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Low power CMOS Gm-C based low pass filter for front end neural signal processing

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ABSTRACT

The sub 100 µV voltage levels and sub 100 Hz frequency range makes the processing of most popular signal electroencephalograph (EEG) for brain functionality analysis, a complex task. The low frequency content of EEG (useful signals below 70 Hz) is commonly used for diagnosis of various brain related disorders making low-pass filter (LPF) a key block in front-end processing as noise reduction and resolution enhancement is crucial for precise recovery of these information. This paper is aimed to design reduced transconductance (Gm) based low power and small area CMOS LPF with cutoff frequency (fc) around 70 Hz. The proposed design is simulated using Cadence virtuoso tool and gives cut-off frequency of 72.958 Hz with low output noise of 3.0609 µV/√Hz and power consumption of 264.060 nW at operating voltage of 0.4 V. The simulation results show linearity of performance over -40 to 100 °C. Layout of circuit takes up area of 86.74×81.21 µm and post layout simulation shows 5% variation in power consumption as compared to pre layout simulations.

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1. INTRODUCTION

The continuous monitoring of patient's physical condition by portable medical devices such as electroencephalogram (EEG) and electrocardiogram (ECG) allows health teams to detect any abnormality in heart rate, respiratory rate, and brain related disorder [1], [2]. Block diagram of analog front end processing circuits as shown in Figure 1 consists of a transducer that converts the various measured parameter into an electrical signal; followed by a low-noise preamplifier (LNP) [3] for signal amplification; low pass filter (LPF) for rejection of unwanted noise and analog to digital converter (ADC) for data conversion for further signal processing by digital processor [4].

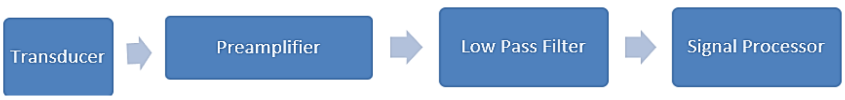

Figure 1. Block diagram of analog front end processing circuit

For the removal of unwanted noise and precise recovery of biomedical signals, it is required to have LPF with good noise rejection and fc in the suitable range [5]. Table 1 shows the types and specification of different biological signals. EEG is used to record the complex signal activity of the brain from various locations on the scalp [6]–[8]. Nowadays, there are multiple brain imaging techniques including functional magnetic resonance imaging (fMRI) [9] which are superior noninvasive alternative tests used to diagnose medical conditions of the brain, but for portable monitoring we still consider EEG to be the best alternative [10]. For regular monitoring using EEG, there is a need to design a fully integrated LPF with fc below 70 Hz [11] meeting performance specifications of reduced silicon area, better noise immunity, high dynamic range, and lower power consumption.

Active R-C technique is a popular method in wireless communication having excellent linearity but biomedical signals have a low cut off frequency which requires a very large resistor and capacitor which covers too much chip area; hence, active R-C is not suited for biomedical instrumentation. Therefore, we have used Gm-C based LPF which gives a solution to achieve compact chip area and power consumption. Gm-C filter operate in subthreshold region realize a small transconductance to replace the large resistor.

The low pass filter implementations can be done with topology like Gm-C, active RC [12], OTA-C [13], [14] and the choice of the filter topology is based on the frequency requirement. Simple topology-based Gm–C LPF [15] shown in Figure 2. This topology is considered to be the most feasible approach for the analog pre-conditioning stage in the biomedical processing unit. The operational transconductance amplifier (OTA) is an amplifier whose differential input voltage produces an output current. Thus, it is a voltage controlled current source (VCCS). For a single-ended G_m-C LPF shown in Figure 2, the cutoff frequency is given.

$$f_c = G_m/2\pi C$$

Where G_m is the overall OTA transconductance and C is the integrating capacitance.

