2007 IEEE International Conference on Signal Processing and Communications (ICSPC 2007), 24-27 November 2007, Dubai, United Arab Emirates

High-Order Gm-C Filters with Current Transfer Function Based on Multiple Loop Feedback

Mohamed O.Shaker
Electronics and Communications Department,
Cairo University
Giza, Egypt

Soliman A. Mahmoud
Electrical and Electronics Engineering Department,
German University in Cairo
Cairo, Egypt

Ahmed M. Soliman
Electronics and Communications Department,
Cairo University
Giza, Egypt

Abstract

Despite the wealth of literature on Gm-C filters, the synthesis of high-order filter characteristics is still an active topic. In this paper the realization of Gm-C filters with current transfer functions based on multiple loop feedback structures are presented. The new method presents 32 structures in case of third-order filter. All the filter architectures contain minimum number of components and all internal nodes in canonical realizations have grounded capacitors. PSpice simulation result for band-pass filter with current transfer function derived from the proposed model verifying the analytical results using 0.35µm technology is also given.

***Index Terms*—**Gm-C filters, OTA, BOTA, DOTA, synthesis.

I. INTRODUCTION

The performance of low-order Gm-C filters has been proved and a body of literature has been published for the design of second order Gm-C filters [1], [2]. Recently, the design of high-order Gm-C filters has received a great interest and has been thoroughly investigated by several methods. The first method is the cascade of biquadratic sections, which can realize any arbitrary transmission zeros but leads to an unacceptable high sensitivity to component parameter variations [3], [4]. The second method is the ladder simulation; it has a very low sensitivity to component parameter variations but can realize transmission zeros only on the imaginary axis [5]-[7]. The third method depends on the multiple loop feedback. This method has both advantages, It has a low sensitivity to component variations and can realize any arbitrary transmission zeros [8]-[10]. Practical consideration in high frequency Gm-C filter design may specify using grounded capacitors and reducing the number of components [5]. The former is because the grounded capacitor can be implemented on a smaller area than the floating counterpart and it can absorb equivalent shunt capacitive parasitics. The latter is due to the fact that a large number of components may increase power consumption, chip areas, noise, and parasitic effects. Thus the design method and resulting filter structures should be based on grounded capacitors and canonical architectures. The aim of this paper is to present new high-order Gm-C filter models with current transfer function employing only fully differential transconductors and grounded capacitors. The first model is capable of providing lowpass function. The second model is obtained by inserting multiple input current sources to the first one. Any nth-order current transfer function can be realized by the second one, which simultaneously enjoys several attractive criteria: the minimum components, it needs only n fully differential transconductors to realize nth order filter, and only 2n grounded capacitors. The symbol of the fully differential transconductor is shown in Fig. 1 in which the differential output current Io2-Io1 is linearly proportional to the differential input voltage V1-V2 such that

$$Io2 - Io1 = G(V1 - V2) \quad (1)$$

Where G is the equivalent transconductance. In section II, the first model and the possible generated structures are introduced. In section III, the second model, which can realize any type of filters, is presented. Design example is given in section IV. Finally, conclusions are stated in section V.

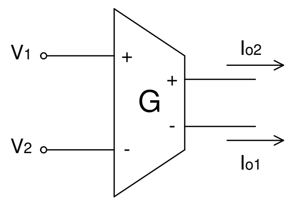

Fig. 1: The symbol of the fully differential transconductor.

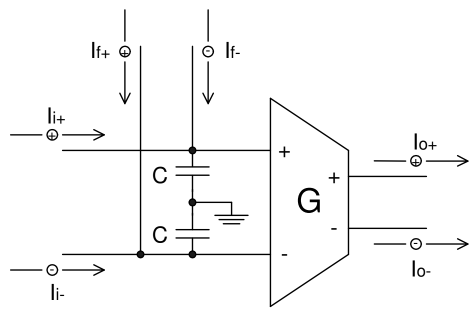

Fig. 2: The symbol of the differential current integrator.

