Electronically Tunable Current-Mode Universal Filter Using VDTAs and Grounded Capacitors

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***Abstract*—In this paper, an electronically tunable current-mode universal filter with three inputs and one output employing two voltage differencing transconductance amplifier (VDTA) and two grounded capacitors is proposed. The presented circuit can configure to realize all the five standard biquadratic filter functions; lowpass, bandpass, highpass, bandstop and allpass without changing the circuit configuration and needing an external passive resistor. The proposed filter is capable of providing an independent current-control of the natural angular frequency (ω_o) and quality factor (Q) through the VDTA's transconductance and low incremental active and passive sensitivities. The performance of the proposed filter is tested using PSPICE simulation program, and the results agree well with the theoretical analysis.**

***Index Terms*— Voltage differencing Transconductance Amplifier (VDTA), universal filter, current-mode circuit**

I. Introduction

IN 2008, some new active building blocks providing the potentiality in analog circuit design were and are being introduced [1], such as current differencing transconductance amplifier (CDTA) [2], current conveyor transconductance amplifier (CCTA) [3], difference current conveyor transconductance amplifier (DDCCTA) [4], and so on [1]. Among these, the voltage differencing transconductance amplifier (VDTA) is a recently introduced active element. The VDTA device is composed of the current source controlled by the difference of two input voltages and a multiple-output transconductance amplifier, providing electronic tuning ability through its transconductance gains. Therefore, the VDTA device is very suitable for electronically tunable active circuit synthesis. Another advantageous feature of the use of the VDTA as an active element is that compact structures in some application can be achieved easily [1], [5-8]. However, all of them operate in voltage-mode.

Recently, current-mode biquad filter with multiple inputs and one output terminals have been reported in open literature [9]-[22]. However, the filters in [9]-[14] do not include electronically tunability and needed external passive resistors. Moreover, filter structures in [11]-[14] employ non-grounded passive resistors. Although the electronically tunable biquad filters were reported in [15]-[18], they do not exhibit independent tuning characteristic of the parameter ω_o and Q. In [19]-[22], with orthogonal the current-mode biquadratic filters have an orthogonal ω_o-Q tuning were proposed, but they employs three or more active components. Moreover, the works configuration in [20]-[22] also needed external passive resistors.

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In this paper, an electronically tunable current-mode universal biquadratic filter having three inputs and single output using is proposed. The developed filter is constructed two VDTAs and two grounded capacitors, which is suitable for integrated circuit (IC) implementation. By properly selecting the input signals, the proposed circuit can realize all the five standard biquadratic filtering functions, namely lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS) and allpass (AP) simultaneously, from the same circuit configuration. The filter has an orthogonal electronic adjustment of the characteristic parameters ω_0 and Q, and low incremental active and passive sensitivities.

II. Description of the VDTA

In 2008, the conceptual of the VDTA was firstly suggested in [1]. The schematic symbol of the VDTA is represented in Fig.1, where the port relations can be defined by the following expression [5].

$$\begin{bmatrix} i_z \\ i_{z-} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} +g_{mF} & -g_{mF} & 0 & 0 \\ -g_{mF} & +g_{mF} & 0 & 0 \\ 0 & 0 & +g_{mS} & 0 \\ 0 & 0 & -g_{mS} & 0 \end{bmatrix} \begin{bmatrix} v_p \\ v_n \\ v_z \\ v_{z-} \end{bmatrix} \quad (1)$$

In equation (1), g_{mF} and g_{mS} are the first and second transconductance gains of the VDTA respectively. The differential input voltage from the terminals p and n (v_p - v_n) is transformed into output currents at the terminals z and z- with first transconductance g_{mF}. The voltage drop at the terminal z (v_z) is transformed into output currents at the terminals x+ and x- with second transconductance g_{mS}.

