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A low-power multi-mode and multi-output high-order CMOS universal Gm-C filter

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Abstract This paper presents a new CMOS high-order Gm-C universal filter which can realize multi-mode (current, voltage, trans-resistance and trans-conductance) filtering functions, using grounded capacitors to absorbing shunt parasitic capacitances and a reduced number of active elements which leads to the minimum chip size and power consumption. Furthermore, in current-mode implementation, the proposed circuit produces simultaneously multiple filtering functions while uses just one configuration of inputs. Also, as the result of sensitivity analysis shows, the new filter structure has a very low sensitivity to the values of capacitors and trans-conductance elements. However, the proposed Gm-C filter is designed and simulated in HSPICE using 0.18 μm CMOS technology parameters and HSPICE simulation results have very close agreement with theoretical results obtained from MATLAB which justifies the design accuracy and low-power, multi-mode, multi-output universal filtering performance of the proposed circuit.

Keywords CMOS · Gm-C · Universal filter · Low-power

1 Introduction

A continues-time filter is one of the most important building blocks in analog circuits. It plays a very important role in many applications such as communication systems [1], portable electronic systems [2], implantable medical devices [3], etc. However, Gm-C circuit is a well-known technique to realize continues-time filters. Some filter circuits based on Gm-C technique are reported in literature [1–10, 16–27]. However, in order to reduce the chip area, universal filters which can realize all filtering functions such as (LP, HP, BP, AP, BR) are discussed in [5–10, 16, 18–21]. Furthermore, as discussed in the literature [6–8, 16], universal filters are operating in different functioning modes such as voltage-mode, current-mode, trans-resistance mode and trans-conductance mode. Universal filters can also be classified into single-input single-output [10], single-input multi-output [11, 12], multi-input single-output [13, 14] and multi-input multi-output [15] structures. Since the frequency behavior of higher-order filters are very close to the response of the ideal filters, so, in this paper a multi-mode high (nth)-order and multi-output universal Gm-C filter is designed. However, some high-order Gm-C filters are discussed in [16–18, 20]. A high-order Gm-C universal filter based on digitally programmable versatile-mode is reported in [16] but, the digitally programmability for voltage-mode is done using n + 1 switches. Another high-order All-pass and Band-reject filter based on single-ended-input OTA reported in [17] but the main drawback of this circuit is the lack of universal filtering function and having only voltage-mode filtering operation. A high-order current-mode universal filter is discussed in [18]. However, it is not a multi-mode filter. Another all-pass high-order filter is reported in [20] but the main drawback of this circuit is the lack of multi-mode and universal filtering operation. Giving the above facts, the main drawback of the discussed circuits is that, these circuits cannot produce all filtering functions simultaneously with just one configuration of inputs. In other words, different filtering functions require of reconfiguration in the arrangement of inputs.

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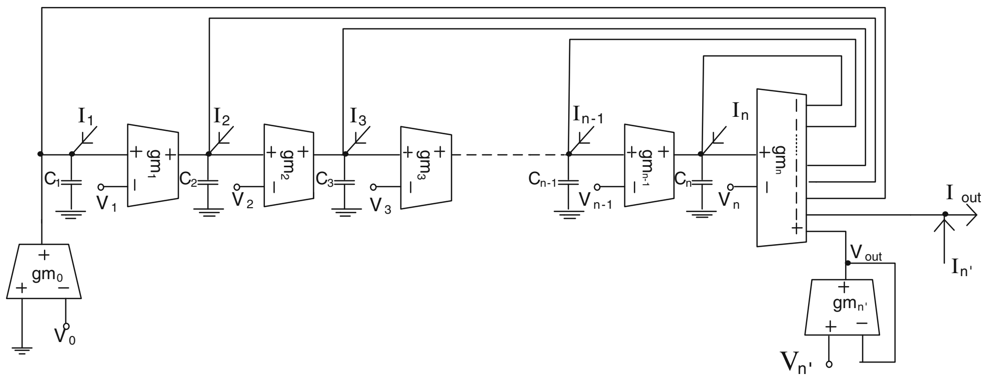


Fig. 1 Basic structure of the proposed nth-order universal Gm-C filter

This paper is organized as follows: in Sect. 2, the proposed circuit topology is described in details. In Sect. 3, the sensitivity analysis of the proposed circuit is presented. In Sect. 4, HSPICE simulation results are presented where they are compared with analytical results obtained from MATLAB in order to justify the performance and accuracy of the proposed circuit. In Sect. 5, the performance of the proposed circuit is compared with previous work. Finally, the conclusions are presented in Sect. 6.

