# REALIZATION OF ANALOG FILTERS USING VOLTAGE DIFFERENCE TRANSCONDUCTANCE AMPLIFIER

Thesis Submitted For the Award of the Degree of

## DOCTOR OF PHILOSOPHY

**in**

**Physics**

**By**

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**PUNJAB**

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# DECLARATION

I, hereby declare that the presented work in the thesis entitled “**REALIZATION OF ANALOG FILTERS USING VOLTAGE DIFFERENCE TRANSCONDUCTANCE AMPLIFIER”** in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision Of **Dr. Uma Kamboj**, working as Associate Professor, in the **Department of Physics, School of Chemical Engineering and Physical Sciences** of **Lovely Professional University**, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made wherever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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# CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled “**REALIZATION OF ANALOG FILTERS USING VOLTAGE DIFFERENCE TRANSCONDUCTANCE AMPLIFIER”** submitted in fulfilment of the requirement for the award of degree of **Doctor of Philosophy [Ph.D.]** in the Department of Physics, School of Chemical Engineering and Physical Sciences, is a research work carried out by **Masooma Zaffer**, **11916617**, is bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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# Acronym

| | |
|---|---|
| 1. ABB | Active building block |
| 2. PSPICE | Personal simulated program with integrated circuit emphasis |
| 3. ADC | Analog to digital converter |
| 4. DSP | Digital signal processing |
| 5. DAC | Digital to analog converter |
| 6. CM | Current mode |
| 7. VM | Voltage mode |
| 8. TAM | Transadmittance mode |
| 9. TIM | Transimpedance mode |
| 10. MM | Mixed mode |
| 11. LPF | Low pass filter |
| 12. BPF | Band pass filter |
| 13. HPF | High pass filter |
| 14. BRF | Band reject filter (notch) |
| 15. APF | All pass filter |
| 16. BW | Bandwidth |
| 17. SIMO | Single input multi-output |
| 18. MISO | Multi-input single output |
| 19. FOUF | First order universal filter |
| 20. OA | Operational amplifier |
| 21. VDTA | Voltage difference transconductance amplifier |
| 22. MO-VDTA | Multi-output voltage difference transconductance amplifier |
| 23. CCI | Current conveyor first generation |
| 24. CCII | Current conveyor second generation |
| 25. CF | Current follower |
| 26. MO-CCII | Multi-output current conveyor second generation |
| 27. DVCCII | Differential voltage current conveyor second generation |

| | |
|---|---|
| 28. DDCC | Differential difference current conveyor |
| 29. DXCCII | Dual X current conveyor second generation |
| 30. ICCII | Inverting second generation current conveyor |
| 31. FDCCII | Fully difference second generation current conveyor |
| 32. CCIII | Third generation current conveyor |
| 33. UCC | Universal current conveyor |
| 34. CBDA | Current difference buffered amplifier |
| 35. OTA | Operational transconductance amplifier |
| 36. CCCII | Current controlled second generation current conveyor |
| 37. CDTA | Current difference transconductance amplifier |
| 38. CFTA | Current follower transconductance amplifier |
| 39. CCCBDA | Current controlled Current difference buffered amplifier |
| 40. CCCDTA | Current controlled Current difference transconductance amplifier |
| 41. MI-DDTA | Multi-input Differential difference transconductance amplifier |
| 42. CFOA | Current follower operational amplifier |

# Symbols

| | | |
|---|---|---|
| 1. | $\omega_0$ | Pole frequency |
| 2. | H | Gain |
| 3. | Q | Quality factor |
| 4. | $\beta$ | tracking error |
| 5. | $\omega_0/Q$ | Bandwidth |
| 6. | B | Gain bandwidth product. |
| 7. | $C_{ox}$ | Gate oxide capacitance |
| 8. | µn | Carrier mobility of NMOS |
| 9. | $I_B$ | Bias current |
| 10. | $S^x_y$ | Sensitivity of y with respect to x |
| 11. | g | Transconductance gain |
| 12. | Hz | Hertz |
| 13. | V | volt |
| 14. | A | Ampere |
| 15. | $\varphi$ | Phase angle |
| 16. | n | nano $(10^{-9})$ |
| 17. | p | pico $(10^{-12})$ |
| 18. | m | milli $(10^{-3})$ |
| 19. | K | kilo (103) |
| 20. | M | Mega $(10^6)$ |
| 21. | G | Giga $(10^9)$ |

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## Abstract

The technology has been optimized for digital circuits as digital signal processing (DSP) offer many advantages such as the accuracy, and reproductively of the results, reliability (better immunity to unwanted signals) cheaper and easy to design, over ASP. But in this world the information which is to be processed is in the continuous time form (analog signals), thereby necessitating the need for analog systems to be incorporated with digital systems. Figure 1.1 shows the complete system. The information is amplified and filtered before converting to digital signals. After DSP the signal is converted to analog signal, again filtered and amplified before feeding to the world. Analog circuits, with their unique advantages, will remain an indispensable component of VLSI digital systems for the foreseeable future. In recent years, the need for smaller and cheaper electronic systems have led manufacturers to integrate both analog and digital circuits onto a single chip that is now becoming common practice. While analog and digital VLSI circuits can be integrated onto a single chip. Certain signal processing applications are still better suited for analog circuits. This is particularly true for tasks that demand high-frequency operation or low power consumption, where analog systems excel. Ever increasing demand for analog filters, has received significant attention and matured filters are proposed in the literature. The filters separate modulated signals (containing information) from noise signals (unwanted signals). The filters are used since 1915. Up to 1960, these filters were realized using resistors, inductors, and capacitors (RLC filters). The operational amplifier in the IC form revolutionized communication, biomedical, music systems. The use of OA in the filters has paved the way for the realization of filters (active filters) that offer various advantages over passive filters. OA has dominated the electronic industries over several decades though filters based on OA suffer from various disadvantages like:

1. less slew rate,
2. higher propagation delay,
3. less dynamic range,
4. poor linearity,
5. higher circuit complexity,
6. limited gain bandwidth product, and

7. higher power consumption

In recent years, the quest for versatile current mode active building blocks has led researchers to consider other active building blocks. As a sequel, new ABBs were formulated. These building blocks are more versatile and minimize most of the disadvantages offered by filters based on OAs. Thus, filters using the current mode approach based on these ABB are more versatile. Filters are classified depending upon the frequency of operation: i) low pass (LP), ii) band pass (BP), iii) high pass (HP), iv) band reject (BR), and v) all pass (AP). The order of filters is also considered, first order, second order, and, higher order (third, fourth fifth, etc.). The first order implements three filtering functions LP, HP, and AP while the second order implements, band pass (BP), and band reject or band elimination or notch (BR) filtering functions, in addition to AP, HP and LP. Also the number of inputs and outputs available in a filter are considered too. Filters can have one input and one output (SISO), a single input and more than one output (SIMO), more than one input and one output (MISO), and having more than one input and output (MIMO). The universal filters are the filters which implement all the filtering functions simultaneously. The nature of input and output signals is also considered.

- Voltage mode: input and output are voltage signals,
- Current mode: input and output are current signals,
- Transadmittance mode: input is voltage signal and output is current signals,
- Transimpedance mode: input is current and output is voltage signals.

The OA which dominated the filter technology over almost two decades, was replaced by more versatile ABB like operational transconductance amplifier (OTA), current conveyor first generation (CCI), second generation (CCII), third generation (CCIII), various variant of current conveyors, current follower (CF), current feedback operational amplifier (CFOA or CFA) and other devices. These ABBs lack the most important feature of electronic tunability except OTA. To include electronic tunability features more ABBs were introduced. The current difference transconductance amplifier (CDTA) has a current difference input which is followed by a transconductance amplifier, current controlled conveyor (CCCII), Current controlled current difference buffered amplifier (CCCDBA), current controlled current difference transconductance amplifier (CCCDTA), etc. Actually at the output of the existing current conveyor, CBDA, four terminal floating nullor (FTFN), a transconductance amplifier is placed giving various ABBs which have the feature of electronic tunability. A voltage difference transconductance amplifier (VDTA) is ABB having a voltage difference unit at the input and a transconductance amplifier at the output. VDTA has received considerable attention from researchers due to advantages of dual control of transconductance gains by bias current. VDTA is a device whose current is controlled by the difference of voltage applied at the inputs. The input and output impedance of VDTA is high. VDTA has two input voltage terminals ($V_P$, $V_N$) which is transferred to current at the terminal Z by the first transconductance gain, and the voltage drop at terminal Z is transferred to the current at terminals X+ and X- by the second transconductance gain. Both transconductance gains are electronically controllable by external bias currents. VDTA is highly beneficial for the construction of analog signal circuits as it exhibits two different values of transconductance gain. Multiple copies of currents *Iz* are provided to increase the universality of the element. VDTA has been employed to construct various analog signal processing circuits. The survey of the literature reveals various filters like first order, second order SISO, MIMO, SIMO, and MISO reported in the literature. However, the reported filters use either excessive components, input and output of the filter based on VDTA are not at desired impedances, and not using grounded passive components. Also, it is observed that only a single research paper on first order AP filters is reported in the literature compared to second order filters based on VDTA. Still, less number of research papers realizing second order filters are reported in the literature leaving much scope to explore the potentialities of the VDTA.

In this research work, six first order and three second order filters are proposed**.** The first filter realizes LP and HP filtering functions while the second realizes only the AP filtering function. Both filters employ a single VDTAs and one OA. The third filter uses two VDTA and a single OA implements LP, HP, and AP filtering functions simultaneously (FOUF). The fourth filter also realizes all filtering functions and uses a single MO-VDTA and one OA. The filter operates in CM. The above mentioned filters use the pole model of OA. The fifth and sixth filters use capacitor and VDTA. The fifth filter is two input and two output types and implements LP, HP, and AP filtering functions in VM and TAM depending upon the choice of the inputs. The sixth filter uses one VDTA, a single grounded resistor, and one capacitor. The filter has a single input and two outputs implementing AP filtering functions in AM and TAM simultaneously. Three second order filters are proposed. The first filter has three inputs and two outputs. The filter implements all filtering functions two at a time in VM and TAM. The filter uses one VDTA, a single OA, and one capacitor. The second filter is BP and operates in CM. The filter uses two CGs and two VDTAs. The filter performance factors are independently tunable. The third filter has a single input and six outputs (three voltage and three current outputs). The circuit uses two GCs. All the filters have been verified using the software Electronic Workbench and Multisim version 14.1. The simulation findings closely match the theoretical predictions, effectively validating the performance of the proposed filters.

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# Chapter 1: Basic filter theory and active devices

## Introduction

In this thesis, mathematical and theoretical analyses of the proposed filters are presented. The workability of these proposed filters are confirmed by the Electronic workbench and Multisim 14.3 Software. Novel ideas, such as combining the pole model of operational amplifier (OA) and voltage difference transconductance amplifier (VDTA), are used for the realization of filters. To date, no such innovative idea has been presented. In addition, a few more circuits using capacitors that are preferably grounded are also presented. All these filters employ the least number of components, have low sensitivity figures, and offer other advantages discussed in detail in the thesis.

## 1.1 Analog signal processing

There is no doubt that we live in a world of digital technology. Almost all electronic devices such as cellular phones, Laptops, Computers, and biomedical systems, are based on digital technology. Analog technology has been hampered because it has been optimized for digital technology. A single mixed analog and digital integrated circuit (IC) contains only a fraction of analog circuits but requires a large design time resulting in “design time syndrome”. However, these circumstances are now changing as a new generation of technology-specific is being developed for analog design. It is a well-known fact that the information to be processed in the real world is in analog form. Thus the digitally operating devices interface with the real world “a world of continuous-valued, analog signals”, has an analog part Reference [1]. Alternatively, we can say that without analog parts, digital systems cannot work. The signal containing information is augmented, filtered, and converted into a digital signal by an electronic circuit ADC (analog-to-digital converter) and is fed to digital system for processing. Digital signal obtained is transformed back to analog by DAC. The extracted signal undergoes filtering and amplification to reach the desired power level, ensuring the desired outcome, as demonstrated in Figure 1. Thus the signal before and after digital signal processing is filtered and amplified to have the required outcome. Therefore, both the analog and digital circuits are fabricated onto the same chip. In recent years, the manufactures integrate entire system needed for processing on a single chip resulting smaller and cheaper electronic systems. A single chip commonly incorporates both a digital signal processor and all the required analog interface circuitry to interact with the analog environment outside a computer, as cited in references [2] and [3].However, there are still a lot of signal processing jobs that are best handled by analog circuits. In some applications, primarily those with excessively high operating frequencies or those requiring very low supply voltages, complete analog systems will still be necessary Reference [4].

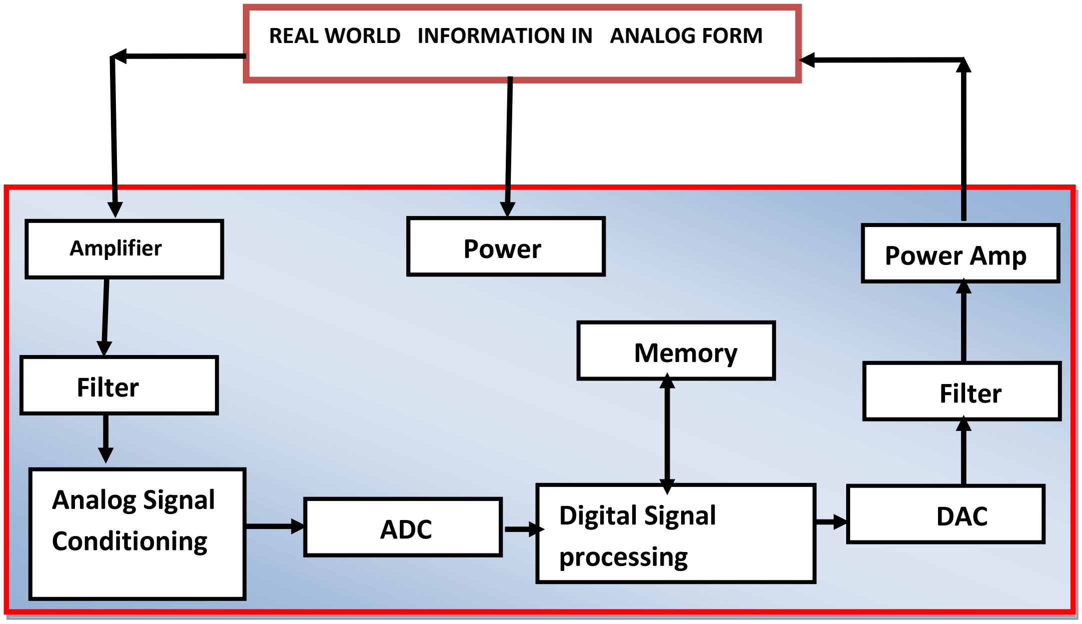


Figure 1.1: Need of analog signal processing system

## 1.2 . Basic Filter Theory

Signals containing information are associated with the unwanted signals (noise) need to be filtered out before processing. The network that allows desired frequency components containing information to be transmitted from input to output whereas unwanted components (noise) are attenuated is called filter. In all communication systems, measurement and biomedical industries, electronic filters are used in large numbers. Below are some examples of analog filters' uses in relation to analog signal processing Reference [5].

i) In communication systems, active filters are employed to separate information- carrying signals from other modulated signals.

Before converting analog signals to digital signals, these filters can be applied to reduce the bandwidth of the analog signals.

ii) Analog filters used in audio systems to convey different frequencies to different speakers. For instance, recording & playback apparatus are required to regulate the music industry's frequency components.

iii) In biological instruments, active filters are employed to link psychological sensors with diagnostic instruments and data logging.

Digital filter show excellent performance up to 1 Hz and trend changes and at 10 Hz show moderate performance (need sophisticated hardware) and again at 100 KHz trend changes and beyond 100 KHz the filters show poor performance (need hardware which is beyond scale of the art). Analog filters show poor performance up to 0.1 Hz due to need of too large capacitors, and beyond 0.1 Hz the trend changes up to 1 Hz beyond which analog filters shows excellent performance up to 1 MHz. Again at 1 MHz trend again changes and beyond 10 MHz filters show poor performance and need high speed devices. Passive filters show poor performance up to 10 HZ due to need of large capacitors and inductors and beyond show moderate performance due to poor tuning qualities, however beyond 10 MHz show excellent performance [6]

Filters realized using capacitors (C), resistors (R), and inductors (L) called passive filters were used up to 1960. The introduction of Operational Amplifier in integrated form after 1965, have made it possible to replace the bulky and costly inductors especially at low frequency, thereby facilitating the realization of low cost and small size filters, called active filters [3]. The active filters which use active devices like transistors or operational amplifiers have distinct advantage over passive filters, such as, small size, low cost, best performance at low and mid frequencies, light weight which is important for airborne apparatus, easy tuning procedure of filter performance factors such as gain, bandwidth, quality factor and pole frequency. Passive filters also have some advantages over active filters like, best performance at high frequency, and do not require power supplies.

Transfer function is the useful concept for analyzing and synthesis of filter which is the ratio of output to the input signals [6], [7].

$$T(s) = \frac{N(s)}{D(s)} = \frac{a_m s^m + a_{m-1} s^{m-1} ------ + a_0}{b_n s^n + b_{n-1} s^{n-1} ------- + b_0} \tag{1.1}$$

for practical realization m ≤ n. In factored form, equation (1.1) can be written as [6,7]:

$$T(s) = \frac{N(s)}{D(s)} = \frac{a_m}{b_n} \frac{(s-Z_1)(s-Z_2)-------(s-Z_m)}{(s-p_1)(s-p_2)-------(s-pn)} \tag{1.2}$$

$Z_i$ are referred to as zeros of transfer function as amplitude equals to zero when s = $Z_i$. Similarly transfer function T(s) = $\propto$, when s = $p_i$, called poles, where the magnitude of transfer function becomes infinity. The above transfer function is useful for studying the various types of filters. The transfer function which is used to analysis the filter network has two parts namely magnitude and phase part. The magnitude frequency response is called as magnitude (or gain) response or simply frequency response while as response between frequency and phase is called phase response. The magnitude and phase of the transfer function is given by [6,7]:

$$|T(j\omega)| = \left|\frac{X_o(j\omega)}{X_i(j\omega)}\right| \tag{1.3}$$

The gain in dB is given by:

$$H = 20log|T(j\omega)| \tag{1.4}$$

and the phase of the transfer function is given by:

$$\arg T(j\omega) = arg\left|\frac{X_o(j\omega)}{X_i(j\omega)}\right| \tag{1.5}$$

If input $X_i$ and output $X_o$ are voltage signals, filter is referred to as voltage mode (VM) filter, for current mode (CM) input and as well as the output are current signals. For transadmittance mode (TAM), the filter has input as voltage signal and output as current signal. If input is current signal and output in voltage form, the filter is called transimpedance mode (TIM) filter. Analog filters are used as interface circuit so they must have cascading features for cascading with other circuits. The condition for cascading for various filters is given below:

a) For VM filters, the output impedance should preferably be zero and the input impedance should be high, ideally infinite,
b) Input impedance for CM filters should be low (preferably zero), and output impedance should be high (ideally infinite),
c) The input and output impedances of TAM filters should be both high (ideally infinite), and
d) The input and output impedances for TIM filters should both be low, ideally zero.

If these conditions are not met, we need additional devices for impedance matching.

### 1.3 Types of filters

The filters can be divided into various types depending upon the frequency of the signal either to pass or stops, such as low pass filter, (LP), band pass filter (BP), high pass filter (HP), band reject or notch filter (BR), and all pass filter (AP).

**Low pass filters.** Low pass filters are those electric networks which allow a band of signals having low frequency including d. c. to pass and band of signals of higher frequency to stop. The filter is specified with its cut-off frequency $f_1 < f <$ fs. $f_1$ is the cut-off frequency and $f_2$ is the stop band frequency. The characteristic is completely monotonic i.e. the derivatives of the magnitude does not change sign over a given range of frequencies. In most of the cases the zeros of LP filter are located at infinity in complex s-plane. The numerator polynomial is of zero degree viz. constant (independent of s).

**High pass filter.** High pass filter stops band of signals having low frequency including d. c. to some specified value $f_s$ while allows band of signals at high frequency to pass specified by cut-off frequency. However it is to mention here that terminology to describe HP is similar to LP filter. The HP filter functions have almost all their zeros located at origin of complex s-plane.

**Band pass filter.** Band pass which is third type of filter allows passing band of signals having intermediate frequency and attenuates band of frequencies below and above the pass band. The range of frequencies that is passed is the bandwidth (BW) of filter and is given by the difference between the frequencies that defines the edge of pass band frequency $f_2$ and $f_1$. The bandwidth is given by [6,7]:

$$BW = f_2 - f_1 \tag{1.6}$$

The centre frequency $f_0$ is given by the geometric mean of the band edge frequencies

$$f_0 = \sqrt{f_1 f_2} \tag{1.7}$$

In most of the cases, the network function has half zeros at the origin and other half at infinity in complex s-plane.

**Band reject or Notch or Band Elimination filter.** It is fourth type of filter and is inverse of band pass filter. It stops signals having intermediate frequency while pass signals of low and high frequency. The terminology of BR filter is similar to that of BP filter.

**All pass filter.** It is the fifth type of filter. This type of filter allows signals of all the frequency to pass, but the phase of the signal depends upon the frequency. We know that any type of filter whether LP, BP, HP or BR introduces phase shift while filtering. For audio or voice frequency applications this is of little importance, however for video frequencies or digital applications phase change or delay can cause intolerable distortion in the shape of time-domain video or digital signals. Thus, there is a need to circumvent this problem and as a sequel all pass filters are utilized. The AP function is formed by collecting into $N(j\omega)$ all right hand plane zeros and into $D(j\omega)$ all poles which are mirror images of right-hand plane zeros. The phase difference is given [6,7] as:

$$argT(j\omega) = \frac{\arg N(j\omega)}{argD(j\omega)} = argN(j\omega) - argD(j\omega) \quad (1.8)$$

## 1. 4 Filter transfer functions

The transition region is not narrow and ideally speaking it should be zero. However, to make transition region narrow the higher order filters are needed. The higher order filters are obtained at the expenses of large number of components. For example, first order need only one capacitor and a single resistor while the second order need two capacitors and more than two resistors. Higher order filters are obtained by cascading first and second order filters. Thus higher order filter are more expensive, occupy large space, and the complexity of network increases. In this work only first and second order filters are discussed. Transfer functions for first and second-order for all the types are given below

First order:

$$T_{LP}(s) = \frac{H\omega_0}{s+\omega_p} \quad (1.9)$$

$$T_{HP}(s) = \frac{Hs}{s+\omega_p} \quad (1.10)$$

$$T_{AP}(s) = H\frac{s-\omega_0}{s+\omega_p} \quad (1.11)$$

$$T_{Ap}(s) = -H\frac{s-\omega_0}{s+\omega_p} \quad (1.12)$$

The phase angle $\varphi(s)$ of the AP first order filter is, $\varphi(s) = \pi - 2tanarc(\omega_0/\omega_p)$. The phase angle varies from 180° to 0°. This is referred to as non-inverting AP filter. The phase of inverting AP filter is given by $\varphi(s) = -2tanarc(\omega_0/\omega_p)$ .The phase angle varies from 0° to -180°. The second order transfer functions of the filter are given below:

$$T_{LP}(s) = H_o\frac{\omega_0^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} \quad (1.13)$$

$$T_{HP}(s) = \; H_o \frac{s^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} \tag{1.14}$$

$$T_{BP}(s) = \; H_o \frac{\frac{\omega_o}{Q_0}s}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} \tag{1.15}$$

$$T_{BR}(s) = \; H_o \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} \tag{1.16}$$

$$T_{AP}(s) = \; H_o \frac{s^2 - \frac{\omega_o}{Q_0}s + \omega_0^2}{s^2 + \frac{\omega_p}{Q_p}s + \omega_p^2} \tag{1.17}$$

For realization of AP filtering functions in first order and second order filters the realization condition $\omega_0 = \omega_p$ . $\omega_0$and $\omega_p$ are respectively critical frequencies at which transfer function becomes zero and infinity.

### 1.5 Filter parameters

A brief description of the filter parameters which describes the performance of the filter circuit are given below:

#### (a) Transition Band

The rapid signal amplitude drop occurs in the frequency response's transition band, which is located between the pass band and stop band. Higher order filters have a narrow transition band. The roll-of-rate of the amplitude depends upon the order of the filter and realizable approximation to ideal filters. For first order the roll-of-rate in the transition band is 20dB/decade and for second order it is 40dB/decade for nth-order it is n20dB/decade.

#### (b) Cut-off Frequency

The cut-off frequency of a filter is the frequency at which there is a -3dB reduction in signal amplitude. The -3dB point is the frequency at which cut in power is exactly 1/2 and is thus known as half power point. This frequency is also known as corner frequency. A BP or BR filter normally has two cut-off frequencies while HP or LP filter has just one cut-off frequency. It is an important parameter while choosing a filter for a particular application.

### (c) Bandwidth

This is the difference between the two frequencies $f_1$ and $f_2$ at which the magnitude response is 3db below its maximum value (at $f_o$ ) [6,7]

$$BW = f_2 - f_1 \tag{1.18}$$

$$f_0 = \sqrt{f_1 f_2} \tag{1.19}$$

Bandwidth is an important parameter of a filter circuit. It measures the range of frequency which a filter allows to pass and the frequencies outside the given range in not allowed. The filters offers minimum or no attenuation to the signal whose frequency is within the pass band range and offers infinite or maximum attenuation to the signals having frequency which lie outside the pass band range . $f_1$ and $f_2$ are first and second cut-off frequency and $f_0$ is the central frequency.

### (d) Quality-Factor (Q-Factor):

Quality factor or Q-factor is an important parameter of filter circuits because it measures the selectivity of the filter. Selectivity is defined as the ability of a system to distinguish between desired and undesired signals. A filter is considered to have a high Q when it selects or rejects a condensed subset of frequencies in relation to its operating frequency. The Q-factor is given by:

$$Q = \omega_o/BW \tag{1.20}$$

Higher the value of Q, the more selective is the filter or bandwidth (BW) is more narrow i.e., the response curve here will be sharply peaked thereby making the circuit highly selective. Lower values of Q mean wider BW and poor selectivity. Thus the degree of peaking in a resonant filter is a measure of Q. A high Q filter will pick out a desired frequency from noise, etc. For BP and BR (notch) frequency responses, Q is associated with the sharpness of the amplitude response curve i.e., by increasing Q, sharpness increases, while for LP and HP frequency responses, show peaks in their response curves near the corner frequency**.**

## 1.6 Pole-zero of transfer function

Equation (1.2) describes the transfer function which is ratio of two polynomials. $Z_i$ are zeros of transfer function while as $p_i$ are the poles. Poles and zeros are critical frequencies at which the transfer function becomes infinite and vanishes respectively. The complex frequency is given:

$$s = \sigma + j\omega \qquad (1.21)$$

$\sigma$ is the neper frequency (1 neper = 8.686 dB) taken along x-axis and denotes the magnitude. $j\omega$ taken along y-axis represents phase of the signal in s-plane (system of coordinate axes). Pole zero of a network is used to perfectly identify the time response. The zero decides magnitude while as pole decide nature of the response. The poles (real and complex) to left of the s-plane are stable and controllable while as poles to the right of s-plane response of network is unstable. Simple and non-repetitive poles on jω axis produce pure sinusoidal response. The repetitive poles on jω axis produce growing oscillations. A simple pole at the origin produce step type response while the repetitive poles at origin produce unstable response. The poles of the filter always lie on left hand side of s-plane while as zeros lie at infinity for low pass filter, origin for high pass filter. For band pass filters one zero lie at origin and other at infinity while for band reject filter one zero on lie on positive side jω and other zero on negative side of jω. For all pass filters the zeros are mirror images of zeros.

## 1.7 Realizable approximation to ideal filters

It is already mentioned that the transition band in the filter is not narrow as is required in most of the applications. The sharp fall-off in magnitude to zero value at cut-off frequency is an ideal approximation which cannot be realized in actual practice due to inherent limitations in the active and passive devices. As a result, a number of realizable filter approximations have been developed among which commonly used are:

a) Maximally Flat (Butterworth)
b) Equi-ripple (Chebyshev)
c) Elliptical (Cauer)

In maximally flat filters the transfer function up to cut-off frequency is flat. At cut-off frequency the magnitude response decrease at the rate of 20 dB per decade for first order filters. With increasing order of filter, roll-off rate increases. Another way of increasing roll-off rate is adding ripples in the stop band or in the pass band or in both bands. If the ripples are added in pass band this is referred to as Equi-ripple or Chebyshev filter type I. In Chebyshev filter type II, ripples are introduced in stop band. In elliptic or cauer filter ripples are introduced in both pass band and stop band resulting transition band narrower. It is worth to mention that low order elliptically filter realizes the specifications for which Chebyshev filter of high order and Butterworth filter of much higher order is required. Thus elliptical approximation is more efficient followed by Chebyshev and Buttherworth approximations. The reason for this behaviour is the introduction of ripples in pass band and stop band. Also, regarding delay performance, elliptical filters have best and Chebyshev and Butterworth the worst one.

## 1.8 Sensitivity

Sensitivity is a measure of the change in some performance characteristics of the filter such as H (gain), ω (cut-off frequency) and Q (quality factor), as a consequence of the change in the nominal values of devices such as capacitance, transconductance gain. High sensitivity of the network renders it useless in practice though the network is attractive from theoretical point of view. The researcher finds it difficult to compare with other possible realizations that met same specifications. It is the sensitivity which the circuit designer uses to evaluate his design. The concept of the sensitivity is one of the vital criteria for comparing circuit configuration and for confirming their practical utility in meeting desired requirements.

The sensitivity is denoted by $S_x^y$. Where the superscript y represents the performance charactiristics like H, ω and Q and subscript x is the elements value like value of a capacitor, resistor, and transconductance gain. y is function of x. If nominal value of x is $x_o$, then variation in y(x) produced by change in x can be expressed by the Tailor's series as given below:

$$y(x) = y(x_0) + \left(\frac{\partial y}{\partial x}\right)_{x=x_0} dx + -----$$

For small changes in x higher order derivatives are neglected. Thus

$$\Delta y(x_0) = y(x) - y(x_0) = \left(\frac{\partial y}{\partial x}\right)_{x=x_0} dx$$

$\Delta y(x_0)$ = change in y due to variation in x. Since we are interested in relative sensitivity changes in y and x, we add normalizing terms to above relation.

$$\frac{\Delta y(x_0)}{y(x_0)} = \left(\frac{\partial y}{\partial x}\frac{x}{y(x)}\right)_{x=x_0} \frac{dx}{x_0}$$

$$\frac{\frac{\Delta y(x_0)}{y(x_0)}}{\frac{dx}{x_0}} = \left(\frac{\partial y}{\partial x}\frac{x}{y(x)}\right)_{x=x_0}$$

The relation $\frac{\frac{\Delta y(x_0)}{y(x_0)}}{\frac{dx}{x_0}}$ represents the sensitivity function. We may formally define it as:

$$S_x^y = \frac{xdy}{ydx} = \frac{\partial(lny)}{\partial(lnx)} \tag{1.22}$$

### 1.2.1 Active Device and Proportional Blocks

It was up to 1960, passive filters were used as no active building blocks were available though some researchers used transistors to realize active-RC filters. But due to serious problems encountered by these filters were abandoned. It was recognized earlier that the size eventually cost can be reduced drastically by replacing heavy and bulky inductors with active circuits having the property of duplicating the terminal characteristics of real inductors. It goes long back to World War II when operational Amplifiers (OA) solely made of tubes were in use Reference [8]. In the early 1970s, the economic potential began to envision for active-RC filters to be realized with batch-processed thin-film hybrid circuits (HICs). However, it was soon realized operational amplifier suffers from the main drawback of frequency dependent gain which limits its bandwidth (this was later used to realize the filter in which capacitors are eliminated) Reference [9]–[11]. High speed operation, low power supply, low power consumption, a greater slew rate, a higher bandwidth, a higher dynamic range, and simple circuitry are all potential benefits of current mode (CM) circuits. Currents are less prone to parasitic capacitances, (which limit higher frequency operation), as a result, support higher bandwidth. Miniaturization of the devices has paved the way for low supply voltages. Also, microelectronics technology in the present state of affairs needs electronic circuits to have lower power consumption and the low supply voltage. The higher dynamic range is due to the non-dependence of current swings on supply voltage. Addition or subtraction operation is simply attained by tying the current terminals, while for VM circuits the additional devices are needed. These potential advantages led the circuit designers to the considerations and cause to work in the current domain rather than in the voltage domain. Branch currents instead of node voltages are thus used to process the information. This has motivated researchers to develop current mode active building blocks. It should be noted, nonetheless, that there are still circumstances in which mixed mode circuits are also examined in order to optimise the interface sub-blocks, which operate in various modes. As a result, not only CM but also mixed mode (MM) and voltage mode (VM) are to be examined side by side Reference [12], [13].

### 1.2.2 Active current mode devices

With the advancements made in the last three decades in IC technology, researchers have exploited the CM technique to develop elegant and versatile CM active building Blocks. Sedra and Smith introduced the first generation of the current conveyor, known as the current conveyor first generation (CCI), in 1968, marking the initial step in this direction, as referenced in [14]. However, just after two years, a more versatile current device, the current conveyor second generation (CCII) was introduced by the same authors and is treated to be a universal device Reference [15]. After almost two decades one more current conveyor called the current conveyor third generation (CCIII) was introduced Reference [16]. However, CCI and CCIII could not attract the attention of researchers due to low input impedance terminals, which are not suitable for VM and MM applications. CCII proved a very efficient active device and has been used in CM, VM, and MM applications. CCII has y input terminal of high impedance, x terminal is a low impedance and output z is a high impedance terminal. Thus CCII is best suitable for Current mode, voltage mode, and mixed mode applications. The primary advantage of CCII is its compatibility with CM. When the device's terminal y is grounded, the current entering the low-impedance x terminal is seamlessly duplicated into the z terminal through the current mirror. This device is referred to as a current follower (CF) Reference [17]. Since the inception of CCII in 1970, many modifications were made and the resulting variants of CCII have been presented. To increase the universalities more output current terminals were provided to existing CCII called multi-output CCII (MO-CCII). If the number of outputs is two, the device is referred to as a double-output CCII (DO-CCII). This device has the advantage of implementing both positive CCII (CCIIp or CCII+ Current having the same direction) and negative CCII (CCIIn or CCII- current having opposite direction). Devices created by dividing the input terminal y into the $y_1$ and $y_2$ terminals is known as Differential voltage CCII (DVCCII) devices Reference [18]. Differential Difference CC (DDCC) is an extension of DVCC in which the y terminal is split into three terminals $y_1$, $y_2$, and $y_3$ Reference [19]. Differential CC (DCC), a further generalisation of CC, replaces the input of x with a pair of $x_1$ and $x_2$ Reference [20]. The disparity in the current passing through the $x_1$ and $x_2$ terminals equates to the current flowing through the z terminal. DXCCII (Dual X CCII), which combines CCII and ICCII, is another kind of CC Reference [21]. In aforesaid CC either one or two terminals are made differential. Ensuring analog circuitry remains impervious to digital noise is pivotal in contemporary mixed systems where both analog and digital components coexist on a single chip. Consequently, analog subsystems necessitate a fully balanced architecture in their design. Fully Differential CCII (FDCCII) also called Fully Balanced CC (FBCII) having terminals (x, y, and z) in pairs Reference [22]. Finally, universal CC (UCC) was realized which can implement any of the desired CC Reference [23]. In addition to above mentioned ABBs, more ABBs were introduced like Four Terminal Floating Nullor (FTFN) Reference [24], and Current Difference Buffered Amplifier (CBDA) Reference [25].

### 1.2.3 Electronically tunable active building blocks

Electronic tunability is treated as an important feature of ABBs. This feature facilitates the control of parameters of a given circuit through bias currents which in turn can be controlled by bias voltages. In integrated circuit technology (IC technology) electronic tunability is needed. Moreover, it is widely acknowledged that signal processing circuits tend to diverge from their intended design values over time, owing to factors such as aging, inherent parasitic elements, and process tolerances. Due to these drawbacks, the parameters of the ABB can vary which affects drastically the performance of the circuits. Thus there is always a need for such measures which can either remove or minimize these difficulties. It is the electronic tuning of the ABB which can be used to tackle the problem. Additionally, there are instances where automatic adjustment of the circuit parameters is necessary, such as in music and voice synthesis. This can be achieved by electronic tuning. The ABB whose gain parameter can be adjusted by external bias current/voltage is referred to as electronic tuning. In this subsection electronically tunable ABBs are presented.

At the outset, an operational transconductance amplifier (OTA) is presented Reference [26]. OTA introduced in 1970, is a differential voltage current source (DVCC) that offers electronic tuning of its gain ($g_m$) by external bias current. However up to 1985, OTA did not attract the attention of researchers, due to the advantage of OA, but a new class of circuits were realized without resistors, called OTA-C ($g_m$-C) Reference [27], [28]. These circuits besides offering electronic tunability have the advantage of implementation in IC technology. However, OTA based circuits have a dynamic range (DR = distortion less output/total RMS noise voltage at output) depending upon the power supply, which means low power supply resulting in lower DR. The other disadvantage of OTA based circuits is the slew rate. When OTA is loaded with a capacitor to produce the integrating effects, encounters slewing rate problem ($SR = d(V)/dt = \omega V$). The input and output impedance is also of great concern that should be ideally infinite. The OTA based on bipolar transistors has finite impedance, but for CMOS OTA the input impedance is very high. Thus while working with OTA these impedances are to be taken into account. In 1996 Febre proposed a new ABB called current controlled conveyor second generation (CCCII), extending second generation current conveyor applications to the domain of electronically adjustable functions Reference [29], [30]. The x-port of CCII, which follows the voltage from the y terminal to the x terminal, was replaced by voltage follower implementation using a translinear loop instead of OA. The serial parasitic resistance $R_x$ of the translinear loop depends upon the bias current leading the electronic tunability to the circuits using CCII. This type of ABB is more versatile than OTA in respect of increased bandwidth and less power consumption due to using fewer transistors. The dependence of $R_x$ on the power supply and temperature dependence, limit its applications. The researcher started to search for other novel ABBs having a wide electronic tuning range. The main motivations for searching for other ABBs are to increase the universality while preserving the simplicity of its structure, analog or digital control, minimizing parasitic effects, the trade-off between speed and accuracy, and designing ABBs so that least number of these blocks are needed. The Current Difference Buffered Amplifier (CDBA) is an amplifier featuring an input stage that handles current differences and an output stage equipped with a buffer. This ABB proved very useful for many applications; however, it lacked electronic tunability. A new ABB was realized by replacing the buffer at the output with TA, called Current Differencing Transconductance Amplifier (CDTA) Reference [31]. The universality of CDTA can be increased by providing a Z copy (copy of the current through the Z terminal). A replication of current Z is achieved using a high-impedance current mirror. CDTA has a two current inputs and output current equals to difference of input currents. The voltage at z terminal is converted to current by the transconductance amplifier. However, if one of the inputs is left unused, there are chances for picking up noise leading to increased noise at the output. CDU in CDTA was replaced by CF, CI (current Inverter), or CCII, giving rise to CFTA, CITA, and CCTA. The input terminal of CDTA and CBDA is low impedance terminals and the serial resistance of these terminals depends on bias current as mentioned above. New ABB were framed out, called current controlled CBDA (CCCBDA) and current controlled CDTA (CCCDTA) Reference [32]. The complete catalogue of ABBs can be found in Reference [33]. In this research article, the authors in a systematic manner presented the review of ABBs used for analog signal processing and proposed new ABBs with their potential advantages. There are situations where differential inputs are needed for example in mixed mode applications. We can have a voltage difference unit (VDU) at the input and TA at output. Since OTA is a VDU having feature of gain which can be controlled by bias current is used at the front-end and followed by another TA realizing a novel ABB called Differential Voltage Transconductance Amplifier (VDTA) Reference [34], [35]. The universality of the VDTA can be increased by providing a Z copy of the current ($Z_{C}$, Copy).

### 1.3.1 Voltage Difference Transconductance Amplifier

The first CMOS circuit of the Voltage Difference Transconductance Amplifier (VDTA) was given by the authors, Yesil, Kacar and Kuntaman in 2011. The researcher presented a research paper published in journal of Radioengineering Reference [34].

The ABB has received considerable attention from researchers due to the advantage of dual control of transconductance gain by bias currents. VDTA is actually an active device whose output currents are controlled by the difference of voltages applied at the input. The input and output impedance of VDTA is high. VDTA has two input voltage terminals ($V_P$, $V_N$). Voltages difference ($V_P$-$V_N$) is converted by first transconductance gain to current available at terminal Z. The voltage drop at terminal Z again converted into current by second transconductance gain and is provided at the X terminals. The terminal X can have both polarities represented by $X_+$ and X-. Since transconductance gains can be adjusted externally by bias current/voltage lending electronically tunability features to the device. As the device possesses dual transconductance gains which is highly favourable for the realization of analog circuits. The universality of the VDTA is further increased by numerous copies of Iz currents. Additionally, by assigning Z copy ($I_{ZC}$), VDTA has a fascinating application capability. For example, the emulation of a floating, lossless inductor can be accomplished using just one Voltage Differencing Transconductance Amplifier (VDTA) alongside a grounded capacitor. The characteristic equation of the VDTA is provided below:

$$\begin{bmatrix} I_Z \\ I_{X+} \\ I_{X-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} \tag{1.23}$$

The circuit symbol and behavioral model is shown in Figures 1.2. and 1.3. Figure 1.4 show implementation of VDTA using OTAs. Figures 1.5 and 1.6 shows CMOS realization of VDTA. Two Arbel– Goldminz transconductances cell are used for realization of basic VDTA Reference [35]. The transconductance gain is determined by the transconductances of output transistors, and is given below:

$$g_{m1} = \frac{g_1 g_2}{g_1+g_2} + \frac{g_3 g_4}{g_3+g_4} \tag{1.24}$$

$$g_{m2} = \frac{g_5 g_6}{g_5+g_6} + \frac{g_7 g_8}{g_7+g_8} \tag{1.25}$$

Where transconductance gain in terms of bias current $I_B$ is given below:

$$g_{m1} = \sqrt{I_{B1}\mu_n C_{ox}\left(\frac{W}{L}\right)_1} \qquad (126)$$

$$g_{m2} = \sqrt{I_{B2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2} \qquad (1.27)$$

From the above equations it is clear that the transconductance gain can be adjusted by bias currents $I_B$.

$\mu_n$ = Carrier mobility and

$C_{ox}$ = Gate-oxide capacitance per unit area of the NMOS transistor

Aspect ratio = $(W/L)_i$ ( i = 1.2)

W and L length and width of channel of NMOS transistor.

