DESIGN AND IMPLEMENTATION OF SIGNAL PROCESSING CIRCUITS USING OTRA

Submitted in fulfilment
for the award of the degree of
MASTERS OF ENGINEERING
IN
ELECTRONICS & COMMUNICATION

Submitted By:-
Garima
Roll No.- 8571

Under the guidance of
Mrs. RAJESHWARI PANDEY

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING
DELHI COLLEGE OF ENGINEERING
UNIVERSITY OF DELHI, DELHI – 110042
(Session 2008-2010)

CERTIFICATE

This is to certify that the report entitled **"DESIGN AND IMPLEMENTATION OF SIGNAL PROCESSINGN CIRCUITS USING OTRA"** which is submitted by **Garima** in the Department of Electronics & Communication Engineering, Delhi College of Engineering, Delhi, is a bona fide record of the work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of this report, which has reached the requisite standard.

(Project Guide)

Mrs. Rajeshwari Pandey

Asstt. Professor

Department of Electronics &
Communication Engg.

Delhi Technologicl University
Bawana Road, Delhi – 110042

Prof. Rajiv Kapoor

HOD

Department of Electronics &
Communication Engg.

Delhi Technologicl University
Bawana Road, Delhi - 110042

ACKNOWLEDGEMENT

I am thankful to **Delhi College of Engineering** for giving me the opportunity to undertake the project in area of my interest. The faculty at DCE with their informal candidness and helping attitude made it pleasure to work. My association with them has been a good learning experience and has provided me with invaluable feedback.

I would like to express my deep gratitude to my Project Guide **Mrs. Rajeshwari Pandey** (Asstt. Prof., Dept. of ECE, DTU) for allowing me to undertake the project and to guide me throughout the project with her invaluable suggestions, which was crucial for the successful completion of the project.

Garima

Roll No.-8571

ABSTRACT

With the evolution of submicron technologies the supply voltages have been reduced. This makes it difficult to design a voltage mode CMOS circuits with high linearity and wide dynamic range. Also as signal processing extends to higher frequencies, the traditional design methods based on voltage operational amplifiers are no longer adequate. A traditional operational amplifier has a bandwidth which is dependent on the closed- loop voltage gain. To overcome this problem, circuits operating in current mode are preferred. Various analog building blocks operating in the current mode are available. Operational Transresistance Amplifier(OTRA) is one of them. Both its input & output terminals are characterized by low impedance, therefore eliminating response limitations incurred by capacitive time constants. Thus using the OTRA as the active building block various signal processing and generating circuits can be realized with more flexibility in controlling the frequency of waveforms.

The Operational Transresistance Amplifiers (OTRAs) are presently not available in an IC form. An OTRA can be implemented by adopting the commercial AD844AN integrated chips with current feedback architecture. Also various CMOS realizations of OTRA are available in the literature.

In this project various CMOS realization of OTRA and wide variety of signal processing and generation applications such as voltage and current mode filters, passive component realization and oscillators have been realized. The circuits are simulated with PSPICE program ORCAD 16.0 version. The simulation results verify that the circuit topologies using OTRAs for realizing signal generating circuits are simple, effective, flexible, versatile, and easily tunable. Hence these circuits can be expected to find wide applications such as pulse-width modulation controlled circuits, time delay circuits, phase-detected circuits, in electronic instrument systems where higher frequencies up to MHz & variable duty cycles are demanded.

Table of Contents

CHAPTER-1

INTRODUCTION

Analogue Integrated Circuit Design is becoming increasingly important with growing opportunities. Coupled with the various technological improvements are the ever shrinking feature size of the devices on IC's and the consequent reduction of power supply voltages. This has led to creation of alternate analogue design techniques.

Historically analogue design was viewed as a voltage dominated form of signal processing. This is apparent from the fact that current signals were transferred into voltage domain before any analogue signal processing could be done. But due to the advances in the process technology a shift is made to current mode of signal processing. Analog IC design is receiving a tremendous boost from the development and application of current mode processing which has an inherent performance feature of wider bandwidth[1].

1.1 CURRENT MODE BUILDING BLOCKS

The growth of analog IC design has been impeded by the process technologies that are mostly optimized for digital applications only. With the evolution of submicron technologies such as 0.18 micron and 0.13 micron, the supply voltages have been reduced to 3.3 Volts and lower. This makes it difficult to design a voltage mode CMOS circuits with high linearity and wide dynamic range. Recently, current mode circuits have become a viable alternative for future applications because of their inherent advantages over voltage mode circuits[1].

The main advantage of using current mode technique is because the non-linear characteristics exhibited by most field effect transistors. A small change in the input or controlling voltage results in a much larger change in the output current. Thus for a fixed supply voltage, the dynamic range of a current mode circuit is much larger than that of a voltage mode circuit. If a supply voltage is lowered, one can still get the required signals represented by the current.

A second advantage of current mode circuits is that they are much faster as compared to voltage mode circuits. The parasitic capacitances present in the analog circuits must be charged and discharged with the changing voltage levels. In a current mode circuit, a change in current level is not necessarily accompanied by a change in the voltage level. Hence, the parasitic capacitances will not affect the operating speed of the circuit by a significant amount.

Other advantages of using current mode circuits are that they do not require specially processed capacitors or resistors; they are more compatible with digital CMOS technology making integration of mixed signal circuits more feasible. Due to all the advantages of current mode analogue signal processing there has been an emergence of new analogue building blocks ranging from the current conveyor, OTA, OTRA and current feedback op-amps through to sampled data current circuits such as dynamic current mirrors and analogue neural networks.

1.1.1 Current Conveyor

The current conveyor (CC) is the basic building block of a number of applications both in the current and voltage and the mixed modes. The principle of the current conveyor of the first generation was published in 1968 by K. C. Smith and A. S. Sedra [2]. Two years later, today's widely used second-generation CCII was described in [3], and in 1995 the third-generation CCIII [4]. However, initially, during that time, the current conveyor did not find many applications because its advantages compared to the classical operational amplifier (OpAmp) were not widely appreciated. An IC Current Conveyor, namely PA630, was introduced by Wadsworth in 1989 (mass produced by Phototronics Ltd. of Canada) and about the same time, the now well known AD844 (operational transimpedance amplifier or more popularly known as a current feedback op-amp) was recognized to be internally a CCII+ followed by a voltage follower. An excellent review of the state-of-the-art of current-mode circuits prior to 1990, was provided by Wilson in [5]. Today, the current conveyor is considered a universal analog building block with wide spread applications in the current mode, voltage mode, and mixed mode signal processing. There have been various types of current conveyors like CCI, CCII, CCIII, DVCC, DDCC, etc. Several generations of current conveyors have been defined over the years. Undoubtedly, the second generation conveyor (CCII) is the more well known of the device.

Using standard notation, the terminal relations of a CCII can be characterized by

$$
\begin{array}{cccc}
 & & 0 & 0 \\
= & 0 & 0 & 0 \\
 & 0 & \pm & 0
\end{array}
$$

where $= 1 - \in$ and $\beta = 1 - \in$ $, | \in | << 1$ and $| \in | << 1$ represent the current and voltage tracking errors, respectively. where the subscripts *x, y*, and *z* refer to the terminals labeled X, Y and Z in fig1 The CCII is defined in both a positive and a negative version where the +sign in the matrix is used for the CCII+ type conveyor and the –sign is used for the CCII- type conveyor. Its features find most applications in the current mode, when its voltage input *y* is grounded and the current, flowing into the low-impedance input *x*, is copied by a simple current mirror into the *z* output.

The demand for a multiple-output current conveyor led to the DO-CCII (Dual-Output CCII), which provides currents *Iz* of both directions, thus combining both the positive and the negative CCII in a single device. If both currents are of the same polarity, the conveyors are of the CCII+ or CCII- types.

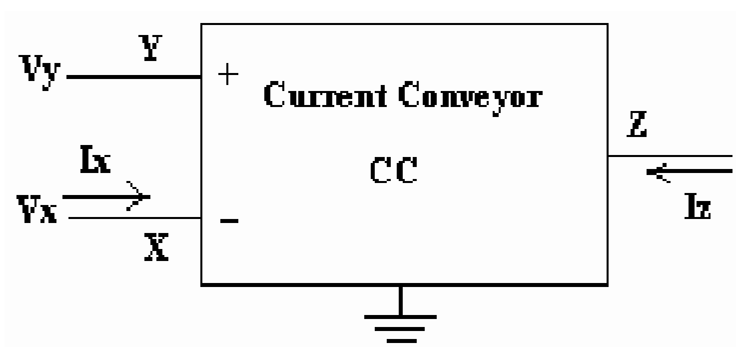

Fig. 1.1 Block diagram of CCII

1.1.2 Operational Transconductance Amplifier

The **operational transconductance amplifier** (**OTA**) is an amplifier whose differential input voltage produces an output current[6]. 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. But its difference from op-amp is that its output is current and it is usually used "open-loop"; without negative feedback in linear applications[6]. 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. The circuit symbol of an ideal OTA is as shown in fig.1.2.

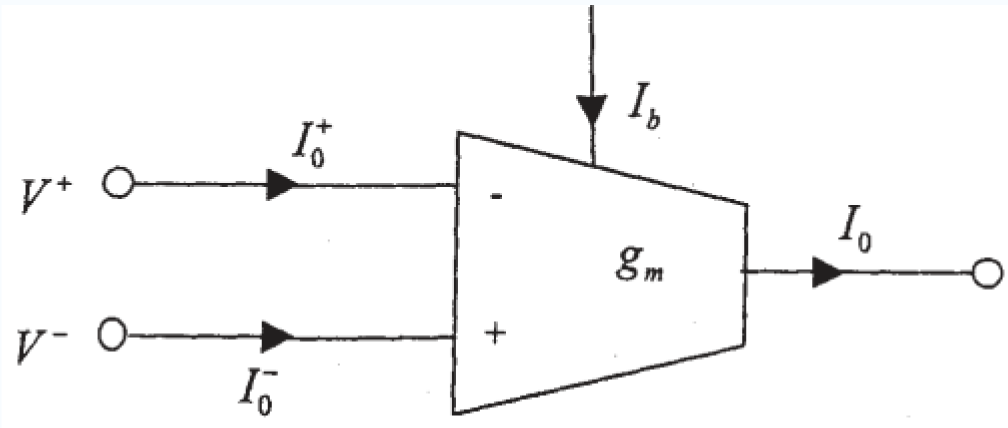

Fig.1.2 Circuit Symbol of OTA

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

$$I_{\mathrm{out}} = (V_{\mathrm{in+}} - V_{\mathrm{in-}}) \cdot g_{\mathrm{m}}$$

where V_{in+} is the voltage at the non-inverting input, V_{in-} is the voltage at the inverting input and g_m is the transconductance of the amplifier.

The amplifier's output voltage is the product of its output current and its load resistance:

$$V_{\mathrm{out}} = I_{\mathrm{out}} \cdot R_{\mathrm{load}}$$

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

$$G_{\mathrm{voltage}} = \frac{V_{\mathrm{out}}}{(V_{\mathrm{in+}} - V_{\mathrm{in-}})} = R_{\mathrm{load}} \cdot g_{\mathrm{m}}$$

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.

The first commercially available integrated circuit units were produced by RCA in 1969, in the form of the CA3080, and they have been improved since that time. One of its principal uses is in implementing electronically controlled applications such as variable frequency oscillators and filters and variable gain amplifier stages which are more difficult to implement with standard op-amps.

1.1.3 Current Feedback Operational Amplifier

The **current feedback operational amplifier** or **CFOA** is a type of electronic amplifier whose inverting input is sensitive to current, rather than to voltage as in a conventional voltage-feedback operational amplifier (VFA)[6]. The CFA was invented by David Nelson at Comlinear Corporation, and first sold in 1982 as a hybrid amplifier, the CLC103. The first integrated circuit CFAs were introduced in 1987 by both Comlinear and Elantec (designer Bill Gross). They are usually produced with the same pin arrangements as VFAs, allowing the two types to be interchanged without rewiring when the circuit design allows. In simple configurations, such as linear amplifiers, a CFA can be used in place of a VFA with no circuit modifications, but in other cases, such as integrators, a different circuit design is required. The circuit symbol of CFOA is as shown in fig.1.3. Its port relations can be characterized by the following matrix form:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \\ V_O \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \\ I_O \end{bmatrix}$$

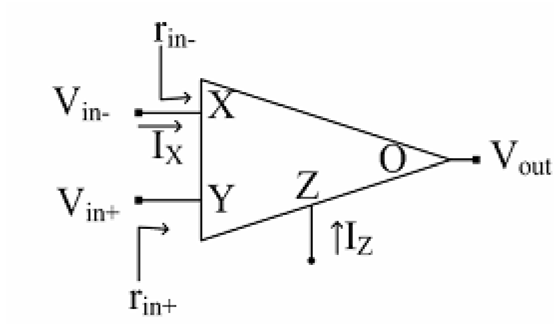

Fig.1.3 Circuit Symbol of CFOA

Current-Feedback Operational Amplifiers (CFOAs) are employed as an alternative to conventional voltage opamps because of their inherent advantages:

- The CFOA closed-loop bandwidth is independent of its close-loop gain, provided that the feedback resistance is kept constant
- The CFOA input and output stages work both in class AB and give high slew-rate values

Advances in bipolar processes and the inherent better current-drive capability, leave BJTs as the most suited for the implementation of CFOAs. More recently, CMOS architectures have also been presented that were focused on a particular performances like offset compensation, high current-drive capability, high-frequency and low-voltage operation .

1.1.4 Operational Transresistance Amplifier

The OTRA is a three terminal analog building block. Both the input and output terminals are characterized by low impedance. The circuit symbol of the OTRA is illustrated in Fig.1.4. The port relations of an OTRA can be characterized by the following matrix form[7]:

$$\begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ I_z \end{bmatrix}$$

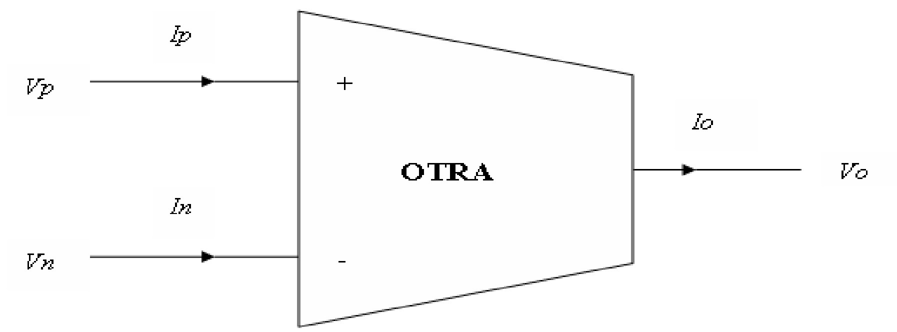

Figure 1.4: Circuit symbol of OTRA

It eliminates response limitations incurred by capacitive time constants leading to circuits that are insensitive to the stray capacitances at the input terminals. For ideal OTRA, the Transresistance gain, R_m, approaches infinity and external negative feedback must be used which forces the input currents to be equal[8]. Thus the OTRA must be used in a negative feedback configuration. Practically the Transresistance gain is finite and its effect should be considered.

In practice, the operational transconductance amplifier, which is widely used as the basic VLSI circuit block, can be substituted by the operational Transresistance amplifier. The operational Transresistance amplifier transfer characteristic is formed by V_{out} / I_{in}, which is opposite to that of operational transconductance amplifier. The operational Transresistance amplifier can be applied in many circuits such as analog divider / multiplier & continuous time filters. The advantages of OTRA is that it has high slew rate & wide bandwidth because of its current processing capabilities at the input terminals. Also, since the OTRA is not slew limited in the same fashion as op-amps, it can provide amplification of high frequency signals with a constant bandwidth virtually independent of the gain.

CHAPTER-2

LITERATURE SURVEY

Traditionally, most analog signal processing operations have been accomplished employing the voltage as the signal variable. But due to the increasing demand for operation in the high frequency region, and the finite gain-bandwidth product associated with operational amplifiers, a change from voltage mode circuits is required. Recently, current-mode analog integrated circuits in CMOS technology have received considerable interest. Current-mode techniques using the OTRA as the active element can achieve a considerable improvement in amplifier speed, accuracy and bandwidth, overcoming the finite gain–bandwidth product associated with operational amplifiers. Literature survey reveals the emergence of OTRA as an alternate analog building block. A variety of papers have been reported on OTRA during last one and a half decade. This includes various CMOS realization of OTRA and wide variety of signal processing and generation applications such as voltage and current mode filters, passive component realization, oscillators and multivibrators.

2.1OTRA REALIZATION

2.1.1 CMOS Realization

The commercial realizations of operational transresistance amplifier under the name of current differencing amplifier or Norton amplifier are not widely used as they do not provide internal ground at the input port and they allow the input current to flow in one direction only. The former disadvantage limited the functionality of the OTRA whereas the latter forced to use external dc bias current leading to complex and unattractive designs [7]. In recent years, several high-performance CMOS OTRA realizations have been presented [7]-[9]. This leads to growing interest for the design of OTRA-based analog signal processing circuits.

2.1.2 CFOA Realization

OTRA can also be realized using commercially available CFOA's IC. Two AD844AN IC's are used to realize a single OTRA.

2.2 OTRA APPLICATIONS

2.2.1 Filters

Various filters have been designed using the CMOS implementation of OTRA. These filters can be classified in two categories: voltage mode and current mode filters.

Ref[10] presents a current mode all pass filter. In it both inverting and non-inverting types of first-order all-pass filters are realized using only a single OTRA, two resistors and a capacitor, without matching constraints and providing independent gain adjustment.

Voltage mode all pass filters are realized in[11]-[13]. Ref[11] gives two realizations, first and second order all pass filter depending on the value of admittance. First-order allpass, second-order allpass and notch filters are realized in[12,13] gives both CFOA and CMOS realization of OTRA while ref[13] uses only CMOS OTRA.

Ref [14] presents an OTRA based transimpedance type biquadratic filter configuration which realizes all five different filtering functions, namely low-pass, high-pass, band-pass, notch and all-pass.

A generalized Tow Thomas and univerasal filter configurations are given in[15]. These are used to realize all the filtering functions like low-pass, high-pass, band-pass, notch and all-pass.

2.2.2 Oscillators

A novel OTRA-based single-resistance-controlled sinusoidal oscillator (SRCO) is proposed in[16]. It uses single OTRA, three resistors and two capacitors.

Ref[17] introduces several active RC oscillator circuits using OTRA as the basic active building block. A general configuration using a single OTRA is introduced, from which a minimum component oscillator is generated. Four new oscillator circuits using two OTRAs are also proposed. Also a quadrature oscillator is built by cascading an inverting and a noninverting allpass filter and closing the loop to provide a loop gain equal to -1 at the pole frequency[13].

2.2.3 Component Realization

OTRA can be used to realize grounded immitance[18] and negative inductance[19]. In [18] a two OTRA based parallel grounded immitance is proposed. Three topologies are given and a current mode multi output filter is realized using the proposed parallel R-L topology.

Ref[19] presents a grounded negative inductance emulator with full independent control on the inductance value. It uses a single OTRA, a capacitor, and five resistors, two of which are for independent control.

2.2.4 Multivibrators

Various multivibrators using OTRA as the active element are present in the literature. In [20] three current mode monostable multivibrators are presented. Two of these circuits are operated respectively under positive and negative triggering modes. However, the third topology which can work in either triggering mode, features a tunable recovery time. The current-mode monostables proposed in [20] are simpler compared to their counterparts composed of operational amplifiers.

Ref[21] presents a voltage-mode multivibrator. In this two bistable multivibrators are presented. The first consists of only one OTRA and a simple positive feedback network while the second utilizes a single pole double throw(SPDT) switch along with a bias voltage source.

CHAPTER-3

CMOS Realization Of OTRA

3.1 INTRODUCTION

Operational transresistance amplifier is commercially available from several manufacturers under the name of current differencing amplifier or Norton amplifier, but it was not widely used until recently[8]. These commercial realizations do not provide internal ground at the input port and they allow the input current to flow in one direction only. The former disadvantage limited the functionality of the OTRA whereas the latter forced to use external dc bias current leading to complex and unattractive designs [10]. In recent years, several high-performance CMOS OTRA realizations have been presented in the literature[7]-[9]. This leads to growing interest for the design of OTRA-based analog signal processing circuits.

3.2 OTRA CMOS REALIZATION-1

The OTRA presented in [8] is shown in fig.3.1. It is based on the cascaded connection of the modified differential current conveyor (MDCC) [22] and a common source amplifier. The MDCC provides the current differencing operation, whereas the common source amplifier provides high gain.

