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An Electronically Tunable Universal Filter Employing Single CCCCTA and Minimum Number of Passive Components

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Abstract. This paper presents new realization of electronically tunable second order voltage-mode and current-mode universal filters using a recently reported active building block (ABB), namely the current controlled current conveyor transconductance amplifier (CCCCTA). The proposed circuits use single CCCCTA and two capacitors and do not use any external resistor. The circuits provide all the filter responses without changing the circuit topology. All capacitors are virtually grounded. The use of grounded capacitors makes the circuit favourable for monolithic implementation. The quality factor and pole frequency can be tuned independently via the bias currents. The non-ideal analysis and sensitivity analysis have been included. Both the active and passive sensitivities are not more than unity. The proposed circuits are designed in bipolar technology and the performances are verified through PSpice simulations. The results agree well with the theoretical anticipation. The power dissipation of the circuit is found as 2.94mW at ±1.5V supply voltages.

Keywords: Universal filter; Current controlled current conveyor transconductance amplifier (CCCCTA); Voltage-mode; Current-mode; Pole frequency; Quality factor.

1. Introduction

Analog filters are the important building blocks in the field of electrical engineering. They are widely used in data communication systems, measurement and instrumentation, regulation, electro acoustics and control systems [1]. In the last decade there has been significant interest to design multiple input and single output voltage-mode universal filter. Nowadays, a filter working in the current-mode technique is more suitable rather than the conventional voltage-mode technique. The current-mode structures are more favourable because of their advantages such as, higher signal bandwidth, larger dynamic range, greater linearity and simple circuitry [2].

Many voltage-mode and current-mode universal filters based on various active elements have been proposed. These include filters using second generation current conveyor (CCII) [3], fully differential second generation current conveyor (FDCCII) [4-5], current feedback amplifier (CFA) [6-7], differential difference current conveyor (DDCC) [8], differential voltage current conveyor (DVCC) [9] and current follower transconductance amplifier (CFTA) [10]. But a careful study of these reported literatures indicates that

- The circuits proposed in [4, 6, 8] use multiple ABBs and the circuits in [3-6, 8-10] employ excessive number of passive components, particularly resistors. Therefore they have high power dissipation.
- Can not provide all standard filter functions [3-4, 6, 8-10].
- The quality factor (Q) and pole frequency (ω_o) can not be controlled independently in [7].
- Electronic tuning of either the pole frequency or the quality factor is not possible in [3-6, 8-9].
- The DDCC based voltage-mode multifunction filter [8] uses two DDCCs and the second DDCC has two of its input Y terminals grounded. Thus, the circuit is overlarge due to partial utilization of the input terminals.

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Due to the above limitations these circuits are not suitable for monolithic implementation. In 2005, an active building block, namely the current conveyor transconductance amplifier (CCTA) has been proposed [11]. This can operates in both current-mode and voltage-mode. But the CCTA performance can not be controlled by the parasitic resistance at the X input terminal. So when it is used in various circuits, it requires external resistor. Recently, a modified version of the CCTA has been developed called the current controlled current conveyor transconductance amplifier (CCCCTA) [12] whose parasitic resistance at the port X can be controlled by the bias current. Several implementations of voltage-mode and current-mode universal filters employing the CCTA and CCCCTA have been reported in the literatures [12-19]. Unfortunately, these filter circuits suffer from the following weaknesses. The filter circuits in [13-14] use external resistors and in [12] there is a requirement of additional circuits for obtaining inverting type input signal, inverting type double input signal in the voltage-mode and double input signal in the current-mode. Also it uses a capacitor at the X terminal in series with X terminal parasitic resistance R_X. This limits the application of this filter in high frequency region [14]. The filter circuits in [15-18] use two or three active elements and the circuits proposed in [15-16, 18-19] can not provide all the standard filter responses.

The purpose of this paper is to design a universal filter based on single CCCCTA and capacitors that overcomes the above drawbacks. The proposed voltage-mode filter is a three input and single output universal filter. The proposed voltage-mode structure has been transformed into the equivalent current-mode structure using the adjoint transformation method [20]. The proposed filter circuits provide all the filter functions i.e., low-pass, high-pass, band-pass, notch and all-pass filter without changing the circuit topology. The pole frequency and the quality factor can be tuned electronically via bias currents. The circuit offers independent control of the quality factor and the pole frequency. Non-ideal analysis and the sensitivity analysis are presented. The circuit offers low active and passive sensitivities. The proposed filter circuits have been simulated using PSpice that validate the workability of the filter circuits.

