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A Low Power Low-Noise Low-Pass Filter for Portable ECG Detection System

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ABSTRACT

The design of a low power low noise fully differential operational transconductance Amplifier-C (OTA-C) filter for ECG detection system has presented in this paper. As OTA is the basic element responsible for the noise and linearity of the filter so a low power CMOS linear OTA is designed working in weak inversion region. The proposed design uses the technique like current cancellation,current division and source degeneration so as to achieve linearity, low transconductance and to reduce the odd order harmonic distortion as well as input referred noise significantly. The projected OTA is used to implement a fifth order ladder-type low pass Butterworth filter in 180 nm CMOS technology. Simulation is carried out under 1V power supply using spectre simulator in cadence virtuoso and simulation result shows the -3 dB cutoff frequency of 7.3 Hz having input referred noise of 60 μV/√Hz and output referred noise of 3 nV/√Hz for 100mV input @ 100 Hz. The third harmonic distortion (HD3) of -56 dB is obtained with Dynamic Range (DR) of 55dB at very low power consumption of 3.25 μW. The results reflect the ability of the proposed design to filter the ECG signal falling within the frequency range of 10 Hz.

Keywords: low power low pass filter, weak inversion, inversion coefficient, third harmonic distortion, OTA-C Filter, implantable devices, portable devices.

1. INTRODUCTION

As the world of biomedical electronics is touching the new heights with the developments in designs and emerging new technologiesSo nowadays biomedical devices are becomingmore accurate, precise, condensed in size and more comfort to use with added features. Power consumption has become as significant as other parameters in portable biomedical devices because of its battery lifetime. The proposed designs for portable biomedical devices must give better noise performance at low power depending upon biomedical signal characteristics. [9][10]

With the advancement in microelectronics in the past few years, we are dealing with ultra low amplitudesignals and accordingly we need systems to measure such kind of signals in different areas like the devices to be implant in biomedical applications. Monitoring the different biomedical signals of the human being is very attractive topic as it helps us to acquire very vital health information about the human body. This information is very helpful for medical practitioners to diagnose different diseases. The

Table 1
Most Common Biomedical Signals

Signal	*Frequency*	*Amplitude*
ECG	0.01 Hz - 300 Hz	50μV – 3mV
EEG	0.1 Hz -100 Hz	1μV – 1mV
EMG	50 Hz - 3KHz	1μV – 100mV

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characteristics of different biomedical signals like electrocardiogram (ECG), Electroencephalogram (EEG), Electromayogram (EMG) are presented in Table 1.

The typical system to preprocess the Electrocardiogram (ECG signal or cardiac signal) is shown in Fig. 1. As the amplitude of ECG signals is low, normally in the range of 50 μV–3 mV, so we need a preamplifier in order to amplify the signal 10 to 100 times. After amplifier, the next stage is low-pass filter having lower cut-off frequency <300 Hz to eliminate the noise [1, 7]. The design of LPF is the very significant part in the entire ECG signal detection system because the accuracy of this system depends a lot upon low pass filter. The major parameters to be kept in mind while designing such LPF are the low cut-off frequency, input referred noise, linearity and low power consumption. The high linearity is needed in order to achieve low threshold and low input referred noise.

The other challenge is to implement the LPF with low frequency on an integrated chip (IC).As the typical values of capacitor and resistor permitted to be integrated within the IC is 10 pF and 10 KΩ respectively [2]. But a resistance of the order of 100MΩ is needed to implement LPF with low frequency. That means we need active components for the realization [1]. There are basically two techniques to realize the analog integrated low pass filters.

1. Using Switched Capacitor (SC)
2. Continuous time OTA-C implementations

The Switched Capacitor filters are rarely used as it is slow, needs high supply voltage for the sampling process and having high switching noise. But OTA-C filters are having high speed and low noise as compare to SC filters as sampling is not required. Therefore we need such a technique to implement this filter using continuous time (OTA-C) filters in which cut-off frequency of filters will be a function of the transconductance (Gm) of the Gm cell and the capacitors. So an OTA with typical value of Gm of the order of a few nA/V is needed. The low value of Gm cause higher noise in theOTA, so it is always a challenge for the designers to achieve low Gm with lower value of input referred noise. So an optimized design is required to cater the needs of low power biomedical world.