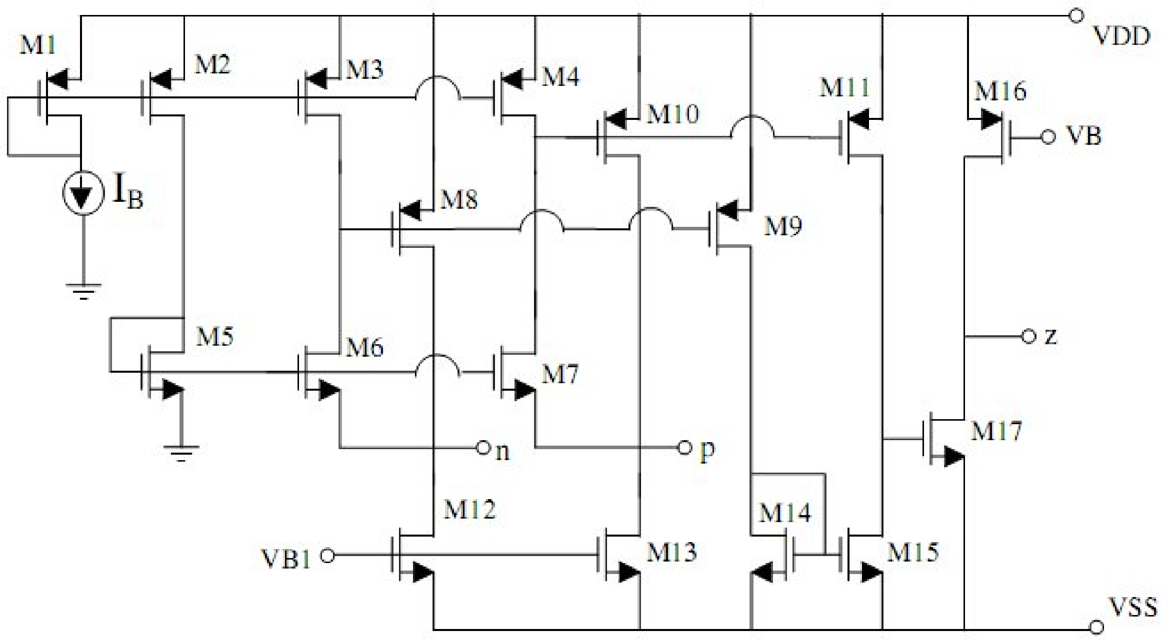

Fig.3.1 CMOS Realization of OTRA

Assuming that. The current mirrors formed by (M4-M7) forces equal currents (IB) in the transistors M1, M2 and M3. This operation drives the gate to source voltages of M1, M2 and M3 to be equal and consequently, forces the two input terminals to be virtually grounded. The current mirrors formed by the transistor pairs (M4 and M5), (M8 and M9), (M10 and M11) and (M14 and M15) provide the current differencing operation, whereas the common source amplifier (M17) achieves the high gain stage. [8]In this operation it is assumed that each of the groups of the transistors (M1-M3), (M4-M7), (M8 and M9), (M10 and M11), (M12 and M13) as well as (M14 and M15) are matched and all the transistors operate in saturation region. The PSpice schematic of the circuit proposed in[8] is shown in fig.3.2. Simulated DC response of the above circuit is shown in fig.3.3.

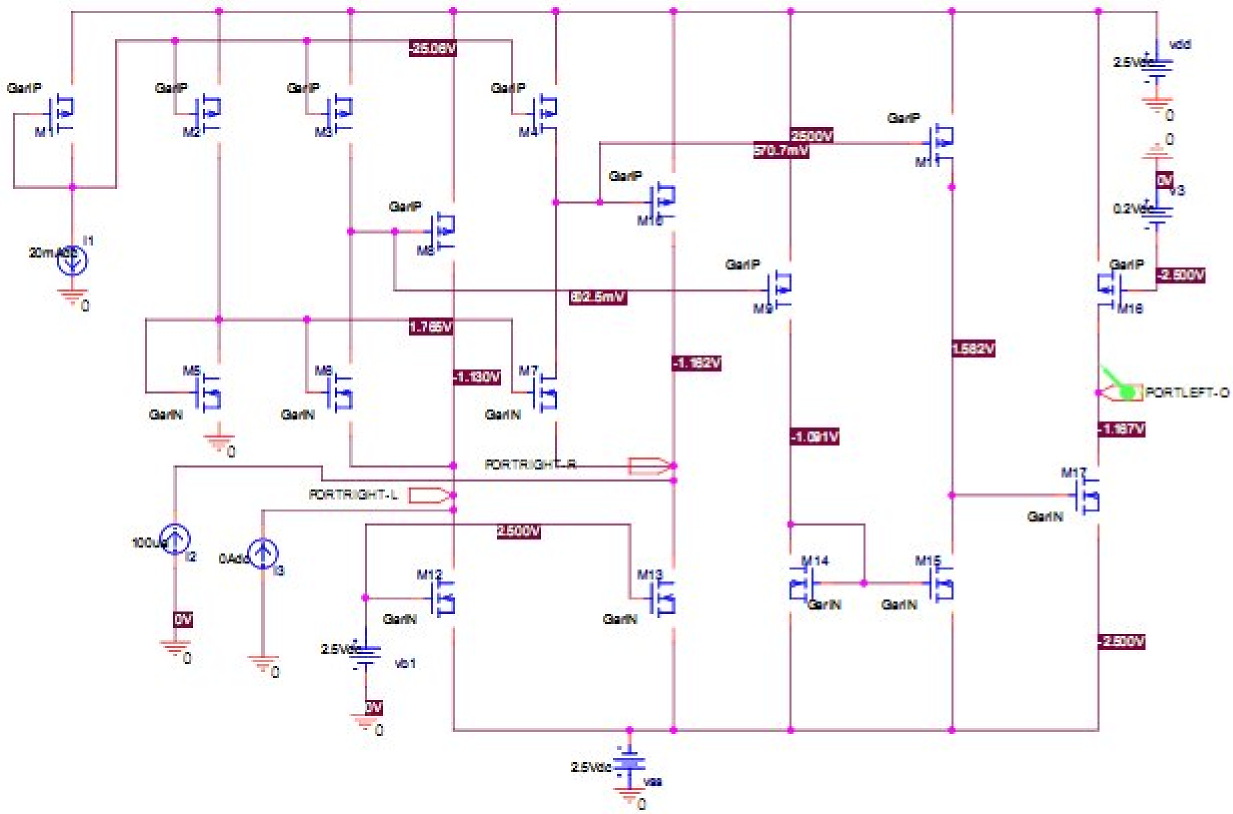

Fig.3.2 PSpice Schematic Of OTRA Circuit (Internal Block 1)

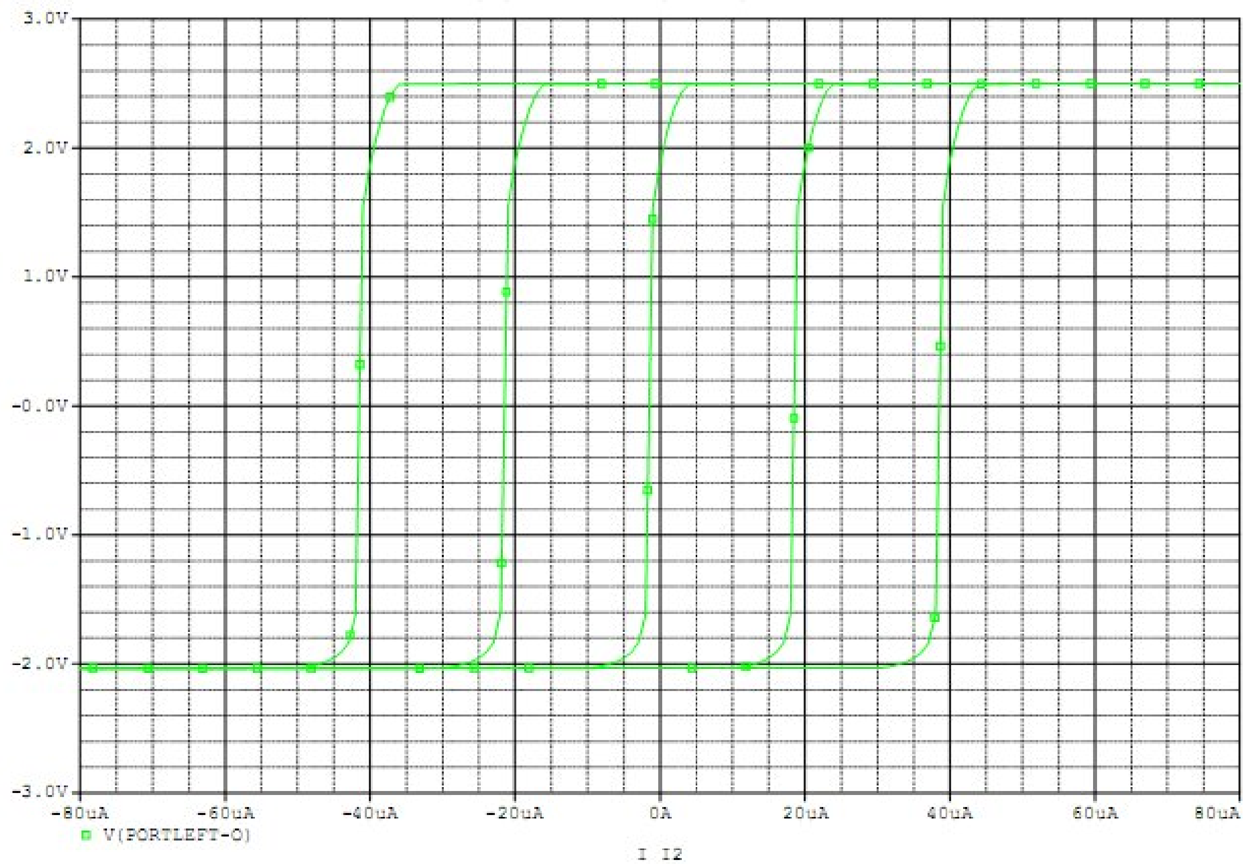

Fig.3.3 Simulated DC Response of the OTRA Circuit

3.3 OTRA CMOS REALIZATION-2

Another CMOS realization of OTRA as presented in [10] is shown in fig.3.4. It consists of a differential current controlled current source (DCCCS) followed by a voltage buffer.

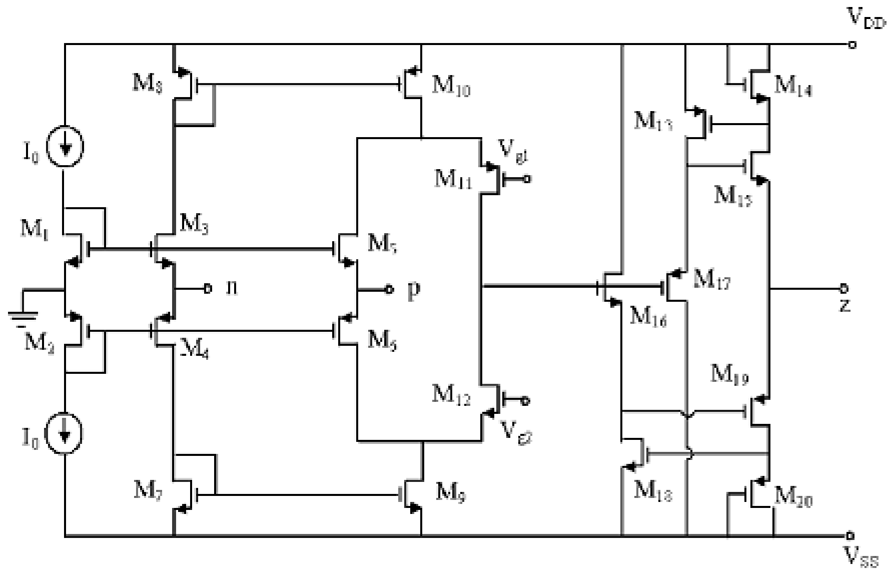

Fig.3.4 CMOS Realization of OTRA

In this circuit, the aspect ratio of the transistor M3 (M4) should be twice as large as those of M1 (M2) and M5 (M6). If the transistor M5 and M6 are removed, the implementation in fig. 3.4 becomes a CFOA, composed of a CMOS CCII followed by the voltage buffer. Since the OTRA can be considered as a collection of current and voltage-mode unity gain cell, this element is free from many parasitic and is expected to be suitable for high-frequency operation [6]. The PSpice schematic of OTRA is shown in fig.3.5 and its simulated DC response is shown in fig.3.6.

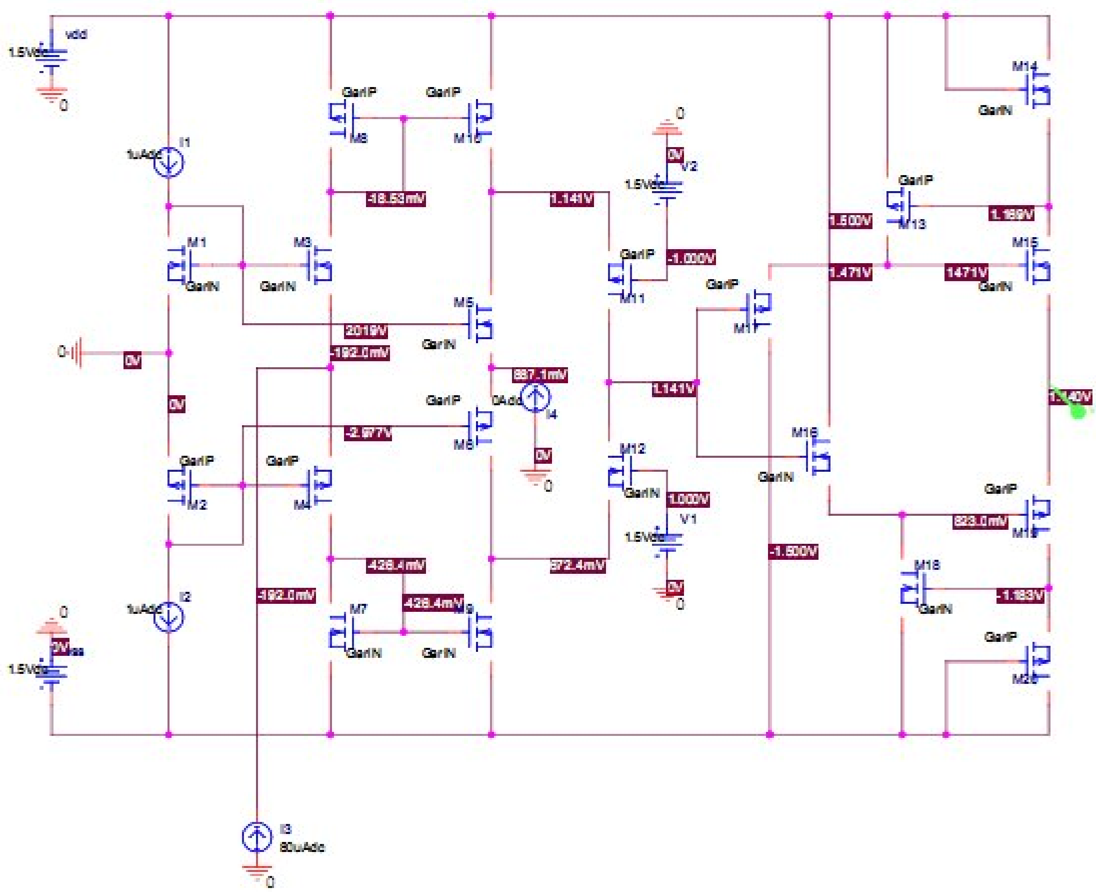

Fig.3.5 Pspice Schematic of CMOS realization of OTRA(Internal Block 2)

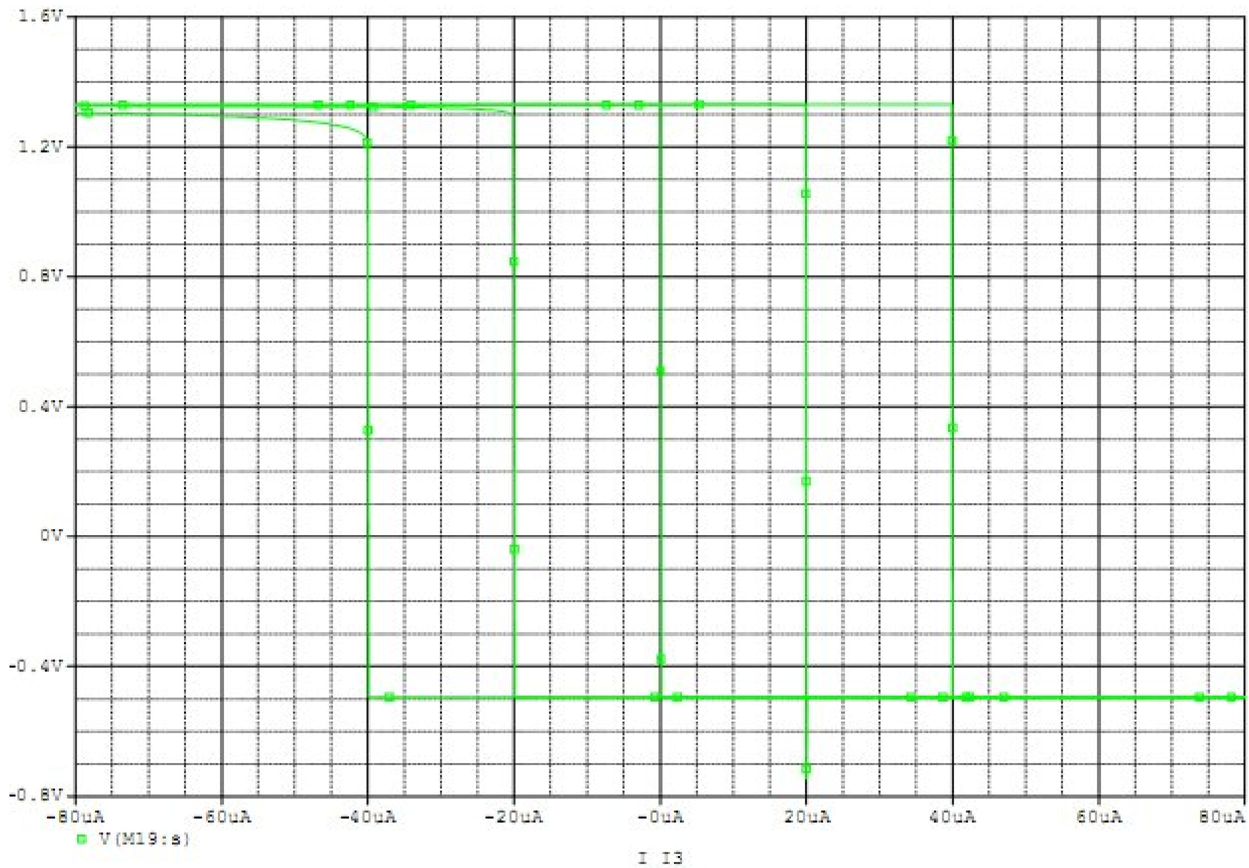

Fig.3.6 DC analysis of the realized OTRA

3.4 OTRA CMOS REALIZATION-3

Another CMOS realization of the low power wide band OTRA as presented in [9] is shown in circuit 3.7. It is based on the cascaded connection of the modified differential current conveyor (MDCC) and a common source amplifier.

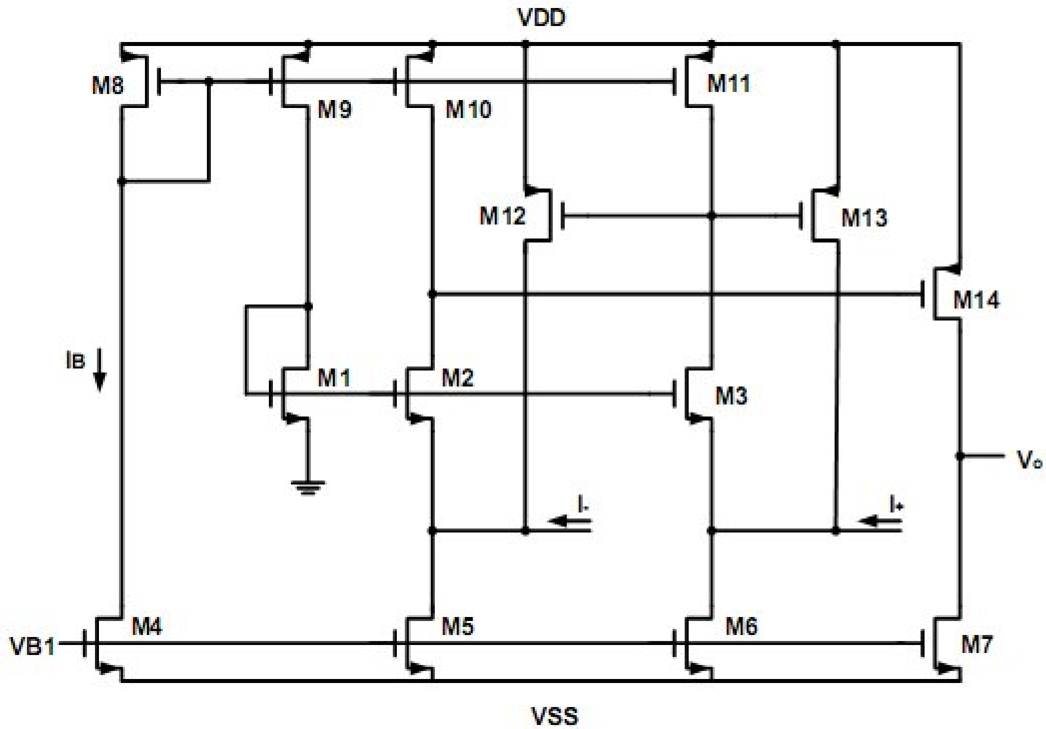

Fig.3.7 CMOS Realization of OTRA

Assuming that each of the groups of the transistors (M1-M3), (M5 and M6), (M8-M11) and (M12 and M13) are matched and assuming that all the transistors operate in the saturation region, the circuit operation can be explained as follows.

The current mirrors formed by (M8-M11) forces equal currents ( ) in the transistors M1, M2 and M3. This operation drives the gate to source voltages M1, M2 and M3 to equal and, consequently, forces the equal terminals to be virtually grounded.

The current mirrors formed by the transistor pair (M10 and M11) and (M12 and M13) provide the current differencing operation, whereas the common source amplifier (M14) achieves high gain. The modified OTRA has smaller number of current mirrors than the OTRA introduced in [8] which reduces the transistor mirror mismatch effect and also increases the frequency capabilities. Moreover, this OTRA uses smaller number of transistors which reduces the power dissipation. The PSpice schematic of the OTRA is shown in fig.3.8 which is further referred as internal block 2. The simulated DC response is shown in fig.3.9.

