# PERFORMANCE ASSOCIATION AND DISCRIMINATION BETWEEN CURRENT-MODE AND VOLTAGE-MODE OPERATION OF MONOLITHIC LINEAR CIRCUITS

*Yonghua Cong, Student Member, IEEE and Randall L. Geiger, Fellow, IEEE*

Department of Electrical and Computer Engineering
Iowa State University
Ames, Iowa 50011
congyh@iastate.edu and rlgeiger@ieee.org

## ABSTRACT

In recent years a host of "new" current-mode continuous-time filters have been proposed. Although there is widespread acceptance of the premise that current-mode structures are more suitable for high frequency and low voltage applications than their voltage-mode counterparts, a valid comparison of voltage-mode and current-mode structures is conspicuously absent in the literature. In an attempt to unify current-mode and voltage-mode approaches to filter design and quantify the perceived distinctions in performance, it is shown that several of the popular continuous-time "current-mode" filters offer no performance benefits from either speed or power supply voltage viewpoints over corresponding "voltage-mode" structures beyond the obvious differences in the input and output interfaces. It is also shown that the several of the popular "current-mode" structures are topologically equivalent to well-known "voltage-mode" counterparts.

## I. INTRODUCTION

For many years, essentially all discrete and integrated continuous-time filters were characterized as two-port networks in which the input and output port variables of interest were the port voltages. In those applications where an input or output port variable of interest was a current instead of a voltage, a transresistance or a transconductance block was invariably added to the input port or to the output port to perform a current to voltage or a voltage to current conversion of the input or output variable. The issue of whether the filter was operating in the "current mode" or the "voltage mode" was not addressed but invariably an analysis of these filter circuits resulted in a set of linear equations in which the variables in the equations were node voltages. This was somewhat natural as most filter circuits have fewer nodes than branches thus favoring a nodal analysis in which the variables are inherently the nodal voltages.

Many of the filter structures used high-gain heavily-compensated operational amplifiers (Op Amps) as an active element with feedback to render the filter parameters insensitive to the variability and nonlinearity of the gain of the operational amplifiers. Feedback filter structures, whether they be continuous-time active filters or discrete-time switched-capacitor filters, that use high open-loop gain Op Amps with heavy compensation were and are plagued by a substantial degradation of performance at higher frequencies.

With the economic incentives to achieve monolithic filters that are capable of operation at higher frequencies, there has been increasing pressure to look for filter structures that do not require a high-gain Op Amp as the basic gain element. Throughout the 1980's, several different approaches to designing monolithic filters were proposed that did not use high-gain Op Amps but which operated at much higher frequencies than the Op Amp-based filters. Many of these structures also inherently performed well with reduced power supply voltages. Invariably these used some type of open-loop architecture. Towards the end of the decade, some researchers used port currents rather than port voltages to describe the operation of some of these open-loop structures and used the term "current-mode" to categorize the corresponding filters. Although many authors have used the term "current-mode" to describe various open-loop filter structures, there seems to be some discrepancies in the literature about what structures are really "current-mode" structures [1]-[12] and which are "voltage-mode" structures.

Paralleling this ambiguity in precisely what the term "current-mode" really means has been a growing acceptance of the "fact" that current-mode circuits, or filters in particular, are inherently better suited for operation at high frequencies and at lower supply voltages than their voltage-mode counterparts. Numerous journal publications refer to this property such as the quotation from [10] "… current-mode functions exhibit higher frequency potential, simpler architectures, and lower supply voltage capabilities than their voltage-mode counterparts." A similar statement appeared in [11] "…To overcome these drawbacks of the voltage-mode filters, the current-mode filter circuits, which process current signals, have been developed".

