Current-Mode KHN Biquad Filter Using Modified CFTAs and Grounded Capacitors

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***Abstract*—In this paper, a current-mode Kerwin-Huelsman-Newcomb (KHN) filter structure employing four modified current follower transconductance amplifiers (MCFTAs) and two grounded capacitors is proposed. The circuit structure has one low-impedance current input and three high-impedance current outputs, and enables realizing lowpass, bandpass and highpass current responses simultaneously. The bandstop and allpass responses can also be obtained by connecting appropriate output currents directly without additional devices. The proposed filter is capable of providing an independent current-control of the natural angular frequency (ω_o) and quality factor (*Q*) through the transconductance of the MCFTA. Moreover, high-*Q* value filter can be realized by simply tuning the ratio of MCFTA's transconductance. To support the theoretical results, the properties of the presented filter have been verified by simulation results.**

***Index Terms*— Current Follower Transconductance Amplifier (CFTA), Kerwin-Huelsman-Newcomb (KHN), biquad filter, current-mode circuit**

I. INTRODUCTION

THE state variable type filter, also known as the KHN filter for inventors Kerwin-Huelsman-Newcomb biquad or KHN biquad is one of the best known multifunction filtering structures [1]. It consists of two integrators and a summing amplifier to provide second-order lowpass (LP), bandpass (BP) and highpass (HP) filtering responses simultaneously. It also provides several advantage features such as low component spread, low passive and active sensitivities and good stability behavior [2]. In the current technical literature, various solutions of the KHN biquad structure using different types of active devices have been reported in [2]-[10]. Some of them operate in voltage-mode [2]-[7]. As is well-known, the current-mode circuits offer certain advantages such as greater linearity, wider bandwidth, less power consumption, larger dynamic range and simplicity in circuit implementation compared to their voltage-mode counterparts. Therefore, some current-mode KHN biquads can be found in [7]-[10]. However, with three inputs and single output, the works in [7]-[8] cannot realize all the biquadratic filter responses simultaneously. Also, the input terminals of these filters do not exhibit low-input impedances. In [9], the current-mode KHN-biquad using differential voltage current conveyors has been reported. It provides LP, BP and HP responses simultaneously, but it suffers from high-input impedance due to a resistor connected to its input. Recently, using three current follower transconductance amplifiers (CFTAs), the KHN-equivalent filter working in current-mode has been presented [10]. The presented circuit provides the three standard biquadratic filter responses simultaneously, while the bandstop (BS) and allpass (AP) responses can be obtained with interconnection of the relevant output currents. In addition, it possesses a low-input impedance and high-output impedance characteristic, resulting in easy cascadability for current-mode process. However, its natural frequency (ω_0) and quality factor (*Q*) cannot be tuned independently.

This paper is presenting the design of the current-mode KHN-equivalent biquad with low-input and high-output impedance is proposed. The developed filter is constructed four modified CFTAs (MCFTAs) and two grounded capacitors, which is suitable for integrated circuit (IC) implementation. The circuit realizes LP, BP and HP current responses simultaneously with an independent electronic control of ω_0 and *Q* by means of adjusting the bias current of the MCFTAs. Moreover, the BS and AP responses can be obtained simply by interconnecting their relevant output currents without using extra active devices. In addition, high *Q*-value filters can easily be obtained by adjusting the ratio of two independent bias currents. Because of the low-input and high-output impedances of the circuit, it is easily cascadable. The circuit parameter sensitivities are all low. Simulation results confirming the theoretical results are also included.

II. DESCRIPTION OF MODIFIED CFTA (MCFTA)

The schematic symbol and its ideal behavioral model of the MCFTA are represented in Figs.1(a) and (b). The MCFTA element is a slight modification of the CFTA element by extending the circuit with an auxiliary terminal z, called z_1 [11]. As a consequence, a number of applications based on MCFTAs can be increased. The MCFTA operation is defined by the following expression :

$$\begin{bmatrix} v_f \\ i_z \\ i_{z1} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_f \\ v_z \\ v_{z1} \\ v_{x+} \\ v_{x-} \end{bmatrix} \tag{1}$$

where g_m is the transconductance gain of the MCFTA, which can be controlled electronically.

