CURRENT DIFFERENCING TRANSCONDUCTANCE AMPLIFIERS (CDTAs) AND THEIR APPLICATIONS IN SIGNAL PROCESSING

DISSERTATION REPORT

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CERTIFICATE

This is to certify that the dissertation titled "**Current Differencing Transconductance Amplifiers (CDTAs) and their applications in Signal Processing**" submitted in partial fulfilment of the requirements for the award of the degree of Master of Technology in Control and Instrumentation (C&I) by **Pramila (Roll No: 2K11/C&I/07)** is a bonafide record of the candidate's own work carried out by her under my supervision and guidance.

This work has not been submitted earlier in any university or institute for the award of any degree to the best of my knowledge.

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ABSTRACT

The basic important building blocks which are frequently employed in Analog Signal Processing are Amplifiers, Oscillator and Filters. In the present work an active building block Current Differencing Transconductance Amplifier, especially suitable for analog signal processing is presented. CDTA is a current mode element whose input and output signals are currents where output current of CDTA can be electronically adjusted. In this dissertation various other active devices which are useful in analog signal processing are briefly described. PSPICE simulation results of CDTA using the parameters of 0.5µm MIETEC CMOS technology and transistor model parameters of PR100 N(PNP) and NR100 N(NPN) of the bipolar arrays ALA400 from AT&T are included to verify the expected values. Various signal processing applications of CDTA namely, amplification, integration, differentiation have been presented. Current-mode, Voltage-mode and mixed-mode filter circuits using CDTA as the active building block have been included in the dissertation. Applications of CDTAs in realization of harmonic oscillators have also been presented. Finally a resonator based universal filter using CDTA has been presented.

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Chapter 1

Introduction

1.1 Introduction to Signal Processing

This dissertation presents Current Differencing Transconductance Amplifiers (CDTAs) and their applications in Signal Processing. Signal processing is the enabling technology for transformation, interpretation and generation of information. Signal processing is involved in many applications such as instrumentation, communication systems, biomedical systems, control systems etc, and can be implemented in two different ways: analog signal processing and digital signal processing.

1.1.1 Analog signal processing

Any signal processing conducted on analog signals by analog means is termed Analog signal processing. "Analog" indicates something that is mathematically represented as a set of continuous values. Analog values are typically represented as a voltage, electric current, in electronic/electrical systems. This differs from "digital" which uses a series of discrete quantities to represent signal. An error or noise affecting such physical quantities will result in a corresponding error in the signals represented by such physical quantities.

The various analog signal processing techniques used are Convolution, Laplace transform, Fourier transform etc.

1.1.2 Digital signal processing

In most general form Digital Signal processing refers to the processing of analog signal by means of discrete time operation implemented on digital hardware. In digital signal processing the input and output signals are analog but the processing is done on the equivalent digital signals. A digital signal processing system can be understood as follows:

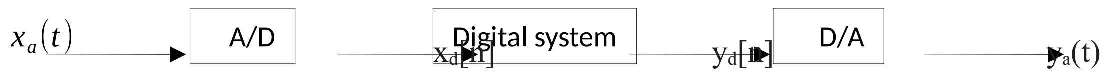


Figure 1.1 Digital signal processing system

1.2 Brief summary of various devices used in analog signal processing

Traditionally analog signal processing had been performed with discrete components available commercially at a particular point of time. Vacuum tube based amplifiers, Bipolar Transistors and Field Effect Transistors have all been used in different signal processing applications namely, amplification, integration, differentiation, filtering and signal generation. With the advent of integrated circuits IC based devices replaced the discrete devices used in analog signal processing. Voltage operational amplifier more popularly known as Op-Amp was introduced in market around mid-sixties and became the most popular active building block used in most of the analog signal processing application. Soon afterwards other active building blocks like operational transconductance amplifier (OTA), current conveyor (mostly in integrable form), current feedback amplifier (CFA) were also introduced in the domain of analog signal processing. Each of these devices had some special feature not available in traditional Op-Amp. The OTA for example was a differential voltage controlled current source in which the output was a controlled current (a natural choice for current mode circuits). Similarly the CFA has a very high value of slew rate (around 2500v/µsec) compared to the traditional Op-Amp (0.5 v/µsec.). During the last decade and half, because of rapid advances in semiconductor technology the supply voltage requirements for digital subsystems, which are generally integrated on the same chip along with analog subsystems has gone down. This has necessitated introduction of new analog building blocks capable of working with very low supply voltages. In the following we present a review of some of the active building blocks which have been introduced in the domain of analog signal processing during the last two decades. The section starts with a very brief introduction of current conveyors, operational transconductance amplifiers and current feedback amplifiers because most of the new building blocks are based on modification of the basic architecture of these blocks.

Current Conveyors

Current conveyor is a versatile current mode circuit and has widely been accepted as both a theoretical as well as practical building block. The current conveyor, with one high impedance input (y), one low impedance input (x) and one high impedance output (z) is a suitable element for both voltage-mode and current-mode circuits. Current mode circuits are receiving significant attention due to their higher band-width, greater linearity, simpler circuitry, lower power consumption, larger dynamic range, and reduced chip area as compared to their voltage mode counterparts like Operational Amplifiers. In recent years, due to the integration suitability with CMOS technology, current mode devices are finding even more consideration in circuit designs [1, 2].

Figure 1.2 shows the symbol and equivalent circuit of the second generation Current Controlled Conveyor (CCCII). A CCCII-based circuit, whether positive, negative or dual output [3], provides electronic tunability and wide tunable range of its resistance at X^- terminal [6]. As the CCCII is current controlled current source, the CCCII based circuit is very suitable for high frequency operation. These features are very attractive to circuit designers [4].

VY Y

CCCII Z IZ

X

VX

Figure 1.2 Circuit symbol of current conveyor

It is characterized by the following matrix equation (Eq.1.1):

$$\begin{bmatrix} V_X \\ I_Y \\ I_Z \end{bmatrix} = \begin{bmatrix} R_X & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_X \\ V_Y \\ V_Z \end{bmatrix} (1.1)$$

Operational Transconductance Amplifiers (OTAs)

The OTA is a transconductance device in which the input voltage controls the output current. The op-amps are voltage controlled voltage source whereas the transconductance g_m makes the OTA as voltage controlled current source. An ideal OTA [7] is defined by the equation (Eq. 1.2):

$$I_O = g_m (V^{+} - V^{-}) \quad (1.2)$$

Where input and output impedances are infinite. The transconductance g_m is directly proportional to control bias current I_B. Characteristics of Ideal OTA [8] can be summarized as follows:

Input impedance (Zin) = ∞

Output Impedance (Z_o) = ∞

Non-inverting input current I_{o+} = Inverting input current I_{o-}

Bandwidth = ∞

The Figures 1.3 and 1.4 show the basic schematic and equivalent circuit of OTA.

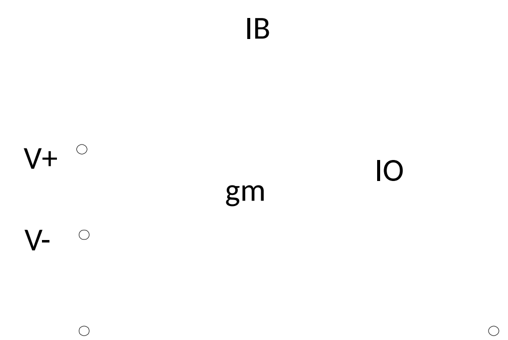


Figure 1.3 Circuit symbol of OTA [1]

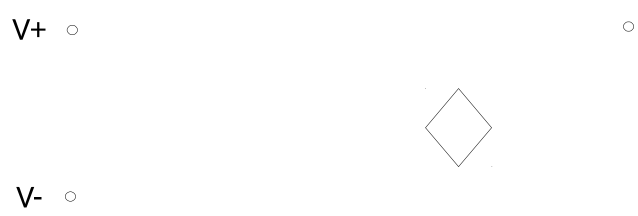


Figure 1.4 Small signal equivalent of OTA [1]

The symbol used for the OTA is shown in Figure 1.3, and the ideal small signal equivalent circuit is shown in Figure 1.4. It is assumed that the transconductance gain, g_m, is proportional to I_B.

$$g_m = h I_B \quad (1.3)$$

The proportionality constant h depends upon temperature, device geometry, and the process.

As shown in the model, the input and output impedances in the model assume ideal values of infinity. Current control of the transconductance gain can be directly obtained with control of I_B. Since techniques abound for creating a current proportional to a given voltage, voltage control of the OTA gain can also be attained through the I_B input. Throughout this paper, when reference is made to either the current or voltage controllability of OTA based circuits' it is assumed to be attained via control of g_m by I_B.

Current Feedback Operational Amplifier

The current feedback operational amplifier also known as CFOA or CFA 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).

The circuit symbol of current feedback operational amplifier (CFOA) is shown in Figure 1.5. It is a four terminal device where X and Y are input terminals and Z, W are output terminals.

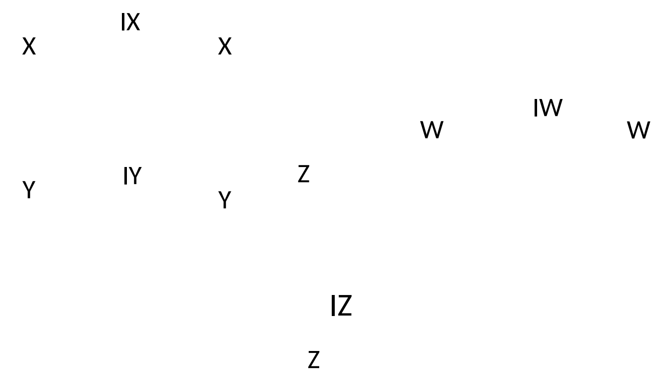


Figure 1.5 Symbol of CFOA

The operation of CFOA can be described by the following matrix equation (Eq. 1.4):

$$\begin{bmatrix} I_Z \\ I_Y \\ V_Z \\ V_W \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_X \\ V_X \\ V_Y \end{bmatrix} (1.4)$$

Current Differencing Buffered Amplifier (CDBA)

To provide further possibilities in the circuit synthesis and to simplify the implementation Current differencing buffered amplifier (CDBA) was introduced by Acar and Ozoguz. Features of CDBA include wide bandwidth, simple implementation for internally grounded input terminals, high-slew rate and is also suitable for integrated circuit (IC) implementation in both bipolar and CMOS technologies.

The circuit symbol of the current differencing buffered amplifier (CDBA) is shown in Figure 1.6, where P and N are input terminals, W and Z are output terminals.

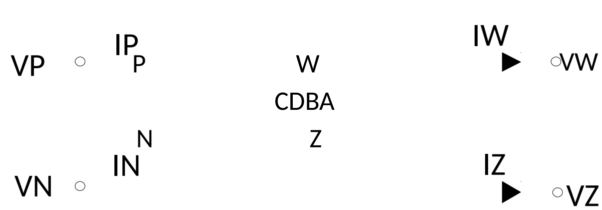


Figure 1.6 Symbol of CDBA

The equation below describes the CDBA characteristics

$$\begin{bmatrix} I_z \\ V_w \\ V_p \\ V_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix} (1.5)$$

According to the above matrix equation and equivalent circuit shown Figure 1.6 the Z-terminal is called current output as the current through Z-terminal is the difference of the currents through P-terminal and N-terminal. It is called voltage output since the voltage at the W-terminal follows the voltage of Z-terminal. The input terminals, are internally grounded where the input impedance of the terminals P and N are internally zero ideally.

Current Controlled CDBA (CC-CDBA)

Maheshwari and Khan proposed the current controlled CDBA in 2003 in which the parasitic resistances are current-controlled using mixed translinear input loops and current mirrors. CDBA offers advantage of a buffered voltage output as well as high impedance current output. The port relationship in the CDBA can be summarized as

$$V_p = V_n = 0, \quad I_z = I_p - I_n, \quad V_w = V_z . \quad \ldots\ldots\ldots\ldots\ldots(a)$$

The two input terminals (P and N) offer a finite parasitic resistance which can be current-controlled in a CCCDBA whose symbol is given in Figure 1.7. The circuit implementation consists of mixed translinear loops realizing two input terminals with a ground potential. The P- and N- terminal resistance can be obtained by the following relationship:

$$R_{p,n} = V_T / 2Io \quad \ldots\ldots\ldots\ldots\ldots\ldots(b)$$

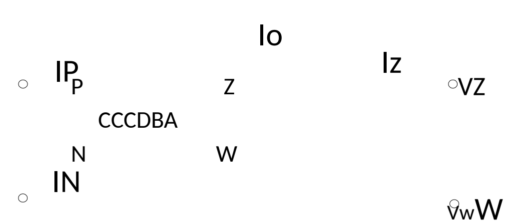


Figure 1.7 CC-CDBA symbol

Thus from the above relationship, it can be clearly seen that the P- and N- resistances can be varied by external bias current (I_o) of the CCCDBAs. This circuit can be IC implemented by replacing the current sources used in buffer stage by transistorized circuitry.

Digitally Controlled CDBA (DC-CDBA)

Prasertsom, Tangsrirat and Surakampontorn proposed a low voltage digitally controlled CDBA in 2008, DC-CDBA which is realized by interconnecting a current differencing circuit, a current division network (CDN), and a unity-gain voltage amplifier. The digital control proves to be more attractive in low voltage applications where tuning is limited. To provide a digital control of the current gain of the DC-CDBA, a novel CDN circuit is also proposed.

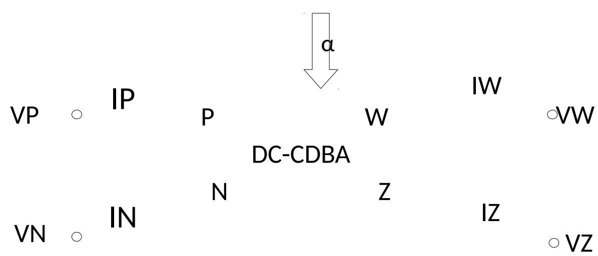


Figure 1.8 Circuit symbol of DC-CDBA

Symbolical representation of the proposed versatile analog building block DC-CDBA is as given in Figure 1.8 and mathematically, it can be represented by the following equation (Eq. 1.6):

$$\begin{bmatrix} I_z \\ V_w \\ V_p \\ V_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & \alpha & -\alpha \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix} \quad (1.6)$$

Where α is the current gain that is controlled digitally. The block diagram of the circuit is as shown below:

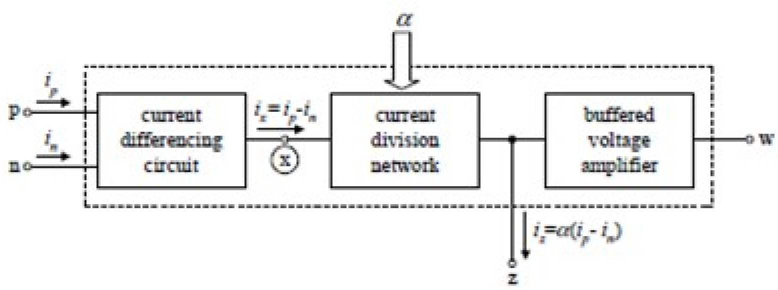


Figure 1.9 Block diagram of DC-CDBA

According to the equation above, this device consists of three stages. The input stage is a current differencing circuit to provide the difference of the input currents (i_p and i_n) through the terminals p and n into the x-terminal current (i_x). The second stage is a CDN, which is based on the linear current division principle. At this stage, the current i_x is copied to the z-terminal and is digitally controlled by the current gain parameter α. The last stage is simply a voltage buffer, since the voltage at the w-terminal follows the voltage of the z-terminal.

(i) Current Differencing Circuit

The current differencing circuit takes two inputs i_p and i_n and is composed of two unity-gain current amplifiers. Due to the current mirror, the signal current flowing out of the terminal x (i_x) can be expressed as :

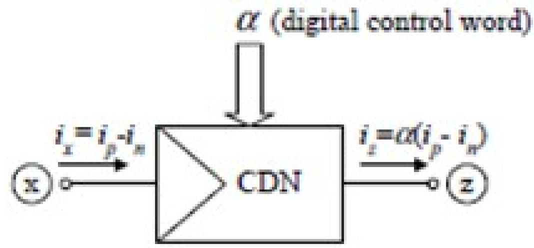
$$i_x = i_p - i_n$$

The input resistances r_p and r_n are very low due to the factors from the feedback.

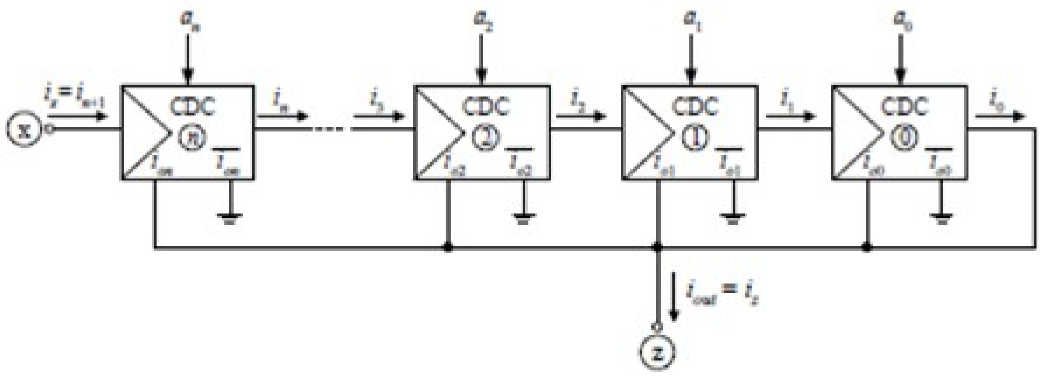
(ii) Current Division Network

The symbol for current division network (CDN), consisting of n CDCs, is shown in Figure 1.10 (a) and the circuit diagram is shown in Figure 1.10 (b).

As can be seen, the output current i_i of the CDC_i (i = 0, 1, 2, …, n) is used as an input current of the next stage and the current i_0 is added to i_{oi}.



(a)



(b)

Figure 1.10 CDN (a) Circuit Symbol (b) Circuit Diagram

Therefore, the output current (i_{out}) of the proposed CDN can be described by

$$i_{out}=\left(\frac{1}{2^{n+1}}\right)\left[1+\sum_{i=0}^{n} a_i 2^i\right] i_x$$

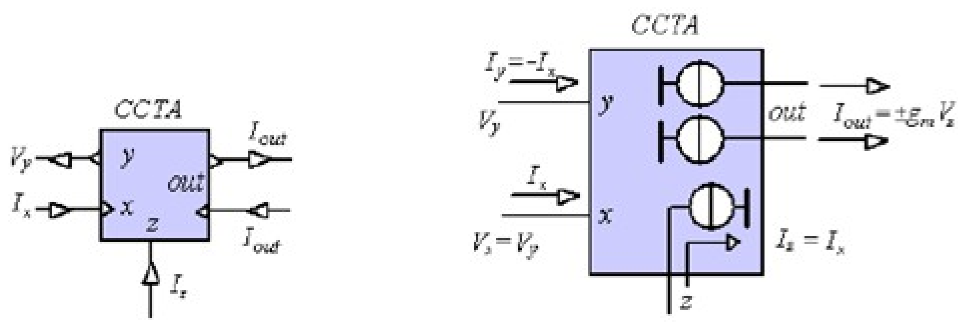
$$\propto=\frac{i_z}{i_p-i_n}=\frac{i_{out}}{i_x}=\left(\frac{1}{2^{n+1}}\right)\left[1+\sum_{i=0}^{n} a_i 2^i\right]$$

The current gain (α) of the proposed CDN can be controlled digitally, where α is less than, or equal to, unity.

Current Conveyor Transconductance Amplifier (CCTA)

Proposed by Prokop and Musil in 2005, CCTA (Current Conveyor Transconductance Amplifier) is a newly designed type of analog block that was inspired by transimpedance amplifier. A transimpedance amplifier is a current feedback amplifier which is built from CCII conveyor followed by voltage buffer. CCTA is a good choice in case of hybrid (voltage-current) circuits and is also designed for usage mostly in current mode circuits.

The circuit symbol is as shown in Figure 1.11 (a) and the behavioral model of the CCTA is shown in Figure 1.11 (b). Two basic blocks constitute the CCTA device. From its behavior the possible internal structure can be seen as shown in Figure 1.12.



(a) (b)

Fig. 1.11 CCTA (a) Circuit symbol; (b) Behavioral model

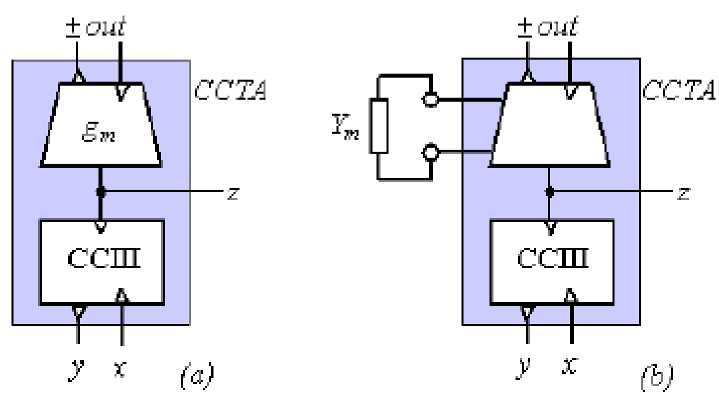


Figure 1.12 (a) CCTA element as a connection of CCIII and OTA element

(b) CCTA with possibility to choose “transconductance” by an outside two-pole

The input behavior is mostly given by properties of the CCIII conveyor. Conveyor output current flows out of the CCTA terminal "Z" into an outside load. The voltage across the Z-terminal is converted through a transconductance gm into a two output currents with opposite polarity. The transconductance can be either fixed or given by external component or controlled electronically from an auxiliary terminal as well. The CCTA is brought in as the new convenient element for current mode signal processing.

Current Controlled CCTA (CC-CCTA)

A modified-version CCTA, which is named current controlled current conveyor transconductance amplifier (CCCCTA) was proposed by Siripruchyanun and Jaikla. One drawback of CCTA is that it cannot control the parasitic resistance at input port. In CCCCTA, the parasitic resistance at current input port can be controlled by an input bias current, and then it does not need a resistor in practical applications. The symbol for the circuit and the equivalent circuit is shown in Figure 1.13 (a) and (b) respectively.

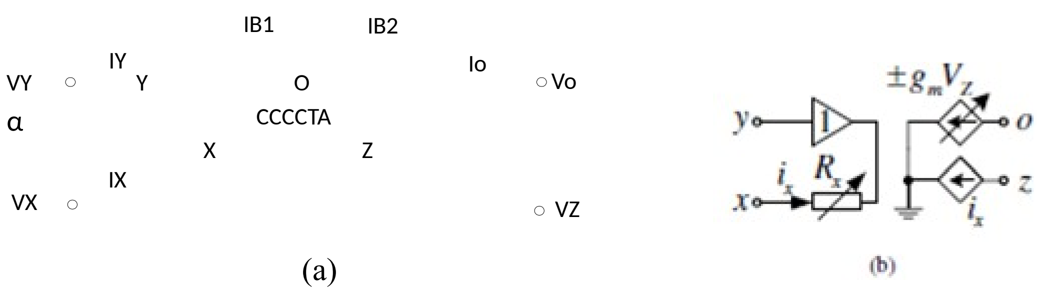


Figure 1.13 CCCCTA: (a) Symbol; (b) Equivalent Circuit

CCCCTA properties are similar to the conventional CCTA, except that the CCCCTA has finite input resistance *Rx* at the *x* input terminal. This parasitic resistance can be controlled by the bias current I_{B1} as shown in the following equation

$$\begin{bmatrix} I_y \\ V_x \\ I_z \\ I_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ R_x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & \pm g_m & 0 \end{bmatrix} \begin{bmatrix} I_y \\ V_y \\ V_z \\ V_o \end{bmatrix} \quad (1.7)$$

Where

$$R_x = \frac{V_T}{2 I_m}, g_m = \frac{I_{B2}}{2 V_T}$$

where g_m is the transconductance gain of the CCCCTA and V_T is the thermal voltage.

MO-CCCCTA

A modified CCCCTA was proposed by Pandey, Bazaz and Manocha. Although, CCCCTA which is relatively newly proposed current mode active building block, can be operated in both current and voltage modes, providing flexibility and offering several advantages such as high slew rate, high speed, wider bandwidth and simpler implementation, the MO-CCCCTA is enhanced with various advantages such as output current gain controllability, resistorlessness and compactness in chip area when added to the original unit.

The circuit symbol for the MO-CCCCTA is shown in Figure 1.14 below.

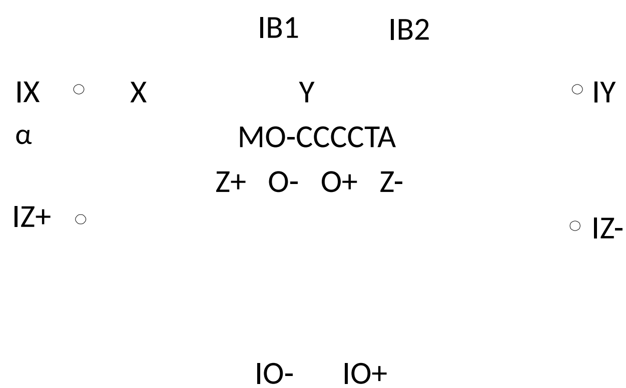


Figure 1.14 Symbol for MO-CCCCTA

The MO-CCCCTA has a finite input resistance R_X at the X input terminal and an additional transconductance g_m amplifier in the output side. The parasitic resistance R_X and the transconductance g_m can be controlled by bias currents I_{B1} and I_{B2}, respectively. The intrinsic resistance (R_X) and transconductance (g_m) are expressed as

$$R_x = \frac{V_T}{2 I_{B1}}, g_m = \frac{I_{B2}}{2 V_T}$$

where I_{Bi} (i = 1, 2) and V_T are the bias currents and the thermal voltage, respectively.

Differential Voltage CCTA (DVCCTA)

Differential voltage current conveyor transconductance amplifier (DVCCTA), a recently proposed active building block has DVCC as input block and is followed by TA. The DVCCTA has all the good properties of CCTA or CCCCTA including the possibility of inbuilt tuning of the parameters of the signal processing circuits to be implemented and also all the versatile and special properties of DVCC such as easy implementation of differential and floating input circuits. The symbol which gives the port relationship for the DVCCTA circuit is shown in Figure 1.15 below.

IO

IY1 ○ Y1 Z+ ○IZ+

α DVCCTA Z-

○ IZ-

Y2 X O-

IY2 ○

○ IO-

IX

Figure 1.15 DVCCTA circuit symbol

The DVCCTA is based on DVCC and consists of differential amplifier as input, current mirrors and transconductance amplifier. It can be characterized by the following matrix:

$$\begin{matrix} I_{y1} \\ I_{y2} \\ ¿ \\ V_x \\ z+¿ \\ z-¿ \\ I¿I¿I_{o-¿} \\ ¿ \end{matrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_m & 0 & 0 \end{bmatrix} \begin{matrix} V_{y1} \\ V_{y2} \\ ¿ \\ I_x \\ z+¿ \\ z-¿ \\ V¿V¿V_{o-¿} \\ ¿ \end{matrix} \quad (1.8)$$

where g_m is transconductance of the DVCCTA. The value of gm is given as :

$g_m = \sqrt{2 \mu C_{ox} (W/L) I_{ox}}$ which can be adjusted by bias current I_0.

Differential Difference CCTA (DDCCTA)

The DDCCTA can easily be implemented from a DVCCTA by adding the Y3 terminal. The circuit symbol is as shown in Figure 1.16.