2. Current Controlled Current Conveyor Transconductance Amplifier

The current controlled current conveyor transconductance amplifier (CCCCTA) is an active building block which consists of two principal building blocks, a second generation translinear current controlled current conveyor (CCCCII) at the front end and operational transconductance amplifiers (OTAs) at the rear end [12]. It possesses all the good properties of CCCCII and OTAs. The circuit symbol of the CCCCTA is shown in Fig. 1. The port relationship of the CCCCTA can be characterized by the following equations

$$I_Y = 0,\ V_X = V_Y + I_X R_X,\ I_{Z+} = +I_X,\ I_{Z-} = -I_X,\ I_{O+} = +g_m V_{Z+},\ I_{O-} = -g_m V_{Z+} \quad (1)$$

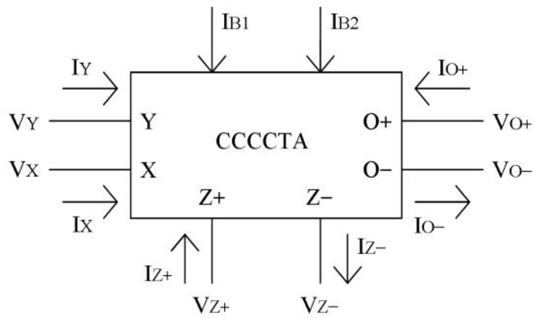

Fig. 1: The schematic symbol of the CCCCTA.

where R_X represents the finite input resistance at the X terminal and g_m represents the transconductance of the CCCCTA. For bipolar implementation of the CCCCTA as shown in Fig. 2, the parasitic resistance and the transconductance can be adjusted by the bias currents I_{B1} and I_{B2} as shown in the following equations

$$R_X = V_T / 2I_{B1} \text{ and } g_m = I_{B2} / 2V_T \quad (2)$$

where V_T is the thermal voltage whose value is 26mV at 27 ℃.

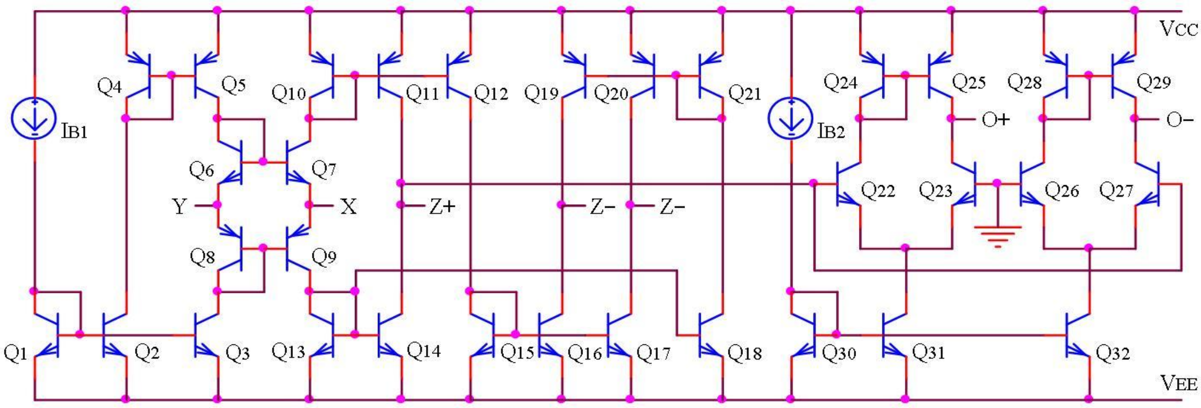

Fig. 2: A possible bipolar implementation of the CCCCTA.

3. Proposed Filter Design

The proposed three input and single output voltage-mode universal filter is shown in Fig. 3. It employs single CCCCTA and two capacitors. Using (1) and doing routine circuit analysis, the output voltage of the proposed filter circuit is given as follows

$$V_{out} = [s^2 C_1 C_2 R_X V_{in1} + (sC_2 + g_m) V_{in2} - sC_2 g_m R_X V_{in3}] / D \quad (3)$$

where $D = s^2 C_1 C_2 R_X + sC_2 + g_m$ (4)

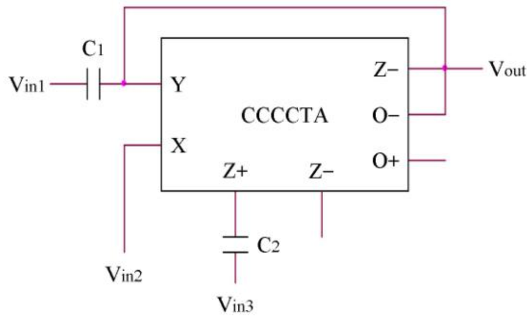

Fig. 3: CCCCTA based filter working in the voltage-mode.

