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Comparative study of symmetrical OTA performance in 180 nm, 130 nm and 90 nm CMOS technology

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ABSTRACT

In this paper, the comparative study of symmetrical Operational Transconductance Amplifier (OTA) performance between 180 nm, 130 nm and 90 nm CMOS technology have been done thoroughly to find the relationship between voltage supply and bias current with performance parameters (gain, power consumption and Common-Mode Rejection Ratio (CMRR)). The OTA which adopts symmetrical topology is designed carefully and simulated using Synopsys HSpice software and the results are carefully analyzed and compared. The symmetrical OTA designed in 90 nm CMOS technology is found to be the best because the power consumed is only 9.83 µW from ±0.9 V voltage supply and the OTA achieved 55.9 dB of the DC gain. The CMRR of the symmetrical 90 nm OTA is 140 dB which is sufficient to reject the common-mode signals in electrocardiogram (ECG) input signal. The symmetrical 90 nm OTA is suitable to be implemented as bioamplifier in ECG signal detection system as it consumed low power and has a high CMRR characteristic.

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1. INTRODUCTION

Recently, the trend of developing the bio-medical devices using portable battery is rising in current electronic market [1], [2]. This trend is due to improvement and advancement in VLSI scaling technology which leads to more development of analog and digital circuits in sub-micron size [3], [4]. This condition has its own benefits where the circuit can be operated at lower voltage supply and having lower power consumption. But, due to short-channel effects (SCEs) appeared due to technology scaling, most of analog and digital electronic circuits experienced degradation in the performance aspect.

In medical world, bio-potential signals detection is the most famous and reliable way used by medical practitioner to diagnose the medical conditions of their patients. There are several bio-potential signal detections being known in medical world such as electroencephalography, electromyography and electrocardiography. The common bio-potential signals produced by human body are electroencephalogram (EMG), electromyogram (EMG) and electrocardiogram (ECG). These bio-potential signals have common characteristics; low voltage amplitude and low frequency range. Table 1 shows the voltage amplitude range and frequency of stated bio-potential signal [5].

Electrocardiography is one of the bio-potential signal detection adopted in medical world where it is a process of recording electrical waveforms called ECG that are produced by activities of human heart [6]. The ECG signals contain information in the form of waves and several time intervals between them which are denoted as PQRST segments [6]–[9]. Each segment has different interpretations of the heart condition itself which must be translated precisely to ensure the diagnosis of health of the patient heart is accurate. Based on the literatures [8], [10], [11], the voltage amplitudes of ECG ranges from 5 µV to 4 mV and the frequencies ranges from 0.05 Hz to 250 kHz.

Table 1. Characteristics of the Stated Bio-Potential Signals [5]

Organs	Bio-potential Signals	Amplitude (mV)	Frequency Range (Hz)
Brain	EEG	0.0005 to 0.3	0.5 to 150
Heart	ECG	0.5 to 4	0.01 to 250
Muscles	EMG	0.1 to 5	Up to 2K

In ECG detection system, there are several main components implemented such as operational amplifier, low-pass filter and analog-to-digital converter (ADC) [12]. Operational amplifier in ECG detection system is called as bioamplifier where it functions to amplify the minute amplitude of ECG signal into higher and acceptable amplitude level so that the ECG signal can be processed by next components in detection system. As bioamplifier is the main building block in the detection system, it will consume lots of power during operation and increasing the power consumption of the detection system itself [1]–[3], [10].

As a result, in order to design a suitable bioamplifier with ultra-low power consumption with sufficient signal swings, a new topology is needed to be implemented in the circuit design of the bioamplifier. Based on the literatures, symmetrical or current mirror Operational Transconductance Amplifier (OTA) topology is implemented in designing the bioamplifier to achieve ultra-low power consumption with better noise immunity. In addition of having those ultra-low and low-noise characteristics, the bioamplifier should also be able to amplify the ECG signal up to acceptable level for better processing in the next stage of detection system.

This paper is organized as follows. In section 2, the proposed design of symmetrical OTA is discussed in details. The current mirrors and performance parameters also are described with details in this section. In section 3, the simulation steps are shown together with detailed reports on the simulation results and lastly, in section 4 the conclusion.

