VLSI Implementation of Current Feedback Operational Amplifier and Operational Transconductance Amplifier

Project Report submitted in partial fulfillment of the requirement for the degree of

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in

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Under the Supervision of

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Certificate

This is to certify that project report entitled **"VLSI Implementation of Current Feedback Operational Amplifier and Operational Transconductance Amplifier"**, submitted by **Kunal Dutt**, **Hemank Mehta**, **Naina Agarwal** in partial fulfillment for the award of degree of Bachelor of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

This work has not been submitted partially or fully to any other University or Institute for the award of this or any other degree or diploma.

Date: May 28, 2013

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List of Abbreviations and Symbols

Expression	Title
Op-Amp	Operational Amplifier
VFOA	Voltage Feedback Operational Amplifier
CFOA	Current Feedback Operational Amplifier
OTA	Operational Transconductance Amplifier
BJT	Bipolar Junction transistor
CMOS	Complementary Metal Oxide Field Effect Transistor
CMRR	Common Mode Rejection Ratio
SR	Slew Rate
SVRR	Supply Voltage Rejection Ratio
g_m	Transconductance
β	Feedback Factor
μ	Micro= 10^(-6)
Ω	Ohm= Unit of Resistance
dB	Decibels
V/µs	Volts/ Microseconds= Unit of Slew Rate
W	Watts= Unit of Power

Abstract

The operational amplifier is an extremely efficient and versatile device. Its applications span the broad electronic industry filling requirements for signal conditioning, special transfer functions, analog instrumentation, analog computation, and special systems design. The analog assets of simplicity and precision characterize circuits utilizing operational amplifiers.

The first part of the project is to design Voltage Feedback Operational Amplifier (VFOA) using BJT and calculate the following parameters: Voltage Gain, Input and Output Impedance, Supply Voltage Rejection Ratio (SVRR), Common Mode Rejection Ratio (CMRR) and Slew Rate to obtain the performance of the circuit. The next stage is to design Current Feedback Operational Amplifier (CFOA) using BJT and CMOS and compare them on the basis of above said parameters. As we move on from one part of the project to the other our main focus is to maximize the CMRR.

To improve the CMRR further we implemented another type of amplifier- the Operational Transconductance Amplifier (OTA). We have designed three types of OTA i.e. Simple Differential OTA, Fully Differential OTA and Balanced OTA. The Balanced OTA was observed to be the best out of the three.

In order to get the optimum value of CMRR we have proposed the design of Balanced OTA in which the Standard Current Mirror is replaced by - Bulk Driven Current Mirror and Low Voltage Current Mirror. The improved CMRR using Low voltage Current Mirror was observed to be 110dB.

CHAPTER 1: INTRODUCTION

1.1 Operational Amplifier (Op-amp):

Op-amps are linear devices which have properties required for amplification of the input signal. Op-amps are built with vastly different levels of complexity to be used to realize functions ranging from a simple dc bias generation to high speed amplifications. An op amp is a direct coupled high gain amplifier. It is a versatile device used to amplify dc as well as ac signals. Operational amplifiers are linear devices which have nearly all the properties required not only for amplification but also for mathematical operations. Its name comes from the fact that initially it was designed to compute mathematical functions such as addition, subtraction, multiplication and integration. Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific device.

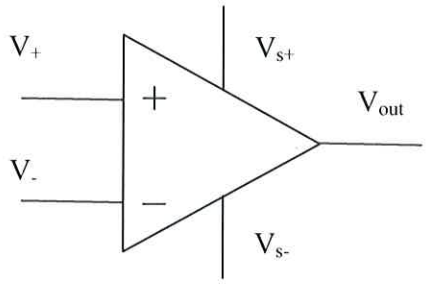
1.2 Operation:

The amplifier's differential inputs consist of a V_+ input and a V_- input, and ideally the op-amp amplifies only the difference in voltage between the two, which is called the differential input voltage [1,2]. The output voltage of the op-amp is given by the equation

$$V_{out} = A_{oL} (V_+ - V_-)$$

where V_+ is the voltage at the non-inverting terminal, V_- is the voltage at the inverting terminal and A_{oL} is the open-loop gain of the amplifier (the term "open-loop" refers to the absence of a feedback loop from the output to the input). The magnitude of A_{oL} is typically very large—100,000 or more for integrated circuit op-amps—and therefore even a quite small difference between V_+ and V_- drives the amplifier output nearly to the supply voltage. Situations in which the output voltage is equal to or greater than the supply voltage are referred to as saturation of the amplifier.

1.3 Circuit Notation:



- V_+ : non-inverting input
- V_- : inverting input
- V_{out} : output
- V_{S+} : positive power supply
- V_{S-} : negative power supply

Figure 1.1: Op-amp Notation

1.4 Commonly used Op-Amp:

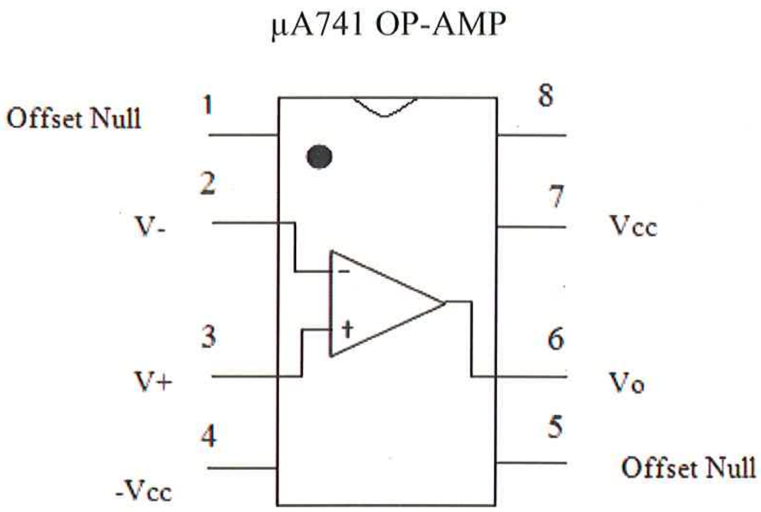


Figure 1.2: Pin Diagram of μA741 OP-AMP

Pin No. 1 and 5- Offset Null:

Used to nullify the offset that is seen at the output due to mismatches in the differential circuit.

Pin No. 2 and 3- Inputs:

Pin No. 2 for negative input and Pin No. 3 for positive input.

Pin No. 4 and 7- Supply Voltages:

Pin No. 4 for negative supply voltage and Pin No. 7 for positive supply voltage.

Pin No. 6-Output:

Pin No. 6 for measuring the output.

Pin No. 8-No connection:

Pin No. 8 is left open.

1.5 Types of Feedback-Amplifiers:

- **Voltage Feedback (Series-Shunt Feedback):**

The feedback is also called as voltage series feedback [3]. It is a combination of voltage sampling or shunt sampling and series mixing. A is the voltage gain of the amplifier and β is the feedback factor where

$$\beta = V_f \,/\, V_o$$

V_o is the output signal and V_f is the feedback signal.

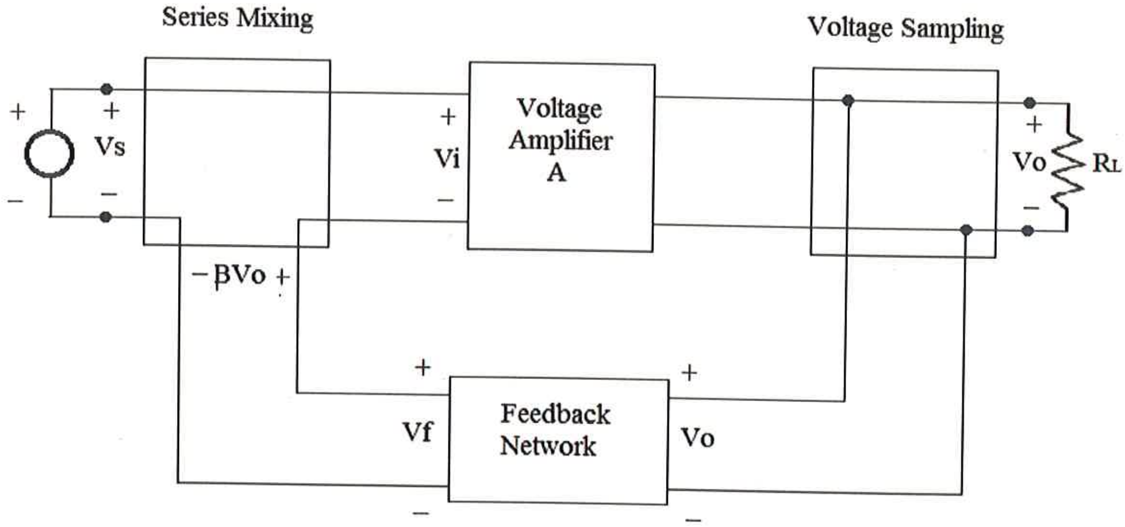


Figure 1.3: Series-Shunt Feedback

- **Current Feedback (Shunt-Series Feedback)**

The feedback is also called as current shunt feedback. It is a combination of current sampling or series sampling and shunt mixing. A is the current gain of the amplifier and β is the feedback factor where

$$\beta = I_f \,/\, I_o$$

I_o is the output current and I_f is the feedback current.

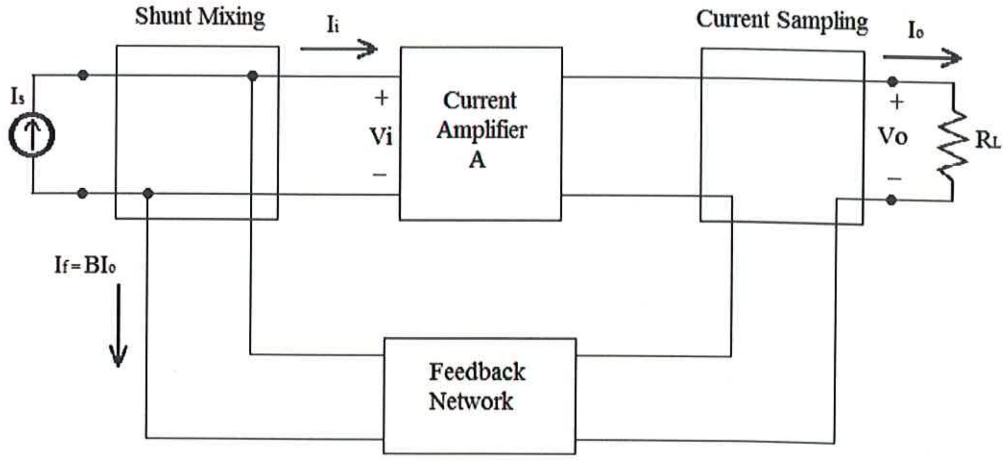


Figure 1.4: Shunt-Series Feedback

- **Trans-resistance Feedback (Shunt-Shunt Feedback)**

  The feedback is also called as voltage shunt feedback. It is a combination of voltage sampling or shunt sampling and shunt mixing. A is the current gain of the amplifier and β is the feedback factor where

$$\beta = I_f / V_o$$

V_o is the output voltage and I_f is the feedback current.

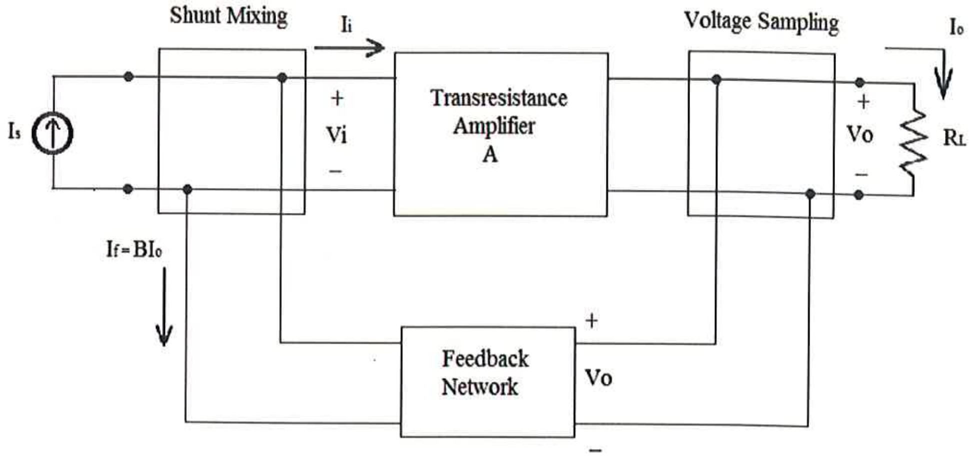


Figure 1.4: Shunt- Shunt Feedback

- **Trans-conductance Feedback (Series- Series Feedback)**

  The feedback is also called as current series feedback. It is a combination of series sampling or current sampling and series mixing. A is the voltage gain of the amplifier and β is the feedback factor where

$$\beta = V_f / I_o$$

I_o is the output current and V_f is the feedback signal.