II. THE LOW-PASS FILTER MODEL

The basic building block in the construction of Gm-C filters is the integrator in which the differential output current can

be obtained as:

$$I_o = \frac{G}{sC}(I_i - I_f) \quad (2)$$

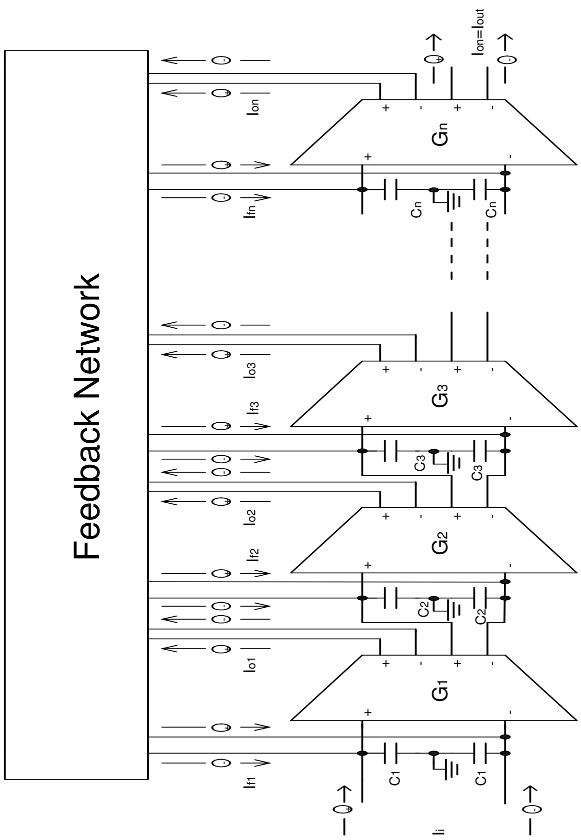

Fig. 3: The proposed multiple loop feedback filter model with current transfer function.

where $I_o = I_{o+} - I_{o-}$, the differential output current, $I_i = I_{i+} - I_{i-}$, the differential input current, and $I_f = I_{f+} - I_{f-}$,the differential feedback current.

The proposed nth-order multiple loop feedback model is shown in Fig. 3. This model is composed of a feedforward network consisting of n Gm-C integrators connected in cascade and a feedback network that contains only pure wire connections to keep the condition of minimum number of components. This model can be described as

$$I_f = FI_o \quad (3)$$

where $I_o = [I_{o1} \quad I_{o2}.......I_{on}]^t$, the differential output current vector of integrators, $I_f = [I_{f1} \quad I_{f2}.......I_{fn}]^t$, the differential feedback current vector, and $F = [f_{ij}]_{n*n}$, the feedback coefficient matrix.

The equations of the feedforward network can be written as

$$s\tau_1 I_{o1} = I_i - I_{f1} \quad (4)$$

$$s\tau_{j+1} I_{oj+1} = I_{oj} - I_{fj+1} \quad (5)$$

where the time constant $\tau_j = C_j/G_j$.

Eqn. (4) and (5) can be condensed in a matrix form as

$$I_o = M(s)^{-1}(BI_i - I_f) \quad (6)$$

where

$$M(s) = \begin{bmatrix} s\tau_1 & & & & & \\ -1 & s\tau_2 & & & & \\ & -1 & s\tau_3 & & & \\ & & & . & & \\ & & & & . & \\ & & & & -1 & s\tau_n \end{bmatrix} \quad (7)$$

And $B = [1 \quad 0........0]^t$ (8)

So, the equations for the whole system can be obtained as

$$A(s)I_o = BI_i \quad (9)$$

Where the system coefficient matrix is

$$A(s) = M(s) + F \quad (10)$$

Eqn. (9) establishes the relationship between the overall circuit input and the integrator outputs including the overall circuit output. The circuit transfer function can be formulated as

$$\frac{I_o}{I_i} = A(s)^{-1}B$$

$$= \frac{1}{|A(s)|}\begin{bmatrix} A_{11}(s) \\ A_{12}(s) \\ . \\ . \\ A_{1n}(s) \end{bmatrix} \quad (11)$$

where $|A(s)|$ and $A_{ij}(s)$ represent the determinant and cofactors of $A(s)$, respectively.

Note the structural feature of M(s) and that F is an upper triangular matrix, the transfer function T(s) can be simplified as

$$T(s)=\frac{I_{out}}{I_i}=\frac{I_{on}}{I_i}=\frac{A_{1n}(s)}{|A(s)|}=\frac{1}{|A(s)|} \quad (12)$$

The feedback matrix F is defined by eqn. (3) and has the property that

$$f_{ij}\begin{cases}=1 & \text{If there is a direct connection between } I_{fi} \text{ and } I_{oj}\\ =0 & \text{Otherwise}\end{cases} \quad (13)$$

The minimum component realization, or canonical realization, means that for realizing the nth-order all pole lowpass filter, only n fully differential transconductors and 2n grounded capacitors are required. For the model shown in Fig. 3, the canonical realization is clearly equivalent to no components existing in the feedback network. Alternatively, it can be said that for canonical architectures, the feedback matrix F defined by eqn. (3) obviously has only zero and unit elements, since feedback can only be achieved by direct connections.