2. PROPOSED DESIGN

The OTA with symmetrical or balanced topology is implemented in bio-potential detection system because of larger transconductance, larger slew rate and larger gain bandwidth (GBW) produced during operation of the OTA. The design of circuit is constructed from several current mirrors which acting as active load to each other. Symmetrical OTA is also called as three current mirrors OTA where the differential input pair consists of two NMOS transistors. There are self-biased inverters and three simple current mirrors adopted to bias the inverters in the circuit.

Based on [13], the voltage gain, AV of symmetrical OTA is given as Equation 1 and Equation 2.

$$A_v = B\left(\frac{g_{m1}}{g_{ds5} + g_{ds6}}\right) \tag{1}$$

$$B = \frac{(\mathrm{W/L})_8}{(W/L)_3} = \frac{(W/L)_5}{(W/L)_4} \tag{2}$$

The gain bandwidth, BW value is given by Equation 3,

$$BW = B\frac{g_{m1}}{2\pi C_L} \tag{3}$$

with C_L as the load capacitance and the slew rate, SR is given by Equation 4,

$$SR = B\frac{I_{DC}}{C_L} \tag{4}$$

where the IDC is the biasing circuit. The designed bioamplifier should work in inversion region as mentioned in [14]. The symmetrical amplifier with gain bandwidth of 500 kHz will produce about 300 mV/µs as written in Equation 5.

$$SR = 4\pi n V_T * BW \cong 600mV * BW \tag{5}$$

where *n* is slope factor in weak inversion. So based on the statement above, it can be said that SR/BW is directly proportional with I_{DC}/g_m as stated in Equation 6.

$$\frac{SR}{GBW} \infty \frac{I_{DC}}{g_m} \tag{6}$$

Therefore in order to improve the slew rate of the amplifier without affecting the gain bandwidth, the bias current to turn on each transistor in the bioamplifier must be increased which consequently would increase the total power consumption of the bioamplifier. Hence based on the symmetrical OTA theory, certain techniques must be adopted into the OTA to ensure there are trade-offs between bioamplifier performance in terms of slew rate and gain bandwidth with the total power consumption of the bioamplifier.

The symmetrical OTA is designed by fixing the dimension of transistors in differential input pair stage and current mirrors stage as stated in [15] which are given by Equation 7 and Equation 8.

$$S_{M1} = (W / L)_1 \tag{7}$$

$$S_{M1} = S_{M2}, S_{M3} = S_{M4}, S_{M5} = S_{M6}, S_{M7} = S_{M8} \tag{8}$$

where S is the dimension of the transistors in the OTA.

This technique of designing symmetrical OTA is easier to be implemented as it reduced the number of changeable parameters to four dimension of transistors and one tail current or bias current into the OTA. In this paper, the symmetrical OTA is designed with three complementary metal oxide semiconductor (CMOS) technologies which are 180 nm, 130 nm and 90 nm. Each of the OTA designed in 180 nm, 130 nm and 90 nm used the same symmetrical topology and the same dimension of transistors as calculated earlier. The dimension of transistors are calculated carefully to ensure there is a balance trade-offs between power consumption and gain of the OTA. Figure 1 shows the structure of the symmetrical OTA and dimension of transistors is shown in Table 2.

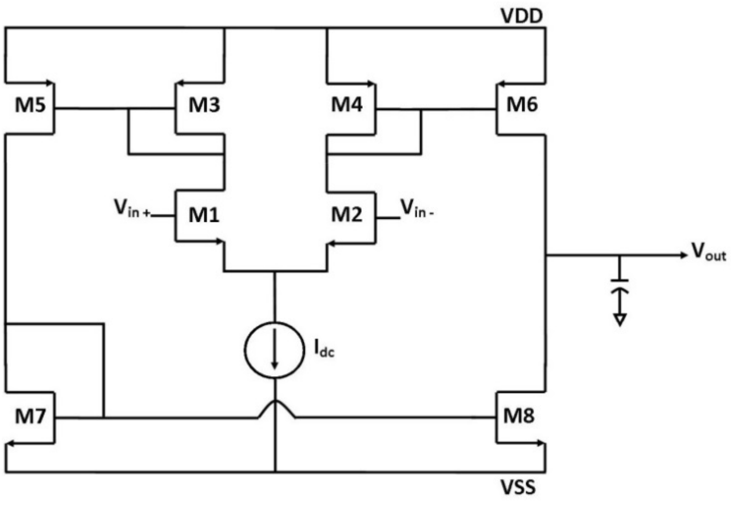

Figure 1. Structure of symmetrical OTA [15]

