A

Dissertation

On

STUDY OF NON-LINEAR CIRCUITS AND IMPLEMENTATION OF DUAL MODE BIQUADRATIC FILTER

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This is to certify that the report entitled **"STUDY OF NON-LINEAR CIRCUITS AND IMPLEMENTATION OF DUAL MODE BIQUADRATIC FILTER"** submitted by **Divyesh Sachan,** Roll. No-**2K12/VLS/05**, in partial fulfilment for the award of degree of Master of Technology in VLSI Design & Embedded System at **Delhi Technological University, Delhi**, is a bonafide record of student's own work carried out by him under my supervision and guidance in the academic session 2012-14. The matter embodied in dissertation has not been submitted for the award of any other degree or certificate in this or any other university or institute.

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ABSTRACT

The reduction of the minimum feature size of an MOS transistor for digital VLSI circuits has been ongoing for the past few decades. As the channel length is scaled down into deep sub micrometer dimensions, the lower power supply voltage is required to ensure the device reliability. To be compatible with digital VLSI technologies, analogue integrated circuits, which can operate at low supply voltages, are also receiving significant attention. This has resulted in development of various current mode analog building blocks.

Analog filters can be found in almost every circuit, audio systems use them for pre-amplification, equalization and tone control, communication system filters are used for tuning in specific frequencies and eliminating others whereas digital signal processing systems use filters to prevent aliasing of out of band noise and interference. However, a multivibrator is an electronic circuitry that switches between two or more states by means of positive feedback. The common applications of Multivibrators are in square wave generator, timer or where timed intervals are required. \

The objective of the project is to design a monostable multivibrator using latest analog building block which overcomes the limitation of minimum pulse width, electronic tunability in multivibrator and to design circuit of filters which can work in both current and voltage mode with high bandwidth. Keeping the commercialization of the circuit in mind all circuits are simulated using commercial available IC’s.

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ABBREVATIONS

OTA	Operational Transconductance Amplifier
OTRA	Operational Trans Resistance Amplifier
DVCC	Differential Voltage Current Conveyor
CCI	First Generation Current Conveyor
CCII	Second Generation current conveyor
OFCC	Operational Floating Current Conveyor
CDBA	Current Differencing Buffered Amplifier
CDTA	Current Differential Transconductance Amplifier
CFOA	Current Feedback Operational Amplifier
FDNR	Frequency Dependant Negative Resistor
SNR	Signal to Noise Ratio
CM	Current Mode
VM	Voltage Mode
VCCS	Voltage Controlled Current Source
VCVS	Voltage Controlled Voltage Source
DISO-OTA	Differential Input Single Output –OTA
Zc-CDTA	Z Copy Current Differential Transconductance Amplifier
DXCCII	Dual X Second Generation current conveyor
MOCCII	Multi Output Second Generation current conveyor

Chapter 1

Introduction

1.1. Motivation

Any signal processing accompanied on analog signals by analog means is termed as Analog signal processing. "Analog" specifies something that is mathematically symbolized as a set of continuous values. It differs from "digital" where signal representation is done using a series of discrete quantities. In electronic devices, analog values are normally characterized as voltage, current or electric charge around components. A noise or error affecting such physical quantities will result in corresponding error in the signals represented by such physical quantities. The primary motivation behind digital computation is speed and precision along with a smaller circuit area. However, these are achieved at the expense of higher power consumption and greater circuit complexity [1]. In certain applications, it is difficult or even impossible to replace analog functions with their digital counterparts, regardless of advances in technologies. For instance, at low-to-moderate levels of precision (such as medical prosthetic devices), analog implementation of certain computations can be vastly more efficient in terms of power dissipation, circuit area, or both than its digital equivalent design. This efficiency is achieved by performing most of the processing in analog domain. In such designs, usually, only small subsets of internal computations are performed using a digital signal processing system [2]. Whereas pre and post signal processing is performed in analog domain.

Today most of analog circuits like Amplifiers, Filter, Oscillators, Multivibrators, etc. are constructed using different Analog Building Blocks like OTRA (Operational Transresistance Amplifier) [17], OTA (Operational Tranconductance Amplifier) [18] [21-23], CCI, CCII, CCIII (Different Generations of Current Conveyors) [8][9][11][12], DVCC (Differential Voltage Current Conveyor) [20], CDTA (Current

Differential Transconductance Amplifier)[13], CDBA (Current Differential Buffer Amplifier), CFOA (Current Feedback Operational Amplifier), OFCC (Operational Floating Current Conveyor)[6][15], etc. These ABB's offers unique port characteristics by which circuits employed these blocks can be easily optimized for targeted behavior.

1.2. Some Analog Signal Processing Modules

There are number of analog signal processing modules preforming wide variety of tasks. Out of these, the modules which are relevant to our work carried out within the thesis are discussed in following sub-sections.

1.2.1. Filters

Analog filters can be found in almost every circuit, audio systems use them for pre-amplification, equalization and tone control, communication system filters are used for tuning in specific frequencies and eliminating others whereas digital signal processing systems use filters to prevent aliasing of out of band noise and interference. In analog system, all input signals are composed of sinusoidal components of various frequencies, amplitude and phases. If we are interested in certain range of frequencies, we can design filter to eliminate frequency component outside range. As opposed to lumped passive filters with resistor, capacitor and inductor, filter comprises of active components are called active filters.

Passive Filters:

Till late 1960s, filters were constructed using resistors, capacitors and inductors. Since these components were passive in nature, the designed filters were termed as *passive filters*. Passive filters have a number of advantages. Since they do not contain any active component, they do not require any power supply. They are not restricted by the bandwidth limitations of active devices. They can work well at very high frequencies. However in low frequency applications (dc to 100 KHz) the required inductors are large, physically bulky and such inductors are impossible to fabricate in monolithic form and are incompatible with any of the techniques for assembling a modern electronic system. Passive filters also generate lesser noise when compared to circuits using active gain elements.

However, passive filters exhibit significant drawbacks when employed in certain applications. Since they do not use any active elements, they cannot provide a signal gain. Input impedances can be lower than desirable, and output impedances can be higher than optimum, hence buffer amplifiers may be needed.

Active Filters:

In the 1950's it was recognized that substantial size and cost reduction could be achieved by replacing large and expensive passive inductors with active circuitry. However, high quality active components such as operational amplifiers became commercially available only in the mid 1960's. Filters based on active devices are accordingly termed as *active filters*. Such filters also use other amplifying elements such as operational transconductance amplifiers, current conveyors etc. with resistors and capacitors in their feedback loops, so as to synthesize the desired filter characteristics. Active filters can have high/low input/output impedance, and virtually any arbitrary gain. They are also usually easier to design than passive filters. Their most significant advantage is that they do not contain inductors, thereby reducing the problems associated with such components [3]. Performance at high frequencies is limited by the gain-bandwidth product of the amplifying elements. However, within the amplifier's operating frequency range, active filter can achieve very good accuracy, provided that low tolerance resistors and capacitors are used.

Mathematical Representation:

Mathematically, filters can be categorized as first order, second order or higher order on the basis of the transfer function obtained [4]. The generic transfer function of any order filter can be represented as:

$$T(s) = \frac{a_M s^M + a_{M-1} s^{M-1} + a_{M-2} s^{M-2} + \cdots + a_0}{b_N s^N + b_{N-1} s^{N-1} + b_{N-2} s^{N-2} + \cdots + b_0} \tag{1.1}$$

T(s) in eqn. 1.1 is a rational function of complex variable 's' with real coefficients. The numerator and the denominator have a degree of M and N respectively. For a stable filter operation, the degree of the numerator should be less than or equal to that of the denominator i.e. $M \leq N$. The coefficients in the numerator and the denominator i.e. a_0, a_1, a_2 ... a_M and b_0, b_0, b_2 ... b_{N-1} are real numbers. N is considered to be the order of the filter. Solving for the roots of the equation determines the poles (denominator) and zeros (numerator) of the circuit. Each pole will provide a –6 dB/octave or –20 dB/decade response. Each zero will provide a +6 dB/octave or +20 dB/decade response. These roots can be real or complex. When they are complex, they occur in conjugate pairs.

First-Order Filters:

The general first-order transfer function is expressed as:

$$\mathrm{T(s)} = \frac{\mathrm{a_1 s + a_0}}{\mathrm{s} + \omega_o}$$

Which characterizes a first-order filter with a pole at $s = -\omega_o$ and a transmission zero at $s = -a_0/a_1$.

A first-order section can be built in a variety of ways. The simplest design uses a passive RC configuration. The center frequency of this filter is $1/(2\pi RC)$. Correspondingly, an active RC configuration can also be used.

Second-Order Filters:

Second-order filters are also known as biquadratic filters. The standard transfer function of such filters can be expressed as [4]:

$$\mathrm{T(s)} = \frac{\mathrm{a_2 s^2 + a_1 s + a_0}}{\mathrm{s^2} + \left({}^{\omega_0}/_{Q}\right)\mathrm{s} + \omega_0{}^2}$$

Where ω_0 and Q determine the poles (p_1, p_2) of the filter:

$$p_1, p_2 = -\frac{\omega_o}{Q} + j\omega_o\sqrt{1-(1/4Q^2)}$$

Depending on the constants a_2, a_1 and a_0, filters are also categorized as low-pass ($a_2 = a_1 = 0$), high-pass ($a_1 = a_0 = 0$), band-pass ($a_2 = a_0 = 0$) and band-stop ($a_1 = 0$).

Higher-Order Filters:

There are numerous techniques which are used to design higher-order filters. Some of these techniques are Direct Form (simulated inductance approach and frequency dependent negative resistance (FDNR) approach), Cascade approach, Multiple-loop feedback or coupled-biquad approach, ladder simulation approach (Simulating signal flow graph of ladder).

1.2.2. Multivibrators

A multivibrator is an electronic circuitry that switches between two or more states by means of positive feedback. It has two main components, one or two passive networks and a timing circuit, connected in a shared feedback loop. In case of astable circuit this network can be both resistive-capacitive, In case of monostable this could be resistive-capacitive and a resistive, and in case of bistable both are resistive. The common applications of Multivibrators are in square wave generator, timer or where timed intervals are required. Other application comprises initial television systems, where several line and frame frequencies were kept synchronized by pulses incorporated in the video signal. Depending on the operation, multivibrator can be categorized into astable, monostable and bistable.

Astable Multivibrator:

In Astable Multivibrator, circuit is not stable in either state. It continually switches from one state to another. This action produces a train of square wave pulses at a fixed frequency. Like oscillators, it does not require any input signal or clock pulse. It is also known as free-running multivibrator.

Monostable Multivibrator:

In Monostable Multivibrator, one of its states is stable and another state is unstable (transient). Circuit enters into unstable state by means of a trigger signal. After entering into unstable state circuit will return to the stable state after a set amount of time. This circuit is also known as a one shot multivibrator. Such a circuit is very useful for producing a timing period of fixed extent in response to some external event.

Bistable Multivibrator:

In Bistable Multivibrator, circuit is stable in both of its states. The circuit can be reversed from one state to the other by an external trigger signal or event. Bistable multivibrators are also called latch or flip-flop which has two stable states producing a single pulse of either positive or negative in value.

1.3. Voltage Mode versus Current Mode

All conventional analog circuits are voltage mode circuits (VMCs) where the circuit performance is determined in terms of voltage level at various nodes including the input and the output nodes. But these circuits suffer from the following disadvantages: (i) output voltage cannot change instantly when there is a sudden change in the input voltage due to stray and other circuit capacitances, (ii) bandwidth of opamp based circuits is usually low because of finite unity-gain bandwidth, (iii) slew rate is dependent on the time constants associated with the circuit, (iv) circuits do not have high voltage swings, and (v) require higher supply voltages for better SNR. Clearly, VMCs are not suitable for use in high frequency applications. This unsuitability is due to the fact that in voltage-mode circuits, the high-valued resistors with parasitic capacitances create a dominant pole at a relative low frequency, which limits the bandwidth.

