Methodology Article

Designing an Inverter-based Operational Transconductance Amplifier-capacitor Filter with Low Power Consumption for Biomedical Applications

Abstract

The operational transconductance amplifier-capacitor (OTA-C) filter is one of the best structures for implementing continuous-time filters. It is particularly important to design a universal OTA-C filter capable of generating the desired filter response via a single structure, thus reducing the filter circuit power consumption as well as noise and the occupied space on the electronic chip. In this study, an inverter-based universal OTA-C filter with very low power consumption and acceptable noise was designed with applications in bioelectric and biomedical equipment for recording biomedical signals. The very low power consumption of the proposed filter was achieved through introducing bias in subthreshold MOSFET transistors. The proposed filter is also capable of simultaneously receiving favorable low-, band-, and high-pass filter responses. The performance of the proposed filter was simulated and analyzed via HSPICE software (level 49) and 180 nm complementary metal-oxide-semiconductor technology. The rate of power consumption and noise obtained from simulations are 7.1 nW and 10.18 nA, respectively, so this filter has reduced noise as well as power consumption. The proposed universal OTA-C filter was designed based on the minimum number of transconductance blocks and an inverter circuit by three transconductance blocks (OTA).

Keywords: *Biomedical signals, inverter circuit, low power consumption, operational transconductance amplifier-capacitor filter, subthreshold activation*

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Introduction

Due to their numerous advantages (including wide frequency range, easy functioning in combination with operational transconductance amplifier (OTA) transconductance blocks, integrated circuit implementation, and electronic adjustability), OTA-capacitor (OTA-C) filters are among the best realizations of continuous-time filters. An OTA-C filter comprises two basic parts: the OTA block and the capacitor. Different OTA-C filters can be obtained from different combinations of OTA (as the transconductance block) and C (as the capacitor).

Due to its wide frequency range, OTA-C filters have found different applications in portable medical equipment in the field of recording vital biosignals, maritime telecommunications systems, and wireless applications including mobile and Bluetooth receivers. A number of continuous-time OTA-C filters were reported in a study by Mahmoud *et al*., Casson and Rodriguez, Yang *et al*., Kumngern *et al*., and Shuenn-Yuh Lee and Chih-Jen Cheng.[1-5] As the universal filters[6-9] can use a single structure to implement/realize all the desired filter states/responses, they have attracted the attention of analog-integrated circuit designers. Designing high-performance analog-integrated circuit chips with minimum power consumption has long been a major concern to electronic circuit designers. Power consumption in systems designed for biomedical engineering applications is particularly challenging. For this reason, researchers constantly endeavor to propose solutions to reduce power consumption. The idea of subthreshold activation in integrated circuits is one such solution.[12-14]

Use of transconductance inverter-based OTA-C filters was proposed by Barthélemy *et al*., Lo and Hungm, and Pirmohammadi and Zarifi.[10-12] Such filters are used to realize circuit simplification. The transconductance inverter block comprises P-type metal-oxide-semiconductor and

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N-type metal-oxide-semiconductor transistors which lead to reduction of both the effective chip area occupied by transistors and power consumption.

The transconductance inverter-based OTA-C filters reported in studies by Barthélemy *et al*.[10] and Pirmohammadi and Zarifi[12] have two problems: (1) They realize only one low-pass frequency response and (2) they use an inverter structure with 64 and 128 transistors. In addition, the filters introduced in studies by Bhaskar *et al*. and Chang and Pai[15,16] also have too many transistors in their inverter-based transconductance blocks. The third-order OTA-C filter proposed in this study has the following advantages:

1. Using a single structure to receive all the standard filter responses, that is, low-, band-, and high-pass responses
2. Simultaneous reception of the filter responses at the output
3. Low sensitivity of the central frequency and quality factor (Q) to circuit transconductors and capacitors
4. Nonuse of passive elements in the design of the filter structure
5. The inverter-based filter is so designed that it occupies the least space possible on the electronic chip and has reduced power consumption
6. The proposed filter can be used in medical applications and bioelectric systems
7. The subthreshold MOSFET activation technique was used to reduce the effective power consumption in the proposed filter.

