Extremely Low–Power Fifth–Order Low–Pass Butterworth Filter

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Abstract—**A fifth-order Butterworth low–pass filter using multiple-input operational transconductance amplifiers (OTAs) is proposed in this paper. It is expressed that the number of OTAs that used for realizing fifth–order low–pass filter can be reduced using multiple–input OTA and results to decrease the power consumption and the active area. N–input OTA can be obtained using multiple-input bulk-driven quasi-floating gate technique. Subthreshold technique is used to achieve extremely low power consumption which can be applied to biomedical systems. The proposed topology is simulated using 0.18 µm standard CMOS process. Simulation results show that the proposed filter has a bandwidth located within 250 Hz, a power consumption of 41 nW and a dynamic range of 61 dB.**

Keywords—fifth–order low–pass filter, multiple–input OTA, subthreshold region, bulk–driven quasi–floating gate technique

I. INTRODUCTION

The continuous-time filters can be used to application in biomedical systems: electroencephalography (EEG)/ electromyography (EMG)/ electrocardiography (ECG)/ applications. Fig. 1 shows ECG acquisition system which biological signal is typically in the range of 100 µV−5 mV while the frequency is below 250 Hz [1]. The ECG signal in the range of 100 µV−5 mV is amplified by preamplifier and the low-pass filter will be used to limit the frequency band. The low–pass filter with a cut–off frequency of 250 Hz is used to reject the out–of–band noise. This work focuses on the low–pass filter which should be applied as this part of ECG acquisition system. To design continuous–time low–pass filters for applications in ECG acquisition system, several parameters should be considered: power consumption, dynamic range (DR) and chip area. However, the design of very low–frequency filters is not simple, especially for integrated circuit implementations when chip realization of large time constants is needed. Namely, a few nA/V transconductances and capacitors larger than 100 pF are needed. Unfortunately, very small transconductances lead to higher noise level and practical capacitances are limited to below 50 pF due to silicon area limitations.

There are continuous–time low–pass filters that can be designed for applying to ECG acquisition system available in literature, for example, see [2]–[10]. This work focuses only fifth–order Butterworth low-pass filters [3], [7]–[9]. The Butterworth response is interesting because the phase has a better linearity and consistent response within the bandwidth.

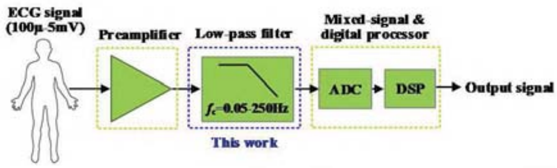


Fig. 1. ECG acquisition system.

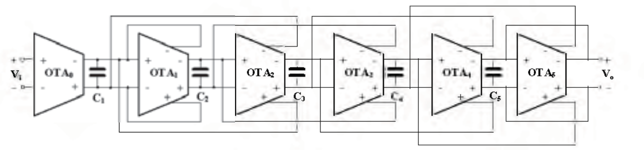


Fig. 2. Fifth–order Butterworth low–pass filter using MODI OTAs [7].

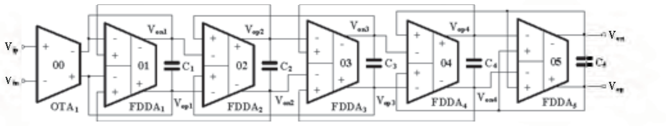


Fig. 3. Fifth–order Butterworth low–pass filter using FDDAs [9].

In [3], fifth–order Butterworth low–pass filter employing eleven OTAs and five capacitors has been reported. Fig. 2 shows the structure of fifth–order Butterworth low–pass filter using multiple-output differential–input OTA (MODI–OTA) [7]. This circuit employs six OTA and five capacitors. High-order low–pass filter using multiple–output fully differential operational transconductance amplifiers (MOFD OTAs) has been reported in [8]. However, to obtain fifth–order filter Butterworth low–pass filter, the topology in [8] employs six MOFD OTAs and five capacitors. In [9], fifth-order Butterworth low–pass filter employing five fully differential difference transconductance amplifier (FDDTA) and one OTA has been reported as shown in Fig. 3. The filters [7]–[9] provide a good performance of Butterworth low-pass filter that can be applied in ECG acquisition system, but these filters employ six active devices such as OTA and FDTA.

