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The Realization of Current-Mode Electronically Tunable Square-Root Domain Low-pass Filter Based on CMOS Technology for Biomedical Applications

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Abstract

In this study, a second-order low-pass filter with low-power and voltage, current mode and square-root domain was designed for biomedical implementations at low frequencies using the state-space-synthesis method. The filter, which is activated at 3V supply voltage, is formed using current mirrors, current-mode square-root circuits, and grounded capacitors. To indicate the performance of the filter, some simulations are carried out using process parameters of TSMC 0.25µm CMOS in the program of ORCAD Capture CIS. The results of these simulations show that the center frequency of low-pass filter can be tuned electronically between the range of 1 kHz and 120 kHz and that there appears to be a 0.5% total harmonic distortion. The proposed circuit has some advantages, such as activating at low-frequency operation, low power supply, tunability, and low total harmonic distortion.

Keywords: Biomedical, Companding, Current-mode, Low-frequency, Low-pass, Square-root-domain

1. Introduction

Logarithmic-domain and square-root domain circuits are companding circuits that are classified under Externally-Linear-Internally-Nonlinear (ELIN) circuits. Logarithmic-domain circuits rely on a nonlinear relation between the base-emitter-voltage and collector-current of Bipolar Junction Transistors (BJT), and thus they have a translinear characteristic. First introduced by Adams in 1979, the low-pass filter is the nonlinear transformation, which is over state variables of state-space definition of direct transfer functions [1]. Seevinck proposed a trans-linear integrator, a special type of logarithmic-domain circuit, in 1990 [2]. Frey introduced a complete theory of logarithmic-domain circuits in 1993 [3]. In 1994, Toumazou et al. presented logarithmic-domain filters which contained Metal Oxide Semiconductor Field-Effect Transistors (MOSFET, MOS Transistor) operating in weak inversion regions [4]. The most important disadvantage of these circuits is that their operating frequencies are limited, which leads to disharmony in transistors. Therefore, in 1996, Eskiyerli et al. designed the filters and integrators using MOS transistors, which operate in the saturation region [5]. These circuits rely on the translinear characteristic of the MOS transistor and its square relation between drain-current and gate-source voltage. For this reason, they are called square-root domain circuits [6]-[19].

Today, the increase in living standards and the need for low-cost but more practical sanitary applications determine the rate of progress of biomedical systems. For some biomedical devices, portability and compact design are the essential targets for design. Thus, filters which have a wide dynamic range in low-voltage supply, provide linearity and low power consumption, have frequency characteristics that can be electronically tunable, and need smaller chip area are of great importance to biomedical devices.

When it is considered that the real world is analog, but signal processing is getting more digital day by day, it is seen that analog front ends are necessary to receive analog signals and process them properly in digital processing steps. The developments in techniques to get physiological signals determine the need to design smaller and ultra-low-power circuits for portable biomedical devices. New circuit designs are needed for low-powered, portable, smaller and more accurate signal acquisition systems. Since biomedical signals such as electromyogram (EMG), electrocardiogram (ECG) and electroencephalogram (EEG) are of low voltage and low frequency, unwanted signals may occur during their reception. For removing that noise from a biopotential signal, some filtering operations are held depending on the features of the signal. The general blog of analog front end in a biomedical signal acquisition system comprises an instrumentation amplifier, a high-pass filter to remove baseline wander, a band reject filter (50/60 Hz) to remove power line interferences, a low-pass filter to remove undesired signals and an Analog-to-Digital Converter (ADC).

