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Novel OTA-C Current-Mode Third-Order Band-Pass Filters

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Abstract: In this paper, a general two-admittance current-mode circuit structure using Dual-Output OTA (DO-OTA) is explored to derive new third-order unsymmetrical band-pass filters. The proposed circuits are attractive as they require less number of OTAs and use only grounded capacitors. The other advantageous features offered by proposed filters are ease of design, good sensitivity and orthogonal tunability of pole-Q. PSPICE simulation results are also given for the proposed circuits.

Keywords: Third-order filters, OTA-C filters, Continuous-time (CT) filters, SO-OTA, DO-OTA, Current-mode circuits

I. INTRODUCTION

The OTA-C design approach [1]-[9] is one of the most preferred methods for continuous-time (CT) integrated filter design at high frequencies. The design of current-mode OTA-C filters employing analog blocks like Dual Output OTAs (DO-OTA) [2]-[4] and Multiple Output OTAs (MO-OTA) [5]-[7] have been reported. The biquads are generally used as basic building blocks for the realization of CT filters of higher order. In the literature, different circuit configurations for realization of current-mode biquads using OTA have been described i.e., a single DO-OTA and five admittance model [3], two-integrator loop structure [4]-[6] etc. The realization of current-mode OTA-C universal biquads using DO-OTA based general two-admittance circuit configuration [7] with two input currents has been discussed.

The realization of third-order filters also have been researched in the literature. The integrator-based current-mode universal OTA-C filter structure with a canonical Follow-the-Leader Feedback (FLF) configuration and an input distribution or output summation network for realizing second- order and third-order filters are discussed by Sun and Fidler [8]. The universal current-mode filters based on Multiple Loop Feedback (MLF) structure using active devices like multi-output transconductors (MO-OTA) or current conveyors (CC) and current followers (CF) have been investigated [9], [10]. The third-order filters based on different approaches like Active-R [11], Active-only [12], [13], Switched Capacitor (SC) [14] have been developed. The third-order current-mode state-variable universal OTA-C filters [15] are reported. Third-order voltage-mode filters using single Operational Transresistance Amplifier (OTRA) have been recently reported in [16], [17].

In this paper, the proposed DO-OTA based general current-mode two-admittance circuit structure is presented in Section II. In Section III, the proposed general basic topology is used to explore third-order unsymmetrical band-pass filters by considering proper admittances in place of Y_n and Y_p. The proposed third-order OTA-C band-pass filters are compared with other filter circuits in Section IV. SPICE simulation results are presented in Section V to demonstrate the practical usefulness of the proposed band pass filters. The concluding remarks are given in Section VI.

II. PROPOSED DO-OTA BASED TWO-ADMITTANCE CIRCUIT CONFIGURATION

The circuit symbol of DO-OTA is shown in Fig. 1. Note that

$$I_{o1}+ = I_{o2}+ = g_m(V_i^+ - V_i^-) \quad (1)$$

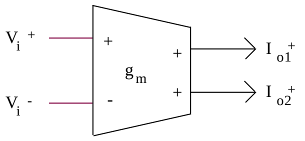


Figure 1: Circuit symbol of DO-OTA

Here, I_{o1}^+, I_{o2}^- are the two output source currents, V_i^+ and V_i^- denote non-inverting and inverting input voltages of the DO-OTA respectively.

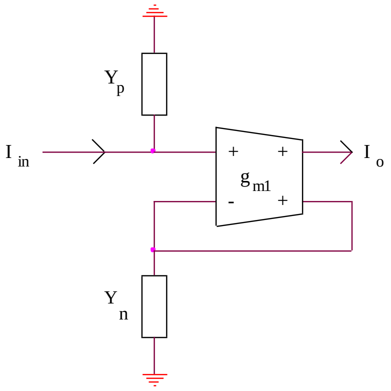


Figure 2: DO-OTA based general current-mode two-admittance circuit configuration with single input current