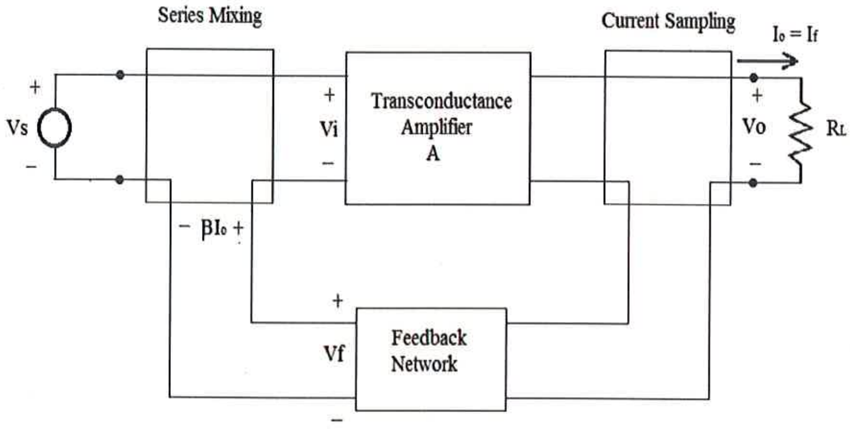


Figure 1.5: Series-Series Feedback

1.6 Op-Amp Configurations:

An Op-Amp has the following three configurations:

- **Non-Inverting Amplifier:**

  The input is applied only to the non- inverting input terminal and the inverting terminal is connected to ground [4].

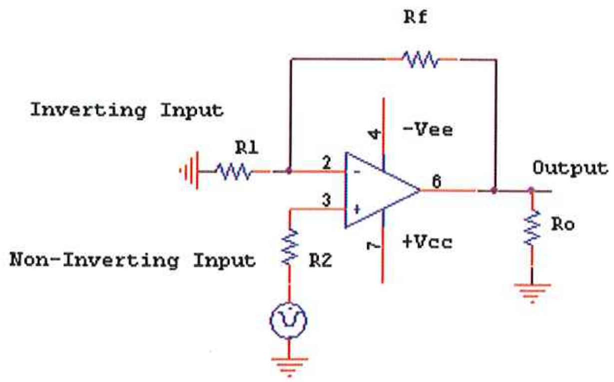


Figure 1.6: Non-Inverting Operational Amplifier

- **Inverting Amplifier:**

  The input is applied only to the inverting input terminal and the non-inverting terminal is connected to ground.

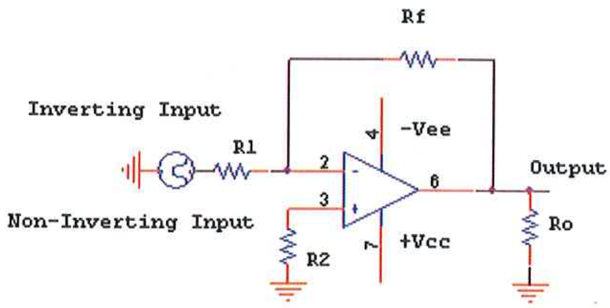


Figure 1.7: Inverting Operational Amplifier

- **Differential Amplifier:**

  The input is applied only to the inverting input terminal as well as the non-inverting terminal ground. The op-amp amplifies the difference between the two signals.

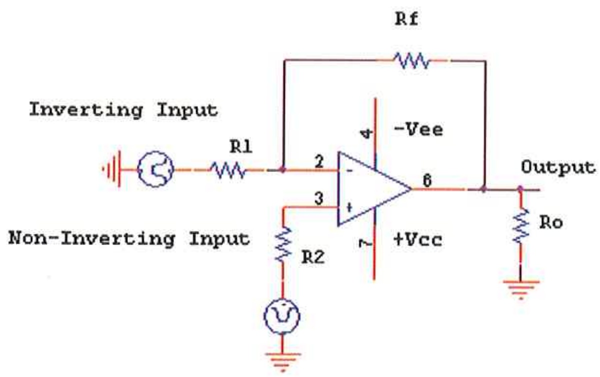


Figure 1.8: Differential Operational Amplifier

1.7 Operational Amplifier Parameters:

- **Input Impedance:**

  It is defined as the ratio of input voltage to input current.

$$R_i = V_i / I_i$$

- **Output impedance:**
  It is defined as the ratio of output voltage to output current.

$$R_o = V_o / I_o$$

- **Common mode rejection ratio(CMRR):**
  It is defined as the ratio of differential gain to common mode gain. A high CMRR helps to reject common mode signals such as noise successfully.

$$CMRR = A_d / A_{cm}$$

$$CMRR\ (\text{dB}) = 20 \log (A_d / A_{cm})$$

- **Slew rate (SR):**
  It is defined as the maximum rate of change of output voltage per unit time and it is expressed in volts/ microseconds.

$$SR = \max\ [dV_o / dt]$$

- **Supply voltage rejection ratio (SVRR):**
  The change in an op-amps input offset voltage (ΔV_{ios}) caused by variation in the supply voltage is called supply voltage rejection ratio.

$$SVRR = \Delta V_{ios} / \Delta V$$

1.7 Why this Project?

There are four types of amplifier- voltage amplifier, current amplifier, transimpedance amplifier, transconductance amplifier.

Voltage feedback operational amplifier is a type of voltage amplifier which has properties required for amplification of the input signal. It is a direct coupled high gain amplifier and is used to amplify dc as well as ac signals. It takes the input voltage to give amplified output voltage.

We switched over to current feedback operational amplifiers because of its advantages over voltage feedback operational amplifier. The current feedback amplifier is a type of transimpedance amplifier which takes current as input and gives the corresponding amplified output voltage. The current feedback amplifier has same ideal closed loop equations but has higher slew rate. The current feedback amplifier often is the best circuit available with its cost effective combination of high gain and high performance. Substituting, a current feedback amplifier for a voltage feedback amplifier in the design of production stages will result in better performance and lower cost.

In our project, we have also implemented operational transconductance amplifier which is a type of transconductance amplifier which takes input voltage to give corresponding amplified output current . The operational transconductance amplifier comes out to be the best on the basis of parameters-CMRR and slew rate.

1.9 PSpice

SPICE-Simulation Program for Integrated Circuits Emphasis

Computer simulation is a common technique for predicting the real world behavior of a circuit. Although simulation software only reflect the capability of the model used in the back-plane and they cannot substitute the real-time experimentation, they have proven educationally useful due to their easy to construct and visual properties. OrCAD PSpice is a general purpose circuit simulator and one of various versions of SPICE family, capable of handling analog, logical and mixed-signal parts, circuits and systems. PSpice simulations provide the advantage of the hierarchical circuit structures, where design takes place using sub-circuits. In the simulation procedure different approaches may be followed, namely, electrical component level, subsystem functional block level and higher system level comprising both of the previous ones.

1.8.1 PSpice Components

1.8.1.1 PSpice A/D

The platform for the PSpice A/D is shown in figure. The circuit that is described by statements and analysis commands is simulated by the run command from the platform. The output results can be displayed and viewed from platform menus.

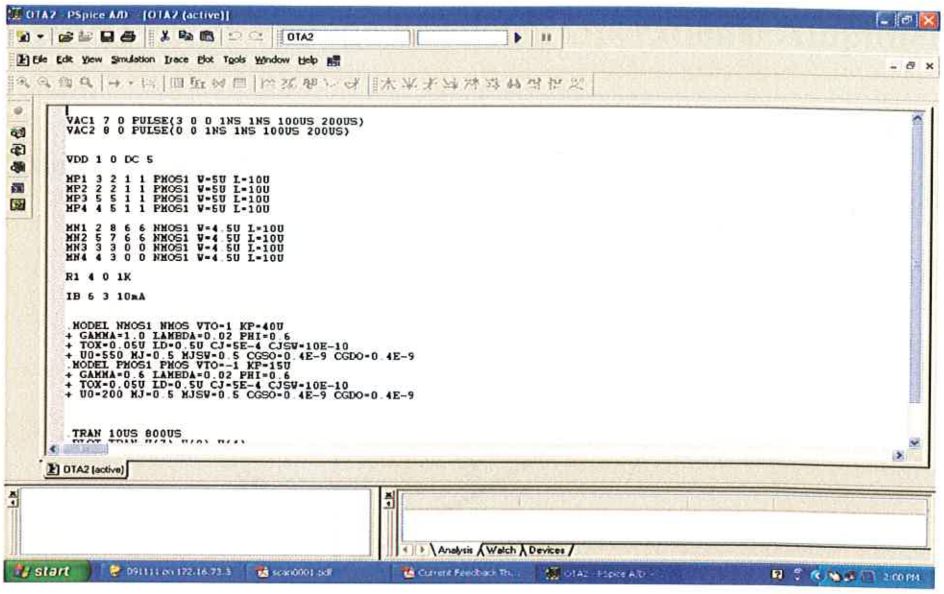


Figure 1.10: PSpice A/D Platform

1.8.1.2 OrCAD Capture

The platform for OrCAD Capture is shown in figure. The circuit that is drawn on the platform is run from the PSpice menu. The simulation types and its settings are specified from the PSpice menu. After the simulation run is completed, the Capture automatically opens the PSpice A/D platform for displaying and viewing the results.

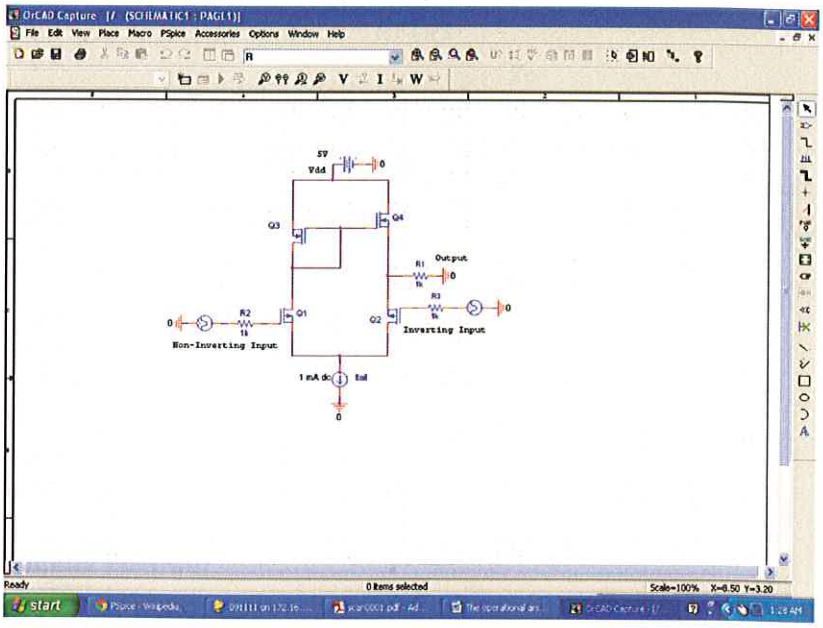


Figure 1.11: OrCAD Capture Platform

CHAPTER 2: Voltage Feedback Operational Amplifier

2.1 Understanding Voltage Feedback Operational Amplifier:

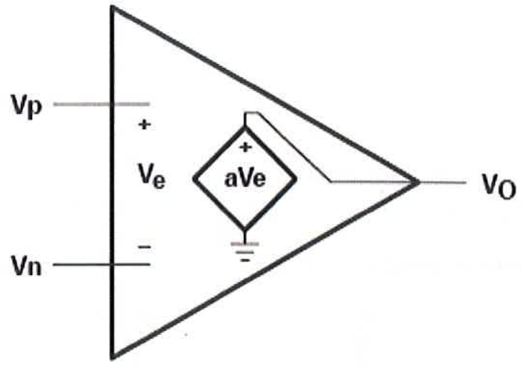


Figure 2.1: Internal Circuitry of Voltage Feedback Operational Amplifier

In a VF op amp, when negative feedback is applied, the action of the op amp is to drive the error voltage to zero thus the name voltage feedback For each circuit, solving for Vo in relation to Vi gives the transfer function of the circuit. In the VF circuit, Equation 1 still holds true so that,

$$V_o = aV_e \text{ where } V_e = V_p - V_n. \text{ Now } V_p = V_i.$$

$$Vn = Vo\frac{R1}{R1+R2}$$

Substituting and solving for $\frac{Vo}{Vi}$

$$\frac{Vo}{Vi} = \left[\frac{a}{1+a\left(\frac{R1}{R1+R2}\right)}\right] = \left(\frac{R1+R2}{R1}\right)\left[\frac{1}{1+\left(\frac{1}{a}\right)\frac{(R1+R2)}{R1}}\right] = \left(\frac{1}{b}\right)\left[\frac{1}{1+\left(\frac{1}{ab}\right)}\right]$$

2.2 Voltage Feedback Op-amp (VFOA):

It has four stages

- Dual Input Balanced Output.
- Dual Input Unbalanced Output.
- Emitter Follower.
- Push-Pull Amplifier.