The different kinds of designs have been discussed in the literature [1, 2, 4, 5] and [6]. Soliman A. Mahmoud has proposed a low pass filter using digitally programmable fully differential OTA [1]. E. Rodriguez-Villegas proposed a second order micro-power continuous-time filter with the help of the FGMOS transistor [4]. A. Veeravalli proposed a Second order filter based on very small transconductance OTA. In this design the

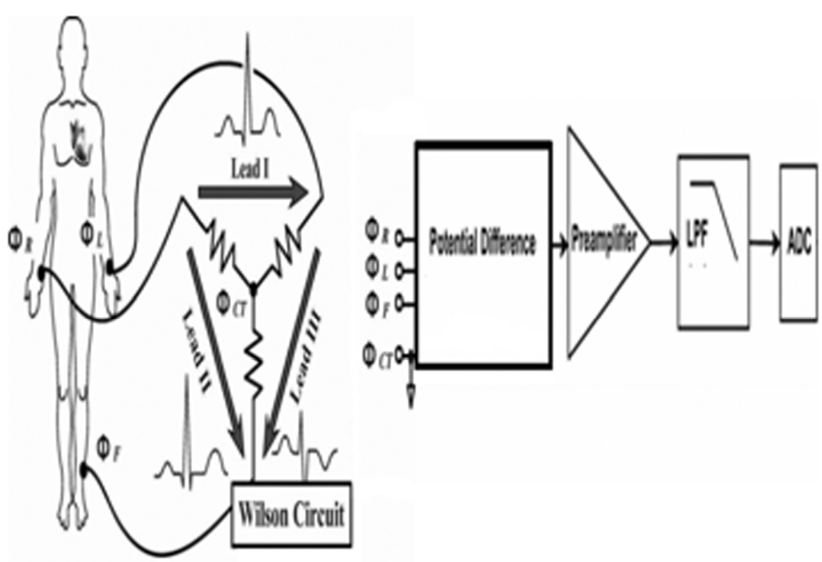

Figure 1: A typical ECG signal detection system

various techniques like current division, floating-gate techniques and source degeneration are implemented in order to lower down the transconductance [5]. S-S Bustos has proposed a Low-distortion OTA using current division and a current cancellation technique to design low-frequency sixth order low pass filter [6].

In this research work a low power fully differential operational transconductance Amplifier-C (OTA-C) filter is described for application in portable ECG detection systems. A low power CMOS linear OTA is designed operating in weak inversion. The proposed configuration uses the technique like current cancellation, currentdivision and source degeneration so as to achieve linearity, low transconductance and to reduce the odd order harmonic distortion as well as input referred noise density significantly. The projected OTA is used to implement a fifth order ladder-type low pass Butterworth filter in 180 nm CMOS technology. The design is basically aimed to get the low cut-off frequency with low HD3 and low noise within ultra low power budget.This paper organized as follows: The proposed OTA design and its simulation results are discussed in section II. Section III presents the different characteristics and specifications of the design and the simulation results. Finally, the Section IV presents the conclusions. [9]

2. OTA DESIGN

The basic considerations to be taken into account while designing OTA-based filter design is to determine the specifications of the design and accordingly choose the topology and basic building cell so that it can easily acquire and process the bio-medical signal perfectly. So keeping the design specifications like very small linear transconductance, low THD and low input referred noise a fully differential OTA is designed

