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Design and analysis of current mirror OTA in 45 nm and 90 nm CMOS technology for bio-medical application

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ABSTRACT

This paper proposed a design and performance analysis of current mirror operational transconductance amplifier (OTA) in 45 nm and 90 nm complementary metal oxide semiconductor (CMOS) technology for bio-medical application. Both OTAs were designed and simulated using Synopsys tools and the simulation results were analysed thoroughly. The OTAs were designed to be implemented in bio-potential signals detection system where the input signals were amplified and filtered according to the specifications. From the comparative analysis of both OTAs, the 45 nm OTA managed to produce open loop gain of 45 dB, with common mode rejection ratio (CMRR) of 93.2 dB. The 45 nm OTA produced only 1.113 µV√Hz of input referred noise at 1 Hz. The 45 nm OTA also consumed only 28.21 nW of power from ± 0.5 V supply. The low-power consumption aspect displayed by 45 nm OTA made it suitable to be implemented in bio-medical application such as bio-potential signals detection system where it can be used to amplify and filter the electrocardiogram (ECG) signals.

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1. INTRODUCTION

In analog electronic circuit design, operational amplifier is one of the most important building blocks for its versatility [1–3]. Operational amplifier or Op-Amp is basically implemented in circuit designs to realize functions from DC bias generation to voltage or current amplification and signal filtering [4]. There is a variation of Op-Amp called as operational transconductance amplifier (OTA). It is a type of amplifier that takes in differential input voltages and produced output current thus it is categorized as voltage controlled current source [5].

While Op-Amp is mostly popular in telecommunication application, its usage in bio-medical application is also prominent as it is implemented in bio-amplifier system to amplify small bio-potential signals from human body to be analyzed by medical practitioner [4, 6-11]. There are three types of bio-potential signals produced by human body; electroencephalogram (EEG) produced by brain activity, electrocardiogram (ECG) produced by heart activity and electromyogram (EMG) produced by muscle activity [12]. All bio-potential signals have same characteristics; small amplitude, small frequency range and contain external noise. The amplitude and frequency ranges of those three bio-potential signals are tabulated in Table 1. The current trend in bio-medical application is by using portable battery as the power source and designed in small size [6, 8, 9, 13-16]. This can be achieved as the current complementary metal oxide semiconductor (CMOS) field-oxide transistor scaling technology has reached into sub-micron region which is less than 100 µm. But due to short-channels effect (SCEs) in short-channel CMOS, the power consumption are degraded and affecting the overall performance of bio-amplifier system.

Table 1. Characteristics of bio-potential signals [12]

Bio-potential Signals	Organ	Amplitude (mV)	Frequency Range (Hz)
EEG	Brain	0.001 to 0.3	0.5 to 100
ECG	Heart	0.5 to 4	0.01 to 250
EMG	Muscle	0.1 to 5	Up to 500

Currently, there are several popular topologies that adapted OTA structure such as two-stage Miller OTA, telescopic cascode OTA, folded cascode OTA and current mirror OTA. The two-stage OTA consists of differential input stage and common source structure as output stage [17, 18]. The differential input stage produces higher gain and the output stage produces higher output voltage swing. Usually, the PMOS transistors are used in differential input as it produces lesser flicker noise when compared to NMOS [17]. However, the drawback of the two-stage OTA is it consumes higher power as it consists of two stages and it also needs compensation method to stabilize the frequency response of the OTA. Thus, Miller compensation is implemented in the circuit by placing the pole splitting capacitor between the input stage and output stage [9, 17, 19]. Telescopic cascode OTA compensates the drawback of two-stage OTA by stacking two transistors to form cascode structure [6]. This cascode structure reduces the capacitance of the OTA input pair and the OTA produces higher and better frequency response. The power consumption of the telescopic cascode is also better when compared to two-stage OTA but it has one disadvantage where the output swing of the OTA is smaller when compared to other topologies [20-22]. Folded cascode OTA is a topology where differential input pair is connected to the output stage that implemented telescopic cascode topology. The advantages of implementing folded cascode OTA are low noise, high gain, high output voltage swing and also better Power Supply Rejection Ratio (PSRR) [20, 21, 23, 24]. But, as the OTA has two extra current legs and more transistor numbers in the circuit, this increases the overall power consumption and total input referred noise. As for current mirror OTA, this topology is considered as single-stage OTA as it only has one differential input pair and several current mirror structures. This topology is usually applied in wide range of application as it produces high output impedance, transconductance multiplier capability and low power consumption [25]. Meanwhile, the drawback of this topology is when implemented in submicron node technology, the frequency response of OTA is badly affected [26].