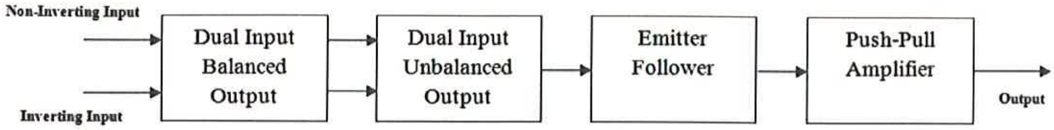


Figure 2.2: Block Diagram of BJT VFOA

2.2.1 Stage1: Dual Input Balanced Output:

The two transistors Q_1 and Q_2 have identical characteristics. The resistances of the circuits are equal, i.e. $R_{E1} = R_{E2}$, $R_{C1} = R_{C2}$ and the magnitude of $+V_{CC}$ is equal to the magnitude of $-V_{EE}$. These voltages are measured with respect to ground.

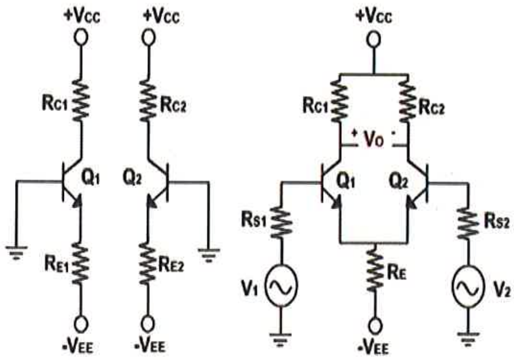


Figure 2.3: Dual Input Balanced Output

To make a differential amplifier, the two circuits are connected as shown in the figure 2.3 The two $+V_{CC}$ and - V_{EE} supply terminals are made common because they are same. The two emitters are also connected and the parallel combination of R_{E1} and R_{E2} is replaced by a resistance RE. The two input signals V_1 & V_2 are applied at the base of Q_1 and at the base of Q_2. The output voltage is taken between two collectors hence it is referred to as a balanced output.

2.2.2 Stage 2: Dual Input Unbalanced Output:

In this stage 2 input signals are used; however the output is measured at only one of the two collectors with respect to the ground.

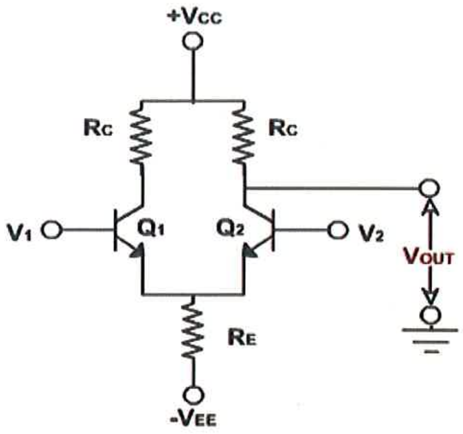


Figure 2.4: Dual Input Unbalanced Output

2.2.1.3 Stage 3: Emitter Follower:

Because of the direct coupling the dc level at the emitter rises from stages to stage. This increase in dc level tends to limit the output voltage swing and may even distort the output signal. To shift the output dc level to zero, level translator circuits are used.

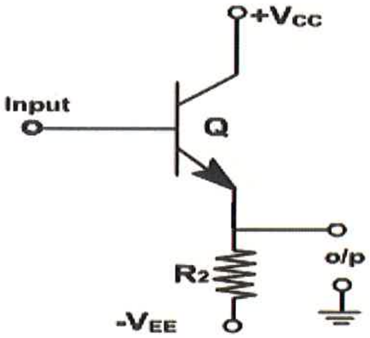


Figure 2.5: Emitter Follower

2.2.1.4 Stage 4: Push-Pull Amplifier:

- The stage has an NPN and a PNP device.
- The NPN and PNP circuits look the same.
- The stage can both source and sink current

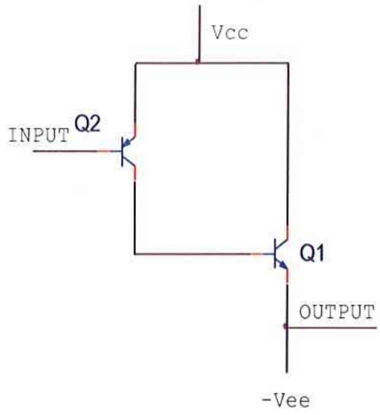


Figure 2.6: Push-Pull Amplifier

Because the circuit is really only a couple of emitter followers driving the same load, the operation is simple; Q_1 conducts on positive swings; Q_2 conducts on negative swings.

The four stages are now combined to form the Voltage Feedback Operational Amplifier using BJT.

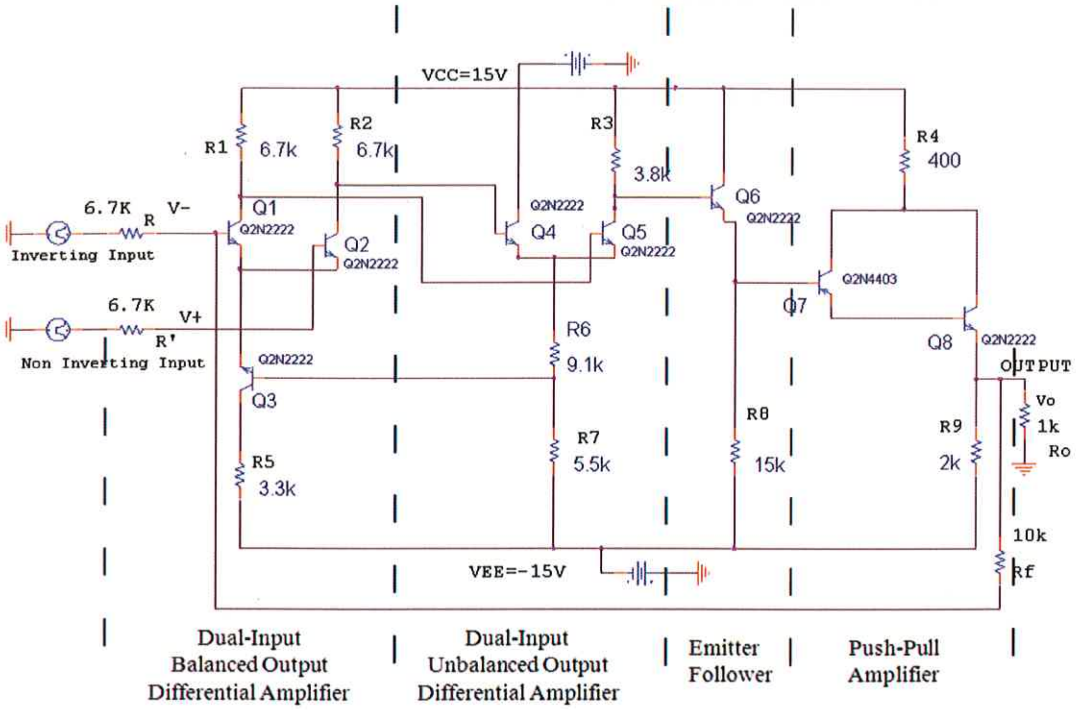


Figure 2.7: Voltage Feedback Operational Amplifier using BJT

2.3 Results and Discussions:

2.3.1 Simulation Output in Non-Inverting Mode for VFOA

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(3) is grounded as the Op-Amp is being operated in Non-Inverting Mode.

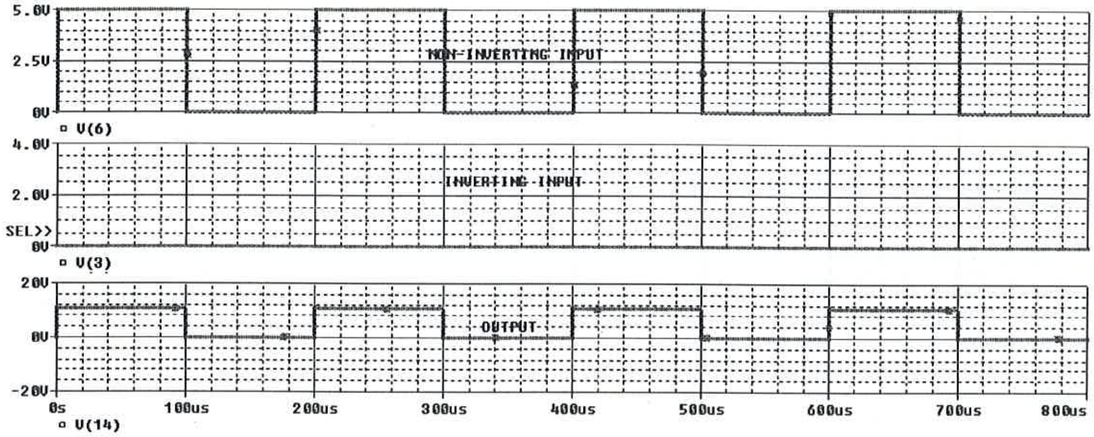


Figure 2.8: Simulation Waveform in Non-Inverting Mode for VFOA

2.3.2 Simulation Output in Inverting Mode for VFOA

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(6) is grounded as the Op-Amp is being operated in Inverting Mode.

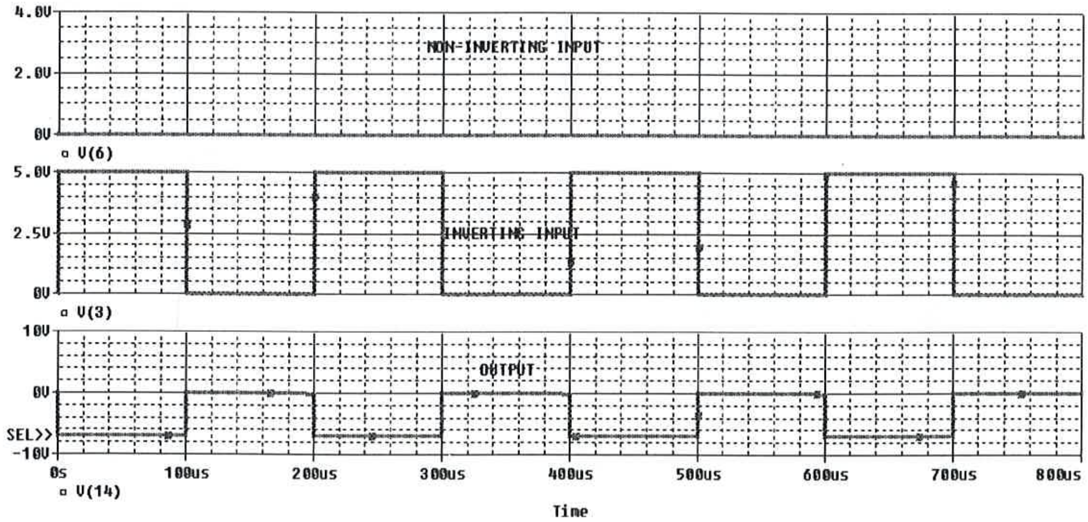


Figure 2.9: Simulation Waveform in Inverting Mode for VFOA

2.3.3 Simulation Output in Differential Mode for VFOA

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform.

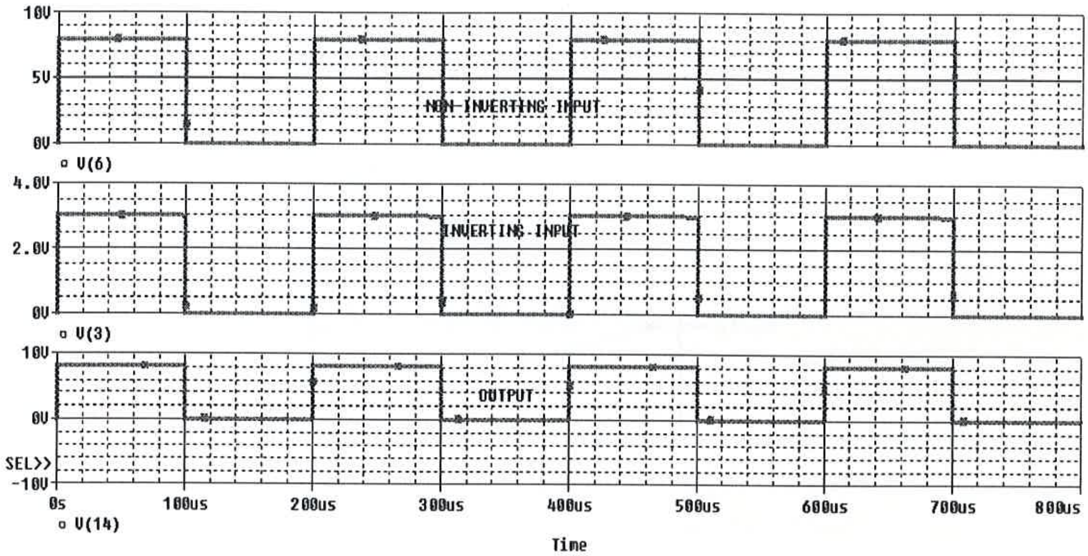


Figure 2.10: Simulation Waveform in Differential Mode for VFOA

2.3.4 Comparison Table:

Table 2.1: Parameters for VFOA (BJT)

Parameter/Type	Non-Inverting	Inverting	Differential
Output Impedance	69.5Ω	97.6Ω	78.4Ω
Input Impedance	270kΩ	201kΩ	241kΩ
Slew Rate	.25V/μs	.29V/μs	.27V/μs
CMRR	33.27dB	31.17dB	32.37dB
Power Dissipation	3.87E-01 W	4.23E-01 W	3.92E-01 W
Voltage Gain	2.4	-1.4	1.6
SVRR	48.28dB	42.39dB	45.52dB

As observed from the above table the Non-Inverting Mode is the best out of the three.

