requires less number of stages, can operate much faster and in wider dynamic range also, its frequency response is superior than opamp based circuits. Being a VCCS, it uses capacitors as integration component in the design of any structure which are less likely incorporated by the VCVS design. Another feature of the OTA is its programmability which helps to tune different electronic circuits also, its regular and modular structure is very suitable for VLSI design. A special specification of the OTA is that its transconductance, bandwidth, bias current, gain can be controlled through an external resistor, thus the transconductance is considered as a design-parameter much like resistor or capacitor. As a simple yet powerful topology its parameters like gain, output voltage swing, CMRR deliver good values. The OTA has been implemented widely in CMOS, bipolar also in BiCMOS and GaAs technology but CMOS technology is usually preferred due to its less power consumption and high performance in analog and digital systems although, the threshold voltage of the CMOS is a constraint that does not drop much less. The mobility and accuracy of the OTA has effect on the speed and accuracy of the whole system, however, the limitation of the OTA remains in maintaining linearity for input voltage swing.

1.2 Objective of Research

As previously stated due to the limitations of opamp, operational transconductance amplifier finds its use as a replacement for versatile building block in many electronic systems. The objective of this research is to discuss different applications for the operational transconductance amplifier as a voltage controlled current source (VCCS) element.

1.3 Thesis Outline

The work of this thesis has been arranged in five chapters.

Chapter 2 introduces to the operational transconductance amplifier. The working principle and the transconductance versus bias current characteristic have been discussed.

Chapter 3 briefly discusses different configurations for the operational transconductance amplifier. Overview of different topologies is presented and a few of the ICs for the OTA are mentioned.

Chapter 4 includes most important applications for the OTA. The OTA as voltage control element, current source element, driving element in different electronic circuits have been discussed extensively and in an efficient manner.

Chapter 5 ends with the conclusions and future works also have been suggested.

CHAPTER 2

INTRODUCTION TO OPERATIONAL TRANSCONDNUCTANCE AMPLIFIER

2.1 Introduction

Operational transconductance amplifier is a voltage controlled current source (VCCS) whose output current is a function of the difference between two input voltages [1]. The output current is given by

$$I_{out} = g_m(V_{1_{in+}} - V_{2_{in-}}) \qquad (2.1.1)$$

It has infinite input impedance, infinite output impedance, can afford wide range of bandwidth. The output current to input voltage ratio of an operational transconductance amplifier is defined as transconductance (g_m), which is denoted by

$$g_m = KI_{bias} = I_{bias}/2V_T \qquad (2.1.2)$$

Where, K is the transconductance parameter, I_{bias} is the input bias current and V_T is the thermal voltage. The transconductance of the OTA can be changed by varying the bias current [1].

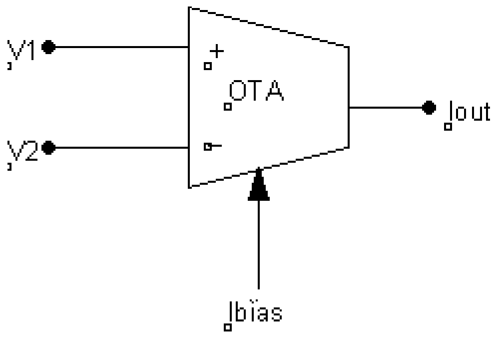

Figure 2.1 OTA Symbol

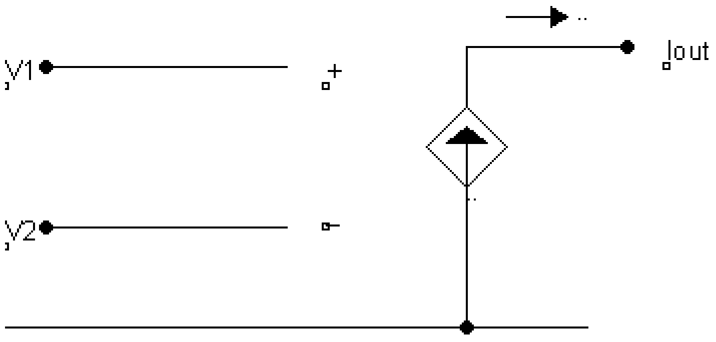

Figure 2.2 OTA Small Signal Equivalent Circuit

Parameters considering when an operational transconductance amplifier is in operation are,

Input impedance: It is the measure of impedance between the inverting and non-inverting terminal of an OTA. Ideally its value is infinite.

Output impedance: It determines how much load an OTA can drive. Typically an ideal OTA has infinite output impedance.

Input bias current: It is the average value of current flowing in two input terminals when the output is zero.

Open loop gain: It is the gain of the amplifier when there is no feedback in the circuit.

PSRR: It is defined as the change in output to the change in supply voltage.

Slew rate: It is defined as the rate of change of output signal to step input signal.

Output voltage swing: The maximum output voltage that an OTA can deliver without going into saturation.

CMRR: It is the ability of the amplifier to cancel out the signal that is common to both inputs.

Gain bandwidth product: It is the product of open loop voltage gain and the frequency at which it is measured.

Settling time: It is the time required for output of an OTA to reach within specified error range of its final value.

2.2 OTA Principle of Operation

In this differential mode of operation, the bias current setup by the MOSFET M3 drives the MOSFETs M1 and M2 in saturation region even when gate voltages to both of them are off. When the voltage or the current in M1 increases, the corresponding voltage and current in M2 decrease thus, the sum of the output current remains constant. So after saturation, even if the gate voltage is increased it does not affect the biasing current as it is the constant sum of two drain currents [2].

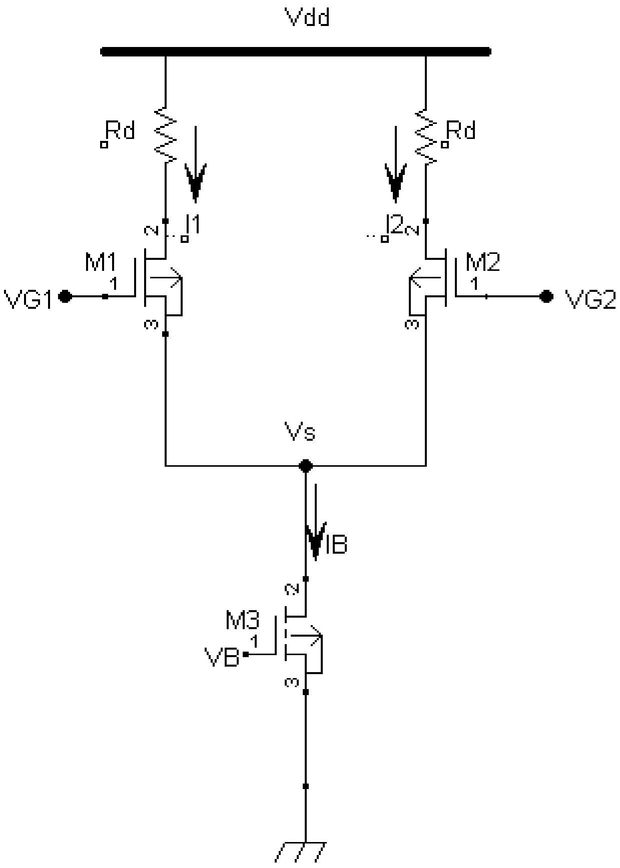

Figure 2.3 Differential OTA

Drain source current of a MOSFET operating in the saturated region is

$$I_{sat} \cong I_0 exp(kV_G - V_s)$$

I_0 = A constant

I_{sat} = Saturation drain current

V_G = Gate voltage

V_S = Source voltage

And, $k = \frac{q}{KT} = \frac{1}{V_T}$

Saturation drain currents for the MOSFETS M1 and M2 are

$$I_{sat1} \cong I_1 \cong I_0 exp(kV_{G1} - V_S) \tag{2.2.1}$$

$$I_{sat2} \cong I_2 \cong I_0 exp(kV_{G2} - V_S) \tag{2.2.2}$$

As the bias current I_B is the sum of two drain currents I_1 and I_2

$$I_B = I_1 + I_2$$

$$= I_0 exp(kV_{G1} - V_s) + I_0 exp(kV_{G2} - V_s)$$

$$= I_0 e^{-V_S}(e^{kV_{G1}} + e^{kV_{G2}}) \tag{2.2.3}$$

Dividing the equation (2.3.1) and equation (2.3.2) by equation (2.3.3) respectively

$$\frac{I_1}{I_B} = \frac{I_0 exp(kV_{G1} - V_s)}{I_0 e^{-V_S}(e^{kV_{G1}} + e^{kV_{G2}})}$$

$$\text{Or, } I_1 = I_B \frac{e^{kV_{G1}}}{(e^{kV_{G1}} + e^{kV_{G2}})} \tag{2.2.4}$$

And,

$$\frac{I_2}{I_B} = \frac{I_0 exp(kV_{G2} - V_D)}{I_0 e^{-V_S}(e^{kV_{G1}} + e^{kV_{G2}})}$$

$$\text{Or, } I_2 = I_B \frac{e^{kV_{G2}}}{(e^{kV_{G1}} + e^{kV_{G2}})} \tag{2.2.5}$$

For the transconductance amplifier, the output current is proportional to the difference between these two currents.

$$I_{out} = \Delta I = I_1 - I_2 = I_B \frac{e^{kV_{G1}} - e^{kV_{G2}}}{e^{kV_{G1}} + e^{kV_{G2}}}$$

$$= I_B \frac{e^{k(V_{G1} - V_{G2})/2} - e^{-k(V_{G1} - V_{G2})/2}}{e^{k(V_{G1} - V_{G2})/2} + e^{-k(V_{G1} - V_{G2})/2}}$$

$$= I_B tanh \frac{k(V_{G1} - V_{G2})}{2}$$

$$\approx I_B \frac{k(V_{G1}-V_{G2})}{2} \qquad (2.2.6)$$

If V_i is the differential voltage and V_{cm} is the common-mode voltage then

$V_{G1} = V_{cm} + \frac{V_i}{2}$ and $V_{G2} = V_{cm} - \frac{V_i}{2}$

So, $\Delta V = V_{G1} - V_{G2} = V_i$

The transconductance is derived as, $g_m = \frac{\partial \Delta I}{\partial \Delta V} = I_B \frac{k}{2} = \frac{I_B}{2V_T}$ (2.2.7)

2.3 Transconductance vs Bias Current Relationship

The graph shows the transconductance versus bias current characteristic for a typical OTA. The transconductance increases linearly with the bias current. The constant of proportionality is the slope of the line. The allowable range of the bias current for accurate operation is from .5 µA to .5 mA [3].

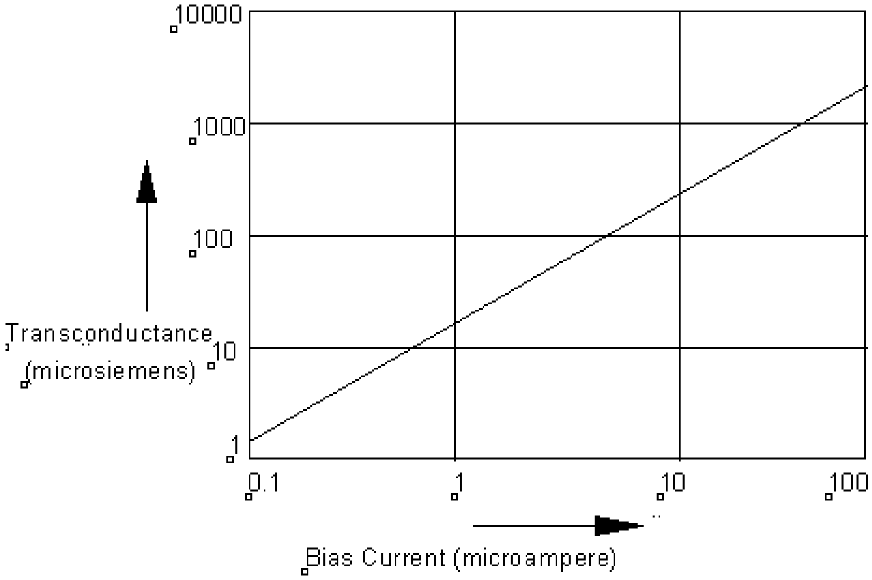

Figure 2.4 Transconductance vs Bias Current Characteristic for a Typical OTA

CHAPTER 3

OTA CONFIGURATIONS AND ICS

3.1 Introduction

Like an ordinary transistor it has three terminals − a high input impedance base, a low input/output impedance emitter and a current output collector. However, unlike a bipolar transistor, it is self biased and the output may be either of source or sink type. An OTA can operate in one of the three basic modes: common base, common collector, common emitter [4]. In general sense, OTA is an opamp without buffer at the output.

3.1.1 Common Emitter Amplifier

The amplifier is in non-inverting mode because a current flowing out of the emitter will also flow out of the collector. The input and output can be ground-referenced without any biasing. The output impedance of the common emitter terminal is $\frac{1}{g_m}$, where, g_m is the transconductance of the OTA and the overall gain of this configuration is $\frac{R_L}{R_E+\frac{1}{g_m}}$ [4, 5].

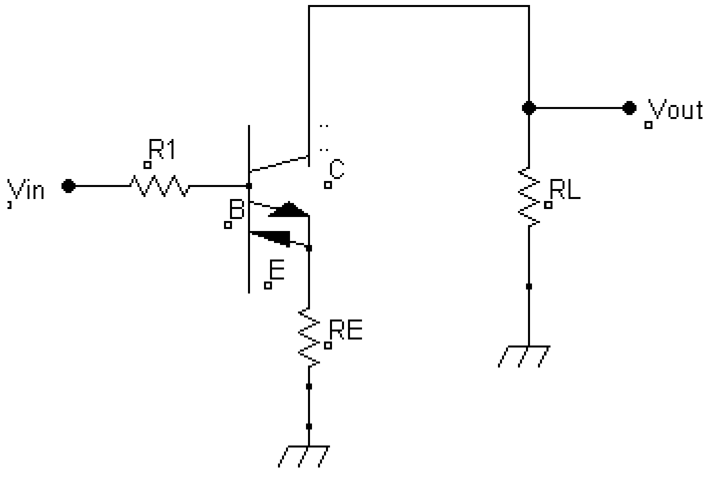

Figure 3.1.1 Common Emitter Amplifier

3.1.2 Common Collector Amplifier

The OTA is connected as an emitter follower or voltage buffer. The output impedance and the overall gain of this configuration are $\left(\frac{1}{g_m}\|R_E\right)$ and $\frac{1}{1+\frac{1}{g_m R_E}}$ respectively. The larger the value of R_E, the closer will be the gain to unity. A low value of series resistor R_1 to the B-input helps in to isolate trace parasitic from the input [4, 5].

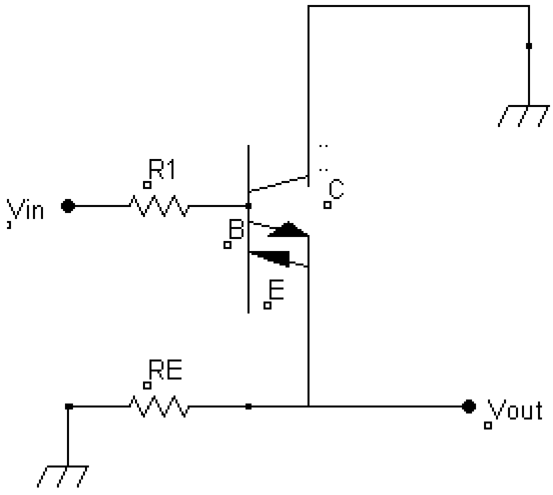

Figure 3.1.2 Common Collector Amplifier

3.1.3 Common Base Amplifier

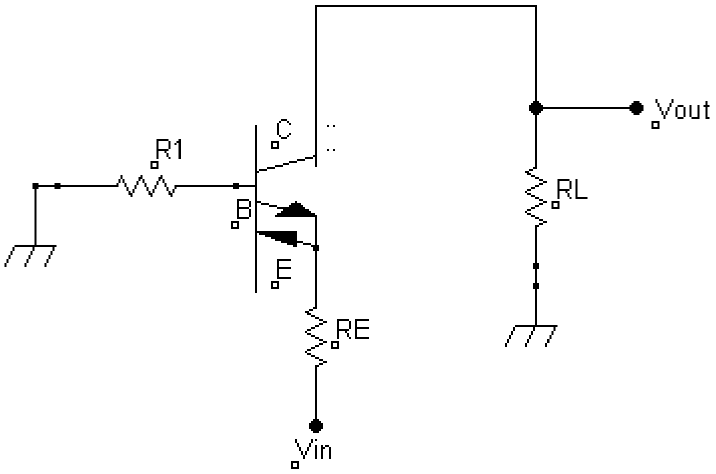

Figure 3.1.3 Common Base Amplifier

This configuration has an inverting gain and low impedance input. This low impedance can be converted into high impedance by adding a buffer amplifier in series. The overall gain of this configuration is $\frac{R_L}{R_E+\frac{1}{g_m}}$ [4, 5].

3.1.4 Direct Feedback Amplifier

In this topology the voltage feedback from the collector output to the emitter is added. The currents at the emitter and collector flow in the same direction. The current from the collector terminal causes a voltage drop across X_e and R_e, which is in opposite polarity to the base-emitter voltage. This difference in voltage causes the reduced current flow at the emitter and hence, the output current at the collector is reduced. Thus, it functions like a double feedback and the feedback ratio can be adjusted by $R2$, R_e and X_e [5].

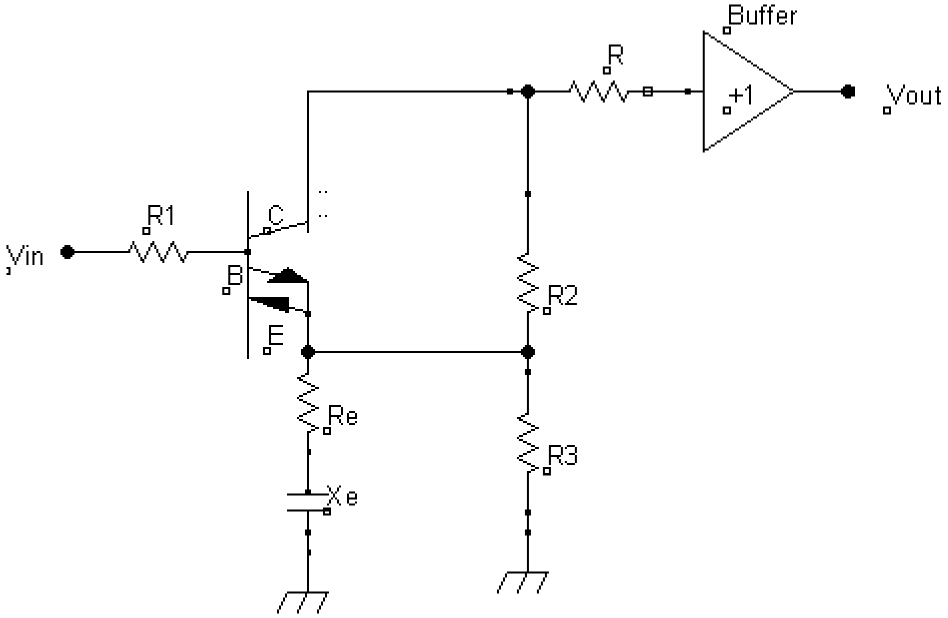

Figure 3.1.4 Direct Feedback Amplifier

3.1.5 Current Feedback Amplifier

The following figure shows the non-inverting current feedback amplifier configuration. C_1 is the output parasitic capacitance and R_2 is the input impedance to the buffer. Poles formed by R_2 and C_1 control the frequency response of the circuit. Bandwidth can be changed over wide range by changing the feedback resistance R_f. Signal delay time is shorter for this configuration, but it has disadvantages of low input impedance and low CMRR [5].