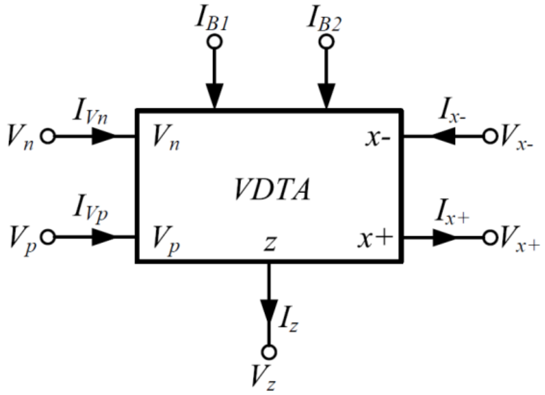


Figure 1.2: VDTA’s circuit symbol

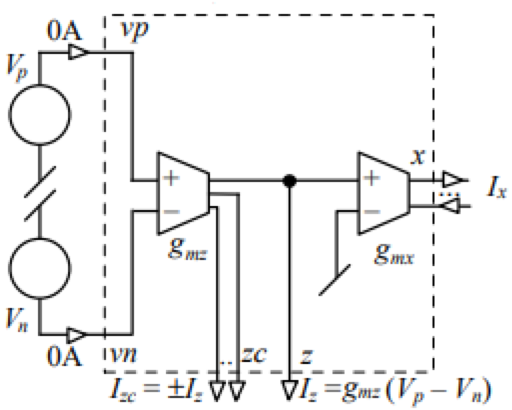


Figure 1.3: Behavioral model of VDTA [33]

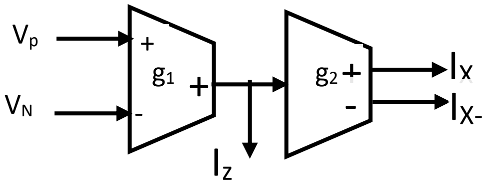


Figure 1.4: Implementation of VDTA using OTAs

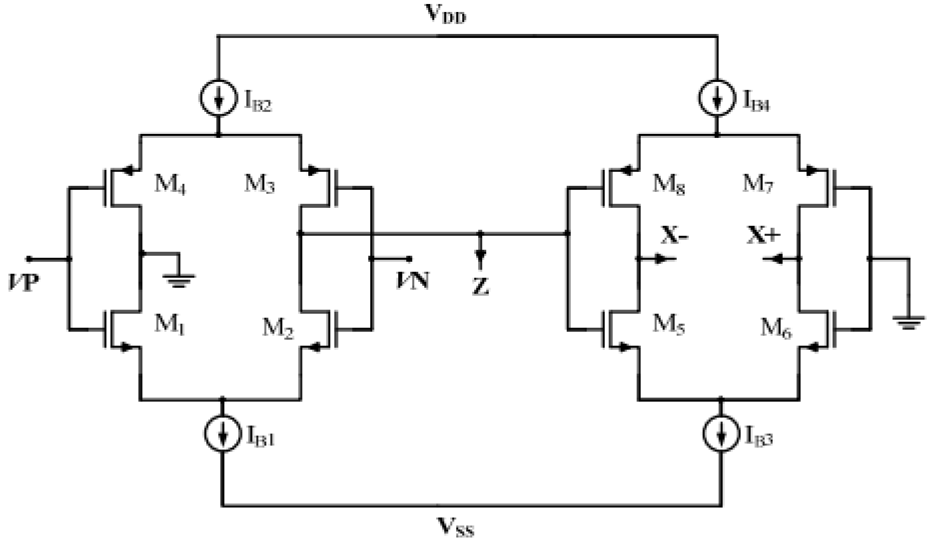


Figure 1.5: Basic VDTA CMOS implementation [34]

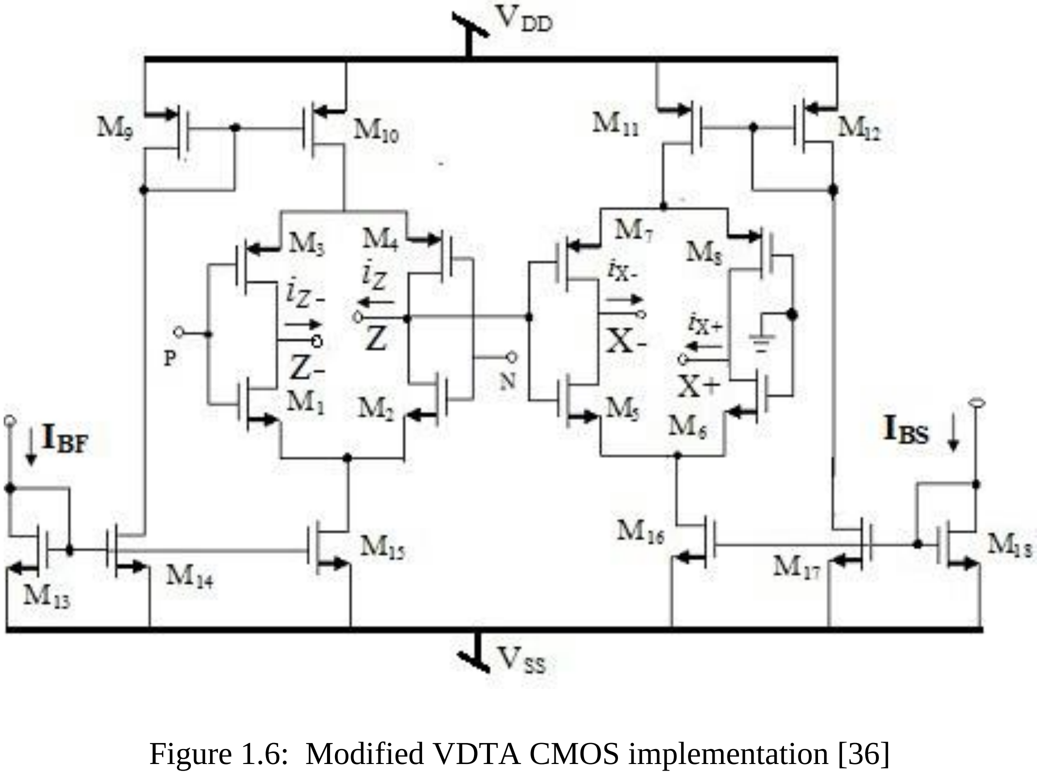


Figure 1.6: Modified VDTA CMOS implementation [36]

### 1.3.2 Parasitic of VDTA

All of the VDTA's ports exhibit infinitely high input and output impedances in theory, but in practise, these ports possess high, but finite impedances. The parasitic impedance is a parallel combination of parasitic capacitance and parasitic resistance. The filter's design should be designed to minimise the impacts of the parasitic impedances, which have an impact on the filter's parameters and must be taken into account. Also, these impedances are frequency dependent which limits the employment of these devices at high frequency.

In addition to the parasitic of VDTA, the transconductance gain of VDTA is frequency dependent. The gain of VDTA at high frequency is described by the relation Reference [36]**.**

$$g_{mi} = \frac{g_{mi0}}{1+s\tau_i} \qquad \text{where i = 1,2} \tag{1.28}$$

$g_{mi}$ is the transconductance gain at high frequency and $g_{mi0}$ is the gain at low frequency. $\omega_i$ is the pole frequency $\omega_i = 1/\tau_i$.

Another non-ideality that VDTA encounter is due to a mismatch of MOS transistors. The port relation of VDTA is described by the relation:

$$\begin{bmatrix} I_z \\ I_{x+} \\ I_{x-} \end{bmatrix} = \begin{bmatrix} \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ 0 & 0 & \beta_2 g_{m2} \\ 0 & 0 & -\beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} \tag{1.29}$$

Where $\beta_1$ and $\beta_2$ are tracking errors and are slightly less than one.

The transconductance gain of VDTA depends upon the temperature Reference [34]. The transconductance gain is given by:

$$g_m = \mu_x C_{ox} \frac{W}{L} \left(V_{gs} - V_T\right) \tag{1.30}$$

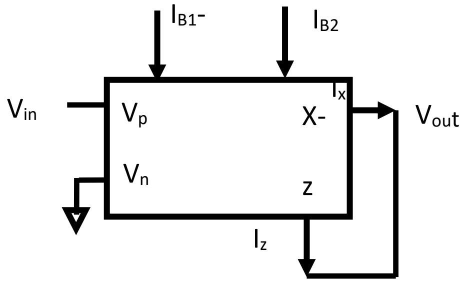
The absolute change in $V_T$ is -2.4mV/$^0$C. Also, the mobility which is also temperature dependent is given by

$$\mu(T) = \mu(T_0)\left(\frac{T}{T_0}\right)^{-1.5} \tag{1.31}$$

The mobility decreases with temperature in order 1.5%, although the threshold voltage reduces in order 0.24%. Obviously, mobility reduction dominates the transconductance gain (gm) and gets worse as the temperature rises. However, the temperature compensation scheme is already given in the Reference [37].

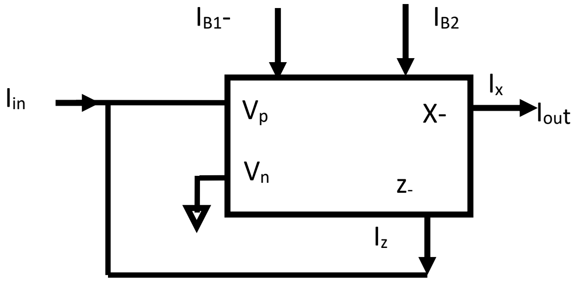
### 1.3.3 Building Blocks using VDTA

Building blocks are very essential for the realization of filters. These building blocks are proportional blocks, lossy and lossless integrators, inductance simulators, (floating and grounded), and capacitance multiplier. Several inductor simulator series and parallel R-C, immittance (impedance and admittance) are presented in the literature [38], [39]. It is a well-known fact that inductors cannot be realized in IC form and instead, VDTA along with capacitors are used to simulate the inductors. These inductors have the advantage of changing their value electronically which is not possible with the coil type inductor. Below are given various building blocks with their transfer functions.



$$\frac{V_{out}}{V_{in}} = \frac{g_1}{g_2}$$

Figure 1.7: voltage mode proportional block



$$\frac{I_{out}}{I_{in}} = \frac{g_2}{g_1}$$

Figure 1.8: current mode Proportional block

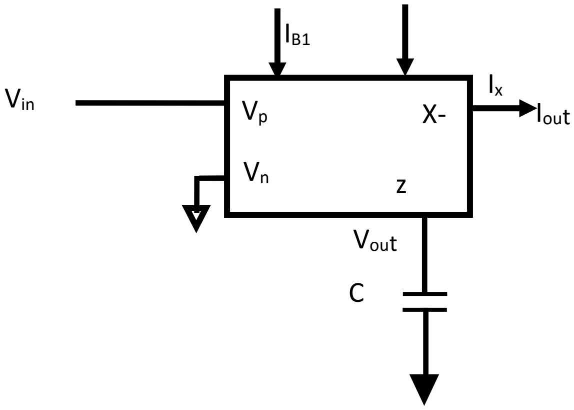
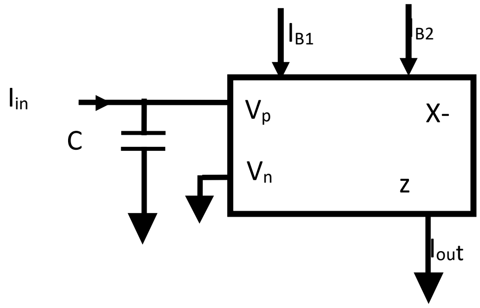


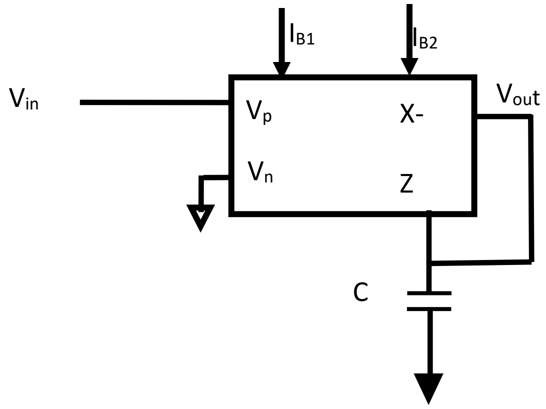
Figure 1.9: Lossless VM and TAM integrator

$$\frac{V_{out}}{V_{in}} = \frac{g_1}{sC}, \qquad \frac{I_{out}}{V_{in}} = g_2\,\frac{g_1}{sC}$$



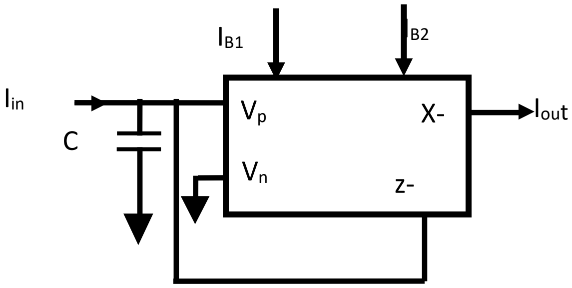
$$\frac{I_{out}}{I_{in}} = \frac{g_1}{sC}$$

Figure 1.10: Lossless Current mode integrato



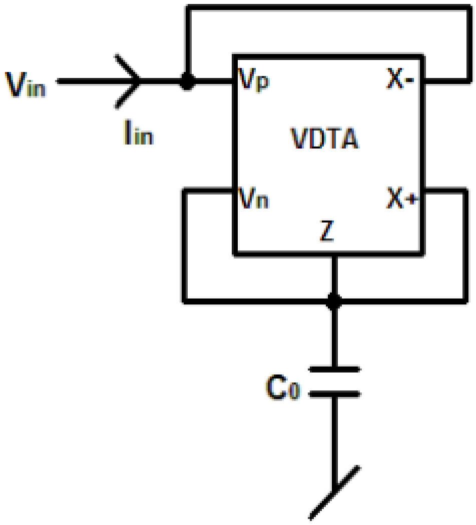
$$\frac{V_{out}}{V_{in}} = \frac{g_1}{sC + g_2}$$

Figure 1.11: Voltage mode lossy integrator



$$\frac{I_{out}}{I_{in}} = \frac{g_2}{sC + g_1}$$

Figure 1.12: Current mode lossy integrator



$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{sC_0}{g_1 g_2} \; and \; L_{eq} = \frac{C_0}{g_1 g_2}$$

Figure 1.13: Grounded inductance simulator [38]

## 1.4 Active-only filters: Frequency dependence gain of OA (pole Roll-off Model)

Analog signal processing has benefited significantly from the introduction of the operational amplifier. Since its invention five decades ago, the operational amplifier has dominated the area and has been utilised to realize many analog signal processing circuits. It was already recognized, however, that the OA has a number of problems, including input and output impedance (ideally, input impedance should be infinite and output impedance should be zero), the most serious frequency dependent gain, and a non-zero phase. The device's gain tends to decrease with increasing frequency. In addition to restricting the use of filters in the low-frequency region, these challenges also compromise sensitivity and stability. Methods of compensation have been created to minimise their impact on the filter performance variables. Instead of being problematic, frequency-dependent gain of OA was used to create active-R filters, as described in the technical literature Reference [4].

Operational Amplifier is basically voltage controlled voltage source (VCVS). The port relation of OA is:

$$V_o(s) = A(s)\left[V^+(s) - V^-(s)\right] \tag{1.32}$$

Where A(s) which is a function of frequency is the open loop gain of OA. $V^+$ is non-inverting terminal and $V^-$ inverting terminal. For ideal OA, input and output impedances are infinite and zero respectively. However, in actual practice, the ideal OA differs from the real one. Real OA has finite input impedance, but for FET input stages, it is so high and can be taken infinite for almost all applications. On the other hand, output impedance is not equal to zero but is located in the range of $50\ \Omega \le R_o \le 100\ \Omega$. The open loop gain of OA is of important concern and is assumed to be of the following form:

$$A(s) = \frac{B_i \sum_{j=1}^{m} \omega_i}{s \prod_{j=1}^{m} (s + \omega_j)} \approx \frac{B}{s}(1 - \prod_{j=1}^{m} \tau_j s) \tag{1.33}$$

The above equation reduces to after considering first order approximation,:

$$A(s) = \frac{A_0}{1 + s\tau_1} = \frac{A_0\omega_0}{s + \omega_0} \approx \frac{B}{s} \quad \text{for } s >> \omega_0 \tag{1.34}$$

where $A_0$ depicts open loop dc gain, $\omega_0$ = 3db-frequency of the OA where $\omega_0 = \frac{1}{\tau_1}$ and B represents gain bandwidth product. From Equation (1.34) it is clear that OA acts as an ideal integrator when the effect of 3-db frequency is neglected. Thus using the pole model of OA needs only OAs and resistors to realize filters. Later on in the mid-nineties resistors were replaced by OTAs giving rise to more versatile filters called active-only filters. Numerous active-R and active-only filters are reported in the literature Reference [40] and the references there are cited. Taking into consideration the second and third poles, the gain can be written as:

$$\mathrm{A(s)} = \frac{B}{s}\left[1 - s(\tau_2 + \tau_3)\right] \tag{1.35 }$$

Where $\tau_2 = \frac{1}{\omega_2}$ is second pole and $\tau_3 = \frac{1}{\omega_3}$ is the third pole.

## 1.5 Thesis Structure

The thesis is made up of six chapters. The first chapter deals with basic filter theory and active devices. In basic filter theory following are points which have been discussed., types of filters and filter performance factors, order of filters and approximations of filter, and the most important sensitivity of the filters. Active building blocks, which are used to implement active filters are presented for reference. The introduction of ABBs is described in a systematic manner. Electronic tunable active devices are also given. Finally voltage difference transconductance amplifier VDTA is described in detail. The building block of VDTA which is used in this thesis is described in detail. Building blocks such as proportional blocks, integrators both in CM and VM, inductor simulators, grounded are included in the thesis. These blocks play pivot role in the realization of filters. Finally pole model of OA is discussed. The pole model of OA is used as a design parameter for realization of filters. Chapter second presents the literature review. Research papers which have been published from 2013 employing ABBs other than VDTA, and papers which are based on VDTA are from the inception of VDTA are included in the thesis for review and comparison. The circuits presented in the literature included first order and second order filters in chronological order. This section is divided into subsections depending on filter order and the mode of operation of filter. At the outset first order APFs are given. These filters perform only one filtering operation. The first order universal filter (FOUF), which carries out all three filtering operations concurrently, comes next. These filters operate either in CM or VM or in mixed mode (MM). Second order filters operating in CM, VM, and MM filters are also presented. Finally, papers which employ VDTA as ABBs are also given. Similarly, these filters are subdivided according to their operation. It is worth to mention that only one VM and TAM all pass filter using VDTA is presented in the literature. . In third chapter research gap, methodology and objectives of the proposed work is given. Fourth and fifth section pertains to the work done in which new filters are proposed. The fourth chapter deals with the first order filters. Six first order filters which are proposed are presented in this chapter. A unique filter with a single input and two outputs (LP and HP) is given first. Second filter having single input and single output is APF. This filter needs additional proportional block to increase the tuning range of the filter. The third one uses two VDTAs and offers three outputs, implementing simultaneously LP, HP, and AP filtering functions. The gain of the filter is electronically tunable. Fourth filter operating in CM using a single MO-VDTA is presented. The filter has three outputs and one input. The filter's additional benefit is that it is not subject to the realizability condition. The above filters presented use pole model of OA. The fifth filter uses a single capacitor and a single VDTA having two inputs and two outputs. The filter implements VM and TAM filtering functions simultaneously. The filter realizes AP, HP and LP filtering functions depending upon the choice of inputs. However, AP filter is free from realizability condition but need inverter to invert one of the inputs. The filter realizes both inverting and non-inverting AP filtering functions. Sixth filter use a single VDTA, one capacitor and a grounded resistor. The filter realizes AP filtering function in VM and TAM. However, filter is not free from realizability condition. All the filters presented use single output VDTA except fourth one. Single output VDTA is more advantageous than MO-VDTA in respect of non-idealities. In fifth chapter proposed three second order filters are presented. Depending on the inputs used the filter, which has three inputs and two outputs, realises all filtering functions in both the VM and TAM at the same time is described first. The circuit employs one VDTA, one Capacitor and a single OA. Second filter presented operates in CM, uses two single output VDTA and two GCs and implement BP filtering function. The filter performance factor like gain, quality factor and cut-off frequency are tunable electronically in an independent manner. It is worth to mention that the filter use minimum number of components. The third filter has a single voltage input, six outputs, and only uses two MO-VDTA and two grounded capacitors. The filter simultaneously performs three filtering operations in VM and three in TAM. The filter is capable of providing notch and AP filtering functions for TAM, however for VM it needs additional components. Sixth chapter discusses future plane for implementation of higher order filters. Here, it is important to note that first and second order filters serve as the fundamental building blocks for the development of filters having order higher than two. All the proposed filters presented in the thesis have been validated by using Multisim 14.3 version and electronic workbench 5.3 version. The VDTA has been implemented by cascading two LT1128 OTAs and OA used is LM 741. Sixth chapter presents Conclusion and future scope.

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# Chapter 2: Literature review

## 2. Introduction

Active building blocks have been presented in the first chapter. Now these ABBs have been used extensively to construct analog circuits. Continuous time filters are one of the most important networks which are being employed in every field of science and technology. As already stated in Chapter first, filters are classified depending upon the use of ABB, nature of input and output, number of inputs and outputs, and order of filters (first order, second order). After an extensive literature survey, work done in the realization of filters that have been published during the last decade is included in this chapter. At the outset, a literature review of first order filter is presented.

### 2.1.1. First order all pass filters

Here those filters are considered References [1]–[8] which realize only one filtering function namely the AP filtering function.

The filter operating in current mode use a single DX- MOCCII (dual X multi-output CCII) and one GC and one grounded resistor is presented in Reference [1]. The filter has low input and high output impedance making it suitable for cascading. The filter is free from realizability condition. The filter employing two OTAs, four resistors, and one GC is given in Reference [2]. The input circuit has either current or voltage and has two outputs (current and voltage) both at high impedance. The current is taken through the second output of OTA (DO-OTA). The circuit has to satisfy the realization condition. If DO-OTA is replaced by single output OTA then it implements only CM filter. The filter proposed in Reference [3] uses one VDCC, one GC, and two floating resistors. The circuit operates in voltage mode and has a single input and output. The filter is subject to realizability condition in terms of resistor ratio while frequency is tunable through transconductance gain of VDCC. In this work Reference [4], APF is based on a current difference amplifier that employ seven MOS transistors and a capacitor. Since it uses the least number of components consumes less power and operates at low voltage. Two APF are proposed in the research paper Reference [5]. First APF employs two CFOAs, one GC, and as many as five resistors. APF is coupled with realizabilty condition while as this filter offer a gain control. The second circuit use three CFOAs and one GC, and six resistors. This circuit provides two outputs implementing inverting and non-inverting AP functions simultaneously. Here the resistors are replaced by MOS transistors. Two APFs are proposed in Reference [6] using one DXCCII one GC and two resistors. The first filter provides non-inverting while the second one provides inverting APF. In this research paper Reference [7], the authors proposed four AP filters, the first two are VM, the third one is CM, and the fourth is TAM filter. The active element used is DXCCDITA. The first circuit employs one DXCCDITA, and one capacitor. The circuit has a single input and one output. The second one uses one active element, a grounded resistor, and one capacitor. The circuit has one voltage input and two voltage outputs implementing inverting and non-inverting APF functions simultaneously. The third one operates in CM and has three outputs. Similarly, TAM uses one active element and a grounded capacitor. The filter proposed in this paper Reference [8] is similar to the paper presented in Reference [2].

### 2.1.2. First Order Universal Filter (FOUF)

In this subsection first order filters implementing LP, HP, and AP filtering functions are presented in References [9]–[25]. In this publication Reference [9] CM filter using a single CCDDCC and two grounded impedances is proposed. The circuit implements LPF, HPF and APF depending upon choice of impedances. The two outputs provide inverting and non-inverting filtering functions at high impedances. In this paper Reference [10], two APFs are given, both employing one CCDDCCTA and a GC. Both the circuit have dual input and one output. The configurations are subjected to realization condition for APF. The circuit implements LP and HP also. Two GCs and one DX-CCTA based APF operating in CM is proposed in this paper Reference [11]. The circuit realizes LPF and HPF simultaneously and APF is obtained by tying the LP and HP outputs. The circuit needs realization condition for the implementation of AP in terms of capacitors values. In this paper, subtractors are being utilized for implementation of LPF, HPF and APF, Reference [12]. LPF is obtained by simply one resistor and a one GC. First subtractor is used to obtain HPF and the second one is employed to obtain APF. In this paper authors propose VM APF Reference [13]. Here the circuit is based on a single M-CCCCTA (Modified-CCCCTA), one grounded resistor, and one GC. The circuit has two inputs and one output, can implement all the three basic filtering functions depending on the inputs used. For APF, the circuit needs realization condition in terms of resistor and parasitic resistance. The CM circuit employs one EX-CCCII (Extra X-CCCII) and a grounded capacitors Reference [14]. The circuit implements LPF and HPF filtering functions simultaneously. By tying of terminals for LPF and HPF, APF is achieved. The EX-CCCII has seven outputs. The filter possesses high output impedance and low input impedance. The circuit use one CCDDCCTA, and one capacitor Reference [15]. The circuit operate in VM and has two inputs and one output. The circuit realize AP, LP, and HP filtering functions depending on the choice of inputs. First order filter operating in CM use a single MO-DXCCTA and a single GC is presented Reference [16]. The filter has independent LP and HP outputs and by tying these terminals AP filtering function is obtained. The filter is coupled with realizations condition in terms of transconductance gains of MO-DXCCTA. The filter use two MO-CCII, one GC and one grounded resistor Reference [17]. The filter operates in CM. The circuit has three outputs and a single input. It realizes LP, and HP simultaneously. While the AP filtering functions is obtained by tying LP and HP output terminals. The circuit is free from realizabilty Condition. Two VCIIs, three resistors and a GC having single current input and two outputs (voltage and current), first order filter is presented Reference [18]. The circuit operates in CM and TIM. However, if CM filtering function is not needed one resistor can be omitted. For APF realization condition in terms of resistors is required. This research work proposes a first order current mode filter employing one GC and a single ABB (DD-DXCCII: differential difference dual-X second generation current conveyor) Reference [19]. The proposed filter provides simultaneously LP, HP and AP responses. Two input and single output APF using one OTRA along with two resistors and two capacitors is presented in Reference [20]. The circuit provides LP, HP and AP filtering function by choosing the inputs. The circuit is coupled with realizability conditions for capacitors as well as resistors. Here CM, filter using two ICCII+ one resistor and a GC is presented Reference [21]. The circuit provides two current outputs LP and HP simultaneously. By tying the LP and HP outputs APF is obtained. LT1228 (OTA followed by buffer) based triple input and one output VM first order filter is depicted in the research paper Reference [22]. The circuit realizes AP inverting and non-inverting in addition to LP, and, HP, by suitably selecting inputs. The circuit utilizes one capacitor along with two resistors. The filter is coupled with realizability condition. In this paper the author proposed two first order filters using a single CFOA, a GC and three resistors. The circuits have two inputs and two outputs Reference [23]. The first filter, realize LP, HP, and AP in VM and TAM while the second one realize CM and TIM, by suitable y choosing the inputs. However, the APFs are associated with realizable condition. In this research paper four first order voltage mode (VM) all pass filter (APF) based on two single output positive differential voltage current conveyors (DVCCs) is presented Reference [24]. The first and second filters implement AP filtering function with unity-gain. The filters have high input impedance and low-output impedances. These two filters are based on two DVCCs, a grounded capacitor, and a grounded resistor. The third and fourth proposed filters having facility of variable gain control which has been achieved by adding two resistors to each of the first two VMAPFs. Reference [25], corresponds to the electronically tunable first order universal filter using a single voltage differencing-differential input buffered amplifier (VD-DIBA), a capacitor and two resistors. The filter operates in VM implementing AP, HP, and LP filtering functions without changing circuit topology.

## 2.2. Second order filters

In this sub section second order filters using different ABB reported in literature, is presented. This section is divided into four subsections, depending upon the nature of excitations and responses (input and output). The references presented are from [26]-[61].

### 2.2.1. Voltage mode filters

The filter, reported by the author is multi-input and a single-output (MISO) type filter Reference [26]. The filter uses two VD-DIBAs and two GCs (grounded capacitors). The circuit has single output and three inputs. The circuit realizes all the filtering function. The circuit provides electronic tunability to the filter performance factors, however lack independent tunability. The input impedance is high while as output impedance is low. The circuit reported in Reference [27] employs one VDCC two grounded capacitors, one grounded resistor and a floating resistor. The circuit has one input and four outputs and realizes HP, BP, LP, and notch filtering functions simultaneously. The circuit offers electronic tunability to pole frequency only while quality factor (Q) is tuned through resistor without disturbing pole frequency. The filter possesses input impedance low and output impedance high. In this research article the authors presented a filter having a single high impedance input and four low impedance outputs Reference [28]. The circuit employs two VDDDAs, two CGs, and two resistors. The filter implements LPF, HPF, and two BPFs functions simultaneously. The pole frequency is electronically tunable while quality factor is tunable through either of the resistors in an independent manner. The circuit use two VDIBA and two GCs Reference [29]. The circuit is TISO type. The filter has electronic tunability features for pole frequency and quality factor, but lack independent tunability features. Circuit offers high input impedance for LPF only and remaining filtering functions have low impedance, however the output impedance is low. The circuit implements all the five filtering functions. Reference [30] corresponds to a filter circuit based on two VDDDAs, and two grounded capacitors. The filter has a single output and five inputs. The filter offers electronic tunability to filter performance factors, but not in an independent manner. The circuit has the features of cascadibility as its input impedance is high and output impedance low. In Reference [31] proposed filter realize all filtering functions. The filter employs one LT 1228 as an active building block, besides two capacitors and a single resistor. The filter is TISO (three input and single output) type, and realizes all filtering functions. Filter performance factors are controllable in independent manner, but Q factor lack electronic tunability. For LP filtering function input impedance is high and output impedance is low due to LT 1228, which is an OTA followed by buffer. In Reference [32], another circuit using one VDVTA, one GC, one floating capacitor, and resistors (implemented by using MOS transistors) is presented. The circuit is of TISO type, and realize all filtering functions. The circuit have low input impedance for BP and HP, while for LPF it is high, and output impedance is also high. In another filter circuit based on six OTAs and two GCs, having five inputs and a single output is reported in Reference [33]. The circuit offers independent electronic tunability of pole frequency and quality factor Q. The circuit have high input and output impedances. In this paper the authors proposed single output and four inputs filter using six OTAs and two grounded capacitors Reference [34]. The filter implements all filtering functions. The input and output impedance of the filter is high. The filter performance factors are independently and electronically tunable. Five OTAs and two GCs having three inputs and a single output is presented in Reference [35]. The circuit achieves all filtering functions. The filter offers electronic tunability of filter performance factors in dependent manner. The circuit's output and input impedance is high. VDBA based circuit using two capacitors and a single resistor is presented in Reference [36]. The circuit offer electronic tunability of pole frequency only. Besides, the circuit lack independent tunability of quality factor and pole frequency. Here input and output impedances are low. In this work authors proposed universal filter operating in VM using six OTAs, two GCs and two MOS resistors Reference [37]. The filter implements all filtering functions by choosing inputs. The filter performance factors are electronically tunable through bias current of OTAs. Reference [38] reports filter based on an active element FTFN (Four terminal floating nullor) and two resistors in addition to two capacitors. The circuit has three inputs, one output but lack electronic tuning capability. Low input and output impedance are features of the circuit. Reference [39] presents another single VDDC using as active element. The passive components used are each of two capacitors and resistors. The filter implements all filtering functions. The circuit lack independent electronic tunability of Q. The circuit exhibits low input and output impedances. In this reference [40] the author proposed a filter circuit having five inputs and use five OTAs and two grounded capacitors. The filter has a single output. The filter realizes all filtering functions by suitably choosing the inputs. Both the impedances of the filter is high. In another topology mentioned in the Reference [41] is similar to that described by filter reported in Reference [40] with slight modification and has three outputs implementing three filtering functions at a time depending upon choice of inputs. The filter is capable of implementing five filtering functions (LPF, BPF, IHPF, BRF, IBR, and APF). In Reference [42] single input filter using one CDTA, and four admittances is presented. Filter realizes different filtering functions but one at a time, depending upon the choice of admittances. Another filter presented in Reference [43] use three CFOAs, three resistors, and two GC having three outputs and two inputs. The filter realizes three basic filtering functions simultaneously for one input however, for other input filter realizes IBPF and HPF filtering functions only. The filter parameters are independent tunability but are devoid of electronic tunability. Topology has feature of cascadibility as its input impedance is high and output impedance is high. In Reference [44] one VDCC and five admittances having single input and a single output is presented. The filter realizes all filtering functions depending upon the choice of admittances. Both the filters are coupled with conditions in terms of admittances for realization of different filtering functions. In Reference [45] three different filters using OTAs and capacitors are described. BSF function is realized using two OTAs and two capacitors Figure 2, second one shown in Figure 3 implements APF functions while as Figure 4 use three OTAs and two capacitors realize APF and BPF functions. Three CFOAs, two GCs, and four resistors with dual inputs and triple outputs having high input impedance is described in Reference [46]. Though the filter has features of independent tunability of filter performance factors but lack electronic tunability. However, the circuit possesses low output impedance making the circuit suitable for cascading. The filter implements different filtering function depending upon inputs. The quality factor Q can be tuned by changing two resistors independent of pole frequency. In Reference [47] the authors proposed a filter using four OTAs and two

GCs. The filter has four inputs and three outputs. The filter implements various filtering functions for different inputs. Four MI-OTAs (Multi-Input OTA) based filter having seven inputs and a single output is presented in Reference [48]. Filter also uses two grounded capacitors. The circuit offer electronic tunability to performance factors independently. The input and output impedances are high. The filter implements eleven filtering functions depending upon inputs chosen. The implemented filtering functions are LP, BP, HP, BR, and their inverting versions, and AP. One more filter based on two LT1228 devices, two GCs, and five resistors having one input with low impedance is presented Reference [49]. The filter has three inputs. Filter is capable of offering electronic tunability to pole frequency only. The impedances of the filter are low for some outputs and high for other outputs. In Reference [50] two filter configurations are proposed based on VD-DIBAs, GCs, and resistors. The circuit employs two active devices and four passive components (two capacitors and two resistors). One topology is having one input and provide four outputs. The second configuration is of TITO type (three inputs and three outputs). The filter offers electronic tunability to pole frequency only. The input impedance is high while offer low impedance only for LPF, while for HPF, BRF, and BPF the impedance is high. Five OTAs and two GCs having four inputs is presented in Reference [51]. The filter is having one output. Filter offers electronic tunability to filter performance filters in non interactive manner. Input and as well as output impedances of the filter is high. Three DDTA and two GCs having four inputs and five outputs with, high output and input impedances, is proposed in Reference [52]. The filter offers electronic tunability to filter performance factors. Configuration is capable of realizing five LP and HP filtering functions, nine BP filtering functions two each of BS and AP filtering functions. The filter is capable of realizing both non-inverting and inverting filtering functions. The filter implement filtering functions depends upon the choice inputs.

Reference [53] reports CFOA based SITO type filter. The circuit has CFOAs three in number, four resistors, and two GCs. The filter realizes LP, HP, and BP filtering functions simultaneously. However, the circuit lacks independent electronic tunability of filter performance factors but offers gain adjustment to filtering functions independent of other two factors such as quality factor and pole frequency. Filter configuration having three inputs, using two LT1228, four resistors, and two GCs is depicted in Reference [54]. Topology is having one output. The filter realizes all filtering functions. The filter offers electronic tunability to pole frequency but lacks independent tunability. The circuit reported in Reference [55] is similar to that of the Reference [52] but having eight inputs and five outputs. The filter implements as many as thirty six filtering functions including non-inverting and inverting. Eight LP, ten BP, seven HP, five BS and six AP filtering functions is implemented by the filter. Two LP, two BP, two HP, three BS and two AP filtering functions have the gain adjustment.

One more filter based on CFOA is proposed in Reference [56], here five CFOAs and two GCs, and as many as six resistors are used. The circuit implements all the filtering functions simultaneously. The filter parameters are independently tunable but lack electronic tunability. In the Reference [57] authors proposes two MI-transconductor (MI-Gm) based filters, one employs five Gm cells and two GCs. This filter has five inputs and three outputs, the filter implements all filtering functions depending upon the choice of inputs. The other circuit employ three MI-Gm cells and two 2GCs. The filter has six inputs and three outputs. This version also implements all filtering functions. Both the filters have high input and output impedances. Five OTAs and two GCs filter having four excitations and a single response is presented in Reference [58]. Filter implements all filtering functions and offer electronic tunability to pole frequency. The input and output impedance of the circuit is high. The circuit described in Reference [59] has a single input, uses three LT1228, and five outputs. The filter realizes LPF, HPF and BPF simultaneous at three outputs. While at other two outputs realize BPF and LPF whose gain is independently tunable. The filter can simultaneously generate HPF, BPF, and LPF second order transfer functions. The filter permits the orthogonal tunability of its performance factors. The filter has high input impedance appropriate for cascading voltage input stages and low impedance outputs allow cascading voltage output stages for HPF, BPF, and LPF responses. This research article Reference [60] corresponds to four input and one output configuration based on three VDTAs and two GCs. The filter realizes all filtering tasks depending upon inputs. The input as well as output impedances are high. The circuit performance factors are independently tunable through the bias currents of VDTAs. The research paper presented in Reference [61] use two MI-DDTA along with two GCs. The circuit has six input terminals and two output terminals. The circuit implements all inverting and non-inverting filtering functions two at a time. The filter performance factors are electronically tunable but lack independent tunability features.

### 2.2.2. Current mode filters

In this subsection CM filters are presented. The references are from [62]-[81]. At the outset a filter Reference [62] proposed by the authors is of three input and single output (TISO) type using gain-control voltage difference current conveyor (GC-VDCC) is presented. The filter implements all generic filtering functions, by suitably choosing inputs. The filter performance factors such as quality factor, gain, and pole frequency, are independently tunable. The filter reported Reference [63] uses two CDTAs and two GCs. The filter is TISO type. The filter realizes all filtering functions by choosing inputs. The filter provides electronic tuning to pole frequency, and quality factor. However, lacks independent tunability. In this filter Reference [64], the authors proposed one input and multi output filter using one multi-output current follower amplifier (MO-CFA), two balanced operational transconductance amplifiers (BOTA), one multi-output OTA, and a single transimpedance amplifier. The passive elements used are two GCs. The filter implements three basic filtering functions simultaneously. The other two filtering function are obtained by tying the outputs for example tying of HP and LP output currents give band stop (BS) filtering function while tying of LP, BP, and HP together, all pass filtering function is realized. The filter performance factors are electronically tunable through transconductance gains of respective elements. The input as well as output impedances are suitable for cascading purpose. The circuit proposed in this Reference [65] employs two CFTAs, two GCs, and a single grounded resistor. The circuit provides LPF and BPF functions at high impedance while HPF is taken along the grounded capacitor. The filter needs an additional active device to have an HP current at high impedance. The pole frequency is electronically tunable by the CFTA's transconductance gain, while the quality factor can be varied through the grounded resistor without disturbing pole frequency. Two Current conveyor third generation (CCIII) and a single three output OTA based filter is proposed in Reference [66]. The circuit uses two grounded capacitors and one grounded resistor. One of the CCIII is dual-output, and the other is triple-output. The circuit implements three filtering functions simultaneously while as other two can also be obtained by connecting the appropriate nodes. The transconductance gain of the OTA can adjust the pole frequency, while the quality factor can be controlled by the resistor. The circuit possesses low input and high output impedances. Reference [67] pertains to three input CM filter and has three outputs. The filter is based on a single CFTA, and two GCs. The CFTA is slightly modified to obtain double transconductance gain. The filter has the feature of either using it as a one input and three outputs or three inputs and single output configuration. Both types of filter realize basic filtering functions. In SITO, the filter realizes three basic filtering functions, HP, LP, and BP simultaneously. Though the filter possesses the features of electronic tuning but lacks independent tunability features. In this circuit Reference [68] the author proposes a single input and four output CM filter using triple-output CCII, triple-output OTA, and a single five-output OTA along with two GCs. The filter implements four filtering functions viz. BS, LP, BP, and HP simultaneously. The filter performance factors are electronically tunable. However, it lacks independent tunability features. In this Reference [69] the authors proposed a filter circuit using two DO-OTAs and a single CCIII besides two GCs, and a resistor. The circuit has a single excitation and three responses. The LP and BP filtering functions are at high impedance while HP is taken along a grounded capacitor. The bias current of OTAs controls the pole frequency while the quality factor is changed by changing the grounded resistors. Reference [70] pertains to the single input filter circuit employing a single DO-CCIII, single output CCIII, and one DO-OTA. The passive components used are two capacitors, and a single resistor which are all grounded. The filter has three outputs at high impedance. The pole frequency is electronically tunable, while quality factor depends upon resistor. The circuit lacks independent tunability. Single input and three output filter operating in CM using one each of DO-CCIII, DO-OTA and triple output OTA along with two GCs is presented in Reference [71]. The filter provides three basic filtering functions simultaneously. The other two can be obtained by connecting respective outputs. Transconductance gains of OTAs are used to tune the filer performance factors. Authors proposed a filter using one active element viz. current controlled current difference transconductance amplifier (CCCDTA) and two grounded capacitors Reference [72]. Topology has a single input and three outputs. Low pass output is available at high impedance while other two filtering functions HP and BP currents are taken through grounded capacitors. The filter provides electronic tunability to pole frequency and quality factor in an independent fashion. The filter uses parasitic input resistance of CDTA which eliminates the need for resistors. The same filter can be employed to operate in VM also. The filter realizes all filter functions by choosing inputs. The filter presented in Reference [73] is a single input and three outputs and uses one DO-VDBA, two GCs, and two resistor, (one is grounded and other is floating). The filter realizes LP, BP ad HP filtering functions simultaneously. The currents are taken along grounded passive components. For cascading the circuit need high output impedance and thus needs additional active devices to retrieve the currents at high impedance. Further, the circuit possesses independently tunability features to the pole frequency and quality factor. Two inputs and five outputs filter using two current controlled current follower transconductance amplifier (CCCFTA) and two GCs based filter having is proposed in this research paper Reference [74]. CCCFTA is of multi-outputs. The filter realizes all the five basic filtering functions at high impedances. The pole frequency and quality factors are tunable in an independent manner. Besides the circuit provides sinusoidal signals two in CM and two in VM which are in $90^0$ phase difference. Single input and three output filter using three multi-output current controlled current conveyor second generation (MO-CCCII) and two GCs is discussed in this Reference [75]. The input impedance is low and the output impedance is high and is suitable for cascading. The filter provides HP, LP, and, BP filtering functions simultaneously. BR and AP filtering functions can be obtained by tying respective current outputs. The filter performance factors are electronically and independently tunable. Single DV-EXCCCII, one grounded resistor, and two GCs is proposed in this Reference [76]. The filter has TISO type. The circuit implements AP, BR, HP, BP, and LP filtering functions depending upon the choice of input currents. The performance factors of the filter are electronically tunable, but lack independent tunability. Reference [77] corresponds two inputs and a single output filter using one four terminal floating nullor transconductance amplifier (FTFNTA). The filter uses as many as six admittances. The filter realizes only LP, BP, and HP filtering functions one at a time depending upon the choice of admittances and input. The number of admittances used for each filtering function is four. The filter performance factors are electronically tunable only for HP and BP filtering functions. In this research paper, the filter circuit proposed uses two VDCCs (multi-output), two GCs, and three resistors Reference [78]. The circuit implements three basic filtering functions all at high impedances. The other two functions viz. BS and AP functions are obtained by providing more outputs to the respective VDCC. The filter performance factors are independently adjustable. The filter reported is single input and three output type and employ two EXCCTA and two GCs Reference [79]. The filter implements three basic filtering functions simultaneously. The output impedance is high. The filter lacks electronic independent tunability of pole frequency and quality factor. The authors proposed a single input and three output filter using MO-VD-DXCC, two GCs, and two grounded resistors Reference [80]. The filter implements three filtering functions LP, BP, and HP simultaneously. The filter provides all outputs at high impedance. The circuit parameters are tunable independently in an orthogonal manner. However, Q is tunable by the grounded resistors. In this research paper, the author proposed a filter having three inputs and a single output Reference

[81]. The filter employs a single DV-EXCCCII and two grounded capacitors. The filter realizes all filtering functions by choosing inputs. The filter performance factors are electronically tunable through bias current of DV-EXCCCII. However, it lacks an independent tuning facility for quality factor and pole frequency.

### 2.2.3. Transadmittance mode filters

Transadmittance mode filters are presented in this subsection from references [82]-[87]. In this paper, the authors proposed a transadmittance filter having three inputs and a single output (TISO) Reference [82]. The filter is based on three CFTAs and two capacitors. The filter realizes all filtering functions by simply choosing inputs. However, the filter has low input impedance for BPF and HPF functions. While for LPF it is high. The output current is available at high impedance thus making the circuit cascadable. The filter lacks independent tunability of pole frequency and quality factor. TAM filter using two DVCCTAs, two GCs, and three grounded resistors is proposed Reference [83]. The circuit demonstrates high input and output impedances. It simultaneously achieves Low Pass Filter (LPF), Band Pass Filter (BPF), and Band Reject Filter (BRF) functions. However, other two functions BPF and APF are obtained by tying suitable terminals. The filter offers electronic tunability of pole frequency and quality factor in an orthogonal manner. Three inputs and a single output filter using three VDCCs, two GCs, and three grounded resistors is proposed Reference [84]. The filter provides all filtering functions by suitable choosing the inputs. The filter performance factors are adjustable independently. The input and output impedances are high. The filter proposed uses three five-output operational floating current conveyor (OFCC), two GCs, and three grounded resistors Reference [85]. Although the circuit provided all five filtering functions simultaneously, the circuit is complicated due to the presence of five outputs of OFCC. All the passive devices are grounded making it amenable from the fabrication point of view. Both input and output impedances are high. The filter parameters are independently tunable. Voltage Differencing Current Conveyor (VDCC), based universal filter employing and all grounded passive elements is proposed Reference [86]. The proposed circuit realizes LP, BP HP, BR, and AP. The input and output impedances are high. The circuit in addition to independent gain adjustment, offer orthogonal tunability of its quality factor and pole frequency. A novel circuit using modified current controlled current conveyor transconductance amplifier (M-CCCCTA) and implement all five standard filtering functions is presented Reference [87]. The filter is based on two M-CCCCTAs and two GCs only. The input and output impedances are high. The filter has the facility of realizing all filtering functions. The filter parameters pole frequency, quality factor, and pass band gain are electronically tunable in an independent manner.

### 2.2.4. Transimpedance mode filter

This subsection deals with the transimpedance mode filters from references [88]-[89]. The circuit employs one DVCCTA, two GCs, and two grounded resistors Reference [88]. The circuit has one current input and four voltage output nodes. The circuit implements LP, HP, BP, and BR filtering functions simultaneously. The filter performance factors are independently tunable. The input and output impedances are high. In this research paper, the authors propose six MOS-C based band pass filters Reference [89]. The circuit uses two to five MOS transistors. Also, two capacitors are used. The entire configurations realize BPF functions.