The article arrangement is as follows: Section 2 presents the proposed filter circuit and the required complementary explanations; Section 3 addresses the effect of noise in the proposed filter; in Section 4, the HSPICE simulation results are presented for the proposed filter; Section 5 compares the performance of the proposed filter circuit with those obtained from previous studies; and Section 6 presents a summary of the discussed topics as well as the conclusion.

Topology of the proposed circuit

To realize circuit simplification, an inverter-based OTA structure was used in implementing the proposed universal third-order OTA-C filter. Use of inverters is not limited to digital integrated circuits and inverters. Due to their realizing circuit simplification, inverters can also be used for designing analog complementary metal-oxide-semiconductor (CMOS)-integrated circuits. Figure 1 shows the three general symbols used to represent inverters, with Figure 1a showing a particular type of inverter, Figure 1b showing a more common representation, and Figure 1c showing a transconductance inverter.

Due to the significant reduction of power consumption in the proposed third-order OTA-C filter, the inverter structure in Figure 2 must be biased in the subthreshold region where the following relation exists between transistor current and voltage:

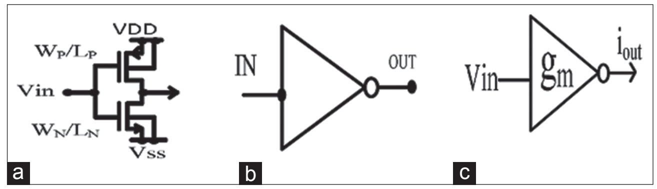

Figure 1: The different symbols used for inverters : a) showing a particular type of inverter; b) a more common representation and c) transconductance inverter

$$I \oplus S := \{z | (S)_z \bigcap I \neq \varnothing\} \quad (1)$$

In the above relation, W and L are the width and length of the MOSFET channels, respectively, I_0 is the specific current (which is dependent on the manufacturing process), is the subthreshold slope factor (which can be assumed to remain constant in the low-inversion region), and V_T is the thermal voltage.

For V_{ds} >4V_T, the transistor current is almost independent of V_{ds}, and the subthreshold transconductance (gm) can be expressed as follows:

$$gm = \frac{\partial I_D}{\partial V_{gs}} = \frac{I_D}{\eta V_T} \quad (2)$$

The subthreshold inverter transconductance is in turn obtained from the following relation:

$$gm = \left(\frac{1}{\eta V_T}\right) I_{D\,sub_n} + \left(\frac{1}{\eta V_T}\right) I_{D\,sub_P} \quad (3)$$

Note that there are only eight inverters (16 MOSFETs) in the inverter structure used for implementing the proposed universal OTA-C filter. This particular inverter structure was proposed to reduce the space occupied (by transistors) in the chip as well as power consumption in the filter. Figure 3 shows the proposed universal OTA-C filter.

The single-input multiple-output structure (SIMO) current mode was used in the proposed OTA-C filter. The SIMO filter structure was intended for realizing simultaneous receiving of the desired filter responses at the output. This simultaneity is considered an important characteristic of an optimal OTA-C filter design. Advantages of the proposed filter include low sensitivity (due to the filter being active), universal usability, and applicability in biomedical equipment. The following relations and transform functions were obtained upon analyzing the proposed current-mode OTA-C filter circuit in the low-, band-, and high-pass filter modes as given below:

$$\frac{I_{HP}}{I_{in}} = -\frac{S^3 C_1 C_2 C_3 gm_2 gm_3}{D(s)} \quad (4)$$

$$\frac{I_{LP}}{I_{in}} = -\frac{gm_1 gm_2 gm_3}{D(s)} \quad (5)$$

$$\frac{I_{BP}}{I_{in}} = -\frac{S C_2 gm_1 gm_2}{D(s)} \quad (6)$$

$$D(s) = S^3C_1C_2C_3gm_3 + S^2C_1C_2gm_3gm_2 + SC_2gm_1gm_2 + gm_1gm_2gm_3 \quad (7)$$

These relations show that the proposed filter is capable of generating the standard filter responses in all the three low-, band-, and high-pass modes.

Effects of noise

Examining the effect of noise on the structure of the proposed filter is of particular importance. To study the filter performance under each filter mode, noise frequencies at different responses were duly examined. In other words, the sources of noise were analyzed as input signals in the filter circuit. Figure 4 shows the circuit model used for noise analysis under low-, band-, and high-pass filter conditions.