CM circuits offer a better alternative to VMC in high-frequency applications. In the CM approach, the circuit description is presented in terms of current. This implies that both, the input and the output, are taken in current form rather than in voltage form. Hence CM signal processing techniques can be defined as the processing of current signals in an environment where voltage signals are irrelevant in determining circuit performance [ab].

CM signal processing lead to a higher frequency of operation, since the signal current is delivered into a small (ideally short circuit) load resistance. The parasitic pole frequency, due to such a small resistance (pole frequency being inversely proportional to the resistance), will be very high and hence, a high-frequency signal can be processed without substantial impairment due to the presence of such a high-frequency parasitic pole. In summary, the following are the advantages of the CM approach: (i) extended bandwidth, (ii) easy addition, subtraction and multiplication of signals, (iii) higher dynamic range, (iv) suitability of operation in reduced power supply environment, (v) simpler circuit structure, (vi) low-power consumption, (vii) low-voltage operation, and (viii) micro-miniaturization.

1.4. Chapter Organization

For better understanding of the readers following sections explain the organization of this thesis from Chapter 2 onwards.

In chapter 2 different analog building blocks which are used in our circuits are discussed in brief along with their port relationships. In chapter 3 the literature review is shown where previous work done in this field is discussed with problem formulation and objective of the project. In Chapter 4 a dual mode biquadratic filter is proposed and discussed along with its non-linear analysis. A new implementation of OFCC using AD844 is also shown in this chapter and it is used for the simulation of proposed filter. In chapter 5 a Monostable Multivibrator-I is proposed and its detailed working, usage and problems are discussed. Further, an improved Monostable Multivibrator-II is proposed which overcomes the limitation of proposed multivibrator-I, is also shown and results are compared. A brief conclusion of proposed circuit and their future scope are discussed in chapter 6.

Chapter 2

Brief Overview of Analog Building Blocks

There are number of analog building blocks having their unique port relationship and features. Out of these, the building blocks which are relevant to our work carried out within the thesis are discussed in following sub-sections.

2.1. DISO-OTA

The OTA is a transconductance type device, which means that the input voltage controls an output current by means of the device transconductance, labeled g_m. This makes the OTA a voltage-controlled current source (VCCS), which is in contrast to the conventional op-amp, which is a voltage-controlled voltage source (VCVS). What is important and useful about the OTA's transconductance parameter is that it is controlled by an external current, the amplifier bias current, I_B, which gives

$$g_m = \frac{I_B}{2V_T}$$

The DISO (Differential Input Single Output)-OTA or generally OTA is a four-terminal active device that includes two high-impedance voltage inputs, one high-impedance current output and a bias current input terminal. A OTA has two different operation modes (linear and nonlinear modes).

In the linear mode, a OTA acts as an amplifier in which transconductance gain g_m is adjustable by the bias current of OTA. Port characteristics of OTA in linear mode

$$I_O = g_m(V+ - V-)$$

In the nonlinear mode, an OTA can be regarded as a voltage comparator. When a OTA is operated in the nonlinear mode, the port characteristics can be described as [21]

$$I_o = I_B \qquad if\ V+ > V-$$

And

$$I_o = -I_B \qquad if\ V+ < V-$$

Figure 2.1 shows the circuit symbol and port characteristics of a DISO-OTA operated in the nonlinear mode. The most important feature of a OTA is that its output current, I_O, can be adjusted by the bias current, I_B. Thus, electronic circuits built with OTAs have current-tunable properties.

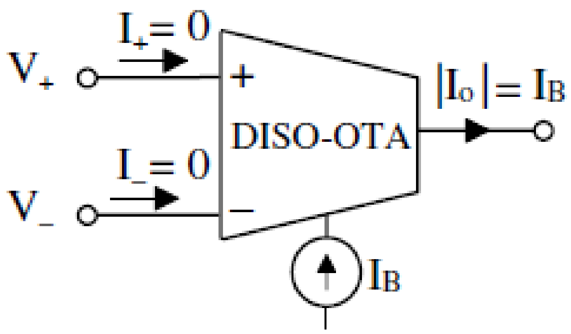

Fig 2.1: DISO-OTA Operated in Non-Linear Mode [21]

In 1969, RCA manufactured first integrated circuit of OTA and make it commercially available in the form of CA3080, and from the time it is being improved. Some other OTA Integrated Chips are known as LM13600, LM13700. OTA is mostly used in applications where electronics tuning is required such as filters, variable frequency oscillators and variable gain amplifiers since it is difficult to implement it with op-amp. Since the output of OTA is current, it is not as useful by the massive majority of standard op-amp functions as the ordinary op-amp.

2.2. Current Conveyor

2.2.1. First Generation Current Conveyor (CCI)

The first ideal current mode circuits were first generation current conveyors introduced by Sedra and Smith in 1968. These are denoted by CCI±, where polarity specify the direction of the output current is same as that of current flowing into port X or not. It is basically a three terminal device as shown in figure 2.2.

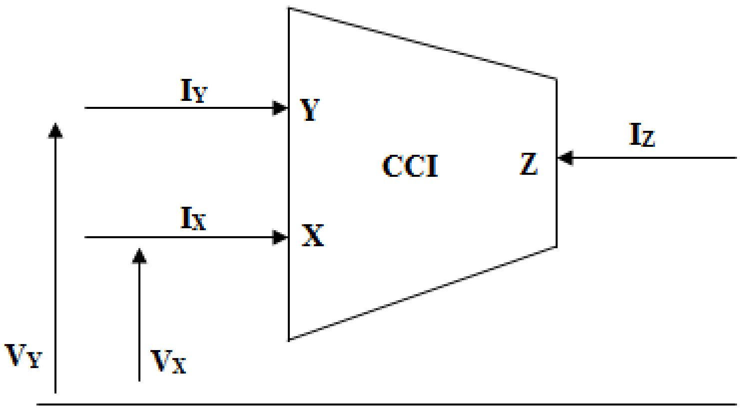

Fig: 2.2 Block Representation of CCI [25]

The relation between the terminal voltages and current of CCI can be given by the following matrix relation,

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ Y_Z \end{bmatrix} \tag{2.1}$$

From the above matrix description it is found that, if a potential is applied on port Y then equal voltage will appear at port X and this voltage is independent of current supplied to port X. Thus circuit exhibits a virtual short circuit at port X. Also, the current flows through port Y is equal to the current supplied to port X and this current is independent of voltage at port Y. Thus circuit exhibits a virtual open at port Y. Finally, the current supplied to X is also conveyed to the output port Z which is at a high impedance level.

The impedance level at port X and Y of first generation current conveyor is is very low (ideally zero) whereas impedance level of port Z is very high (ideally infinite).

The application of CCI± becomes difficult because both the ports X and Y have zero input impedance in order to sink currents. The port Y needs to control a current rather than to control a voltage, which is usually difficult to obtain in practical designs. This is the perhaps the greater limit of the CCI device and this reduces its flexibility and versatility.

2.2.2. Second Generation Current Conveyor (CCII)

The second-generation current conveyor (CCII) is one of the most functionally flexible and versatile analog building block. Since its first introduction, by A. Sedra and K. Smith in 1970 [5], it has been used in high frequency analog signal applications such as filters and CM oscillators. This current conveyor differs from the first generation current conveyor in a sense that the port Y is a high impedance port i.e. there is no current flowing into port Y. The port Y of the second generation current conveyor is used as a voltage input and port Z is used as a current output port. Whereas, the port X can be used as a voltage output or as a current input port. Therefore, this current conveyor can be used to process both voltage and current signals. The CCII is a three-terminal device whose properties are governed by the following matrix:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (2.2)$$

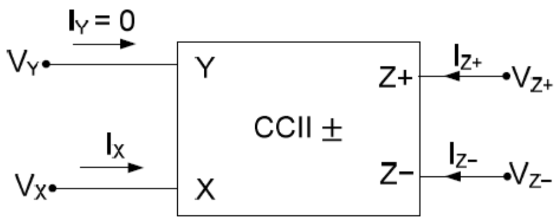

Fig 2.3: Block Diagram of CCII

The symbol of CCII is shown in figure 2.3. The device comprises a low-impedance current input/voltage output terminal X, a high-impedance voltage input terminal Y and a current output terminal Z. The current supplied to X is conveyed to the output terminal Z with either a positive polarity (in CCII+) or a negative polarity (in CCII−).

By convention, positive is taken to mean that both I_X and I_Z are flowing simultaneously towards or away from the conveyor.

Most commonly used commercial IC for CCII implementation is AD844 which is a combination of CCII+ followed by buffer. Figure 2.4 shows the block diagram of AD844. The current voltage terminal characteristics of ideal CFOA are same as of CCII. However, voltage tracking error, current tracking error and non-idealities affects circuit performance realized using CFOA. Taking account of all errors and non-idealities current-voltage terminal characteristics of CFOA becomes:

$$\begin{bmatrix} I_y \\ V_x \\ I_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \beta & 0 & 0 \\ 0 & \alpha & 0 \end{bmatrix} \begin{bmatrix} V_y \\ I_x \\ V_z \end{bmatrix} \tag{2.3}$$

and

$$V_o = \gamma V_Z$$

Where α, β and γ are non-ideal current and voltage gain.

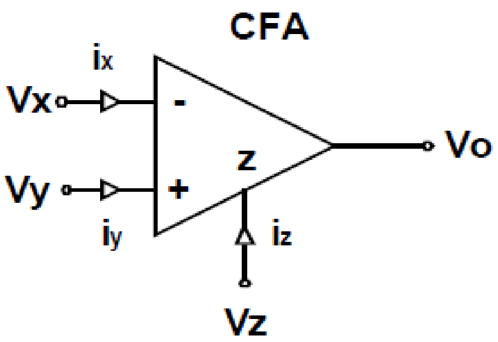

Fig 2.4: Symbol of Current Feedback Operational Amplifier (AD844)

2.3. Operational Floating Current Conveyor (OFCC)

OFCC which was introduced in [6] as OFC, is a general purpose building block which features both Second generation current conveyor CCII and Current Feedback Operational amplifier (CFOA) which are widely used in current-mode signal processing circuits. Fig 2.5 shows block diagram of OFCC

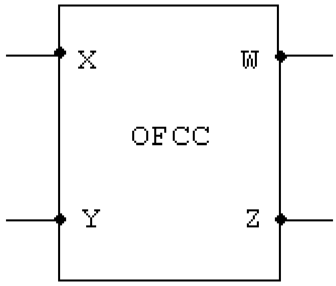

Fig 2.5: Block diagram of OFCC

The port relationship matrix of OFCC is

$$\begin{bmatrix} V_x \\ I_y \\ V_w \\ I_z \end{bmatrix} = \begin{bmatrix} 0 & \beta & 0 & 0 \\ 0 & 0 & 0 & 0 \\ Z_t & 0 & 0 & 0 \\ 0 & 0 & \alpha & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ I_w \\ V_z \end{bmatrix} \tag{2.1}$$

$$\alpha = 1 - \varepsilon_+ \cong 1$$

$$\beta = 1 - \varepsilon_v \cong 1$$

Where ε_v is finite voltage tracking error between port X and port Y and ε_+ is finite current tracking error between port Z and port W. The output voltage at V_W is the multiplication of input current at I_X and open loop transimpedance gain Z_t .Its low impedance current Input port X follows the voltage at high impedance voltage input port Y, thus voltage tracking at input port is available. Its terminal W is a low impedance voltage output port and terminal Z is a high impedance current output port [7].

Chapter 3

Literature Review

In recent years multi output universal filters received a considerable interest, A number of voltage mode multi output [8-11] and current mode multi output [11-14] universal biquadratic filter have been proposed earlier using CCII+ [8][11], TOCCII [9], OTA [10], DXCCII [12], Zc-CDTA [13] and OFC [14]. All of these filters except [11] operates either in voltage mode or in current mode and most of them uses more than 1 active building block. Literature survey shows that two current mode OFC based universal SIMO filters has been proposed earlier in [14][15] uses more than 1 active block and operates only in current mode.