### 2.2.5. Mixed mode filters

In this subsection mixed mode filters are discussed and the references included are from [90]-[104]. Filters that implement more than one type of filtering function from the same topology are referred to as mixed mode filters (MM filters). Some of the filters realize all four types while some filters realize only two types of filter functions. In Reference [90] the filter proposed uses a versatile active element Dual X Current Conveyor Differential Input Transconductance Amplifier (DXCCDITA). The filter uses two capacitors and two resistors. The filter operates in CM, VM, TAM and TIM depending upon the choice of inputs. The circuit has three voltage inputs and five current inputs. The filter realizes all filtering functions in CM, VM, and TIM while for TAM the filter implements only HP and BP filtering functions. The filter's pole frequency and quality factor can be adjusted electronically. The filter provides low input impedance for voltage signals as well as for current inputs. Both voltage and current outputs are available at high impedances. The filter employs five OTAs and two GCs Reference [91]. The circuit has four voltage and three current inputs. The circuit has a single voltage and a single current output. The circuit realizes two filtering functions either in CM, VM, TAM, and TIM simultaneously. The filtering functions depend upon the choice of inputs. The input and output terminals are at high impedances. The filter's performance factors are independently tunable. Here author introduced a filter circuit using single output three OTAs and two GCs Reference [92]. The circuit has three voltage and current inputs and a single voltage output. To provide current output fourth transconductance which converts the voltage signal into the current signal is placed at the voltage output terminal. The filter implements all filtering functions viz. LP, BP, HP. BR, and AP filtering functions from the same topology in VM, CM, TIM, and TAM. The filter performance filters are tunable through the transconductance gain of respective OTAs. In this proposed filter three CDTAs, two resistors, and two GCs, have one voltage and one current input (SITO) Reference [93]. The filter has three voltage outputs and three current outputs. The LP and HP current signals are available at high impedance while BP is taken along a grounded capacitor. The filter realizes basic filtering functions LP, BP, and HP simultaneously. The filter lacks independent tunability of its performance factors but have the features of electronic tunability. The input impedance for the current signal is low but for voltage input, it is high and voltage outputs are at high impedances. The filter presented uses three DDCCs, four resistors, and two GCs Reference [94]. The filter has three current inputs and voltage inputs all at high impedances. The circuit features a solitary high-impedance current output and four voltage outputs. The circuit realizes all filtering functions in all the four modes. The filter performance factors are electronically tunable but not an in independent fashion. The filter employs five OTAs and two GCs Reference [95]. The filter has three voltage and current inputs, and a single voltage and current output. The filter realizes all filtering functions. The input and output impedances are high. The filter performance factors are tunable electronically in an independent fashion. The filter uses a single VDGA, two resistors, and two GCs Reference [96]. The filter has one current and voltage input and has three voltage and current outputs. The currents are taken along passive components. The input impedances and output impedances are high. The filter executes all filtering functions in all four modes. The filter performance factors are tunable in an independent way. The circuit uses one VD-EXCCII, two capacitors (one grounded), and as many as three resistors reported in Reference [97]. The circuit has three voltage inputs and current inputs and provides VM output, TIM output, and CM/TAM outputs. This circuit is capable of realizing three filtering functions simultaneously in three different modes. The circuit parameters are tunable in an independent manner. In this filter, a single FTFNTA, two capacitors (one grounded), and a single resistor having a single voltage and current input is presented Reference [98]. The circuit performs all filtering functions across its four modes. However, the currents are taken along passive components except for the LP function. The performance factors are not tunable independently. In this research paper Reference [99] the authors proposed two filters structure one filter operating in VM and TAM and other filter operates in CM and TIM. VM and TAM filter employs three VDBAs and two capacitors (one grounded). The filter has three voltage inputs while as one voltage and two current outputs. The filter realizes all the filtering functions in VM and TAM mode. The other filter which operates in CM and TIM uses three VDBAs, two GCs, and a grounded resistor. This filter has three current inputs and one current and voltage output. This filter also implements all filtering functions in CM and TIM. For both the filters pole frequency and quality factors are independently tunable. The filter reported in Reference [100] uses three VDBAs, two GCs, and a single resistor. The filter has three voltage inputs and four current outputs. The filter has voltage and, transimpedance outputs separately, while Current/transadmittance output is available at the single terminal. Filter realizes three filtering functions in three modes simultaneously. The filter performance factors are electronically tunable in an independently fashion. The circuit proposed in Reference [101] makes use of five DDTAs and two GCs. The circuit has two voltage and current inputs while five voltage outputs and four current outputs. The circuit achieves all filtering functionalities in four different modes. The circuit is capable of realizing nine filtering functions simultaneously. The filter's pole frequency is controllable electronically while the quality factor is controllable by the ratio of capacitors. The filter offers high input impedance for both voltage and current signals. Current output terminals are at high impedance while three voltage outputs are available at low impedance. The circuit presented in Reference [102] is made up of two VD-VDCC, two GCs, and three grounded resistors. The filter has three current and voltage inputs and two outputs. The structure simultaneously executes two filtering functions. The filter performance factors are electronically tunable independently. For VM and TAM modes of operation, the filter has high input impedance. In addition, the CM and TAM responses are available from high impedance terminals. A single voltage differencing gain amplifier (VDGA), one resistor, and two capacitors are utilised in each of the circuit designs for a mixed mode universal filter reported in this article Reference [103]. Three voltage inputs and one current input comprise the proposed circuit. The circuit has two voltage outputs and three current outputs. The filter implements all filtering functions in all modes. The filter performance factors are tunable in an independent manner. One input is having high impedance while one voltage output is low impedance. Similarly, the two current outputs are at high impedance while one current is taken along the grounded capacitor. In this research paper, the author proposed a VM and TAM filter using three DDTAs and two GCs Reference [104]. The filter has seven voltage inputs and three voltage outputs and a single current output. Since the number of inputs are five and three voltage outputs and one current output. The filter realizes the variety of filtering functions in VM, for example nine filtering functions at one output node, fourteen filtering functions at other mode and eleven filtering functions at third node. Similarly eleven filtering functions are obtained at the current output in TAM. The circuit offers electronic tunability to filter performance factors independently.

## 2.3. Filter based on VDTA

This section pertains to the work carried out for the realization of filters using VDTA as an active element. This section is divided into four subsections. In subsection 1, VM filters are presented while in subsections 2, 3, and 4 CM, MM, and first order filters are considered. References are from [105] to [126].

### 2.3.1. Voltage mode filters using VDTA

This paper presents three inputs and a single output voltage mode filter Reference [105]. The filter is based on one VDTA, one grounded resistor, and two capacitors. The filter realizes all filtering functions depending upon the choice of inputs. Two inputs are applied at the capacitors while the third input is at the high impedance terminal of VDTA. The output is at high impedance. The paper pertains to a single VDTA, two capacitors, and a single resistor Reference [106]. The filter has three inputs at low impedance and a single high impedance output. The filter realizes as usual all filtering functions by choosing suitable inputs. The filter's pole frequency is adjusted by bias current of VDTA and quality factor through the resistor. Reference [107] describes filter using one resistor, two capacitors and two VDTAs. Besides realizing quadrature oscillator, the circuit realizes two filtering functions namely LP and BP. The structure has a single input and two outputs all at high impedances. However, the filter offers tunability of gain for both filtering functions. The filter presented in the research paper, is a single input and three outputs, using one VDTA, two GCs, and NMOS transistor which acts as a resistor Reference [108]. The filter realizes three basic filtering functions simultaneously. The pole frequency and quality factor are independently and electronically tunable. In this research article, Reference [109] four inputs and single output universal filter based on three VDTAs and two GCs is reported. The type of filtering functions realized by the filter depends upon inputs chosen. The input impedances are high thus making it cascadable while output impedance is also high. The circuit performance factors are independently tunable through the bias current of VDTAs.

### 2.3.2. Current mode filters using VDTA

The circuit is SITO type having a single input and three outputs Reference [110]. The circuit employs one VDTA and two GCs. The LP is available at high impedance while HP and BP filtering functions are taken through grounded resistors. The filter parameters are tunable through the transconductance gain of VDTA. The filter lacks independent tunability features. Here the authors proposed three inputs and a single output current mode filter using two VDTA and two GCs Reference [111]. The filter is capable of implementing all filtering functions from the same topology. The output current is available at high impedance. The filter performance factors are electronically tunable through the transconductance gain of VDTA in an independent manner. In this circuit, a single VDTA, two GCs, and a grounded resistor is employed Reference [112]. The circuit has a single input and three outputs. The LP output is available at high impedance while BP and HP are taken along the grounded capacitors. The pole frequency is tunable electronically while as quality factor is controlled by a grounded resistor. A novel current mode three input single output (TISO) type universal filter is shown in this study Reference [113]. The proposed filter uses one VDTA and two GCs. The circuit realizes all the generic filtering functions by choosing the inputs. The transconductance gain of the VDTA can be changed to electronically regulate the filter's pole frequency and quality factor. In addition, another useful TISO architecture with orthogonal pole frequency and quality factor adjustment has been developed by slightly altering the proposed filter. One extra VDTA has been added in order to accomplish this. The output impedance is high. The authors proposed three inputs and single output filter operating in CM. The filter employs two VDTAs, two GCs, and two grounded resistors Reference [114]. The output terminal at high impedance facilitates the cascadibility feature to the circuit. The filter parameters are tunable electronically in an independent manner. The gain of all the filtering functions is also tunable electronically. This paper presents a filter structure based on a single VDTA, two GCs, and a grounded resistor Reference [115]. The filter has three inputs and a single high impedance output. The filter realizes all filtering functions by choosing suitable inputs.

The filter parameters are controllable independently by transconductance gain of VDTA and grounded resistor. The filter proposed by the authors makes use of three VDTAs and two GCs Reference [116]. The filter is of SITO type. The filter offers three basic filtering functions simultaneously. The other two viz. BR and AP are obtained by connecting respective outputs. The filter provides LP and BP at high impedance. The filter parameters are tunable in an independent manner.

### 2.3.3. Mixed mode filters using VDTA

In this paper, Reference [117] the author proposed a mixed mode filter using two VDTAs and two capacitors (one permanently grounded) and has three voltage inputs (two inputs at high impedance). The circuit has four high impedance current outputs and one voltage output at high impedance. HPF is obtained by connecting two outputs. The filter offers four filtering functions simultaneously one in VM and three in TAM. The filter performance factors are tunable electronically in an independent manner. In this research note, Reference [118] the authors proposed a TAM filter using two VDTAs and two GCs. The circuit has a single voltage input at high impedance and three current outputs (one output taken along the grounded capacitor). The filter implements three basic filtering functions simultaneously. The filter performance factors are electronically tunable in an independently manner. In this research paper, Reference [119] TAM filter using two VDTAs and two capacitors (one grounded permanently). The filter has three voltage inputs, (one is at the capacitor), and the other two are at the high impedance terminal of VDTA. It has one voltage output, and three current outputs, two at high impedance, and one is taken through the capacitor. The filter realizes all filtering functions in VM and TAM. The filter parameters are electronically tunable in an independent manner. This paper, Reference [120] pertains to TAM having a single voltage input and two current outputs. The filter employs one VDTA, two GCs, and a resistor. One of the outputs is taken along the capacitor and the other outputs are available at high impedance. The filter parameters are tunable electronically. The filter, reported in Reference [121] uses two VDTAs, two capacitors (one permanently grounded), and two grounded resistors. The filter has three inputs two at high impedance and single output at high impedance. The circuit realizes all filtering functions depending upon the choice of inputs. The filter parameters are tunable in an independent manner. In this paper, Reference [122] a single VDTA, two capacitors, and a single resistor based filter is reported. The circuit has a single voltage input and four current outputs namely LP, BP, HP, and BR. However, all outputs are taken along capacitors and resistors except the LPF function. The filter performance factors are tunable through the grounded resistor and the transconductance gain of VDTA in an independent manner. In this presentation, Reference [123] filter based on a single VDTA, three capacitors, and a single resistor having a single current input and a single voltage input is reported. The circuit provides six outputs three in voltage mode and three in current mode. However, the current outputs are taken along the capacitors and resistor. Of course the filter operates in all four modes, but for currents outputs needs additional device to retrieve the currents at high impedance for further processing. The input voltage is applied at the capacitor while as input current is also applied at high impedance. The output voltages are at high impedance. In this research paper, Reference [124] the authors proposed a filter having a single voltage input and three current outputs and three voltage outputs (total six outputs). Thus filter realizes six filtering functions simultaneously, three in VM and three in CM. The circuit employs three VDTAs and two GCs. The input and all output nodes are at high impedance. The filter parameters are tunable through the transconductance gains of VDTAs. The filter reported in this paper, Reference [125] is similar to reported in Reference [122]. There is nothing new, except the filter operates at low voltage.

### 2.3.4. First order filters using VDTA

Survey of the available literature show that only one paper pertaining to first order filter using VDTA is reported. In this publication Reference [126] the authors proposed APF using a single VDTA and a single capacitor. The circuit has a single voltage input and two outputs one is voltage and other is current, thus implementing VM and TAM filtering functions simultaneously. The current output is due to dual output of the second transconductance of the VDTA.

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# Chapter 3: Research gap, methodology and objective

## 3.1 Research Gap

Literature review revel that numerous research papers on the realization of analog filters using different active devices are reported in journals and/or presented in the international conferences. These reported filters use different active building blocks like OA, OTA, CFOA, FTFN etc. However a little work have been carried out for designing filters using recently introduced active device VDTA, especially Mixed-Mode filters. Also it have been observed that the filters using only active building blocks called active-only filters have not been reported which employ VDTA and OA only. The use of OA circumvent the need of capacitor. It is to note that active-only filters have already been designed and are reported in the literature which uses only active devices like OTA, CCCII and OA.

## 3.2. Objectives

1. To realize and study different types of analog filters especially Mixed-Mode (MM), based on newly introduced building block VDTA and capacitors. In addition Pole model of OA will also be used for realization of filters, leading to active-only filter. Realized filters offer following advantages:-

- Electronic tunability to filter performance factors
- low sensitivity figures
- suitable for implementation in IC technology

2. Experimental verification of realized circuits and analysis of their performance factors like- gain, pole frequency, bandwidth, Quality factor by using electronic software.

3. To study the effects of parasitic capacitances and other parasitic factors on the filter performance factors

In this thesis nine filters are proposed, six first order and three second order. All the filters employ minimum number of components and realize more than one filtering functions simultaneously. The four first order filters are active only using VDTA and OA while other two use capacitors and VDTAs. Active only filters are suitable for IC implementation. Fifth filter is based on a single capacitors and one VDTA while sixth filter employ one capacitor, single VDTA and one grounded resistor. The grounded resistor can be replaced by MOSFET lending resistor-less filter.  Thus all the filters are suitable for IC implementation.

The second order filters employ only VDTA capacitors and are devoid of resistors.  The first filter employ one VDTA, a single OA and a single capacitor.  While the other two filters employ VDTAs and grounded capacitors which are suitable for IC implementation.

The gain ($g_m$) of VDTA is electronically tunable.  The filter performance factors thus depend upon the transconductance gain of VDTA thus lending electronically tunability to all the proposed filters.  Also filter performance factors are tunable in an independent but sequential manner which makes the circuit more versatile.

The sensitivity figures of the all proposed filter is low.  For first order sensitivity is unity and for second order it is in between 1 to 0.5.

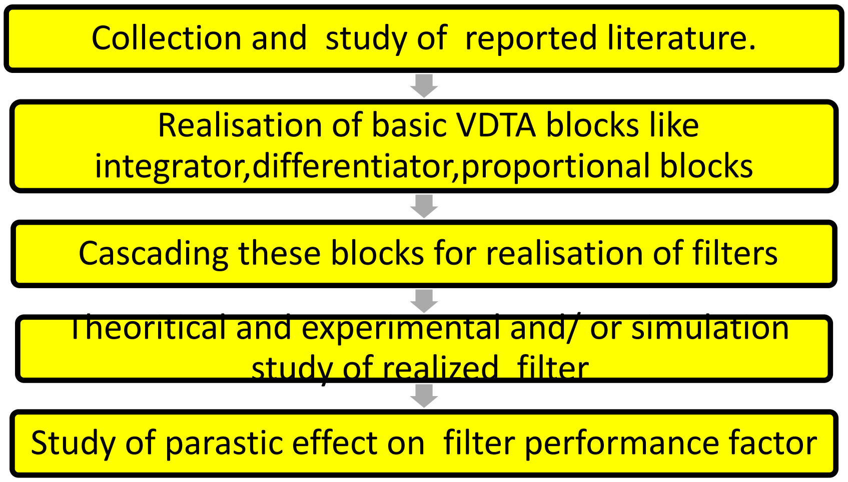
The workability of the filters developed theoretically were checked using PSPICE.  The proposed filters are simulated for a desired pole frequency, quality factor and gain (if any) by choosing the elemental values such as transconductance gain, capacitor and gain bandwidth product of OA.  The simulation results for which the filters are checked include.

1. Gain response or frequency response
2. Phase response
3. Transient response
4. Variation of filter performance factors with bias current (transconductance gain) of VDTA
5. Monte Carlo analysis which shows the effect of variation of filter performance factors when nominal values of device change due to environment, aging, process tolerances.
6. Effect of temperature on the gain and phase frequency response of proposed filters.

The non-ideal behavior of the filters is also discussed, and the effects on filter performance factors are also included.

### 3.3 Methodology

The methodology followed for carrying out the research on the topic is given below in flow chart:-



The building blocks based on the VDTA are discussed in the chapter first. These blocks are suitable cascaded to implement filters. The first order filters use only one integrator figures 1.10 to1.14 which can be either implemented by using VDTA and a capacitor or a single OA through its pole model. The second order use two integrators suitably cascaded to produce filtering action. Also lossy integrators are utilized for the realization of filters. Beside integrators we use proportional blocks as already mentioned in chapter first. These integrators and proportional blocks H (summing amplifier) Figure 1.8 and 1.9 are connected to produce desired filtering functions. For first order filter the block diagram is given below.

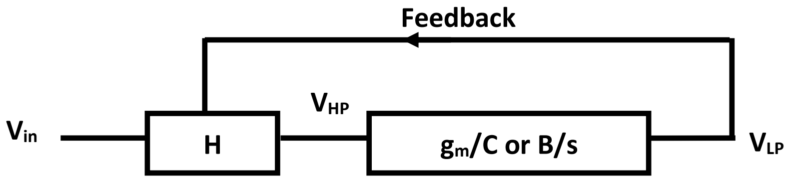


Figure 3.1: Basic building block for implementation of first order filter

For obtaining second order filters in addition to proportional blocks, need two integrator either lossy or lossless. The method used to realize the filters are state variable technique. The filter is capable of realizing basic three filtering functions simultaneously. The block diagram as given below:

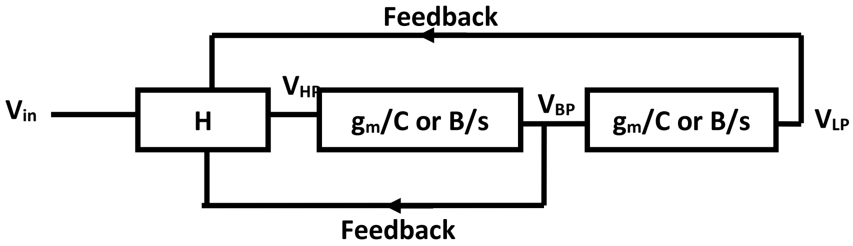


Figure 3.2: Basic building block for implementation of second order filter

# Chapter 4: Proposed first order filters

## 4. Introductions

In this section first order filters which have been realized using VDTAs and other devices like OAs and Capacitors are presented. Six new first order filters are presented. At the outset a new filter that realizes first order HP and LP filter is proposed (published in Indian journal of pure and applied physics). This filter uses a single OA and a single VDTA. The second one which also uses a single OA and VDTA realizes the AP filtering function. The third one uses one OA and two VDTAs. This filter has the advantage of independent gain control. One more APF is proposed but this operates in CM. The filter uses a single OA and a single MO-VDTA. Two more filters operating in VM and TAM are also proposed. These two filters use a single capacitor and a single output VDTA. One of the filter has two inputs and the other filter has a single input but uses an additional grounded resistor. All the proposed filters have low sensitivity figures, equal to one. All the proposed filters have been verified using the PSPICE program. For some of the filters non-ideal and parasitic of the active building block used are also taken into account and the measures to minimize them are given. The port relations for VDTA and the pole model of OA which are discussed in chapter 1 are here again reproduce for reference.

Ideal port relation of VDTA

$$\begin{bmatrix} I_Z \\ I_{X+} \\ I_{X-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} \qquad (1.23)$$

Non-ideal port relation of VDTA:

$$\begin{bmatrix} I_z \\ I_{x+} \\ I_{x-} \end{bmatrix} = \begin{bmatrix} \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ 0 & 0 & \beta_2 g_{m2} \\ 0 & 0 & -\beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} \tag{1.29}$$

$\beta_1$ and $\beta_2$ are slightly less than 1.

Pole model of OA

$$A(s) = \frac{A_0}{1 + s\tau_1} = \frac{A_0\omega_0}{s + \omega_0} \approx \frac{B}{s} \quad \text{for s} >> \omega_0 \tag{1.32}$$

Non-ideal pole model of OA

$$\text{A(s)} = \frac{B}{s}\left[1 - s\left(\tau_2 + \tau_3\right)\right] \tag{1.35}$$

Where $\tau_2 = \frac{1}{\omega_2}$ and $\tau_3 = \frac{1}{\omega_3}$ are second and third poles in the frequency range of interest.

### 4.1. Proposed LP and HP first order filter using pole model of OA

The proposed filter uses only two components one VDTA and a single OA as shown in Figure (4.1.1). The filter input impedance is high while as output impedance for the LP is low and for the HP is high. The filter uses the OA pole model. Using the port relations of the VDTA equation (1.23) and OA equation (1.32). Routine analysis of the proposed filter gives the following transfer functions.

$$\frac{V_{LP}}{V_{in}} = \frac{B^{g_1}/_{g_2}}{s+B^{g_1}/_{g_2}} \tag{4.1.1}$$

$$\frac{V_{HP}}{V_{in}} = \frac{s^{g_1}/_{g_2}}{s+B^{g_1}/_{g_2}} \tag{4.2.2}$$

The natural angular frequency $\omega_0$ is given by:

$$\omega_0 = B\, {g_1}/{g_2} \tag{4.1.3}$$

In terms of bias current, the pole frequency is given by:

$$\omega_0 = B\,\frac{\sqrt{I_{B1}\mu_n C_{ox}\left(\frac{W}{L}\right)_1}}{\sqrt{I_{B2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2}} \tag{4.1.4}$$

$$H_{HP} = {g_1}/{g_2} \tag{4.1.5}$$

It is clear that the frequency is electronically tunable through the bias current of transconductance gains of VDTA. Besides the gain of the HP filtering function is also tunable but the gain cannot be varied without disturbing pole frequency.

The sensitivities of the filter performance factors with respect to various device parameters are given by:

$$S_{g_1}^{\omega_0} = -S_{g_2}^{\omega_0} = S_B^{\omega_0} = 1$$

Which all are unity.

### Non-idealities of OA

Considering the non-idealities of OA described by equation (1.35) and the transfer functions of the proposed LP filter modifies to:

$$\frac{V_{LP}}{V_{in}} = \frac{B\frac{g_1}{g_2} - \left(B\frac{g_1}{g_2}\right)s(\tau_1+\tau_2)}{s\left[1+\left(B\frac{g_1}{g_2}\right)(\tau_1+\tau_2)\right]+B\frac{g_1}{g_2}} \tag{4.1.6}$$

From equation (4.1.6) it is clear that undesirable terms appear in the transfer function due to higher poles of OA. However, these effects can be minimized by satisfying the condition $g_2 >> g_1$.

## Simulations

In order to verify the proposed circuit, simulations were carried out by using PSPICE. VDTA was obtained by cascading two LT 1228 OTAs ($g_{mi} = 10I_i$, $i = 1,2$) and OA LM 741 with gain bandwidth product $B = 2\pi X(1.5)$ MHz is used for simulation. The circuit was constructed for a pole frequency of 150 KHZ. The value of transconductance $g_1 = 1mA/V$ and $g_2 = 10mA/V$. The gain and phase responses of the proposed circuit are shown in Figures (4.1.2) and (4.1.3) for the LP filter and in Figures (4.1.4) and (4.1.5) for the HP filter. Figures (4.1.6) and (4.1.7) show the transient response of LP and HP filtering functions respectively. The input of 1V and 100 KHz sinusoidal signal was used to study the larger signal behaviour of the proposed filter. The applied signal is in the pass band in LPF and the stop band in HPF.

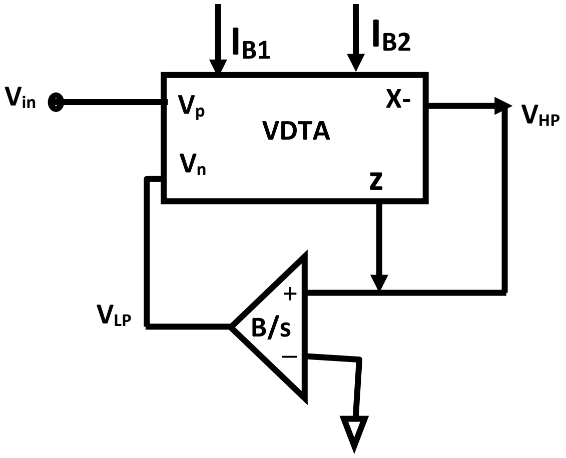


Figure 4.1.1: Proposed LP and HP filter

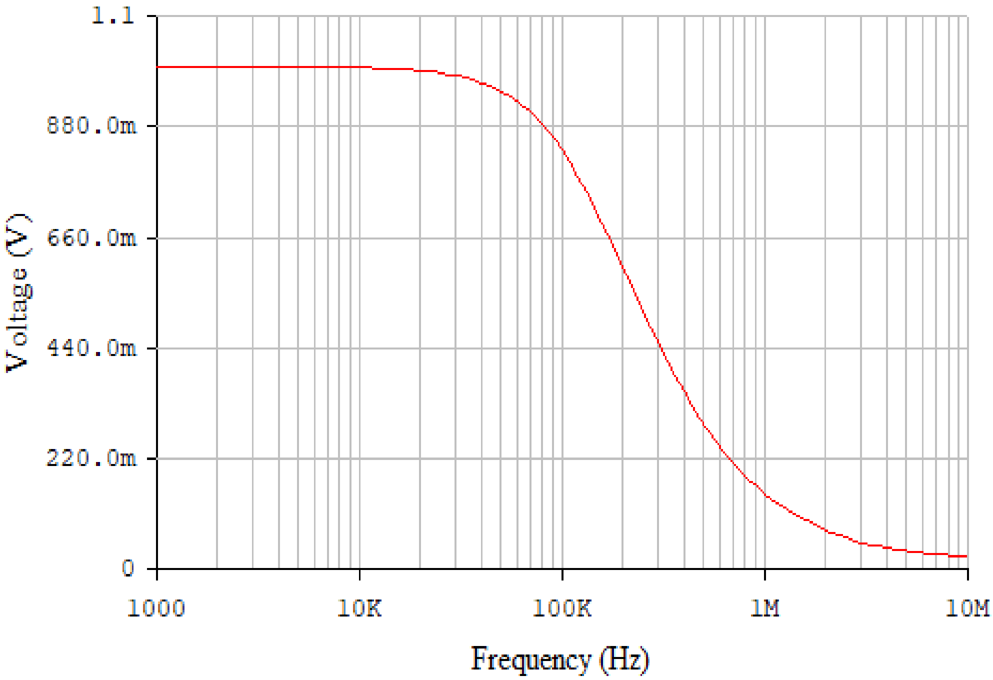


Figure 4.1.2: Frequency response for LP filter

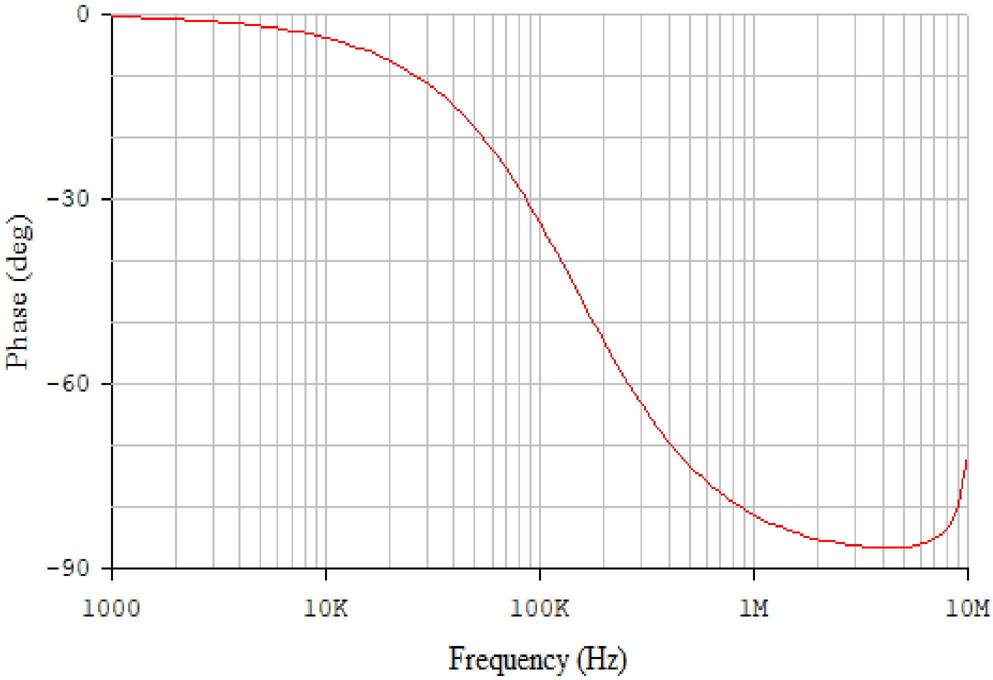


Figure 4.1.3: Phase response for LP filter

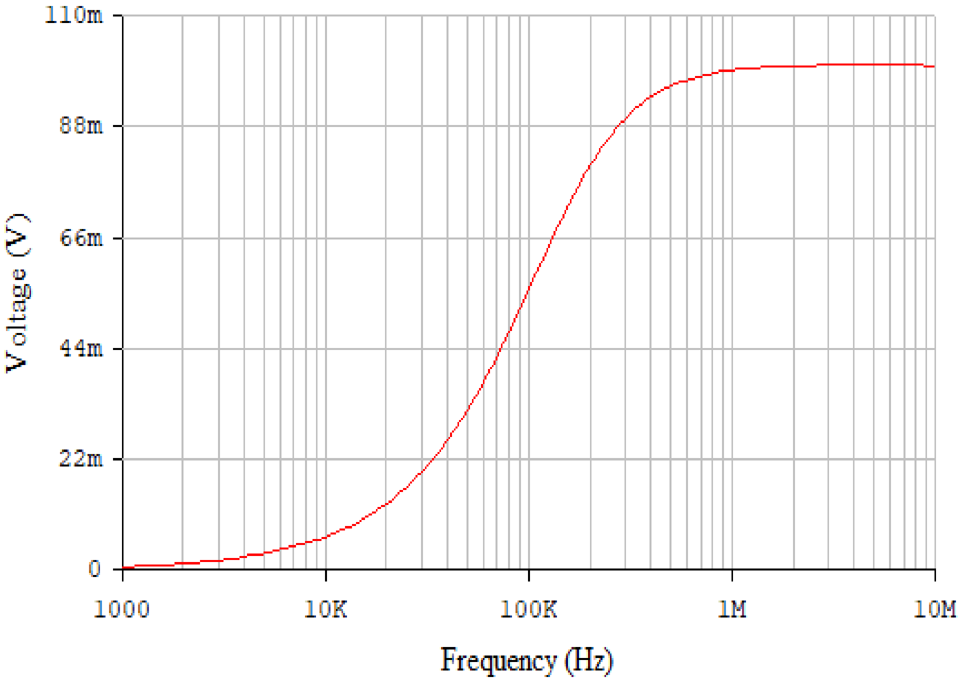


Figure 4.1.4: Frequency response for HP filter

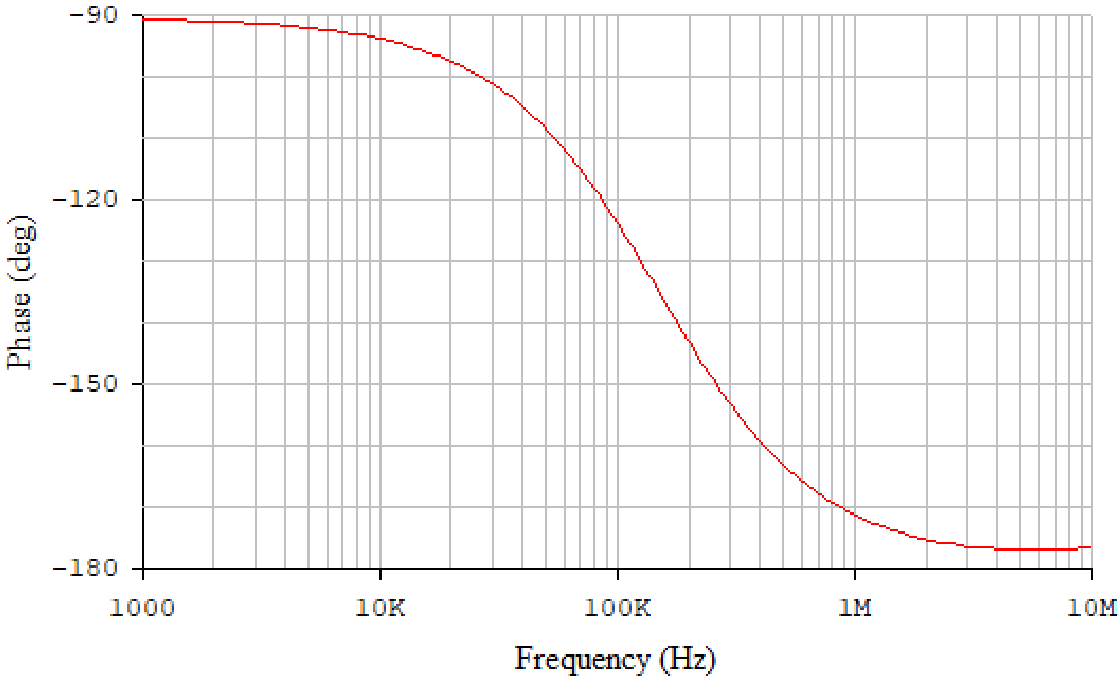


Figure 4.1.5: Phase response for HP filter

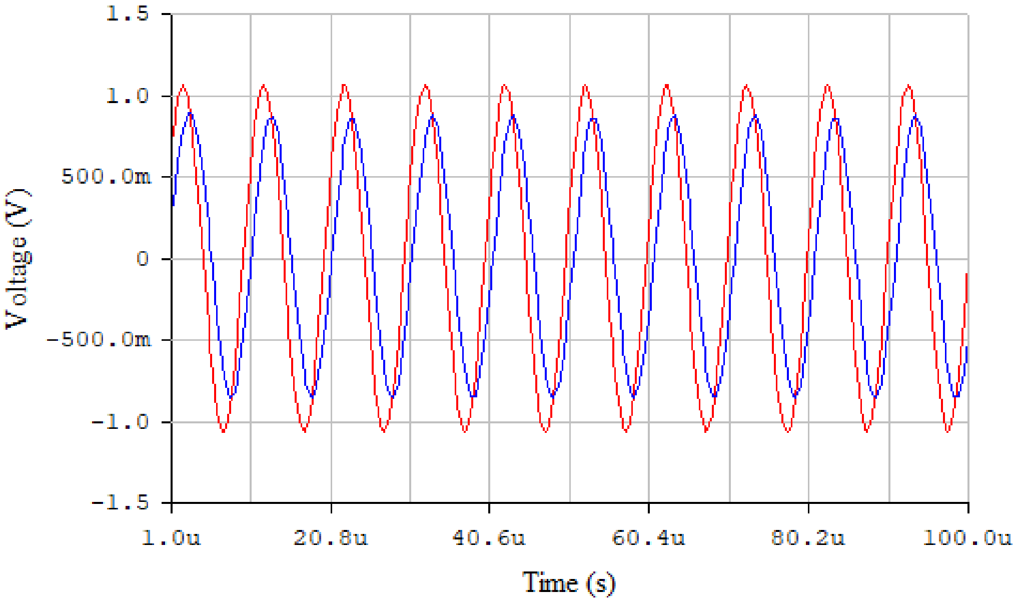


Figure 4.1.6: Transient response for LP filter (Red trace is input and Blue trace is output)

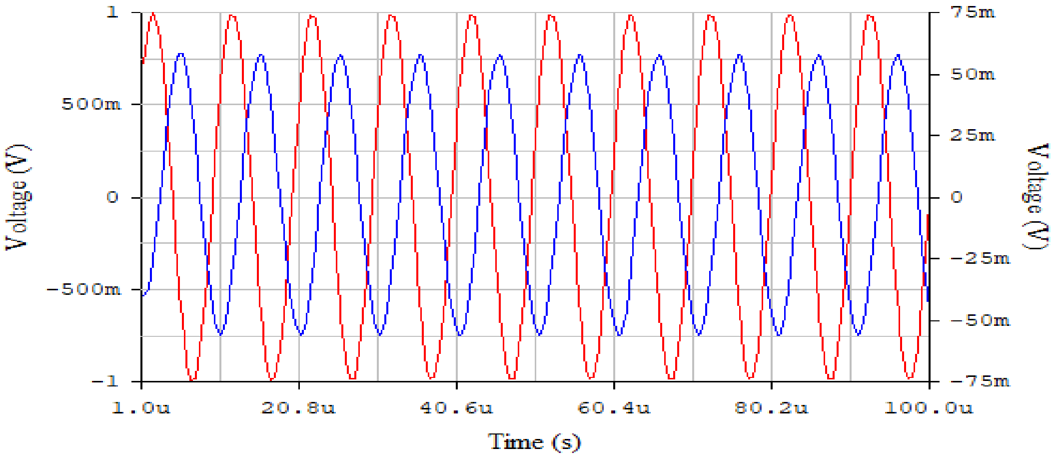


Figure 4.1.7: Transient response for HP filter (Red trace is input and Blue trace is output)

## 4.2 All pass filter using OA and VDTA

The proposed all pass filter employing only a single OA and one VDTA is shown in Figure (4.2). The filter operates in voltage mode. The circuit is coupled with the realizability condition. The routine analysis yields the following transfer function:

$$\frac{V_o}{V_{in}} = -\frac{sg_1 - Bg_1}{sg_2 + Bg_1} \tag{4.2.1}$$

The realization condition for AP is $g_1 = g_2$ The pole frequency $\omega_0$ is given by:

$$\omega_0 = B \tag{4.2.2}$$

The phase response is given by:

$$\varphi = -2tan^{-1}(\omega_0/B) \tag{4.2.3}$$

The bias current of OA can tune the frequency electronically. To make the tuning procedure more versatile the proportional block of gain K is introduced between the non-inverting input terminal $V_p$ (at the point A) of VDTA and the output of OA. The transfer function modifies and is given by:

$$\frac{V_o}{V_{in}} = -\frac{s - KB}{s + KB} \tag{4.2.4}$$

Where $K = g_{p1}/g_{p2}$

$$\varphi = -2tan^{-1}(\omega/KB) \tag{4.2.5}$$

From Equation (4.2.5) it is seen that the frequency can be varied by changing the transconductance gain of proportional block

### Non-idealities of OA and VDTA

Taking the non-idealities of the OA equation (1.21) and VDTA equation (1.15) into consideration the transfer function modifies to:

$$\frac{V_{AP}}{V_{in}} = -\frac{\beta_2 g_2 - \beta_1 g_1 B(\tau_1 + \tau_2)}{\beta_1 g_1 \left(1 + B(\tau_1 + \tau_2)\right)} \frac{s - g_1\left(\frac{B}{(\tau_1 + \tau_2)B + 1}\right)}{s + \frac{B\beta_1 g_1}{\beta_2 g_2 - B\beta_1 g_1(\tau_1 + \tau_2)}}$$

If $g_1 = g_2$ and $\beta_1 = \beta_2$, the above Equation simplifies to:

$$\frac{V_{AP}}{V_{in}} = -\frac{1 - B(\tau_1 + \tau_2)}{\left(1 + B(\tau_1 + \tau_2)\right)} \frac{s - \left(\frac{B}{1 + B(\tau_1 + \tau_2)}\right)}{s + \frac{B}{1 - B(\tau_1 + \tau_2)}}$$

It is seen that the non-idealities of OA and VDTA introduce undesirable terms in transfer function. The sensitivity of the performance factor of the filter is equal to unity.

$$S_{g_1}^{\omega_0} = -S_{g_2}^{\omega_0} = S_B^{\omega_0} = 1$$

## Simulation Results

PSPICE simulation has been used to verify the proposed circuit. In the simulation VDTA is achieved by connecting two LT 1228 OTAs ($g_i = 10I_i, i = 1,2$) LT1228 is an OTA followed by a buffer. LM741 OA with gain bandwidth product B = 2πX (1.0) MHz is used. The circuit is constructed for a pole frequency of 1 MHz with $g_1 = g_2 = 1$ *mV/A*. The magnitude and the phase response of the proposed filter are shown in Figures (4.2.2) and (4.2.3). To check the larger signal performance of the circuit a sinusoidal signal of 500 mV and 1 MHz is used. The simulated response is shown in Figure (4.2.4). To check the tunability of the phase angle the proportional block is introduced in the circuit. The transconductance gain $g_{p1}$ is varied from 0.1 to 0.5 mA/V and the simulation result is shown in Figure (4.2.5). The simulation results confirm the workability of the proposed filter.