Table 1. Types and specification of different biological signals

Types of signals	Frequency range	Amplitude
EEG	0.5-70 Hz	15-100 µV
ECG	0.05-250 Hz	100 µV for child 5 mV for adult
EMG	10-200 Hz	0.1-5 mV
ENG	250-5000 Hz	0-100 µV

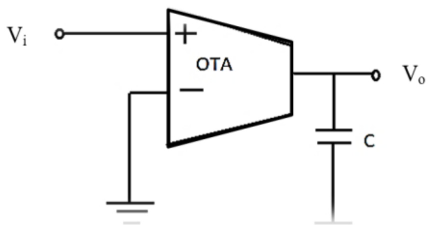

Figure 2. Gm-C low pass filter

To attain desired low fc, we require either a low value of Gm or a large capacitance value [16]–[18]. However, for efficient utilization of the silicon chip area, the maximum capacitance value is set to 50 pF. Thus, we need to design an OTA with reduced Gm which makes it necessary to incorporate a transconductance reduction technique [19]–[22]. The literature review done for this work focusing on OTA-based LPF in biomedical application substantiate different design techniques used for Gm reduction, moreover, each technique is trading-off with at least one key performance parameter. Gm reduction by factor M with current division (CD) technique [23] results in improved linear performance which results in better resolution and reduced silicon chip area at the cost of larger power consumption and poor noise performance. Floating gate (FG) or bulk driven (BD) MOSFETs [24], [25] is another viable approach for Gm reduction, however, for further Gm reduction BD+CD approach results in a wide linear range at the expense of higher power consumption and FG+CD techniques achieve slow power and better noise performance at the cost of increased chip area due to internal capacitance [26]. Series parallel CD results in low input noise but is limited by the larger silicon area [27]. Thus, a different transconductance reduction approach is required for the design of low fc LPF realizing a highly efficient analog front-end system with reduced area, low power, and high dynamic range. Current steering was used and results in a better power-area-dynamic range tradeoff to achieve low transconductance OTA for Gm–C based LPF [28]. Therefore, the current steering based approach for reduced transconductance is considered in this work which results in desired cut-off frequency required for EEG signal processing.

2. THE PREPOSED METHOD

2.1. Implementation of reduced G_m topology for the realization of G_m-C LPF

The filter circuit design proposed by Bailon *et al*. [28] is taken as the base circuit for the design of our proposed EEG filter that allows all signals below 70 Hz. The low frequency content of EEG signals found below 70 Hz, therefore we have designed LPF which could be used as a key block in front-end neural signal processing. The circuit simulation results of Bailon *et al*. [28] show that it operates at a higher supply voltage and has higher output noise levels. The cut-off frequency in this paper is also of the order of kHz and hence not suitable for sub-Hz frequency levels.

Biomedical signals are usually found in the 10 mHz to 100 Hz frequency range and hence require sub-Hertz frequency filters to condition the signal before processing. The proposed filter circuit can pass neural signals below 70 Hz, that operate with low supply voltage and low output noise levels. The higher value of the capacitor used also makes the area of this circuit very large. Figure 3 shows the base filter circuit design composed of mirrored cascade OTA as the core structure.