2.1. Proposed OTA Design

The fully differential OTA with the benefits of current cancellation, currentdivision with extra source degeneration is shown in Fig. 2. Transistors M_M and M_N are current division and current cancellation transistors respectively. The transconductance ratio between transistors M_M, M_1 and M_N is M:1: N to reduce the overall transconductance. The internal Gm cell is used as source degeneration element to improve linearity as well as to reduce the overall transconductance. The internal Gm cell transistor M_B and M'_B, are biased in moderate inversion and linear region to obtain linear transconductance. [8]

The transconductance of internal Gm cell can be approximated as

$$G_{mi} = \frac{g_{mbB}}{1 + \frac{{}^{r}D + {}^{r}L}{r_{OB}} + g_{mB}\left(r_D + r_L\right) + g_{mbB^{r}L}} \tag{1}$$

All NMOS transistors work in subthreshold region. PMOS transistors M_M, M_1, M_N, M_B, M_5, M_6, M_2 and M_3 work in subthreshold region, while PMOS transistors M'_M, M'_1, M'N, M'_B, and M_4 work in linear region for low power operation. Transistor pairs M_D, M_8 and M'_D, M_9 act as current mirror. The transconductance of internal Gm cell is kept low with acceptable linearity because the linearity of proposed OTA depends on it. The moderate inversion characteristic current I_S can be approximated by

$$I_S = 2\mu C_{ox}\eta V_T^2 \frac{W}{L} \tag{2}$$

Where μ = Carrier effective mobility, η = subthreshold slope factor and V_T = kT/q,

(V_T is approximately 25 mV @ room temperature).

The inversion coefficient (I_C) is expressed as

$$I_c = \frac{I_d}{I_s} \tag{3}$$

Where I_D = channel current and I_S = moderate inversion characteristic current.

If, $10 > I_C > 0.1$ reflects that device operates in the moderate inversion region.

The transconductance (G_m) of complete cell can be calculated as

$$G_m = \frac{1-N}{1+N+M}\frac{G_S}{1+Gs/G_{mi}} \tag{4}$$

Where G_m is overall transconductance, G_{mi} is internal Gm cell transconductance and G_S represent the admittance through the source of input stage and is given by $(1 + N + M)g_m$.