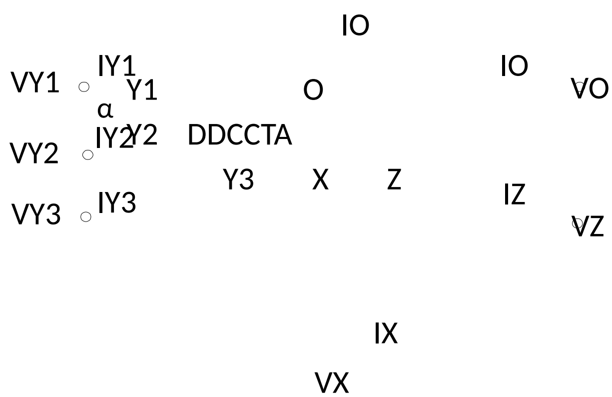


Figure 1.16 Circuit symbol of DDCCTA

It is based on the use of the DDCC as an input stage and the OTA as an output stage. The port characteristics of the DDCCTA can be described by the following expressions:

$i_{Y1} = i_{Y2} = i_{Y3} = 0$, $v_X = v_{Y1} - v_{Y2} + v_{Y3}$,

$i_Z = i_X$, $i_O = g_m v_Z$

The transconductance gain (g_m) of the DDCCTA can be given by:

$$g_m = \sqrt{\mu C_{ox} \frac{W}{L} I_B}$$

where I_B is an external DC bias current, μ is the effective channel mobility, C_{ox} is the gate-oxide capacitance per unit area, W and L are channel width and length, respectively.

It should be noted that the g_m-value of the DDCCTA can be adjustable electronically by I_B.

Voltage Differencing Transconductance Amplifier (VDTA)

In VDTA, differential input voltage (V_{VP} ,V_{VN}) is transferred to current at the terminal Z by first transconductance gain and the voltage drop at the terminal Z is transferred to current at the terminals X^+ and X^- (negative of X^+) by second transconductance gain. Both transconductance are electronically controllable by external bias currents.

The circuit symbol for VDTA can be drawn as shown below.

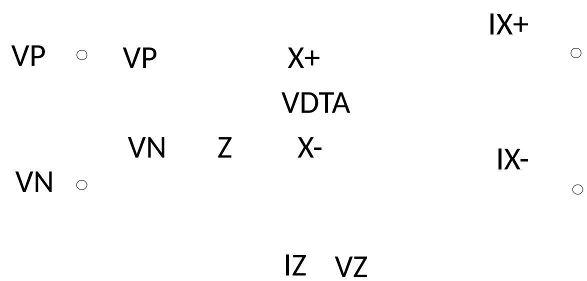


Figure 1.17 Symbol for VDTA

V_P and V_N are input terminals and Z, X^+ and X^- are output terminals. All terminals exhibit high impedance values. Using standard notation, the terminals relationship of an ideal VDTA can be characterized by:

$$\begin{bmatrix} I_z \\ I_{x+} \\ I_{x-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_{VP} \\ V_{VN} \\ V_Z \end{bmatrix} \quad (1.9)$$

The above describing-equations, the input stage and output stage can be simply implemented by floating current sources. According to input terminals, an output current at Z terminal is generated. The intermediate voltage of Z terminal is converted to output currents.

g_i is the transconductance value of ith transistor defined by

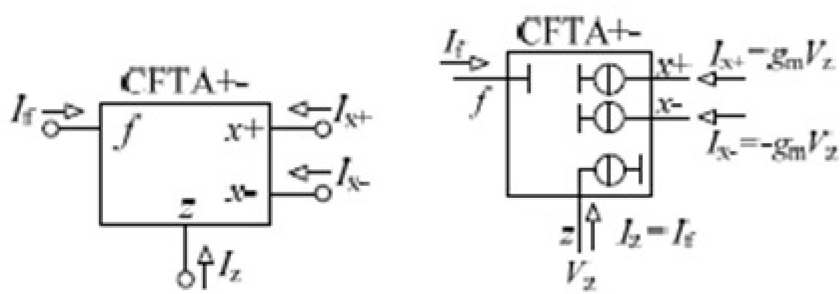
$$g_i = \sqrt{I_{Bi}\mu_i C_{ox}\left[\frac{W}{L}\right]_i} \quad ,$$

μ_i is (i = n, p) the mobility of the carrier for NMOS (n) and PMOS (p) transistors, C_{OX} is the gate-oxide capacitance per unit area, W is the effective channel width, L is the effective channel length and I_{Bi} is bias current of ith transistor.

Important feature of this block is that it can be used easily at transconductance mode applications owing to input terminals is voltage and output terminals is current.

Current Follower Transconductance Amplifier (CFTA)

Herencsar, Koton, Vrba, and Lattenberg introduced this new active element in 2008. The schematic symbol of the CFTA element is shown in Figure 1.18 (a) and the ideal behavioral model of the CFTA element is shown in Figure 1.18 (b).



(a) (b)

Figure 1.18 CFTA: (a) Symbol; (b) Behavioral Model

The element is a combination of the Current Follower (CF), which is the input part of the designed element, and the Balanced Output Transconductance Amplifier (BOTA), which forms the output part of the element.

The element has been defined in compliance with network convention i.e. all currents are flowing into the circuit. It has one low impedance current input *f*. Current from the terminal *f* is transferred by the Current Follower to auxiliary terminal *z*. The voltage V_z on this terminal is transformed into current using the transconductance g_m, which flows into output terminals *x*+ and *x*-.

Relations between the individual terminals of the CFTA+- element can be described in matrix form as follows:

$$\begin{bmatrix} I_z \\ x+\text{¿} \\ x-\text{¿} \\ I_{\text{¿}} I_{\text{¿}} V_f \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ g_m & 0 & 0 & 0 \\ -g_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_z \\ x+\text{¿} \\ x-\text{¿} \\ V_{\text{¿}} V_{\text{¿}} I_f \end{bmatrix} (1.10)$$

Z-Copy CFTA (ZC-CFTA)

The ZC-CFTA is slightly modified from the conventional CDTA by replacing the current differencing unit with a current follower and complementing the circuit with a simple current mirror for copying the z-terminal current. Thus, the ZC-CFTA element can be thought of as a combination of the current follower, the current mirror and the multi-output operational transconductance amplifier. As a consequence, a number of applications based on ZC-CFTAs can be extended. The Symbol of the circuit can be given as shown in Figure 1.19 (a). The equivalent circuit is shown in Figure 1.19 (b).

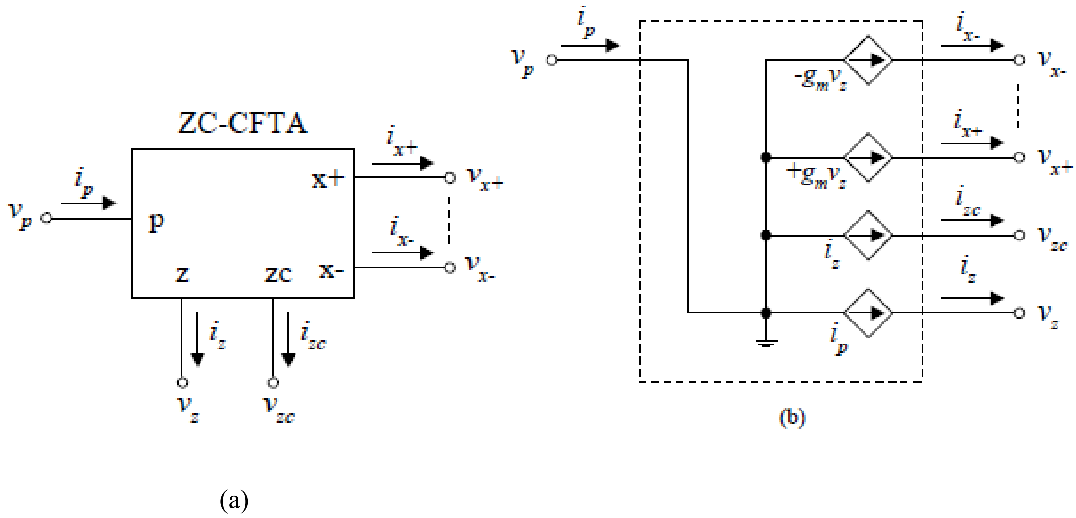


Figure 1.19 ZC-CFTA (a) Circuit Symbol; (b) Equivalent Circuit

Using standard notation, the port relations of the ZC-CFTA can be defined by the following matrix equation

$$\begin{bmatrix} v_p \\ i_z \\ i_{zc} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_p \\ v_z \\ v_{zc} \\ v_{x+} \\ v_{x-} \end{bmatrix} \quad (1.11)$$

where $+g_m$ and and $-g_m$ correspond for the positive output current (i_{x+}) and negative output current (i_{x-}), respectively. In general, the g_m-value is electronically controllable by external bias current/voltage.

The ZC-CFTA element consists of low-impedance input P, high-impedance outputs Z, Zc, X and X^+. The voltage drop at the terminal Z (v_z) is transformed into output currents via a multi-output transconductance stage with a transconductance gain (g_m).

Voltage Differencing Buffered Amplifier (VDBA)

An alternative to the existing CDBA (Current Differencing Buffered Amplifier) is proposed as the circuit principle called VDBA (Voltage Differencing Buffered Amplifier). The circuit symbol is as shown in Figure 1.20 (a) and the behavioral model is shown in Figure 1.20 (b).

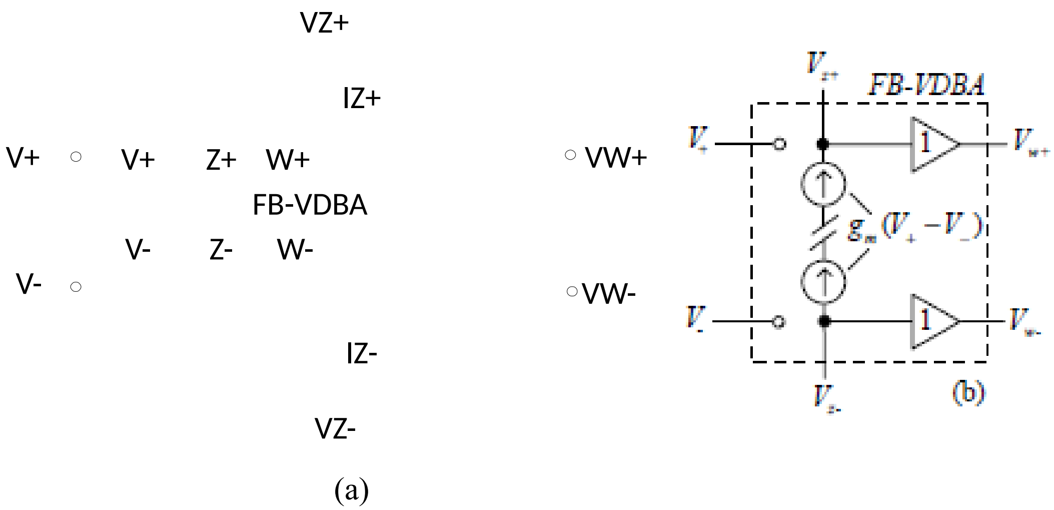


Figure 1.20 VDBA (a) Circuit Symbol; (b) Behavioral Model

The input stage of VDBA is composed of the differential-input OTA. The voltage buffer is connected to the OTA current output. This structure is semi-differential. A method of augmenting the voltage buffer by an inverting output with the corresponding abbreviation DOBA (Differential Output Buffered Amplifier) is also in use. Replacing the voltage buffer in the VDBA by the DOBA yields a fully differential circuit element. Such an element should be specified as VDDOBA (Voltage Differencing Differential Output Buffered Amplifier). A specific drawback of the VDDOBA consists in the necessity to implement both the voltage buffer and the inverter. Among other shortcomings, it implies a more complicated circuit structure.

Therefore, another solution was proposed by Biolkova, Kolka and Biolek which is based only on voltage buffers, concurrently providing more versatility than VDDOBA. To differentiate it from VDDOBA, it was termed FB-VDBA (Fully Balanced VDBA).

The model can be described by the following set of circuit equations:

$$\begin{matrix} z+¿ \\ z-¿ \\ w+¿ \\ ¿ \\ I_¿ I_¿ V_¿ V_{w-¿} \\ ¿ \end{matrix} = \begin{bmatrix} g_m & -g_m & 0 & 0 \\ -g_m & g_m & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} +¿ \\ -¿ \\ z+¿ \\ ¿ \\ V_¿ V_¿ V_¿ V_{z-¿} \\ ¿ \end{matrix} (1.12)$$

FB-VDBA has a pair of high-impedance voltage inputs *v*+ and *v*-, a pair of high-impedance current outputs Z^+ and Z^-, and two low impedance voltage outputs *w*+ and *w*-. When connecting two identical grounded resistors to the Z^+ and Z^- terminals, the voltage drops on them will be of equal value but different directions.

The output voltages of *w*+ and *w*- terminals thus will be *Vw*- = -*Vw*+. In this way, the voltage inversion is achieved without the utilization of voltage inverter.

Current Follower/Inverter Buffered Transconductance Amplifier (CFBTA, CIBTA).

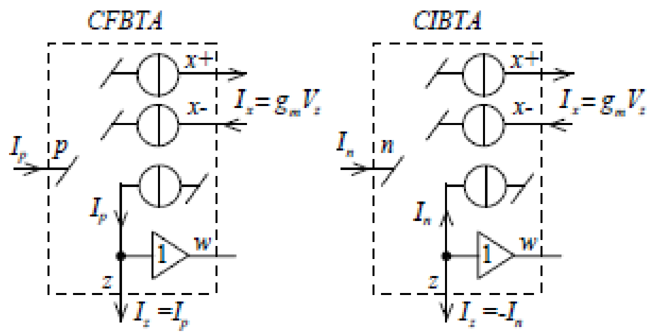
Bajer, Vavra and Biolek proposed an approach in which the conventional CDTA is modified such that the CDU is replaced by the current follower or inverter, and the Z^- terminal voltage is buffered by the voltage follower

The *P* and *N* input terminals behave as grounded because their voltages are zero. The Z^- terminal current is a copy of the *P* or *N* terminal current, flowing out of the device for CFBTA and into the device for CIBTA. Moreover, the *Z* terminal voltage is copied to the low–impedance *w* terminal and transferred to the *X* terminal currents via the OTA transconductance g_m. The symbols and behavioral models of proposed active elements are shown in Figure 1.21 (a) and (b) respectively.

IX
X+
○
VX
VP ○ IP P CFBTA X-
○
Z W
○VW
IZ
VZ

IX
X+
○
VX
VN ○ IN N CIBTA X-
○
Z W
○VW
IZ
VZ

(a)



(b)

Figure 1.21 CFBTA/CIBTA (a) Circuit Symbol; (b) Behavioral Model

The corresponding circuit equations can be arranged in the following matrix form:

$$\begin{bmatrix} I_z \\ V_w \\ I_x \\ V_{p(n)} \end{bmatrix} = \begin{matrix} 0 \\ 0 \\ 0 \\ -¿ \\ ¿ \\ 1 \\ ¿ \\ 1 \\ ¿ \\ 0 \\ ¿ \\ 0 \\ ¿ \\ 0 \\ ¿ \\ ¿ \quad g_m \quad ¿ \quad (0¿0¿0¿0¿0¿0¿) \\ ¿ \end{matrix} \begin{bmatrix} v_z \\ I_w \\ V_x \\ I_{p(n)} \end{bmatrix} (1.13)$$

CFBTA and CIBTA, represent two main improvements in comparison to the well–known CDBA and CDTA. The first one is more universal output stage, containing both the multiple–output OTA for providing current outputs and the voltage buffer for supplying subsequent blocks with voltage–type signal and second is the simplified input stage in the form of current follower or inverter.

1.3 Summary and Conclusion

The whole work of dissertation is organized in six chapters.

Chapter 1 presents the general introduction of analog signal processing, digital signal processing and some devices (operational transconductance amplifiers, current conveyors, current feedback operational amplifiers and current differencing buffered amplifier), that are used in analog signal processing.

In chapter 2 CMOS and bipolar implementation of CDTA and some of its applications are presented.

In chapter 3 application of CDTA in biquad filter realization is presented.

In chapter 4 oscillator realization using CDTA is given.

In chapter 5 universal filter is proposed using RLC resonator circuit, in which the grounded inductor is replaced by simulated inductance using CDTAs circuit, resulting in an CDTA-RC resonator.

Chapter 6 describes the conclusion and further scope of the work.

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Chapter 2

Implementation of Current Differencing Transconductance Amplifier

In this chapter we have discussed the basic structure and operation of CDTA. CDTA is implemented by bipolar and CMOS technology. Many other types of realization of CDTA are there and their performance is examined by PSPICE simulation.

2.1 Architecture of CDTA

Current differencing transconductance amplifier (CDTA) is a current mode five terminal active device [1]. It has two input terminals P and N of low resistance, which takes current as input, an intermediate terminal Z of very high resistance. This intermediate terminal takes the difference of two input currents I_P and I_N. An external resistance is connected at Z terminal, which causes a voltage at the terminal Z. Two output terminals of very high resistance which gives dual output currents I_X^+ and I_X^-. These output currents have equal and opposite values. The voltage developed at Z terminal causes an output current which is given by the product of voltage generated at Z terminal and the transconductance (g_m) of the device.

Figure 2.1 shows the basic CDTA device and its equivalent circuit diagram. CDTA consists of two stages. In the first stage a current differencing unit which is a second generation current conveyor (CCII) unit, which takes the difference of the two input currents. This current is given as the input to the next stage.

V_P P I_P X+ I_X+ V_X+

CDTA

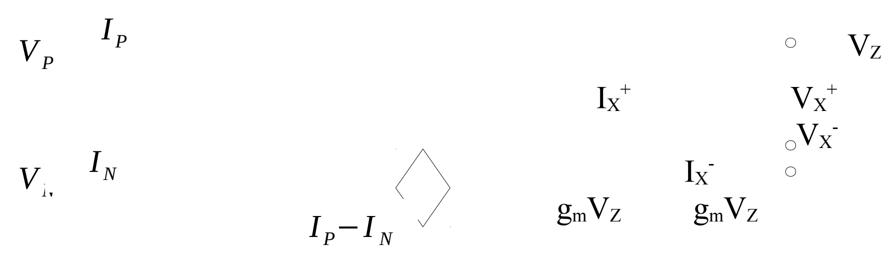
N Z X-

I_N

V_N I_X- V_X-

V_Z

(a)



(b)

Figure 2.1 (a) Circuit symbol (b) Equivalent circuit [2]

CDTA is a five terminal current-mode active building block [1]. The characteristics of the ideal CDTA are represented by the following equations (Eq.2.1-2.4):

$$V_P = V_N = 0 \quad (2.1)$$

$$I_Z = I_P - I_N \quad (2.2)$$

$$I_{X^{+}} = g_m V_Z \quad (2.3)$$

$$I_{X^{-}} = -g_m V_Z \quad (2.4)$$

Where g_m is the transconductance of CDTA.

Considering the deviation of the voltage and current gains from their ideal values, the defined equation of the CDTA in Figure 2.1(b), becomes (Eq. 2.5-2.8):

$$V_P = V_N = 0 \quad (2.5)$$

$$I_Z = \alpha_P I_P - \alpha_N I_N \quad (2.6)$$

$$I_{X^{+}} = g_m V_Z \quad (2.7)$$

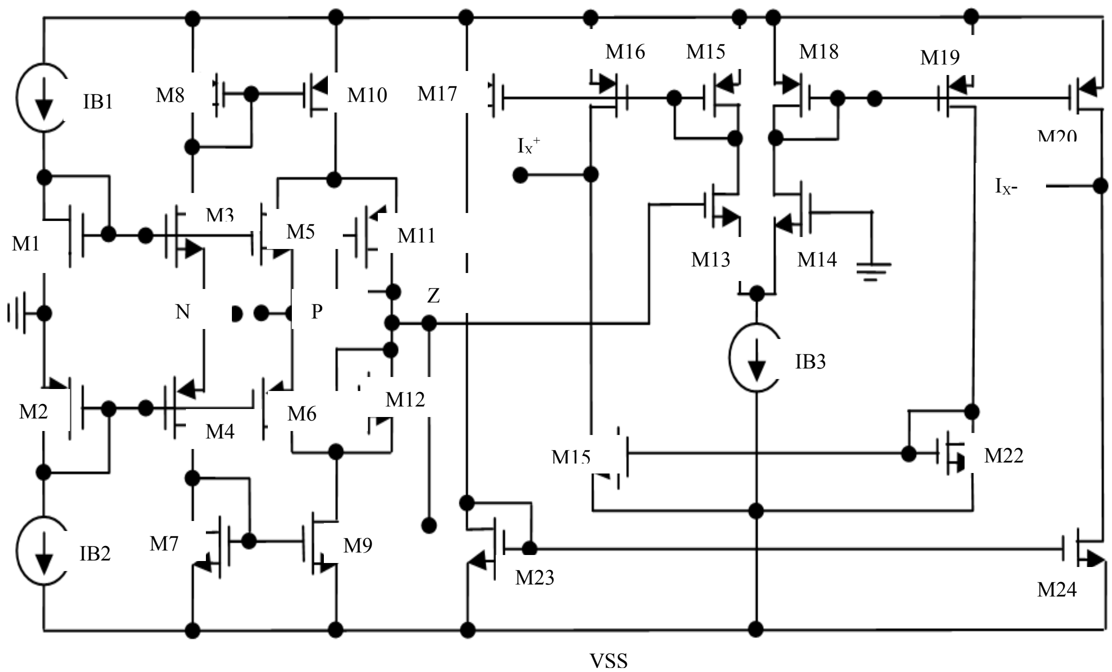
$$I_{X^{-}} = -g_m V_Z \quad (2.8)$$

Where current gains are denoted by α_P and α_N, and $\alpha_P = 1-\varepsilon_p$, $\alpha_N = 1-\varepsilon_n$. Here, ε_p and ε_n denote the current tracking errors whose absolute values are much less than the unit value. The differential input current flows over the Z terminal. Usually, external impedance is connected to this node and the voltage over this impedance is converted to the output currents by the output transconductors with transconductance g_m for the positive output and $-g_m$ for the negative output. According to above equations and circuit of Figure 2.1, the current through the terminal Z follows the difference of the currents through the terminals P and N (I_P-I_N), and flows from the terminal Z into an impedance $R_{Z.}$ The voltage drop at the terminal Z is transferred to a current at the terminal X (Ix) by a transconductance gain (g_m), which is electronically controllable by an external bias current. Thus, the CDTA can be considered as familiar to the CDBA and the transconductance amplifier. Intermediate Z terminal of the CDTA can be very handy if a circuit is to be designed with all grounded passive elements which are good in view of process dependent realization issues. Since input differential current flows over that Z terminal it is possible to use one or more than one grounded passive elements to convert this differential current to voltage which seems a very promising method to obtain compact designs.

2.2 CMOS Realization of CDTA

A possible CMOS CDTA circuit realization suitable for the monolithic IC fabrication is given in Figure 2.2. In this circuit, transistors from M1 to M12 perform the current differencing operation while transistors from M13 to M24 convert the voltage at the z-terminal to output currents at the two outputs of the DO-OTA section. DO-OTA's transconductance (g_m) is controllable via its bias current IB_3. Also, a resistor (R_Z)

connected at the Z-terminal can be used to adjust the gain of CDTA, while the voltage at the input of DO-OTA is $V_z = I_z.R_z$. The gate terminals of the output transistors M11 and M12 in current-differencing section are connected to bias voltages to provide drain output and high impedance at Z terminal (ideal current controlled current source, CCCS). Since an external resistor with relatively low resistance value (at the order of few KΩ) is connected to the Z-terminal, the use of diode-connected transistors M11 and M12 becomes advantageous from IC manufacturing point of view. This is due to the fact that the need for two additional bias-voltages is eliminated by using diode-connected transistors.



$I_{B1}=I_{B2}=85\mu A$, $I_{B3}=200\mu A$, bandwidth = 400MHz, VDD = -VSS = 2.5V

Figure 2.2 CMOS implementation of CDTA [2]

Using PSPICE, the performance analysis of CDTA is verified. The MOS transistors are simulated using 0.5µm MIETEC model parameters.

For the performance analysis of CDTA DC, AC and Transient analysis is performed in PSPICE and characteristics are drawn.

CDTA transconductance is controlled by I_{B3}. SPICE simulations have verified that for I_{B3} in the range from 20 to 700mA, g_m is proportional to the logarithm of I_{B3}. For 200µA, g_m=548µA/V. The corresponding external resistance connected to the Z terminal is 2.88 KΩ. The input resistances R_P and R_N are rather high for this topology. Small-signal analysis leads to approximate values of R_P=6.0193KΩ and R_N=2.215KΩ.

Aspect ratios for all MOSFETs in the circuit are shown in Table 1.

Table 1: Transistor W/L ratios, that is used in CDTA circuit simulations [2]

Transistor	**W/L(µm)**
M1-M6	8/1
M7-M10	5/1
M11-M12	20/2
M13-M14	16/1
M15-M20	6/1
M21-M24	4/1

Characteristics of CMOS CDTA

Characteristics of CMOS CDTA are shown in Table 2:

Supply Voltages	±2.5V
Bias Currents	I_{B1}=I_{B2}=85µA I_{B3}=200µA
Technology	0.5µm MIETEC
Input Resistance at P	6.019KΩ
Input Resistance at N	2.215KΩ
Resistance at intermediate terminal Z	683.638KΩ
Output Resistance at X^+	2.693 KΩ
Output Resistance at X^-	10.2 KΩ
Linear DC Limit of input current	-200 µA to +200 µA
Transconductance (g_m)	548 µA/V
Bandwidth	400MH_Z
Power dissipation	4.22mwatts

2.3 Bipolar Realization of CDTA

Another possible bipolar-based CDTA circuit realization suitable for the monolithic IC fabrication is displayed in Figure 2.3. In this circuit, transistors from Q1 to Q11 perform the current differencing operation while transistors from Q12 to Q23 convert the voltage at the Z-terminal to output currents at the two outputs of the DO-OTA section. DO-OTA's transconductance (g_m) is controllable via its bias current I_{B3}. Also, a resistor (R_Z) connected at the Z-terminal can be used to adjust the gain of CDTA, while the voltage at the input of DO-OTA is $V_z = I_z.R_z$. The collector terminals of the output transistors Q9 and Q11 in current-differencing section are connected to bias voltages to provide drain output and high impedance at Z terminal (ideal current controlled current source, CCCS). Since an external resistor with relatively low resistance value (at the order of few KΩ) is connected to the Z-terminal, the use of diode-connected transistors Q9 and Q11 becomes advantageous from IC manufacturing point of view. This is due to the fact that the need for two additional bias-voltages is eliminated by using diode-connected transistors.