2 The proposed circuit topology

The schematic of the proposed multi-mode, high-order universal filter is shown in Fig. 1. As it is obvious in Fig. 1, $I_n, I_{n-1}, \ldots, I_1, I_{n'}$ and $V_n, V_{n-1}, \ldots, V_0, V_{n'}$ are the filter input currents and voltages respectively which determine the filtering functions (LP, HP, BP, BR, AP) and I_{out} is the output current of the filter while V_{out} is the output voltage of the filter. The general transfer function of the nth-order filter is as follows:

$$I_{out} = I_{n'} - \frac{\sum_{K=0}^{K=n-1} a_K I_{K+1} S^K}{D(S)} \tag{1}$$

$$V_{out} = V_{n'} - \frac{\sum_{K=0}^{K=n} a_K V_K S^K}{D(S)} \tag{2}$$

$$D(S) = \sum_{K=0}^{K=n} a_K S^K \tag{3}$$

$$a_0 = gm_1 gm_2 \ldots gm_{n-1} gm_n = \prod_{i=1}^{i=n} gm_i \tag{4}$$

$$\begin{cases} a_K = \prod_{i=K+1}^{i=n} gm_i \prod_{j=1}^{j=K} C_j & K = 1, 2, 3, \ldots n-1 \\ a_K = C_1 C_2 C_3 \ldots C_{n-1} C_n = \prod_{j=1}^{j=n} C_j & K = n \end{cases} \tag{5}$$

where (a_n, a_{n-1},…,a_0) are constant filter coefficients and considered as design variables. The main filtering performance parameters (ω_0, Q) are controllable in the proposed circuit by changing gm_i and capacitances values C_i. Using the above equations, different filtering functions can be realized as follows:

Case (I)–current mode and trans-resistance mode If, $V_0 = V_1 = V_2 = \cdots = V_n = V_{n'} = 0$, the following responses are obtained:

(a) *Low-pass*: Only $I_1 = I_{in}$, $I_2 = I_3 = I_n = I_{n'} = 0$.

$$LP_I(S) = -\frac{gm_n gm_{n-1} \ldots gm_1}{D(S)} \tag{6}$$

(b) *Band-pass*: Only $I_{(n/2+1)} = I_{in}$ for even n and $I_{(n+1)/2} = I_{(n+3)/2} = I_{in}$ for odd n.

$$\begin{cases} BP_I(s) = -\dfrac{gm_n gm_{n-1} \ldots gm_{m(n/2+1)} C_{n/2} C_{(n/2-1)} \ldots C_2 C_1 S^{n/2}}{D(S)} & \text{for even n.} \\ BP_I(s) = -\dfrac{gm_n gm_{n-1} \ldots gm_{(n+3)/2} C_{(n-1)/2} \ldots C_2 C_1 \left(C_{(n+1)/2} S^{(n+1/2)} + gm_{(n+1)/2} S^{(n-1)/2} \right)}{D(S)} & \text{for odd n.} \end{cases} \tag{7}$$

(c) *High-pass*: $I_1 = I_2 = \cdots = I_n = I_{n'} = I_{in}$.

$$HP_I(s) = \frac{S^n C_n C_{n-1} \ldots C_2 C_1}{D(s)} \quad (8)$$

(d) *Band-reject*: $I_2 = I_3 = \cdots = I_n = I_{n'} = I_{in}$ and $I_1 = 0$ where, $S^k = (S^2)^m$ in transfer function is valid for an odd m, $I_1 = 2I_{in}$ and $I_2 = I_3 = \cdots = I_n = I_{n'} = I_{in}$for an even m.

$$\begin{cases} BR_I(S) = \dfrac{S^n C_n C_{n-1} \ldots C_2 C_1 + gm_n gm_{n-1} \ldots gm_1}{D(S)};\ for\ odd\ m. \\ BR_I(S) = \dfrac{S^n C_n C_{n-1} \ldots C_2 C_1 - gm_n gm_{n-1} \ldots gm_1}{D(S)};\ for\ even\ m. \end{cases} \quad (9)$$

(e) *All-pass*: $I_{n'} = I_{in}$ and $I_1 = I_3 = \cdots = I_n = 2I_{in}$for an odd n, $I_{n'} = I_{in}$ and $I_2 = I_4 = \cdots = I_n = 2I_{in}$ for an even n.

$$\begin{cases} AP_I(s) = \dfrac{a_n S^n - a_{n-1} S^{n-1} + a_{n-2} S^{n-2} - \cdots + a_2 S^2 - a_1 S + a_0}{D(S)}; \quad for\ even\ n. \\ AP_I(s) = \dfrac{a_n S^n - a_{n-1} S^{n-1} + a_{n-2} S^{n-2} - \cdots - a_2 S^2 + a_1 S - a_0}{D(S)}; \quad for\ odd\ n. \end{cases} \quad (10)$$

In addition, voltage-mode and trans-conductance mode filtering functions can be realized as follows:

Case (II)–voltage mode and trans-conductance mode If $I_1 = I_2 = \cdots = I_n = I_{n'} = 0$, the following responses are obtained:

$$\begin{cases} AP_V(s) = -\dfrac{gm_n(a_n S^n) + gm_n(a_{n-1} S^{n-1}) + \cdots + gm_n(a_1 S) + gm_0(a_0)}{gm_{n'}(D(S))}\ ; for\ even\ n. \\ AP_V(s) = -\dfrac{(gm_n(a_n S^n) - gm_n(a_{n-1} S^{n-1}) + \cdots + gm_n(a_1 S) - gm_0(a_0))}{gm_{n'}(D(S))}\ ; for\ odd\ n. \end{cases} \quad (15)$$

(a) *Low-pass*: Only $V_0 = V_{in}$.

$$LP_V(s) = -\frac{gm_0(gm_n gm_{n-1} \ldots gm_1)}{gm_{n'}(D(s))} \quad (11)$$

(b) *Band-pass*: Only $V_{n/2} = V_{in}$ for an even n and only $V_{(n\pm1)/2} = V_{in}$for an odd n.