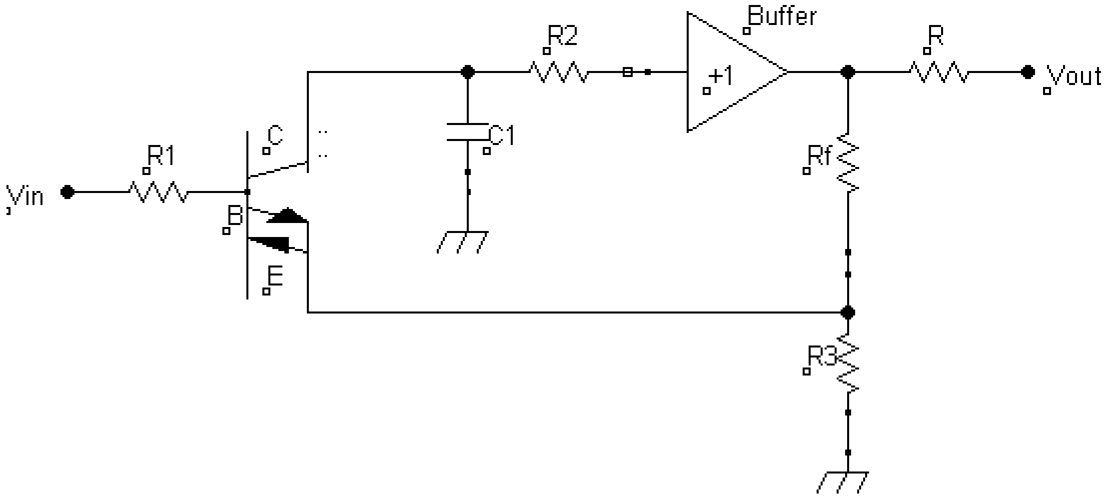

Figure 3.1.5 Current Feedback Amplifier

3.2 OTA ICs

First commercially available OTAs were CA3080 made by the RCA. As the construction element mostly bipolar transistors were used rather than field effect transistors. The differential input circuit is same as that found on modern operational amplifier. The rest is current mirror incorporated as the ideal element in most of the ICs [6]. A convenience in the design of this chip is the integration of an output buffer amplifier which converts the output current to voltage.

3.2.1 OTA CA3080

OTA CA3080 is simple in configuration, includes one differential amplifier and four current mirrors. Its amplifier bias input can be used either for gating or for linear gain control. Total current consumption of CA3080 is twice its bias current, making it useful for true micro-power application. Slew rate of CA3080 is $50V/\mu S$ [7]. The following figures show the internal circuit and pinout diagram of OTA CA3080 respectively.

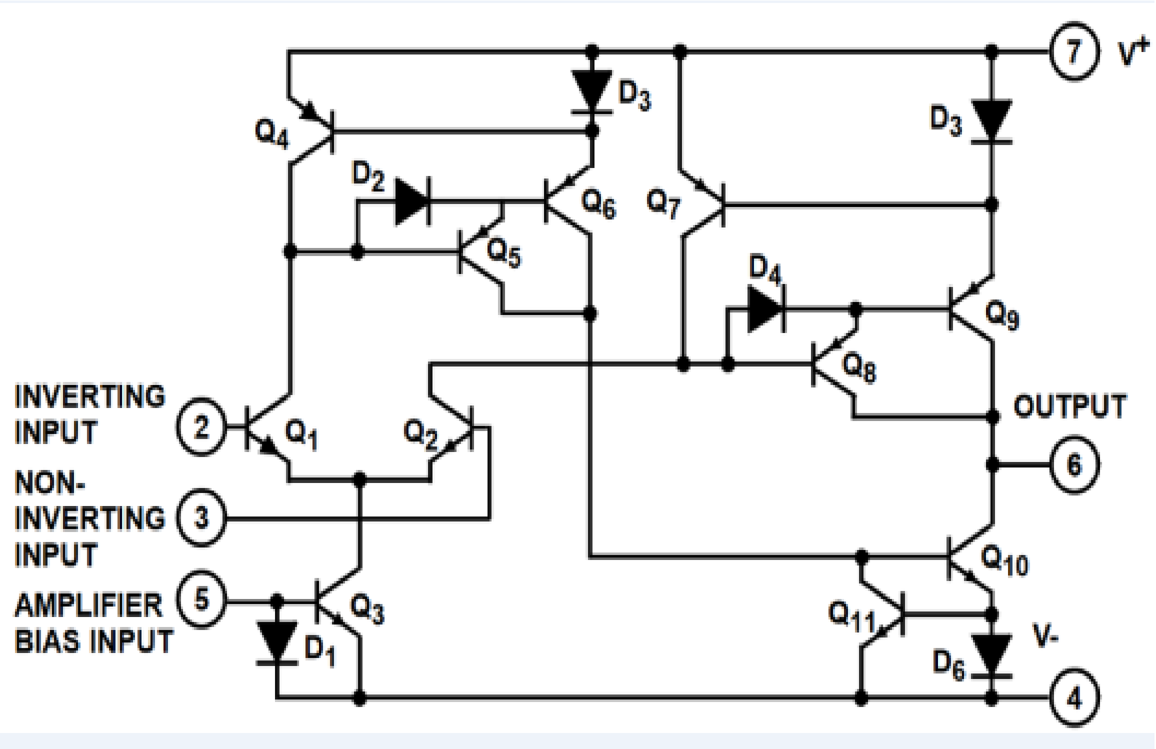

Figure 3.2.1 CA3080 Internal Circuit

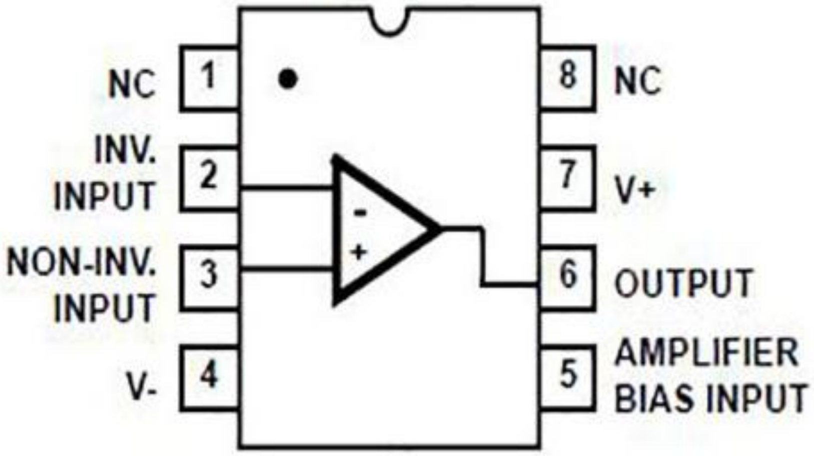

Figure 3.2.2 Pinout Diagram of CA3080

3.2.2 LM13700 Dual OTA

It is an improved version of CA3080 consisting of two current controlled transconductance amplifiers each with differential inputs, linearizing diodes and controlled buffer output. Linearizing diodes are provided to greatly reduce the signal distortions and to allow for higher input levels. The two OTAs of lm13700 share common supply rails excellently matched but fully independent integrated on a single chip. Maximum I_D and I_{bias} will be limited to 2mA [8].

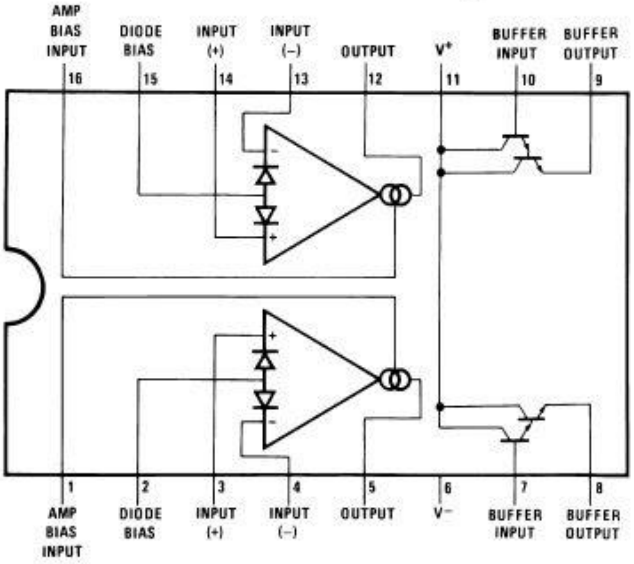

Figure 3.2.3 Pin Connection of LM13700 Dual OTA

3.2.3 CA3094

It is an improved version of CA3080 with additional pair of transistors, capable of high power handling capability and circuit flexibility. These ICs dissipate a few microwatts of power with quiescent current of about 300mA peak. Its gain and open loop bandwidth can be controlled between wide limit. They are intended for operation up to 24V [9].

3.2.4 MAX435/MAX436

They are high speed wideband OTAs with differential high impedance inputs. Circuit gain is determined by the input impedance and an internally set gain factor. It offers a bandwidth of about 275MHZ at a 800V/µS slew rate and common mode rejection ratio of about 53dB at 10MHZ. It tolerates wide differential input voltages without amplifier saturation [10].

3.2.5 OPA660

This versatile monolithic compound is designed for high bandwidth system. Like an ideal transistor, it has three terminals- base, emitter and collector but it is far more linear. The transconductance of the OTA can be adjusted with an external resistor, so that its bandwidth, bias current and gain trade-offs can be optimized. Its buffer section is an open loop buffer consisting of complementary emitter followers [11].

CHAPTER 4

OPERATIONAL TRANSCONDNUCTANCE AMPLIFIER APPLICATIONS

4. Introduction

The versatility of operational transconductance amplifier makes it useful as a basic building block for many types of electronic systems. Highly linear high current carrying capacity OTAs are used in extremely broad range of circuits in consumer and industrial applications [9]. High speed wideband OTAs can be used in differential line driver and receiver applications [10]. They are also used as a basic electronic building block of light emitting diode circuit, pulse integrator, RF and IF circuitry, telecommunication equipment, CCD image processing, high speed data acquisition system. OTAs with excellent slew rate are used as multiplexer, S/H, gain control circuit [7]. Different other types of interesting applications include timer, Schmitt trigger, instrumentation amplifier, voltage controlled oscillator, voltage controlled filter, modulator/multiplier, voltage controlled impedance, regulator, power amplifier, music synthesizer etc.

4.1 Schmitt Trigger

For an OTA the maximum output current can be the bias current and in saturated output stage the output current becomes equal to the bias current. So if the output is fed back to the non-inverting reference terminal, the threshold limit is set by this bias current with the resistance R, and the input voltage is large enough to drive the OTA in a saturated high state with the positive reference voltage $I_{bias} \times R$ generated. As long as this input voltage is less than the reference voltage, the output doesn't change but if the input exceeds this value the output switches to a saturated low and a negative reference voltage $-I_{bias} \times R$ is generated. When V_{in} drops below this new reference voltage, the output switches to high again and positive reference voltage $I_{bias} \times R$ is generated. The threshold voltages can be varied, either through the control of bias current I_{bias} or by changing the resistance R. This is a micro-power application of OTA [12].

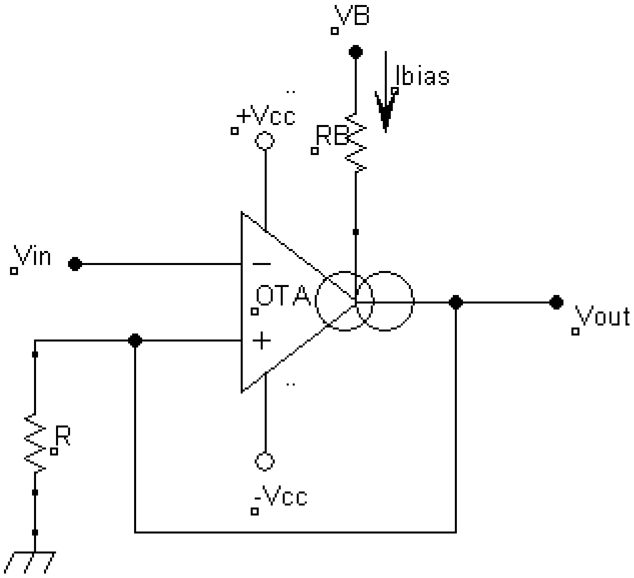

Figure 4.1a Schmitt Trigger

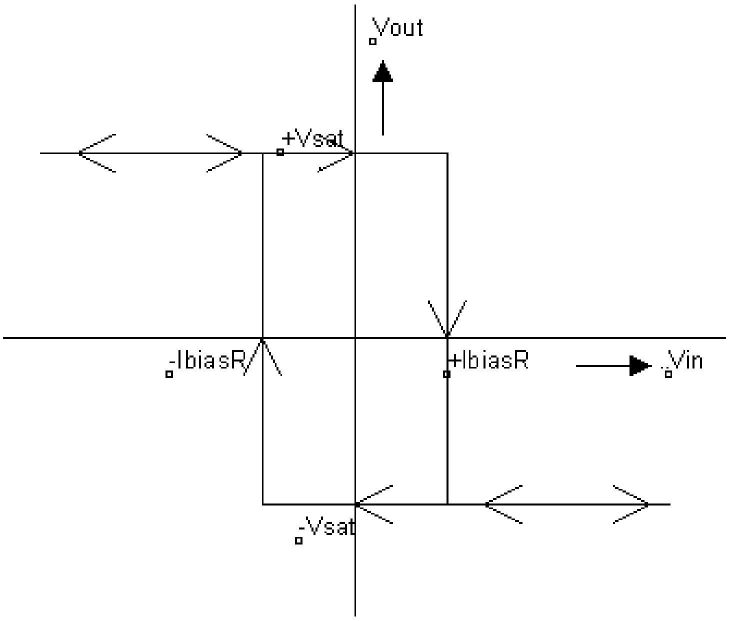

Figure 4.1b Input vs Output Characteristic of a Schmitt Trigger

4.2 Comparator

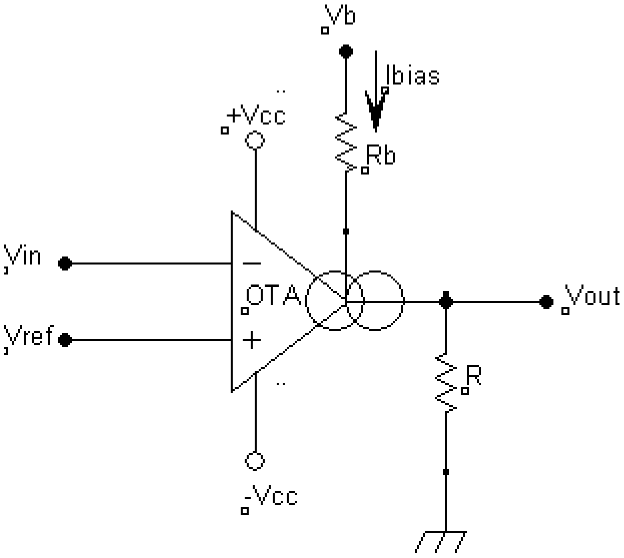

Figure 4.2a Comparator Using OTA

An OTA can be used as a comparator when a test input is applied at the inverting terminal and a reference input is applied at the non-inverting terminal. The circuit acts in such a way that when the test input is less than the reference input, the output current tends to a positive saturated value but when the test input is more than the reference voltage the output current tends to a negative saturated value [12]. The limits, at which the output current saturates, are determined by the bias current. If the OTA has a good slew rate, it acts as a fast comparator.

When the reference voltage is zero volts, the output crosses its axis every time and represents a square wave as the input becomes greater or less than zero volts. In this manner the OTA acts as a **zero crossing detector**. The positive maximum and the negative maximum value of this output rectangular wave can be adjusted by changing the bias current.

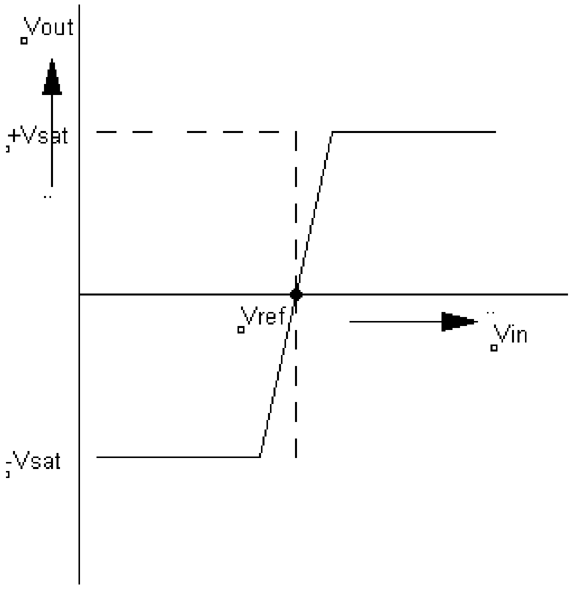

Figure 4.2b Input - Output Relationship for a Comparator

4.3 Voltage Controlled Resistor

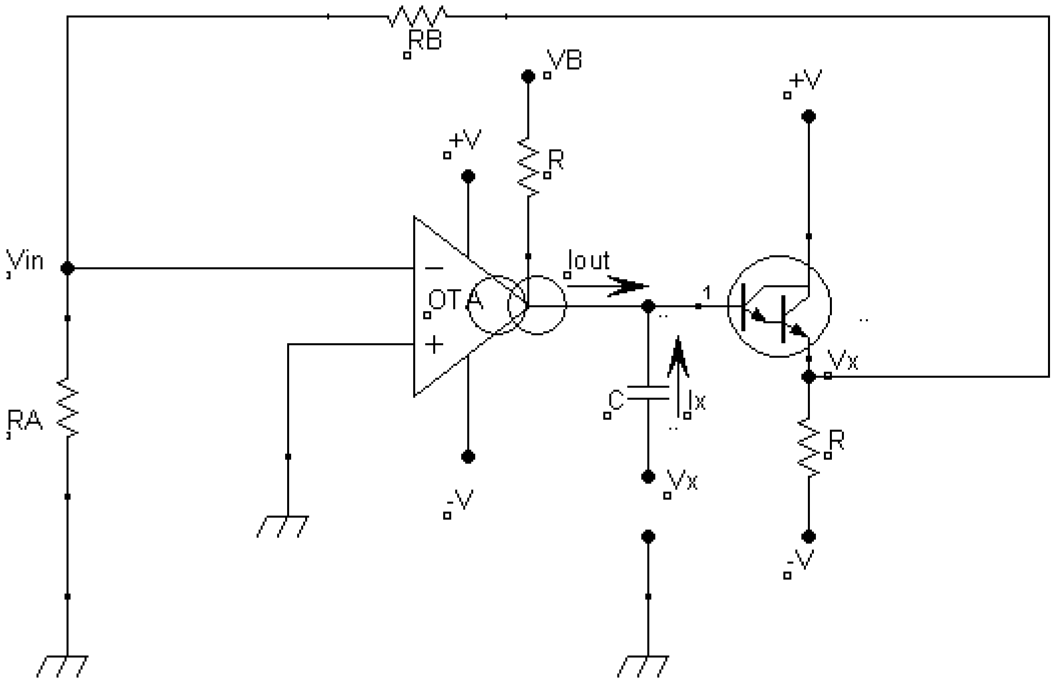

Figure 4.3 Voltage Controlled Resistor

If a voltage V_x is applied at the output of the OTA and its output, followed by the Darlington pair (buffer stage) which acts as emitter follower, is fed back to the inverting terminal of the OTA through the voltage divider consisting of R_A and R_B, then the output current of the OTA is given by,

$$I_{out} = -g_m \times v_{in} \qquad (- \text{ sign is due to inverting input})$$

$$= -g_m \times V_x \frac{R_A}{R_A+R_B} \qquad (4.3.1)$$

If I_x is the current due to application of the voltage V_x then $I_x = -I_{out}$ (4.3.2)

$$\text{So, } I_x = g_m \times V_x \frac{R_A}{R_A+R_B}$$

$$\text{Or, } \frac{V_x}{I_x} = g_m \frac{R_A+R_B}{R_A} \qquad (4.3.3)$$

The term "$\frac{V_x}{I_x}$" is equivalent to effective resistance R_x which depends on the transconductance g_m. Through the variation of g_m by bias voltage V_B, the OTA can be realized as a voltage controlled resistor.

4.4 Voltage Controlled Amplifier

In the following circuit the input signal V_{in} is applied to the inverting terminal through the resistive divider formed by the resistors R_1 and R_2.

The output current of the transconductance amplifier is

$$I_{out} = -V_{in} \frac{R_1}{R_1+R_2} g_m \qquad (4.4.1)$$

And it appears via low impedance buffer stage as

$$V_{out} = I_{out} R_L \qquad (4.4.2)$$

$$\text{Or, } V_{out} = -V_{in} \frac{R_1}{R_1+R_2} g_m R_L \qquad (4.4.3)$$

So, the voltage gain (A_v) is $A_v = \frac{V_{out}}{V_{in}} = \frac{R_1 R_L}{R_1+R_2} g_m$ (4.4.4)

As the voltage gain is dependent on g_m and g_m is proportional to bias current, the gain can be varied through R_B and external gain controlled voltage V_B. The gain can be varied with the gain controlled voltage changing from the positive supply to the negative supply.