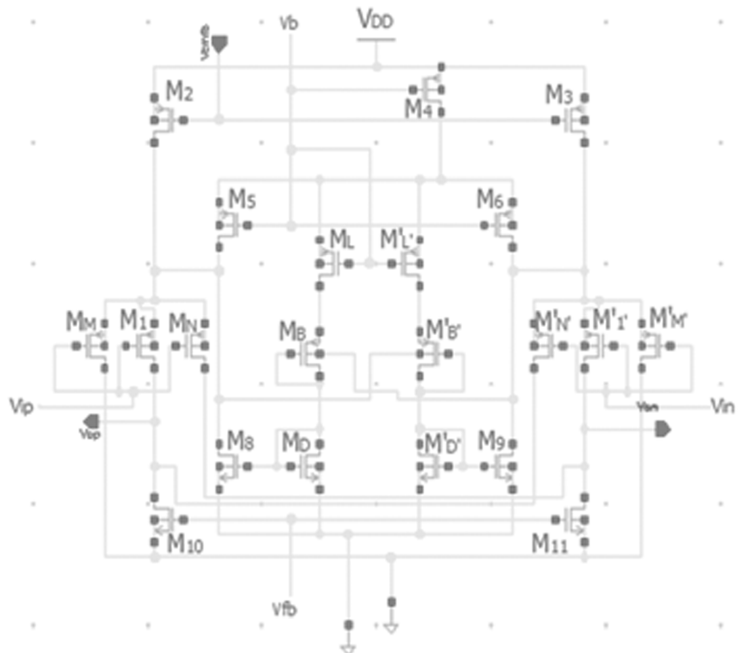

Figure 2: Proposed OTA at power supply of 0.85V

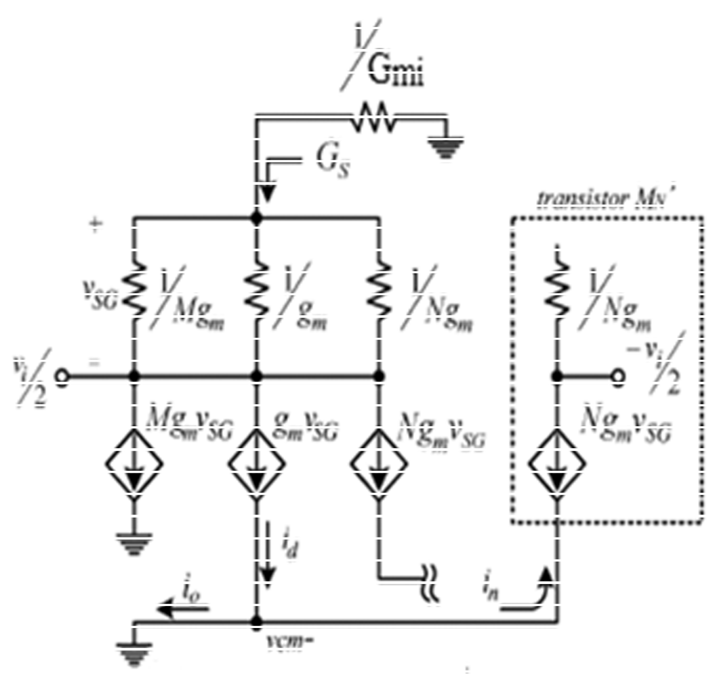

Figure 3: Small signal model of half circuit equivalent of Proposed OTA

2.2. Simulation Results of OTA

The proposed OTA is designed on Cadence Virtuoso in 180nm CMOS process. The simulator used is spectre simulator for simulations to obtain the results. Fig. 4s hows the transconductance vs. input differential