The noise density for each noise source is obtained from Eqs. 8-10 as follows:

$$\overline{I^2_{HP}} = \overline{I^2_{n1}}\left(\frac{S^3C_1C_2gm_1gm_3}{D(s)}\right)^2 + \overline{I^2_{n2}}\left(\frac{S^3C_1C_2gm_1gm_3}{D(s)}\right)^2 + \overline{I^2_{n3}}\left(\frac{S^3C_1C_2gm_1}{D(s)}\right)^2 + \overline{I^2_{n4}}\left(\frac{SC_2gm_2gm_3}{D(s)}\right)^2 \quad (8)$$

$$\overline{I^2_{BP}} = \overline{I^2_{n1}}\left(\frac{S^2C_1C_2gm_1gm_3}{SC_3gm_3D(s)}\right)^2 + \overline{I^2_{n2}}\left(\frac{S^2C_1C_2gm_1gm_2}{SC_3gm_3D(s)}\right)^2 + \overline{I^2_{n3}}\left(\frac{gm_1gm_2}{gm_3D(s)}\right)^2 + \overline{I^2_{n4}}\left(\frac{gm_1gm_2}{gm_3D(s)}\right)^2 \quad (9)$$

$$\overline{I^2_{LP}} = \overline{I^2_{n1}}\left(\frac{gm_1gm_2}{D(s)}\right)^2 + \overline{I^2_{n2}}\left(\frac{gm_1gm_2}{D(s)}\right)^2 + \overline{I^2_{n3}}\left(\frac{gm_3}{D(s)}\right)^2 + \overline{I^2_{n4}}\left(\frac{gm_2}{D(s)}\right)^2 \quad (10)$$

Simulation

The proposed universal OTA-C filter was simulated via HSPICE in 180 nm CMOS technology. The simulation results obtained for the subthreshold region in the biased inverter circuit of the proposed filter are summarized in Table 1. Due to the transistor threshold voltage (Vth = ±0.45V)and the supply voltage (0.3 V) used, the inverter block was biased in the subthreshold region. Subthreshold performance/activation caused an effective and significant reduction in the power consumption of the proposed OTA-C filter. This reduced power consumption makes the proposed filter particularly suitable for portable medical and bioelectric equipment used for recording vital biosignals, and is an important advantage of this filter. The inverter circuit in Figure 2 was also subjected to the important fast Fourier transform analysis. To this end, a 5 MHz sinusoidal signal with a peak-to-peak amplitude of 180 mV was applied to the OTA circuit input. The analysis

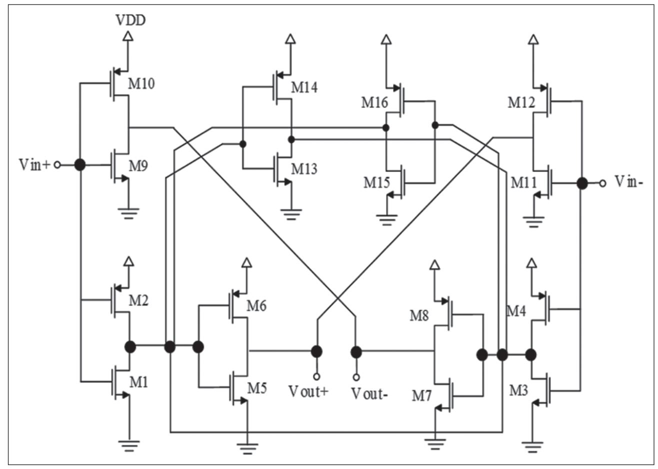

Figure 2: The inverter-based transconductance circuit used in the operational transconductance amplifier-capacitor filter

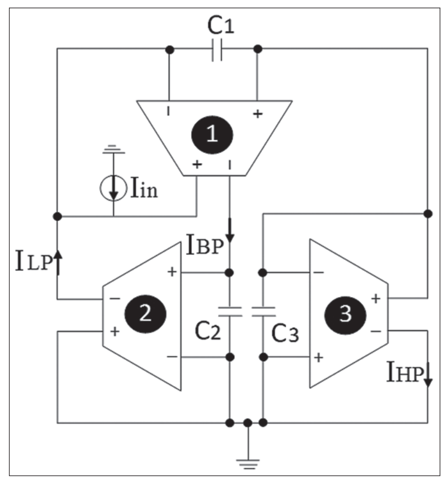

Figure 3: The proposed third-order universal operational transconductance amplifier-capacitor filter

