Novel mixed-mode KHN-equivalent filter using Z-copy CFTAs and grounded capacitors

Norbert Herencsar, Jaroslav Koton, Kamil Vrba, and Abhirup Lahiri

***Abstract*—**In this paper, a novel mixed-mode (voltage input/current output) Kerwin-Huelsman-Newcomb (KHN)-equivalent filter is presented. Proposed mixed-mode filter structure uses three Z-copy current follower transconductance amplifiers (ZC-CFTAs) as active elements, one external resistor and two grounded capacitors. The circuit simultaneously provides low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS), and all-pass (AP) responses directly without using additional active elements. SPICE simulation results using TSMC 0.35 μm CMOS process parameters are given to verify the theoretical analyses.

***Keywords*—**Analogue signal processing, Kerwin-Huelsman-Newcomb filter, mixed-mode, ZC-CFTA.

I. Introduction

FREQUENCY filters are linear electric circuits that are used in wide area of electronics and also are basic building blocks in analog signal processing [1]. In the last decade, the Kerwin-Huelsman-Newcomb (KHN)-equivalent filter design has received considerable attention due to their advantages, such as the universality, independent control of natural frequency and quality factor, and low sensitivity [2]. Number of solutions concerning this issue can be found in [3]–[12]. These papers deal with current- and/or voltage-mode KHN-equivalent filters using different active elements, such as current differencing buffered amplifiers (CDBAs) [3], current-controlled second generation current conveyors (CCCIIs) [4], differential difference current conveyors (DDCCs) [5], electronically tunable DDCCs (EDDCCs) [6], differential voltage current conveyors (DVCCs) [7]-[9], voltage conveyors and current active elements [10], or universal voltage conveyors (UVCs) [11]. Only [12] presents mixed-mode realization, where DVCCs are used as active elements. Therefore, there is still the need to propose novel KHN-equivalents with better properties. Hence, the aim of this paper is to present new mixed-mode KHN-equivalent using Z-copy current follower transconductance amplifiers (ZC-CFTAs). Compared with above mentioned circuit in [12], here presented solution simultaneously provides all five standard filter functions directly without using additional active elements. SPICE simulation results are given to confirm the feasibility of proposed circuit.

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II. Description of the ZC-CFTA

The Z-copy current follower transconductance amplifier (ZC-CFTA), which schematic symbol is shown in Fig. 1, consists of an input current follower that transfers the input current to the *z* terminal and an output transconductance amplifier stage, which is used to convert the voltage at the *z* terminal to output currents. The transconductance parameter $+g_m$ corresponds for the positive output and $-g_m$ for the negative output [13]–[15]. There is also *zc* terminal, which copies the *z* terminal current in direct direction. Relations between the individual terminals of ZC-CFTA can be described by the following hybrid matrix:

$$\begin{bmatrix} v_f \\ i_z \\ i_{zc} \\ i_{z+} \\ i_{z-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 & 0 \\ \gamma & 0 & 0 & 0 & 0 \\ 0 & +g_m & 0 & 0 & 0 \\ 0 & -g_m & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_f \\ v_z \\ v_{zc} \\ v_{z+} \\ v_{z-} \end{bmatrix}, \tag{1}$$

where $\alpha = 1 - \varepsilon_i$ and $\gamma = 1 - \varepsilon_j$. Here, ε_i and ε_j ($|\varepsilon_i|$, $|\varepsilon_i| \ll 1$) are current tracking errors from *f* terminal to *z* and *zc* terminals, respectively. The transconductance g_m of ZC-CFTA can be given by:

$$g_m = \sqrt{I_B \mu_0 C_{OX} \left(W/L\right)}, \tag{2}$$

where the current I_B is used to control the transconductance g_m, μ_0 is the free electron mobility in the channel, C_{OX} is the gate oxide capacitance per unit area, W and L are the channel width and length.