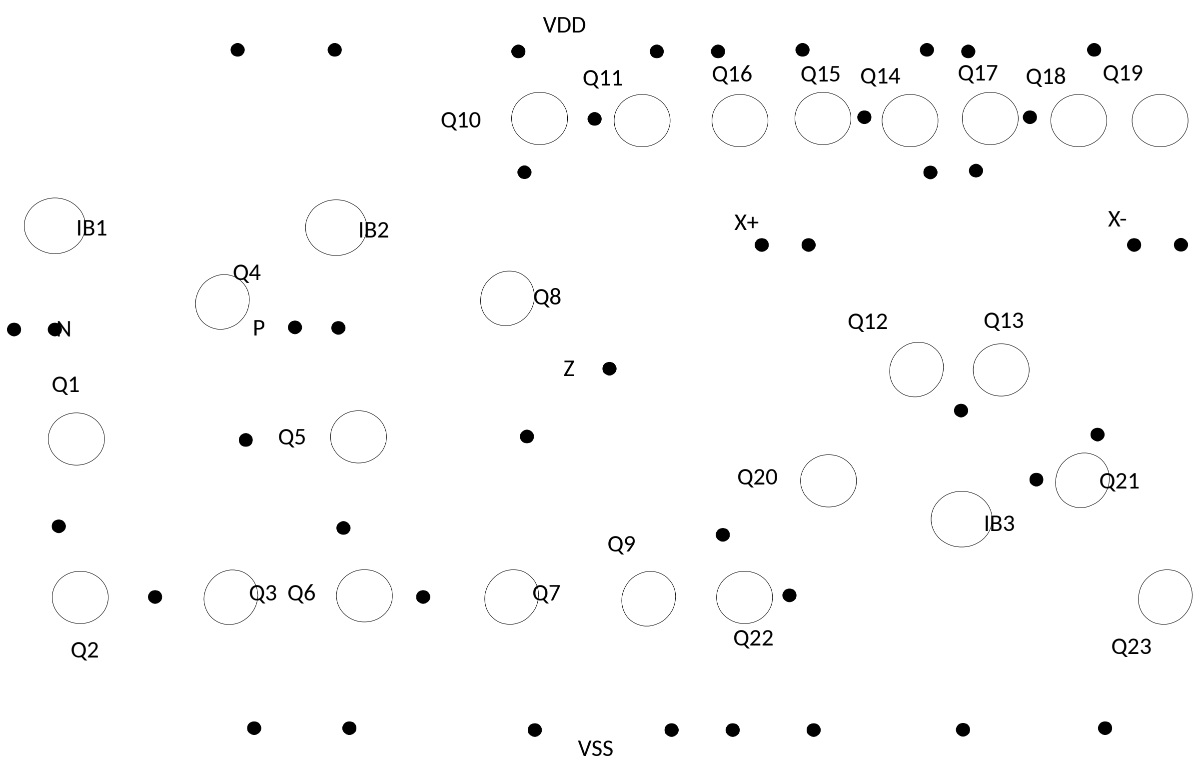


Figure 2.3 Bipolar implementation of CDTA [4]

Characteristics of Bipolar CDTA

Characteristics of CMOS CDTA are shown in Table 3:

Supply Voltages	±3V
Bias Currents	$I_{B1}=I_{B2}=100\mu A$ $I_{B3}=50.9\mu A$
Technology	PR100 N(PNP) and NR100 N(NPN) of ALA400 from AT&T
Resistance at intermediate terminal Z	378.647KΩ
Linear DC Limit of input current	-100 µA to +100 µA
Transconductance (g_m)	1 mA/V
Bandwidth	$85MH_Z$
Power dissipation	3.89mwatts

2.4 Application of CDTAs

CDTA is a versatile building block for analog signal processing circuit designs. To prove the validity of CDTA, some of the applications of CDTA in analog signal processing are mentioned are:

- Amplifiers (both inverting and non-inverting)
- Integrator
- Differentiator
- Filters (current mode and voltage mode)
- Oscillator

2.4.1 Amplifiers

An electronic amplifier or amplifier is an electronic device that increases the power of a signal which is done by taking energy from a power supply and controlling the output to match the input signal shape but with larger amplitude. Thus, an amplifier modulates the output of the power supply.

In various applications, numerous types of electronic amplifiers are specialized. An amplifier can refer to anything either an electrical circuit that uses a single active component or a complete system such as a packaged audio hi-fi amplifier.

Non-Inverting Amplifier

When the input current is applied at the positive terminal i.e. at the non-inverting terminal, then obtained amplifier is called non-inverting amplifier. In this case inverting terminal is open circuited. The CDTA based non-inverting amplifier circuit is shown in Figure 2.4.

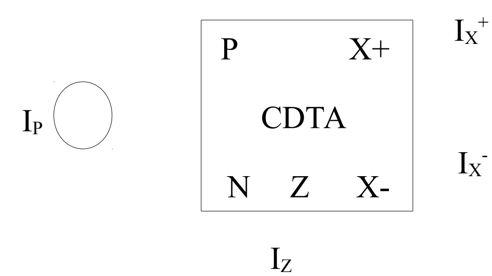
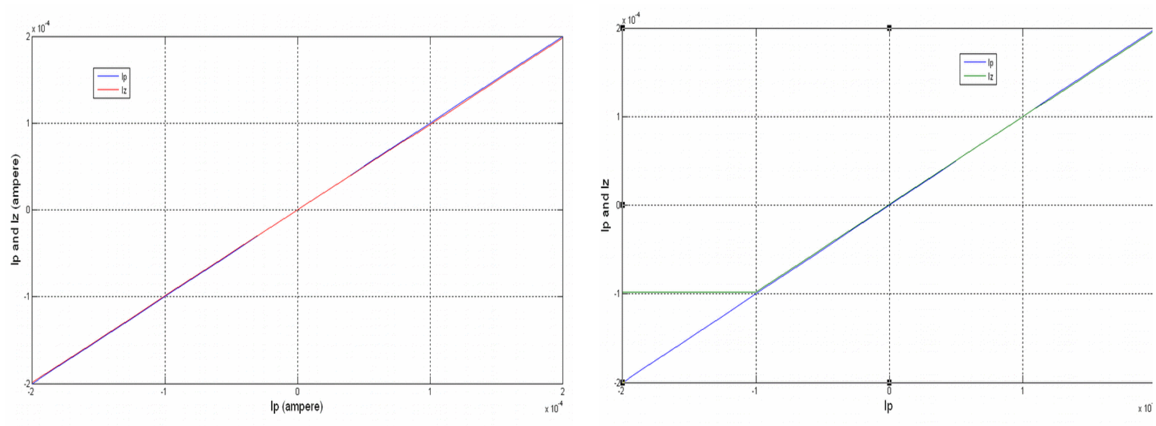


Figure 2.4 CDTA based non-inverting amplifier

DC Analysis

The CDTAs shown in Figure 2.2 is used to implement the amplifier circuit given in Figure 2.4. Input terminals current transfer characteristics are given in Figure 2.5, 2.6 and 2.7. These figures are obtained when the inverting terminal is open circuited.

Input stage transfers the difference of the input currents to the Z terminal with good accuracy as demonstrated by the figures.



(a) (b)

Figure 2.5 Current transfer from P to Z (I_N=0) for (a) CMOS (b) Bipolar

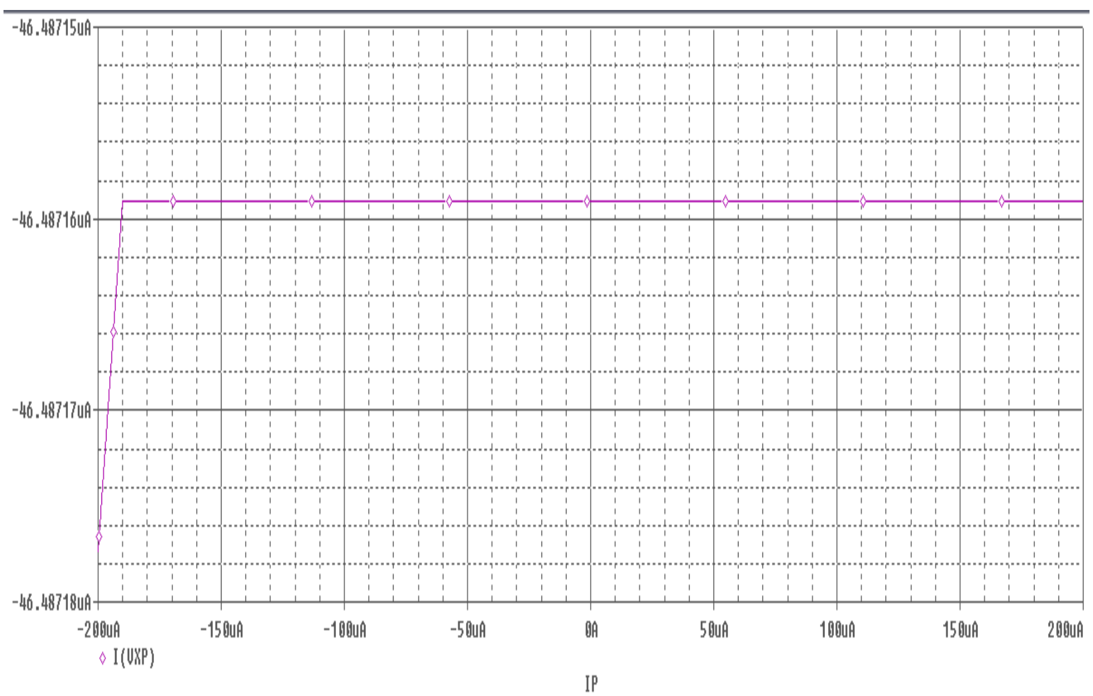


Figure 2.6 Output current characteristics I_X^+ (I_N=0)

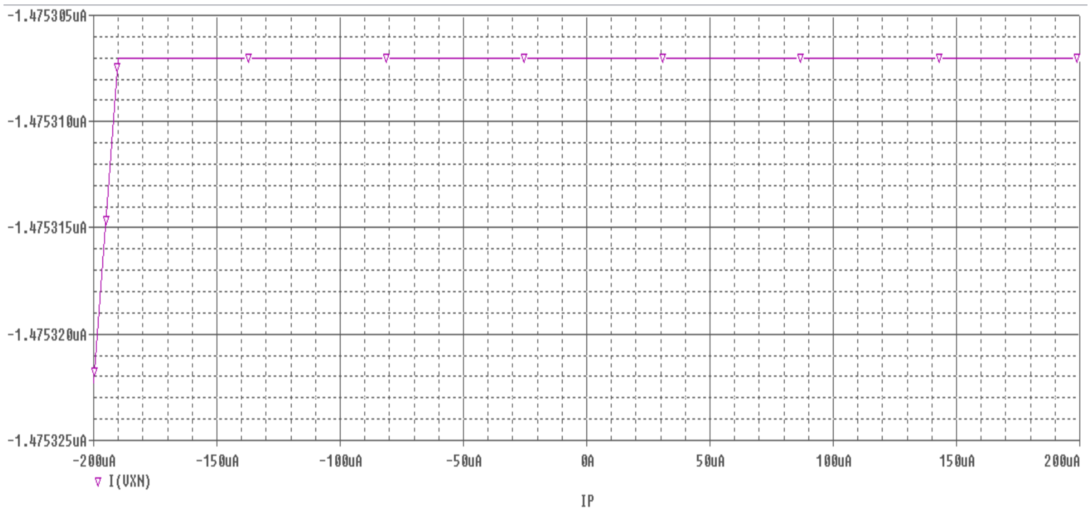
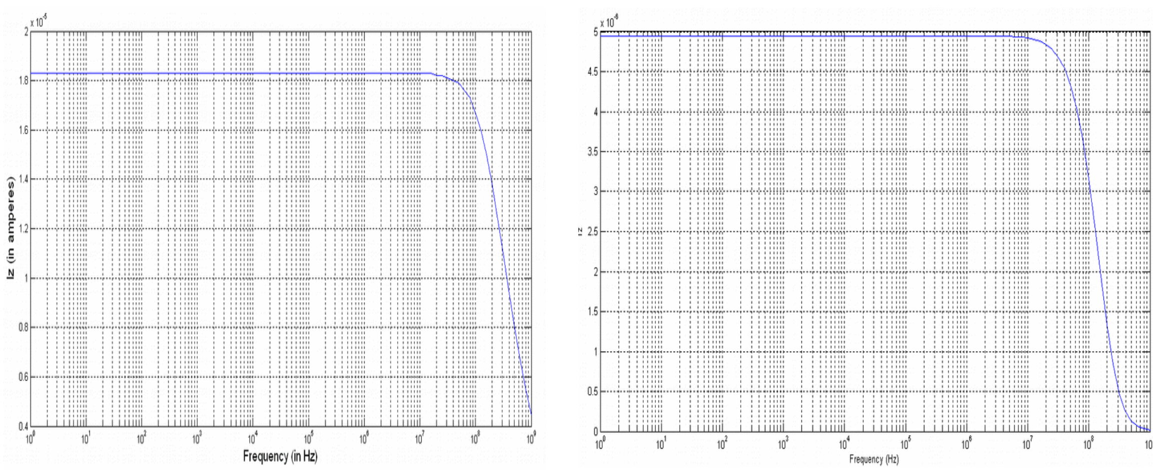


Figure 2.7 Output current characteristics I_X^- (I_N=0)

AC Analysis

Since few internal nodes exist over the signal path from input to the Z terminal of the input stage, high-frequency operation is satisfied exploiting the high-frequency capability of current mode signal processing. Figures 2.8, 2.9, 2.10, 2.11 and 2.12 show the AC responses of the variation of the current at the Z terminal with to input currents.



(a) (b)

Figure 2.8 Frequency response of I_Z (I_N=0) (a) CMOS (b) Bipolar

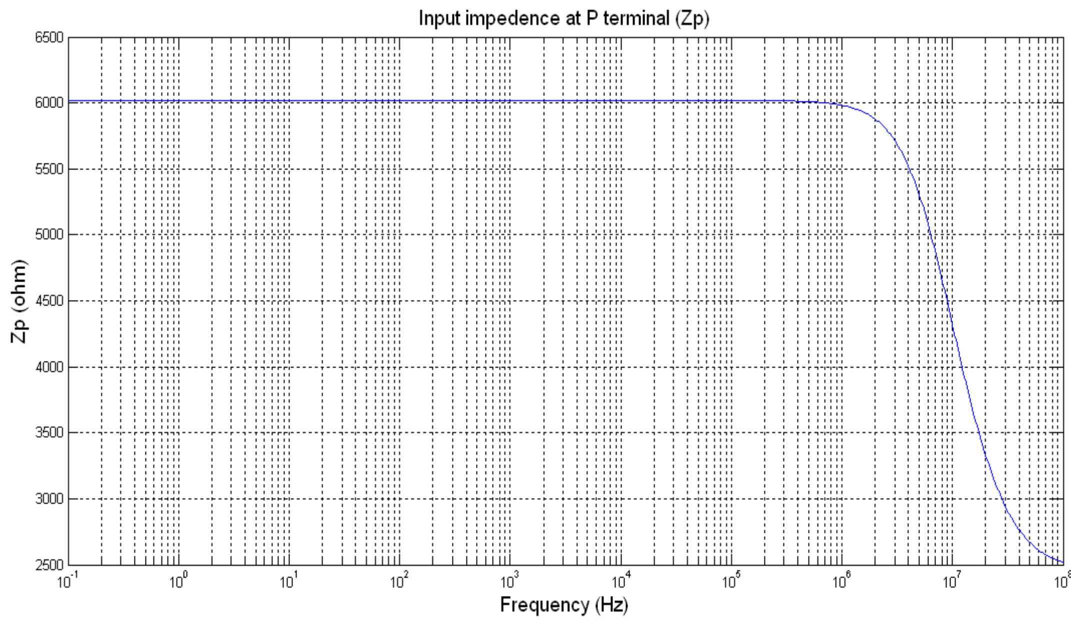


Figure 2.9 Frequency response of the input impedance at P terminal

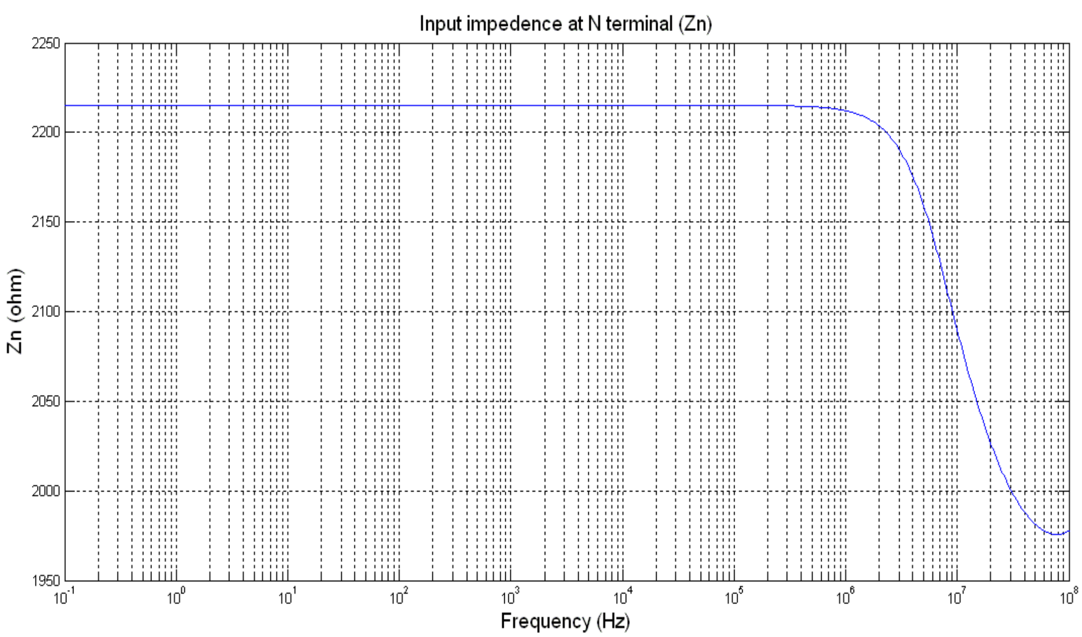
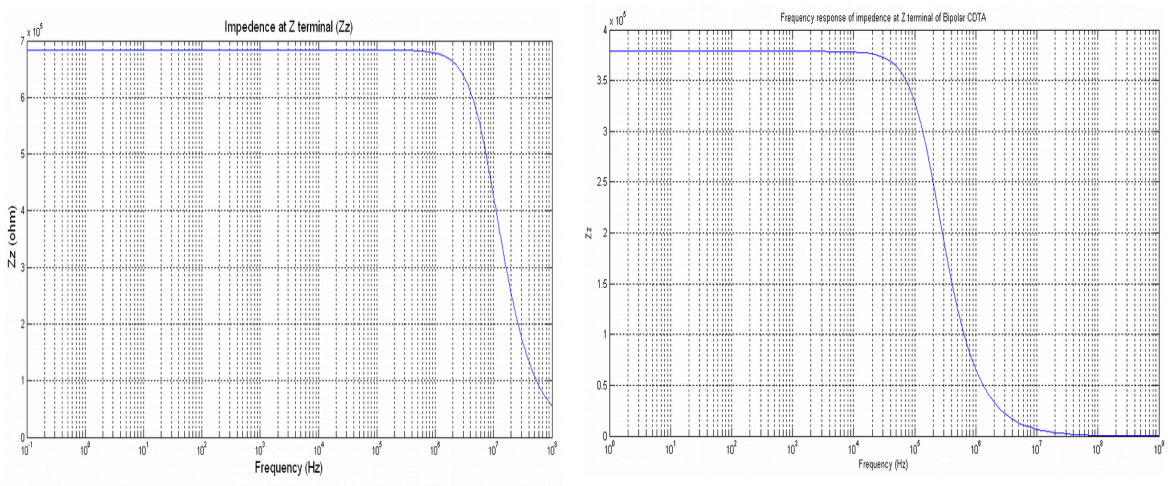
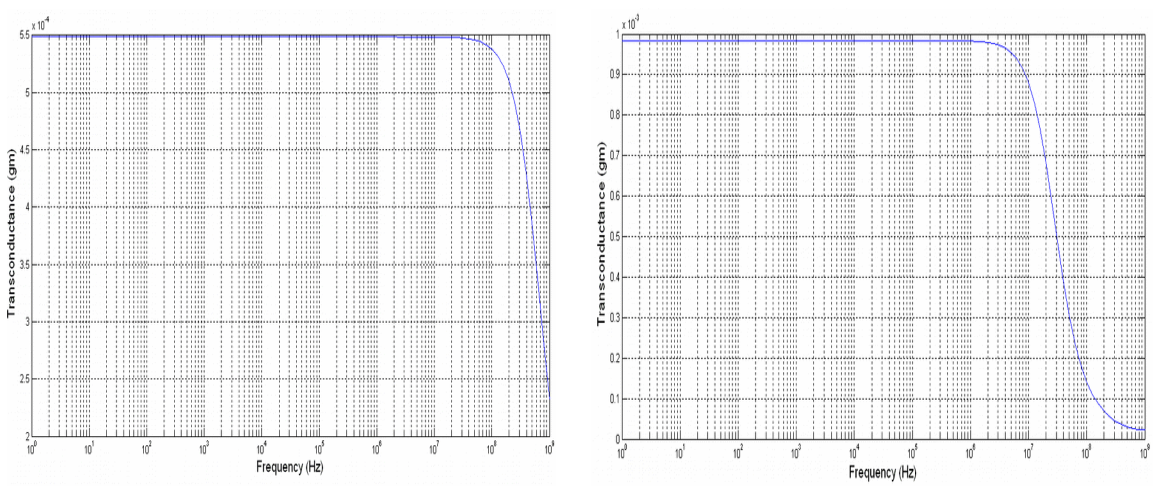


Figure 2.10 Frequency response of input impedance at N terminal (Z_N)



(a) (b)

Figure 2.11 Frequency response of impedance at Z terminal Z_Z (a) CMOS (b) Bipolar

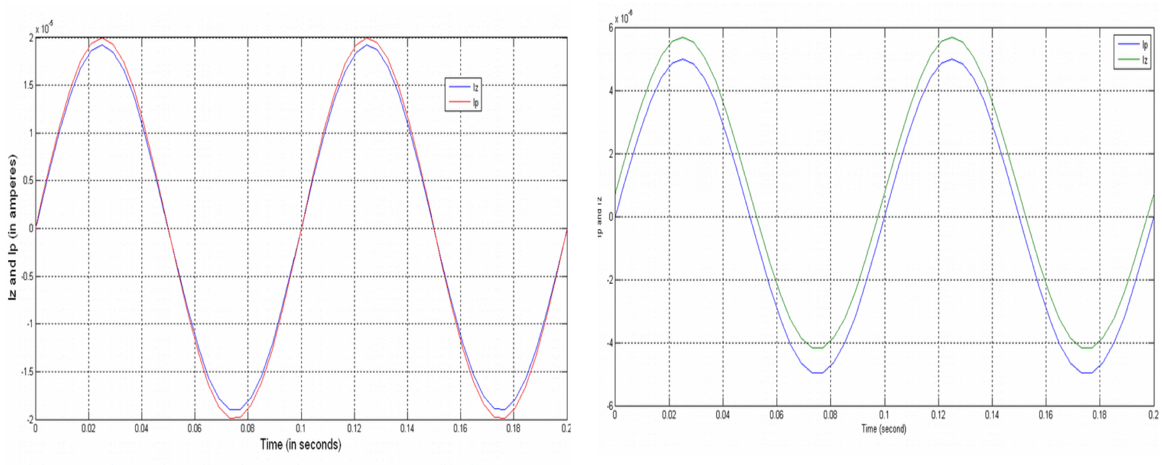


(a) (b)

Figure 2.12 Transconductance g_m (a) CMOS CDTA (b) Bipolar CDTA

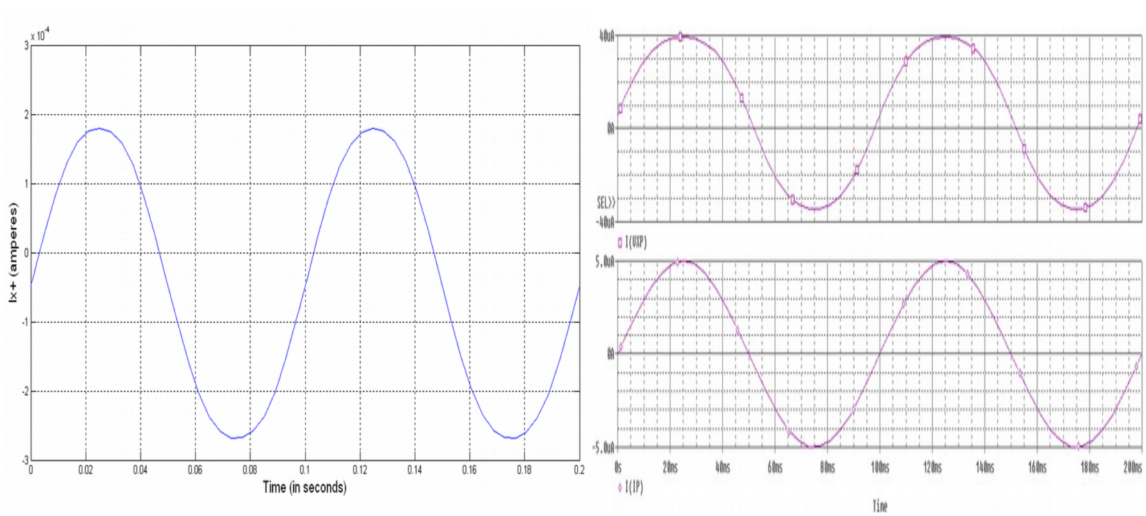
Transient analysis

Figures 2.13, 2.14 and 2.15 shows the time response of CDTA based amplifier.



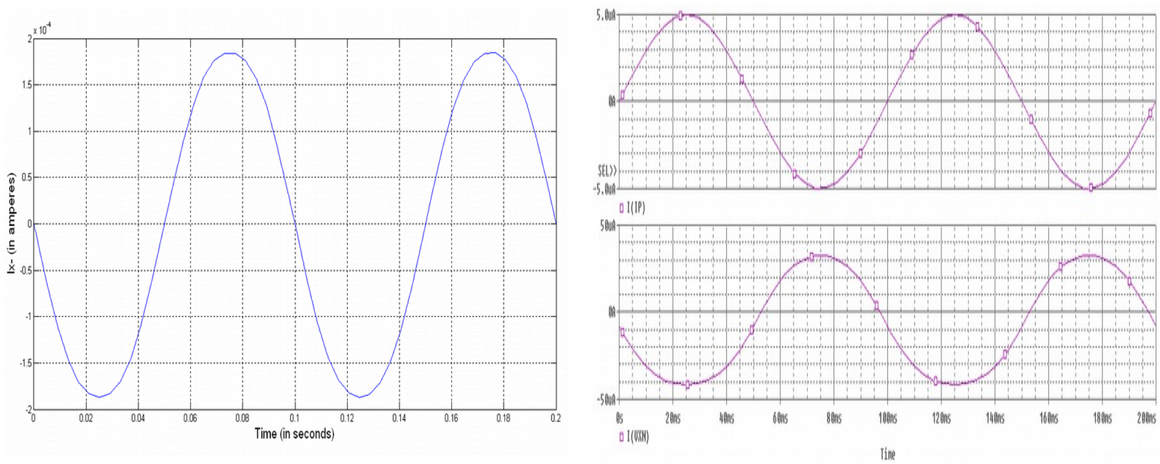
(a) (b)

Figure 2.13 Current transfer from I_P to I_Z (I_N=0) (a) CMOS (b) Bipolar



(a) (b)

Figure 2.14 Output current at non-inverting terminal (I_X^+) (a) CMOS (b) Bipolar



(a) (b)

Figure 2.15 Output current at inverting terminal (I_X^-) (a) CMOS (b) Bipolar

Inverting Amplifier

When the input current is applied at negative terminal i.e.at the inverting terminal, then it is called inverting amplifier. In this case non-inverting terminal is open circuited and output current is 180º out of phase with the input current. The CDTA based inverting amplifier circuit is shown in Figure 2.16.

