



**MARMARA UNIVERSITY**  
**INSTITUTE FOR GRADUATE STUDIES**  
**IN PURE AND APPLIED SCIENCES**



**MOS ONLY AND MOS-C CIRCUIT DESIGN**

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ŞAFAK MURAT KIZILIRMAK

**MASTER THESIS**

Department of Electrical Engineering

**Thesis Supervisor**

Assoc.Prof. Emre ARSLAN

ISTANBUL, 2019

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Şafak Murat KIZILIRMAK, a Master of Science student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended his thesis entitled “MOS- Only and MOS-C Circuit Design”, on 23 July, 2019 and has been found to be satisfactory by the jury members.

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This thesis wrote in my Master of Science education at Marmara University in Istanbul.

**July, 2019**

**Şafak Murat Kızılırmak**

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## **ABSTRACT**

### **MOS-ONLY AND MOS-C CIRCUIT DESIGN**

Active filters have taken a considerable attention as a necessary building block of analog circuit design. There are many applications that need filters such as radio communication, audio electronics, biomedical applications, Very Large Scale Integrated circuits, etc. In design of active filters, passive elements like resistors and capacitors are also used with active elements like opamps, current conveyors, and OTAs, etc. These passive elements cause some limitations and they determine the quality of filters from many perspectives.

Biomedical signal processing circuits need filters with very low cut-off frequencies. In order to obtain such small frequency range, the designer has to adjust the capacitance and resistance values. The only way to obtain a very small cut-off frequency is to use large valued capacitance or resistance values. This means an increase in the layout area, price, noise values, and power consumption, etc.

Filter circuits, that exploit the intrinsic capacitors,  $C_{gs}$  and  $C_{gd}$ , and also the transconductance,  $g_m$ , of the MOS transistor, instead of external passive circuit components such as resistors, capacitors or inductors, have received considerable attention in the last decade. It is clear that these circuits serve some important advantages some of which are: low chip area, high frequency of operation, low power consumption, low noise values, etc.

Until now, a considerable amount of MOS-Only and MOS-C active filters suggested.

In the thesis, the first step is to give and argue the opamp based active filters. Then the proposed MOS-Only filters are introduced.

## ÖZET

### SADECE MOS VE MOS-C DEVRE TASARIMI

Analog devre tasarımında aktif filtreler kullanılması gerekli bloklar olarak dikkat çekmektedir. Radyo haberleşme, audio elektronik, biyomedikal elektronik, VLSI Sistemler gibi birçok uygulama alanında filtrelemeye ve filter devrelerine ihtiyaç duyulur. Aktif filtrelerde direnç, kapasite gibi pasif elemanların yanında OPAMP, akım taşıyıcılar ve OTA gibi aktif elemanlarda kullanılır. Filtre devrelerinde kullanılan bu pasif elemanlar filtrenin kalitesini belirlemede birçok sınırlamalara neden olurlar.

Bütün bunların yanında özellikle biyomedikal uygulamalarda çok düşük frekans aralıklarında çalışmak gerekmektedir. Bu düşük sinyal aralığını yakalamak için tasarımcı pasif elemanların değerleri ile oynamak zorundadır. Pasif filtrelerde düşük frekans aralığı elde etmek için yüksek değerlerde kapasite ve dirençler kullanmak gerekmektedir. Bütün bu ayarlamalar çip alanine, maliyeti ve güç tüketimini arttırmaktadır.

Son yıllarda, pasif direnç ve kapasitelerin yerine MOSFET'in iç kapasite değerleri olan  $C_{gs}$ ,  $C_{gd}$  ve aynı zamanda transkondüktans  $g_m$  'i kullanarak filter devresini kurmak büyük önem kazanmıştır. Bu şekilde kurulan filter devreleri daha az çip alanı kaplamaları, az güç tüketmeleri gibi avantajlara sahiptirler. Bugüne kadar çeşitli MOS-Only ve MOS-C aktif filtreleri önerilmiştir.

Bu tezde de OPAMP bazlı aktif filtrelerden başlanacak ve sonrasında önerilen MOS-Only devreler sunulacaktır.

## SYMBOLS

<b>L</b>	: channel length of the transistor
<b>W</b>	: channel width of the transistor
<b>C</b>	: capacitance
<b>C<sub>ox</sub></b>	: oxide capacitance
<b>μ<sub>n</sub></b>	: the mobility of the electrons
<b>μ<sub>p</sub></b>	: the mobility of the holes
<b>g<sub>m</sub></b>	: transconductance of the transistor
<b>G<sub>m</sub></b>	: transconductance
<b>C<sub>gs</sub></b>	: gate-source capacitance of MOS
<b>C<sub>gb</sub></b>	: gate-bulk capacitance of MOS
<b>Q</b>	: quality factor
<b>ω<sub>0</sub></b>	: pole angular frequency
<b>f<sub>0</sub></b>	: center frequency
<b>f<sub>c</sub></b>	: cut-off frequency
<b>A</b>	: gain
<b>Z</b>	: impedance
<b>R</b>	: resistance
<b>g<sub>ds</sub></b>	: drain source output transconductance
<b>C<sub>gd</sub></b>	: gate drain capacitance of MOS
<b>g<sub>mb</sub></b>	: bulk gate transconductance
<b>P</b>	: power
<b>λ</b>	: channel-length modulation
<b>V<sub>DS</sub></b>	: drain source voltage of MOS
<b>V<sub>GS</sub></b>	: gate source voltage of MOS
<b>V<sub>BS</sub></b>	: bulk source voltage of MOS
<b>I<sub>DS</sub></b>	: drain source DC current of MOS

## ABBREVIATIONS

<b>CMOS</b>	: Complementary Metal Oxide Semiconductor
<b>CCII</b>	: Second Generation Current Conveyor
<b>CCIII</b>	: Third Generation Current Conveyor
<b>ECCII</b>	: Electronically Controllable Second Generation Current Conveyor
<b>OTA</b>	: Operational Transconductance Amplifier
<b>CDTA</b>	: Current Differencing Transconductance Amplifier
<b>CDBA</b>	: Current Differencing Buffered Amplifier
<b>VDTA</b>	: Voltage Differencing Transconductance Amplifier
<b>TRANSEC</b>	: Transmission Security
<b>HAVEQUICK</b>	: U.S. and Allied military aircraft have used AM radios in the NATO harmonized 225–400 MHz UHF band
<b>DC</b>	: Direct Current
<b>AC</b>	: Alternating Current
<b>MEMS</b>	: Microelectromechanical Systems
<b>BB</b>	: Baseband
<b>RF</b>	: Radio Frequency
<b>VHF</b>	: Very High Frequency
<b>IC</b>	: Integrated Circuit
<b>ADC</b>	: Analog to Digital Converter
<b>DSP</b>	: Digital Signal Processor
<b>DAC</b>	: Digital to Analog Converter
<b>FOM</b>	: Figure of Merit
<b>BP</b>	: Band Pass
<b>HP</b>	: High Pass
<b>LP</b>	: Low Pass
<b>AP</b>	: All Pass
<b>BS</b>	: Band Stop
<b>CM</b>	: Current Mode
<b>VM</b>	: Voltage Mode
<b>ECG</b>	: Electrocardiogram
<b>EMG</b>	: Electromyographic
<b>PCG</b>	: Phonocardiographic
<b>SIMO</b>	: Single Input Multi Output
<b>MISO</b>	: Multi Input Single Output
<b>PE</b>	: Passive Elements

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# CHAPTER 1-INTRODUCTION

## 1.1 MOS Only and MOS-C Circuits

Nowadays, MOS-Only and MOS-C circuits have received significant interest in analog circuit design. In analog circuit design, passive elements are really important but their restrictions, costs and size on chip are their disadvantages. In many applications active and passive elements are used together and every circuit design needs different passive elements which have different values. Due to difficulty of finding different valued passive elements on the market, designing analog circuits with critical cut-off frequencies is troublesome.

There are some approaches which use the internal capacitance and transconductance values of transistors instead of passive circuit elements and they are commonly called MOS-Only or MOS-C circuits design approaches. These approaches make it possible to use MOS devices own parameters instead of passive elements [1].

MOS devices are used in many applications such as logic circuits, oscillators, filters, and rectifiers, etc. Nowadays, MOS-Only and MOS-C circuits gain significant importance and have received significant interest because of their advantages.

The main goal of such circuits is to use only MOS transistors instead of active elements for analog circuit applications like filters, oscillators, etc. Thus, designers don't need to think about passive elements and their disadvantages while they are designing analog circuits.

The main advantage of MOS-Only circuits is the reduced chip area. As it is known, the circuits which are built using passive elements cover a lot of area on the chip and that kind of circuits have high costs when compared to MOS-Only circuits. Other advantage is the reduced power consumption. When compared to filter circuits that employ active and passive elements, MOS-Only circuits use very few transistors, which mean reduced power consumption in addition to reduced layout area. Therefore, using only MOS devices and their internal parasitic parameters instead of passive circuit elements is becoming really important.

## 1.2 Analog Filters

Analog filters are circuits which allow to pass desired signal at the certain frequency range and block other part of signal. Frequency range allowed by the filter is known as passband, frequency range blocked by filter is named with stopband [2].

Generally, filters are categorized in two types, active and passive. Passive filters include resistors, inductors, capacitors and don't need external power supply. Furthermore they don't use any active components such as opamp.

Active filters benefit the active elements such as opamp, current conveyor, OTA, etc. and they need external power supply for proper operation. Although, by definition, they don't need passive elements, in some applications active filters use resistors and capacitors.

Filters have set of specifications that define filters frequency response like stopband and passband frequency and gain at these frequencies.

Usually the filters are defined by their gain responses, which is given in decibel (dB). Gain is the ratio of the output signal to the input signal. The gain equation can be given as:

$$\alpha(\omega) = 20\log|H(j\omega)|dB \quad (1.1)$$

$$|H(j\omega)| = \frac{|V_2(j\omega)|}{|V_1(j\omega)|} \quad (1.2)$$

Equation shown in (1.3) demonstrates that resistors and capacitors are used to determine the cut-off (or center) frequencies of the filters. Passive filters utilize resistors, capacitors, and inductors in order to tune the operation frequency of the filter circuit. Especially for low frequency operation, passive filters have some disadvantages. In order to have a very small cut-off frequency values, passive filters have to use very large valued passive elements which cause the increase of layout area and also power consumption.

$$f_c = \frac{1}{2\pi RC} \quad (1.3)$$

On the other hand, passive filters have some loss of signal on the output and that loss may be in passband section.

Passive filters don't obtain any power or voltage gain and that filters have an issue with inductors, capacitors at low frequencies. Another important point is that, capacitors and inductors are physically big elements and they are being more expensive when they are getting bigger. One of the most important issues is the impedance isolation problem. Current mode filters should have low input impedance and high output impedance values. If the filter circuit does not have a proper impedance isolation there exist a problem to drive loads that have changing values. This change in the load impedance value may cause significant changes in the filter's frequency response. So, the designer has to take into account the load impedance effect while determining the filters response.

Although all disadvantages of passive filters, Active filters could realize filter transfer functions without any need for passive elements or their dependency of passive elements is lower. So active filters could utilize passive elements like capacitors and resistors with lower values.

Some of the advantages of active filter circuits are: less cost, flexibility of gain and frequency adjustment, reduced size and weight.

Active filters find a wide range area of usage in analog signal processing at last two decades. First active filters have been utilized with operational amplifiers harmoniously; therefore, active filters gained more importance and their usage became widespread.

By operational transconductance amplifier (OTA) existence and realizations, active filters with the wide range frequency realization became possible [3]. Then Sedra-Smith introduced their current conveyor concept [4]. After that, several active circuits such as Fully Differential Current Conveyor (FDCCII) [39], Current Differencing Transconductance Amplifier (CDTA) [40], Dual output CCII (DO-CCII) [41], Modified Current Follower Transconductance Amplifier (MCFTA) [42], Dual Output Current Controlled Current Differencing Transconductance Amplifier (DO-CCCDTA) [43], Operational Transconductance Amplifier (OTA) [44], Differential Voltage Current Conveyor (DVCC) [5] are introduced in literature.

Nowadays, it has gained importance to build active filters with no use of passive elements. That kind of circuits are called MOS-Only circuits. The demand for MOS-Only circuits

has become important for their low cost, low power consumption and their reduced layout area covering on the chip. MOS Only filters utilize their internal gate-to-source capacitance  $C_{gs}$  and the transconductance  $g_m$  instead of passive circuit elements like resistors and capacitors [1].

In last years, Low frequency filters occupy a very important part especially in biomedical applications that use such as Electromyographic (EMG), electrocardiogram (ECG), phonocardiographic (PCG) signals [6].

### **1.3 Organization**

In this thesis; starting with filter classification, general filter types and their frequency response, active-R, active-C and active RC filters then integrator based filters from the literature are examined.

Afterwards, MOS-Only circuits and filters are introduced, then electronically tunability property of these filters are studied. After this introduction part, we mentioned about the capacitance multiplier, MOS capacitors, MOS resistors and show how to use them on the filter circuits step by step.

Capacitance multiplier circuit will be simulated and its applicability to MOS-only filter circuits will be studied as a next step. Then MOSFET capacitors (moscap) will be used as moscap capacitor instead of internal capacitors on the capacitance multiplier circuit.

With our suggested circuit; instead of gate-to-source capacitances of the MOS transistors, very high valued capacitances which are obtained using capacitance multipliers are used to obtain cut-off frequencies available for biomedical circuits. The high valued resistances in the capacitance multiplier circuit are obtained using MOS resistors [29].

The applicability of the proposed circuits is shown by using LTSPICE simulations. The frequency responses of the proposed and classic circuits are compared also with LTSPICE. These simulations prove that the simulation results are in a good harmony with the theoretical results. The proposed circuits are capable of working in a wide frequency range and what is important is that, the proposed circuits can be used in very low frequency range to be used in biomedical applications. The proposed filters have many advantages some of which are: very low capacitance values, very high MOS resistance values, electronic adjustability, reduced chip area, low power consumption and low cost.

## 1.4 General Features of Filters

Signals in real world, consist of both signal parts which carry wanted and unwanted informations. Consequently, these two information forms must be isolated before analysis.

Filters are generally classified with their output signal form which produced when a sinusoidal input signal applied. There are two frequency bands are defined along frequency range, first of them is pass band and other one is stop band. Pass Band is defined as range of frequencies where transfer function  $|H|=1$ ,  $\alpha=0$  and Stop Band is defined as range of frequencies where transfer function  $|H|=0$  and  $\alpha=-\infty$ .

Basically, filters are categorized such as high-pass, low-pass, band-pass, notch and all-pass.

Low-pass filters allow to pass low frequency signals and don't allow to pass signals which are have higher frequency than cut-off frequency  $\omega_c$ . Low-pass filter's pass band is extending from  $\omega=0$  to  $\omega=\omega_c$ . If high frequency components undesired on signal, it is good to use lowpass filter. For example low frequency sensing systems, we have to use lowpass filters [2].

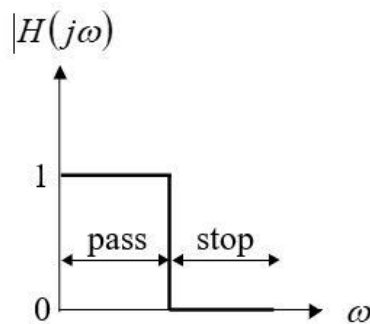


Figure 1. 1 Idealized Low-pass Filter Response

High-pass filters allow to pass higher frequency components of the signal and don't allow to pass lower frequency components of the signal. Band-pass filters have a stop band frequency range between 0 to cut-off frequency  $\omega_c$  and pass band is defined as  $\omega_c$  to infinity. For  $\omega > \omega_c$ ,  $|H|=1$  and for  $\omega_c > \omega$   $|H|=0$ .

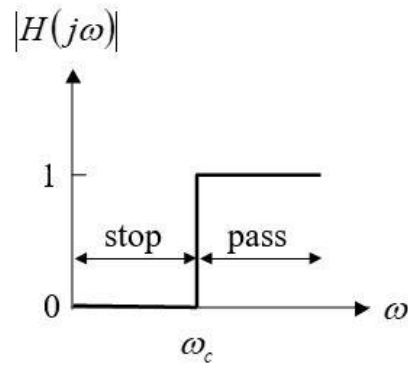


Figure 1. 2 Idealized High-pass Filter Response

Highpass filters use at applications with requiring just allow to pass high frequency components of signal. For example music system, in music system loudspeaker has to take high frequency signals for that highpass filters used in loudspeaker in music systems [2].

The bandpass filter is allow to pass interval of two special frequency  $\omega_L$  and  $\omega_H$ . Frequencies between  $\omega_L$  and  $\omega_H$  are passed, all other frequencies are reject. Band-pass filters frequency band is defined as  $\omega_L < \omega < \omega_H$ . Band-pass filters are used in wireless communication systems or wireless systems, optics, electrocardiograms.

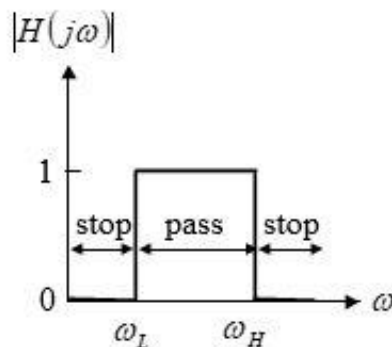


Figure 1. 3 Idealized Band-pass Filter Response

The Notch filter is rejected to pass of signal parts between  $\omega_L$  and  $\omega_H$ . Notch filters stop band is defined as  $\omega_L < \omega < \omega_H$ . Frequencies between  $\omega_L$  and  $\omega_H$  are rejected and all other frequencies are passed. Notch filters are used in medical applications like Band-pass filters.

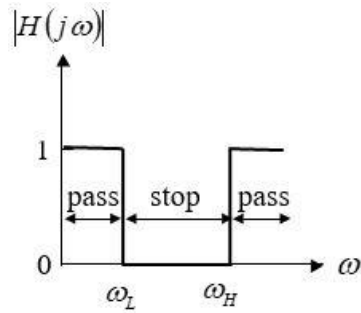


Figure 1. 4 Idealized Notch Filter Response

All pass filters pass signals without changing signals amplitude but it delays signals according to signal frequencies. All pass filters are used for delay equalizers, phase shift networks.

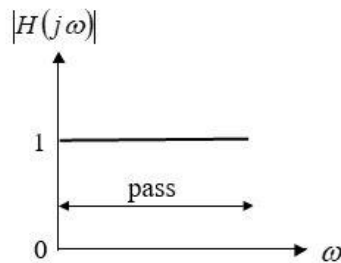


Figure 1. 5 Idealized All-pass Filter Response

### 1.5 Filter Approximations

Fundamentally, filters have 4 approximation types. These are Bessel, Butterworth, Chebyshev and Elliptic approximations which are shown in Fig. 1.6.

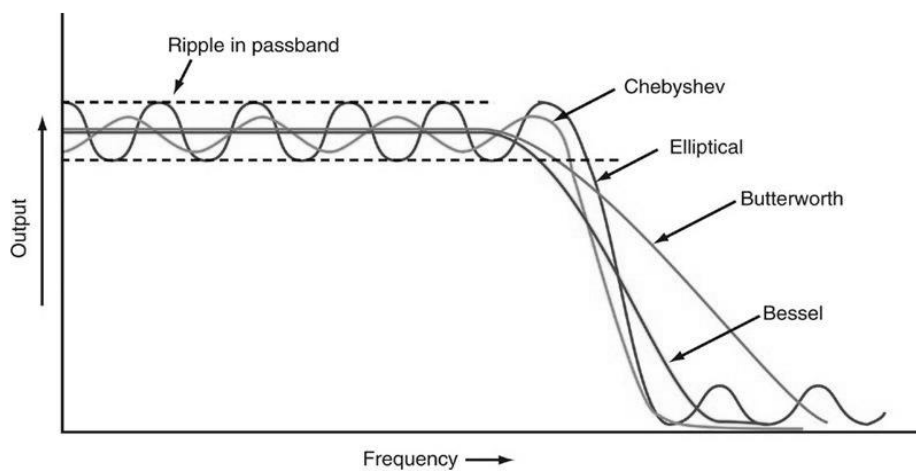


Figure 1. 6 Filters Approximations Frequency Responses

The Bessel Filters provide a linear phase response and that response look like ideal phase characteristics. Its cut-off characteristic is not very sharp and that filter types are used for applications where phase is important. The Bessel Filters doesn't approximate ideal amplitude frequency response, they are well at phase responses. That approximations are good to use at pulse applications [7].

The Butterworth Filters provide amplitude frequency response which is more clearly near to ideal response [8]. They have a nonlinear phase shift in frequency response and they have clearest attenuation.

The Chebyshev Filters provide sharper cut-off frequency than Butterworth. The Chebyshev Filters have maxima gain and minima gain below the cut-off frequency and that ripple is adjustable parameter with design. That types of filter are used for applications which need very sharp roll-off [8].

The Elliptic Filters have ripples at both passband and stopband regions. These ripples are adjustable and they are used for many applications where applications need a very fast transition between passband and stopband regions [9].

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## CHAPTER 2-BUILDING BLOCKS FOR ACTIVE FILTERS

Active filters comprise active circuit elements as well as passive elements like resistors, capacitors and inductors. In general, the most used active elements in active filters are the operational amplifiers (OPAMP). Active filters offer high accuracy, less cost, flexibility of gain and phase adjustment, immunity to electromagnetic interference, etc.