CHAPTER 3: Current Feedback Operational Amplifier

3.1 Understanding CFOA (Current Feedback Operational Amplifier):

It is a type of Trans-Impedance Amplifier

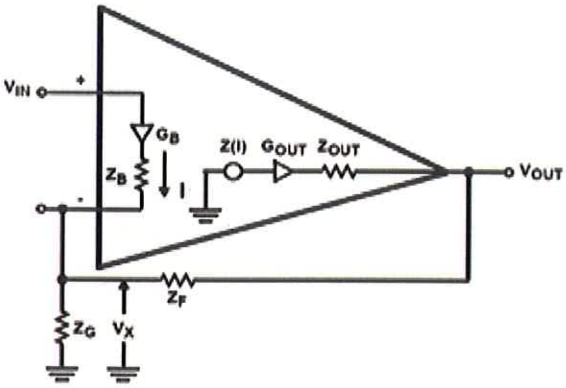


Figure 3.1: Internal Circuitry of Current Feedback Operational Amplifier

In a CFA model, it can be seen that the non inverting input is connected to the input of a unity gain, which usually takes the form of emitter follower circuit, and is modeled by G_B and Z_B (Figure 1).Because the non inverting input is actually the input of a buffer, it's a high-impedance input [5,6]. Also, because this buffer's output connects to the inverting input, CFAs have lower inverting-input impedance, Z_B. The current I, flowing through the inverting input generates a voltage that is equal to the current times the transimpedance, *Z*. This voltage is modeled by the output voltage source, *Z(I)*. This voltage becomes the output voltage after passing through the output buffer, which is modeled by G_{OUT} and Z_{OUT}.

$$I = \frac{Vx}{Zg} - \frac{Vout - Vx}{Zf} \qquad \text{Eqn 1}$$

$$Vx = Vin - IZb \qquad \text{Eqn 2}$$

$$Vout = IZ \qquad \text{Eqn3}$$

$$\frac{Vout}{Vin} = \frac{\left(\frac{A}{B}\right)}{1+\left(\frac{Z}{B}\right)} \qquad \text{Eqn 4}$$

Where
$$A = Z\left[1 + \left(\frac{Zf}{Zg}\right)\right]$$

$$B = Zf(1 + \left(\frac{Zb}{Zf}\right) || Zg)$$

$$\frac{Vout}{Vin} = \frac{A}{1+A\beta} \qquad \text{Eqn 5}$$

Equation 1 is the current equation at the inverting input of the circuit shown in Fig. 1.

Equation 2 is the loop equation for the input circuit.

Equation 3 is the output equation of the cicuit.

Equation 4 is the non-inverting closed loop circuit equation.

Equation 5 is the standard feedback equation where A is the direct gain and β is the feedback factor.

3.2 CFOA designed using BJTs:

It has two stages:

- Input Buffer Stage.
- Output Buffer Stage.

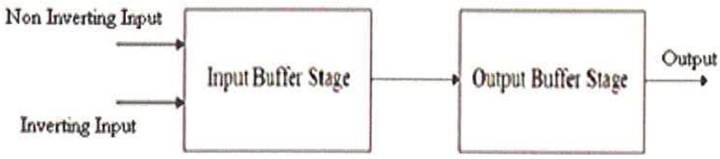


Figure 3.2: Block Diagram of BJT CFOA

3.2.1 Input Buffer Stage:

It is configured as an emitter-follower. We have given non-inverting input at the base of the transistor therefore it has high impedance and we have given inverting input at the emitter of the transistor therefore it has low impedance.

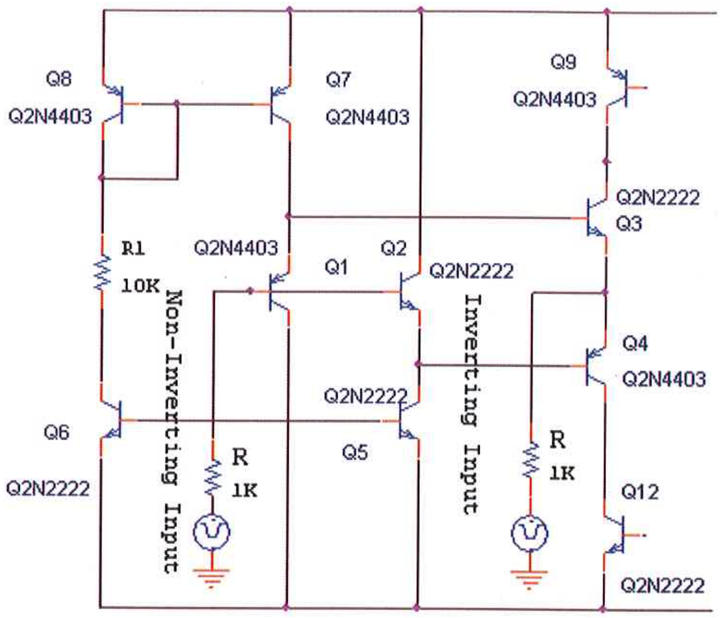


Figure 3.3: Input Buffer Stage

3.2.2 Output Buffer Stage:

Current flows through the inverting input that generates a voltage which is equal to current times the transimpedance.

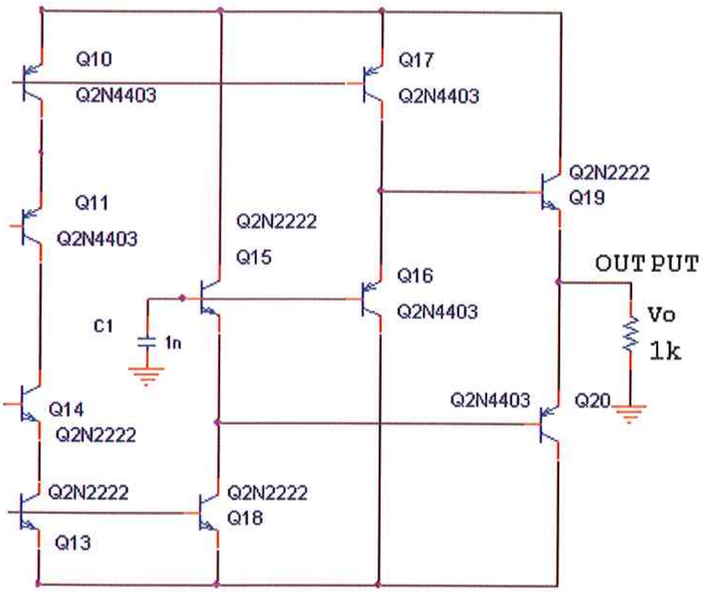


Figure 3.4: Output Buffer Stage

This converts high input impedance to low output impedance which must be present at the load to get maximum current in order to drive load of the op-amp.

The two stages are now combined to form the Current Feedback Operational Amplifier using BJT.

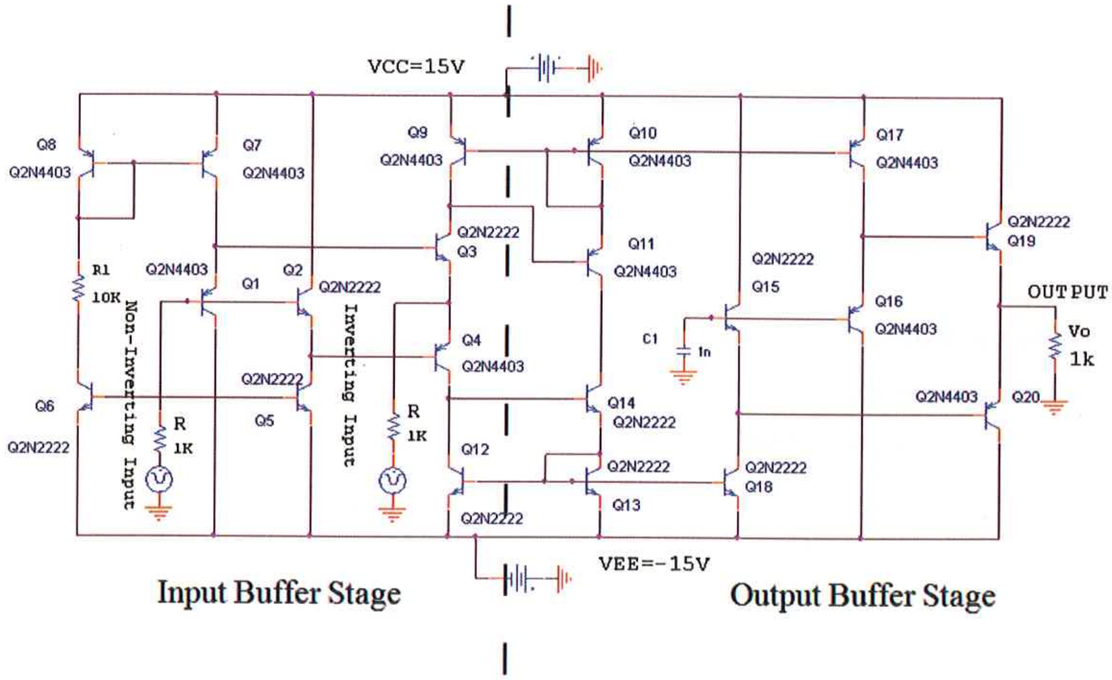


Figure 3.5: Current Feedback Operational Amplifier using BJT

3.3 CFOA designed using CMOS:

It comprised of three subsections of circuit, namely [7,8]

- Differential Gain Stage.
- Second Gain Stage.
- Bias Strings.

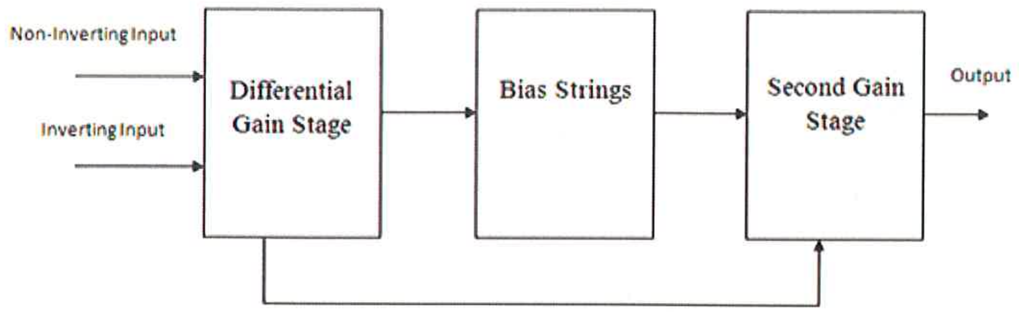


Figure 3.9: Block Diagram of CMOS CFOA

3.3.1 Differential Gain Stage:

Transistors Q_1, Q_2, Q_3, and Q_4 form the first stage of the op amp the differential amplifier with differential to single ended transformation. Transistors Q_1 and Q_2 are standard N channel MOSFET (NMOS) transistors which form the basic input stage of the amplifier. The gate of Q_1 is the inverting input and the gate of Q_2 is the non-inverting input. A differential input signal applied across the two input terminals will be amplified according to the gain of the differential stage. The gain of the stage is simply the transconductance of Q_2 times the total output resistance seen at the drain of Q_2.The current mirror topology performs the differential to single-ended conversion of the input signal.

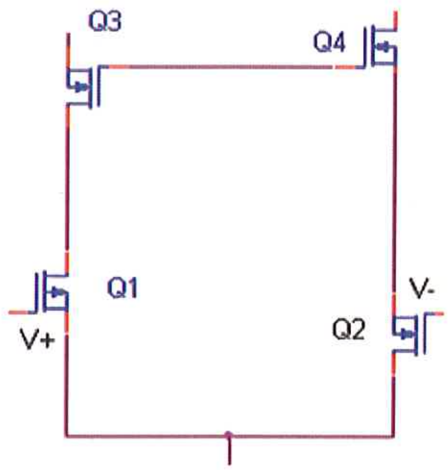


Figure 3.10: Differential Gain Stage

The differential current from Q_1 and Q_2 multiplied by the output resistance of the first stage gives the single-ended output voltage, which constitutes the input of the second gain stage.

