Simulation and Analysis of OTA-C Ladder Butterworth filter for Sensors & Biomedical Applications

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Abstract--**Amplitude and frequency of signals in general capacitive sensors and biomedical applications remain characteristically very low (10-100 µV and 40-260 Hz) which necessitates analog domain amplification and filtering process before the signals are digitally processed and analyzed. In a typical analog front end circuit for capacitive sensors, recorded signals are first amplified by an high CMRR and high input impedance instrumentation amplifier with 10-100 time amplification factor and then out of band interference is removed by a low pass filter having a cutoff frequency of 10- 260 Hz. Pass band ripples are not tolerable in sensors and biomedical applications. Thus a Butterworth filter approximation is suitable for such applications. This paper discusses the simulation and analysis of 5th order Butterworth filter with 260 Hz cutoff for Sensors & Biomedical Application. To reduce the influence of coefficient sensitivity ladder type architecture has been employed. To replace resistance and inductances of ladder with their equivalent active implementations, a bulk driven OTA is designed. Bulk driven capability of OTA provides 30 nS transconductance which helps in keeping filter capacitances in pF range. Proposed OTA also has wide linear range. The OTA is operated in the sub threshold region to save power under the supply voltage of 1 V. The simulation and analysis have been performed in Tanner EDA Tool using 180 nm technology model file.**

Keywords: Capacitive sensors, Bulk-input, Low-power supply, OTA, ECG and Butterworth filter.

I. INTRODUCTION

THE continuous reduction of feature length in CMOS technology with advancing VLSI technologies along with the trend of using small portable devices needs reduced power supply voltages [1]. Similarly sensors and biomedical instrumentation field has obeyed same trend and demand for mobile biomedical instruments is rising nowadays. Mobile Biomedical instrumentation requires low voltage and low power integrated circuits. An ECG signal reproduces electrical activities of the heart graphically and helps in clinical diagnosis of heart deceases. Conventional ECG systems can only be used for short term recording of patients because they are too big to carry. While a portable ECG system comprising wearable electrodes and handheld mobile ECG recorder with wireless data communication capability like Zigbee can be easily carried by patients and record up to 100 thousand cardiac cycles uninterruptedly for 24 hours. A critical design issue for such a mobile instrument is power consumption which forces the circuit designers to design low power circuits. The low amplitude (10-100µV) and low frequency (0.5 – 300 Hz) characteristics of ECG signal makes them very sensitive to noise and small noise mixed with original signal make it very hard to detect signal changes [2].

A typical analog frontend for an ECG system consists of an instrumentation amplifier with high CMRR and 10- 100 amplification power which comes right after ECG electrodes. Then a 260 Hz cutoff low pass filter is used to eliminate high frequency noise from recorded signal. Then a 0.5 Hz cutoff High Pass filter is used in transmission line to remove DC noise elements. A 60 HZ notch filter is used to reject 60 Hz hum [3].

This paper discusses the simulation and analysis of 5th baseband filter with 260 Hz cutoff for ECG detection. The Proposed fifth order Filter adopts Butterworth filter approximation because in medical signal detection filters, Pass band ripples are not acceptable. [4] In existing literature, it has been proposed to use OTA based gm-c filters for ECG systems. Continuous time filters realized using Operational Transconductance Amplifier (OTA) and Capacitors are called gm-C filters. Fig. 1 shows a first order OTA-C filter with its frequency response. Eqn (1) shows the transfer function of first order filter while filter cutoff is given by eqn (2).

$$A_v(s) = -\frac{g_m}{SC_L + g_m} \tag{1}$$

$$W_{-3dB} = \frac{g_m}{C_L} \tag{2}$$

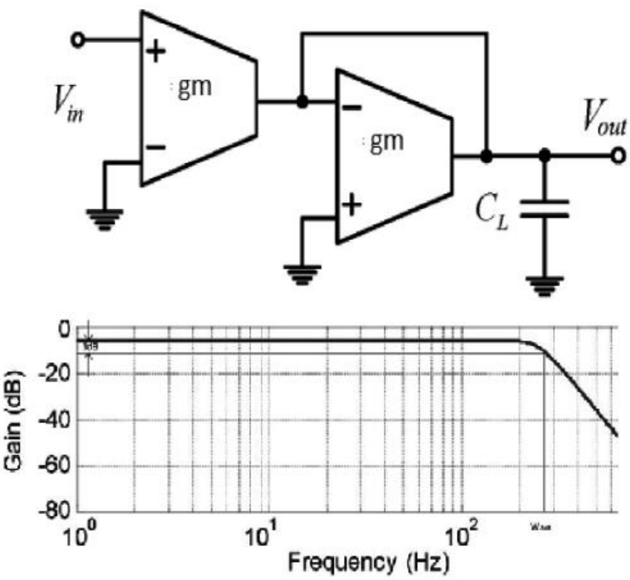

Figure 1. OTA-C filter and its frequency response.