### 2.1 Basic Building Blocks Used in Filters

#### 2.1.1 Ideal Integrator

Ideal integrators are fundamental blocks of filter circuits. Ideal opamp integrators are used for obtain output signal which is time integral of input signal. For example, if input signal is square wave, circuit provide triangle waveform at output.

Transfer function of ideal integrator blocks is shown below equation (2.1) [10].

$$A(s) = \frac{B}{s}, \quad |A(j\omega)| = \frac{B}{\omega} \quad (2.1)$$

At this equation,  $B$  is called the bandwidth gain. Generally, integrators are obtained by using operational amplifiers.

Active opamp integrators have high input resistance and low output resistance and this property allows building cascade blocks of integrators.

Ideal opamp integrators use capacitors which are connected between the output terminal and the inverting input terminal.

Integrator circuits are mainly used in analog to digital converters, analog computers, filters, wave shaping circuits and charge amplifiers.

Ideal opamp integrators are commonly constructed by transistors and transistors properties provide us to adjust opamp characteristics electronically.

The change in ideal integrators amplitude with frequency is shown in Fig. 2.1.

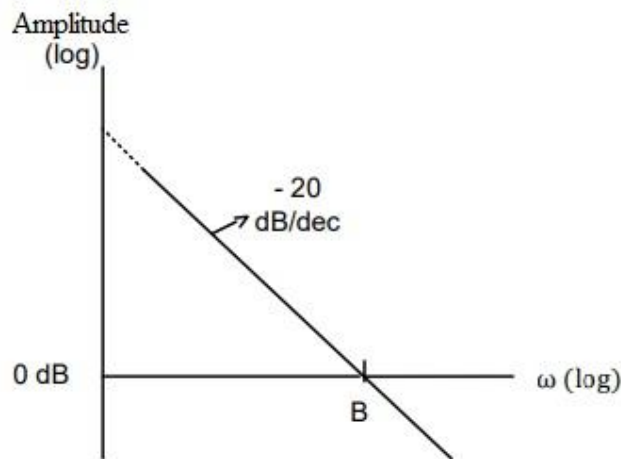


Figure 2. 1 Ideal Integrators Amplitude Characteristic [10]

The voltage integrator is a device which performs time integration of electric voltage. The current integrator is performing with time integration of current [10].

### 2.1.2 Practical (Lossy) Integrator

In literature, building blocks of filters which consist in more than one amplifier stage, are commonly constructed with ideal/lossy integrators. During the implementation of those blocks, there are some non-ideal parameters. Detailed analysis of those non-ideal parameters is really important for design point of view [45]. Actually, to obtain a filter with high success, it is important to use lossy integrator that has a high performance. There are some different integrator structures some of which are OTA-C integrators [46],  $g_m$ -C integrators [47] and opamp integrators [10].

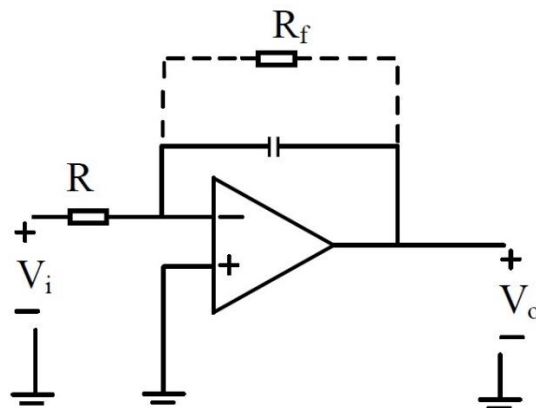


Figure 2. 2 Lossy Opamp Based Integrator

Transfer function of a lossy integrator block given in Fig. 2.2 can be given as (2.2) [10]:

$$A(s) = A_0 \frac{\omega_1}{s + \omega_1}, \omega \gg \omega_1, |A(j\omega)| = \frac{A_0 \omega_1}{\omega} \cong \frac{B}{\omega} \quad (2.2)$$

The change on amplitude with frequency is demonstrated in Fig. 2.3

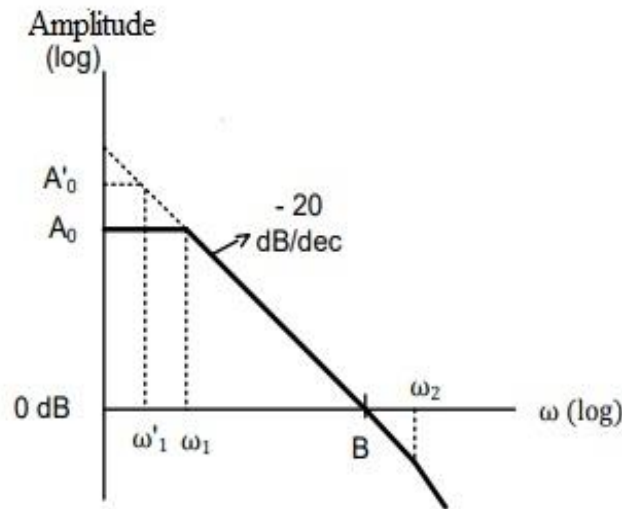


Figure 2. 3 Lossy Integrators Amplitude Characteristic [10]

There are different ways in order to fix the non-ideal parameters of lossy integrator structures. The first way is to realize the integrator with using OTA (Operational Transconductance Amplifier) [44]. It is possible to analyze the non-ideal characteristics of non-ideal integrators with the circuit given in Fig. 2.4:

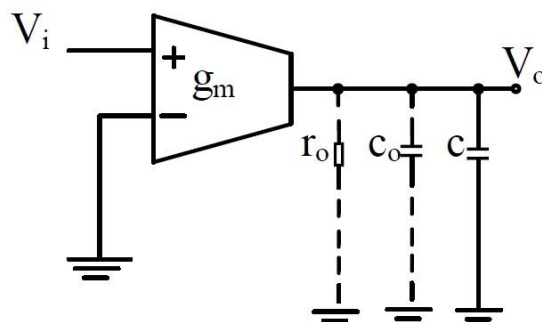


Figure 2. 4 Active Integrator Constructed With OTA [10]

The circuit given in Fig. 2.4 has a transfer function as:

$$\frac{V_o}{V_i}(s) = \frac{\frac{g_m}{C}}{s} \quad (2.3)$$

at the first look; but taking the output resistance and output capacitance  $C_0$  into consideration, the total admittance seen at output port will be  $g_0 + s(C + C_0)$  and the transfer function of the integrator circuit will be (2.3) [10]:

$$\frac{V_o}{V_i}(s) = \frac{g_m}{s(C + C_0) + g_0} = \frac{g_m}{g_0} \frac{\frac{g_0}{C'}}{s + \frac{g_0}{C'}} \quad , \quad C' = (C + C_0) \quad (2.4)$$

As can be seen from equation (2.4) [10], the output resistance is not infinite, for that reason it can be said that the circuit shown in Figure 2.4 is not possible to act like an ideal integrator. If the output does not contain a capacitive load, equation (2.4) can be rewritten as:

$$\frac{V_o}{V_i}(s) = \frac{\frac{g_0}{C}}{s + \frac{g_0}{C}} \quad , \quad \omega_1 = \frac{1}{r_0 C_0} \quad (2.5)$$

In this situation, the circuit obtained is called pure active integrator circuit. As shown in equation (2.5) [10], if  $\omega_1$  decreases the structure will act like an ideal integrator. If the output resistance increases as  $r'_0 > r_0$ , low frequency pole and low frequency gain (DC gain) becomes to equation (2.6) [10]:

$$\omega_1' = \frac{g_0}{C_0} \quad , \quad K_{v0} = \frac{g_m}{g_0} \quad (2.6)$$

With this new situation, bandwidth gain of the circuit becomes  $B = \frac{g_m}{C_0}$ . Also with that new gain equation, if the output resistance increases, B remains constant and the frequency pole value decreases.

On the other hand, it is seen that the change in parasitic capacitance  $C_0$  also changes the B (Bandwidth Gain). So, the value of the parasitic capacitance effects the value of the frequency and that effect makes it possible to adjust the circuit's bandwidth gain.

## 2.2 Different Circuit Blocks Used in Active Filters

### 2.2.1 Operational Transconductance Amplifier

Operational amplifiers occupy a large application area in active filter design. During the design of active filters with operational amplifiers, an assumption is made that opamp has an infinite input resistance and zero or almost zero output resistance. Furthermore, to make the filter gain independent of the opamp gain, there is a need to apply appropriate feedbacks at the circuit. The practical active filter designs with opamps are evolved with this method. Opamp restrictions prevent the active filters to be used in high frequencies. Besides, there are no existing internal voltage or current control designs to adjust these filter's characteristics. Designers have to make this control mechanism externally.

After realizing the possibility of using MOS devices with their parasitics in amplifier and filter applications, there is an idea of how to obtain filter and amplifier transfer functions only with MOS devices without using any other active circuits like opamps [11].

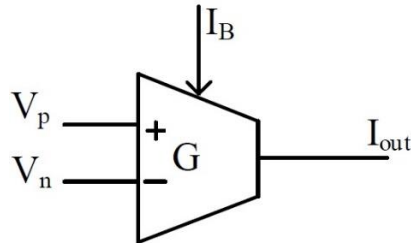


Figure 2. 5 Operational Transconductance Amplifier

The symbol for OTA is given in Fig. 2.5 and OTA's characteristics are described by formulas shown below:

$$g_m = I_B h \quad , \quad I_{out} = g_m (V_p - V_n) \quad (2.6)$$

As can be seen from the above equation it is possible to say that transconductance gain is proportional to  $I_B$  and "h" depends on temperature, design geometry, etc.

Ideal OTA equivalent circuit is shown below in Fig. 2.6.

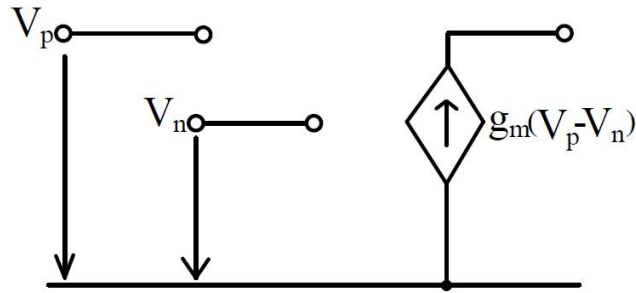


Figure 2. 6 Ideal OTA Equivalent Circuit

The current control of the transconductance gain is obtained with control of “ $I_B$ ”. The output current which is controlled by the given voltages, “ $I_B$ ” is an important parameter. Designers use transconductance of OTA instead of resistors [11]. It is possible to obtain integrators or filters with using OTA and some passive elements.

### 2.2.2 Current Conveyors

First generation Current conveyors are introduced in 1968, second generation Current conveyors are introduced in 1970 by Sedra-Smith. Current conveyors are used as main building blocks like opamps at analog signal processing. Applications which are constructed with opamps, are used commonly since late 1940s and it was really hard to realize applications without using opamps which show similar behaviors with opamps.

Opamps are not performed well for applications which need to produce current at the output terminal. With these disadvantages, there appeared an opportunity for current conveyors and current conveyor applications. Some important features of current conveyors over opamps are: current conveyors need no feedback systems and provide high frequency of operation [12].

Current conveyors have 3 terminals which are provided sufficient functions at analog signal processing when they are used with different electronic elements together. Current conveyors simplify the circuit structure like opamps. Real current conveyors show similar features to ideal current conveyors and this provide convenience to designers to realize their theoretical designs and their estimations [13].

Current conveyors can be classified by a lot of features but mostly they are classified by their different generation types. Commonly, there are 3 types of current conveyors, namely first generation current conveyor (CCI), second generation current conveyor

(CCII), third generation current conveyor (CCIII). Furthermore, they can be classified such as positive, negative, direct, inverted, current controlled and multi output current conveyors.

The CCI is a device with 3 terminals which was introduced by Sedra-Smith in 1968 [14] and the symbol can be given in Fig. 2.7:

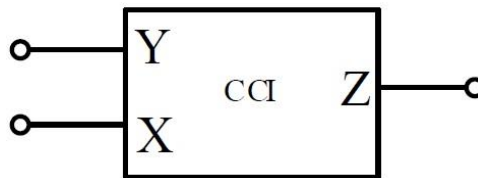


Figure 2. 7 First Generation Current Conveyor

Operation principles of current conveyors are defined like this; if a voltage is applied to Y node then an equal voltage will appear at X node, in a similar way if an input current is flowing through X node an equal current will flow through Y node and then a same current will flow through Z node [13].

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & A & 0 \\ B & 0 & 0 \\ 0 & \pm C & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (2.7)$$

From equation (2.7) if A, B, C are equal to 1 it is easy to see that the current through Y node is equal to X node and voltage value at the X terminal is equal to Y node. Consequently, the current flowing at Z node is equal to X node but current of Z node can have positive or negative polarities according to CCI types such as positive or negative [13]. It is possible to classify the current conveyors according to polarities. If voltage at X and Y nodes have the same polarity it is possible to say that current conveyor is non inverting type (B=1). Otherwise if X and Y nodes have different polarities (B=-1), then the current conveyor is an inverting type and the voltage of X node will have an opposite polarity when compared to the Y node voltage.

On the other hand, if the polarity of current flowing through Y node is equal to X node (A=1), current conveyor is called a CCI. If there is no current flowing at Y node (A=0), conveyor is a CCII. A=-1 means that X and Y nodes have opposite polarities, then the conveyor is a CCIII [15].

If Z terminal has both positive and negative output, it is called composite port current conveyor.

### 2.2.2.1 Second Generation Current Conveyor

Among the current conveyor types, the most popular current conveyor type is the CCII. That type of conveyors can be applied in all analog circuits.

Many publications have proved that adjustability and versatility of CCII since their first introduced in 1970 [16].

Ideal CCII has the relations among X, Y, Z ports as shown below;

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \beta & 0 & 0 \\ 0 & \pm\alpha & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (2.8)$$

$\beta$ ,  $\alpha$  are equal to 1 ideally and they represent the voltage and current transfer ratios. If  $\alpha$  has a positive sign, it specifies that the conveyor is a positive type otherwise it specifies that the conveyor is a negative type.

Terminal Y has an infinite impedance and there is no current flow through Y. A voltage which is applied to Y terminal is copied to X terminal and X terminal has low impedance value. A current which is injected into X terminal is copied to Z port which has high impedance value.

For all this operation CCII must have two followers. The first follower is between Y-X terminals and it is a voltage follower, other one is between X-Z terminals which is a current follower. Non-ideal CCII has some parasitic parameters which disturb the characteristics of ideal conveyor [15].

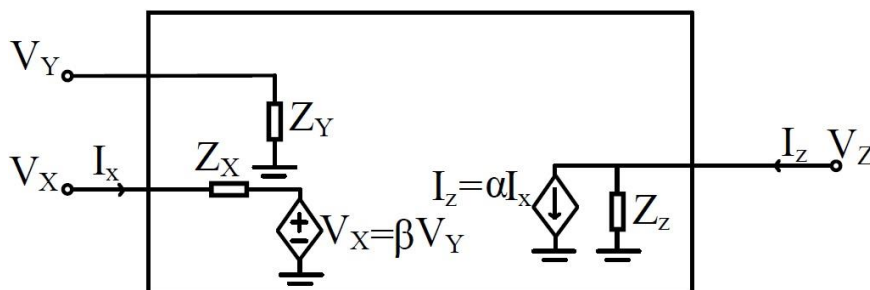


Figure 2. 8 CCII+ Equivalent Circuit

The CCII has some limitations at high frequencies. The circuit shown in Fig. 2.8 can be used to materialize the real CCII behaviors. Voltage and current transfer ratios are described by equations (2.9) and (2.10) as below [15]:

$$\frac{V_o}{V_i}(s) = \frac{g_m}{s} \quad (2.9)$$

$$\alpha(s) = \frac{\alpha_0}{1 + \frac{s}{\omega_\alpha}} \quad (2.10)$$

$\alpha_0$  and  $\beta_0$  represent the gain of transfer functions at low frequencies and their values are almost unity.  $\omega_\alpha$  and  $\omega_\beta$  represent the poles of the transfer function.

Y terminal has an admittance of  $(G_y+sC_y)$ , the admittance of Z terminal is  $(G_z+sC_z)$  and  $R_x$  is the resistance of X terminal which is measured at low frequencies [17, 18]. The ideal CCII has an infinite input impedance at Y and Z terminals and zero impedance at X terminal. The impedance levels of non-ideal CCII is given in the matrix below [15]:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} G_y+sC_y & 0 & 0 \\ \beta(s) & R_x & 0 \\ 0 & \pm\alpha(s) & G_z+sC_z \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (2.11)$$

It is clear to see that the parasitic parameters of the non-ideal CCII effect the behavior and the designer should adjust these parameters in order to obtain ideal CCII behavior.

Consequently, current conveyors are the most commonly used active devices for signal processing applications where current mode operation is needed. Unlike the voltage mode operations, current mode operations are comprised current signals instead of voltage signals. There are a lot of current mode active devices like current feedback amplifier, current mode operational amplifier, current differencing buffered amplifier and current conveyor, etc. The most popular one between those devices is second generation current conveyors which have features that are described at above sections [21].

### 2.3 MOS Devices Used for Active Filters

Active filters generally use active devices which have high linearity and high performance like operational amplifiers (opamps), operational transconductance amplifiers (OTAs)

and current conveyors. All these elements consist a large number of transistors which increase the power consumption, complexity, layout area and cost of the circuit [22, 23].

A new approach to design active filters is to use MOSFET devices and their parasitic parameters instead of passive circuit elements like resistors and capacitors. The design of filters that utilize only MOSFETS has many advantages some of which are low power consumption, tunability and high frequency of operation.

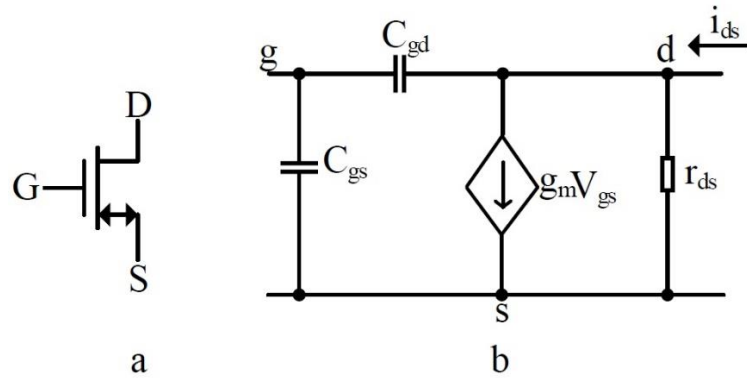


Figure 2. 9 a) MOS Transistor b) Small Signal Model of MOS Transistor

MOSFET's gate-to-source capacitance,  $C_{GS}$ , and transconductance,  $g_m$ , can be used to design filters without passive circuit elements. During the design of active filters with only MOS transistors, parasitic gate-to-source capacitances are used instead of passive capacitances and the transconductance is used instead of passive resistors.

Although there are so many advantages for that type of filters, designers must be careful for dynamic range limitations and harmonic distortions [24]. In Fig. 2.9 MOS transistor structure and MOS transistor small signal model are shown and it is easy to see their parasitic parameters that are used instead of passive circuit elements.

### 2.3.1 MOSFET Capacitances

MOS devices parasitic capacitances are divided into two group; first group is oxide-related capacitances, second group is junction-related parasitic capacitances. In our work we focused on oxide-related parasitic capacitances. The capacitance that exists between gate and other three terminals are called gate-to-source capacitance, gate-to-drain capacitance and gate-to-bulk capacitance. The gate-to-source capacitance is gate-channel capacitance which is seen between gate and source terminals.

Likely, the gate-to-drain capacitance is gate-channel capacitance which is seen between gate and drain terminals. MOS parasitic capacitances are shown in Fig. 2.10.

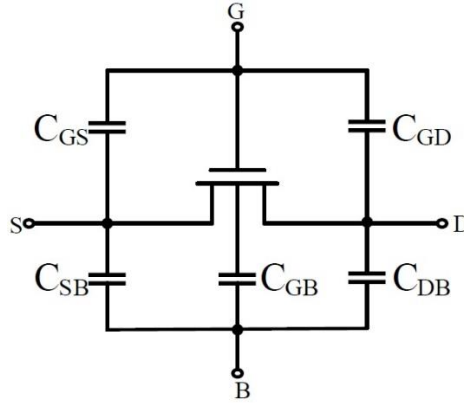


Figure 2. 10 MOSFET Parasitic Capacitances

MOS parasitic capacitances are bias-dependent and for different regions of operation the values of these capacitances change [25].

At cut-off region, there is no conduction between drain and source terminals, thus gate-to-source and gate-to-drain capacitances are zero and gate-to-bulk capacitance is approximately equal to  $C_{gb} \cong C_{ox} \cdot W \cdot L$  [25].

In linear region, the channel is formed between drain and source regions and it has a uniform shape. The total capacitance between the gate and channel is divided into two equal parts between gate-drain and gate-source.