Some biomedical implementations of low-pass filters have been found in the literature [20]-[25]. In [20], a low-power CMOS second-order low-pass filter was proposed and simulated for biomedical applications such as ECG and EEG. The design employs low-power, low-transconductance OTAs as core building blocks, and the filter's cut-off frequency can be tuned via a control voltage. [21] presents the design of a CMOS-based 4th-order low-pass filter for biomedical applications. The filter is formed by cascading 2nd-order P-FVF and N-FVF biquads, operating in the sub-threshold region. Implemented in 90nm CMOS technology using Cadence, the design achieves a cut-off frequency of 114.4 Hz. In [23], a digitally controlled low-pass filter is presented in accordance with the efficiency and flexibility features that are important for electronic devices. The proposed Gm-C filter is designed for biomedical implementations. A Butterworth Gm-C low-pass filter for the front ends of biomedical signal processing is proposed in [24]. A low-pass OTA-C filter suitable for biomedical signal acquisition systems is presented in [25]. Also, there are some studies on square-root domain design for biomedical engineering in the literature [26], [27]. These studies suggest square-root domain low-pass [26] and band pass filters [27] with low voltage/power that can operate at high frequencies.

In this study, via the state-space-synthesis method, a second-order low-pass filter, low power/voltage, current mode, and can operate at low frequencies, was designed to remove undesired signals at the analog front end of a biomedical signal acquisition system. The novelty of this study lies in the design of a current-mode, second-order low-pass filter based on state-space synthesis in the square-root domain. Featuring CMOS-only implementation with grounded capacitors, the filter offers electronically tunable cut-off frequency, low THD, and wide dynamic range. Its low-voltage, low-power operation and use of MOSFETs in the saturation region make it highly suitable for power-efficient biomedical applications.

The outline of the article is as follows: square-root circuits are presented in Section 2.1. Section 2.2 includes the design of a second-order low-pass filter in the square-root domain. The results of the simulation are given in Section 3, and the conclusions are given in Section 4.

2. Materials and Methods

2.1. Square-Root Domain Basic Blocks

Square-root domain basic blocks rely on the second-order relation between drain-current and gate-source voltage of the MOS transistor, which operates at the saturation region of square-root domains. They also rely on the translinear characteristics of the MOS transistor. In the positive current mirror, seen in Figure 1, transistors M1 and M2 operate in the saturation region. Thus, the drain current is as seen in Equation 1.a and 1.b.

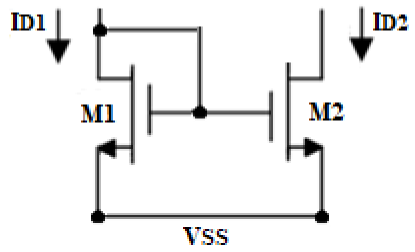

Figure 1. Positive current mirror [28]

$$I_{D1} = \frac{\beta_1}{2}(V_{GS1} - V_{TH})^2 \tag{1.a}$$

$$I_{D2} = \frac{\beta_2}{2}(V_{GS2} - V_{TH})^2 \tag{1.b}$$

In Equation 1.a and 1.b, V_{TH} is the threshold voltage, V_{GS1} and V_{GS2} are gate-source voltages, I_{D1} and I_{D2} are drain currents. The parameters of transconductance seen at the equations have the equation below:

$$\beta_1 = \beta_2 = \beta = \frac{\mu_0 C_{ox} W}{L} \tag{2}$$

In Equation 2, μ_0 is the mobility, C_{ox} is oxide capacity per unit area, W is the MOS transistor channel width, and L is the MOS transistor channel length.

$$\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \frac{(V_{GS2} - V_{TH2})^2}{(V_{GS1} - V_{TH1})^2} \tag{3}$$

In Equation 3, if $V_{GS1} = V_{GS2}$ and $V_{TH1} = V_{TH2}$, the current sources of transistors will be as follows [29].

$$\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \tag{4}$$

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The implementation of square-root domain blocks requires two different nonlinear circuits, which are square-root and squarer/divider circuits [6]. The symbol of the square-root circuit is seen in Figure 2. A square-root circuit, also called a Geometric Mean Circuit, has two inputs and one output, and it takes the square root of the multiplication of currents. Figure 3 shows a basic geometric mean circuit used by Wiegerink in 1993 [30].