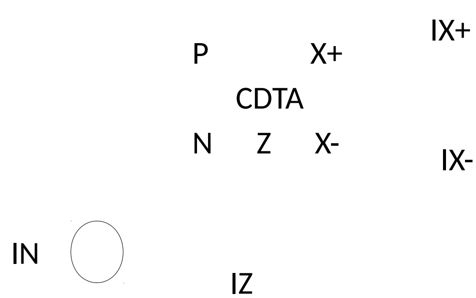
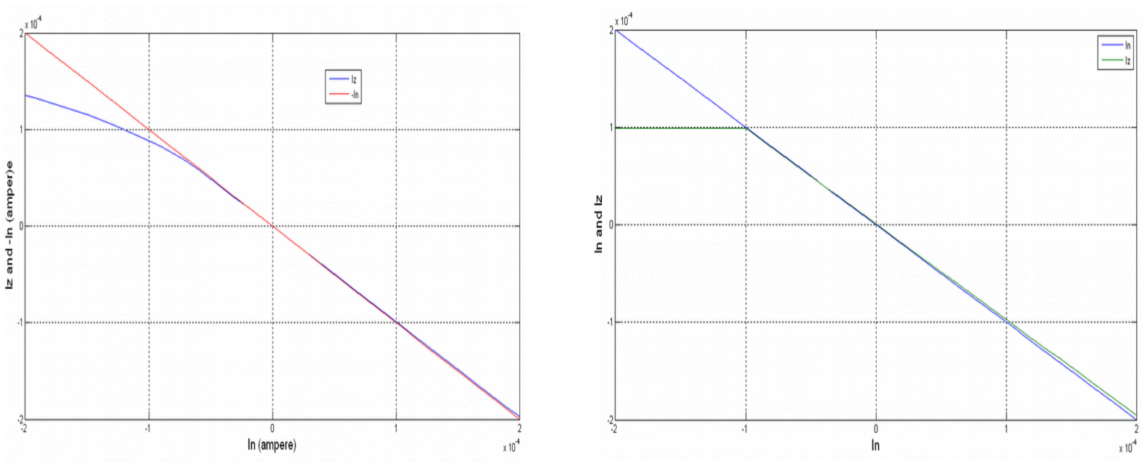


Figure 2.16 CDTA based inverting amplifier

DC analysis



(a) (b)

Figure 2.17 Current transfer from N to Z (I_P=0) (a) CMOS (b) Bipolar

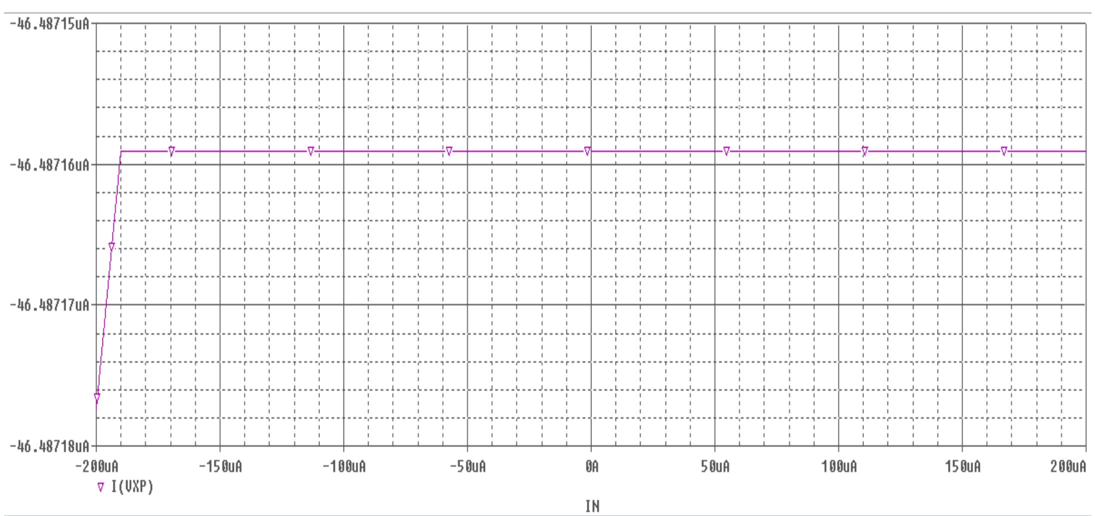


Figure 2.18 Output current characteristics I_X^+ (I_P=0)

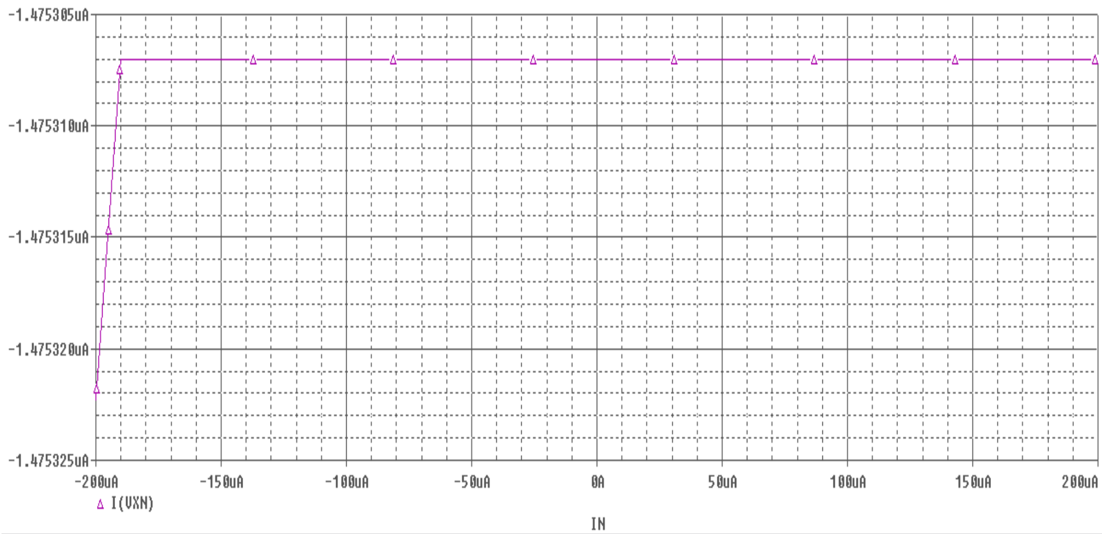


Figure 2.19 Output current characteristics I_X^- (I_P=0)

AC analysis

AC response of inverting amplifier is shown in Figure 2.20.

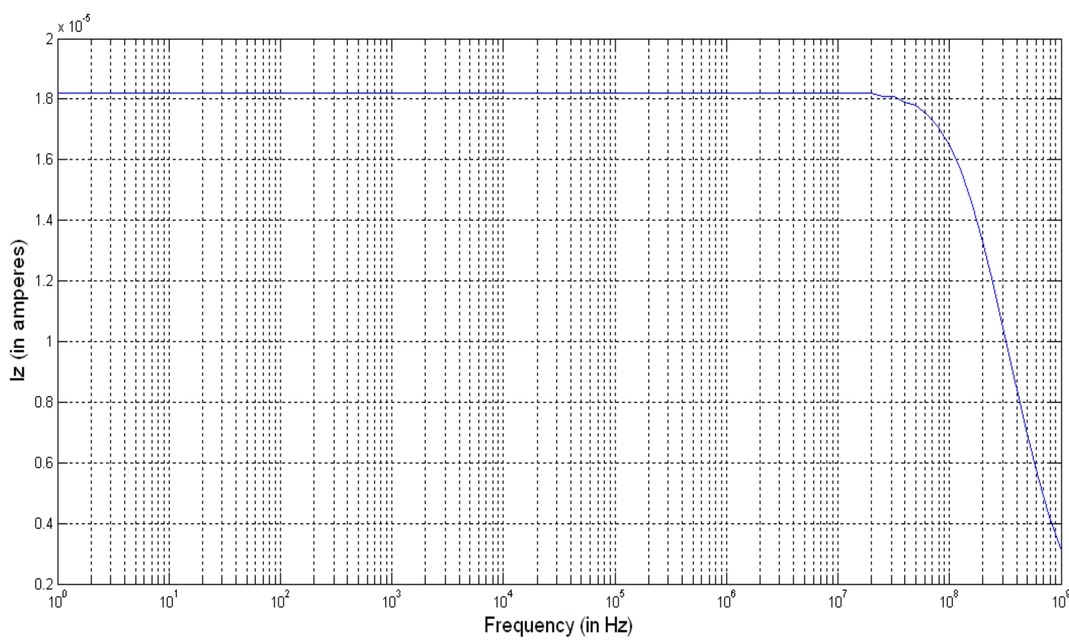
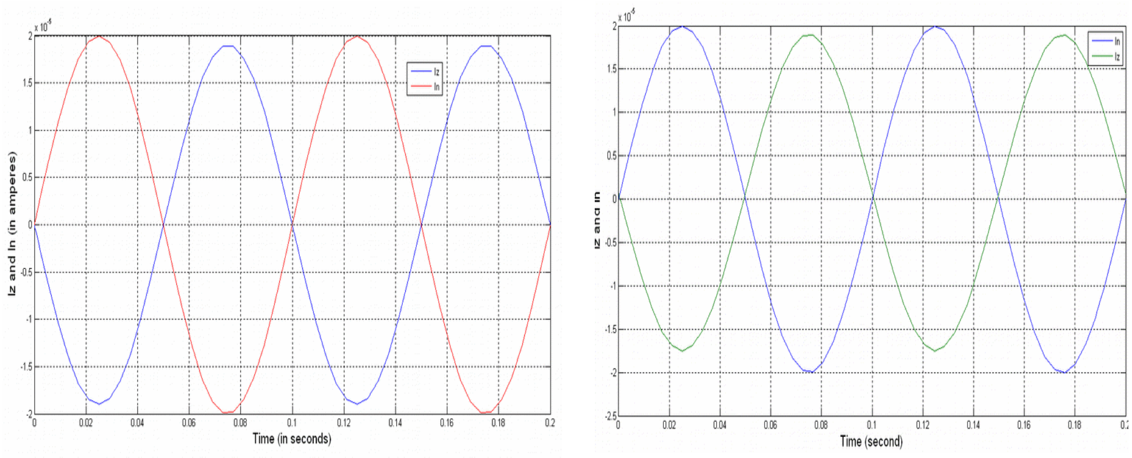


Figure 2.20 Frequency response of I_Z (I_P=0)

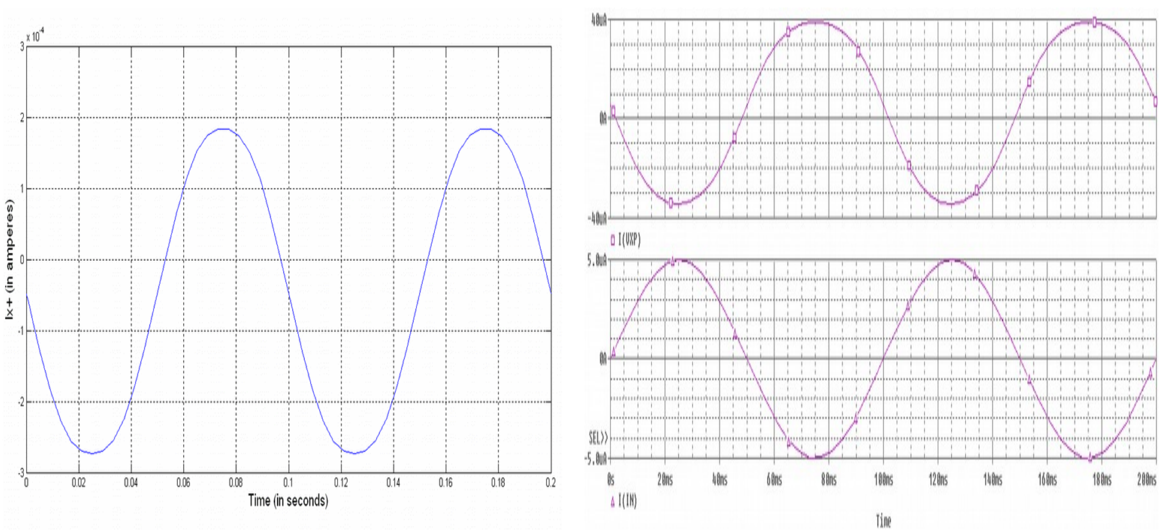
Transient analysis

Figure 2.21, 2.22 and 2.23 shows time response characteristics of inverting amplifier.



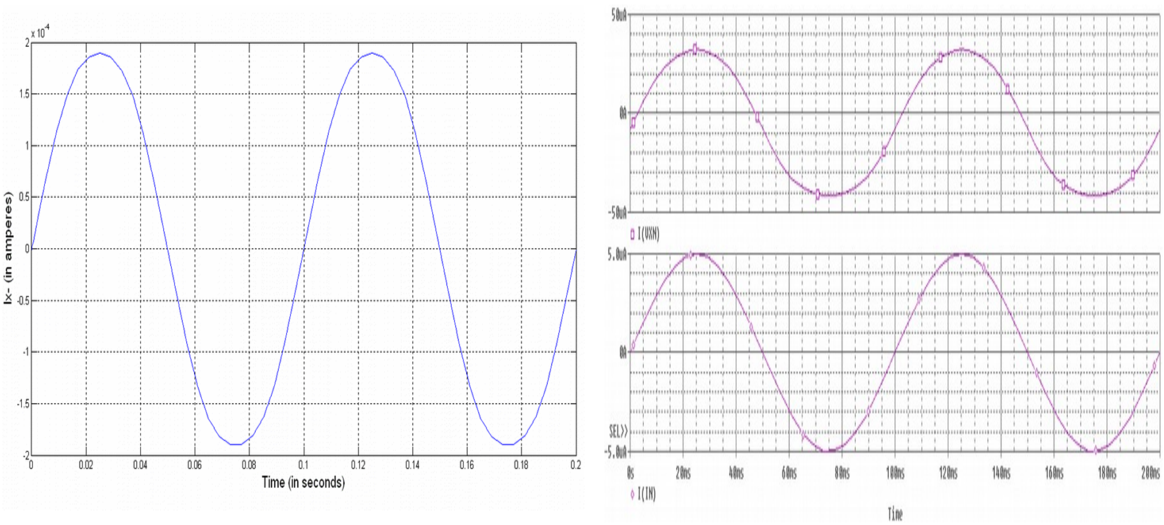
(a) (b)

Figure 2.21 Current transfer from I_N to I_Z (I_P=0) (a) CMOS (b) Bipolar



(a) (b)

Figure 2.22 Output current at the non-inverting terminal (I_X^+) (a) CMOS (b) Bipolar



(a) (b)

Figure 2.23 Output current at inverting terminal (I_X^-) (a) CMOS (b) Bipolar

From the above obtained results overall response of the CDTA can be summarized in Table 2.

2.4.2 Integrator Circuit Design

The behaviour of CDTA as an integrator can be verified by applying a square wave input at the current input terminals P or N and detemining the current at output terminals X^+ or X^-. This integrator circuit consists of single CDTA and a grounded capacitor and is represented by Figure 2.24.

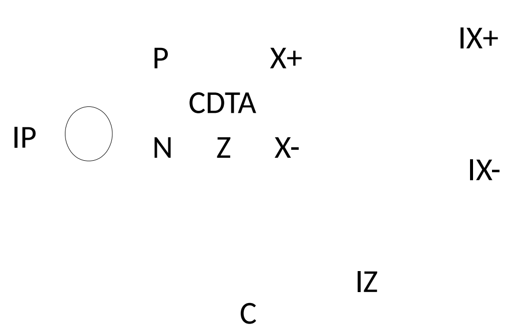


Figure 2.24 Integrator Circuit using CDTA

CDTA as an integrator can be derived as follows:

$$I_Z = I_P$$

$$V_Z = \frac{I_Z}{Cs}$$

$$X^{+¿} = \frac{g_m}{Cs} I_Z$$
$$I_{¿}$$

$$X^{-¿} = \frac{-g_m}{Cs} I_Z$$
$$I_{¿}$$

$$X^{+¿} = \frac{g_m}{Cs} I_P$$
$$I_{¿}$$

$$X^{-¿} = \frac{-g_m}{Cs} I_P$$
$$I_{¿}$$

$$I_X = \frac{g_m}{Cs} I_P$$

$$\frac{I_X}{I_P} = \frac{g_m}{Cs}$$

$$I_X = \frac{g_m}{C} \int I_p dt \; (2.9)$$

Equation (2.9) represents the integrator equation and the time constant for the charging of capacitor is given by $T = \frac{C}{g_m}$

The CDTA circuit [2] is used for the simulation of integrator and the component values taken are: C=3nF, g_m= 548μA/V. To prove the integration behavior of the circuit a square wave input current of magnitude 2.5μA is applied.

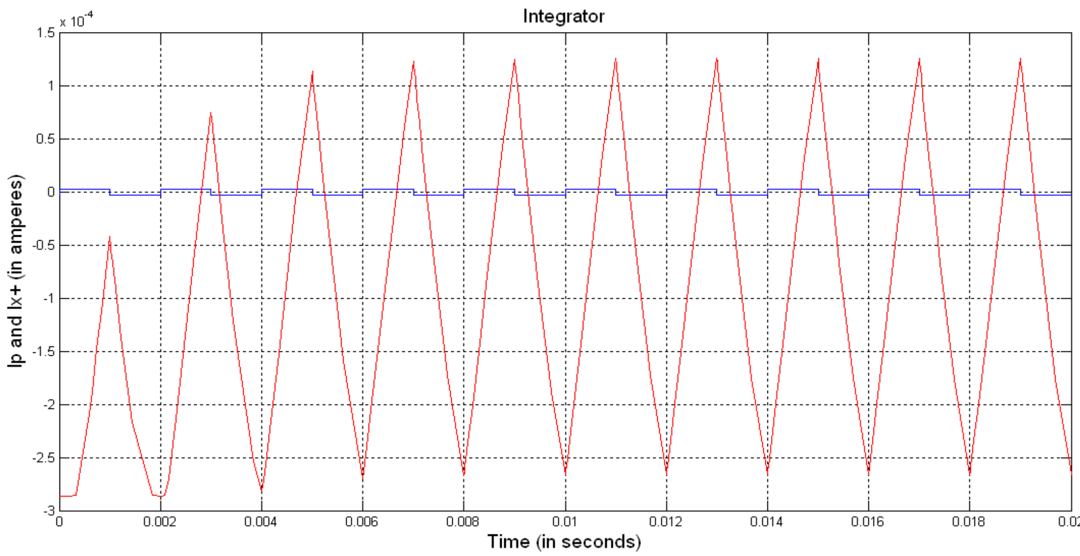


Figure 2.25 Transient response of integrator circuit

From the simulation we can see that the current obtained at the output is a triangular wave.

2.4.3 Differentiator Circuit Design

Differentiator circuit is designed by using a single CDTA and a grounded capacitor. For this circuit a voltage source is applied. Behaviour of differentiator circuit employing CDTA is verified using triangular input voltage. Figure 2.26 represents the differentiator circuit.

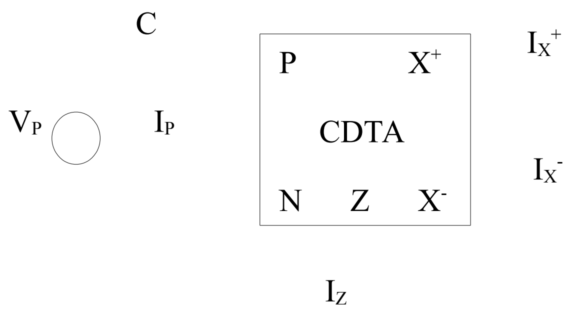


Figure 2.26 Differentiator Circuit

The characteristic equations of differentiator circuit employing CDTA, shown in Figure 2.26 are:

$$V_P = \frac{I_P}{Cs}$$

$$I_P = Cs\,V_P$$

$$I_Z = I_P$$

$$I_Z = Cs\,V_P$$

$$I_{X^{+}} = g_m V_Z$$

$$V_Z = I_Z R_Z$$

$$I_{X^{+}} = g_m I_Z R_Z$$

$$I_{X^{+}} = g_m Cs V_P R_Z$$

$$X^{-¿} = -g_m Cs V_P R_Z$$
$$I_¿$$

$$I_X = (g_m C V_P R_Z) s$$

$$I_X = g_m C R_Z \frac{d(V_P)}{dt} (2.10)$$

Where R_Z is externally connected resister at Z terminal. From equation (2.10) we can see that the circuit configuration in Figure 2.26 act as differentiator.

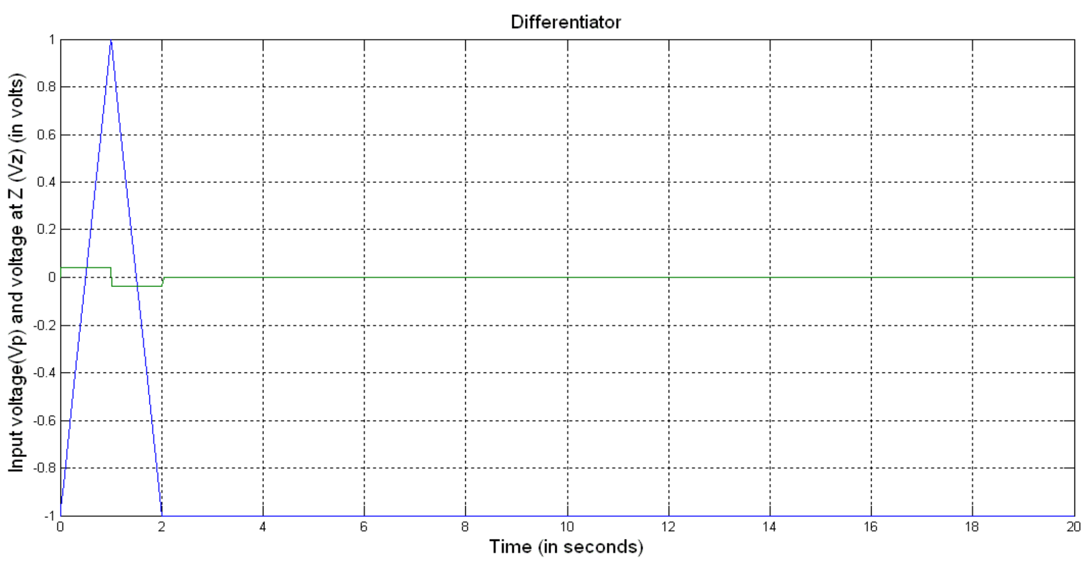


Figure 2.27 Transient response of differentiator circuit

For the simulation of differentiator circuit Bipolar CDTA [4] is used. Bipolar based CDTA is simulated with the transistor model parameters of PR100 N(PNP) and NR100 N(NPN) of the bipolar arrays ALA400 from AT&T [7]. The component values taken are:

C= 10µF, g_m=1mA/V.

From the simulation result it is proved that CDTA can act as a differentiator.

2.5 Conclusion

In this chapter CMOS and Bipolar implementation of CDTA have been discussed. The characteristics of CDTA have been simulated in PSPICE and various applications of CDTA in analog signal processing are presented. Simulated device characteristics show that the circuit presented in this chapter exhibits a very good performance. The simulation results confirm high linearity and high performance of the circuit in terms of good input and output resistances and wide bandwidths for both of the voltage and current operations.

References

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[3] A. U. Keskin D. Biolek, “Current-mode KHN filter employing current differencing transconductance amplifiers”, Int. J. Electron. commun.(AEU) 60: 443-446, 2006.
[4] D. Prasad, D. R. Bhaskar, A. K. Singh, “Multi-function biquad using current differencing transconductance amplifier”, Analog Integrated Circuit Signal Process 61:309–313, 2009.
[5] J. Satansup W. Tangsrirat, “Realization of current-mode KHN-equivalent biquad filter using ZC-CFTAs and grounded capacitors”, Indian J Pure & Appl. Phys, Vol. 49, December 2011.
[6] A. S. Sedra, K. C. Smith, “Microelectronic circuits”, Oxford University Press, 2004, 5^{th} edition.
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Chapter 3

Application of CDTA in Biquad Filter Realization

In this chapter we have discussed the application of CDTA in biquad filter realization.

3.1 Introduction

Biquad filters are second order filters. These filters are of great importance because several cells of that kind can be connected in cascade to implement higher order filters. First order and second order filters can also be cascaded to realize a high order filter. Cascade design is in fact one of the most popular methods for the design of active filters. These filters are classified based on type of input output, fixed structure or variable structure and number of input output.

Filter based on input output are characterized by its transfer function. The transfer function of a filter is the ratio of the output signal to that of the input signal as a function of the complex frequency. Since the filters are constructed of discrete components, their transfer function will be the ratio of two polynomials in, i.e. a rational function of numerator and denominator. The general second order (biquadratic) filter transfer function is usually expressed in the standard form (Eq. 3.1):

$$T(s)=\frac{a_2 s^2+a_1 s+a_0}{s^2+\frac{\omega_0}{Q}s+\omega_0^2} \quad (3.1)$$

Where ω_0 and Q determine the natural modes according to the location of poles.

Based on the transfer function, filters can be of voltage mode, current mode and mixed mode. In voltage mode filters both input and output are in voltage form. Current mode filters has both input and output in current form and in mixed mode filters input is voltage/current and output is current/voltage (i.e. transadmittance or transresistance type filters).

A filter can have single input or multiple inputs and also can deliver single output or multiple outputs. Filters based on this topology can be single input single output (SISO), single input multiple output (SIMO), multiple input single output (MISO) and multiple input multiple output (MIMO). In the following we present a review of some of the biquad filters realized with CDTA as the active building block. The filter circuits reviewed include multifunction filters in both current mode and voltage mode as well as in mixed mode. In chapter 4 where a new circuit of universal filter as been proposed and in this chapter we will present the CDTA based universal filters.

Because of the current mode advantage of CDTA, many applications in the design of active filter using CDTAs as active elements have received considerable attention. A current mode (CM) Kerwin–Huelsman–Newcomb (KHN) filter employing only two current differencing transconductance amplifiers (CDTA) and two grounded capacitors was proposed by Keskin, Biolek and Biolková [1]. The proposed circuit provides all the LP, HP, and BP transfer functions, with the low impedance input and high-impedance outputs [1].

Dumawipata, Tangsrirat and Surakampontorn [2] proposed the cascadable current-controlled current-mode multifunction filter with three inputs and one output using current differencing transconductance amplifiers (CDTAs) as active component, comprising only three CDTAs and two grounded capacitors. It provides low-input and high-output impedances, which is important for easy cascading in the current-mode operations. The proposed circuit can realize the standard filter functions namely lowpass (LP), bandpass (BP), highpass (HP), without any component matching conditions. The proposed filters are found to have low sensitivities with respect to the circuit active and passive components. The multifunction filter circuit is given in Figure 3.1.

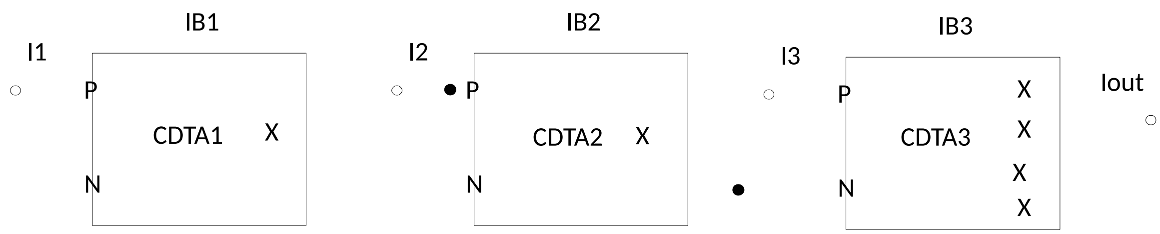


Figure 3.1 Multifunction filter configuration [2]

Siripruchyanun and Jaikla [3] designed a current-controlled current differencing Transconductance amplifier (CCCDTA) as a basic current-mode building block for analog signal processing. Its parasitic resistances at two current input ports can be controlled by an input bias current. As it can be applied in current-mode of all terminals, it is very suitable to use in a current-mode signal processing. A current-mode biquad filter is implemented using CCCDTA. It employs only one active element and two grounded capacitors, which is easy to fabricate.