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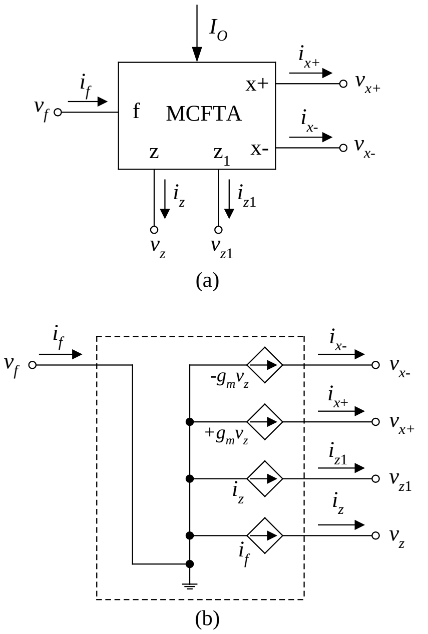

Fig. 1 MCFTA
(a) schematic symbol (b) behavioral model

The possible equivalent realization of the MCFTA based on bipolar transistor technology is shown in Fig.2. In this case, the g_m-value of the MCFTA is directly proportional to an external DC bias current (I_O), which is given as [12] :

$$g_m = \frac{I_O}{2V_T} \tag{2}$$

where V_T is the usual thermal voltage (approximately 26 mV at room temperature 27°C).

III. PROPOSED CURRENT-MODE KHN BIQUAD FILTER

Fig.3 shows the realization of the proposed current-mode KHN-equivalent biquad. It employs two lossless integrators (MCFTA1, C_1 and MCFTA2, C_2) and current-controlled gain block (MCFTA3 and MCFTA4) [13]. Note that the circuit uses only grounded capacitors as passive elements, thus it is advantageous from integration point of view. Another advantage is that it has a low-input impedance and high-output impedance property. Hence, it permits easy cascadability. Routine analysis of the proposed circuit given in Fig.3 gives the following filter transfer functions :

$$LP(s) = \frac{I_{LP}(s)}{I_{in}(s)} = \frac{\left(\dfrac{g_{m1}g_{m2}}{C_1C_2}\right)}{D(s)} \tag{3}$$

$$BP(s) = \frac{I_{BP}(s)}{I_{in}(s)} = \frac{\left(\dfrac{g_{m1}g_{m4}}{g_{m3}C_1}\right)s}{D(s)} \tag{4}$$

$$HP(s) = \frac{I_{HP}(s)}{I_{in}(s)} = \frac{s^2}{D(s)} \tag{5}$$

and

$$D(s) = s^2 + \left(\frac{g_{m1}g_{m4}}{g_{m3}C_1}\right)s + \left(\frac{g_{m1}g_{m2}}{C_1C_2}\right) \tag{6}$$

Therefore, the proposed filter simultaneously realizes second-order LP, BP and HP current responses without requiring any component matching condition.

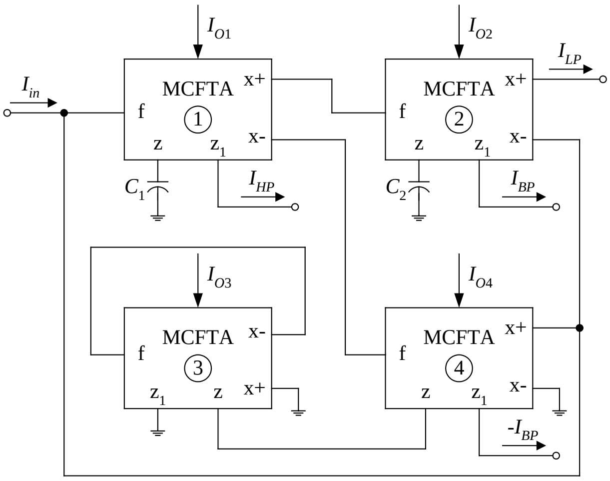

Fig.3 : Proposed current-mode KHN biquad filter using MCFTAs.