This paper a fifth–order Butterworth low–pass filter based on multiple-input OTAs (MI-OTAs) is proposed. It can be expressed that multiple–input OTA–based fifth–order low–pass filter can be reduced the number of used OTAs. MI-OTA can be realized using bulk–driven quasi–floating gate MOS transistors. Subthreshold technique is used to obtain ultra-low power consumption. The proposed filter has been simulated based on 0.18 µm CMOS process from TSMC. The proposed filter can be applied to biomedical systems.

II. Proposed Circuit

The symbol and the CMOS realization of MIBD–QFG MOST are shown in Fig. 4(a) and (b) [10], respectively. The one side of gate (G) terminal and other side of the bulk (B) terminal are capacitively coupled to the input voltage terminals V_{ini} (i=1, 2, ... N). In the similar way each of input capacitor C_{Bi}, the DC signal path is ensured by connecting a high resistance shunt resistor R_{Li}. The connection of the gate terminal to suitable bias voltage V_b through the high resistance shunt resistor R_L provides the channel between the source (S) and the drain (D) terminals. The shunt resistor R_L is replaced and implemented by transistors M_L configured in cutoff region as shown in Fig. 4(b). The signal voltage at the gate terminal (V_G) could be simplified as

$$V_G \approx \sum_{i=1}^{N} \frac{C_{Gi}}{C_{\Sigma G}} V_{ini} \tag{1}$$

where C_{Gi} (i =1, 2, ... N) is the G terminal coupling capacitance. $C_{\Sigma G}$ is the total capacitance seen from the G terminal and given by

$$C_{\Sigma G} = C_{GS} + C_{GD} + C_{GB} + \sum_{i=1}^{N} C_{GD-MLi} + \sum_{i=1}^{N} C_{Gi} \tag{2}$$

where C_{GS}, C_{GD}, C_{GB} is the parasitic capacitance of gate to source, gate to drain and gate to bulk of the transistor, respectively, and C_{GD-MLi} is the parasitic capacitance of gate to drain of the transistor M_{Li}. Similarly, the signal voltage at the bulk terminal (V_B) could be approximated as

$$V_B \approx \sum_{i=1}^{N} \frac{C_{Bi}}{C_{\Sigma B}} V_{ini} \tag{3}$$

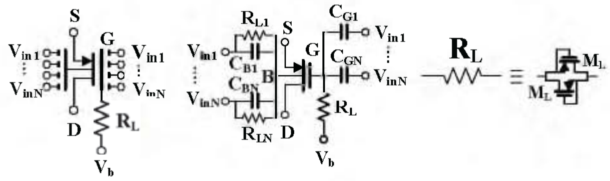
where C_{Bi} (i=1, 2,.. N) is the B terminal coupling capacitance. $C_{\Sigma B}$ is the total capacitance seen from the B terminal and given by

$$C_{\Sigma B} = C_{BS} + C_{BD} + C_{BSUB} + \sum_{i=1}^{N} C_{GD-MLi} + \sum_{i=1}^{N} C_{Bi} \tag{4}$$

where C_{BS}, C_{BD}, C_{BSUB} is the parasitic capacitance of bulk to source, bulk to drain, bulk to substrate of the transistor, respectively. The input voltage V_{in} is attenuated at the gate and bulk terminals by the factors of $C_{Gi}/C_{\Sigma G}$ and $C_{Bi}/C_{\Sigma B}$, respectively as shown in (1) and (3), consequently the input voltage swing range is extended. The input transconductances g_{mi} of MIBD-QFG MOST (from i–th input) is given [10] by

$$g_{mi} = \frac{C_{Gi}}{C_{\Sigma G}} g_m + \frac{C_{Bi}}{C_{\Sigma B}} g_{mb} \tag{5}$$

where g_m and g_{mb} is transconductance of the gate and bulk, respectively.



(a) (b)

Fig. 4. MIBD–QFG MOS transistor, (a) symbol, (b) realization.

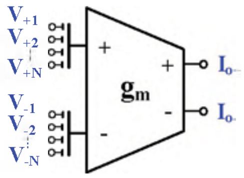


Fig. 5. Symbol of multiple-input OTA.