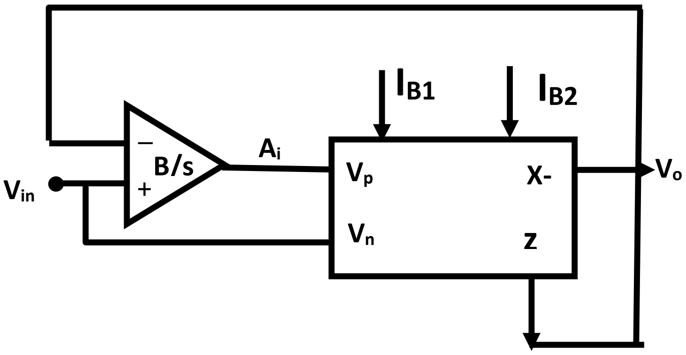


Figure 4.2.1: Proposed all pass Filter

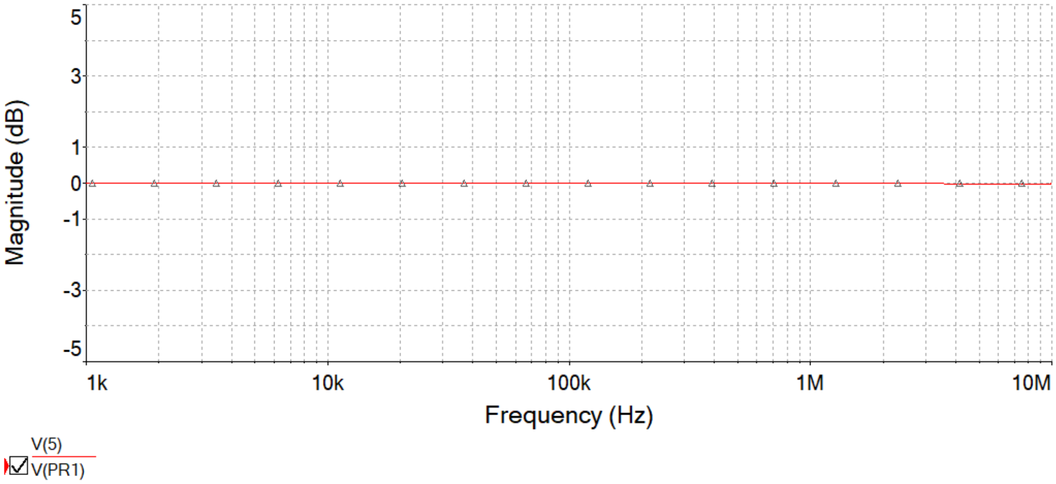


Figure 4.2.2: Gain response of AP filter

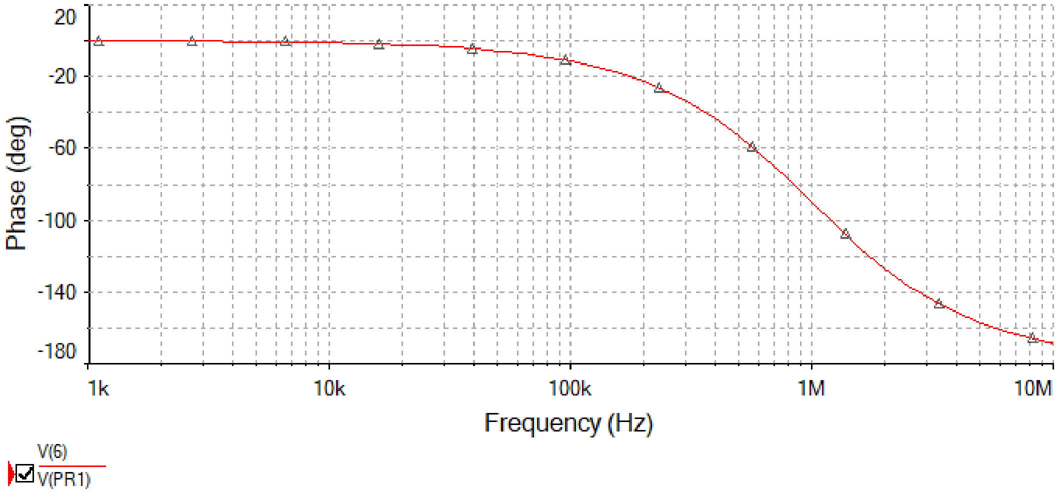


Figure 4.2.3: Phase frequency response

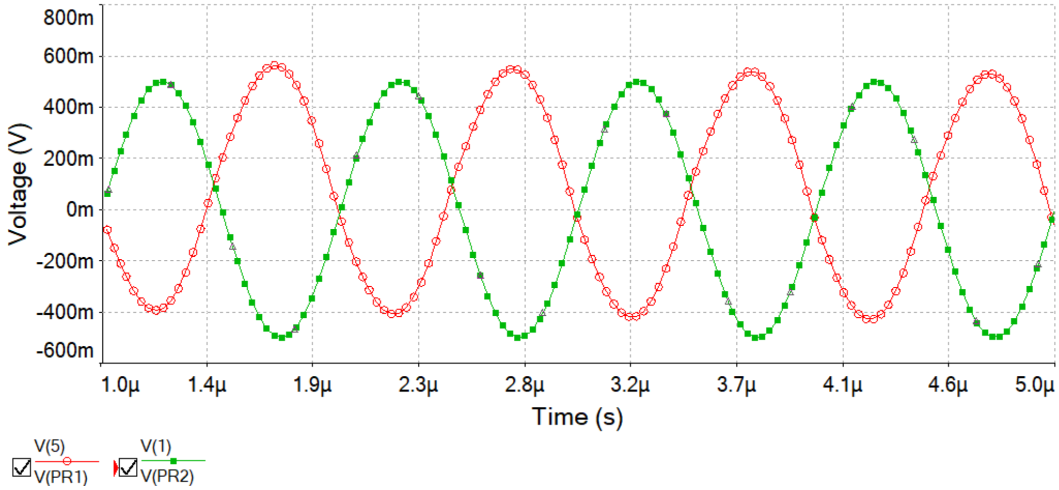


Figure 4.2.4: Transient response (green colour trace is input while as red colour is output signal)

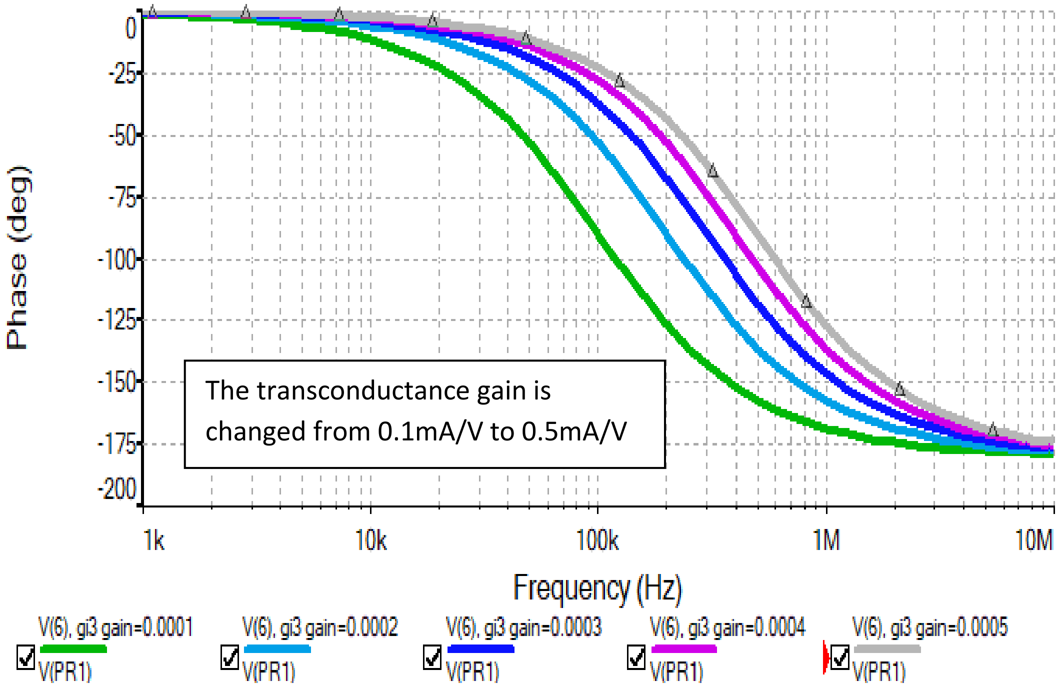


Figure 4.2.5: Variation of Phase with transconductance gain of proportional block

### 4.3 Proposed VM first order universal filter with gain control

In this configuration, novel all pass filter is proposed as shown in Figure (4.3.1). The circuit uses a single OA and two VDTAs, providing LP, HP and AP filtering functions simultaneously. The novelty of the circuit is that its gain can be controlled with the transconductance gain of VTDA. Using the pole model of OA and the characteristic equation of VDTA, the routine analysis gives the following transfer functions.

$$\frac{V_{LP}}{V_{in}} = \frac{B^{g_1}/g_2}{s+B^{g_1}/g_2} \tag{4.3.1}$$

$$\frac{V_{HP}}{V_{in}} = \frac{s^{g_1}/g_2}{s+B^{g_1}/g_2} \tag{4.3.2}$$

$$\frac{V_{AP}}{V_{in}} = -\frac{g_3}{g_4}\left(\frac{s-B}{s+B}\right) \tag{4.3.3}$$

The realization condition for the AP filtering function is $g_1 = g_2$. From equations (4.3.1), (4.3.2), and (4.3.3) it is seen that the filter realizes all the filtering functions simultaneously. The pole frequency is given by

$$\omega_0 = B \tag{4.3.5}$$

gain H is given by $H = \frac{g_3}{g_4}$ (4.3.6)

phase angle for AP filter is given by is given by

$$\varphi = -2tan^{-1}(\omega/B) \tag{4.3.7}$$

Equation (4.3.6) shows that the gain of AP can be tuned by the transconductance gain $g_3$ or $g_4$. The pole frequency equals to gain bandwidth product of OA. The sensitivities are equal to 1.

$$S_{g_1}^{\omega_0} = -S_{g_2}^{\omega_0} = S_B^{\omega_0} = 1$$

$$S_{g_3}^{H} = -S_{g_4}^{H} = 1$$

### Simulation Results

To verify the theoretical results PSPICE simulations are carried out. As usual, VDTA has been implemented by cascading two LT1228s. The filter is constructed for a pole frequency of 1 MHz. The operational amplifier used is LM 741 with gain bandwidth product B = $2\pi$ X(1.0) MHz. The transconductance gains chosen are 1 mA/V ($I_{bias}$ =100 uA). The simulation results are shown in Figures (4.3.2) to (3.4.10). Figures (4.3.2) to (4.3.5) correspond to gain frequency and phase frequency responses for LPF and HPF respectively. Figures (4.3.6) and (4.3.7) show the gain frequency and phase response of the APF. Similarly, the Transient response obtained for an input signal of 100mV at 1 MHz frequency is depicted in Figure (4.3.8). Figures (4.3.9) and (4.3.10) show the variation of gain of the AP filter concerning change in transconductance gain $g_3$ in frequency and time domain. The transconductance gain changed from 1.5 mA/V ($I_{bias}$ 100 - 500 uA). To check the effect of the variation in the values of components on the performance of the filter, Monte Carlo (MC) statistical analysis of the filter at pole frequency 1 MHz was carried out with 10% tolerance of transconductance gains. Figures (4.3.11) and (4.3.12) show the MC simulation results of the filter’s gain and phase responses for 50 random runs with uniform distribution. The results suggest that the effects on filter performance are small. To check the influence of temperature on the filter performance factors, the temperature is varied from $20^o$ to $80^o$ C in steps of $15^o$C, Figures (4.3.13) and (4.3.14) show the simulation results for gain and phase responses.

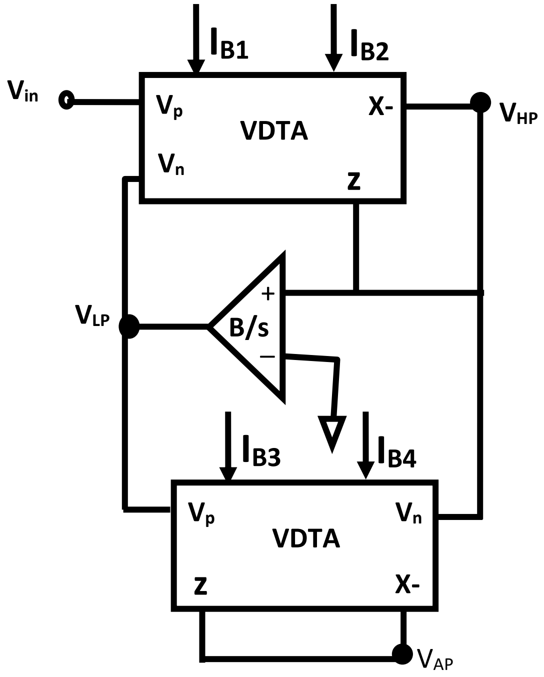


Figure 4.3.1: proposed FOUF

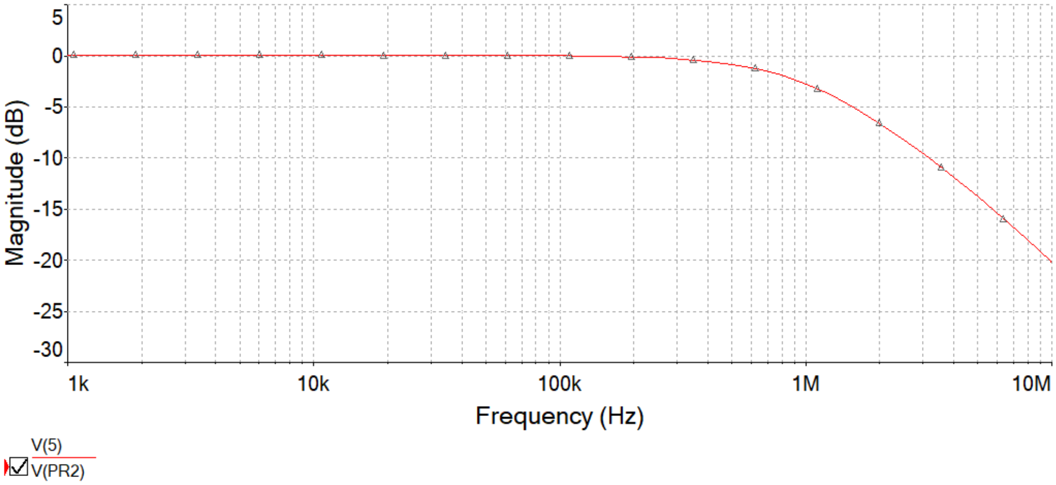


Figure 4.3.2: Frequency response of LP filter

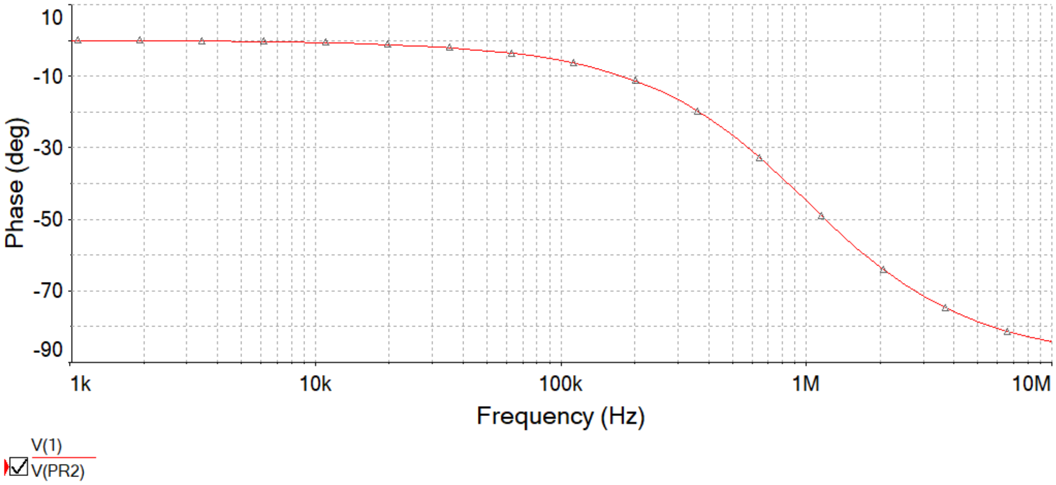


Figure 4.3.3: phase response of LP filter

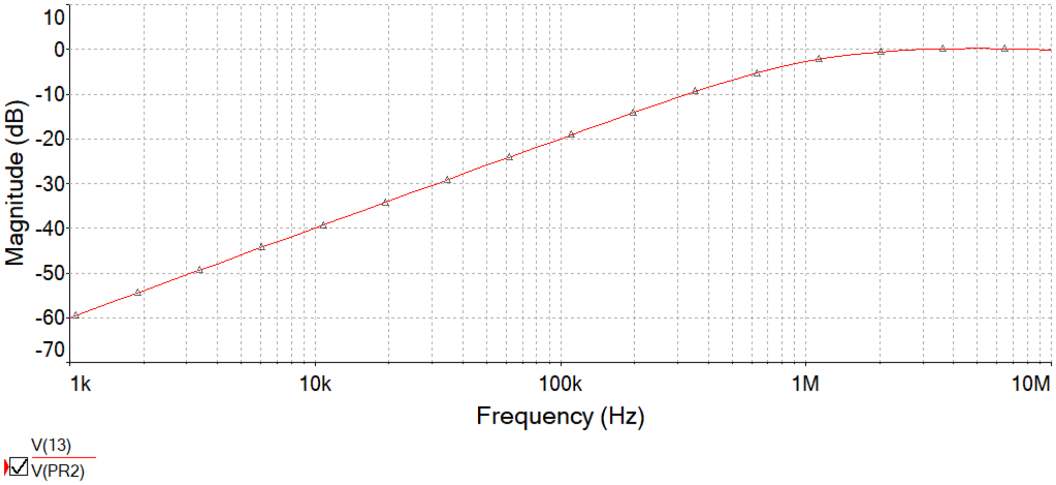


Figure 4.3.4: Frequency response of HP filter

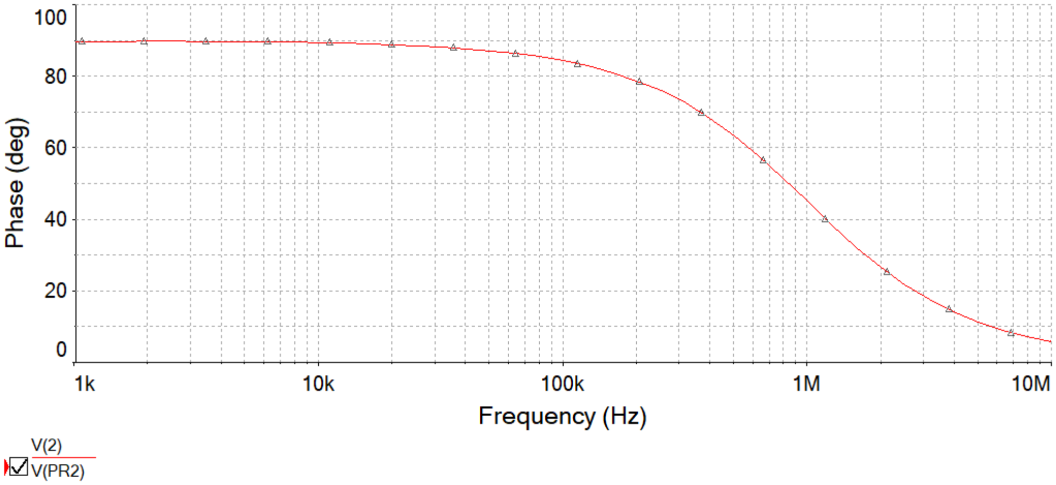


Figure 4.3.5: Phase response of HP filter

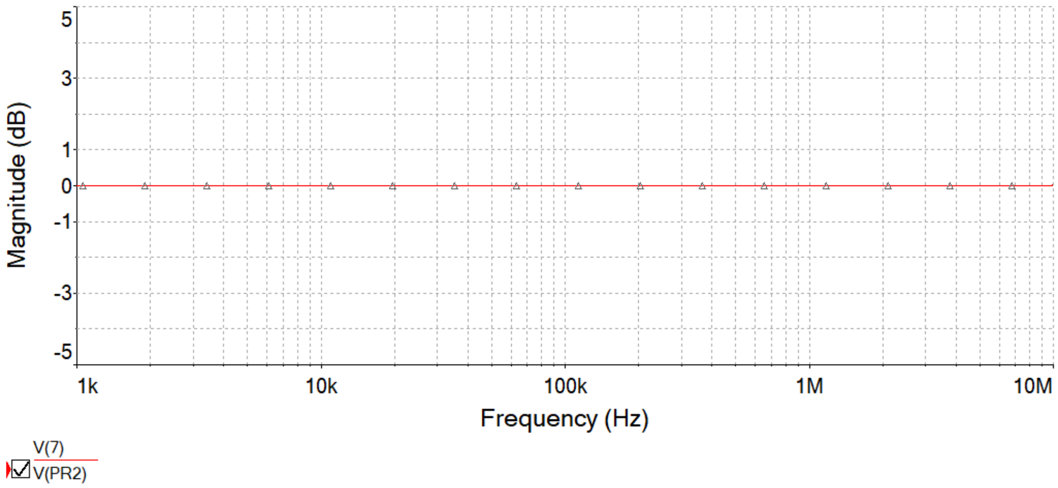


Figure 4.3.6: Frequency response of AP filter

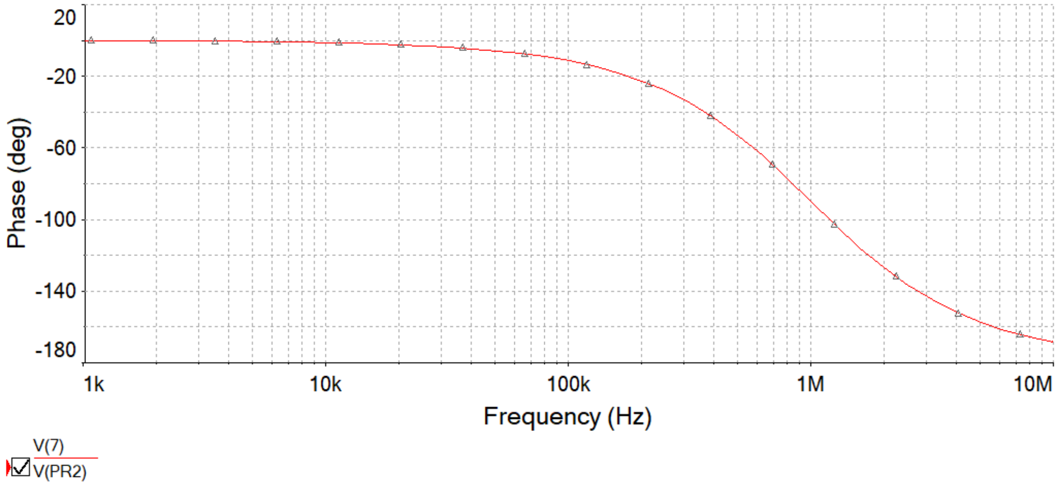


Figure 4.3.7: Phase response of AP filter

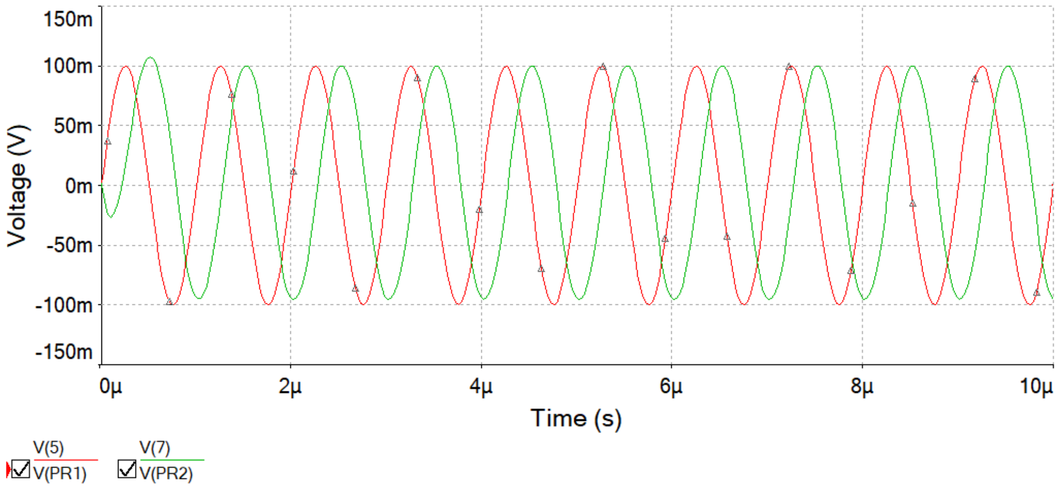


Figure 4.3.8: Transient response of AP filter obtained with input signal 100mV peak to peak and frequency 1 MHz.

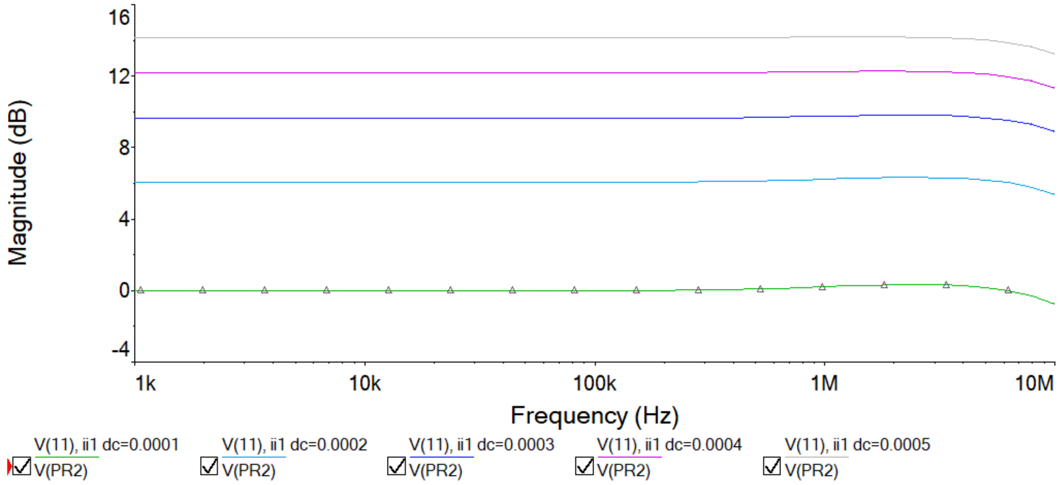


Figure 4.3.9: Variation of gain of AP filter in frequency domain

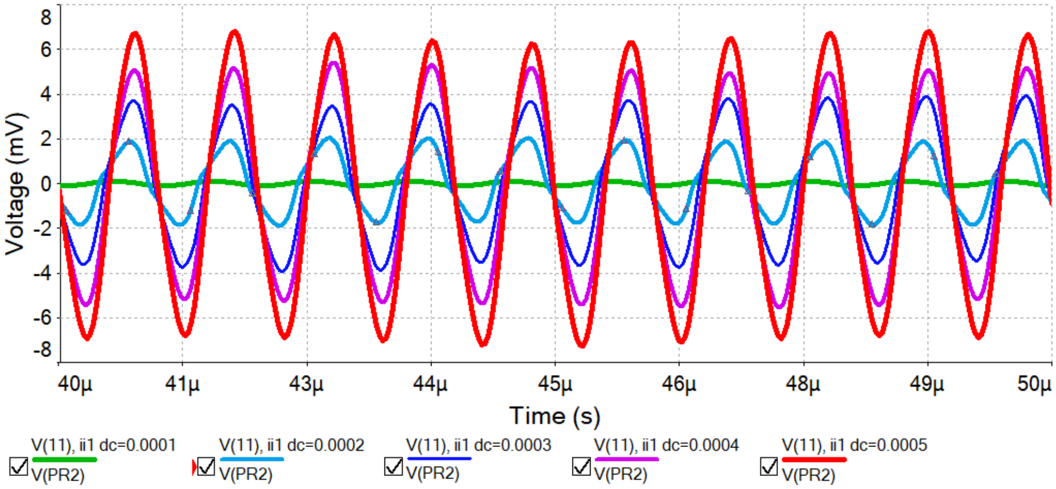


Figure 4.3.10: Variation of gain of AP filter in time domain

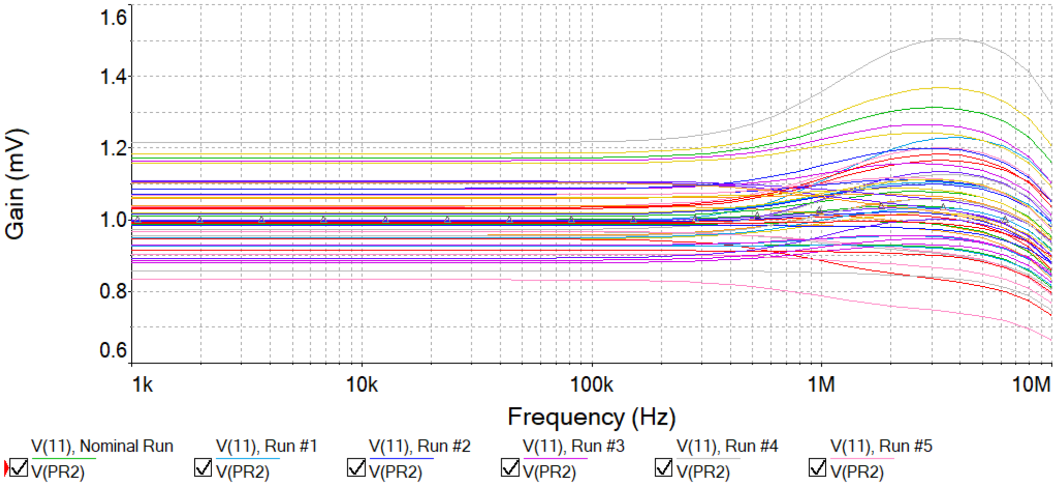


Figure 4.3.11: MC analysis (10% and uniform distribution) of gain response

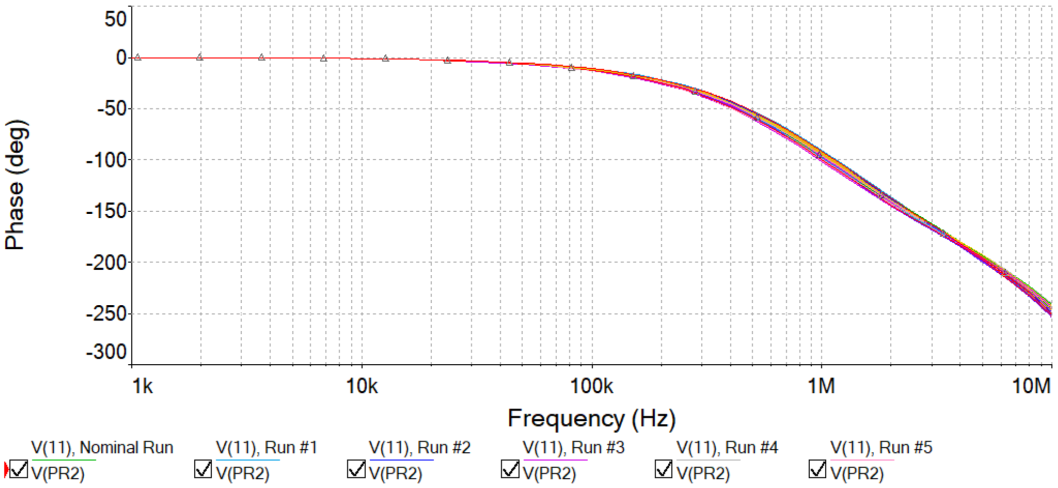


Figure 4.3.12: MC analysis of phase response

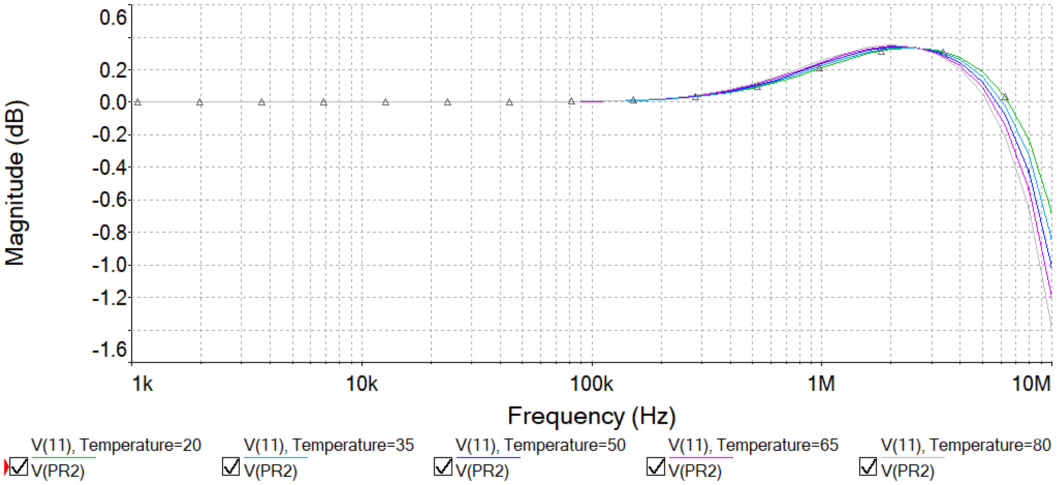


Figure 4.3.13: Frequency response of AP filter at different temperature

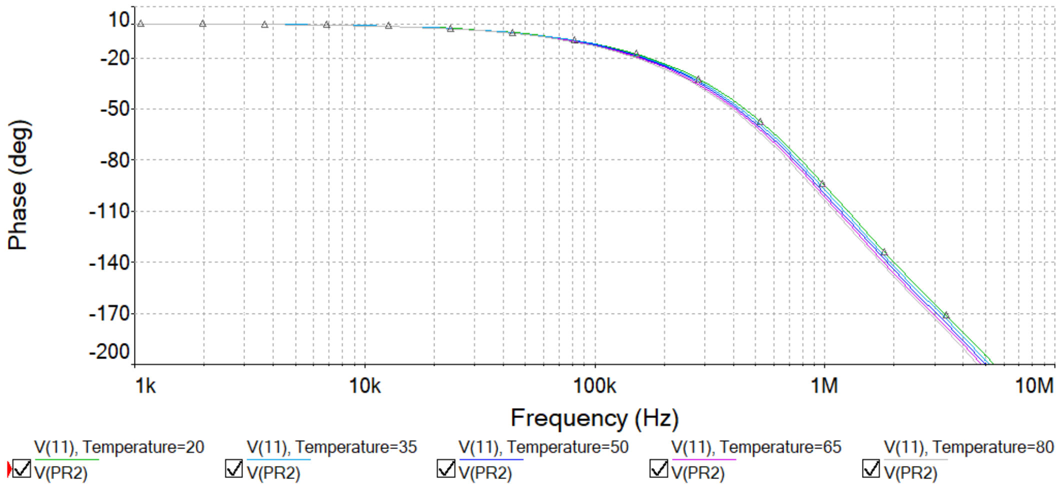


Figure 4.3.14: Phase response of AP filter at different temperatures

### 4.4 Current mode first order universal filter

A novel all pass filter using a single OA and one MO-VDTA (Multi-output VDTA) operating in the current mode is presented in this subsection. The phase is electronically tunable through the transconductance gains of VDTA. The filter realizes the LP, HP and AP filtering functions simultaneously. The filter has following advantages:

a) High frequency operation as it uses the pole model of OA,
b) Free from realizability conditions,
c) Since it is active-only in nature and is thereby amenable to integration,
d) The filter is cascadable as the output currents are available at high impedances, and
e) Sensitivities figures are unity

Using the port relations of VDTA and OA the transfer functions of the circuit is given by:

$$\frac{I_{LP}}{I_{in}} = \frac{B\frac{g_1}{g_2}}{s+B\frac{g_1}{g_2}} \qquad (4.4.1)$$

$$\frac{I_{HP}}{I_{in}} = \frac{s}{s+B\frac{g_1}{g_2}} \qquad (4.4.2)$$

$$\frac{I_{Ap}}{I_{in}} = \frac{s-B\frac{g_1}{g_2}}{s+B\frac{g_1}{g_2}} \qquad (4.4.3)$$

The pole frequency is given by

$$\omega_0 = B\frac{g_1}{g_2} \qquad (4.4.4)$$

The phase angle is given by:

$$\varphi = \pi - 2tan^{-1}\left(\frac{\omega g_2}{Bg_1}\right) \qquad (4.4.5)$$

From equations (4.4.4) and (4.4.5) it is seen that the pole frequency and hence phase angle can be electronically tuned either by $g_1$ or $g_2$.

The sensitivities of the filter are unity and is given by:

$$-S_{g_2}^{\omega_0} = S_{g_1}^{\omega_0} = S_B^{\omega_0} = 1$$

.

### Simulations

PSPICE simulation has been used to verify the proposed circuit. In the simulation, VDTA is achieved by connecting two LT 1228 OTAs ($g_i = 10I_i, i = 1,2$). LT1228 is an OTA followed by a buffer. LM741 OA with gain bandwidth product B = 2πX (1.0) MHz is used. The circuit is constructed for a pole frequency of 1 MHz with $g_1 = g_2 = 1$ *mA/V*. The LP and HP gain and phase responses are shown in Figures (4.4.2) to (4.4.5) respectively. While Figures (4.4.6) and (4.4.7) depict the gain and phase response of APF. Since the pole frequency hence phase is tunable and Figure (4.4.8) shows the variation of phase angle with transconductance gain $g_2$, which is varied from 0.5 to 1 mA/V ($I_{bias}$ from 50 uA to 100 uA). To check the large signal performance of the circuit a sinusoidal signal of 100 uA at 1 MHz is used. The simulated response is shown in Figure (4.4.9). The MCA (Monte Carlo Analysis) measures the responses of the filter when the device model parameters randomly change between the specified tolerances limits. Theses variations can be due processing of the device used their mismatches and environmental effects. To check these effects on the filter performance MC simulation is performed on the transconductance gains with a tolerance 10% and 50 random runs. The results are shown in Figures (4.4.10) and (4.4.11). Form the simulation results it is clear that the filter performances are as per theoretical results. However, due to process tolerance, mismatch of the devices and other environmental affects the simulated results deviate from ideal results within tolerable limits.

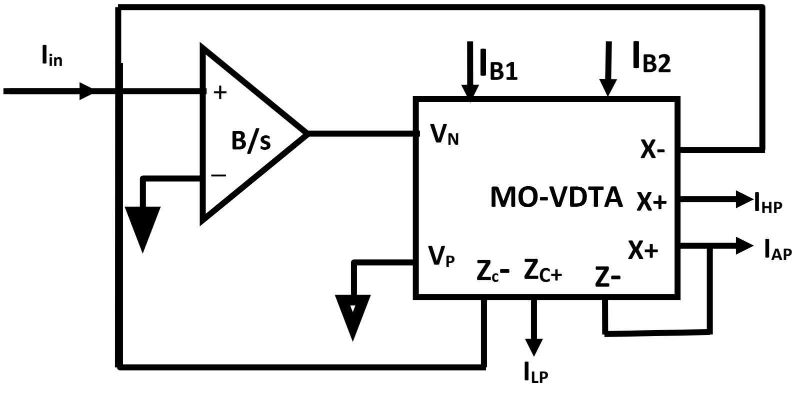


Figure 4.4.1: Proposed CM all pass filter

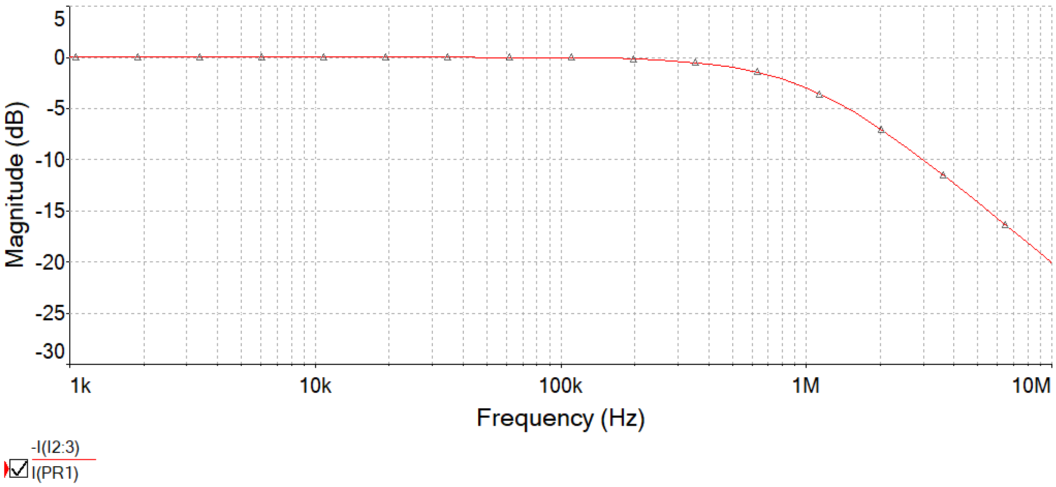


Figure 4.4.2: Gain frequency response of LP filter

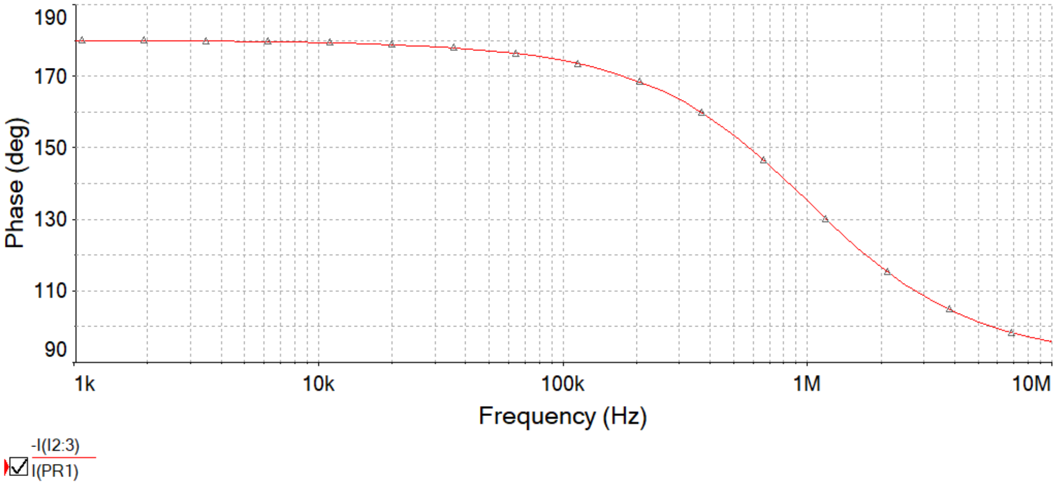


Figure 4.4.3: Phase frequency response of LP filter

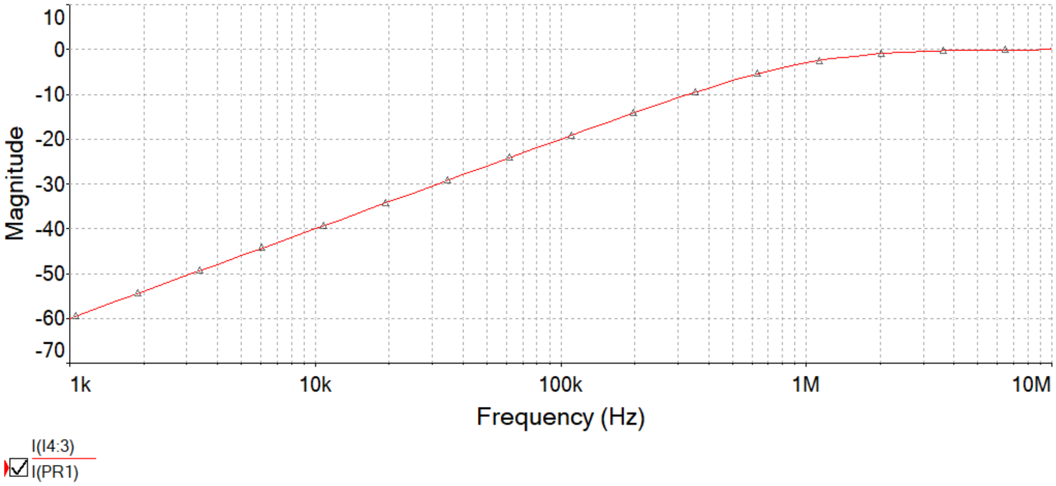


Figure 4.4.4: Gain frequency response of HP filter

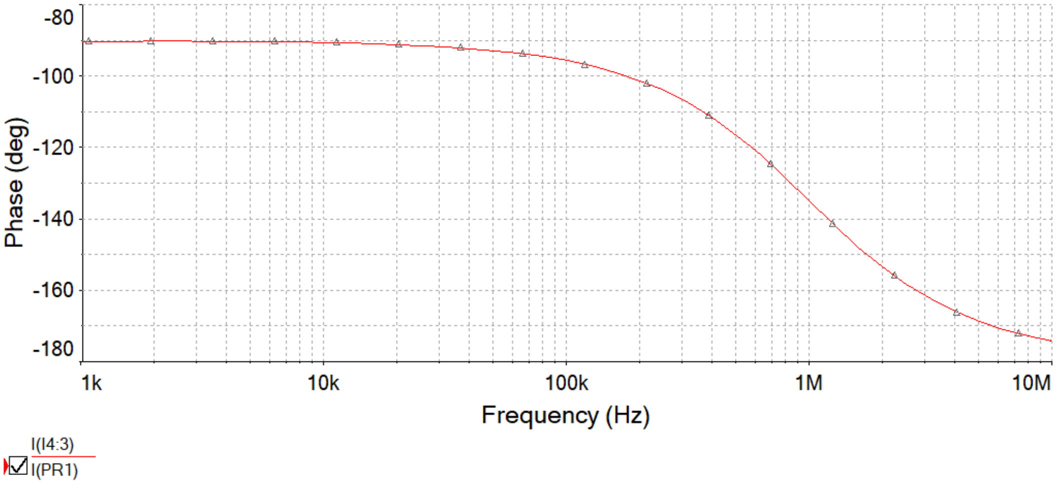


Figure 4.4.5: Phase frequency response of HP filter

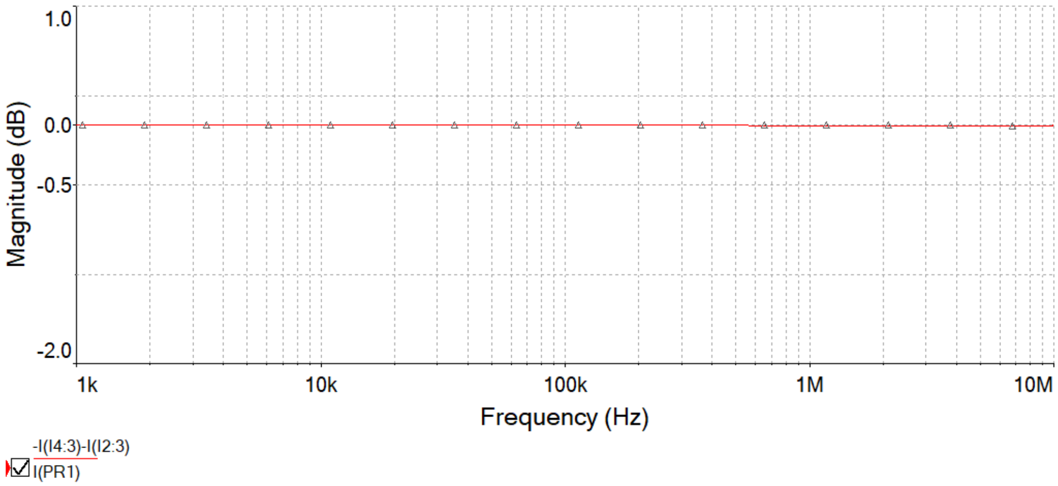


Figure 4.4.6: Gain response of AP filter

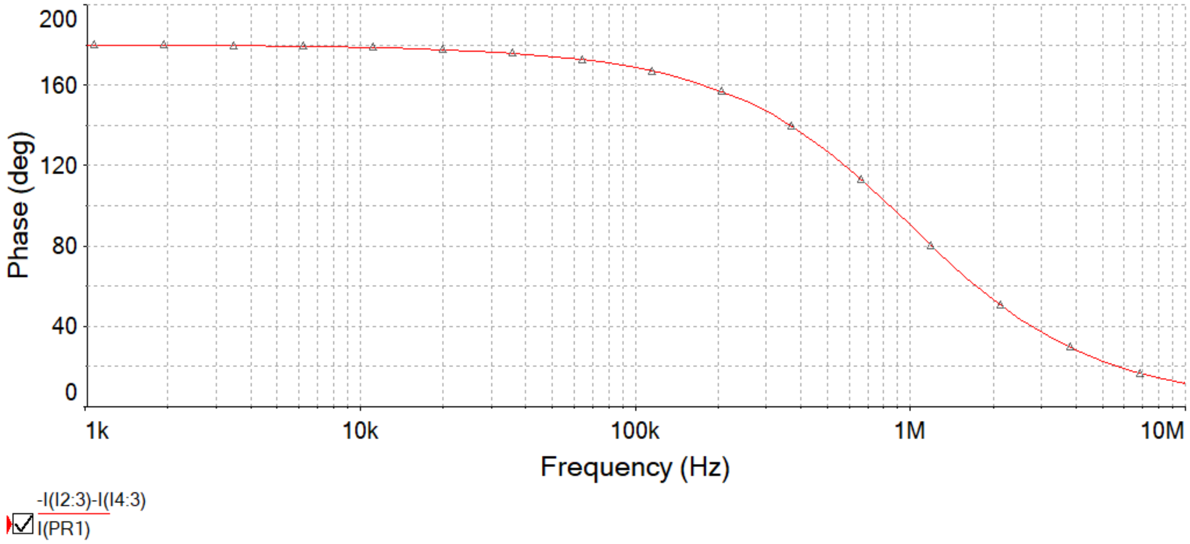


Figure 4.4.7: Phase response of AP filter

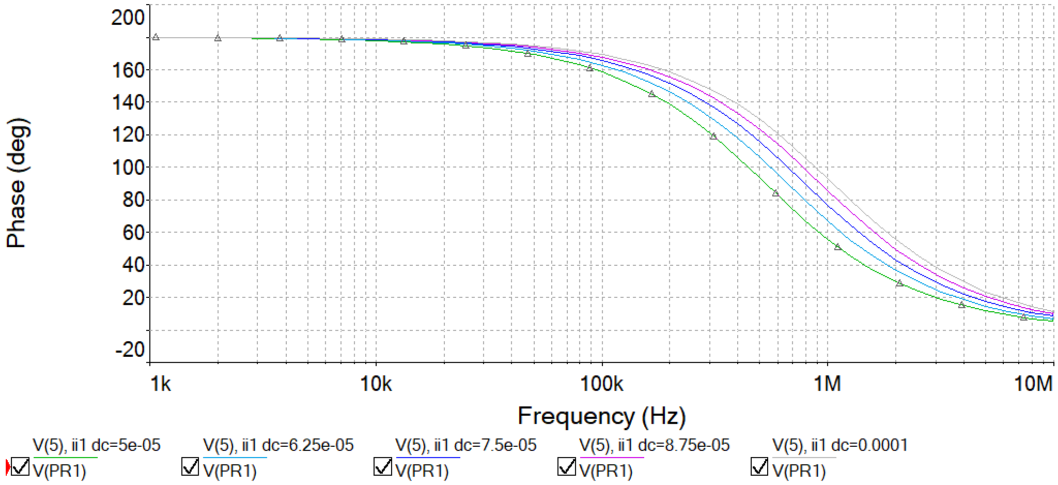


Figure 4.4.8: Variation of phase angle with transconductance gain

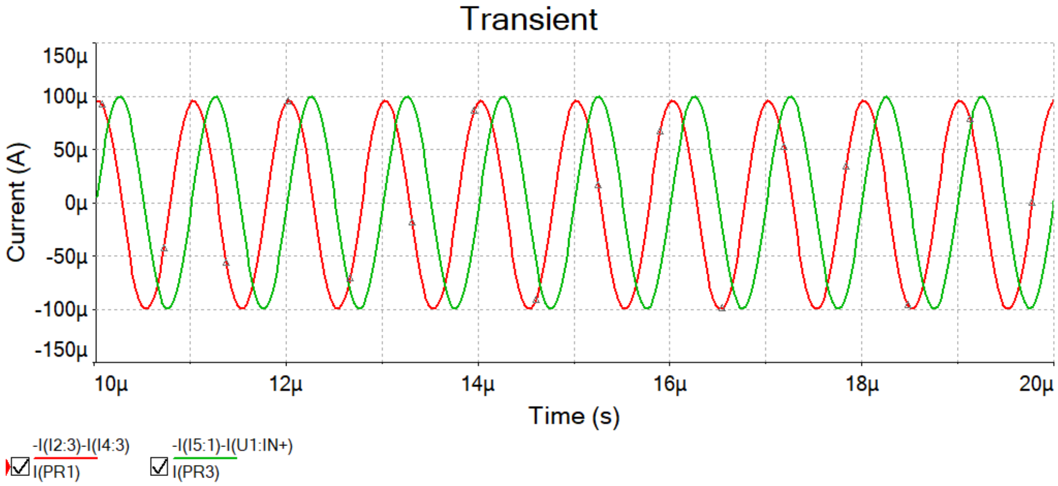


Figure 4.4.9: Transient response of AP filter

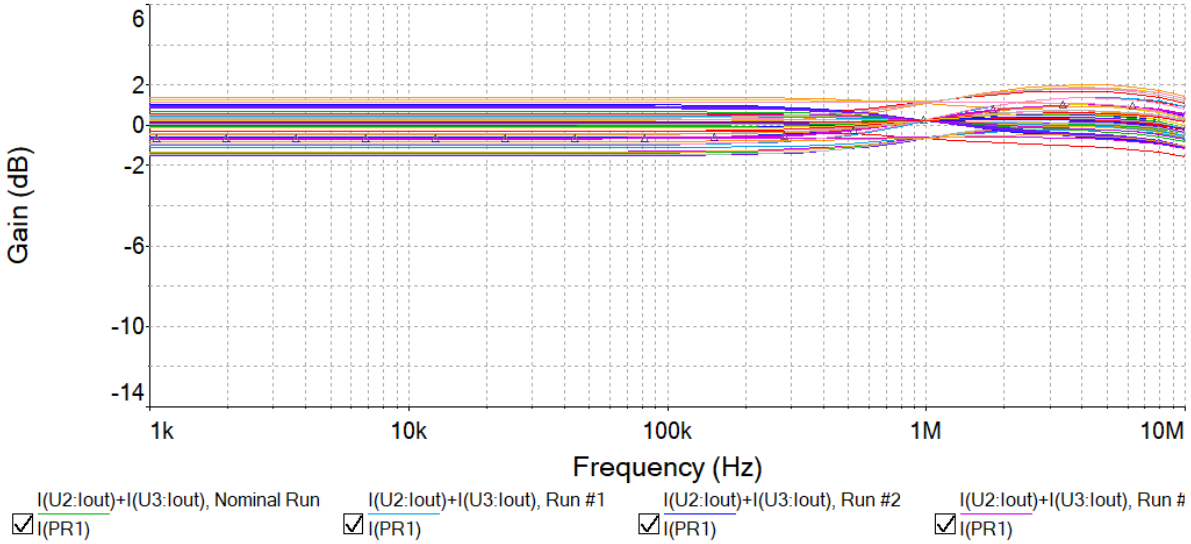


Figure 4.4.10: MC analysis for gain for APF.