The DO-OTA based two-admittance general current-mode configuration with two input currents has been discussed in [7]. The circuit configuration with single input current for realizing OTA-C third-order band-pass filters is shown in Fig. 2. The generalized current-input current-output (CICO) transfer function for this circuit can be shown to be

$$\frac{I_o}{I_{in}} = \frac{g_{m1} Y_n}{Y_p (g_{m1} + Y_n)} \tag{2}$$

III. NEW THIRD-ORDER CURRENT-MODE OTA-C UNSYMMETRICAL BAND-PASS FILTERS

In this section we show that the general basic topology of Fig. 2 can be used to realize two third-order band-pass filter circuits.

A. Current-mode OTA-C third-order Band-pass filter BP3

A current-mode third-order band-pass filter circuit is obtained by using the basic structure of Fig. 2 by replacing the admittance Y_p with a parallel RLC resonator (consisting of grounded inductor L_1, grounded OTA simulated resistor $1/g_2$ and grounded capacitor C_1) and Y_n with grounded capacitor C_2. Note that the inductance L$_1$ of value $C_3/g_3\,g_4$ is realized by OTAs g_3 and g_4 and capacitor C_3. The resulting circuit is presented in Fig. 3.

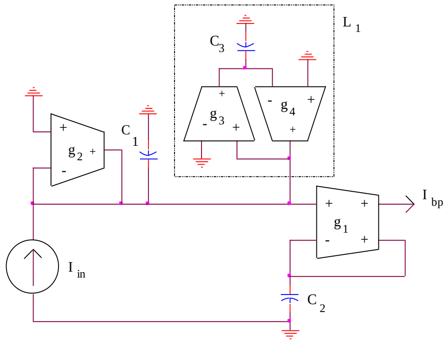


Figure 3: Current-mode DO-OTA based third-order unsymmetrical band-pass filter BP3 derived from the configuration of Fig. 2

The current-mode third-order band-pass transfer function realized for the circuit of Fig. 3 are given by

$$\frac{I_{bp\,3}}{I_{in}} = \frac{s^2\left(\frac{g_1}{C_1}\right)}{s^3 + s^2\left(\frac{g_1}{C_2} + \frac{g_2}{C_1}\right) + s\left(\frac{g_1 g_2}{C_1 C_2} + \frac{g_3 g_4}{C_1 C_3}\right) + \frac{g_1 g_3 g_4}{C_1 C_2 C_3}} \tag{3a}$$

The general third-order filter transfer function [13], [18], [19] is shown to be

$$T(s) = \frac{\alpha_3\, s^3 + \alpha_2\, s^2 + \alpha_1\, s + \alpha_0}{s^3 + s^2 \omega_o [(1/Q) + 1] + s{\omega_o}^2 [(1/Q) + 1] + {\omega_o}^3} \quad (3b)$$

By comparing coefficients in (3a) and (3b), the pole frequency and quality factor of the proposed third-order band-pass filter in Fig. 3 can be obtained as

$$f_o = \frac{1}{2\pi} \sqrt[3]{\frac{g_1 g_3 g_4}{C_1 C_2 C_3}}$$

$$Q = \frac{\sqrt[3]{\frac{g_1 g_3 g_4}{C_1 C_2 C_3}}}{\left(\frac{g_1}{C_2} + \frac{g_2}{C_1}\right) - \sqrt[3]{\frac{g_1 g_3 g_4}{C_1 C_2 C_3}}} \tag{3c}$$

The sensitivity of f_o with respect to component values are given as

$$S_{g_1}^{f_o} = S_{g_3}^{f_o} = S_{g_4}^{f_o} = -S_{C_1}^{f_o} = -S_{C_2}^{f_o} = -S_{C_3}^{f_o} = 0.33 \quad (3d)$$