Recently many single active element biquadratic filters were proposed. However some circuits need to change passive element in order to realize different filter function [8] and some circuit are capable of realizing only three standard filter function at most. Filter reported in [10] requires different voltage input level for realization of notch and all pass function which is practically hard to implement and requires additional circuitry for voltage division and multiplication. A CCII+ Filter proposed in [11] uses single active block and is capable of working both in current and voltage mode which has three input and two output terminals.

Multivibrators [17-24] or Pulse–waveform generators play an important role in instrumentation, communication, and signal processing applications. Typically, a monostable multivibrator is employed to implement such function. Conventionally, a monostable multivibrator is constructed by using a voltage comparator and a clamp diode, together with a timing resistor and a timing capacitor. Although the above implementation is widely adopted in general applications, there still exist some problems as listed below.

- The height of the output pulse is dependent on the supply voltages and not adjustable [17-21][24].
- The required recovery period puts a limit on the maximum repetitive triggering frequency [18][21][22].
- The retriggerable feature, which is more preferable to the engineers for a monostable multivibrator, is usually unavailable [17-21][23][24].

Since the current-mode technique was brought up, it has received considerable interests due to its high performance and functional versatility. Until now, many novel active building blocks have been developed and employed to perform different applications. In the recent years several schemes of monostable multivibrators had been published.

There are many papers published in multivibrators which overcomes above listed limitations such as reduced recovery time [17-20], retrigger function [22], dependency of pulse peak on input supply voltage[22][23], but these circuits has other previously listed limitations. Moreover Multivibrator presented in [22][23] is better than in [17-21][24] because it overcomes limitation of tunable pulse height and width and retriggering[22]. Also it has better recovery time than circuit presented in [20].

A current controlled monostable multivibrator is proposed in [23] has both pulse height and width tuning properties and it can be tuned via the bias currents of the OTAs or the external resistor. In this paper, two more economic schemes are presented. Both of the proposed circuits are composed of two OTAs, one resistor, one capacitor, and an analog switch. Compared to the OTRA-based topologies in [17][24], the proposed monostable circuits, using OTAs feature the following advantages

1. Fewer passive elements are required.
2. Grounded capacitors and resistors are much better than the floating ones considering the easier IC manufacture process and the improved parasitic effects.
3. The pulse width and height are electronically tunable.

A novel current-controllable monostable multi-vibrator is proposed in [22] to achieve a retriggerable characteristic and solve the recovery time problem. The output pulse fluctuates between zero and one positive level, which is different from the previous designs [17-19], and is suitable for electronic circuits operated with a single power supply. Additionally, a ramp function with predefined frequency and peak value can be obtained at the timing capacitor terminal.

A novel monostable multivibrator has been proposed in paper [21] has current tuning property having compact topology. The circuit proposed in this paper has single differential input single output operational transconductance amplifier (DISO-OTA) with a few passive components. It was operated by a negative-edge triggering signal to generate an output pulse. The pulse height and width were tunable by the bias current of DISO-OTA and the external resistors. The proposed multivibrator is more compact than the existing topologies.

Chapter 4

Dual Mode Biquadratic Filter

4.1. Introduction

A number of voltage mode multi output [8-11] and current mode multi output [11-14] universal biquadratic filter have been proposed earlier using CCII+ [8][11], TOCCII [9], OTA [10], DXCCII [12], Zc-CDTA [13] and OFC [14]. Literature survey shows that two current mode OFC based universal SIMO filters has been proposed in [14][15] uses more than 1 active block. OFCC which was introduced in [6] as OFC, combines the feature of current conveyor and CFOA. In our realization, a single OFCC based MIMO universal biquadratic filter has been proposed which is able to realize all second order filter function such as LP, HP, BP, Notch and AP without changing circuit topology and is able to work in both voltage and current modes.

4.2. Circuit description

4.2.1. Voltage Mode Operation

The proposed voltage mode circuit Fig 4.1 has two resistors two capacitors with one active component (OFCC). From the circuit in Fig 4.1 node equations can be written as

$$SC_1(V_{o1} - V_{o2}) + G_1(V_{o1} - V_1) = 0 \tag{4.1}$$

$$SC_1(V_{o1} - V_{o2}) + SC_2(V_{o2} - V_1) + G_2(V_{o2} - V_2) = 0 \tag{4.2}$$

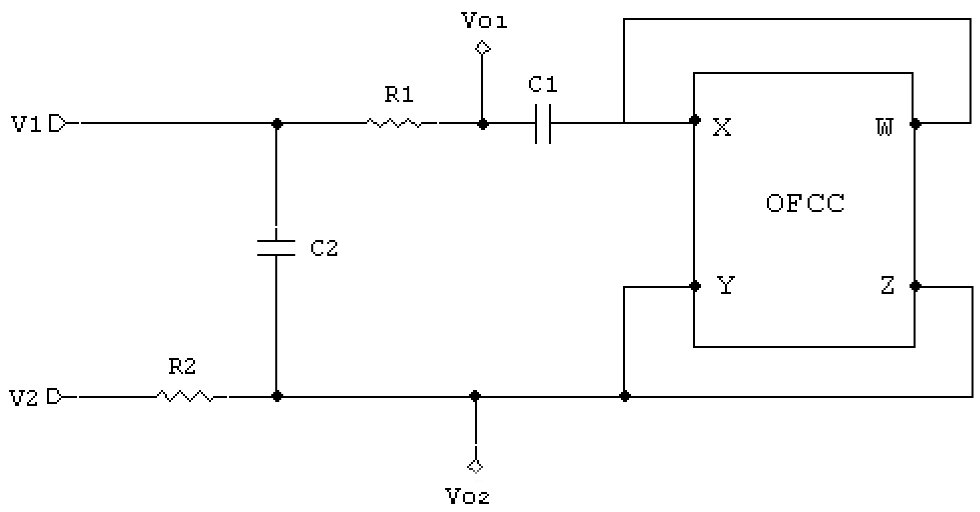

Fig 4.1: Proposed Voltage Mode Filter

Solving for V_{o1} and V_{o2} from equation 4.1 and 4.2

$$V_{o1} = \frac{S^2C_1C_2V_1 + S\{C_1G_2V_2 + (C_2 - C_1)G_1V_1\} + G_1G_2V_1}{S^2C_1C_2 + S(C_1G_2 + C_2G_1 - C_1G_1) + G_1G_2} \tag{4.3}$$

$$V_{o2} = \frac{S^2C_1C_2V_1 + S\{C_1G_2V_2 + (C_2 - C_1)G_1V_1\} + G_1G_2V_2}{S^2C_1C_2 + S(C_1G_2 + C_2G_1 - C_1G_1) + G_1G_2} \tag{4.4}$$

From the equation (4.3) and (4.4) we can see that:

- If $V_2 = V_{in}$ and $V_1 = 0$ (ground), Band Pass response can be obtained at V_{o1} and Low Pass response can be obtained at V_{o2}.
- If $V_1=V_{IN}$, $V_2 = 0$ (ground) and $C_1=C_2$, Notch response can be obtained at V_{o1} and High Pass response can be obtained at V_{o2}.
- If $V_1=V_{IN}$, $V_2 = 0$ (ground) and $C_1=2C_2$, All Pass response can be obtained at V_{o2}.

Therefore, our circuit is able to realize all transfer functions i.e. LP, HP, Band Pass, Notch and All Pass. Without changing the circuit topology same circuit can work in current mode as shown in fig 4.2.

4.2.2. Current Mode Operation

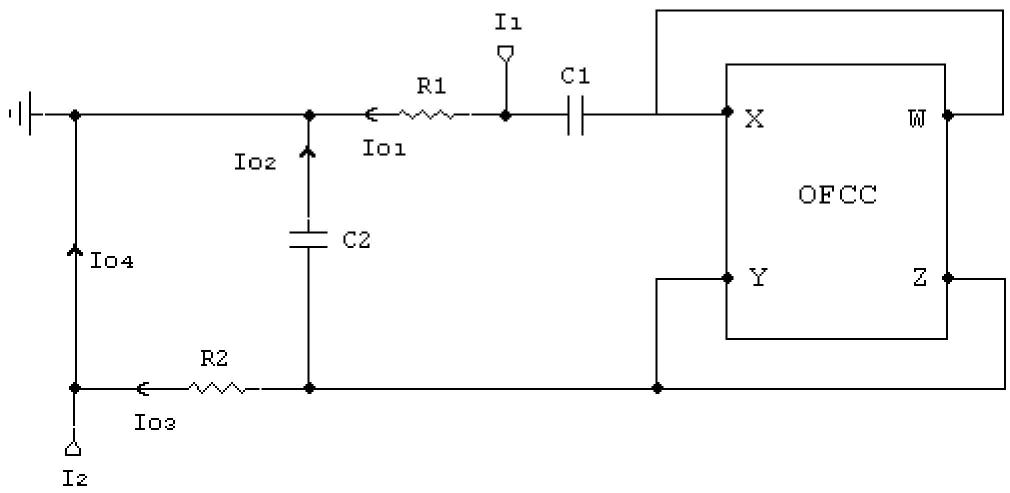

Fig 4.2: Proposed Current mode filter

From the circuit output current I_{o1}, I_{o2}, I_{o3}, I_{o4} can be calculated as:

$$I_{o1} = \frac{S\{(C_2 - C_1)G_1 I_1\} + G_1 G_2 I_1}{S^2 C_1 C_2 + S(C_1 G_2 + C_2 G_1 - C_1 G_1) + G_1 G_2} \tag{4.5}$$

$$I_{o2} = \frac{-S^2 C_1 C_2 I_1}{S^2 C_1 C_2 + S(C_1 G_2 + C_2 G_1 - C_1 G_1) + G_1 G_2} \tag{4.6}$$

$$I_{o3} = \frac{-S C_1 G_2 I_1}{S^2 C_1 C_2 + S(C_1 G_2 + C_2 G_1 - C_1 G_1) + G_1 G_2} \tag{4.7}$$

$$I_{o4} = \frac{S^2 C_1 C_2 I_2 + S\{(C_1 G_2 + C_2 G_1 - C_1 G_1) I_2 - C_1 G_2 I_1\} + G_1 G_2 I_2}{S^2 C_1 C_2 + S(C_1 G_2 + C_2 G_1 - C_1 G_1) + G_1 G_2} \tag{4.8}$$

From equations 4.5-4.8, following can be observed

- If $I_1=I_2=I_{IN}$ and $C_1=C_2$, Low Pass response can be obtained at I_{o1}, High Pass response can be obtained at I_{o2}, Band Pass response can be obtained at I_{o3} and Notch response can be obtained at I_{o4}.
- If $I_1=I_2=I_{IN}$ and $C_1=2C_2$, All Pass response can be obtained at I_{o4}.

From the above analysis it has been seen that voltage and current mode filter responses can be obtained without changing circuit topology where each of circuit uses two resistors, two capacitors and one OFCC.