A circuit technique for realizing a current-mode second-order notch filter using CDTA-based first order allpass sections is presented by Tanjaroen and Tangsrirat [4]. The proposed circuit employs only four CDTAs and two virtually grounded capacitors, and exhibit low-input and high-output impedances, which is suitable for cascading in current-mode operation. The circuit also has low passive and active sensitivities. Moreover, if the active and passive component values are properly chosen, the circuit permits the realization of second-order allpass current response.

A current-controlled multiple-input single-output (MISO) current-mode universal filter employing current differencing transconductance amplifiers (CDTAs) as active elements is described by Dumawipata, Tangsrirat and Surakampontorn [5]. The proposed circuit offers employment of only two grounded passive capacitors which provides the advantage of an electronic tuning capability and is especially interesting from the IC fabrication point of view. Minimum number of active and passive components are employed and realization of all the standard filtering functions are carried out simultaneously. There is no requirement of component matching conditions and the parameter ω_o/Q can be orthogonally and electronically tuned through adjusting the transconductance gain of the CDTA. The circuit proposed by [5] is presented in Figure 3.2.

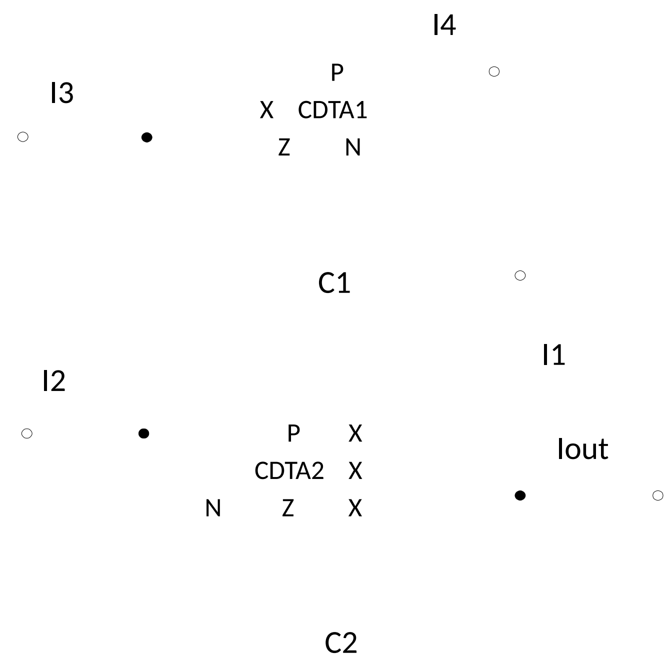


Figure 3.2 CDTA-based current-mode MISO multifunction filter [5]

Uygur and Kuntman [6] implemented an active filter using CDTA with multiple outputs which are simultaneously realizing lowpass, bandpass and highpass transfer functions. Uygur and Kuntman presented the circuit shown in Figure 3.3.

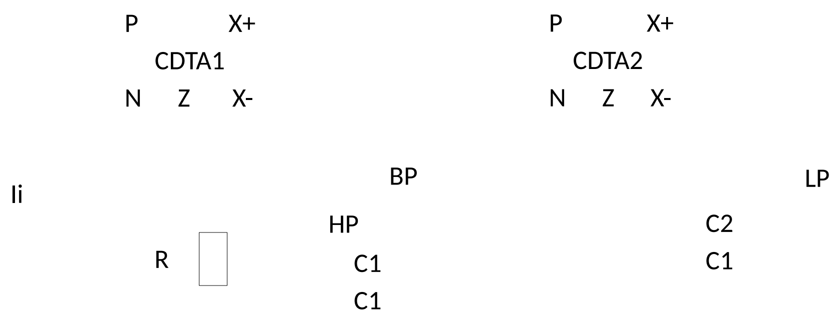


Figure 3.3 Multi function filter [6]

Prasad, Bhaskar and Singh [7] proposed a multi input single output (MISO) multi-function biquad using single current differencing transconductance amplifier (CDTA). It employs only one current differencing transconductance amplifier as the active element, two capacitors and three resistors and realizes Low Pass, High Pass, Band Pass filters without changing the circuit topology. The LP response enjoys an additional advantage of having both the capacitors grounded. The circuit offers very low active and passive sensitivities [7].

A three input single-output transadmittance type filter was implemented by Kacar and Kuntman [8]. A new improved CMOS configuration of CDTA is presented, providing low input impedances at ports p and n, very high out impedances at ports z and x, a good linearity and high input/output gain ratio for current transfer. The CDTA offered contains only MOS transistors and is designed to be implemented in CMOS technology. The proposed filter can realize LP, BP, HP filter responses from the same topology. The circuit also requires no component matching conditions.

A single current difference transconductance amplifier (CDTA) based all-pass current mode filter is proposed by Pandey and Paul [9] in 2011. The proposed configuration makes use of a grounded capacitor which makes it suitable for IC implementation. Its input impedance is low and output impedance is high, hence suitable for cascading. The circuit does not use any matching constraint. The non-ideality analysis of the circuit is also given. Two applications, namely, a quadrature oscillator and a high Q band pass filter are developed with the proposed circuit. It possesses attractive feature of electronic tunability of pole frequency and phase characteristics [9].

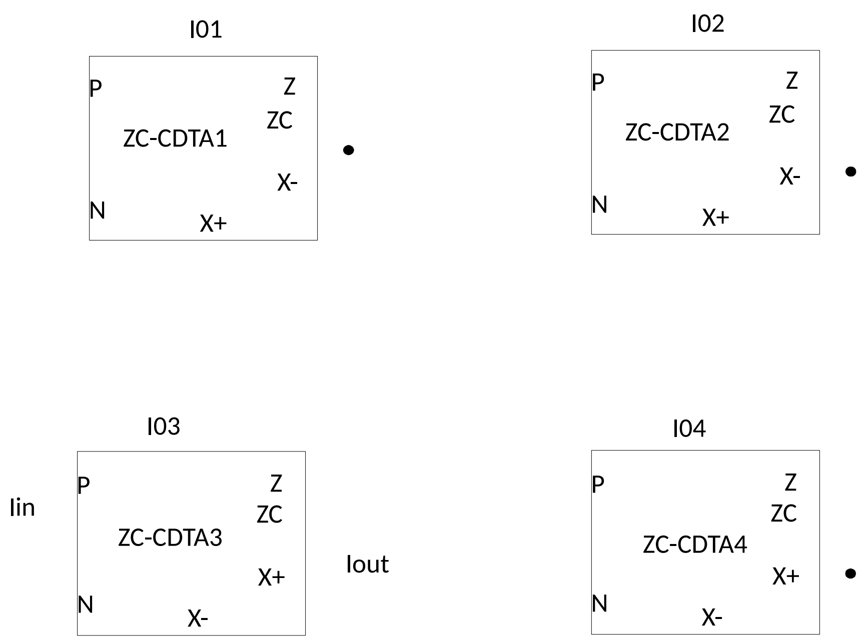


Figure 3.4 Circuit configuration of Bandpass filter [9]

3.2 Realization of Voltage Mode Filters

In the following we have presented the analysis and simulation result of voltage mode filter employing CDTA as a building block. As CDTA is a device with high output impedance current output, its application in the realization of voltage mode biquads has been very limited. In [7] Prasad, Bhaskar and Singh have presented a voltage mode filter circuit using CDTA. In voltage mode filters, both input and output are voltages. A universal multi input single output type filter employing a single CDTA as an active element, two capacitors and three resistors is presented in Figure 3.5. The circuit in Figure 3.5 realizes all the filter transfer functions of low pass, band pass, high pass, band pass and band reject filters.

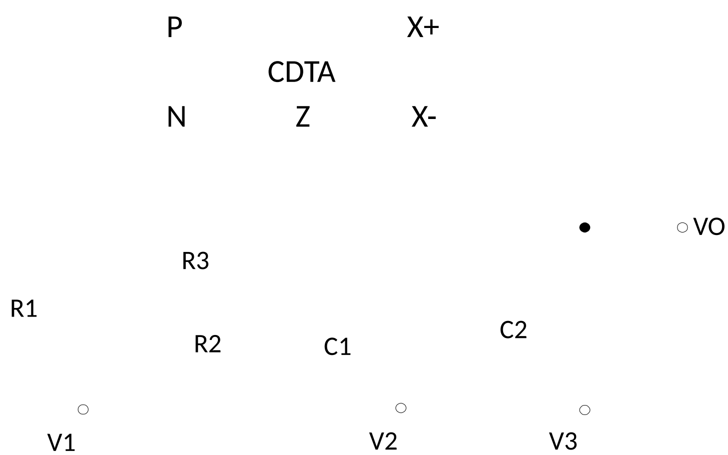


Figure 3.5 Multi-function voltage mode biquad filter [11]

The output of all the five filters is delivered by the filter circuit given in Figure 3.5- low pass (LP), high pass (HP), band pass (BP), all pass (AP) and band reject (BR) filter, depending on the values of input voltages V_1, V_2 and V_3. In the four different cases deriving the voltage transfer functions gives the following equations (Eq. 3.2-3.6):

i. Low pass filter: When $V_1 = V_{in}$ and $V_2 = V_3 = 0$

$$\frac{V_o}{V_{\text{¿}}} = \frac{g_m g_1 / C_1 C_2}{s^2 + \left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)s + \frac{g_2 g_3}{C_1 C_2}} \quad (3.2)$$

ii. Band pass filter: When $V_2 = V_{in}$ and $V_1 = V_3 = 0$

$$\frac{V_o}{V_{\text{¿}}} = \frac{-\left(g_m / C_2\right)s}{s^2 + \left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)s + \frac{g_2 g_3}{C_1 C_2}} \quad (3.3)$$

iii. High pass filter: When $V_3 = V_{in}$ and $V_1 = V_2 = 0$

$$\frac{V_o}{V_{¿}} = \frac{s^2}{s^2 + \left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)s + \frac{g_2 g_3}{C_1 C_2}} \quad (3.4)$$

iv. All pass filter: When $V_1 = V_2 = V_3 = Vin$

$$\frac{V_o}{V_{¿}} = \frac{s^2 + \left(\frac{-g_m}{C_1} - \frac{g_m}{C_2} + \frac{g_2}{C_1}\right)s + \frac{g_m g_1}{C_1 C_2}}{s^2 + \left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)s + \frac{g_2 g_3}{C_1 C_2}} \quad (3.5)$$

v. Band reject filter: $V_1 = V_3 = V_{in}$ and $V_2 = 0$

$$s^2 \frac{g_m g_1 + (¿¿ C_1 C_2)}{s^2 + \left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)s + \frac{g_2 g_3}{C_1 C_2}} \quad (3.6)$$

$$\frac{V_o}{V_{¿}} = ¿$$

Where

$$g_i = \frac{1}{R_i}, i = 1, 2, 3$$

The parameters natural frequency and the quality factor of voltage mode filter are presented by equations (Eq. 3.7, 3.8):

$$\omega_0 = \sqrt{\frac{g_2 g_3}{C_1 C_2}} \quad (3.7)$$

$$Q = \frac{\sqrt{\frac{g_2 g_3}{C_1 C_2}}}{\left(\frac{g_3}{C_2} + \frac{g_2}{C_1} - \frac{g_m}{C_1}\right)} \quad (3.8)$$

To verify the theoretical results of the voltage mode multi function biquad filter circuit bipolar CDTA [7] circuit is used. Bipolar based CDTA is simulated with the transistor model parameters of PR100 N(PNP) and NR100 N(NPN) of the bipolar arrays ALA400 from AT&T [10].

The component values used are C_1 = 2 nF, C_2 = 1 nF, R_1 = 1 KΩ, R_2 = 1 KΩ and R_3 = 1.08 KΩ, the CDTA was biased with ±3 V D.C. power supplies with $I_{B1} = I_{B2}$ = 100 μA I_{B3} = 50.9 μA and $g_m = 1\,mA/V$. I_{B1} and I_{B2} are the biasing currents for the devices to perform the current differencing operation, while CDTA transconductance is controlled by I_{B3}.

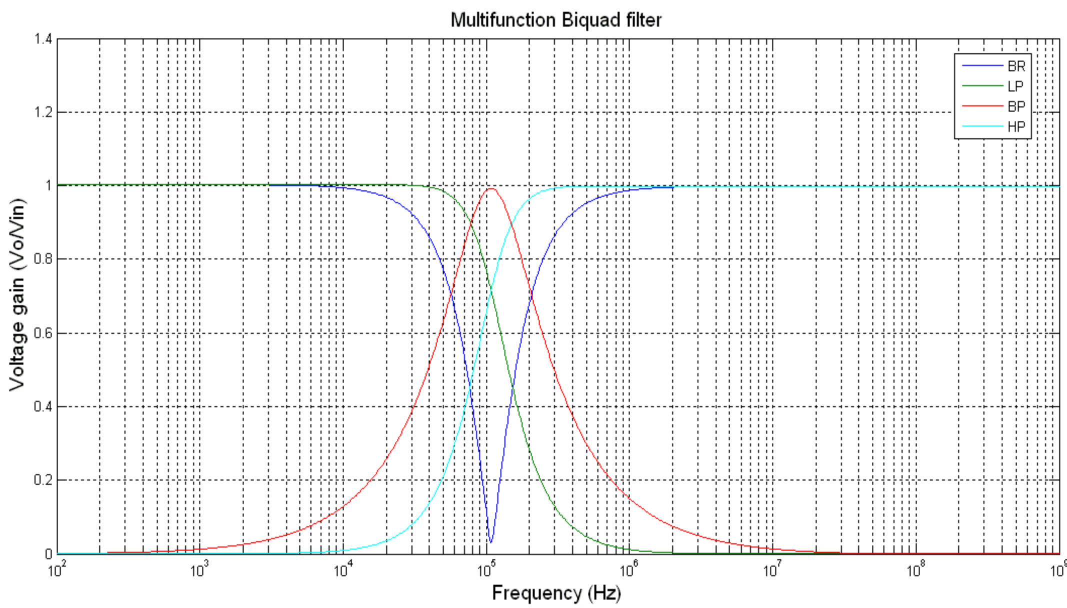


Figure 3.6 Frequency response of multi-function filter

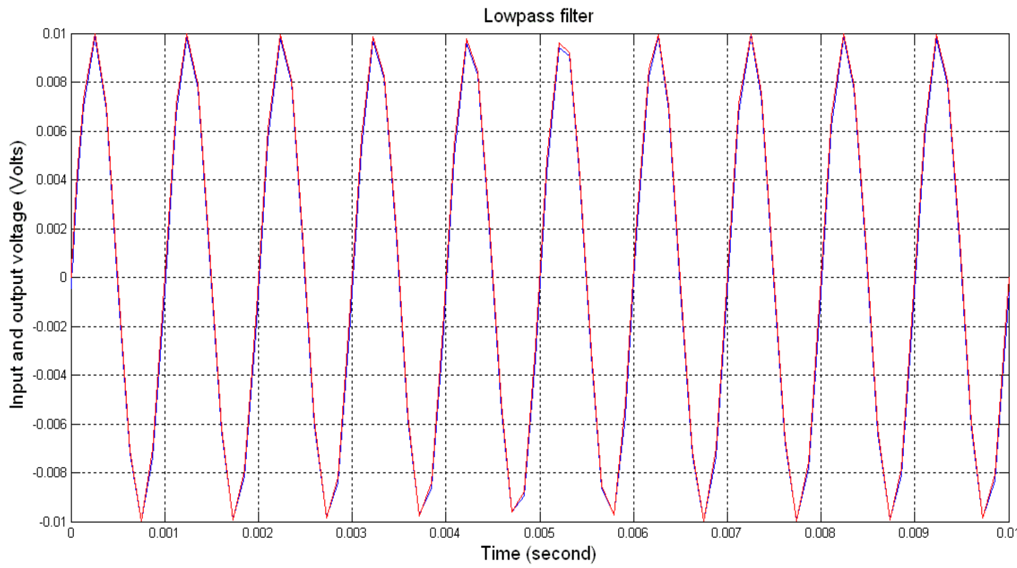


Figure 3.7 Transient response of Lowpass filter

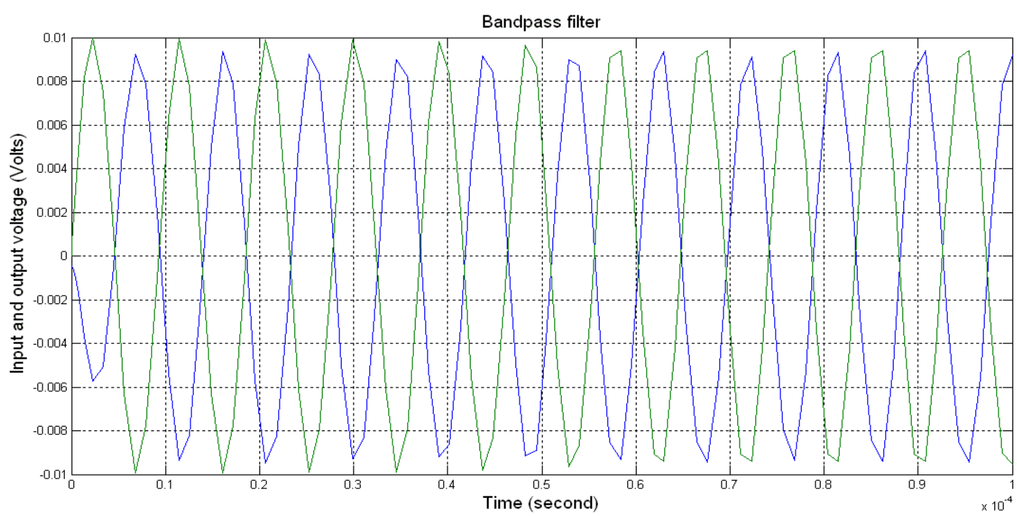


Figure 3.8 Transient response of Bandpass filter

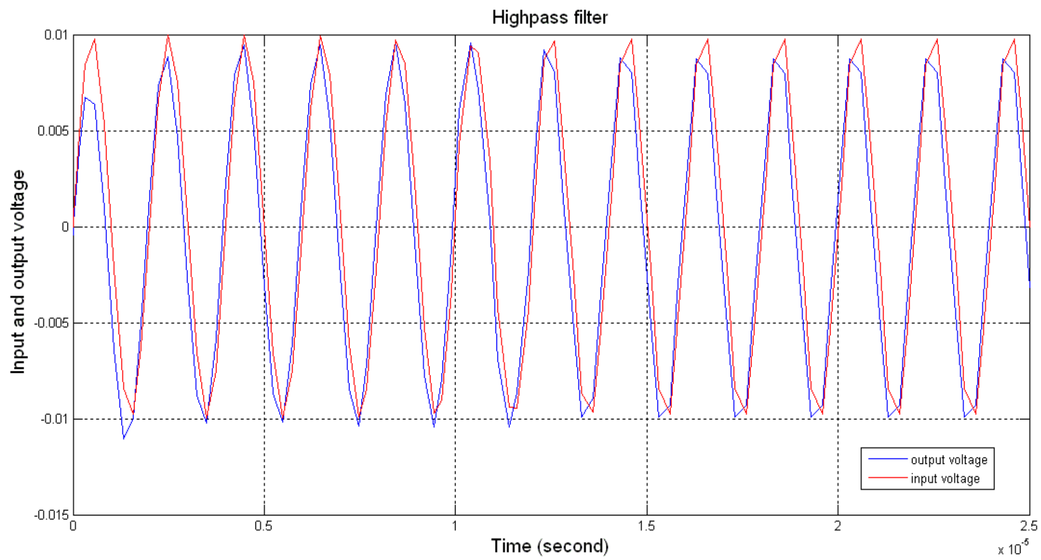


Figure 3.9 Transient response of Highpass filter

Figures 3.6-3.9 shows the simulated filter responses of LP, BP and HP. These results thus confirm the validity of the circuit configuration [7].

3.3 Realization of Current Mode Filters

These types of filters have their input as current and also output as current. Recently, current-mode circuits have been receiving considerable attention, due to their potential advantages such as inherently wide bandwidth, greater linearity, higher slew-rate, simple circuitry, wider dynamic range and low power consumption [10]. In the following we have presented current mode filter using CDTA. The analysis and simulation of [1] is performed in this section.

KHN biquad filter

The Kerwin-Huelsman-Newcomb biquad (KHN) filter is a state variable type filter [11]. General KHN biquad structure has two integrators and a summer, which provide the simultaneous responses of second order low pass (LP), high pass (HP) and band pass (BP) filters, thus it is also called universal filter. Basic structure of KHN biquad filter is presented in Figure 3.10.

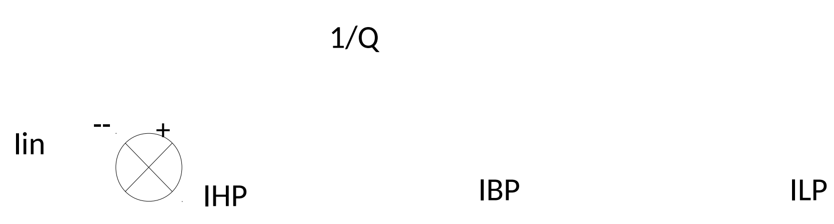


Figure 3.10. Basic structure of KHN biquad filter [12]

Based on the general structure of KHN biquad, the filter circuit employing two CDTAs and two grounded capacitors are presented in Figure 3.11. The grounded capacitors C_1 and C_2 perform the function of two integrators.

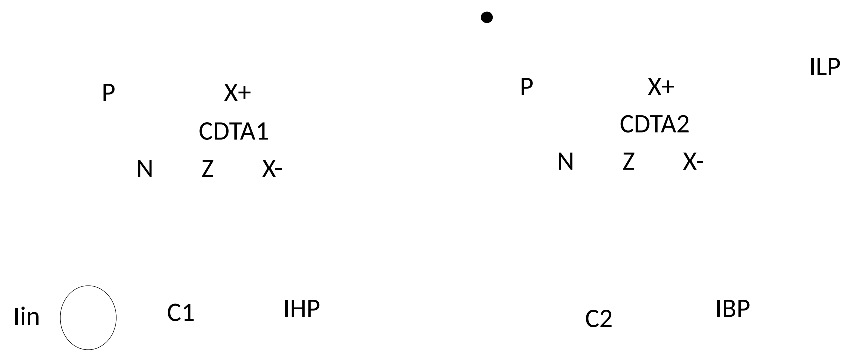


Figure 3.11. Second Order Current Mode KHN Filter [1]

The filter circuit demonstrated in Figure 3.11 represents universal filter which shows the behaviour of all the three filters- high pass (HP), low pass (LP) and band pass (BP).

The following current transfer functions (Eq.3.7- 3.11) give the performance of the filter circuit in Figure 3.11:

$$\frac{I_{HP}}{I_{¿}} = \frac{-s^2}{s^2 + \frac{g_{m1}}{C_1}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \quad (3.9)$$

$$\frac{I_{BP}}{I_{¿}} = \frac{-\frac{g_{m1}}{C_1}s}{s^2 + \frac{g_{m1}}{C_1}s + \frac{g_{m1}g_{m2}}{C_1C_2}} \quad (3.10)$$

$$\frac{I_{LP}}{I_{¿}} = \frac{-\frac{g_{m1} g_{m2}}{C_1 C_2}}{s^2 + \frac{g_{m1}}{C_1} s + \frac{g_{m1} g_{m2}}{C_1 C_2}} \quad (3.11)$$

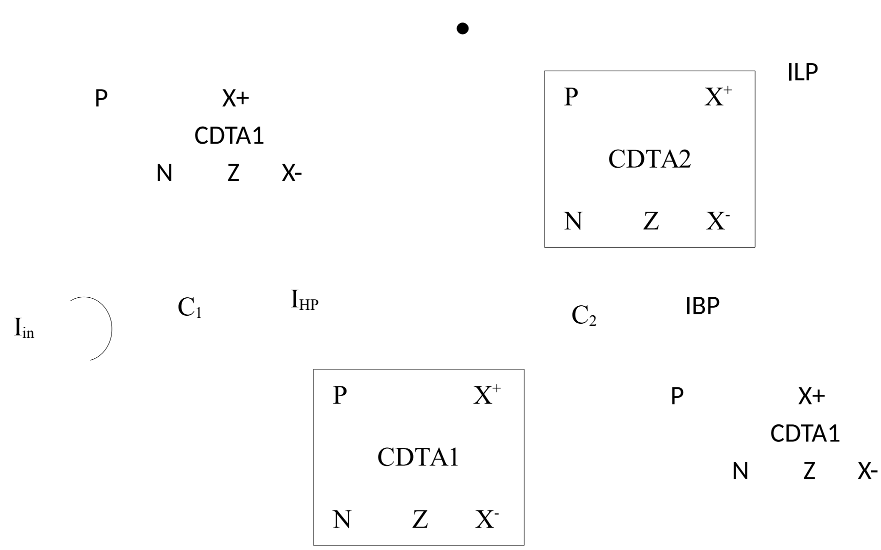
The parameters natural frequency and the quality factor of current mode KHN filter are presented by equations (Eq. 3.12, 3.13):

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}} \quad (3.12)$$

$$Q = \sqrt{\frac{g_{m2} C_1}{g_{m1} C_2}} \quad (3.13)$$

Current through the capacitors C_1 and C_2 are grounded in Figure 3.11 as grounded capacitors are used. These currents cannot be used directly. To make the usability of these currents a copy is generated using two more CDTAs. As it is the property of CDTA to transfer the input current to the Z terminal so this active device can be used to copy the currents through the grounded capacitors.

The circuit configuration of filter using four CDTAs is shown in Figure 3.12. The circuit consists of four CDTAs and two capacitors. These capacitors are virtually grounded as the CDTA has its input terminal voltage $V_P = V_N = 0$. The current through the grounded capacitor is connected at the input terminal P and thus this current is transferred to Z terminal.



I_{HP} I_{BP}

Figure 3.12 Current mode KHN filter

KHN biquad filter circuit is simulated in PSPICE to verify the desired results. For the simulation 0.5µm MIETEC CMOS technology is taken into account. The simulation results show that the CDTA has 400MH$_Z$ bandwidth. To demonstrate the results of current mode KHN filter the values of C_1=C_2=50pF and g_{m1}=g_{m2}=548µA/V are taken. Figure 4.15 represents frequency response of current mode KHN filter. The simulation results shows the frequency of f = 1.62MH$_Z$, in agreement with the theoretical value of frequency f = 1.744MH$_Z$.