(c) *High-pass*: Only $V_n = V_{in}$.

$$HP_V(s) = -\frac{gm_n(S^n c_n c_{n-1} \ldots c_2 c_1)}{gm_{n'}(D(s))} \quad (13)$$

(d) *Band-reject*: Only $V_0 = V_n = V_{in}$.

$$BR_V(s) = -\frac{gm_n(S^n c_n c_{n-1} \ldots c_2 c_1) + gm_0(gm_n gm_{n-1} \ldots gm_1)}{gm_{n'}(D(s))} \quad (14)$$

(e) *All-pass*: $V_0 = -V_1 = V_2 = \cdots = -V_{n-1} = V_n = V_{in}$ and $V_{n'} = 0$for an even n, $-V_0 = V_1 = -V_2 = \cdots = -V_{n-1} = V_n = V_{in}$ for an odd n and$V_{n'} = 0$.

For an example to the above equations, if a sixth-order band-pass Gm-C filter is required, the following current-mode transfer function is resulted:

$$\begin{cases} BP_V = -\dfrac{gm_n(gm_{n-1} \ldots gm_{n/2+1} gm_{n/2} C_{n/2} C_{n/2-1} \ldots C_2 C_1 S^{n/2})}{gm_{n'}(D(S))}\ ;\ for\ even\ n. \\ BP_V = -\dfrac{gm_n(gm_{n-1} \ldots gm_{(n+1)/2} C_{(n-1)/2} \ldots C_2 C_1 (C_{(n+1)/2}) S^{(n+1)/2} + gm_{(n-1)/2} S^{(n-1)/2})}{gm_{n'}(D(S))}\ ;\ for\ odd\ n. \end{cases} \quad (12)$$

$$BP_I(S) = -\frac{(gmSC)^3}{(SC)^6 + gm(SC)^5 + gm^2(SC)^4 + gm^3(SC)^3 + gm^4(SC)^2 + gm^5SC + gm^6} \quad (16)$$

In Fig. 1, if $gm_1 = gm_2 = \cdots = gm_n = gm_{n'}$, then, gm_0 can be eliminated. So, the proposed filter structure employs n + 1single-output OTA blocks and one multi-output OTA block for implementing nth-order filter which leads to a reduced power and chip area scheme. In this case, the multi-mode filtering operation can be done as follows:

Current and trans-resistance modes are similar to Case (I). However, for realizing voltage and trans-conductance modes, the following configuration is required:

(a) Low-pass: $V_1 = V_2 = \cdots = V_n = V_{n'} = V_{in}$ for all n.
(b) High-pass: Only $V_n = V_{in}$ for all n.
(c) Band-pass: Only $V_{(n\pm1)/2} = V_{in}$ for an odd n, only $V_{(n/2)} = V_{in}$ for an even n.
(d) Band-reject: $V_1 = V_2 = \cdots = V_{n-1} = V_{n'} = V_{in}$ and $V_n = 0$.
(e) All-pass: $V_{n'} = V_{in}$ for all n.

However, the main drawback of filtering functions discussed in case I and case II, is that the filter circuit can only produce just one filtering behavior at the output node with one configuration of inputs. So, in order to solve the above problem, it is necessary to use multi-output gm blocks which leads to a multi-output filter circuit in which