The value of these capacitances will be:

$$C_{gs} \cong C_{gd} \cong \frac{1}{2} C_{ox} WL \quad (2.12)$$

If the MOSFET is in saturation region, channel does not extend to drain terminal because of the pinch-off effect. Therefore, the gate-to-drain capacitance becomes zero. The gate-to-source capacitance becomes:

$$C_{gs} \cong \frac{2}{3} C_{ox} WL \quad (2.13)$$

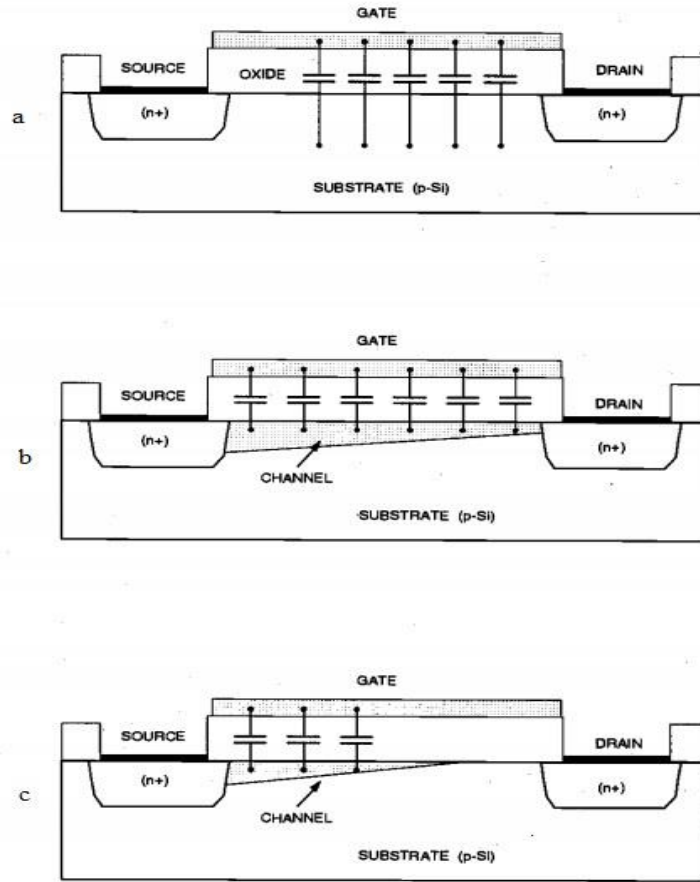


Figure 2. 11 MOSFET Oxide Capacitances at a) Cut-Off b) Linear c) Saturation Region [25]

### 2.3.2 Using Transconductance and Output Resistance of MOSFET

MOS devices are described as voltage controlled current source and that feature is defined by their transconductance. MOS transconductance is important to determining of MOS devices strength [26]. Transconductance is defined the voltage-current convert transfer performance. MOS transconductance formula for NMOS is shown below;

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \quad (2.14)$$

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) \quad (2.15)$$

Transconductance is linear proportional to W and L for given  $(V_{GS} - V_{TH})$  at the same time its proportional to  $(V_{GS} - V_{TH})$  for given W and L.

$$g_m = \frac{2I_D}{(V_{GS} - V_{TH})} \quad (2.16)$$

As seen at equation (2.16), transconductance,  $g_m$  is proportional to  $I_D$  for given  $(V_{GS} - V_{TH})$  and otherwise transconductance is inversely proportional to  $(V_{GS} - V_{TH})$  for given drain current. For understand to transconductance working principles, it is important to understand mos devices small signal model [26].

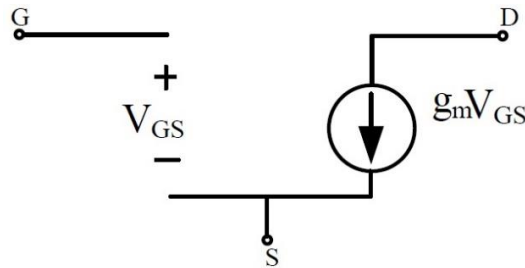


Figure 2. 12 Small Signal Model of NMOS

With the channel-length modulation, there is output conductance or resistance exists on the small signal model. The presenting of channel-length modulation is shown below;

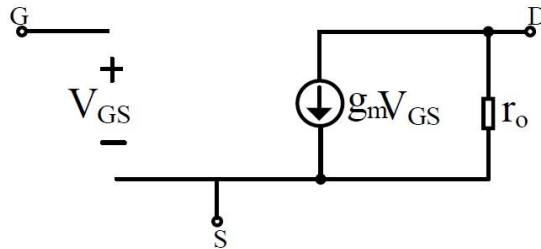


Figure 2. 13 Small Signal Model with Channel Length Modulation

$$r_o = \left( \frac{\partial I_D}{\partial V_{GS}} \right)^{-1} \quad (2.17)$$

$$r_o = \frac{1}{\lambda I_D} \quad (2.18)$$

In MOS-Only circuit, passive resistors are replaced with MOS output resistance or MOS transconductance. For use MOS device like resistance there are some connecting configurations such as diode connected MOS or use MOS as a current source. Diode connected MOS devices are obtained by connecting gate and drain terminals.

Therefore, that configuration is acted like resistor in small signal analysis [26]. Diode connected MOS configuration is shown below;

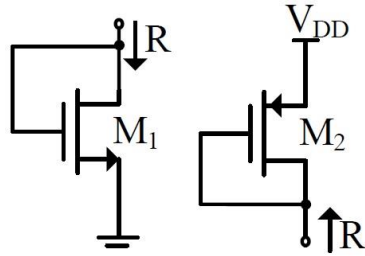


Figure 2.14 Diode Connected Configurations for NMOS and PMOS

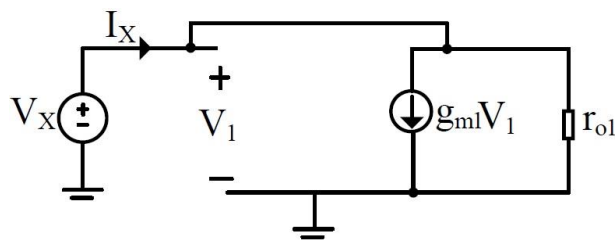


Figure 2.15 Small Signal Model of Diode Connected NMOS Device

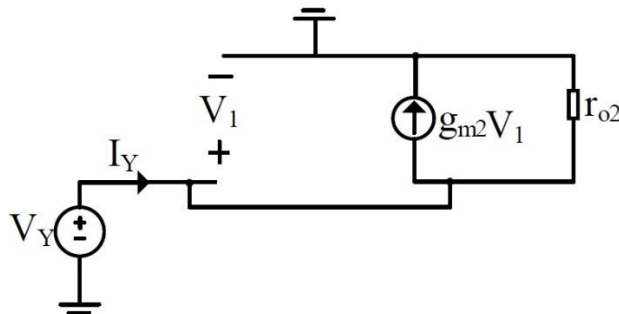


Figure 2.16 Small Signal Model of Diode Connected PMOS Device

As seen as Fig. 2.15 and Fig. 2.16 if channel length modulation coefficient is zero small signal resistance of Fig. 2.15  $R_x$  is equal to;

$$R_x = \frac{V_x}{I_x} \quad (2.19)$$

$$R_x = \frac{1}{g_{m1}} \quad (2.20)$$

If channel length modulation coefficient is not equal to zero, we must take into account output resistance  $r_o$ , parallel with  $1/g_{m1}$  when calculating of small signal resistance [26]. A new small resistance is shown at equation 2.21.

$$R_x = \frac{1}{g_{m1}} // r_o \quad (2.21)$$

Otherwise small signal resistance of PMOS diode connected is same with NMOS device. MOS devices are acted like current source with some configurations in saturation region, also this feature is provide us to obtain resistance [26].

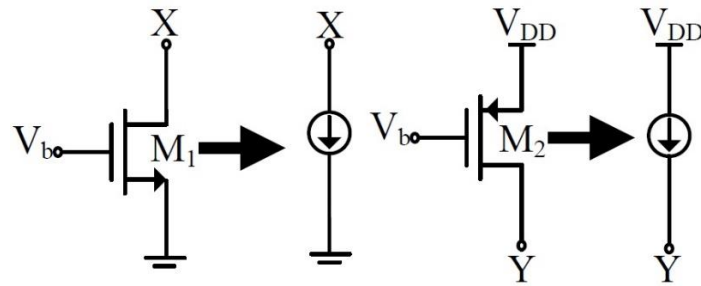


Figure 2. 17 MOS Devices Act as Current Source

Small signal models of MOS current sources are acted like diode connected configurations and they are revealed resistance of  $1/g_m$  for  $\lambda=0$ .

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## CHAPTER 3- MATERIAL AND METHOD

In this chapter we will discuss some different materials and methods which are used for obtain pure MOS-Only filters and MOS-C filters in our proposed circuits. These methods and materials which are MOS Resistor, Capacitance Multiplier will be introduced and then there are some MOS-Only and MOS-C filters in literatures will be introduced. After that, there are some proposed circuits will be analyzed with not using that methods then proposed circuits will be analyzed with using that methods.

### 3.1 CMOS Resistor

In many electronic application High Value Resistors (HVR) are important elements. High Value Resistors are used for biasing techniques at different application or used for low frequency filtering circuits [27, 28]. Beside to obtain High Value Resistors, it is important for design, to obtain resistors with electronic adjustability and controllability. For understand to floating tunable CMOS resistor, it is important to look Body Effect of mos devices.

#### 3.1.1 Body Effect of MOS Devices

Generally, we supposed that MOS device's bulk terminal is connected to source terminal or ground. If source terminal voltage has a potential different to zero, voltage difference is occurred between source and bulk terminals. With this phenomenon the threshold voltage of devices is changes. This phenomenon is known as Body Effect and that effect is shown with equation 3.1 [26].

$$V_{TH} = V_{TH0} + \gamma(\sqrt{|2\phi_F + V_{SB}|}) - \sqrt{|2\phi_F|} \quad (3.1)$$

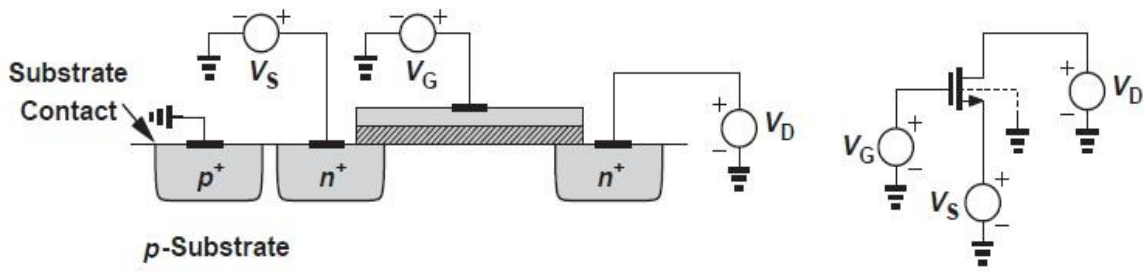


Figure 3. 1 Body Effect [26]

### 3.1.2 Floating Tunable CMOS Resistors

For obtain a resistor with MOS devices, conventionally MOS devices biased in triode region is used but to obtain resistor in triode region is needed MOS devices with long channel. In paper [29], it shows us different way to obtain resistor with MOS devices.

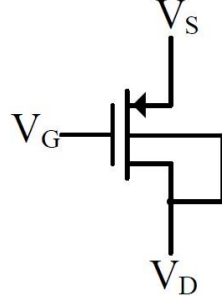


Figure 3. 2 Bulk-Drain Connection of PMOS Devices [29]

With connection of bulk and drain terminals, first, there is increasing of source-drain voltage thus threshold voltage of device changes and then drain current increase [29]. This feature produces us electronically adjustable and controllable wide range MOS resistor. Controlling and adjusting of MOS resistor are provided by adjusting of drain current. Equations (3.2), (3.3), (3.4) [30] based on EKV model [31, 32] which shown below;

$$I_{SD} = I_0 e^{\frac{V_{DG} - V_{T0}}{n_p U_T}} (e^{\frac{V_{SD}}{U_T}} - 1) \quad (3.2)$$

$$I_D = 2n_p \mu C_{ox} \frac{W}{L_{eff}} U_T^2 \quad (3.3)$$

Thus, equivalent resistance is;

$$R_{SD} = \left( \frac{n_p U_T}{I_{SD}} \right) \left( \frac{e^{V_{SD}/U_T} - 1}{(n_p - 1)e^{V_{SD}/U_T} + 1} \right) \quad (3.4)$$

$$R_{SD} = \frac{n_p U_T}{I_0 e^{\frac{V_{DG} - V_{T0}}{n_p U_T}} [(n_p - 1)e^{V_{SD}/U_T} + 1]} \quad (3.5)$$

As seen as equation (3.4) this configuration of MOSFET is can be used like a resistor [30]

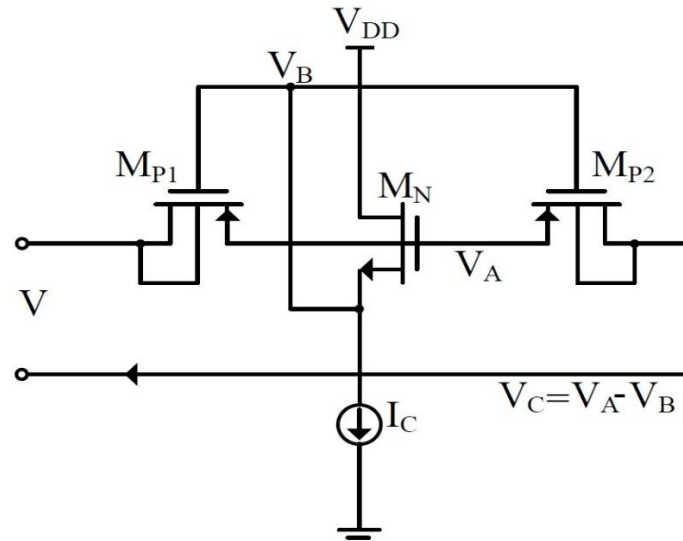


Figure 3. 3 Floating MOS Resistor [30]

As seen as Fig. 3.3 two back to back MOS transistor and another adjusting MOS transistor with this configuration is provide us to obtain floating wide range MOS resistor. In Fig.3.3 Mp1 and Mp2 transistors are used for obtain a high resistance values,  $M_N$  is used for to provide biased voltages or source gate voltages for Mp1 and Mp2. This floating resistor value is obtained by changing of gate source voltages of PMOS transistors by adjusting bias current of  $M_N$  with  $I_C$  [30].

Resistance values of that floating MOS resistor have wide range which is adjusted by changing of biased current of  $M_N$ . That wide range of resistivity is shown below in Fig.3.4 [30].

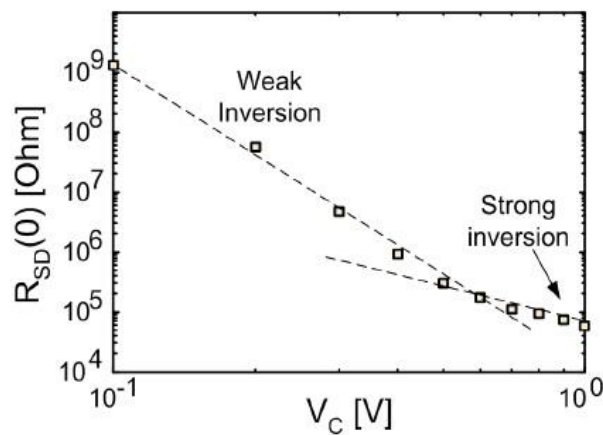


Figure 3. 4 Measured Resistance of Floating Resistor Respect to G-S Voltage of NMOS Device [30]

The resistance of this proposed circuit in [29, 30], is varied between 100k ohm and 1G ohm. The source gate voltages of these PMOS devices described by equation shown below;

$$V_C = V_{SG} = V_A - V_B \quad (3.6)$$

If  $V_{SG}$  values are low, NMOS devices are operates in subthreshold region and equivalent resistance of floating resistor is very high and that resistivity can be adjust with wide range. Otherwise  $V_{SG}$  has a higher values and NMOS devices are in strong inversion region. Note that resistivity and tunability of floating resistor are increase with weak inversion region and decrease with strong inversion [29, 30].

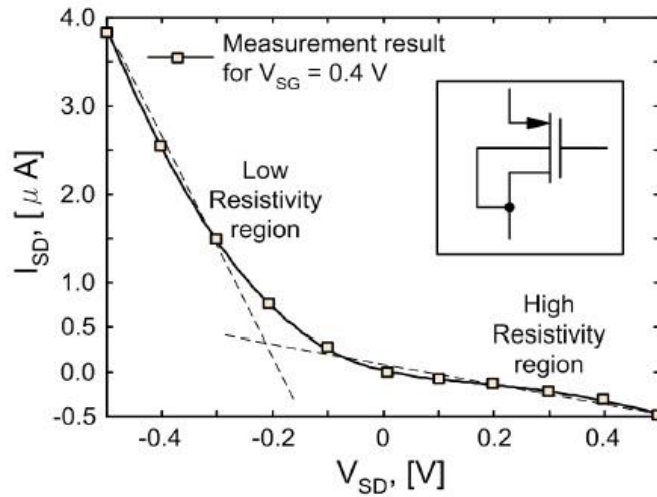


Figure 3. 5 Measured I-V Characteristics for Proposed Floating Resistor [30]

### 3.2 Capacitance Multiplier

In integrated circuit and discrete circuit areas, capacitances and their usage area are find a wide range application. Analog integrated circuits are generally needed high valued capacitors which are linear and have high accuracy. High valued capacitors are important for analog integrated circuits but their cost and fabrication area are increased when capacitor value increase [33]. For this reason some capacitance multiplier approximations occurred in literature. With these approximations, using configuration of small value capacitor and some active elements is necessary to obtain high valued capacitor. There are a lot of configurations for obtain capacitance multiplier, some configurations which based different active elements are CCII-, ICCII based multipliers [34] etc.

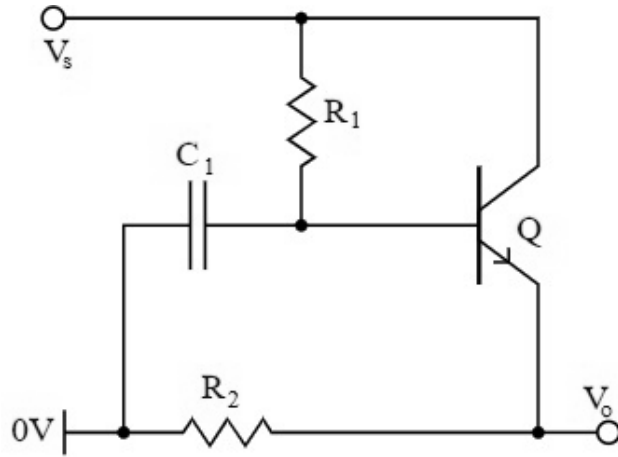


Figure 3. 6 Transistor Based Capacitance Multiplier [35]

In Fig. 3.6 total capacitance which viewed by load is calculated with equation (3.7) shown below

$$C_{total} = C_1(\beta + 1) \quad (3.7)$$

With this configuration, circuit obtain a high value capacitances with utilizing of small value capacitors and that capacitance value is electronically adjustable with transistors current gain.

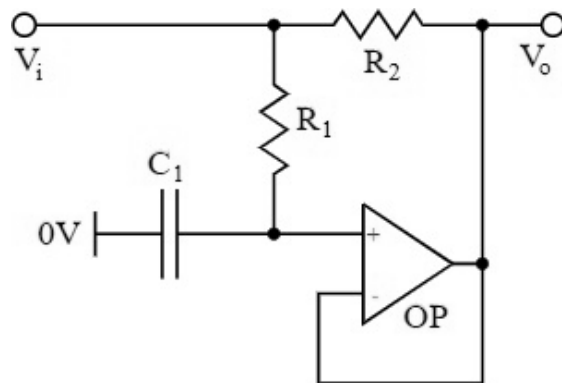


Figure 3. 7 Opamp Based Capacitance Multiplier [35]

With configuration where shown in Fig. 3.7, capacitance multiplier is obtained which has two resistor, one capacitor and one opamp. Operational amplifier in Fig. 3.7 is used for buffer. Total capacitance of this circuit is calculated with equation (3.8) shown below

$$C_{total} = C_1 \left( 1 + \frac{R_1}{R_2} \right) \quad (3.8)$$

Total capacitance of this capacitance multiplier configuration is electronically adjustable with ratio of resistors. Total capacitance of opamp based capacitance multiplier is equal to equation (3.8) if look at  $V_i$  node. There are many type of capacitance multiplier which are floating and grounded in literature but for our work opamp based grounded capacitance multiplier is used. When building a filter configuration, capacitance multipliers are really important. For example in Fig. 3.8 shown below basic R-C lowpass filter is realized with one resistor, one capacitor and one second generation current conveyor which used as capacitor multiplier [36].