3.3.2 Second Gain Stage:

The second stage is a current sink load inverter. The purpose of the second gain stage, as the name implies, is to provide additional gain in the amplifier.

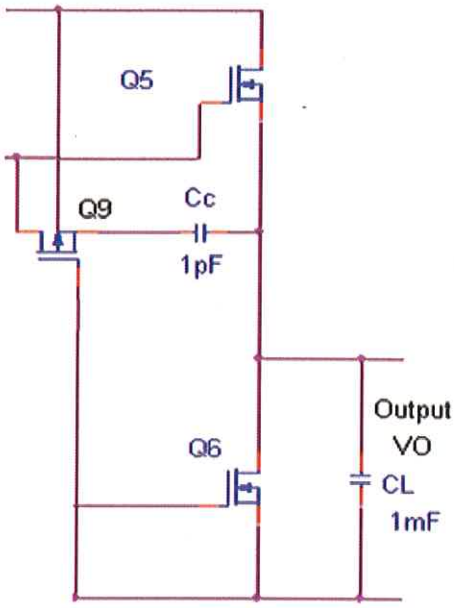


Figure 3.11: Second Gain Stage

Consisting of transistors Q_5 and Q_6, this stage takes the output from the drain of Q_2 and amplifies it through Q_5 which is in the standard common source configuration. Again, similar to the differential gain stage, this stage employs an active device, Q_6, to serve as the load resistance for Q_5 [9]. The gain of this stage is the transconductance of Q_5 times the effective load resistance comprised of the output resistances of Q_5 and Q_6.

3.3.3 Bias String:

The biasing of the operational amplifier is achieved with only four transistors [6,7]. Transistors Q_8 and Q_7 form a simple current mirror bias string that supplies a voltage between the gate and source of Q_7 and Q_6. Transistors Q_6 and Q_7 sink a certain amount of current based on their gate to source voltage which is controlled by the bias string.

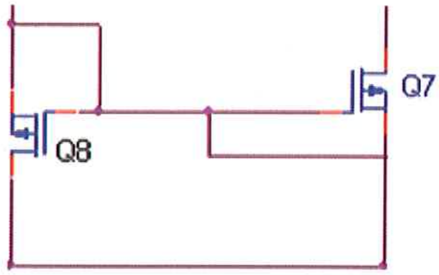


Figure 3.12: Bias String

Q_8 and Q_9 are diode connected to ensure they operate in the saturation region. Proper biasing of the other transistors in the circuit (Q_1- Q_5) is controlled by the node voltages present in the circuit itself [10, 11]. Most importantly, Q_5 is biased by the gate to source voltage (VGS) set up by the VGS of the current mirror load as are the transistors Q_1 and Q_2.

The three stages are now combined to form the Current Feedback Operational Amplifier using CMOS.

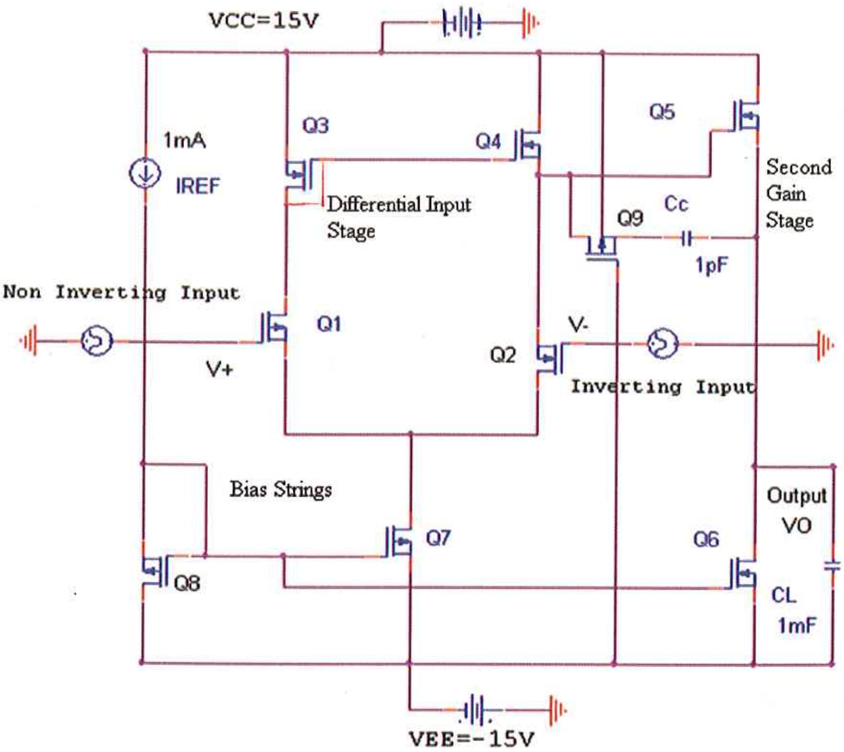


Figure 3.13: Current Feedback Operational Amplifier using CMOS

3.4 Results and Discussions:

3.4.1 Simulation Output in Non-Inverting Mode for CFOA (BJT)

V (6) and V (3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(3) is grounded as the Op-Amp is being operated in Inverting Mode.

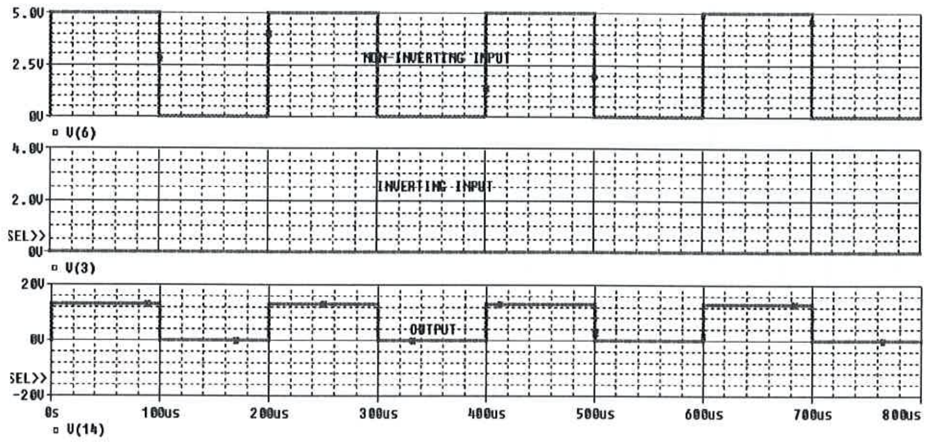


Figure 3.6: Simulation Waveform in Non-Inverting Mode for CFOA using BJT

3.5.2 Simulation Output in Inverting Mode for CFOA (BJT)

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(3) is grounded as the Op-Amp is being operated in Inverting Mode.

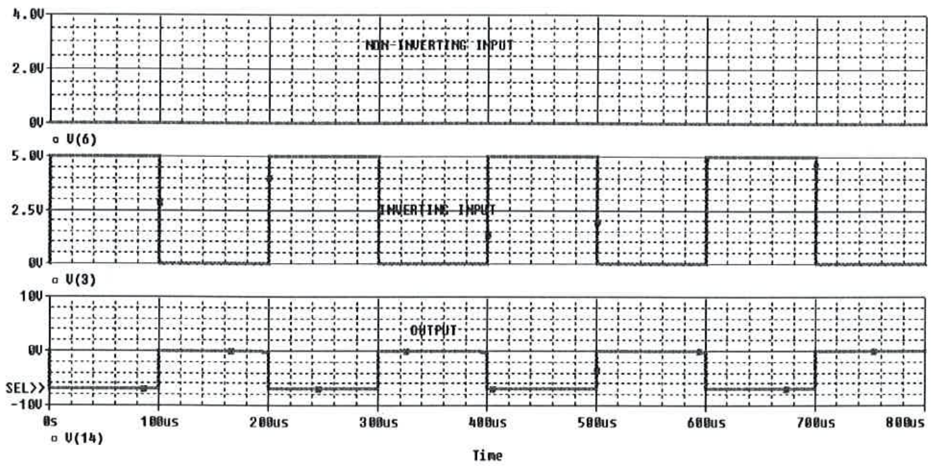


Figure 3.7: Simulation Waveform in Inverting Mode for CFOA using BJT

3.5.3 Simulation Output in Differential Mode for CFOA (BJT)

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform.

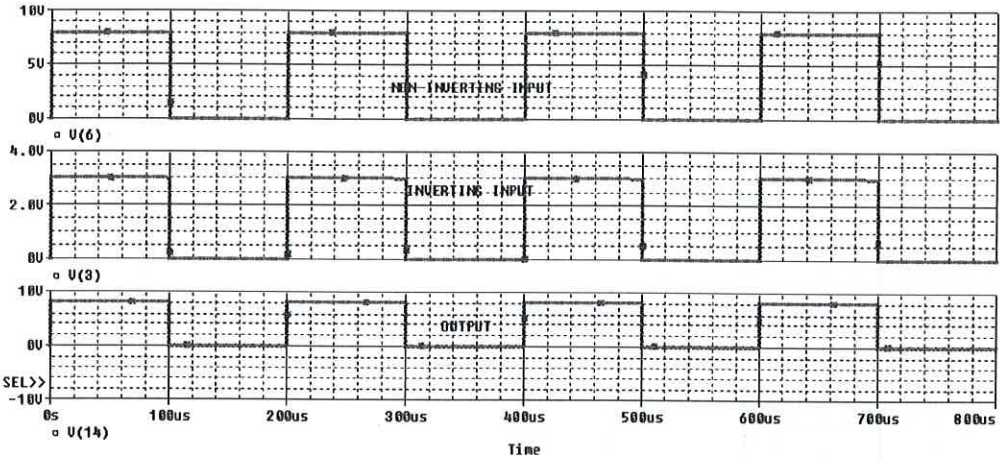


Figure 3.8: Simulation Waveform in Differential Mode for CFOA using BJT.

3.5.4 Simulation Output in Non-Inverting Mode for CFOA (CMOS)

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(3) is grounded as the Op-Amp is being operated in Inverting Mode.

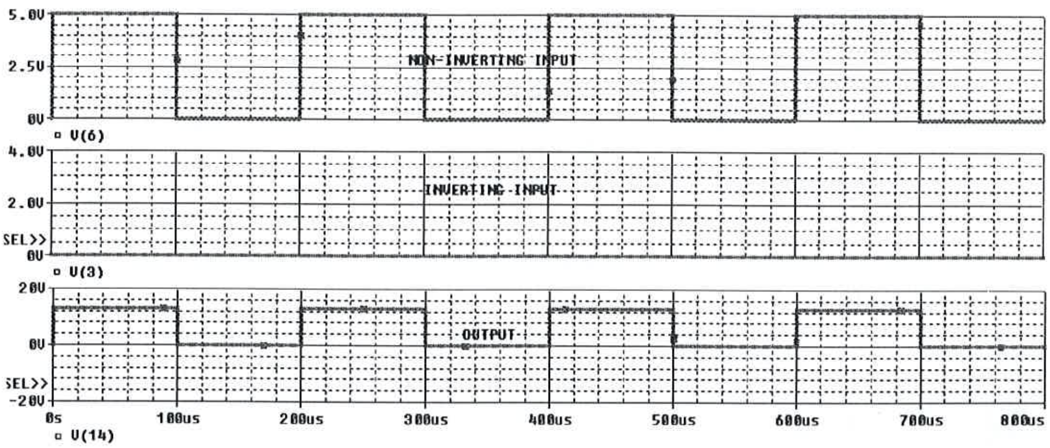


Figure 3.14: Simulation Waveform in Non-Inverting Mode for CFOA using CMOS

3.5.2 Simulation Output in Inverting Mode for CFOA (CMOS)

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform. The voltage V(3) is grounded as the Op-Amp is being operated in Inverting Mode.