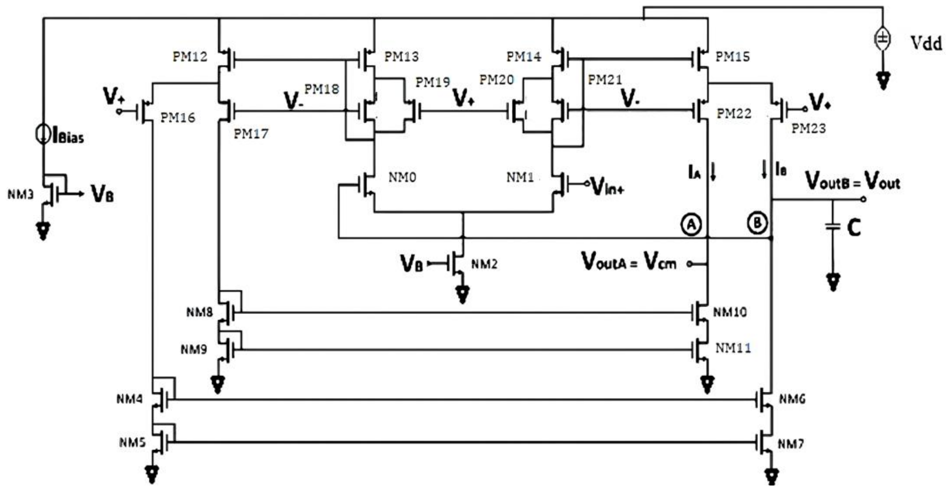

Figure 3. Mirrored cascade OTA based LPF based on reduced G_m approach

The Gm reduction is done by exploiting a current steering technique at the output stage. The aspect ratio (W/L) of MOSFETs in the current mirror of Gm-C filter circuit and current steering circuit is optimized resulting in further reduction of Gm. The transconductance Gm is proportional to square root of the aspect ratio (W/L) and also in the current mirror the circuit mirror factor depends on W/L [29]. Optimizing W/L ratio results in low transconductance and thus gives the desired cutoff frequency. Applying this concept, we decreased the aspect ratio of transistors NM0 and NM1 from 7.5/10 to 1/10, PM12, PM13, PM14, and PM15 from 10/4 to 8/4 and PM16, PM17, PM18, PM19, PM20, PM21, PM22, and PM23 from 5/4 to 4/10 keeping all other remaining transistors at their original aspect ratio as in [30]. We have also reduced the Vdd from 1.8 V to 0.4 V and taken VCM = Vdd/2 = 0.2 V in place of 0.9 V as in [28] to get better power efficiency. Applying the proposed approach for Gm reduction we got desired low cut-off frequency with better noise, and power performance. The aspect ratio of each MOSFET is summarized in Table 2.

Table 2. Aspect ratio of MOSFETs

MOSFETs	Aspect ratio	MOSFETs	Aspect ratio	MOSFETs	Aspect ratio
PM12	W=8u l=4u	PM20	W=4u l=10u	NM4	W=1u l=10u
PM13	W=8u l=4u	PM21	W=4u l=10u	NM5	W=1u l=10u
PM14	W=8u l=4u	PM22	W=4u l=10u	NM6	W=1u l=10u
PM15	W=8u l=1u	PM23	W=4u l=10u	NM7	W=1u l=10u
PM16	W=4u l=10u	NM0	W=1u l=10u	NM8	W=1u l=10u
PM17	W=4u l=10u	NM1	W=1u l=10u	NM9	W=1u l=10u
PM18	W=4u l=10u	NM2	W=2u l=10u	NM10	W=1u l=10u
PM19	W=4u l=10u	NM3	W=2u l=10u	NM11	W=1u l=10u

3. RESULTS AND DISCUSSION

Table 3 summarizes the performances of the proposed LPF and a comparison has been done with those of previously reported works. The two reference works compared in this table, used higher supply voltage and gives a high level of noise at the output. A higher value of capacitor used by these circuits also results in higher chip area utilization. The filter circuit proposed in this paper provides a very low cutoff frequency with a simple and compact topology, preserving low power and significantly increased dynamic range concerning previous implementations, providing a reliable solution to achieve our objective. The current steering technique used above for Gm reduction can also be used for tunability in LPF designing.

Table 3. Comparison of proposed LPF with previous work

Parameters	This work	Bailon *et al.* [28]	Rodriguez *et al.* [11]
Technology	180 nm	180 nm	350 nm
Cut-off frequency	72.958 Hz	2.5 KHz	90 Hz
Supply voltage, V_{DD}	0.4 Volt	1.8 Volt	1.0 Volt
Supply voltage at output A, V_{CM}	0.2 Volt	0.9 Volt	1 Volt
Input voltage magnitude	100 mV at 1 KHz	1 mV at 1 KHz	10 mV at 1 KHz
Output bias current	78.746 zA	1.5 µA	5 nA
Output load capacitance	0.1 pF	50 Pf	40 pF
Total power consumption	264.060 nW	2.7 µW	5 nW
Temperature range for faithful results	-40 – 100 ℃	40 - 120℃	NA
Gain at V_B (in magnitude)	1.544 m	NA	NA
Input noise	2.4466 mV/$\sqrt{Hz}$	11.3 µV/$\sqrt{Hz}$	NA
Output noise	3.0609 µV/$\sqrt{Hz}$	NA	32 µV/$\sqrt{Hz}$
THD at respective amplitudes	25.1E-06 %	0.72%	0.96%