This latter quotation, "current-mode filter circuits which process current signals" reflects what is generally the most common definition of a current-mode filter. Unfortunately, the concept of processing of current signals still leaves some room for ambiguity. Most authors that refer to current-mode circuits have used current variables (specifically branch currents) when describing the operation of the circuits and invariable include only current equations when describing how a circuit operates. Often no mention of a "voltage" is made anywhere in the discussion of the operation of the circuit. In the context of this paper, the issue of ambiguity of the term "current-mode" which is in reference to continuous-time filter circuits should not be extended to the use of the same term by John Hughes [12] in his introduction of the concept of "switched-current" filters which are appropriately termed "current-mode" circuits.

The widely accepted premise that current-mode circuits are suitable for operation at higher frequencies and lower supply voltages is generally based upon a qualitative argument that since node voltages are of no concern in current-mode signal processing, circuits can be designed in which currents change with a signal but in which the node voltages remain relatively constant (and small). With a constant node voltage, the parasitic capacitances on the node do not need to charge and discharge as the signal is processed and hence the signal processing operations are not limited in speed in the same way that the circuit would be limited if voltage signals were being processed. The low supply voltage operation is achieved because small voltages appear on the nodes.

Some authors have struggled to deal with the concept of "current-mode". The first book that focused specifically on current-mode circuits titled **Analogue IC design; the current-mode approach** [13] contained a chapter by Schaumann and Tan in which they made the comment "*We shall in this chapter present a brief overview of a few important synthesis and implementation methods for current-based continuous-time synthesis and implementation methods for current-based continuous-time filters. The designs do not stay exclusively in the current domain; instead, because transconductances are voltage driven with a current output, the circuits are constructed such that each transconductance "sees" a … load impedance that converts the outpout current into a voltage which in turn becomes the input for the next transconductance stage. Thus, the signals alternate quite naturally between voltages and currents*." Indeed, any element that appears in any filter circuit has a port variable relationship that relates the port voltage variables to the port current variables.

## II. AMBIGUITY IN CURRENT MODE CONCEPTS

A simple circuit may be useful for illustrating the ambiguity associated with the current mode concept. A first-order low-pass filter is shown in Fig. 1a. Since the specified port variables are the input voltage and the output voltage, this is widely viewed as a voltage-mode circuit. By the same argument, the circuit of Fig. 1b which designates only current variables is probably viewed as a current-mode circuit (which incidentally does operate well at very high frequencies and at very low voltages).

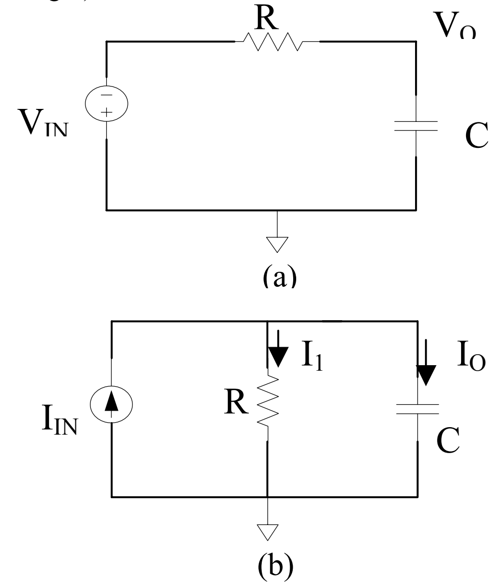


Fig. 1 A simple RC Circuit a) Voltage-Mode, b) Current-mode

It should be observed from this simple example that one circuit is simply obtained from the other by a Thevenin to Norton transformation of the source. It should also be observed that the key performance feature of this circuit, the pole location, is identical irrespective of whether it is viewed as a current-mode circuit or as a voltage-mode circuit suggesting that, at least in this example, the performance is not affected by the "mode" of operation.

A more interesting circuit, a simple MOS transistor, appears in Fig. 2. The question of whether this circuit operates in the current mode or the voltage mode is not apparent but irrespective of which mode of operation the device operates in, its performance is the same suggesting that the performance of the MOS transistor is not dependent upon whether it is considered to be operating in the voltage mode or the current mode.