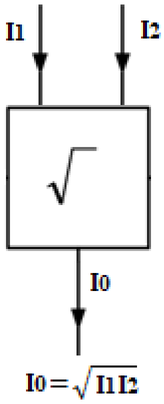

Figure 2. The symbol of geometric mean circuit [28]

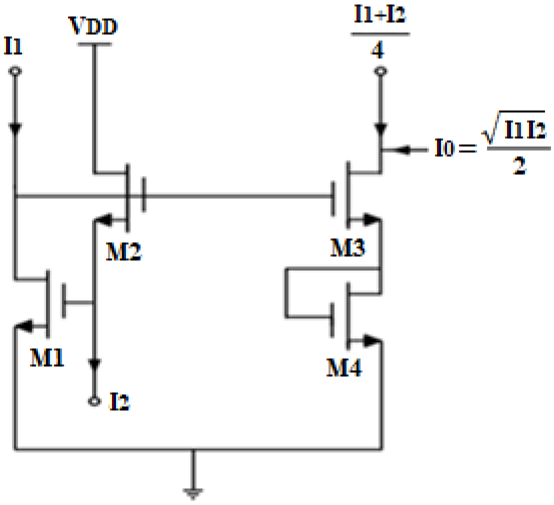

Figure 3. Basic geometric mean circuit [28]

If all the transistors seen in Figure 3 are equal and if their transconductance parameters and threshold voltage are accepted as equal, then the relation among the currents will be as in Equation 5.

$$\sqrt{I_{D1}} + \sqrt{I_{D2}} = \sqrt{I_{D3}} + \sqrt{I_{D4}} \tag{5}$$

If drain currents of transistors are put to the relevant places in equation, then Equation 6 is acquired.

$$\sqrt{I_1} + \sqrt{I_2} = 2\sqrt{\frac{I_1 + I_2}{4} + I_0} \tag{6}$$

When all necessary mathematical operations are done, output current becomes as in Equation 7.

$$I_0 = \frac{\sqrt{I_1 I_2}}{2} \tag{7}$$

If the transconductance parameters of the transistors M3 and M4 double those of transistors M1 and M2, and if the drain current of transistor M3 is $I_0 + \frac{I_1 + I_2}{2}$, then the process steps to obtain the output current are as follows:

$$\beta_1 = \beta_2 = \beta \tag{8}$$

$$\beta_3 = \beta_4 = 2\beta \tag{9}$$

$$(\sqrt{2I_1} + \sqrt{2I_2}) = 2\sqrt{\frac{I_1 + I_2}{2} + I_0} \tag{10}$$

In this case, the output current is as in Equation 11.

$$I_0 = \sqrt{I_1 I_2} \tag{11}$$

Two sub-circuits are used to obtain designed filter circuit. The first sub-circuit includes square-root circuit whereas the second one involves square-root circuit and squarer/divider circuits [6]. The square-root circuit and squarer/divider circuit used in this study are seen in Figure 4 and 5 [8], [9]. The block diagram of second sub-circuit is given in Figure 6. The current-mode squarer/divider circuit is acquired in line with [9].