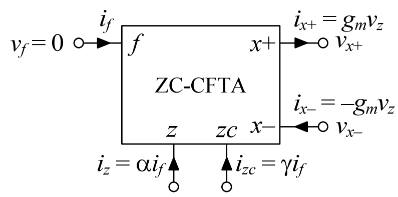


Fig. 1 Schematic symbol of ZC-CFTA

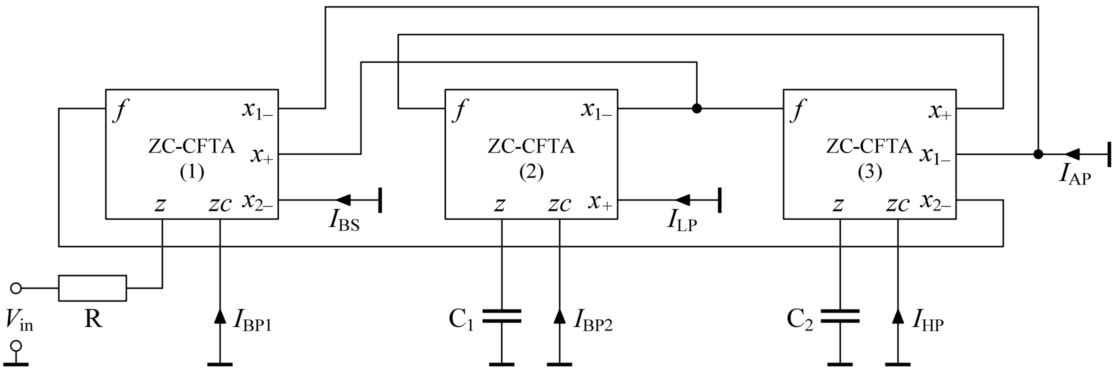


Fig. 2 Proposed KHN-equivalent filter employing ZC-CFTAs

III. Proposed Circuit

The proposed mixed-mode (voltage input/current output) filter employing three ZC-CFTAs, single resistor ($R = 1/G$), and two grounded capacitors (C_1, C_2) is shown in Fig. 2. Routine analysis yields following ideal ($\alpha_n = 1$ and $\gamma_n = 1$, where $n = 1, 2, 3$) filter transfer functions:

$$\frac{I_{\mathrm{LP}}}{V_{\mathrm{in}}} = \frac{\dfrac{g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{g_{m1}g_{m3}}{GC_2} + \dfrac{g_{m2}g_{m3}}{C_1C_2}}, \tag{2a}$$

$$\frac{I_{\mathrm{BP1}}}{V_{\mathrm{in}}} = -\frac{I_{\mathrm{BP2}}}{V_{\mathrm{in}}} = \frac{s\dfrac{g_{m1}g_{m3}}{C_2}}{s^2 + s\dfrac{g_{m1}g_{m3}}{GC_2} + \dfrac{g_{m2}g_{m3}}{C_1C_2}}, \tag{2b,c}$$

$$\frac{I_{\mathrm{HP}}}{V_{\mathrm{in}}} = \frac{s^2 g_{m1}}{s^2 + s\dfrac{g_{m1}g_{m3}}{GC_2} + \dfrac{g_{m2}g_{m3}}{C_1C_2}}, \tag{2d}$$

$$\frac{I_{\mathrm{BS}}}{V_{\mathrm{in}}} = \frac{s^2 g_{m1} + \dfrac{g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{g_{m1}g_{m3}}{GC_2} + \dfrac{g_{m2}g_{m3}}{C_1C_2}}, \tag{2e}$$

$$\frac{I_{\mathrm{AP}}}{V_{\mathrm{in}}} = \frac{s^2 - s\dfrac{g_{m1}g_{m3}}{C_2} + \dfrac{g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{g_{m1}g_{m3}}{GC_2} + \dfrac{g_{m2}g_{m3}}{C_1C_2}}. \tag{2f}$$

The natural angular frequency ω_0, the quality factor Q, and the bandwidth BW (ω_0/Q) of the filter can be found as:

$$\omega_0 = \sqrt{\frac{g_{m2}g_{m3}}{C_1C_2}},\ Q = \frac{G}{g_{m1}}\sqrt{\frac{g_{m2}C_2}{g_{m3}C_1}},\ BW = \frac{g_{m1}g_{m3}}{GC_2}. \tag{3a,b,c}$$

It should be noted that the parameters Q and BW can be adjusted by changing the g_{m1} of the ZC-CFTA1 without disturbing the parameter ω_0.