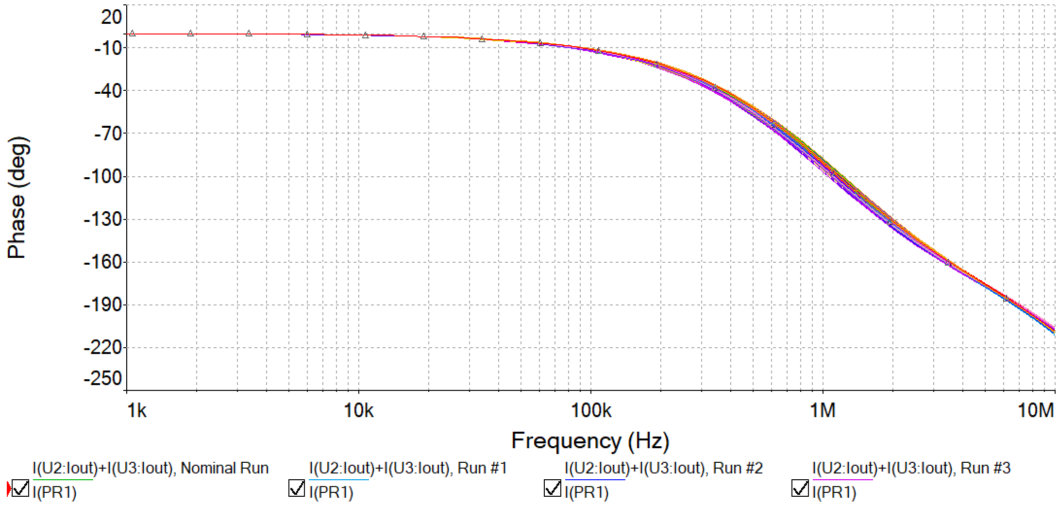


Figure 4.4.11: MC analysis of Phase for APF.

## 4.5. Two input and two output first order filter using single output VDTA

A novel minimum component VM and TAM all pass filter employing a single VDTA and a single capacitor shown in Figure (4.5.1) is presented. The VDTA used has both single output terminals while implementing VM and TAM transfer functions. The circuit is capable of implementing all three basic filtering functions viz. LP, HP, and AP from the same topology depending upon the choice of inputs. The filter is free from realizability condition. Also, the pole frequency hence the phase angle of the all pass filter is electronically tunable through the transconductance gain of VDTA. The gain of the TAM filter is also electronically tunable. The sensitivities figures are unity. The routine analysis gives the following transfer function:

$$V_o = \frac{V_{in1}g_1 + V_{in2}sC}{g_1 + sC} \tag{4.5.1}$$

$$I_o = g_2 \frac{V_{in1}g_1 + V_{in2}sC}{g_1 + sC} \tag{4 .5.2}$$

The filter is capable of implementing the following filtering functions depending upon the choice of inputs as depicted in Table 4.1.

**Table 4.1**

| $V_{in1}$ | $V_{in2}$ | Filtering function implemented in VM and TAM |
|---|---|---|
| $V_{in}$ | 0 | Low pass |
| 0 | $V_{in}$ | High pass |
| $V_{in1} = V_{in}$ | $V_{in2} = -V_{in}$ | Inverting all pass |
| $V_{in1} = -V_{in}$ | $V_{in2} = V_{in}$ | Non-inverting all pass |

The pole frequency and phase angle of all pass filter is given by

$$\omega_0 = \frac{g_1}{C} \tag{4.5.3}$$

Non-inverting $\varphi = \pi - 2tan^{-1}\left(\frac{\omega C}{g_1}\right)$ (4.5.4)

Inverting $\varphi = -2tan^{-1}\left(\frac{\omega C}{g_1}\right)$ (4.5.5)

From equations (4.5.4) and (4.5.5) it is clear that the pole frequency hence phase angle can be electronically tuned by $g_1$ and gain of TAM filter by $g_2$. The sensitivity figures are equal to unity in magnitude as given below:

$$S_{g_1}^{\omega_0} = -S_{C}^{\omega_0} = 1$$

### Non-idealities of VDTA

Considering the non-idealities of VDTA as depicted in equation (2.7) the transfer function is given by:

$$V_o = \frac{V_{in1}\beta_1 g_1 + V_{in2}sC}{\beta_1 g_1 + sC} \quad (4.5.1)$$

$$I_o = \beta_2 g_2 \frac{V_{in1}\beta_1 g_1 + V_{in2}sC}{\beta_1 g_1 + sC} \quad (4.5.2)$$

non-idealities of VDTA have negligible effects on the filter performance factors. Considering parasitic capacitances and resistance at the input and output terminals of VDTA, the transfer function is given by:

$$V_o = \frac{V_{in1}\beta_1 g_1 + V_{in2}sC}{\beta_1(g_{1+}G^*) + s(C + C^*)}$$

Where $C^* = C_N + C_Z$ and $G^* = G_N + G_Z$

### Simulations

To check the proposed filter PSPICE simulations are carried out. VDTA is achieved by cascading two OTAs. The filter is constructed for the pole frequency of 159 KHz. The value of the capacitor is chosen as 1 nF and transconductance gains $g_1 = g_2 = 1mA/V$ ($I_{bias}$ = 100uA). For VM, Figures (4.5.2) and (4.5.3) show the magnitude and phase response of LPF, while Figures (4.5.4) and (4.5.5) depict the magnitude and phase response of HPF. Figures (4.5.6) and (4.5.7) depict the gain response of LP and HP TAM filter. Magnitude and phase responses of non-inverting VM APF are shown in Figures (4.5.8) and (4.5.9). The phase response of inverting APF is depicted in Figure

(4.5.10). The gain and phase frequency response of TAM non-inverting APF is shown in Figures (4.511) and (4.5.12). Transient response is shown in Figure (4.5.13) for which input signal of 159 KHz and 100 mV signal is used. Variation of pole frequency with the bias current of VDTA that is varied from 100uA to 500uA ($g_1$ = 1 mA/V to 5 mA/V) and the results are shown in Figure (4.5.14). To check the influence of temperature which is varied from 10 to $70^0$C on the filter performance factors for VM APF, simulations are carried and the results are shown in Figure (4.5.15). It is seen from the Figures that the temperature affects the gain at low and high frequencies, while for phase there is a slight shift in phase responses.

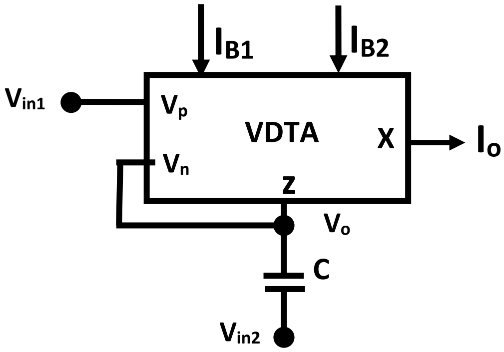


Figure 4.5.1: Proposed AP filter

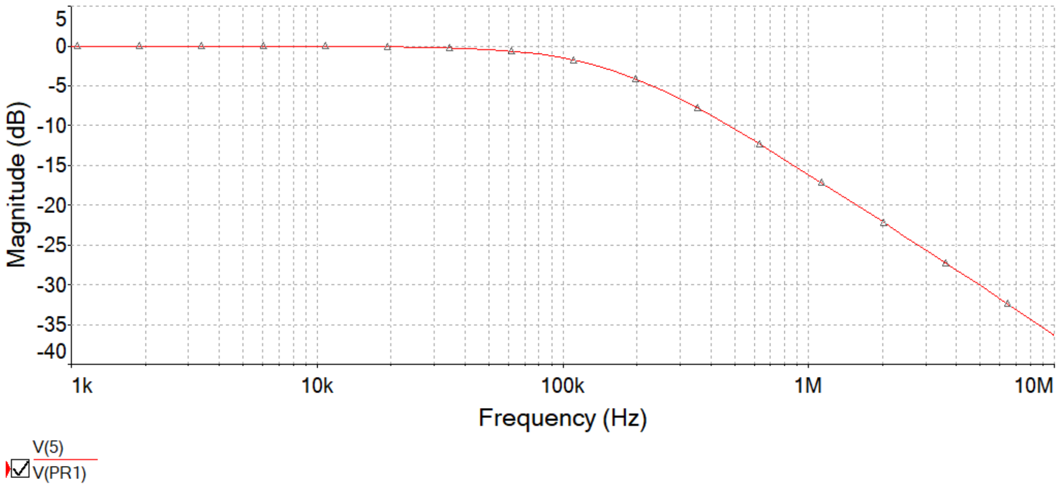


Figure 4.5.2: Frequency response of  VM LPF

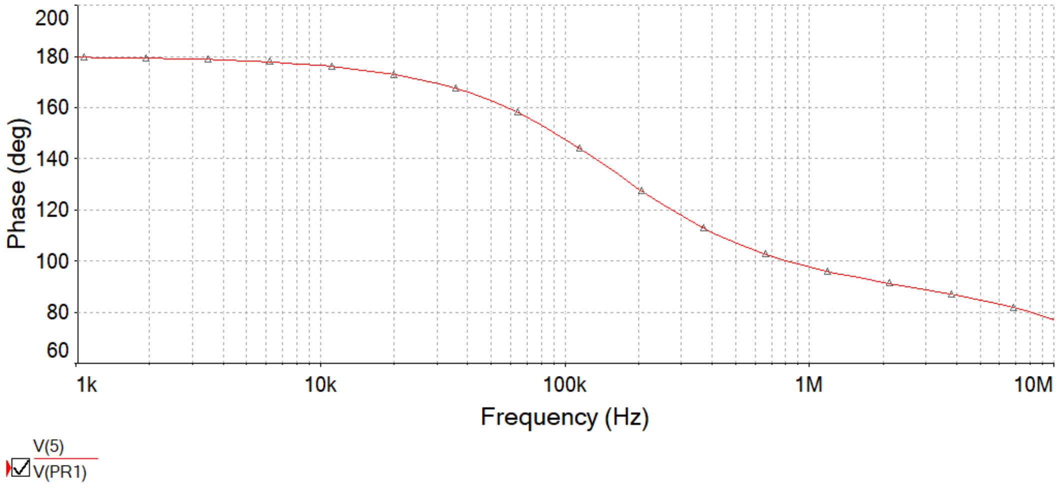


Figure 4.5.3: Phase response of VM LPF

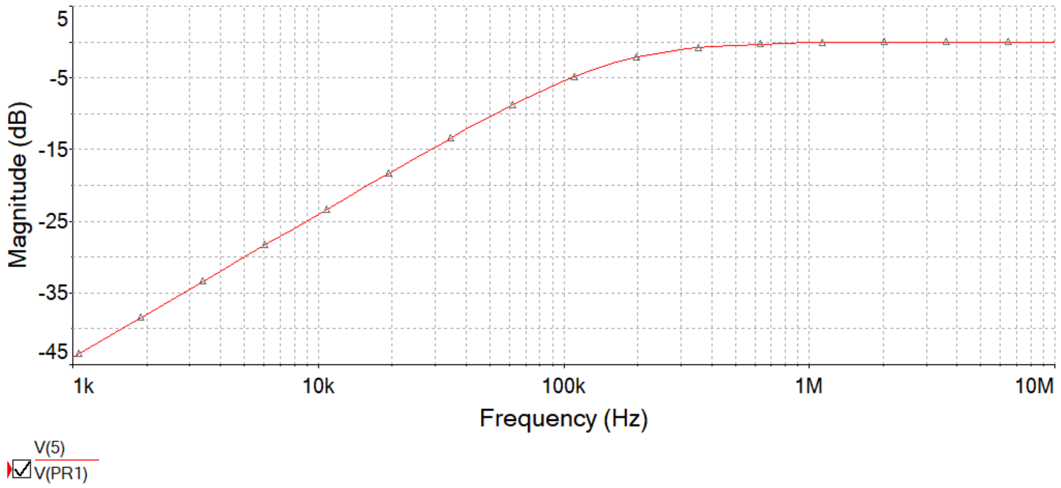


Figure 4.5.4: Frequency response of VM HPF

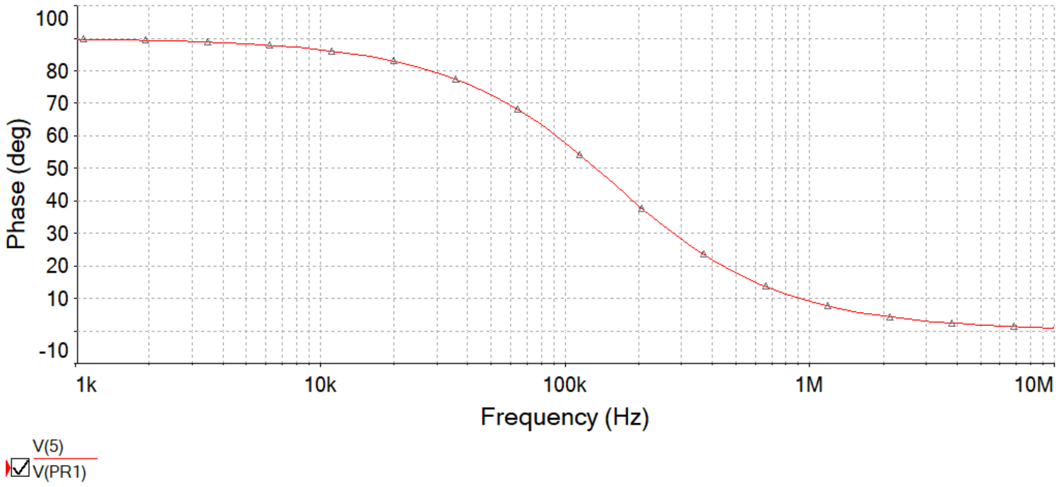


Figure 4.5.5: Phase response of VM HPF

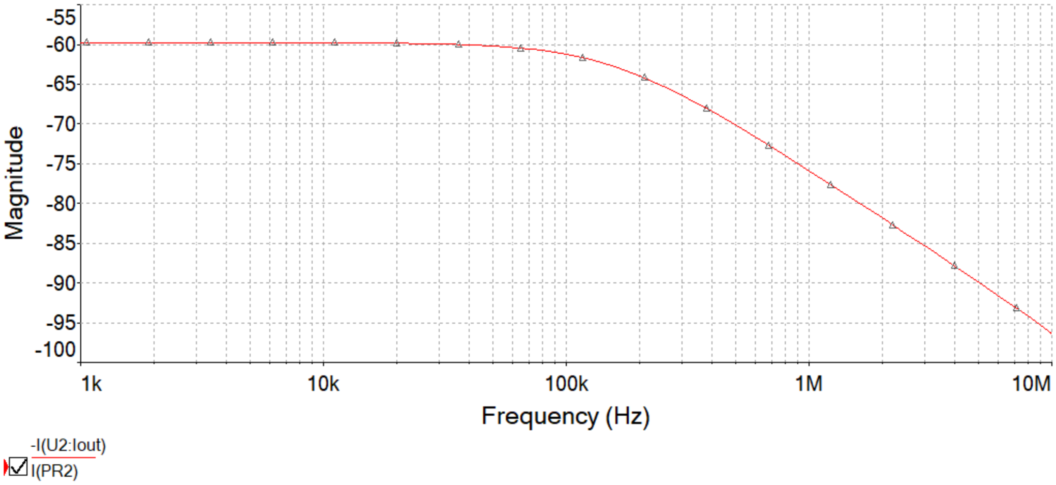


Figure 4.5.6: Frequency response of TAM LPF

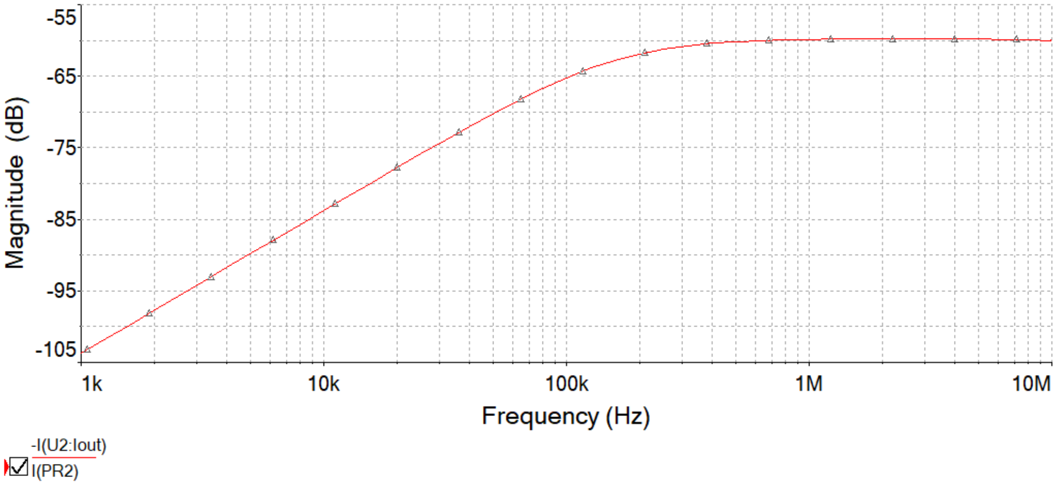


Figure 4.5.7: Frequency response of TAM HPF

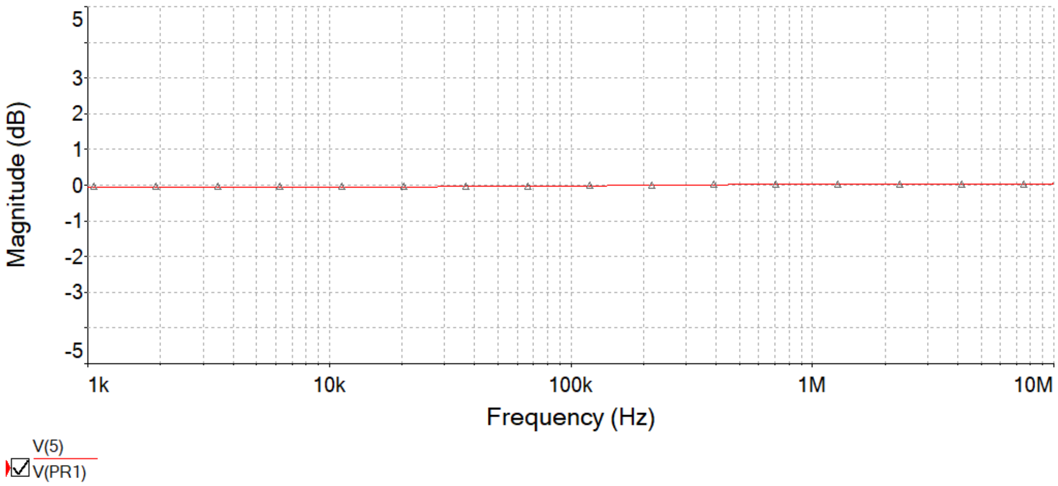


Figure 4.5.8: Frequency response of  VM APF

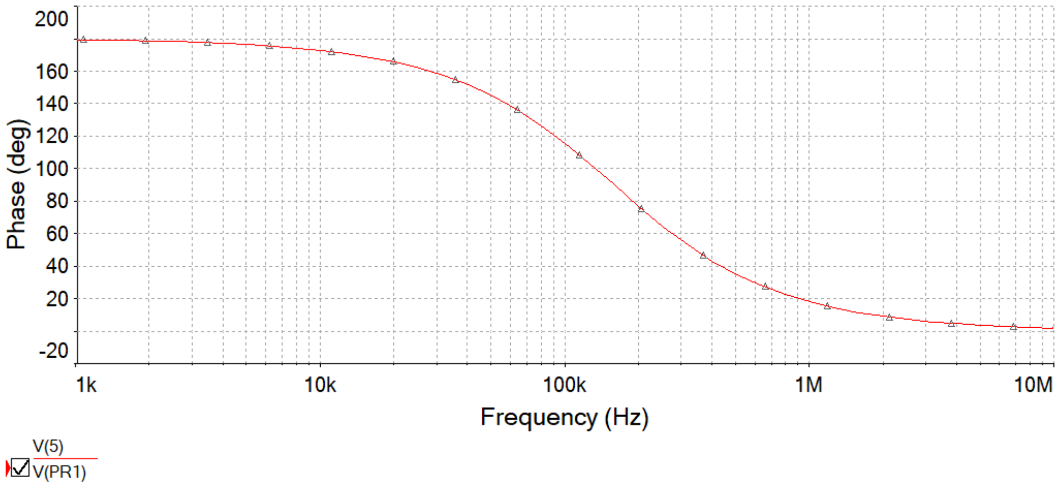


Figure 4.5.9: Phase response of  VM non-inverting APF

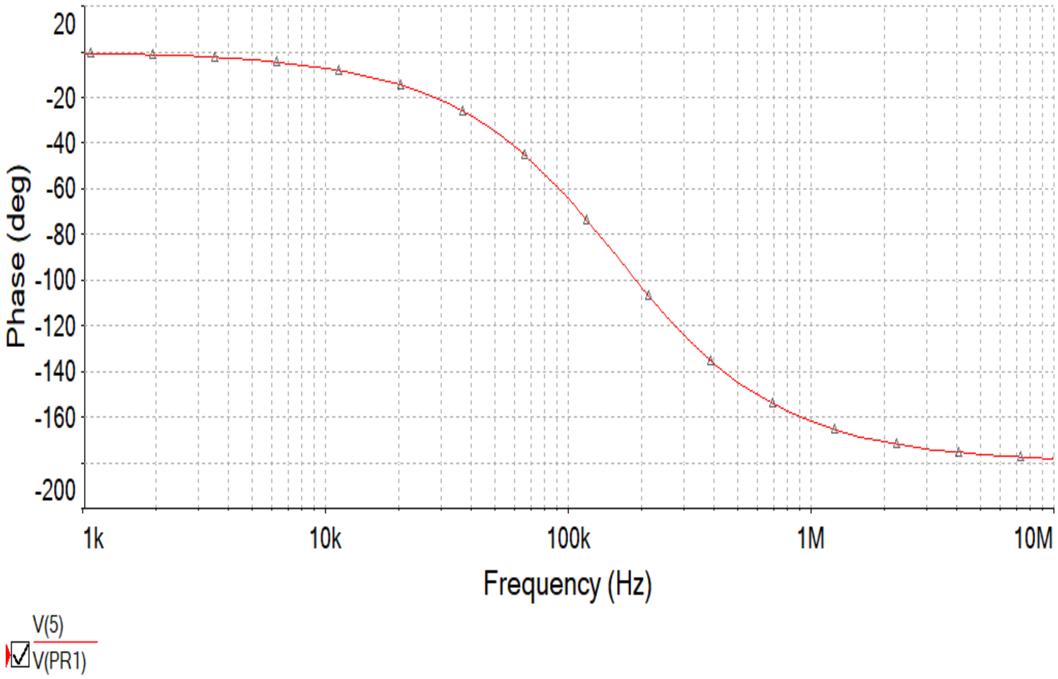


Figure 4.5.10: Phase response of inverting APF

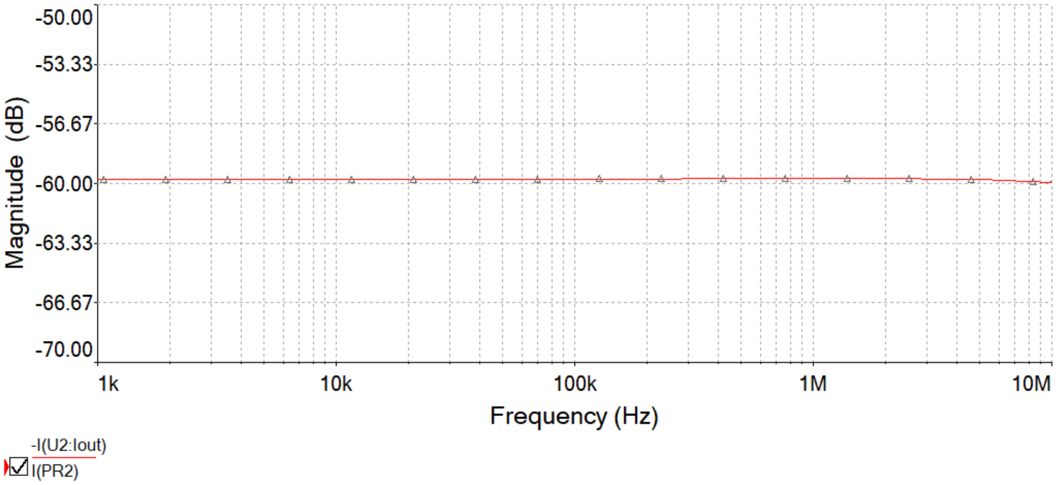


Figure 4.5.11: Frequency response of TAM APF

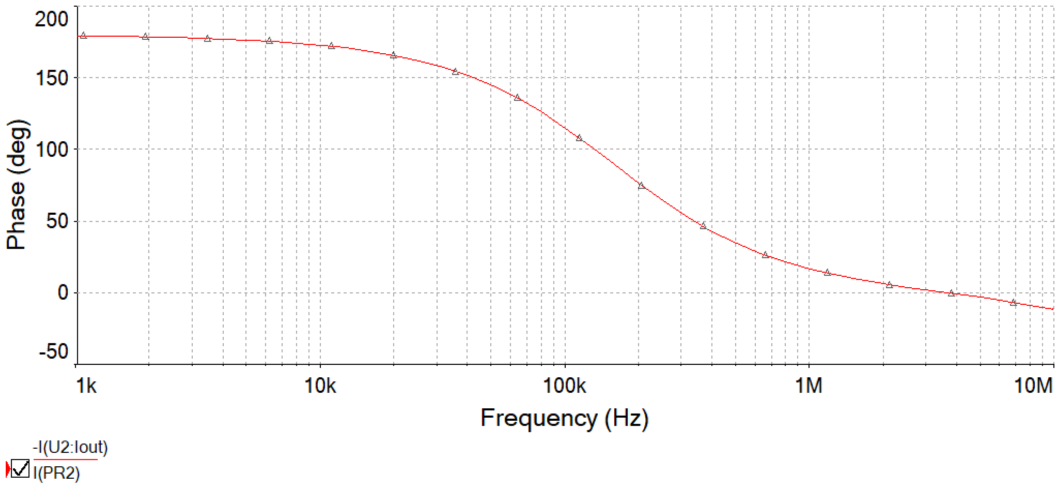


Figure 4.5.12: Phase response of TAM non-inverting APF

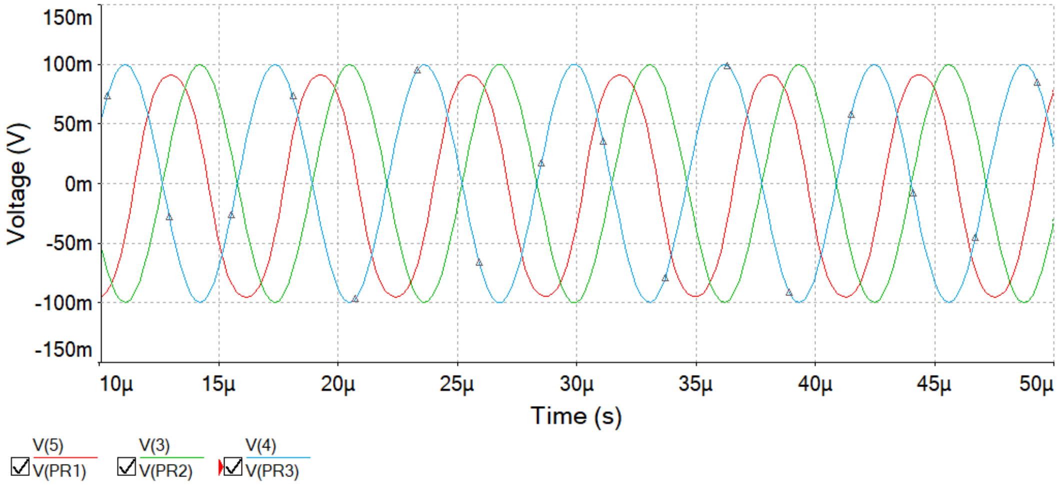


Figure 4.5.13: Transient response for VM APF (Red colour signal is output)

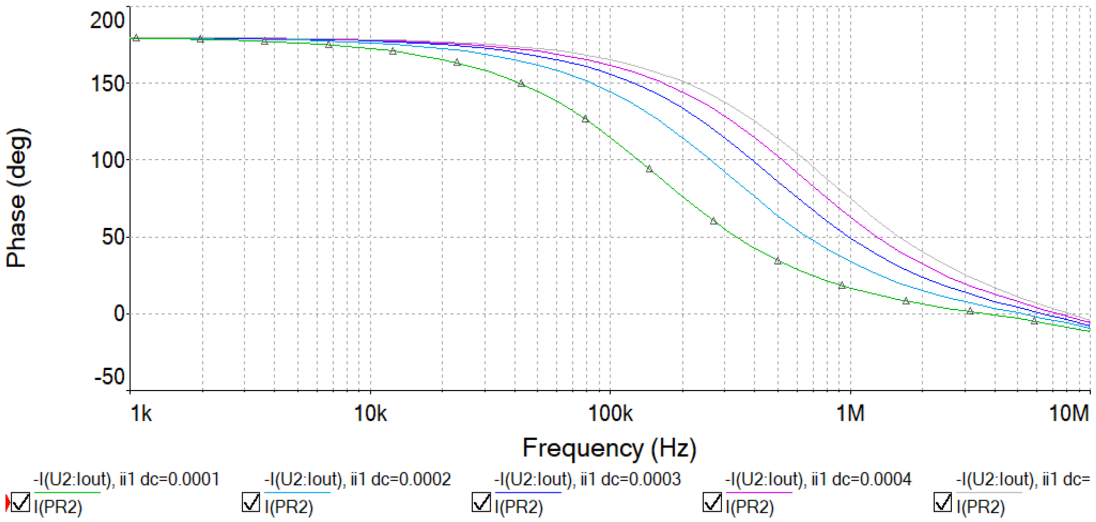


Figure 4.5.14: Variation of phase with transconductance gain VM APF

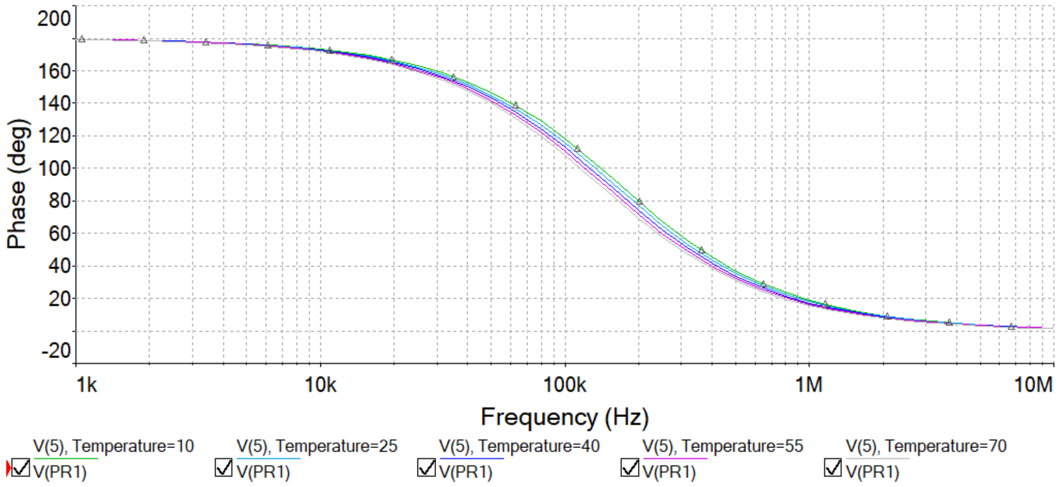


Figure 4.5.15: Phase response of VM APF at different temperatures

## 4.6. VM and TAM all pass filter using single output VDTA

In this subsection, a novel VM filter using one capacitor, one VDTA, and a single grounded resistor is presented. The filter has single voltage input and two outputs thus implementing two filtering functions in VM and TAM simultaneously. However, the filter needs a realizability condition in terms of transconductance gain to realize the AP filtering function. The circuit diagram of the proposed filter is shown in Figure (4.6.1). The routine analysis gives the following transfer function:

$$\frac{V_o}{V_{in}} = \frac{s - g_{1/C}}{s + g_{1/C}} \qquad g_1 = 1/R \qquad (4.6.1)$$

$$\frac{I_o}{V_{in}} = g_2 \frac{s - g_{1/C}}{s + g_{1/C}} \qquad (4.6.2)$$

From equations (4.6.1) and (4.6.2) it is clear that the filter act as the AP filter and implements VM and TAM filtering functions simultaneously. The filter is constrained by the realizability conditions the $g_1 = 1/R$. The pole frequency and phase angles are given by:

$$\omega_0 = \left( {}^{g_1}\!/_{C} \right) \qquad (4.6.3)$$

Phase angle is given by $\varphi = \pi - 2tan^{-1}\left( {}^{\omega C}\!/_{g_1} \right)$ (4.6.4)

The pole frequency of the filter can be tuned by the capacitor without disturbing the realizability condition. The sensitivity figures are equal to unity.

$$S_{g_1}^{\omega_0} = -S_C^{\omega_0} = 1$$

**Simulations**

To check the workability of filter simulations are carried and is constructed for pole frequency 159 KHz. The values of various parameters chosen are, g = 1mA/V, R = 1 K ohms ,and c = 1nF. The simulated results are shown from Figure (4.6.2) to (4.6.12). The various simulated results include gain, phase, transient, MC and temperature responses.