Using equal transconductance approach $g_1 = g_2 = g_3 = g4 = g$ and considering $C1 = C$, $C2 = kC$ and $C3 = k2C$, the expression for pole frequency and quality factor in (3c) can be shown to be

$$f_o = \frac{g}{2k\pi C} \quad \text{and} \quad Q = \frac{1}{k} \tag{3e}$$

*B. Current-mode OTA-C third-order Band-pass filter BP3**

Alternatively, current-mode third-order band-pass filter circuit shown in Fig. 4 can be realized from the basic structure of Fig. 2 by replacing the admittance Y_p with a parallel RLC resonator (consisting of grounded inductor L_1, grounded OTA simulated resistor $1/g_2$ and grounded capacitor C_1) and Y_n with grounded inductor L_2. Here the inductance L$_1$ of value $C_2/g_3\,g_4$ is realized by OTAs g_3 and g_4 and capacitor C_2. Similarly the inductance L$_2$ of value $C_3/g_5\,g_6$ is realized by OTAs g_5 and g_6 and capacitor C_3.

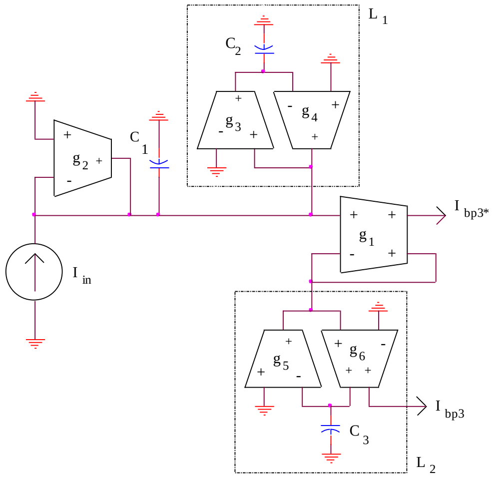


Figure 4: Current-mode DO-OTA based third-order unsymmetrical band-pass filter BP3* derived from the configuration of Fig. 2

The two current-mode third-order band-pass transfer functions realized for the circuit of Fig. 4 are given by

$$\frac{I_{bp\,3*}}{I_{in}} = \frac{s\left(\frac{g_5 g_6}{C_1 C_3}\right)}{D(s)} \tag{4a}$$

$$\frac{I_{bp\,3}}{I_{in}} = \frac{s^2\left(\frac{g_6}{C_1}\right)}{D(s)} \tag{4b}$$

where

$$D(s) = s^3 + s^2\left(\frac{g_2}{C_1} + \frac{g_5 g_6}{g_1 C_3}\right) + s\left(\frac{g_3 g_4}{C_1 C_2} + \frac{g_2 g_5 g_6}{g_1 C_1 C_3}\right) + \frac{g_3 g_4 g_5 g_6}{g_1 C_1 C_2 C_3}$$

By comparing coefficients in (4a), (4b) and (3b), the pole frequency and quality factor of the proposed third-order band-pass filter in Fig. 4 are shown to be

$$f_o = \frac{1}{2\pi} \sqrt[3]{\frac{g_3 g_4 g_5 g_6}{g_1 C_1 C_2 C_3}}$$

$$Q = \frac{\sqrt[3]{\frac{g_3 g_4 g_5 g_6}{g_1 C_1 C_2 C_3}}}{\left(\frac{g_2}{C_1} + \frac{g_5 g_6}{g_1 C_3}\right) - \sqrt[3]{\frac{g_3 g_4 g_5 g_6}{g_1 C_1 C_2 C_3}}} \tag{4c}$$

The sensitivity of f_o with respect to component values are given as

$$S_{g_3}^{f_o} = S_{g_4}^{f_o} = S_{g_5}^{f_o} = S_{g_6}^{f_o} = 0.33$$

$$S_{C_1}^{f_o} = S_{C_2}^{f_o} = S_{C_3}^{f_o} = S_{g_1}^{f_o} = -0.33 \qquad (4d)$$

