Electronically Controllable Resistorless Dual-Mode Multifunction Filter

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***Abstract*— A circuit topology using two compact tunable transconductance cells (G_m-cells) and three capacitors is presented for realization of an electronically tunable resistorless dual-mode multifunction filter. The presented multifunction filter can operate either in voltage-mode or current-mode, and can realize the highpass, bandpass and lowpass filter responses simultaneously. The filter parameters, i.e. the natural angular frequency (ω_o) and the quality factor (Q), are electronically controllable by means of the transconductance gains. No element matching constraints are necessary, and the active and passive component sensitivities are low. PSPICE simulation results based on TSMC 0.25-μm CMOS real process agree closely with the theoretical calculations.**

***Keywords*— transconductance cell (G_m-cell); multifunction filter, voltage-mode circuit; current-mode circuit; electronically tunable**

I. INTRODUCTION

By now, it is well recognized that the voltage-to-current converter circuits or the transconductance cells (G_m-cells) are essential circuit elements for realizing various analog signal processing circuits and solutions, especially in the design of active filters and sinusoidal oscillators. They are used in interface circuits, instrumentation amplifiers, and continuous-time-filters. When the transconductance is electronically variable, they can also be applied in automatic, gain control circuits, and analog multipliers.

The design of multifunction filter with a single input and three outputs (SITO), which can simultaneously realize highpass (HP), bandpass (BP) and lowpass (LP) filtering functions, is widely found in many applications, such as, the phase-locked-loop frequency modulation stereo demodulator, the touch-tone telephone, and the crossover network used in a three-way high-fidelity speaker [1]. Therefore, many networks for realizing SITO multifunction biquadratic filters were proposed in [2]-[14]. However, a careful observation indicates that the existing circuits in [2]-[7] operated in voltage-mode, while the ones in [8]-[14] operated in current-mode. Moreover, the configurations of [2]-[6], [8]-[10] require at least four passive components for their realizations. The dual-mode multifunction filter that can operate in both voltage-mode and current-mode seems to be more flexible and universality for several telecommunication engineering and signal processing applications.

The aim of this work is to develop a tunable dual-mode multifunction filter constructed by a compact transconductance cell (G_m-cell) and passive capacitor elements. Based on this method, an electronically tunable dual-mode multifunction filter consisting of two G_m-cells and three capacitors can be made resistorless, and operated in both voltage- and current-mode without changing the circuit configuration. Also, the developed filter is capable of realizing the HP, BP and LP filter responses simultaneously. The natural angular frequency (ω_o) and the quality factor (Q) of the filter circuit can be tuned electronically through the external bias currents. For equal-valued capacitor, the ω_o can also be adjusted independently by changing the bias currents only. Several computer simulations with PSPICE program are drawn to demonstrate the circuit performance and to confirm the theoretical ones.

II. TUNABLE TRANSCONDUCTANCE CELL

Fig.1 shows a compact tunable G_m-cell used as an essential active element for realizing the proposed dual-mode multifunction filter. This cell is based on the use of a floating current source [15], which realizes the dual-output transconductance, and converts the differential input voltage (v^+ - v^-) into the output currents i_{o+} and i_{o-}. In this case, the transconductance value (G_m) of this element can be determined by the output transistor transconductances, which is approximated to :

$$G_m \cong \left(\frac{g_{m1}g_{m2}}{g_{m1}+g_{m2}}\right)+\left(\frac{g_{m3}g_{m4}}{g_{m3}+g_{m4}}\right) \tag{1}$$

where g_{mi} = $[\mu C_{ox}(W_i/L_i)I_B]^{1/2}$ is the transconductance parameter of the i-th transistor (i = 1, 2, 3, 4), μ is the effective carrier mobility, C_{ox} is the gate-oxide capacitance per unit area, W_i and L_i are respectively the effective channel width and length, and I_B is an external DC bias current of this element. From eq.(1), it is essential to note that the value of G_m is electronically tunable by controlling the value of I_B.