Table 1: Selection of appropriate values of the input voltages

Filter responses	Inputs		
V_{out}	V_{in1}	V_{in2}	V_{in3}
LP (R_X=1/g_m)	0	1	1
HP (R_X=1/g_m)	1	0	0
BP (R_X=1/g_m)	0	0	1
Notch (R_X=1/g_m)	1	1	1
AP (R_X=2/g_m)	1	1	1

From (3), the values of the input voltages V_{in1}, V_{in2} and V_{in3} are chosen with digital method as shown in Table 1 to obtain the desired filter responses. Therefore, it is capable of realizing all types of filter responses.

The proposed multiple input and single output voltage-mode universal filter is ingeniously transformed into the equivalent single input and multiple output current-mode universal filters by using the adjoint transformation method [20]. The current-mode filter is shown in Fig. 4. The current transfer functions are given by

$$I_{out1}/I_{in} = s^2 C_1 C_2 R_X / D = K_{HP}, \quad I_{out2}/I_{in} = g_m / D = K_{LP},$$
$$I_{out3}/I_{in} = sC_2 / D = K_{BP1}, \quad I_{out4}/I_{in} = sC_2 / D = K_{BP2}, \; I_{out5}/I_{in} = -sC_2 / D = K_{InverseBP},$$
$$(I_{out1} + I_{out2})/I_{in} = (s^2 C_1 C_2 R_X + g_m)/D = K_{Notch},$$
$$(I_{out1} + I_{out2} + I_{out5})/I_{in} = (s^2 C_1 C_2 R_X - sC_2 + g_m)/D = K_{AP} \quad (5)$$

Therefore the current-mode structure in Fig. 4 will be used as a universal filter of equivalent properties to those of voltage-mode universal filter of Fig. 3. For all these filter responses the pole frequency (ω_o), quality factor (Q) and bandwidth (BW) can be expressed as

$$\omega_o = \sqrt{g_m / C_1 C_2 R_X}\,,\;\; Q = \sqrt{g_m C_1 R_X / C_2}\,,\; BW = \omega_o / Q = 1/C_1 R_X \tag{6}$$

The above equations reveal that the pole frequency (ω_o) can be controlled independently of the quality factor (Q) with simultaneously changing R_X and g_m such that the product $g_m R_X$ remains constant and the quotient g_m/R_X varies and vice versa. The pole frequency (ω_o) can be controlled independently of the bandwidth (BW) by changing g_m and C_2.

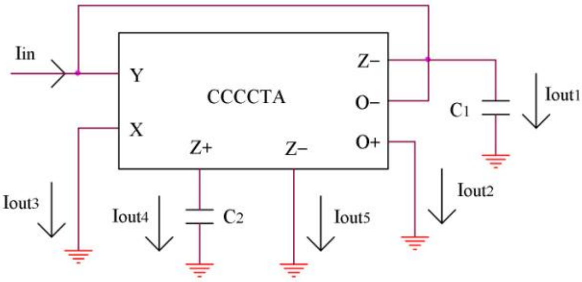

Fig. 4: CCCCTA based filter working in the current-mode.

4. Non-Ideal Analysis and Sensitivity Analysis

For the non-ideal case, the CCCCTA can be characterized by the following equations [18]

$$I_Y = 0,\; V_X = \beta V_Y + I_X R_X\,,\; I_{Z+} = +\alpha_1 I_X\,,\; I_{Z-} = -\alpha_2 I_X\,,\; I_{O+} = +\gamma_1 g_m V_{Z+},\; I_{O-} = -\gamma_2 g_m V_{Z+} \tag{7}$$