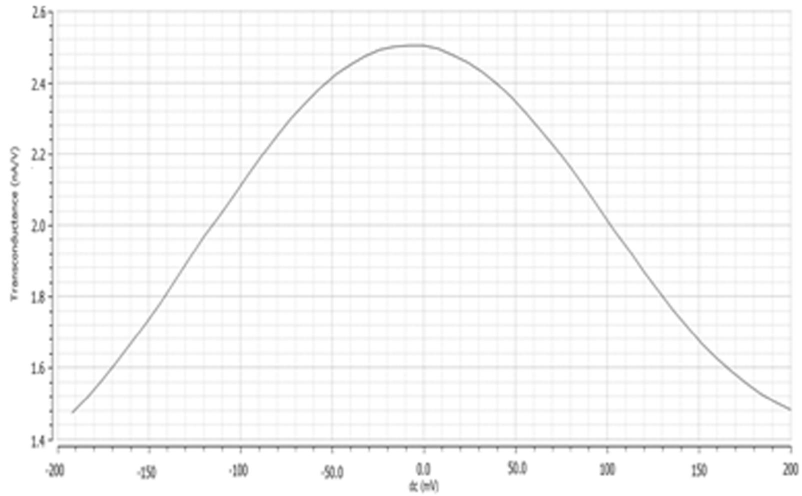

Figure 4: Proposed OTA Transconductance vs. input Differential Voltage

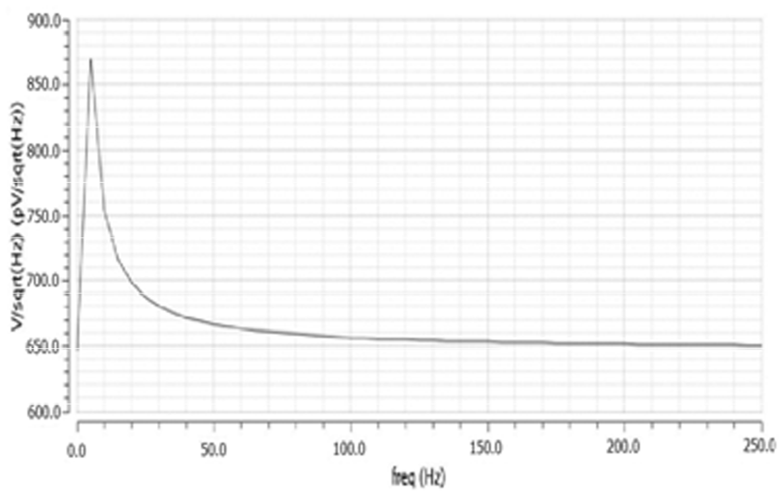

Figure 5: Output referred noise vs. frequency plot of proposed OTA

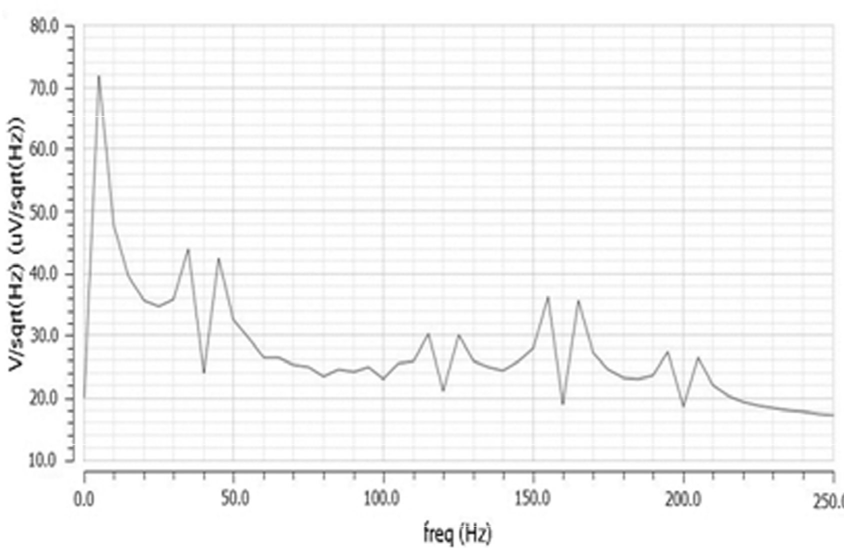

Figure 6: Input referred noise vs. frequency plot of proposed OTA

voltage plot. The nominal Gm value of our final transconductor is 2.5 nS. Fig. 5 and Fig. 6 show output referred noise and input referred noise vs. frequency respectively. The input referred noise is 23 µV/sqrt(Hz) and output referred noise is 650 pV/sqrt(Hz) at 100 Hz.

3. FILTER DESIGN USING PROPOSED OTA

For application in ECG detection system the filter should be able to attenuate the noise properly and reject the interference frequencies. So, the order of the filter and cut –off frequency are the parameters of prime importance in order to attenuate out-of-band interference. The filter design for ECG detection system has many constraints like the order of the filter, low threshold, Dynamic Range (DR), low input referred noise and low power consumption.[1][3] The value of all these parameters should be within the limits as given in table 2.

Table 2
Different performance parameters and their typical value

Parameter	*Value*
Order of the filter	Typically above 4th order
THD	<–50 dB
Input referred noise	(< 400 µVrms/√Hz
Dynamic Range	(>60 dB)
Power Consumption	(<50 µW)

Topology selection for high order filter is also playing a significant role. Ladder topology is usually preferred as it is insensitive to component variation within the pass band. [25]

3.1. Design of 5th Order Butterworth Low Pass Filter for ECG Signal Detection

An active Butterworth low pass filter of 5th order is designed using proposed OTA. The proposed low pass filter works at 1V power supply with input 100mVpp and the values of different capacitors are: C1 is 1.3 pF, C2 is 3.36pF, C3 is 4.2 pF, C4 is 3.36pF and C5 is 1.3 pF.