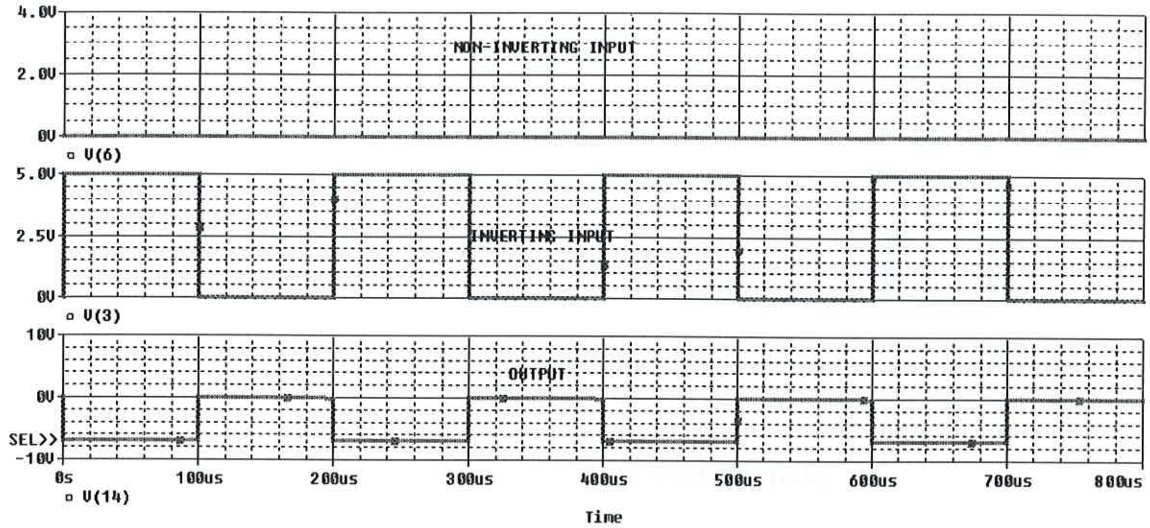


Figure 3.15: Simulation Waveform in Inverting Mode for CFOA using CMOS

3.5.6 Simulation Output in Differential Mode for CFOA(CMOS)

Voltage V(6) and V(3) represent the Non-Inverting Input and Inverting Input respectively whereas the voltage V(14) is the Output Waveform.

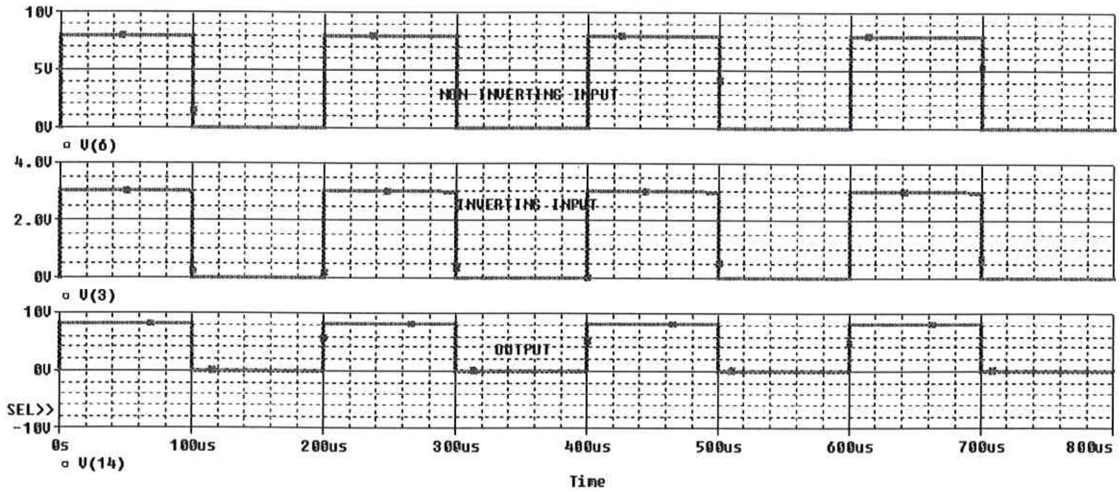


Figure 3.16: Simulation Waveform in Differential Mode for CFOA using CMOS

3.5.7 Comparison Tables

Table 3.1: Parameters for CFOA (BJT)

Parameter/Type	Non-inverting	Inverting	Differential
Output Impedance	14Ω	16.9Ω	14.5Ω
Input Impedance	562kΩ	469kΩ	516kΩ
Slew Rate	5.59V/µs	4.62V/µs	5.27V/µs
CMRR	25.68dB	19.68dB	23.94dB
Power Dissipation	6.18E-03 W	7.16E-03 W	6.96E-03 W
Voltage Gain	2.5	-1.4	1.6
SVRR	30.69dB	33.64dB	31.29dB

As observed from the above table the Non-Inverting Mode is the best out of the three

Table 3.2: Parameters for CFOA (CMOS)

Parameter/Type	Non-Inverting	Inverting	Differential
Output Impedance	10Ω	14Ω	11.5Ω
Input Impedance	500kΩ	461kΩ	421kΩ
Slew Rate	6.9V/µs	6.62V/µs	6.79V/µs
CMRR	35.68dB	26.68dB	29.98dB
Power Dissipation	4.10E-03 W	5.16E-03 W	4.96E-03 W
Voltage Gain	1.6	-1.4	-1.4
SVRR	32.64dB	29.64dB	33.64dB

As observed from the above table the Non-Inverting Mode is the best out of the three.

Table 3.3: Comparison of CFOA (CMOS) in Non-Inverting Mode and CFOA (BJT) in Non-Inverting Mode

Parameter/Type	CFOA (CMOS) Non-Inverting Mode	CFOA (BJT) Non-Inverting Mode
Output Impedance	10Ω	69.5Ω
Input Impedance	500kΩ	270kΩ
Slew Rate	6.9V/μs	5.59V/μs
CMRR	35.68dB	25.68dB
Power Dissipation	4.10E-03 W	6.18 E-03 W
Voltage Gain	1.6	2.4
SVRR	32.64dB	30.69 dB

CFOA (CMOS) - Non-Inverting Mode has a better count on power dissipation and slew rate and CMRR.

CHAPTER-4: Operational Transconductance Amplifier

The operational transconductance amplifier (OTA) is an amplifier whose differential input voltage produces an output current [12]. Thus, it is a voltage controlled current source (VCCS). There is usually an additional input for a current to control the amplifier's transconductance. The OTA is similar to a standard operational amplifier in that it has a high impedance differential input stage and that it may be used with negative feedback.

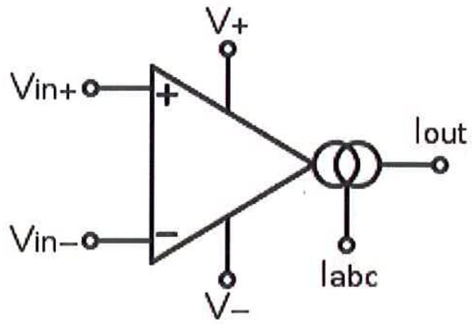


Figure 4.1: OTA Notation

4.1 Principal differences from standard operational amplifiers

1. Its output of a current contrasts to that of standard operational amplifier whose output is a voltage.
2. It is usually used "open-loop"; without negative feedback in linear applications. This is possible because the magnitude of the resistance attached to its output controls its output voltage. Therefore a resistance can be chosen that keeps the output from going into saturation, even with high differential input voltages.
3. Since the OTA is a current source, the output impedance of the device is high, in contrast to the op-amp's very low output impedance.

4.2 Basic Operation

In the ideal OTA, the output current is a linear function of the differential input voltage, calculated as follows:

$$I_{out} = (V_+ - V_-).\, g_m$$

where V_{in+} is the voltage at the non-inverting input, V_{in-} is the voltage at the inverting input and gm is the transconductance of the amplifier. The amplifier's output voltage is the product of its output current and its load resistance where

$$V_{out} = I_{out} \,.\, R_{load}$$

Voltage gain is then the output voltage divided by the differential input voltage:

$$G_{voltage} = V_{out} / (V_+ - V_-) = g_m \,.\, R_{load}$$

The transconductance of the amplifier is usually controlled by an input current, denoted I_{abc} ("amplifier bias current"). The amplifier's transconductance is directly proportional to this current. This is the feature that makes it useful for electronic control of amplifier gain, etc.

4.3 Types of Current Mirrors

4.3.1 Standard Current Mirror:

The main problem with the small power supply concerns the current mirrors [13]. The chosen technology has threshold voltages of ±500mV. This means that a standard current mirror will require an output voltage of approximately ±600 mV to remain in the active mode of operation. Here, two current mirrors are required, leaving only 600mV for Op-amp operation. This problem can be minimized to some extent by realizing that the entire Op-amp input and output currents do not need to be sensed; only the current in the output stages. However, the output swing of this configuration would still be severely limited. It is clear that an alternative is needed.

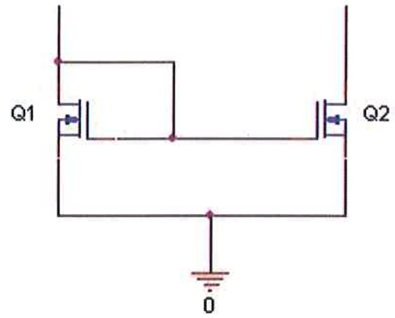


Figure 4.2: Standard Current Mirror

4.3.2 Bulk Driven Current Mirror:

Several low-voltage current mirrors exist that are capable of operating with far less output voltage requirements. One alternative is the bulk-driven current mirror. In this layout, the gates of the two transistors are tied to the most positive (or negative) supply rail. This ensures that the devices are operating in the active mode of operation. The bulk terminals are tied together, and are connected to the input transistors drain.

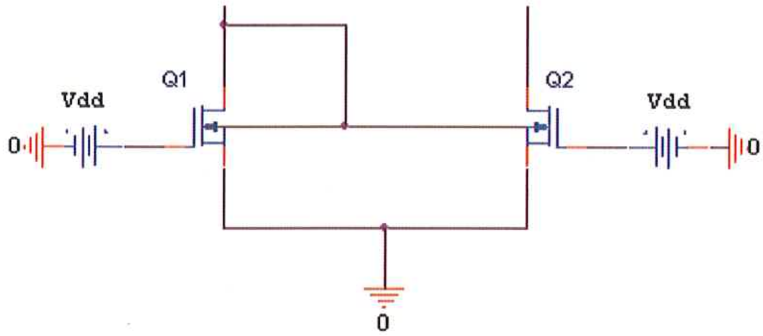


Figure 4.3: Bulk Driven Current Mirror

4.3.3 Low-Voltage Current Mirror:

Another alternative to the standard current mirror is a low-voltage current mirror that employs a level-shifter between the gate and drain of the input transistor. In this case, the level-shifter is implemented using a source follower stage.

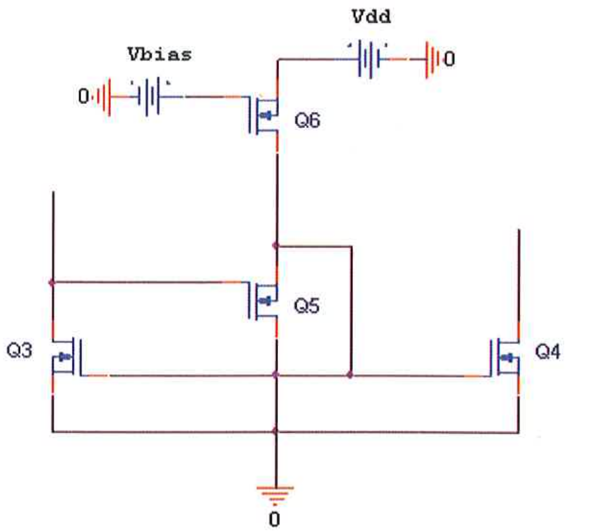


Figure 4.4: Low-Voltage Current Mirror

4.3 Block Diagram of Operational Transconductance Amplifier (OTA):

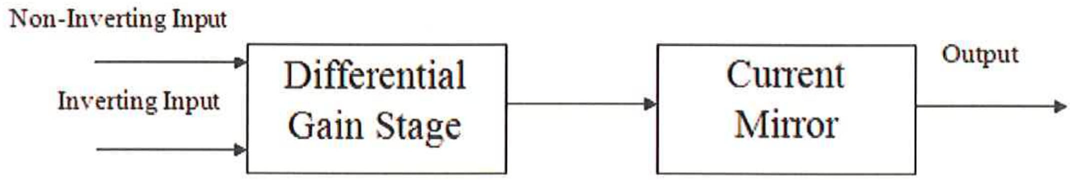


Figure 4.5: Block Diagram of OTA

4.5 Types of Operational Transconductance Amplifier (OTA):

- Simple Differential OTA
- Fully Differential OTA
- Balanced OTA

4.5.1 Simple Differential OTA:

The simple differential operational transconductance amplifier consists of four transistors Q_1, Q_2, Q_3 and Q_4. R_1, R_2, R_3 are the three resistances used. Q_1 and Q_2 form a differential pair i.e., the input voltage is applied at their base terminals and the difference between the voltages is amplified by the transistors [14]. They work as a differential amplifier.

Transistors Q_3 and Q_4 form a current mirror. The current at the left point gets copied at the right point. Voltage supply Vdd (5 V) is applied to activate all the transistors.