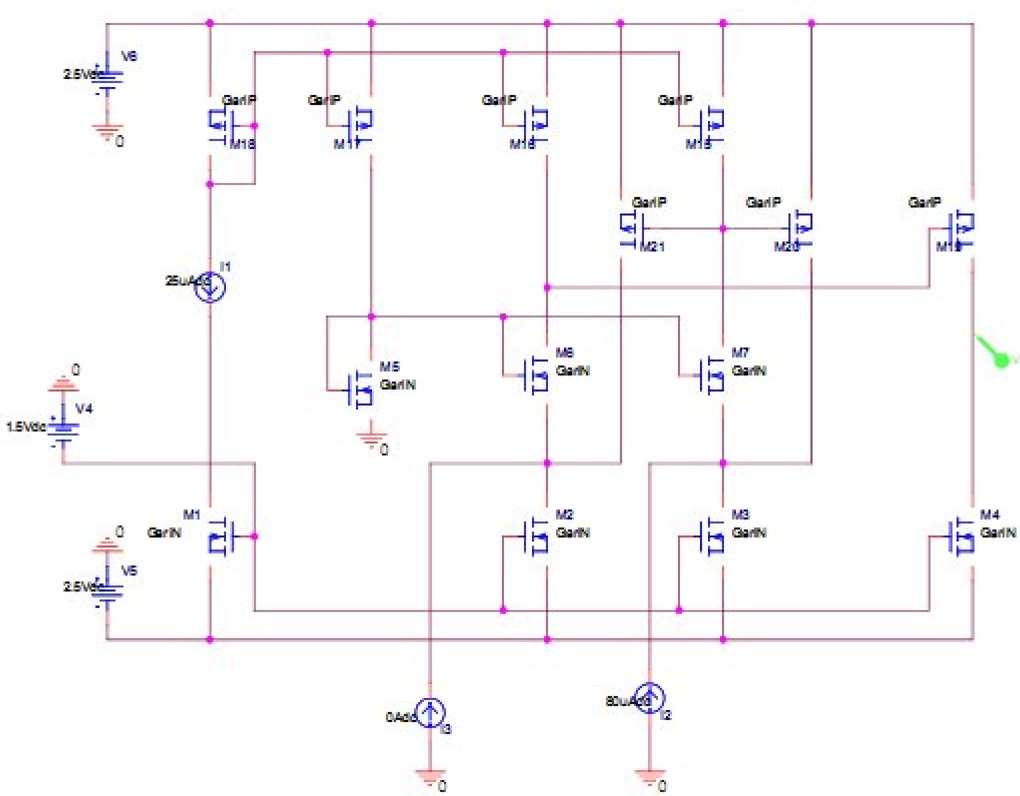

Fig.3.8 CMOS realization of OTRA (Internal Block 3)

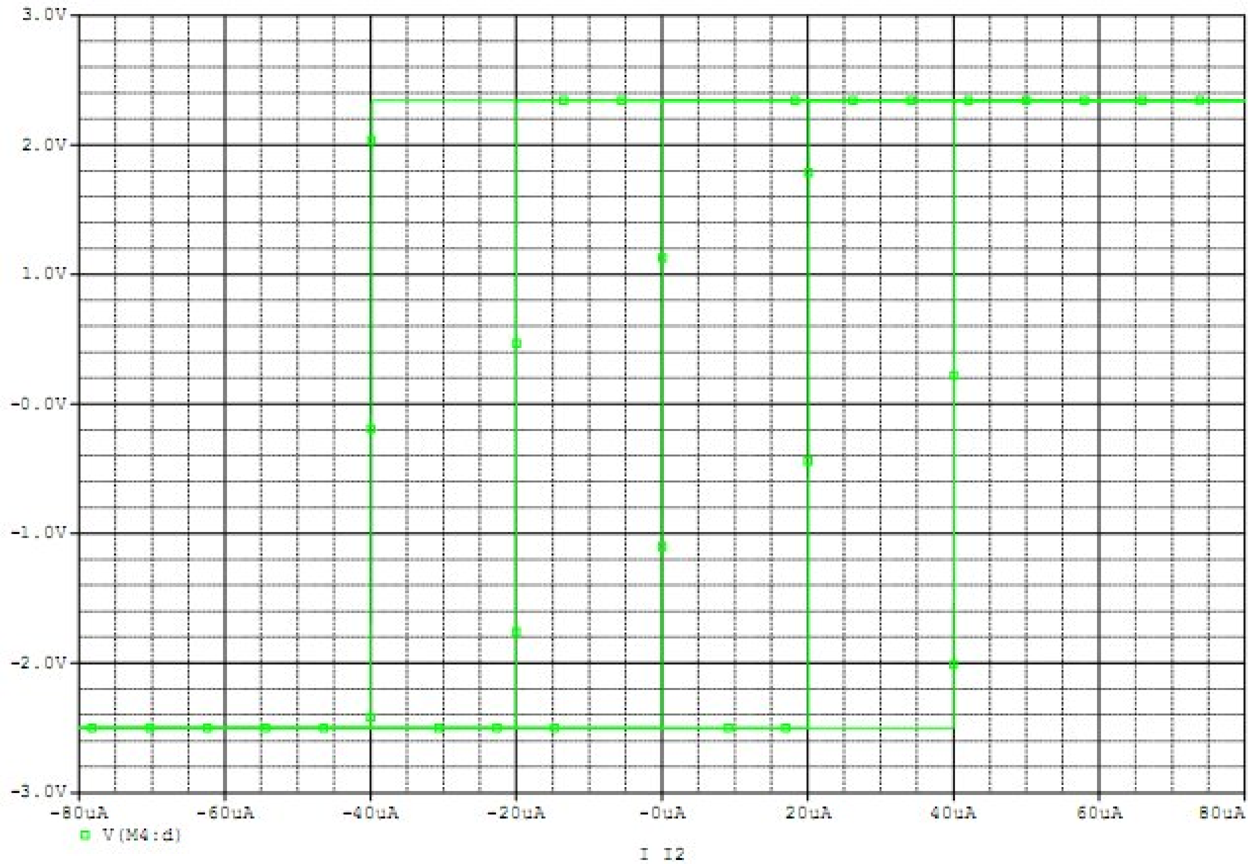

Fig.3.9 DC analysis of the realized OTRA

CHAPTER-4

SIGNAL PROCESSING APPLICATIONS

4.1 INTRODUCTION

In the literature various filter functions are realized using OTRA as the active element. Filters are very common building blocks of analog signal processing applications. Each signal requires some form of filtering before it could be applied to some use. Various active building blocks can be used to realize filter circuits such as operational amplifiers, current conveyor (CCII), current feedback op-amps (CFOA), operational transconductance amplifier (OTA), four-terminal floating nullor (FTFN) and operational transresistance amplifier (OTRA),etc. In this section various filter responses have been discussed and simulation results using PSpice are presented.

4.2 ALL PASS FILTER REALIZATION USING OTRA

All pass filters are most widely used in signal processing. They are generally used for introducing a frequency-dependent delay while keeping the amplitude of the input signal constant over the desired frequency range. In fig.4.1 an all pass filter configuration which is proposed in[10] is shown.

4.2.1 Filter Circuit 1

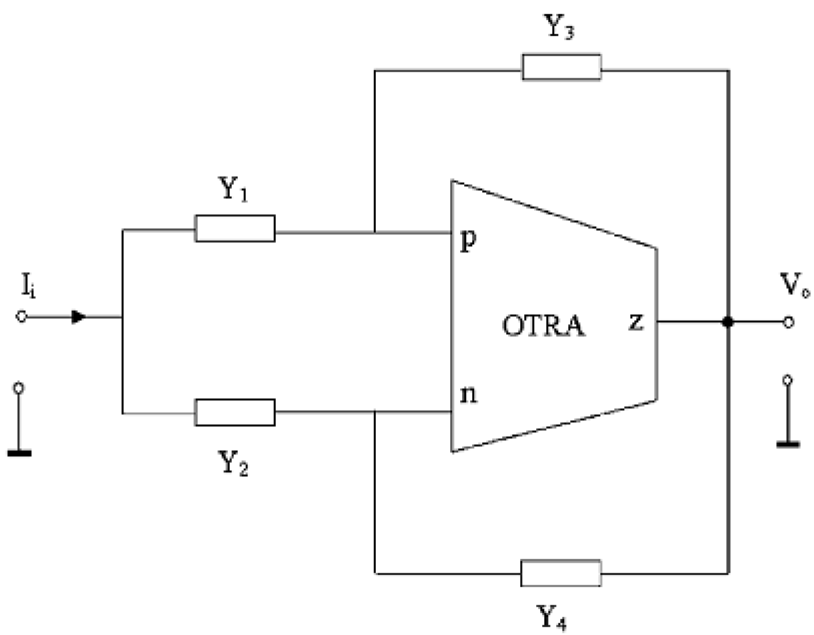

Fig 4.1 All Pass Filter Configuration

Analysis of the circuit yields the transfer function as follows:

$$\frac{V_o}{I_i} = \frac{1}{Y_4 - Y_3} \frac{Y_1 - Y_2}{Y_1 + Y_2}$$

Two types of all pass filter can be realized depending on the value of Y

Case I: For = , =1/ , = 1/ , = 0;

the transfer function becomes

$$\frac{V_o}{I_i} = -R_3 \frac{s - \frac{1}{C_1 R_2}}{s + \frac{1}{C_1 R_2}}$$

Case II: For = , =1/ , = 1/ , = 0;

The transfer function becomes

$$\frac{V_o}{I_i} = R_4 \frac{s - \frac{1}{C_1 R_2}}{s + \frac{1}{C_1 R_2}}$$

Thus both inverting and non inverting type first order all pass filter can be realized. Block 2 is used to realize the OTRA. The filter realization of the circuit using pspice is as shown in fig4.2.

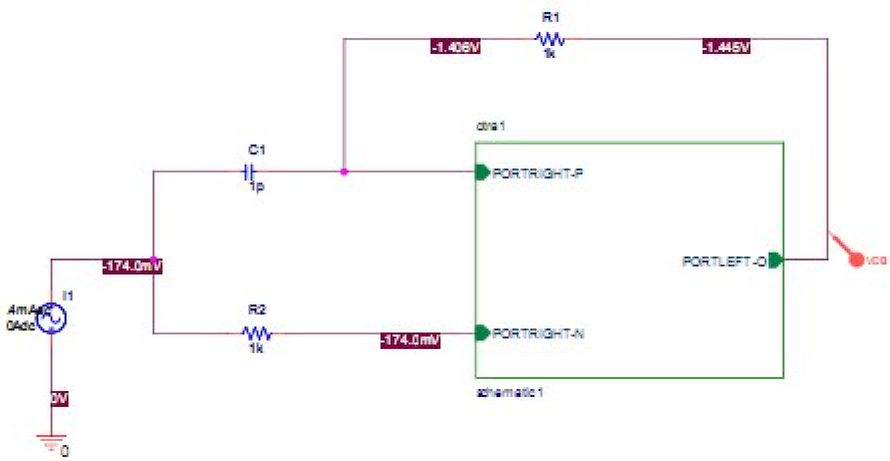

Fig.4.2 PSpice Schematic Of All Pass Filter

The circuit is simulated using 0.5um process parameters and the output is as shown in fig.4.3.

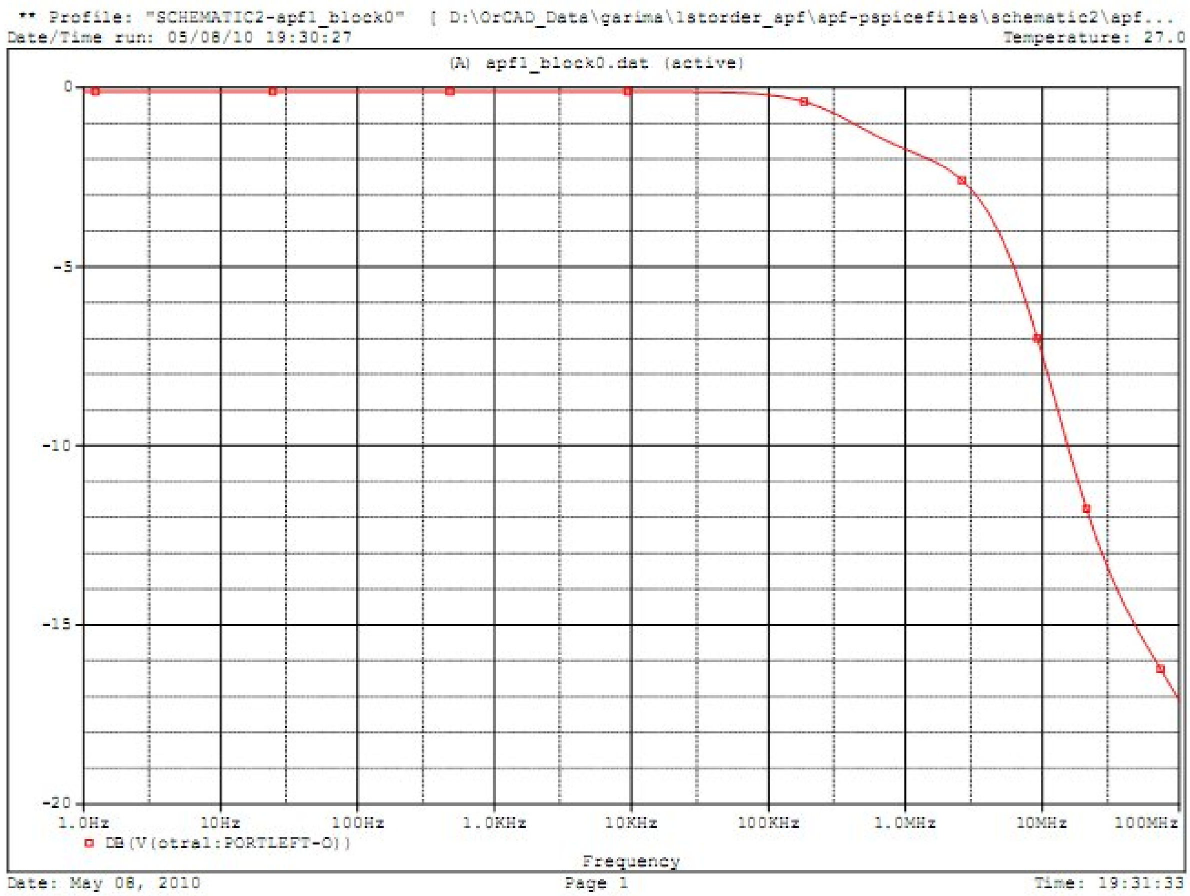

Fig.4.3 Simulated output of all pass filter

4.2.2 Filter Circuit II

The all pass filter circuit shown in fig.4.4 is presented in[11].

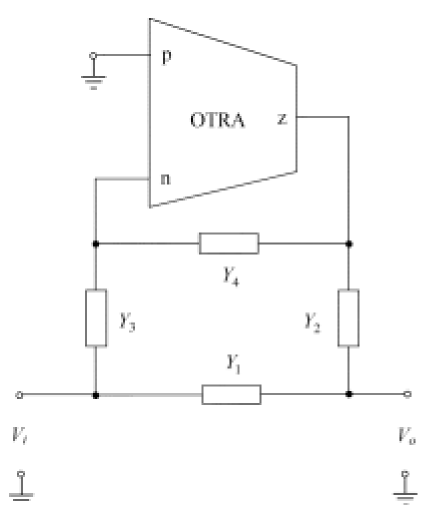

Fig.4.4 All-Pass Filter Configuration

The transfer function can be expressed as:

$$\frac{V_o}{V_i} = \frac{Y_1 - \frac{Y_3}{Y_4} Y_2}{Y_1 + Y_2}.$$

A first order all pass filter is realized using this circuit by choosing the passive components as

= , =1/ , = = 1/ ;

The transfer function then becomes:

$$\frac{V_o}{V_i} = \frac{s - \frac{1}{C_1 R_2}}{s + \frac{1}{C_1 R_2}}.$$

In this filter also block 2 is used for internal realization of OTRA. The pspice schematic of the above circuit is as shown in fig.4.5.

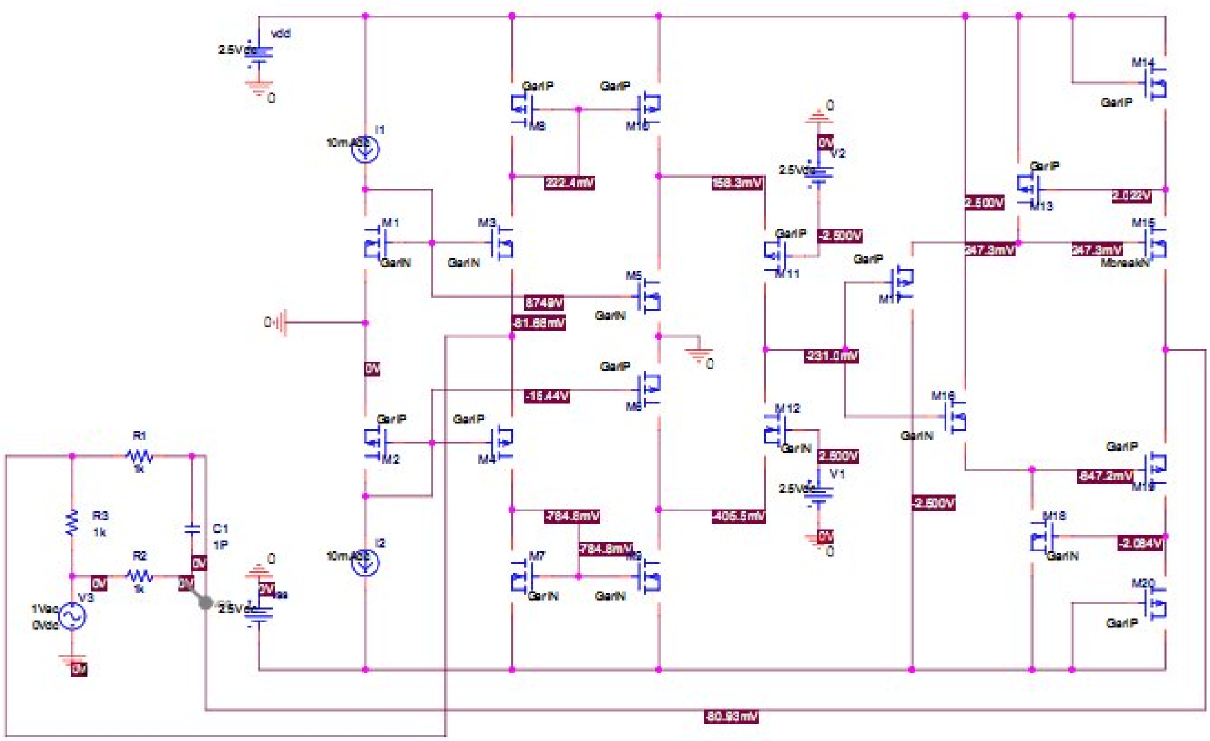

Fig.4.5 PSpice Schematic of All-Pass Filter

0.5um process parameters are used for circuit simulation and the value for passive components are chosen as R=1k and C=1pF. The simulated output showing the frequency response of the all pass filter is shown in fig.4.6.

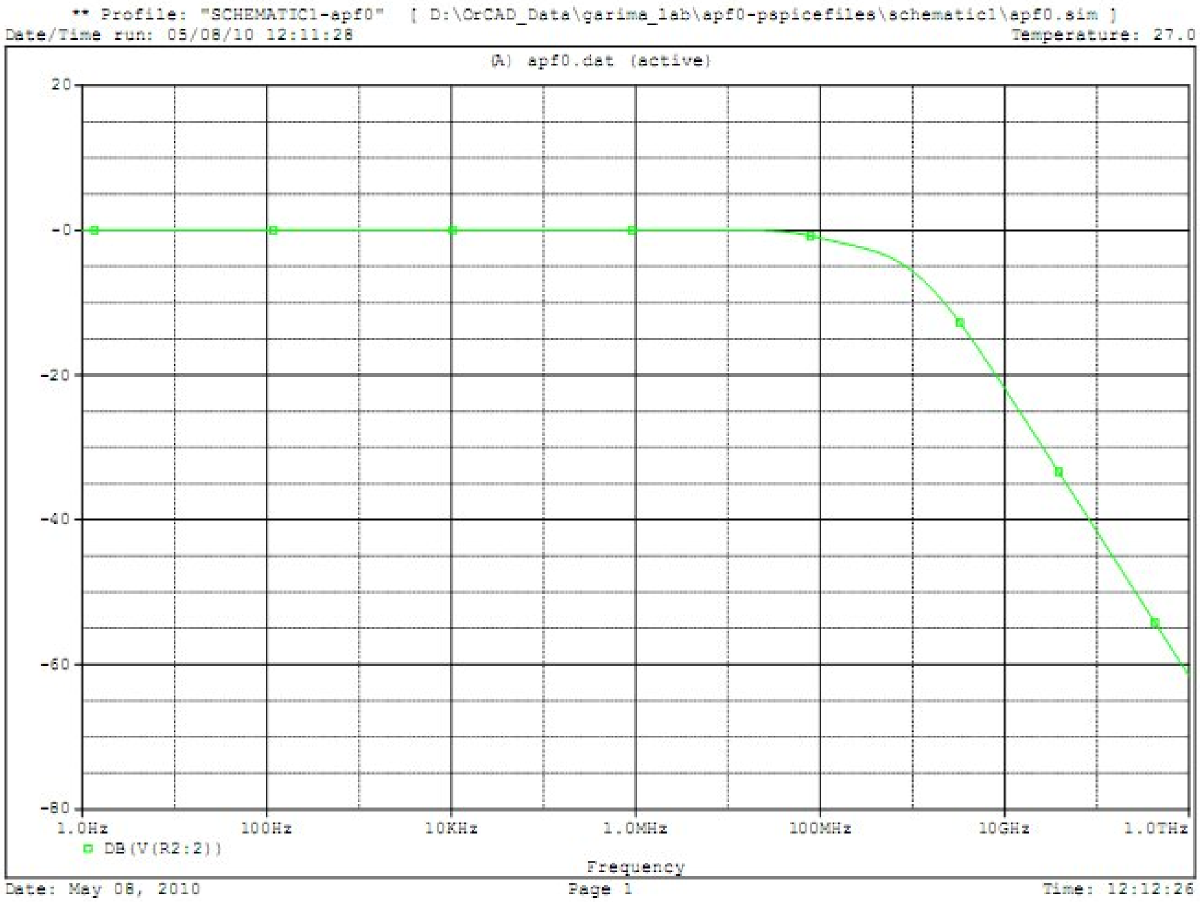

Fig.4.6 Simulated All Pass Response

The simulation shows 3db frequency as 400MHz.