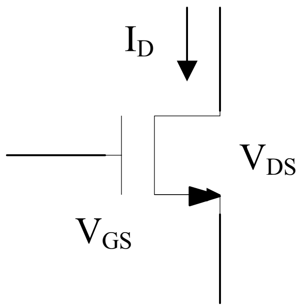


Fig. 2 A simple MOS transistor – Current-mode or Voltage-mode?

It can be thus observed that all components that comprise a filter can be considered to operate in either the voltage mode or the current mode but the filter performance is independent of the mode of operation of the components. Specifically, the poles of the filter are characteristic of the filter and do not have units of current or voltage and are the same whether obtained from an analysis involving current variables or from voltage variables or from a mixture of the two.

With this observation, the question naturally arises – do current-mode circuits really perform better at high frequencies and do they really operate at lower supply voltages than their voltage-mode counterparts. Although there have been numerous papers that have appeared in the past decade that introduce current-mode continuous-time filter circuits that are claimed to inherit these two key properties of current-mode circuits, the authors of this paper are not aware of any attempt by any of the authors to substantiate these advantages. Further, there have been a host of papers that have appeared in the same timeframe that have introduced filters that make no mention of "current-mode" operation that have performance at high frequencies and at low supply levels that is comparable to that demonstrated by the current-mode structures.

Although it is difficult to make a comparison of all current-mode filters with all voltage-mode filters, it can be observed that many of the high frequency filters in either the voltage mode class or the current mode class are integrator based and involve either cascaded two integrater loop biquads or leapfrog structures. In what follows, we will compare the performance of basic current-mode and voltage-mode integrators and then, using these integrators, compare the performance of these two classes of continuous-time filter structures. For notational convenience, we will not show biasing sources nor the multiple input and output ports on either the integrator or the filter structures but inclusion of these issues do not impact the conclusions that we will draw.

## III. INTEGRATORS

Two classes of integrators are widely used to build high-frequency continuous-time filters. One is based upon the transconductance amplifier and a capacitor and the other is based upon a single MOS transistor and an amplifier. Lossless versions of these two classes of integrators are shown in Fig. 3-6 in both the voltage-mode and the current-mode implementations. The current-mode structures were introduced in some of the referenced literature. Current mirrors are denoted by the M-gain block. For notational convenience, a comparison of the lossy integrators will not be made but the results for lossy integrators parallel that for the lossless integrators.

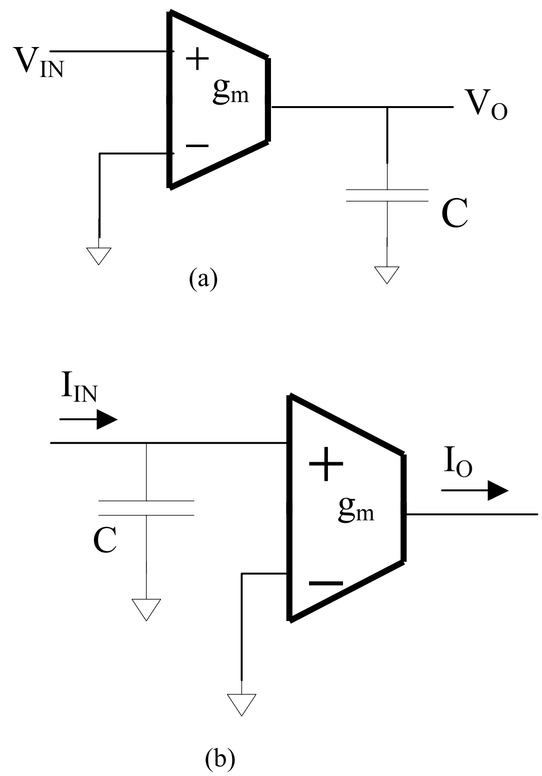


Fig. 3 Losless Non-inverting Gm-C Integrators
a) Voltage- Mode, b) Current-Mode

The gain function for the lossless non-inverting Gm-C integrators are given by the expressions

$$\frac{V_O}{V_{IN}} = \frac{g_m}{sC} \tag{1}$$

$$\frac{I_O}{I_{IN}} = \frac{g_m}{sC} \tag{2}$$

The gain functions for the inverting lossless Gm-C integrators are given by the expressions