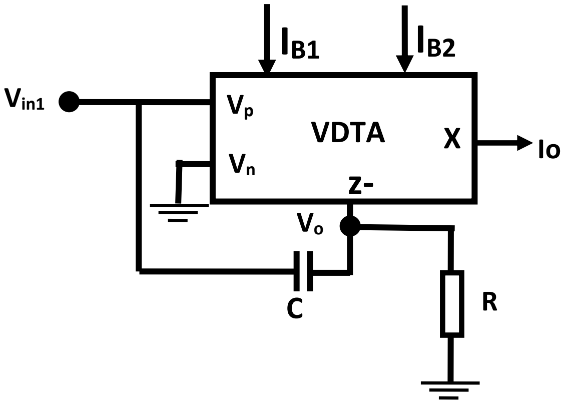


Figure 4.6.1: Proposed AP filter

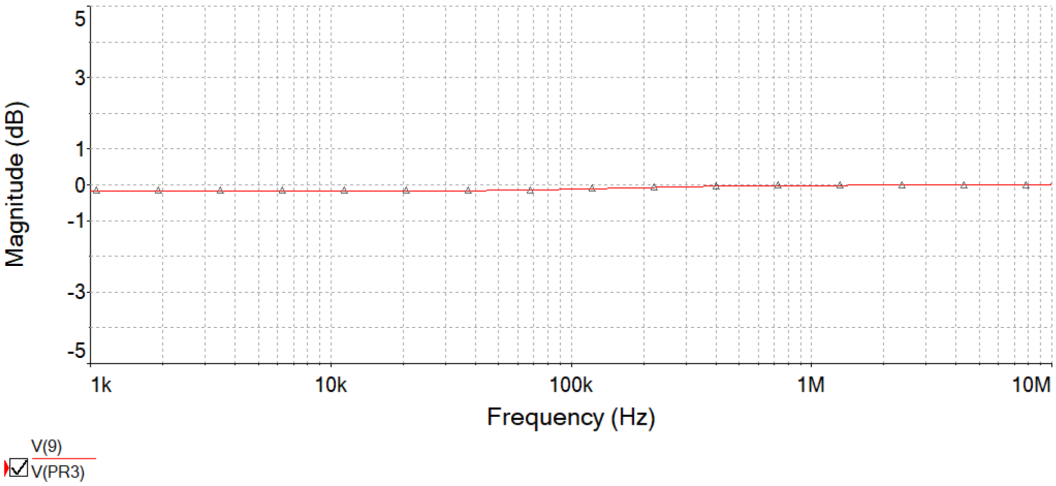


Figure 4.6.2: Frequency response of VM AP

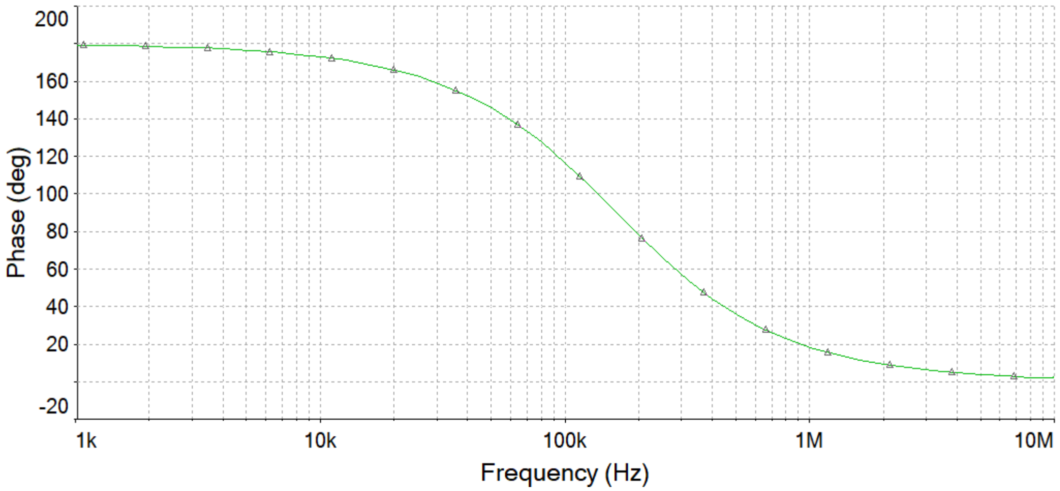


Figure 4.6.3: Phase response of  VM AP

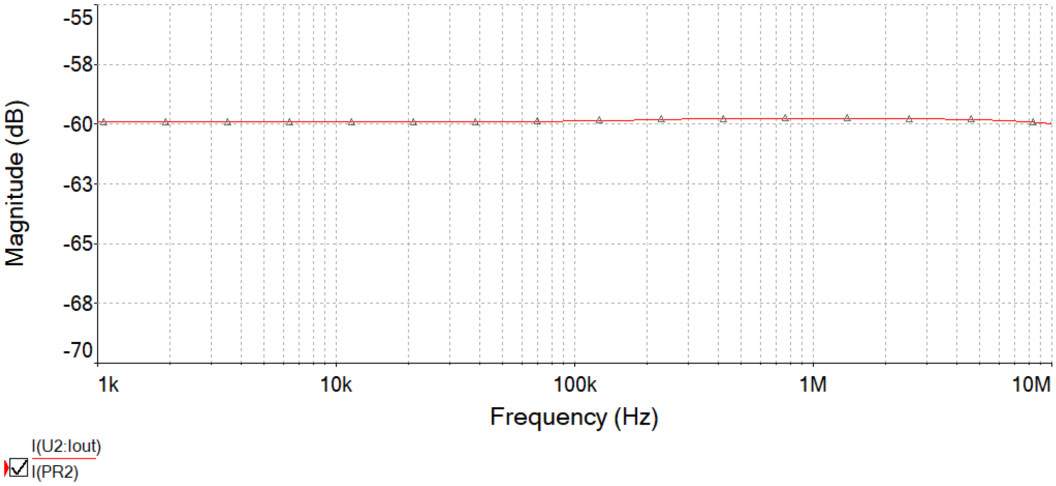


Figure 4.6.4: Frequency response of TAM AP

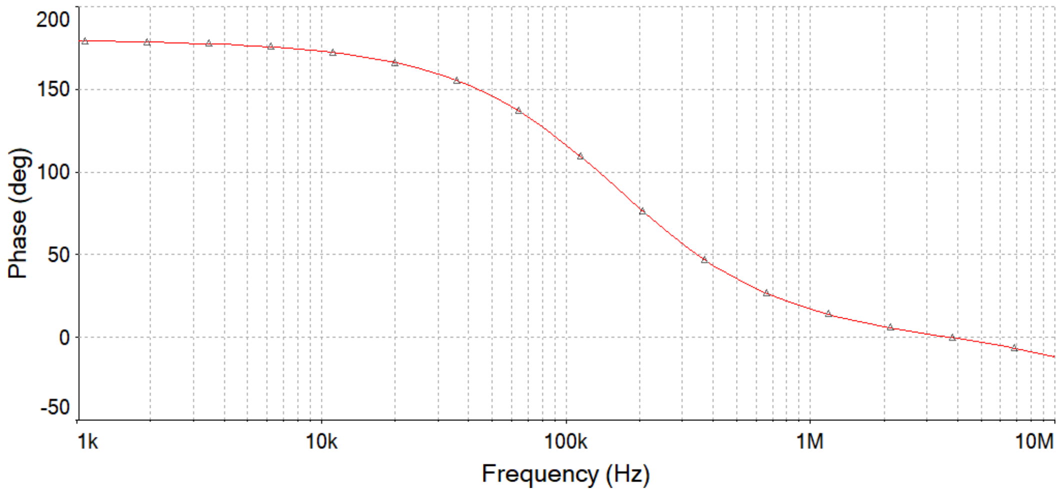


Figure 4.6.5: Phase response of TAM AP

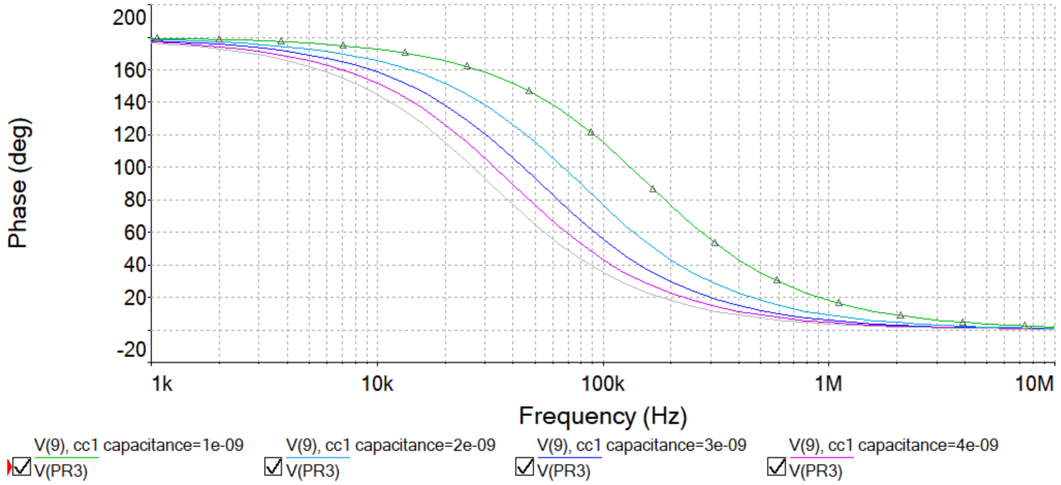


Figure 4.6.6: Variation of phase with capacitor

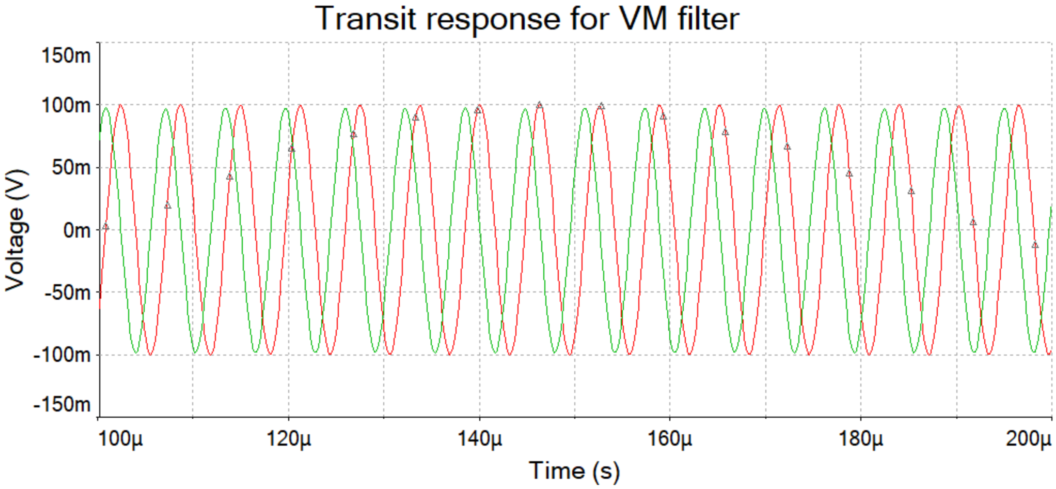


Figure 4.6.7: Transient response of VM AP

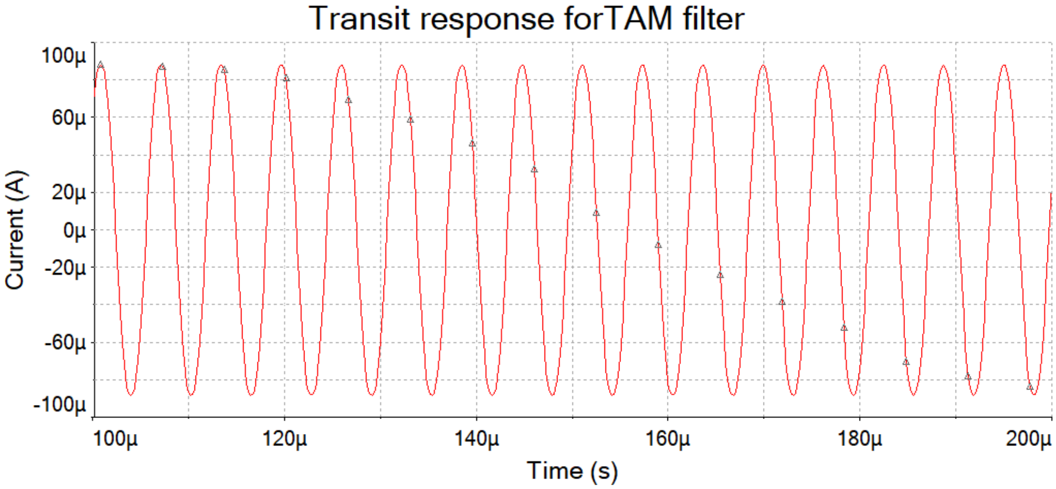


Figure 4.6.8: Transient response of TAM AP

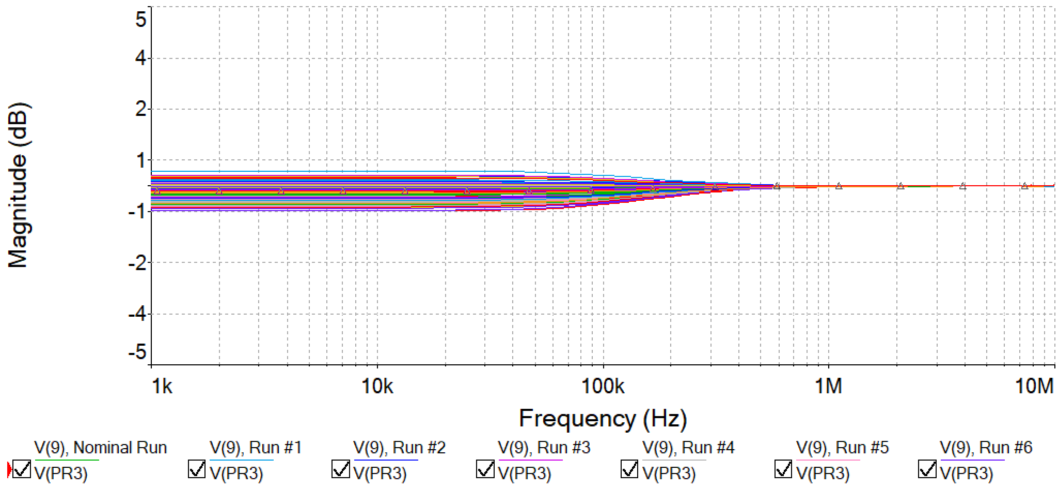


Figure 4.6.9: MC analysis of gain for VM AP

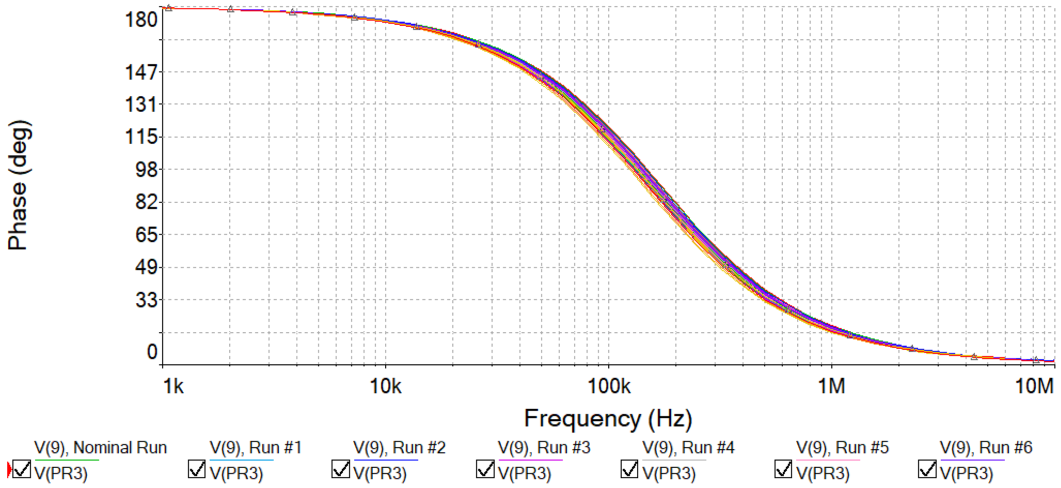


Figure 4.6.10: MC analysis of phase of  VM AP

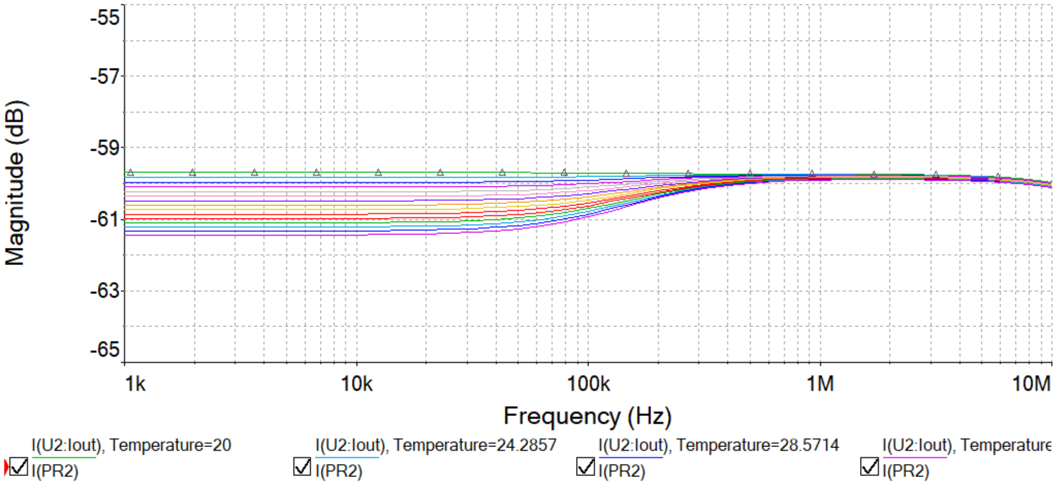


Figure 4.6.11: Variation of gain of VM AP filter with temperature

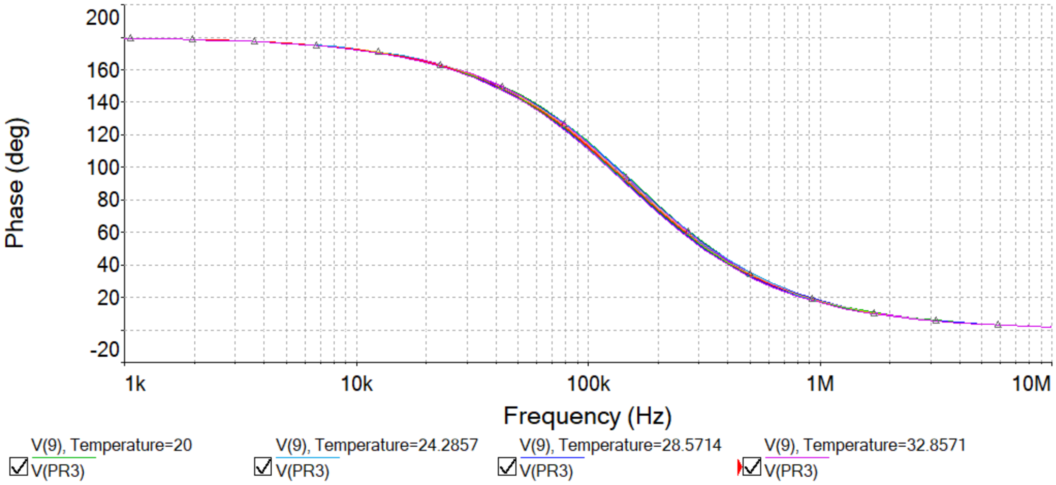


Figure 4.6.12: Variation of phase of VM AP filter with temperature

## 4.7. Summary

In this section, six first order filters are presented. The first filter realizes two VM filtering functions simultaneously viz. LP and HP (4.1). The second filter uses one OA and one VDTA and realizes the AP filtering function in VM. (4.2) Third one implements all filtering functions simultaneously and uses one OA and two VDTAs and operates in VM (4.3). Fourth one employs one OA and one MO-VDTA and implements all CM filtering functions simultaneously. These four filters are active-only in nature and are thus suitable in IC implementation. Besides the circuit use VDTA with gain, which is electronically tunable leading electronic tuning to filter performance factors. The fifth one uses single output one VDTA and a single capacitor and has two inputs. The filter implements VM and TAM filtering functions simultaneously. The filter is capable of realizing LP, HP, and AP filtering functions depending upon chose of inputs. The sixth filter uses one single output VDTA, one capacitor, and a grounded resistor. All the proposed filters are devoid of resistors except last one. However the resistor is grounded can be replaced by MOSFET rendering it resistor-less. The filters realize the AP filtering function in VM and TAM. First, fourth and fifth are free from realizability condition making the circuits more versatile. All six filters have been verified using PSPICE (multisim 14.3 version). The simulation results are in close agreement with theoretical results. The VDTA used is implemented by cascading two LT1228 OTAs. From simulation results for which the filters are checked are gain response, phase response, transient response, Monte Carlo analysis and temperature analysis. Besides these simulations the variation of pole frequency with the transconductance gain are also include. It is clear that the filters work as per theoretical analysis. However the results show some deviations from the theoretical values due to non-ideal behaviour and parasitic of the active devices used. The deviations are from theoretical results are small and are within tolerable limit. It is worth mentioning that only one first order filter is reported in the available literature.

# Chapter 5: Proposed second order filters

## 5. Introduction:

In this section second order filters are presented. Three filter configurations are proposed. The first filter employs one VDTA, one OA, and a single capacitor. This filter has three inputs and two outputs, one is the voltage and the other is current. The filter implements two filtering functions one in VM and other in TAM simultaneously. The filter implements all filtering functions depending upon choice of inputs. The second filter operates in pure CM and implements BP filtering function. The filter performance factors of this filter, viz. Pole frequency, quality factor and gain are independently and electronically tunable through the bias currents of VDTAs. The filter uses two grounded capacitors and two single output VDTAs. Third one use two MO-VDTAs, two grounded capacitors. The filter has single voltage input and realize six filtering functions simultaneously, three in VM and three in TAM.

### 5.1. Resistor-less three input and two output VM and TAM universal filter

Three input and two output second order, voltage mode (VM) and transadmittance mode (TAM) filter using the least number of components is presented. The circuit implements two filtering functions viz. VM and TAM simultaneously. The circuit uses a single operational amplifier (OA), one voltage difference transconductance amplifier (VDTA), and a single capacitor. The circuit is useful for higher frequency as it uses pole mode of OA. The circuit implements all the generic filtering functions viz. LP, HP, BP, notch and AP by suitable choosing inputs. The quality factor (Q) and cut off frequency ($\omega_0$) are independently tunable through the transconductance gain of VDTA. The band pass and low pass filtering functions are attractive, as the input impedance for these filtering functions is high, beside the capacitor is grounded. The sensitivity figures of the filter parameters are low. PSPICE simulation results confirm the theoretical results. The proposed filter offers the following advantages:

i) The circuit realizes all the generic functions viz. LP, BP, HP, Notch, and AP

ii) The proposed filter offers independently electronic tuning of cut-off frequency and quality factor Q.

iii) The sensitivity figures are very low.

iv) The input impedances for LP and BP filtering functions are high. Thus there is no need for buffers for the realization of higher order filters, besides the capacitor being grounded.

v) There is no need for an additional device for the implementation of the filtering functions except for the AP filtering function that need matching condition $g_1 = g_2$ and inverter to invert one of the input.

vi) the filter is suitable for high frequency operation and offers saving of one capacitor which otherwise is necessary to realize second order transfer functions

Using the port relations of the VDTA and the OA, the transfer functions of the filter are given by:

$$Vo \; = \frac{V_1 s^2 + V_2 s\frac{g_1}{C} + V_3 B\frac{g_1}{C}}{s^2 + s\frac{g_2}{C} + B\frac{g_1}{C}} \tag{5.1.1}$$

$$Io \; = \; g_2\left(\frac{V_1 s^2 + V_2 s\frac{g_1}{C} + V_3 B\frac{g_1}{C}}{s^2 + s\frac{g_2}{C} + B\frac{g_1}{C}}\right) \tag{5.1.2}$$

From equations (5.1.1) and (5.1.2), it is clear that the proposed filter implements LP, HP, BP, BS, and AP filtering functions in VM and TAM without changing filter topology, need for additional device, and is devoid of matching conditions except for AP, where $g_1 = g_2$. The filtering functions offered by the circuit depending upon the choice of inputs and are as given below:

1) $V_1 = V_2 = 0$ and $V_3 = V_{in}$, the filter realizes LP filtering function,

2) $V_1 = V_3 = 0$ and $V_2 = V_{in}$, the filter realizes BP filtering function,

3) $V_3 = V_2 = 0$ and $V_1 = V_{in}$, the filter realizes HP filtering function,

4) $V_2 = 0$ and $V_1 = V_3 = V_{in}$, the filter realizes Notch filtering function,

5) $V_1 = -V_2 = V_3 = V_{in}$, the filter realizes AP filtering function

The filter performance factors, pole frequency, bandwidth and, quality factor is given by

$$f_0 = \frac{1}{2\pi}\sqrt{B\frac{g_1}{C}} \tag{5.1.3}$$

$$\frac{\omega_0}{Q} = \frac{g_2}{C} \tag{5.1.4}$$

$$Q = \frac{1}{g_2}\sqrt{Bg_1C} \tag{5.1.5}$$

From equations (5.1.3), (5. 1.4) and (5.1.5) it is seen that the filter parameters are electronically tunable independently. The pole frequency ($\omega_0$) can be tuned through $g_1$ and quality factor (Q) by $g_2$ without disturbing pole frequency. The gain of BP is given by $g_1/g_2$.

### Non-idealities of OA and VDTA

Considering the non-idealities of OA and VDTA the transfer functions modifies to:

Where $\beta_1$ and $\beta_2$ are tracking errors of first and second transconductance gain. Using equations (1.29) and (1.35), the analysis of Figure 2 yields the following relations:

$$V_o = \frac{V_1 s^2 - V_2 s\beta_1\frac{g_1}{C}(1-\tau_1) + V_3 B\beta_1\frac{g_1}{C}}{s^2 + \frac{s}{C}(g_2\beta_2 - g_1\beta_1\tau_1) + B\frac{\beta_1 g_1}{C}} \tag{5.1.6}$$

$$I_o = g_2\left(\frac{V_1 s^2 - V_2 s\beta_1\frac{g_1}{C}(1-\tau_1) + V_3 B\beta_1\frac{g_1}{C}}{s^2 + \frac{s}{C}(g_2\beta_2 - g_1\beta_1\tau_1) + B\frac{\beta_1 g_1}{C}}\right) \tag{5.1.7}$$

The filter parameters are given by

$$f_0 = \frac{1}{2\pi}\sqrt{\beta_1 B\frac{g_1}{C}} \tag{5.1.8}$$

$$\frac{\omega_0}{Q} = \frac{(g_2\beta_2 - g_1\beta_1\tau_1)}{C} \tag{5.1.9}$$

and $$Q = \frac{1}{(g_2\beta_2 - g_1\beta_1\tau_1)}\sqrt{\beta_1 CBg_1} \qquad (5.1.10)$$

From equations (5.1.8) to (5.1.10), it is seen that the simulated pole frequency and the quality factor is slightly affected due to the presence of tracking errors. However, the pole frequency is independent of the non-idealities of OA. To minimize the effect on Q of the second pole of OA, the condition $g_2 >> g_1$ are to be met.

## Sensitivities

Sensitivity is the measure of the variation of performance factor with the changing of nominal value of the device. It is represented by $S_x^y$ where y represents filter performance factor like pole frequency, quality factor etc. and x represents nominal value of the element.

$$-S_C^{\omega_0} = S_{\beta_1}^{\omega_0} = S_B^{\omega_0} = S_{g_1}^{\omega_0} = \frac{1}{2}$$

$$S_{\beta_1}^{Q} = S_B^{Q} = S_{g_1}^{Q} = S_C^{Q} = \frac{1}{2}$$

$$S_{g_2}^{Q} = \frac{\beta_2\, g_2}{\beta_2\, g_2 - \tau\beta_1 g_1}, \qquad S_{\beta_1}^{Q} = \frac{\beta_2\, g_2 + \tau\beta_1\, g_1}{2(\beta_2\, g_2 - \tau\beta_1 g_1)}$$

$$S_{\tau_1}^{Q} = \frac{-\beta_1\, g_1}{(\beta_2\, g_2 - \tau_1\beta_1 g_1)}$$

It is seen from above equations that the sensitivities of filter performance factors are low.

## Simulation results

To verify the theoretical results, PSPICE simulations are carried out. VDTA has been implemented using two LT1228 OTAs. The circuit has been designed for the frequency of 400 KHz. and the quality factor 2.5. The gain bandwidth product of OA, B = 2π ($1\text{x}10^6$) Hz. The value of the transconductance gains of the VDTA is chosen $g_2$ and $g_1$ is 1mA/V and value of capacitor as C = 1nF. The simulated responses are shown from

Figure (5.1.2) to Figure (5.1.27). The Figures from (5.1.2) to (5.1.6) shows the gain frequency responses of HP, BP, HP, notch, and AP filters while Figure (5.1.7) shows the phase frequency response of AP filter. The Figure (5.1.8) depicts the variation of quality factor Q of VM BP filter, when bias current $I_{B2}$ is varied from 50 to 100 uA ($g_2$ is varied 500 to 1000 uA/V). Similarly, Figure (5.1.9) represents the simulation results of gain frequency response of VM BP filter, when value of bias current $I_{B1}$ is varied from 100 to 500 uA. Figure (5.1.10) represents the transient response of VM BP filter. Input signal (red trace) of 50 mV peak-to-peak at frequency of 400 KHz is used to study the response. The output signal is represented by green trace. Monte Carlo analysis to check sensitivity analysis for VM BP response is performed for 50 runs with 10% tolerance of the capacitors and the transconductance gain, and for uniform distribution, and effects is shown in Figure (5.1.11) for the gain response and Figure (5.1.12) for the phase response. Similarly, the simulation analysis for TAM filter is also carried out and the results are shown from Figure (5.1.13) to (5.1.27). From the simulation results it is seen that the filter performs well as per theoretical results.

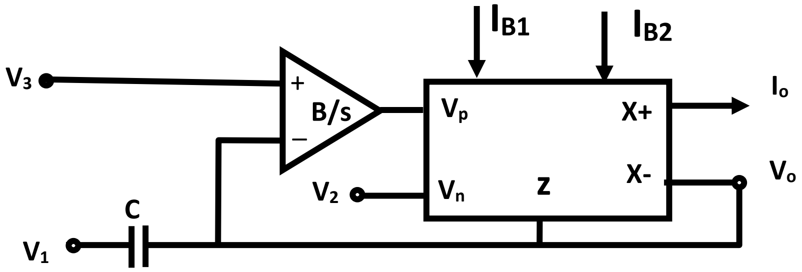


Figure 5.1.1: Proposed filter

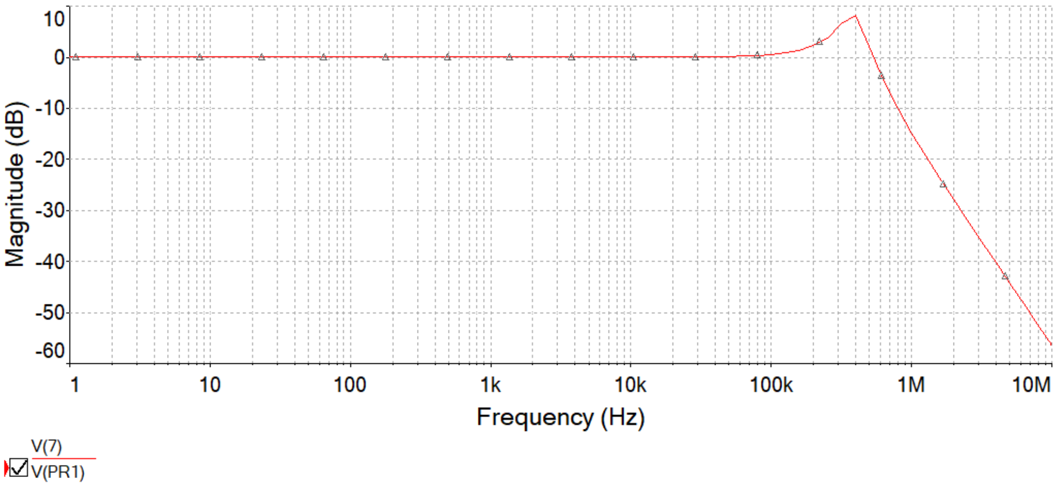


Figure 5.1.2: Gain response of VM LP filter

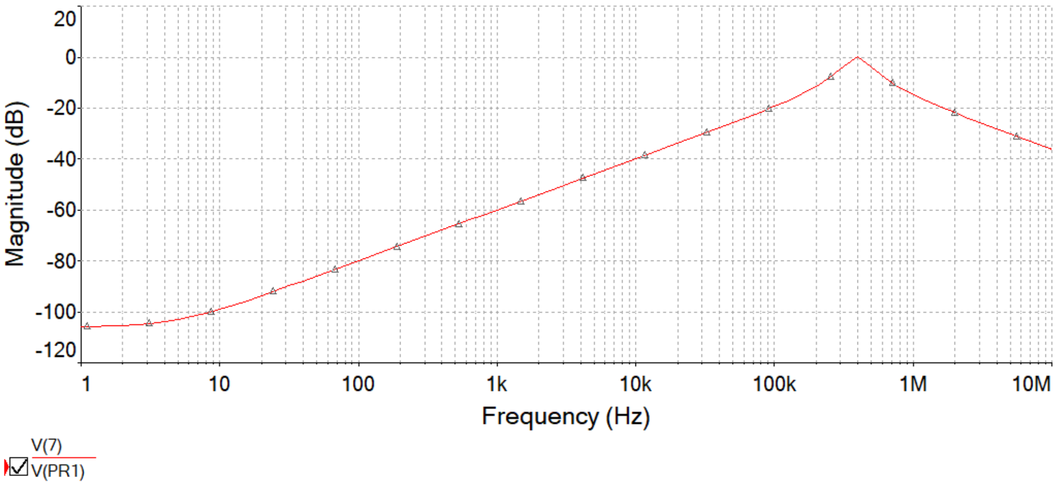


Figure 5.1.3: Gain response of VM BP filter

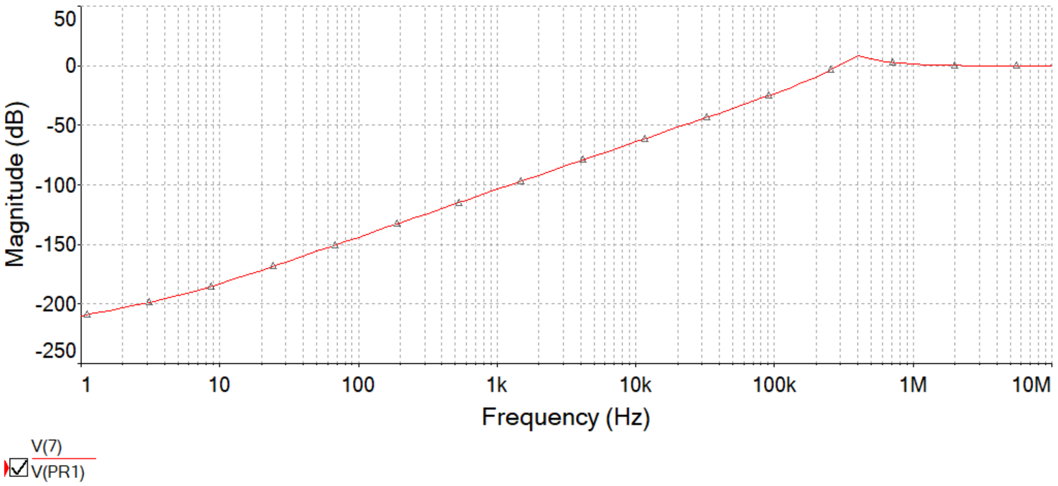


Figure 5.1.4: Gain response of VM HP filter

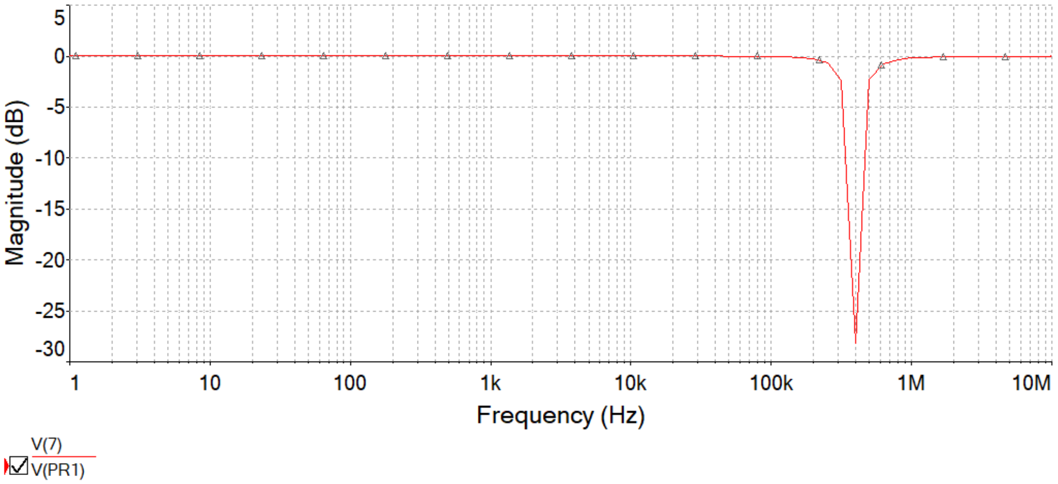


Figure 5.1.5: Gain response of VM notch filter

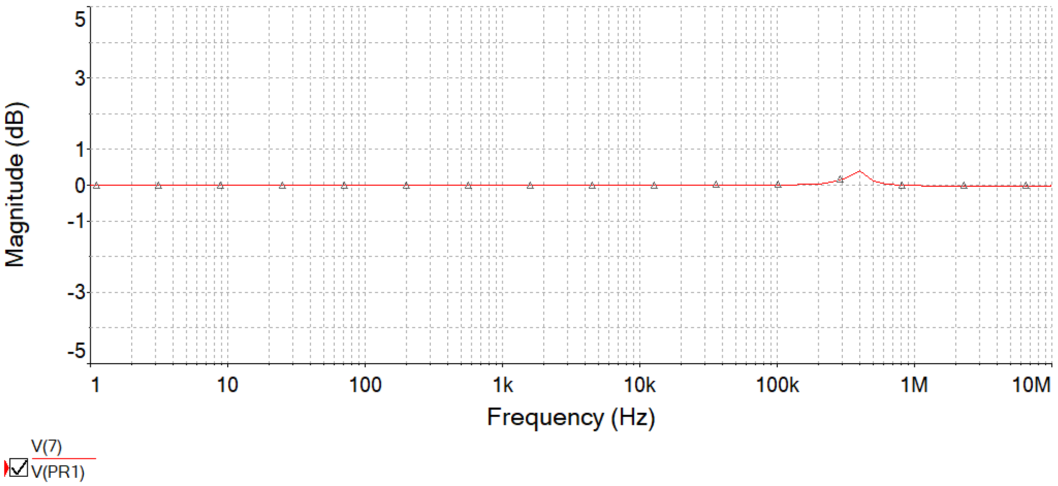


Figure .5.1.6:  Gain response of VM AP filter

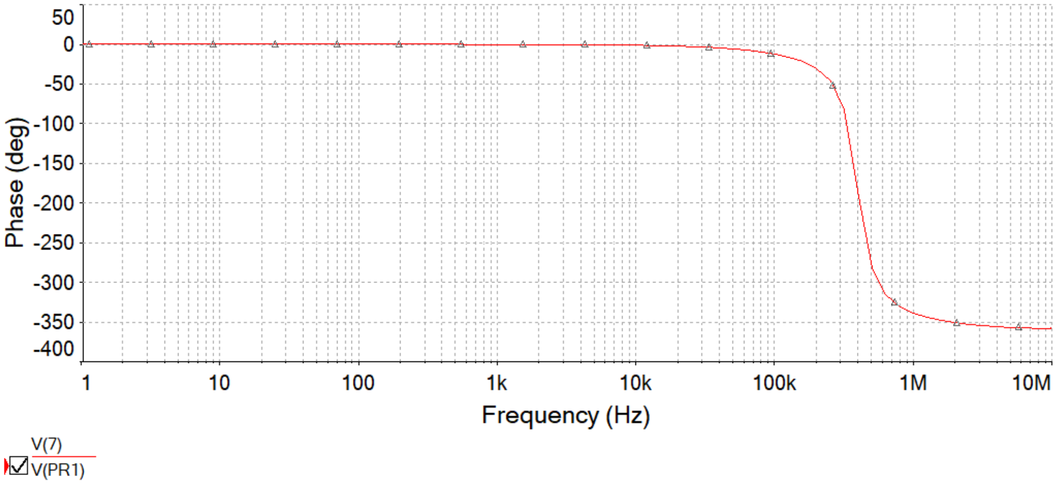


Figure 5.1.7:  Phase response of VM AP filter

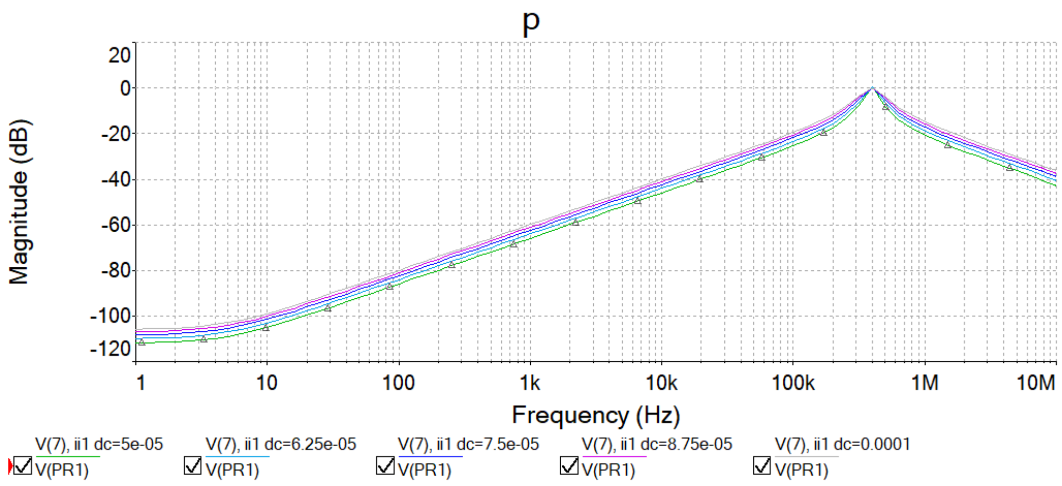


Figure 5.1.8: Gain response of VM BP filter for various values of Q

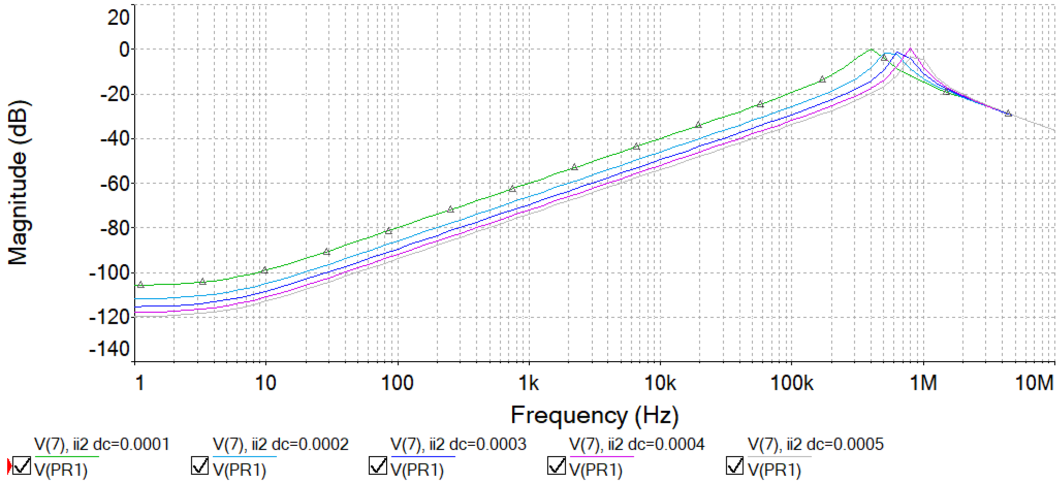


Figure 5.1.9: Gain response of VM BP filter for various frequencies

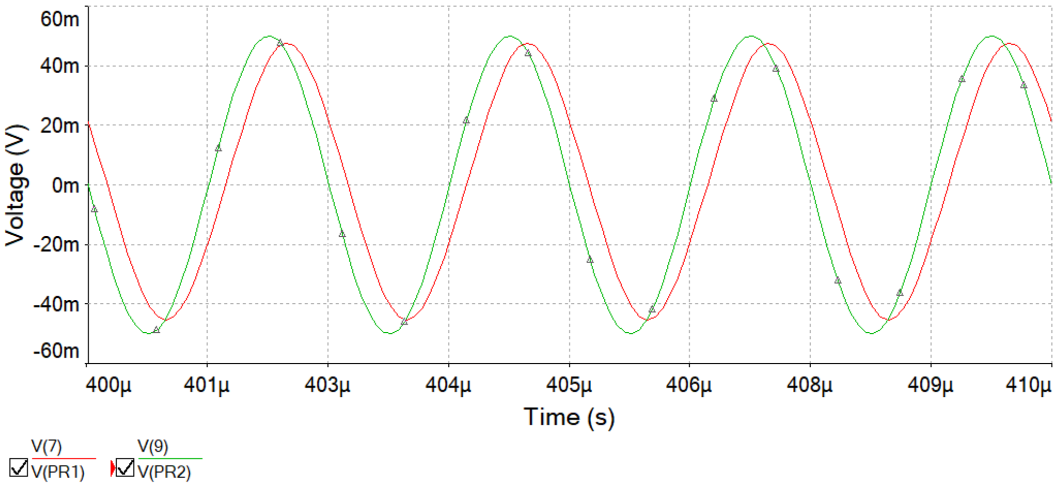


Figure 5.1.10: Transient response of VM BP filter (Red trace input and green trace output)