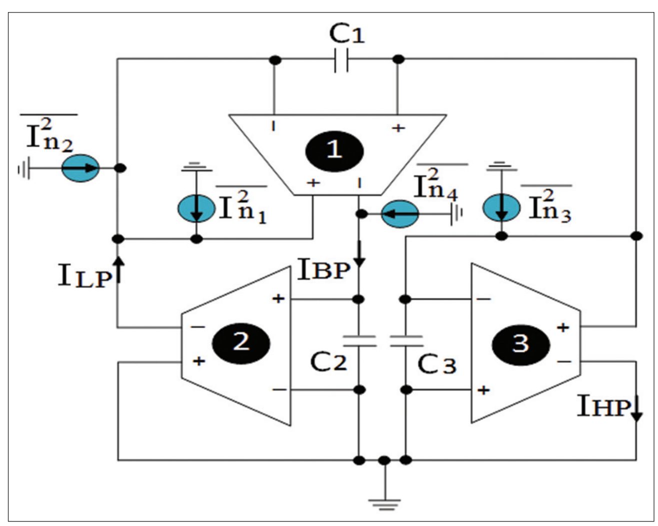

Figure 4: Circuit model used to study noise in the proposed third-order current-mode universal operational transconductance amplifier-capacitor filter

results are shown in Figure 5. As can be observed in this figure, the second (HD2) and third (HD3) harmonics were obtained as −38.95 dB and −57.65 dB, respectively. In addition, the total sum of the circuit harmonics was obtained as 0.93%. A summary of the analysis results obtained from the OTA circuit is presented in Table 1.

Furthermore to study more closely the inverter circuit in Figure 2, the AC analyses for obtaining common mode rejection ratio (CMRR) and power supply rejection ratio (PSRR) were conducted. As shown in Figure 6, the CMRR magnitude obtained for the desired inverter circuit was 52.2 dB and in Figure 7, you can see the PSRR magnitude obtained for the inverter-based OTA circuit was 49.6 dB.

The simulation results for the inverter circuit shown in Figure 2 are presented in Table 1.

The following is a description of the simulation results obtained for the proposed universal OTA-C filter. Figure 8 shows the frequency response obtained for this current-mode filter. The simulation results show that a transconductance gain of 1.25 nS was obtained for the proposed filter with 1pF load capacitors. Conductance values of gm1 = gm2 = gm3 = 1.25 nS were obtained for the filter circuit. The circuit quality factor was obtained as Q = 1. According to the simulation results, the proposed filter is suitable for medical applications since it can operate within the frequency range used for medical systems and has very low power consumption as well as favorable input noise characteristics. Under the mentioned operating conditions, the proposed filter circuit consumes only 7.1 nW of power.

Figure 8 shows that the proposed filter can realize the standard low-, band-, and high-pass filter responses in the subthreshold region. For a closer examination of this, the frequency responses of the proposed OTA-C filter are presented separately below. The diagrams in Figure 11 show the low-, band-, and high-pass frequency responses for the proposed filter. As shown in Figure 9, the proposed universal OTA-C filter can pass frequencies below 236.9 Hz in the low-pass state. For this reason, this filter can be used in medical equipment for recording vital EEG and ECG biosignals.

Figure 10 shows the band-pass frequency response for the proposed filter. As can be observed, the low and high cutoff frequencies obtained for the proposed filter in this state are 114.59 Hz and 331.96 Hz, respectively. At these frequencies, the output signal amplitude reached −3 dB. Therefore, in the band-pass range, the proposed filter passes input signals with frequencies between 114.59 Hz and 331.96 Hz while weakening the input signals with different frequencies.