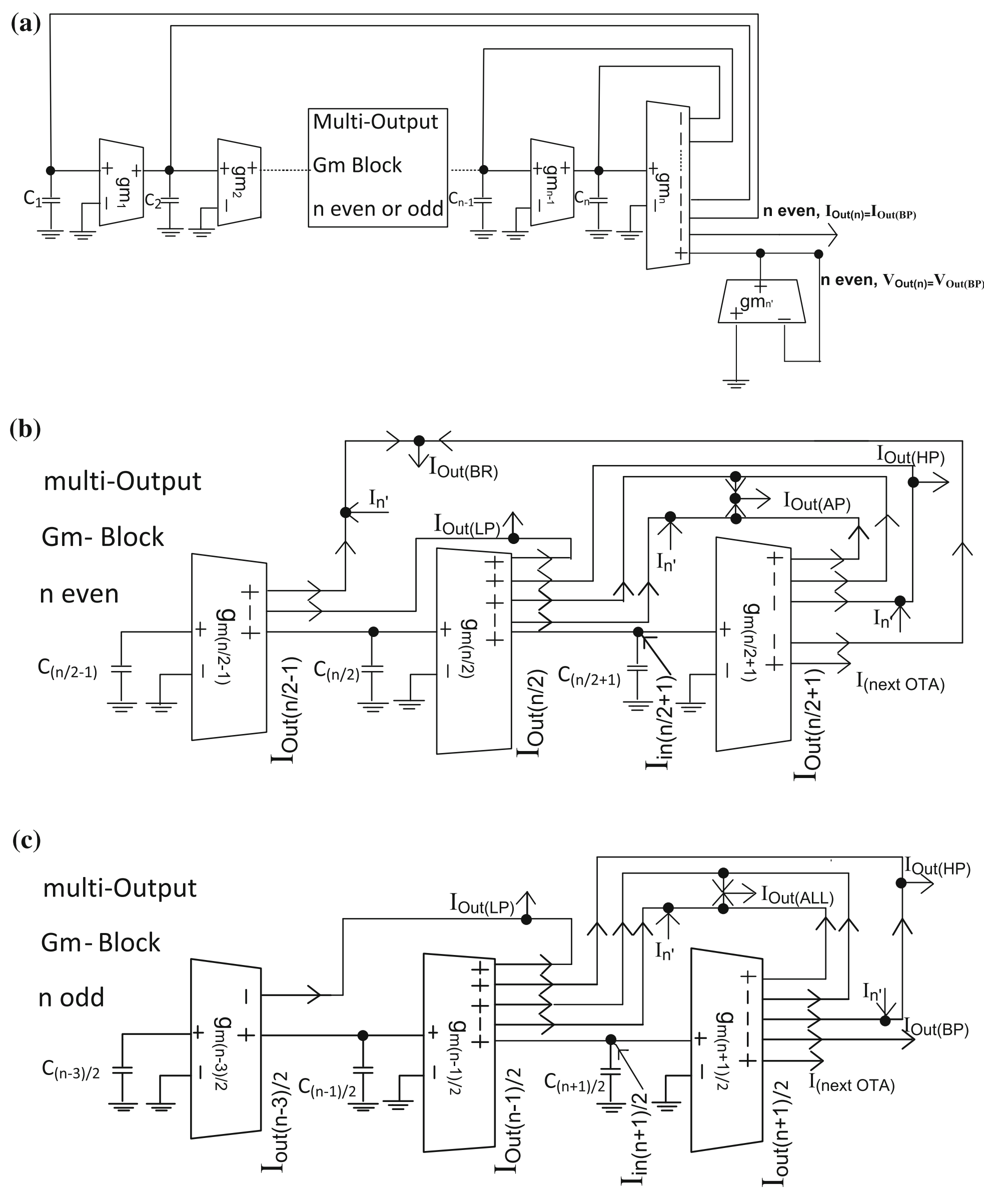


Fig. 2 **a** Schematic of the proposed simultaneously multi-output, nth-order universal filter. **b** Multi-output Gm block for an even n. **c** Multi-output Gm block for an odd n

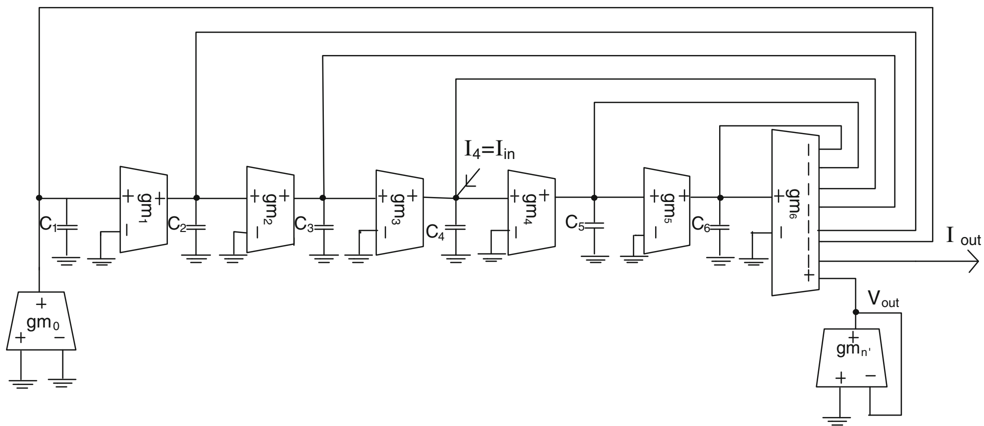
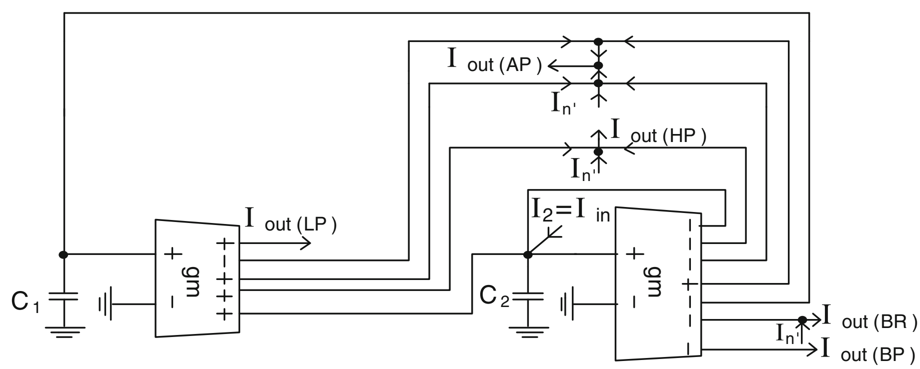