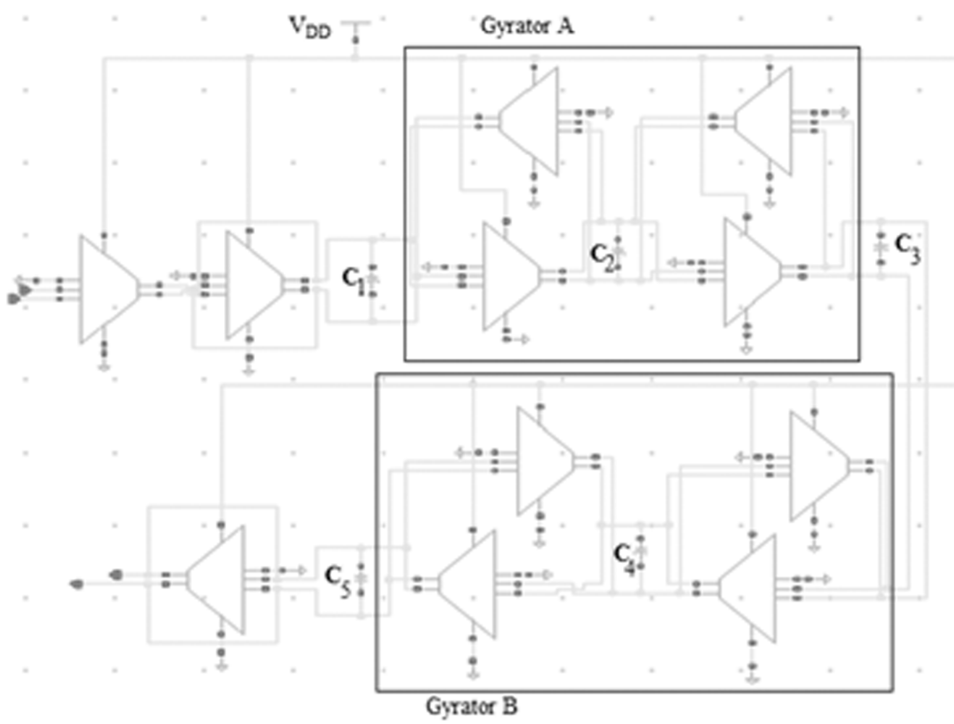

Figure 7: 5th order low pass Butterworth filter schematic

3.2. Simulation Result of designed Low Pass Filter

The simulation result shows improved cut-off frequency of 7.3 Hz, DR 55dB and HD3 of -56dB at low power 3.25 µW with acceptable input referred noise 60 µV//□√Hz and output referred noise 3 nV//√Hz for

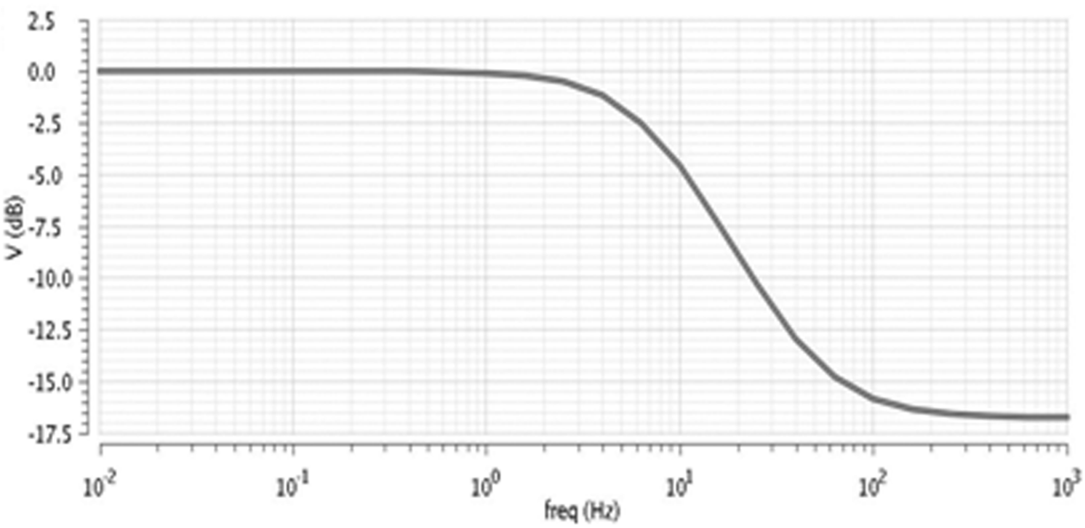

Figure 8: Gain vs frequency at VDD 1V and 100mV ac Input @ 100Hz.