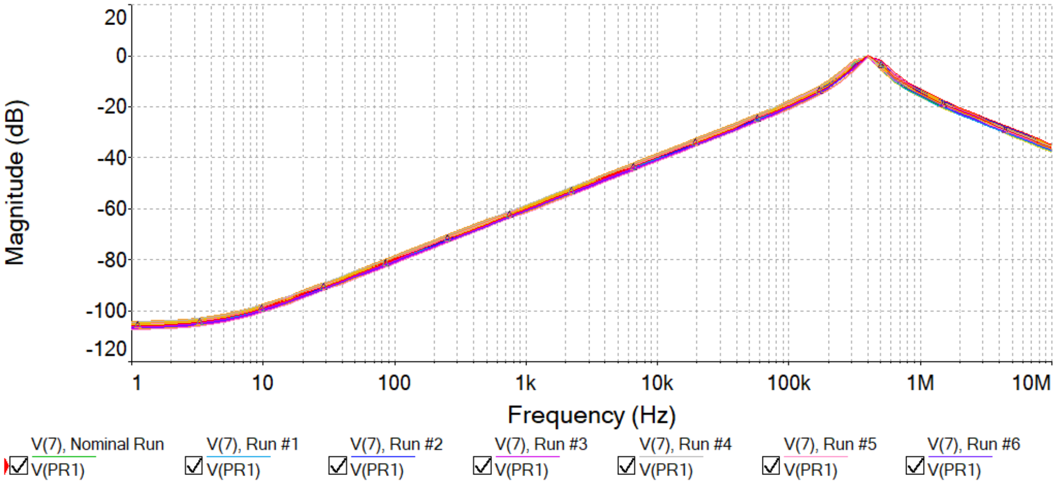


Figure 5.1.11: MC analysis of gain for VM BP filter

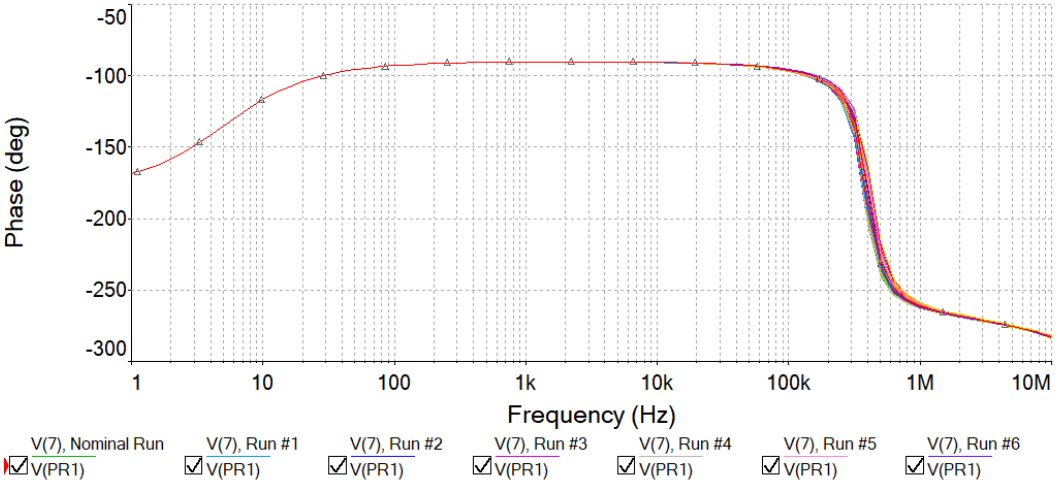


Figure 5.1.12: MC analysis for phase for VM BP filter

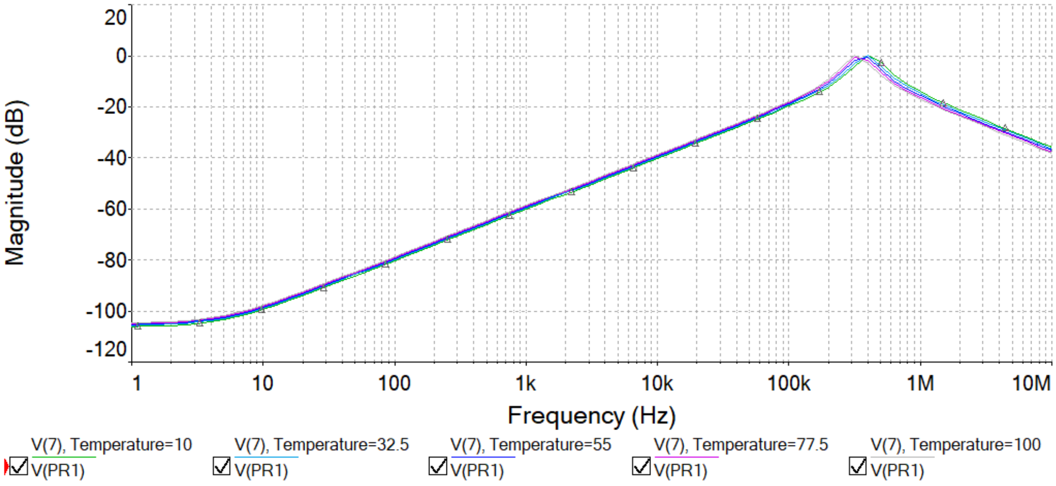


Figure 5.1.13: Gain response of VM BP filter at various temperatures

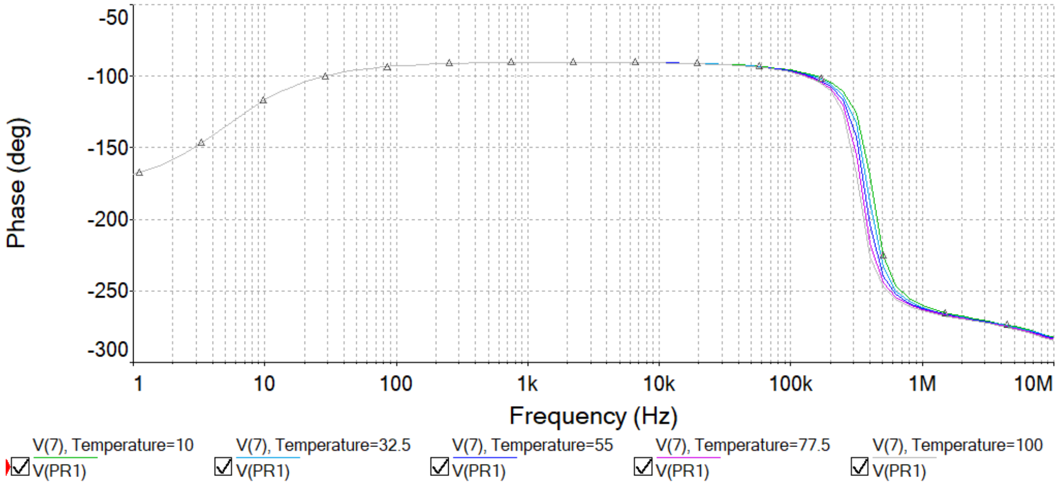


Figure 5.1.14: Phase response of VM BP filter for various temperatures

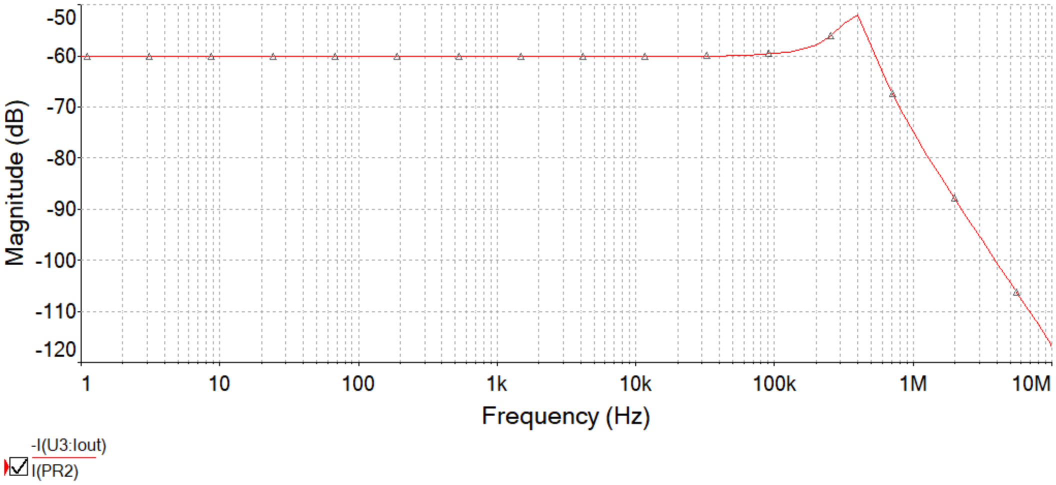


Figure 5.1.15: Gain response of TAM LP filter

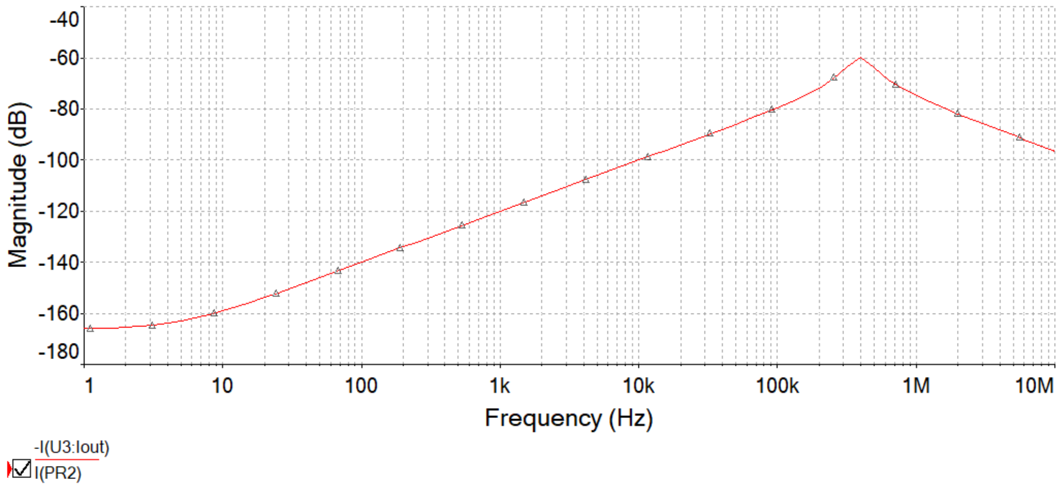


Figure 5.1.16: Gain response of TAM BP filter

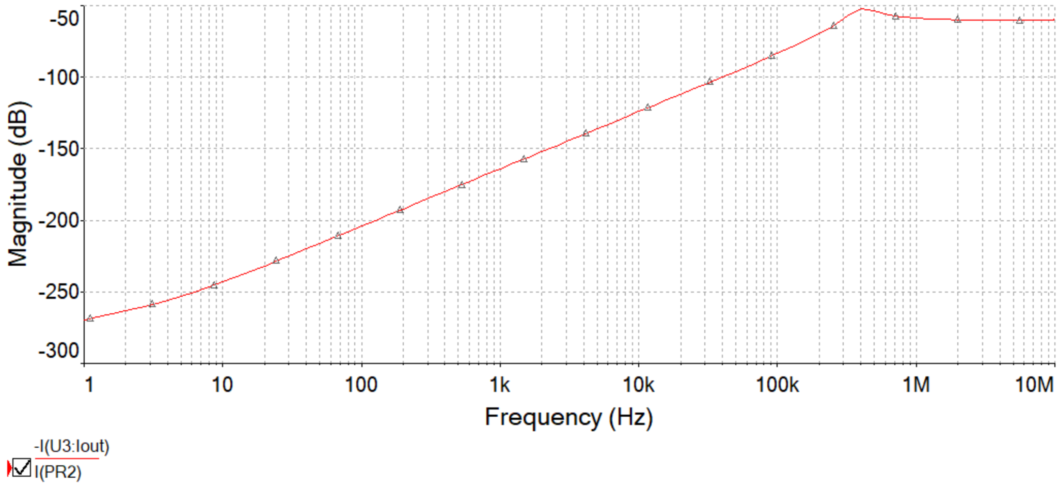


Figure 5.1.17: Gain response of TAM HP filter

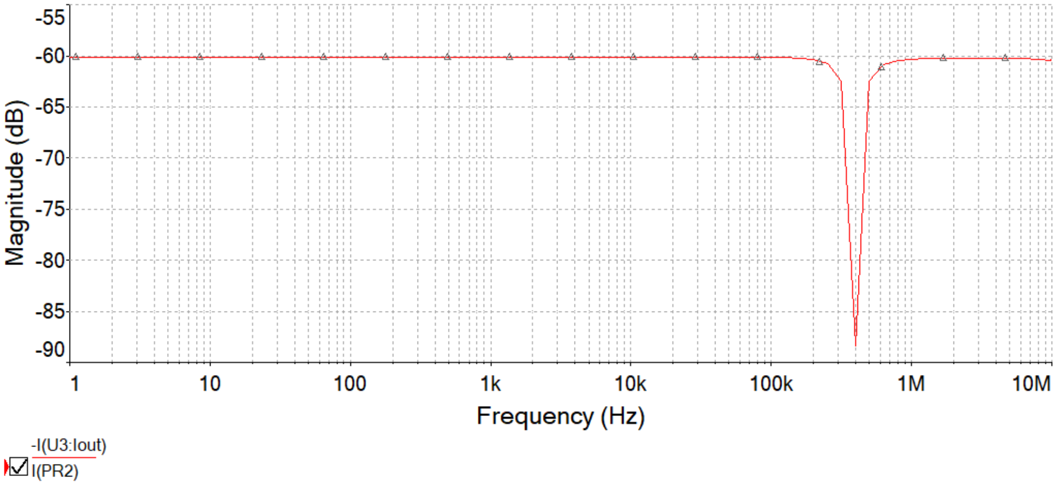


Figure 5.1.18: Gain response of TAM notch filter

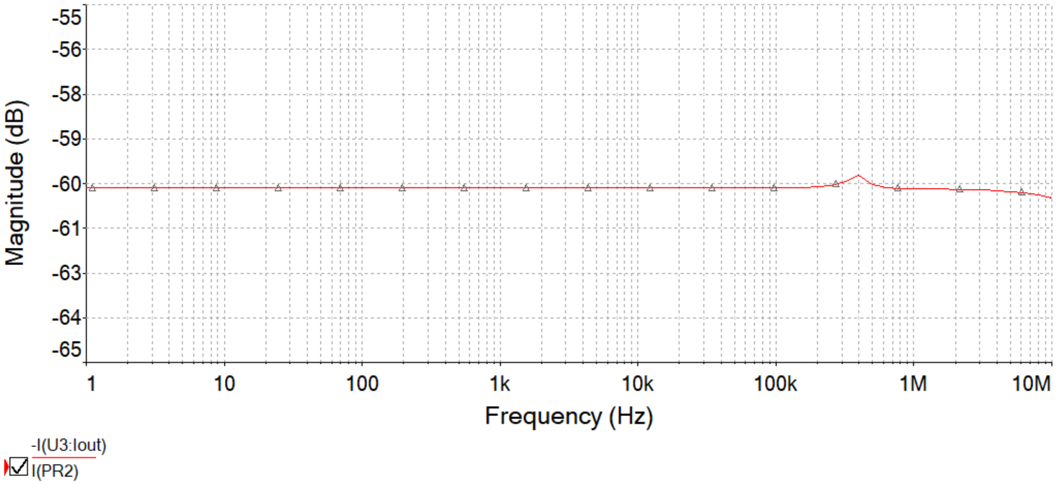


Figure 5.1.19: Gain response of TAM AP filter

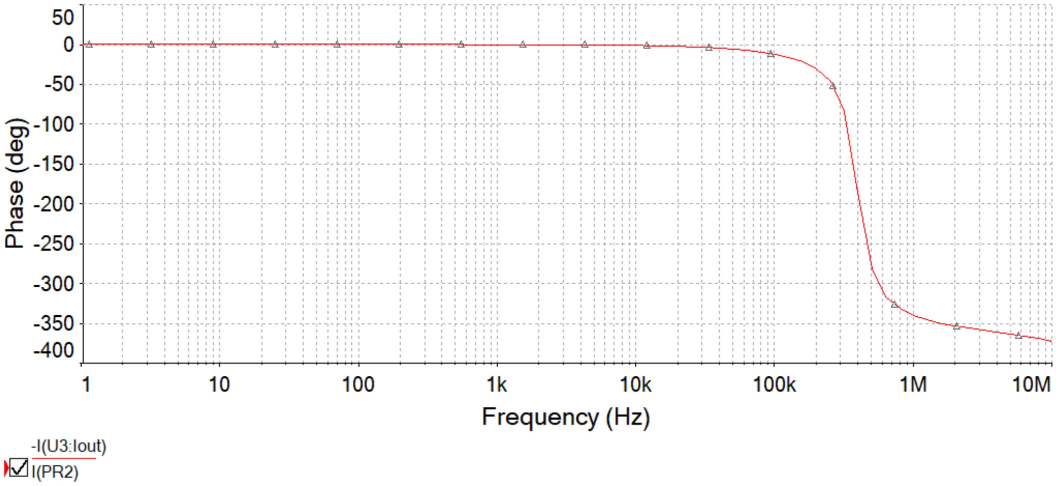


Figure 5.1.20: Phase response of TAM AP filter

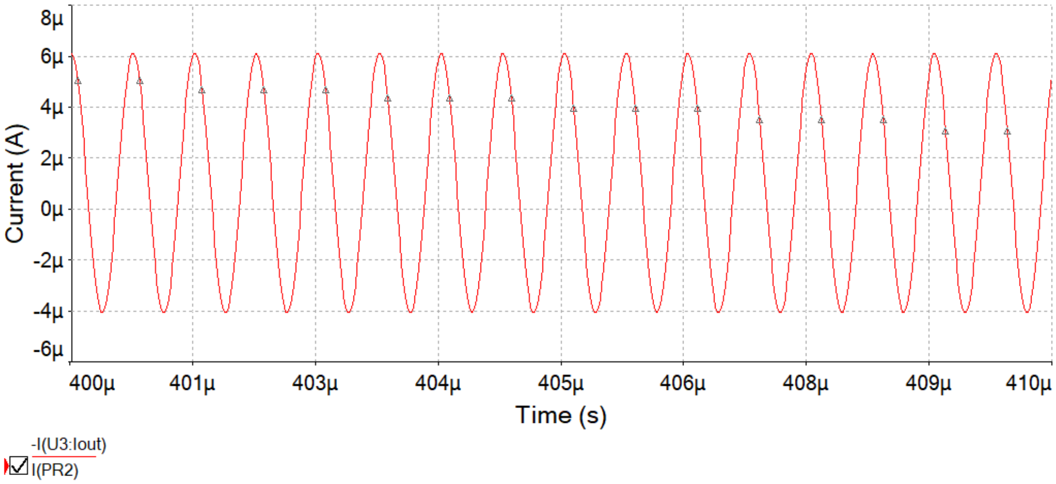


Figure 5.1.21: Transient response of TAM BP filter

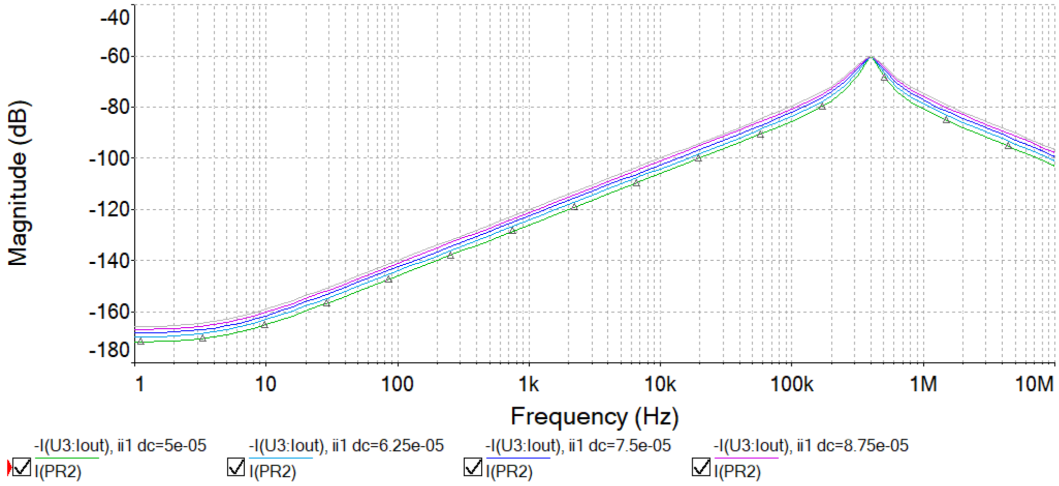


Figure 5.1.22: Gain response of TAM BP filter for different values of Q

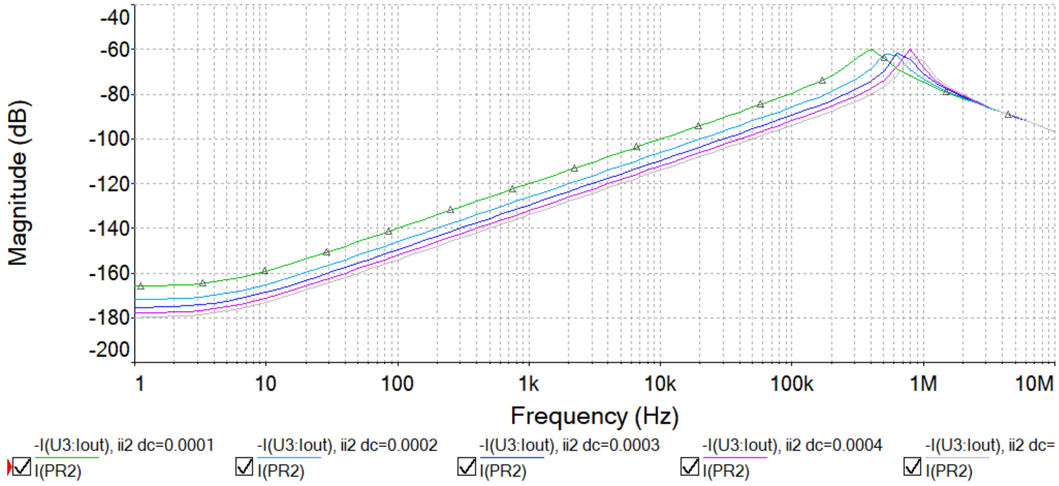


Figure 5.1.23: Gain response of TAM BP filter for different pole frequencies

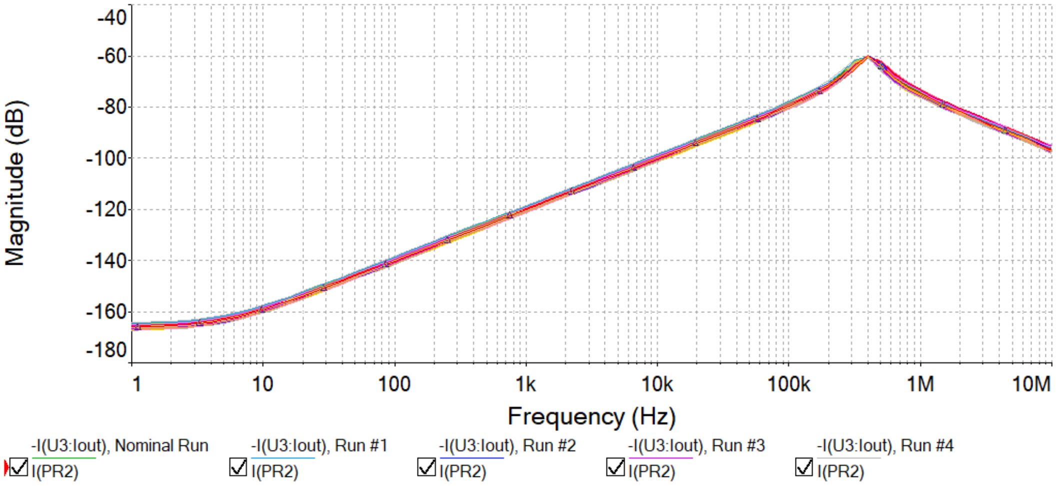


Figure 5.1.24: MC analysis of gain for TAM BP

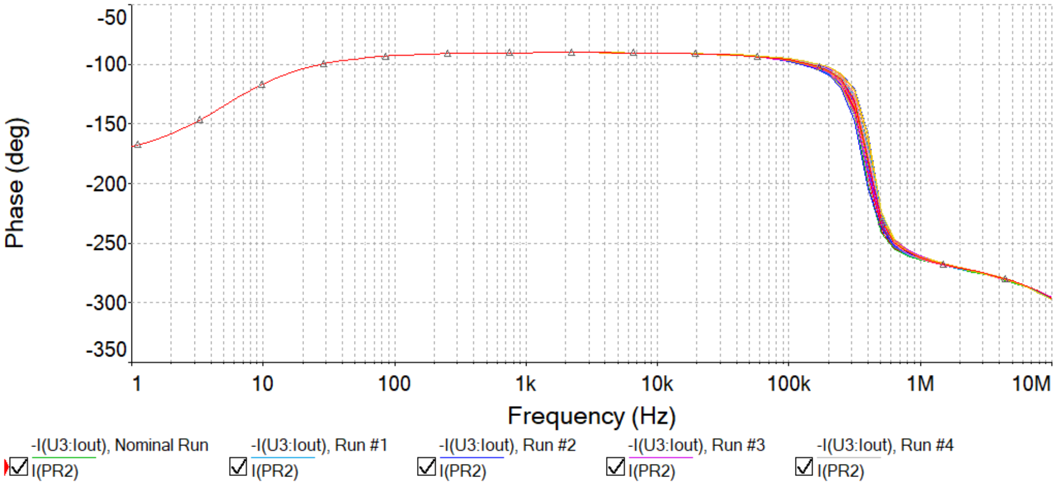


Figure 5.1.25: MC analysis of phase for TAM BP

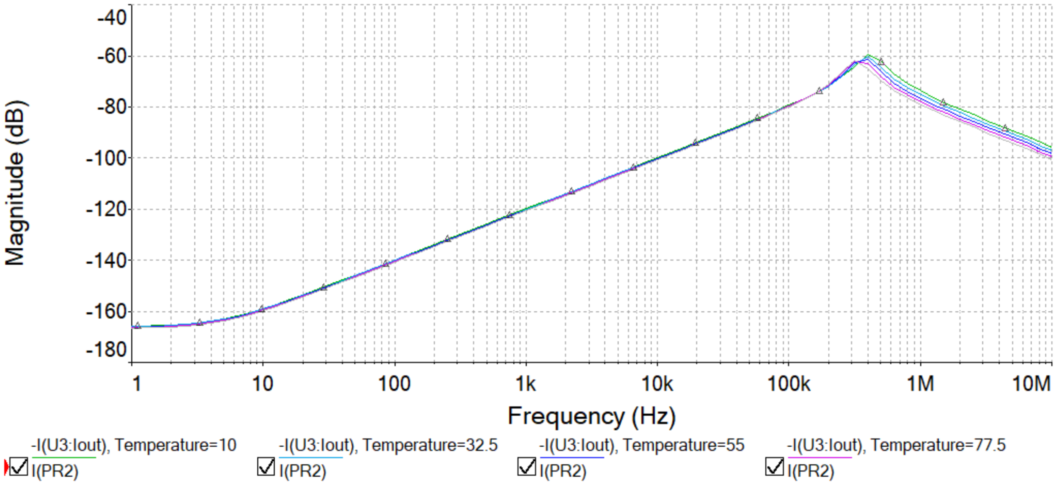


Figure 5.1.26: Gain response of TAM BP filter at various temperatures

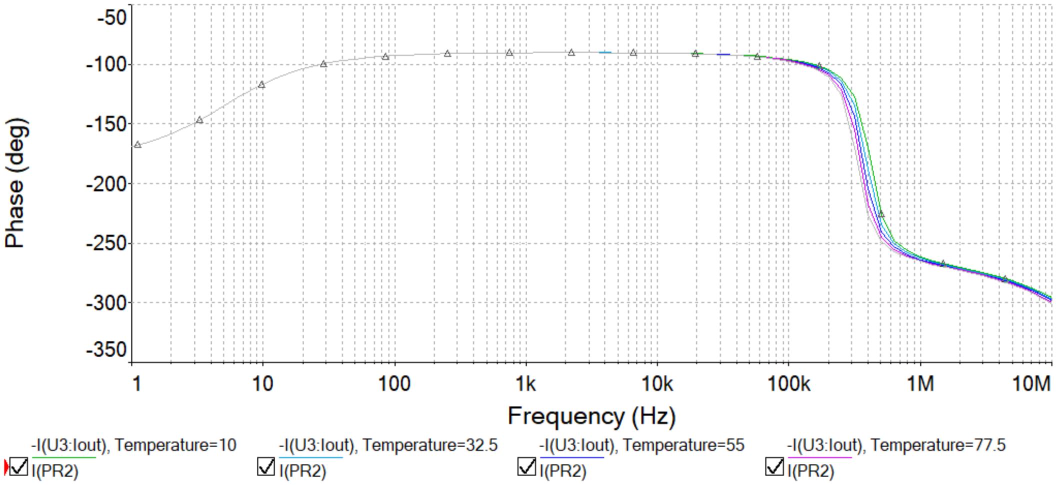


Figure 5.1.27: Phase response of TAM BP filter at various temperatures

## 5.2. CM band pass filter using VDTA and grounded capacitors

In applications such as automatic control, music synthesis, instrumentation and communication, the need arise to have filters having facility of non-interactive tuning procedure for filter parameters. Towards this end a novel minimum component CM band pass filter is presented shown in Figure (5.2.1). Following are features of the filters:

a) using minimum number of active and passive components,
b) grounded capacitors,
c) non-interactive tuning of gain, quality factor and pole frequency,
d) high output impedance facilitating cascadablity, and
e) low sensitivity figures.

Analysis of the CM band pass filter shown in Figure (5.2.1) using the port relation of VDTA is given as:

$$\frac{I_{BP}}{I_{in}} = \frac{g_4}{g_1}\frac{s\,{}^{g_1}/_{C_1}}{s^2+s\,{}^{g_1}/_{C_1}+\frac{g_2 g_3}{C_1 C_2}} \tag{5.2.1}$$

The filter performance factors are given below:

Pole frequency: $$\omega_0 = \sqrt{\frac{g_2 g_3}{C_1 C_2}} \tag{5.2.2}$$

Bandwidth: $$\frac{\omega_0}{Q} = \frac{g_1}{C_1} \tag{5.2.3}$$

Quality factor: $$Q = \frac{1}{g_1}\sqrt{\frac{C_1 g_2 g_3}{C_2}} \tag{5.2.4}$$

Gain: $$H = \frac{g_4}{g_1} \tag{5.2.5}$$

### Non-idealities of VDTA

Considering the non-ideal behaviour of VDTA due to mismatch of transistors, the filter parameters are given below:

Pole frequency: $\omega_0 = \sqrt{\frac{\beta_2\beta_3 g_2 g_3}{C_1 C_2}}$

Bandwidth: $\frac{\omega_0}{Q} = \frac{\beta_1 g_1}{C_1}$

Quality factor: $Q = \frac{1}{\beta_1 g_1}\sqrt{\beta_2\beta_2\frac{C_1 g_2 g_3}{C_2}}$

Gain: $H = \frac{\beta_4 g_4}{\beta_1 g_1}$

From equations (5.2.2) to (5.2.5), it is seen that the filter performance factors are electronically tunable through the bias currents of VDTAs. The pole frequency can be tuned by $g_2$ or $g_3$. The quality factor Q (or bandwidth) can be varied by $g_1$ without disturbing pole frequency. The gain can be changed by $g_4$ without disturbing pole frequency or quality factor. The non-ideal behaviour of VDTA produces shift in the filter performance factors. Taking into account the tolerances of the components the sensitivities analysis is employed to find its effects on filter performance factors. It is seen that the sensitivities are low as given below:

$$S_{g_2}^{\omega_0} = S_{g_3}^{\omega_0} = -S_{C_1}^{\omega_0} = -S_{C_2}^{\omega_0} = \frac{1}{2}$$

$$S_{g_1}^{Q} = -1, \qquad S_{g_2}^{Q} = S_{g_3}^{Q} = S_{C_1}^{Q} = -S_{C_2}^{Q} = \frac{1}{2}$$

$$-S_{g_1}^{H} = S_{g_4}^{H} = 1$$

The sensitivity figures of the pole frequency and quality factor are 0.5while for the gain parameter it is 1.

### Simulation

To check the proposed filter simulations are carried out. The VDTAs used are realized by the employment of LT1228 OTAs. The value of the capacitors chosen is 1 nF while the transconductance gains are 1 mA/V ($I_{bias}$ = 100uA). The filter parameters calculated are pole frequency $f_0$ = 159 KHz, gain H = 1, and quality factor Q = 1. The simulation results are shown in Figures (5.2.2) to (5.2.10). Figure (5.2.2) represents the gain response. Figures (5.2.3), (5.3.4), and (5.2.5) depict the variation of gain, quality factor, and frequency of the filter with respective transconductance gains of VDTAs. Figures (5.2.6) shows the transient responses. Figures (5.2.7) and (5.3.8) represent MC analysis in frequency and time domain respectively. Figures (5.2.9) and (5.2.10) show the effect of temperature on the gain in frequency and time domain respectively.

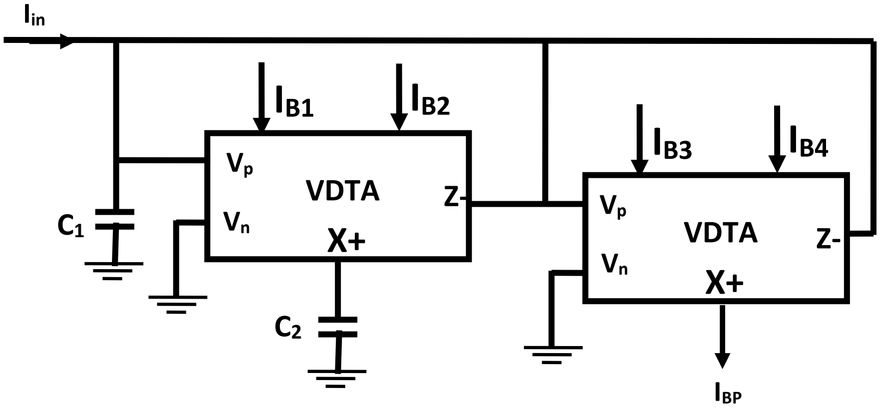


Figure 5.2.1: Proposed CM band pass filter

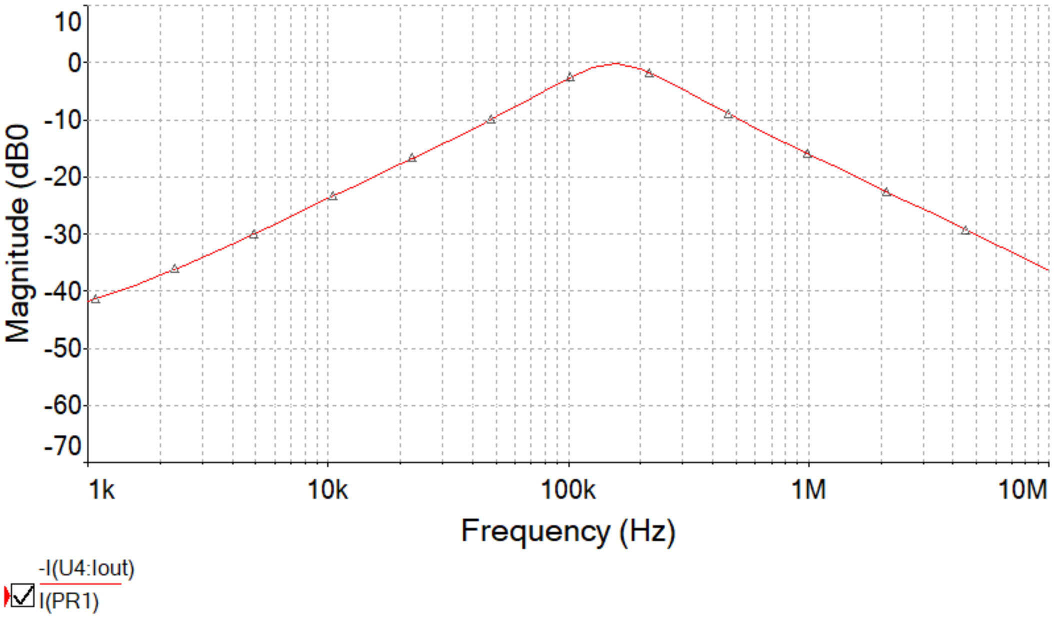


Figure 5.2.2: Gain response of BP filter

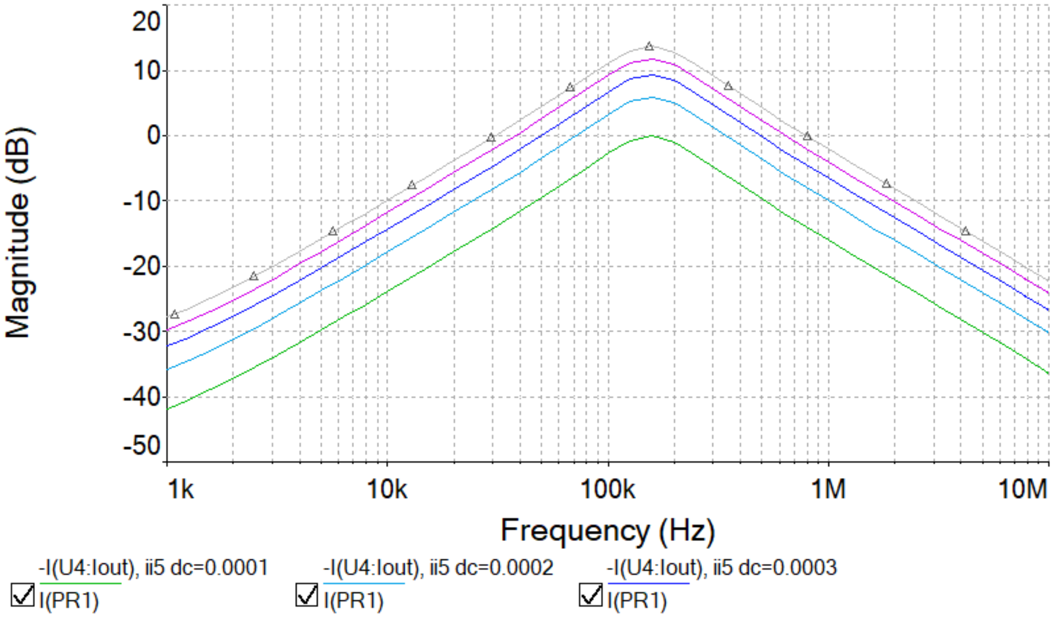


Figure 5.2.3: Variation of gain of BP filter with $g_4$

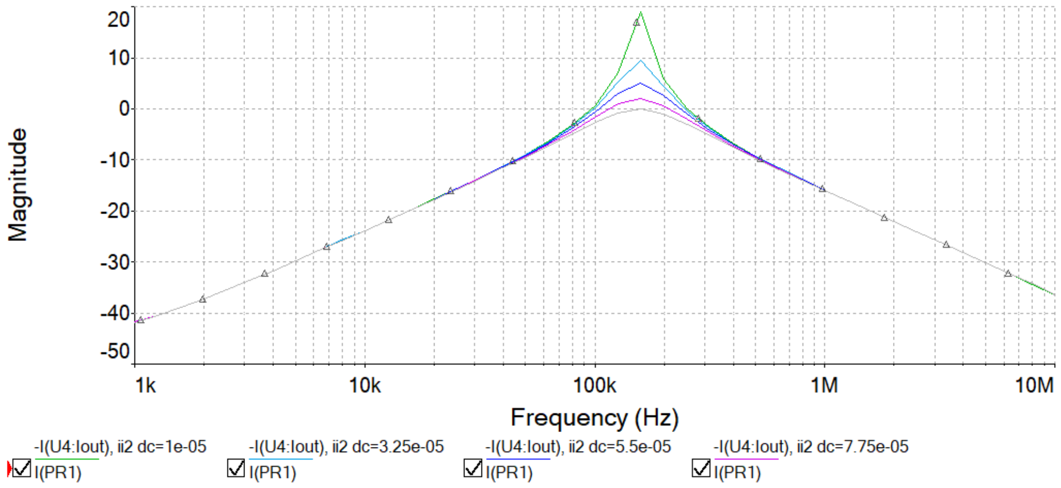


Figure 5.2.4: Variation of quality factor of BP filter with $g_1$

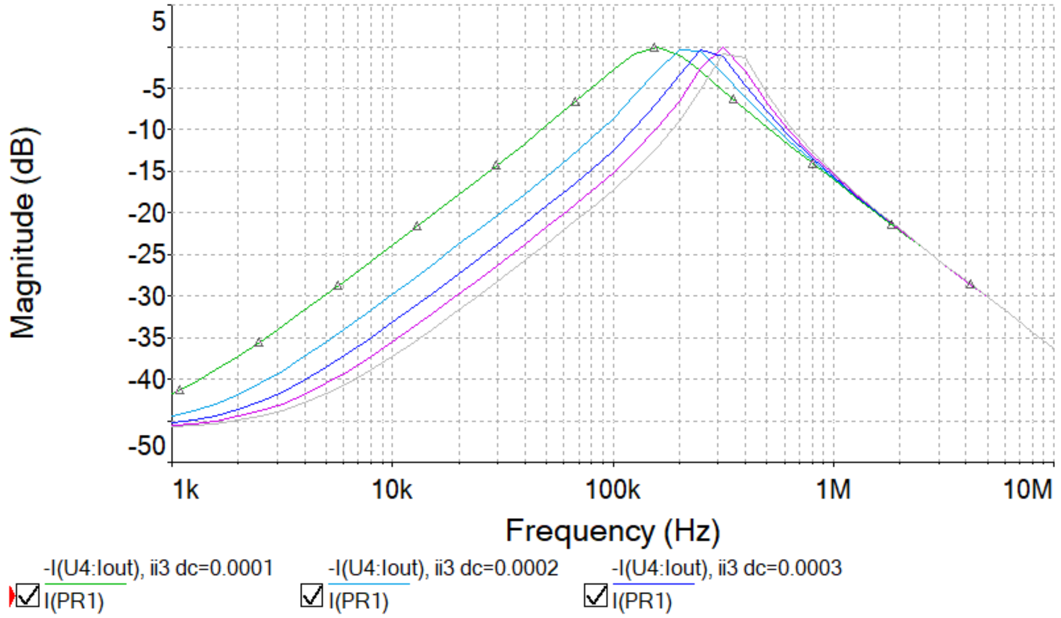


Figure 5.2.5: Variation of frequency with $g_2$ of BP filter

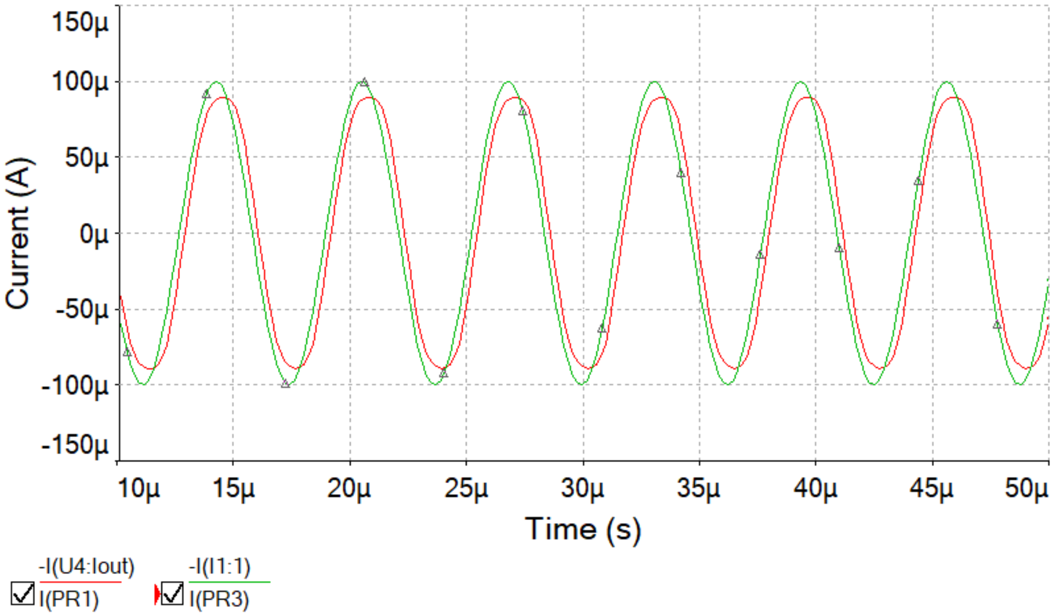


Figure 5.2.6: Transient response of BP filter

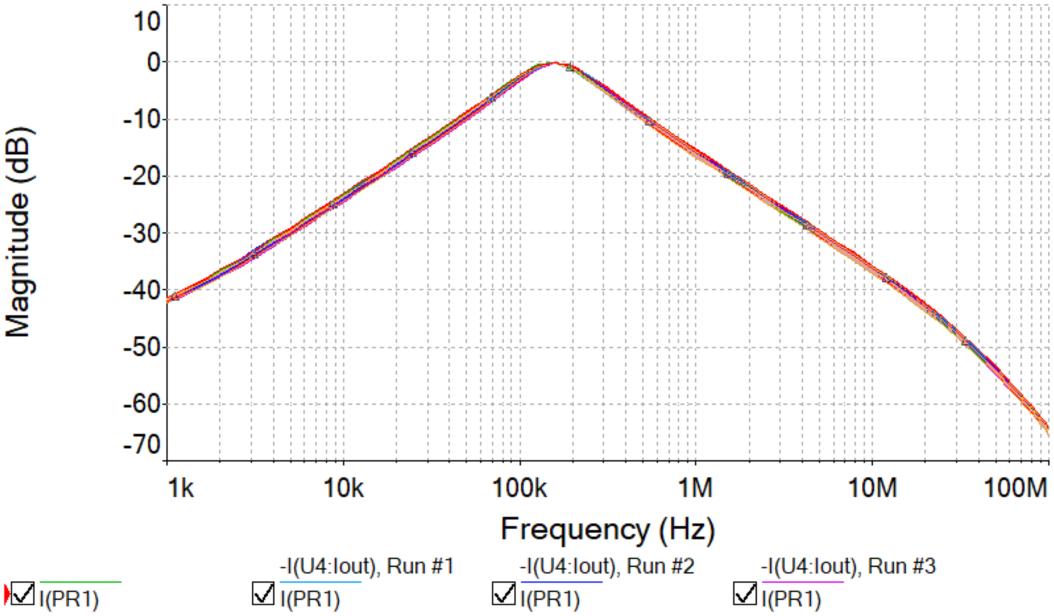


Figure 5.2.7: MC analysis of BP filter in frequency domain

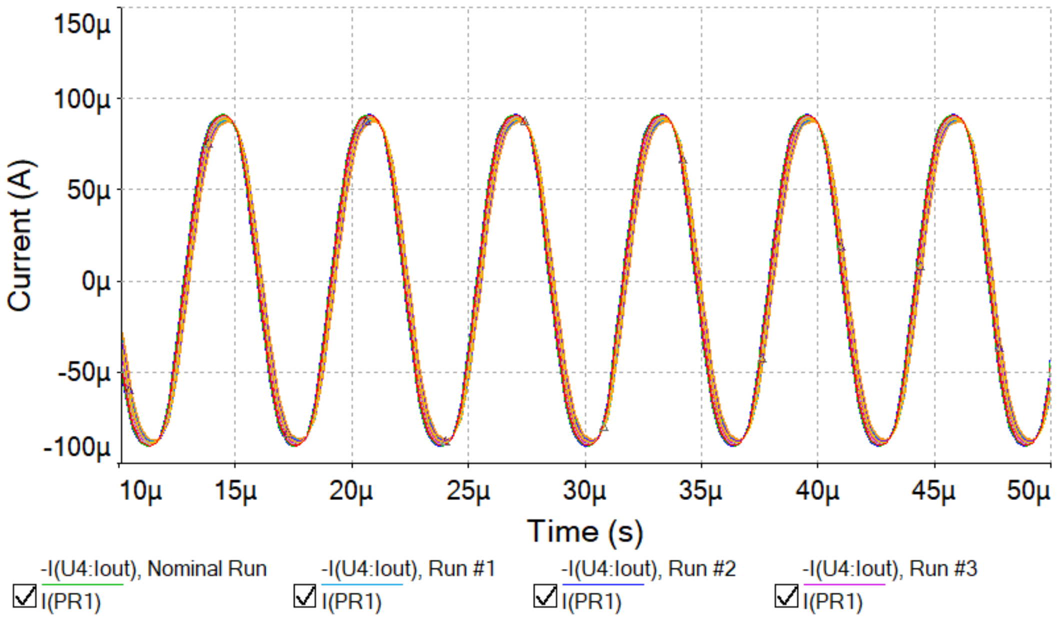


Figure 5.2.8: MC analysis of BP filter in time domain

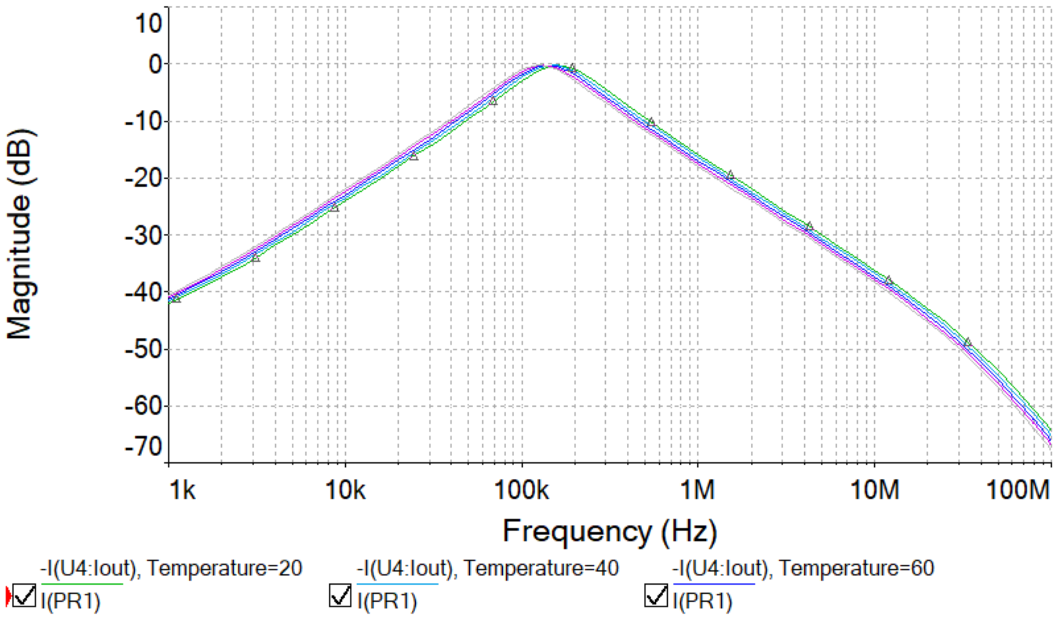


Figure 5.2.9: Gain response of BP filter at various temperatures in frequency domain