where β is the voltage transfer gain, α_1, α_2, γ_1 and γ_2 are the current transfer gains. They depend on the transistor parameters, frequency of operation and temperature. In practical, $\beta = 1-\varepsilon_1$, $\alpha_1 = 1-\varepsilon_2$, $\alpha_2 = 1-\varepsilon_3$, $\gamma_1 = 1-\varepsilon_4$ and $\gamma_2 = 1-\varepsilon_5$. The parameter ε_1 ($|\varepsilon_1| \langle\langle 1$) denotes the voltage tracking error of the voltage inverting stage and ε_2, ε_3, ε_4 and ε_5 ($|\varepsilon_2|,|\varepsilon_3|,|\varepsilon_4|,|\varepsilon_5| \langle\langle 1$) are the current tracking error of the current inverting stage of the CCCCTA. These gains are ideally equal to unity. Taking into account the aforementioned non-idealities the modified expression of the output voltage and currents of the proposed filter circuits as shown in Fig. 3 and Fig. 4 are

$$V_{out} = [s^2 C_1 C_2 R_X V_{in1} + (sC_2\alpha_2 + \alpha_1\gamma_2 g_m)V_{in2} - sC_2\gamma_2 g_m R_X V_{in3}]/D \tag{8}$$

$$I_{out1}/I_{in} = s^2 C_1 C_2 R_X / D = K_{HP}\,,\;\; I_{out2}/I_{in} = \alpha_1\beta\gamma_1\, g_m / D = K_{LP}\,,$$

$$I_{out3}/I_{in} = sC_2\beta/D = K_{BP1},\; I_{out4}/I_{in} = sC_2\alpha_1\beta/D = K_{BP2},\; I_{out5}/I_{in} = -sC_2\alpha_2\beta/D = K_{InverseBP},$$

$$(I_{out1} + I_{out2})/I_{in} = (s^2 C_1 C_2 R_X + \alpha_1\beta\gamma_1 g_m)/D = K_{Notch},$$

$$(I_{out1} + I_{out2} + I_{out5})/I_{in} = (s^2 C_1 C_2 R_X - sC_2\alpha_2\beta + \alpha_1\beta\gamma_1 g_m)/D = K_{AP} \tag{9}$$

where $D = s^2 C_1 C_2 R_X + sC_2\alpha_2\beta + \alpha_1\beta\gamma_2 g_m$ (10)

In this case, the pole frequency (ω_o), quality factor (Q) and bandwidth (BW) are changed to

$$\omega_o = \sqrt{\alpha_1\beta\gamma_2 g_m / C_1 C_2 R_X}\,,\;\; Q = 1/\alpha_2 \sqrt{\alpha_1\gamma_2 g_m C_1 R_X / \beta C_2}\,,\; BW = \alpha_2\beta / C_1 R_X \tag{11}$$

The sensitivity of any active network is given as

$$S_e^F = \frac{e}{F}\frac{\partial F}{\partial e} \tag{12}$$

where F represents a network function and e represents the element of variation of the filter. A sensitivity study of the filter parameters for the proposed circuits is analyzed here. The non-ideal sensitivities of the pole frequency (ω_o), quality factor (Q) and bandwidth (BW) with respect to active and passive elements are given by

$$S_{\alpha_1}^{\omega_o} = S_{\beta}^{\omega_o} = S_{\gamma_2}^{\omega_o} = S_{g_m}^{\omega_o} = 1/2,\;\; S_{C_1}^{\omega_o} = S_{C_2}^{\omega_o} = S_{R_X}^{\omega_o} = -1/2,$$

$$S_{\alpha_1}^{Q} = S_{\gamma_2}^{Q} = S_{g_m}^{Q} = S_{C_1}^{Q} = S_{R_X}^{Q} = 1/2,\;\; S_{\beta}^{Q} = S_{C_2}^{Q} = -1/2,\;\; S_{\alpha_2}^{Q} = -1,$$

$$S_{\alpha_2}^{BW} = S_{\beta}^{BW} = +1,\; S_{C_1}^{BW} = S_{R_X}^{BW} = -1 \tag{13}$$

Therefore it is evident that the magnitudes of the active and passive sensitivities are not more than unity.

5. Results and Discussions

The proposed voltage-mode and current-mode universal filter circuits have been simulated in PSpice by using the bipolar implementation of the CCCCTA as shown in Fig. 2. The proposed circuits are designed for $f_{osc}=\omega_o/2\pi$=61.24kHz and Q=1. The CCCCTA is biased with ±1.5V power supplies. The passive components were chosen as C_1=10nF and C_2=10nF. The input bias currents were chosen as I_{B1}=50 μA and I_{B2}=200 μA. Fig. 5(a) shows the gain responses of the low-pass, high-pass, band-pass, all-pass and notch filter in case of voltage-mode. Fig. 5(b) shows the gain responses of the current-mode filter. It yields the pole frequency of 60.39kHz, where the calculated value of the pole frequency from (6) is 61.24kHz (deviated by 1.39%). It is noted that the simulation results agree well with the theoretical results as expected. The deviation arises due to the non-ideal properties of CCCCTA employed in the proposed circuit. The gain response of the band-pass functions for constant Q value and different values of f_{osc} is shown in Fig. 6(a). It is found that the pole frequency can be adjusted without disturbing the quality factor, as shown in (6). The gain response of the band-pass functions for constant f_{osc} and different values of Q is shown in Fig. 6(b). This indicates that the quality factor can be adjusted without affecting the pole frequency. The power dissipation of the voltage-mode filter for the design values is 2.94mW.