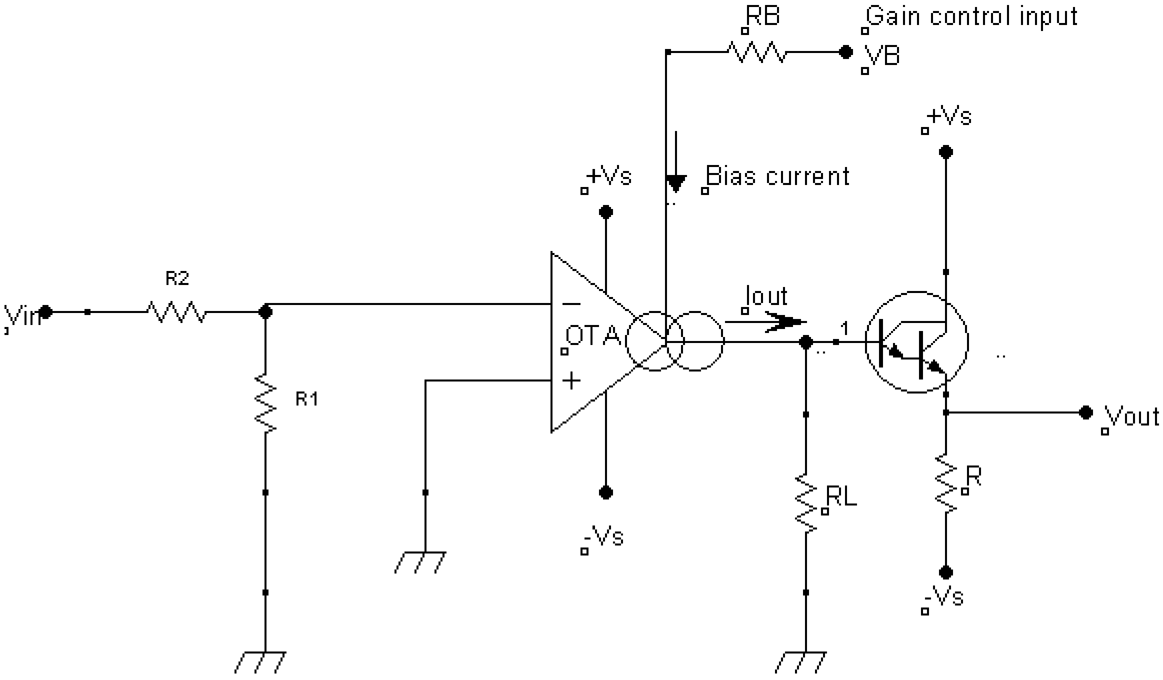

Figure 4.4 OTA as a Voltage Controlled Amplifier

4.5 Sample and Hold Circuit

By the application of pulsating bias current, OTA can be used in voltage follower configuration with the charge holding capacitor to purpose the function of a sample and hold circuit. For the hold capacitor to work accurately neither charging amplifier nor the signal output circuit would alter the charge stored on the capacitor. The output resistance of the OTA is of higher order during cut-off condition and its loading on the charging capacitor is very little and for the output readout circuit a 3N138 insulated gate field effect transistor is used because its impedance is of the order of $(10^3 \mathrm{M\Omega})$ and maximum gate leakage current is about $(10\mathrm{pA})$, as a result its loading on the charge holding capacitor is negligible. The MOSFET acts as a source follower in the feedback loop, hence the output follows the input during the sample period and during the hold period the capacitor provides the last stored sampled value. For the stability of the circuit the largest possible phase compensation capacitor is required with maximum allowable tilt and required slew rate [7].

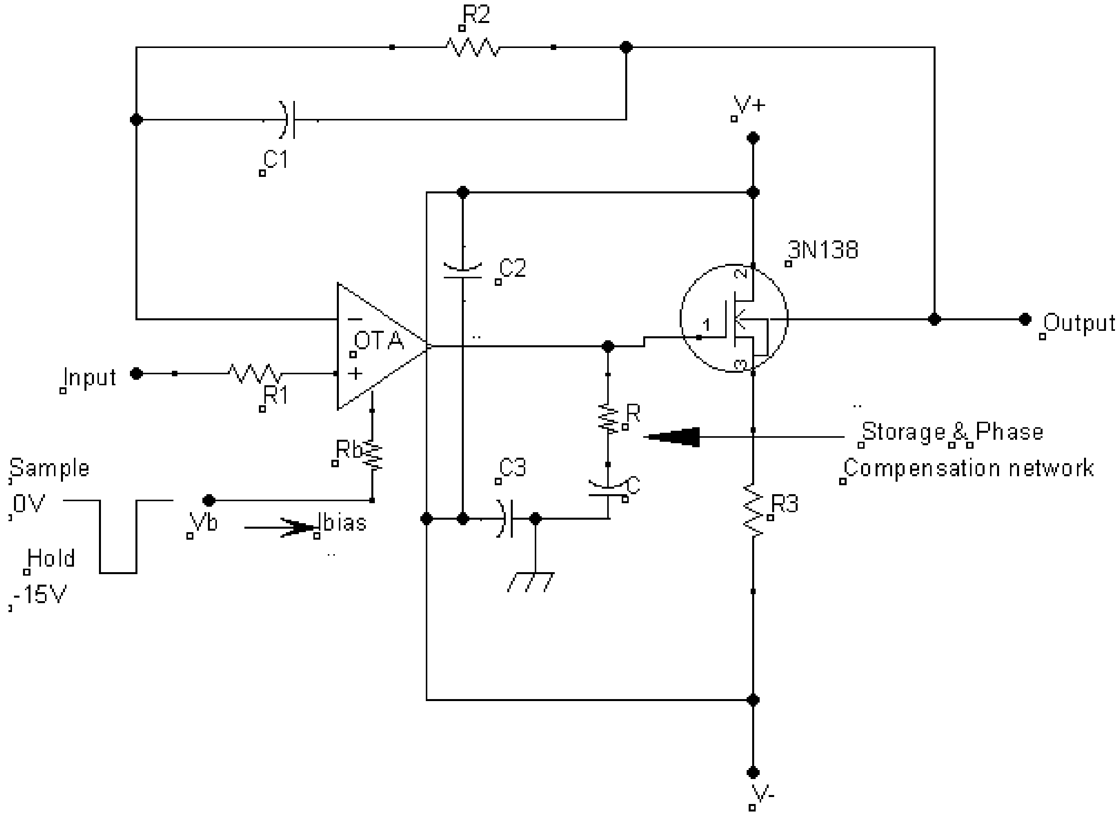

Figure 4.5 Sample and Hold Circuit Using OTA

4.6 Multiplexer

Outputs from the CMOS flip-flop driven by clock, when employed to the bias terminal of an OTA it can serve as a multiplexer [7]. In the following circuit a two channel multiplexer using two OTAs has been designed. The IC flip-flop is powered by the positive supply. Outputs from the flip-flop are applied through the common ground base configuration of the PNP transistors to minimize the feed-through capacitor coupling. When OTA1 is turned on by the bias current, its input acts on the output and when OTA2 is turned on, it controls the output. RC is the phase compensation network at the output. The maximum clock rate is limited by the slew rate and difference $(V_{in1} - V_{in2})$ at its maximum allowable limit.

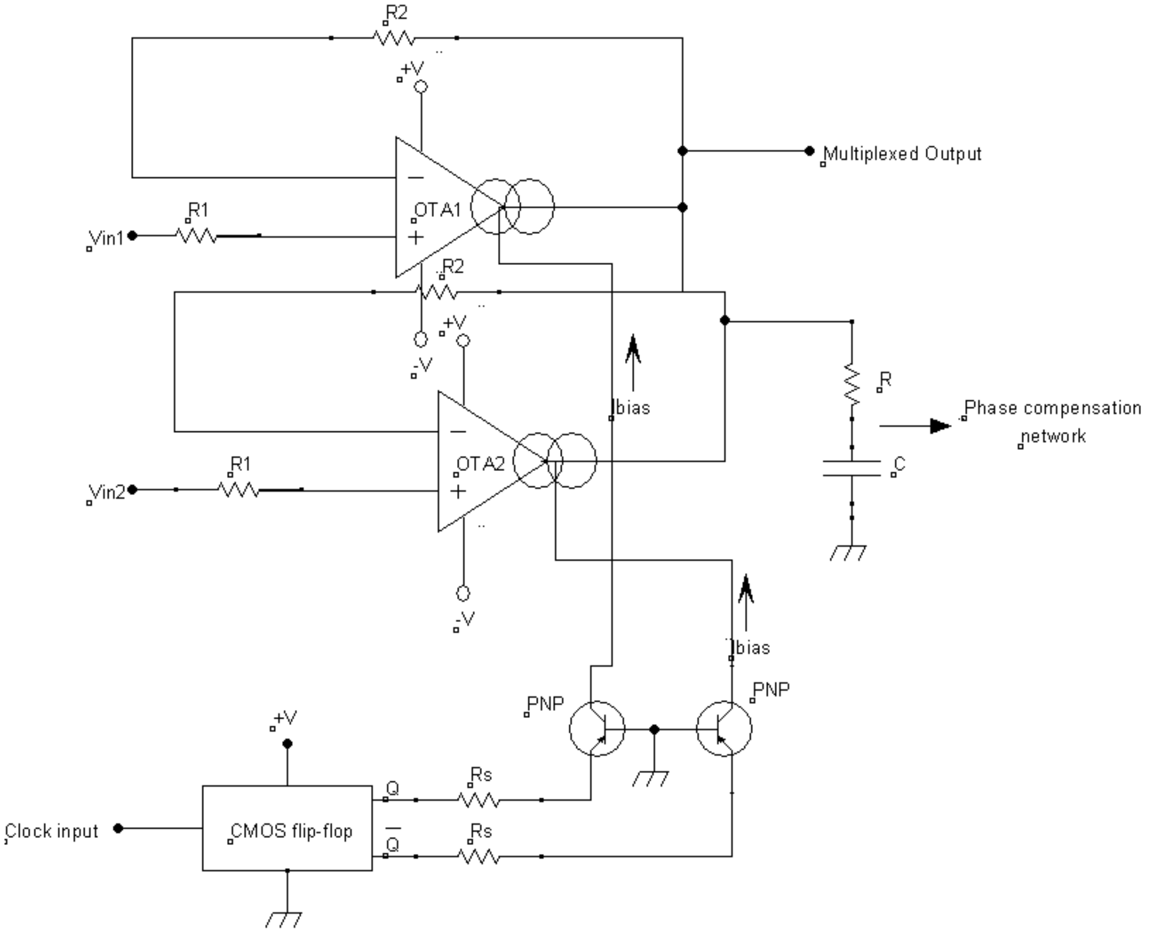

Figure 4.6 OTA Based Multiplexer

4.7 Amplitude Modulator

As the gain of the operational transconductance amplifier is proportional to the input bias current and the output current is the product of transconductance (g_m) and input voltage (V_{in}), the OTA can be used for modulation purpose. By applying a modulating signal (V_M) to the bias input and a carrier signal (V_{in}) to the inverting terminal, the amplitude of the output signal will vary according to the modulating voltage at the bias input.

As the modulating voltage (V_M) is established through resistor R_M, the bias current (I_B) is

$$I_B = \frac{V_M - (\mathrm{V-}) - 1.4v}{R_M}. \tag{4.7.1}$$

$\mathrm{V}-$ is the negative supply voltage and $1.4v$ is the internal voltage drop across the connection of base emitter transistor and diode [1].

The modulated output signal is

$$I_{out} = -g_m V_{in} \tag{4.7.2}$$

$$= -KI_B V_{in} = \frac{-K(V_M - (\mathrm{V}-) - 1.4v)V_{in}}{R_M}$$

$$= \frac{K((\mathrm{V}-)+1.4v)V_{in}}{R_M} - \frac{KV_M V_{in}}{R_M} \tag{4.7.3}$$

The first term corresponds to the fixed carrier input at $V_M = 0$ bias condition. The second term represents the modulation.

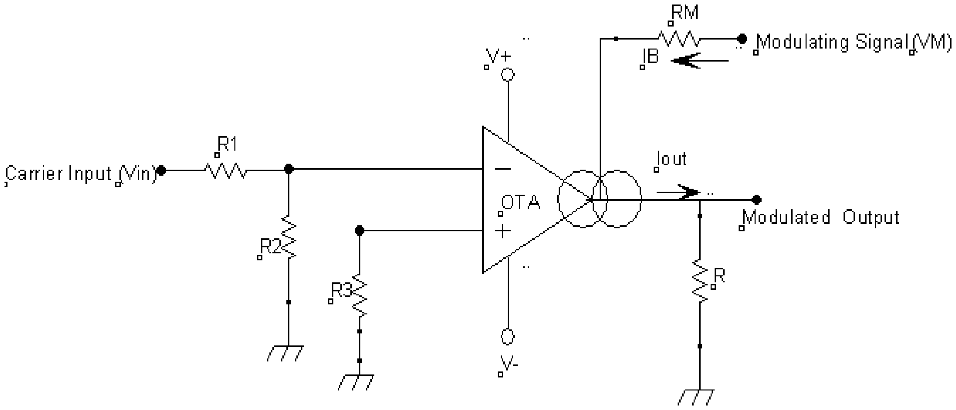

Figure 4.7a Amplitude Modulator

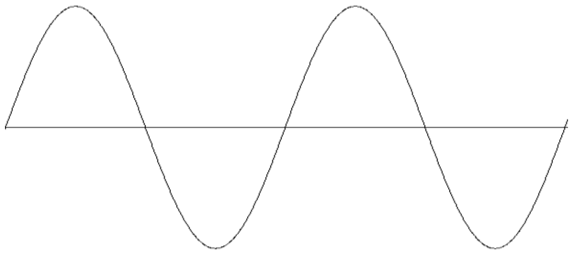

Figure 4.7b Modulating Signal

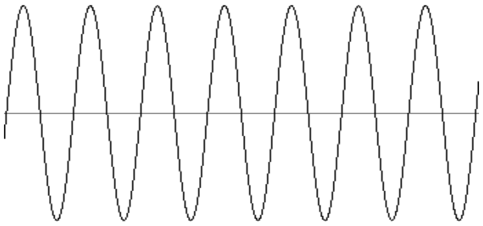

Figure 4.7c Carrier Input

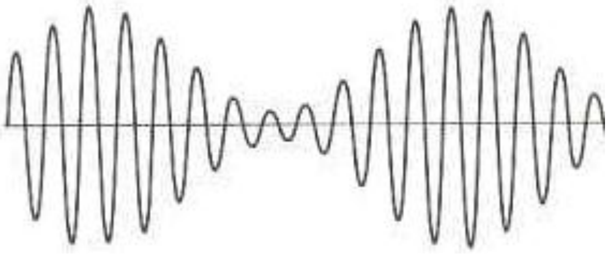

Figure 4.7d Amplitude Modulated Output Waveform

4.8 Four Quadrant Multiplier

From the modulating signal output equation (4.7.3) it can be observed that the polarity of the output signal depends on both the carrier signal and modulation signal. When the modulating voltage is at zero volts, the output is zero volts but as the modulating voltage increases and becomes positive, the output is inverted with respect to carrier input and when the modulating voltage is negative, the output remains in the same polarity with the carrier input. In the following circuit the resistor R_f is connected between the input and output terminal. If modulating signal is zero volts, the inverted signal current is exactly balanced by the non-inverting signal current via R_f hence, the output becomes zero volts. When the modulating input is positive the output of the OTA exceeds the current of R_f network and an inverted gain controlled output obtained, if the modulating input is negative the current of R_f network exceeds the output of the OTA and non-inverted gain controlled output obtained [12].

For R_f is chosen as $\frac{1}{g_m}$, the output current is given by

$$I_{out} = -\frac{KV_M V_{in}}{R_M} \tag{4.8.1}$$

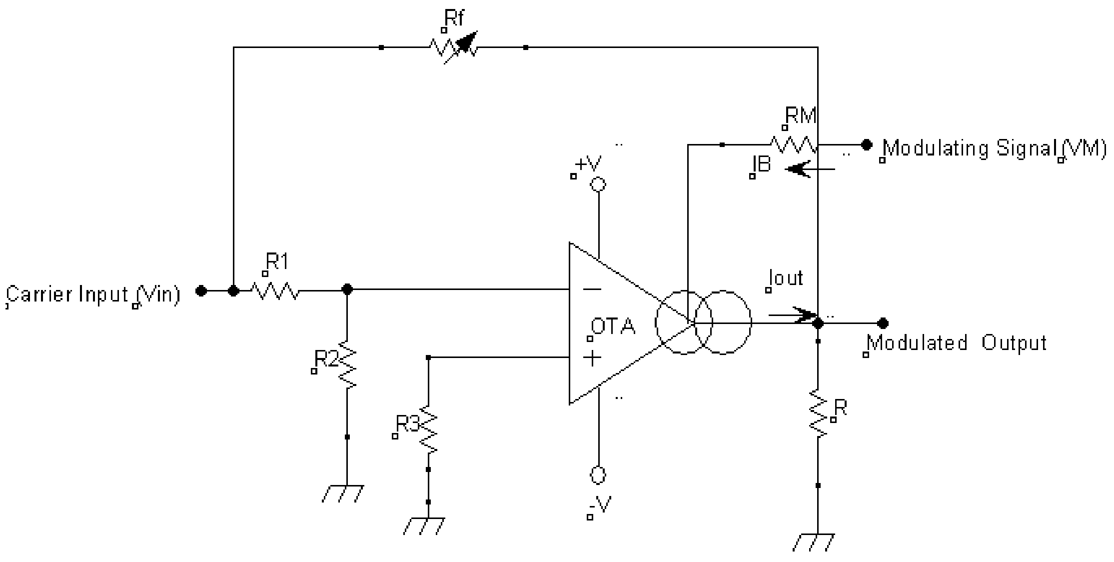

Figure 4.8 Four Quadrant Multiplier

When independent ac signals are applied to two inputs it acts as a **ring modulator**. If the carrier input is a square wave with frequency f_c then its Fourier series representation is

$$\sin f_c t + \frac{1}{3}\sin 3f_c t + \frac{1}{5}\sin 5f_c t + \frac{1}{7}\sin 7f_c t + \cdots\cdots\cdots$$

And if the modulating signal is a sine wave with frequency f, then the modulated output will consist of sine waves with frequencies $f + f_c, f + 3f_c, f + 5f_c,$ etc.... at decreasing amplitudes according to the Fourier series representation of the carrier input.

When identical sine waves are applied to two inputs it performs as a **frequency doubler**.

For $V_M = V_{in} = A\sin\omega t,$ the output current is

$$I_{out} = -\frac{KA^2 sin^2\omega t}{R_M}$$

$$= \frac{KA^2(cos\,2\omega t - 1)}{2R_M} \qquad (4.8.2)$$

Thus, the output frequency doubles the frequency of input signals.

4.9 Timer (Monostable Multivibrator)

The OTA is turned on by the rising edge of the trigger through the resistance R_b. The output becomes high when the voltage at the non inverting terminal is greater than that at the inverting terminal. The capacitor C_1 at the inverting terminal charges towards the voltage level that at the non-inverting terminal and when it exceeds, the output switches to low and the capacitor starts to discharge until the voltage at inverting terminal becomes equal to that at non-inverting terminal. The timer switches itself off automatically via the connection between bias input and output of OTA. A special feature of this timer is that it does not consume any power in quiescent state [13].