Thus in gm--C filters, cutoff frequency is a linear function of OTA transconductance [5]. By tuning transconductance of OTA, filter cutoff can be tuned easily. It provides the flexibility to correct filter cutoff which might get changed due to various reasons like fabrication technology parameter changes, component tolerances and ambient temperature changes.

Another form of OTA-C filter include LCR ladders simulated using OTA and capacitors. Such filters show excellent insensitiveness to element tolerances and process variations [6]. Thus to reduce the influence of coefficient sensitivity and maintain an undistorted ECG signal, ladder type architecture has been employed.

To replace resistance and inductances of ladder with their equivalent active implementations, a bulk driven OTA is designed. Bulk driven capability of OTA is necessary as only with this configuration, OTA transconductance in nS range can be achieved which helps in keeping capacitive component values in pFs for the filter with few hundred Hz cutoff like ECG (Eqn 2). The MOSFET devices in the propsed OTA are operated in sub threshold region to realize a very low power circuit.

Generally, the input stage of OTA consists of a differential pair which shows nonlinear input voltage vs output current characteristic. [7] It degrades the linearity of OTA-C filter [8]. In literature, several linearization techniques have been proposed to linearize the transconductance response of the OTA [9, 10].

The use of two cross-coupled differential pairs at unequal bias to cancel nonlinear terms of output differential currents of OTA has been proposed by [5]. Use of source and drain degeneration with multi tanh bump linearization schemes has been proposed by [11]. A voltage-tunable and highly linear three input transconductor has been presented by [12]. To remove the intrinsic nonlinearity of a Balanced OTA, a cascaded architecture of two balanced OTAs through a active resistor has been proposed by [13]. The use current division, current cancellation and source-degeneration linearization schemes in a subthreshold mode fully differential OTA has been proposed by [14].

This paper is organized as follows. The proposed OTA and the design of proposed ECG detection filter are in section II and III discussed respectively. Simulation results are presented in section IV and Concluding remarks are given in section V.

II. PROPOSED OTA

OTA (operational transconductance amplifier) means output current is controlled by input differential voltage multiplied by OTA transconductance (g_m). Proposed OTA circuit is shown in Fig 2. Proposed OTA is operated in sub threshold region, which provide the value of g_m is few nano-amperes per volt [14, 15]. In integrated circuits, the substrate is usually common to many MOS transistors. In order to maintain the cut off condition for the entire substrate-to-channel junction, the substrate is usually connected to the most negative power supply in an NMOS circuit (the most positive in a PMOS circuit). The resulting reserve-bias voltage between source and body (Vw_S in an n-channel device) will have an effect on device operation. The reverse bias voltage widens the depletion region. This in turn reduces the channel depth. To return the channel to its former state, V_{GS} has to be increased. The effect of V_{ws} on the channel can be most conveniently represented as a change in the threshold voltage V_t. Specifically, it has been shown that increasing the reverse substrate bias voltage V_{ws} result in an increase in V_t according to relationship.

$$V_t = V_{to} + \gamma\left[\sqrt{2\varphi_f + V_{ws}} - \sqrt{2\varphi_f}\right] \tag{3}$$

where,

V_t = Threshold voltage for V_{SB} = 0;