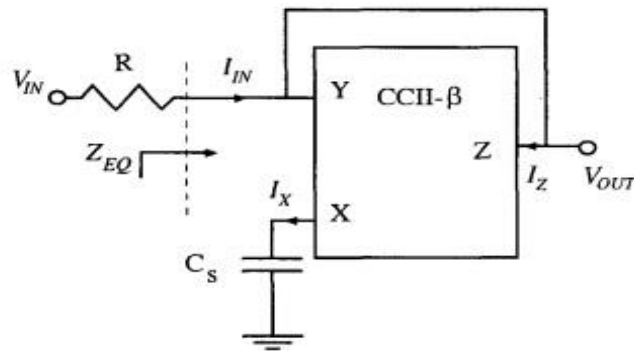


Figure 3. 8 Schematic of R-C filter with CCII Multiplier [36]

### 3.3 Biomedical Signals

There are too many types of electronic signals in world and all components of environment are described by these signals. Biomedical systems are taken important place in signal systems. As all other systems, biomedical systems are described by their signals. In biomedical industry, it is too important to understand how body is working. For example, in examinations, doctors want to see working of certain region of body before they identify illness. All human body parts produce signals which shows that organs working. For doctors that signals are meaningless information. With electronic measuring and sensing, that meaningless informations are become significant data and then all these data collections are transmitted to monitoring systems for last users. For transmits data collections to monitoring systems and first sensing of biomedical signals too important. Some of those important biomedical signals are biochemical signals such as neurotransmitters, hormones and biomechanical signals such as temperature, pressure and bioelectric signals such as currents, voltages [37]. There are commonly bioelectric signals such as the electromyogram (EMG) which shows activity of muscle cells, the

electrocardiogram (ECG) which shows activity of hearts cells, the electroencephalogram (EEG) which shows activity of brain, the electrogastogram (EGG) which shows activity of stomach, the phonocardiogram (PCG) which shows audio recording of hearts activity, the electroretinogram (ERG) which shows activity of retina cells, the electrooculogram (EOG) which shows activity of eye muscles [37].

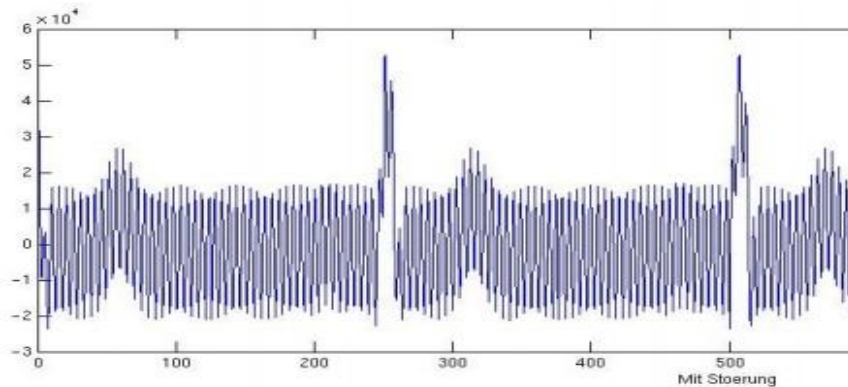


Figure 3. 9 ECG Signal Before Filtering [38]

In Fig. 3.9 electrocardiogram signal shown before filtering and in Fig. 3.10 electrocardiogram signal shown after filtering operation.

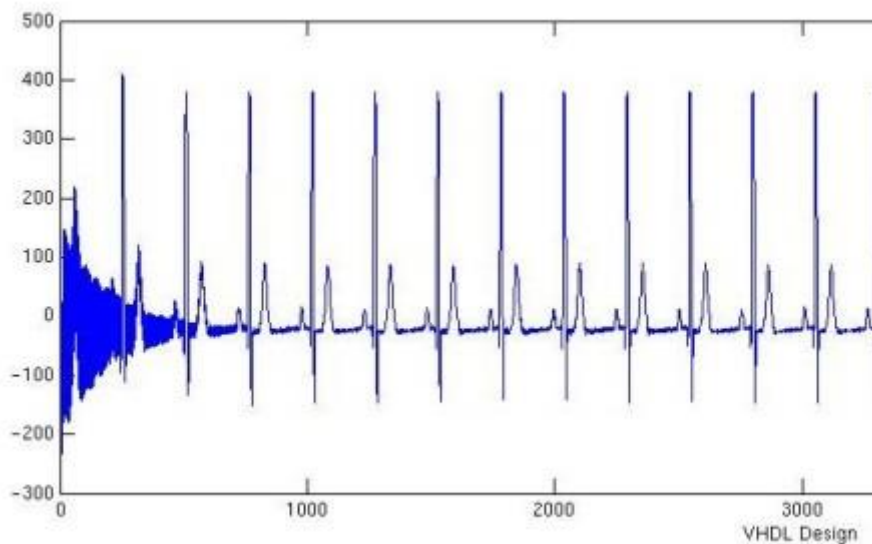


Figure 3. 10 ECG Signal After Filtering [38]

All of bioelectric signals have a different range of frequency. For example, three basic bioelectric signals ECG (electrocardiogram), EEG (electroencephalogram), EMG (electromyogram) have a different frequency range such as ECG has a frequency range

between 0.05 Hz and 100 Hz, EEG has a frequency range between 0.5 Hz and 100 Hz and EMG has a signals which have frequency range as high as 10 kHz. Among that three basic signal types EEG assessed brain activity with four frequency ranges which are alpha, beta, theta, delta. Alpha frequency ranges between 8 - 13 Hz, Beta frequency ranges between 13 - 30 Hz, Theta frequency ranges between 4 - 7 Hz, Delta frequency ranges between below 3.5 Hz.

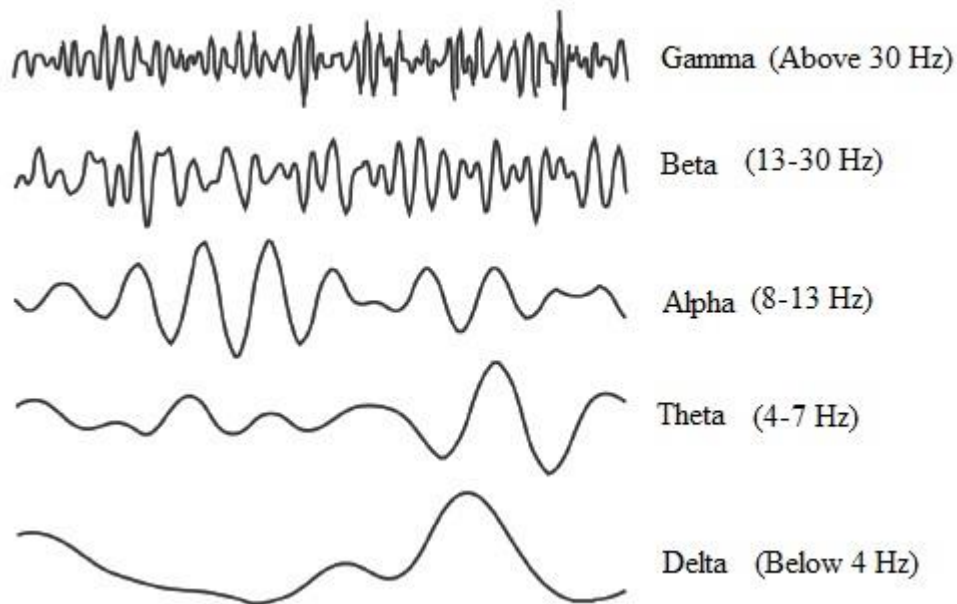


Figure 3. 11 Brain Wave Samples

In Fig. 3.11, five frequency ranges of EEG for 1 second are shown. These four frequencies of brain wave are informed us to know brain's working situation. Beta frequencies show us normal waking situations, concentration; Alpha frequencies show us relaxing mode, creativity; Theta frequencies show us REM (dreaming) sleep, insight; Delta frequencies show us deep sleeping without dreaming, trance.

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## CHAPTER 4- PROPOSED CIRCUITS

In this chapter current mode filters are presented. Gate source capacitances and transconductances of MOS transistors are used instead of passive resistors and passive capacitors. All proposed circuits show simplicity, reduced chip area, wide frequency range, lower transistor count.

### 4.1. Proposed Circuit-1

First current mode dual output filter core circuit is shown below in Fig. 4.1

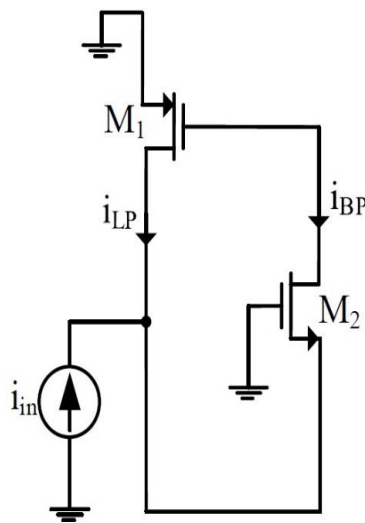


Figure 4. 1 Proposed Filter with MOS Transistors without Biasing

Filtering functions are achieved by transistors which are  $M_1$ ,  $M_2$ . Transistor  $M_1$  is provided lowpass filtering function, transistor  $M_2$  is provided bandpass filtering function. This circuit also use its parasitic gate-source capacitance and transconductances for passive resistor and capacitors.

This circuit is suitable for applying capacitance multiplier with mos resistors. With applying this method we just adjust current which flows mos resistors and then control the capacitance value which connected between gate and source terminals. This way provide us advantages on application which needs operation point is low frequency such as biomedical applications. The circuit with capacitance multiplier and its simulations will be demonstrated in further sections.

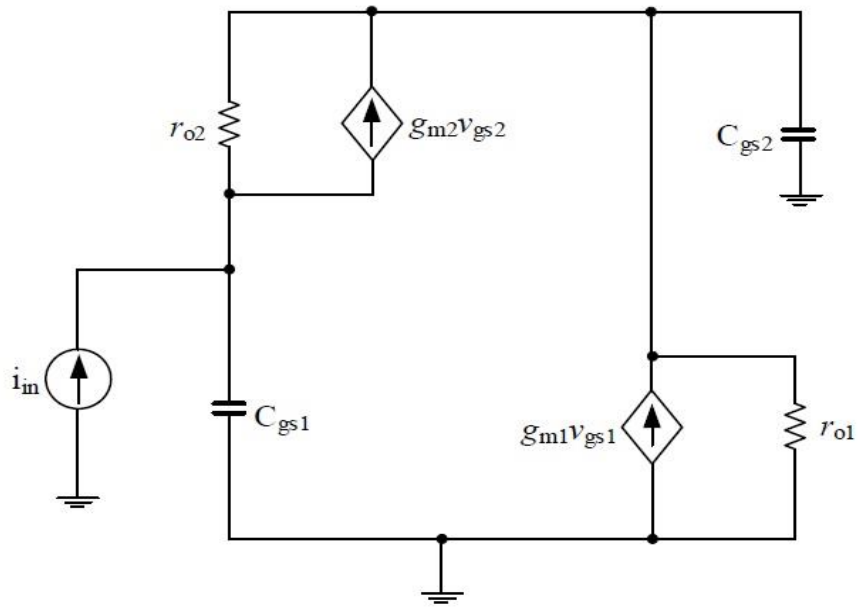


Figure 4. 2 Small Signal Model of Proposed Circuit-1

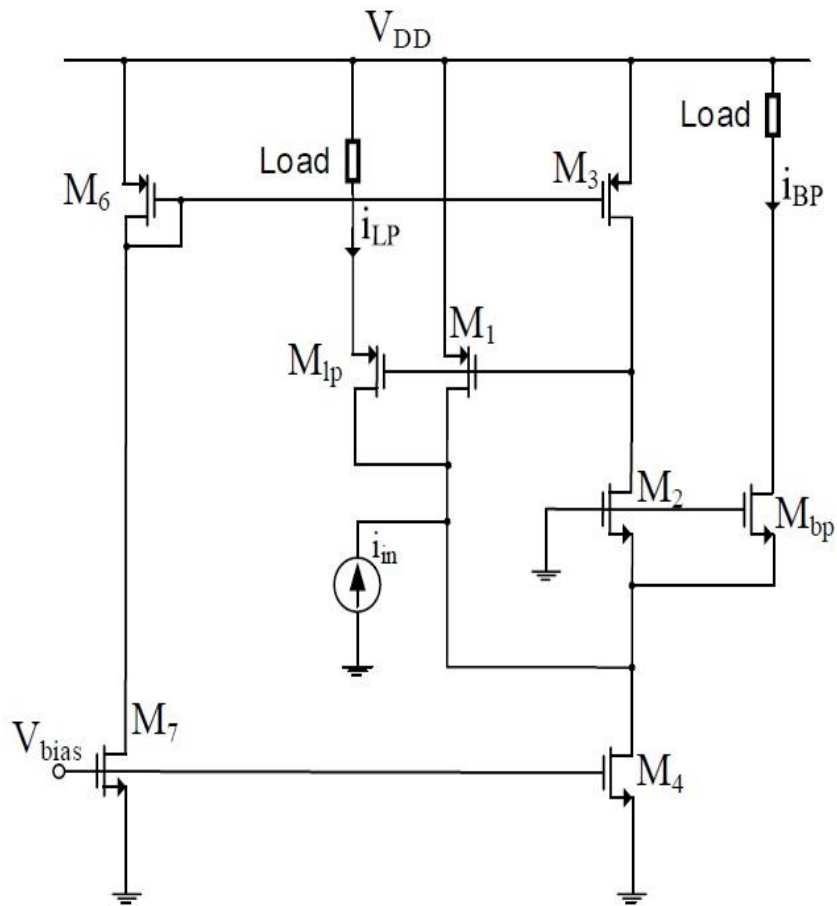


Figure 4. 3 The Complete Schematic of Proposed Circuit-1

Transistors  $M_3, M_4$  are used for provided DC currents for core transistors. To pick up LP and BP filtering currents, additional  $M_{1p}, M_{bp}$  transistors are connected in parallel to  $M_1$  and  $M_2$ . Following transfer functions are obtain for filter operations shown below in equation (4.1) and (4.2)

$$\frac{I_{LP}}{I_{in}} = \frac{g_{m1}g_{m2}}{g_{m1}g_{m2} + g_{m2}C_{gs1}s + C_{gs1}C_{gs2}s^2} \quad (4.1)$$

$$\frac{I_{BP}}{I_{in}} = -\frac{C_{gs1}g_{m2}s}{g_{m1}g_{m2} + g_{m2}C_{gs1}s + C_{gs1}C_{gs2}s^2} \quad (4.2)$$

Radial pole frequency and Quality factor of filter is shown below in equation (4.3) and equation (4.4)

$$Q = \sqrt{\frac{C_{gs2}g_{m1}}{C_{gs1}g_{m2}}} \quad (4.3)$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}}} \quad (4.4)$$

Transistor	Aspect Ratio( $\mu\text{m}/\mu\text{m}$ )
M1	3/0.1
M2	5/0.1

Table 4. 1 Aspect Ratios of Proposed Circuit-1

Aspect ratios of transistors in proposed circuit-1 are shown in Table 4.1. LTSpice AC simulations of proposed circuit-1 with  $0.35\mu\text{m}$  process parameters is shown in Fig. 4.4 for  $C_{gs1}$  and  $C_{gs2}$  are 1nF and 2nF respectively.

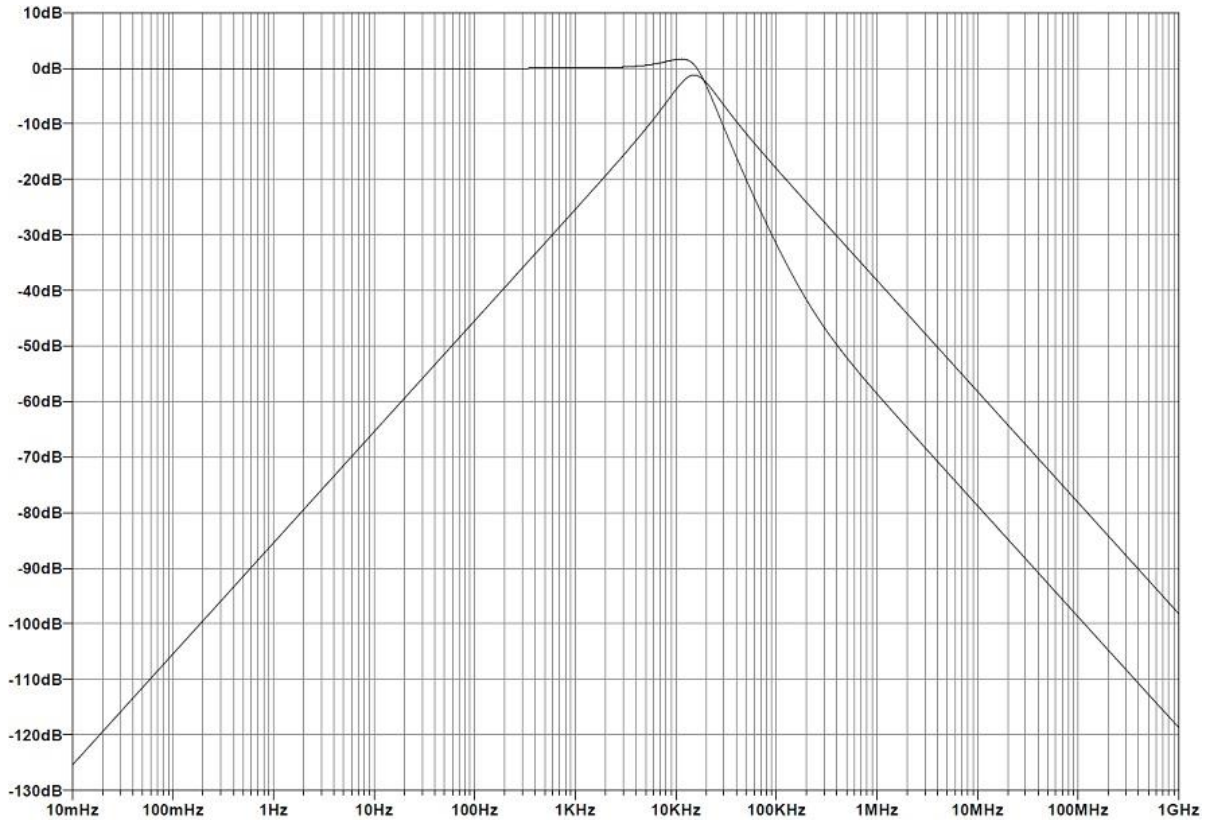


Figure 4. 4 BP and LP Frequency Response of Proposed Circuit-1

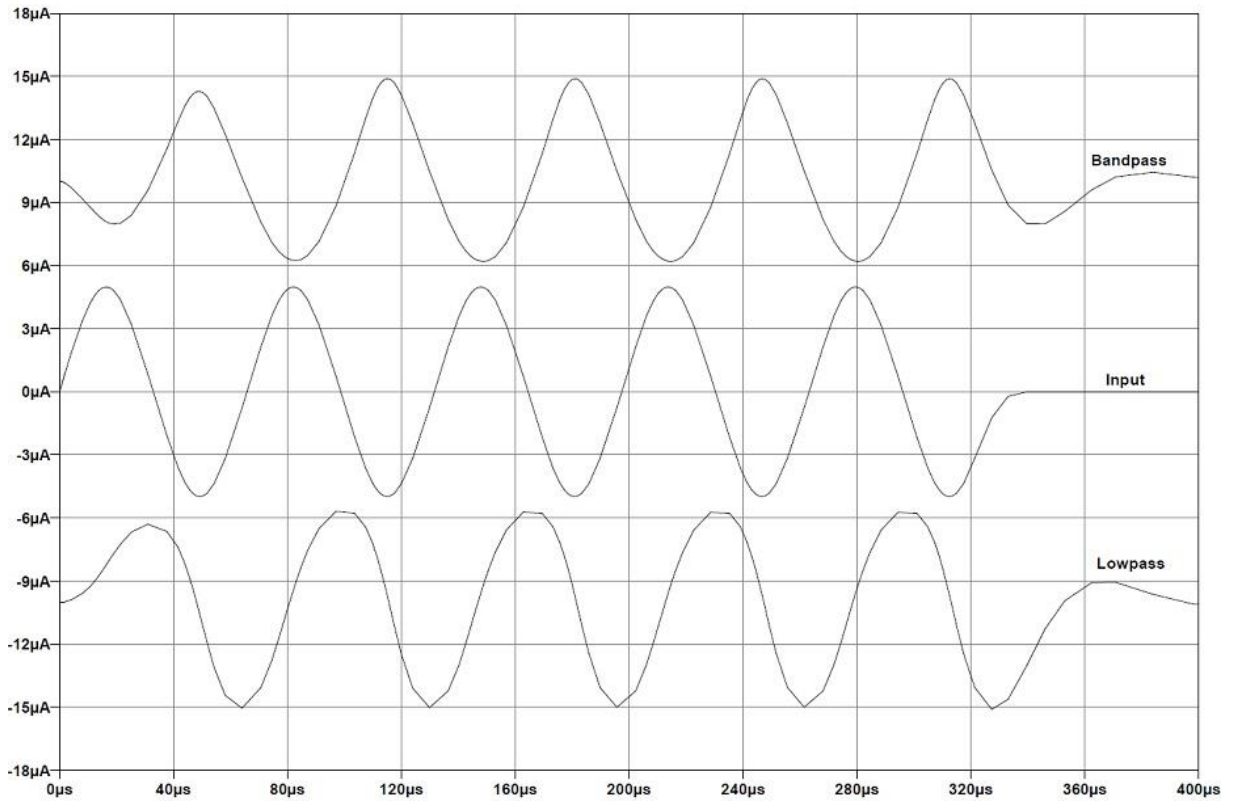


Figure 4. 5 Time Domain Simulation Results for Sinusoidal Input

Transient analysis of this circuit is shown above in Fig. 4.5. Sinusoidal input current is applied which has amplitude with  $5\mu\text{A}$  and frequency is  $15.2\text{kHz}$ . For obtain a lower cut-off frequency for filtering, gate-source capacitances are must be higher.