Using equal transconductance approach $g_1 = g_2 = g_3 = g_4 = g_5 = g_6 = g$ and considering $C_1 = C$, $C_3 = kC$ and $C_2 = k^2C$, the expression for pole frequency and quality factor in (4c) are same as in (3e). From (3e), it is clear that both band-pass filters in Fig. 3 and Fig. 4 can be designed for different values of pole frequency and pole-Q. The sensitivity of f_o and Q with respect to g, C and k in (3e) are shown to be

$$S_g^{f_o} = -S_C^{f_o} = -S_k^{f_o} = -S_k^Q = 1$$

IV. COMPARATIVE SUMMARY OF PROPOSED THIRD-ORDER BAND-PASS FILTERS

Using the proposed DO-OTA based circuit configuration of Fig. 2, two third-order unsymmetrical band-pass filter circuits are shown to be realizable. In Table 1 the proposed third-order unsymmetrical current-mode band-pass filters are compared with the filters presented in [8], [9], [12], [15]. The proposed third-order band-pass filter BP3 of Fig. 3 requires four OTAs, one extra output and three grounded capacitors. The other proposed band-pass filter BP3* of Fig. 4 realize two current-mode band-pass transfer functions and require six OTAs, two extra outputs and three grounded capacitors. The proposed third-order OTA-C band-pass filters use only grounded capacitors. These are found to be attractive due to their features like ease of design, programmability, good sensitivity and independent pole-Q tunability.

Table 1 Comparative summary of various current-mode third-order band-pass filter circuits

Author /Reference	No. of OTAs	No. of extra OTA outputs	No. of capacitors (grounded/ floating)	Need for other building blocks
Third-order band-pass (derived from Fig. 1 in [12])	4	2	Nil	3 OAs
Third-order band-pass (derived from Fig. 1 and Fig. 2 in [8])	7 / 8	3	3 grounded	No
Third-order band-pass BP1/ BP2 (derived from Tab. 1, Fig. 4 in [9], Fig. 2 in [15])	3	-	3 grounded	CF with 4 current outputs
Third-order band-pass BP3 (Fig. 3) in this paper	4	1	3 grounded	No
Band-pass BP3/ BP3* (Fig. 4) in this paper	6	2	3 grounded	No

CF: CURRENT FOLLOWER, OA: OPERATIONAL AMPLIFIER

V. SIMULATION RESULTS

The proposed current-mode third-order unsymmetrical band-pass filter circuits in Fig. 3 and Fig. 4 have been simulated using PSPICE simulator using Level 3 0.5μm MOSIS model parameters and device dimensions (W = 4 μm and L = 2 μm) and supply voltages V_{dd} = +2V, V_{ss} = -2V following Tsukutani et al. [6]. The proposed current-mode filter circuits were also simulated using behavioral voltage controlled current source (VCCS) model of OTA (i.e., ideal transconductor with infinite R_o and zero C_o) to obtain the ideal characteristics. The schematic circuit of DO-OTA used in our simulation is presented in Fig. 5.