ϕ_f = a physical parameter with ($2\phi_f$) typically 0.6 V

γ = is a fabrication-process parameter is given by

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_S}}{C_{ox}} \tag{4}$$

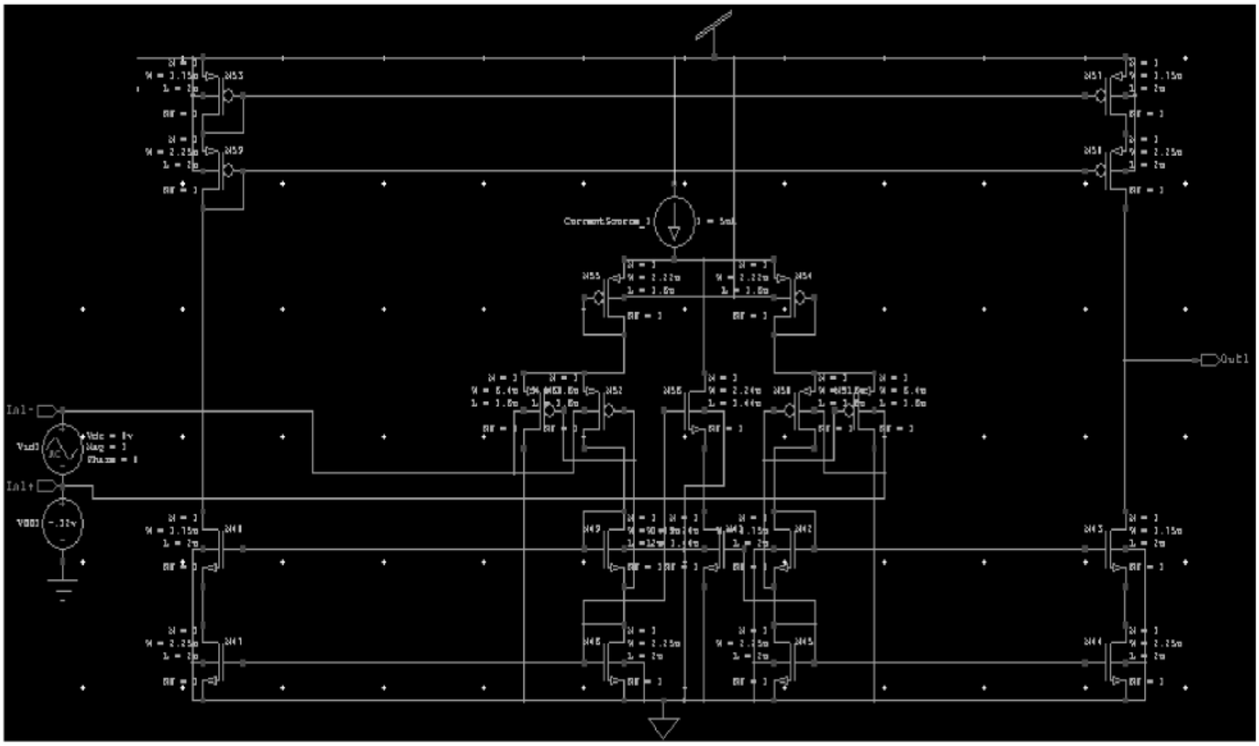

Figure 2. OTA circuit diagram.

Eq. (2) indicates that can incremental change in V_{ws} gives rise to an incremental change in V_t , Which in turn results in an incremental change in i_D even though V_ϕ might have been kept constant. It follows that the body voltage controls drain current i_D . Thus the body terminal in MOSFETs acts as another gate. The current expression for bulk input MOS transistor in sub threshold mode is given by:-

$$i_{DS} = I_O \exp\left(\frac{-KV_{GS}}{U_T}\right)\exp\left[\frac{-(1-K)}{U_T}V_{WS}\right] \quad (5)$$

Gate, Source and Well Transconductances for OTA are given by following equations respectively.

$$g_{gt} = -K\left(\frac{I_{DS}}{U_T}\right),\ g_{wl} = -(1-k)\frac{I_{DS}}{U_T},\ g_S = \frac{I_{DS}}{U_T} \quad (6)$$

Gate, Well and source Transconductance Normalized by (I_{DS}/U_T) are as follows.

$$g_{gt} = -K\ ,\ g_{wl} = -(1-K)\ ,\quad g_{Sn} = 1 \quad (7)$$

As $K \cong 0.7$, So $g_{wl} < g_{gt}$ (in magnitude), So well is preferable over gate as a low transconductance input. Well transconductance of Differential amplifier is given as follow.

$$g_w = \frac{1-k}{1+\frac{1}{k_P}+\frac{k}{k_n}} \times \frac{I_B}{2U_T}\ \ I_{OUT} = I_B \tanh\left[\frac{g_w(V_{id})}{2U_T}\right] \quad (8)$$

where, I_{out} is the output current, I_B the Bias current of transistor.

III. PROPOSED FILTER FOR ECG DETECTION

In order to precisely diagnose the heart disease, the detection circuits must be capable of attenuating the out-of-band interference and the noise before analog-to-digital converter to avoid the aliasing [3]. Therefore we have designed a fifth-order Butterworth OTA-C Ladder baseband filter with a -3 dB cutoff frequency of 260 Hz. Figure 3 shows the proposed filter circuit.

IV. SIMULATION RESULTS

Proposed bulk driven subthreshold mode OTA with 65nA bias current and 1V power supply, was simulated for OTA specifications like frequency response, slew rate, and settling time etc (Figures 4-8).