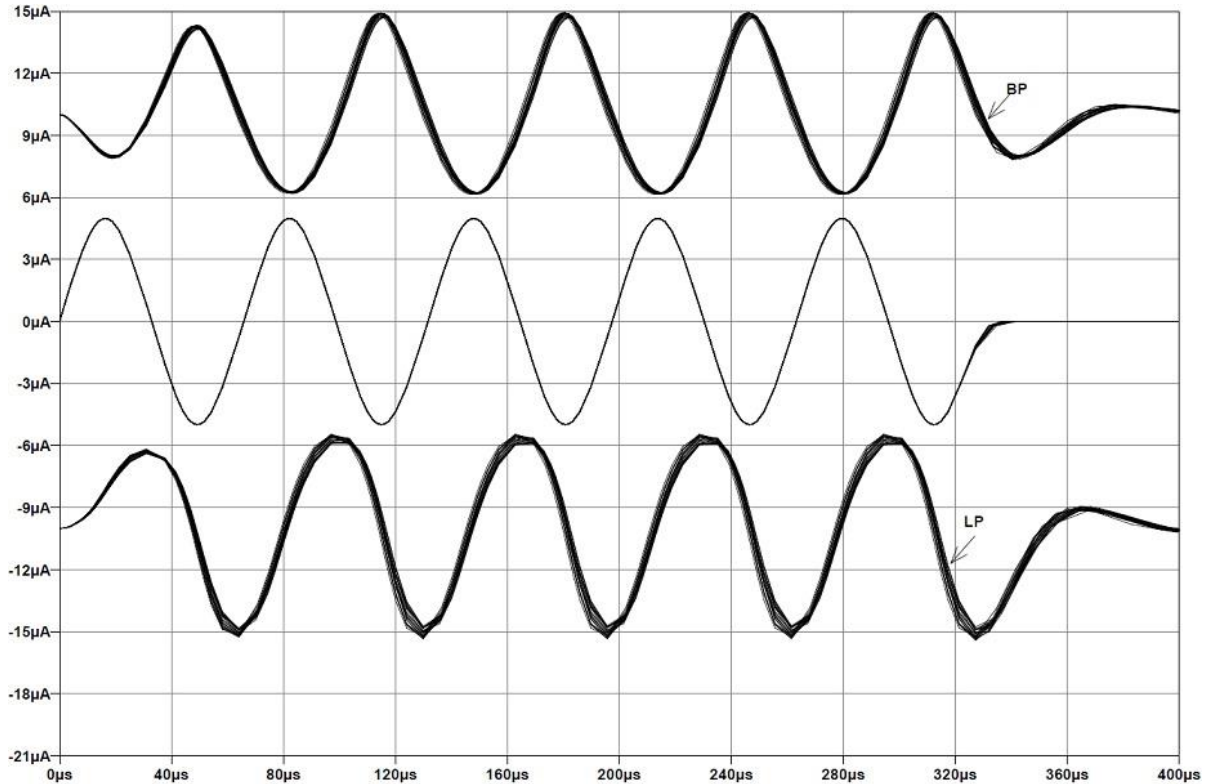


Figure 4. 6 Monte-Carlo Simulations for the Time Domain

With applying capacitance multiplier to circuit that lower cut-off frequency is obtained.

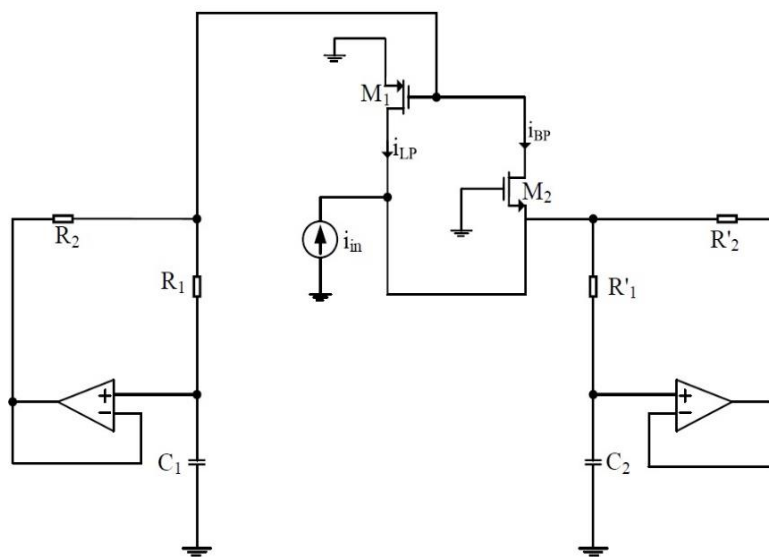


Figure 4. 7 Proposed Circuit-1 with Capacitance Multiplier

For  $R_2$  and  $R_2'$  are equal to  $10\Omega$ ,  $R_1$ ,  $R_1'$  are equal to  $1k\Omega$  and  $C_1$ ,  $C_2$  are equal to  $1nF$ .  
New LP and BP frequency response is shown below:

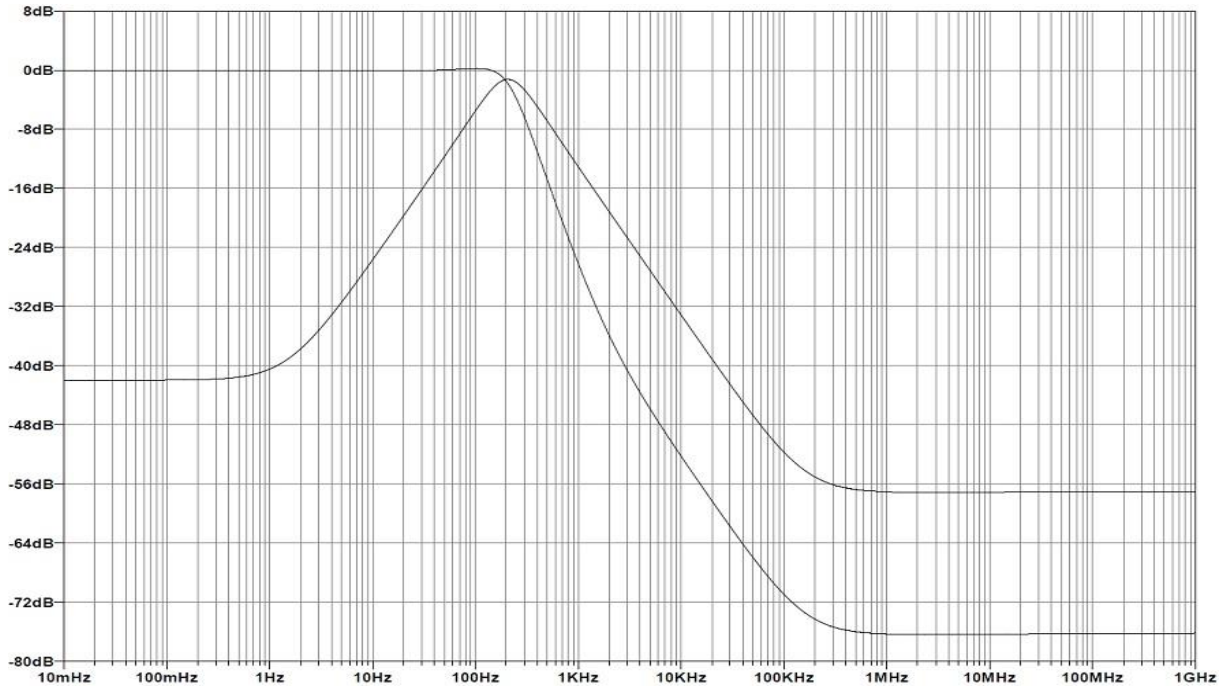


Figure 4. 8 LP and BP Filter Frequency Response of Proposed Circuit-1 with Capacitance Multiplier Step-1

For  $R_2$  and  $R_2'$  are equal to  $10\Omega$ ,  $R_1$ ,  $R_1'$  are equal to  $10k\Omega$  and  $C_1$ ,  $C_2$  are equal to  $1nF$ .  
New LP and BP frequency response is shown below:

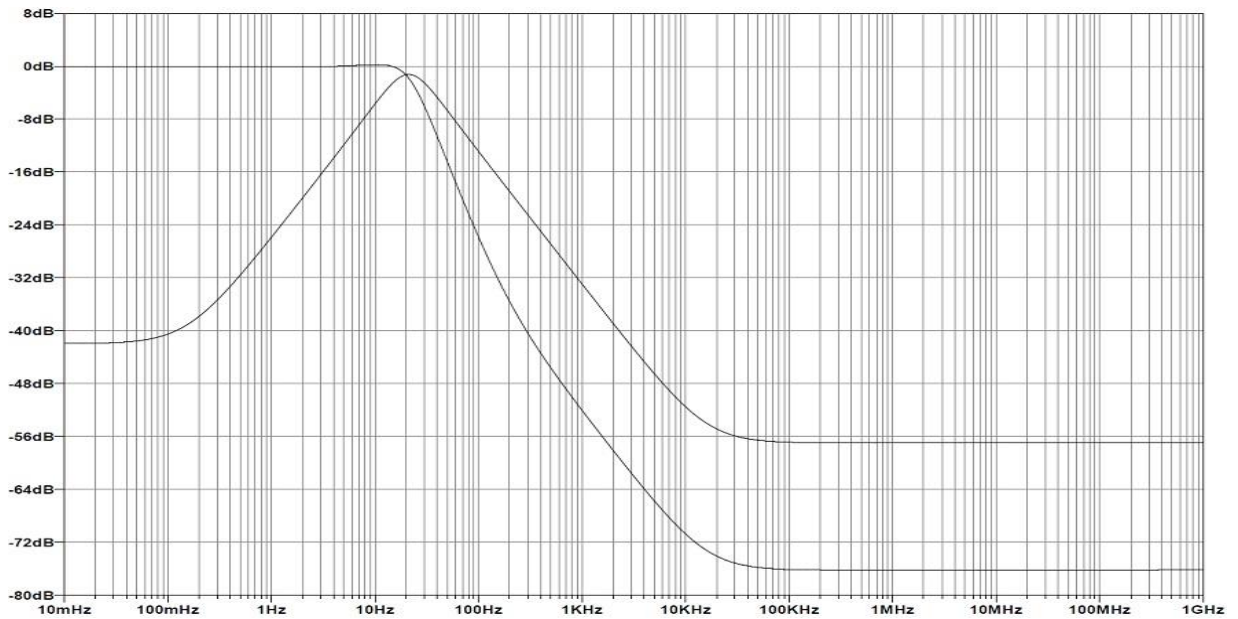


Figure 4. 9 LP and BP Filter Frequency Response of Proposed Circuit-1 with Capacitance Multiplier Step-2

For  $R_2$  and  $R_2'$  are equal to  $10\Omega$ ,  $R_1$ ,  $R_1'$  are equal to  $100k\Omega$  and  $C_1$ ,  $C_2$  are equal to  $1nF$ . New LP and BP frequency response is shown below:

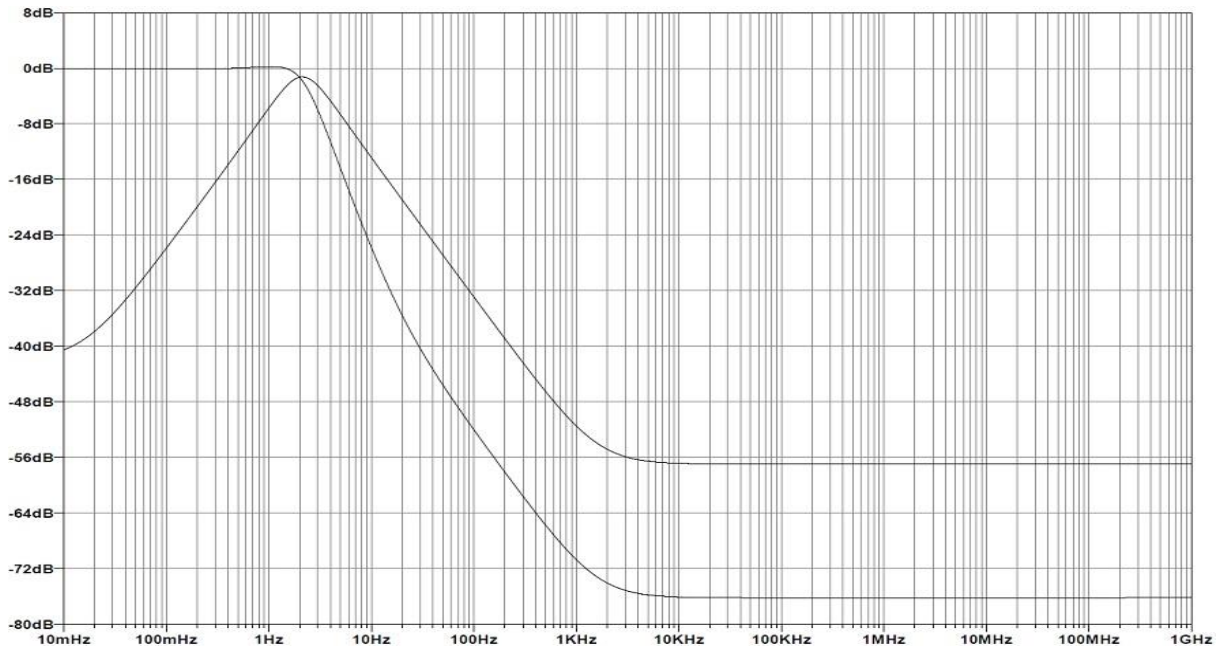


Figure 4. 10 LP and BP Filter Frequency Response of Proposed Circuit-1 with Capacitance Multiplier Step-3

In capacitance multiplier, if Floating MOS Resistor [29] is used instead of  $R_1$  and  $R_1'$  a new schematic of filter is shown in Fig. 4.11.

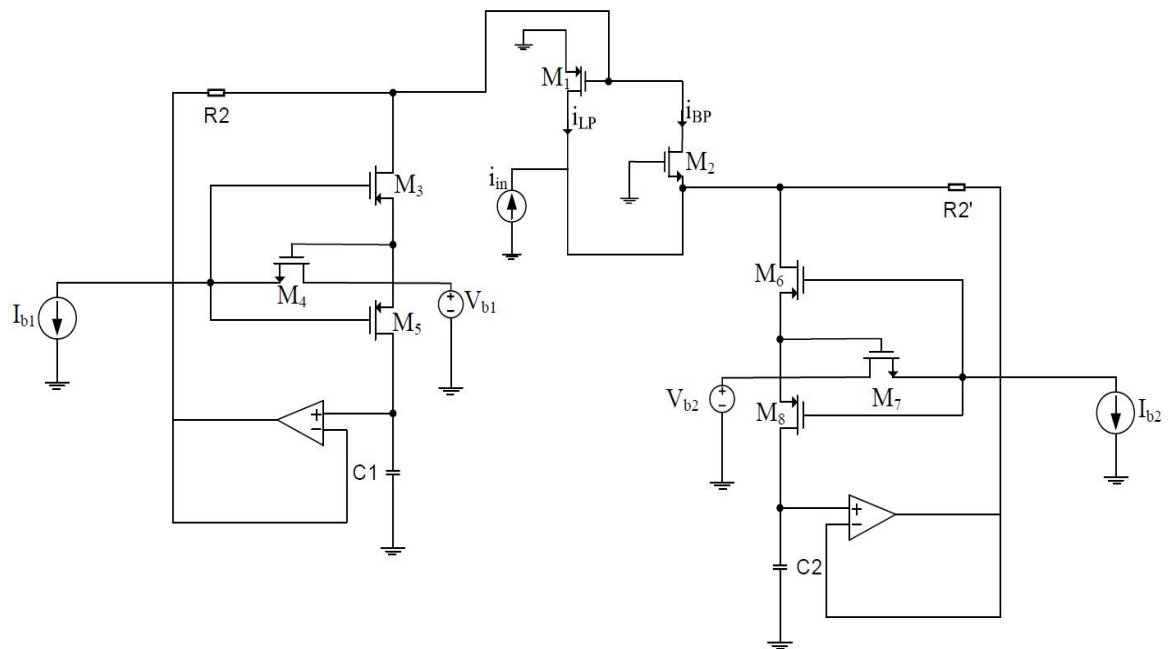


Figure 4. 11 Proposed Circuit-1 with Capacitance Multiplier with Floating MOS Resistor

Transistor	Aspect Ratio ( $\mu\text{m}/\mu\text{m}$ )
M1	6/0.1
M2	100/0.1
M3	10/0.35
M4	10/1.1
M5	10/0.35
M6	10/0.35
M7	10/1.1
M8	10/0.35

Table 4. 2 Aspect Ratios of Proposed Circuit-1 with Floating MOS Resistor

With aspect ratios which are shown in Table 4.2 and  $I_{b1}$  and  $I_{b2}$  are equal to  $100 \mu\text{A}$  and  $R_2, R_2'$  are equal to  $10 \Omega$ , AC simulation result is as seen as Fig. 4.12.

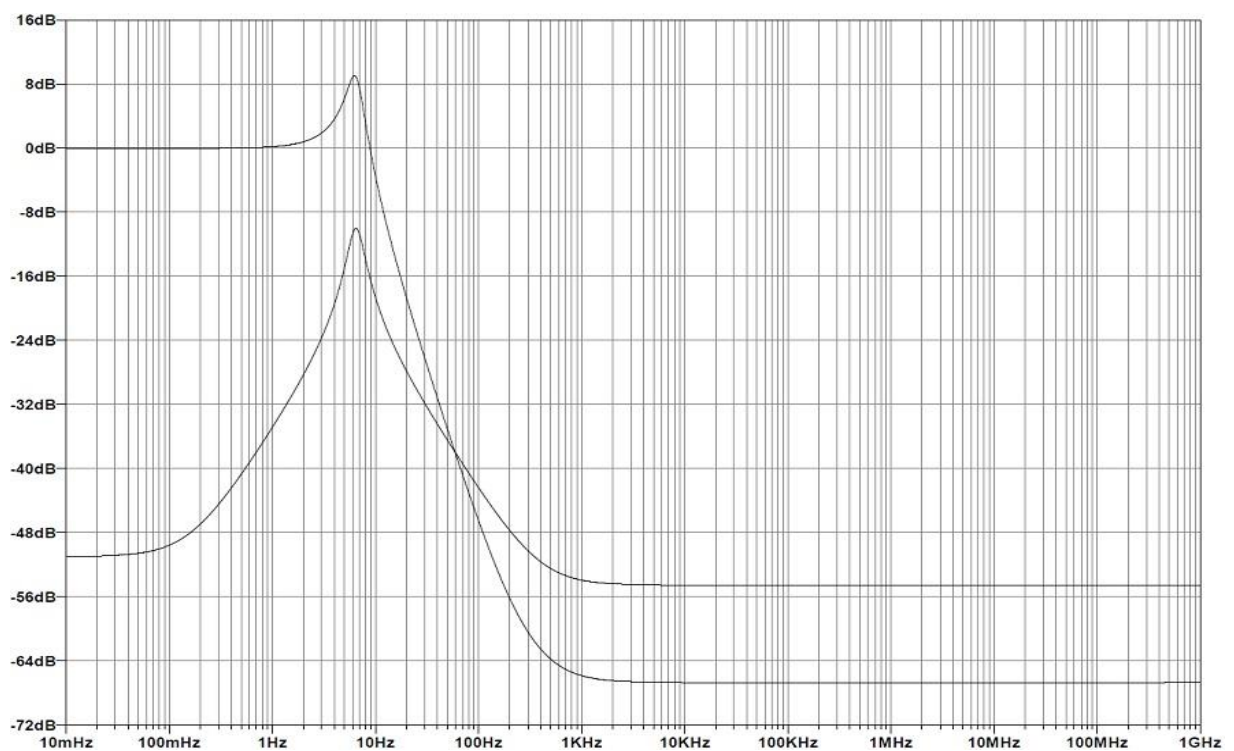


Figure 4. 12 Frequency Response of Proposed Filter Circuit-1 with MOS Resistor

For bias currents are equal to  $10\mu\text{A}$  AC simulation result is as seen as Fig. 4.13.