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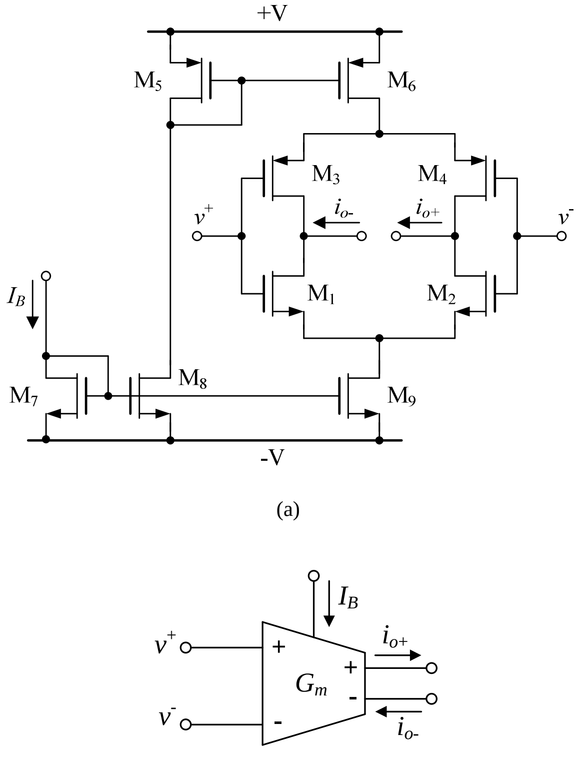

(a)

(b)

Fig.1 Tunable G_m cell.

(a) simple CMOS implementation (b) its circuit representation.

III. PROPOSED FILTER CONFIGURATION

The proposed configuration for implementing an electronically controllable dual-mode multifunction filter is shown in Fig.2. It is realized by using only two tunable G_m-cells of Fig.1 as active components, together with two grounded capacitors and one floating capacitor as passive components. Although the proposed filter contains a floating capacitor C_1, it can be realized even in recent integrated circuit technology of a decade ago with a CMOS process, which provides a second poly layer [16]. When the input current is removed ($i_{in} = 0$), the proposed configuration in Fig.2 can be considered as a voltage-mode multifunction filter with single input and three output terminals. Circuit analysis yields the following voltage transfer functions :

$$\frac{v_{o1}}{v_{in}} = H_{HP}\left[\frac{s^2}{D(s)}\right] , \tag{2}$$

$$\frac{v_{o2}}{v_{in}} = H_{BP}\left[\frac{s\left(\frac{G_{m1}}{C_1}\right)}{D(s)}\right] , \tag{3}$$

and

$$\frac{v_{o3}}{v_{in}} = H_{LP}\left[\frac{\frac{G_{m1}G_{m2}}{C_1C_2}}{D(s)}\right] \tag{4}$$

where

$$D(s) = s^2 + s\left(\frac{G_{m1}}{C_1}\right) + \left(\frac{G_{m1}G_{m2}}{C_1C_2}\right) \tag{4}$$

and G_{mi} represents the transconductance gain of the i-th G_m-cell (i = 1, 2). From above expressions, it is seen that the HP, BP, and LP filter responses can respectively be obtained from v_{o1}, v_{o2} and v_{o3} without needing component-matching constraint. The passband gains, the natural angular frequency (ω_o), and the quality factor (Q) of the filter are found as, respectively :

$$H_{HP} = 1 \ ; \ H_{BP} = \frac{C_1}{C_2} \ ; \ H_{LP} = \frac{C_1}{C_3} \tag{5}$$

$$\omega_o = 2\pi f_o = \sqrt{\frac{G_{m1}G_{m2}}{C_1C_2}} , \tag{6}$$

and

$$Q = \sqrt{\frac{G_{m2}C_1}{G_{m1}C_2}} . \tag{7}$$

It is evident from eqs.(6) and (7) that all the active and passive component sensitivities are found to be 0.5 in magnitude. Moreover, for equal-valued capacitor, the important filter parameters ω_o and Q can be adjusted arbitrarily by only controlling biasing currents externally.