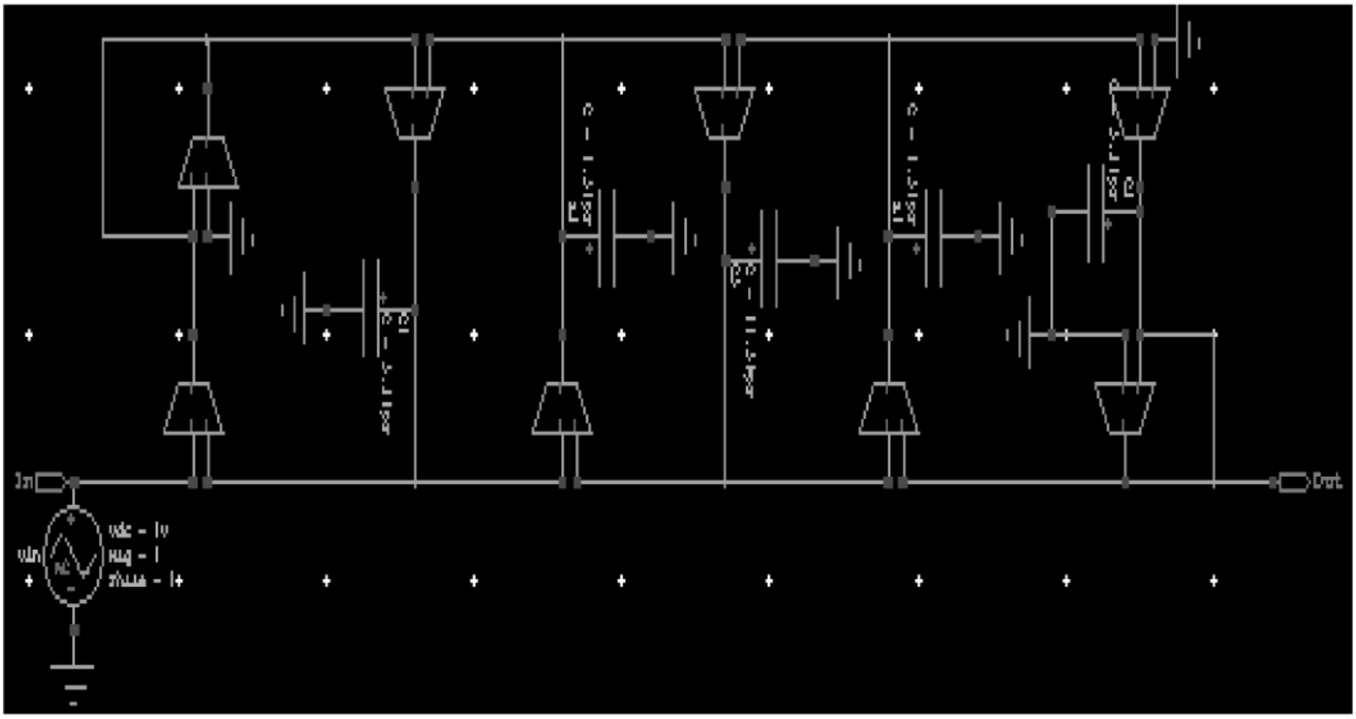

Figure 3. Fifth order Butterworth OTA-C filter.