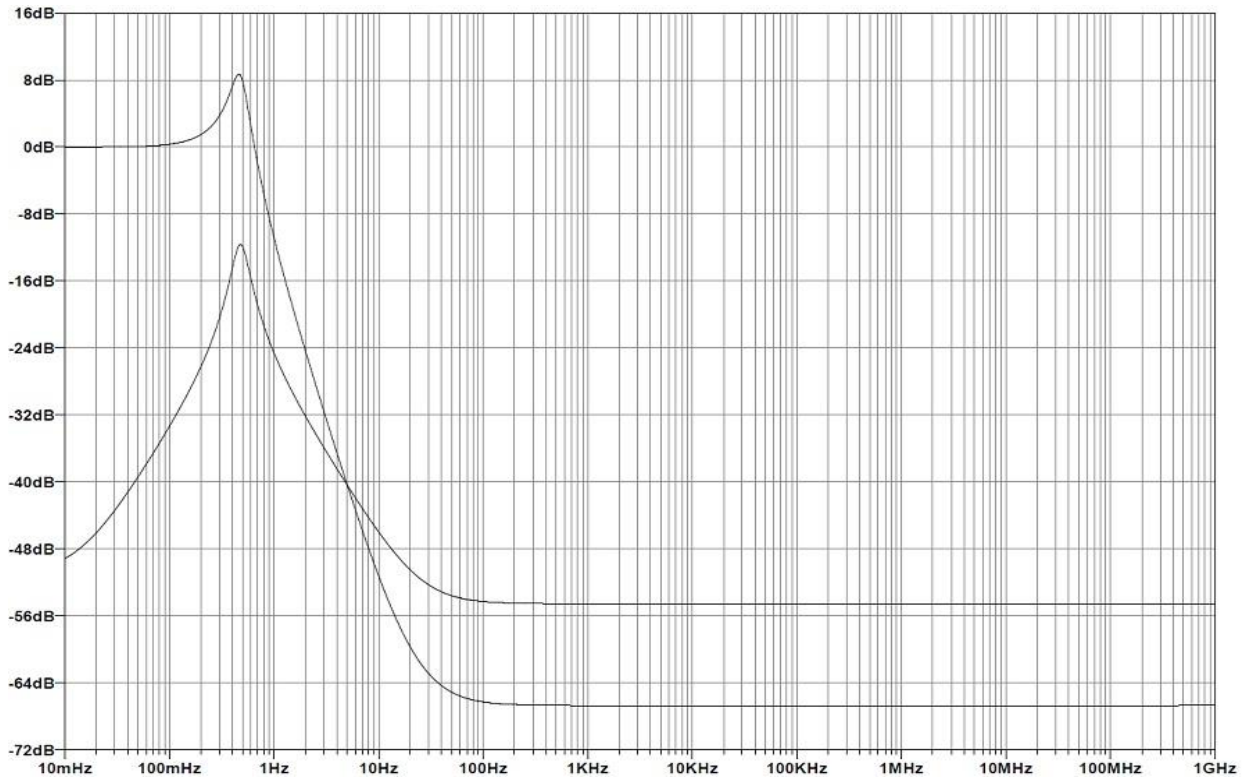


Figure 4. 13 Frequency Response of Proposed Filter Circuit-1 with MOS Resistor Step-2

## 4.2. Proposed Circuit-2

Many biomedical applications need low frequency operation range as we mention in section 3.3. In MOS Only or MOS-C filters, cut off frequency is arranged by gate-source capacitance or passive capacitance. For low frequency the circuit need high value capacitor and this may be disadvantages for different aspects such as chip area, marketing cost, power consumption. Cause of that reasons, we suggest a new concept for obtain filters which have low cut off frequency with lower value capacitor.

As we mentioned in section 3.2 and section 3.1.2, using capacitance multiplier concept is really helpful for obtain filters which applicable for biomedical applications [35, 29]. First applying of capacitance multiplier on filters will be shown and then capacitance multiplier which used Floating MOS Resistor will be shown.

The MOS Only multi-function biquad filter [1] which shown in Fig. 4.14 below, has a two filter functions which are LP and BP.

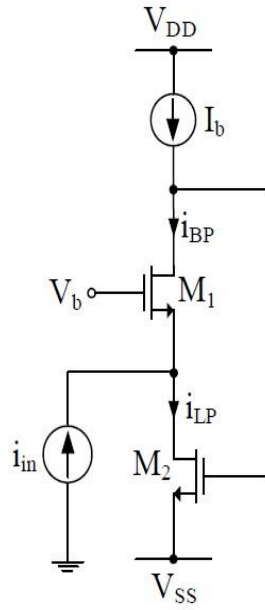


Figure 4. 14 The MOS Only multi-function Biquad filter [1]

Equivalent capacitance at the drain node is shown below [1]:

$$C_x = C_{gs2} + C_{gd1} + C_{gdbias} \quad (4.5)$$

$$\frac{I_{LP}}{I_{in}} = \frac{(g_{m1} + g_{mb1})g_{m2}}{\Delta} \quad (4.6)$$

$$\frac{I_{BP}}{I_{in}} = -\frac{(g_{m1} + g_{mb1})sC_x}{\Delta} \quad (4.7)$$

Where  $C_x$ :

$$C_x = (g_{m1} + g_{mb1})g_{m2} + (g_{m1} + g_{mb1})sC_x + s^2C_{gs1}C_x \quad (4.8)$$

Transistor	Aspect Ratio( $\mu\text{m}/\mu\text{m}$ )
M1	10/1.1
M2	10/1.1

Table 4. 3 Aspect Ratios of Filter Circuit [1]

Using aspect ratios shown in Table 4.3 and gate-source capacitances for M1 and M2 1nF and 1nF. For Vb is 1.5V DC and bias current is 100u, AC simulation result is shown in Fig. 4.15 below.

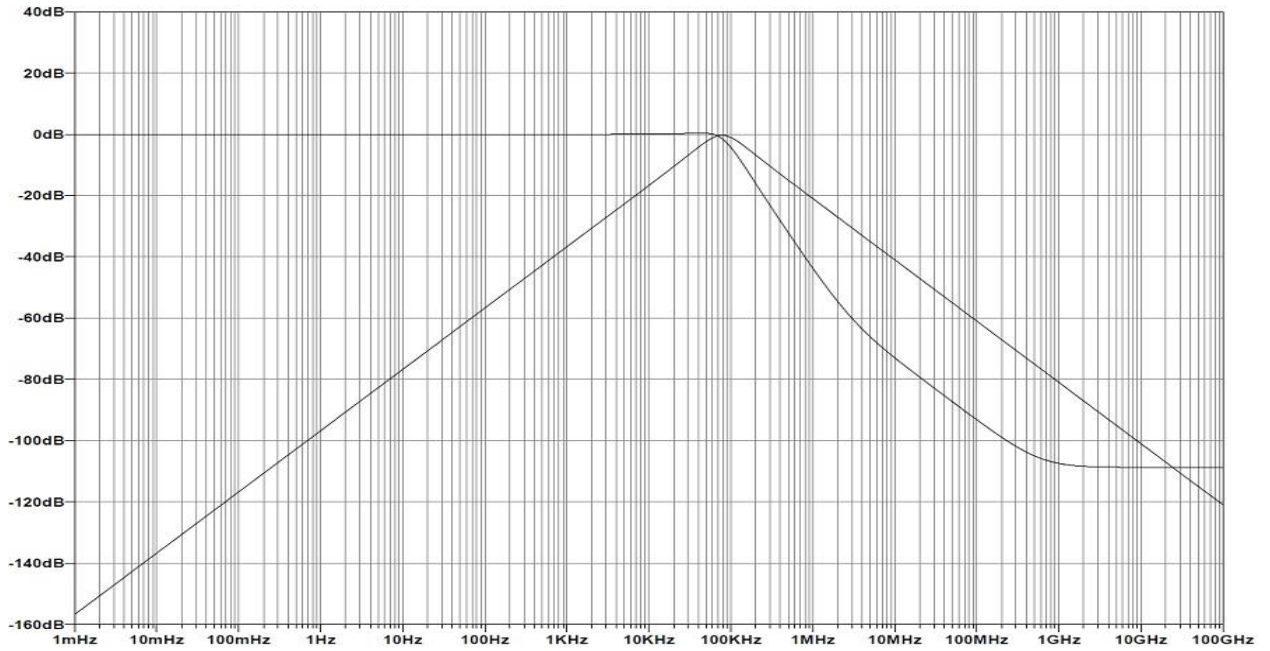


Figure 4. 15 BP and LP Frequency Response of Filter [1]

As seen on Fig. 4.15 cut off frequencies of BP and LP filters are not suitable for applications which need low frequency operation such as biomedical applications. For lower frequency, we must increase the gate-source capacitance values but this way is not applicable properly. For biomedical application, filters cut off frequencies must be below 10 kHz and many applications need 100 Hz and below. For obtain these cut off frequencies, capacitance multiplier is applied filters in our suggestion. With applying capacitance multiplier on Filter [1], new circuit schematic is shown in Fig. 4.16.

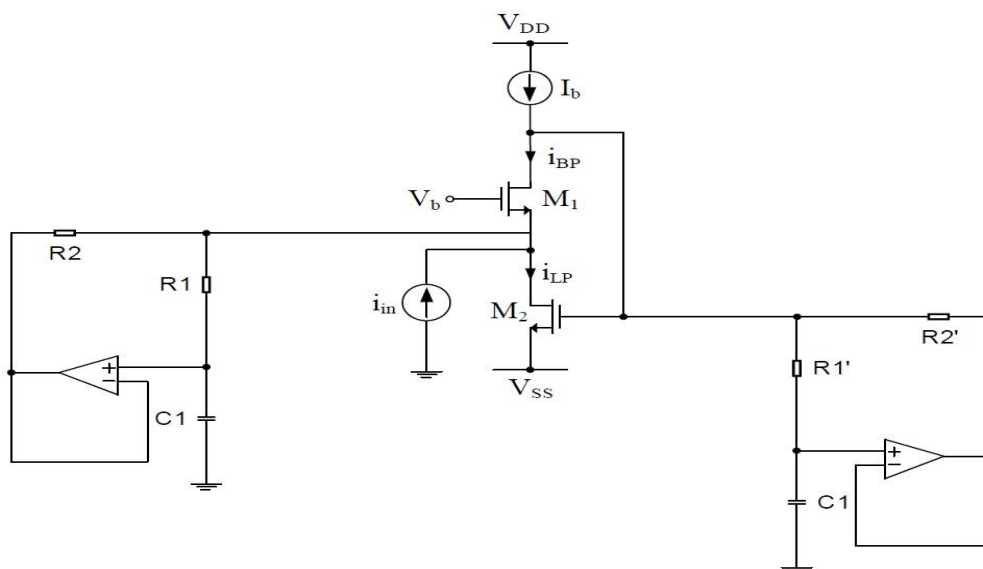


Figure 4. 16 Filter [1] with Capacitance Multipliers

New LP and BP filters cut off frequencies are shown below in Fig. 4.17, for  $R_2, R_2'$  are equal to  $10\Omega$  and  $R_1, R_1'$  are equal to  $1k\Omega$ .

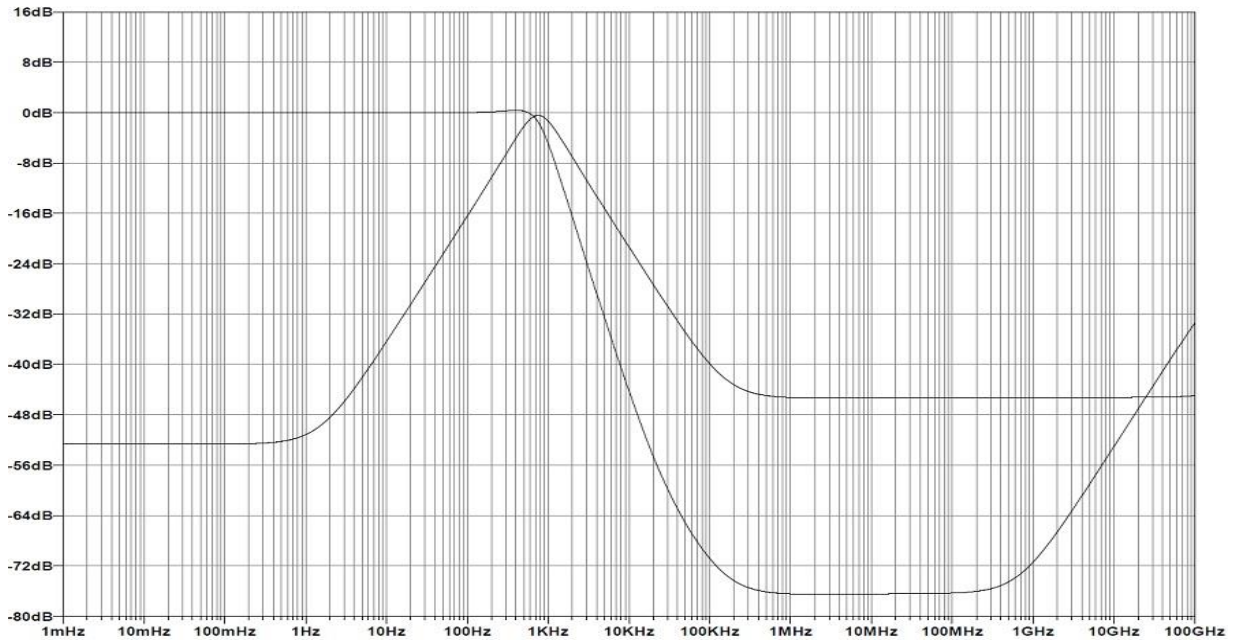


Figure 4. 17 LP and BP Filter Frequency Response with Capacitance Multiplier Step-1  
For  $R_2, R_2'$  are equal to  $10\Omega$  and  $R_1, R_1'$  are equal to  $10k\Omega$  a new simulation result is shown below in Fig. 4.18.

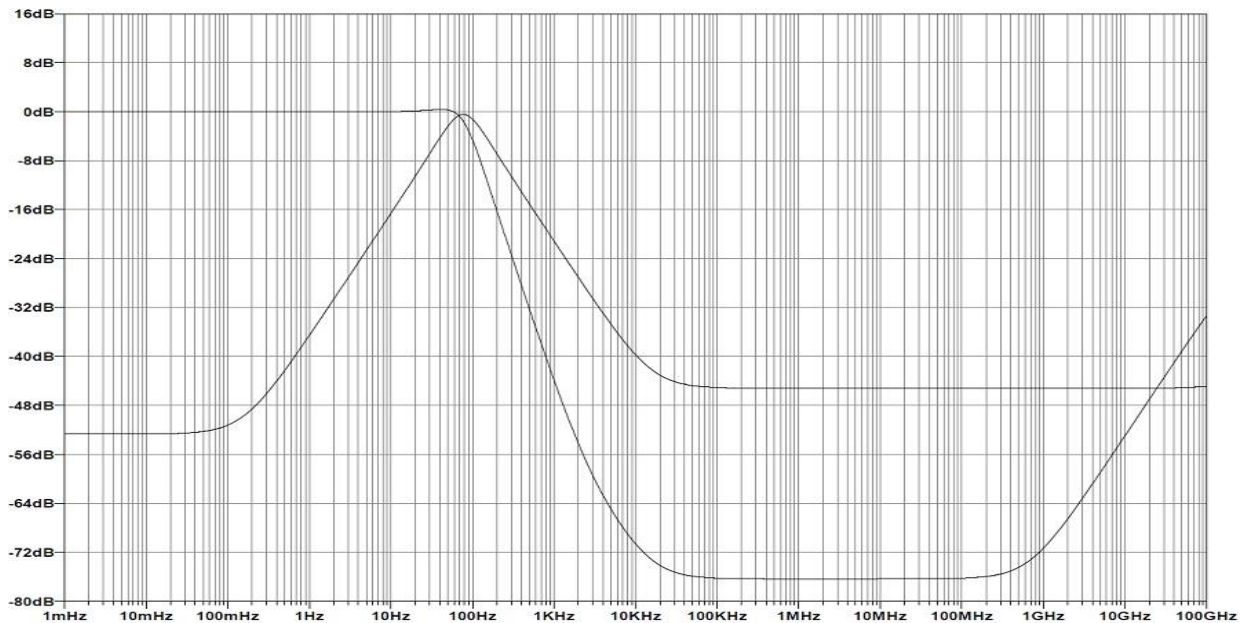


Figure 4. 18 LP and BP Filter Frequency Response with Capacitance Multiplier Step-2  
As seen this capacitance multiplier approximation, filter functions can be adjustable for lower frequencies with changing on  $R_1$  and  $R_1'$ . For  $R_1$  and  $R_1'$  are equal to  $1k\Omega$  cut off

frequencies are about to 1 kHz and then for R1 and R1' are equal to 10kΩ, cut off frequencies decreases to 100 Hz. For R1 and R1' are equal to 100 kΩ frequency response of filter is shown below in Fig. 4.19.

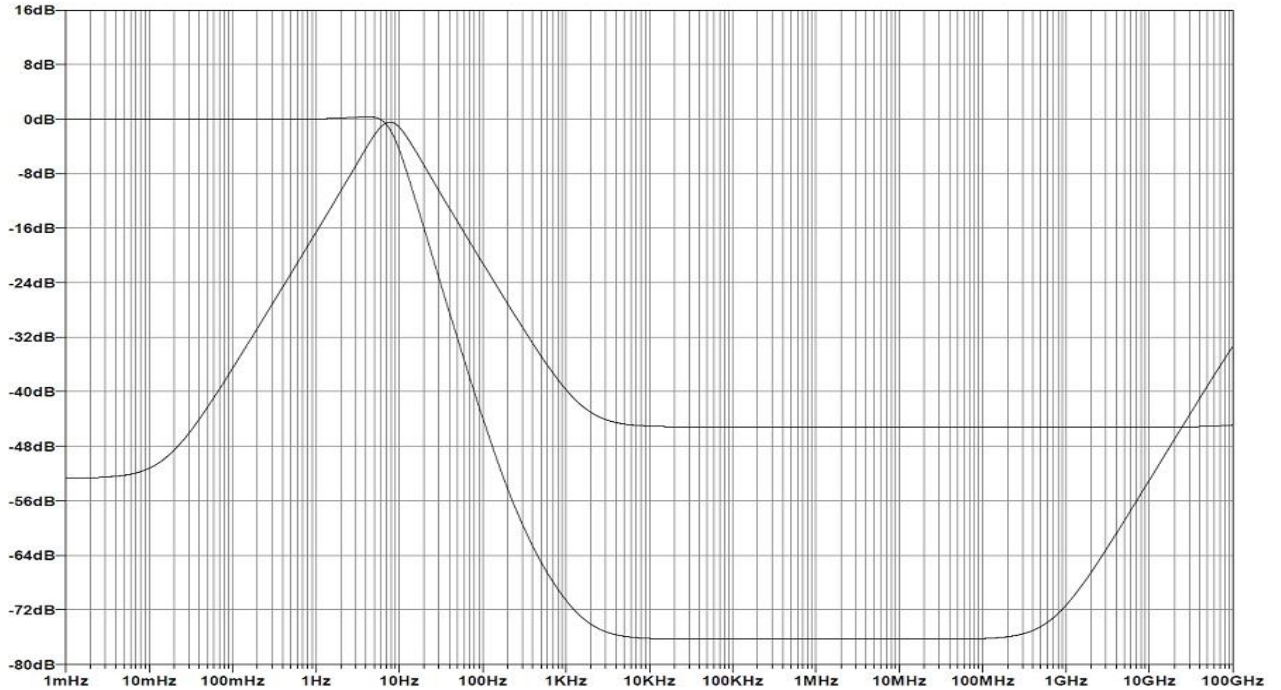


Figure 4. 19 LP and BP Filter Frequency Response with Capacitance Multiplier Step-3

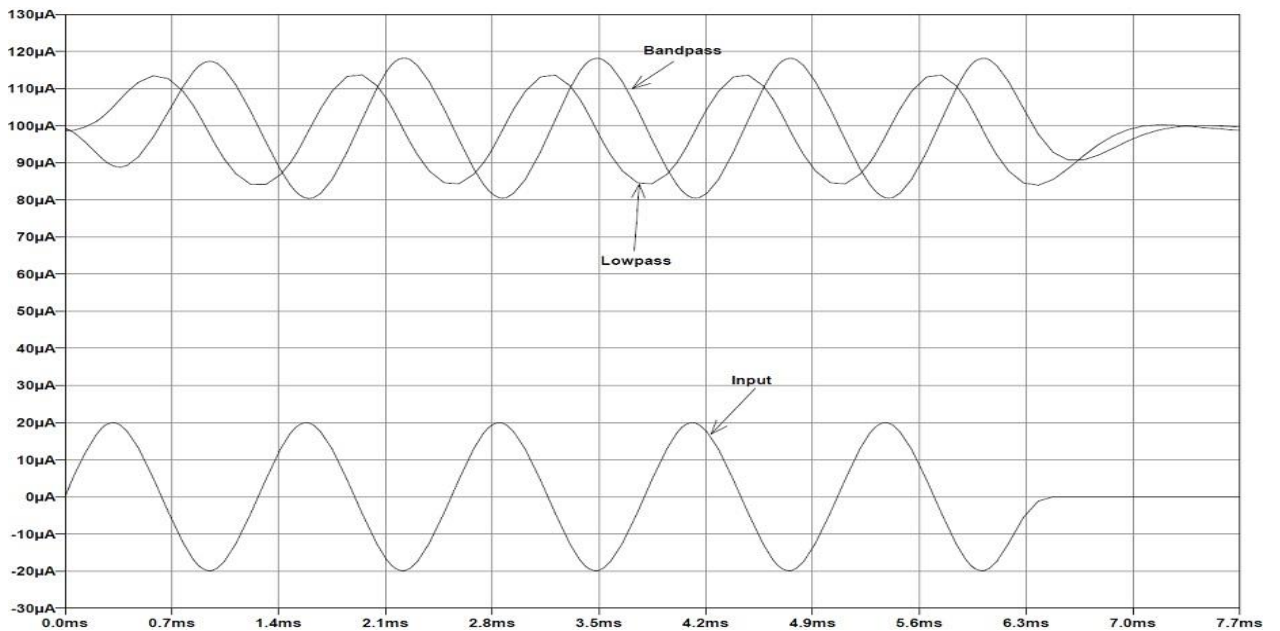


Figure 4. 20 Time Domain Simulation Results for Sinusoidal Input

Transient analysis of circuit with capacitance multiplier is shown above in Fig. 4.20. Sinusoidal input current is applied which has amplitude with 20uA and frequency is 790Hz. In capacitance multiplier.