Table 2. Dimension of Transistors in OTA

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

2.1. Current Mirror

In analog integrated circuit (IC) design and in the operational amplifier circuit itself, one of the essential sub-circuits being extensively used is current mirrors. Current mirrors are implemented in operational amplifier as biasing elements to power up all transistors and acts as active load in amplifier to produced high AC voltage gain [16]. In this proposed design, simple current mirror is used because it consumed lesser power when compared to the cascode current mirror [4]. The proposed OTA bioamplifier consists of three simple current mirrors, M3 and M5, M4 and M6 and M7 and M8. For the sub-circuits in the OTA, M1 and M3 and M2 and M4 act as self-biased inverters. The principle of current mirror is the channel current of two transistors with equivalent gate-source potential should be equal [16]. The output current and reference current in simple current mirror can be described by Equation 11 with the assumption M1 is in saturation mode as indicated in Equation 9

$$V_{DS1} = V_{GS1} \tag{9}$$

Another assumption is V_{DS2} must greater than V_{T2}, as in Equation 10

$$V_{DS2} \geq V_{GS2} - V_{T2} \tag{10}$$

With these conditions the MOSFET equation is in saturation mode as shown by Equation 11

$$\frac{I_{out}}{I_{ref}} = (\frac{W_2 L_1}{W_1 L_2})(1 + \frac{\lambda V_{DS2}}{\lambda V_{DS1}}) \tag{11}$$

2.2. Performance Parameters

Several parameters extracted from the OTA are gain, CMRR and power consumption. These parameters are extracted from the designed OTA by analyzing the results from the simulations and are used to determine the level of performance of the designed OTA.

Open Loop DC Gain

The ratio of change in output voltage to the change in input voltage of the OTA can be defined as open loop DC gain which can be measured using Equation 12. The open loop gain is also known as differential mode voltage amplification or gain.

$$A_D = 20\log\frac{V_{PP(\mathrm{OUT})}}{V_{PP(IN)}} \tag{12}$$

Common Mode DC Gain

The ratio of change in output voltage to input voltage when both of input voltages supplied into the OTA is in the same phase. It also known as common mode voltage amplification and can be measured using Equation 13.

$$A_C = 20\log\frac{V_{PP(\mathrm{OUT})}}{V_{PP(IN)}} \tag{13}$$

Common Mode Rejection Ratio (CMRR)

CMRR is defined as ratio of differential mode gain to common mode gain and can be measured using Equation 14. It is also known as measurement used to quantify the ability of electronic device to reject common mode signals. The ideal value of CMRR should be infinity where the value of common mode gain is zero and differential mode gain is as high as possible (according to the specification).

$$CMRR(dB) = 20\log\frac{A_D}{A_C} \tag{14}$$

Power Consumption

Power consumption in OTA is really important as the MOSFET technology have reached the sub-micron size. This improvement in MOSFET technology leads to the unwanted short-channel effects occurred in the transistors itself which affecting the OTA performance in a bad ways. One of the main sources of high power consumption in OTA is leakage current in MOSFET. The power consumption of OTA designed in this paper can be measured using Equation 15.

$$P = (I_5 + I_6 + I_{DC}) * (V_{DD} + V_{SS}) \tag{15}$$

3. SIMULATION RESULTS AND ANALYSIS

In this section, a comparison of the simulation results for symmetrical OTA designed using different CMOS technology; 180 nm, 130 nm and 90 nm were presented. Each of the OTA is also simulated using different supply voltage and bias current to deduce the relationship of supply voltage and bias current towards the performance of OTA in terms of gain, CMRR, slew rate and power consumption. The testbench circuit of simulation consists of OTA and a load capacitor with differential inputs. The input signals chosen are positive peak-to-peak voltage with amplitude of 2 mV and -2 mV with frequency of 250 Hz. The reason in choosing those values of voltage and frequency are to imitate the ECG signal at its maximum amplitude and frequency. Figure 2 shows the testbench circuit for simulations of the symmetrical OTA.