Fig. 3 Sixth-order filters in current-mode and trans-resistance mode

Fig. 4 Structure of the proposed second-order simultaneously multi-output filter



all filtering responses (LP, HP, BP, AP, BR) can be realized simultaneously by using just one configuration of inputs. Giving the above facts, in order to implement a simultaneously multi-output universal Gm-C filter, some modifications should be done in the proposed circuit by replacing some single-output gm blocks with multi-output gm circuits. So, after doing the above modifications, the schematic of the proposed simultaneously multi-output nth-order universal filter, is resulted and shown in Fig. 2(a, b, c). As it is obvious in Fig. 2(a), a multi-output Gm block is used in the structure of the proposed filter. However, the schematic of the multi-output Gm block is shown in Fig. 2(b, c), for even and odd n respectively.

As it is discussed before, the main advantage of the proposed circuit is the ability of realizing multi-output filtering functions simultaneously. So, the general transfer function of the current-mode simultaneously multi-output nth-order filter is as follows:

For an even n: Only $I_{(n/2+1)} = I_{in}$

(a) Band-pass: $I_{out(n)} = I_{out\,(BP)}$
(b) High-pass: $I_{n'} - (I_{out(n/2+1)} - I_{out(n/2)}) = I_{out(HP)}$
(c) Low-pass: $I_{out(n/2)} - I_{out(n/2-1)} = I_{out(LP)}$
(d) Band-reject: $I_{n'} + I_{out(n/2-1)} - I_{out(n/2+1)} = I_{out\,(BR)}$ where $S^K = (S^2)^m$ in transfer function is valid for an odd m while, $2I_{out(n/2)} + I_{n'} - I_{out(n/2-1)} - I_{out(n/2+1)} = I_{out(BR)}$ is valid for an even m.
(e) All-pass: $I_{n'} - \left(I_{out(n/2+1)} - I_{out(n/2)}\right) + I_{out(n/2+1)} - I_{out(n/2)} = I_{out(AP)}$

For an odd n: Only $I_{out(n+1)/2} = I_{in}$

(a) Band-pass: $I_{out\,(n+1)/2} = I_{out\,(BP)}$
(b) High-pass: $I_{n'} - (I_{out(n+1)/2} - I_{out(n-1)/2)}) = I_{out(HP)}$
(c) Low-pass: $I_{out(n-1)/2} - I_{out(n-3)/2} = I_{out(LP)}$
(d) All-pass: $I_{n'} - (I_{out(n+1)/2} - I_{out(n-1)/2)}) + I_{out(n+1)/2} - I_{out(n-1)/2} = I_{out(AP)}$

As an example to the above equations, a sixth-order current-mode and trans-resistance mode band-pass filter is shown in Fig. 3. Also, in Fig. 4 a current-mode second order simultaneously multi-output filter is realized.

3 Sensitivity analysis

The sensitivities for the transfer function of the proposed nth order universal filter which is shown in Fig. 1, to the values of individual capacitance and trans-conductance elements (C_j, gm_j) are discussed in the following.

The sensitivities of the current-mode filtering functions to the values of components (C_j, gm_j) are:

$$S^{LP_I}_{C_j} = -\frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\ S^{LP_I}_{gm_j} = 1 - \frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \tag{17}$$

$$S^{HP_I}_{C_j} = 1 - \frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\ S^{HP_I}_{gm_j} = -\frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \tag{18}$$

$$S^{BP_I}_{C_j} = 1 - \frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\ S^{BP_I}_{gm_j} = -\frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \tag{19}$$

$$S^{BR_I}_{C_j} = S^{LP_I}_{C_j} + S^{HP_I}_{C_j}\ S^{BR_I}_{gm_j} = S^{LP_I}_{gm_j} + S^{HP_I}_{gm_j} \tag{20}$$