4.2.3 Filter Circuit III

Reference [12] presents a voltage-mode filter configuration and is shown in fig4.7. The presented topology uses single OTRA and can realize first-order allpass, second-order allpass and notch filtering functions. These circuits are insensitive to parasitic capacitances and resistances due to internally grounded input terminals of OTRA. Low output impedance of the configuration enables the circuits to be cascaded without additional buffers.

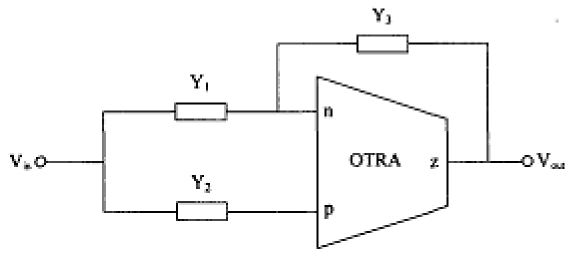

Fig4.7 Filter Configuration Using Single OTRA

The transfer function of the circuit shown in fig.4.7 is as below

$$T(s) = \frac{V_{out}}{V_{in}} = \frac{Y_2 - Y_1}{Y_3}$$

For the realization of a first order all pass filter the admittances are chosen as follows:

$$Y_1 = \frac{G}{2}, \quad Y_2 = \left(\frac{1}{G} + \frac{1}{sC}\right)^{-1}, \quad Y_3 = \frac{G}{2}$$

Or

= , = , = +

The transfer function becomes:

$$T_{1,2}(s) = \frac{sC - G}{sC + G}$$

The block 1 CMOS realization of the OTRA is used in this filter. The pspice schematic of the above filter is shown on fig.4.8. The simulated output showing the frequency response of the all pass filter is shown in fig.4.9.

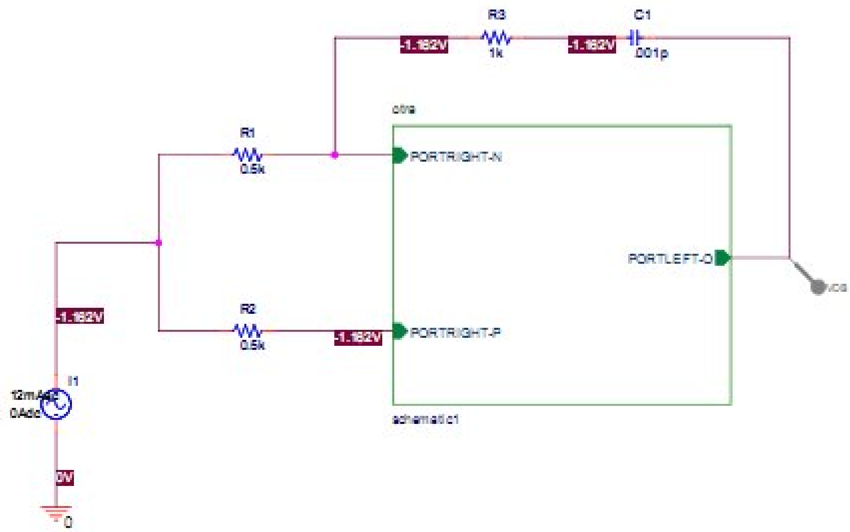

Fig.4.8 PSpice Schematic of the All Pass Filter

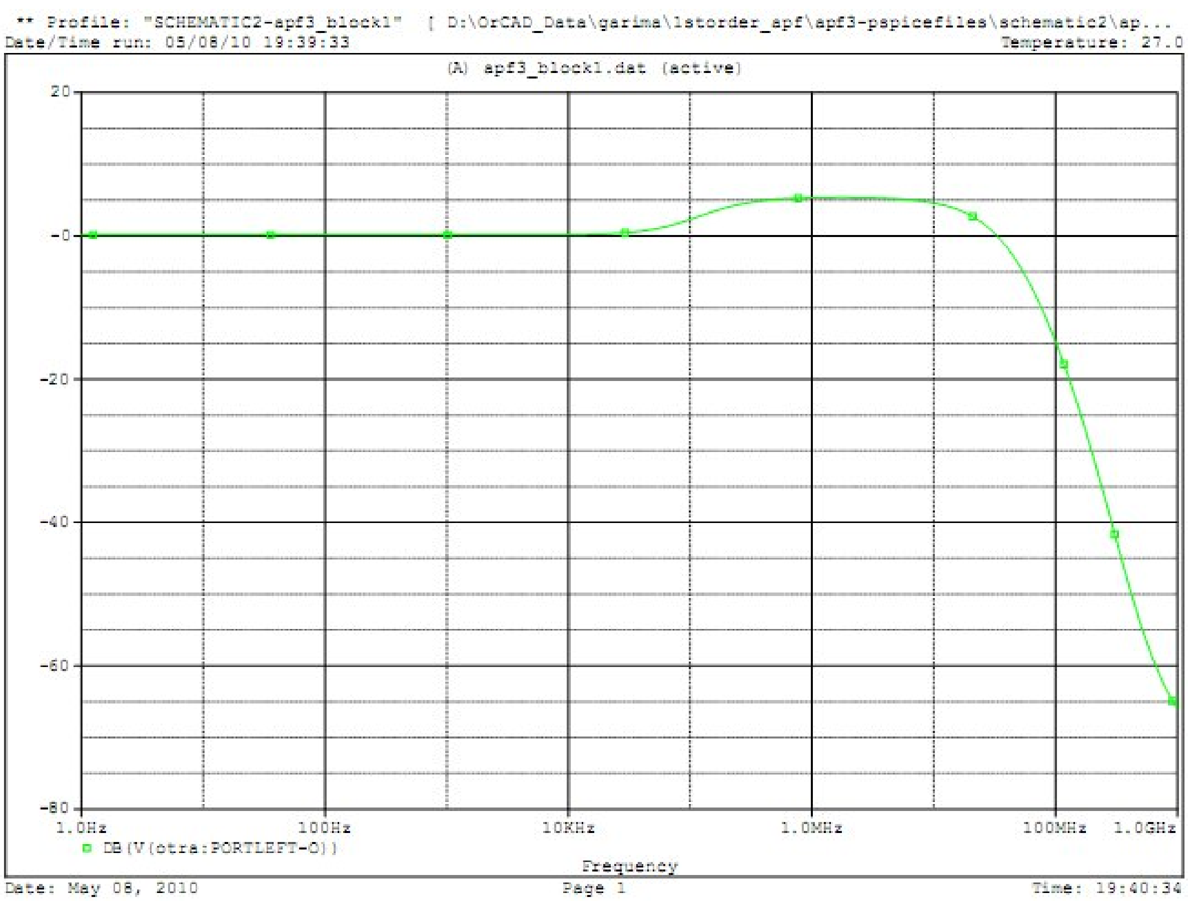

Fig.4.9 Simulated Output Response

4.3 NOTCH FILTER

The Notch filter passes all frequencies but stops a few selective ones. It is used when a very fine range of frequencies is to be rejected.

With the filter Realization given in fig.4.4 and selecting the admittances as below

= + 1/ , =1/ (+1/s), =1/ , =1/ , the transfer function becomes

$$\frac{V_o}{V_i}=\frac{s^2+s\left(\frac{1}{C_1R_2}+\frac{1}{C_2R_2}-\frac{1}{C_1R_3}\frac{R_4}{R_3}\right)+\frac{1}{C_1C_2R_1R_2}}{s^2+s\left(\frac{1}{C_1R_2}+\frac{1}{C_2R_2}+\frac{1}{C_1R_3}\right)+\frac{1}{C_1C_2R_1R_2}} \quad \text{.................................... (6.3)}$$

If (+) = and = a second-order notch filter can also be realized. The depth of the notch filter depends on the matching condition (+) =

The notch filter designed using pspice is shown in fig.4.10.

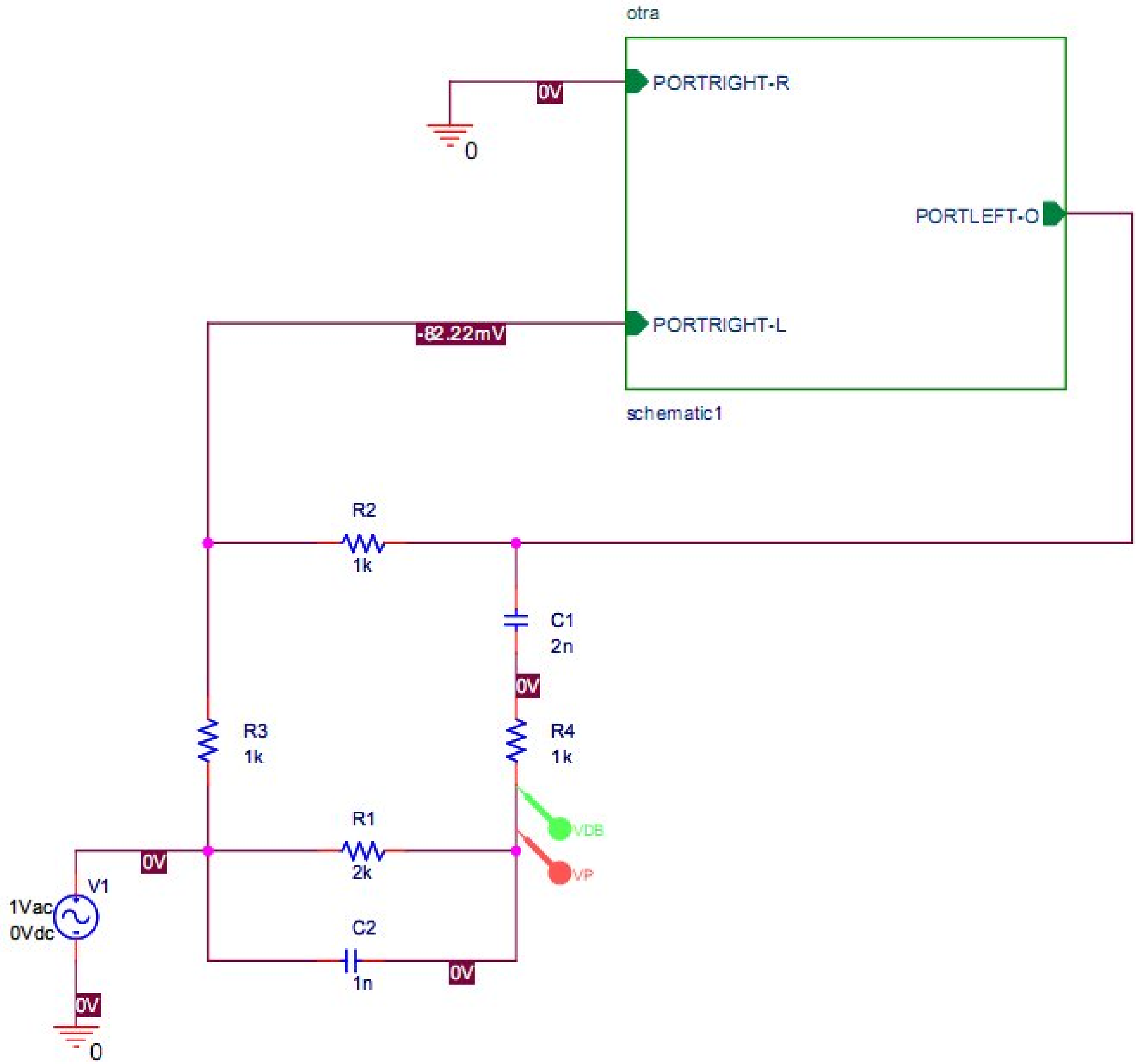

Fig.4.10 PSpice Schematic of Notch Filter

The simulated magnitude and phase response of the notch filter, using 0.5um CMOS parameters, is shown in fig.4.11 and fig.4.12.

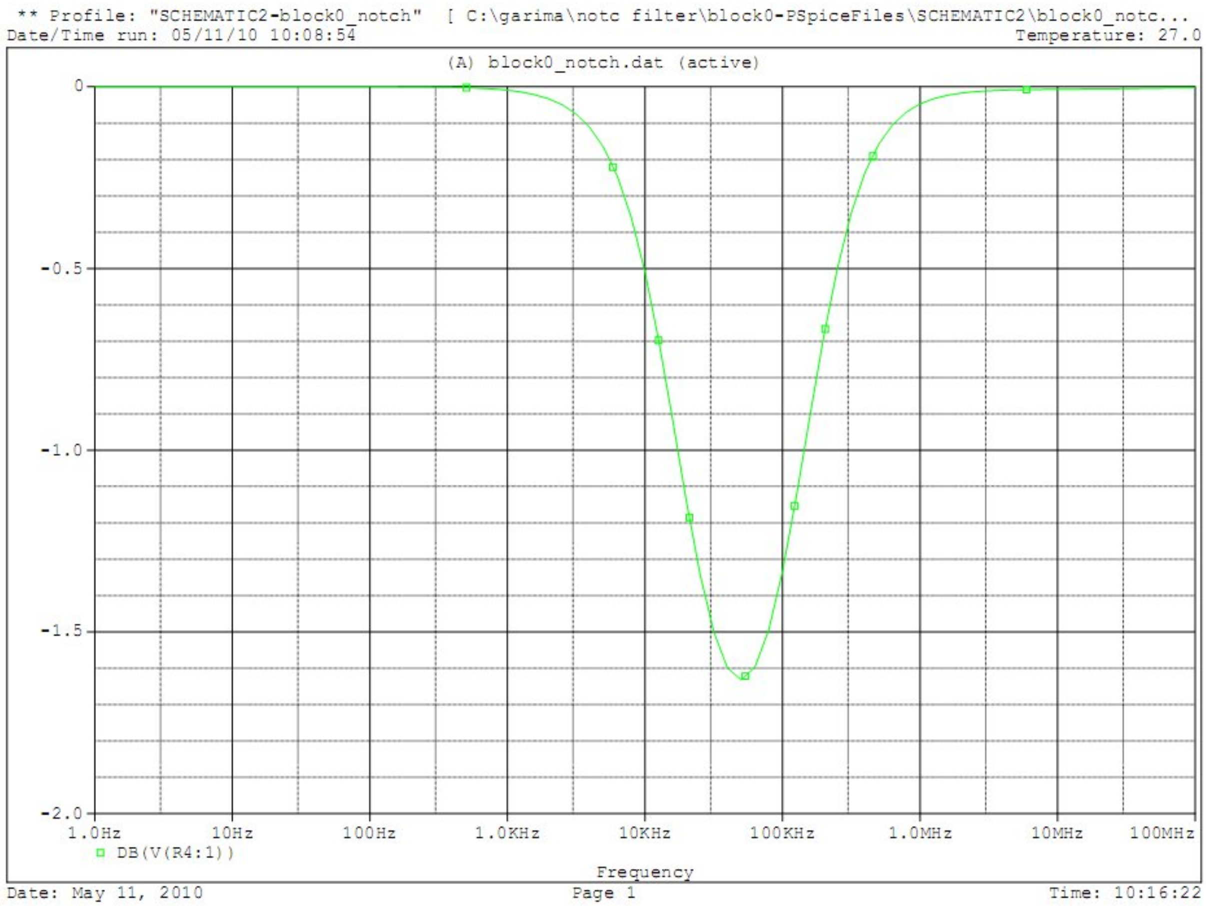

Fig.4.11 Magnitude Response of Notch Filter

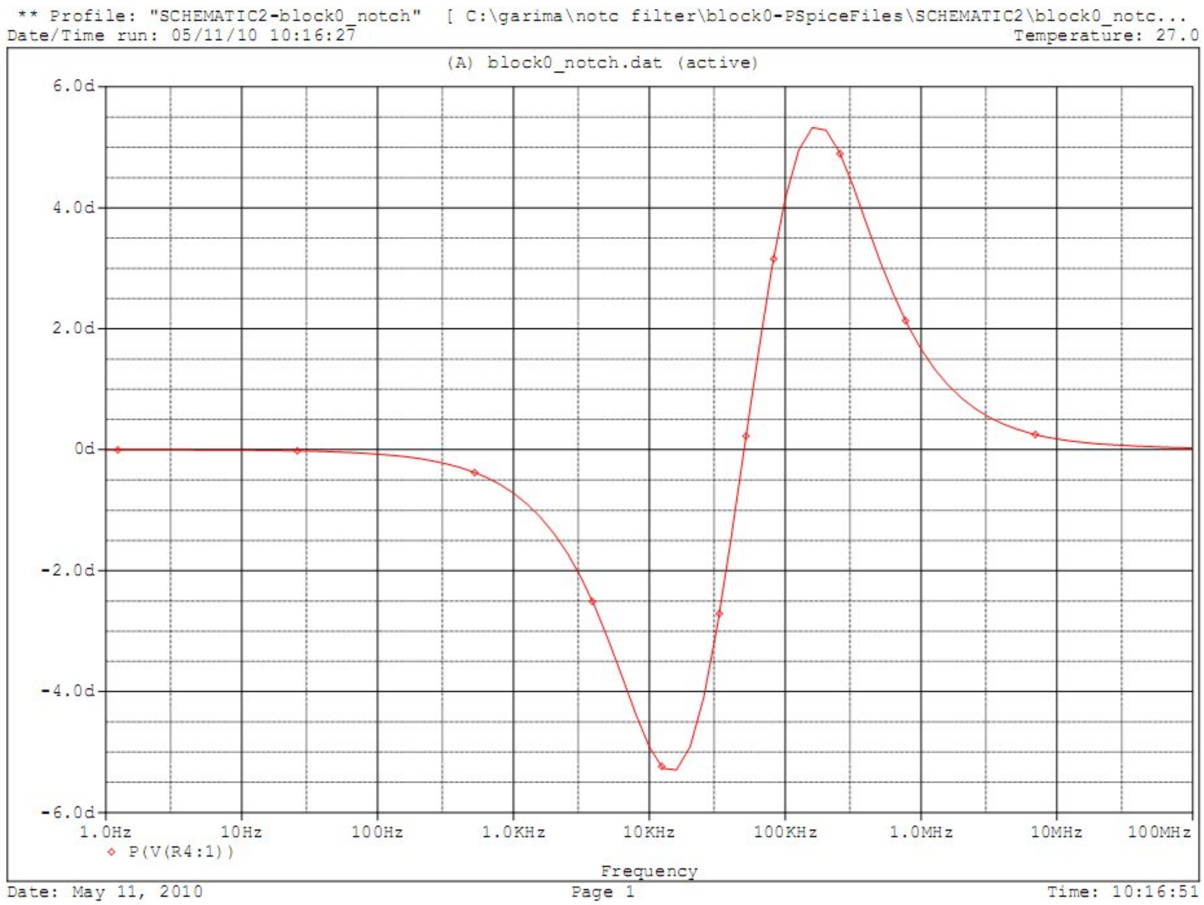

Fig.4.12 Phase response of notch filter

As can be seen from the simulation results, the notch filter selectivity attenuates frequencies around 50 KHz while it passes the rest without any attenuation. The phase response of the filter is also approaching an ideal form.

4.4 BIQUAD FILTER

Ref[14] presents a biquad configuration which can realize various filtering functions like all-pass, high-pass, band-pass, low-pass and notch. This filter configuration is shown in fig.4.13. Various filtering functions can be realized from this configuration by choosing the admittances as shown in table4.1. Also the realized Natural frequency, quality factor and gain of the filters obtained are given in table4.2.

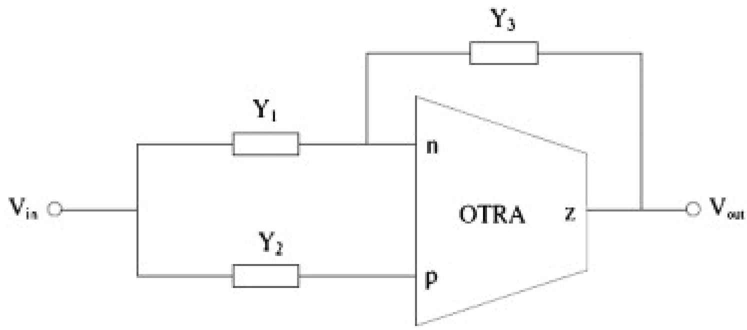

Fig.4.13 Single OTRA Filter Topology

Filter	$\boldsymbol{Y_1}$	$\boldsymbol{Y_2}$	$\boldsymbol{Y_3}$
Lowpass	1 $\frac{1}{\ } + \frac{1}{\ }$	G_2=G_1	G_3+sC_3
Highpass	1 $\frac{1}{\ } + \frac{1}{\ }$	sC_2=sC_1	G_3+sC_3
Bandpass	0	1 $\frac{1}{\ } + \frac{1}{\ }$	G_3+sC_3
Notch/allpass	1 $\frac{1}{\ } + \frac{1}{\ }$	G_2+sC_2	G_3+sC_3=G_2+sC_2

Table 4.1 Admittance values for realization of various filters

Filter	**Natural frequency**	**Quality factor**	**Gain**
Lowpass	$\sqrt{\frac{G_1G_3}{C_1C_3}}$	$\frac{\sqrt{G_1G_3C_1C_3}}{G_1C_3+G_3C_1}$	$\frac{G_1}{G_3}$
Highpass	$\sqrt{\frac{G_1G_3}{C_1C_3}}$	$\frac{\sqrt{G_1G_3C_1C_3}}{G_1C_3+G_3C_1}$	$\frac{C_1}{C_3}$
Bandpass	$\sqrt{\frac{G_2G_3}{C_2C_3}}$	$\frac{\sqrt{G_2G_3C_2C_3}}{G_2C_3+G_3C_2}$	$\frac{G_2C_2}{G_2C_3+G_3C_2}$
Notch/allpass	$\sqrt{\frac{G_1G_2}{C_1C_2}}$	$\frac{\sqrt{C_1C_2G_1G_2}}{C_1G_2+C_2G_1}$	1

Table4.2 Natural frequency, quality factor and gain of various filter responses

4.4.1 Low Pass Filter

A low pass filter passes all the frequencies below a certain frequency called cut-off frequency. The pspice schematic of the low pass filter is as shown in fig.4.14. The block 1 CMOS realization of the OTRA is used.