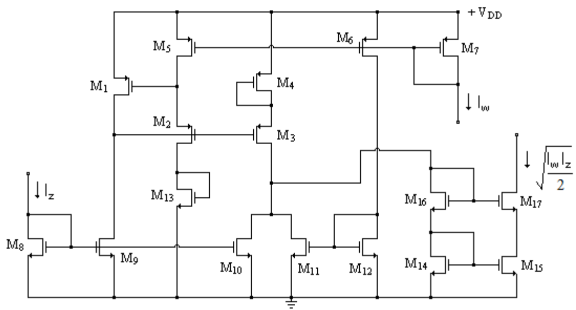

Figure 4. Square-root circuit

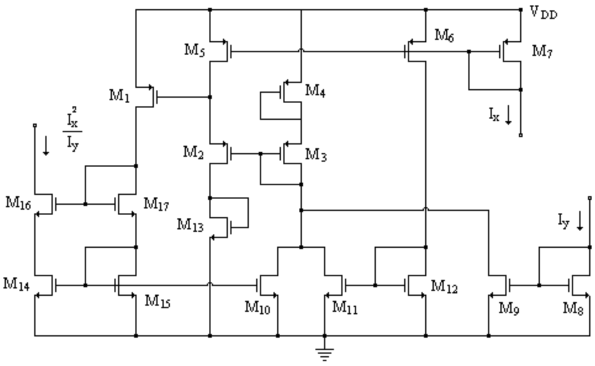

Figure 5. Squarer/divider circuit

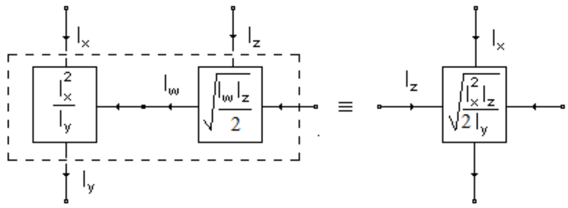

Figure 6. Second sub-circuit

2.2. The Design of Square-root Domain Second-order Low-pass Filter

In this study, a square-root domain second-order low-pass filter with current mode is designed with a method of state-space-synthesis. The second-order low-pass filter's transfer function corresponds as below:

$$H(s) = \frac{\omega_0{}^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0{}^2} \tag{12}$$

In the equation, ω_0 is center frequency while Q means quality factor. The space-state equations of second-order low-pass filter are stated below:

$$\dot{x}_1 = -\omega_0 Q x_2 + \omega_0 Q u \tag{13}$$

$$\dot{x}_2 = \frac{\omega_0}{Q}x_1 - \frac{\omega_0}{Q}x_2 \tag{14}$$

Output equation is acquired as

$$y = x_2 \tag{15}$$

In the equations, u symbolizes the input whereas y is the output. Moreover, x_1 and x_2 represent state-variables. Equations 13 and 14 can be converted to sets of node equations by using square transformations of input and state-variables. Thus, the following transformations can be applied to the quantities in equations:

$$x_1 = \frac{\beta}{2}(V_1 - V_{TH})^2 \tag{16.a}$$

$$x_2 = \frac{\beta}{2}(V_2 - V_{TH})^2 \tag{16.b}$$

If the derivations of saturation equations are taken, then Equations 17.a and 17.b are acquired.

$$\dot{x}_1 = \beta\dot{V}_1(V_1 - V_{TH}) \tag{17.a}$$

$$\dot{x}_2 = \beta\dot{V}_2(V_2 - V_{TH}) \tag{17.b}$$

After the correlation above is applied to Equation 13 and 14, it is adjusted to form the node equations below:

$$C\dot{V}_1 = -\frac{\omega_0 CQ}{\sqrt{\beta}}\sqrt{\frac{x_2{}^2}{2x_1}} + \frac{\omega_0 CQ}{\sqrt{\beta}}\sqrt{\frac{u^2}{2x_1}} \tag{18}$$

$$C\dot{V}_2 = \frac{\omega_0 C}{Q\sqrt{\beta}}\sqrt{\frac{x_1{}^2}{2x_2}} - \frac{\omega_0 C}{Q\sqrt{\beta}}\sqrt{\frac{x_2{}^2}{2x_2}} \tag{19}$$

In Equation 18 and 19, C is a capacitor value, which appears as a multiplication factor. In Equation 18 and 19 $C\dot{V}_1$ and $C\dot{V}_2$ can be considered as time-dependent currents which are grounded through two capacitors.
I_0 is a positive invariant as indicated below:

$$I_0 = \frac{\omega_0{}^2 C^2}{\beta} \tag{20}$$

Equation 18 and 19 can be adjusted as below:

$$C\dot{V}_1 = -\sqrt{\frac{x_2{}^2 I_0}{2x_1}}Q + \sqrt{\frac{u^2 I_0}{2x_1}}Q \tag{21}$$

$$C\dot{V}_2 = \sqrt{\frac{x_1{}^2 I_0}{2x_2}}\frac{1}{Q} - \sqrt{\frac{x_2 I_0}{2}}\frac{1}{Q} \tag{22}$$