While, the sensitivities of the voltage-mode filtering functions to the values of components (C_j, gm_j) are:

$$S^{LP_V}_{gm_0} = S^{HP_V}_{gm_0} = S^{BP_V}_{gm_0} = S^{BR_V}_{gm_0} = 1 S^{LP_V}_{gm_{n'}} = S^{HP_V}_{gm_{n'}} = S^{BP_V}_{gm_{n'}} = S^{BR_V}_{gm_{n'}} = -1 \tag{21}$$

$$S^{LP_V}_{C_j} = -\frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\ S^{LP_V}_{gm_j} = 1 - \frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \tag{22}$$

$$S^{HP_V}_{C_j} = 1 - \frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\ S^{HP_V}_{gm_{j,j\neq n}} = -\frac{\sum_{K=0,j\neq n}^{K=j-1} a_K S^K}{D(S)};\quad S^{HP_V}_{gm_n} = 1 - \frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \tag{23}$$

$$\begin{cases} S^{BP_V}_{C_j} = 1 - \frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)};\quad S^{BP_V}_{gm_{j,j\neq n/2\neq(n\pm1)/2}} = -\frac{\sum_{K=0}^{K=j-1} a_K S^K}{D(S)} \\ S^{BP_V}_{gm_{n/2,(n\pm1)/2}} = 1 - \frac{\sum_{K=j}^{K=n} a_K S^K}{D(S)} \end{cases} \tag{24}$$

$$S^{BR_V}_{C_j} = S^{LP_V}_{C_j} + S^{HP_V}_{C_j}\ S^{BR_V}_{gm_j} = S^{LP_V}_{gm_j} + S^{HP_V}_{gm_j} \tag{25}$$

It is worth to say that, as it can be seen in Eqs. (26)–(29), if the variations of some relative sensitivities have the same increment, the summation of the sensitivities given in Eqs. (17)–(25) for each filtering transfer function to the values of circuit components (C_j, gm_j), is equal to zero which means a zero group sensitivity that may be considered as another advantage of the proposed circuit.

$$S^{LP_I}_{C_j} + S^{LP_I}_{gm_j} = 0\ S^{HP_I}_{C_j} + S^{HP_I}_{gm_j} = 0\ S^{BP_I}_{C_j} + S^{BP_I}_{gm_j} = 0\ S^{BR_I}_{C_j} + S^{BR_I}_{gm_j} = 0 \tag{26}$$

$$S^{LP_I}_{C_j} + S^{LP_I}_{gm_j} + S^{HP_I}_{C_j} + S^{HP_I}_{gm_j} + S^{BP_I}_{C_j} + S^{BP_I}_{gm_j} + S^{BR_I}_{C_j} + S^{BR_I}_{gm_j} = 0 \tag{27}$$

$$S^{LP_V}_{C_j} + S^{LP_V}_{gm_j} = 0\ S^{HP_V}_{C_j} + S^{HP_V}_{gm_j} = 0\ S^{BP_V}_{C_j} + S^{BP_V}_{gm_j} = 0\ S^{BR_V}_{C_j} + S^{BR_V}_{gm_j} = 0 \tag{28}$$

$$\begin{cases} S^{LP_V}_{C_j} + S^{LP_V}_{gm_j} + S^{HP_V}_{C_j} + S^{HP_V}_{gm_j} + S^{BP_V}_{C_j} \\ + S^{BP_V}_{gm_j} + S^{BR_V}_{C_j} + S^{BR_V}_{gm_j} + S^{LP_V}_{gm_0} + S^{HP_V}_{gm_0} \\ + S^{BP_V}_{gm_0} + S^{BR_V}_{gm_0} + S^{LP_V}_{gm_{n'}} + S^{HP_V}_{gm_{n'}} \\ + S^{BP_V}_{gm_{n'}} + S^{BR_V}_{gm_{n'}} = 0 \end{cases} \tag{29}$$

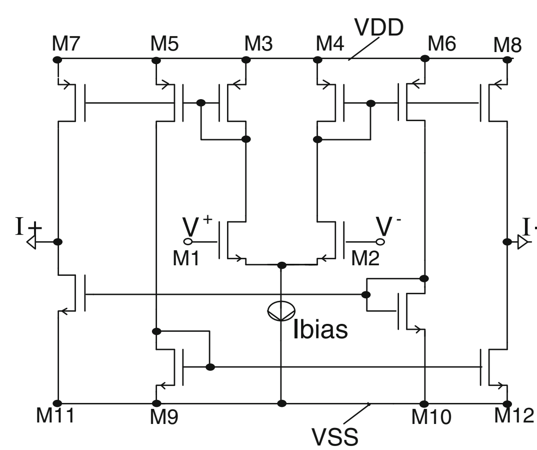


Fig. 5 Circuit structure of the OTA [19]

4 Simulation results

The proposed circuit is simulated in HSPICE using 0.18 μm CMOS technology parameters. The simulation results are obtained using $V_{DD} = -V_{SS} = 1.5V$ and $I_{bias} = 10\mu A$. The trans-conductance (gm) circuit is shown in Fig. 5. The HSPICE simulation results of the frequency response for low-pass, high-pass and band-pass filters based on the circuit in Fig. 3, are shown in Fig. 6 where they are compared with their corresponding theoretical results obtained from MATLAB in order to justify the performance and accuracy of the proposed circuit. As it is obvious in Fig. 6, HSPICE simulation results are in a very close agreement with the theoretical results which justifies good performance accuracy of the proposed filter. Also, Fig. 7(a, b, c, d), show the simulated frequency responses of a 6th order low-pass, band-pass, high-pass, band-reject (notch) and all-pass filters in all modes of operation based on the circuit shown in Fig. 1.