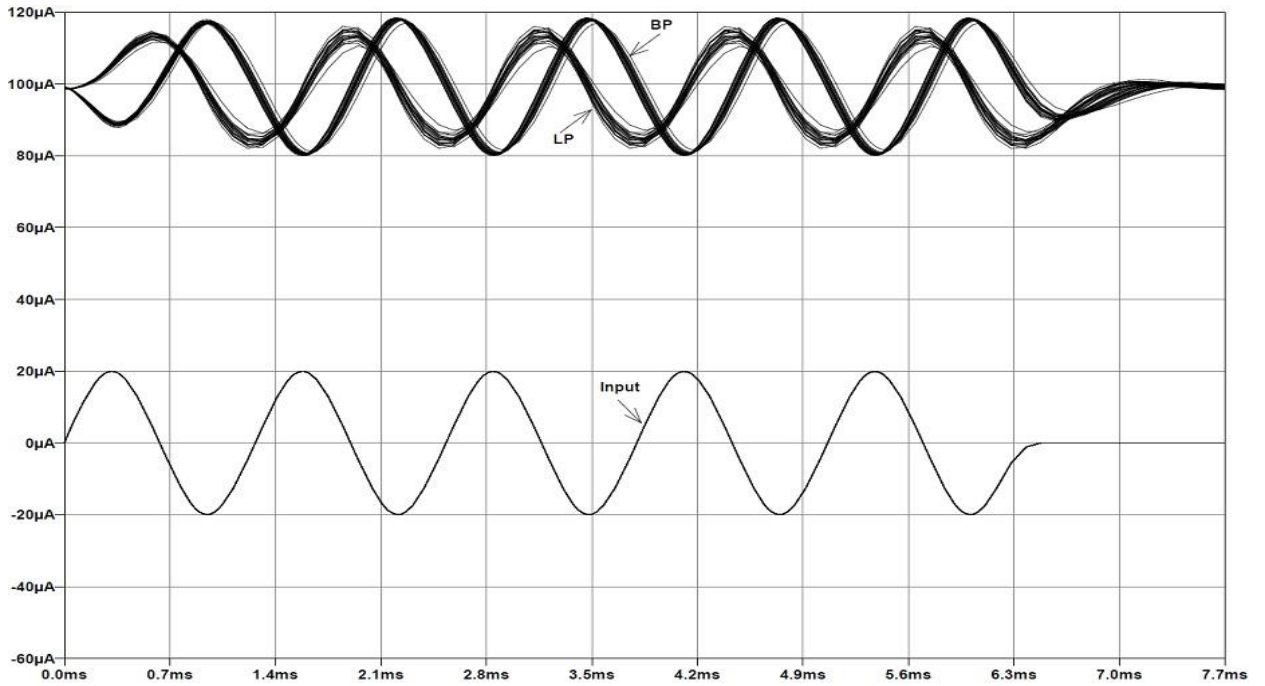


Figure 4. 21 Monte-Carlo Simulations for the Time Domain

if Floating MOS Resistor [29] is used instead of R1 and R1' a new schematic of filter is shown in Fig. 4.22.

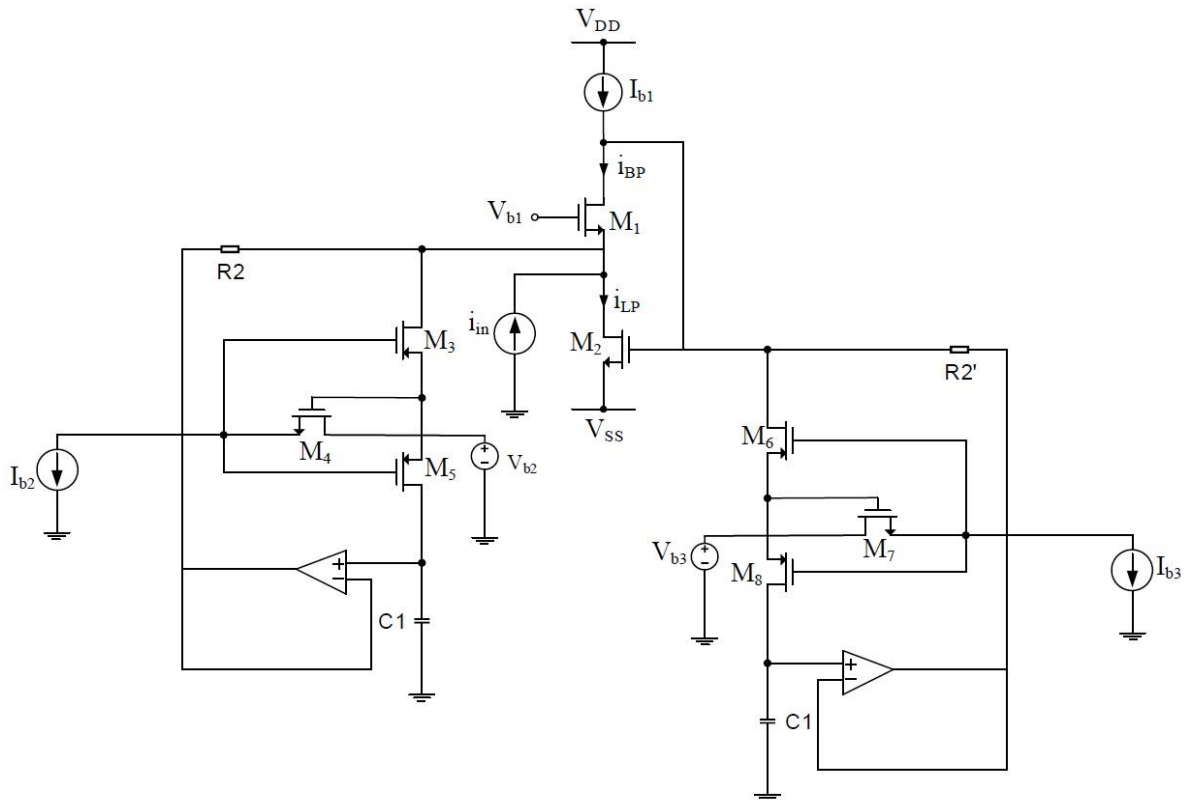


Figure 4. 22 Filter [1] with Capacitance Multiplier with Floating MOS Resistor

Transistor	Aspect Ratio ( $\mu\text{m}/\mu\text{m}$ )
M1	10/1.1
M2	10/1.1
M3	10/0.35
M4	10/1.1
M5	10/0.35
M6	10/0.35
M7	10/1.1
M8	10/0.35

Table 4. 4 Aspect Ratios of Proposed Circuit-2

With aspect ratios of proposed circuit-2 and I bias currents equal to  $100 \mu\text{A}$ , AC simulation result is as seen as Fig. 4.23 which shown below.

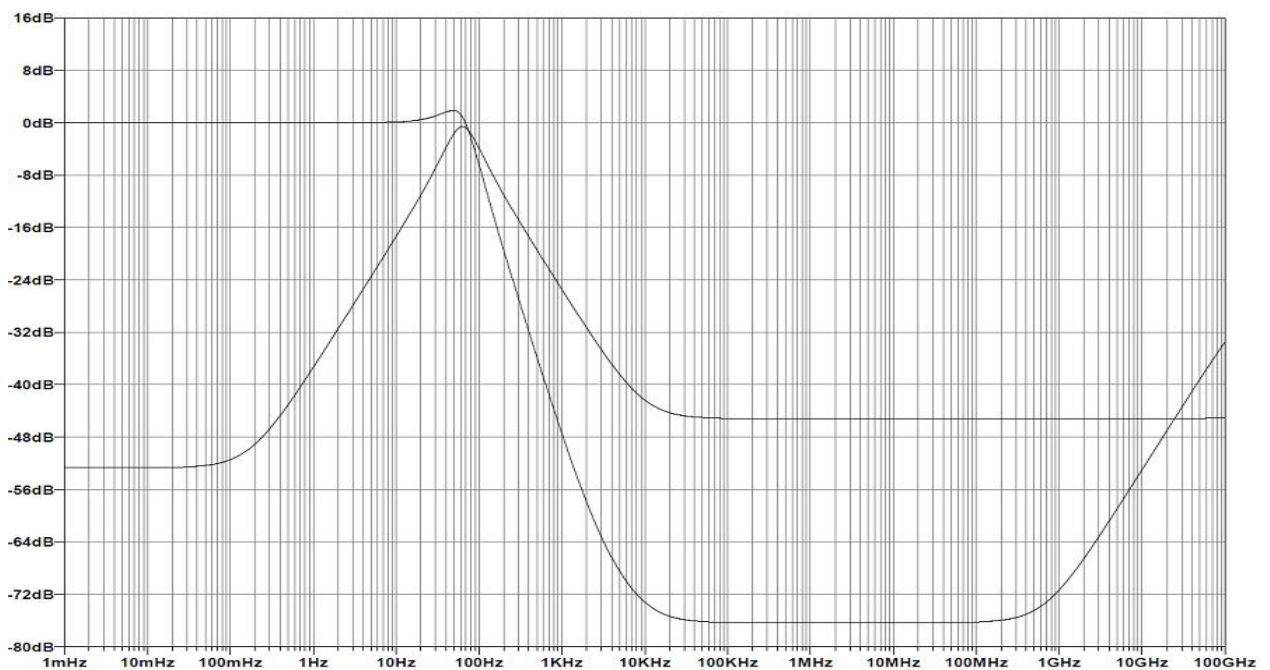


Figure 4. 23 Frequency Response of Proposed Filter Circuit-2 Step-1

As seen as Fig. 4.23 cut off frequencies are about to 100 Hz for  $100 \mu\text{A}$  bias currents. Floating MOS Resistor [29] is adjustable with bias currents with this feature if we attenuated the bias currents to  $10 \mu\text{A}$ , new frequency response is become as seen as Fig.4.24 which shown below.

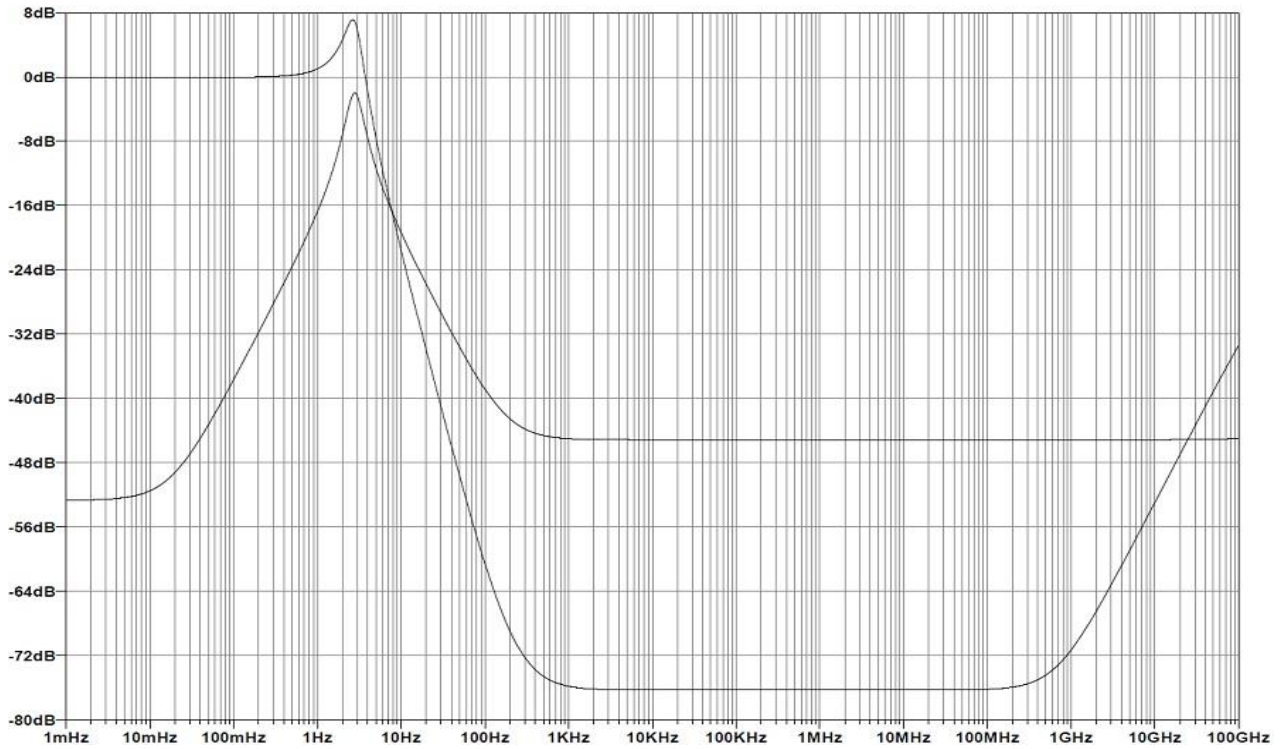


Figure 4. 24 Frequency Response of Proposed Filter Circuit-2 Step-2

As seen as Fig. 4.24 when bias currents are decreased by 10 times, cut off frequencies are decreased almost same ratio. For bias currents are  $1\mu\text{A}$  is shown in Fig. 4.25.

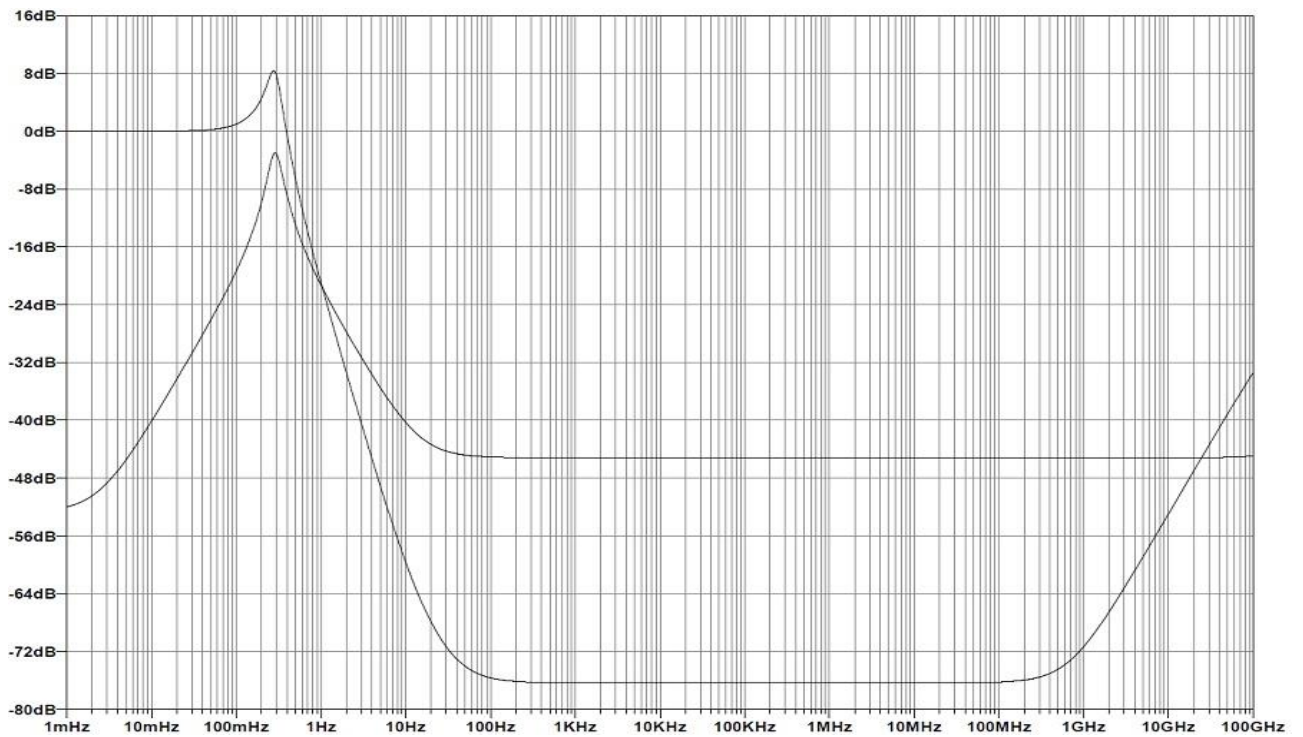


Figure 4. 25 Frequency Response of Proposed Filter Circuit-2 Step-3

### 4.3. Proposed Circuit-3

Current mode dual output filter core circuit shown in Fig. 4.26. Then all bias sources are shown and all bias current sources are replaced by MOS transistors. Passive capacitors are obtained by intrinsic parasitic gate-source capacitances of MOS transistors and  $g_m$  is transconductance gain of MOS transistors.

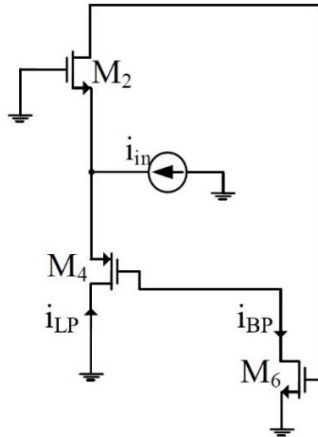


Figure 4. 26 Proposed Filter with MOS Transistors without Biasing

In Fig. 4.26 functional core of proposed circuit is shown. Filtering functions are achieved by these two ( $M_4$ ,  $M_6$ ) transistors. Completed circuit schematic with biasing is shown in Fig. 4.27.

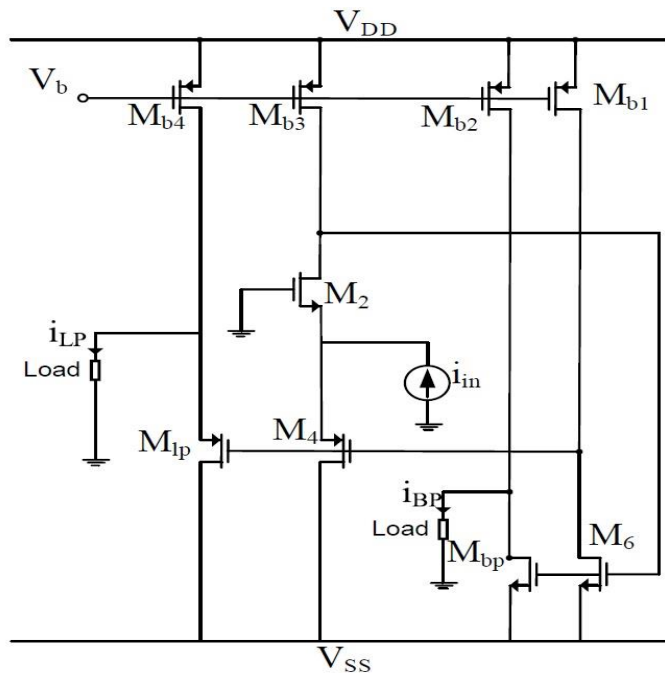


Figure 4. 27 The Complete Schematic of Proposed Circuit-3

Transistors  $M_{b1}$ ,  $M_{b2}$ ,  $M_{b3}$ ,  $M_{b4}$  are used for DC biasing currents.  $M_{b1}$  and  $M_{b3}$  are DC biasing currents for  $M_2$ ,  $M_4$ ,  $M_6$ . To pick up BP and LP currents, transistors  $M_{lp}$  and  $M_{bp}$  are connected in parallel to  $M_4$  and  $M_6$ . Transistors  $M_{b2}$  and  $M_{b4}$  are provided DC biasing currents for  $M_{lp}$  and  $M_{bp}$ . Following transfer functions are obtain for filter operations shown below in equation (4.9) and equation (4.10)

$$\frac{I_{LP}}{I_{in}} = -\frac{g_{m4}g_{m6}}{g_{m4}g_{m6} + g_{m6}C_{gs4}s + C_{gs4}C_{gs6}s^2} \quad (4.9)$$

$$\frac{I_{BP}}{I_{in}} = \frac{C_{gs4}g_{m6}s}{g_{m4}g_{m6} + g_{m6}C_{gs4}s + C_{gs4}C_{gs6}s^2} \quad (4.10)$$

Radial pole frequency ( $\omega_0$ ) and quality factor (Q) for BP and LP filters are given as (4.11) and (4.12) respectively;

$$Q = \sqrt{\frac{C_{gs6}g_{m4}}{C_{gs4}g_{m6}}} \quad (4.11)$$

$$\omega_0 = \sqrt{\frac{g_{m4}g_{m6}}{C_{gs4}C_{gs6}}} \quad (4.12)$$

Transistor	Aspect ratio ( $\mu\text{m}/\mu\text{m}$ )
$M_2$	10/1.1
$M_4$	100/0.1
$M_6$	100/0.1

Table 4. 5 Aspect Ratios

Aspect ratios of core transistors are shown above in Table 4.5. The performance and simulations of proposed circuits is examined by LTSpice program simulations using  $0.35\mu\text{m}$  process parameters.  $C_{gs2}$ ,  $C_{gs4}$ ,  $C_{gs6}$  are 2nF, 4nF, 2nf respectively.