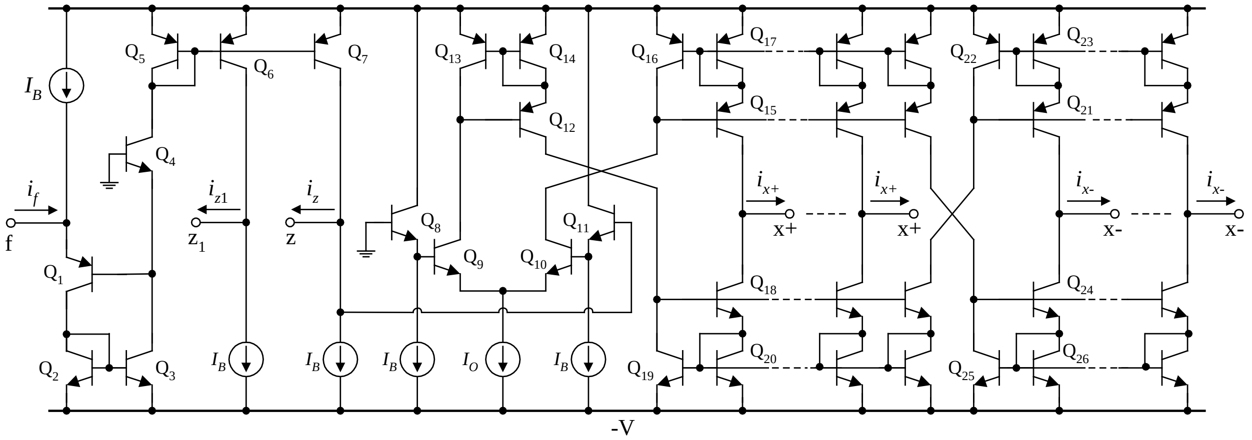

Fig.2 : Schematic bipolar implementation of the MCFTA.

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Moreover, the relevant output currents in equations (3)-(5) can be tied together to obtain the BS and AP responses without any condition or additional circuitry as follows :

$$BS(s) = I_{LP}(s) + I_{HP}(s) \tag{7}$$

and

$$AP(s) = I_{LP}(s) + I_{BP}(s) + I_{HP}(s) \tag{8}$$

The important parameters ω_o and Q of this filter are found as :

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}} \tag{9}$$

and

$$Q = \frac{g_{m3}}{g_{m4}}\sqrt{\frac{g_{m2} C_1}{g_{m1} C_2}} \tag{10}$$

where $g_{mi} = I_{Oi}/2V_T$ and I_{Oi} are g_m and I_O of the i-th MCFTA (i = 1, 2, 3, 4).

Furthermore, for simplicity, substituting $g_{m1} = g_{m2} = g_m$ ($I_{O1} = I_{O2} = I_O$) and $C_1 = C_2 = C$ in equations (9) and (10) yields the following expressions :

$$\omega_0 = \frac{I_O}{2V_T C} \tag{11}$$

and

$$Q = \frac{I_{O3}}{I_{O4}} \tag{12}$$

It should be noted from equations (11) and (12) that the filter parameters ω_o and Q are independently controllable. This means that the ω_o for all filter responses can electronically be tuned without disturbing the Q-value by adjusting I_O. Also, the parameter Q can be tuned independently by the ratio of I_{O3} and I_{O4}. Therefore, the high-Q filters can be obtained by setting this ratio properly. Furthermore, from equation (12), the Q-value is temperature insensitive.