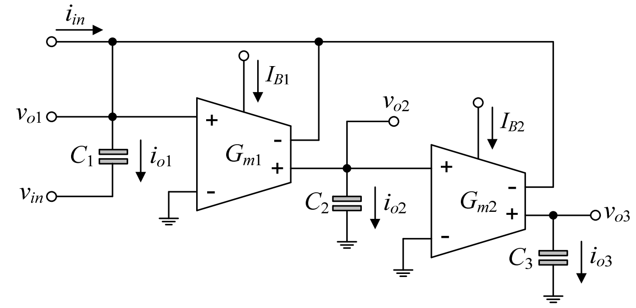

Fig.2 Proposed voltage/current-mode multifunction filter.

On the other hand, if the input voltage of Fig.2 is grounded ($v_{in} = 0$), then the proposed configuration can be transformed into the current-mode SITO multifunction filter. The current transfer function for this case are given by :

$$\frac{i_{o1}}{i_{in}} = H_{HP}\left[\frac{s^2}{D(s)}\right] , \tag{8}$$

$$\frac{i_{o2}}{i_{in}} = H_{BP}\left[\frac{s\left(\frac{G_{m1}}{C_1}\right)}{D(s)}\right] , \tag{9}$$

and

$$\frac{i_{o3}}{i_{in}} = H_{LP}\left[\frac{\frac{G_{m1}G_{m2}}{C_1C_2}}{D(s)}\right] , \tag{10}$$

where $H_{HP} = H_{BP} = H_{LP} = 1$. In all cases, the parameters ω_o and Q of the proposed current-mode filter are the same as given in eqs.(6) and (7).

IV. COMPUTER SIMULATIONS AND VERIFICATIONS

To evaluate the results of the theoretical analysis discussed above, the proposed multifunction biquadratic filter of Fig.2 has been simulated with PSPICE program. For this purpose, the G_m-cell of Fig.1 has been performed using TSMC 0.25-μm CMOS technology. The dimensions of the transistors in the G_m-cell are given in Table I. The supply voltages are set to be : +V = -V = 1.8V.

TABLE I
TRANSISTOR DIMENSIONS OF THE G_M-CELL IN FIG.1.

Transistor	W/L (μm/μm)
M_1 - M_2	14.55/0.25
M_3 - M_4	23.3/0.25
M_5	5.2/0.25
M_6	5.1/0.25
M_7 - M_8	2.8/0.25
M_9	3.2/0.25

The proposed dual-mode filter was used to realize HP, BP and LP filter responses with a natural angular frequency f_o = 10.61 MHz, by setting $C = C_1 = C_2$ = 10 pF, and $G_m = G_{m1} = G_{m2}$ = 667 μA/V ($I_B = I_{B1} = I_{B2}$ = 50 μA). The simulated frequency responses for the proposed filter when working as voltage- and current-mode operations are plotted in Figs.3 and 4, respectively. From these results, the corresponding natural angular frequencies of the proposed filter are measured at : f_o = 10.73 MHz for voltage-mode filter, and f_o = 10.87 MHz for current-mode filter.

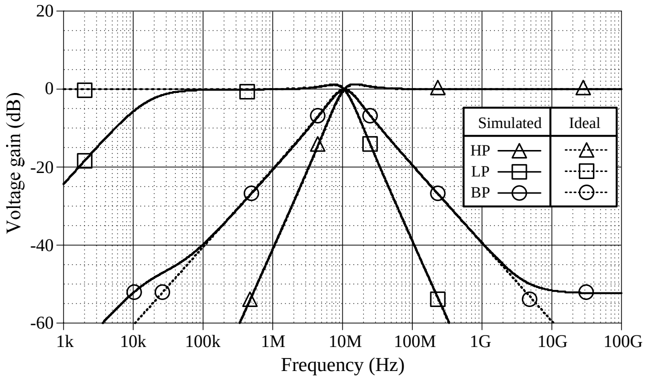

Fig.3 Ideal and simulated frequency characteristics of the proposed dual-mode multifunction filter in Fig.2, when operating in voltage-mode.