The active and passive sensitivities of the filter parameters are following:

$$S^{\omega_0}_{g_{m2},g_{m3}} = -S^{\omega_0}_{C_1,C_2} = \frac{1}{2},\ S^{\omega_0}_{G,g_{m1}} = 0, \tag{4a}$$

$$S^{Q}_{g_{m2},C_2} = -S^{Q}_{g_{m3},C_1} = \frac{1}{2},\ S^{Q}_{G} = -S^{Q}_{g_{m1}} = 1, \tag{4b}$$

$$S^{BW}_{g_{m1},g_{m3}} = -S^{BW}_{G,C_2} = 1,\ S^{BW}_{g_{m2},G} = 0, \tag{4c}$$

that are all not more than unity in magnitude.

By taking into consideration the non-idealities of the ZC-CFTA, Eqs. (2a)-(2f) can be rewritten as:

$$\frac{I_{\mathrm{LP}}}{V_{\mathrm{in}}} = \frac{\dfrac{\alpha_2\alpha_3 g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}, \tag{5a}$$

$$\frac{I_{\mathrm{BP1}}}{V_{\mathrm{in}}} = \frac{s\dfrac{\gamma_1\alpha_3 g_{m1}g_{m3}}{C_2}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}, \tag{5b}$$

$$\frac{I_{\mathrm{BP2}}}{V_{\mathrm{in}}} = -\frac{s\dfrac{\gamma_2\alpha_3 g_{m1}g_{m3}}{C_2}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}, \tag{5c}$$

$$\frac{I_{\mathrm{HP}}}{V_{\mathrm{in}}} = \frac{s^2\gamma_3 g_{m1}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}, \tag{5d}$$

$$\frac{I_{\mathrm{BS}}}{V_{\mathrm{in}}} = \frac{s^2 g_{m1} + \dfrac{\alpha_2\alpha_3 g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}, \tag{5e}$$

$$\frac{I_{\mathrm{AP}}}{V_{\mathrm{in}}} = \frac{s^2 g_{m1} - s\dfrac{\alpha_3 g_{m1}g_{m3}}{C_2} + \dfrac{\alpha_2\alpha_3 g_{m1}g_{m2}g_{m3}}{C_1C_2}}{s^2 + s\dfrac{\alpha_1\alpha_3 g_{m1}g_{m3}}{GC_2} + \dfrac{\alpha_2\alpha_3 g_{m2}g_{m3}}{C_1C_2}}. \tag{5f}$$

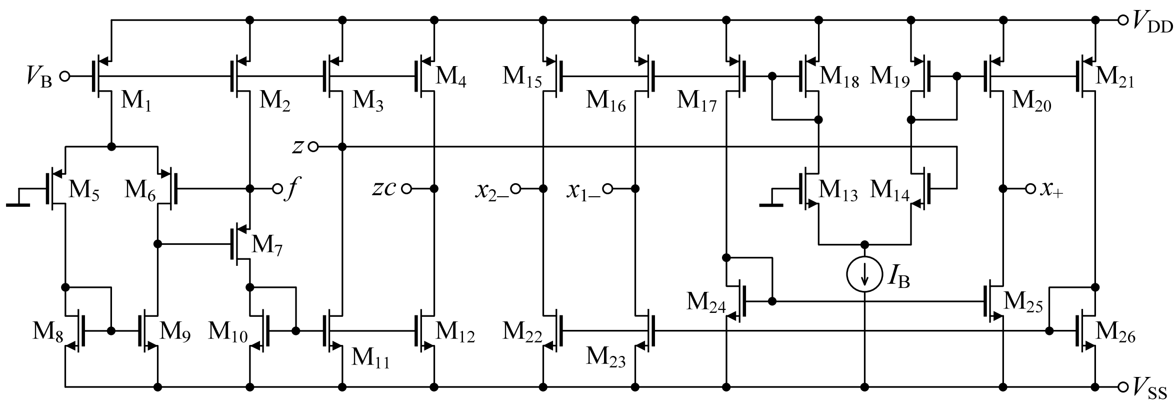


Fig. 3 CMOS implementation of ZC-CFTA

Re-analysis of the proposed filter configuration in Fig. 2 yields the non-ideal parameters ω_0, Q, and BW as:

$$\omega_0 = \sqrt{\frac{\alpha_2 \alpha_3 g_{m2} g_{m3}}{C_1 C_2}}, \tag{6a}$$

$$Q = \frac{G}{\alpha_1 g_{m1}} \sqrt{\frac{\alpha_2 g_{m2} C_2}{\alpha_3 g_{m3} C_1}}, \tag{6b}$$

$$BW = \frac{\alpha_1 \alpha_3 g_{m1} g_{m3}}{G C_2}. \tag{6c}$$

The value of the angular frequency may be altered slightly by effects of current tracking errors of ZC-CFTA1 and ZC-CFTA2. In this case, the deviations in natural frequency (6a) compared with (3a) can be easily compensated by transconductances of mentioned active elements.