Resonant frequency ω_o and Quality factor Q of the circuits proposed in fig 4.1 and fig 4.2 are

$$\omega_o = \sqrt{\frac{1}{R_1R_2C_1C_2}} \tag{4.9}$$

$$Q = \frac{\sqrt{R_1R_2C_1C_2}}{C_1R_1 + C_2R_2 - C_1R_2} \tag{4.10}$$

4.3. Sensitivity and Non-Ideal Analysis

Sensitivity analysis on filter parameters ω_o and Q relating to active and passive parameters R_i and C_i (i=1,2) are:

$$S_{R_1}^{\omega_o} = S_{R_2}^{\omega_o} = S_{C_1}^{\omega_o} = S_{C_1}^{\omega_o} = -\frac{1}{2}$$

$$S_{R_1}^{Q} = \frac{1}{2} - \frac{C_1R_1}{C_1R_1 + C_2R_2 - C_1R_2}$$

$$S_{R_2}^{Q} = \frac{1}{2} + \frac{R_2(C_1 - C_2)}{C_1R_1 + C_2R_2 - C_1R_2}$$

$$S_{C_1}^{Q} = \frac{1}{2} - \frac{C_1(R_1 - R_2)}{C_1R_1 + C_2R_2 - C_1R_2}$$

$$S_{C_2}^{Q} = \frac{1}{2} - \frac{C_2R_2}{C_1R_1 + C_2R_2 - C_1R_2}$$

For LP, HP, BP, Notch filter response $R_1=R_2$, $C_1=C_2$

$$\text{Hence, } S^{Q}_{R_1} = S^{Q}_{R_2} = S^{Q}_{C_1} = -S^{Q}_{C_2} = \frac{1}{2}$$

Taking account of non-ideal OFCC, transimpedance gain Z_t using single pole model is given by,

$$Z_t(s) = \frac{Z_{to}}{1 + \frac{s}{\omega_o}}$$

Where Z_{to} is DC open loop transimpedance gain and ω_o is transimpedance cutoff frequency. For high frequency applications, transimpedance gain $Z_t(s)$ will be

$$Z_t(s) = \frac{1}{sC_p}$$

Where

$$C_p = \frac{1}{Z_{to}\omega_o}$$

Taking account of single pole model (Z_t), the output voltage equations of (4.3) and (4.4) will become:

$$V_{o1} = \frac{S^2\varepsilon C_1C_2V_1 + S\{\varepsilon C_1G_2V_2 + (C_2 - \varepsilon C_1)G_1V_1\} + G_1G_2V_1}{S^2\varepsilon C_1C_2 + S(\varepsilon C_1G_2 + C_2G_1 - \varepsilon C_1G_1) + G_1G_2} \tag{4.11}$$

$$V_{o2} = \frac{S^2\varepsilon C_1C_2V_1 + S\{\varepsilon C_1G_2V_2 + (C_2 - \varepsilon C_1)G_1V_1\} + G_1G_2V_2}{S^2\varepsilon C_1C_2 + S(\varepsilon C_1G_2 + C_2G_1 - \varepsilon C_1G_1) + G_1G_2} \tag{4.12}$$

Where

$$\varepsilon(s) = \frac{1}{1 + sC_pR_1}$$

4.4. REALIZATION OF OFCC USING AD844

The AD844 is a high speed monolithic operational amplifier fabricated using Analog Devices' junction isolated complementary bipolar (CB) process [29]. It combines high bandwidth and very fast large signal response with excellent dc performance. Although optimized for use in current to voltage applications and as an inverting mode amplifier, it is also suitable for use in many non- inverting applications. The AD844 can be used in place of traditional op amps, but its current feedback architecture results in much better ac performance, high linearity and an exceptionally clean pulse response.

This type of op amp provides a closed-loop bandwidth which is determined primarily by the feedback resistor and is almost independent of the closed-loop gain. The AD844 is free from the slew rate limitations inherent in traditional op amps and other current-feedback op amps.

OFCC port relationship can be obtained using AD844 as circuit shown in figure 4.3. From the first AD844 and matrix 2.3 following relations are obtained:

$$V_X = \beta_1 V_Y \tag{4.13}$$

$$V_{o\_AD844\_1} = \alpha_1 \gamma_1 I_X . R_{Zt} \tag{4.14}$$

And from second AD844 and matrix 2.3 following relations are obtained:

$$V_W = \beta_2 V_{o\_AD844\_1}$$

Or it can be rewritten as

$$V_W = \beta_2 \alpha_1 \gamma_1 I_X . R_{Zt} \tag{4.15}$$

And

$$I_Z = \alpha_2 I_W \tag{4.16}$$

Rewriting equations 4.13, 4.14, 4.15 and 4.16 in matrix form and taking all non-linear gain to unity

$$\begin{bmatrix} V_x \\ I_y \\ V_w \\ I_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ R_{Zt} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ I_w \\ V_z \end{bmatrix} \tag{4.1}$$

This is same as OFCC port relationship matrix 2.1. Thus OFCC block in the proposed circuit is realized using AD844 as shown in Fig 4.3 and it is easy to implement than previous realizations in [7][16]. High frequency responses of OFCC realized using AD844 are better than previous OFCC realizations using AD846 and BJT [7] and using CMOS technology [16].

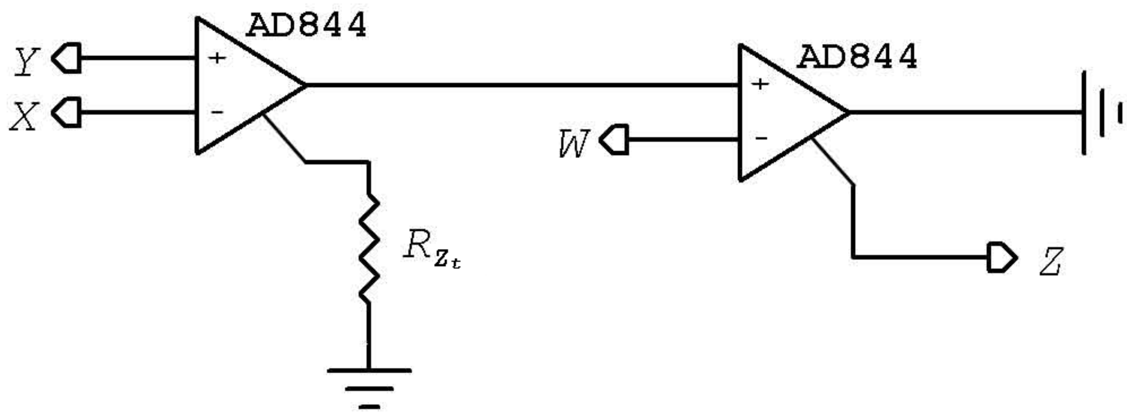

Fig 4.3: Implementation of OFCC using AD844

4.5. SIMULATION RESULTS

Circuit functionality of the proposed voltage mode and current mode biquad shown in fig 4.1 and fig 4.2 has been simulated using Pspice. OFCC has been implemented using commercially available IC AD844 for feasibility as shown in fig 4.3. Experiment has been formed at supply voltage of ±5V. Fig 4.4 shows the experimental frequency response of Notch at V_{o1} and High Pass at V_{o2} obtained simultaneously when V_1=V_{in}, V_2= 0 (grounded) and fig 4.5 shows experimental frequency response of Band Pass at V_{o1} and Low Pass at V_{o2} obtained simultaneously when V_2=V_{in}, V_1=0 (grounded). The values of passive components during simulation were R_1=R_2=1K, C_1=C_2= 0.1n. To obtain all pass response at V_{o2} as shown in fig 4.6 value of C_1 should be chosen double the value of C_2 (C_1=2C_2=0.1n) when V_1=V_{in}, V_2= 0 (grounded) and R_1=R_2=1K.

Notch, HP, BP, LP response curve corresponding to f_o=159KHz, f_o=318KHz, f_o=636KHz, f_o=1.59MHz corresponding to C_1=C_2=1n, C_1=C_2=0.5n, C_1=C_2=0.25n and C_1=C_2=0.1n respectively are shown in Fig 4.7, Fig 4.8, Fig 4.9, Fig 4.10 respectively shows excellent relation with theoretically calculated values.

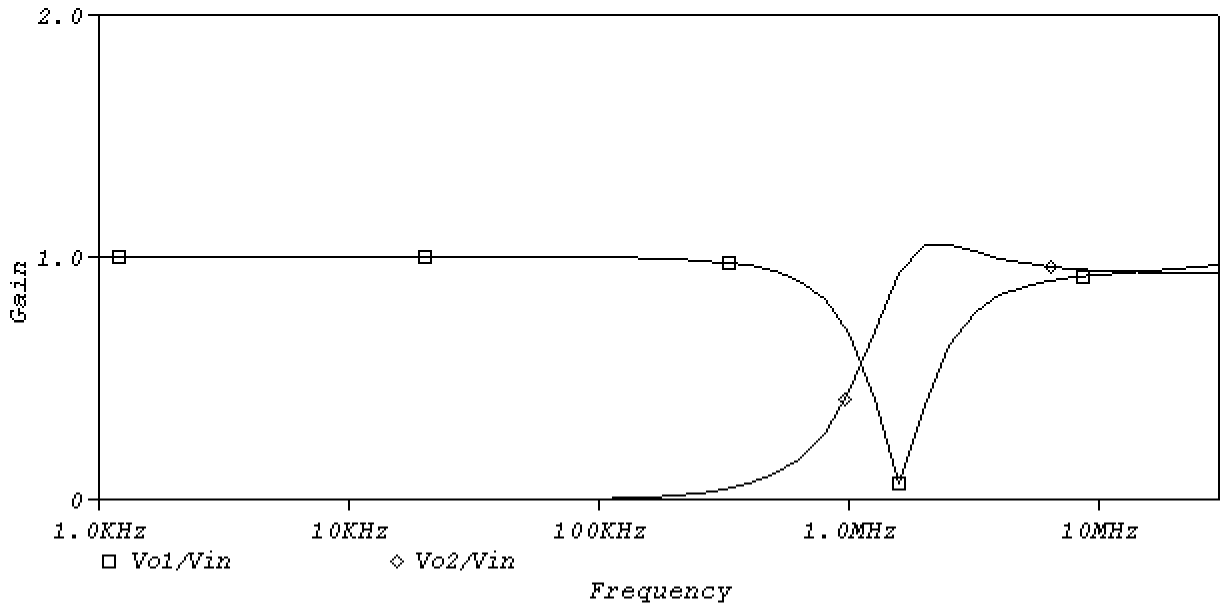

Fig 4.4: Notch response at Vo1 and High pass response at Vo2 {When V1 = Vin, V2= 0 and C1=C2}

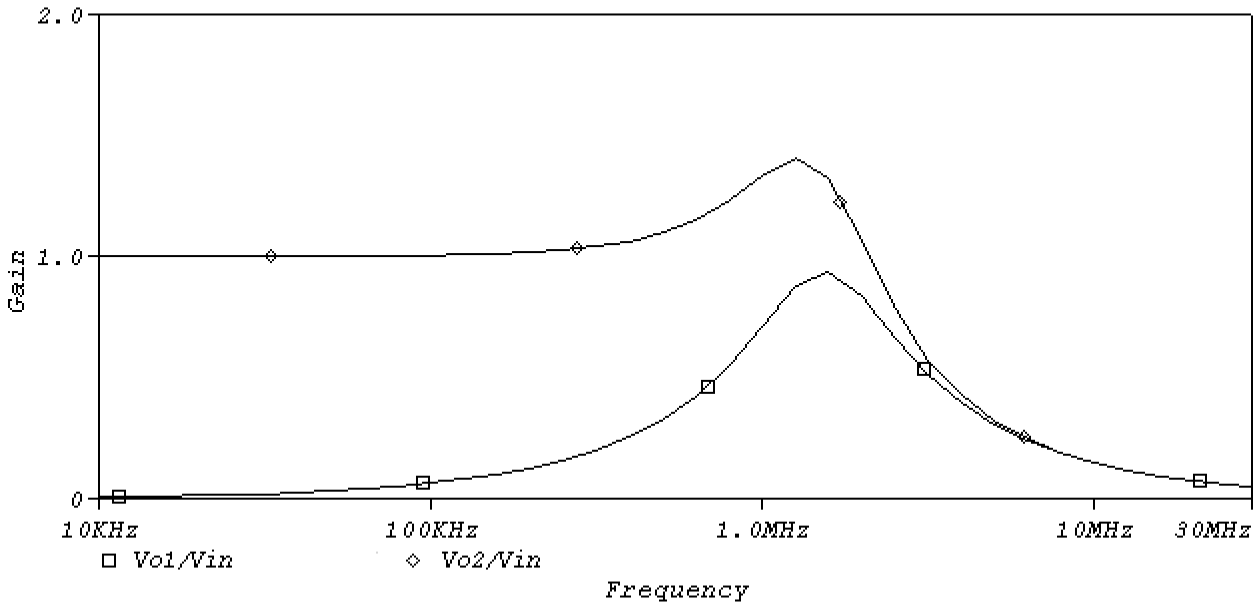

Fig 4.5: Band pass response at Vo1 and Low pass response at Vo2 {When V1 = 0, V2= Vin and C1=C2}