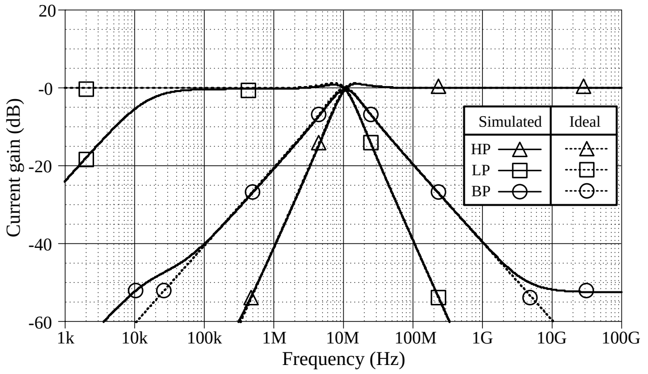

Fig.4 Ideal and simulated frequency characteristics of the proposed dual-mode multifunction filter in Fig.2, when operating in current-mode.

With the above designed component values, the simulated time-domain waveforms of the input and output sinusoidal signal of the proposed BP filters at the operating frequency f = 10.61 MHz are given in Figs.5 and 6, respectively. As expected, the simulation results agree very well with the theoretical results.

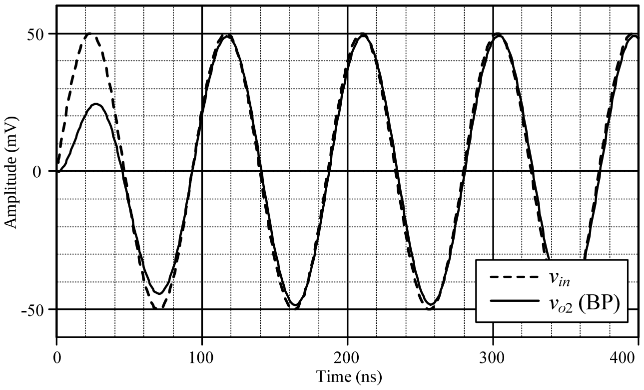

Fig.5 Simulated time-domain responses of the proposed voltage-mode BP filter in Fig.2.

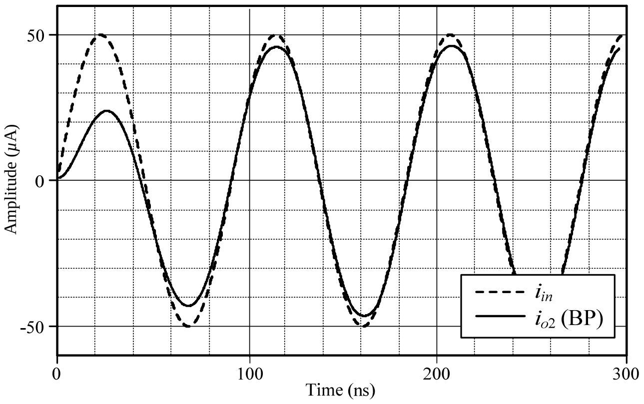

Fig.6 Simulated time-domain responses of the proposed current-mode BP filter in Fig.2.

To further demonstrate the electronic tuning performance of the filter, the external biasing currents are varied as : I_B = 10 μA (G_m = 300 μA/V), 20 μA (G_m = 422 μA/V), 50 μA (G_m = 667 μA/V), and 100 μA (G_m = 943 μA/V), which leads to obtain f_o at 4.48 MHz, 6.53 MHz, 10.73 MHz, and 14.60 MHz, respectively. The simulated magnitude responses of the proposed BP filter of Fig.2 with four different values of I_B are shown in Figs.7 and 8. From Fig.7, the simulated f_o are recorded as : 3.37 MHz, 7.01 MHz, 10.73 MHz, and 14.25 MHz, respectively. In Fig.8, the simulated f_o are found as : 3.10 MHz, 7.07 MHz, 10.87 MHz, and 14.49 MHz, respectively. The results obtained from Figs.7 and 8 verify the workability of the ideas proposed in this study.