$$\frac{V_O}{V_{IN}} = \frac{-g_m}{sC} \quad (3)$$

$$\frac{I_O}{I_{IN}} = \frac{-g_m}{sC} \quad (4)$$

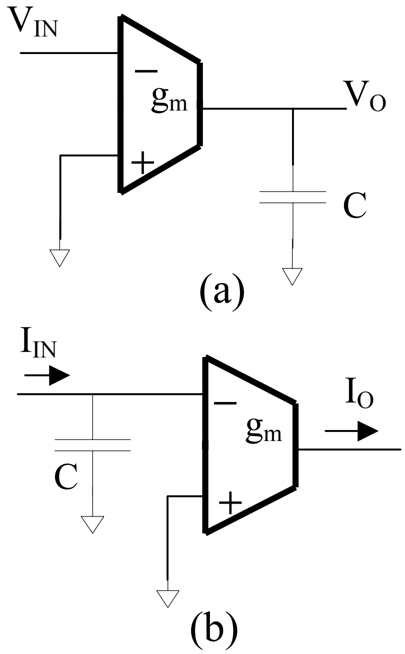


Fig. 4 Inverting Lossless Gm-C Integrators a) Voltage-mode, b) Current-mode

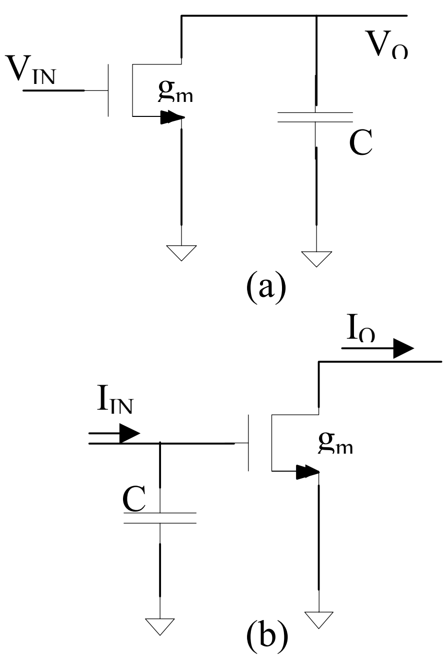


Fig. 5 Inverting Lossless High-Speed Interators a) Voltage-mode, b) Current-mode

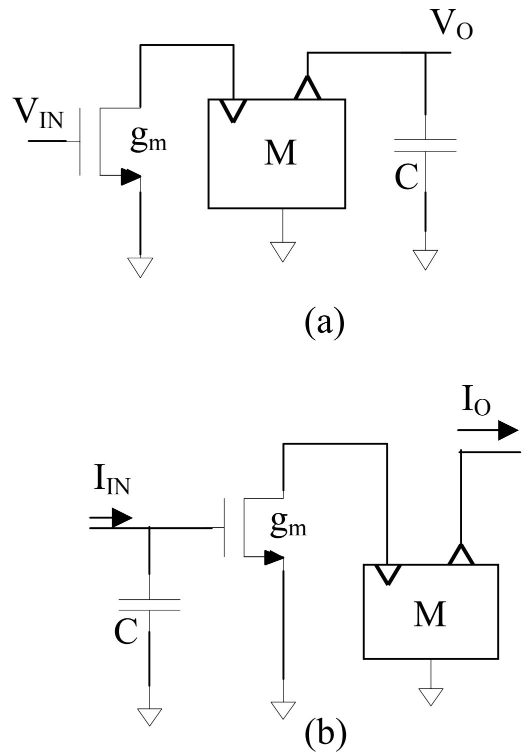


Fig. 6 Non-inverting Lossless High-Gain Intgegrators a) Voltage-mode, b) Current-mode

It can be noted that there is a fundamental difference in the architecture of the current-mode and the voltage-mode integrators. The voltage-mode integrators all see ideally an infinite input impedance and the output is impressed across a load capacitance. In contrast the current-mode integrators all have a capacitive input impedance and ideally an infinite output impedance. These distinct differences suggest that there could be distinct differences in the performance of filters built with the two types of integrators as well. In what follows, it will be seen that at least for two widely used classes of filter structures, there is not a distinction in the performance of the filters.