IV. TRACKING ERRORS AND SENSITIVITY ANALYSIS

By taking the MCFTA non-idealities into consideration, the port relation in equation (1) can be rewritten as :

$$\begin{bmatrix} v_f \\ i_z \\ i_{z1} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \alpha_i & 0 & 0 & 0 & 0 \\ \alpha_i & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_f \\ v_z \\ v_{z1} \\ v_{x+} \\ v_{x-} \end{bmatrix} \tag{13}$$

where $\alpha_i = 1 - \varepsilon_i$ and ε_i ($|\varepsilon_i| << 1$) represents the current tracking error from f to z or z_1 terminals of the i-th MCFTA. Re-analyzing the proposed circuit of Fig.3 with equation (9) yields the following non-ideal parameters :

$$\omega_0 = \sqrt{\frac{\alpha_1 \alpha_2 g_{m1} g_{m2}}{C_1 C_2}} \tag{14}$$

and

$$Q = \frac{\alpha_3 g_{m3}}{\alpha_4 g_{m4}}\sqrt{\frac{\alpha_2 g_{m2} C_1}{\alpha_1 g_{m1} C_2}} \tag{15}$$

It is evident that the values ω_o and Q slightly change by the effect of the MCFTA current tracking error. However, these deviations may be compensated by re-adjusting the g_m-value appropriately. Thus, the desired parameter values can still be satisfied. From equations (14) and (15), all the active and passive sensitivities are within unity in magnitude.

V. SIMULATION RESULTS

To prove the theoretical validity of the filter proposed in Fig.3, this filter was simulated with PSPICE program. The MCFTAs were simulated using the schematic bipolar implementation given in Fig.2 with the transistor model of PR100N (PNP) and NP100N (NPN) of the bipolar arrays ALA400 from AT&T [14]. DC supply voltage = ±2V and DC bias current I_B = 50 μA have been chosen. For all simulations, the capacitance values were chosen as : $C_1 = C_2$ = 1 nF.

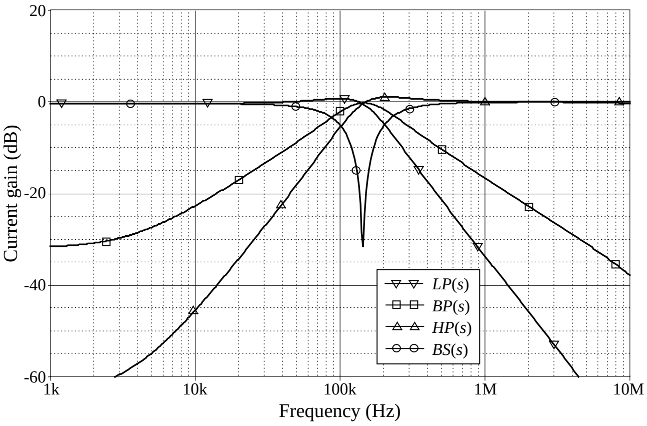

Fig.4 : Simulated LP, BP, HP and BS responses for the proposed filter in Fig.3.

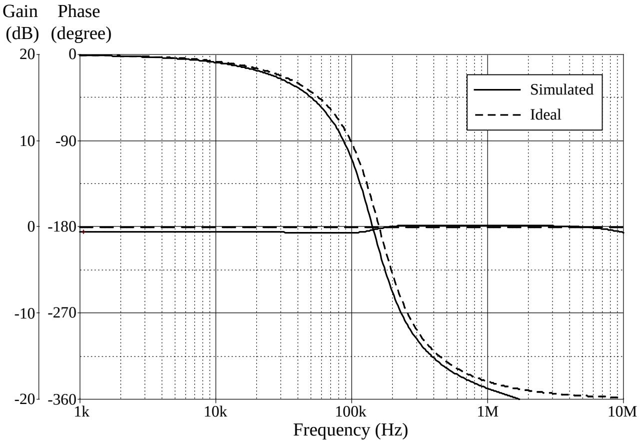

Fig.5 : Ideal and simulated gain and phase responses of the AP filter configuration in Fig.3.