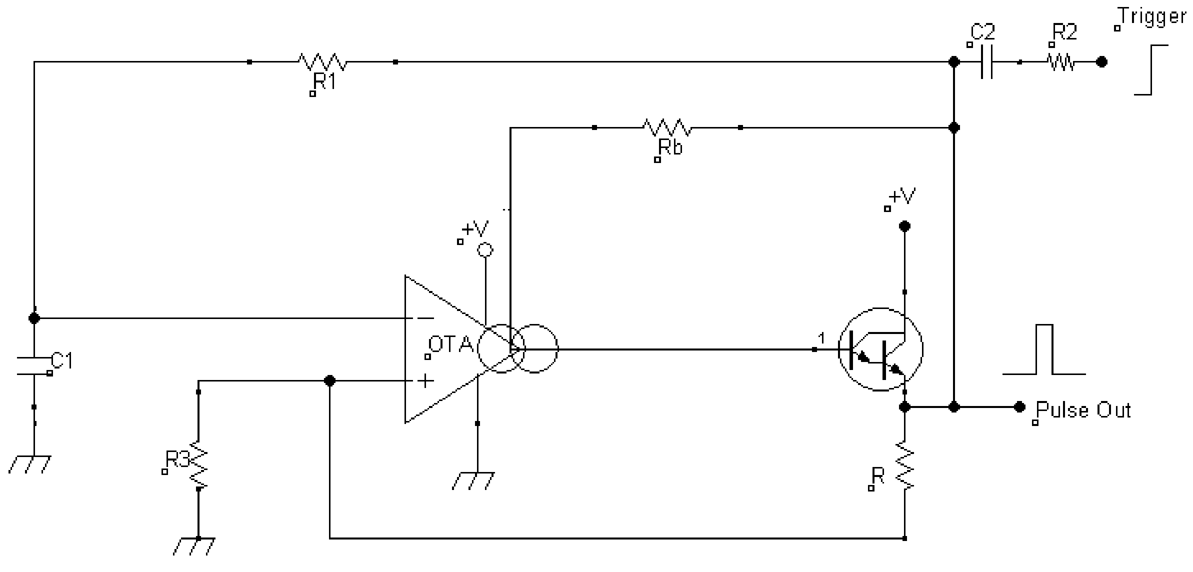

Figure 4.9 Timer Circuit

If V_{out} is the magnitude of the output pulse wave then voltage at the non-inverting terminal of the OTA is $\frac{R_3}{R_3+R}V_{out}$. The capacitor C_1 charges towards this voltage level. If T is the pulse width,

$$V_{out}\left(1 - e^{-\frac{T}{R_1C_1}}\right) = \frac{R_3}{R_3+R}V_{out} \tag{4.9.1}$$

Or, $1 - e^{-\frac{T}{R_1C_1}} = \frac{R_3}{R_3+R}$

Or, $1 - \frac{R_3}{R_3+R} = e^{-\frac{T}{R_1C_1}}$

Or, $-\frac{T}{R_1C_1} = ln\left(\frac{R}{R_3+R}\right)$

Or, $T = R_1C_1 ln\left(1 + \frac{R_3}{R}\right)$ (4.9.2)

4.10 Tachometer (F-V Converter)

This circuit transfers a fixed quantity of charge at the same rate as the input signal i.e. the charge transfer rate is proportional to the input frequency. Whenever an input signal goes from high to low, an amount of charge equals to $(V_H - V_L)C_1$ is sourced into C_2 per cycle, where V_H is the maximum high and V_L is the minimum low voltage swing of the OTA1. For a stable operation the charge transferred from C_1 to C_2 must be equal to the charge lost through R_2. The maximum magnitude of frequency is determined by the time required to charge C_1 from V_L to V_H with the bias current I_B. When OTA1 switches to low, C_1 discharges through D1.

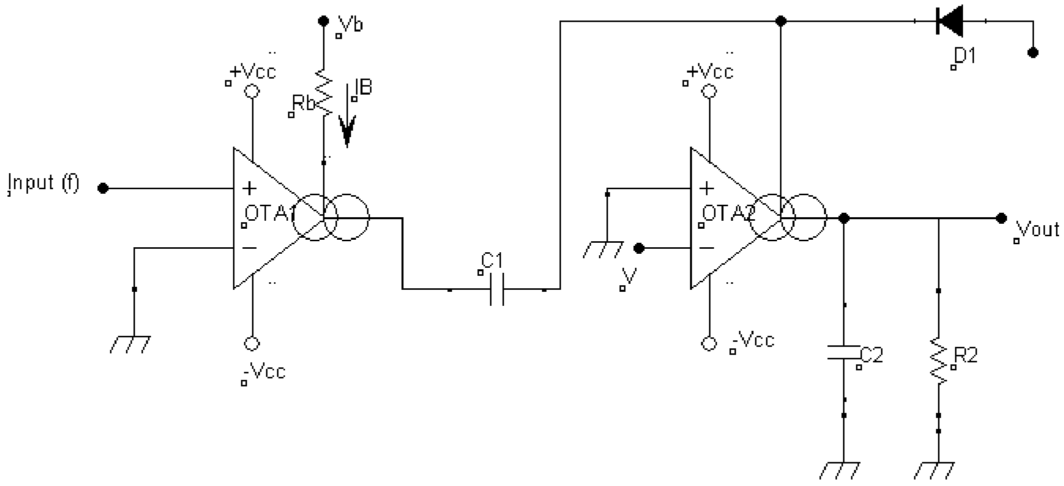

Figure 4.10 Tachometer Using OTA

By the principle of conservation of charge,

$$(V_H - V_L)C_1 = \frac{TV_{out}}{R_2} \qquad (4.10.1)$$

$$\text{Or, } V_{out} = \frac{C_1R_2(V_H - V_L)}{T}$$

$$\text{Or, } V_{out} = fC_1R_2(V_H - V_L) \qquad (4.10.2)$$

4.11 Peak Detector and Hold Circuit

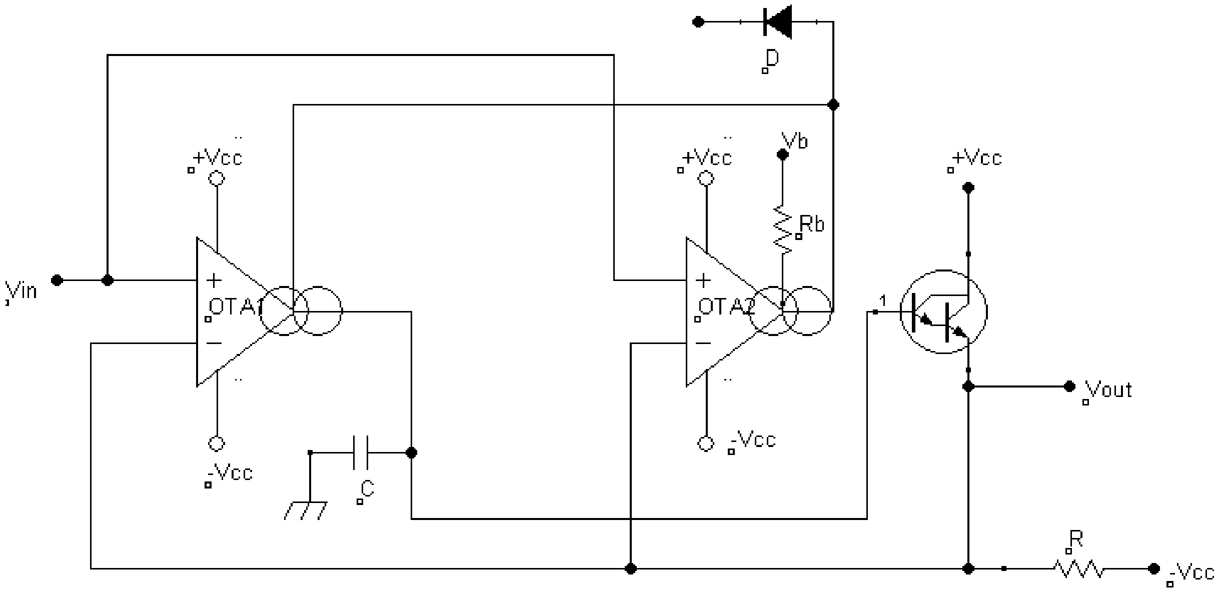

Figure 4.11a Peak Detector and Hold Circuit

In this diagram the output of OTA2 is configured to deliver the bias input of OTA1. The working principle is that whenever an input signal is applied at the non-inverting terminal of OTA1, peak of the input waveform is followed and stored in the capacitor C and appears at the output of Darlington pair. But if the input voltage falls below the voltage stored in the capacitor, the capacitor sticks to the previous higher value. OTA1 is turned off by taking the output of OTA2 through the diode D so that the output remains constant.

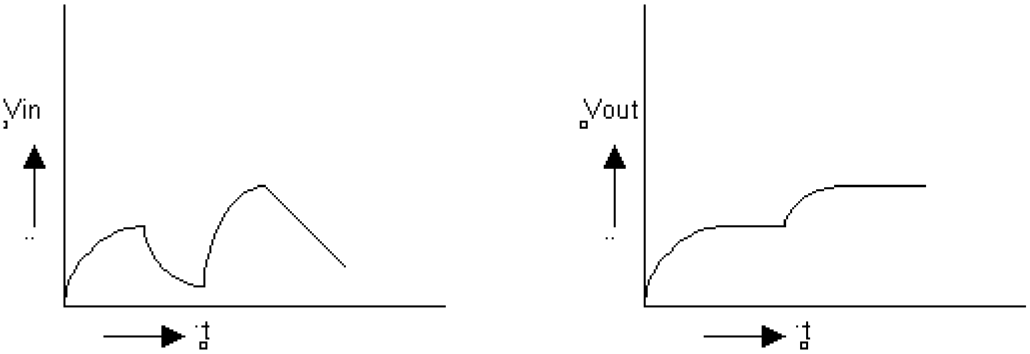

Figure 4.11b Input and Output waveforms for a Peak Detector and Hold Circuit

4.12 Phase Locked Loop (PLL)

OTA1 forms a four quadrant multiplier which drives an oscillator formed by OTA2 [8]. Whenever there is a difference in frequency between the input signal and output signal, the voltage across the capacitor changes which in turn controls the output frequency of OTA2 through its bias terminal as long as the frequency of the input signal becomes same with that of the output signal. At steady state the circuit becomes in lock.

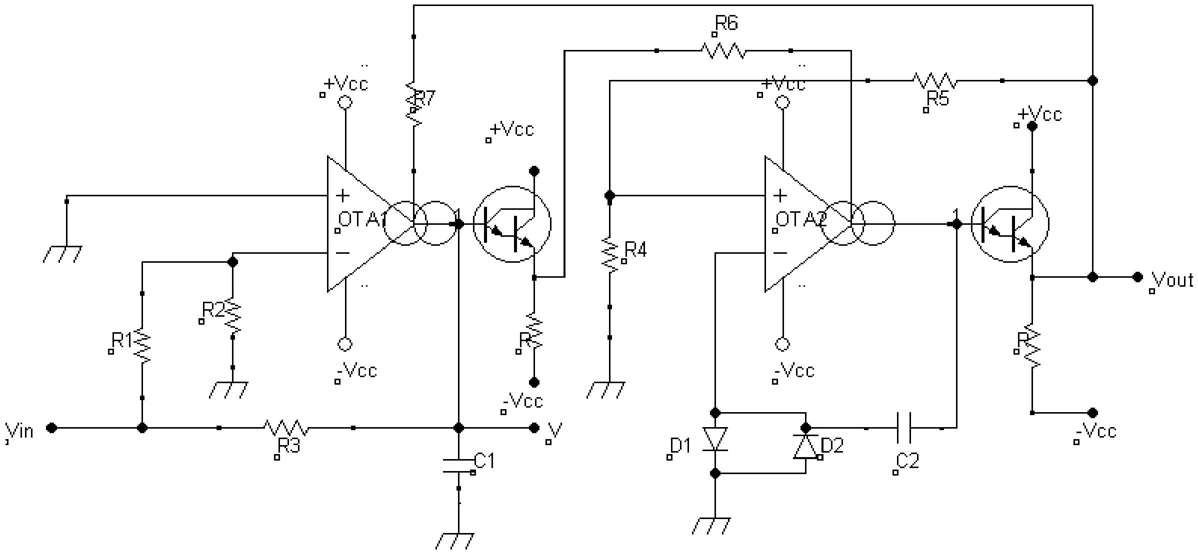

Figure 4.12 PLL Using OTA

From equation (4.8.1), the output current for OTA1 is given by

$$I_{out} = -\frac{KV_{out}V_{in}}{R_7} \qquad (4.12.1)$$

Then the output voltage (V) of OTA1 across the capacitor $C1$ is $\frac{1}{C1}\int_0^t -\frac{KV_{out}V_{in}}{R_7}dt$

At steady state, if the voltage (V) across this capacitor changes from V_1 to V_2 and vice-versa, then the frequency (f) of the output voltage (V_{out}) is

$$f = \frac{KV_{out}V_{in}}{R_7 C(V_2 - V_1)} \quad \text{[Where the output in same phase with the input]} \quad (4.12.2)$$

4.13 Ramp and Hold Circuit

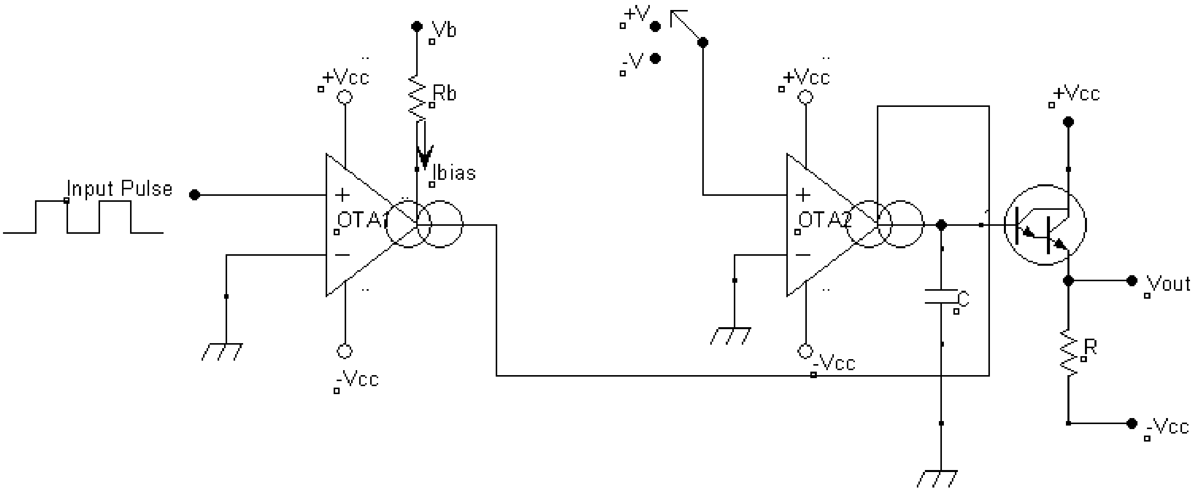

Figure 4.13 Ramp and Hold Circuit

The output of OTA1 drives the bias for OTA2. During the high level of the input pulse at the non-inverting input of OTA1 with $+V$ voltage at the non-inverting input of OTA2, the voltage across the capacitor ramps up (the charging time of the capacitor ≪ duration of high level) by the bias current and the output voltage retains at voltage $+V$ until when the level of input pulse becomes low. When $-V$ voltage is at the non-inverting input of OTA2 and the input pulse at the non-inverting input of the OTA1 becomes high, the voltage across the capacitor C ramps down by the negative bias current & the output voltage retains at voltage $-V$ until when the level of input pulse becomes low.

The ramp up or ramp down time is given by $T = \frac{CV}{I_{bias}}$ (4.13.1)

4.14 Log Amplifier

The following is a logarithmic amplifier circuit [8] where the output voltage is logarithm of the input voltage. Input voltage V_{in} is applied to one OTA and a reference voltage V_{ref} is applied to another OTA. Transistors T1 and T2 are perfectly matched. This circuit provides a wide dynamic range of amplification.

The output voltage is given by

$$V_{out} = \frac{(2V_b - 1.2v)R_4R_5}{(R_3+R_4)R_b} ln \frac{V_{in}R_2}{V_{ref}R_1}$$

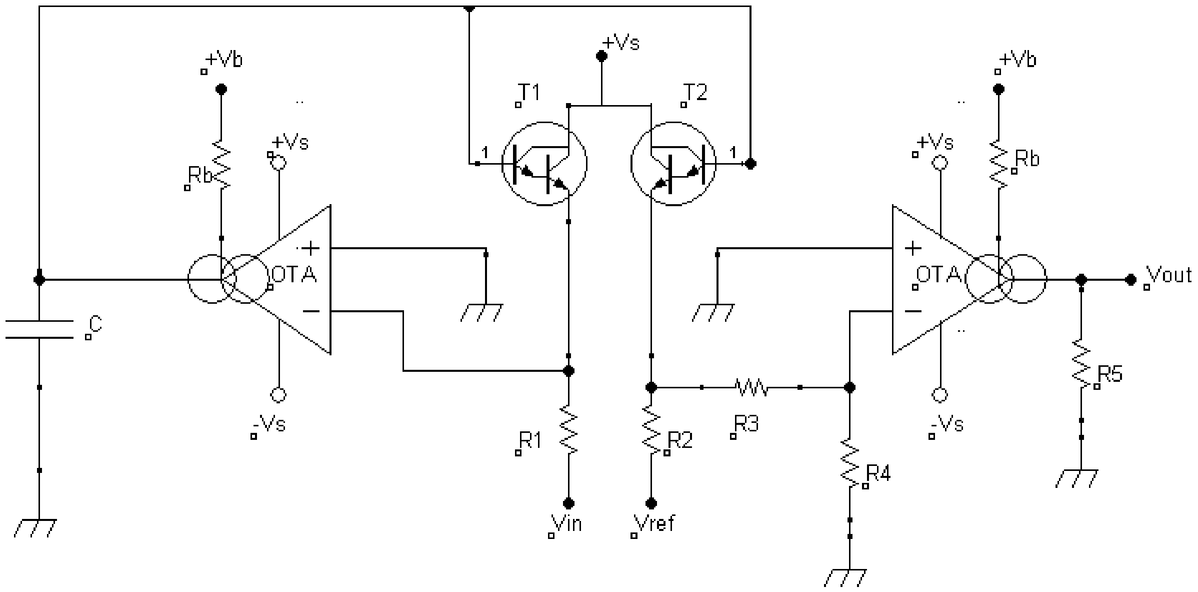

Figure 4.14 Log Amplifier

4.15 Voltage Controlled Low Pass Filter

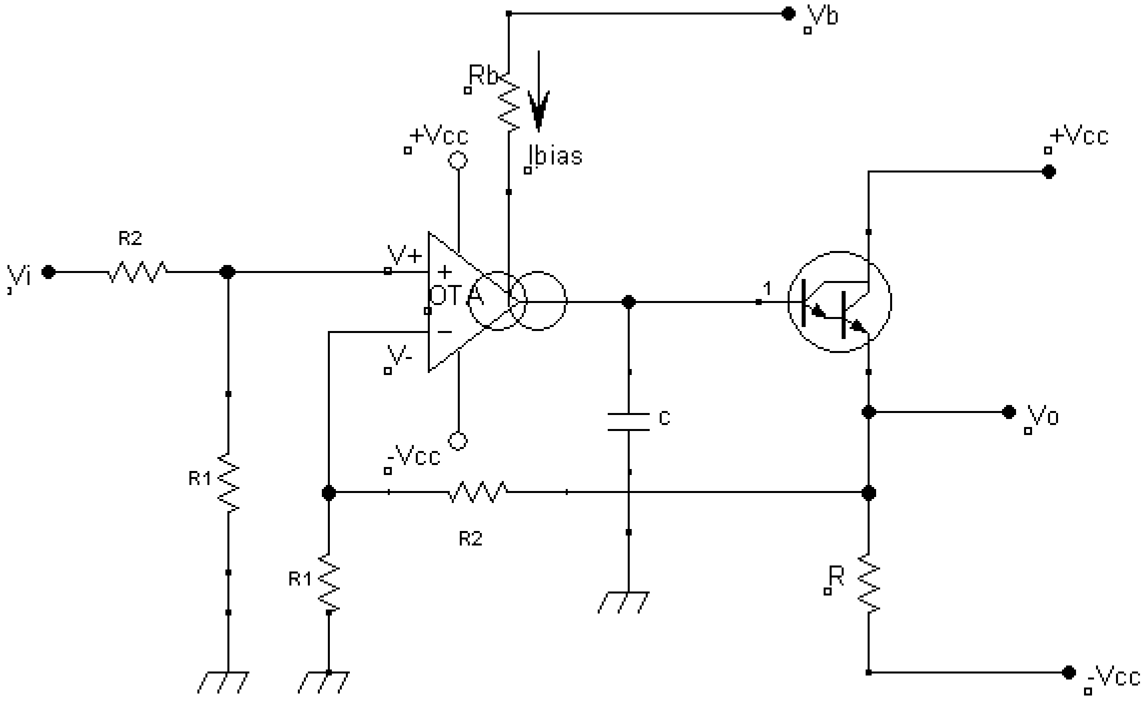

Figure 4.15 Voltage Controlled Low Pass Filter

The circuit performs the action of a first order low pass filter. The input voltage V_i is applied at the non-inverting terminal of the OTA through the voltage divider R_1-R_2.

$$V+ = V_i \frac{R_1}{R_1+R_2} \tag{4.15.1}$$

And the OTA output voltage V_o followed by the buffer stage is fed back at the inverting terminal through an identical voltage divider R_1-R_2.

$$V- = V_o \frac{R_1}{R_1+R_2} \tag{4.15.2}$$

The voltage V_c across the capacitor C is

$$V_c = g_m((V+) - (V-))\frac{1}{Cs}$$

$$= \frac{g_m R_1}{(R_1+R_2)Cs}(V_i - V_o) \tag{4.15.3}$$

Where, g_m is the transconductance of OTA.