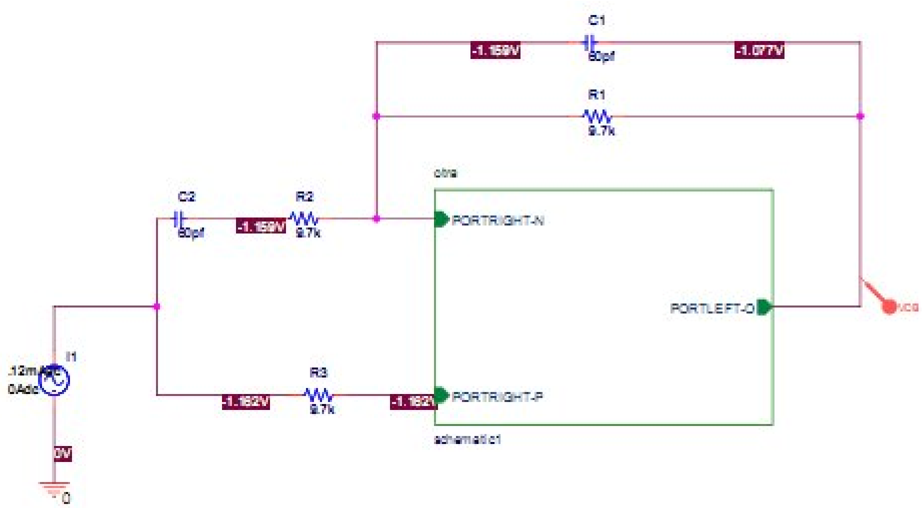

Fig.4.14 PSpice Schematic of low pass filter

The simulated magnitude response of the low pass filter is shown in fig.4.15.

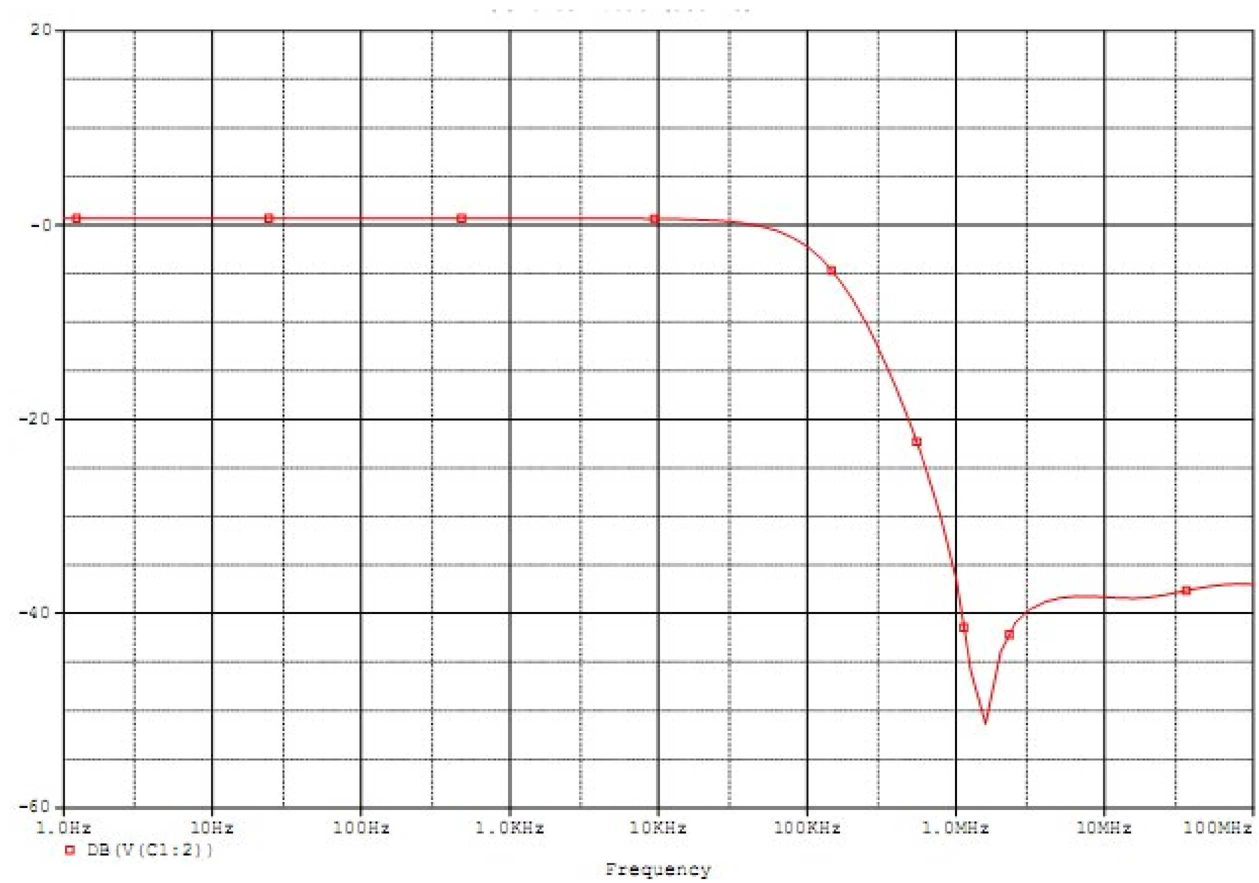

Fig.4.15 Magnitude response of low pass filter

4.4.2 High Pass Filter

A high pass filter passes all frequencies above a certain frequency. The pspice realization of high pass filter is shown in fig.4.16 and the simulated output is shown in fig.4.17.

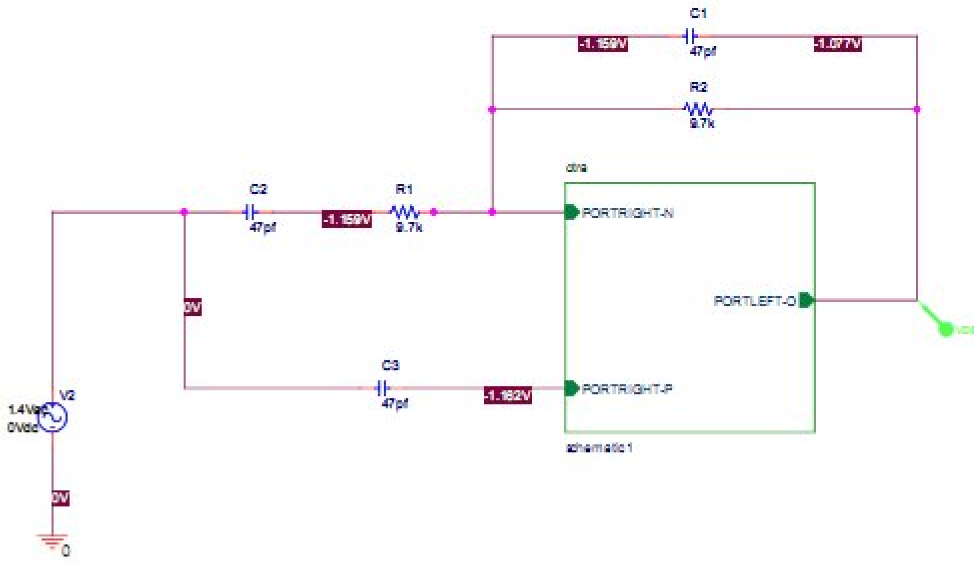

Fig.4.16 PSpice Schematic of High Pass filter

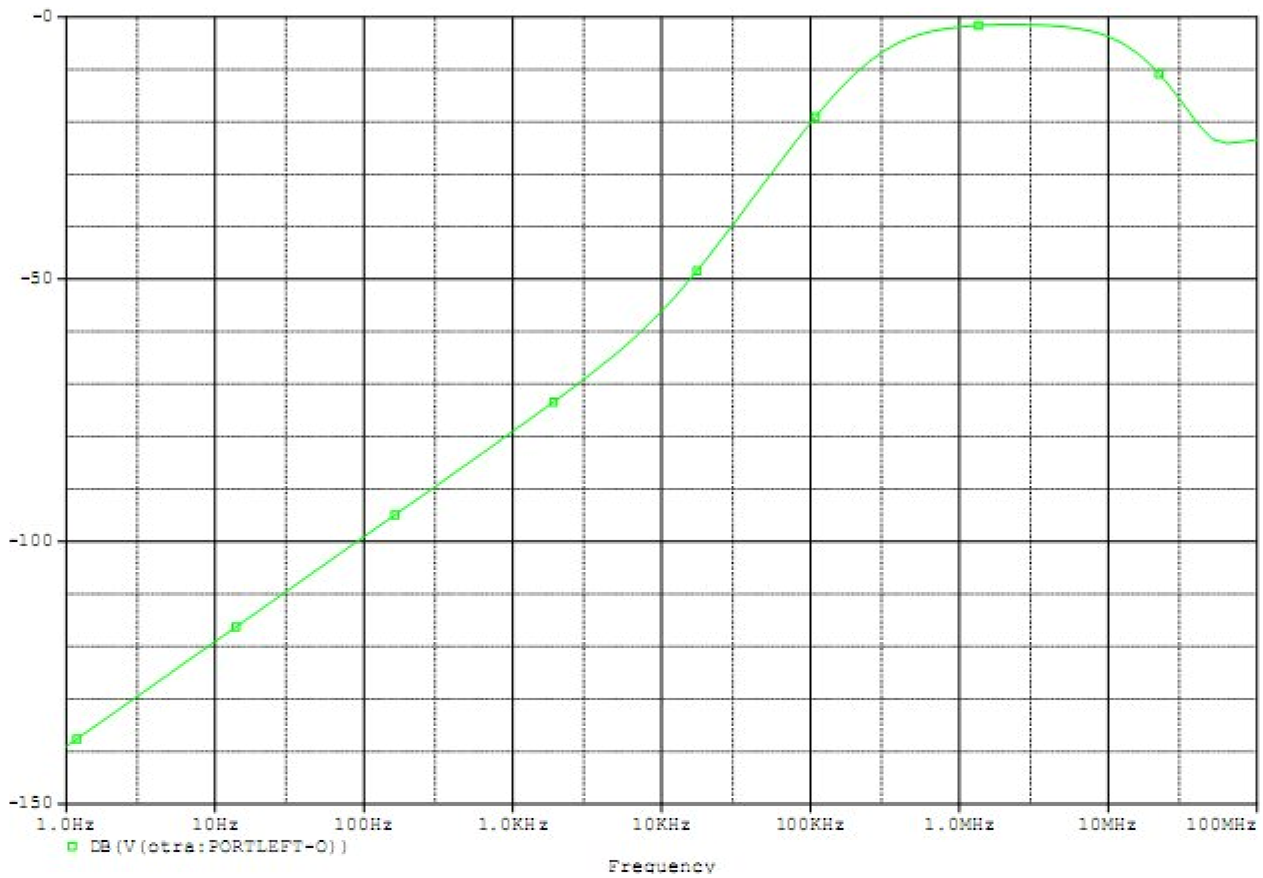

Fig.4.17 Magnitude response of high pass filter

4.4.3 Band Pass Filter

A band pass filter passes only a range of frequencies. It has a higher and lower cut-off frequency. The Pspice schematic of the band-pass filter designed from the biquad filter is shown in fig.4.18 and the magnitude response of the filter is shown in fig.4.19.

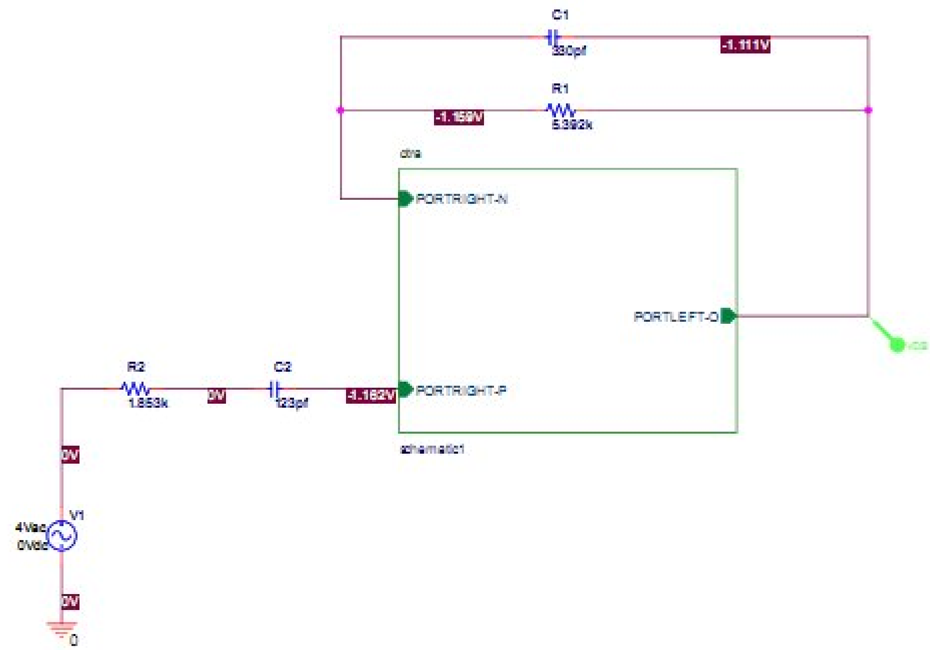

Fig.4.18 PSpice Schematic of band pass filter

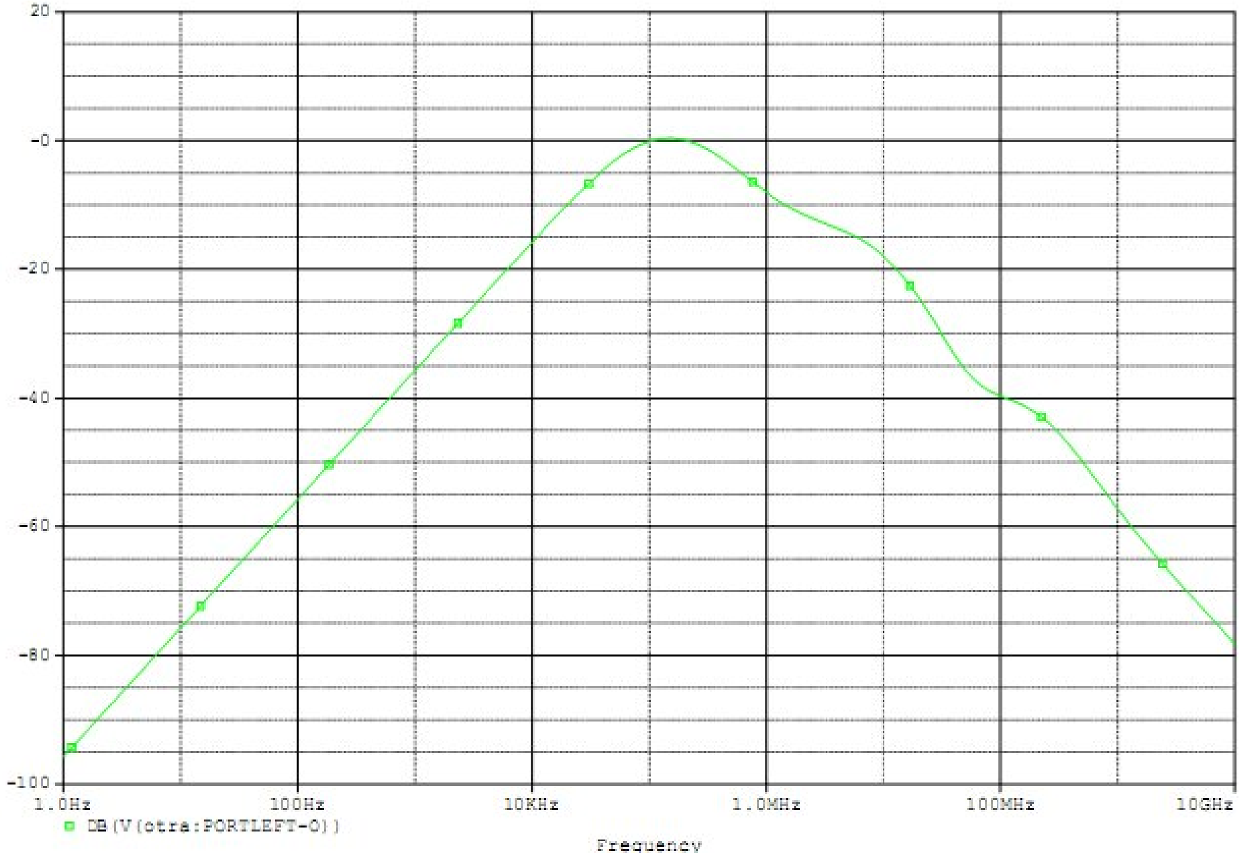

Fig.4.19 Magnitude response of all pass filter

From the response it can be seen that the upper and lower cut-off frequency of the band-pass filter is 51KHz and 440KHz respectively.

4.5 UNIVERSAL FILTER

A universal filter with minimum number of active elements as presented in [15] is shown in fig.4.20.

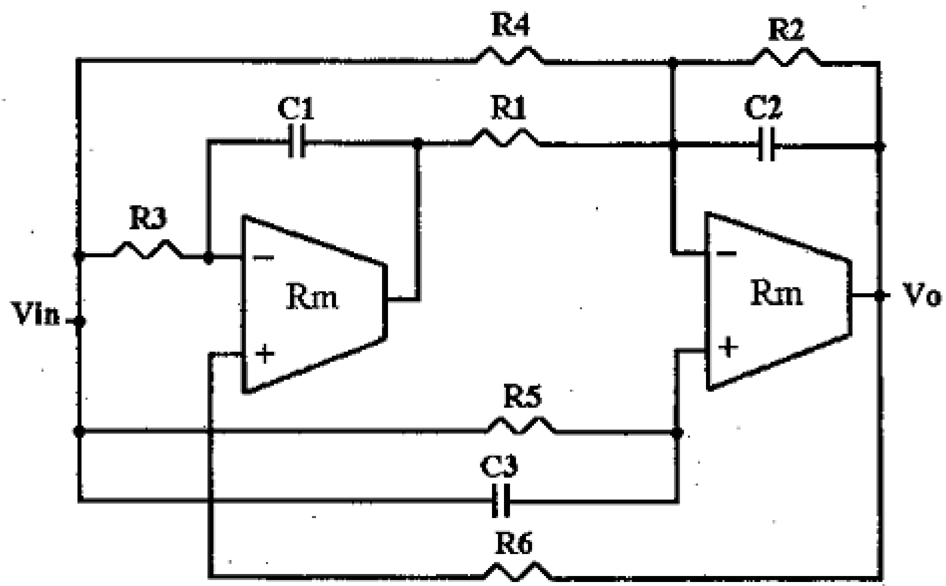

Fig.4.20 Universal Filter

The transfer function of the filter is given by

$$\frac{}{} = \frac{\frac{}{} \quad + \frac{1}{} - \frac{1}{} \quad + \frac{1}{}}{(\ )}$$

Where D(s) is given by

D(s) = $\quad + \frac{}{} \quad + \frac{}{}$

All the possible outputs for the universal filter are given in table 4.3.

Filter Response	Realizability Condition	Passive Elements
High Pass	$= \quad = \quad = \infty$	3C, 3R
Non Inverting Bandpass	$= 0, \quad = \quad = \infty$	2C, 4R
Inverting Bandpass	$= 0, \quad = \quad = \infty$	2C, 4R
Low Pass	$= 0, \quad = \quad = \infty$	2C, 4R
Notch	$= \quad = \infty$	3C, 4R
All Pass	$= \quad , \quad = \quad , \quad = \quad , \quad = \infty$	3C, 5R

Table 4.3 Realizability Conditions for Universal filter

4.5.1 Notch Filter

The pspice schematic of the notch filter designed using the universal filter is given in fig.4.21 and the simulated magnitude response is given in fig.4.22.