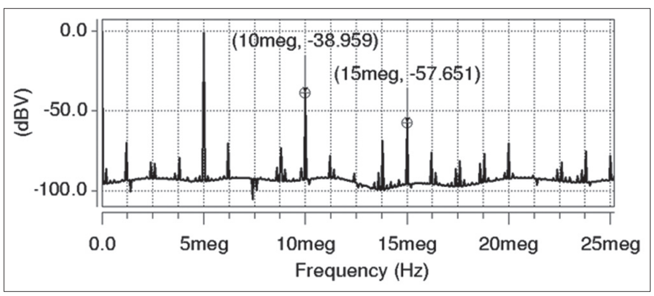

Figure 5: The fast Fourier transform results for the inverter-based operational transconductance amplifier circuit

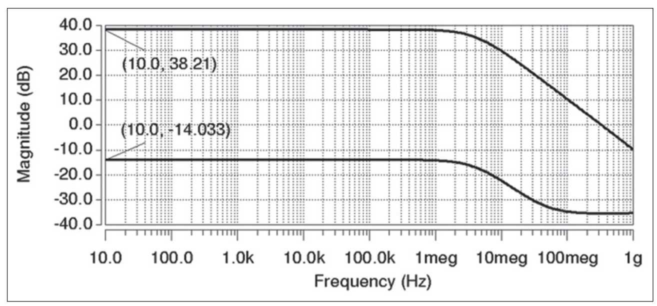

Figure 6: Common-mode rejection ratio obtained for the inverter-based circuit

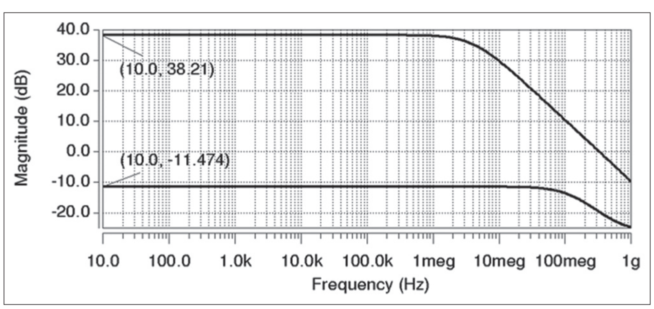

Figure 7: Power supply rejection ratio obtained for the inverter-based operational transconductance amplifier circuit

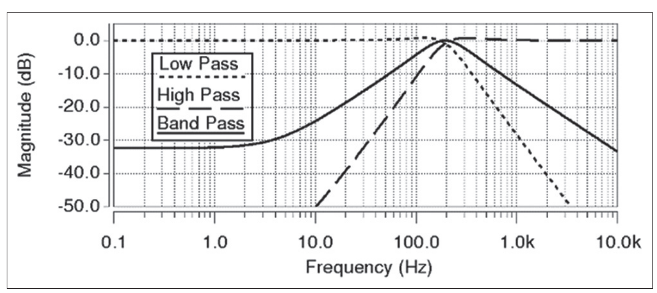

Figure 8: The frequency response obtained for the proposed filter

Table 1: Comparison of the proposed filter performances and other references

Supply voltage	Power consumption	DC gain	PSRR	CMRR	Phase margin	Bandwidth gain	Input noise	HD2	HD3	THD
0.6 V	2.72 nw	38.2 dB	49.6 dB	52.2 dB	76°	329.2 MHz	5.15 $\mu V/\sqrt{HZ}$	−38.9 dB	−57.6 dB	0.93%

CMRR – Common mode rejection ratio; PSRR – Power supply rejection ratio; THD – Total harmonic distortion

Figure 11 shows the high-pass frequency response for the proposed filter. As can be observed in this figure, the cutoff frequency in the high-pass state is 160.55 Hz, at which the output signal amplitude can reach −3 dB. Therefore, the proposed filter can pass input signals with frequencies >160.55 Hz in the high-pass mode and at the same time, weaken the input signals with other frequencies.

Figure 12 compares the theoretical simulation results obtained from MATLAB and HSPICE for filter response at low-, band-, and high-pass states. As observed in Figure 12, the simulation and theoretical results are greatly similar.

Due to impure doping and natural factors such as different moisture contents during the chip manufacturing process, differences (within the acceptable range) might be introduced in transistor channel length (L) and width (W), as well as transistor threshold voltage. Such nonconformities would in turn lead to changes in the performance of the chip as a whole. The Monte Carlo method was used to analyze the effect of these nonconformities on filter performance. This analysis was conducted under the following conditions: Gaussian distribution for variations of transistor channel length and width, 2% variation in the MOSFET threshold voltage (at a standard deviation of 3), and thirty random selections. The results of the Monte Carlo analysis for the proposed filter in the current mode are shown in Figure 13. As can be observed in this figure, the proposed filter operates properly in spite of the existing nonconformities in transistor arrangement and manufacturing.