It is observed from Table 3 that the proposed filter circuit, with a cut-off frequency of 72.958 Hz, consumes very low power 264.060 nW, gives low order THD of 25.1E-06% with output noise 3.0609 µV/$\sqrt{Hz}$ at very low operating voltage 100 mV and DC power supply of 0.4 V than previous implementations. It must be noted that the performance of the proposed OTA greatly depends on the aspect ratio and DC supply voltage. Although lowering the DC power supply reduces the power consumption beyond the threshold limit this degrades the response curve of the filter. An interesting result is also observed that when the channel length of NM0 and NM1 is decreased from 10 while keeping W/L ratio of all other MOSFETs constant, the proposed filter circuit response becomes similar to bandpass filter. This simply implies that proposed low pass filter circuit could also be used as a band pass filter if channel length of transistors NM1 and NM0 is decreased from 10 µm keeping W/L ratio of remaining MOSFETs constant.

Figure 4 shows the frequency response curve of the simulated Gm-C filter which provides a satisfactory cut-off frequency as shown in the figure. Figure 5 represents the total power consumption of the filter circuit. Low power consumption is desirable for portable devices. Its power consumption is satisfactorily low for the realization of a portable biomedical analog front-end interface.

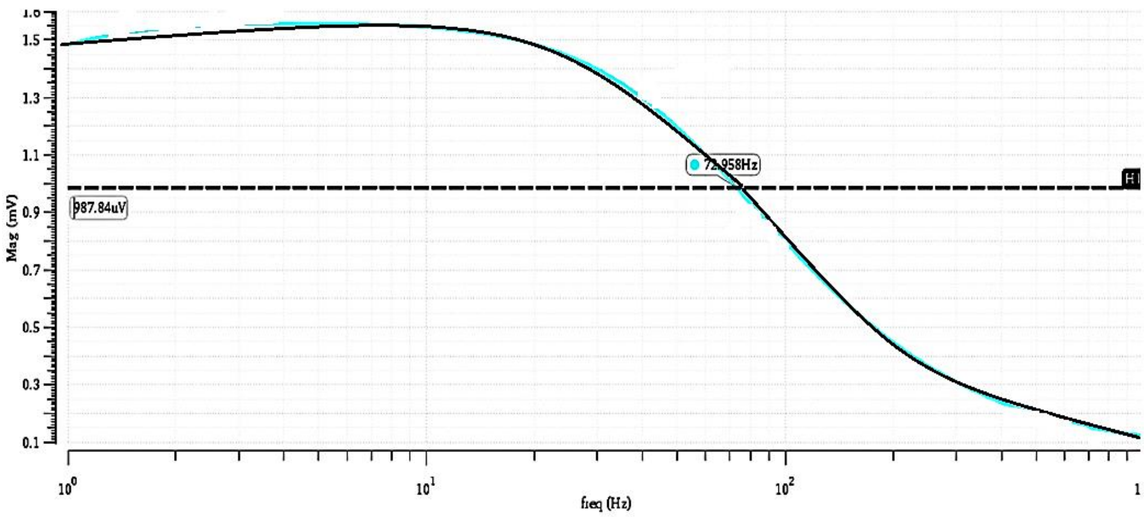

Figure 4. Frequency response curve of OTA based low pass filter

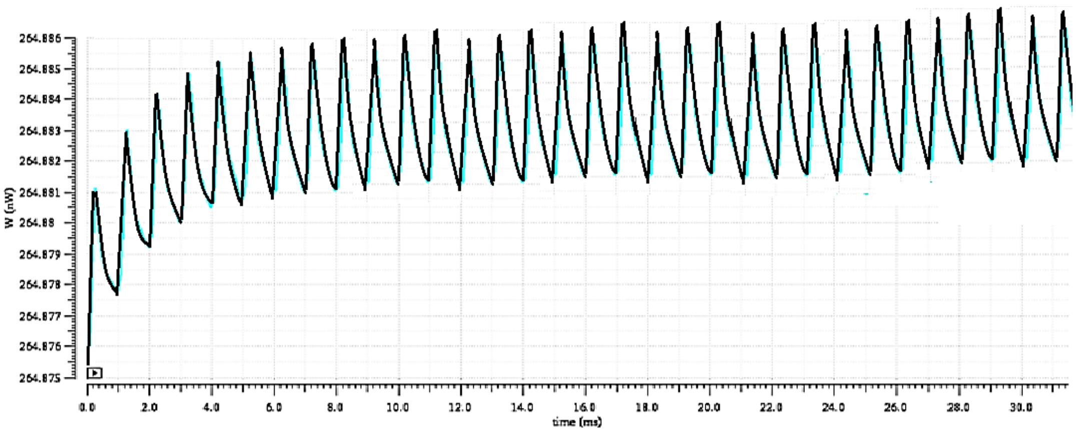

Figure 5. Total power consumption