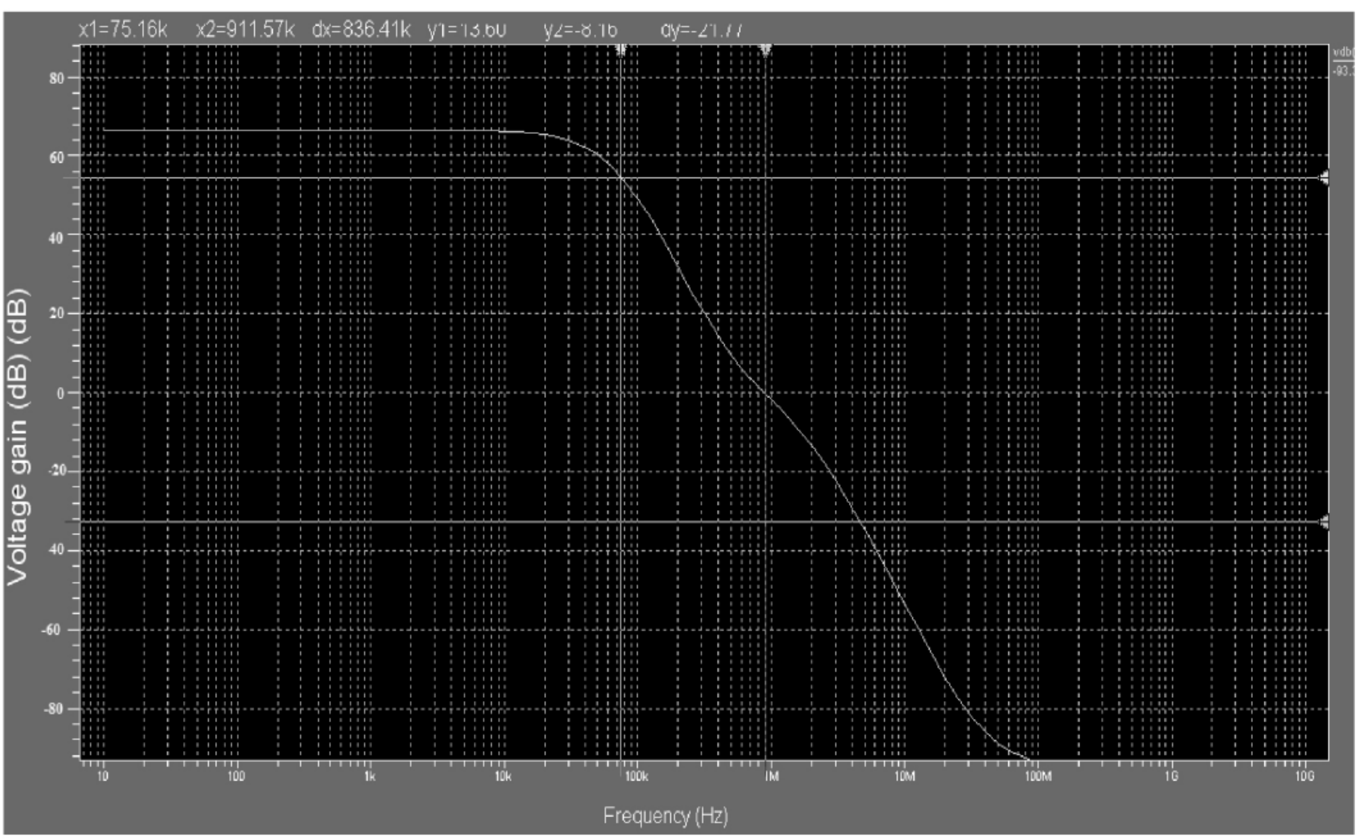

Figure 4. Frequency Response of Proposed OTA.

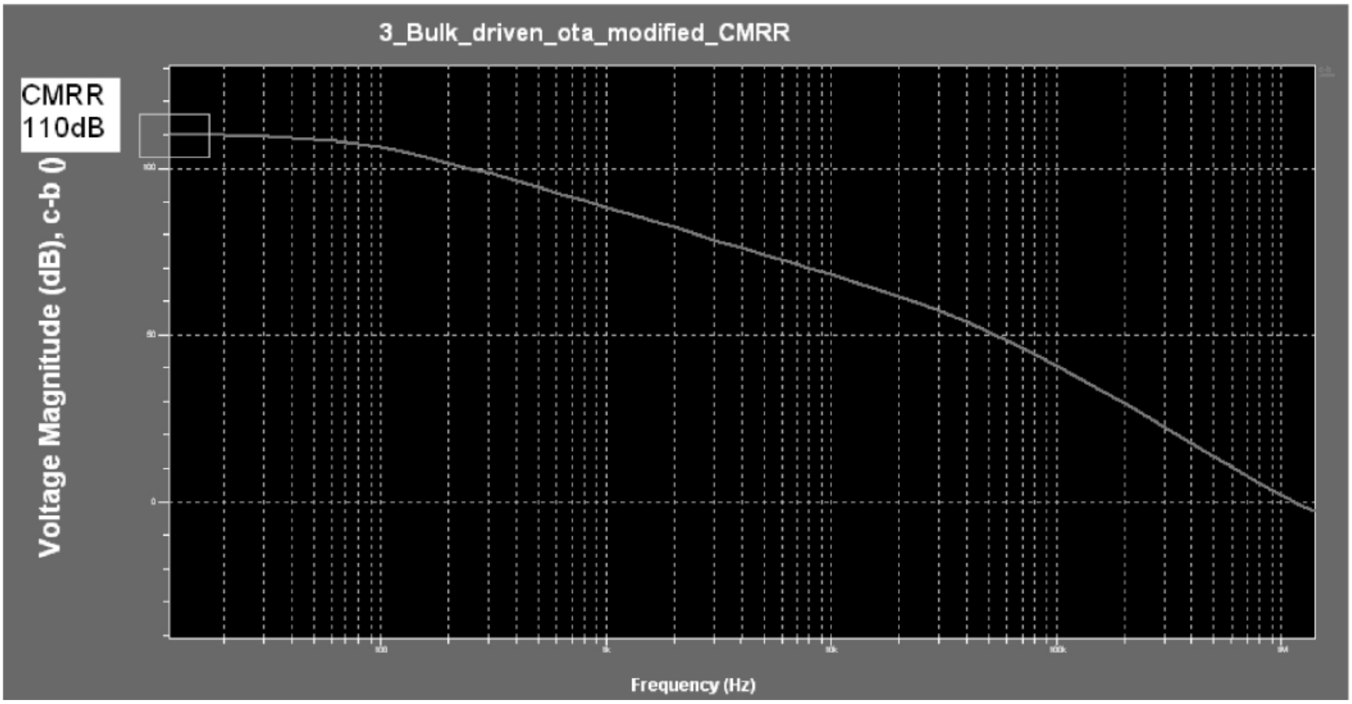

Figure 5. CMRR of Proposed OTA.