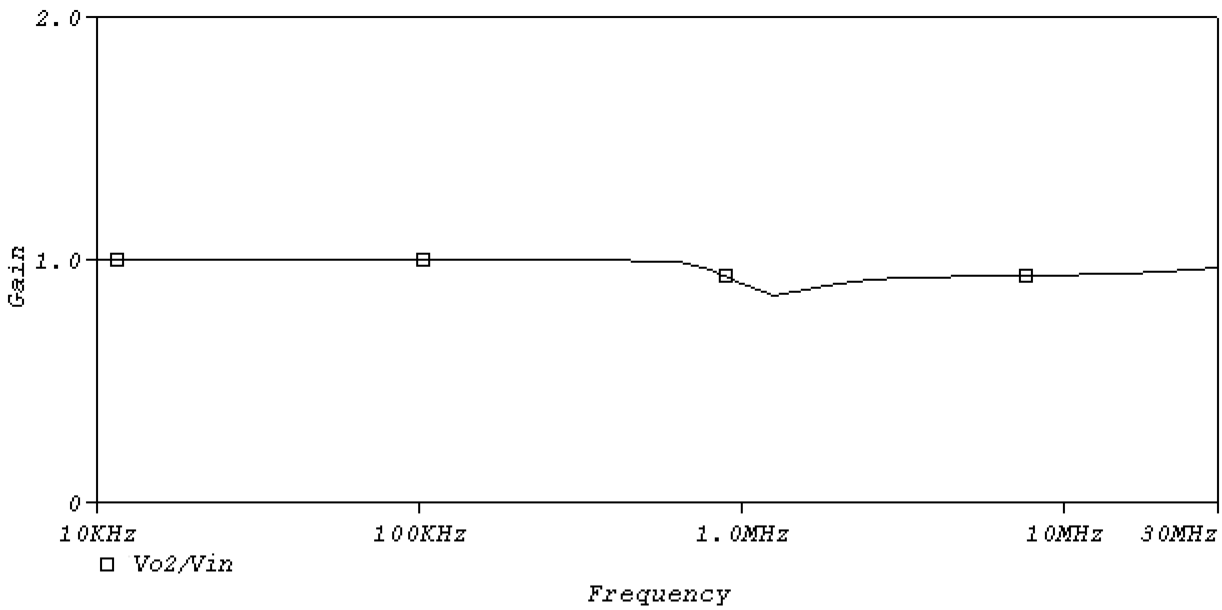

Fig 4.6: All Pass response {When V1 = Vin, V2= 0 and C1=2C2, C2=0.1n}

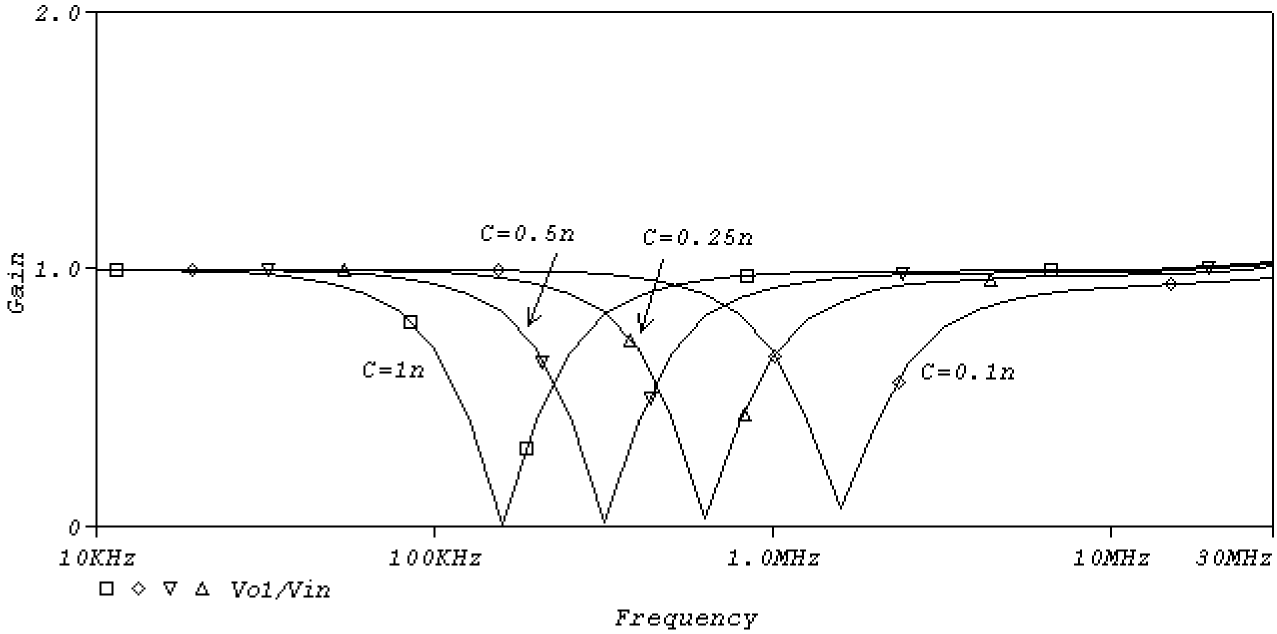

Fig 4.7: Notch response at (C = 1n, 0.5n, 0.25n, 0.1n) at Vo1 {When V1 = Vin, V2= 0 and C1=C2=C}

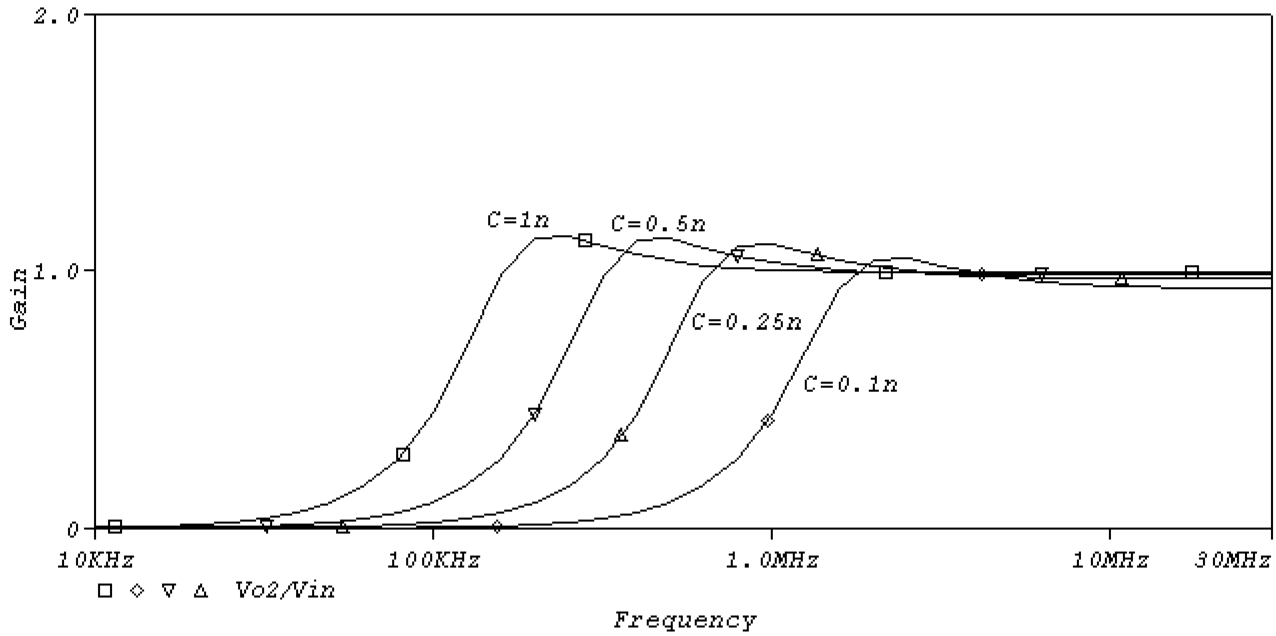

Fig 4.8: High Pass response at (C = 1n, 0.5n, 0.25n, 0.1n) at Vo2 {When V1 = Vin, V2= 0 and C1=C2=C}

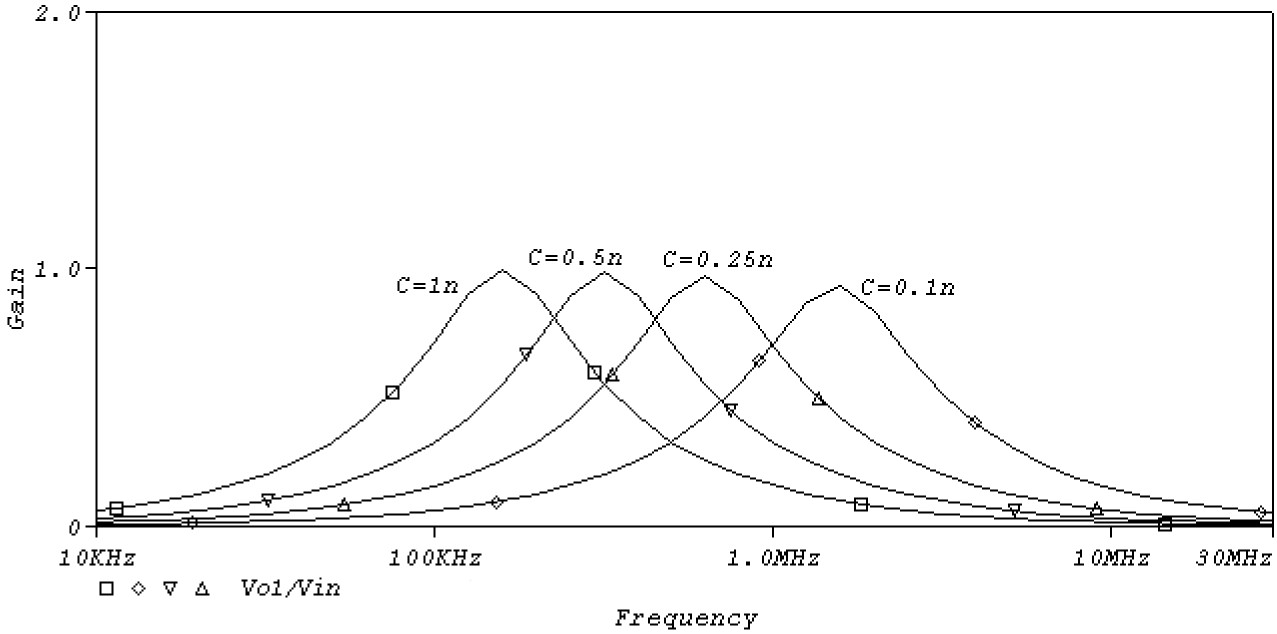

Fig 4.9: Band Pass response at (C = 1n, 0.5n, 0.25n, 0.1n) at Vo1 {When V1 = 0, V2= Vin and C1=C2=C}