If the quality factor is accepted as Q=1 to facilitate the realization process, then the state equations in Equations 21 and 22 can be formed as below:

$$C\dot{V}_1 = -\sqrt{\frac{x_2{}^2 I_0}{2x_1}} + \sqrt{\frac{u^2 I_0}{2x_1}} \tag{23}$$

$$C\dot{V}_2 = \sqrt{\frac{x_1^{\,2} I_0}{2x_2}} - \sqrt{\frac{x_2 I_0}{2}} \qquad (24)$$

Output equation is acquired as

$$y = x_2 = \frac{\beta}{2}(V_2 - V_{th})^2 \qquad (25)$$

As given in Figure 7, square-root domain second-order low-pass filter circuit with current mode is formed with a square-root circuit, a sub-circuit consisting of a square-root circuit and a squarer/divider circuit, current mirrors, and two grounded capacitors by using equations (23), (24) and (25). The center frequency of low-pass filter, as seen in Equation 26, can be tuned by varying the value of current. It is observed that the center frequency changes as inversely proportional to capacitor value and directly proportional to the square-root of current.

$$\omega_0 = \frac{\sqrt{I_0 \beta}}{C} \qquad (26)$$

3. Results and Discussion

While simulating the design of square-root-domain, second-order low-pass filter with current-mode (Figure 7), TSMC 0.25 µm CMOS model transistor parameters were used. The dimensions of the transistor used in second-order low-pass filter circuit are given in Table 1.

Table 1. The transistor dimensions

Circuit	Transistör	W (µm)	L (µm)
Square-root	M_{11}	55	2
	M_1, M_{13}	60	2
	M_{10}	110	2
	M_2-M_4	120	2
	M_5-M_9, M_{12}, M_{14}-M_{17}	220	2
Squarer/divider	M_1, M_2, M_{13}	60	2
	M_{10}, M_{11}	110	2
	M_3, M_4	120	2
	M_5-M_9, M_{12}, M_{14}-M_{17}	220	2
Low-pass filter	M_1-M_4, M_6, M_7	20	20
	M_9, M_{10}, M_{14}-M_{21}	22	8

As can be seen from the equations that the center frequency of the filter is tunable. A gain-frequency variation is obtained for different center frequency values by varying the values of I_0 direct-current sources in the second-order low-pass filter circuit. When the values of I0 direct current sources in the second-order low-pass filter circuit are changed in the range of 0.5 µA-160 µA, the center frequency changes, as well, ranging from 3 kHz to 120 kHz. The gain-frequency curves acquired for different values of I_0 direct-current sources of the filter circuit are given in Figure 10.

The time domain response obtained by giving a sinusoidal signal with amplitude of 10 µA and 88 kHz to the input of the second-order low-pass filter, is shown in Figure 11. The total harmonic distortion of the output signal is measured for different current values. When a sinusoidal signal with amplitude of 10 µA and 88 kHz is applied to the input, the total harmonic distortion (THD) is measured as 0.5%.

A comparison table, including the performances and properties of the filters, has been created by incorporating relevant studies from literature and is presented in Table 2. The proposed design was implemented using the state-space synthesis method. The proposed circuit offers low-voltage and low-power operation, making it ideal for portable biomedical applications. Additionally, it features electronically tunable cut-off frequency, wide dynamic range, low THD, and a simple structure composed of only CMOS transistors and grounded capacitors.