As the Darlington pair at the output of the capacitor acts as a buffer,

$$V_c = V_o = \frac{g_m R_1}{(R_1+R_2)Cs}(V_i - V_o) \tag{4.15.4}$$

$$\text{Or, } \frac{(V_i - V_o)}{V_o} = \frac{(R_1+R_2)Cs}{g_m R_1}$$

$$\text{Or, } \frac{V_o}{V_i} = \frac{1}{1+\frac{(R_1+R_2)Cs}{g_m R_1}} \tag{4.15.5}$$

This is the transfer function of a first order low pass filter with cutoff frequency $\frac{g_m R_1}{2\pi C(R_1+R_2)}$. It has unity gain in the pass band and beyond the cutoff frequency the gain droops at 6dB/octave. As g_m depends on the bias current, the cutoff frequency can be varied by changing the bias voltage V_b.

4.16 Voltage Controlled High Pass Filter

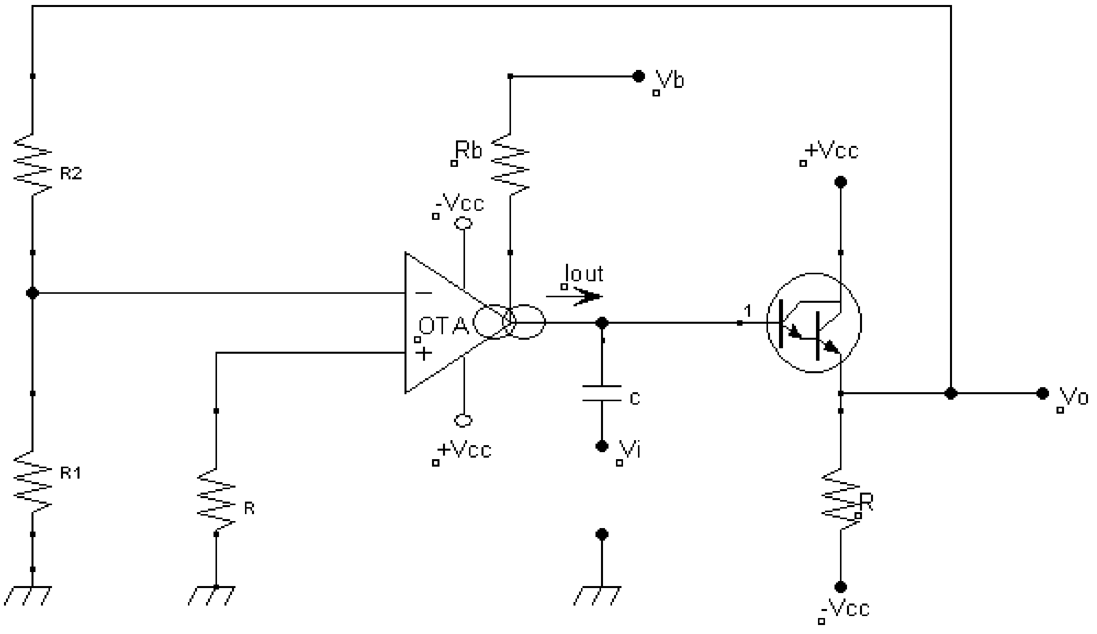

Figure 4.16 Voltage Controlled High Pass Filter

This is a voltage controlled first order high pass filter circuit using OTA. The input voltage V_i is applied to the capacitor at the output of OTA. The output V_o from buffer stage is fed back to the inverting input through the voltage divider R$_1$-R$_2$. The non-inverting terminal is grounded.

The output current is given by

$$I_{out} = g_m((V+) - (V-)) \tag{4.16.1}$$

Or, $$(V_o - V_i)Cs = g_m\left(0 - V_o\frac{R_1}{R_1+R_2}\right)$$

Or, $$\frac{V_o}{V_i - V_o} = \frac{(R_1+R_2)Cs}{g_mR_1}$$

Or, $$\frac{V_o}{V_i} = \frac{s}{s+\frac{g_mR_1}{(R_1+R_2)C}} \tag{4.16.2}$$

This is the transfer function of a first order high pass filter with cutoff frequency $f_c = \frac{g_mR_1}{(R_1+R_2)2\pi C}$. It has unity gain in the passband and provides a single RC roll-off 6dB/octave below the cutoff frequency. As the cutoff frequency is proportional to the transconductance, the cutoff frequency can be varied by changing the bias voltage V_b.

4.17 Voltage Controlled Band Pass Filter

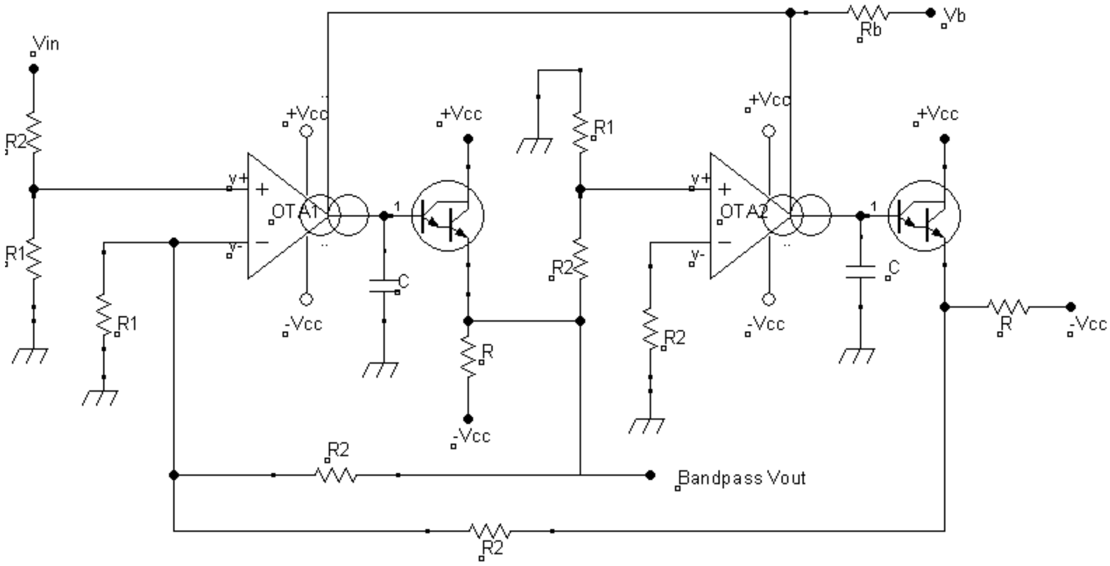

Figure 4.17 Voltage Controlled Band Pass Filter

The circuit uses two OTAs to implement a band pass filter. V_{in} is applied to the non-inverting input of OTA1 through the voltage divider R_1-R_2 and the output of OTA1 is applied to the non-inverting terminal of OTA2 through the Darlington pair buffer stage. The outputs of OTA1 and OTA2 are fed back to inverting input of OTA1 together through an identical voltage divider R_1-R_2. The band pass output of OTA1 is V_{out}.

For OTA2, the output current is

$$I_{out2} = g_{m2}(v_+ - v_-) \tag{4.17.1}$$

Or, $V \times Cs = g_{m2}\left(\frac{V_o R_1}{R_1+R_2} - 0\right)$

Or, $V = g_{m2}\frac{V_o R_1}{(R_1+R_2)Cs}$ (4.17.2)

Where g_{m2} is the transconductance of OTA2.

And V is the output voltage of OTA2.

For OTA1, the output current is

$$I_{out1} = g_{m1}(v_+ - v_-) \tag{4.17.3}$$

Or, $V_{out} \times Cs = g_{m1}((V_{in}\frac{R_1}{R_1+R_2} - \left(V\frac{R_1}{R_1+R_2} + V_{out}\frac{R_1}{R_1+R_2}\right))$ (4.17.4)

Where g_{m1} is the transconductance of OTA1.

Substituting the value of V from (4.17.2) into (4.17.4)

$$V_{out} \times Cs = g_{m1}((V_{in}\frac{R_1}{R_1+R_2} - \left(g_{m2}\frac{V_{out}{R_1}^2}{Cs(R_1+R_2)^2} + V_{out}\frac{R_1}{R_1+R_2}\right))$$

Or, $V_{out}\left(Cs + \frac{g_{m1}g_{m2}{R_1}^2}{Cs(R_1+R_2)^2} + \frac{g_{m1}R_1}{R_1+R_2}\right) = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$

Or, $V_{out}\left(\frac{s^2C^2(R_1+R_2)^2 + sC(R_1+R_2)g_{m1}R_1 + g_{m1}g_{m2}{R_1}^2}{Cs(R_1+R_2)^2}\right) = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$

Or, $\frac{V_{out}}{V_{in}} = \frac{Cg_{m1}R_1(R_1+R_2)s}{s^2C^2(R_1+R_2)^2 + sC(R_1+R_2)g_{m1}R_1 + g_{m1}g_{m2}{R_1}^2}$

Or, $$\frac{V_{out}}{V_{in}} = \frac{\frac{g_{m1}R_1}{C(R_1+R_2)}s}{s^2+\frac{g_{m1}R_1}{C(R_1+R_2)}s+\frac{g_{m1}g_{m2}R_1{}^2}{C^2(R_1+R_2)^2}} \qquad (4.17.5)$$

This is the transfer function of a band pass filter with centre frequency at $f_0 = \frac{R_1\sqrt{g_{m1}g_{m2}}}{2\pi C(R_1+R_2)}$ and quality factor (Q) is $\frac{R_1\sqrt{g_{m1}g_{m2}}}{C(R_1+R_2)} \times \frac{C(R_1+R_2)}{g_{m1}R_1} = \sqrt{\frac{g_{m2}}{g_{m1}}}$

And its bandwidth (B) is given by $\frac{f_0}{Q} = \frac{R_1 g_{m1}}{2\pi C(R_1+R_2)}$. The centre frequency of the response depends on transconductance of the both OTAs but the bandwidth depends on the transconductance of OTA1.

4.18 Voltage Controlled Butterworth Low pass Filter

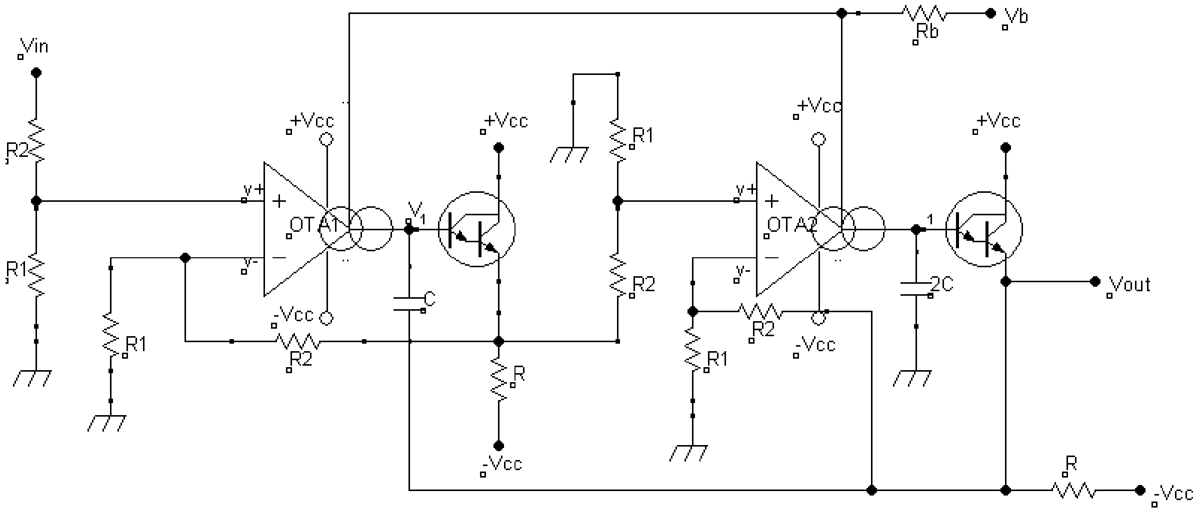

Figure 4.18 Voltage Controlled Butterworth Low Pass Filter

This is a voltage controlled 2nd order low pass Butterworth filter circuit. Input V_{in} is applied to the non-inverting terminal of OTA1 through the voltage divider R_1-R_2 and its output via buffer stage is fed back to the inverting input through an identical voltage divider R_1-R_2. The output of OTA1 is taken to the non-inverting input of OTA2 through the voltage divider R_1-R_2 and its output V_{out} across the capacitor $2C$ via buffer stage is fed back to its inverting input through an identical voltage divider R$_1$-R$_2$. The output of OTA1 and buffer output of OTA2 are connected by the capacitor C.

For OTA1, the output current is

$$I_{out1} = g_{m1}(v_{+} - v_{-}) \tag{4.18.1}$$

Or, $(V - V_{out}) \times Cs = g_{m1}(V_{in} - V)\frac{R_1}{R_1+R_2}$

Or, $V\left(Cs + \frac{g_{m1}R_1}{R_1+R_2}\right) - (V_{out} \times Cs) = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$ (4.18.2)

Where, g_{m1} is the transconductance of OTA1.

For OTA2, the output current is

$$I_{out2} = g_{m2}(v_{+} - v_{-}) \tag{4.18.3}$$

Or, $V_{out} \times 2Cs = g_{m2}\frac{R_1}{R_1+R_2}(V - V_{out})$

Or, $\frac{g_{m2}R_1}{R_1+R_2}V = (2Cs + \frac{g_{m2}R_1}{R_1+R_2})$

Or, $V = V_{out}\frac{R_1+R_2}{g_{m2}R_1}(2Cs + \frac{g_{m2}R_1}{R_1+R_2})$ (4.18.4)

Where g_{m2} is transconductance of OTA2.

Substituting the value of V from (4.18.4) into (4.18.2)

$$V_{out}\frac{R_1 + R_2}{g_{m2}R_1}(2Cs + \frac{g_{m2}R_1}{R_1 + R_2})\left(Cs + \frac{g_{m1}R_1}{R_1 + R_2}\right) - (V_{out} \times Cs) = V_{in}\frac{g_{m1}R_1}{R_1 + R_2}$$

Or, $V_{out}\frac{R_1+R_2}{g_{m2}R_1}\left(2C^2s^2 + \frac{g_{m1}g_{m2}R_1^2}{(R_1+R_2)^2} + \frac{2Cs\,g_{m1}R_1}{R_1+R_2} + \frac{Cs\,g_{m2}R_1}{R_1+R_2}\right) - (V_{out} \times Cs) = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$

Or, $V_{out}(\frac{2C^2s^2(R_1+R_2)}{g_{m2}R_1} + \frac{g_{m1}R_1}{R_1+R_2} + \frac{2Csg_{m1}}{g_{m2}}) = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$

Or, $V_{out}(\frac{2C^2s^2(R_1+R_2)^2+g_{m1}g_{m2}R_1^2+2Csg_{m1}R_1(R_1+R_2)}{g_{m2}R_1(R_1+R_2)} = V_{in}\frac{g_{m1}R_1}{R_1+R_2}$

Or, $\frac{V_{out}}{V_{in}} = \frac{g_{m1}g_{m2}R_1^2}{2C^2s^2(R_1+R_2)^2+g_{m1}g_{m2}R_1^2+2Csg_{m1}R_1(R_1+R_2)}$ (4.18.5)

If $g_{m1} = g_{m2} = g_m$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{g_m^2R_1^2}{2C^2(R_1+R_2)^2}}{s^2+\frac{g_mR_1}{C(R_1+R_2)}s+\frac{g_m{}^2R_1^2}{2C^2(R_1+R_2)^2}} \qquad (4.18.6)$$

And, $\left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\sqrt{1+\left(\frac{\omega}{\frac{g_mR_1}{C(R_1+R_2)}}\right)^4}}$. (4.18.7)

This is a second order Butterworth low pass filter with cutoff frequency at $f_c = \frac{g_mR_1}{2\pi C(R_1+R_2)}$. It has unity gain in the passband and beyond the cutoff frequency the gain droops at 12dB per octave. If the two OTAs have excellent tracking, the filter can perform well over several decades of frequencies.

4.19 Universal Filter

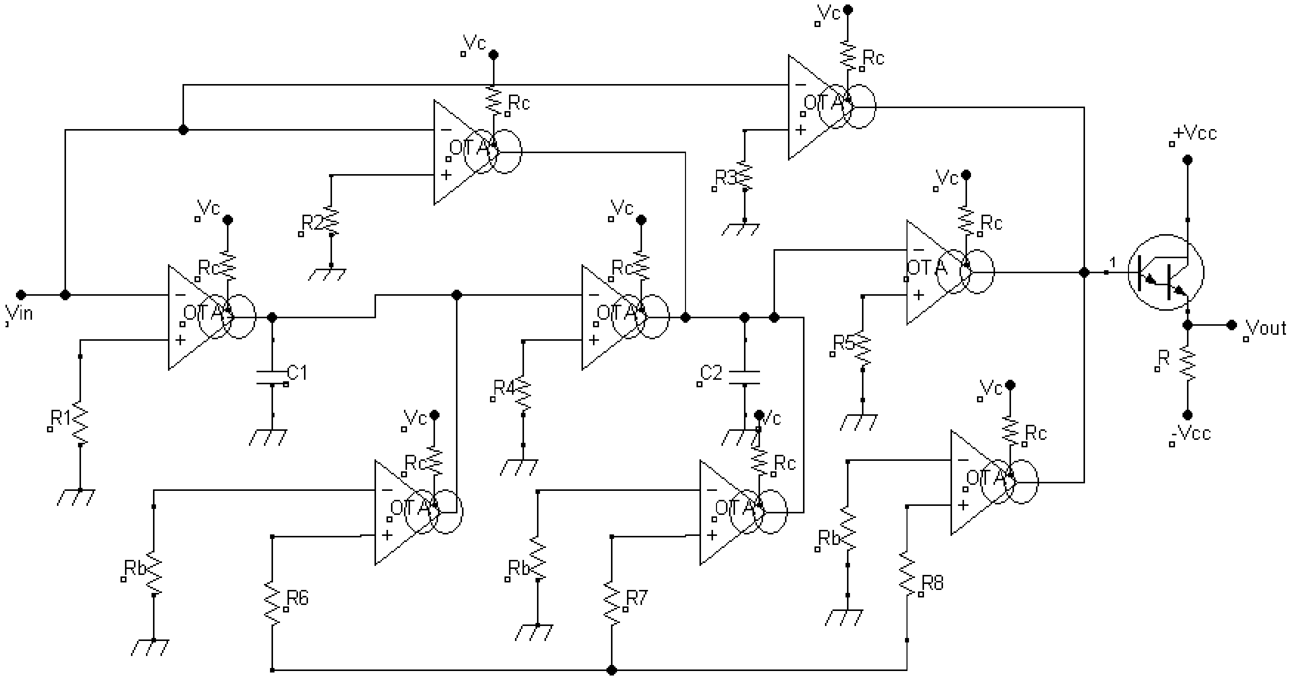

Figure 4.19 Universal Filter

The transfer function of the universal filter is

$$\frac{V_{out}}{V_{in}} = \frac{\frac{C_1C_2R_4R_5}{R_3}s^2+\frac{C_1R_4}{R_2}s+\frac{1}{R_1}}{\frac{C_1C_2R_4R_5}{R_8}s^2+\frac{C_1R_4}{R_7}s+\frac{1}{R_6}} \tag{4.19.1}$$

If R_2 and R_3 are set to ∞, the resulting transfer function becomes that of a low pass filter.

If R_1 and R_2 are set to ∞, the resulting transfer function becomes that of a high pass filter.

If R_3 and R_1 are set to ∞, the resulting transfer function becomes that of a band pass filter.

If $R_3 = R_1$ and R_2 is set to ∞, the filter becomes a band rejection filter.

For an all-pass filter $R_1 = R_6$, $R_2 = R_7$ and $R_3 = R_8$.