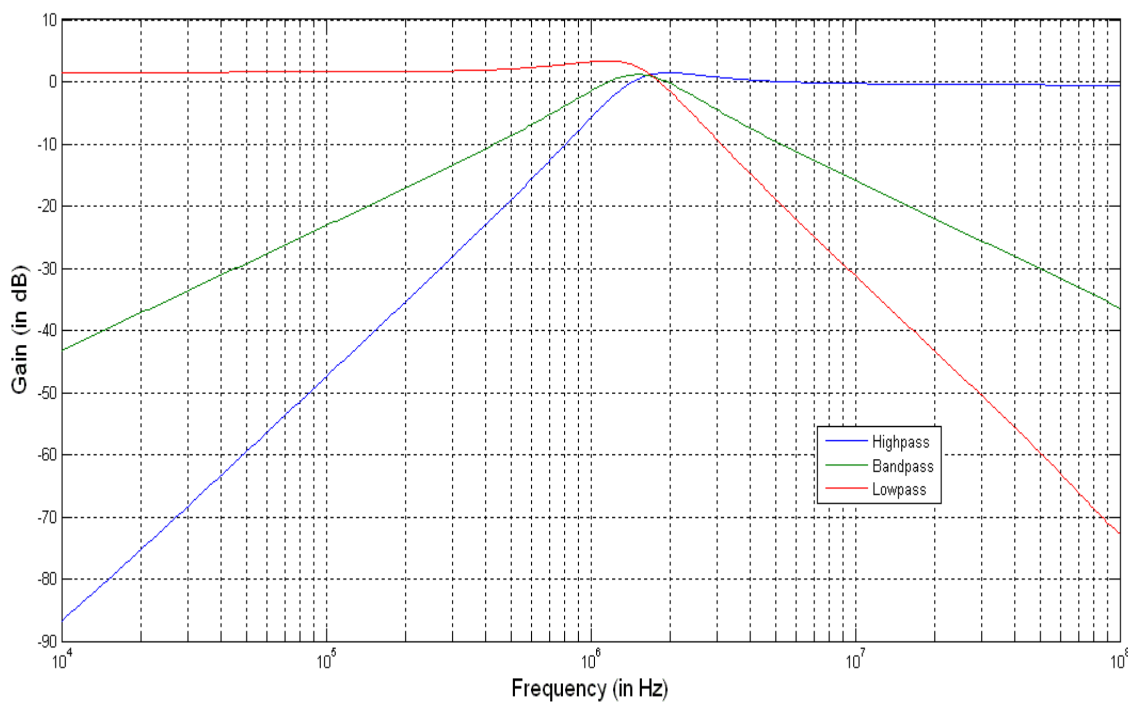


Figure 3.13 Frequency response of current mode KHN filter

Transient analysis

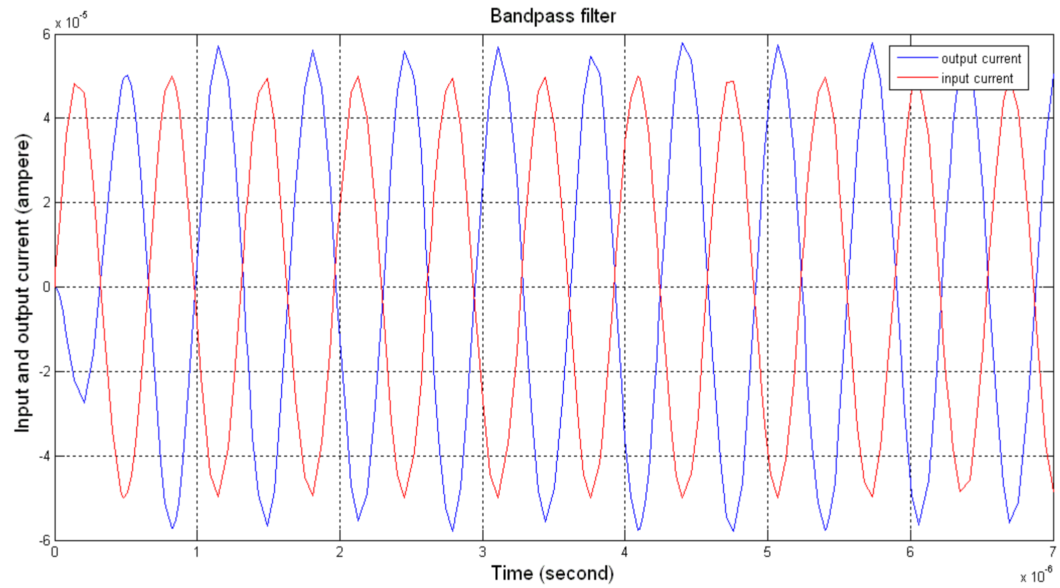


Figure 3.14 Transient response of Bandpass filter

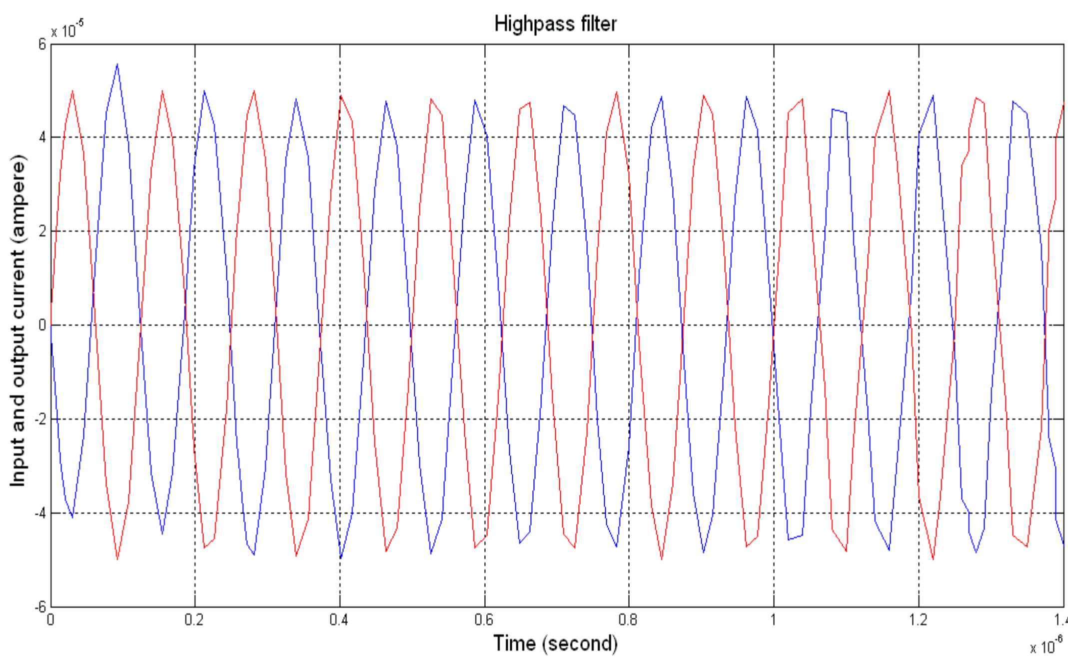


Figure 3.15 Transient response of Highpass filter

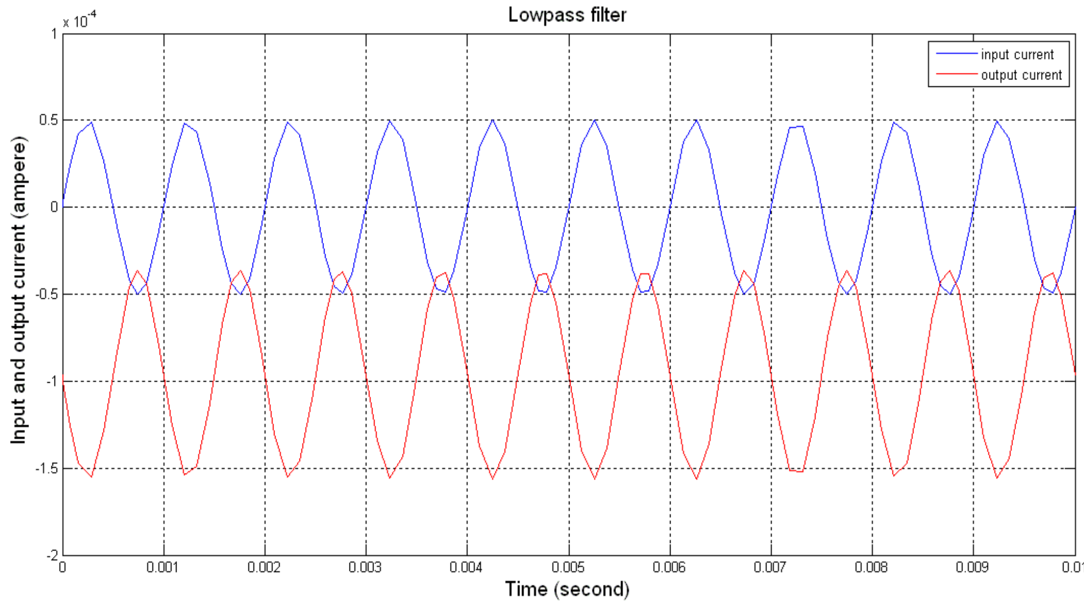


Figure 3.16 Transient response of Lowpass filter

Figure 3.13 shows the frequency response and Figures 3.14, 3.15 and 3.16 shows the transient response of the current mode filter, which validate the behavior of the circuit as a filter.

3.4 Realization of Mixed Mode Filter (Transadmittance type filter)

Mixed mode filter is designed by using two CDTAs, one capacitor and two resistors. The circuit presented in Figure 3.17 proposed by [13] is a transadmittance type filter.

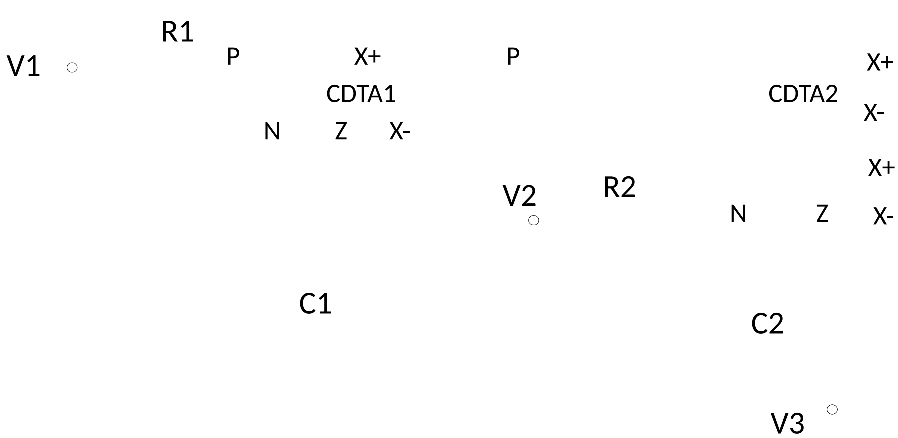


Figure 3.17 Mixed mode transadmittance type biquad filter [13]

Analyzing the circuit configuration in Figure 3.17 yields :

$$X2^{+¿}$$
$$I_{Z1}=\frac{V_1}{R_1}-I_{¿}$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1}-I_{¿}$$
$$V_{Z1}=\frac{1}{C_1 s}¿$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1}-I_{¿}$$
$$X1^{+¿}=\frac{g_{m1}}{C_1 s}¿$$
$$I_{¿}$$

$$X1^{-¿}-\frac{V_2}{R_2}$$
$$X2^{+¿}-I_{¿}$$
$$I_{Z2}=I_{¿}$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1}-I_{¿}$$
$$¿$$
$$X2^{+¿}-\frac{V_2}{R_2}$$
$$I_{Z2}=\frac{g_{m1}}{C_1 s}¿$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1} - I_{¿}$$
$$¿$$
$$\frac{I_{X2^{-¿}}}{C_2 s} - \frac{V_2}{C_2 R_2}$$
$$V_{Z2} = V_3 + \frac{g_{m1}}{C_1 C_2 s} ¿$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1} - I_{¿}$$
$$¿$$
$$\frac{I_{X2^{-¿}}}{C_2 s} - \frac{V_2}{C_2 R_2}$$
$$V_3 + \frac{g_{m1}}{C_1 C_2 s} ¿$$
$$X2^{+¿} = g_{m2} ¿$$
$$I_{¿}$$

$$X2^{+¿}$$
$$\frac{V_1}{R_1} - I_{¿}$$
$$¿$$
$$X2^{+¿} - \frac{g_{m2}}{C_2 s} \frac{V_2}{R_2}$$
$$X2^{+¿} = g_{m2} V_3 + \frac{g_{m1} g_{m2}}{C_1 C_2 s^2} ¿$$
$$I_{¿}$$

$$X2^{+¿}\left(1 + \frac{g_{m1} g_{m2}}{C_1 C_2 s^2} + \frac{g_{m2}}{C_2 s}\right) = g_{m2} V_3 + \frac{g_{m1} g_{m2}}{C_1 C_2 s^2} \frac{V_1}{R_1} - \frac{g_{m2}}{C_2 s} \frac{V_2}{R_2}$$
$$I_{¿}$$

$$\frac{V_3(¿¿1R_2C_1C_2)s^2-(R_1C_1)sV_2+g_{m1}R_2V_1}{R_1R_2C_1C_2s^2}$$

¿
¿

$$X2^{+¿}\left(\frac{s^2+\frac{g_{m2}}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2}\right)=g_{m2}¿$$

$I_¿$

The parameters ω_o and Q of the filters, obtained by equation (3.12) are defined as (Eq. 3.13, 3.14) respectively:

$$\omega_o=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}\quad(3.15)$$

$$Q=\sqrt{\frac{g_{m1}C_2}{g_{m2}C_1}}\quad(3.16)$$

The circuit in Figure 3.17 act as low pass (LP), band pass (BP) and high pass (HP) filter in the following cases depending on the values of V_1, V_2 and V_3.

Case 1: Low pass filter – When $V_2=V_3=0$ and $V_1=V_{in}$

$$\frac{I_{X2^{+¿}}}{V_1}=\frac{g_{m1}g_{m2}/R_1C_1C_2}{s^2+\frac{g_{m2}}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}\quad(3.17)$$

¿

Case 2: Band pass filter - When $V_1=V_3=0$ and $V_2=V_{in}$

$$\frac{I_{X2^{+¿}}}{V_2}=\frac{-g_{m2}R_1C_1s}{s^2+\frac{g_{m2}}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}\quad(3.18)$$

¿

Case 3: High pass filter - When V_1=V_2=0 and V_3=V_{in}

$$\frac{I_{X2^{+}}}{V_3}=\frac{g_{m2}s^2}{s^2+\frac{g_{m2}}{C_2}s+\frac{g_{m1}g_{m2}}{C_1C_2}}\quad(3.19)$$

¿

Simulation Results

For the simulation CMOS based CDTA [1] is used and the values of the parameters taken are:

$R_1 = R_2 = 1K\Omega$, $C_1 = C_2 = 1nF$, $g_{m1} = g_{m2} = 548\mu A/V$

using the values these components theoretical value of the frequency obtained is:

$$f_{theroretical}=87.21\,KH_Z$$

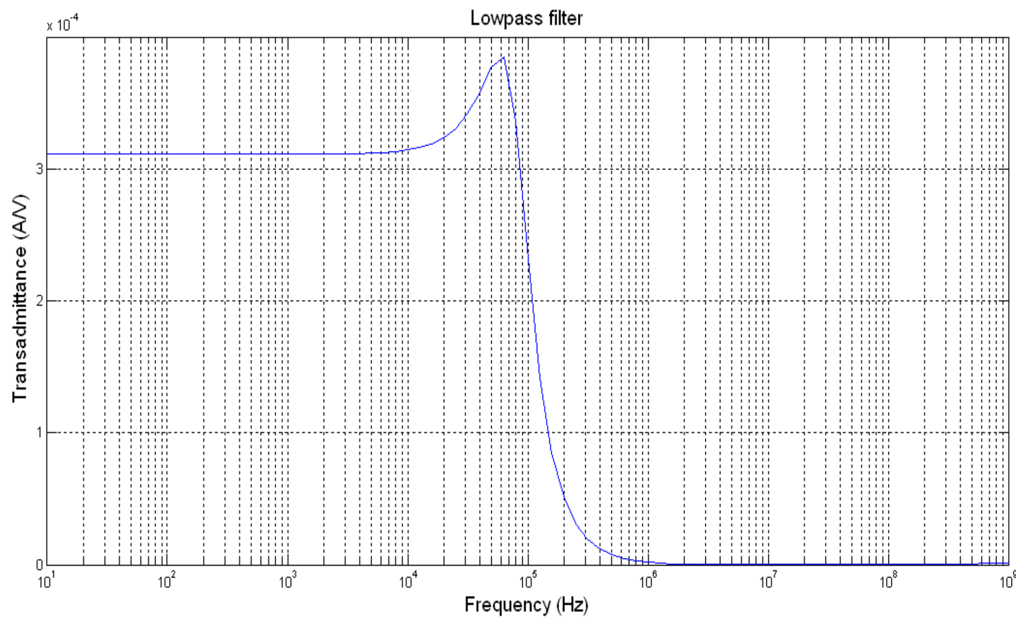


Figure 3.18 Frequency response of transadmittance type lowpass filter

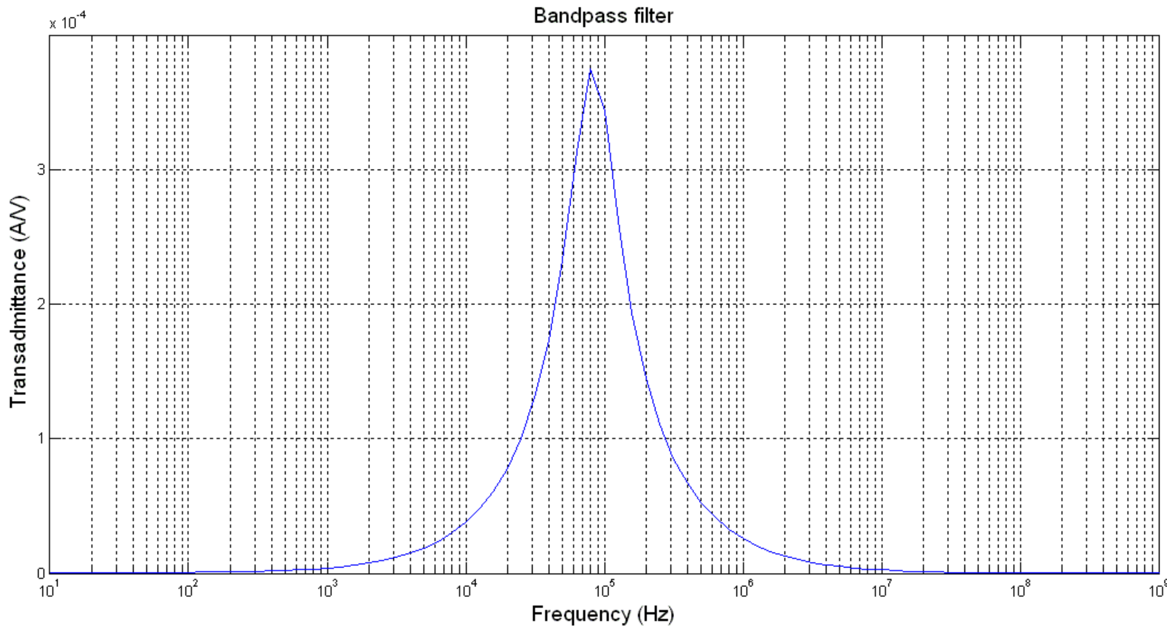


Figure 3.19 Frequency response of transadmittance type bandpass filter

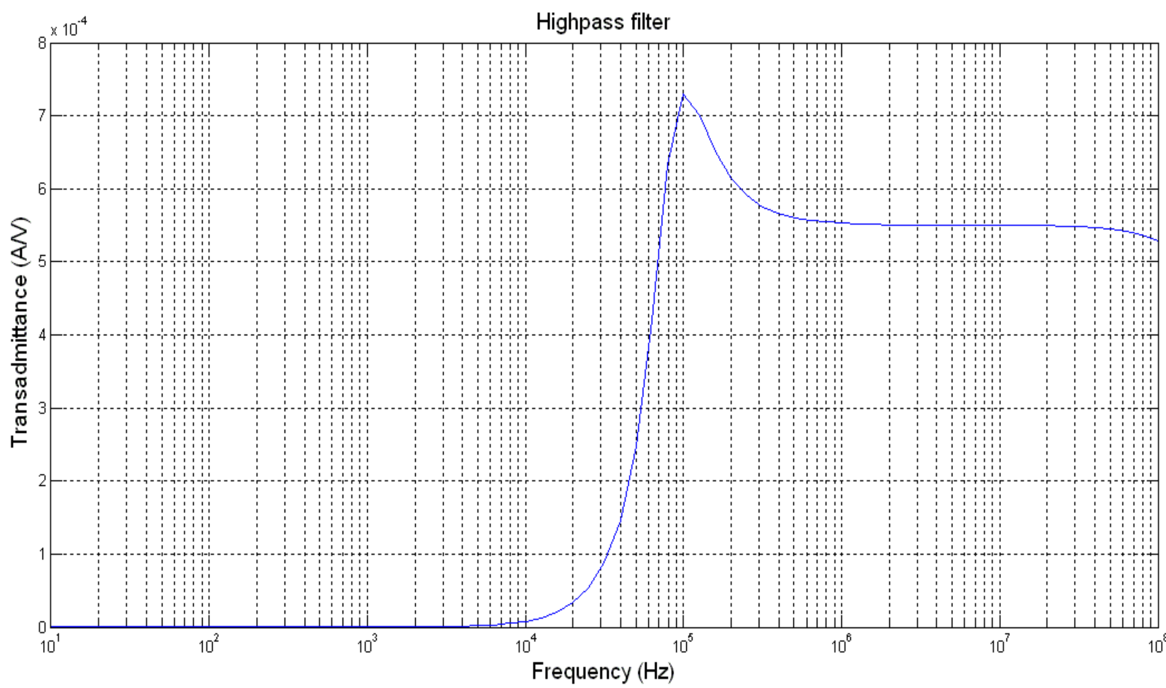


Figure 3.20 Frequency response of transadmittance type highpass filter

Figure 3.21, 3.22 and 3.23 shows the transient responses of all filters.

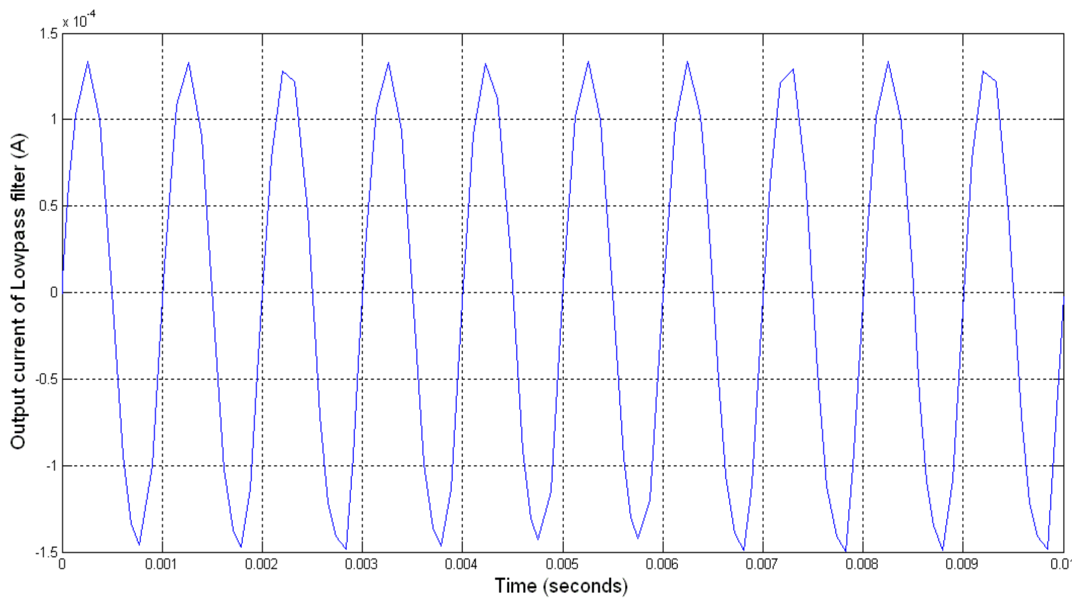


Figure 3.21 Transient response of transadmittance type lowpass filter

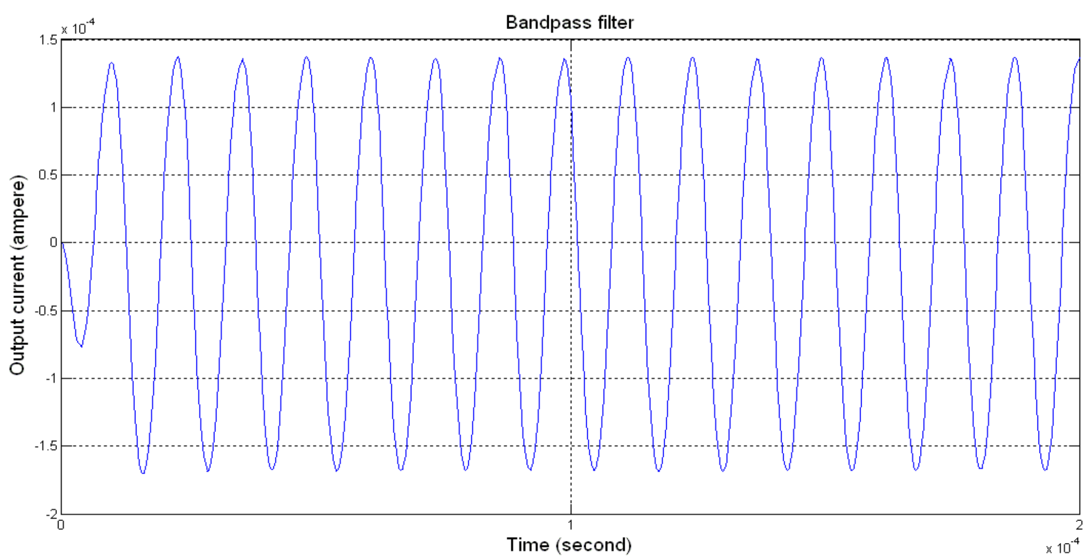


Figure 3.22 Transient response of transadmittance type bandpass filter

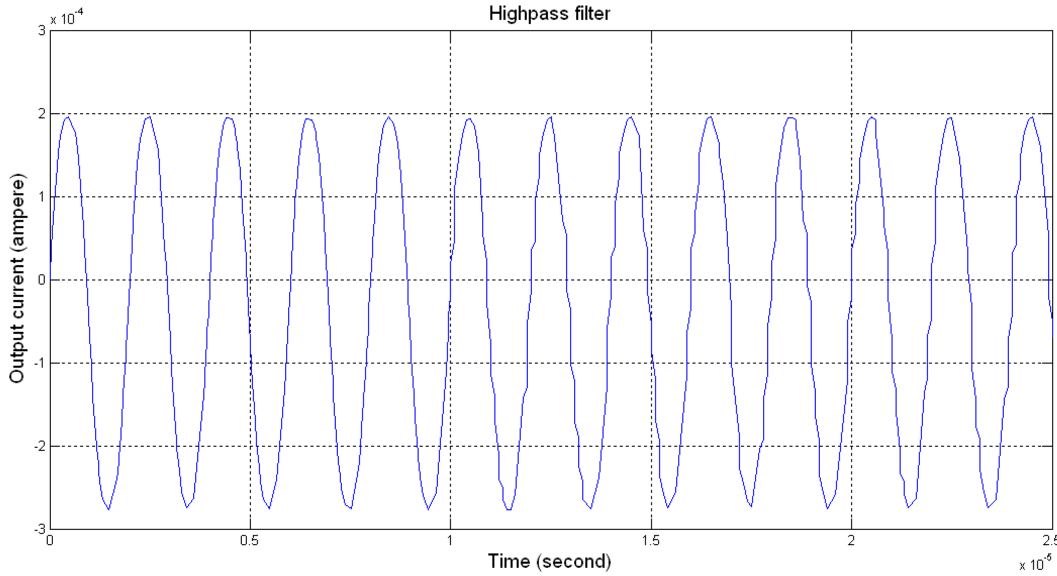


Figure 3.23 Transient response of transadmittance type highpass filter

From the simulation results the validity of the circuit is proved and the cut off frequency obtained is:

$$f_{practical} = 76.433\,K\,H_Z$$

3.5 Conclusion

In this chapter a brief discussion of voltage mode, current mode and mixed mode filter is described. The voltage mode filter, which consists of a single CDTA, two capacitors and three resistors can realize the second order LP, HP, BP, BR and AP filter simultaneously without changing the circuit topology. In this circuit LP filter has the advantage of having both the capacitors grounded. A CM KHN biquad employing only two active and two passive components has been presented. Therefore, the multipurpose CM filter has least component count. Because of CM operation, the filter enjoys advantages in terms of bandwidth and dynamic range with respect to their voltage mode counterparts. This structure can be effectively used in higher-frequency applications. The mixed mode filter presented has three input and single output. All the filter circuits described in this chapter have the advantage that the characteristics can be electronically tuned through biasing current of the transconductance of the DO-OTAs present in the CDTA structure.