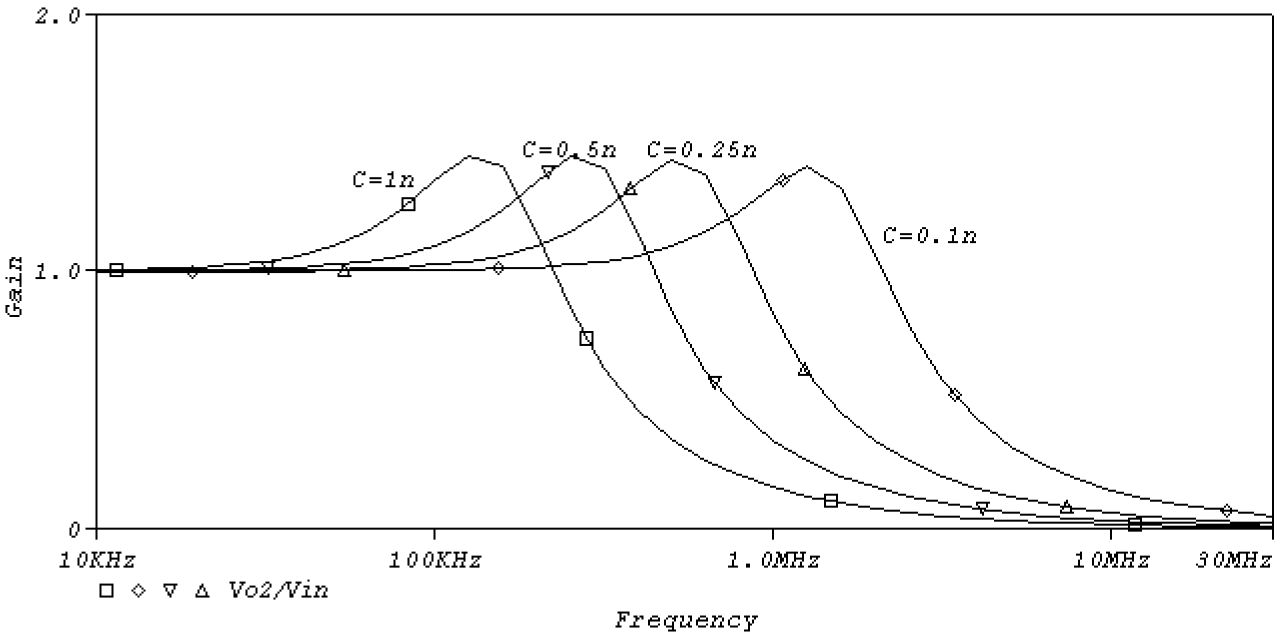

Fig 4.10: Low Pass response at (C = 1n, 0.5n, 0.25n, 0.1n) at Vo2 {When V1 = 0, V2= Vin and C1=C2=C}

Chapter 5
Monostable Multivibrator using CCII+

5.1. Introduction

In early active RC circuit designs, operational amplifier was used in realization of monostable circuits along with number of external passive components [4]. Since the introduction of current conveyor in 1968, various electronic circuits were built using these modern active devices due to their inherent higher signal bandwidth, greater linearity, larger dynamic range, and simpler circuitry. Several novel monostable multivibrators have been proposed in related literature using DVCC[20], OTRA[17][24] , several types of OTA's including SISO-OTA, SIMO-OTA, DISO-OTA, DIMO-OTA[18][21][22][23]. Most of these monostable circuits are based on voltage comparison with either their predefined voltage level or with the voltage level which is tuned electronically. Literature survey reveals that till now no monostable circuit is present using current conveyor because one of its input port has very low impedance level and simple voltage comparator couldn't be formed using it. The Monostable multivibrator using CCII which is proposed here uses the concept of Schmitt trigger proposed in [27].

5.2. Circuit Description and Operation

A monostable multivibrator-I using CCII is proposed. Circuit comprises single CCII+ and four passive components (Two resistors, one capacitor and one analog switch) as shown in fig 5.1. Circuit is triggered by negative-edged triggering signal to produce a pulse of predetermined height and width. The corresponding waveform of the circuit proposed is shown in fig 5.2. In saturation mode voltage at terminal Z is written as

$$V_Z = \begin{cases} V_{SAT+} & if\ V_Y \geq V_X \\ V_{SAT-} & if\ V_Y \leq V_X \end{cases} \tag{5.1}$$

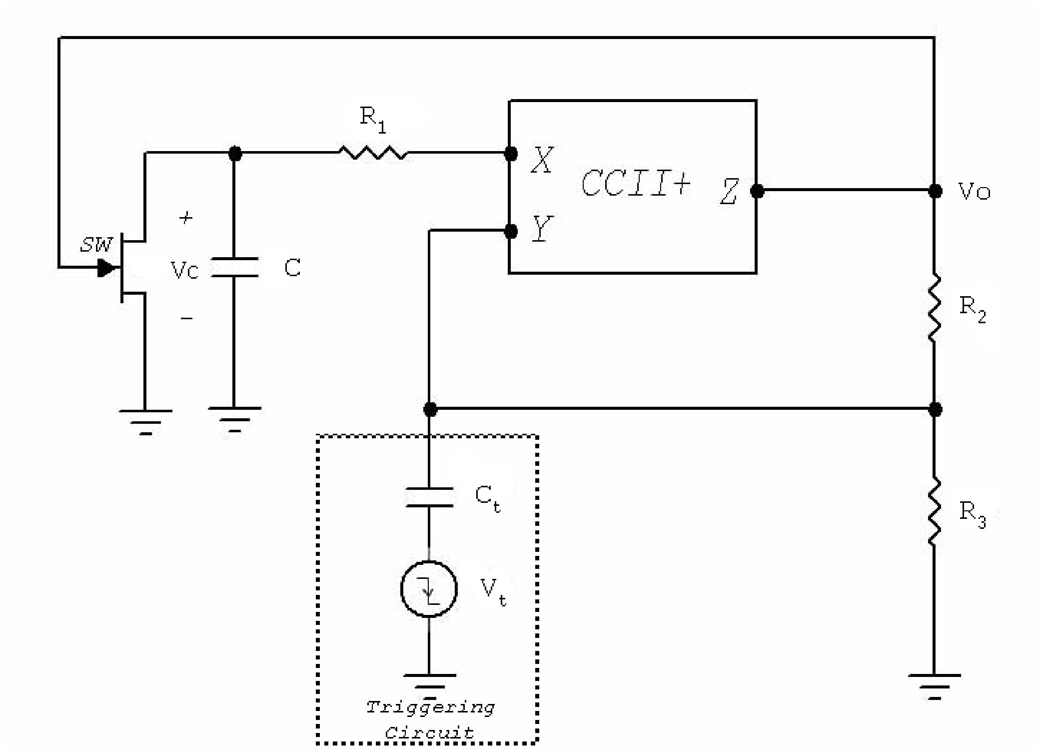

Fig 5.1: Proposed Monostable Multivibrator-I using CCII+

A part of output voltage from terminal Z is fed back to the terminal Y as Schmitt trigger proposed in [27] using CCII.

From [27] the threshold voltage at terminal Y using regenerative feedback for the circuit show in fig 5.1 is

$$V_{TH+} = \frac{R_3 - R_1}{R_3 + R_2} V_{SAT+}$$

(5.2)

$$V_{TH-} = \frac{R_3 - R_1}{R_3 + R_2} V_{SAT-}$$

(5.3)

where V_{SAT+} and V_{SAT-} are the positive and negative output saturation voltage of the CCII respectively.

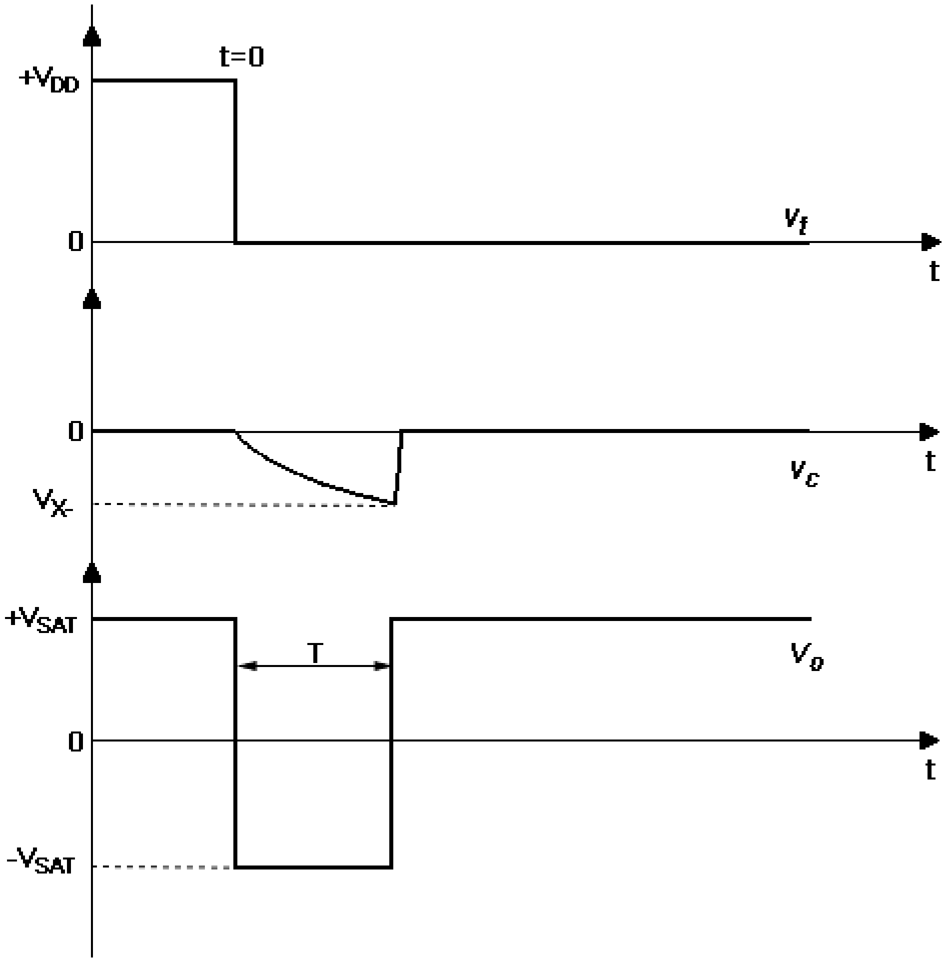

Fig 5.2 Corresponding waveform of the proposed circuit

Circuit operation has been divided into two modes, discussed as follows:

Mode 1 (Stable State): Since feedback from terminal Z is applied to terminal Y of CCII, output voltage of terminal Z will reach either of saturation level V_{SAT+} or V_{SAT-}. Let's assume initially the output voltage of terminal Z is at V_{SAT+} therefore the analog switch which is driven by the node voltage of terminal Z is in on state thus capacitor C is short circuited and V_C=0.

Now from the circuit 5.1, the voltage at terminal Y will be

$$V_{Y+} = \frac{R_3}{R_2 + R_3} V_{SAT+}$$

and voltage of terminal X will be

$$V_{X+} = \beta \frac{R_3}{R_2 + R_3} V_{SAT+}$$

Where $\beta = 1 - \varepsilon_v$ and ε_v is the voltage tracking error between port X and Y. In stable state, terminal voltage Y will be slightly higher than terminal voltage X due to voltage tracking error ε_v.

When a negative-edged triggering signal V_t is applied in terminal Y, circuit enters into quasi-stable state.

Mode 2 (quasi-stable state): When triggering signal V_T falls from high to low level, voltage at terminal Y will fall below the voltage at terminal X and output immediately jumps from positive saturation level V_{SAT+} to negative saturation level $V_{SAT,}$ which turns off analog switch and capacitor starts charging from zero to threshold voltage level V_{TH-} Capacitor voltage V_C can be expressed as

$$V_C = \left(1 - e^{-\frac{t}{R_1 C}}\right) V_{X-}$$

where

$$V_{X-} = \beta \frac{R_3}{R_2 + R_3} V_{SAT-}$$

Current I_X or capacitor charging current as a function of time could be written as:

$$I_X = \frac{V_{X-}}{R_1} e^{-\frac{t}{R_1 C}}$$

Since CCII operates in saturation mode, I_Z can be expressed as

$$I_Z = \frac{V_{SAT}}{R_2 + R_3}$$

As soon as V_C reaches V_{X-} output returns to positive saturation level V_{SAT+}. Now analog switch turns on and prevents further charging and discharging of capacitor C by shorting it.