4.20 Astable Multivibrator

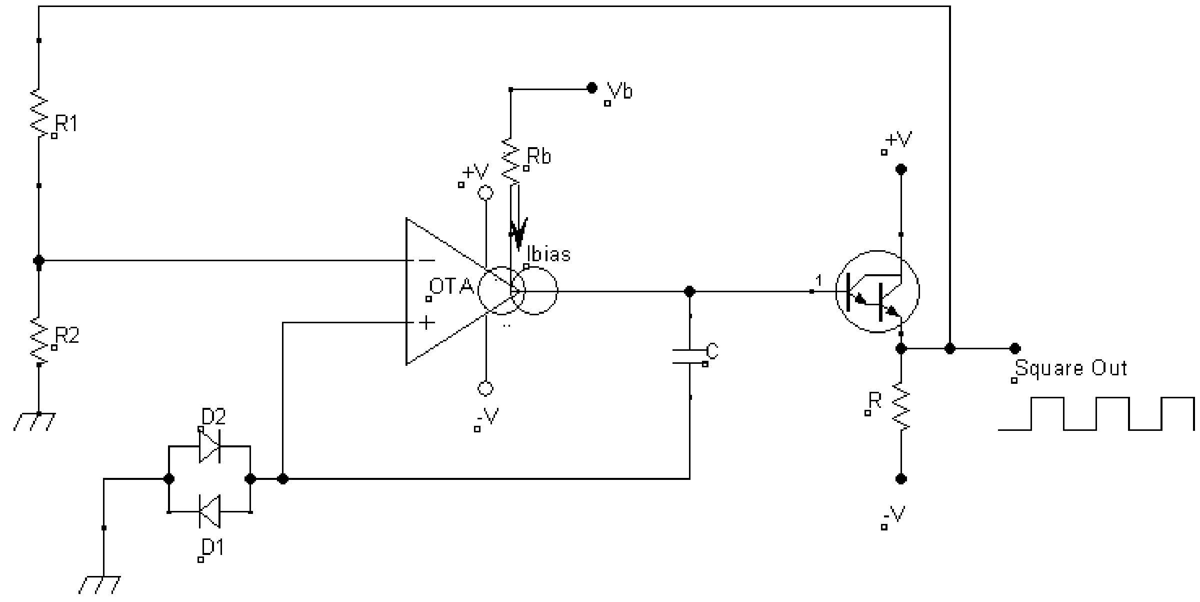

Figure 4.20 Astable Multivibrator

This is an astable multivibrator or a single amplifier VCO circuit implemented with OTA. It provides square wave output. The OTA is basically a comparator determined by the divider R$_1$-R$_2$ ratio and the output of the circuit fully switches between the supply voltages $+V$ and

$-V$. The output is approximately symmetrical and the frequency of output can be changed by controlling the voltage V_b. The capacitor C charges and discharges through D1 and D2 respectively.

During T_{high}, the capacitor charges up to $+V\frac{R_2}{R_1+R_2}$ from $-V\frac{R_2}{R_1+R_2}$ linearly by the positive bias current I_{bias}.

$$\text{So,}\quad \frac{1}{C}I_{bias} \times T_{high} = \frac{2VR_2}{R_1+R_2}$$

$$\text{Or,}\quad T_{high} = \frac{2CVR_2}{I_{bias}(R_1+R_2)} \tag{4.20.1}$$

During T_{low}, the capacitor discharges down to $-V\frac{R_2}{R_1+R_2}$ from $+V\frac{R_2}{R_1+R_2}$ linearly by the negative bias current I_{bias}.

$$\text{So,}\quad \frac{1}{C}I_{bias} \times T_{low} = \frac{2VR_2}{R_1+R_2}$$

$$\text{Or,}\quad T_{low} = \frac{2CVR_2}{I_{bias}(R_1+R_2)} \tag{4.20.2}$$

The frequency of oscillation is $f = \frac{1}{T_{high}+T_{low}} = \frac{I_{bias}(R_1+R_2)}{4CVR_2}$ (4.20.3)

4.21 Sinusoidal Voltage Controlled Oscillator

This circuit comprises 4 OTAs. OTA1, OTA2, OTA3 are configured as low pass circuit mode such that each OTA gives a phase shift of 60° thereby, giving a total phase shift of ($3 \times 60^{\circ} = 180^0$). OTA4 operating as an inverter, gives an additional phase shift of 180^0. Thus, the circuit oscillates at a frequency when total loop phase shift is 360^0 from input to output. This circuit can be used to operate with maximum of 1% total harmonic distortion.

From low pass filter structure its derived transfer function is

$$\frac{V_o}{V_i} = \frac{1}{1+\frac{(R_1+R_2)Cs}{g_m R_1}} \tag{4.21.1}$$

As each filter stage will have a phase shift of 60°

So, $\left|\angle\frac{V_o}{V_i}\right| = \tan^{-1}\omega\,\frac{(R_1+R_2)C}{g_mR_1} = 60^\circ$ (4.21.2)

Or, $\frac{\omega(R_1+R_2)C}{g_mR_1} = \tan 60^\circ$

Or, $\frac{2\pi f(R_1+R_2)C}{g_mR_1} = \sqrt{3}$

Or, $f = \frac{\sqrt{3}g_mR_1}{2\pi(R_1+R_2)C}$ (4.21.3)

The frequency of the sinusoidal output oscillator is $f = \frac{\sqrt{3}g_mR_1}{2\pi(R_1+R_2)C}$. The frequency can be changed through the variation of g_m by controlling voltage V_b.

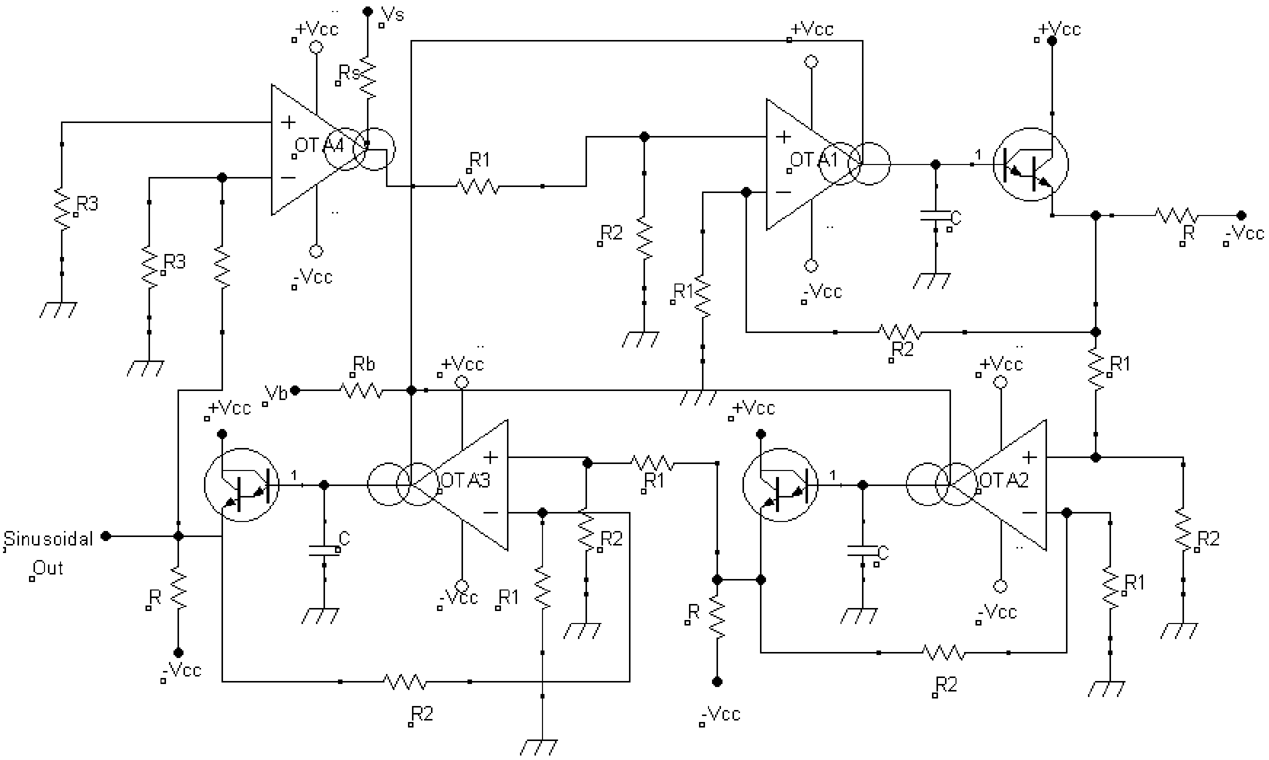

Figure 4.21 Sinusoidal Voltage Controlled Oscillator

4.22 Square/Triangular VCO

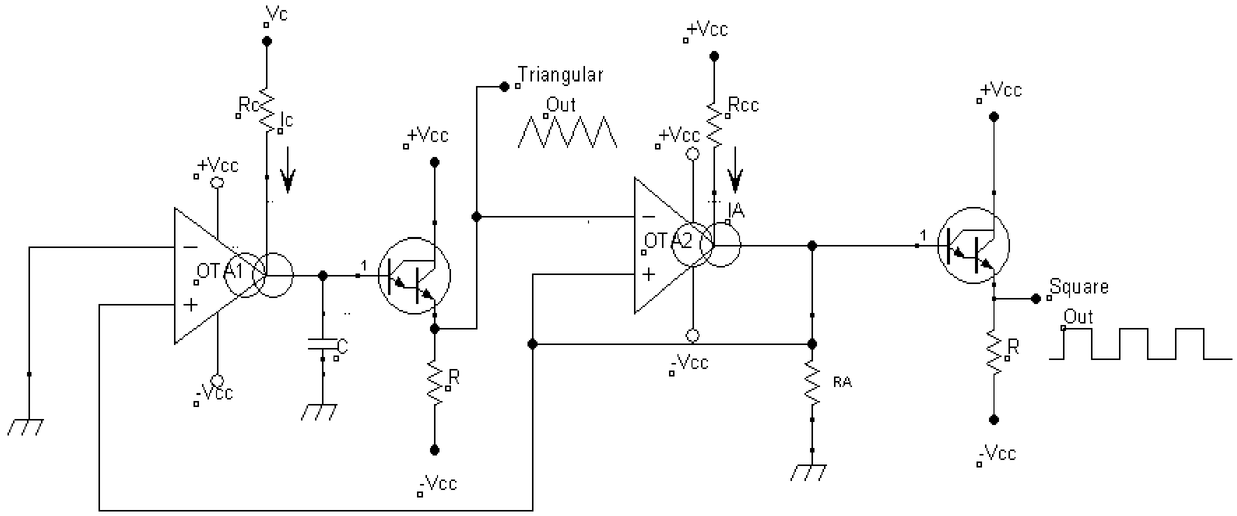

Figure 4.22 Triangular/Square VCO

In this circuit the first OTA generates triangular wave and second OTA generates square wave simultaneously. Both the OTAs are in voltage comparator mode. When the output of OTA2 is on high level of square wave, the positive voltage across R_A is fed back to the non-inverting terminal of the both OTAs and the capacitor C at the output of OTA1 begins to charge up by the current I_c, giving rise to the positive linear ramp voltage which appears at the inverting terminal of OTA2 via Darling buffer stage and when this voltage exceeds that at the non-inverting terminal, the output of OTA2 abruptly switches to negative thus giving the low level of square wave at the output. As a result, a negative voltage across R_A at the non-inverting input of OTA1 causes the capacitor C to discharge linearly until the voltage across it falls to a value equal to that across R_A. At that point output of OTA2 switches to high again. This process repeats infinitely providing the triangular wave at the output of OTA1 and square wave at the output of OTA2.

The voltage across the capacitor is given as

$$V = \frac{1}{C}\int i.dt$$

When the capacitor charges up to $V = I_A R_A$ from $V = -I_A R_A$ linearly during T_{high} by the positive current I_c, the output of OTA2 is on the high level.

So, $2I_A R_A = \frac{I_c T_{high}}{C}$

Or, $T_{high} = \frac{2CI_A R_A}{I_c}$ (4.22.1)

And when the capacitor discharges up to $V = -I_A R_A$ from $V = I_A R_A$ linearly during T_{low} by the negative current I_c, the output of OTA2 is on the low level.

So, $2I_A R_A = \frac{I_c T_{low}}{C}$

Or, $T_{low} = \frac{2CI_A R_A}{I_c}$ (4.22.2)

So, the frequency of the output square wave is $f = \frac{1}{T_{high} + T_{low}} = \frac{I_c}{4CI_A R_A}$ (4.22.3)

The output frequency is voltage controlled over wide range corresponding to the control current.

4.23 Sawtooth/Pulse VCO

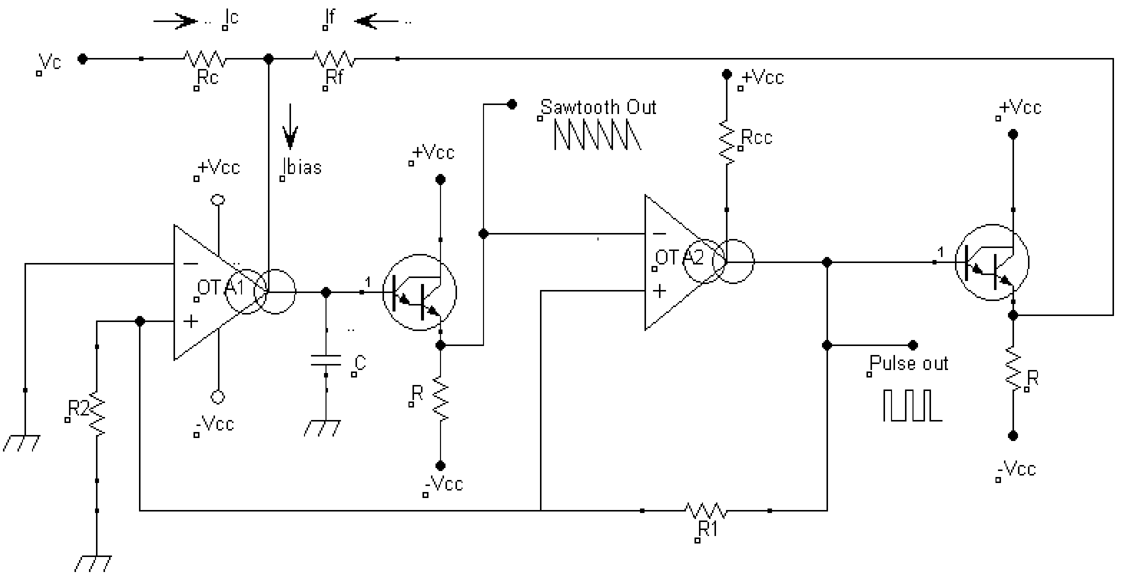

Figure 4.23 Sawtooth/Pulse VCO

This sawtooth/pulse VCO circuit works in the similar manner to the triangular/square VCO circuit. Both the OTAs are in comparator mode. When the output of OTA2 is on high level, the corresponding current I_f added I_c increases the bias current for OTA1 and the capacitor C at the output of OTA1 begins to charge up very quickly by this current. The voltage across this capacitor appears at the inverting terminal of OTA2 through the buffer stage and when this voltage exceeds to that at the non-inverting terminal (the output voltage across R_2 through the voltage divider $\mathrm{R_1}||\mathrm{R_2}$), the output of OTA2 abruptly switches to low level and the corresponding current I_f becomes zero. As a result the capacitor begins to discharge slowly only by I_c $\left(\text{as } I_C \ll I_f\right)$.giving the linearly down ramp voltage and when this voltage at the inverting terminal of OTA2 catches up that at the non-inverting terminal, the output switches to high again. This process continues to repeat making OTA1 to oscillate with the sawtooth output and OTA2 with the pulse output.

The OTA2 output switches between the voltage $+V$ and $-V$ and the voltage at the non-inverting terminal switches between $+V\frac{R_2}{R_1+R_2}$ and $-V\frac{R_2}{R_1+R_2}$.

When the capacitor charges up to $+V\frac{R_2}{R_1+R_2}$ from $-V\frac{R_2}{R_1+R_2}$ during T_{high} by the biasing current $\left(I_C+I_f\right)$, the output of OTA2 is on the high level.

So, $2V\frac{R_2}{R_1+R_2}=\frac{\left(I_C+I_f\right)T_{high}}{C}$

Or, $T_{high}=\frac{2CV}{\left(I_C+I_f\right)}\frac{R_2}{R_1+R_2}$

Or, $T_{high}\approx\frac{2CV}{I_f}\frac{R_2}{R_1+R_2}$ for $\left(I_C \ll I_f\right)$ (4.23.1)

And when the capacitor discharges down to $-V\frac{R_2}{R_1+R_2}$ from $+V\frac{R_2}{R_1+R_2}$ during T_{low} by the biasing current I_c, the output of OTA2 is on the low level.

So, $2V\frac{R_2}{R_1+R_2}=\frac{I_c\,T_{low}}{C}$

Or, $T_{low}=\frac{2CV}{I_c}\frac{R_2}{R_1+R_2}$ (4.23.2)

The output of OTA2 is a pulse wave as $T_{high} \ll T_{low}$ for $(I_C \ll I_f)$ and the frequency of the output wave is $f = \frac{1}{T_{high}+T_{low}} = \frac{(R_1+R_2)}{R_2}\frac{(I_C+I_f)}{2CV} \approx \frac{(R_1+R_2)}{R_2}\frac{I_f}{2CV}$ (4.23.3)

4.24 Instrumentation Amplifier

OTA1 and OTA2 form the differential input stage. When V_{in2} is zero volts or grounded, the current from the output of OTA1 flows through the resistor R to the inverting terminal of OTA2 so that, the output current of OTA1 is same in magnitude but 180° out of phase to the output current of OTA2. To add this two currents together at the inverting input of the opamp a third OTA is used which inverts the output current of OTA2 thus, the two currents become same in magnitude and polarity. To match the propagation delay of the OTA3 a RC compensation network has been used [4]. This circuit provides excellent common mode rejection for the signal that tries to generate current same in magnitude but opposite in polarity across the resistor R.

The output voltage is $V_{out} = -2g_m R_f(V_{in1} - V_{in2})$ (4.24.1)

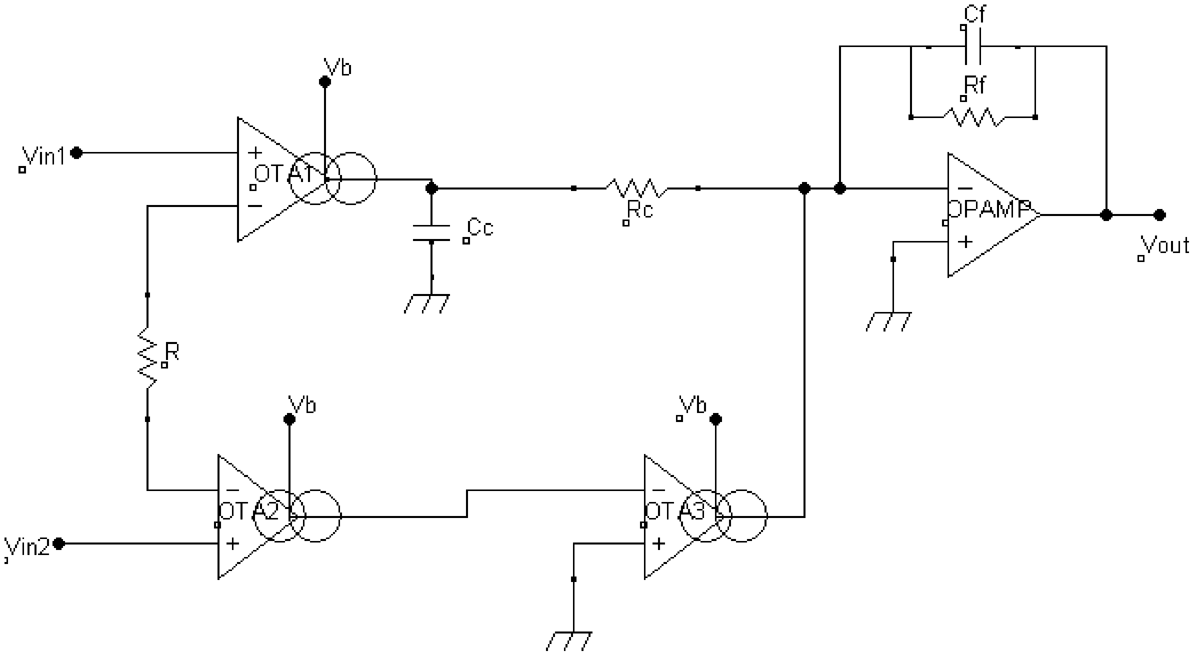

Figure 4.24 Instrumentation Amplifier

4.25 Fast Pulse Integrator

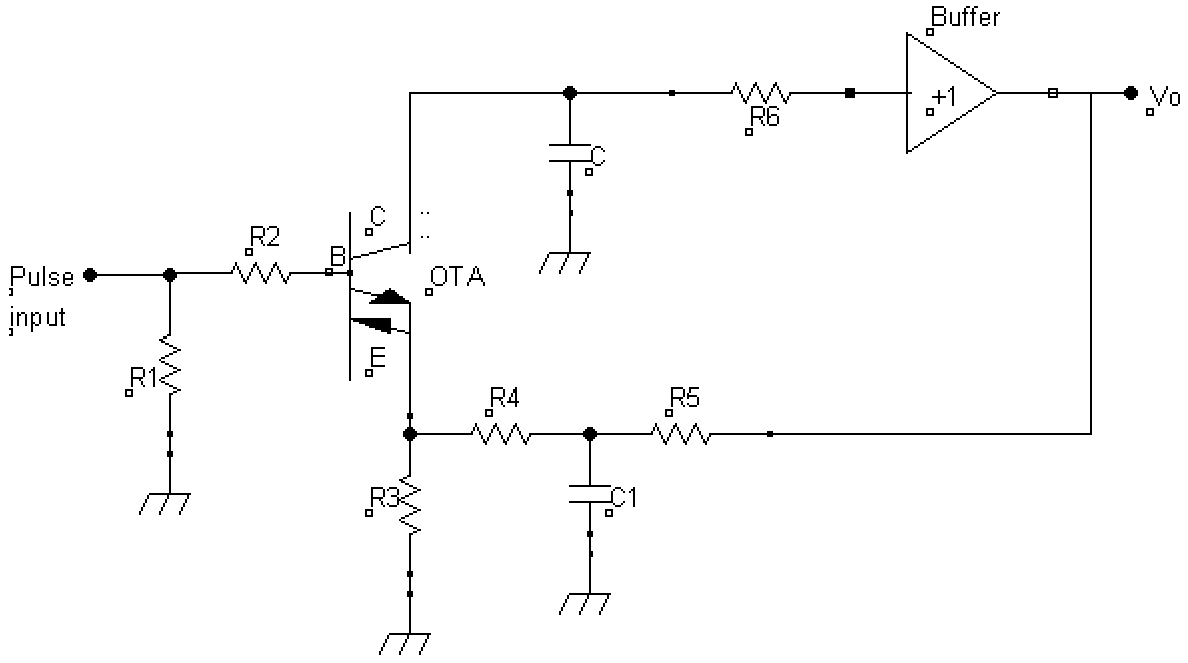

Figure 4.25 Fast Pulse Integrator

This is a very interesting application of OTA. The OTA is used in open loop configuration which can process pulses having rise/fall time of the order of nanoseconds. The output current of the OTA charges the capacitor and increases the average output voltage. To enhance the capacitor charging and to decrease the ripples at emitter, a T network consists of R_4, R_5 & C_1 is fed back from the buffer stage [14].