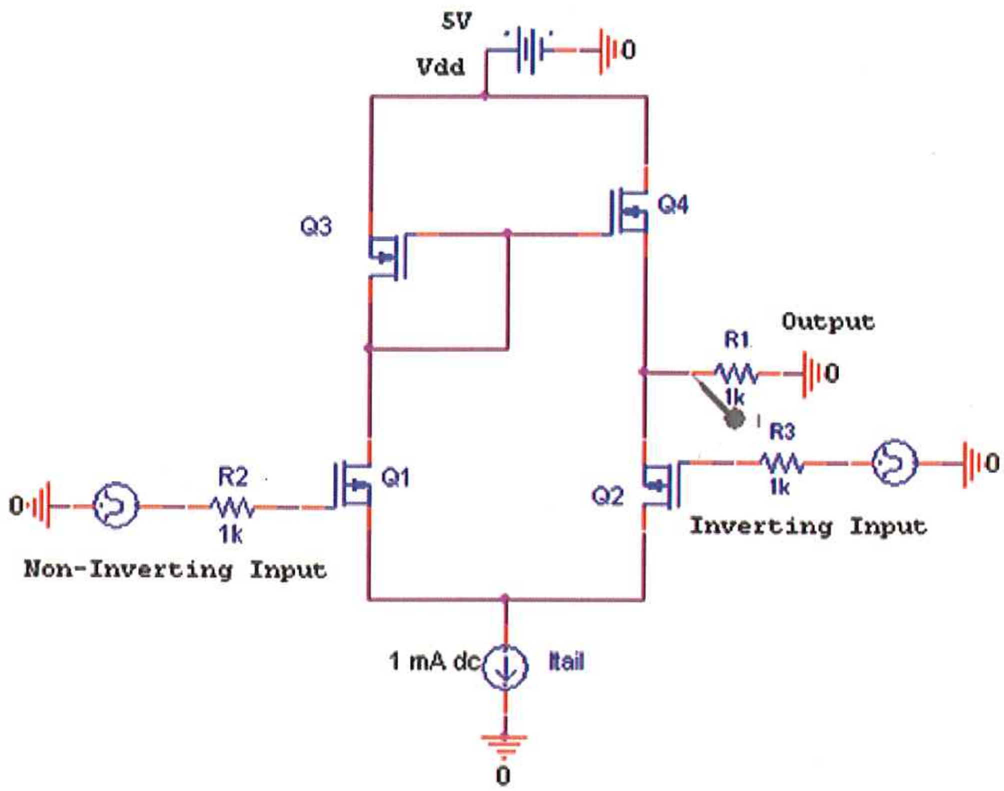


Figure 4.3: Simple Differential OTA

An additional current source I tail is also applied at the source terminals of Q_1 and Q_2. It was observed that by applying this current source the CMRR of the circuit increases. The output is taken at the drain terminal of Q_2 via resistance R_1.

4.5.2 Fully Differential OTA:

The fully differential operational transconductance amplifier consists of six transistors Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6. R_1, R_2, R_3 and R_4 are the four resistances used. Q_5 and Q_6 form a differential pair i.e., the input voltage is applied at their base terminals and the difference between the voltages is amplified by the transistors. They work as a differential amplifier [15].

Transistors Q_1-Q_2 and Q_3-Q_4 form current mirrors. The current at the left point gets copied at the right point. Voltage supply Vdd (5 V) is applied to activate all the transistors.

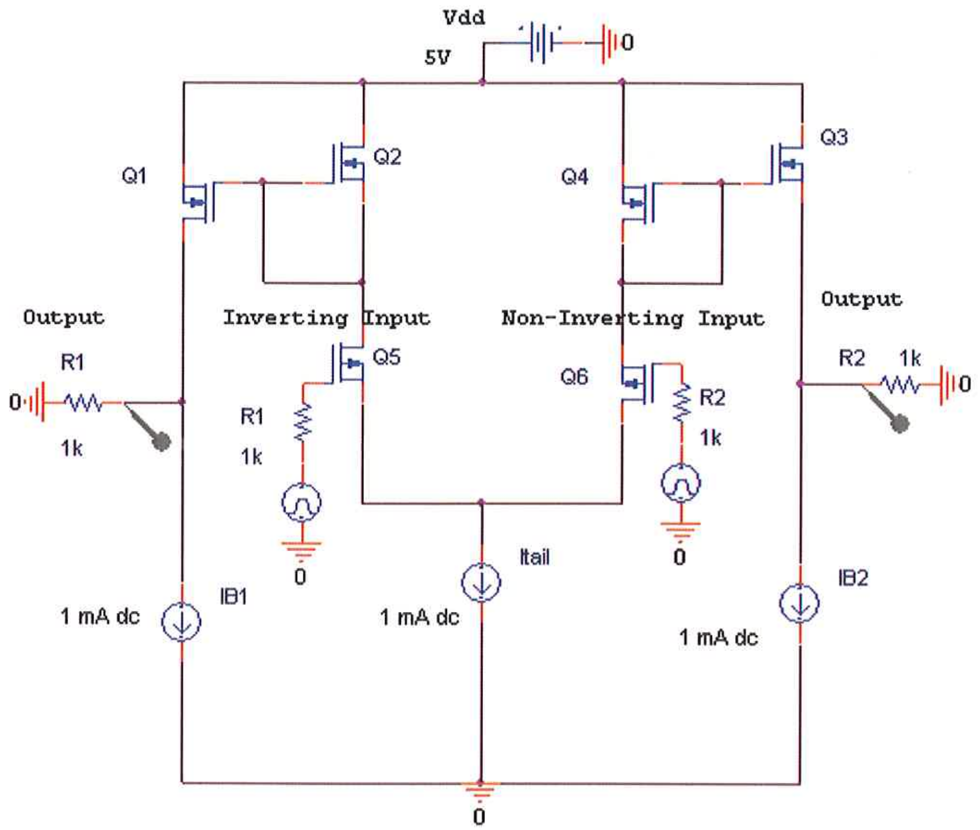


Figure 4.4: Fully Differential OTA

Additional current sources I tail are also applied at the terminals of Q_1, Q_3, Q_5 and Q_6. It was observed that by applying these current sources the CMRR of the circuit increases. The output is taken at resistances R_1 and R_2.

4.5.3 Balanced OTA:

The fully differential operational transconductance amplifier consists of six transistors Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6. R_1, R_2, R_3 and R_4 are the four resistances used. Q_5 and Q_6 form a differential pair i.e., the input voltage is applied at their base terminals and the difference between the voltages is amplified by the transistors. They work as a differential amplifier [16]. Transistors Q_1-Q_2, Q_6-Q_7 and Q_3-Q_4 form current mirrors.

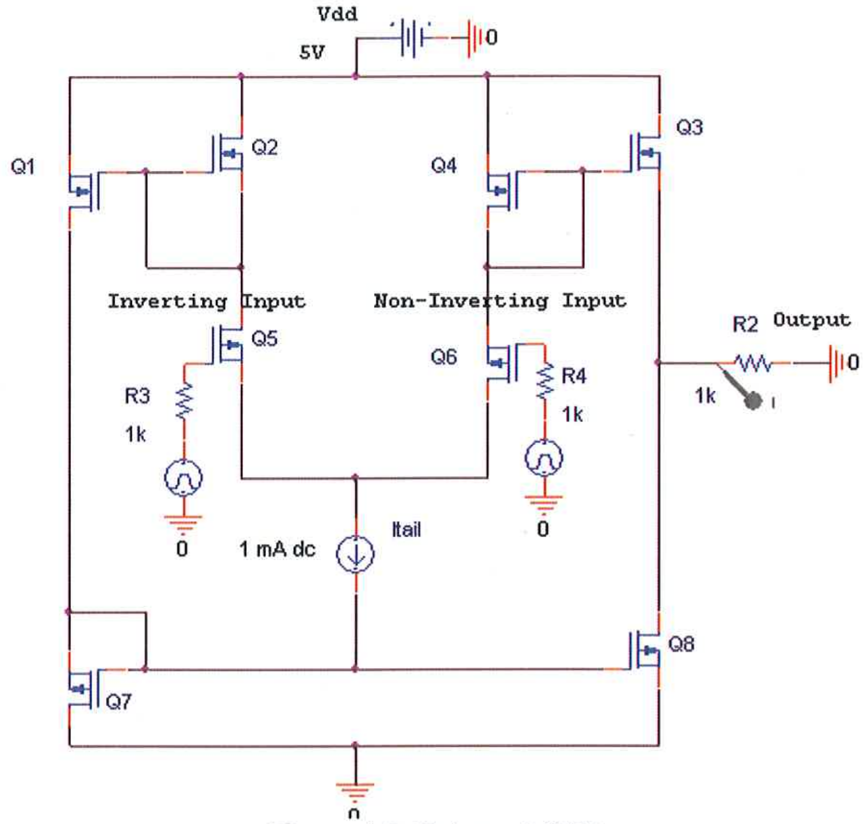


Figure 4.5: Balanced OTA

The current at the left point gets copied at the right point. Voltage supply Vdd(5 V) is applied to activate all the transistors. Additional current source I tail is also applied at the terminals of Q_5 and Q_6 [17, 18]. It was observed that by applying this current source the CMRR of the circuit increases. The output is taken at resistance R_2.

4.4 Results and Discussions:

4.4.1 Comparison Table:

Table 4.1: Table of parameters for OTA

Parameter/Type	Simple Differential OTA	Fully Differential OTA	Balanced OTA
Output Impedance	100 kΩ	60 kΩ	0.375 kΩ
Input Impedance	(0.5 x 10^9) kΩ	(0.5 x 10^9) kΩ	(0.375 x 10^9) kΩ
CMRR	21.8 dB	41.5 dB	60 dB
Power Dissipation	5.34E-03W	1.03E-02W	5.64E-04 W
Transconductance	33μS	20μS	100μS
Slew Rate	1.34V/μs	1.49V/μs	2.32V/μs

As observed from the above table the Balanced OTA is the best out of the three.

The results obtained using the standard current mirror did not provide the optimum CMRR and Slew Rate so the Balanced OTA will now be implemented with the standard current mirror being replaced by Low Voltage and Bulk Driven current mirrors respectively.

4.5 Our Proposal Work

To achieve the optimum level of CMRR we replaced the Standard Current Mirror in the Balanced OTA by Low Voltage Current Mirror and Bulk Driven Current Mirror.

4.5.1 Balanced OTA using Bulk Driven Current Mirror:

This circuit is formed when we replaced the Standard Current Mirror in the Balanced OTA by the Bulk Driven Current Mirror. The improved parameters obtained via this circuit are listed in the Table 4.2 (Section 4.6).The improved CMRR obtained from this circuit is 80dB.

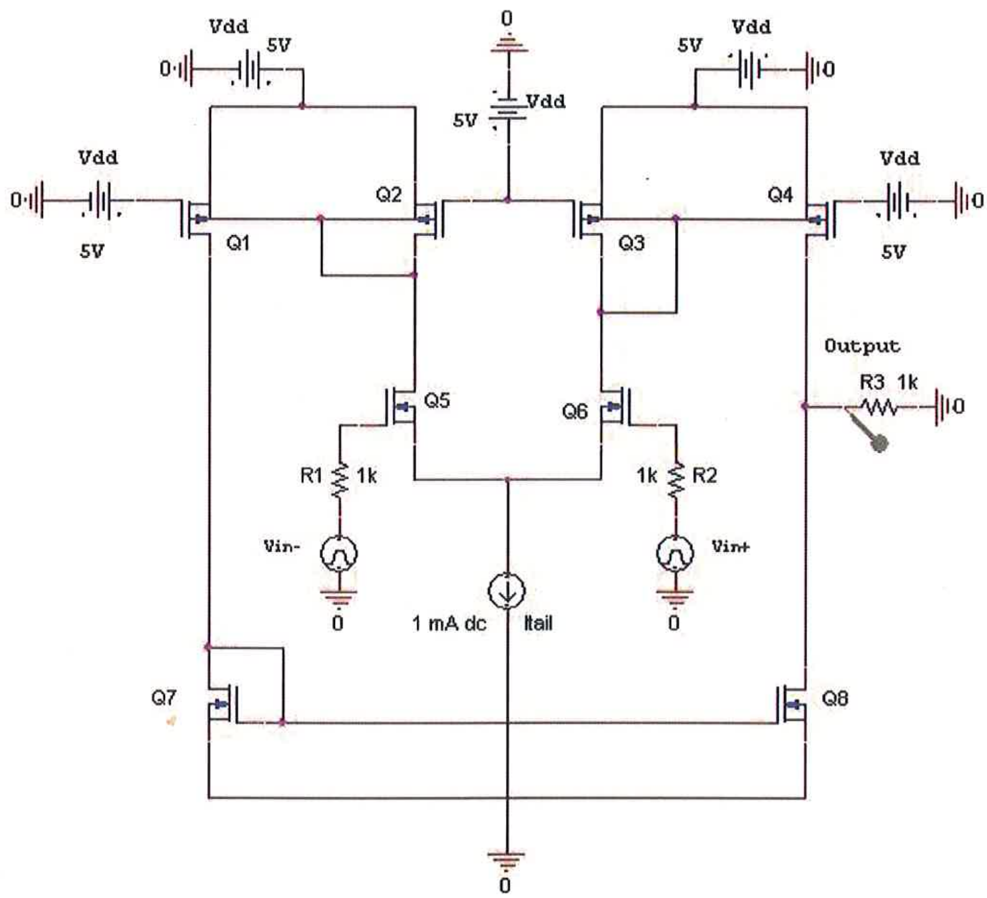


Figure 4.5: Balanced OTA using Bulk Driven Current Mirror

4.5.2 Balanced OTA using Low Voltage Current Mirror:

This circuit is formed when we replaced the Standard Current Mirror in the Balanced OTA by the Low Voltage Current Mirror. The improved parameters obtained via this circuit are listed in the Table 4.2 (Section 4.6). The improved CMRR obtained from this circuit is 110dB.