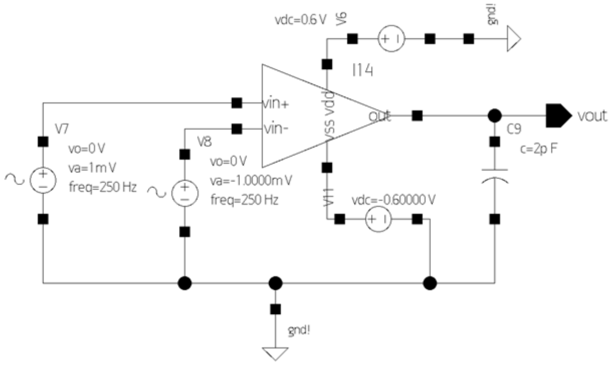

Figure 2. Schematic of testbench circuit for symmetrical OTA

3.1. Supply Voltage and Performance Parameters

In this simulation, the supply voltage of OTA is varied from ±0.6 V up to ±0.9 V in order to investigate the relationship between supply voltage and performance parameters (gain, CMRR and power consumption). For this simulation, the bias current, IDC is fixed at 10 µA. In order to extract DC gain and CMRR parameters from the OTA, the transient analysis is done onto the OTA and the results are analyzed. For the common mode gain, both input signals are set at the same phase (0^o) and for differential mode gain, positive input signal is set at 0^o and negative input signal is set at 180^o. Meanwhile for the average power consumption, the value is extracted from the Simulation and Analysis Environment (SAE) tool in the HSpice software. Figure 3 shows the transient result of differential mode gain, Figure 4 shows the differential mode gain in decibels and Table 3 represents the performance parameters extracted from the transient analysis for 130 nm OTA.

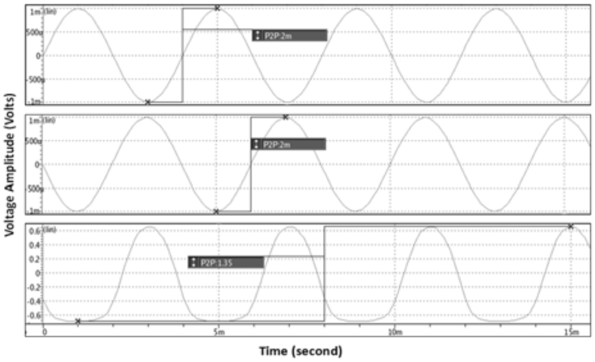

Figure 3. Transient results for differential mode of 130 nm OTA

Based from the tabulated results, it can be said that values of gain and average power consumption are directly proportional with the values of voltage supply. When the voltage supply supplied into the OTA is decreasing, the gain of OTA is decreasing and the power consumption of the OTA is also decreasing.

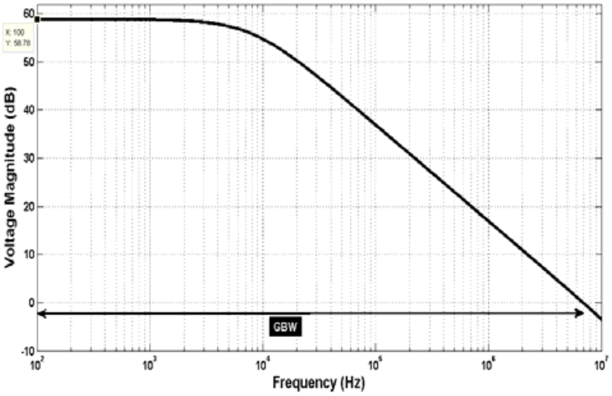

Figure 4. AC analysis of 130 nm OTA in differential mode

Table 3. Comparison of Performance Parameters for 180 Nm, 130 Nm and 90 Nm OTA Versus Different Voltage Supply

OTA	Voltage Supply (V)	Gain (dB)	AVG Power (µW)
180 nm OTA	±0.9	47.4	52.05
	±0.8	46.4	46.45
	±0.7	44	40.83
	±0.6	30.2	34.78
130 nm OTA	±0.9	55.9	51.09
	±0.8	55.2	45.69
	±0.7	54.3	40.29
	±0.6	52.3	34.90
90 nm OTA	±0.9	56	49.30
	±0.8	55.7	44.07
	±0.7	55	38.86
	±0.6	52.9	33.67

3.2. Bias Current and Performance Parameters

In this simulation, the bias current, Idc for the proposed OTA circuit to bias all transistors into saturation mode is varied from 2 µA up to 8 µA. This simulation is executed in order to find the relationship between supply voltage and performance parameters (gain, CMRR and power consumption). The voltage supply is fixed at ±0.9 V for this simulation. Meanwhile for the average power consumption, the value is extracted from the SAE tool in the HSpice software. The testbench circuit is set up similar to the circuit for simulation in investigating supply voltage and performance parameters. Figure 5 shows the transient result of differential mode gain, Figure 6 shows the transient result of the differential mode gain and Table 4 summarized the performance parameters extracted from the transient analysis of 90 nm OTA.