The output voltage (V_o) is the time integral of input (V_{BE}) voltage,

$$V_o = V_c = \frac{g_m}{C}\int_0^t V_{BE} dt$$

$$= \frac{g_m}{C} V_{BE} \times t \qquad (4.25.1)$$

C = The capacitance

V_c = The voltage across capacitor

g_m= The transconductance of OTA

V_{BE} = Base-emitter voltage of the OTA

4.26 Voltage Regulator

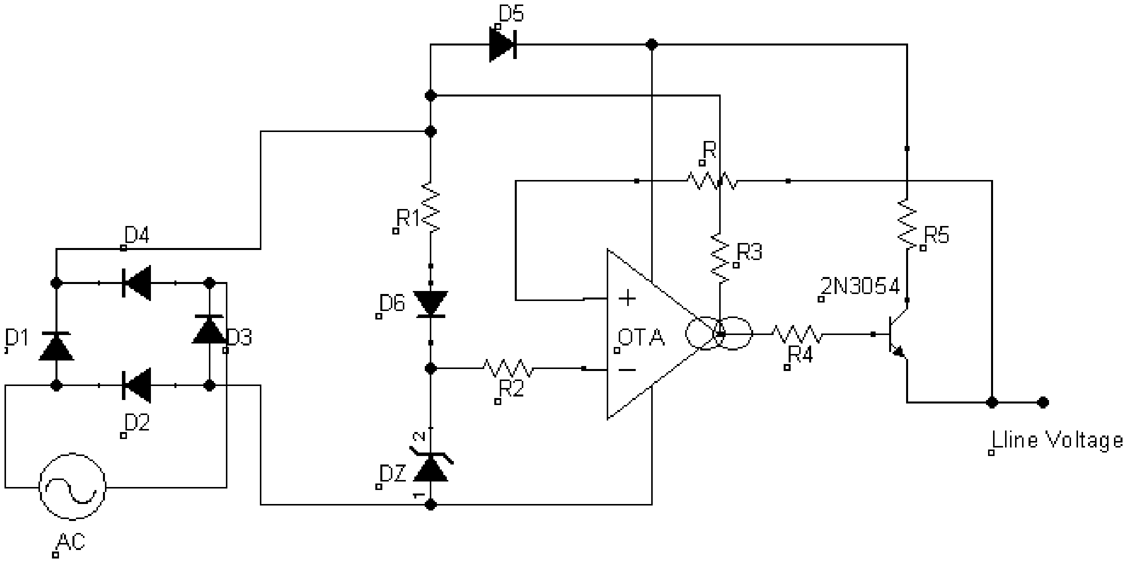

Figure 4.26 Voltage Regulator

A regulator circuit [15] using OTA has been implemented to accurately limit the output voltage as set by the zener diode. When output voltage rises slightly, the current through the feedback resistance *R* to the OTA's non-inverting input reduces the current drive to the pass transistor 2N3054. And when output voltage falls slightly, the feedback current increases the current drive to the pass transistor. This circuit is very useful in battery charger when the power is provided from the AC line.

4.27 Bridge Sensor Application

The differential input of the OTA is connected across the bridge circuit. The arms contain two fixed resistors, one variable resistor for temperature set control and one sensing resistor. The sensor can be a NTC or PTC temperature sensor. OTA is connected to drive the triac for control application [16]. For control purpose the load is a temperature controlling device, must be connected in feedback to the sensor. Depending on the temperature, the resistance of the sensor is varied and so the differential voltage of the OTA is changed. This makes the output current of the OTA to drive the triac accordingly for temperature control purpose.

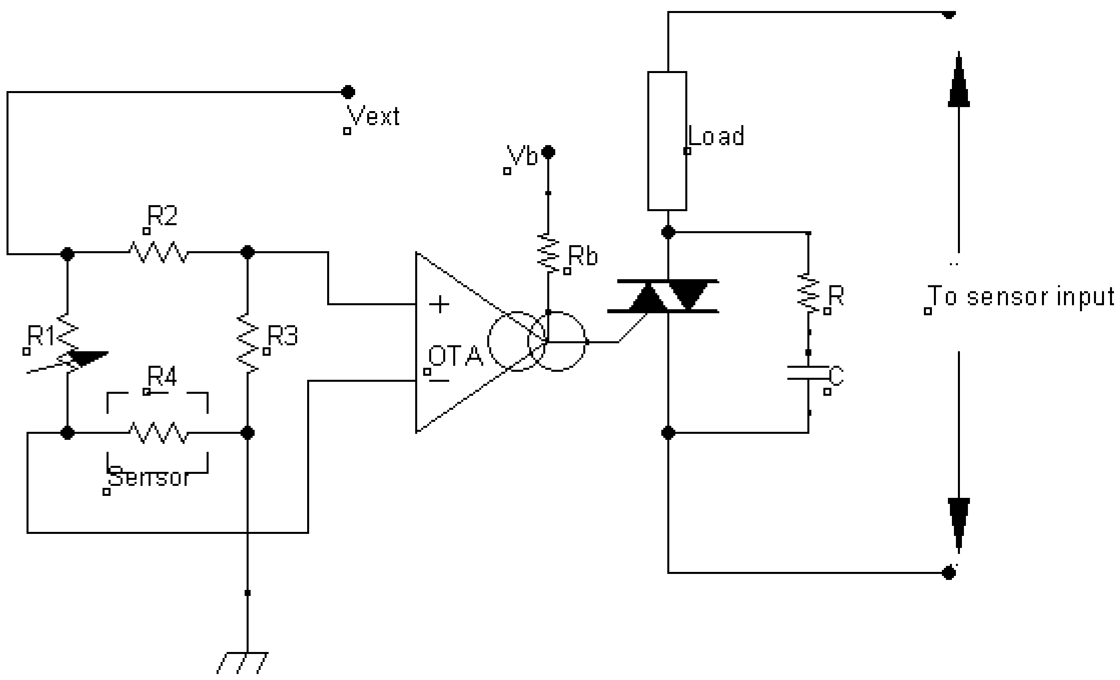

Figure 4.27 Bridge Sensor Application

4.28 Bipolar Pulse Peak Detector

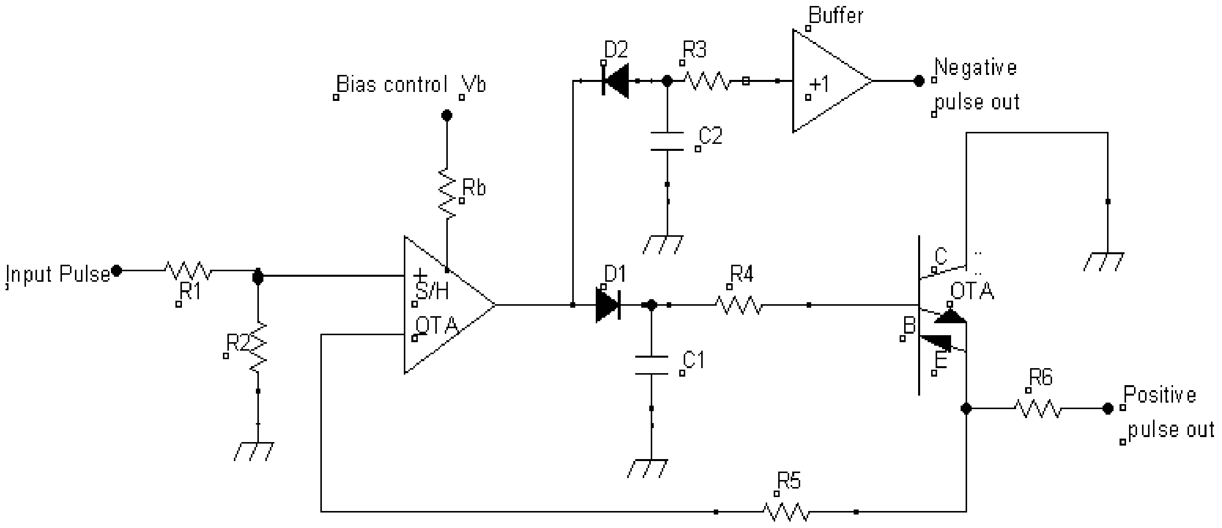

Figure 4.28 Bipolar Pulse Peak Detector

The circuit [14] employs the OTA in S/H mode to detect the positive pulses and negative pulses. During the input positive pulse the output of S/H OTA is high and the capacitor $C1$ charges through D1. This drives the output of OTA connected in common collector configuration high. And when the input pulse is negative, the output of the common collector OTA is low and the capacitor $C2$ charges through D2. This results in the output of buffer high.

4.29 Monochromatic Matrix

In this common base configuration of the OTA, three input signals V_{red}, V_{green}, V_{blue} corresponding to the luminance of the RGB colour section are applied to the inverting terminal of the OTA. The signals are amplified by the OTA and buffer amplifier to become the output signal $V_{luminance}$. The accuracy of the feedback resistances weights the signals differently resulting in different RGB mixing ratio. With the help of signal weighting transformation equation, RGB pictures can be converted into B/W pictures that might drive a monochrome control monitor or an analog printer [5].

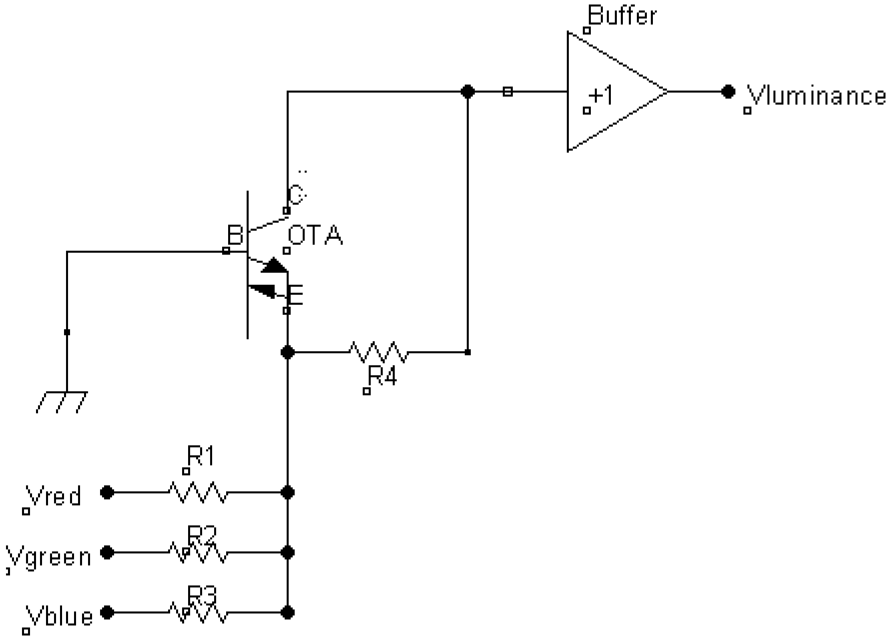

Figure 4.29 Monochromatic Matrix

4.30 Clamp Amplifier for RF Signal

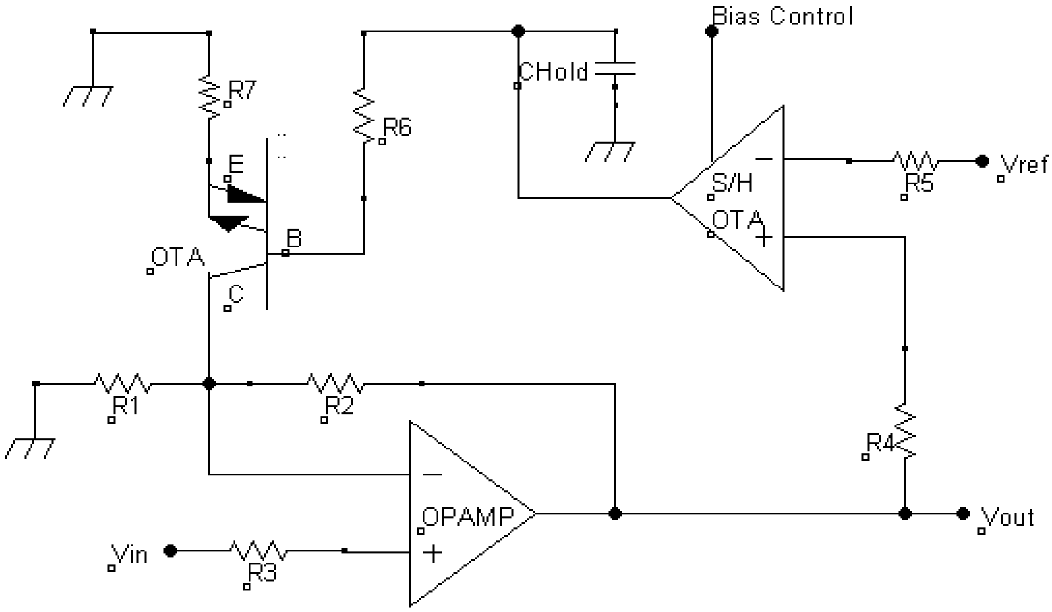

Figure 4.30 Clamp Amplifier for RF signal

The OTA in S/H mode compares the output of op amp with a reference voltage. Any difference between these two voltages will result in an output current that either charges or discharges the C_{Hold} capacitor. This results in a voltage across the capacitor that either drives the OTA in common emitter configuration high or low accordingly. The collector output of the common emitter OTA level-shifts the op amp to a point, where its output voltage equals to the reference voltage. This level-shift closes the control loop and the voltage across the capacitor remains constant until next correction is required.

4.31 Rectifier for RF Signal

The circuit can be used to rectify radio frequency signals in the mV range [5]. The slew rate of the operational transconductance amplifier determines the maximum frequency which can be rectified. The diode at the output of OTA passes the signal to the load during positive half cycle and to the ground during negative half cycle. For a very soft transfer from one diode to another the output current must be zero even during zero crossing. The circuit can be extended for full wave rectification by connecting the second diode antiparallelly instead to the ground.

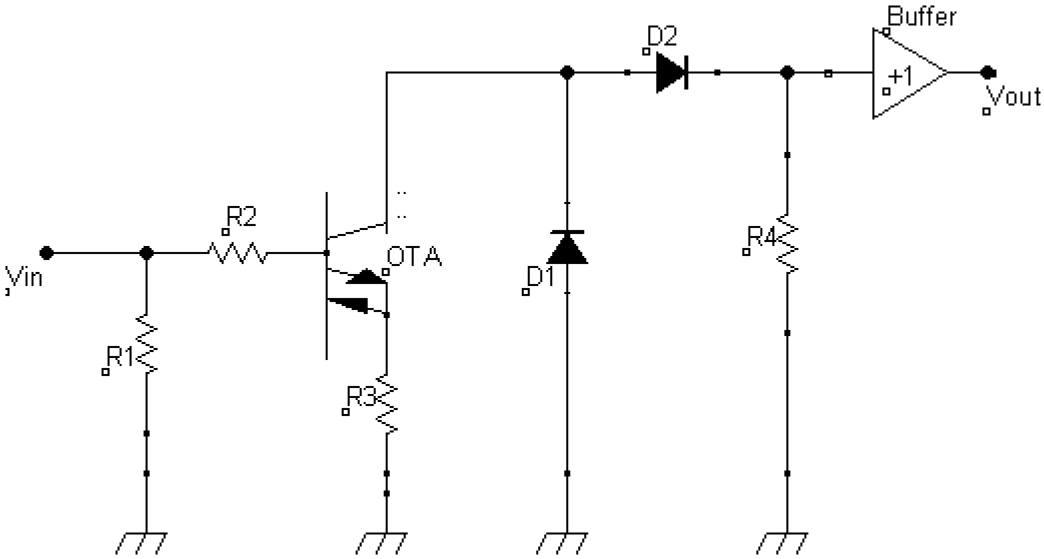

Figure 4.31 Rectifier for RF Signal

4.32 Optical Receiver

This circuit converts light into electrical signal which then can be amplified or processed. In this inverting base configuration of the operational transconductance amplifier, voltage applied at the base by the voltage divider appears at the low impedance emitter. When there is no light the pin diode does not conduct and the voltage above the diode is zero volts. During the exposure of light the pin diode conducts current, either sources or sinks current from the emitter. As a result base-emitter voltage difference manages the collector output current. Current gain of the circuit depends on the diode used and the bias current. As the sensitivity of the diode varies with the diode voltage, the fixed voltage across it improves the linearity.

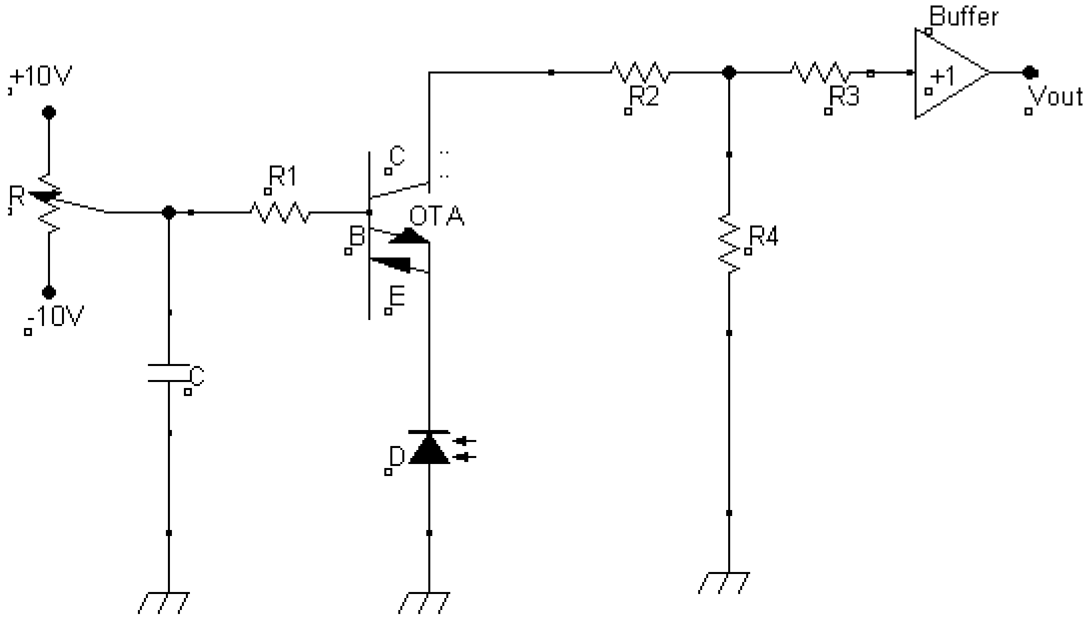

Figure 4.32 Optical Receiver

4.33 Correlated Double Sampler

To reduce the thermal noise in imaging system correlated double sampler [14] is used. In this technique the reference voltage of the signal is subtracted from the unknown voltage of the signal. Two OTAs in sample and hold configuration and one differential amplifier compose the correlated double sampler. At time t_1 the upper S/H OTA goes into the hold mode, takes a sample of V_{in1} which is the reference voltage of the pixel containing ${KT}/{C}$ noise and at time t_2 the lower S/H OTA goes into the hold mode, takes a sample of V_{in2} which is the unknown signal voltage of the pixel. These two voltages are subtracted by the differential amplifier. The resultant output will be noise reduced if the noise remains almost constant from first sample to the second sample.