In order to realize the filter responses with a natural frequency of $f_0 = \omega_0/2\pi \cong$ 159 kHz and a quality factor of Q = 1, the following setting for the presented filter of Fig.3 have been selected as : $I_{O1} = I_{O2} = I_{O3} = I_{O4}$ = 50 μA (g_{m1} =

$g_{m2} = g_{m3} = g_{m4}$ = 1mA/V), which results in total power consumption of 11.2 mW. Fig.4 shows the simulation results for HP, BP, LP and BS filter characteristics. The gain and phase responses of the AP filter configuration are also depicted in Fig.5. It can be observed form both figures that the proposed filter performs all the standard biquadratic filtering functions well, and the simulation results are close to ideal responses.

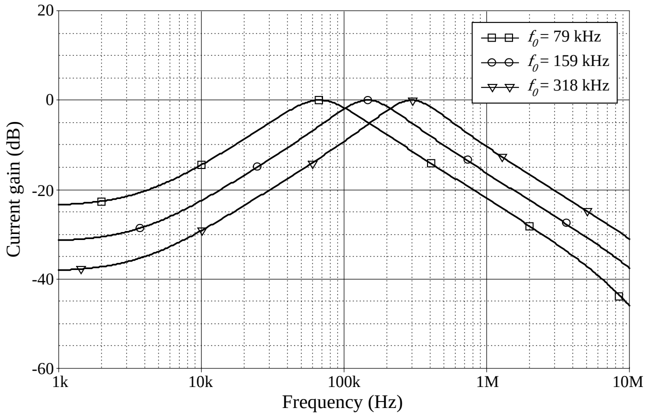

Fig.6 : Simulated frequency responses of the BP filter when f_O is varied and Q = 1.

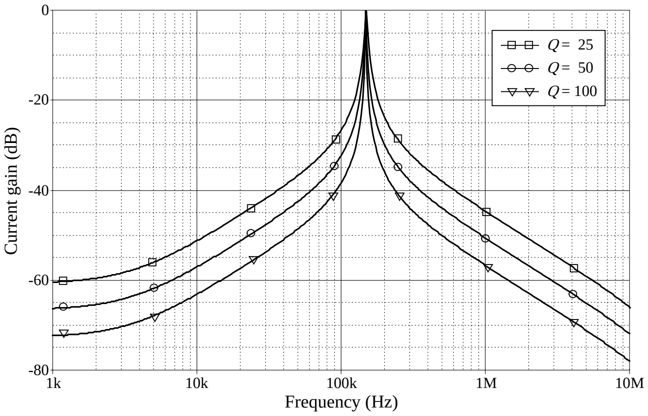

Fig.7 : Simulated frequency responses of the BP filter when Q is varied and $f_O \cong$ 159 kHz.

To demonstrate the electronic controllability of f_0, the tuning bias currents I_O (= $I_{O1} = I_{O2}$) were respectively varied to 25 μA, 50 μA and 100 μA, while keeping $I_{O3} = I_{O4}$ = 50 μA for Q = 1. In this setting, the f_0-values calculated from equation (11) are approximated to 79 kHz, 159 kHz and 318 kHz, respectively. The resulting responses of the BP filter corresponding to different bias currents I_O are given in Fig.6. From the simulations, the corresponding f_0 are found as 74.13 kHz, 151.35 kHz and 302 kHz, respectively.

Fig.7 shows the simulated BP responses with Q-tuning (i.e., Q = 25, 50 and 100). In this case, the bias currents were chosen as : $I_{O1} = I_{O2}$ = 50 μA, I_{O4} = 10 μA, and I_{O3} = 250 μA, 500 μA, 1000 μA, respectively. Note that the high-Q filter can be realized from high value of I_{O3}.

VI. CONCLUSION

The realization of current-mode KHN-equivalent biquad using MCFTAs has been described. The circuit structure employs four MCFTAs and two grounded capacitors, which is convenient for integration. The filter simultaneously realizes LP, BP and HP current responses from the same topology. The circuit can easily be modified to realize BS and AP functions. It provides independent current control of ω_0 and Q, and the filter with high Q value can be obtained by simply tuning the ratio of MCFTA's bias currents. It has both low-input and high-output impedance, thereby permitting easy cascadability. Also, the described circuit requires no component matching conditions, and has low sensitivities.

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