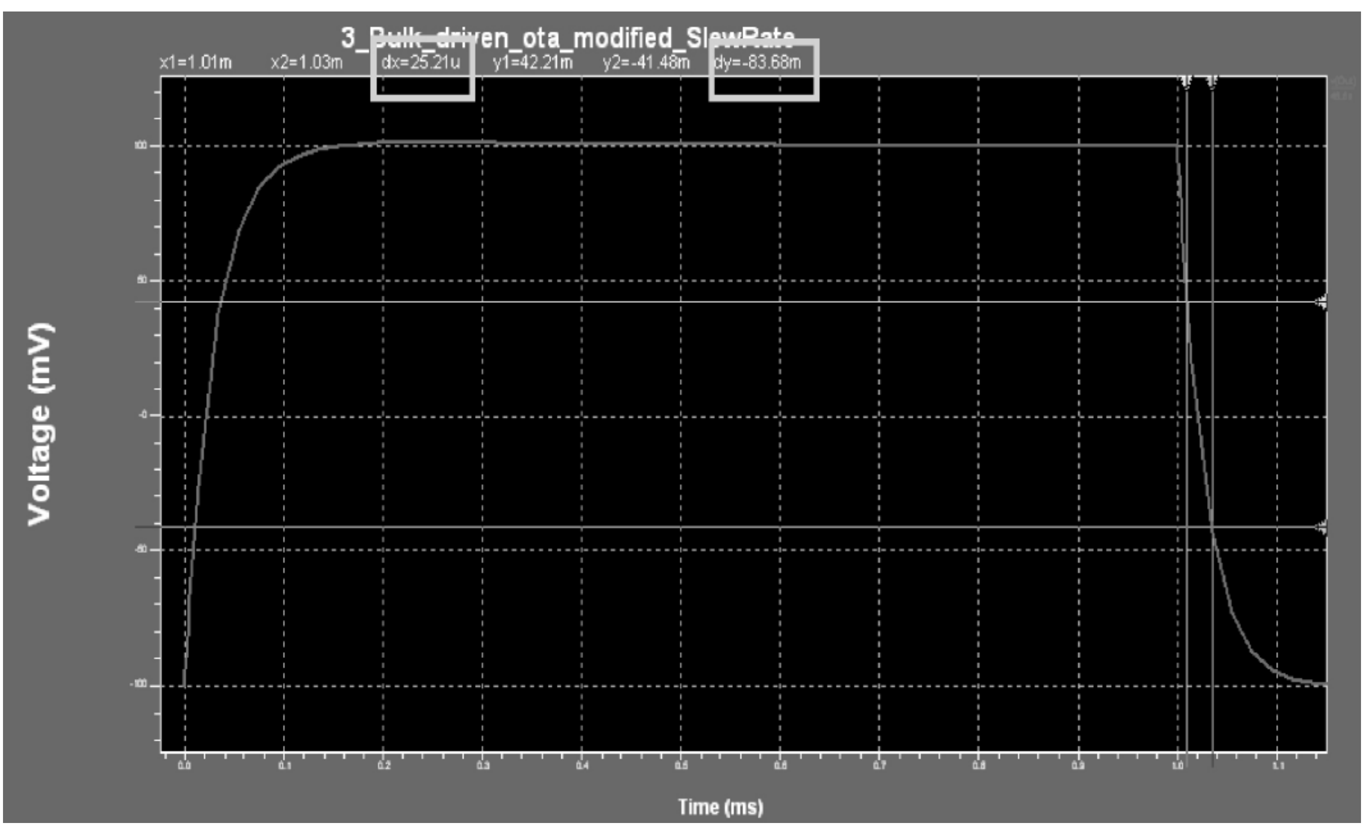

Figure 6. Falling Slew rate of Proposed OTA.