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Chapter 4

Application of CDTAs in realization of Harmonic Oscillator

4.1 Introduction

In the design of electronics systems the need frequently arises for signals having prescribed standard waveform, for example, sinusoidal, square, triangular, or pulse. Systems in which standard signals are required include computer and control systems where clock pulses are needed for communication systems where signals of variety of waveforms are utilized as information carriers; and test and measurement systems where signals, again of a variety of waveforms, are employed for testing and characterizing electronic devices and circuits.

There are two distinct approaches for the generation of sinusoids, the most commonly used of the standard waveforms. The first approach, presented in this chapter, employs a positive feedback loop consisting of an amplifier and an RC frequency selective network. The amplitude of the generated sine waves is limited or set using a nonlinear action, implemented either with a separate circuit or using the nonlinearities of the amplifying device. These circuits generate sine waves utilizing resonance phenomena and they are called linear oscillators. Square, triangular, pulse waveforms more popularly known as relaxation oscillators are generated by the amplifiers working in saturation mode and are called nonlinear oscillators [1].

From the literature survey it is found that many oscillator circuits, both voltage mode and current mode, using CDTA and different derivatives of CDTA have been introduced. In the following we present a brief summary of these oscillators with their important features.

4.2 Harmonic oscillators realized with derivatives of CDTA

Jaikla and Siripruchyanan [2] proposed a quadrature oscillator in which the oscillation condition and oscillation frequency can be adjusted independently by the input bias current. The circuit consists of merely one dual output current controlled current differencing transconductance amplifier (DO-CCCDTA) and two grounded capacitors. This circuit is suitable for IC architecture since it is without any external resistors and uses only grounded elements [2]. In case of no input current and appropriated condition, the proposed circuit can provide quadrature sinusoidal signals in both voltage-mode and current-mode simultaneously. The DO-CCCDTA is composed of complementary current mirrors, mixed loops and translinear elements. DO-CCCDTA properties are similar to the conventional CDTA, except that input voltages of DO-CCCDTA are not zero and have finite input resistances at the P and N input terminals, respectively. The above mentioned parasitic resistances are equal and can be controlled by the bias current. The circuit configuration presented by Jaikla and Siripruchyanan [2] is given in Figure 4.1.

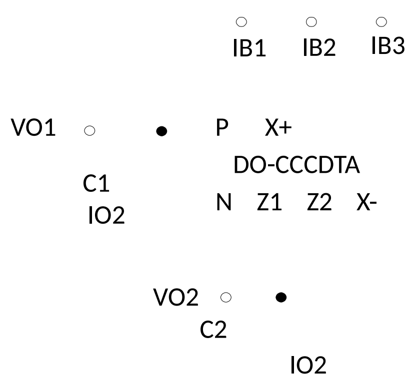


Figure 4.1 Circuit configuration of voltage/current mode quadrature oscillator [2]

If no input current is applied to the circuit as in Figure 4.1, system characteristic equation can be expressed as (Eq. 4.1):

$$s^2+s\frac{1}{C_1}\left(\frac{2}{R_P}-g_m\right)+\frac{g_m}{C_1C_2R_P}=0 \quad (4.1)$$

From equation (4.1) it can be seen that the circuit in Figure 4.1 act as an oscillator if

$$\frac{2}{R_P}=g_m \quad (4.2)$$

Equation (4.2) is called condition of oscillation and thus obtained characteristic equation is (Eq. 4.3):

$$s^2+\frac{g_m}{C_1 C_2 R_P}=0 \quad (4.3)$$

From equation (4.3) frequency of oscillation is given as in equation (4.4):

$$\omega_0=\sqrt{\frac{g_m}{C_1 C_2 R_P}} \quad (4.4)$$

It can be seen that the oscillation frequency (ω_0) can be controlled by bias current as ω_0 is dependent upon g_m which can be controlled by bias current. Furthermore, the quadrature sinusoidal signals can be obtained at I_{01} and I_{02} or V_{01} and V_{02} of Figure 4.1, in current-mode and voltage-mode, respectively, with the same time.

Bumrongchoke, Duangmalai and Jaikla [3] presented a current-mode quadrature oscillator using single current differencing transconductance amplifier (CDTA), one resistor and two grounded capacitors is presented. The proposed oscillator can provide two sinusoidal output currents with 90º phase difference. By adjusting the bias current of the CDTA, the oscillation frequency and oscillation condition can be controlled electronically. The high-output impedance of current-mode oscillators are of great interest because they make it easy to drive loads and they facilitate cascading without using a buffering device. Moreover, circuits that employ only grounded capacitors are advantageous from the point of view of integrated circuit implementation. This concept has been applied in [3] where a current-mode quadrature oscillator using single current differencing transconductance amplifier (CDTA), one resistor and two grounded capacitors is used.

The current-mode quadrature oscillator proposed by Bumrongchoke, Duangmalai and Jaikla was designed by cascading a first-order all-pass filter and a non-inverting lossless integrator. In order to utilize the current through the capacitor C_2, an auxiliary Z_C terminal is used as shown in Figure 4.2. The internal current mirror provides a copy of the current flowing out of the Z terminal to the Z_C terminal.

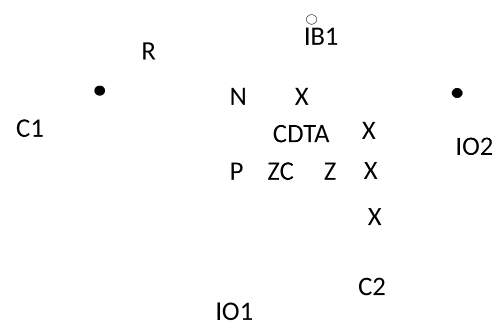


Figure 4.2 CDTA based current-mode quadrature oscillator [3]

The characteristic equation of the proposed oscillator in Figure 4.2 can be expressed as follows:

$$s^2 C_1 C_2 R + s(C_2 - C_1 R g_m) + g_m = 0 \quad (4.5)$$

Condition of oscillation from equation (4.5) is given as (Eq. 4.6):

$$\frac{C_2}{C_1} = R g_m \quad (4.6)$$

Frequency of oscillation obtained is (Eq. 4.7):

$$\omega_0 = \sqrt{\frac{g_m}{C_1 C_2 R}} \quad (4.7)$$

Kumngern [4] presented a new current-mode multiphase sinusoidal oscillator employing current-controlled current differencing transconductance amplifiers (CCCDTAs). The oscillator circuit proposed here employs one grounded capacitor, one grounded resistor for each phase and one CCCDTA. It can generate arbitrary n output current equal-amplitude signals that are equally spaced in phase, all at high output impedance terminals with n being odd or even. The condition of oscillation and the frequency of oscillation can be controlled electronically and independently through adjusting the bias current of the CCCDTA. The proposed oscillator in [4] is highly suitable for integrated circuit implementation. The circuit of current mode multiphase sinusoidal oscillator is presented in Figure 4.3.

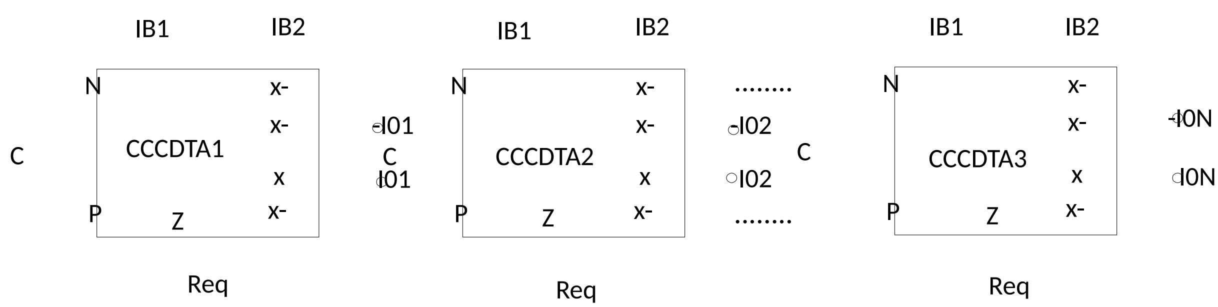


Figure 4.3 Current-mode MSO using CCCDTAs [4]

The circuit can be set to provide a sinusoidal oscillation, if the loop gain is unity:

$$\left(\frac{-R_{eq} g_m}{1+sC R_P}\right)^N_{s=j\omega_0} = 1 \quad (4.8)$$

Equation (4.9) represents the characteristic equation for an Nth-order sinusoidal oscillator of Figure 4.3.

$$\left(1+j\omega_0 C R_P\right)^N + \left(-1\right)^{N+1}\left(R_{eq} g_m\right)^N \quad (4.9)$$

Frequency of oscillation obtained is (Eq. 4.10):

$$\omega_0 = \frac{1}{C R_P \sqrt{3}} \quad (4.10)$$

$$R_{eq} g_m \geq 2 \quad (4.11)$$

From equations (4.10) and (4.11), it can see that the frequency of oscillation and the condition of oscillation can be orthogonally controlled. The condition of oscillation can be controlled by transconductance g_m through adjusting the bias current I_{B2} and the frequency of oscillation can be controlled by resistor R_P through adjusting the bias current I_{B1}.

Kumngern [5] presented a new current-controlled current-mode multiphase sinusoidal oscillator using current controlled current differencing transconductance amplifiers (CCCDTAs). The proposed oscillator circuit, which employs one CCCDTA, one grounded capacitor and one MOS resistor for each phase, can generate arbitrary n output current equal-amplitude signals that are equally spaced in phase (n being even or odd), all at high output impedance terminals. The frequency of oscillation and the condition of oscillation can be controlled electronically and independently through adjusting the bias currents of the CCCDTAs. The proposed multiphase oscillator was highly suitable for integrated circuit implementation. The purpose of this paper was to develop a current mode current-controlled multiphase sinusoidal oscillator employing the modified CDTAs, called a 'current controlled current differencing transconductance amplifiers (CCCDTAs)' [6]. The properties of CCCDTA are similar to the conventional CDTA, but the CCCDTA has finite input resistances at the P and N terminals, respectively, which is controllable by the bias current as shown in Figure 4.4. The condition of oscillation can also be controlled by adjusting the transconductance gain of CCCDTA without disturbing the frequency of oscillation.

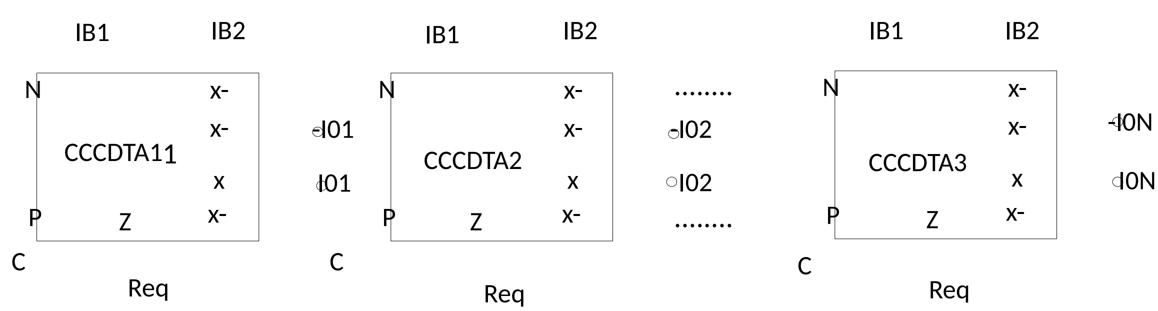


Figure 4.4 CCCDTA based current mode multiphase oscillator [5]

The circuit can be set to provide a sinusoidal oscillation, if the loop gain is unity:

$$\left(\frac{-R_{eq}\,g_m}{1+sC\,R_P}\right)_{s=j\omega_0}^{N}=1\,(4.12)$$

Equation (4.13) represents the characteristic equation for an Nth-order sinusoidal oscillator of Figure 4.4.

$$\left(1+j\,\omega_0 C\,R_P\right)^N+\left(-1\right)^{N+1}\left(R_{eq}\,g_m\right)^N\,(4.13)$$

Frequency of oscillation obtained is (Eq. 4.14):

$$\omega_0=\frac{1}{C\,R_P\sqrt{3}}\,(4.14)$$

$$R_{eq}\,g_m\geq 2\,(4.15)$$

From equations (4.14) and (4.15), it can see that the frequency of oscillation and the condition of oscillation can be orthogonally controlled. The condition of oscillation can be controlled by transconductance g_m through adjusting the bias current I_{B2} and the frequency of oscillation can be controlled by resistor R_P through adjusting the bias current I_{B1}.

4.3 Realization of Harmonic oscillators using CDTA

We now present some circuits of harmonic oscillators realized with CDTA as the active building block. A second-order current-mode quadrature oscillator consists of two CDTAs, four resistors and two capacitors was presented in [8]. However, the capacitors used in this circuit are connected to the input terminals of the CDTAs. Since the input terminals of CDTA have parasitic resistances [9], this quadrature oscillator is not ideal for high frequency applications. In 2006, Biolek et al. proposed a second order current-mode quadrature oscillator based on two-integrator loop technique [10]. The main disadvantage of this oscillator is that there is no control on the condition of oscillation. Horng [12] proposed a CDTAs based current-mode third-order quadrature oscillator circuit. The oscillation condition and oscillation frequency of the proposed quadrature oscillator are orthogonal controllable. The proposed quadrature oscillator uses only grounded capacitors. The use of only grounded capacitors is especially interest from the fabrication point of view [11].

Lahiri [7] proposed the realization of voltage/current-mode (CM) quadrature oscillator (QO) using CDTA. The proposed circuit employs canonic number of components, namely two CDTAs, one resistor and two grounded capacitors. The oscillator is capable of providing two explicit quadrature current outputs and two quadrature voltage outputs. Moreover, the circuit has the advantage of independent control of frequency of oscillation (FO) and condition of oscillation (CO).

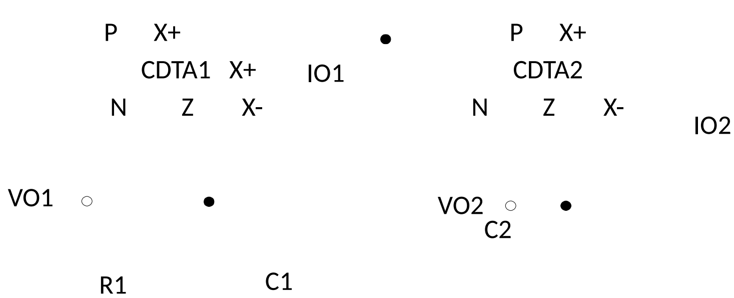


Figure 4.5 CDTA based voltage/current mode quadrature oscillator [7]

From the circuit analysis the characteristic equation for the quadrature oscillator shown in Figure 4.5 can be derived as (Eq. 4.16):

$$s^2 R_1 C_1 C_2 + s C_2 (1 - R_1 g_{m1}) + g_{m1} g_{m2} R_1 = 0 \quad (4.16)$$

From equation (4.16) condition of oscillation (CO) is (Eq. 4.17):

$$R_1 g_{m1} = 1 \quad (4.17)$$

Frequency of oscillation (FO) is (Eq. 4.18):

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m1}}{C_1 C_2}} \quad (4.18)$$

It is clear from equation (4.17) and (4.18) that the CO can be controlled independently of FO by changing R_1. The FO can be controlled by g_{m2} and hence is current controllable by the bias current I_{B2}. The two quadrature currents in Figure 4.5 are available explicitly and they have equal magnitudes. Similarly, the two marked quadrature voltages in Figure 4.5 have equal amplitude.

In Figure 4.6, a CDTAs based current-mode third-order quadrature oscillator circuit is presented. The oscillation condition and oscillation frequency of the proposed quadrature oscillator are orthogonal controllable. The proposed quadrature oscillator uses only grounded capacitors. The use of only grounded capacitors is especially interest from the fabrication point of view [11].

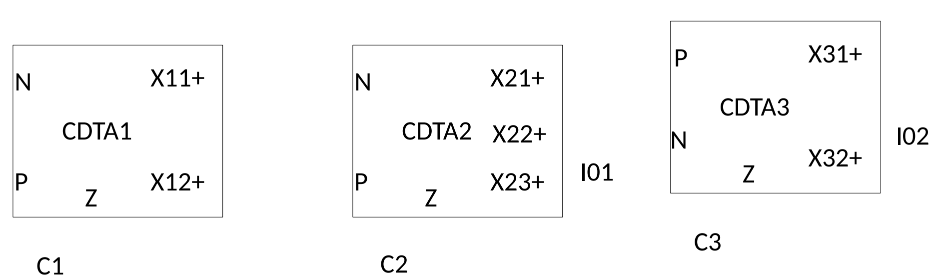


Figure 4.6 Current mode third order quadrature oscillator [12]

The oscillation condition and oscillation frequency can be obtained as (Eq. 4.19) and (Eq. 4.20) respectively

$$g_{m3}=\frac{C_3\left(C_1 g_{m2}+C_2 g_{m1}\right)}{C_1 C_2}\quad(4.19)$$

$$\omega_0=\sqrt{\frac{g_{m1}g_{m1}}{C_1 C_2}}\quad(4.20)$$

From equations (4.19) and (4.20), the oscillation frequency can be controlled by g_{m1} or g_{m2}. The oscillation condition can be independently controlled by g_{m3}. From Figure 4.6, the current transfer function from I_{o2} to I_{o1} is

$$\frac{I_{02}(s)}{I_{01}(s)}=\frac{g_{m3}}{sC_3}\quad(4.21)$$

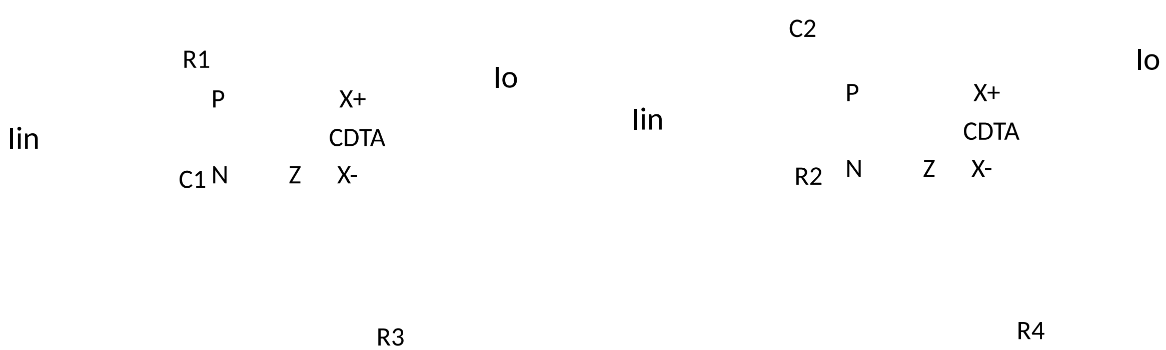
Thus the equation (4.21) shows that I_{02} and I_{01} are in quadrature.

The proposed quadrature oscillator employs only grounded capacitors. The use of grounded capacitors is particularly attractive for integrated circuit implementation [11]. From equation (4.21), the magnitude of I_{o2} and I_{o1} need not the same. For the applications need equal magnitude quadrature outputs, another amplifying circuits are needed.

Keskin and Biolek [8] proposed a quadrature oscillator using CDTAs based all pass filter circuit configurations.

Allpass filters are widely used in analog signal processing in order to shift the phase while keeping the amplitude constant, to produce various types of filter characteristics and to implement high-Q frequency selective circuits. Many AP filter circuits are described in the literature using various types of CM active elements [13-24]. Oscillator circuit can be designed using all pass filter circuit configuration employing single CDTA presented in Figure 4.7.

A CDTA-based quadrature oscillator circuit is presented in Figure 4.8. The circuit employs two current-mode allpass sections in a loop, which provides high-frequency sinusoidal oscillations in quadrature at high impedance output terminals of the CDTAs. Floating capacitors are not connected in the circuit which is advantageous from the integrated circuit manufacturing point of view. Furthermore, the oscillation frequency of this configuration can be made adjustable by using voltage controlled elements (MOSFETs), since the resistors in the circuit are either grounded or virtually grounded.



(a) (b)

Figure 4.7 Two variant circuit configurations of current mode all pass filter section [8]

The oscillator circuit given in Figure 4.8 is designed using two RC frequency selective networks and CDTAs. Here positive feedback connection is used for the oscillator circuit designing.

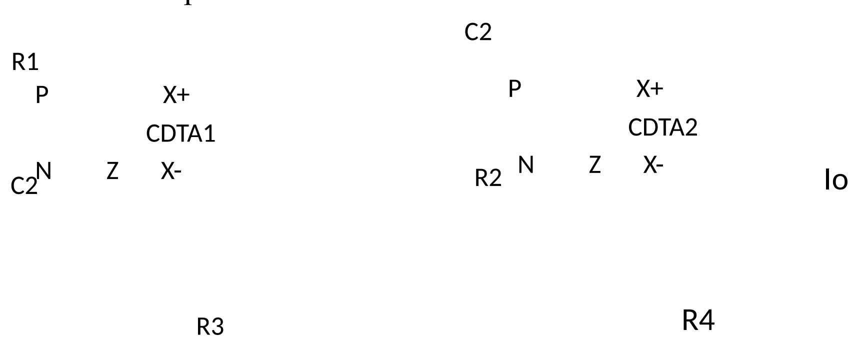


Figure 4.8 Circuit configuration of CDTA based quadrature oscillator [8]

Allpass filter shown in Figure 4.7(a) which gives the current transfer function that is derived as (Eq. 4.22):

$$I_P = \frac{1}{R_1 C_1 s + 1} I_{¿}$$

$$I_n = \frac{R_1 C_1 s}{R_1 C_1 s + 1} I_{¿}$$

$$I_Z = I_P - I_N$$

$$I_Z = \frac{1 - R_1 C_1 s}{R_1 C_1 s + 1} I_{¿}$$

$$V_Z = R_3 I_Z$$

$$I_O = g_m V_Z$$

$$I_O = g_m R_3 \frac{1 - R_1 C_1 s}{R_1 C_1 s + 1} I_{¿}$$

$$\frac{I_O}{I_{¿}} = g_m R_3 \left(\frac{1 - R_1 C_1 S}{1 + R_1 C_1 S} \right) (4.22)$$

Where g_m is the transconductance of CDTA.

The circuit provides the phase shift of

$$\Phi(\omega)=-2\tan^{-1}(\omega_1 R_1 C_1)(4.23)$$

Analyzing the circuit configuration in Figure 4.7(b) yields the equations as:

$$I_P=\frac{R_2 C_2 s}{R_2 C_2 s+1} I_{¿}$$

$$I_N=\frac{1}{R_2 C_2 s+1} I_{¿}$$

$$I_Z=I_P-I_N$$

$$I_Z=\left(\frac{R_2 C_2 s-1}{R_2 C_2 s+1}\right) I_{¿}$$

$$V_Z=R_4 I_Z$$

$$I_O=g_m R_4\left(\frac{R_2 C_2 s-1}{R_2 C_2 s+1}\right) I_{¿}$$

$$\frac{I_O}{I_{¿}}=g_m R_4\left(\frac{R_2 C_2 s-1}{R_2 C_2 s+1}\right)(4.24)$$

The circuit provides the phase shift of

$$\Phi(\omega)=\Pi-2\tan^{-1}(\omega_2 R_2 C_2)(4.25)$$

For the oscillator circuit given in Figure 4.8 characteristic equation obtained is:

$$g_{m1} g_{m2} R_3 R_4\left(\frac{R_2 C_2 s-1}{R_2 C_2 s+1}\right)\left(\frac{1-R_1 C_1 s}{1+R_1 C_1 s}\right)=1$$

$$g_{m1} g_{m2} R_3 R_4 \left[\frac{R_1 R_2 C_1 C_2 s^2 - (R_1 C_1 + R_1 C_2) s + 1}{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_1 C_2) s + 1} \right] = 1 \quad (4.26)$$

The total phase shift of the circuit at $\omega_1 = \omega_2 = \omega_o$ is:

$$\Phi(\omega) = \Pi - 2\tan^{-1} \left(\frac{\omega_o R_1 C_1 + \omega_o R_2 C_2}{1 - \omega_o^2 R_1 R_2 C_1 C_2} \right)$$

According to Barkhausen criterion at frequency ω_o the phase of the loop gain should be either zero or 2π and the magnitude of the loop gain should be unity. This frequency ω_o is the frequency at which the circuit will have a finite output for zero input signal.

Applying Barkhausen criterion

$$\Pi - 2\tan^{-1} \left(\frac{\omega_o R_1 C_1 + \omega_o R_2 C_2}{1 - \omega_o^2 R_1 R_2 C_1 C_2} \right) = 0$$

Obtained oscillation frequency is given by equation (4.27):

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad (4.27)$$

For the condition when both CDTAs have same circuitry i.e. $g_{m1}=g_{m2}$ and if we set $R_1=R_2=R$ and $C_1=C_2=C$ for the circuit uniformity, then the oscillation frequency is given by equation (Eq. 4.28):

$$\omega_o = \frac{1}{RC} \quad (4.28)$$

Thus the frequency of the circuit presented in Figure 4.8 is independent of variation of transconductance, R_3 and R_4.

However the amplitude condition must be fulfilled

$$g_{m1} g_{m2} R_3 R_4 = 1 \quad (4.29)$$

Where g_{m1} and g_{m2} are transconductance of CDTA1 and CDTA2 respectively.

4.4 Simulation Results

The parameter values used for the simulation of oscillator circuit are:

$g_{m1} = g_{m2} = 548\,\mu A/V$, $R_1 = R_2 = 15.9\,K\Omega$, $C_1 = C_2 = 10\,pF$, $R_3 = R_4 = 2.8\,K\Omega$

Substituting the values of above parameters in frequency expression, theoretical value of frequency obtained is $f_{theoretical} = 1\,MH_Z$. Thus the oscillator of frequency $f = 1\,MH_Z$ is designed. To obtain the soft starting of oscillations, the values of R_3 and R_4 are set to $2.8\,K\Omega$.