Figure 6 shows the noise analysis of the filter. As we need a filter having low input and output noise for EEG signal processing. The noise performance of the given circuit is satisfactory and better comparable to [11] and [12]. Figure 7 shows the layout design of the filter designed by Cadence virtuoso tools in 180 nm technology which occupied a small area of 86.74×81.21 µm. It provides a cut-off frequency of 68.520 Hz and power consumption of 277.34 nW and shows a 6% variation in frequency and 5% variation in power consumption compared to simulation result obtained before designing the layout.

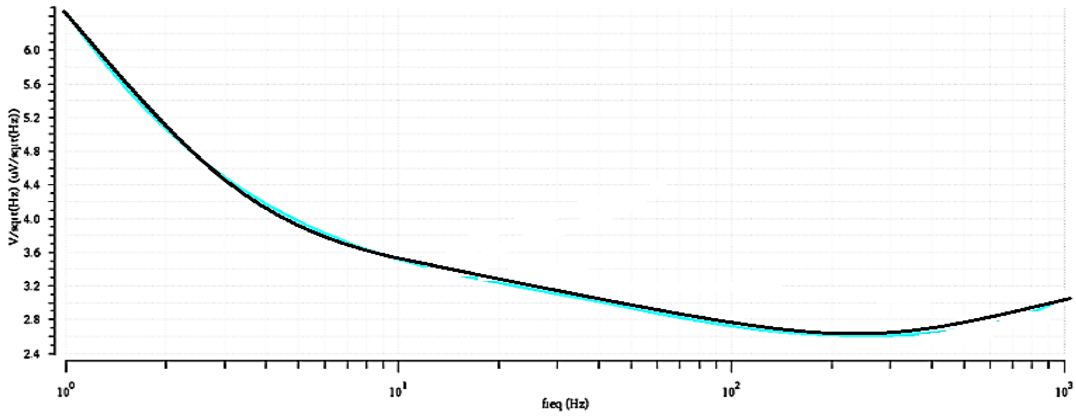

Figure 6. Noise analysis

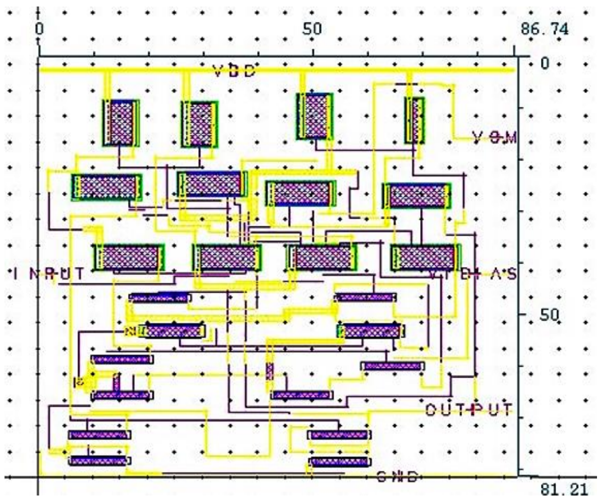

Figure 7. Layout design of Gm-C filter

4. CONCLUSION

A Gm-C LPF with reduced transconductance topology has been implemented and analyzed using Cadence virtuoso tool at 180 nm technology, showing satisfactory performances in terms of achievable low cut-off frequency around 70 Hz and low power consumption with the use of simple Gm reduction current steering technique. The proposed design is based on 180 nm CMOS technology with 0.4 V supply voltage. The observed performance matrices make it highly suitable for portable on-chip sensor interfaces in neural signal recording and processing units. The proposed OTA is found to be simple and relevant in the design of CMOS-based LPF for low-frequency biomedical applications.

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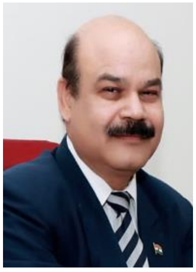

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