## IV. FILTER STRUCTURES

In general, the comparison of the performance of filter structures built with the voltage-mode and with current-mode structures is a challenging task with the issue of how to size the structures and distribute power to make a fair comparison. In what follows, however, the lack of distinction can be seen in a much easier way.

### A. Two-Integrator Loop Biquad

A standard two integrator loop biquad is shown in Fig. 7a along with a Gm-C implementation in both the current-mode and the voltage-mode. Note the same building blocks that were used in Fig. 3 and Fig. 4 are used in the implementation. The lossy integrator is denoted by the Q/Gm impedance but the actual implementation would be simply with a feedback transconductance block and block diagrams similar to those of Fig. 3 and Fig.4 could be used to denote this block in both the current-mode and the voltage-mode. By design, the filters have the same transfer functions, the same gm values and the same capacitor values. It thus follows that they have the same sensitivities, frequency response, and power supply requirements.

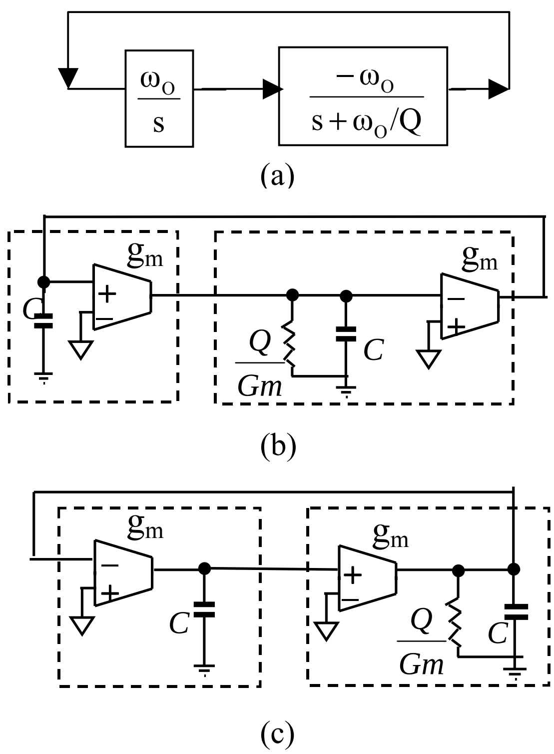


Fig.7 A two-integrator loop biquad a) block diagram b) current-mode implementation c) voltage-mode implementation

The voltage-mode filter of Fig. 7c is redrawn in Fig. 8a and a regrouping of the elements is shown in Fig. 8b. It is apparent from this figure that with the regrouping, the voltage-mode integrator is identical to the current-mode integrator of Fig. 7a. Thus not only is the performance the same, the circuits are identical as well. This shows that for the two-integrator loop, even though the current-mode and voltage-mode integrators are different, the filter implementations are identical. It can thus be concluded that there is no difference in performance between the current-mode implementations and the voltage-mode implementations of the two-integrator loop.