IV. Simulation Results

To verify the theoretical analysis, the proposed filter in Fig. 2 is simulated using SPICE software. In the simulations the internal structure of the ZC-CFTA shown in Fig. 3 is used. Dimensions of transistors are listed in Table I. DC power supply voltages are equal to ±1.5 V and $V_B = 0.5$ V. The simulations are performed based on the TSMC 0.35 µm CMOS technology parameters shown in Table II.

The AC simulation results of all transfers of the ZC-CFTA are shown in Fig. 4. The DC current gains are $\alpha \cong \gamma \cong 1.019$ with bandwidths $f_\alpha \cong f_\gamma \cong 1.64$ GHz and transconductances are $g_{m+} \cong g_{m-} \cong 100.43$ µA/V ($I_B = 16.5$ µA) with bandwidths $f_{gm+} \cong 172.6$ MHz and $f_{gm-} \cong 167.4$ MHz, respectively. The maximum values of terminal voltages and terminal currents without producing significant distortion are computed as ±102.8 mV and ±17.4 µA, respectively.

The active parameters and the passive elements in the proposed filter in Fig. 2 are selected as $I_{Bn} = 16.5$ µA ($g_{mn} = 100.43$ µA/V) for $n = \{1, 2, 3\}$, $C_1 = C_2 = 16$ pF, and $R = 10$ kΩ ($G = 100$ µA/V) that result in $f_0 = 1$ MHz and $Q = 1$. The low- (LP), band- (BP1), high-pass (HP), band-stop (BS), and all-pass (AP) characteristics of the filter are shown in Fig. 5.

For the low-pass filter response LP, the independent control of the natural frequency by varying transconductances of ZC-CFTA2 and ZC-CFTA3 without affecting of the quality factor Q is shown in Fig. 6. Here, the two cut-off frequencies and the mid frequency of tuning $f_0 = 500$ kHz to 2 MHz are shown. For required values $f_0 = \{0.5; 1; 2\}$ MHz bias currents must be $I_{B2} = I_{B3} = \{4; 16.5; 83\}$ µA.

From the simulation results it is evident that the final solution corresponds well to the theory.

TABLE I
Dimensions of CMOS transistors

NMOS Transistors	*W (µm) / L (µm)*
M8–M12	0.7 / 0.35
M13, M14, M22–M26	4.0 / 1.0
PMOS Transistors	*W (µm) / L (µm)*
M1, M5, M6	1.4 / 0.35
M2–M4	2.8 / 0.35
M7	5.6 / 0.35
M15–M21	4.0 / 1.0

TABLE II
Model parameters of TSMC 0.35 µm CMOS technology

.MODEL CMOSN NMOS (LEVEL = 3 TOX = 7.9E-9 NSUB = 1E17 + GAMMA = 0.5827871 PHI = 0.7 VTO = 0.5445549 DELTA = 0 + UO = 436.256147 ETA = 0 THETA = 0.1749684 KP = 2.055786E-4 + VMAX = 8.309444E4 KAPPA = 0.2574081 RSH = 0.0559398 + NFS = 1E12 TPG = 1 XJ = 3E-7 LD = 3.162278E-11 + WD = 7.046724E-8 CGDO = 2.82E-10 CGSO = 2.82E-10 + CGBO = 1E-10 CJ = 1E-3 PB = 0.9758533 + MJ = 0.3448504 CJSW = 3.777852E-10 MJSW = 0.3508721)
.MODEL CMOSP PMOS (LEVEL = 3 TOX = 7.9E-9 NSUB = 1E17 + GAMMA = 0.4083894 PHI = 0.7 VTO = -0.7140674 DELTA = 0 + UO = 212.2319801 ETA = 9.999762E-4 THETA = 0.2020774 + KP = 6.733755E-5 VMAX = 1.181551E5 KAPPA = 1.5 + RSH = 30.0712458 NFS = 1E12 TPG = -1 XJ = 2E-7 + LD = 5.000001E-13 WD = 1.249872E-7 CGDO = 3.09E-10 + CGSO = 3.09E-10 CGBO = 1E-10 CJ = 1.419508E-3 PB = 0.8152753 + MJ = 0.5 CJSW = 4.813504E-10 MJSW = 0.5)