The circuit symbol of multiple-input operational transconductance amplifier (MI–OTA) is shown in Fig. 5 [11]. The MIBD–OTA schematic used in this design is represented in Fig. 6. The circuit consists of a differential pair (M_1, M_2) that is realized using MIBD–QFG MOS transistor in Fig. 4. The MOST of current mirrors (M_3–M_4 and M_5–M_6), which are used to transfer the differential current of input pair to the differential current output of the MI–OTA (I_{o+}, I_{o-}). To increase the output resistance and the DC voltage gain of the MI–OTA consequently, the self–cascode composite transistors have been used to realize both, the set current mirrors M_3–M_4 and M_5–M_6, in addition to the biasing current sources based on M_7–M_{10}.

The large–signal transfer characteristic of MI–OTA in Fig. 6, from i–th input and assuming the other inputs and the differential output are connected to ground, $M_7 = M_8 = M_{11}$, and operating in subthreshold region, can be expressed as

$$I_o = I_{o+} - I_{o-} = 2I_B tanh\left(\frac{V_{+i}-V_{-i}}{2nU_T}\left(\frac{C_{Gi}}{C_{\Sigma G}} + \frac{C_{Bi}}{C_{\Sigma B}}\right)\right) \tag{6}$$

where n is the subthreshold slope factor and U_T is the thermal voltage, I_B is the biasing current. Thus, the small-signal transconductance of MI QFG–OTA can be given as

$$G_m = \frac{I_B}{nU_T}\left(\frac{C_{Bi}}{C_{\Sigma B}} + \frac{C_{Gi}}{C_{\Sigma G}}\right) \tag{7}$$

Thus, the transconductance G_m can be adjusted by the biasing current and a few nA/V transconductances can also obtained using subthreshold region operation.

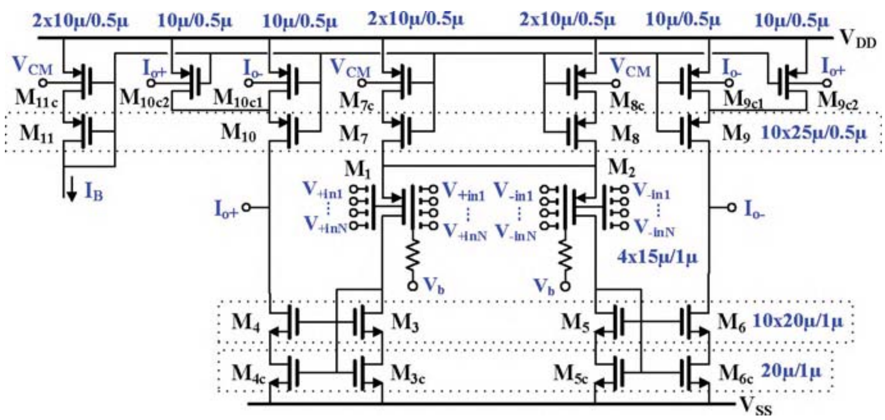


Fig. 6. CMOS implementation for MIBD–QFG OTA.

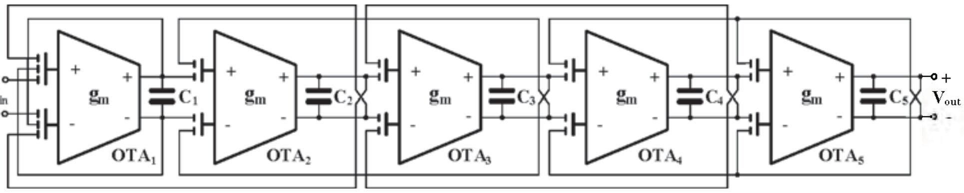


Fig. 7. Proposed fifth–order Butterworth low–pass filter using MI–OTAs.

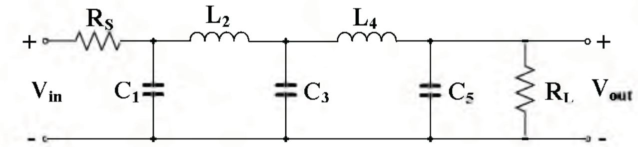


Fig. 8. Fifth–order low–pass RLC ladder filter.