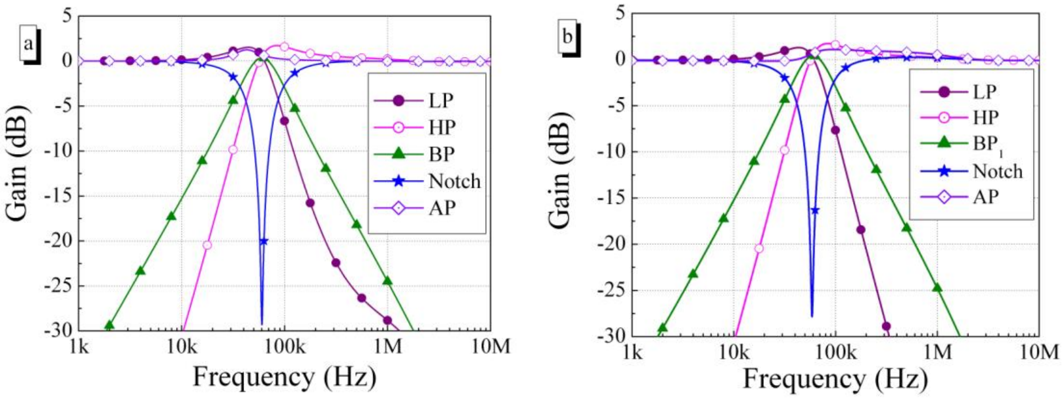

Fig. 5: Gain responses of the universal filter in (a) voltage-mode (b) current-mode.

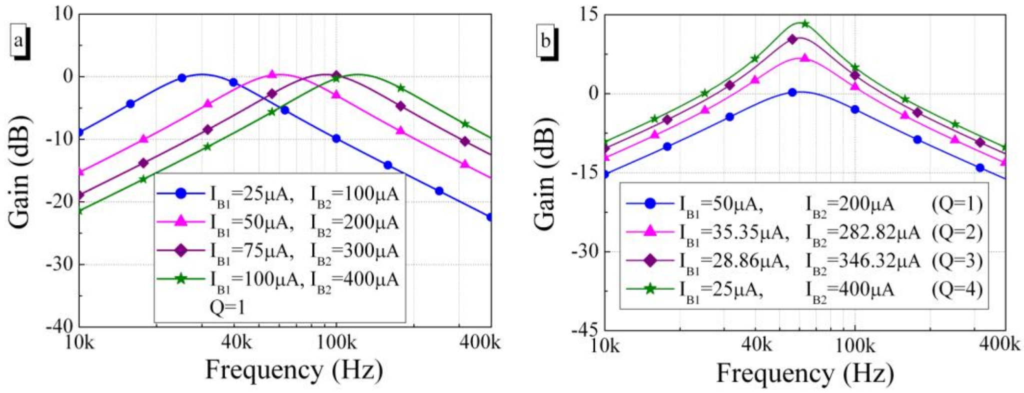

Fig. 6: Band-pass responses for (a) constant Q and different values of f_{osc} (b) constant f_{osc} and different values of Q.

6. Conclusions

New voltage-mode and current-mode second order universal filters based on single CCCCTA have been presented. The circuits require minimum number of passive components to achieve the transfer functions. The proposed filter circuits provide low-pass, high-pass, band-pass, all-pass and notch responses without changing the circuit topology. All capacitors are virtually grounded. The use of grounded capacitors makes the circuit favourable for monolithic implementation. The current-mode structure has been obtained from voltage-mode structure by using the adjoint transformation method. The circuits offer the advantages of electronic tuning of the pole frequency and the quality factor. The quality factor and the pole frequency can be orthogonally adjusted by simultaneously changing I_{B1} and I_{B2} in proper way. The non-ideal analysis and sensitivity analysis are also carried out. The circuits offer low active and passive sensitivities.

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