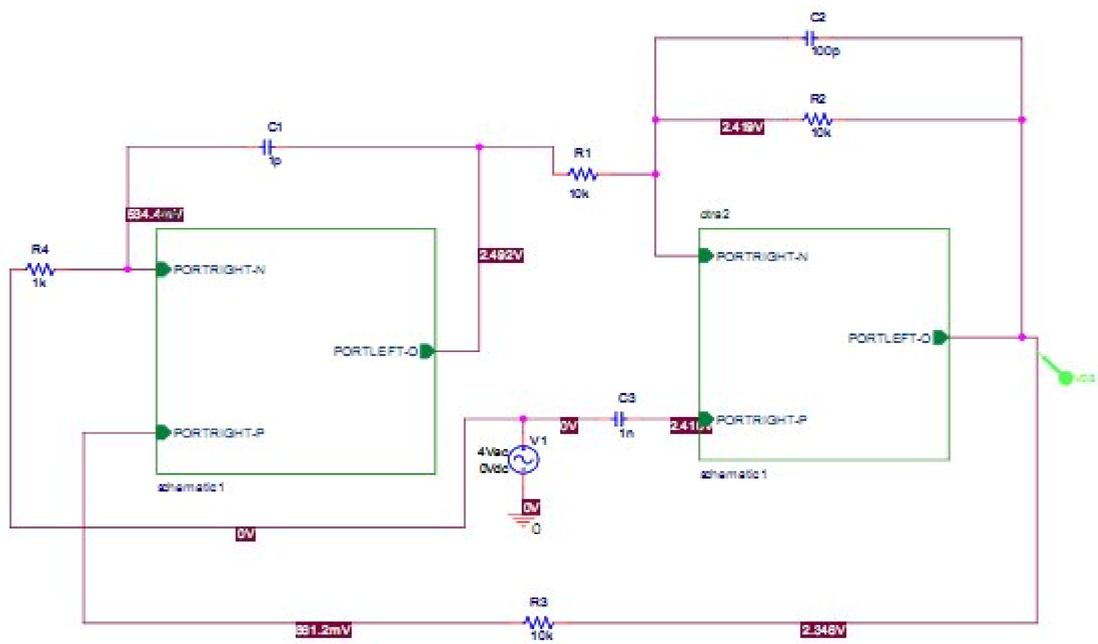

Fig.4.21 PSpice Schematic of Notch filter

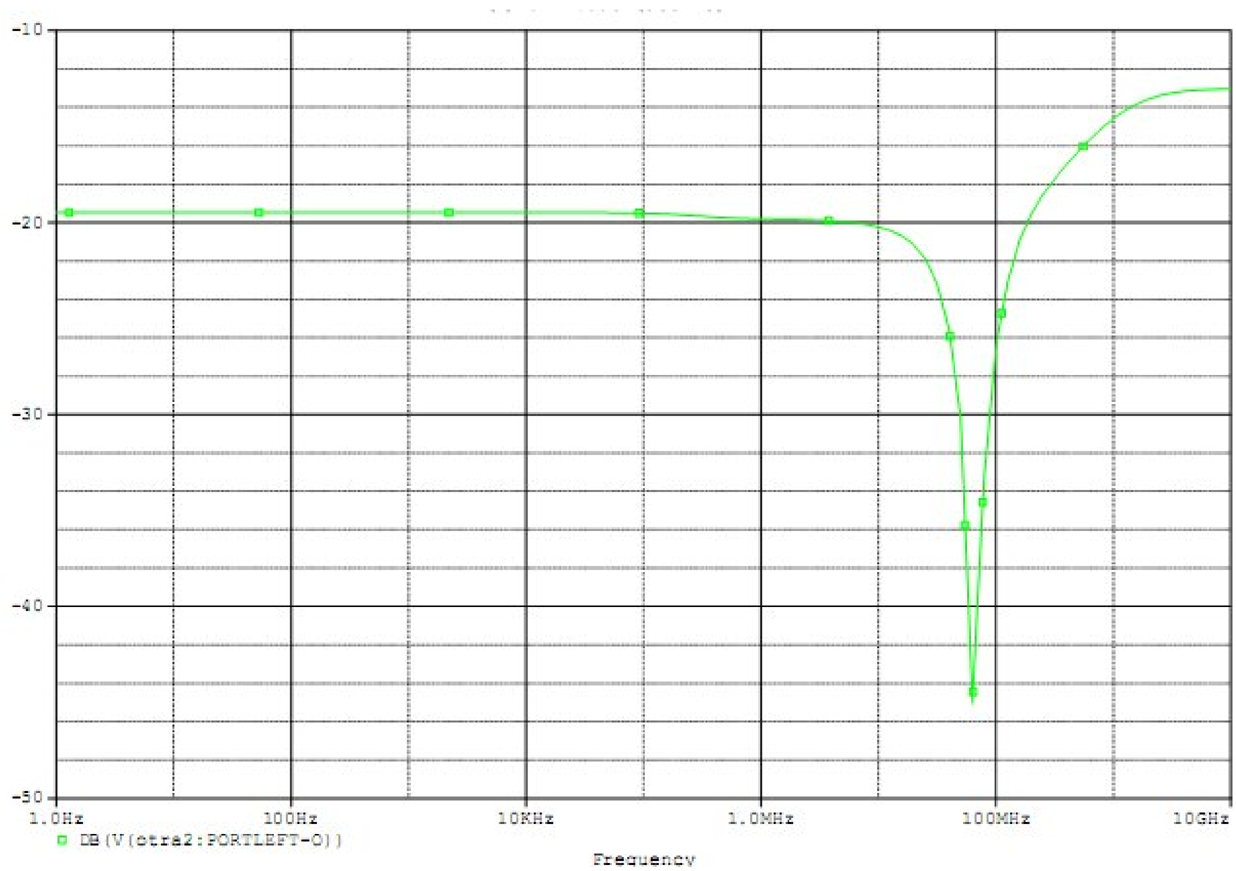

Fig.4.22 Magnitude response of Notch filter

4.5.2 Low-Pass Filter

The pspice schematic of the low pass filter is shown in fig.4.23 and the simulated output is shown in fig.4.24.

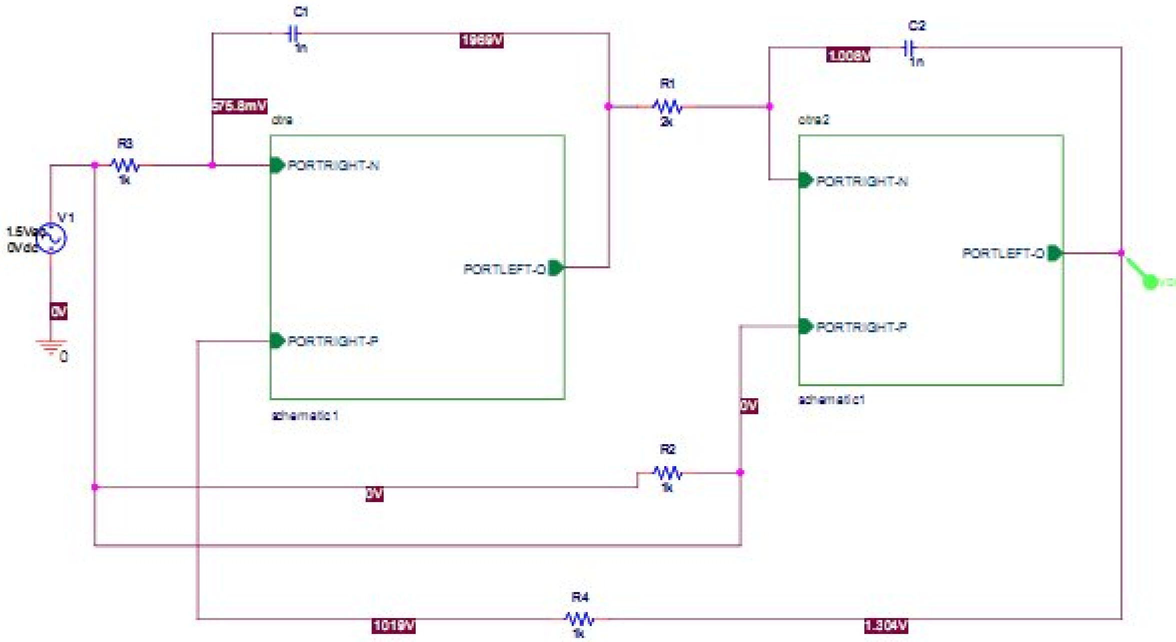

Fig.4.23 PSpice Schematic of Low-Pass filter

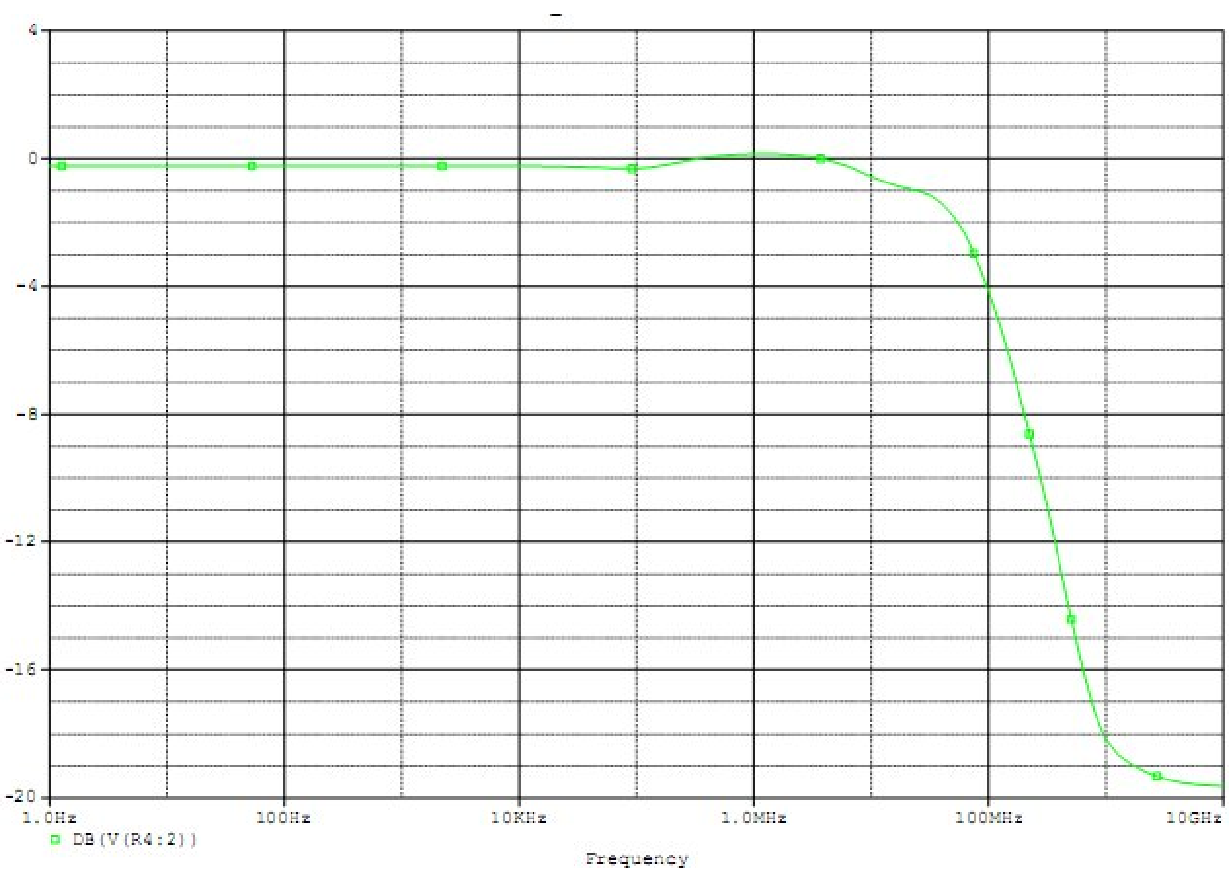

Fig.4.24 Magnitude response of Low-Pass filter

4.5.3 High Pass Filter

The pspice schematic of the high pass filter is shown in fig.4.25 and the simulated output is shown in fig.4.26.

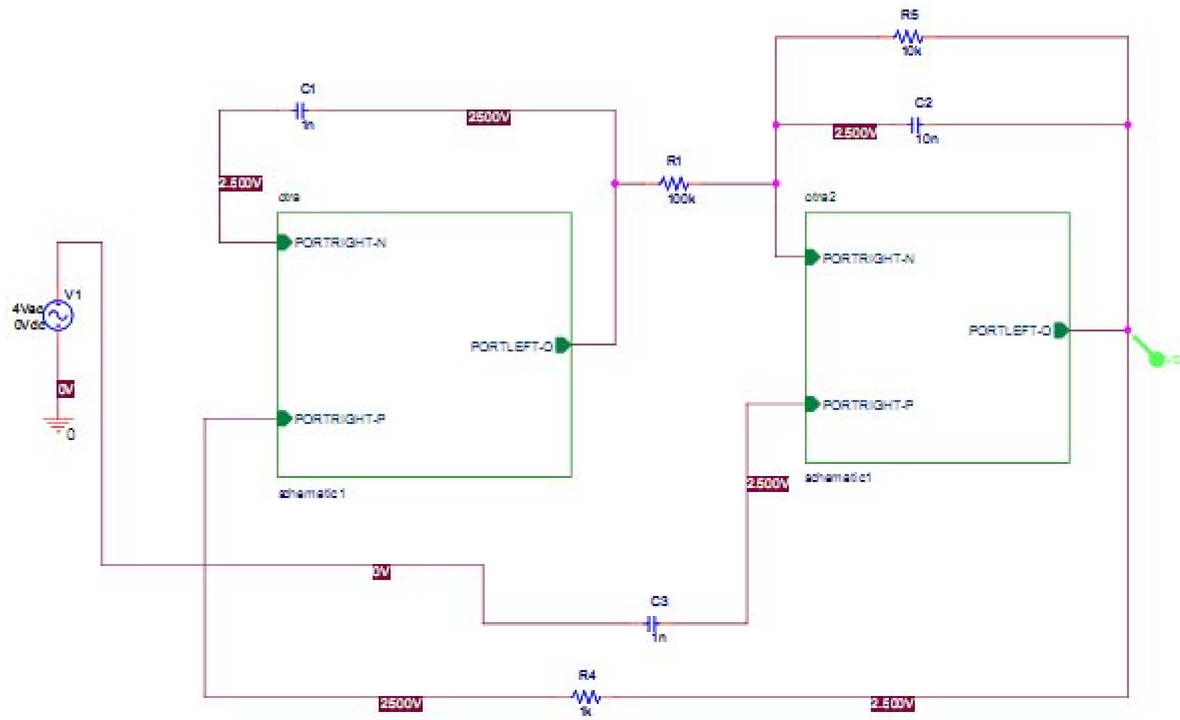

Fig.4.25 PSpice Schematic of High-Pass filter

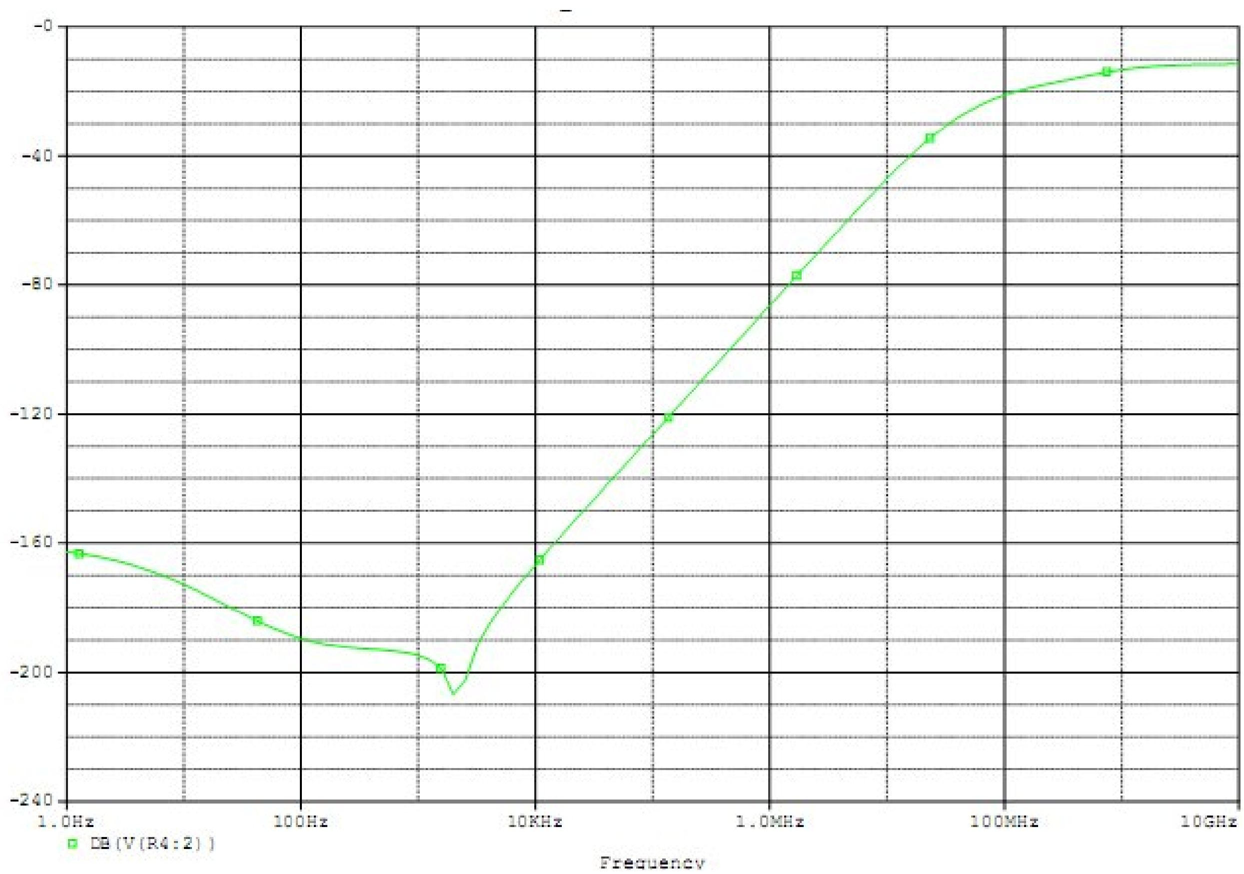

Fig.4.26 Magnitude response of High-Pass filter

CHAPTER 5

REALIZATION OF SINUSOIDAL SIGNAL GENERATORS

Sinusoidal oscillators have a wide range of application in telecommunications, control systems, signal processing & measurement systems. A variety of sinusoidal oscillators using the operational amplifier as the active element are available in the literature The finite gain-bandwidth product of the op-amp affects both the condition and frequency of oscillation. To overcome this problem, several oscillators have been introduced using the current conveyor as the active element [23] or the current feedback operational amplifier [24]. In this chapter several oscillator circuits available in the literature[16,17] are discussed and simulated**.**

5.1 R, C OSCILLATOR

5.1.1 Introduction

Fig.5.1 represents the generalized configuration of the single OTRA oscillator proposed in[17]. Assuming an ideal OTRA the characteristic equation is given by:

$$Z_2 + Z_5\left(1 + \frac{Z_2}{Z_3}\right) = Z_1 + Z_6\left(1 + \frac{Z_1}{Z_4}\right) \quad \text{.......} \quad (5.1)$$

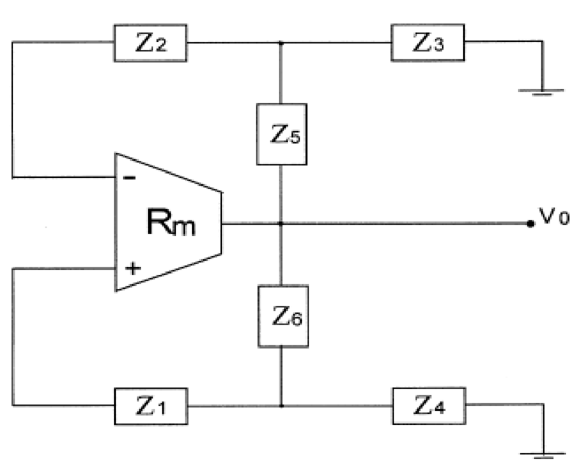

Fig.5.1 The single OTRA generalized circuit

Several oscillator circuits can be generated based on this generalized configuration.

5.1.2 Circuit description

A specific case of generalized circuit is shown in fig.5.2.

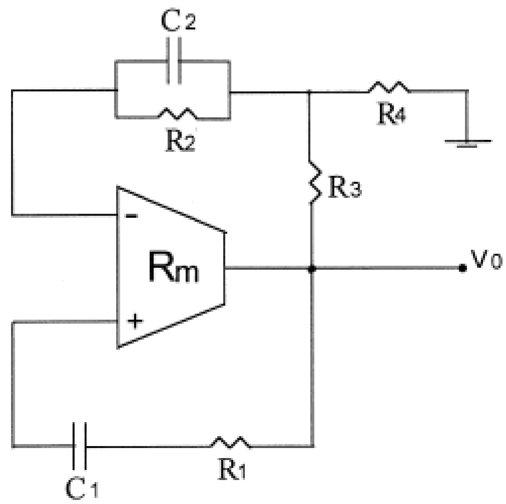

Fig.5.2 R,C oscillator

The condition and frequency of oscillation are given by eqn 5.2 and 5.3 respectively.

$$\frac{R_1}{R_2} + \frac{C_2}{C_1} = 1 + \frac{R_3}{R_2} + \frac{R_3}{R_4}. \quad \text{……………………………..(5.2)}$$

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_1 R_2\left(1 - \frac{R_3}{R_1}\right)}} \quad \text{…………………...…………(5.3)}$$

5.1.3 Simulation results:

OTRA is realized using commercially available ICs- AD844AN. The pspice schematic of the oscillator is shown in figure 5.3.

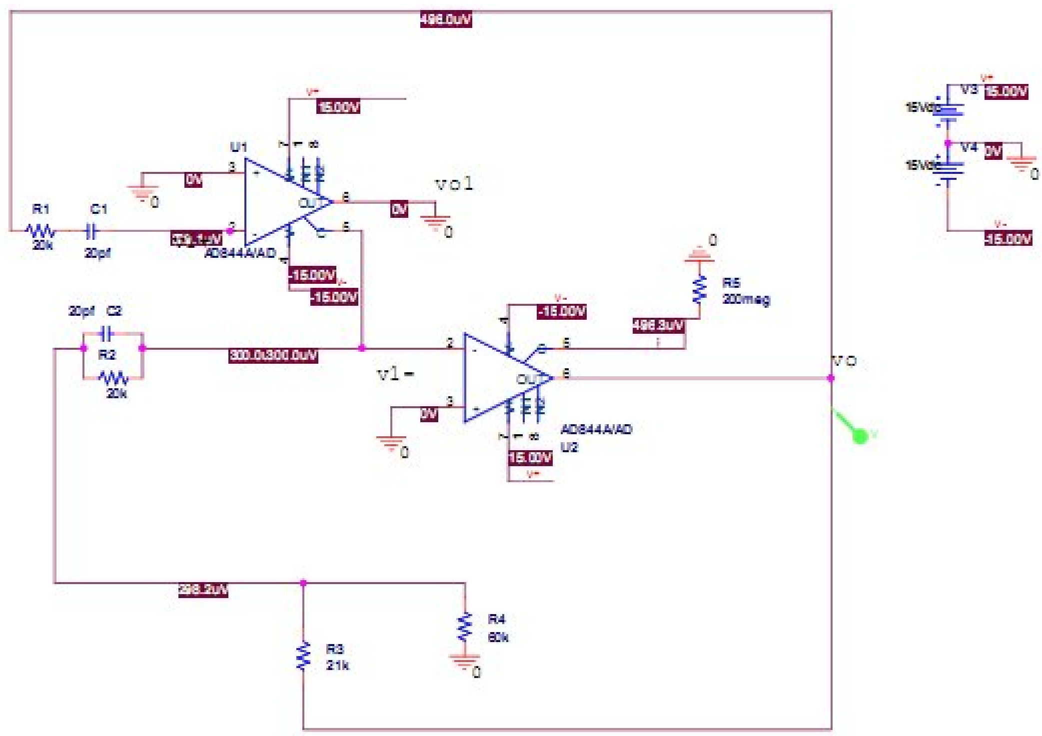

Fig. 5.3 Schematic circuit of R, C oscillator.