As can be observed in Figure 13, the W, L, and V_{th} variations affect the proposed filter behavior only slightly. This shows that the proposed universal OTA-C filter would perform properly within the subthreshold region.

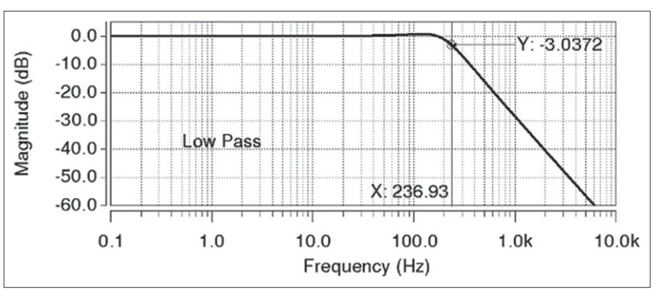

Figure 9: Frequency response for the proposed filter in the low-pass state

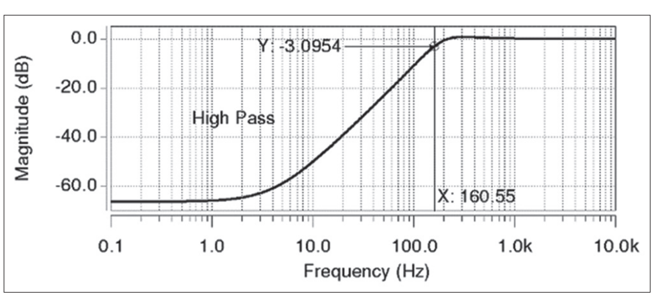

Figure 11: Frequency response for the proposed filter in the high-pass mode

In addition, as the input noise limits the minimum amplitude of the input signal, the noise analysis was conducted on the proposed filter. The necessary HSPICE simulations were conducted at the filter input under different conditions including the low-, band-, and high-pass states. The simulation results are summarized in Table 2. The corresponding noise levels were duly calculated for the filter response at specific frequencies and a bandwidth of 1 Hz.

Comparison with other studies

In this section, the performance of the proposed universal OTA-C filter is compared with that reported in other studies. Important results of proposed OTA-C filter in this study and other research, which investigated the parameters such as power consumption, frequency, filter type, noise, and THD (total harmonic distortion), are presented in Table 3 for comparison. According to the table3, a significant reduction in power consumption (as compared with previous studies) in the proposed filter is of particular importance. The double significance of this reduced power consumption is due to the fact that the proposed filter not only is capable of simultaneously receiving standard

Table 2: The noise referred to the proposed operational transconductance amplifier-capacitor filter inputs

Filter state	Input signal frequency	Noise referred to the input
LP	100 Hz	8.41 $nA/\sqrt{HZ}$
BP	200 Hz	9.26 $nA/\sqrt{HZ}$
HP	5 KHz	10.18 $nA/\sqrt{HZ}$

LP – Lowpass; BP – Bandpass; HP – Highpass

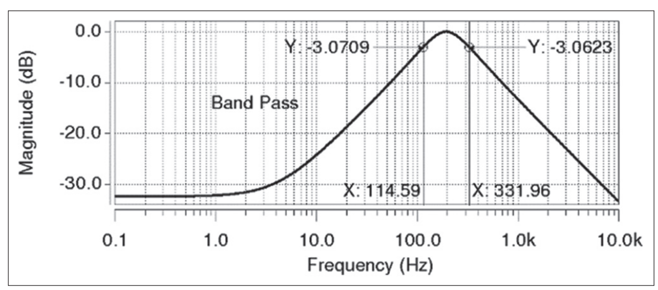

Figure 10: Frequency response obtained for the proposed filter in the band-pass state