Thus in this paper, as the OTA designed is applied in bio-medical application where the important parameters are power consumption, Common Mode Rejection Ratio (CMRR) and DC gain, current mirror topology has been selected as the main design in the OTA. Hence, in this paper efforts have been made for designing and analysing the performance of the designed current mirror OTA in 45 nm and 90 nm node technology in terms of DC gain, CMRR and power consumption. Then, based on the analysis of simulation results and discussion, one of the node technologies between 45 nm and 90 nm is chosen as suitable candidate to be implemented in OTA for bio-medical application system.

2. RESEARCH METHOD

2.1. Current mirror symmetrical OTA

Both OTA with 45 nm and 90 nm CMOS technology implemented symmetrical current mirror topology. The topology has several advantages; larger transconductance, larger slew rate and larger gain bandwidth produced during amplification operation. The OTA was designed from several current mirrors that acted as active load to each other. The input stage of OTA consisted of two NMOSs in differential pair structure and then three simple current mirrors were constructed to bias the inverters in OTA circuit as shown in Figure 1. The OTA circuit was designed by fixing the dimension of differential input pair and current mirrors. The dimension of differential input pair is given by (1) and dimension of the three current mirrors is given by (2). Initially, the dimensions of each transistor in the OTA were obtained through characterization of PMOS and NMOS in Synopsys tools. The 90 nm OTA was designed using SAED_90nm Process Design Kit (PDK) meanwhile 45 nm OTA is designed using 45nm Process Design Kit. Both OTAs were simulated in Synopsys HSpice simulator.

$$S_{M1}=(W/L)_1, S_{M1}=S_{M2} \tag{1}$$

$$S_{M3}=S_{M4}, S_{M5}=S_{M6}, S_{M7}=S_{M8} \quad (2)$$

where S is the ratio of width over length of MOSFET in both designs of the OTA.

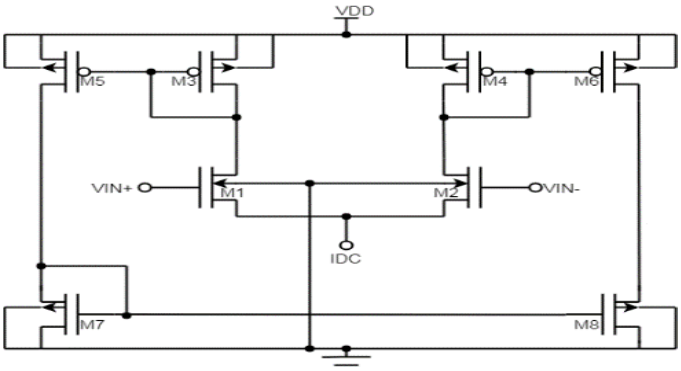


Figure 1. Schematic circuit of current mirror symmetrical OTA

Current mirror symmetrical topology is easier to be implemented as only 4 ratios of W/L are changeable and the OTAs need only one bias current. Table 2 shows the dimension of MOSFETs in both current mirror symmetrical OTA design.

Table 2. Width and length ratio of MOSFET in OTA

Transistor	Width (µm)	Length (µm)
M1 & M2	2	1
M3 & M4	3	1
M5 & M6	6	1
M7 & M8	0.24	1

2.2. OTA specifications for bio-medical application

Both OTAs were designed in 45 nm and 90 nm CMOS technology, and were meant to be applied in bio-medical application. Therefore, there were several specifications that must be declared and followed during the design process and simulation. The current mirror symmetrical OTA specifications are shown in Table 3. The design specifications of current mirror OTA in this paper were based on the standard IEC 60601-2-47:2012 and AAMI 60601-2-27:2011. Both standard documents described minimum performance specifications for ECG recording and including the basic safety and essential performance of ambulatory electrocardiographic systems in hospital environment as well as outside the hospital environments.