Pulse width T can be derived as

$$T = -R_1 C \ln\left(1 - \frac{\alpha(R_3 - R_1)}{\beta R_3}\right)$$

$$V_o = \left(1 - \frac{R_2 + R_3}{R_1}\alpha\beta I_C\right)V_{SAT}$$

Since output is a function of capacitor current, we can see a slight variation in output voltage during quasi-stable state called as pulse height error. To overcome this problem another CCII is used in series and monostable multivibrator-II is proposed as shown in fig 5.3.

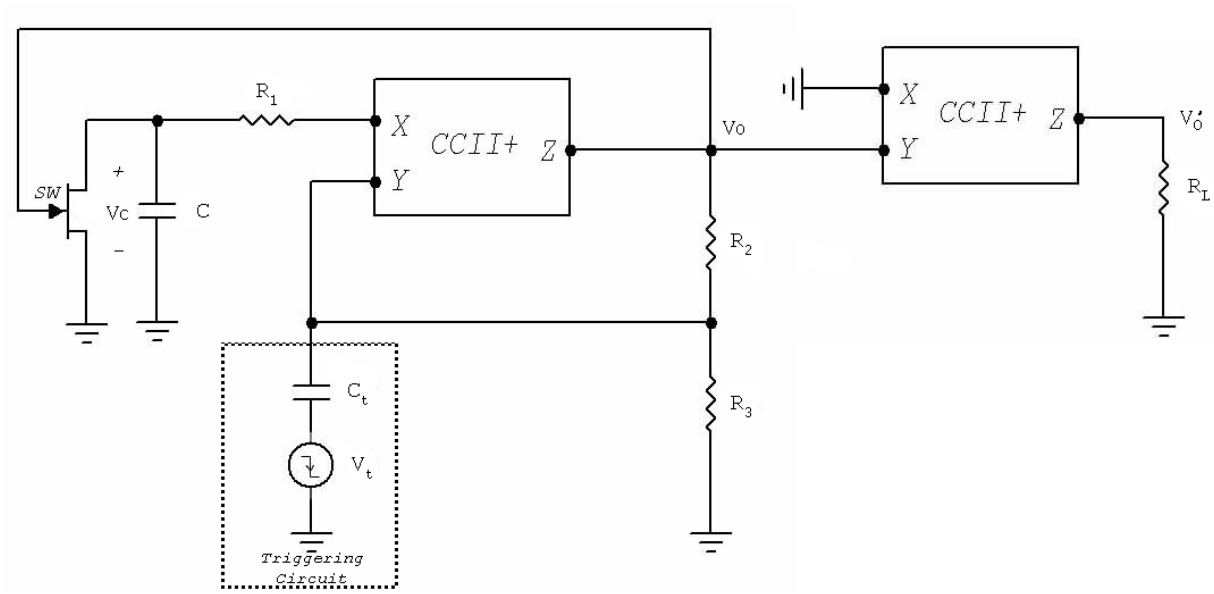

Fig 5.3: Proposed Monostable Multivibrator-II using CCII+

In proposed multivibrator circuit-II, circuit-I is followed by second CCII+ as shown in fig 5.3. The output from second CCII is free from pulse height error, since both CCII are operating in saturation mode. The output voltage from circuit II will be exactly equal to the saturation voltage of CCII+,

$$V'_o = V_{SAT}$$

5.3. Simulation Result

Simulation has been performed to verify the working of circuit using Pspice. A model of AD844/AD has been used to realize CCII+ and CD4066BC for analog switch [28]. All experiments are performed at supply voltage of $\pm 5V$. In triggering circuit C_t = 5pF used. Several tests have been performed according to the design procedure. R_1 = 1k is chosen to minimize the current during stable state. During several experiments with different value of R_2 and R_3 and it has been observed that for proper circuit operation the ratio of R_2/R_3 must be greater than 1 ($R_2/R_3 = 1$). R_2 = 6k is chosen, and for T=15us, T=10us and T=1us value of R_3 is calculated as 6K, 3K and 3k and value of C is calculated as 10uF, 10uF and 1uF respectively. Corresponding waveforms are shown in fig 5.4, fig 5.5 and fig 5.6.

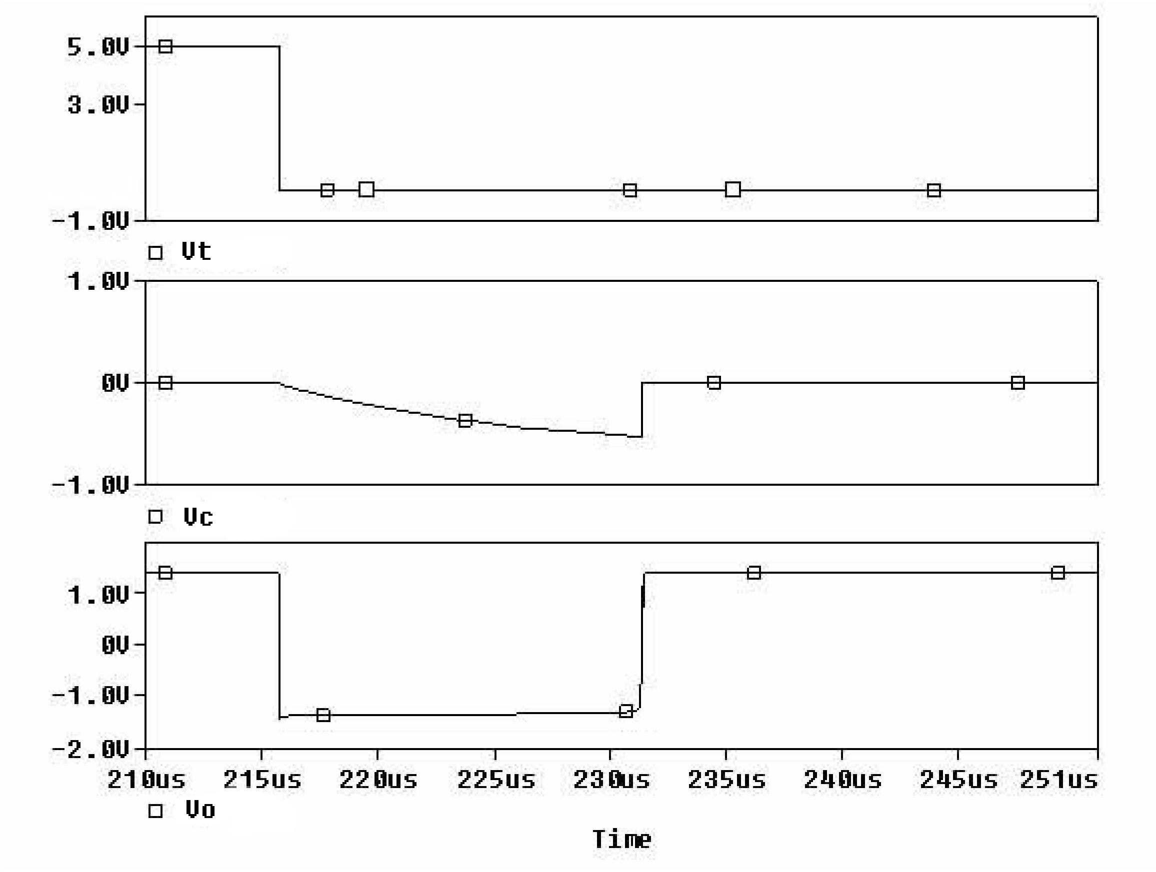

Fig 5.4: Simulation Result (T=15ms)

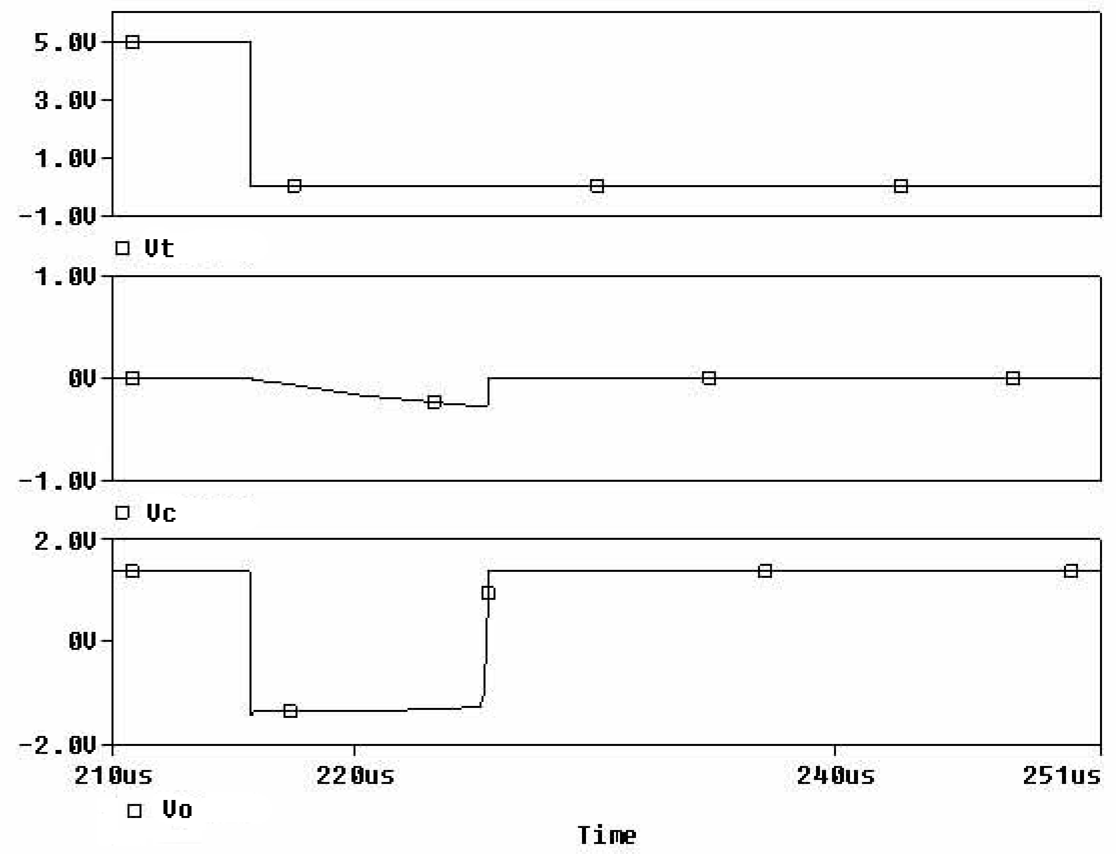

Fig: 5.5: Simulation Result (T=10ms)

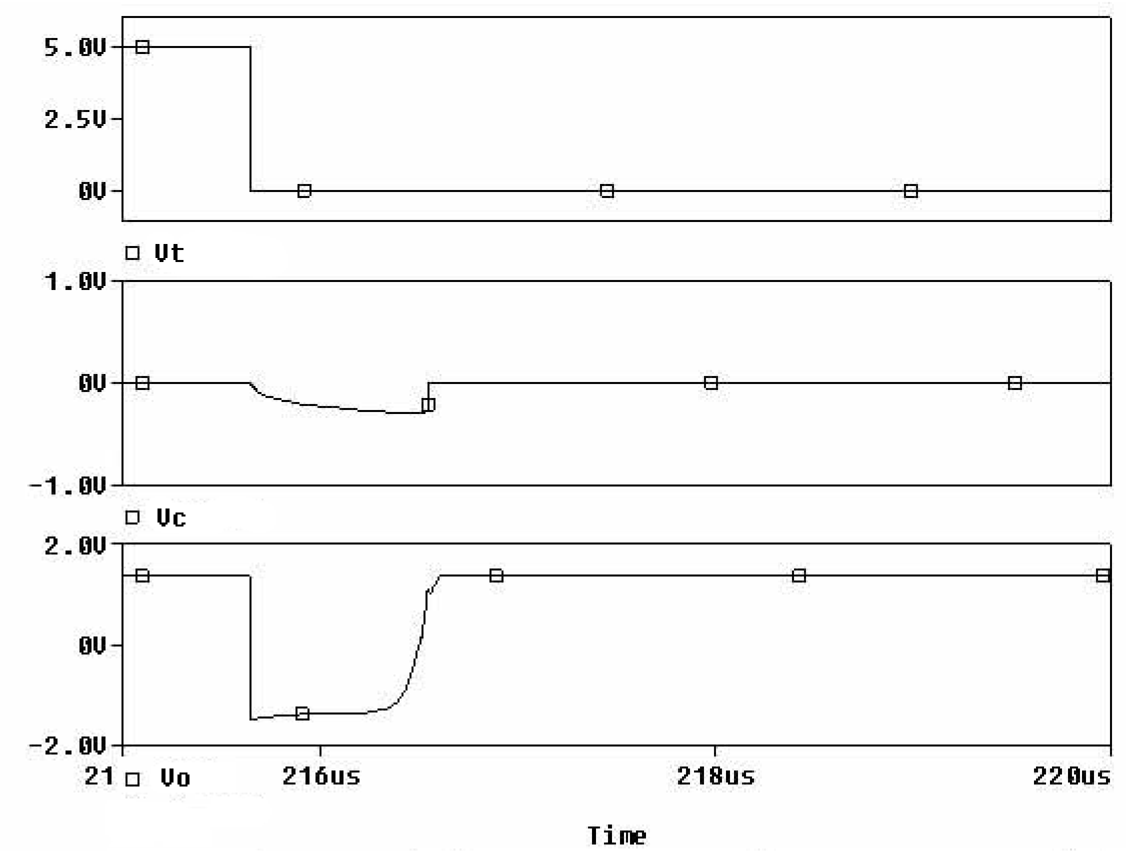

Fig 5.6: Simulation Result (T=1us)

From fig 5.6, pulse height error in output can be easily noticed. From simulations it has been observed that as we decrease T from below 1.5us pulse height error increases significantly imposing a limit on further decrease of pulse width T.