Eqn. (12) can realize nth order low-pass function if at least one of the following conditions is achieved.

A. The first condition

The first condition is that feedback signal is exist in each integrator input nodes. This condition means that the feedback matrix F is an upper triangular matrix, which has at least one unit element in each row.

So, the number of filter structures (m), which equals the number of the possible feedback matrices, could be obtained as

$$m=\prod_{i=1}^{n} m_i,$$

$$m_{i+1}=2m_i+1 \qquad i=1,2,..... \quad (14)$$

$$m_1=1$$

while the number of those derived from the model given in [8] equals n!. It's clear that the proposed model generates more filter structures, that's because any feedback current could be the summation of two or more output currents using only pure wires. In the model given in [8], the feedback voltage is just one of the output voltages to keep the condition of the minimum number of components. This means that the feedback matrix is an upper triangular matrix, which has one and only one unit element in each row.

B. The second condition

The second condition is that the output signal of any integrator is feedback to some circuit node. This condition means that the feedback matrix F is an upper triangular matrix, which has at least one unit element in each column.

So, the number of filter structures could be obtained as given in eqn. (14) while the number of those derived from the model given in [9] equals n! It's clear that the proposed model generates more filter structures, that's because of using multiple output transconductors and the output current of any integrator could be feedback to many circuit nodes. In the model given in [9], the output current of any integrator is feedback to only one circuit node because of using balanced output transconductors. This means that the feedback matrix model is an upper triangular matrix, which has one and only one unit element in each column.

Finally, the proposed model shown in Fig. 3 is a general model which can realize nth order low-pass function if at least one of the previous conditions is achieved and the total number of the filters structures (m) can be obtained as

$$m=2\prod_{i=1}^{n} m_i - \text{The number of redundant structures} \quad (15)$$

For the third-order model that is a derivative version of the proposed model corresponding to n=3, with general F and using eqn. (12), the general transfer function can be formulated as

$$\begin{aligned}T(s)=1/\{&\tau_1\tau_2\tau_3 s^3+(\tau_1\tau_2 f_{33}+\tau_1\tau_3 f_{22}+\tau_2\tau_3 f_{11})s^2\\&+[\tau_1(f_{22}f_{33}+f_{23})+\tau_2 f_{11}f_{33}+\tau_3(f_{11}f_{22}+f_{12})]s\\&+(f_{11}f_{22}f_{33}+f_{11}f_{23}+f_{12}f_{33}+f_{13})\}\end{aligned} \quad (16)$$

It can be found that the proposed model generates 32 filters. It's worth to mention that 9 structures are not practical because they have no solution for the Butterworth approximations, which has been numerically verified, and therefore are rejected.

III. THE GENERAL FILTER MODEL

The general nth-order filter model can be derived from the proposed one by inserting different current signals to all integrators input nodes. The exactly same formulation process as that in section II can be followed to derive the design equations for this model. The only one exception is that instead of $BI_i=[I_i \quad 0........0]^t$, it can now be obtained as

$$BI_i=[I_1\, I_2........I_n]^t \quad (17)$$

This exception is clearly due to the change of input form. In Fig. 3, the input current is applied onto only the first integrator input nodes, while in the present case the input currents are applied onto all integrators input nodes and the last integrator output nodes without any need to extra transconductors.

So, the integrators output currents can be obtained as

$$I_o=A(s)^{-1}[I_1\, I_2........I_n]^t \quad (18)$$

and the overall output current is

$$I_{out} = I_{n+1} + I_{on} = I_{n+1} + \frac{1}{|A(s)|}\sum_{j=1}^{n} A_{jn}(s) I_j \qquad (19)$$

Note that $A_{ij}(s)$ is at least one order less in s than $|A(s)|$. So, I_{n+1} is used to provide the nth order numerator of the transfer function. It's clear that the filter given in [10] is just one case, which can be obtained from the proposed model by selecting the feedback matrix as

$$F = \begin{bmatrix} 0 & 0......... & 0 & 1 \\ 0 & 0......... & 0 & 1 \\ . & & & \\ . & & & \\ 0 & 0......... & 0 & 1 \end{bmatrix} \qquad (20)$$

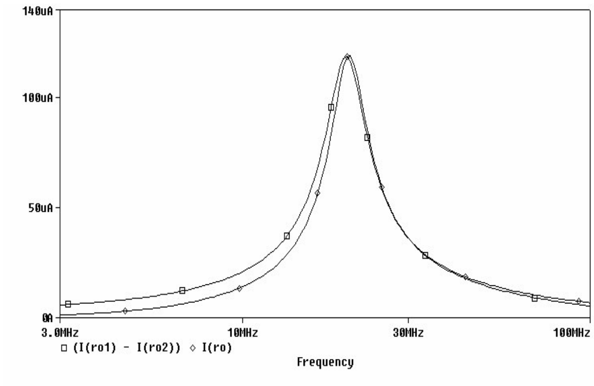

Fig. 5: The magnitude frequency response of the third-order band-pass filter.