Table 3. Design specification of current mirror OTA

Specifications	Value
Voltage Supply (V)	1
Open Loop Gain (dB)	>40
CMRR (dB)	>100
Power Consumption (µW)	<10
Slew Rate (V/µs)	>10
Input Referred Noise (µV/√Hz)	<4

2.3. Performance parameter

Performance parameters were extracted and discussed to determine the performance of both 45 nm and 90 nm OTAs. The parameters were then tabulated and compared with previous research. Open loop gain/differential mode gain (AD) is the ratio of change in output voltage of OTA compared to the input voltage in different phase which can be measured using (3).

$$A_D=20\log\frac{V_{OUT}}{V_{IN}} \quad (3)$$

Common mode gain (AC) is the ratio of change output voltage of OTA compared to the input voltage in same phase and can be measured using (4).

$$A_C = 20\log\frac{V_{OUT}}{V_{IN}} \tag{4}$$

Common mode rejection ratio (CMRR) is the ratio of differential mode gain to common mode gain which is used to quantify the ability of OTA to reject common mode signals or noise. CMRR can be measured using (5).

$$CMRR = 20\log\frac{A_D}{A_C} \tag{5}$$

Power consumption is the total power consumed by OTA from certain voltage supply during operation. Two components contributing to power consumption in OTA are static power and leakage current of MOSFET. The power consumption can be measured using simulator and using (6).

$$P = (I_5 + I_6 + I_{DC}) * (V_{DD} + V_{SS}) \tag{6}$$

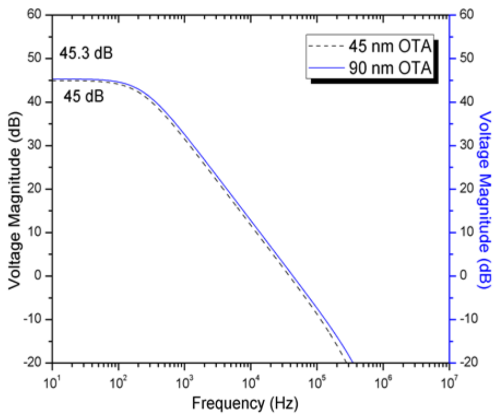
where P is total power consumption, I5 and I6 are the branch current from inverters in OTA. IDC is the bias current supplied into OTA. Meanwhile Vdd and Vss are the voltage supplies of the OTA.

3. RESULTS AND ANALYSIS

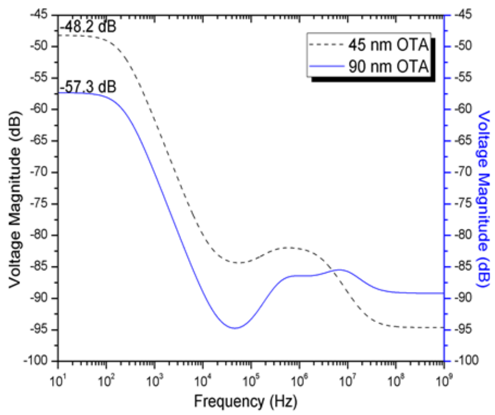
The current mirror symmetrical OTAs were designed using Synopsys Custom Designer software and simulated using HSpice simulator in respective CMOS technology (45 nm and 90 nm). The analysis of simulation results were done within Simulation Analysis Environment (SAE) and Waveview tools embedded in the Synopsys software.

3.1. AC analysis

Both OTAs were simulated using HSpice simulator to find the open loop gain and the phase margin. According to the design specifications, the OTA must produce a gain more than 40 dB in order to efficiently amplify the bio-potential signals. For differential mode gain, AC supply with amplitude of 1 V was fed into positive input pin of OTA, meanwhile 0 V was fed into negative input pin of OTA. The 45 nm OTA produced an open loop gain of 45 dB, while the 90 nm OTA produced 45.3 dB as shown in Figure 2(a). For common mode gain, both input pins of OTA were fed with 1 V of AC supply. The 45 nm OTA produced a common mode gain of -48.2 dB while the 90 nm OTA produced -57.3 dB. The results are shown in Figure 2(b). Both the differential mode gain and common mode gain obtained will be used in the calculation to find the CMRR of both OTAs.