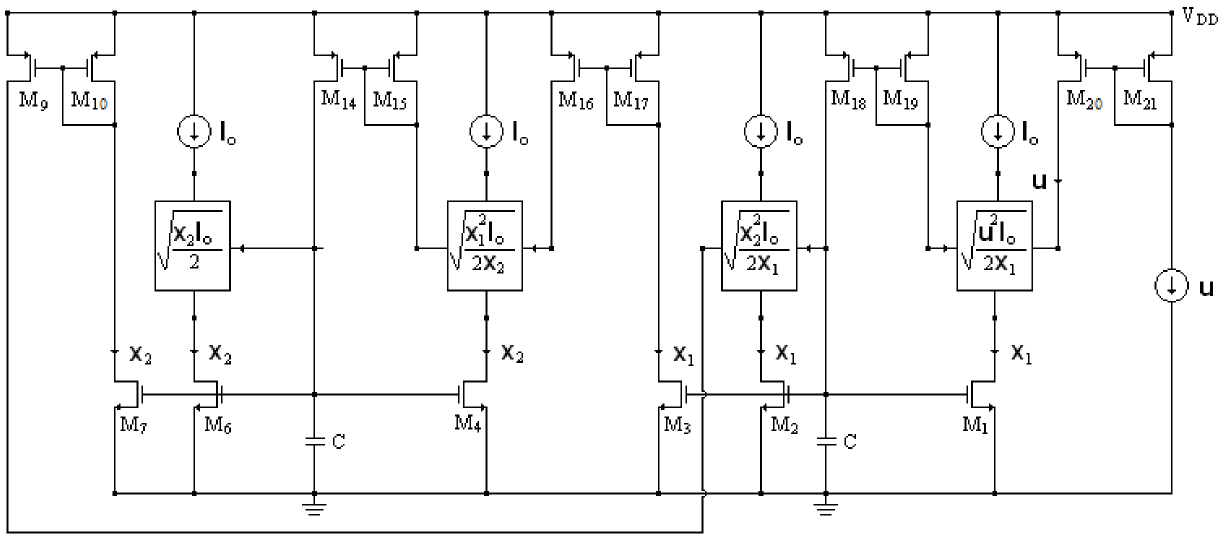

Figure 7. Square-root domain second-order low-pass filter

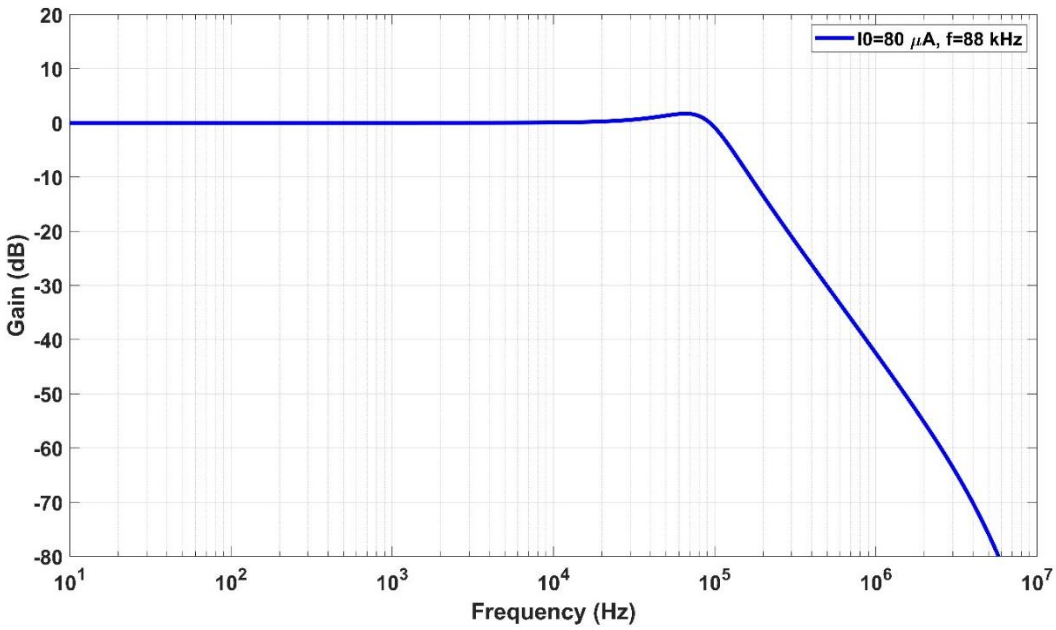

Figure 8. Gain response of second-order low-pass filter