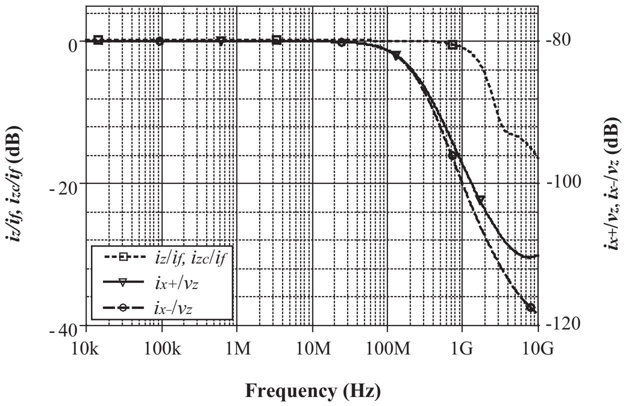
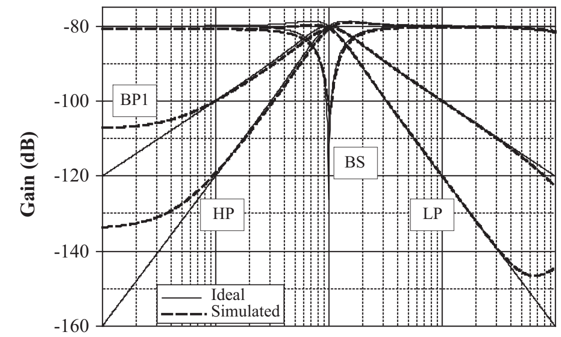
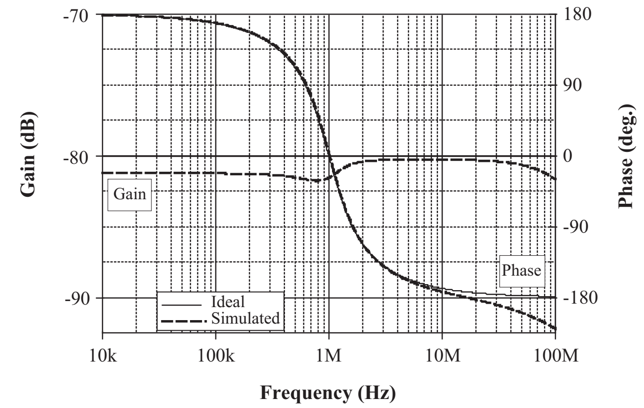


Fig. 4 AC simulation results of the ZC-CFTA



a)



b)

Fig. 5 Simulated frequency characteristics for (a) LP, BP1, HP, BS, and (b) AP responses of the circuit in Fig. 2

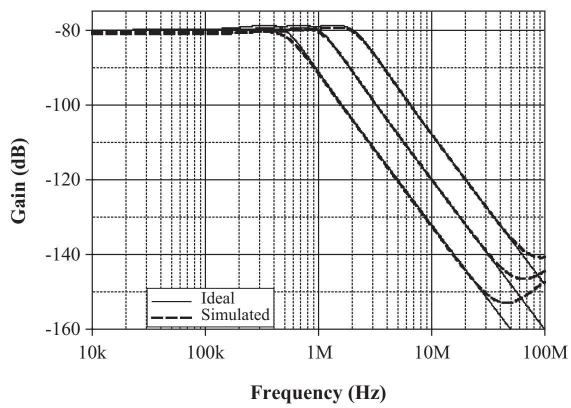


Fig. 6 Simulation results of the low-pass filter

V. Conclusion

In this paper, a mixed-mode KHN-equivalent filter has been presented. The filter employs three ZC-CFTAs, two capacitors, and one resistor. The circuit enjoys the following advantages: 1. providing simultaneously LP, BP1, BP2, HP, BS, and AP responses directly without using additional active elements; 2. use of only grounded capacitors, which is attractive in integrated circuit implementation; 3. control of the quality factor Q without disturbing the parameter ω_0 of the filter; 4. low active and passive sensitivities. The SPICE simulations confirm the feasibility of the proposed circuit.

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