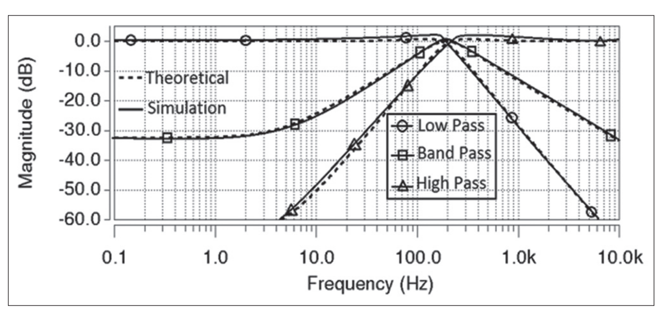

Figure 12: Comparison between theoretical and simulation results obtained for the proposed filter

Table 3: Comparison of the proposed filter with those proposed in other studies

Parameter	[1]	[12]	[13]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	Proposed filter
Year	2013	2012	2012	2013	2009	2012	2008	2010	2014	2016	2013	2016
Technologies	0.25 µm	0.35 µm	0.18 µm	0.5 µm	0.35 µm	0.18µm	0.5 µm	0.18 µm	0.18 µm	0.18 µm	0.35 µm	0.18 µm
Supply voltage	±0.8 V	3.3 V	1 V	±1.5 V	±1.65 V	0.5 V	3.3 V	1 V	0.5 V	1 V	1V	0.3 V
Power consumption	30 µW	445 nW	245 nw	5 mW	30.95 mW	2.6nW	1.32 µW	14.4 nW	2 nW	6 nW	15 nW	7.1 nW
Frequency	243 Hz	10 kHz	150 Hz	1.2 KHz	1 MHz	4 KHz	1.18 KHz	732 KHz	1 KHz	945 Hz	100 Hz	200 Hz
Filter	LP	LP BP	BP	LP	LP BP HP BS AP	BP	BP	BP	BP	BP	LP	LP BP HP
Noise	120 µV	113 nV	-	270 nV	-	-	2.2 mV	50 µV	78 µV	174.2 µV	36 µV	10.18 nA
THD	1%	1%	1.10%	0.17%	-	1.1%	4%	1%	1%	1%	1%	1%

LP – Lowpass; BP – Bandpass; HP – Highpass; BS – Bandstop; AP – Allpass; THD – Total harmonic distortion

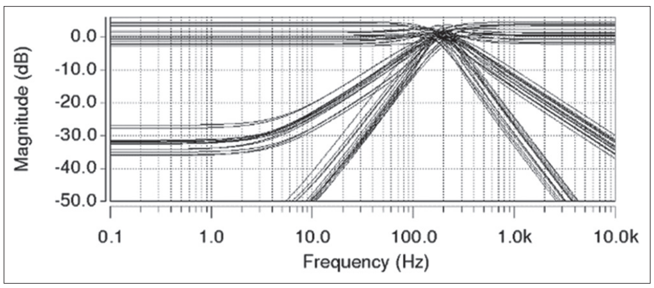

Figure 13: Monte Carlo analysis results obtained for the frequency responses of the proposed filter

filter responses at its output, but also has the additional advantage of serving as a universal standard response filter. The low power consumption reported in certain studies is due to the fact that the respective filters are not universal.

Conclusion

A universal third-order OTA-C filter with the following characteristics was proposed and developed: very low power consumption, simultaneous receiving of all filter responses (low-, band-, and high-pass), and suitable applications in portable medical and bioelectric equipment. In addition to its low power consumption, the proposed filter successfully realized all the standard filter responses with great accuracy. The proposed filter can find numerous applications in the systems used for recording vital biosignals due to its characteristic of correctly obtaining the vital biosignals as well as its low total harmonic distortion value. The nonuse of passive elements in the proposed filter makes it possible to easily use it as a component in CMOS technology-integrated circuits. Moreover, as already mentioned, the low power supply voltage of this filter makes it a suitable option in portable medical and bioelectric applications such as vital biosignals recording systems. The significant power reduction in the proposed OTA filter is due to its inverter-based structure (wherein the least possible number of transistors is used) as well as the subthreshold transistor biasing. Other advantages of the proposed filter are its low central frequency and high-quality factor as compared with other transconductors and capacitors as well as its acceptable noise level. The power consumption measured for the proposed filter was 7.1 nW which makes it particularly suitable for application in the field of biomedical engineering.

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Conflicts of Interest

There are no conflicts of interest.

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