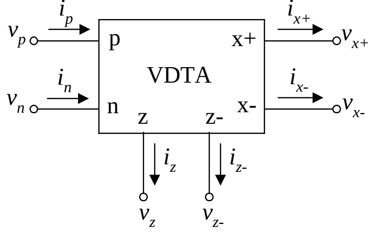

Fig. 1: Electrical symbol of the VDTA.

The CMOS-based internal structure of the VDTA is shown in Fig.2. For this structure, the circuit employs two Arbel–Goldminz transconductance [23]. The first and second

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transconductances are determined by the transconductance of output transistors, which can be expressed as, respectively:

$$g_{mF} = \frac{g_1 g_2}{g_1 + g_2} + \frac{g_3 g_4}{g_3 + g_4} \cong (g_{1,2} + g_{3,4})/2 \qquad (2)$$

$$g_{mS} = \frac{g_5 g_6}{g_5 + g_6} + \frac{g_7 g_8}{g_7 + g_8} \cong (g_{5,6} + g_{7,8})/2 \qquad (3)$$

In above equations, g_i is the transconductance value of the i-th transistor, which is given as:

$$g_i = \sqrt{I_{Bi} \mu C_{ox} \frac{W}{L}} \qquad (4)$$

where I_{Bi} is the dc bias current, μ is effective carrier mobility, C_{ox} is the gate oxide capacitance per unit area and W and L are the effective width and length of the i-th MOS transistor, respectively.

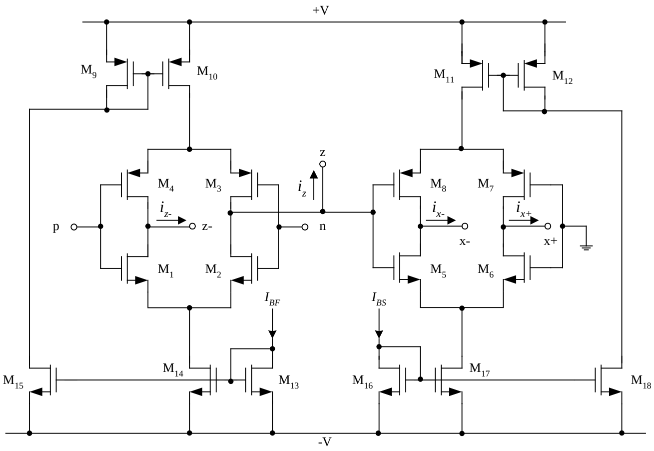

Fig.2: CMOS implementation of the VDTA.

III. Proposed Current-Mode Biquad Filter

The proposed three-input single-output current-mode electronically tunable universal filter consisting only two VDTAs and two grounded capacitors is shown in Fig. 3. Routine circuit analysis using equation (1) shows that the proposed circuit in Fig. 3 has the following output current:

$$I_{out} = \frac{D(s) I_1 + \left(\frac{g_{mS1}}{C_1}\right) s I_2 + \left(\frac{g_{mS1} g_{mS2}}{C_1 C_2}\right) I_3}{s^2 + \left(\frac{g_{mF1}}{C_1}\right) s + \left(\frac{g_{mS1} g_{mS2}}{C_1 C_2}\right)} \qquad (5)$$

The specialization of equation (5) results in the following five standard biquadratic filter fuctions.

1) If $I_3 = I_{in}$ (input current signal), $I_1 = I_2 = 0$, the LP response with a non-inverting unity passband gain can be obtained.

2) If $I_2 = I_{in}$, $I_1 = I_3 = 0$, the BP response with passband gain of g_{mS1}/g_{mF1} can be obtained.

3) If $I_1 = -I_2 = -I_3 = I_{in}$ and $g_{mF1} = g_{mS1}$, the HP response with a non-inverting unity passband gain can be obtained.

4) If $I_1 = -I_2 = I_{in}$, $I_3 = 0$ and $g_{mF1} = g_{mS1}$, the BS response with a non-inverting unity passband gain can be obtained.