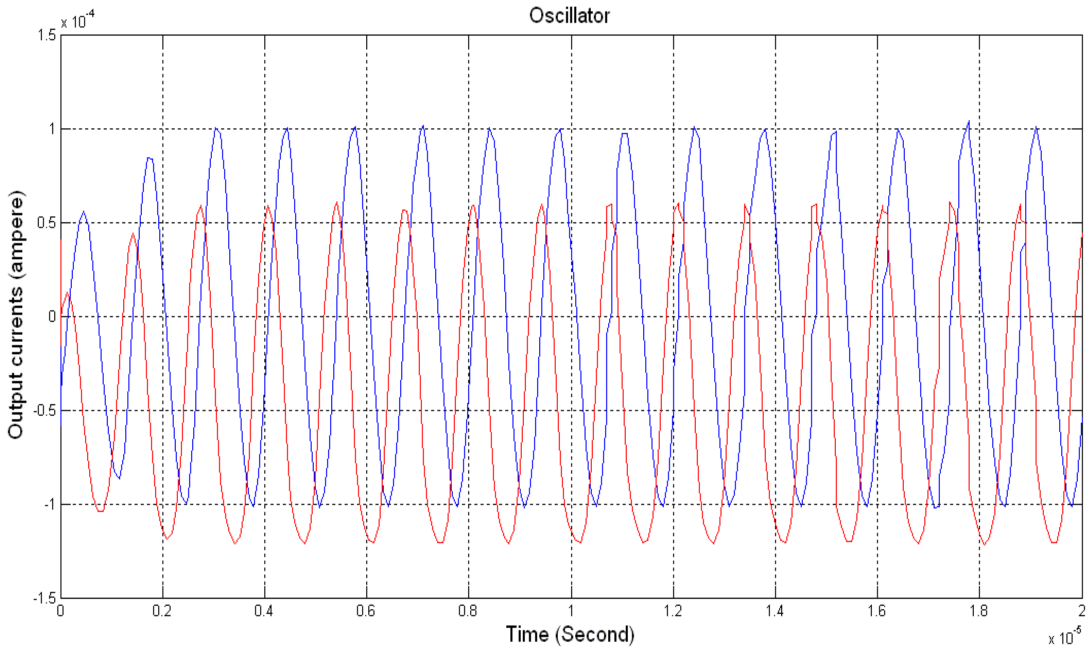


Figure 4.9 Sinusoidal current output at X^+ terminal of CDTA based oscillator circuit

From the simulation results obtained in Figure 4.9 it can be seen that time period of the sinusoidal wave is T = 1.3μs. Thus practically obtained value of frequency of oscillation is given by (Eq. 4.31):

$$f = \frac{1}{T} (4.30)$$

$$f_{practical} = 0.769\, MH_Z$$

Thus the obtained frequency is $0.769\, MH_Z$ instead of $1\, MH_Z$, because of the non-ideal effects in CDTA. These effects are caused by current tracking errors between P to Z and N to Z and these errors would be caused by the parasitic input impedances [8].

4.5 Conclusion

In the present chapter we have presented a brief overview of harmonic oscillators realized with CDTA and its various derivatives. The derivatives of CDTA including CCCDTA, DO-CCCDTA, ZC-CDTA are described. The oscillation frequency and oscillation condition of all the oscillators presented in this chapter is dependent on transconductance of CDTA and the transconductance of CDTA can be controlled by the bias current. Thus it can be concluded that the frequency of oscillation and condition of can be controlled by the bias current. The simulation of quadrature oscillator circuit based on allpass filter section using CDTA has been presented. It can provide high frequency sinusoidal oscillations in quadrature and at high impedance output terminals of the CDTAs

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Chapter 5

A Novel CDTA Based Current Mode Universal Filter

In this chapter a universal filter is proposed using RLC resonator circuit, in which the grounded inductor is replaced by simulated inductance using CDTAs circuit, resulting in a CDTA-RC resonator.

5.1 Introduction

Universal filter is a filter in which all the five standard filter responses namely HP, LP, BP, AP and BR are available in the same circuit. It can be voltage mode/current mode, fixed structure/variable structure type, single input-single output (SISO) type/single input multiple output (SIMO) type, multiple input-multiple output (MIMO) type or multiple input single output (MISO) type. Each of these classifications have certain advantages and limitations. We have proposed a fixed structure type of universal filter falling in the category of SIMO type. In these types of universal filter the structure of the filter is fixed and there is simultaneous availability of different filtering functions.

The first generation technology for realizing filters made use of capacitors and inductors, and the resulting circuits are called passive LC filters. Such filters work well at high frequencies; however, in low-frequency applications (dc to 100KH_Z) the required inductors are large and physically bulky, and their characteristics are quite non-ideal [1]. Furthermore, such inductors are impossible to fabricate in monolithic form and are incompatible with any of the modern techniques for assembling electronic systems. Therefore, there has been considerable interest in finding filter realization that do not require inductors. In the following we present a universal filter based on RLC resonator in which the grounded inductor is replaced with a CDTA based inductor. The RLC resonator method for realization of current mode universal filter was proposed by Senani in [2].

A current mode KHN biquad was proposed by Keskin and Bioslek [4], that uses only two CDTAs and two grounded capacitors. Another Current mode universal filter with four inputs and one output using CDTAs was proposed by Dumawipata, Tangsrirat and

Surakampontorn in [5]. A universal transadmittance filter employing CDTAs as the active element was presented by Shah, Quadri and Iqbal [6]. It employed two CDTAs and two grounded capacitors, which is minimum number of components that are used and in [7]; three CDTAs and two grounded capacitors are used. Another filter application presented in [8] employs single CDTA and two grounded capacitors. Recently a new CMOS current differencing transconductance amplifier (CDTA) is designed by Firat Kacar and Hakan Kuntman and its biquad filter application is presented in [9]. From the literature survey it is found that all the circuits of CDTA based filters uses grounded capacitors which is beneficial for the monolithic IC implementation, but the current through the passive elements cannot be used directly. To make the current through the passive elements useful, a copy of that current is taken using CDTA property. Thus for the implementation of CDTA based universal filter five CDTAs are used in the proposed work.

5.2 Proposed Circuit of novel current mode universal CDTA based filter

The concept of proposed circuit is based on inductor replacement in parallel RLC resonance circuit shown in Figure 5.1(a). The simulated inductance circuit as presented in [10] by Prasad, Bhaskar and Singh is used for RLC filter implementation. The natural response of the resonance circuit can be determined by applying an excitation as shown in Figure 5.1(b), which does not change the natural structure of the circuit. In the circuit 5.1(b), the resonator is excited by a current source I_{in} connected in parallel. Since, as far as the natural response of a circuit is concerned, an independent ideal current source is equivalent to an open circuit, the excitation of the circuit in Figure 5.1(b) does not alter the natural structure of the resonator.

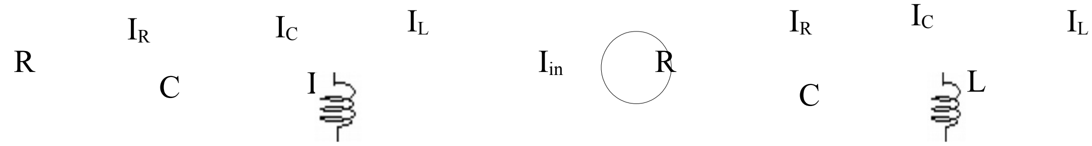

Figure 5.1 (a) A second order parallel RLC resonator [1]   (b) Exciting the resonator of (a) [1]

We can for instance take the voltage V_O across the resonator as the response and thus obtain the response function as given by equation (Eq. 5.4):

$$I_{¿}=\frac{V_O}{R}+V_O Cs+\frac{V_O}{sL}(5.1)$$

$$I_{¿}=\left(\frac{RLC\,s^2+sL+R}{RLs}\right)V_O(5.2)$$

$$I_{¿}=\left(\frac{s^2+\frac{1}{RC}s+\frac{1}{LC}}{\frac{s}{C}}\right)V_O(5.3)$$

$$V_O=\left(\frac{\frac{s}{C}}{s^2+\frac{1}{RC}s+\frac{1}{LC}}\right)I_{¿}(5.4)$$

Analyzing the circuit yields the current transfer functions of all the three filters presented by equations (Eq.5.5-5.7):

- Bandpass filter: When $V_O=R\,I_R$

$$\frac{I_R}{I_{\text{¿}}}=\frac{\frac{s}{RC}}{s^2+\frac{1}{RC}s+\frac{1}{LC}}(5.5)$$

- Highpass filter: When $V_O=\frac{I_C}{Cs}$

$$\frac{I_C}{I_{\text{¿}}}=\frac{s^2}{s^2+\frac{1}{RC}s+\frac{1}{LC}}(5.6)$$

- Lowpass filter: $V_O=sL\,I_L$

$$\frac{I_L}{I_{\text{¿}}}=\frac{\frac{1}{LC}}{s^2+\frac{1}{RC}s+\frac{1}{LC}}(5.7)$$

From the above equations the obtained parameters are:

$$\omega_O=\frac{1}{\sqrt{LC}}(5.8)$$

$$Q=R\sqrt{\frac{C}{L}}(5.9)$$

Where the simulated inductance is given by (Eq. 5.10):

$$L=\frac{C}{4g_{m3}g_{m4}}(5.10)$$

From equations 5.8, 5.9 and 5.10:

$$\omega_0=\frac{2\sqrt{g_{m3}g_{m4}}}{C}(5.11)$$

$$Q=2R\sqrt{g_{m3}g_{m4}}(5.12)$$

The current response in the capacitor, resistor and inductor represent HP, BP and LP responses respectively. By adding the HP and LP responses we can get BR response and by adding the inverted BP, HP and LP response we can get the allpass response. Thus the resonator can act as a universal filter.

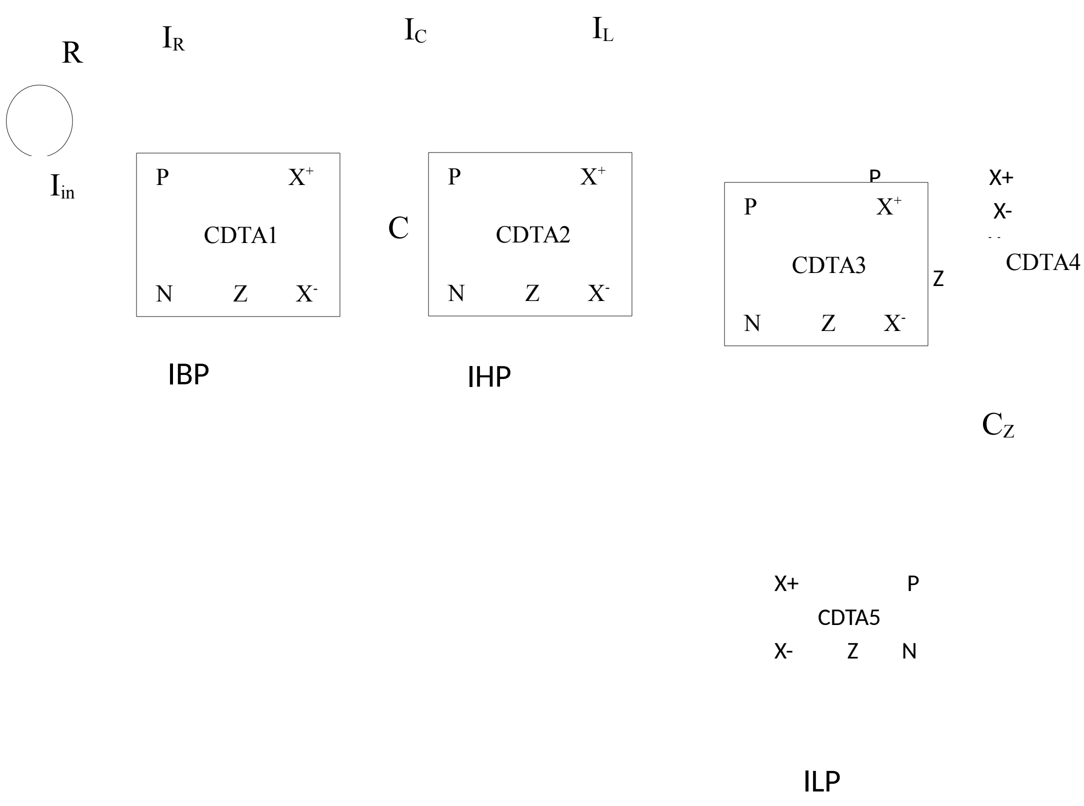

Figure 5.2. Proposed CDTA-RC universal filter circuit configuration

5.3 Simulation Results

To verify the theoretical results of the proposed circuit the simulation is performed in PSPICE using 0.5µm MIETEC CMOS technology.

Considering the non-ideal case of CDTA we see that there exist parasitic impedances at P and N terminals. For the proper operation of CDTA-RC universal filter circuit configuration in Figure 5.2, the negative resistance of the same value of parasitic resistance R_P and R_N are connected at P and N terminals.

The parameters taken for the simulation of the circuit shown in Figure 5.2 are listed below:

R = 4KΩ, C = 0.01nF, Cz = 1nF, L=1.08mH and g_m = 548µA/V. The frequency response of the circuit presented in Figure 5.2 is shown in Figure 5.3.

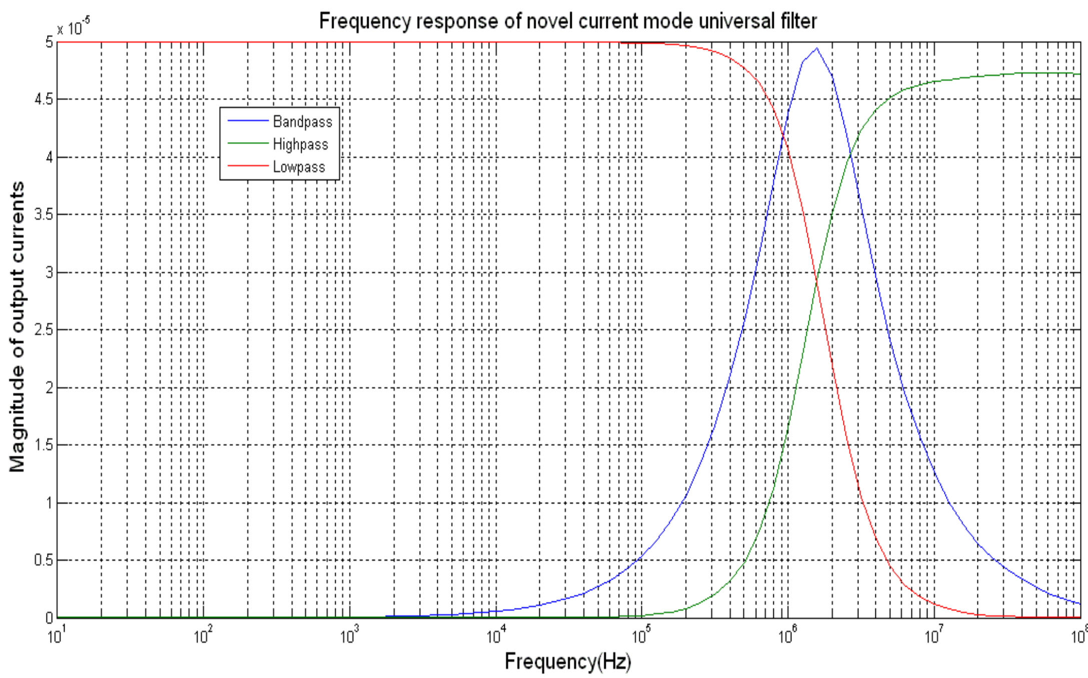

Figure 5.3 Frequency response of novel current mode universal filter

Transient response of the filters is presented in Figures 5.4, 5.5 and 5.6.

Lowpass filter

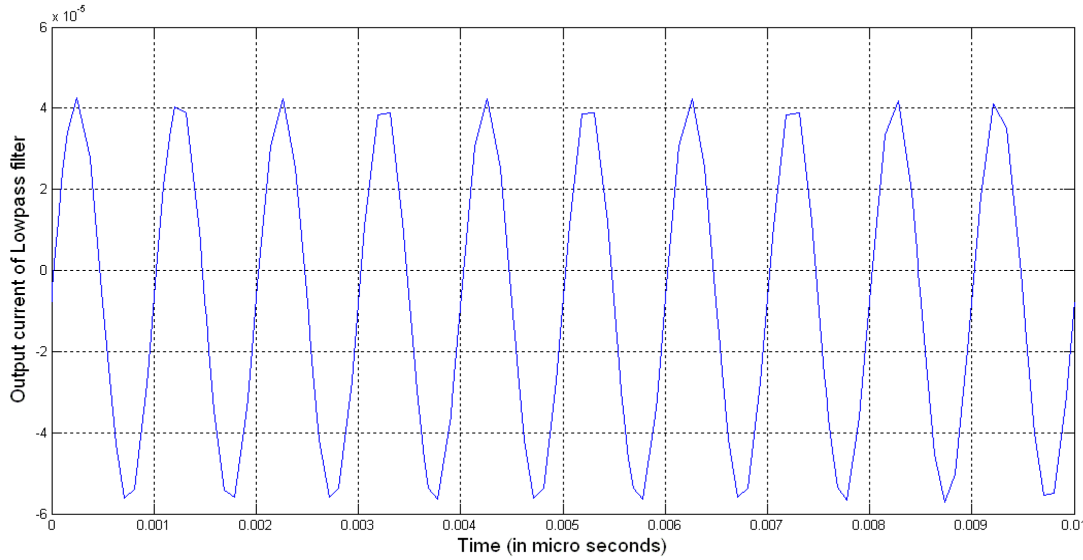

Figure 5.4 Transient response of Lowpass filter

Bandpass filter

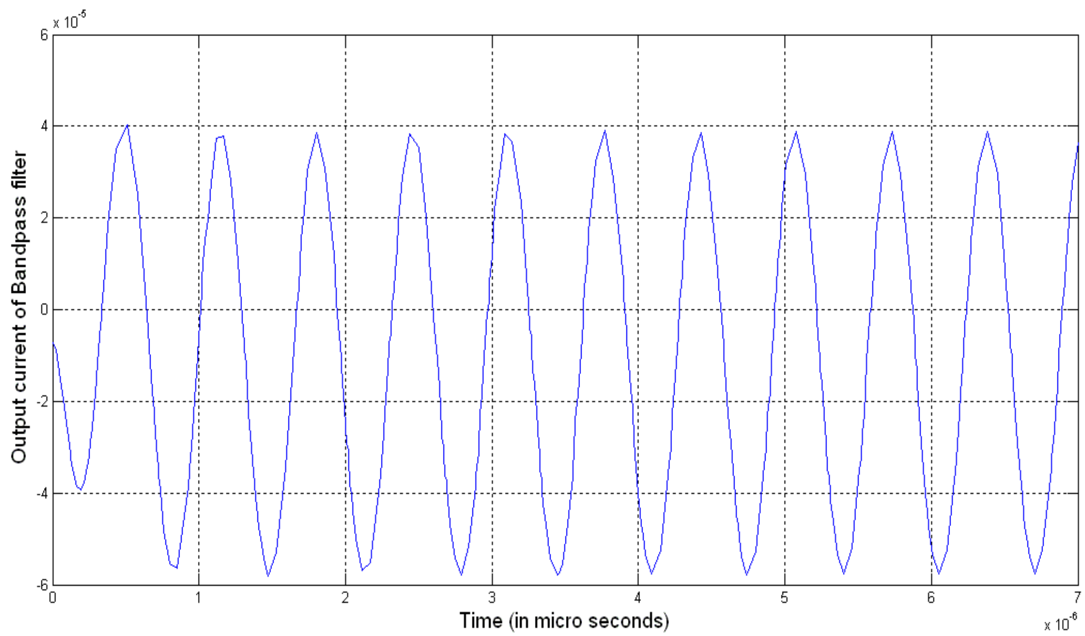

Figure 5.5 Transient response of Bandpass filter

Highpass filter

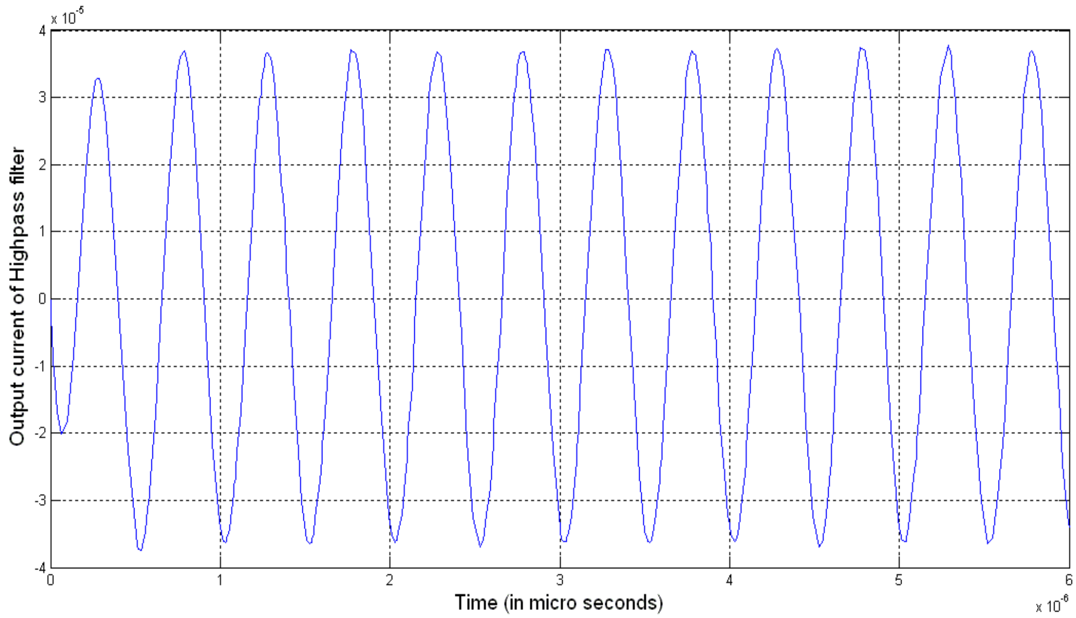

Figure 5.6 Transient response of Highpass filter

5.4 Conclusion

In this chapter a brief discussion of RLC resonator circuit has been presented. By replacing the inductor of RLC resonator with a simulated inductance using CDTA, a new CDTA-RC resonator is obtained. The developed CDTA-RC resonator can be used to realize the various second-order filter functions. The proposed circuit of CDTA-RC has been tested by the simulation in PSPICE. The simulation results verify the behavior of the proposed CDTA-RC universal filter circuit.

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Chapter 6

Conclusion and Scope for Future work

In this work Current differencing Transconductance Amplifiers (CDTAs) and their applications in signal processing have been presented.

In chapter 1 a brief discussion of active devices used in analog signal processing have been presented.

In chapter 2 CMOS and Bipolar implementation of CDTA have been discussed. The characteristics of CDTA have been simulated in PSPICE and various applications of CDTA in analog signal processing are presented. Simulated device characteristics show that the circuit presented in this chapter exhibits a very good performance. The simulation results confirm high linearity and high performance of the circuit in terms of good input and output resistances and wide bandwidths for both of the voltage and current operations.

In chapter 3 a brief discussion of voltage mode, current mode and mixed mode filter is described. The voltage mode filter, which consists of a single CDTA, two capacitors and three resistors can realize the second order LP, HP, BP, BR and AP filter simultaneously without changing the circuit topology. In this circuit LP filter has the advantage of having both the capacitors grounded. A CM KHN biquad employing only two active and two passive components has been presented. Therefore, the multipurpose CM filter has least component count. Because of CM operation, the filter enjoys advantages in terms of bandwidth and dynamic range with respect to their voltage mode counterparts. This structure can be effectively used in higher-frequency applications. The mixed mode filter presented has three input and single output. All the filter circuits described in this chapter has the advantage that the characteristics can be electronically tuned through biasing current of the transconductance of the DO-OTAs present in the CDTA structure.

In chapter 4 we have presented a brief overview of harmonic oscillators realized with CDTA and its various derivatives. The derivatives of CDTA including CCCDTA, DO-CCCDTA, ZC-CDTA are described. The oscillation frequency and oscillation condition of all the oscillators presented in this chapter is dependent on transconductance of CDTA and the transconductance of CDTA can be controlled by the bias current. Thus it can be concluded that the frequency of oscillation and condition of can be controlled by the bias current. The simulation of quadrature oscillator circuit based on allpass filter section using CDTA has been presented. It can provide high frequency sinusoidal oscillations in quadrature and at high impedance output terminals of the CDTAs

In chapter 5 a brief discussion of RLC resonator circuit has been presented. By replacing the inductor of RLC resonator with a simulated inductance using CDTA, a new CDTA-RC resonator is obtained. The developed CDTA-RC resonator can be used to realize the various second-order filter functions. The proposed circuit of CDTA-RC has been tested by the simulation in PSPICE. The simulation results verify the behavior of the proposed CDTA-RC universal filter circuit.

Future Scope:

CDTAs and other derivatives of CDTAs have many potential applications, particularly in the area of fully differential signal processing as the CDTA element is a fully differential element with both input as well as output terminals being differential in nature. The work presented in this differentiation can be extended to include fully differential filters, amplifiers etc.

APPENDIX

PSpice model files used for Process and electrical parameters CMOS 0.5µm from MIETEC Technology

*MIETEC Technology

*Spice Level3 Parameters

.MODEL NMOS1 NMOS (LEVEL=3

+UO=460.5 TOX=1.0E-8 TPG=1 VTO=.9 JS=1.8E-6

+XJ=.15E-6 RS=417 RSH=2.73 LD=0.04E-6 ETA=0

+VMAX=130E3 NSUB=1.71E17 PB=.761 PHI=0.905

+THETA=0.129 GAMMA=0.69 KAPPA=0.1 AF=1

+WD=.11E-6 CJ=76.4E-5 MJ=0.357 CJSW=5.68E-10

+MJSW=.302 CGSO=1.38E-10 CGDO=1.38E-10

+CGBO=3.45E-10 KF=3.07E-28 DELTA=0.42

+NFS=1.2E11)

.MODEL PMOS1 PMOS (LEVEL=3

+UO=100 TOX=1E-8 TPG=1 VTO=-.5 JS=.38E-6

+XJ=0.1E-6 RS=886 RSH=1.81 LD=0.03E-6 ETA=0

+VMAX=113E3 NSUB=2.08E17 PB=.911 PHI=0.905

+THETA=0.120 GAMMA=0.76 KAPPA=2 AF=1

+WD=.14E-6 CJ=85E-5 MJ=0.429 CJSW=4.67E-10

+MJSW=.631 CGSO=1.38E-10 CGDO=1.38E-10

+CGBO=3.45E-10 KF=1.08E-29 DELTA=0.81

+NFS=0.52E11)

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PSpice model files used for Process and electrical parameter Transistor ALA400

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*NR100N - 1X NPN TRANSISTOR

.MODEL NX NPN (RB = 524.6 IRB = 0 RBM = 25 RC = 50 RE = 1

+ IS = 121E-18 EG = 1.206 XTI = 2 XTB = 1.538 BF = 137.5

+ IKF = 6.974E-3 NF = 1 VAF = 159.4 ISE = 36E-16 NE = 1.713

+ BR = 0.7258 IKR = 2.198E-3 NR = 1 VAR = 10.73 ISC = 0 NC = 2

+ TF = 0.425E-9 TR = 0.425E-8 CJE = 0.214E-12 VJE = 0.5

+ MJE = 0.28 CJC = 0.983E-13 VJC = 0.5 MJC = 0.3 XCJC = 0.034

+ CJS = 0.913E-12 VJS = 0.64 MJS = 0.4 FC = 0.5)

*PR100N - 1X PNP TRANSISTOR

.MODEL PX PNP (RB = 327 IRB = 0 RBM = 24.55 RC = 50 RE = 3

+ IS = 73.5E-18 EG = 1.206 XTI = 1.7 XTB = 1.866 BF = 110.0

+ IKF 12.359E-3 NF = 1 VAF = 51.8 ISE = 25.1E-16 NE = 1.650

+BR = 0.4745 IKR = 6.478E-3 NR = 1 VAR = 9.96 ISC = 0 NC = 2

+ TF = 0.610E-9 TR = 0.610E-8 CJE = 0.180E-12 VJE = 0.5

+ MJE = 0.28 CJC = 0.164E-12 VJC = 0.8 MJC = 0.4 XCJC = 0.037

+ CJS = 1.03E-12 VJS = 0.55 MJS = 0.35 FC = 0.5)