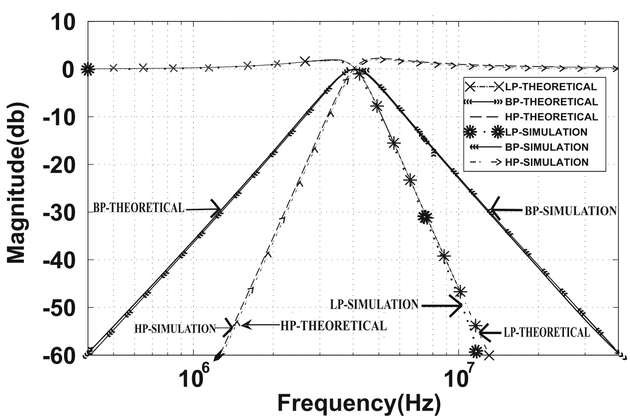


Fig. 6 Comparison between the simulation and theoretical results for a sixth-order filter

However, by choosing $C_1 = C_2 = C_3 = C_4 = C_5 = C_6 = 2pf$ and $gm_0 = gm_1 = gm_1 = gm_3 = gm_4 = gm_5 = gm_6 = gm_{n'} = 51.4$ μS the center frequency of the simulated filters is located at $f_0 = 4$ MHz.

Furthermore, Fig. 8, shows the simulated frequency response of a band-pass filter obtained for different values of the order n (n = 2,4,6) based on the circuit shown in Fig. 1, which is designed for the center frequency $f_0 = 4$ MHz. As it is obvious in Fig. 8, increasing the order of the filter (n), leads to a frequency response close to an ideal filter behavior. Figure 9, shows the simulated frequency response of a current-mode second-order simultaneously multi-output universal filter based on the circuit shown in Fig. 4, which implements different filtering responses simultaneously using just one configuration of

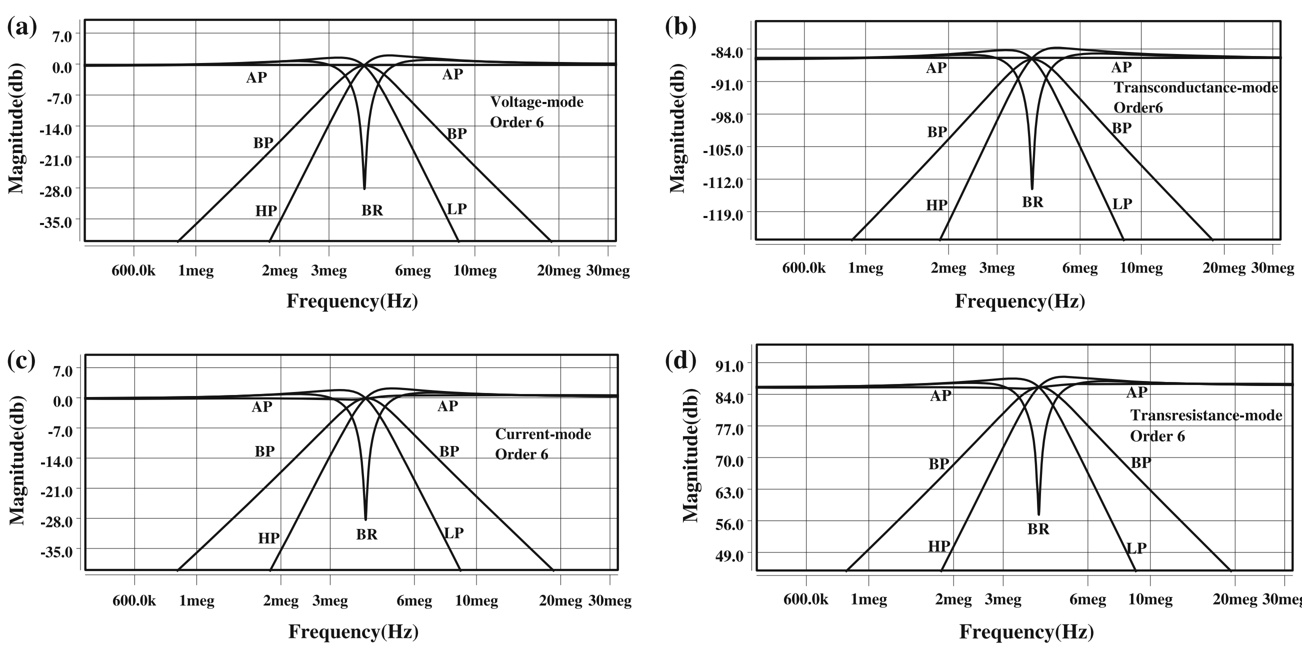


Fig. 7 **a** Voltage-mode frequency response of a sixth-order filter, **b**Trans-conductance mode frequency response of a sixth-order filter, **c** Current-mode frequency response of a sixth-order filter. **d** Trans-resistance mode frequency response of a sixth-order filter

the inputs without the need to reconfigure the arrangement of the inputs, which is the main advantage of the proposed circuit over the previous designs.