For stabilizing the output common-mode voltage, a simple BD common-mode feedback (CMFB) circuit is produced by the upper transistors of pMOS self-cascode current sources (M_{7c}-M_{11c}). These transistors operate in triode region. The MI-OTA output common-mode level is equal to the reference potential (V_{CM}) applied to the M_{7c}, M_{8c} and M_{11c} bulk terminals. If the output common-mode level increase (decrease), the M_{9c}, M_{10c} channel resistances increase (decrease) as well, thus decreasing (increasing) the currents flowing through M_9 and M_{10}, and consequently the common-mode voltage. By connecting the M_{9c1} and M_{9c2} (M_{10c1} and M_{10c2}) in parallel, the outcome shows that there is a decreasing in the circuit sensitivity to differential signals that allows decreasing the nonlinear distortion introduced by the CMFB, and keep high value of the differential voltage gain of OTA. The small-signal voltage gain of MI-OTA is not affected by the CMFB while the second order effects is able to neglect. The loading effects associated with the finite input resistances of the M_{9c} and M_{10c} bulk terminals have an affect which able to neglect on the value of the DC differential voltage gain, even at higher temperatures. The proposed solution of a CMFB circuit is not only un-sophisticate but also no extra power consumption.

The proposed fifth-order Butterworth low-pass filter using MI-QFG OTAs is shown in Fig. 7. It employs five MI-QFG OTA and five capacitors. Compared with [7]-[9] (Figs. 2 and 3), the proposed fifth–order low–pass filter employs lesser active devices which can be possible using multiple-input OTAs. The fifth order low-pass RLC ladder filter in Fig. 8 has been used to implementation.

III. Simulation Results

The proposed filter in Fig. 7 has been simulated using MIBD–QFG OTA in Fig. 6. The MIBD–QFG OTA has been implemented in the standard 0.18 µm TSMC CMOS process with the supply voltage of a 0.5 V. The MI–QFG MOS transistor in Fig. 4 was designed as $(W/L)_{ML}$=4µm/5µm, C_B=0.5pF and C_G=1pF. The fifth–order low–pass RLC ladder filter in Fig. 8 was designed to obtain a cut-off frequency of 250 Hz. Thus, if resistances R_S=R_L=1Ω, the capacitance and inductance can be given by C_1=C_5=1.03 µF, C_3=1.273 mF and L_1=L_2=1.03 mH. When the MIBD–QFG OTA was biased as I_B=2 nA, the transconductance g_m was 8.5 nS. Thus, the capacitances for Fig. 7 were C_1=C_5= 5.853 pF, C_2=C_4=15.31 pF and C_3=18.935 pF.

The frequency responses of the RLC and the proposed fifth-order low-pass filter is shown in Fig. 9. The magnitude at low frequency was -6 dB and -6.5 dB and the cut-off frequency (f_c) was respectively 250 Hz and 250.4 for the RLC and OTA filter. It was evident that the curve of proposed fifth-order low-pass good agreement agree well with RLC ladder prototype. Fig. 10 shows the frequency response of the proposed filter when the bias currents I_B were varied from 1.0 nA to 2.0 nA while the f_c was in the range of 123.0 Hz to 250.1 Hz.

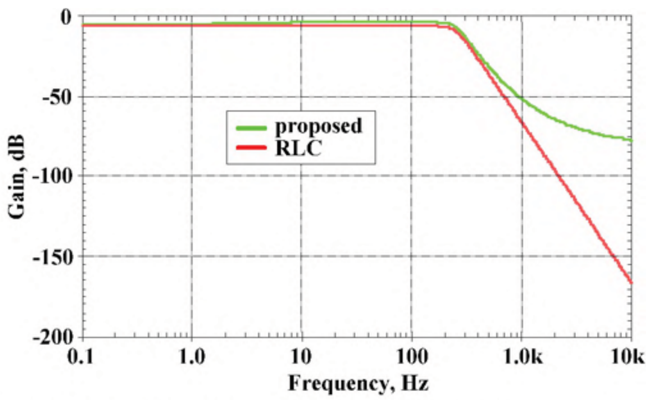


Fig. 9. The magnitude response of fifth–order Butterworth low-pass filter.

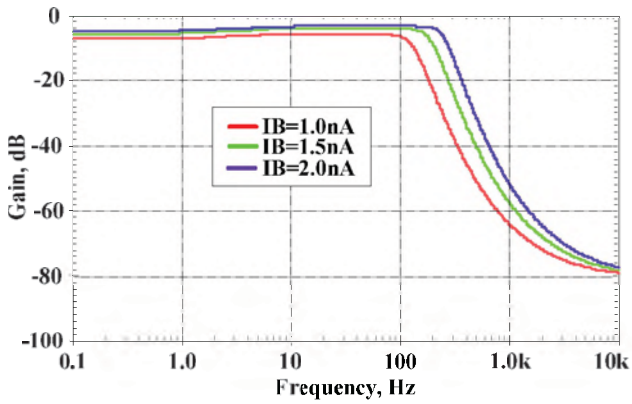


Fig. 10. The magnitude response of filter with different bias currents.