Finally, the practical utility of the proposed filter is investigated for four different values of I_B (i.e., I_B = 10 μA, 20 μA, 50 μA, and 100 μA) by applying a sinusoidal input with the signal frequency of 4.48 MHz, 6.53 MHz, 10.73 MHz, and 14.60 MHz, respectively. In this case, the input signal amplitude is varied and the HP output response is studied for the total harmonic distortion (THD). As shown in Fig.9, the HP output voltage (v_{o1}) is found to show a maximum THD value within 4% for the input voltage amplitude up to 300 mV (peak).

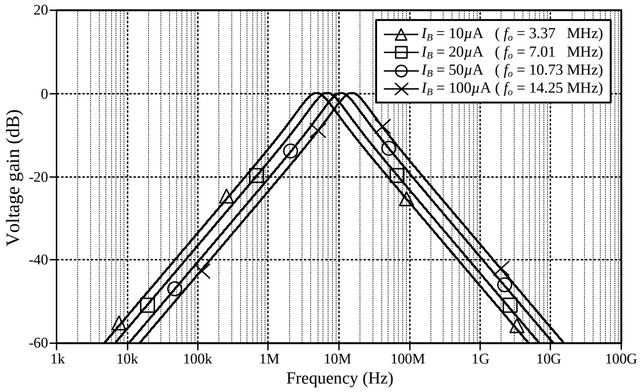

Fig.7 Simulated magnitude-frequency characteristics of the proposed voltage-mode BP filter with electronic f_o-tuning.

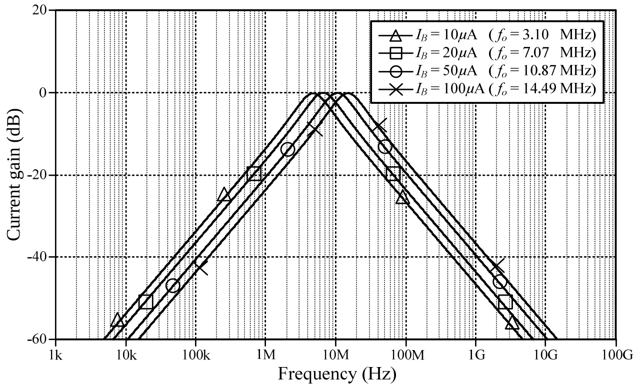

Fig.8 Simulated magnitude-frequency characteristics of the proposed current-mode BP filter with electronic f_o-tuning.

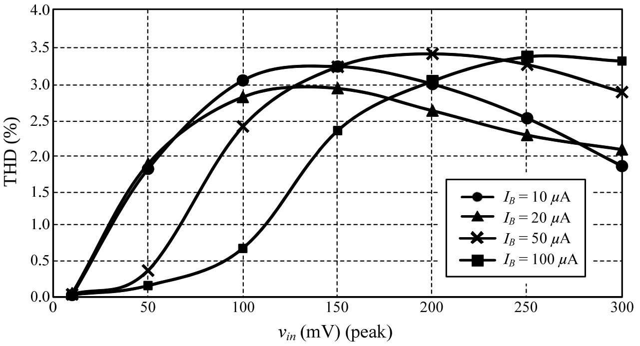

Fig.9 Dependence of THD of HP circuit output voltage on input voltage amplitude.