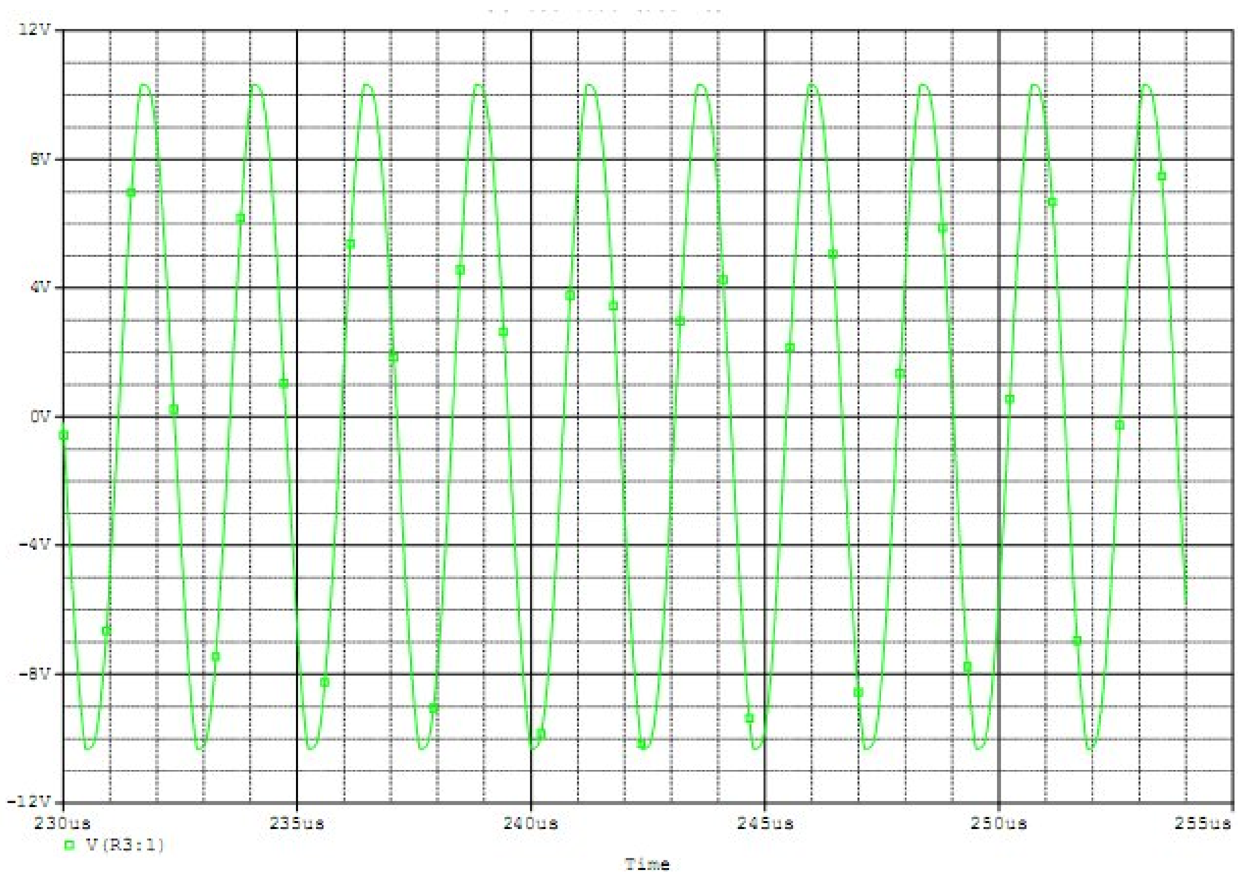

Fig. 5.4 Simulated Vo result of R, C oscillator

The PSPICE simulations were carried out for passive components values:

R_1 = 20KΩ, R_2 = 20KΩ, R_3 = 60 KΩ, R_4 = 15 KΩ, C_1 = 20pf and C_2 = 20pf

The frequency of oscillations, fo = 425.53KHz

5.2 NON CANONIC OSCILLATOR

5.2.1 Introduction

To make it possible to achieve independent control on the frequency of oscillation using a single OTRA, a noncanonic oscillator is used. The fig.5.5 represents a noncanonic single OTRA oscillator [17].

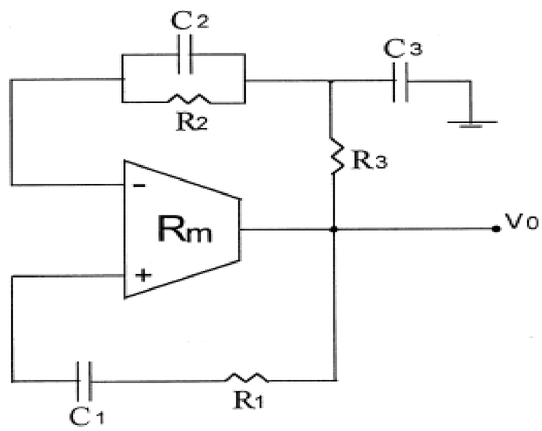

Fig. 5.5 A Non Canonic Oscillator

5.2.2 Circuit description

The frequency of oscillation is given by:

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_1 R_2\left[1 - \frac{R_3}{R_1}\left(1 + \frac{C_3}{C_2}\right)\right]}}.$$

…………………(5.4)

ω_0 can be independently controlled by varying C_3 without affecting the condition of oscillation which is given by:

$$\frac{R_1}{R_2} + \frac{C_2}{C_1} = 1 + \frac{R_3}{R_2}.$$

……………… (5.5)

5.2.3 Simulation results:

PSPICE simulation was performed with OTRA circuit constructed from AD844AN. The pspice schematic of the circuit is shown in fig.5.6 and the simulated output is shown in fig.5.7.

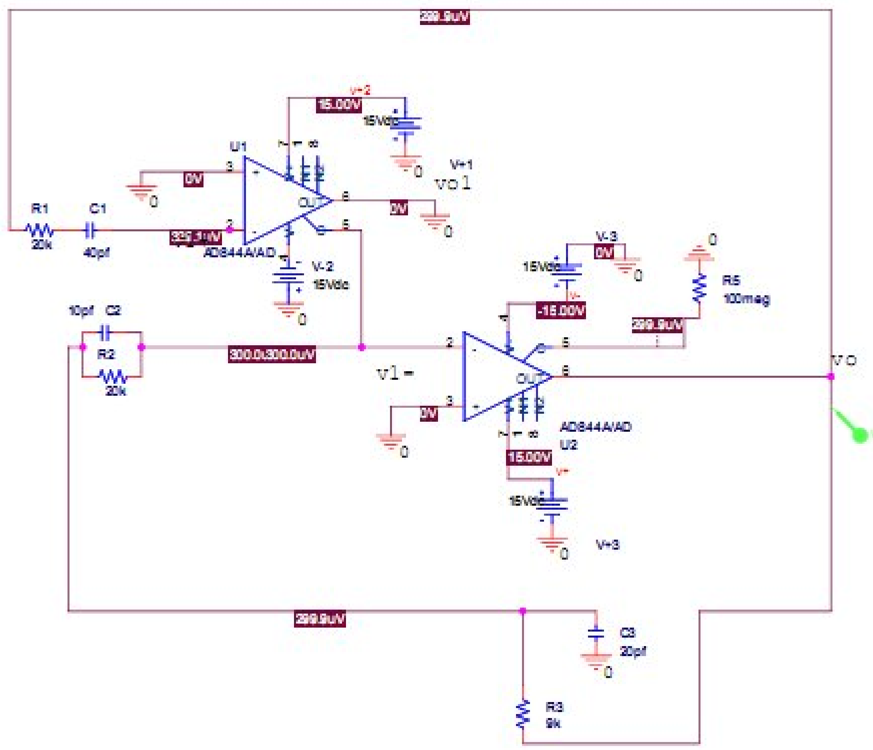

Fig. 5.6 Internal structure of a noncanonic oscillator

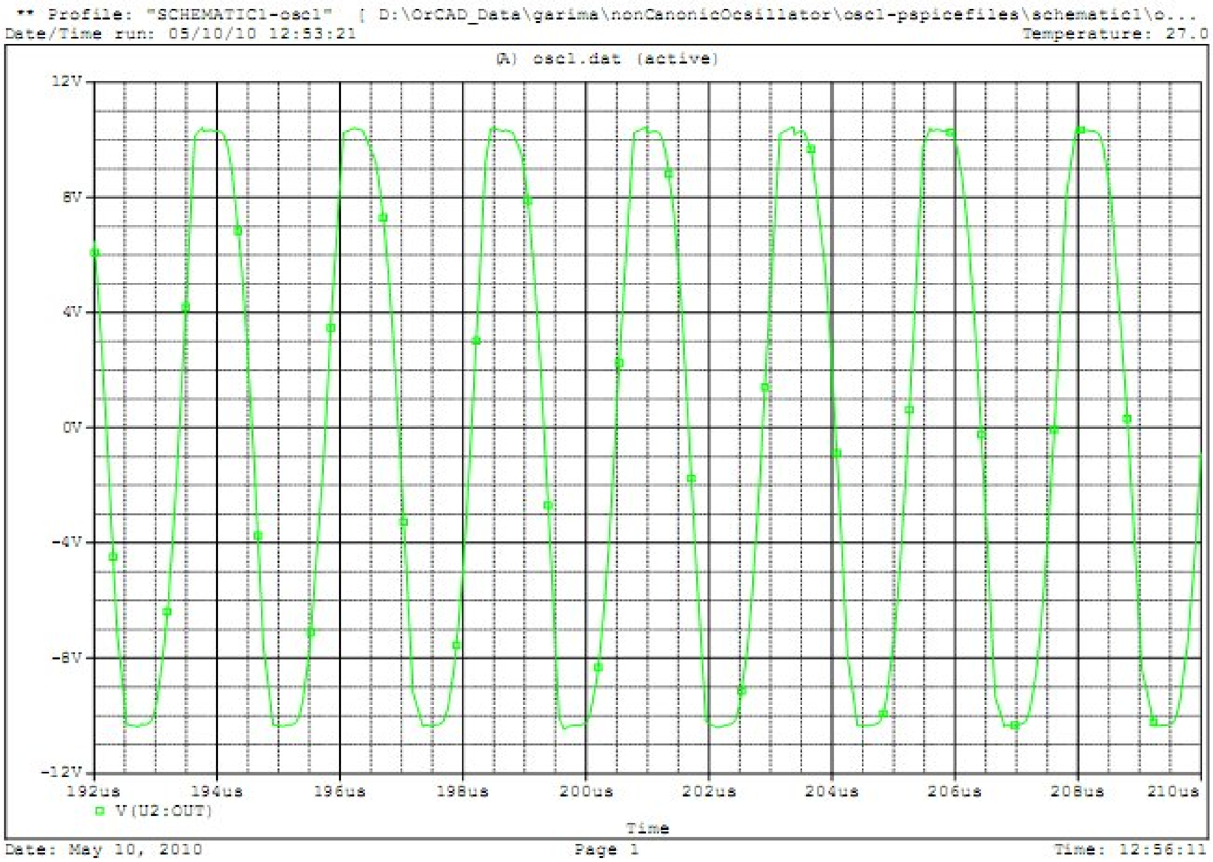

Fig. 5.7 Simulated results of Vo of noncanonic oscillator

5.2.4 Analysis of results

The PSPICE simulations were carried out. The passive components used are:

R_1 = 20KΩ, R2 = 20KΩ, R3 = 9 KΩ, C1 = 40pf, C2 = 10pf & C_3= 20pf

Theoretical frequency of oscillation f = 396.88KHz

Simulated frequency of oscillation fo = 400KHz

% error= 0.7%

5.3 SINGLE- RESISTANCE -CONTROLLED SINUSOIDAL OSCILLATOR

5.3.1 Introduction

Several active RC-oscillator circuits use single active element such as classical voltage op-amp, current conveyor, current feedback amplifier or a four terminal floating nullor. A novel operational transresistance amplifier based single resistance controlled sinusoidal oscillator is presented in [16]. It uses single OTRA, three resistors & two capacitors. The oscillator circuit provides independent control of oscillation frequency without disturbing oscillation condition by a resistor. It has also low passive sensitivities. The oscillator circuit is insensitive to parasitic input capacitances & input resistance due to internally grounded input terminals of OTRA.

5.3.2 Circuit description

The circuit of OTRA based SRCO is shown in fig.5.8.

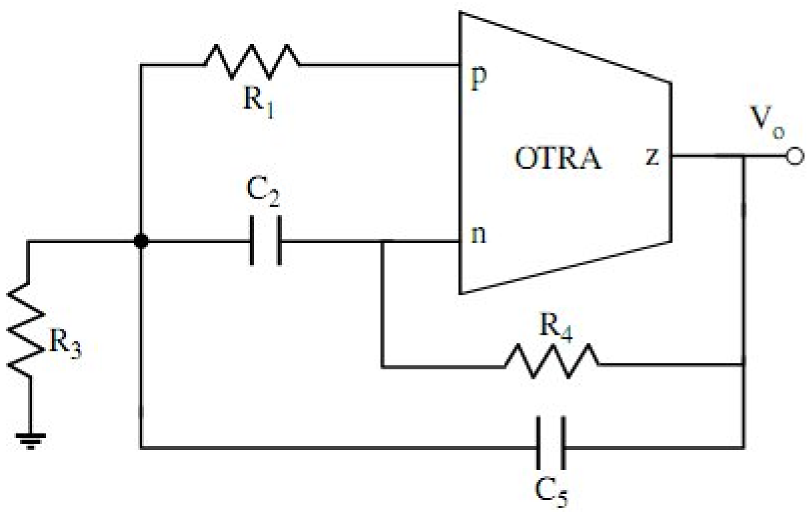

Fig. 5.8 SRCO sinusoidal oscillator

Routine analysis of the circuit, shown in fig.5.8, using terminal equations results in the characteristic equation as follows:

$$s^2C_2C_5 + s(C_2G_4 + C_5G_4 - C_5G_1) + G_4(G_1 + G_3) = 0 \quad \text{......} (5.6)$$

The condition of oscillation and frequency of oscillation are given by eqn 5.7 and 5.8 respectively.

$$C_2G_4 + C_5G_4 = C_5G_1 \quad \text{......} (5.7)$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{G_4(G_1 + G_3)}{C_2C_5}} \quad \text{......} (5.8)$$

5.3.3 Simulation results

The OTRA is realized using CFOA. The pspice schematic of the oscillator is shown in fig.5.9.

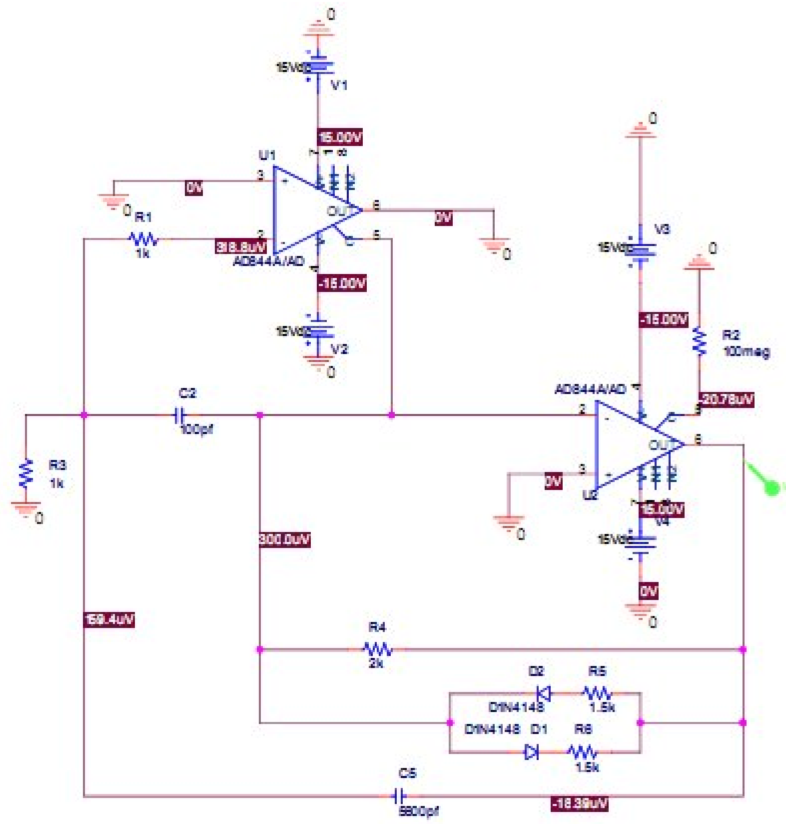

Fig. 5.9 Simulated internal circuit of single resistance controlled oscillator

PSPICE simulation was performed with passive component values chosen as = = 1 Ω, = 2 kΩ, = 100pf, = 5600pf and simulation results are shown in fig.5.10.

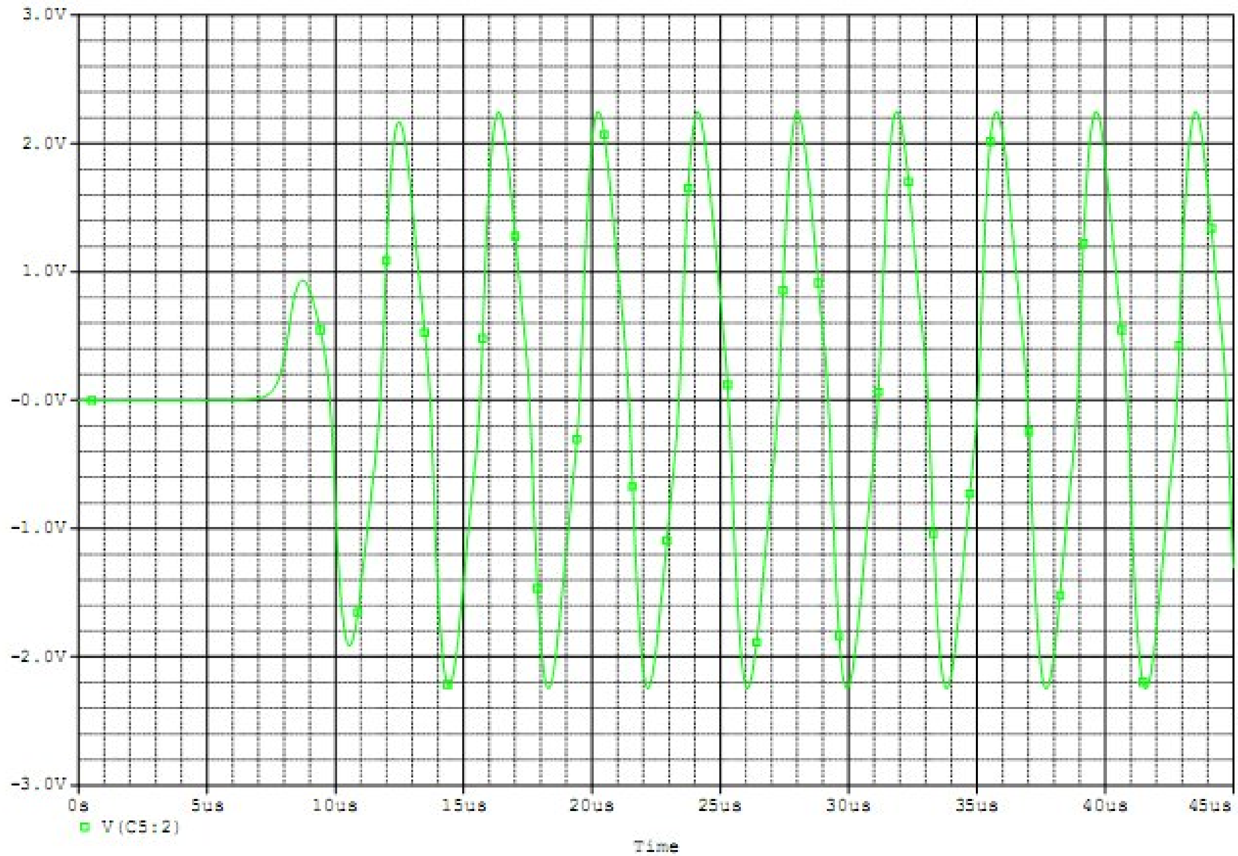

Fig.5.10 Simulated result of V_O vs time for SRCO

5.3.4 Analysis of results

The PSPICE simulations were carried out for current mode single resistance controlled oscillator. The oscillations generated were sinusoidal in nature.

Theoretical frequency of oscillation, f =212.67 KHz

Simulated frequency of oscillation, fo = 1/4us = 250KHz.

The resistor R_3 controls the frequency of oscillations. Two different values of R_3 are selected and its simulation results show that the frequency of oscillations also change in accordance with R_3.

S.No.	Value of Resistance R_3	Frequency of simulated oscillations	Theoretical frequency of oscillation	% Error
1	1KΩ	250KHz	212.67KHz	14.9%
2	10KΩ	169.49KHz	157.77KHz	6.9%

Table 5.3 Effect of Resistance R_3 on frequency of oscillation

5.4 Non-Interactive Control Oscillator

5.4.1 Introduction

An OTRA based sinusoidal oscillator is realized. It provides independent control on frequency and condition of oscillation.

5.4.2 Circuit Description

The circuit is shown in fig.5.11.