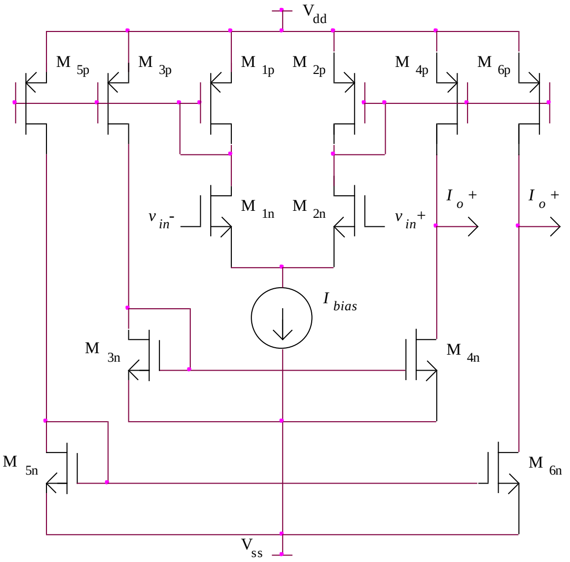


Figure 5: Schematic circuit of CMOS DO-OTA

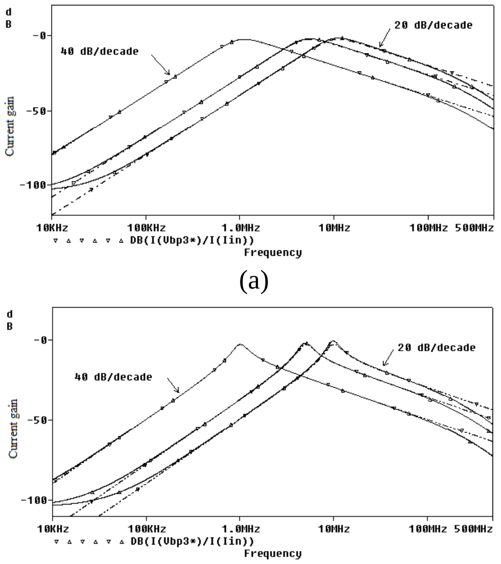
The DO-OTA based third-order unsymmetrical band-pass filter of Fig. 3 has been simulated for different pole frequencies of 1 MHz, 5 MHz and 10 MHz corresponding to Q = 1, 3 using transconductance and capacitance values given in Table 2 and 3 respectively. The resulting amplitude responses are shown in Fig. 6 (a)-(b).

Table 2 Designed values for band-pass filter of Fig. 3 for $Q = 1$ and different f_o

f_o (MHz)	Q	g (μƱ) ($g = g_1 = g_2 = g_3 = g_4$)	I_{bias} (μA)	C (pF) ($C=C_1=C_2=C_3$)
1	1	167	120	26.579
5	1	167	120	5.316
10	1	167	120	2.658

Table 3 Designed values for band-pass filter of Fig. 3 for $Q = 3$ and different f_o

f_o (MHz)	Q	g (μƱ) ($g = g_1 = g_2 = g_3 = g_4$)	I_{bias} (μA)	C_1 (pF)	C_2 (pF)	C_3 (pF)
1	3	167	120	79.737	26.579	8.859
5	3	167	120	15.947	5.316	1.772
10	3	167	120	7.974	2.658	0.886



(a)

(b)

∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Figure 6: Amplitude response of current-mode DO-OTA based third-order band-pass filter of Fig. 3 designed for different pole frequencies f_o = 1, 5, 10 MHz and different values of Q (a) $Q = 1$ (b) $Q = 3$

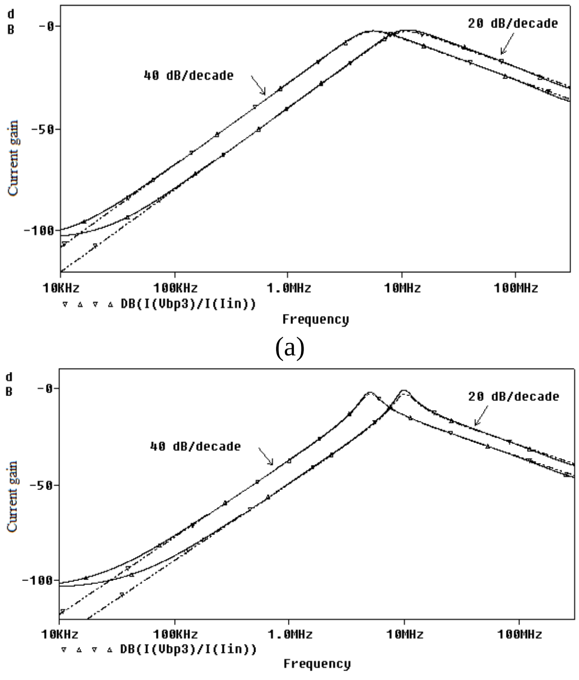
The third-order unsymmetrical band-pass filter of Fig. 4 has been simulated for different pole frequencies of 5 MHz and 10 MHz corresponding to Q = 1, 3 using transconductance and capacitance values given in Table 4 and 5 respectively. The simulated amplitude responses for the current outputs I_{bp3} and I_{bp3*} are given in Fig. 7 and Fig. 8 respectively.