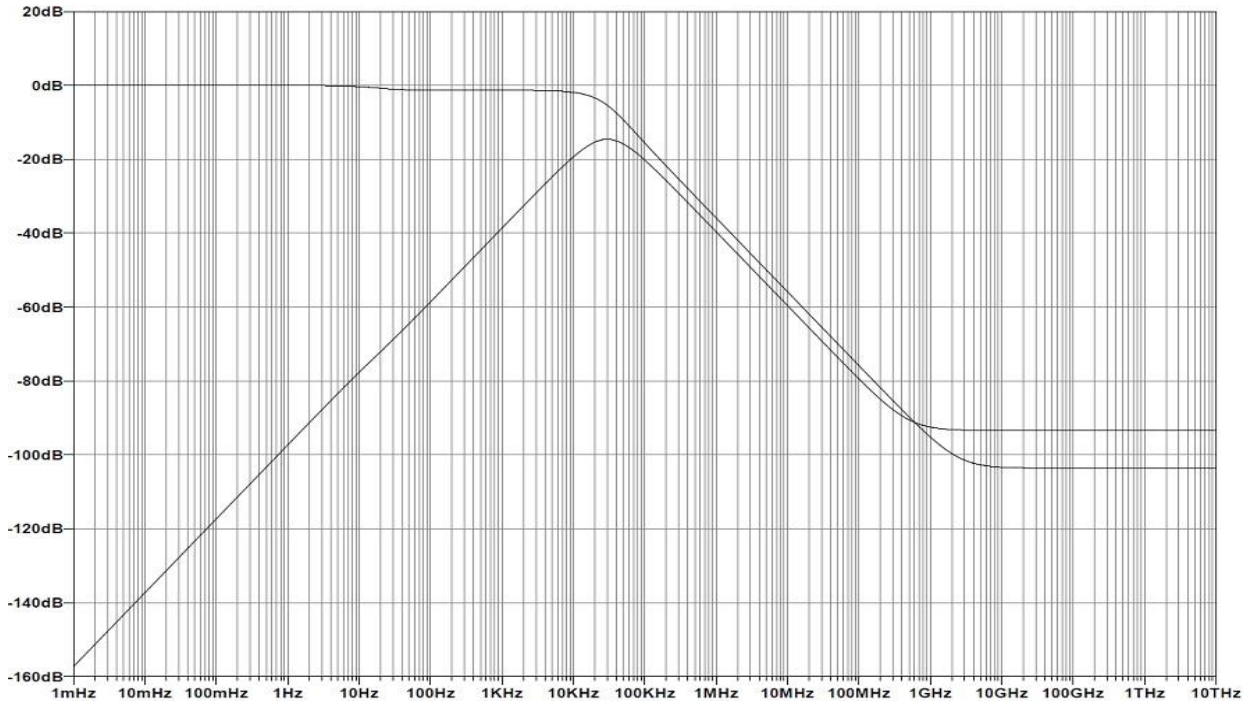


Figure 4. 28 BP and LP Frequency Response of Proposed Circuit-3

AC simulation result of proposed circuit is shown above in Fig. 4.28. Transient analysis of this circuit is shown below Fig. 4.29. Sinusoidal input current is applied which has amplitude with 50uA and frequency is 33.5kHz.

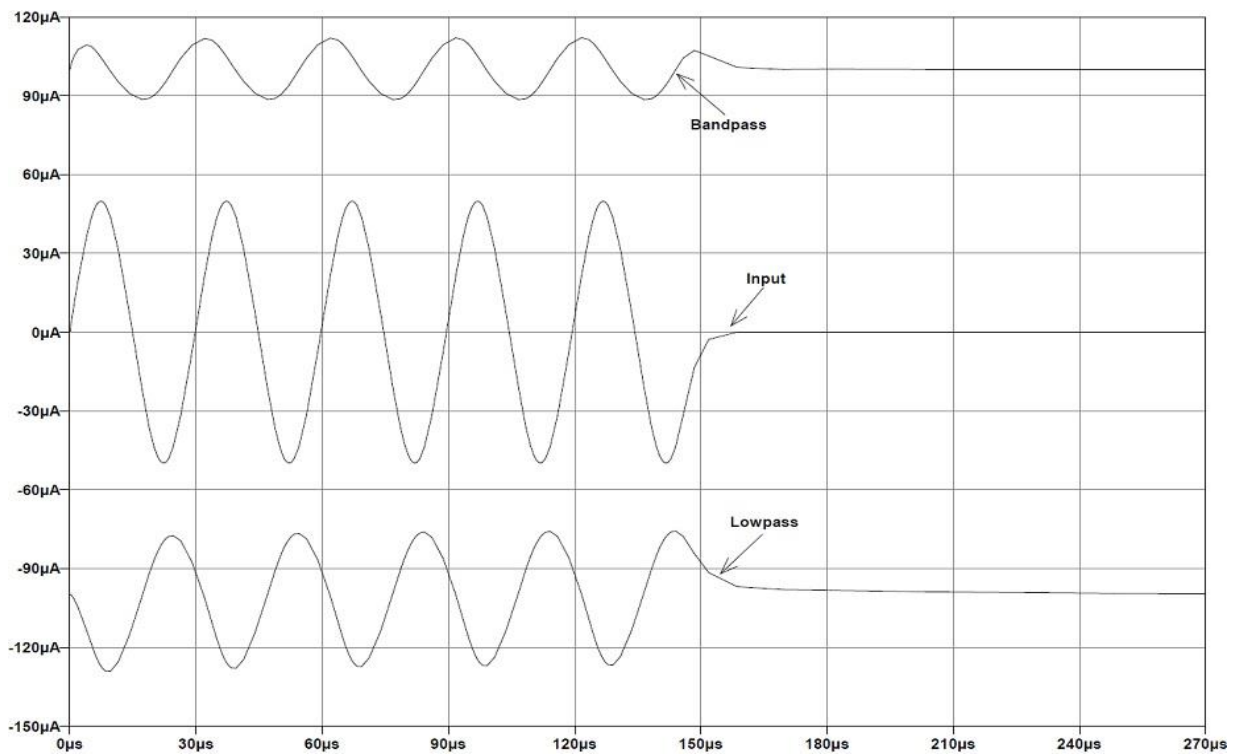


Figure 4. 29 Time Domain Simulation Results for Sinusoidal Input

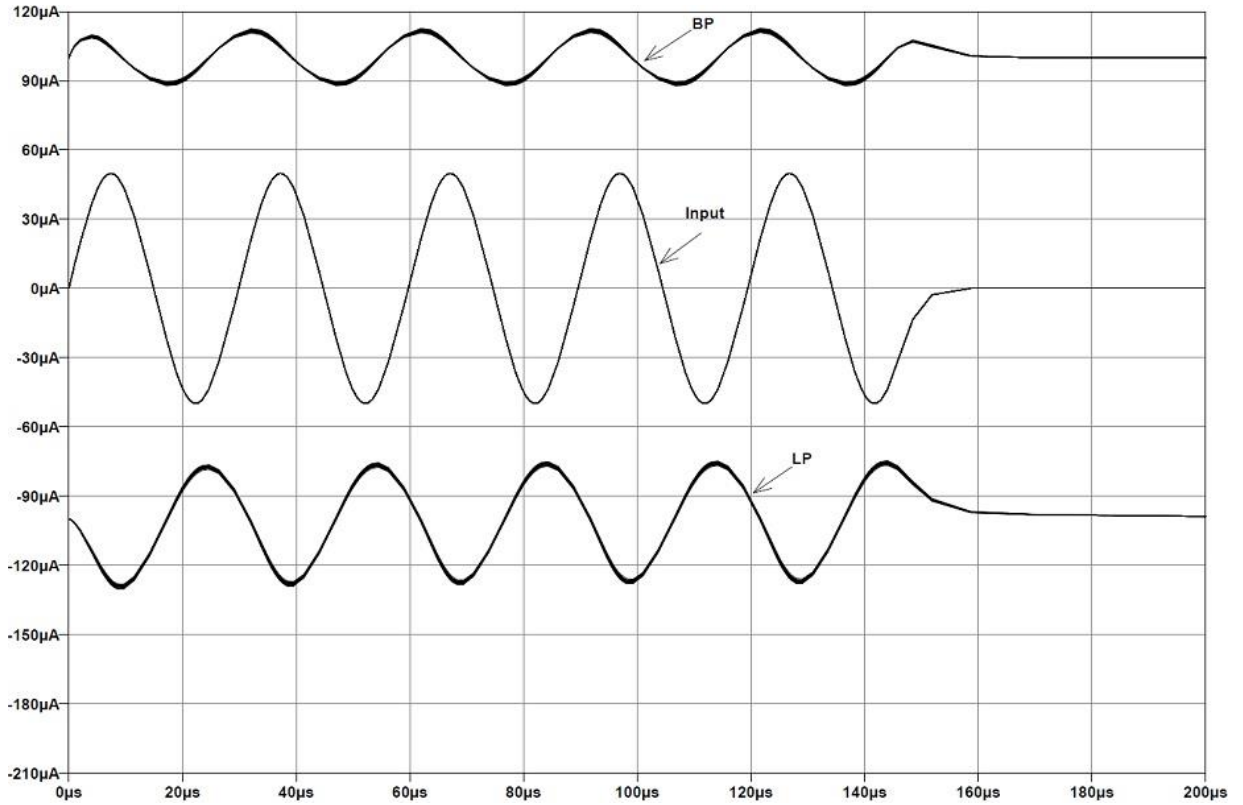


Figure 4. 30 Monte-Carlo Simulations for the Time Domain

#### 4.4. Proposed Circuit-4

Current mode dual output (High-Pass, Band-Pass) filter core circuit is shown below Fig 4.31.

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m3}}{C_{gs1} C_{gs3}}} \quad (4.13)$$

$$Q = \sqrt{\frac{C_{gs1} g_{m3}}{C_{gs3} g_{m1}}} \quad (4.14)$$

Equations 4.13 and 4.14 are Radial pole frequency ( $\omega_0$ ) and quality factor (Q) of proposed circuit-4 respectively

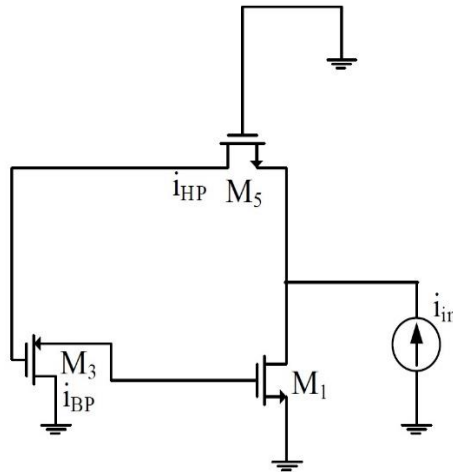


Figure 4. 31 Proposed Circuit-4 Core Circuit without Biasing

Transistor	Aspect ratio ( $\mu\text{m}/\mu\text{m}$ )
$M_1$	10/5
$M_3$	5/0.1
$M_5$	30/0.1

Table 4. 6 Aspect Ratios of Proposed Circuit-4

With aspect ratios shown above and  $C_{gs1}$ ,  $C_{gs3}$  are equal to 1nF AC simulation result is:

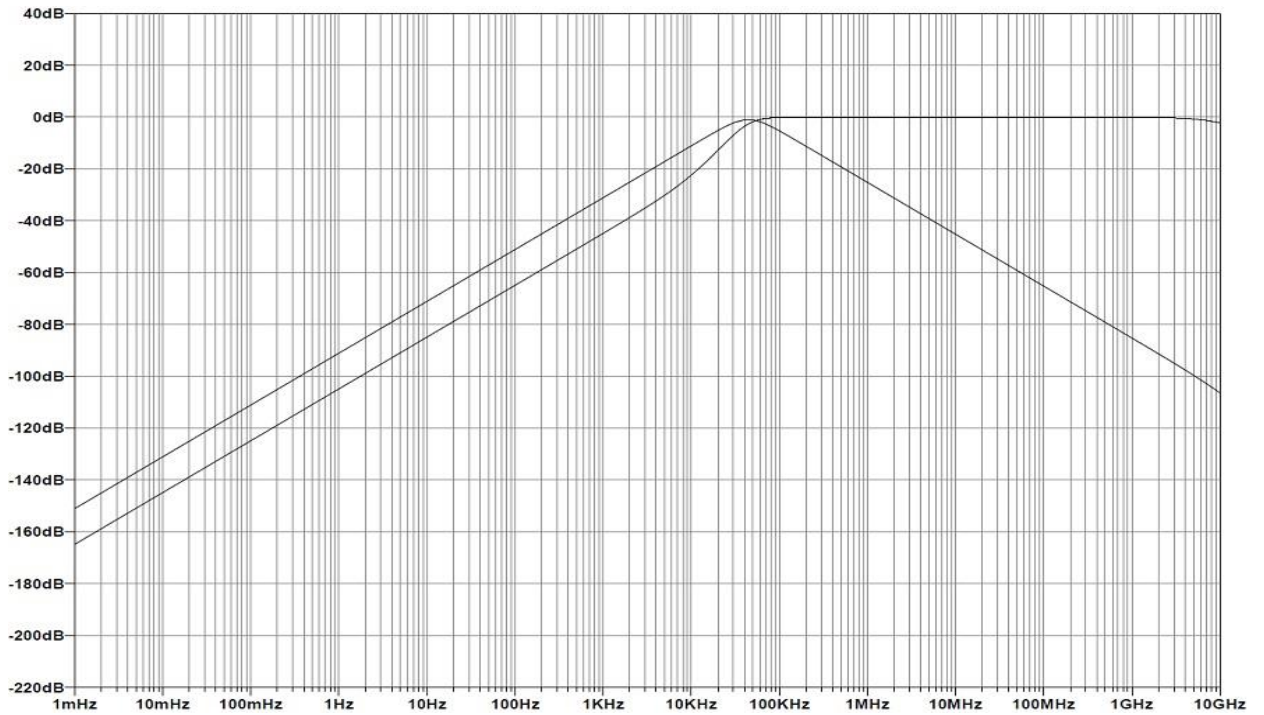


Figure 4. 32 BP and HP Frequency Response of Proposed Circuit-4

Transfer functions of filter (High-pass and Band-Pass) are:

$$\frac{I_{BP}}{I_{in}} = \frac{C_{gs1}g_{m3}s}{g_{m1}g_{m3} + C_{gs3}g_{m1}s + C_{gs1}C_{gs3}s^2} \quad (4.15)$$

$$\frac{I_{HP}}{I_{in}} = \frac{C_{gs1}C_{gs3}s^2}{g_{m1}g_{m3} + C_{gs3}g_{m1}s + C_{gs1}C_{gs3}s^2} \quad (4.16)$$

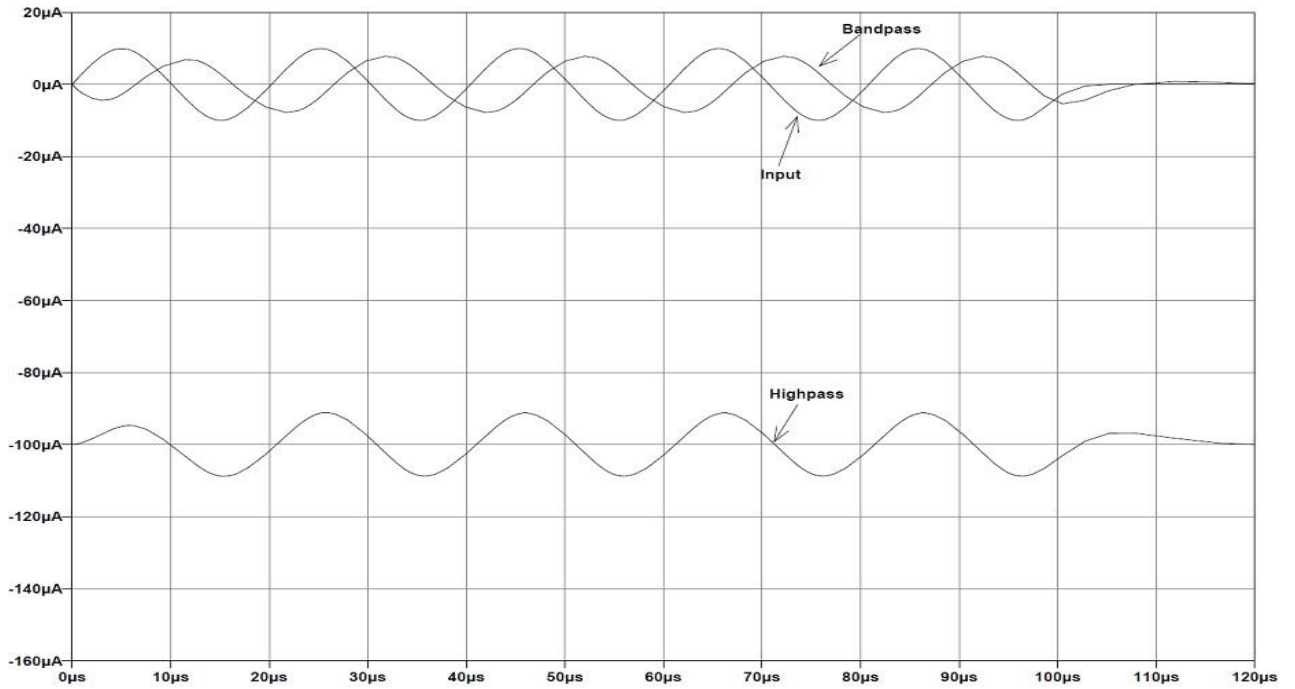


Figure 4. 33 Time Domain Simulation Results for Sinusoidal Input

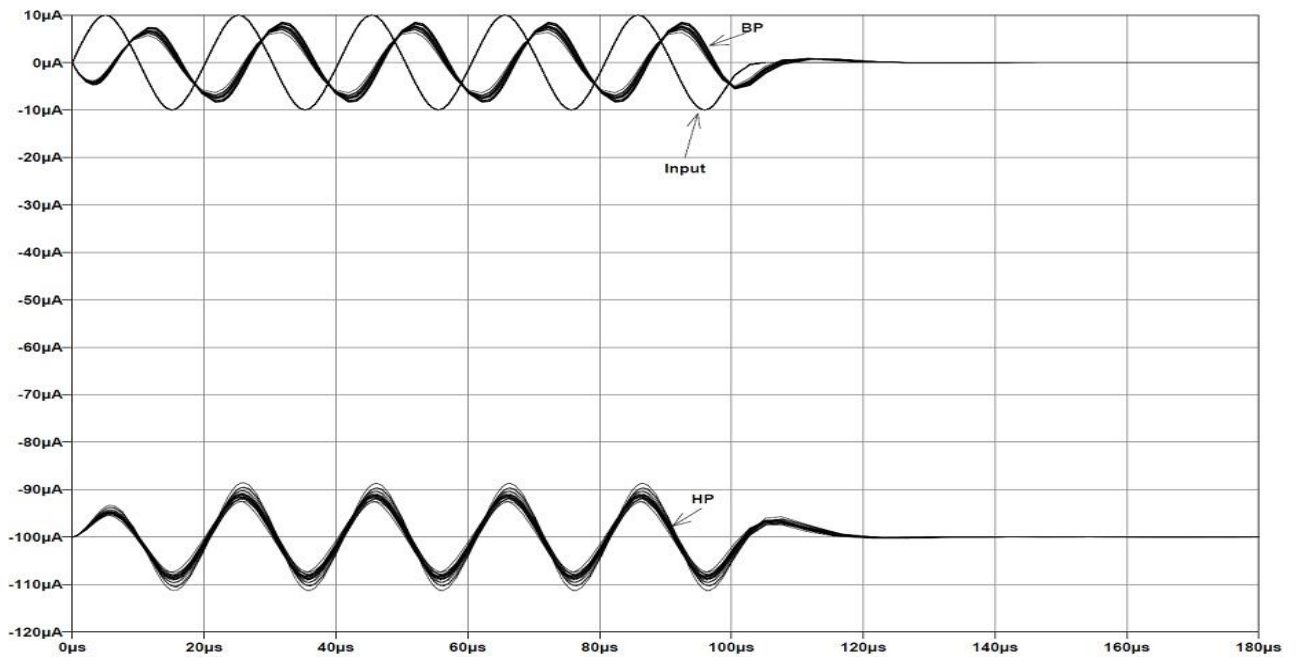


Figure 4. 34 Monte-Carlo Simulations for the Time Domain

Transient analysis of this circuit is shown above Fig. 4.33. Sinusoidal input current is applied which has amplitude with 10uA and frequency is 49.5kHz. Monte Carlo analysis is shown above in Fig 4.34.

## **CHAPTER 5- CONCLUSION**

In this thesis, a convenient way to provide parasitic gate-source capacitance with capacitance multiplier and MOS resistors used for capacitance multiplier's own resistors, are shown. With these properties, capacitance multiplier is become to electronically tunable and applicable to gate-source capacitance with wide range values. It is easy to see that from proposed-1 and proposed-2 circuits, capacitance multiplier with MOS resistors, is make circuits electronically tunable for working frequency range. This is really important for filters which are need to work with lower frequencies or really higher frequencies. Especially, biomedical filters have to work with lower frequency range and classically, obtain like that circuit which work with lower frequency is not easy. Using high valued resistors and high valued capacitors in filter circuit is not efficient way cause of their disadvantages. In this thesis; with our grounded capacitance multiplier with MOS resistors, it is become really easy to obtain filters which has to work on lower frequencies with lower valued passive elements furthermore this method is electronically tunable and this property is more important for chip area and costs.

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