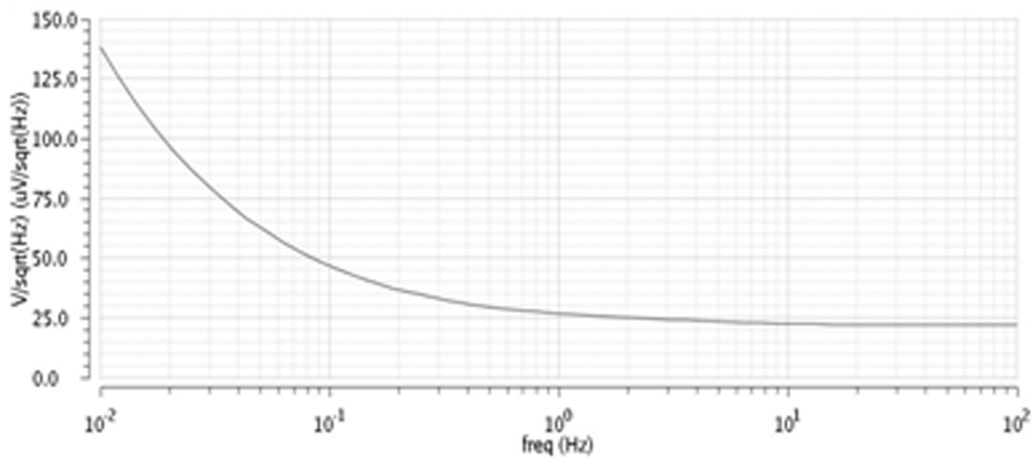

Figure 9: Input referred noise vs frequency

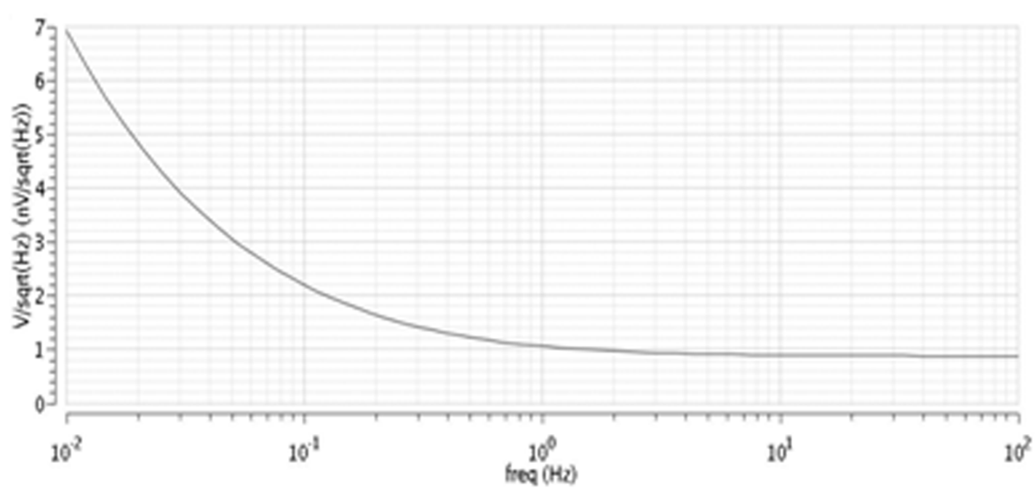

Figure 10: Output referred noise vs frequency

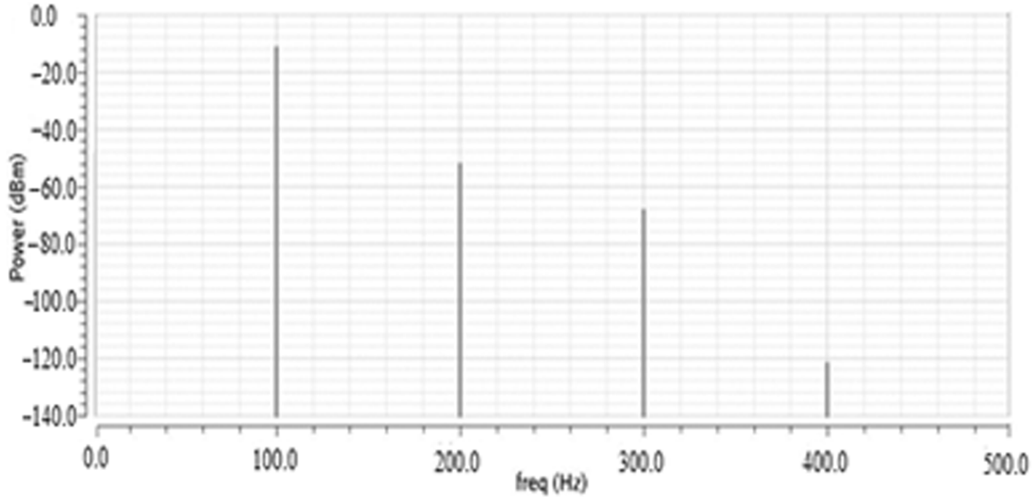

Figure 11: HD3 vs frequency

Table 3
Performance summary and comparison of recent work with previously designed LPF

	2000[6]	2002[5]	2004[4]	2005[3]	2009[2]	2013[1]	This Work
Vdd(V)	±1.5	2.7	1.25	±1.5	1	0.8	1
Vth(V)	0.8	0.9	0.8	0.6	0.5	0.53	0.8
CMOS Tech(μm)	0.8	1.2	0.8	0.35	0.18	0.25	0.18
Filter Order	6(S)*1	2(S)	2(S)	5(S)	5(D)	5(D)	5(D)
BW(Hz)	2.4	0.3	750	37	250	243	7.3
Power	10 μW	8.18 μW	2.5 μW	11 μW	453 nW	30 μW	3.25 μW
Input referred Noise(μV/”Hz)	50	15.6	_	_	340	36	60
THD(dB)	50	45(HD3)	48.5	49.7	48.6	40(HD3)	56(HD3)
DR(dB)	60	70.5	78	57	50	65	55

at 100mV input @ 100 Hz. Fig. 8 shows the magnitude (in dB) verses frequency (inHz) response of the designed filter at 1 V voltage supply for input 100 mVpp at frequency 100 Hz. Fig. 9 and Fig. 10 shows input referred noise and output referred noise vs. frequency respectively. Fig. 11 shows the HD3 verses frequency of the filter.

4. CONCLUSION

This research work has described a low power, low voltage linear small transconductance amplifier design in 180nm CMOS process using current division and current cancellation technique with extra source degeneration technique. The internal Gm cell is used as linear source degeneration resistor which helps to decrease the transconductance. A small overview of applied techniques on the circuit to reduce the transconductance is presented. The fifth order Butterworth low pass filter is designed using proposed OTA. Comparison is also done with previous existing work on the presented topic. The simulation result shows improved cut-off frequency of 7.3 Hz at low power 3.25 μW with acceptable HD3 of -56 dB, input referred noise 60 μV/√Hz and output referred noise 3 nV/√Hz for at 100mV input @ 100 Hz, which is more adequate to be used in ECG data acquisition system as low pass filter for cardiac signal detection in biomedical application for frequencies below 10 Hz.

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