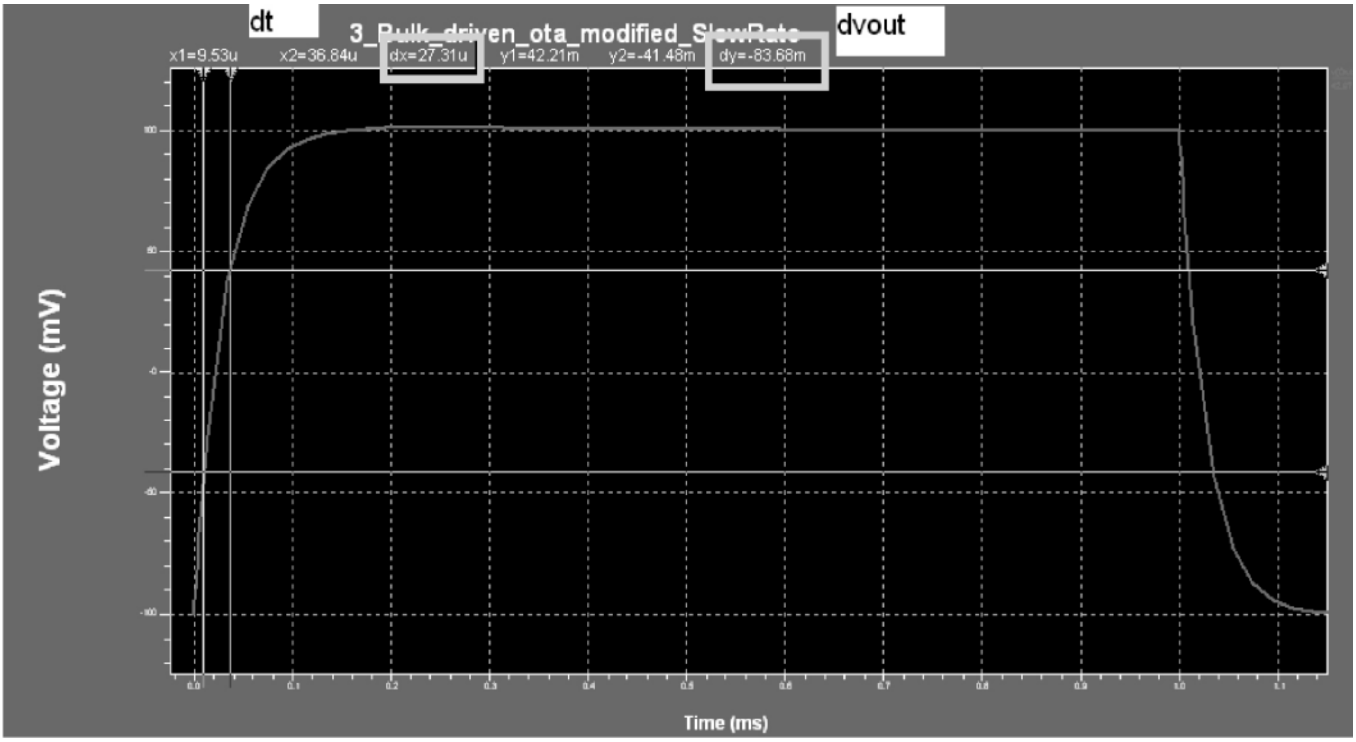

Figure 7. Rising Slew rate of Proposed OTA.

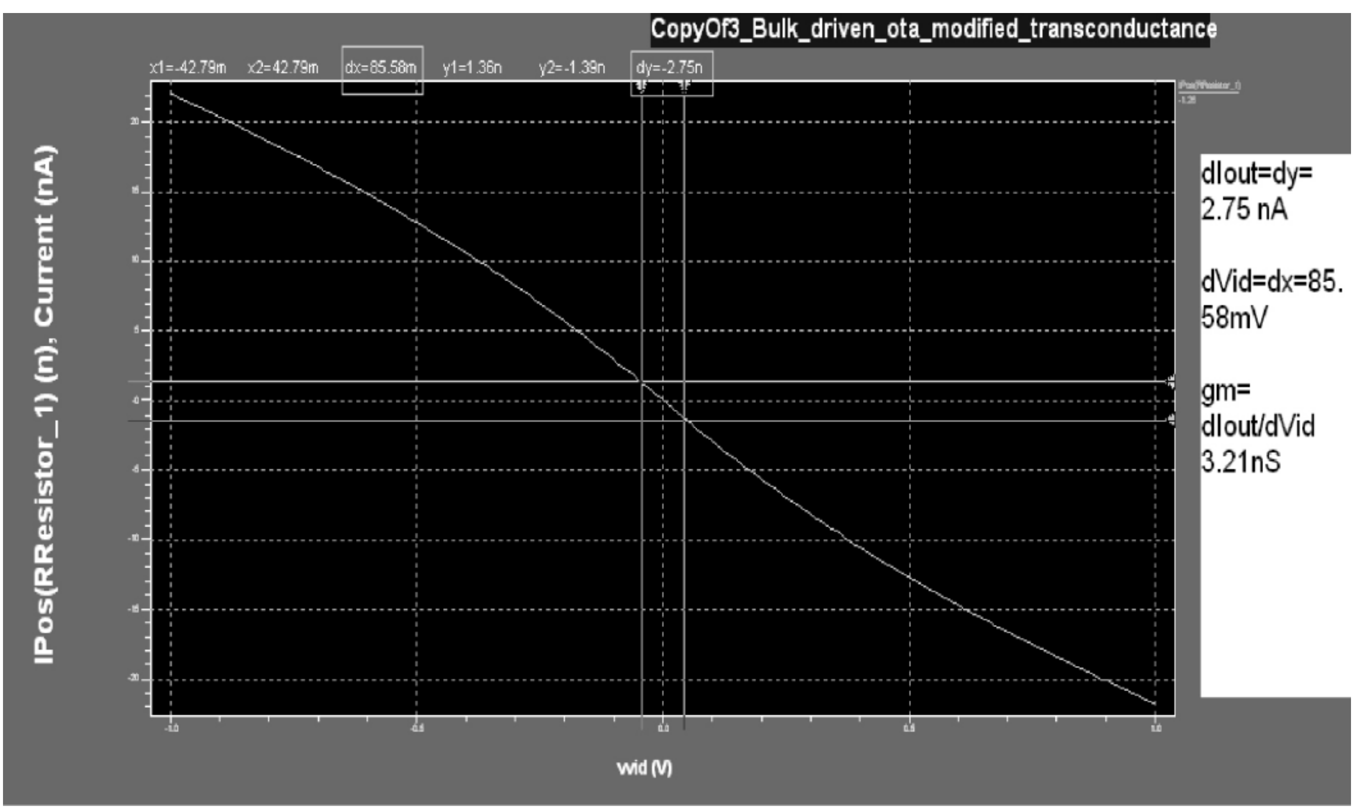

Figure 8. Transconductance of Proposed OTA.