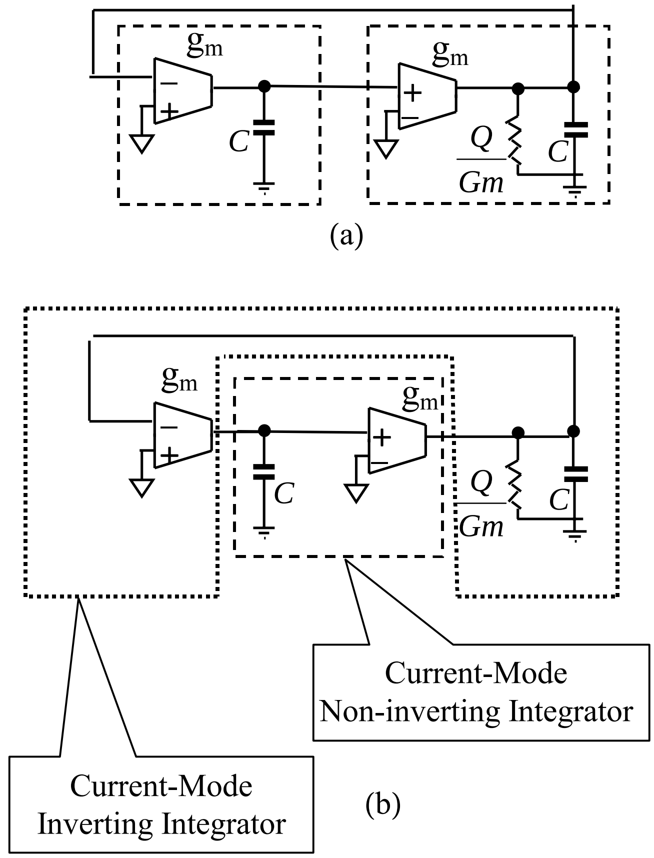


Fig. 8 Two representations of the voltage-mode two-integrator loop a) standard voltage-mode implementation, b) current-mode equivalent

## B. Leapfrog Filters

The block diagram of a leapfrog stage that is used to build leapfrog filters is shown in Fig. 9a. Implementation of the leapfrog section with current-mode integrators is shown in Fig. 9b and an implementation of the leapfrog section with voltage-mode integrators is shown in Fig. 9c. The dashed rectangles show the current-mode and voltage-mode integrators in the figure. As was the case for the two-integrator loop filter, it can be shown that the current-mode filter block is identical to the voltage-mode filter block thus indicating that the performance of current-mode and voltage-mode leapfrog filters are also identical as, (except for possibly the input and/or the output terminations) are the circuits used to implement the filters.

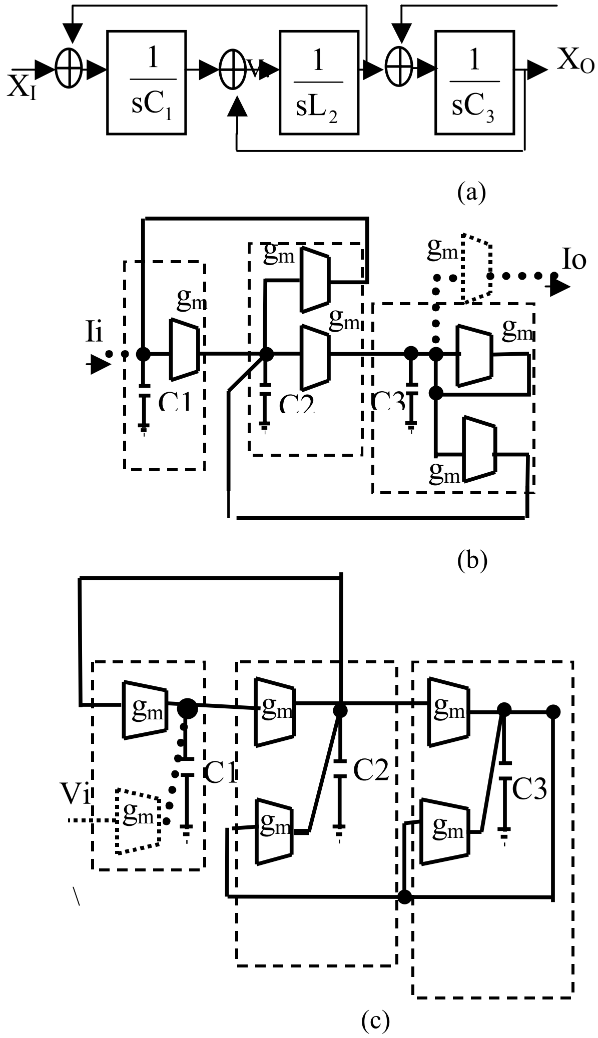


Fig. 9 Leapfrog Block Implementation a) Block Diagram, b) Current-Mode Implementation, c) Voltage-Mode Implementation

## VI. ACKNOWLEDGEMENT

This work was supported, in part, by National Semiconductor and the Roy J. Carver Trust.