5) If $I_1 = -I_2/2 = I_{in}$, $I_3 = 0$ and $g_{mF1} = g_{mS1}$, the AP response with a non-inverting unity passband gain can be obtained.

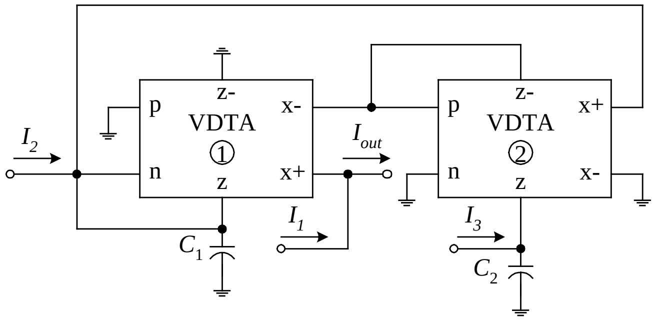

Fig.3: Proposed current-mode biquad filter using VDTAs.

Also from equation (5), the important parameters ω_o and Q of the filter are found as

$$\omega_0 = \sqrt{\frac{g_{mS1} g_{mS2}}{C_1 C_2}} \qquad (6)$$

and

$$Q = \frac{1}{g_{mF1}} \sqrt{\frac{g_{mS1} g_{mS2} C_1}{C_2}} \qquad (7)$$

Furthermore, for simplicity, substituting $g_{mS1} = g_{mS2} = g_{m2}$ and $C_1 = C_2 = C$ in equations (6) and (7) yields the following expressions:

$$\omega_0 = \frac{g_{m2}}{C} \qquad (8)$$

and

$$Q = \frac{g_{m2}}{g_{mF1}} \qquad (9)$$

Note that the parameters ω_o in equation (8) can be tuned electronically by g_{m2}, while Q-value in equation (9) can be tuned independently by g_{mF1} without influencing ω_o.

IV. Tracking Errors and Sensitivity Analysis

Considering the non-ideal characteristics of the VDTA, the port relations of current and voltage in equation (1) can be rewritten as:

$$\begin{bmatrix} i_z \\ i_{z-} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} +\beta_F g_{mF} & -\beta_F g_{mF} & 0 & 0 \\ -\beta_F g_{mF} & +\beta_F g_{mF} & 0 & 0 \\ 0 & 0 & +\beta_S g_{mS} & 0 \\ 0 & 0 & -\beta_S g_{mS} & 0 \end{bmatrix} \begin{bmatrix} v_p \\ v_n \\ v_z \\ v_{z-} \end{bmatrix} \qquad (10)$$

where β_F and β_S are respectively the tracking errors for the first and second stages of the VDTA. Re-analysis the proposed circuit in Fig.3 using equation (10) yields the following non-ideal filter parameters.

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$$\omega_0 = \sqrt{\frac{\beta_{S1}\beta_{S2}g_{mS1}g_{mS2}}{C_1C_2}} \quad (11)$$

and

$$Q = \frac{1}{\beta_{F1}g_{mF1}}\sqrt{\frac{\beta_{S1}\beta_{S2}g_{mS1}g_{mS2}C_1}{C_2}} \quad (12)$$

It is evident that the values of ω_0 and Q may be slightly changed by the effect of the VDTA's tracking errors. However, the small deviation in equations (11) and (12) can be minimized by properly adjusting the VDTA's transconductance values. Hence, the desired parameter values can still be satisfied.