V. CONCLUSIONS

In summary, an alternative configuration for realizing dual-mode multifunction filter using two tunable G_m-cells, and only three capacitors is presented. The presented filter exhibits the following advantage features : operation in both voltage-mode and current-mode; generation of highpass, bandpass, and lowpass signals simultaneously from the same topology; no requirements to impose component-matching choices; low active and passive component sensitivities, and resistorless and simpler structure due to consists of only two G_m-cells and three passive components. PSPICE simulation results using TSMC 0.25-μm CMOS process parameters are used to validate the theoretical analysis.

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REFERENCES

[1] L. D. Paarmann, "Design and anlysis of analog filters", *A Signal Processing Perspective*, Norwell, MA, Kluwer, 2001.

[2] J. W. Horng, J. R. Lay, C. W. Chang, M. H. Lee, "High input impedance voltage-mode multifunction filters using plus-type CCIIs", *Electron. Lett.*, vol.33, no.6, pp.472-473, 1997.

[3] J. W. Horng, M. H. Lee, "High input impedance voltage-mode lowpass, bandpass and highpass filter using current-feedback amplifiers", *Electron. Lett.*, vol.33, pp.947-948, 1997.

[4] C. M. Chang, M. J. Lee, "Voltage-mode multifunction filter with single input and three outputs using two component current conveyors", *IEEE Trans.Circuits Syst.-I: Fundamental Theory Applications*, vol.46, no.11, pp.1364-1365, 1999.

[5] J. W. Horng, W. Y. Chiu, H. Y. Wei, "Voltage-mode highpass, bandpass and lowpass filters using two DDCCs", *Int. J. Electron.*, vol.91, no.8, pp.461-464, 2004.

[6] H. P. Chen, "Universal voltage-mode filter using only plus-type DDCCs", *Analog Integr. Circ. Signal Process.*, vol.50, no.2, pp.137-139, 2007.

[7] W. Tangsrirat, O. Channumsin, "High input impedance voltage-mode multifunction filters using a single DDCCTA and grounded passive elements", *Radioengineering*, vol.20, no.4, pp.905-910, 2011.

[8] M. A. Ibrahim, S. Minaei, H. Kuntman, "A 22.5 MHz current-mode KHN-biquad using differential voltage current conveyor and grounded passive element", *Int. J. Electron. Commun. (AEU)*, vol.59, no.5, pp.311-318, 2005.

[9] A. U. Keskin, U. Cam, "Insensitive high-output impedance minimum configuration SITO-type current-mode biquad dual-output current conveyors and grounded passive components", *Int. J. Electron. Commun. (AEU)*, vol.61, no.5, pp.341-344, 2007.

[10] D. Prasad, D. R. Bhaskar, A. K. Singh, "Universal current-mode biquad filter using dual output current differencing transconductance amplifier", *Int. J. Electron. Commun. (AEU)*, vol.63, pp.497-501, 2009.

[11] S. Minaei, S. Turkoz, "New current-mode current-controlled universal filter with single input and three outputs", *Int. J. Electron.*, vol.88, no.3, pp.333-337, 2001.

[12] W. Tangsrirat, "Novel current-mode and voltage-mode universal filters using single CFTA", *Indian J. Eng. Mater. Sci.*, vol.17, pp.99-104, 2010.

[13] J. Satansup, W. Tangsrirat, "Single VDTA-based current-mode electronically tunable multifunction filter", *Proc. 4th Int. Science, Social Science, Engineering and Energy Conf. (I-SEEC 2012)*, Petchburi, Thailand, December 11-14, 2012.

[14] D. Prasad, D. R. Bhaskar, M. Srivastava, "Universal current-mode biquad filter using a VDTA", *Circuit Syst.*, vol.4, no.1, pp.32-36, 2013.

[15] A. F. Arbel, L. Goldminz, "Output stage for current-mode feedback amplifiers, theory and applications", *Analog Integr. Circ. Sig. Process.*, vol.2, no.3, pp.243–255, 1992.

[16] R. J. Baker, H. W. Li, D. E. Boyce, *CMOS Circuit Design, Layout and Simulation*, Chapter 7, IEEE Press, New York, 1998.