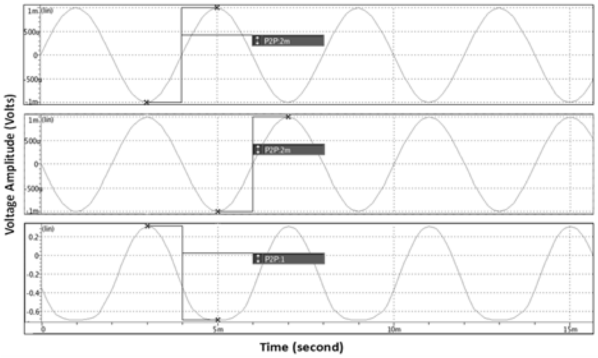

Figure 5. Transient results for differential mode of 90 nm OTA

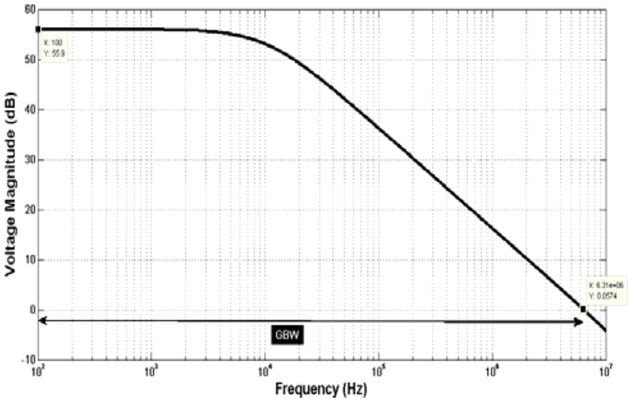

Figure 6. AC analysis of 90 nm OTA in differential mode

Table 4. Comparison of Performance Parameters for 180 Nm, 130 Nm and 90 Nm OTA Versus Different Bias Current

OTA	Bias Current (µA)	Gain (dB)	AVG Power (µW)
180nm OTA	8	48	41.57
	6	48.5	31.10
	4	48.9	20.65
	2	49.4	10.25
130nm OTA	8	56.5	40.73
	6	57.1	30.41
	4	57.9	20.14
	2	58.8	9.966
90nm OTA	8	56.2	39.41
	6	56.4	29.54
	4	56.3	19.67
	2	55.9	9.83

From the tabulated results in Table 4, it can be said that value of gain is inversely proportional with the value of bias current supplied into OTA and the value of average power consumption is directly proportional with the value of bias current supplied into OTA. When the bias current supplied into OTA is decreasing, the gain of OTA is increasing and the power consumed by the OTA is decreasing. But for 90 nm OTA, the value of gain is inconsistent even when the bias current is reduced to 2 µA. This is due to short-channel effects (SCEs) and mismatch affecting the operation of transistors in OTA.

3.3. Common Mode Rejection Ratio (CMRR)

To obtain the CMRR for symmetrical OTA, Equation 14 is used and the calculated results are tabulated in Table 5 and Table 6. As CMRR is used to quantify the ability of OTA rejecting common-mode signals, it is necessary for the OTA to have high CMRR which means it can easily filter out common-mode signals that sourced from external noises.

Table 5. CMRR Of 90 Nm OTA for Different Voltage Supply

OTA	Voltage Supply (V)	CMRR (dB)
90 nm OTA	±0.9	120
	±0.8	119
	±0.7	118
	±0.6	115

Table 6. CMRR Of 90 Nm OTA for Different Bias Current

OTA	Bias Current (µA)	CMRR (dB)
90 nm OTA	8	124
	6	129
	4	135
	2	140

The proposed 90 nm OTA is chosen to be characterized in the CMRR section because its gain is sufficient enough to amplify ECG signal and the power consumption is low, which is about 9.83 µW from ±0.9 V voltage supply. Based on Table 5, the value of CMRR of the OTA is decreasing as the voltage supply decreases from ±0.9 V down to ±0.6 V. For Table 6, the CMRR of the OTA is increasing when the bias current supplied into OTA is decreasing. Based on the tabulated results, in order to get the maximum value of CMRR from 90 nm OTA, the voltage supply supplied into OTA must be fixed at ±0.9 V and 2 µA of bias current to power up transistors in the 90 nm OTA.