## VII. CONCLUSION

A comparison of continuous-time two-integrator loop and leapfrog filter structures has been made when implemented with conventional Gm-C integrators (termed voltage-mode) and the newer current-mode integrators. In contrast to the widely accepted premise that current-mode filters perform better at high frequencies and at low supply voltage levels, this comparison showed the performance is essentially identical. It was further shown that the for these classes of filters, even though there is a fundamental difference in the basic integrator structures, the filter structures are identical.

With the absence in the literature at a quantitative comparison of the performance of current-mode continuous-time filters with their voltage-mode counterpart, the results presented here raise questions about what performance advantages are offered by the current-mode structures.

## REFERENCES

[1] J. Bramirez-Angulo, M. Robinson and E. Sanchez-Sinencio, “Current-mode continuous-time filters: two design approaches,” *IEEE Trans. Circuits and Systems II: Analog and Digital Signal Processing*, vol.39, no.6, June 1992.

[2] S. S. Lee, R. H. Zele, D. J. Allstot and G. Liang, “A continuous-time current integrator,” *IEEE Trans. Circuits and Systems*, vol. 38, pp.1236-1238, Oct. 1991.

[3] S. S. Lee, R. H. Zele, D. J. Allstot and G. Liang, “CMOS continuous-time current-mode filters for high-frequency applications,” *IEEE J. Solid-State Circuits*, vol. 28, pp. 323-329, Mar. 1993

[4] R. H. Zele, S. S. Lee and D. J. Allstot, “A 3V-125MHz CMOS continuous-time filter,” *Proc. IEEE Int. Symp. Circuits and Systems*, 1993, pp. 1164-1167.

[5] S. L. Smith and E. Sanchez-Sinencio, “3V high-frequency current-mode filters,” *Proc. IEEE Int. Symp. Circuits and Systems*, 1993, pp. 1164-1167.

[6] R. H. Zele and D. J. Allstot, “Low-power CMOS continuous-time filter,” *IEEE J. Solid-State Circuits*, vol. 31, pp. 157-168, Feb. 1996

[7] W. M. Snelgrove and A. Shoval, “A balanced 0.9-µm CMOS transconductance-C filter tunable over the VHF range,” *IEEE J. Solid-State Circuits*, vol. 27, pp. 314-323, Mar. 1992

[8] S. T. Dupuie and M. Ismail, “High frequency CMOS transconductors,” in *Analogue IC Design: the current-Mode Approach*, C. Toumazou, F. J. Lidgey and D. G. Haigh, Eds. London: Peter Peregrinus, 1990, pp. 181-238.

[9] B. Nauta, Analog CMOS filters for very high frequencies, Kluwer Academic Publishers, 1993.

[10] A. Fabre, O. Saaid, F. Wiest and C. Boucheron, “High-Frequency High-Q BiCMOS Current-Mode Bandpass Filter and Mobile Communication Application”, IEEE J. Solid-State Circuits, pp. 614 –624, April 1998.

[11] Y.S. Hyun and K.S. Yoon, “A 3V- 50MHz Analog CMOS Current-Mode High Frequency Filter with a Negative Resistance Load,”, IEEE, pp. 260-262, 1996.

[12] J.B. Hughes, N.C. Bird, I.C. Macbeth, “Switched Currents – A New Technique for Analogue Sampled-Data Signal Processing”, *IEEE International Symposium on Circuits and Systems*, pp. 158-1587, 1989.

[13] R. Schaumann and M.A. Tan, “Continuous-Time Filters,” in *Analogue IC Design: the current-Mode Approach*, C. Toumazou, F. J. Lidgey and D. G. Haigh, Eds. London: Peter Peregrinus, 1990, pp. 371-386.