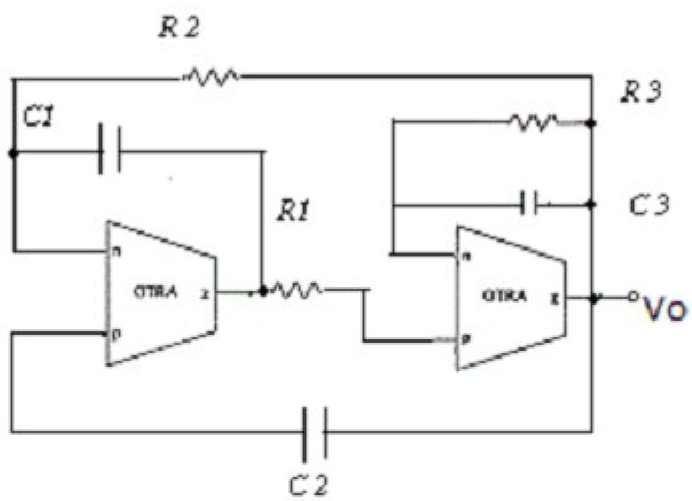

Fig.5.11 Sinusoidal Oscillator

Routine analysis of the circuit yields the characteristic equation as follows:

$+ \ (\quad - \quad) + \quad = 0$ …………………………..(5.9)

From eqn(5.9) the condition and frequency of oscillation can be obtained as given in eqn 5.10 and 5.11 respectively.

Condition of oscillation

$=$ ……………………………………(5.10)

Frequency of oscillation

fo = — …………………………………..(5.11)

5.4.3 Simulation Results

The pspice schematic of the circuit is shown in fig.5.12.

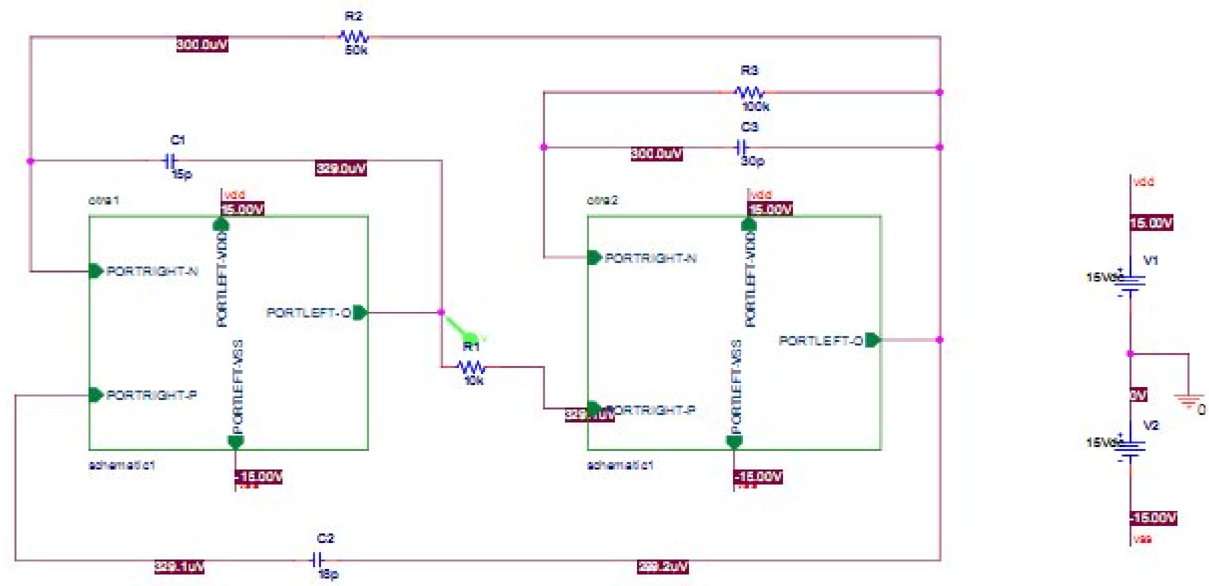

Fig.5.12 Sinusoidal Oscillator

PSPICE simulation was performed with passive component values chosen as

= 100 , = 50 , = 100 Ω, = 15 pf, = 18pf, = 30pf and simulation results are shown in fig.5.13.

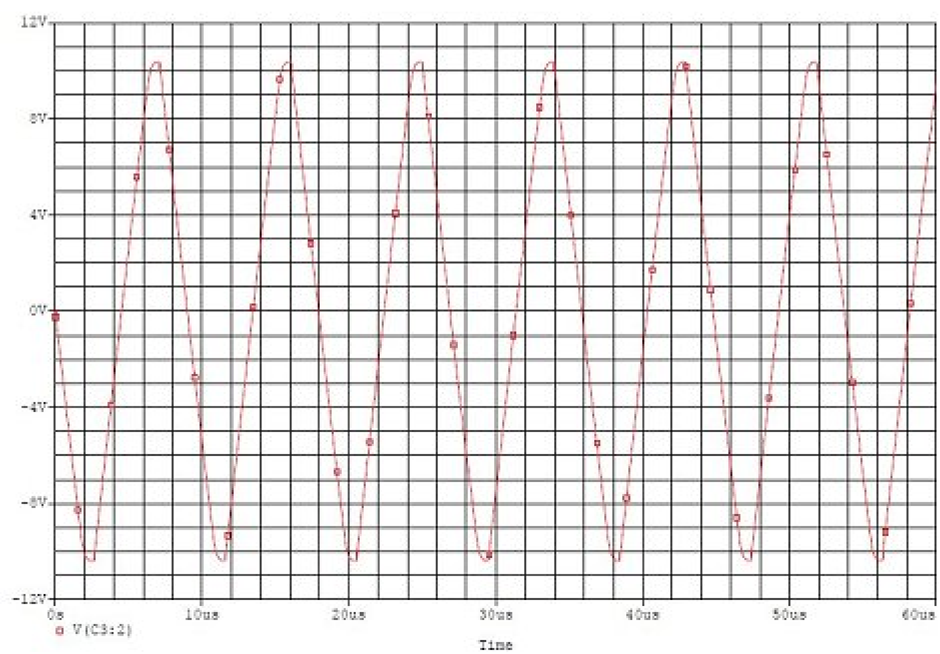

Fig.5.13 Simulated results for Vo

5.4.4 Analysis of results

The PSPICE simulations were carried out. The oscillations generated were sinusoidal in nature.

Theoretical frequency of oscillation, $f = 106.10KHz$

Frequency of oscillation, fo = 111.11KHz

% Error = 4.5%

CHAPTER-6

COMPONENT REALIZATION USING OTRA

In literature various components are realized using OTRA as the active element. In this chapter a Grounded Parallel Immitance simulator is studied and a filter is realized based on it.

6.1 Grounded Parallel Immitance

In [18] a new grounded parallel immitance topology is presented using OTRA as the active element. Various circuits are proposed that can simulate various combinations of parallel lossy inductances. Of the various circuits presented in[18] the topology that represents a (+L) with (+R) is simulated. The circuit is as shown in fig 6.1. Using the simulated parallel grounded immitance a current mode filter is implemented in this chapter. The basic cell is parallel R-L simulator with a parallel capacitor *C* and *R* to form the resonant circuit shown in Fig.6.2. In this figure actively simulated R-L circuit in Fig.6.1 replaces the parallel R-L circuit[18] . The pspice schematic of filter circuit is given in fig 6.3.

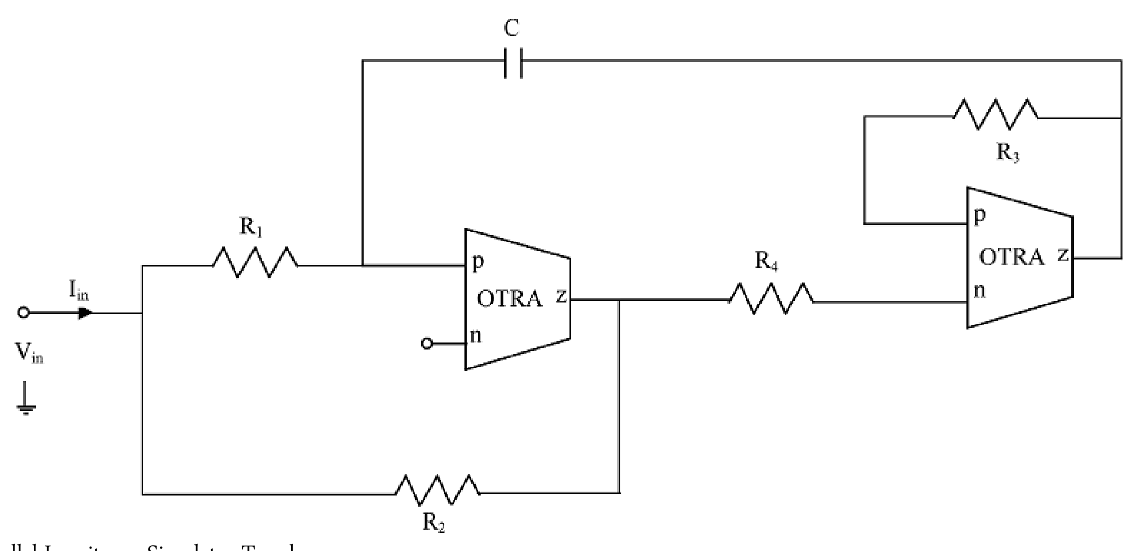

Fig.6.1 Parallel Immitance Simulator Topology

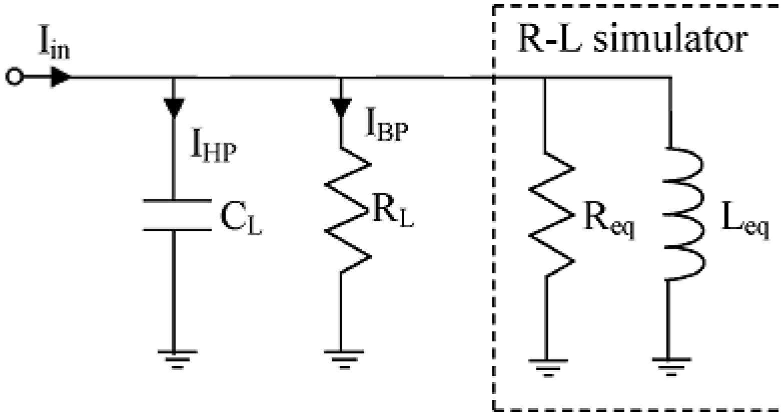

Fig.6.2 Current mode filter with active R-L simulator

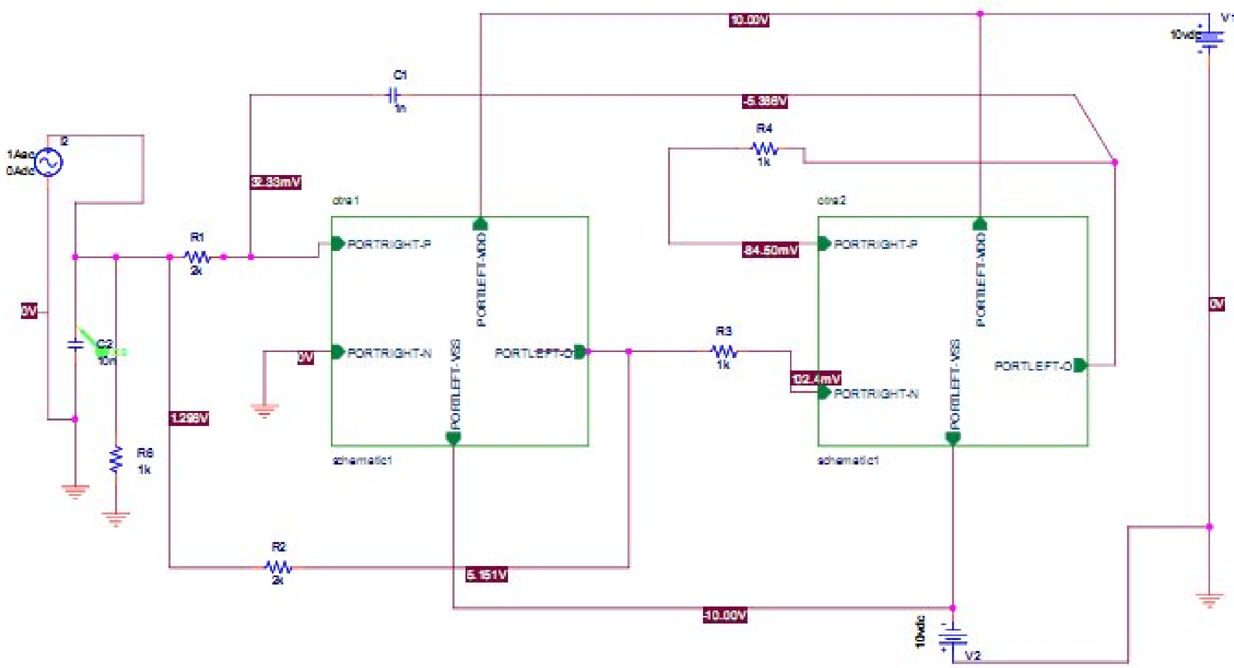

Fig6.3 PSpice schematic of the active filter

The simulated high pass response of the filter is as shown in fig.6.4.

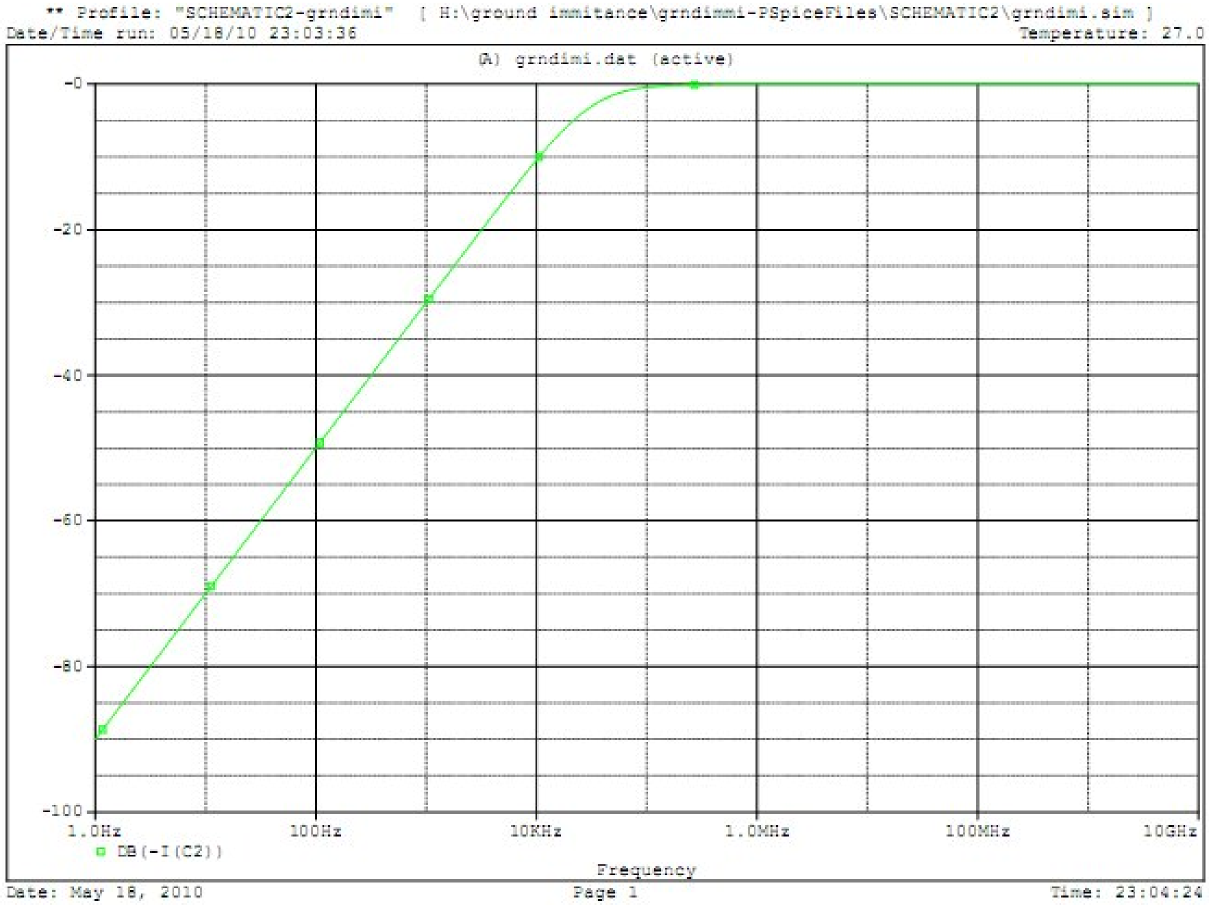

Fig.6.4 High Pass Response of the simulated current mode active filter

As can be seen in fig.6.4 the 3-db frequency of the high pass filter is almost 30KHz.

CONCLUSION AND FURTHER SCOPE

The OTRA is receiving increasing attention as a basic building block in analog circuit design. It is relatively a new building block operating from low voltage supplies and overcomes the finite gain bandwidth product associated with traditional op-amp.The basic principle behind the design of OTRA is to provide amplification of high frequency signals with the ease of using standard operational amplifier.

In this work effort is made to study the role of OTRA as an active building block in analog circuits. Various CMOS realization of OTRA present in the literature are studied and these circuits are used to realize various signal processing and generating circuits. All the circuits were simulated using PSpice program and 0.5um process parameters were used for it. Simulation results show that the various characteristics are in good agreement with the theory. Slight variations in the results arise due to the non ideal behavior of the OTRA used. I have assumed that the transresistance approaches infinity, but practically it has a finite value given by

$$R_m(s) = \frac{R_0}{1 + \frac{s}{\omega_0}}$$

For higher frequencies this reduces to

$$R_m(s) \approx \frac{1}{sC_p}$$

Where,

$$C_p = \frac{1}{R_0 \omega_0}$$

In these circuits most of the parasitic input impedances disappear due to the internally grounded input terminals of the OTRA.

Further, multivibrators can be designed using OTRA. Operational amplifiers and some commercial IC's are commonly used to construct monostable and bistable multivibrators. But these voltage mode circuits have some disadvantages like complex internal circuitries and use of more passive components.

REFERENCES

[1] Toumazou C, Lidjey FJ, Haigh D. Analog IC design: the current-mode approach. Peter Peregrinus, UK: Exeter; 1990.

[2] SMITH, K.C., SEDRA, A. The current conveyor: a new circuit building block. *IEEE Proc. CAS*, 1968, vol. 56, no. 3, p. 1368-1369.

[3] SEDRA, A.S., SMITH, K.C. A second generation current conveyor and its application. *IEEE Trans*., 1970, CT-17, p. 132-134.

[4] FABRE, A. Third generation current conveyor: A new helpful active element. *Electron. Lett.*, 1995, vol. 31, no. 5, p. 338–339.

[5] WADSWORTH, D.C. Accurate current conveyor topology and monolithic implementation. *Proc. IEE G*, 1990, vol. 137, no. 2, p. 88-94.

[6] www.wikipedia.org

[7] J.J. Chen, H.W. Tsao, and C. Chen, "Operational transresistance amplifier using CMOS technology." *Electronics Letters*, vol. 28, no. 22, pp. 2087–2088, 1992.

[8] K.N. Salama and A.M. Soliman, "CMOS operational transresitance amplifier for analog signal processing applications." *Microelectronics Journal*, vol. 30, pp. 235–245, 1999.

[9] Hassan Mostafa, Ahmed M. Soliman, A modified CMOS realization of the operational transresistance amplifier (OTRA) ." Frequenz, 60, pp. 70–76, 2006.

[10] U.Cam,C.Cakir and Oguzhan Cicekoglu,"Novel transimpedance type first order all-pass filter using single OTRA." *AE U—International Journal of Electronics and Communications*, vol. 58, pp. 296–298, 2004.

[11] C. Cakir, U. Cam, and O. Cicekoglu, Novel allpass filter configuration employing single OTRA, *IEEE Trans. Circuits and Systems-II: Express briefs*, vol. 52, no. 3, pp. 122–125, 2005.

[12] S. Kilinc¸andU.C¸am, Cascadable allpass and notch filters employing single operational transresistance amplifier, pp. 391-401,2005.

[13] S. Kilinc¸andU.C¸am, "Operational transresistance amplifier based first-order allpass filter with an application example." *IEEE International Midwest Symposium on Circuits and Systems*, vol. 1, pp. 65–68, 2004.

[14] Ahmet Gocken and U.Cam, "MOS-C single amplifier biquads using the operational transresistance amplifier", 2008.

[15] K.N. Salama and A.M. Soliman, "Active RC applications of the Operational Transresistance Amplifier", Frequenz, pp.171-176,2000.

[16] U.Cam, "A Novel Single-Resistance-Controlled Sinusoidal Oscillator Employing Single Operational Transresistance Amplifier", Analog Integrated Circuits and Signal Processing, 32, pp. 183–186, 2002.

[17] K.N. Salama and A.M. Soliman "Novel oscillators using the operational transresistance amplifier" *Microelectronics Journal*, vol. 31, pp. 39–47, 2000.

[18] U.Cam, Firat Kacar, Oguzhan Cicekkoglu, Hakan Kuntman, and Ayten Kuntman,"Novel Two OTRA-Based Grounded Immitance Simulator Topologies", Analog Integrated Circuits and Signal Processing, 39, pp. 169–175, 2004.

[19] Selcuk Kilinc, Khaled N. Salama, U.Cam, "Realization of fully controllable negative inductance using single OTRA", Circuits Systems Signal Processing, Vol. 25,No.1, pp.47-57, 2006.

[20] Yu-Kang Lo and Hung-Chun Chien, "Curent-Mode monostable multivibrators using OTRAs", IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEFS, VOL. 53, NO. 11, NOVEMBER 2006.

[21] Y. K. Lo, H. C. Chien, H. G. Chiu "Switch Controllable OTRA Based Bistable Multivibrator," IET Circuits Devices Syst., 2008, Vol. 2, No. 4, pp. 373–382.

[22] H.O. Elwan, A.M. Soliman, CMOS differential current conveyors and applications for analog VLSI, Analog Integrated Circuits and Signal Processing 11 (5) (1996) 35–45.

[23] Celma,S.,Martinez,P.A.andCarlosena,A.,"Minimalrealization for single resistance controlled sinusoidal oscillator using single CCII." *Electron. Lett.* 28, pp. 443–444, 1992.

[24] R.Senani and V.K.Singh, "Synthesis of canonic single resistance controlled oscillators using a single current feedback amplifier." *IEE Proc. Circuit Devices and Systems* 143(3), pp. 71–72, 1996.