3.4. Bias Current, Gain Bandwidth and 3-db Frequency

In this section, further simulations are being done to investigate the relationship between bias current provided to OTA circuit with gain bandwidth (GBW) and cut-off frequency (3-dB). Gain bandwidth (GBW) is the frequency of which the open loop gain of the amplifier becomes unity. GBW also means as the range of frequencies in which the amplifier can amplify the input signals. The cut-off frequency or known as 3-db frequency is a frequency where the power output of the amplifier starting to drop or to attenuate where the input signals is not amplified at maximum gain. Comparison of Gain, GBW and 3-Db Frequency Of 90 Nm OTA for Different Bias Current as shown in Table 7.

Table 7. Comparison of Gain, GBW and 3-Db Frequency Of 90 Nm OTA for Different Bias Current

Bias Current (µA)	AVG Power (µW)	Gain (dB)	GBW (Hz)	$f_{3\text{-dB}}$(Hz)
2	9.83	55.9	6.2M	10k
1	4.91	55.2	3.53M	3.17k
0.5	2.46	54.4	1.7M	1k
0.01	0.056	36.7	39k	258

Based on the tabulate results in Table 7, it can be said that power consumption, gain, GBW and cut-off frequency is directly proportional to the bias current level provided into the OTA. OTA with lower bias current have advantage of lower power consumption which is crucial in bio-medical application but from the Table 7, the gain of OTA dropped from 55.9 dB to 36.7 dB which does not meet the bioamplifier gain requirement although the GBW and cut-off frequency is smaller than the OTA with higher bias current.

Smaller GBW and cut-off frequency is to ensure there are less common mode signals and external noise affecting the OTA during amplification of input signals.

3.5. Final Deduction

In order to choose the most suitable OTA to be implemented as bioamplifier, the OTA must have balanced trade-offs between maximum DC gain, power consumption, CMRR, gain bandwidth (GBW) and cut-off frequency. Table 8 shows the comparison of performance between the proposed symmetrical 90 nm OTA in this work with previous research.

Table 8. Comparison of Proposed OTA and Other Existing Amplifiers

	[1]	[2]	[4]	[15]	Proposed OTA
Technology (nm)	350	180	180	180	90
Gain (dB)	73.9	-	45.38	25.52	55.9
GBW (Hz)	533	-	2.9	55.11M	6.2M
$f_{3\text{-dB}}$(Hz)	-	-	-	-	10k
Power (μW)	61	86.63	6.25	44.18	9.83
CMRR (dB)	124	-	-	-	140
Voltage Supply (V)	2	1	1.8	1.8	±0.9

After simulations and comparisons have been made, the 90 nm OTA with ±0.9 V of voltage supply and 2 μA of bias current is the most suitable to be implemented as bioamplifier. This is because it consumed only 9.83 μW of power from ±0.9 V voltage supply and managed to produce a gain of 55.9 dB which is sufficient for ECG signal detection system. It also has a CMRR value of 140 dB which is high when compared to others and this means it can filter out common-mode signals and noises from ECG signal satisfactorily. The GBW is at 6.2 MHz and cut-off frequency is at 10 kHz which are sufficient for ECG signal frequency range to be amplified at the maximum gain.

4. CONCLUSION

In this paper, a symmetrical OTA has been designed by using 180 nm, 130 nm and 90 nm CMOS technology and its performance has been analyzed and compared thoroughly. The comparison between simulation results of the OTA had been done to identify the best combination of CMOS technology, supply voltage and bias current in order to achieve the objective of this paper; designing symmetrical OTA with lowest power consumption with sufficient gain and has good CMRR characteristics. The results show that the designed symmetrical OTA is suitable to be implemented as a bioamplifier and adopted in ECG signal detection system. In order to improve the performance of the symmetrical OTA designed in this paper, the bulk-driven techniques and sub-threshold operation of transistor can be implemented in future works.

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