(a)



(b)

Figure 2. (a) Differential mode gain of 45 nm and 90 nm, (b) Common mode gain of 45 nm and 90 nm OTA

The phase margin (PM) for 45 nm OTA was 82.6˚ and for 90 nm was 85.1˚. Both figures indicated that both OTAs are stable and do not oscillate during amplification process. For the unity gain bandwidth, the 45 nm OTA produced a value of 0.908 GHz and 90 nm OTA produced 0.8091 GHz. Both values are very high when compared to frequency range of bio-potential signals. This means that the designed OTA is suitable to be used as bio-amplifier but needed some modification to reduce the unity gain bandwidth according to design specification.

3.2. Transient analysis

For transient analysis, both OTAs were simulated in two testbench for common input signals and differential input signals. For common input signal analysis, the sinusoidal voltage with amplitude of 2 mV was fed into both positive and negative input terminals. The frequency of sinusoidal voltage supply is set at 150 Hz. Both amplitude and frequency were set in the manner of imitating the electrocardiogram (ECG) signals from human body. Then, for differential input signal analysis, the negative input terminal of OTA was fed with a positive 2 mV of sinusoidal voltage and negative terminal was fed with a negative 2 mV of sinusoidal voltage. Figure 3 shows the transient result of differential input signals analysis for 90 nm OTA and for 45 nm OTA.

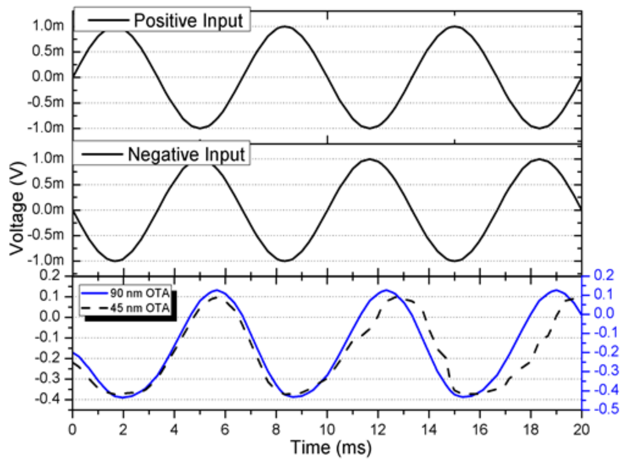


Figure 3. Transient simulation result for 45 nm and 90 nm OTA

Based on Figure 3, both OTAs produced output with nearly identical peak-to peak value. The OTAs amplified input signals of 2 mV peak-to-peak signal up to nearly 500 mV of output voltage. For 45 nm OTA, the output signal was slightly distorted due to mismatch of MOSFET in the differential pair input part. This condition needs to be addressed later during constructing layout view of the design to ensure the output does not become distorted.

3.3. Common mode rejection ratio (CMRR)

By taking into account the differential mode gain and common gain from AC analysis, the CMRR for both OTAs were calculated using (5). The CMRR for 45 nm OTA was 93.2 dB and for 90 nm OTA was 102.6 dB. According to the design specifications, CMRR of OTA should be more than 100 dB in order to reject common mode signal from input efficiently. In bio-potential signals, there are lots of noises and common mode signals are sourced from external such as power line interference, thermal noise and human body-generated noise. The disturbances can cause the amplification process to become less accurate.Based on the results, the 90 nm OTA produced higher value of CMRR when compared to 45 nm OTA. Thus, 90 nm OTA reached the CMRR design specifications and can filter out external noise together with common mode signals efficiently.

3.4. Power consumption

During transient analysis, the power consumption of both OTAs was calculated using Simulation Analysis Environment tools by including the MEAS command. The power consumption can also be calculated manually by analyzing the current flow from source terminal of transistors M5 and M6. Then, the values of both currents at the branches were incorporated in (6) to get the power consumption value.The 45 nm OTA consumed 28.21 nW from ± 0.5 V of supply whereas the 90 nm OTA consumed 28.42 nW. This means the 45 nm OTA can do amplification process with overall power consuming less than the 90 nm OTA. The result obtained met the design specifications. The power consumption is important in bio-medical application as most of bio-medical apparatus to detect and analyze bio-potential signals are using portable batteries and are small in size. Lower power consumption means that the apparatus or system can last longer without depending on external source of power.