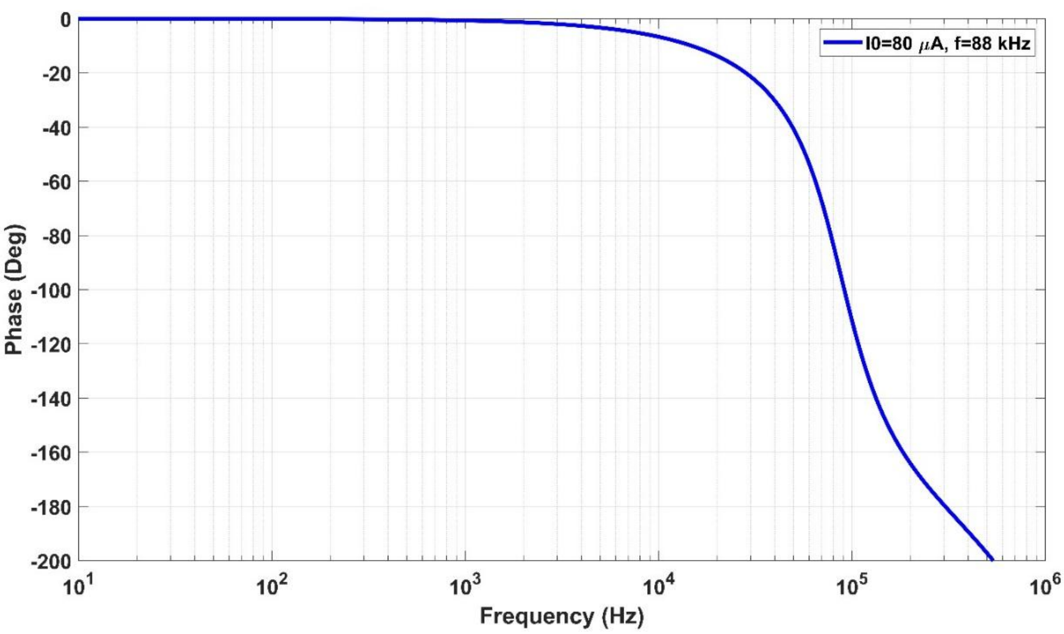

Figure 9. Phase response of second-order low-pass filter

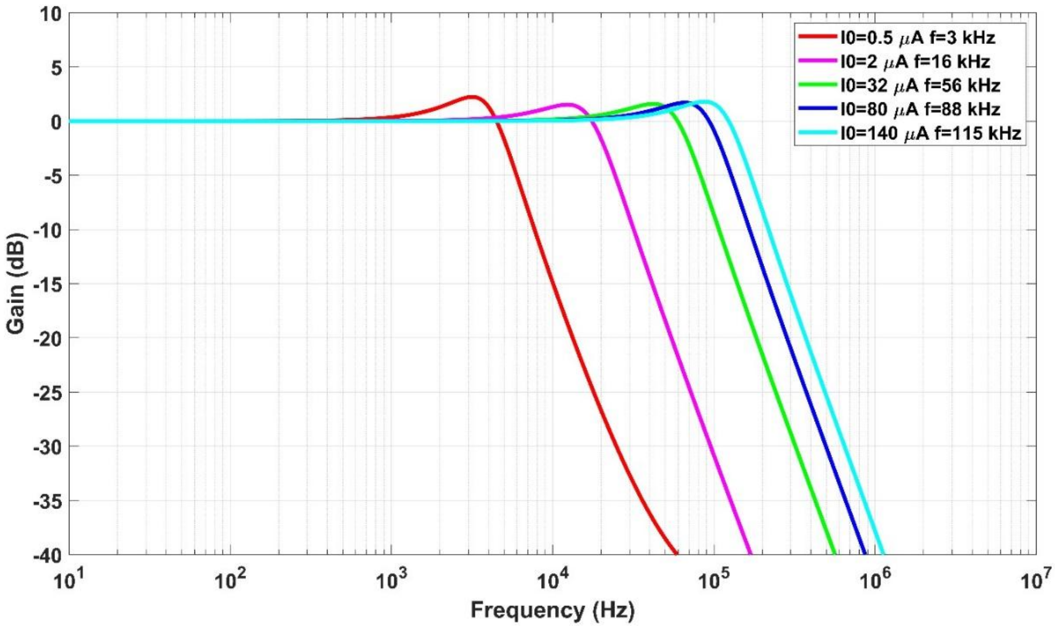

Figure 10. Gain response of for different I0 values of second-order low-pass filter