If $V_{in1} = V_{ref}$ and $V_{in2} = V_{ref} - V_{signal}$, then the output of the differential amplifier is given by,

$$V_{out} = V_{in1} - V_{in2}$$

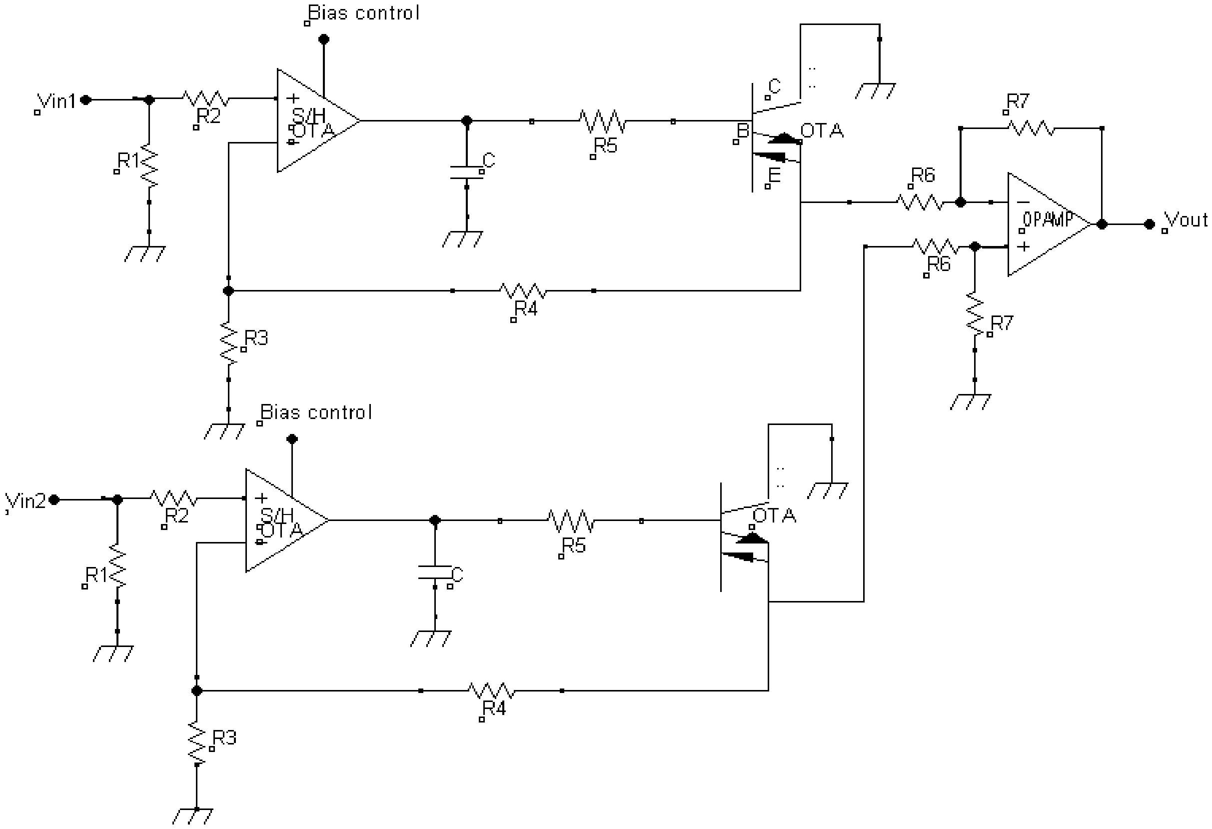

Figure 4.33 Correlated Double Sampler

4.34 Differentiator for Digitized Signals

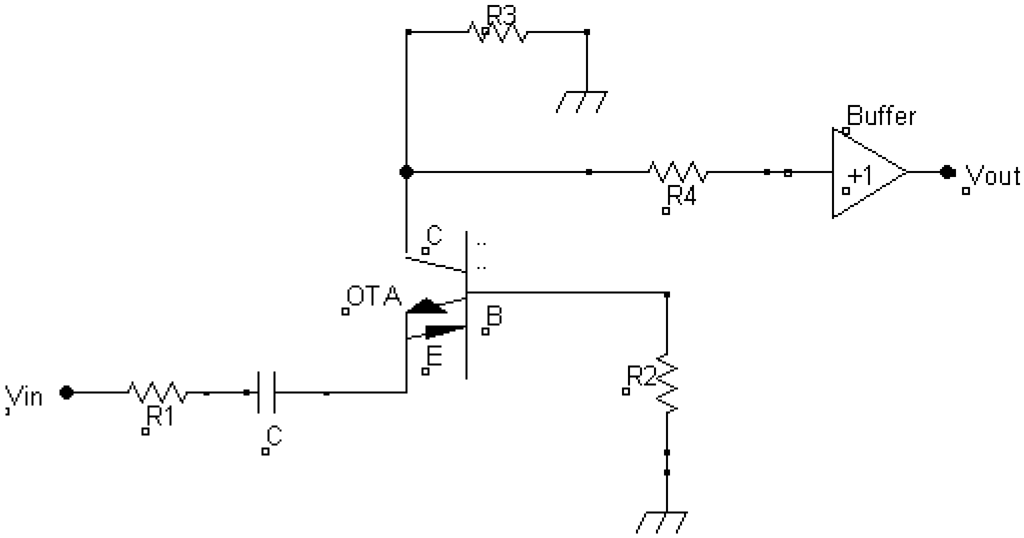

Figure 4.34 Differentiator for Digitized Signals

It is an inverting amplifier with a capacitor at its input. The high impedance output is followed by the buffer. The input can be a ramp, step or impulse signal. The output voltage is the first order derivative of the input voltage. The voltage gain of the differentiator can be controlled by the bias current. This circuit is very useful in magnetic recording to enhance the shape of a digital signal [11].

4.35 LOW IMPEDANCE TRANSMISSION LINE DRIVER

If an operational transconductance amplifier in current feedback configuration can have rated output current of about $\pm 15\text{mA}$, it can drive a coaxial transmission line with line impedance of the order of $50\Omega/75\Omega$ [5]. A resistance R to the output of the driver amplifier is connected so that total output resistance of the driver amplifier and series resistance must match the characteristic impedance Z of the line to transmit without any reflection. If the frequency rises, the output resistance of the operational transconductance amplifier also rises so impedances are no longer matched and hence reflection occurs.

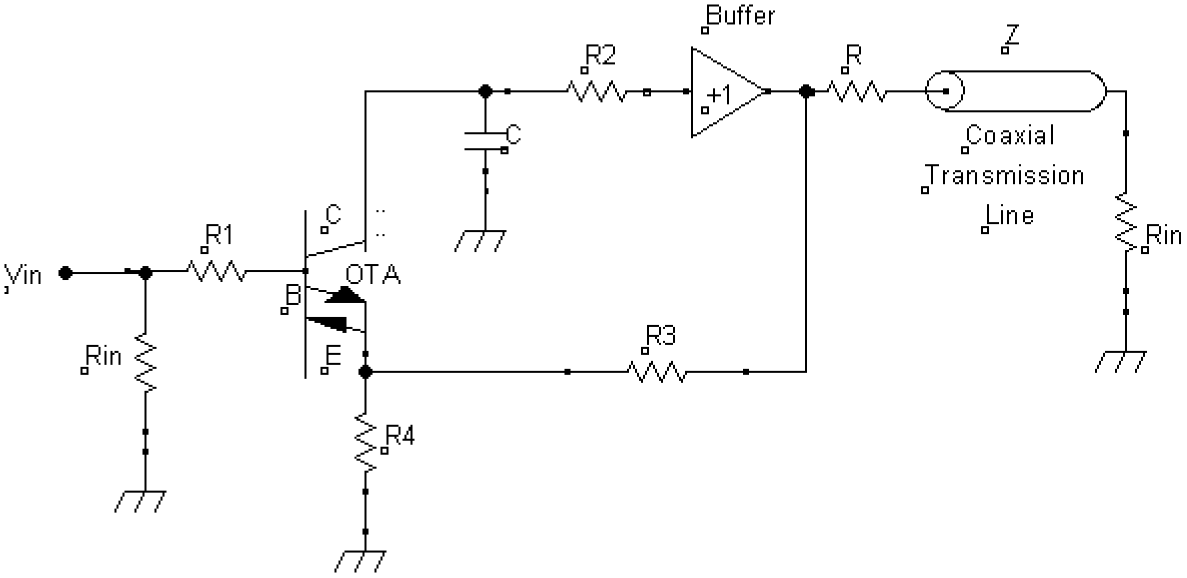

Figure 4.35 Low Impedance Transmission Line Driver

4.36 High Speed Current Driver

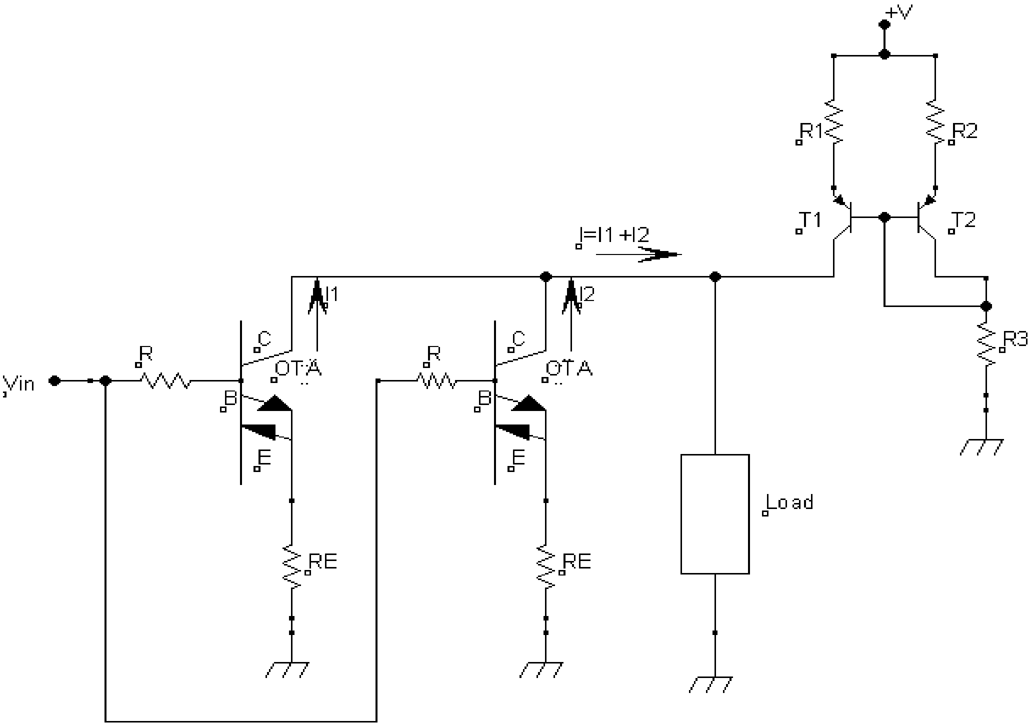

Figure 4.36 High Speed Current Driver

The circuit [11] is a high speed parallel current driving circuit. The input voltage is applied to the base of each OTA through the resistance R. The collectors of the OTAs are connected to the load. The total current flowing to the load is 2 times to that for a single OTA. To increase the output current more OTAs can be connected in parallel. Transistors T1 and T2 form the current mirror which gives the necessary load current for the OTAs. The input resistance performs as current limiter and avoids oscillation. The increase of emitter resistance R_E can increase the input impedance and stability but the transconductance of the OTA will decrease. This circuit is very applicable for driving LEDs.

4.37 Differential ADC Driver

This is a differential ADC driven by two OTAs. The gain of this circuit is set by the internal resistance of the ADC and R_E. The accuracy depends on the input resistance of the ADC. The advantage of this circuit lies in the high CMRR and linearity [17]. They can be used up to 10 bits of linearity.

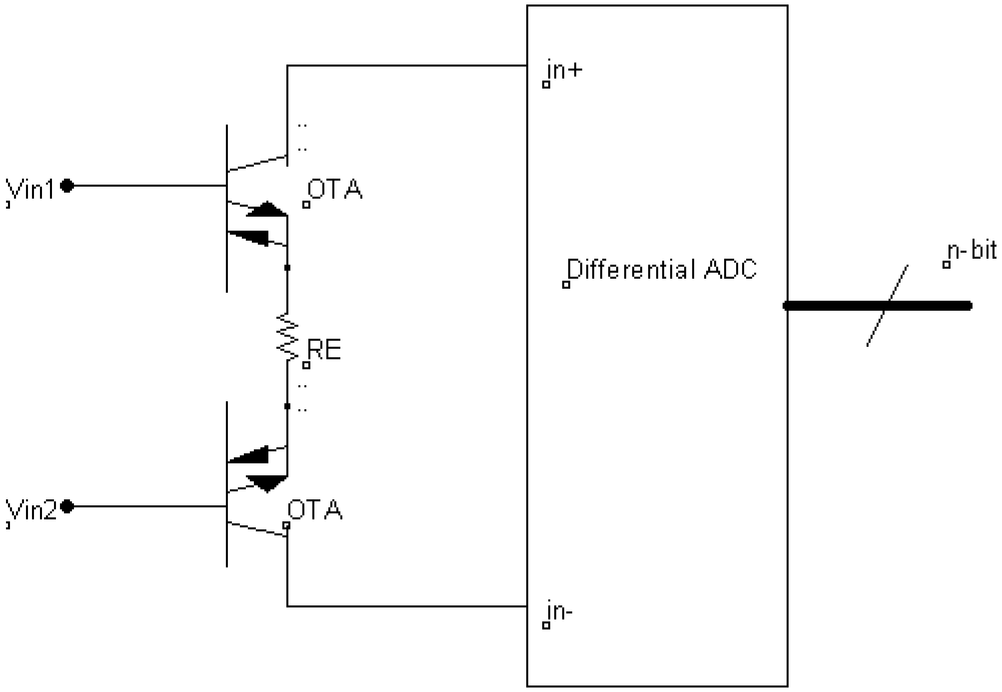

Figure 4.37 Differential ADC Driver

4.38 Single Ended-to-Differential Line Driver

The input voltage is applied to the base of OTA1. The emitter terminals of both OTAs are connected together by the resistance R. The current flowing from the collector output of OTA1 into the collector output of OTA2 is same in magnitude but 180° out of phase. OTAs with high slew rate and wide bandwidth are excellent for single ended-to-differential line driver applications to prevent any attenuation in capacitive loads [17].

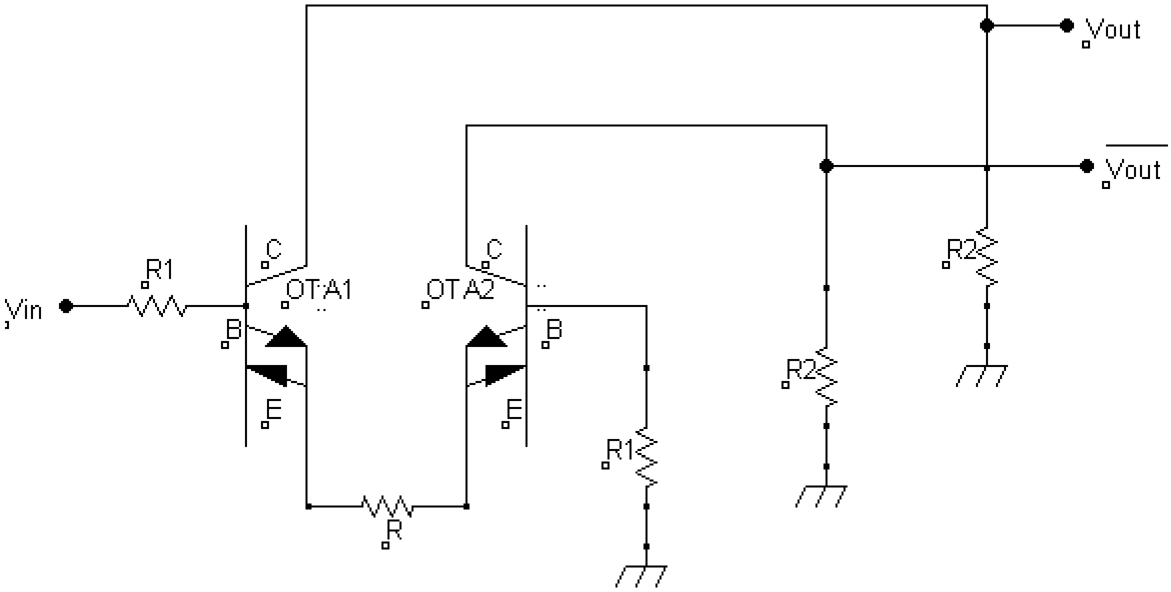

Figure 4.38 Single Ended-to-Differential Line Driver

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The work presents a number of circuits implemented with operational transconductance amplifier as the basic control element. Voltage controlled circuits such as oscillators, filters, amplifier, modulator, S/H circuit, multiplexer, Schmitt trigger, timer etc. have been shown and the behaviour of which can be controlled by the external bias voltage. These circuits can be used in higher frequency applications with adjustable gain and excellent slew rate. Voltage regulator, bridge sensor circuits work very accurately. Rectifier, clamp amplifier, pulse peak detector and optical receiver have been shown that can work well for radio frequency and fiber optic communication. Fast pulse integrator circuit is very useful for physical measurement purpose. Design of instrumentation amplifier exhibits high CMRR and correlated double sampler is a great technique to reduce white noise in signal processing applications. Driver circuits for low impedance transmission line works faithfully without oscillation, differential analog to digital converter works with more linearity and improved CMRR, LEDs driving circuit acts with increased capacity.

5.2 Future Work

Besides the applications illustrated in this thesis, there are many more application circuits which can be developed with the OTA as a basic building block such as:

- Demultiplexer, envelope detector, feedback control amplifier can be designed.
- Class A power amplifier for audio signal processing application.
- Motor speed control application using chopper.

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17. Texas Instruments, “OPA861 Wide Bandwidth Operational Transconductane Amplifier (OTA)”.

APPENDIX A

A.1 Digitally Programmable OTA (DPOTA)

The filter parameters have some manufacturing tolerances as specified by the manufacturers. To get the accurate filter parameters, concept of a digitally programmable OTA can be employed. Here MOSFETs M1 and M2 are connected in parallel with the MOSFET M. MOSFETs M1 and M2 are activated by the digital word bit1 and bit2 respectively. The $W/_L$ ratio of M1 or M2 is ensured smaller than the $W/_L$ ratio of M to avoid the effect of switching on the common-mode feedback.

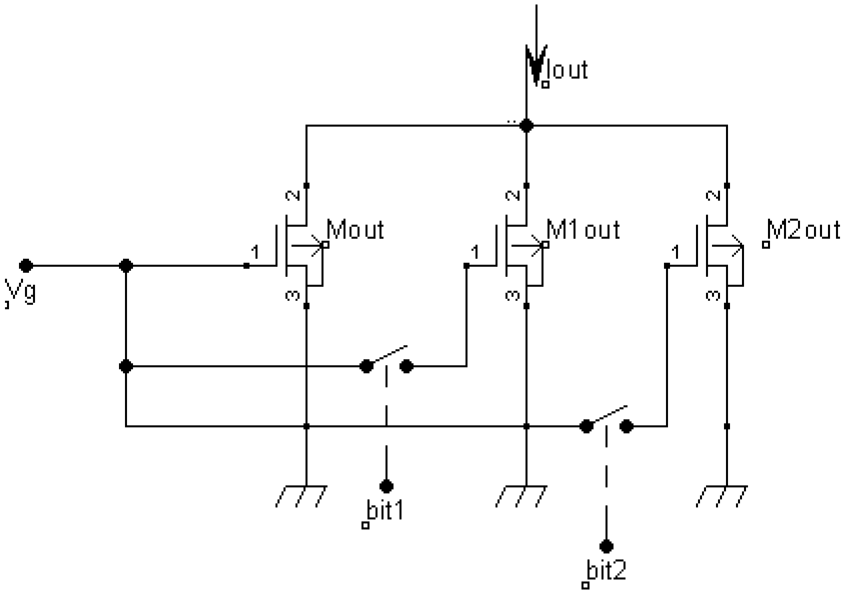

Figure A.1 Concept of a DPOTA