The active and passive relative sensitivities of ω_0 and Q parameter of the filter in Fig.3 are derived as:

$$S^{\omega_0}_{\beta_{F1},\beta_{F2}} = S^{\omega_0}_{g_{mF1},g_{mF2}} = 0 \quad (13)$$

$$S^{\omega_0}_{\beta_{S1},\beta_{S2}} = S^{\omega_0}_{g_{mS1},g_{mS2}} = \frac{1}{2} \quad (14)$$

$$S^{\omega_0}_{C_1,C_2} = -\frac{1}{2} \quad (15)$$

$$S^{Q}_{\beta_{F2}} = S^{Q}_{g_{mF2}} = 0 \quad (16)$$

$$S^{Q}_{\beta_{S1},\beta_{S2}} = S^{Q}_{g_{mS1},g_{mS2}} = \frac{1}{2} \quad (17)$$

$$S^{Q}_{\beta_{F1}} = S^{Q}_{g_{mF1}} = -1 \quad (18)$$

$$S^{Q}_{C_1} = -S^{Q}_{C_2} = \frac{1}{2} \quad (19)$$

Consequently, all of the component sensitivities of ω_0 and Q are very low and not more than unity in magnitude.

V. Simulation Results

To prove the theoretical validity of the filter given in Fig. 3, this filter was simulated with PSPICE program. The VDTA was simulated using the CMOS implementation structure given in Fig. 2 based on the 0.35-μm TSMC process parameters. The aspect ratios of the MOS transistor are given in Table 1.The supply voltages are +V =–V = 2 V. For all simulations, the capacitance values were chosen as: $C_1 = C_2 = 20$ pF.

In order to realize the filter responses with a natural frequency of $f_0 = \omega_0/2\pi \cong 3.03$ MHz and a quality factor of $Q = 1$, the following setting for the presented filter in Fig.3 has been selected as: $g_{mF1} = g_{mS1} = g_{mF2} = g_{mS2} = 381$ μA/V ($I_{BF1} = I_{BS1} = I_{BF2} = I_{BS2} \cong 40$ μA), which results in the total power consumption of about 2 mW. Fig. 4 shows the simulation results for LP, BP,HP and BS filter characteristics. The gain and phase responses of the AP filter configuration are also shown in Fig. 5.

To demonstrate the electronic controllability of f_0, the tuning transconductances g_{mi} (i.e. $I_{Bi} = I_{BF1} = I_{BS1} = I_{BF2} = I_{BS2}$) were respectively varied to 190 µA/V, 381 µA/V and 763 µA/V ($I_{Bi} \cong$ 10 µA, 40 µA and 160 µA), at a constant $Q = 1$. In this setting, the f_0-values calculated from equation (6) are approximated to 1.51 MHz, 3.03 MHz and 6.07 MHz, respectively. The resulting responses of the BP filter corresponding to different bias currents I_{Bi} are given in Fig.6. The corresponding f_0 obtained from the simulations are found as 1.54 MHz, 2.95 MHz and 5.49 MHz, respectively.

Table I
Transistor dimensions of the CMOS VDTA circuit in Fig.2.

Transistors	W (μm)	L (μm)
M1-M2, M5-M6	16.1	0.7
M3-M4, M7-M8	28	0.7
M9-M12	21	0.7
M13,M16	7	0.7
M14-M15, M17-M18	8.5	0.7

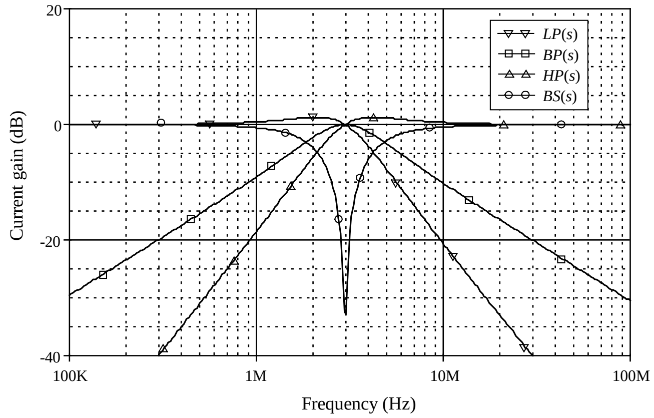

Fig.4: Simulated LP, BP and HP responses for the proposed filter in Fig.3.