IV. DESIGN EXAMPLES

The designed filter is a third-order band-pass filter shown in Fig. 4 with 20 MHz center frequency. The circuit capacitances are $C_1 = 0.6\,pF$, $C_2 = 0.15\,pF$, $C_3 = 1.2\,pF$ and the equal transconductance is adopted with the transconductance value being $50\,\mu A/V$. The fully differential transconductor used for the design was given in [11]. The magnitude frequency response is shown in Fig. 5, which is close to the ideal characteristics.

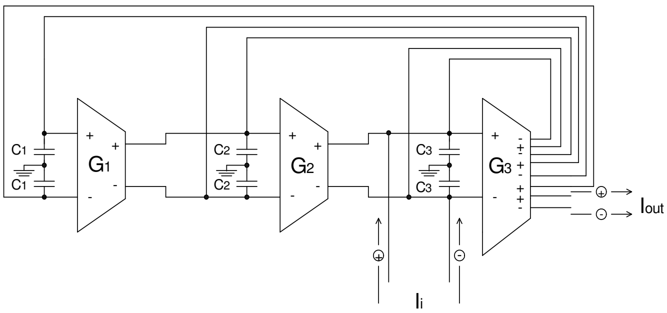

Fig. 4: The third-order band-pass Gm-C filter derived from the model.

V. CONCLUSION

This paper has presented two new Gm-C filter models with current transfer function. The first one provides low-pass function and the second one generates any type of filters. These models generate large number of filters, which keep the condition of minimum number of components and grounded capacitors. The key point is using current instead of voltage to represent signal and using multiple output transconductors. The analytical results have been confirmed using PSpice simulations.

REFERENCES

[1] C. M. Chang and S. K. Pai, "Universal current-mode OTA-C biquad with the minimum components," IEEE Trans. Circuits Syst. I, vol. 47, pp. 1235-1238, 2000.

[2] C. M. Chang, "New multifunction OTA-C biquads," IEEE Trans. Circuits Syst. II, vol. 46, pp. 820-824, 1999.

[3] R. Schaumann, M. S. Ghausi, and K. R. Laker, Design of Analog Filters, Passive, Active RC, and Switched Capacitor. Englewood Cliffs, NJ: Prentice-Hall, 1990.

[4] B. N. Ray, P. K. Nandi, and P. Palchaudhuri, "Synthesis of programmable multi-input current-mode linear analog circuits," IEEE Trans. Circuits Syst. I, vol. 51, pp. 1440-1456, 2004.

[5] B. Nauta, Analog CMOS Filters for Very High Frequencies. Norwell, MA: Kluwer, 1993.

[6] M. A. Tan and R. Schaumann, "Simulating general parameter LC-ladder filters for monolithic realizations with only transconductance elements and grounded capacitors," IEEE Trans. Circuits Syst. I, vol. 36, pp. 299-307, 1989.

[7] J. Ramirez-Angulo and E. Sanchez-Sinencio, "High frequency compensated current-mode ladder filters using multiple output OTAs," IEEE Trans. Circuits Syst. II, vol. 41, pp. 581-586, 1994.

[8] Y. Sun and J. K. Fidler, "Structure generation and design of multiple loop feedback OTA-grounded capacitor filters," IEEE Trans. Circuits Syst. I, vol. 44, pp. 1-11, 1997.

[9] T. Deliyannis, Y. Sun and J. K. Fidler, Continuous-Time Active Filter Design. CRC Press, USA, 1999.

[10] C. M. Chang and B. M. Al-Hashimi, "Analytical synthesis of current-mode high- order OTA-C filters," IEEE Trans. Circuits Syst. I, vol. 50, pp. 1188-1192, 2003.

[11] M. O. Shaker, S. A. Mahmoud and A. M. Soliman, "New CMOS fully differential transconductors and application to a fully differential Gm-C filter," ETRI. J., vol. 28, pp. 175-181, 2006.