3.5. Input referred noise

For input referred noise measurement, the total input noise was measured using Simulation Analysis Environment tools (SAE) by using.NOISE analysis and command. Figure 4 represents the input referred noise of 45 nm and 90 nm OTAs.

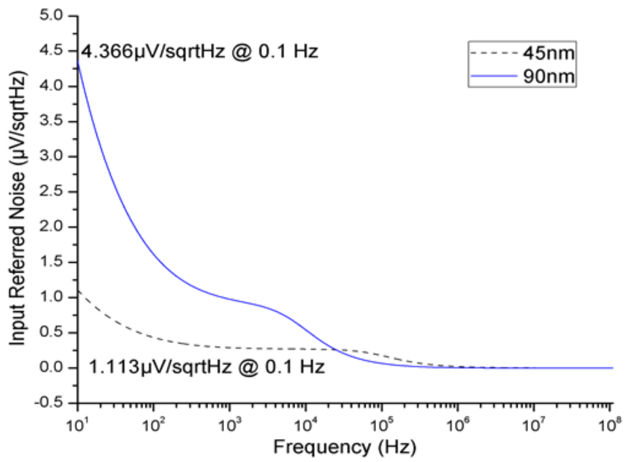


Figure 4. Input referred noise result for 45 nm and 90 nm OTA

The 45 nm OTA only produced 1.113 µV√Hz at 1Hz whereas the 90 nm OTA produced 4.366 µV√Hz at 1Hz. Both OTAs managed to meet the design specification but the 45 nm OTA produced lesser input referred noise when compared to 90 nm OTA. This means that the 45 nm OTA is more suitable to be implemented in bio-medical application as it has lesser total noise in circuit compared to 90 nm OTA.

3.6. Comparison of 45 nm OTA, 90 nm OTA performance with design specifications and literatures

Based on the conducted analyses, the simulation results of both OTAs are tabulated and compared with the design specifications. The OTAs are also compared with chosen literatures. Table 4 shows the simulations results of OTAs, design specifications and previous results from literatures.

Table 4. Comparison of design specification, literatures and results of 45 nm and 90 nm OTA

Parameters	Specifications	[17]	[14]	[26]	[27]	45 nm OTA	90 nm OTA
Voltage Supply (V)	1	1	±0.5	±0.25	1	±0.5	±0.5
Gain (dB)	>40	55.1	48	63.3	100	45	45.3
CMRR (dB)	>90	131	-	-	-	93.2	102.6
Power (W)	<10µ	2.6µ	21n	10.8µ	12µ	28.21n	28.42n
Input Referred Noise (µV√Hz)	<4	1.38	-	-	-	1.113	4.366

From Table 4, both 45 nm and 90 nm OTAs managed to produce gain of 45 dB and 45.3 dB, which exceeded the minimum gain specification. For CMRR, both OTAs are also exceeded the minimum CMRR specifications as both produced CMRR of 93.2 dB and 102.6 dB, respectively. The input referred noise produced by 45 nm OTA was 1.113 µV√Hz meanwhile for 90 nm OTA was 4.366 µV√Hz where both OTAs met the design specifications. It can be said that the 45 nm OTA performs slight better than 90 nm OTA due to less power consumption. The results met the design specification and as the main concern in this research is power consumption, the 45 nm OTA is chosen as suitable to be implemented in bio-potential signals detection system.

4. CONCLUSION

In this paper, the current mirror symmetrical OTAs have been designed and simulated using 90 nm and 45 nm CMOS technology. Both OTAs were designed, simulated and analyzed using Synopsys tools. Simulation results from both OTAs also have been comparatively studied and discussed according to the stated design specifications. The stated design specifications are for bio-potential signals detection purpose and based on the discussion, the 45 nm OTA managed to produce 45 dB of open loop gain, 93.2 dB of CMRR and also only consumed 28.21 nW from ±0.5 V of supply. Further more, the input referred noise produced by 45 nm OTA was 1.113 µV√Hz which is lesser than 90 nm OTA. Thus, the 45 nm OTA is a suitable choice to be implemented in bio-potential signals detection system. However, there are disadvantages by implementing the current mirror symmetrical topology as the gain bandwidth is too large for bio-potential signals detection purpose, so further research must be done to ensure the OTA design can reach optimal performance according to the design specifications.

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