Table 4 Designed values for band-pass filter of Fig. 4 for Q = 1 and different f_o

f_o (MHz)	Q	g (μƱ) ($g=g_1= g_2 = g_3 = g_4 = g_5 = g_6$)	I_{bias} (μA)	C (pF) ($C=C_1=C_2=C_3$)
5	1	167	120	5.316
10	1	167	120	2.658

Table 5 Designed values for band-pass filter of Fig. 4 for Q = 3 and different f_o

f_o (MHz)	Q	g (μƱ) ($g=g_1= g_2 = g_3 = g_4 = g_5 = g_6$)	I_{bias} (μA)	C_1 (pF)	C_2 (pF)	C_3 (pF)
5	3	167	120	15.947	1.772	5.316
10	3	167	120	7.974	0.886	2.658

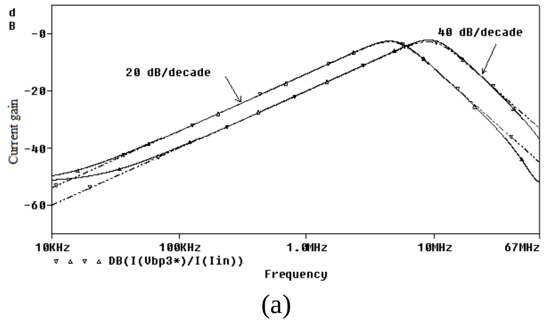


(a)

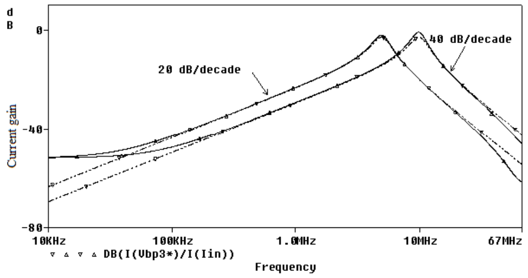
(b)

∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Figure 7: Amplitude response of current-mode DO-OTA based third-order band-pass filter of Fig. 4 (considering current output I_{bp3}) designed for different pole frequencies f_o = 5, 10 MHz and different values of Q (a) $Q = 1$ (b) $Q = 3$



(a)



(b)

∇ …. using behavioral OTA, ∆ __ using Tsukutani OTA

Figure 8: Amplitude response of current-mode DO-OTA based third-order band-pass filter of Fig. 4 (considering current output I_{bp3*}) designed for different pole frequencies f_o = 5, 10 MHz and different values of Q (a) Q = 1 (b) Q = 3 From the simulated amplitude responses, it is seen that the centre frequency and gain roll-off values are found to be in good agreement with theory.

VI. CONCLUSION

In this paper, a general current-input current-output (CICO) two-admittance circuit configuration using a DO-OTA is used to realize two third-order band-pass filter circuits. The circuits require less number of active devices and use only grounded capacitors and hence are suitable for monolithic integrated circuit implementation. The proposed third-order filter circuits can be designed for different values of pole frequency or/ and pole-Q, using equal transconductance (equal capacitance) approach and selecting appropriate capacitor (transconductor) values. All the filter circuits exhibit low sensitivity to component tolerances and provide independent tuning of f_p and Q. The simulation results obtained are in good agreement with theory.

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BIOGRAPHIES

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Dr. D. V. Kamath serves as a reviewer for many international journals and he is member in international professional organizations. He has presented/ conducted key-note address/ tutorials and seminars at various International/ National Level Conferences/ Workshops. Author’s Biography/ Profile is published in the 2011-2012 (11th) Edition of Marquis Who's Who in Science and Engineering and 2014 (31^{st}) and 2015 (32^{nd}) Edition of Marquis Who’s Who in the World, the world-renowned reference directories.