Further, simulation of proposed monostable multivibrator-II with two CCII as shown in figure 5.3 has been performed. Since CCII operates in saturation modes choosing any value of R_L will not affect output pulse height and it has been chosen to 10K (R_L=10K). Tests are performed on improved circuit by selecting the same values as previously calculated R3=3K, C=1uF for T=1us for the simulation, corresponding results are shown in fig. 5.7.

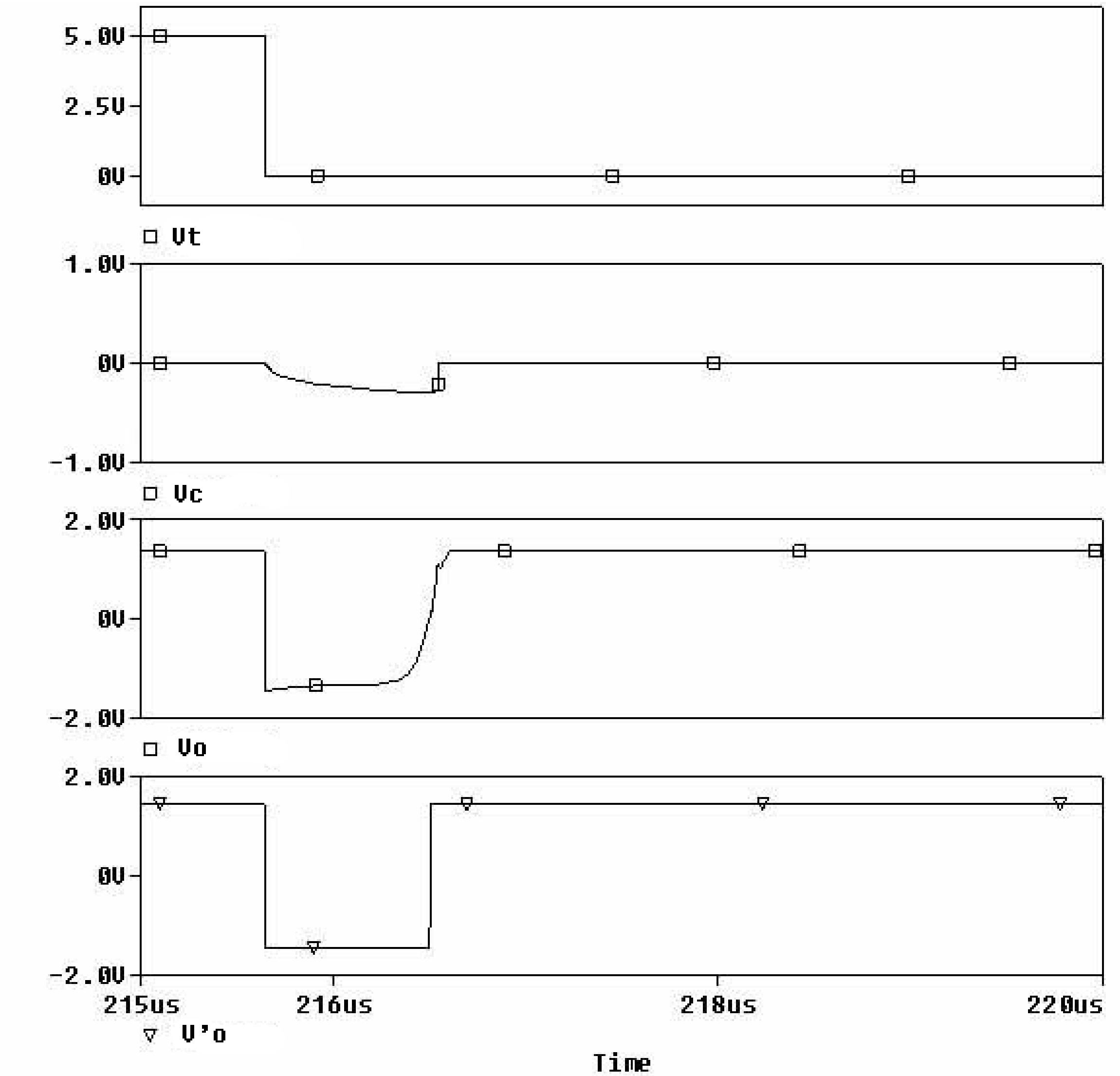

Fig 5.7: Simulation Result for Improved Circuit (T=1us)

Minimum pulse width is mainly limited by the slew rate of IC used AD844. A capacitor of 0.12uF and R_3=3K is taken to execute the experimental test and result is shown in fig. 5.8. The output from first stage V_o which is the output of proposed multivibrator-I is distorted but from second stage V_o' which is the output of proposed multivibrator-II is still useful and pulse width T is found to be 0.12us approximately.

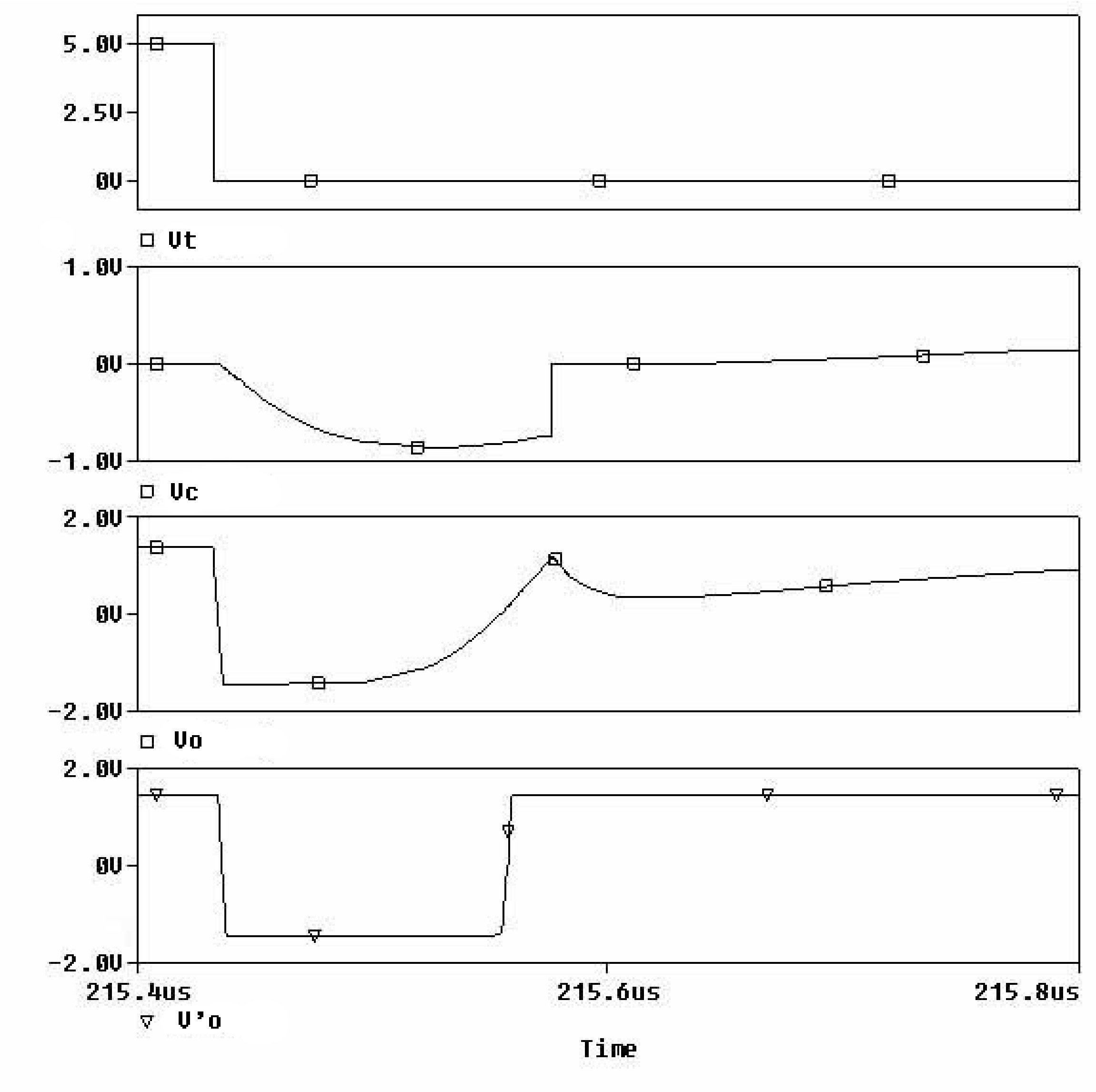

Fig 5.8: Simulation Result for Improved Circuit (T=0.12us)

Chapter 6

Conclusion and Future Work

6.1. Conclusion

A Dual Mode Biquadratic filter using Operational Floating Current Conveyor (OFCC) has been presented with Multi Input Multi Output (MIMO) which can be used either in voltage mode or current mode. In both modes circuit shows excellent relation with the theoretical calculations. Deviation of simulation results from theory was less than 1% and it was due to non-ideal characteristics of the block used. Also a new implementation of OFCC has been shown with widely available commercial CFOA IC AD844 which is better than previous implementations using AD846 and BJT [7] and using CMOS technology [16] in terms of high frequency operation and complexity.

In another section of the thesis, A Monostable Multivibrator using CCII+ has been presented with negligible recovery time. Also the minimum obtainable pulse width from monostable multivibrator was 1.5 us with pulse height error less than 2% which is lowest from the existing circuits available although pulse height depends on supply voltage which is undesirable in some conditions. Output pulse width could also be reduced to less than 0.1us on the cost of error in pulse height. Further, an improved monostable multivibrator using two CCII+ has been proposed which nullifies the error in pulse height which arises when output pulse width was less than 1us and by using improved circuit minimum pulse width achieved at output is 0.1us with sharp rising and falling edges and is mainly limited by the slew rate of IC used AD844.

6.2. Future Work

Presently in current mode of presented biquadratic filter, current output is taken from component itself which is undesirable and further improvements are to be done to make it component-free either by changing circuit topology or by using another building block and by keeping the circuit simple. Also, further improvements are to be done on multivibrator circuit presented to overcome the limitation of dependency of pulse height on supply voltage and to make pulse height electronically tunable.

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