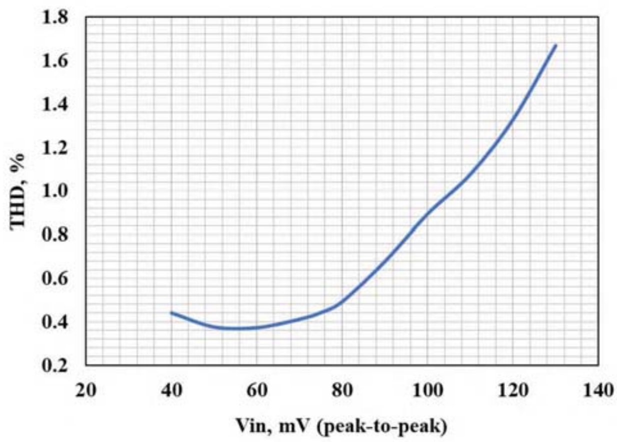
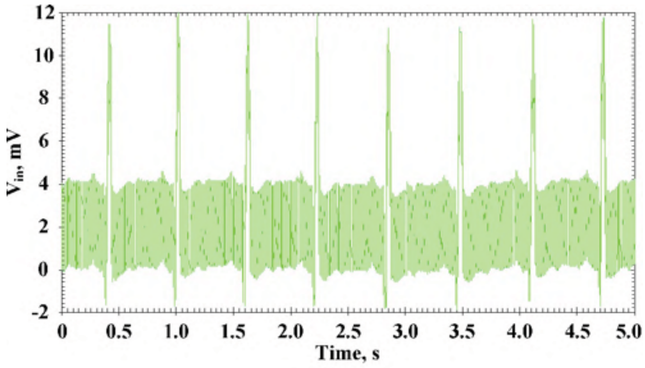


Fig. 11. The harmonic distortion of propose circuit.



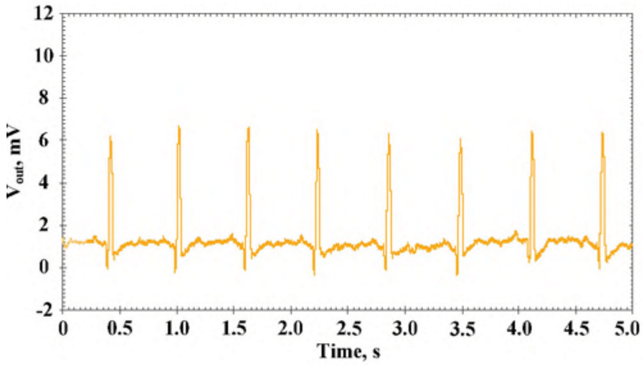


Fig. 12. Transient response of fifth–order Butterworth low-pass filter for ECG signal: (a) input, (b) output.

The linearity of the filter can be tested by applying the input signal frequency of 10 Hz. The total harmonic distortion (THD) was expressed in Fig. 11. The THD is 1 % when input amplitude reached as 110 mV (peak-to-peak). From our simulation, for integrated in-band noise between 0.1 Hz to 250 Hz, the output referred noise was 66 μV_{rms}. Therefore, dynamic range of the proposed filter was 61.4 dB (V_{in}=77.78 mV_{rms}).

Fig. 12 shows the performance of the proposed filter in processing the ECG signal where Fig. 12 (a) shows the ECG signal with a distortion signal of 1 mV/400 Hz that was applied at the input of the filter. Fig. 12 (b) expresses the filtered output signal. It was evident that a distortion signal of 1 mV/400 Hz has been removed which confirms that this filter can be applied to ECG acquisition system.

IV. Conclusion

This paper proposes a new fifth-order Butterworth LPF filter using the MIBD–QFG OTA for ECG signal acquisition application. The MIBD–QFG OTA structure has been implemented in the standard 0.18 µm CMOS process from TSMC which operates with a supply voltage of 0.5 V. The simulation results show that the filter has a bandwidth of 250 Hz, a power consumption of 41 nW, a dynamic range of 61 dB. The proposed filter structure can be reduced the number of OTA using multiple–input OTA.

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