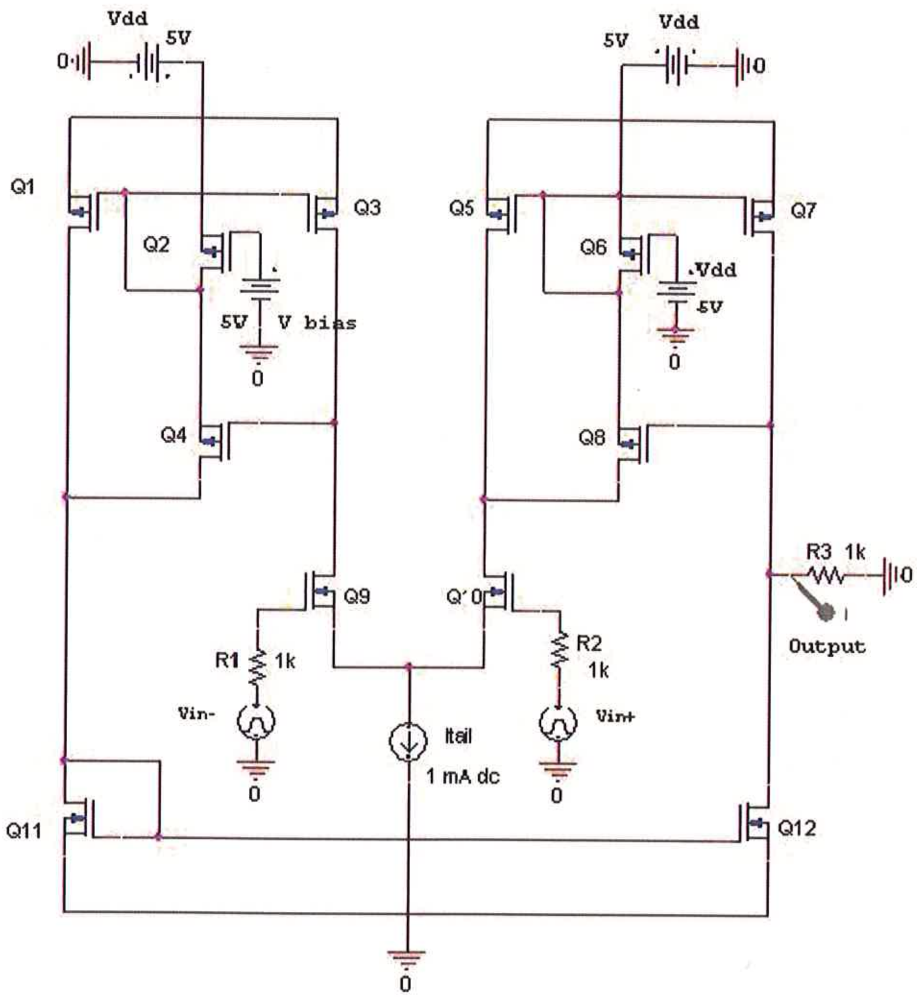


Figure 4.6: Balanced OTA using Low Voltage Current Mirror

4.6 Comparison Table:

Table 4.2: Table of Parameters of Balanced OTA using different current mirrors

Parameter/Type	Balanced OTA using Bulk Driven Current Mirror	Balanced OTA using Low Voltage Current Mirror
Output Impedance	83.3 Ω	10 Ω
Input Impedance	0.175×10^12 Ω	0.875×10^12 Ω
CMRR	80 dB	110 dB
Power Dissipation	4.34E-04 W	1.89E-05 W
Transconductance	200μS	300μS
Slew Rate	1.28V/μs	4.7V/μs

Balanced OTA using Low Voltage Current Mirror is better based upon Transconductance, CMRR and Slew Rate.

CHAPTER-5: Comparisons

This chapter compares the best designs from all the chapters amongst each other.

5.1 Comparison 1:

Table 5.1: Comparison of **VFOA (BJT)** -Non Inverting Mode and **CFOA (CMOS)** - Non Inverting Mode

Parameter/Type	VFOA (BJT) Non-Inverting Mode	CFOA (CMOS) Non-Inverting Mode
Output Impedance	69.5Ω	10Ω
Input Impedance	270kΩ	500kΩ
Slew Rate	.25V/μs	6.9V/μs
CMRR	33.27dB	35.68dB
Power Dissipation	3.87E-01 W	4.10E-03 W
Voltage Gain	2.4	1.6
SVRR	48.28dB	32.64dB

CFOA (CMOS) - Non Inverting Mode has a better count on power dissipation and slew rate and CMRR.

5.2 Comparison 2:

Table 5.2: Comparison of **CFOA (CMOS)** - Non Inverting Mode and **Balanced OTA**

Parameter/Type	Balanced OTA	CFOA (CMOS) Non-Inverting Mode
Output Impedance	0.375 kΩ	10Ω
Input Impedance	(0.375 x 10^9) kΩ	500kΩ
Slew Rate	2.32V/μs	6.9V/μs
CMRR	60 dB	35.68dB
Power Dissipation	5.64E-04 W	4.10E-03 W
Voltage Gain /Transconductance	1.6	1.6

Balanced OTA scores better on the basis of Input Impedance, CMRR, Slew Rate and Power Dissipation.

5.3 Comparison 3:

Table 5.3: Comparison of **Balanced OTA using Standard Current Mirror** and **Balanced OTA using Low Voltage Current Mirror**

Parameter/Type	**Balanced OTA using Standard Current Mirror**	**Balanced OTA using Low Voltage Current Mirror**
Output Impedance	0.375 kΩ	10 Ω
Input Impedance	(0.375 x 10^9) kΩ	0.875×10^12 Ω
CMRR	60 dB	110 dB
Power Dissipation	5.64E-04 W	1.89E-05 W
Slew Rate	100μS	300μS
Voltage Gain /Transconductance	2.32V/μs	4.7V/μs

Balanced OTA using Low Voltage Current Mirror has a better count because of CMRR, Slew Rate, Transconductance and Power Dissipation.

CONCLUSION

We have implemented Voltage Feedback Operational Amplifier in three modes- non-inverting, inverting and differential. The Voltage Feedback Operational Amplifier in non inverting mode came out to be better based upon the values of CMRR = 33.27dB, SVRR= 48.28dB and Power Dissipation = 3.87E-01W.

To improve CMRR further we have designed Current Feedback Operational Amplifier using CMOS and BJT. The CFOA implemented using CMOS in Non-Inverting in mode was observed to be better on the basis of CMRR = 35.68dB, Slew Rate = 6.9 V/μs and Power Dissipation = 4.10E-03W.

After CFOA we have implemented Operational Transconductance Amplifier as Fully Differential, Simple Differential and Balanced. The Balanced OTA scored the better on the basis of CMRR = 60dB, Transconductance = 100μS and Power Dissipation = 5.64E-04W.

In order to get the optimum value of CMRR we have proposed the design of Balanced OTA in which the Standard Current Mirror is replaced by - Bulk Driven Current Mirror and Low Voltage Current Mirror. Here the Balanced OTA using Low Voltage Current Mirror was observed to the best on the basis of CMRR=110dB and Transconductance = 300 μS.

In case of further improvements in CMRR - Current Differencing Transconductance Amplifier (CDTA) and Current Controlled Current Differencing Transconductance Amplifier (CCCDTA) can be used.

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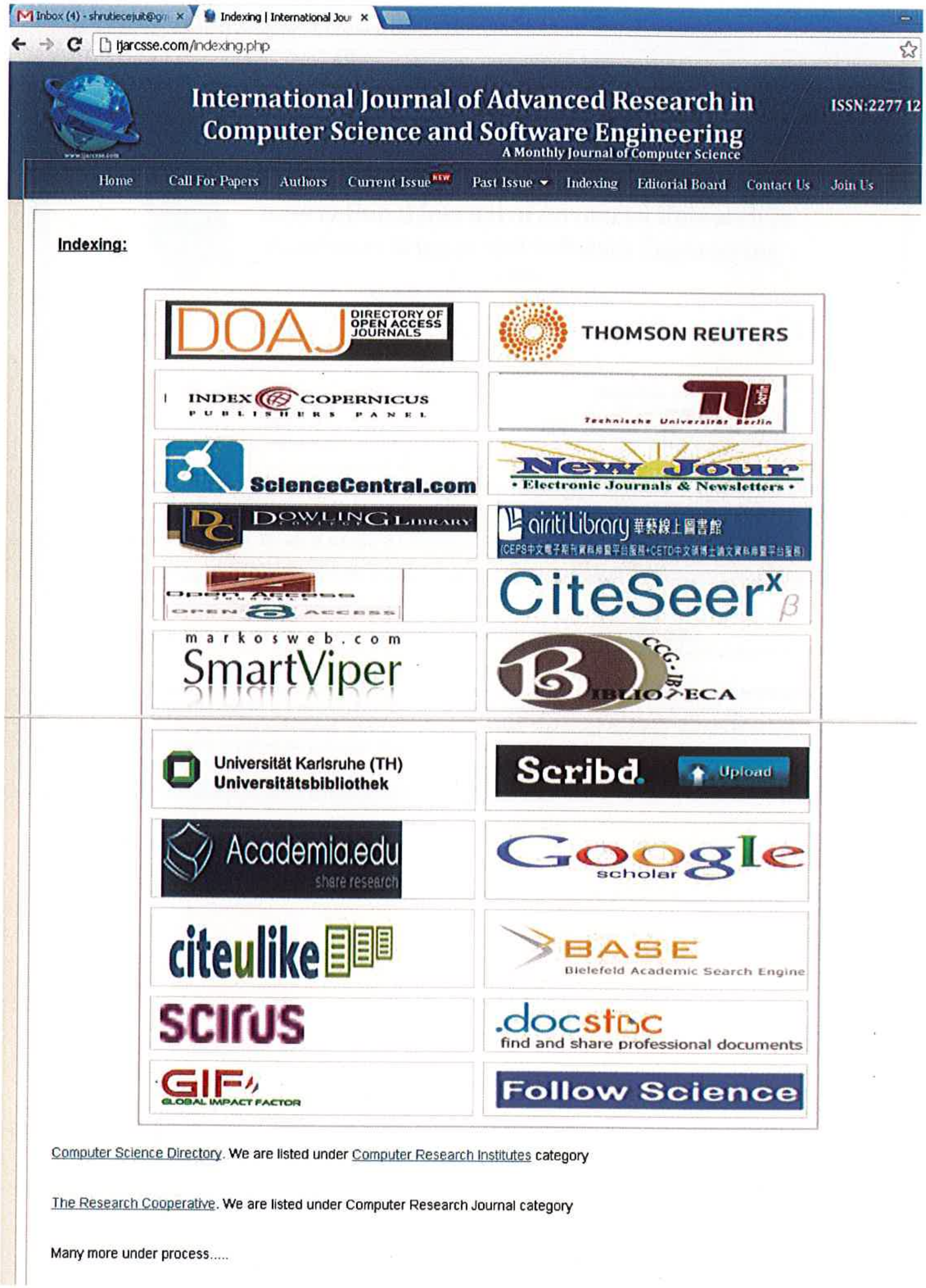
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Effect of Current Feedback Operational Amplifiers using BJT and CMOS

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Abstract*— The operational amplifier is an extremely efficient and versatile device. Its applications span the broad electronic industry filling requirements for signal conditioning, special transfer functions, analog instrumentation, analog computation, and special systems design. The analog assets of simplicity and precision characterize circuits utilizing operational amplifiers. The aim of the paper is to compare the CFOA implemented using BJT and the Current Feedback Operational Amplifier(CFOA) implemented using CMOS on the basis of Voltage Gain, Input and Output Impedance, Supply Voltage Rejection Ratio (SVRR), Common Mode Rejection Ratio (CMRR) and Slew Rate using Simulation Program with Integrated Circuit Emphasis (SPICE) simulation.

***Keywords*— Inverting amplifier, Non inverting Amplifier, Differential amplifier, BJT, CMOS,CFOA**

I. INTRODUCTION

An operational amplifier is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers [1, 2]. The operational amplifier is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for performing mathematical operations. Originally, the term, "Operational Amplifier," was used in the computing field to describe amplifiers that performed various mathematical operations. It was found that the application of negative feedback around a high gain DC amplifier would produce a circuit with a precise gain characteristic that depended only on the