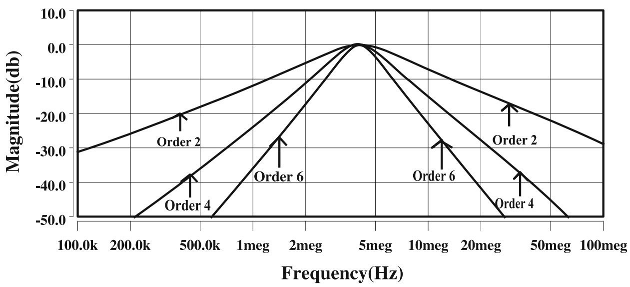


Fig. 8 Frequency response of a current-mode band-pass filter for different orders $n = 2, 4, 6$

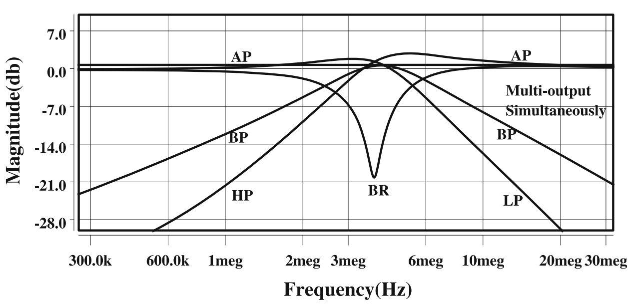


Fig. 9 Frequency response of a current-mode, second-order, simultaneously multi-output filter

5 Comparison with previous work

In order to compare the performance of the proposed circuit with the previous reported designs, some performance measures such as the ability of multi-mode operation and producing simultaneously multi-output filtering responses are considered here. Table 1, compares the performance of the proposed circuit with other designs reported in [17, 18, 20, 23]. As it is obvious in Table 1, the proposed circuit has the ability of working in all modes of operation (current, voltage, trans-resistance and trans-conductance) while the main advantage of the proposed circuit is the ability of producing simultaneously multi-output (LP, HP, BP, BR, AP) filtering functions. Furthermore, Table 2 compares the power consumption, fabrication technology, center frequency, distortion and noise values of the proposed circuit with other reported designs. As it is obvious in Table 2, the proposed circuit has a higher center frequency while consumes lower power in a reduced distortion value which is another advantage of the proposed circuit over the previous designs. Finally, for a given order (n), the proposed nth-order universal filter uses only n and n + 2 single-output OTA for current and voltage mode filters respectively while uses only n grounded capacitors and only one multi-output OTA block. Comparing the proposed nth-order filter structure (Fig. 1) and those reported in [24–27], it can be seen that the proposed multi-mode, multi-output nth-order universal Gm-C filter uses a reduced number of OTAs, while, the proposed circuit uses only one multi-output OTA unlike those reported [17, 21].

Table 1 Functional and multi-mode comparison between the proposed circuit and other reported designs

Filtering functions	[18]	[20]	[17]	[23]	Proposed
High-order(nth-order)	Yes	Yes	Yes	Yes	Yes
Voltage-mode	No	No	Yes	Yes	Yes
Voltage-mode universal	No	No	Only (AP, BR)	Only (LP, BP, HP)	Yes
Current-mode	Yes	Yes	No	No	Yes
Current-mode universal	Yes	No	No	No	Yes
Transconductance-mode	No	No	No	No	Yes
Transconductance-mode universal	No	No	No	No	Yes
Transresistance-mode	No	No	No	No	Yes
Transresistance-mode universal	No	No	No	No	Yes
Simultaneously output	No	No	No	Only (LP, BP, HP)	Yes (LP, HP, BP, BR, AL)

Table 2 Comparison between power consumption, fabrication technology and center frequency

Performance measure	[8]		[22]		Proposed	
Power consumption	Order2	30.95 mW	Order2	390 µW	Order2	309 µW
					Order4	520 µW
					Order6	722 µW
					Order10	1.36 mW
Center frequency	$F_0 = 1$ MHz		$F_0 = 1.5915$ MHz		$F_0 = 4$ MHz	
Noise	–		–		$98 \frac{nV}{\sqrt{hz}}$	
THD %	–		0.77 % @ 400mVpp, f = 0.5 MHz		0.74 % @ 400 mVpp, f = 0.5 MHz	
Technology	0.35-µm		0.25-µm		0.18-µm	

6 Conclusion

This paper reported a high-order multi-mode and simultaneously multi-output universal Gm-C filter which can realize all filtering functions (LP, HP, BP, BR,AP) in four different modes of operation (voltage mode, current mode, trans-conductance mode and trans-resistance mode). Also, it uses grounded capacitors to absorbing shunt parasitic capacitances while uses a reduced number of active elements (OTA) which leads to the minimum chip area and power consumption in comparison with other reported designs. However, the theoretical design equations are formulated in MATLAB and calculated design variables were transferred to HSPICE for circuit simulations. Finally, as discussed in the paper, the theoretical results are in a close agreement with circuit simulation results which justifies the design accuracy and good performance of the proposed circuit.

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