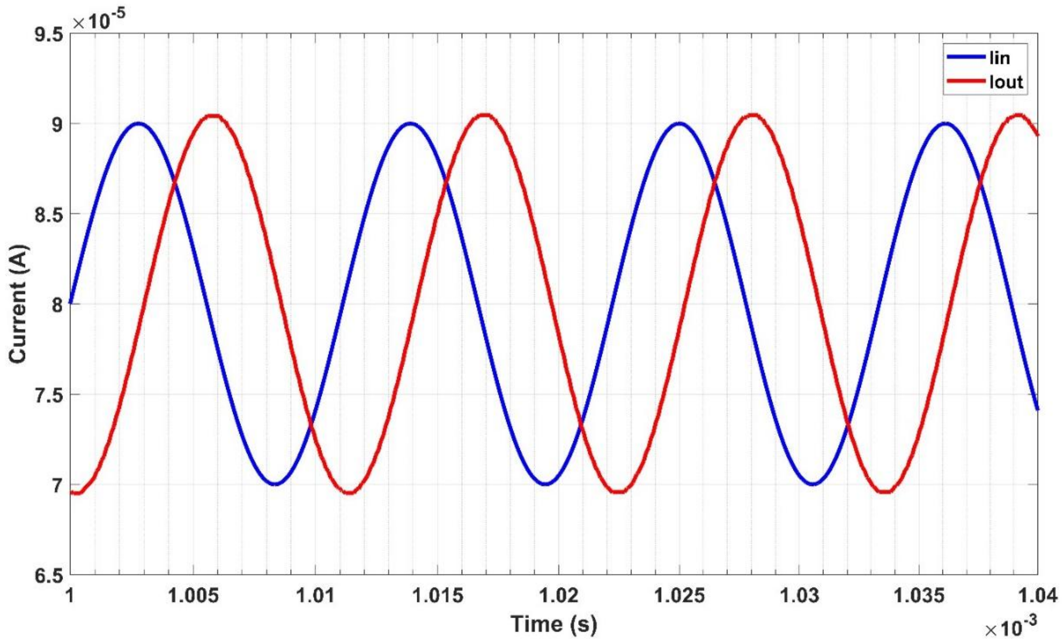

Figure 11. Time-domain response of square-root domain second-order low-pass filter

Table 2. Comparison of filter performances and properties with existing studies in literature

	[23]	[25]	[27]	Proposed
Method of synthesis	Gm–C	Gm–C	State-space	State-space
Supply voltage	1.2V	0.6 V	1 V	3 V
Cut-off frequency	114 Hz-12 MHz	750 Hz-1MHz	0.4 MHz-2.9 MHz	1 kHz- 120 kHz
Order	4	2	2	2
Dynamic range	-	-	-	≈60 dB
Technology	90nm CMOS	0.18 µm CMOS	0.35 µm CMOS	0.25 µm CMOS
THD (%)	-	0.82%	0.7%	0.5%

4. Conclusion

In this study, a second-order low-pass filter has been designed in a square root domain for low-frequency applications. The designed circuit is defined as a current-mode circuit because all input and output signals are current. The designed circuit has many advantages such as being in current mode, consisting only of grounded capacitors and MOSFETs, providing a wide dynamic range and low THD, having center frequencies that are electronically tunable with external current sources, and being suitable for low voltage/power applications. In addition, the proposed circuit is designed with state-space synthesis method, which is very useful for compounding circuits. In biomedical applications, it is thought that using MOSFETs operating in the saturation region in square root domain is very useful as the power loss of the system should be as low as possible to extend the life of a portable device in low power environments.

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Author's Contributions

Fatma Zuhal Adalar: Drafted and wrote the manuscript, performed the experiment and result analysis.

Ali Kırçay: Assisted in analytical analysis on the structure, supervised the experiment's progress, and result interpretation.

Ethics

There are no ethical issues after the publication of this manuscript.

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