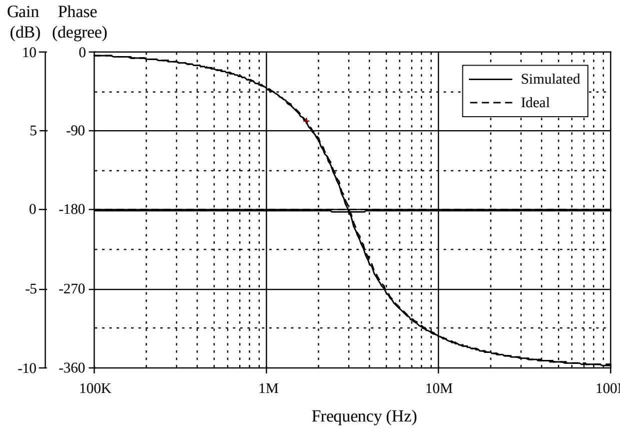

Fig.5. Ideal and simulated gain and phase responses of the AP filter

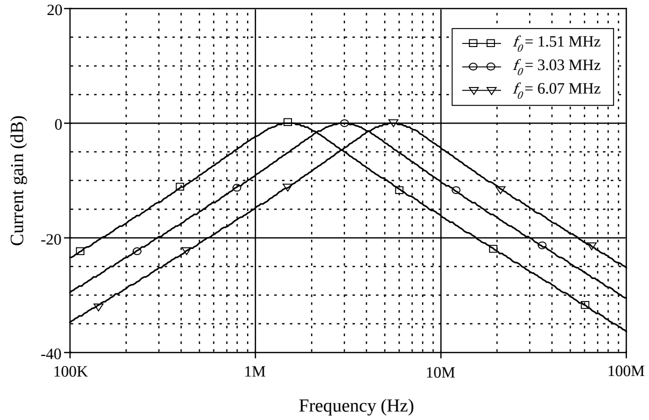

Fig.6: Simulated frequency responses of the BP filter when f_O is varied and $Q = 1$.

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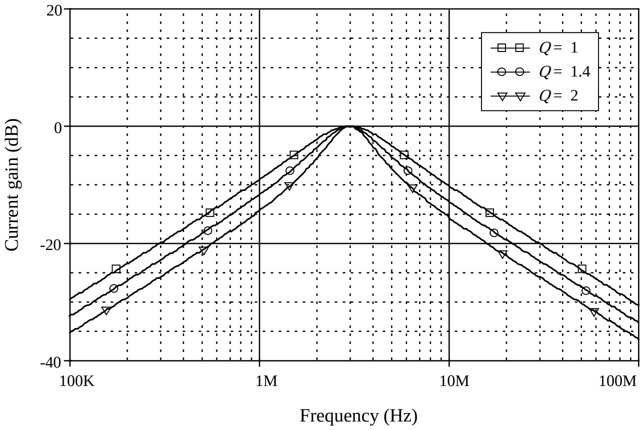

Fig.7: Simulated frequency responses of the BP filter when Q is varied and $f_O \cong 3.03$ MHz.

Fig.7 shows the simulated BP responses with Q-tuning. In this case, the bias currents were chosen as: $I_{BS1} = I_{BF2} = I_{BS2} =$ 40 μA for a constant $f_0 \cong 3.03$ MHz and I_{BF1} = 10 μA, 20 μA, 40 μA, respectively.

VI. Conclusion

In this work, an electronically tunable current-mode universal filter with three inputs and single output using VDTA has been described. The proposed circuit employs two VDTAs and two grounded capacitors, which is convenient for integration. The circuit can realize all the five standard biquadratic filter functions with interconnection of the relevant input current. It also provides the advantage of non-interactive electronic control of the important parameters ω_0 and Q through the transconductance of the VDTA, and low sensitivity performance. It was demonstrated that the simulation results are in good agreement with the expected values.

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