Simulation results for OTA are tabulated as shown in the Table 1. Results prove that the proposed OTA is suitable candidate for designing a fifth-order Butterworth OTA-C Ladder baseband filter for ECG detection.

TABLE 1
SIMULATION RESULTS OF PROPOSED OTA

Property	Proposed OTA
Bias current	65 nA
Power supply	1 V
Power consumption	65 nW
DC Gain	68 dB
UGB	85 MHz
GBW	75.16 KHz
CMRR	110 dB
Rising slew rate @ C_L = 1pF	3.06 V/ns
Falling slew rate @ C_L =1pF	3.31 V/ns
Settling Time @ C_L = 1pF	561.21 µS
g_m	3.21 nS

Designed filer circuit was simulated for filter ac response (Figure 9). Table 2 show the frequency response of filter.

TABLE- 2 EXPERIMENTAL RESULTS

Parameter	**Measured Values**
Filter order	5th
Filter Approximation	Butterworth
Filter Architecture	OTA-C Ladder
Power Consumption	520 nW
-3dB Bandwidth	262.46 Hz
DC gain	-8 dB

IV. CONCLUSION

This paper discusses the simulation and analysis of Butterworth filter by using bulk driven OTA for ECG detection. To reduce the influence of coefficient sensitivity and maintain an undistorted ECG signal, a fifth order ladder type low pass Butterworth is employed. The OTA based circuit is operated in the sub threshold region to save power under the supply voltage of 1 V. The frequency response of filter is 262.46 Hz, OTA CMRR is 110 dB and DC gain is 68 dB. GBW of OTA is 75.16 KHz. The settling time of OTA is 561.21 µsec. The simulation and analysis has been performed in tanner EDA Tool (S-Edit13.0, T-Spice v 13.0 and W-Edit) Microsoft Vision.

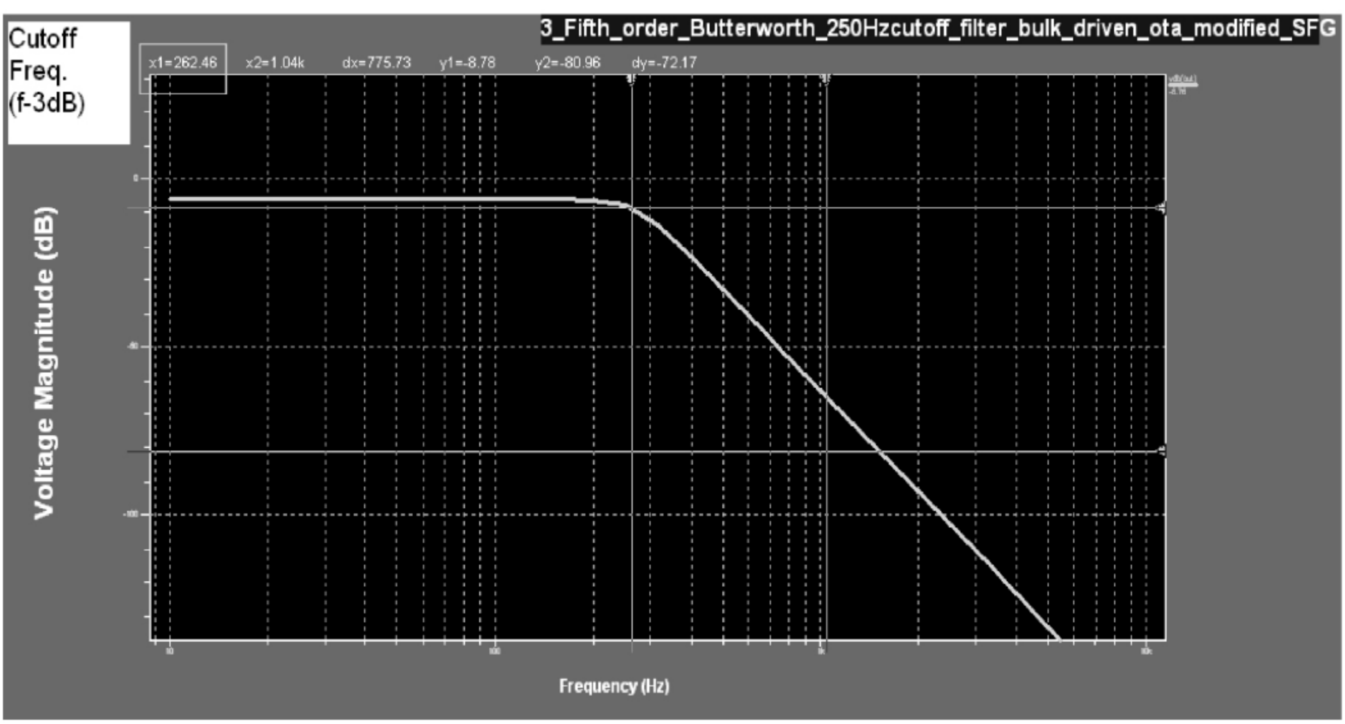

Figure 9. Frequency response of the Filter

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