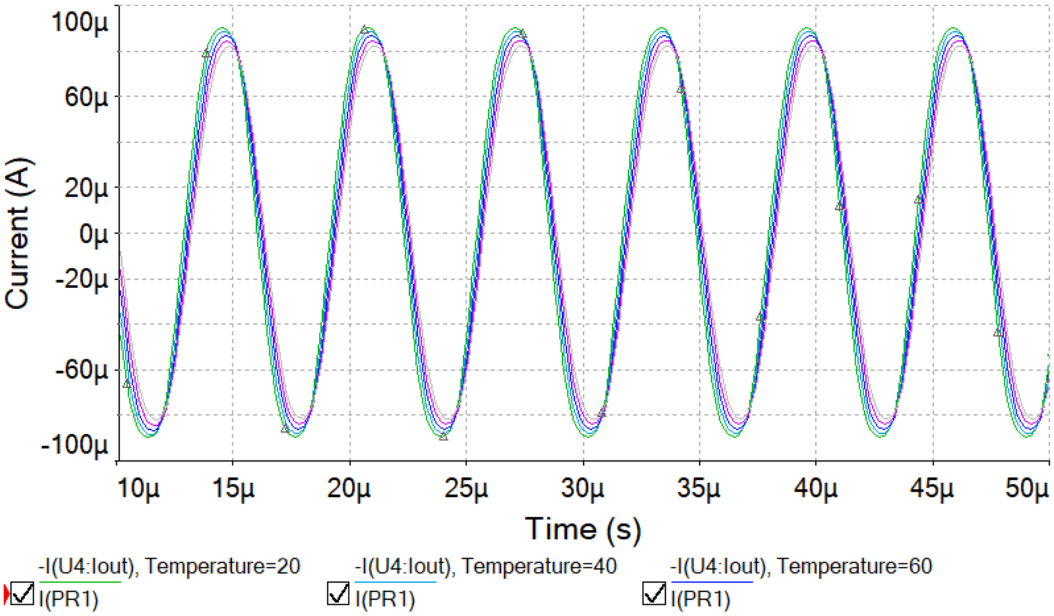


Figure 5.2.10: Gain response of BP filter at variations temperatures in time domain

### 5.3 Single input and multi output VM and TAM filter using grounded Capacitors

A novel universal filter having a single voltage input and six outputs is presented. The outputs available are three in VM and three in CM. Thus the filter realizes six filtering functions simultaneously. The filter employs only two MO-VDTA and two grounded capacitors. The input and output impedances of the filter are high and thus do not need additional devices for cascading. The grounded capacitors are highly suitable for integration. The filter performance factors gain, bandwidth and pole frequency are electronically tunable in an independent manner. However, quality factor of the filter cannot be varied independently. It is to mention here that the signal suffers loss in the processing and needs additional circuitry to amplify the signal. The proposed filter acts as an amplifier also. Using port relations of VDTAs, routine analysis of the proposed filter shown in Figure (5.3.1), gives the following transfer functions in VM and TAM:

$$\frac{V_{HP}}{V_{in}} = \frac{g_1}{g_2}\left(\frac{s^2}{D(s)}\right) \tag{5.3.1}$$

$$\frac{V_{BP}}{V_{in}} = \frac{g_1}{g_2}\left(\frac{s\frac{g_3}{C_1}}{D(s)}\right) \tag{5.3.2}$$

$$\frac{V_{LP}}{V_{in}} = \frac{g_1}{g_4}\left(\frac{\frac{g_3 g_4}{C_1 C_2}}{D(s)}\right) \tag{5.3.3}$$

$$\frac{I_{HP}}{V_{in}} = g_1\left(\frac{s^2}{D(s)}\right) \tag{5.3.4}$$

$$\frac{I_{BP}}{V_{in}} = g_1\left(\frac{s\frac{g_3}{C_1}}{D(s)}\right) \tag{5.3.5}$$

$$\frac{I_{LP}}{V_{in}} = g_1\left(\frac{\frac{g_3 g_4}{C_1 C_2}}{D(s)}\right) \tag{5.3.6}$$

$$\frac{I_{Notch}}{V_{in}} = \frac{I_{HP}+I_{LP}}{V_{in}} = g_1\left(\frac{s^2+\frac{g_3 g_4}{C_1 C_2}}{D(s)}\right) \tag{5.3.7}$$

$$\frac{I_{AP}}{V_{in}} = \frac{I_{HP} - I_{BP} + I_{LP}}{V_{in}} = \; g_1 \left( \frac{s^2 - s\frac{g_3}{C_1} + \frac{g_3 g_4}{C_1 C_2}}{D(s)} \right) \tag{5.3.8}$$

For the realization of the AP filter, the condition is $g_2 = g_3 = g_4$

where $$D(s) = \; s^2 + s\frac{g_3}{C_1} + \; \frac{g_3 g_4}{C_1 C_2} \tag{5.3.9}$$

The notch and all pass filtering functions of TAM are obtained by tying together appropriate current outputs. However, to obtain notch and all pass filtering functions in VM, the filter needs additional devices. The filter performance factors, gain, bandwidth, quality factor, and pole frequency are given by:

$$\omega_0 \; = \; \sqrt{\frac{g_3 g_4}{C_1 C_2}} \tag{5.3.10}$$

$$\frac{\omega_0}{Q} = \frac{g_3}{C_1} \tag{5.3.11}$$

$$Q \; = \; \sqrt{\frac{g_4 C_1}{g_3 C_2}} \tag{5.3.12}$$

$$H_{HP} \; = \frac{g_1}{g_2}, \quad H_{BP} \; = \frac{g_1}{g_3}, \; H_{LP} = \frac{g_1}{g_2} \tag{5.3.13}$$

From equations (5.3.1) to (5.3.6), it is seen that the filter implements basic filtering functions three in VM and three in CM simultaneously. The other two filtering functions in TAM notch and AP are implemented by tying appropriate node currents as depicted in equations (5.3.7) and (5.3.8). The pole frequency can be tuned by changing $g_4$, while $g_3$ is used to change the bandwidth. However, Q cannot be tuned independently. The gain of all responses is tuned by $g_1$ without disturbing other filtering functions as shown in equation (5.3.13).

## Non-idealities of VDTA

Considering the non-ideal behaviour of VDTA due to a mismatch of transistors to filter performance factors modify to:

$$\omega_0 = \sqrt{\frac{\beta_3\beta_4 g_3 g_4}{C_1 C_2}}$$

$$\frac{\omega_0}{Q} = \beta_3 \frac{g_3}{C_1}$$

$$Q = \sqrt{\frac{\beta_4 g_4 C_1}{\beta_3 g_3 C_2}}$$

$$H_{HP} = \left(\frac{\beta_1}{\beta_2}\right)\frac{g_1}{g_2}, \quad H_{BP} = \left(\frac{\beta_1}{\beta_3}\right)\frac{g_1}{g_3}, \ H_{LP} = \left(\frac{\beta_1}{\beta_4}\right)\frac{g_1}{g_2}$$

From the above equations, it is clear that the non-idealites affect the filter performance factors.

The active and passive sensitivities low and are given below:

$$S_{\beta_3}^{\omega_0} = S_{\beta_4}^{\omega_0} = S_{g_3}^{\omega_0} = S_{g_4}^{\omega_0} = -S_{C_1}^{\omega_0} = -S_{C_2}^{\omega_0} = \frac{1}{2}$$

$$S_{\beta_3}^{\frac{\omega_0}{Q}} = -S_{C_1}^{\frac{\omega_0}{Q}} = S_{g_3}^{\frac{\omega_0}{Q}} = 1$$

$$-S_{\beta_3}^{Q} = S_{\beta_4}^{Q} = -S_{g_3}^{Q} = S_{g_4}^{Q} = S_{C_1}^{Q} = -S_{C_2}^{Q} = \frac{1}{2}$$

$$S_{\beta_1}^{H_{HP}} = -S_{\beta_2}^{H_{HP}} = S_{g_1}^{H_{HP}} = -S_{g_2}^{H_{HP}} = 1$$

$$S_{\beta_1}^{H_{BP}} = -S_{\beta_3}^{H_{BP}} = S_{g_1}^{H_{BP}} = -S_{g_3}^{H_{BP}} = 1$$

$$S_{\beta_1}^{H_{LP}} = -S_{\beta_4}^{H_{LP}} = S_{g_1}^{H_{LP}} = -S_{g_4}^{H_{LP}} = 1$$

Thus the sensitivities are in the range of 0.5 to 1.

## Simulation Results

To check the performance of the filter PSPICE simulation is used in which VDTA is obtained by cascading two LT1228s. The filter is constructed for a pole frequency of 1.59 MHz. The transconductance gains of VDTAs are set to 1 mA/V ($I_{bi}$ = 100uA, i = 1,2,3,4) and capacitor values are chosen equal to 100 pF. Figures (5.3.2) and (5.3.3) shows the gain response of LP, HP and BP, in VM and TAM. Figure (5.3.4) depicts the gain response of the notch filter while figures (5.3.5) and (5.3.6) show the gain and phase response of TAM AP filter. The variation of gain of the LP, BP, and HP in both modes is shown in figures (5.3.7) and (5.3.8). Similarly, the variation of gain of the notch and AP is shown in figures (5.3.9) and (5.3.10). The transient response for input signal 1.59 MHz and 50 mV peak-to-peak is obtained for LP response of VM filter and is shown in Figure (5.3.11). Figures (5.3.11), (5.3.11), and (5.3.11) show the MC analysis results of HP, BP, and AP (phase). The MC analysis is obtained with 50 runs, 10% tolerance of capacitors, and uniform distribution.

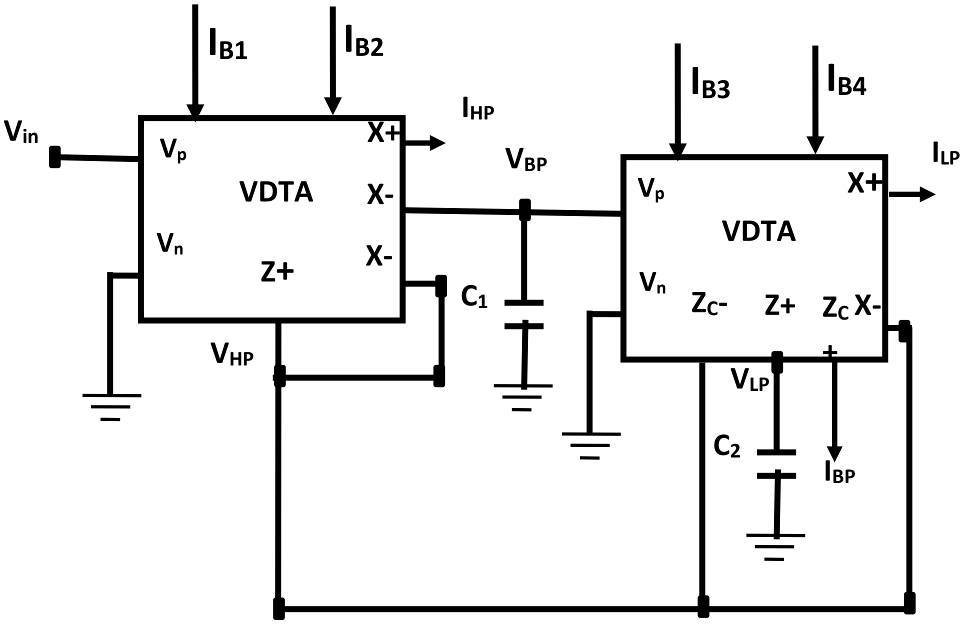


Figure 5.3.1:  Proposed CM and TAM universal filter

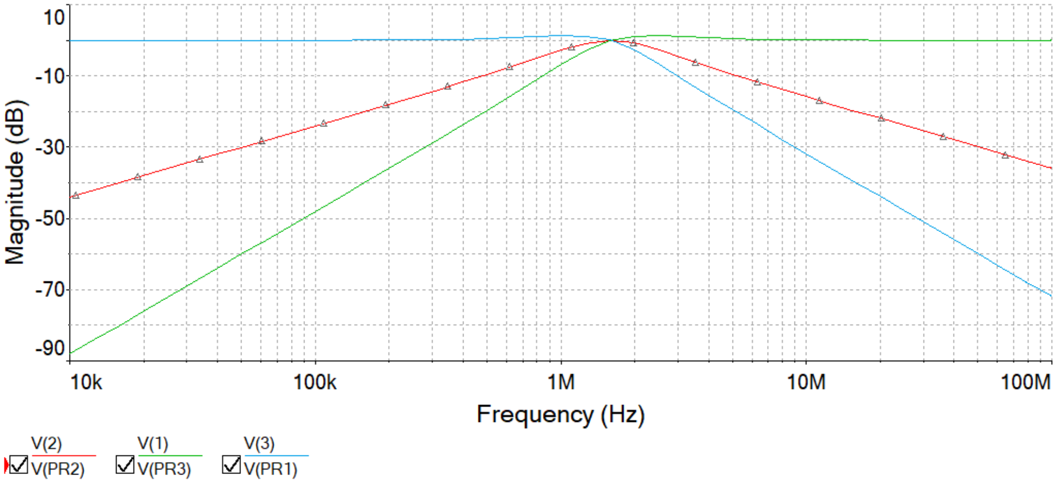


Figure 5.3.2:  LP, HP and BP response of proposed VM filter

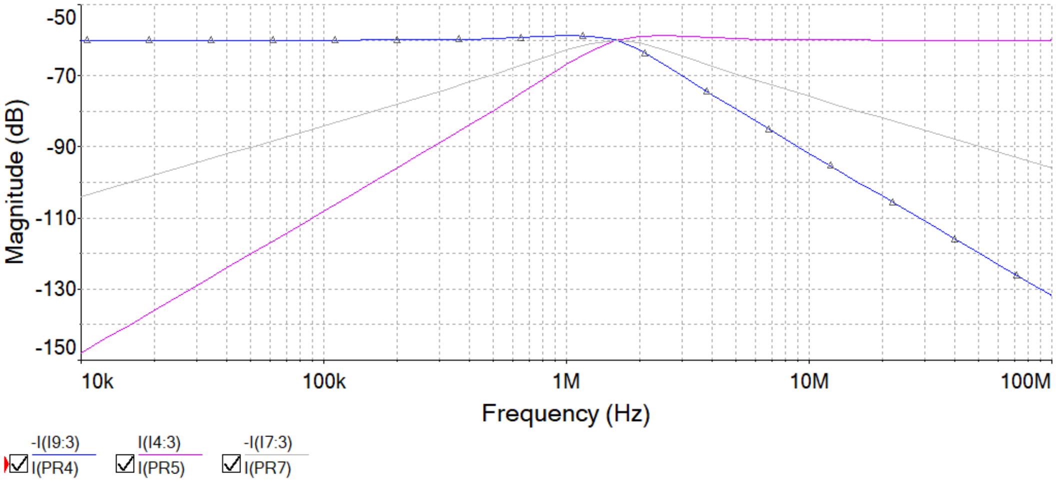


Figure 5.3.3:  LP, HP and BP response of proposed TAM filter

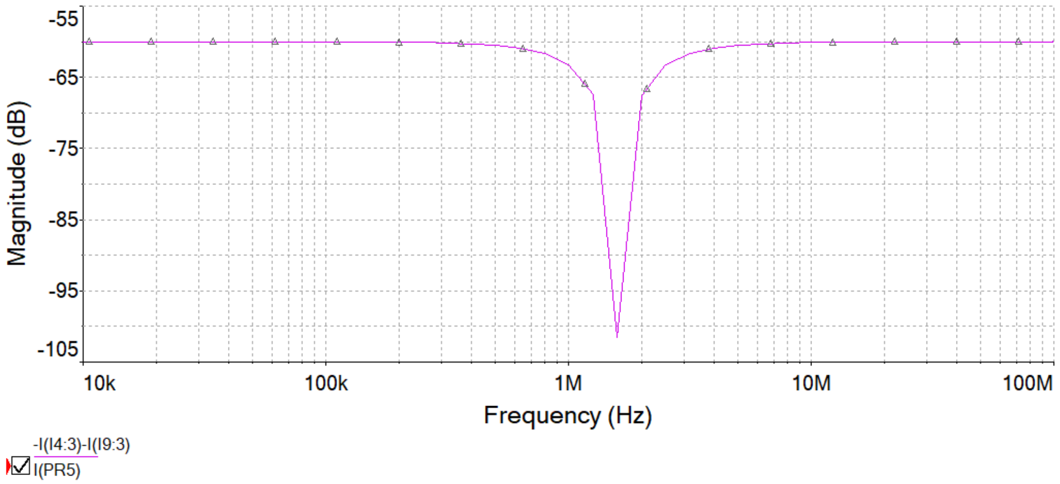


Figure 5.3.4: Notch response of proposed TAM filter

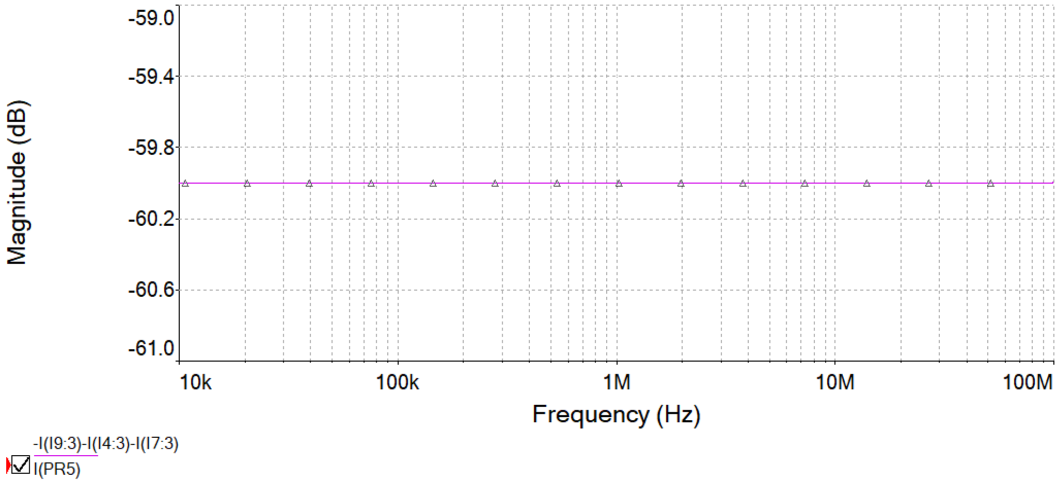


Figure 5.3.5: AP gain response of proposed TAM filter

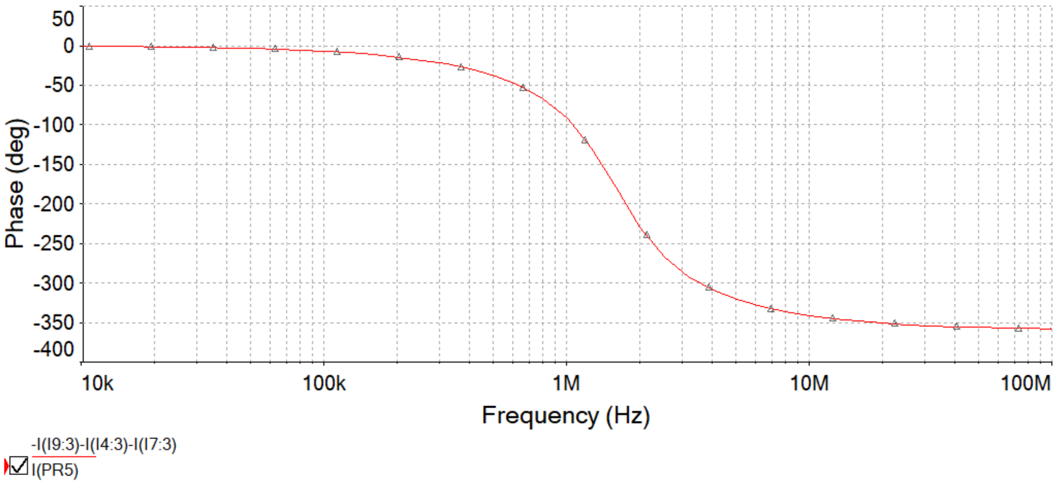


Figure 5.3.6: AP phase response of proposed TAM filter

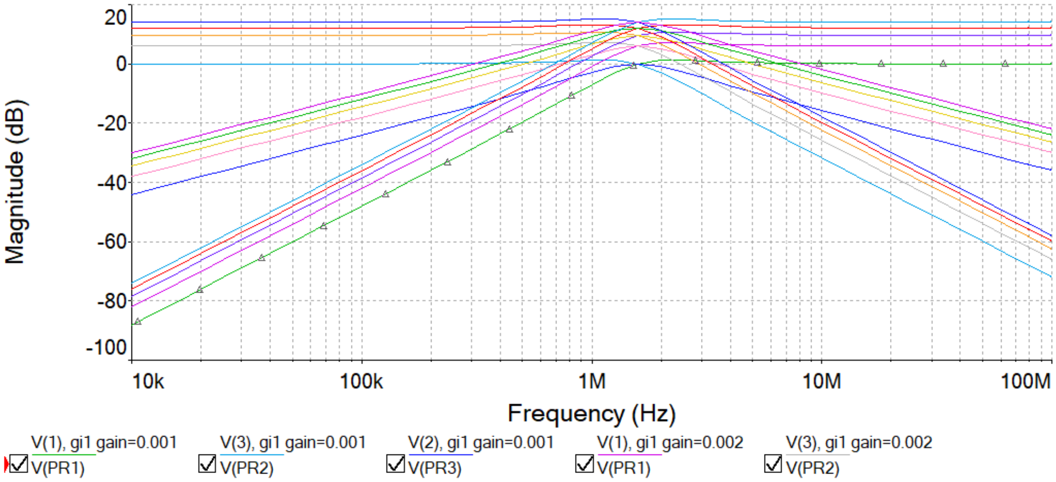


Figure 5.3.7: Variation of gain of LP, HP, and BP VM filter

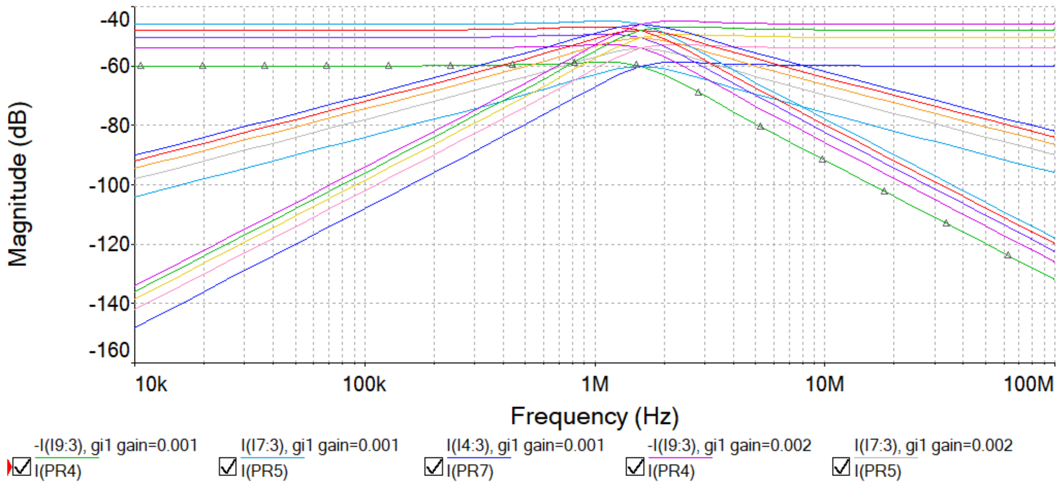


Figure 5.3.8: Variations of gain of LP, HP, and BP response of TAM filter

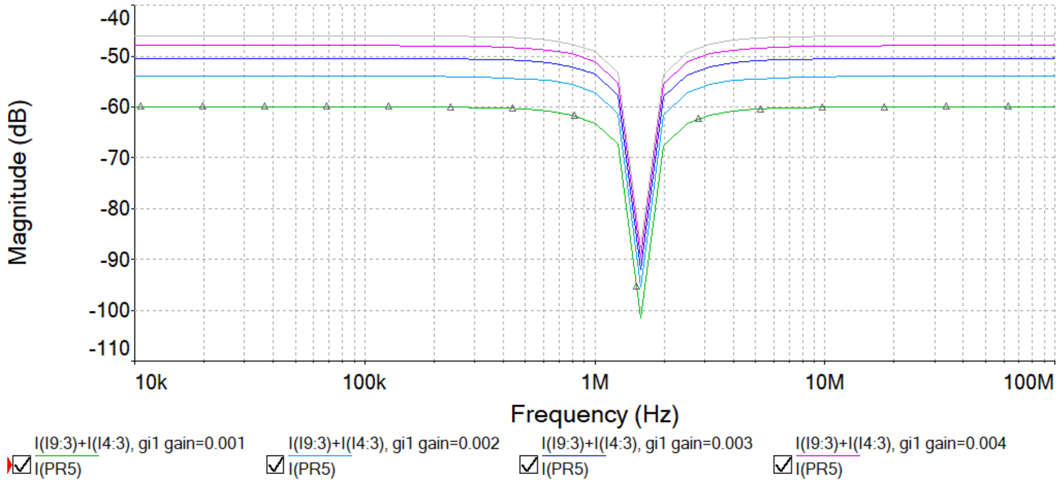


Figure 5.3.9: Variation of gain of notch response of TAM filter

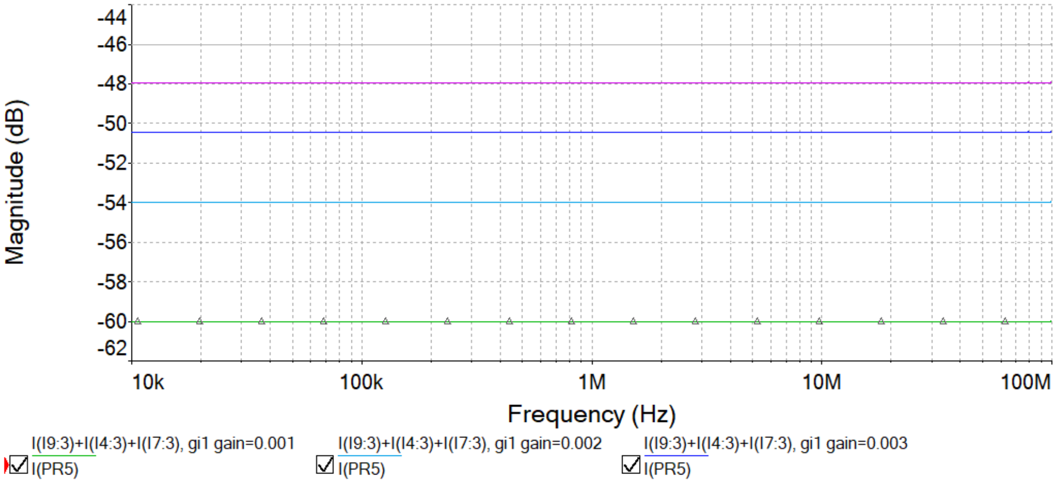


Figure 5.3.10: Variations of gain of AP proposed TAM filter

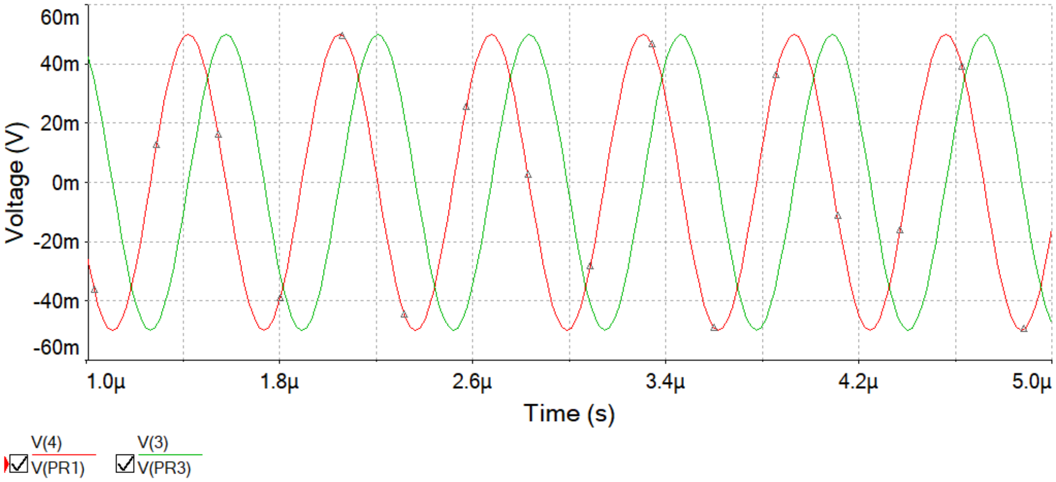


Figure 5.3.11: Transient response of VM LP filter (red trace is input and green trace is output)

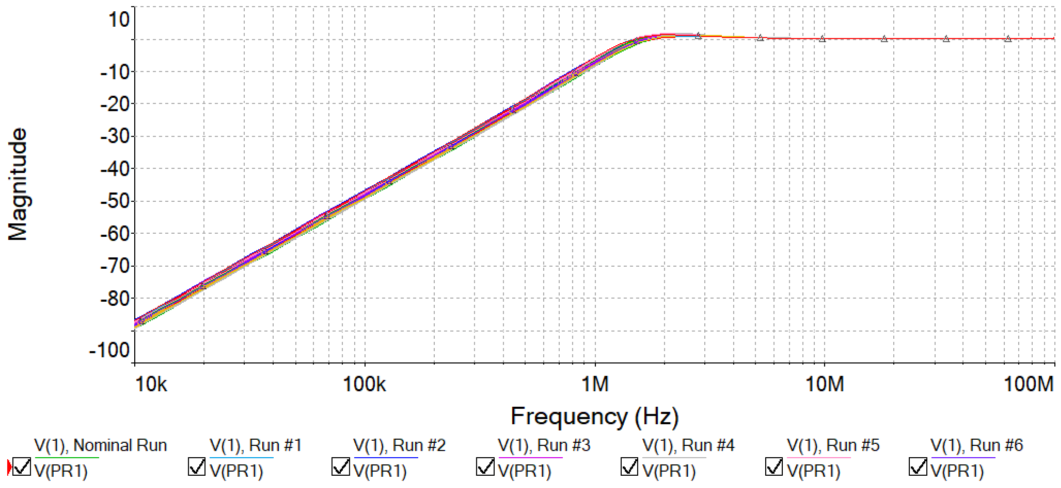


Figure 5.3.12: MC analysis of VM HP filter

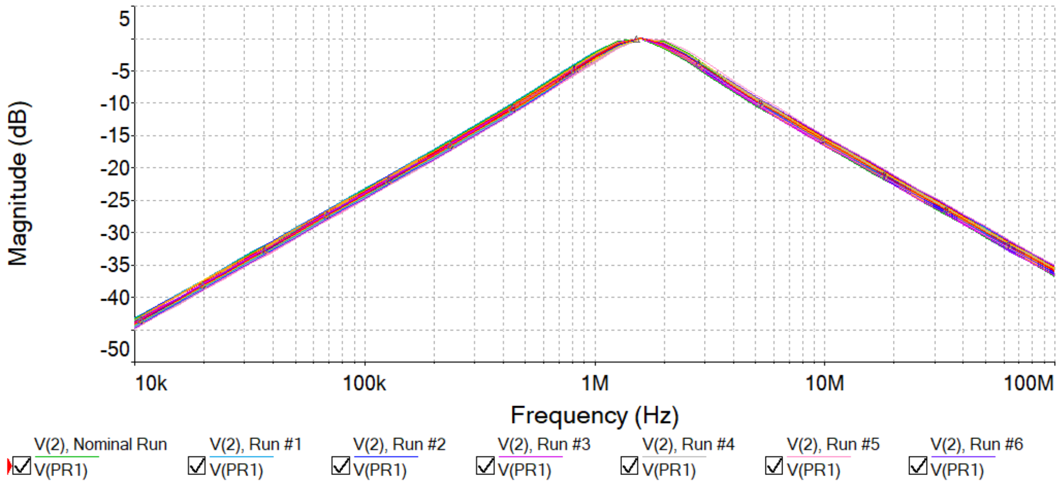


Figure 5.3.13: MC analysis of VM BP filter

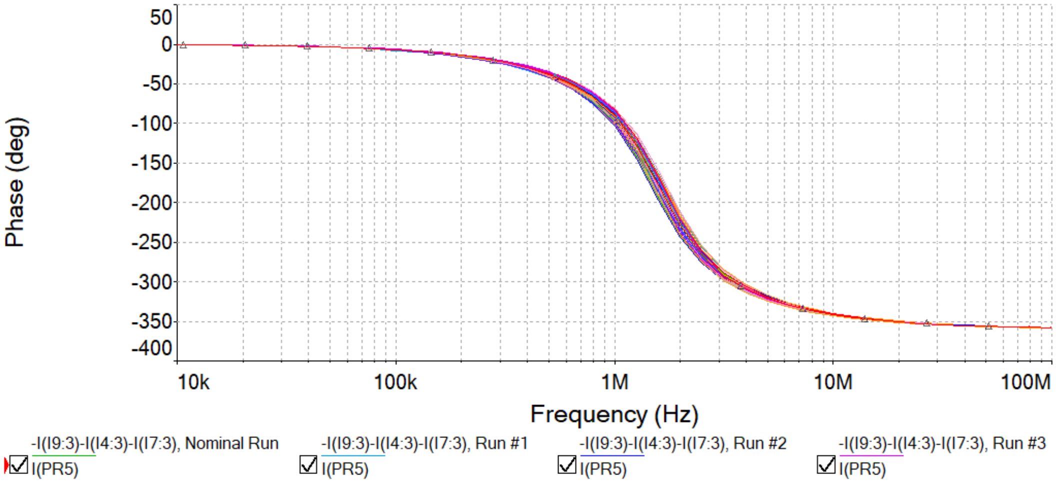


Figure 5.3.14: MC analysis of phase of TAM AP filter.

## 5.4 Summary

In this section, three second order filters are presented. The filters are of novel type and use a minimum number of components. All the filters are devoid of resistors. First proposed filter has three inputs and two outputs one in VM and the other in CM and realizes all filtering functions by choosing suitable inputs. The filter uses the least number of devices. The performance factors of the filter are electronically tunable independently. The LPF and BPF are more attractive as input impedance is high and capacitor is grounded. The filter is free from realizability condition except APF. The second filter is current mode band pass filter. The filter employs two single output VDTAs and two grounded capacitors making the circuit suitable for IC implementation. The gain, quality factor, and pole frequency are electronically tunable in an independent manner. Filter finds applications where all the parameters need to be varied electronically. The filter employs the least number of components. Third filter is a mixed mode (MM) type filter and has single high impedance voltage input and six outputs, three voltage and three currents. This filter uses only two MO-VDTAs and two grounded capacitors only. The filter provides six filtering functions three in TAM and three in CM simultaneously. The other two functions notch and all pass that can be obtained by tying appropriate nodes for TAM only. It to mention that all the filters are free from realizability condition except APF. For VM to realize notch and all pass filtering functions additional devices are needed. The sensitivity figures of the proposed filter are very low. The theoretical results of the proposed filters have been verified through PSPICE. The simulation results obtained are in close agreement with theoretical results verifying the workability of the proposed filters. However, the simulated results show some deviations within tolerable limits. This is attributed to the non-ideal behaviour of the devices.

# Chapter 6 Conclusion and future scope

## 6.1 Conclusion

The aim of this research is to realize the filters using voltage difference transconductance amplifier (VDTA). In this research work, proposed filters realized are suitable for IC implementation, electronic tunability of filter performance factor: gain, quality factor, and pole frequency in an independent fashion. The proposed filters use minimum number of components, and have low sensitivity figures. Nine new filters are proposed in this research work, six first order and three second order. First four first order filters use VDTA and OA only (active-only filters). These filters are highly suitable for IC implementation, have low sensitivity figures and are electronic tunable. Here it is to mention that OA and VDTAs to realize the filter is new idea presented in this thesis. Fifth and sixth filter use capacitors and VDTAs for realization of filters. Three second order filters are proposed. First filter use one OA, one VDTA and one capacitor. This filter has three inputs and two outputs, implementing all the five filtering functions without need of additional devices and is devoid of realization condition except APF. The filter performance factors are electronically tunable in an independent manner. Second one is CM, BP filter use two grounded capacitors and two single output VDTAs having the facility of tunability of gain, quality factor and pole frequency in an independent manner. Third filter employ two grounded capacitors and two MO-VDTAs, having single input and six outputs provides six filtering functions simultaneously. All the filters have been verified through PSPICE.

## 6.2 Future scope

Advancement in the realization of filters can only be possible with continuous improvement through more research. The work done in this thesis is based on the realization of the first order and second order filters. In this work, all the filters are maximally flat (Butterworth) filters. The other approximation of filters that is equi-ripple (or Chebyshev), and elliptic (or cauer) filters are to be investigated. These filters are somewhat close to the ideal approximation. The second unexplored aspect of this research is the realization of higher order filters. It is to mention that there are several ways in which higher order filters are realized. Here the first and second order filters form the basic building blocks. The outline methods employed for higher order filters are mentioned for reference. The first method is simple in which the transfer function of higher order is factored into subnetworks of second order. The second order filter is realized by any method mentioned above and then cascaded such that the product implements the desired function. This approach offers two advantages: the bandwidth of the cascade filter is easily tunable and due to identical structures leading to a simple IC implementation. However, this method has the disadvantage of being sensitive to component variation in the pass band gain. The second method is multiple loop feedback (or coupled biquad approach). This method also uses the same approach but subnetworks are interconnected in some type of feedback configuration. This feedback creates a coupling of the biquads (second order filters) and is carefully chosen to reduce the transfer function sensitivities. The third method is the ladder simulation approach in which the inductor is replaced by the network duplicating properties of the inductor (inductor simulation). Besides these unexplored areas, other areas are to be explored such as filter processing signal at very high, very low and sub-Hertz frequencies (below one Hz). The filters operating at high frequency are used in telecommunication. The filters working in the low and sub-hertz frequency range are employed in the medical and measuring equipments. The other field which need further investigation: design of rectifiers, oscillators, capacitor multipliers, and inductance simulators. Also the manufacturing of the VDTA especially in nanotechnology, operating at low voltages, consuming less power, is to be investigated which are present requirement, due to downsizing of the portable devices such as laptops, mobile phones and other mobile equipments especially used in medical and measuring instrumentation

## Index

# List of Publications

## Journal paper

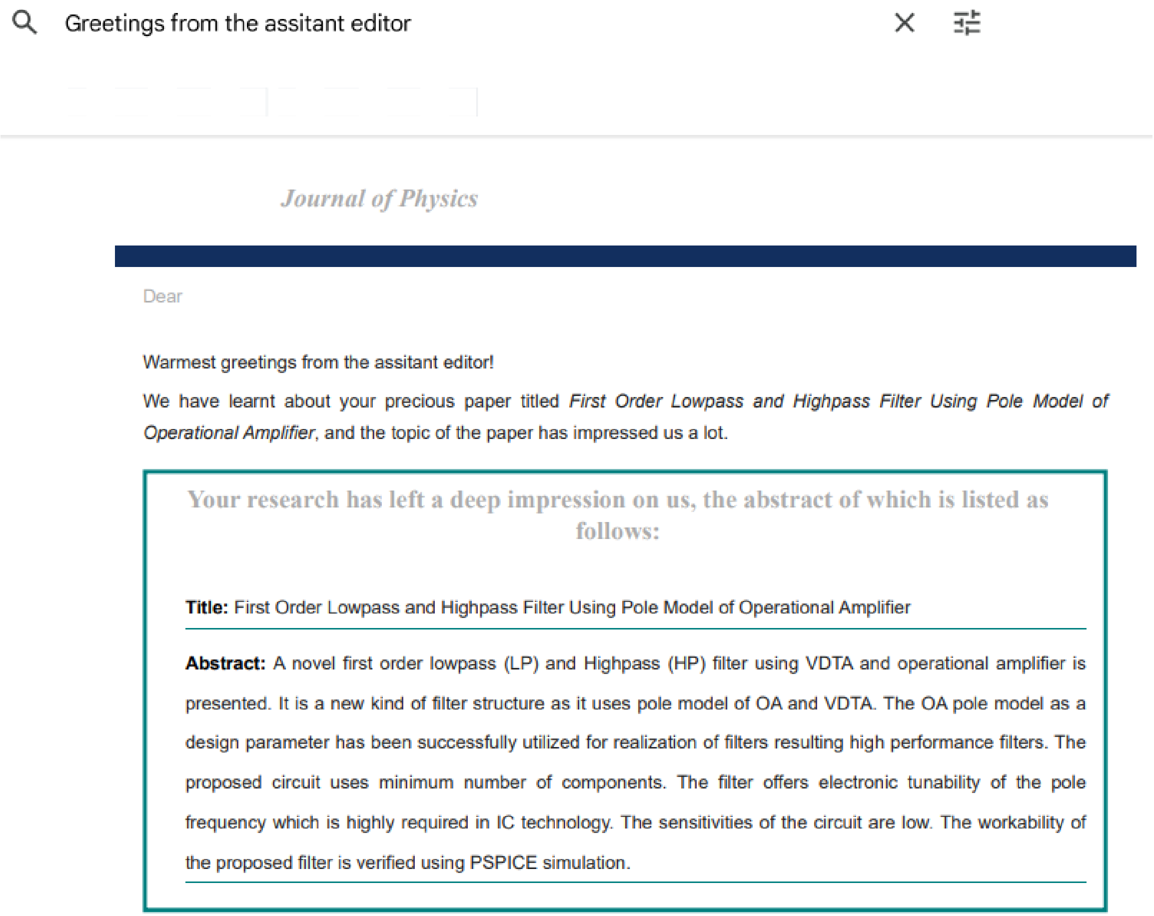
1. Uma Kamboj & Masooma Zaffer. "First Order Lowpass and Highpass Filter Using Pole Model of Operational Amplifier" Indian Journal of Pure & Applied Physics, Vol. 60, July 2022, pp. 567-571.
2. Masooma Zaffer and Uma Kamboj. "Application of voltage difference transconductance amplifier (VDTA) for realization of analog active filter: Review." Journal of physics, conference series 2267(2022)012045 doi:10.1088/1742-6596/1/012045

## Conference paper

3. Masooma Zaffer and Uma Kamboj. " Pole model of operational amplifier as a design parameter: Review." Presented paper in XIII Biennial National Conference Of Physics Academy of North East (PANE-2022) Department of Physics, Manipur University 8-10, Nov. 2022.
4. Masooma Zaffer and Uma Kamboj "Voltage Mode First-Order All-pass filter using OA and VDTA." Presented paper in RAFAS 2023.

## Papers to be submitted

1. Voltage mode first order universal filter with gain control.
2. Current mode first order universal filter.
3. Two input output first order filter using single output VDTA.
4. VM and TAM all pass filter using single output VDTA.
5. Resistor-less three input and two output VM and TAM universal filter.
6. Current mode band pass filter using VDTA and grounded capacitors.
7. Single-input and multi-output VM and TAM filter using grounded capacitors.



Journal of Physics

Dear

Warmest greetings from the assitant editor!

We have learnt about your precious paper titled *First Order Lowpass and Highpass Filter Using Pole Model of Operational Amplifier*, and the topic of the paper has impressed us a lot.

Your research has left a deep impression on us, the abstract of which is listed as follows:

**Title:** First Order Lowpass and Highpass Filter Using Pole Model of Operational Amplifier

**Abstract:** A novel first order lowpass (LP) and Highpass (HP) filter using VDTA and operational amplifier is presented. It is a new kind of filter structure as it uses pole model of OA and VDTA. The OA pole model as a design parameter has been successfully utilized for realization of filters resulting high performance filters. The proposed circuit uses minimum number of components. The filter offers electronic tunability of the pole frequency which is highly required in IC technology. The sensitivities of the circuit are low. The workability of the proposed filter is verified using PSPICE simulation.