Resistorless Cascadable Current-Mode Filter Using CCCFTAs

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Abstract. *The realization of current-mode biquad filter using current controlled current follower transconductance amplifiers (CCCFTAs) and grounded capacitors is presented. The proposed filter can simultaneously provide three standard transfer functions (low pass, high pass and band pass filter). The tuning of quality factor can be done without affecting the pole frequency. Low input and high output impedances of the configurations enable the circuit to be cascaded without additional current buffers. The use of only grounded capacitors is ideal for integration. The circuit performances are depicted through PSpice simulations, they show good agreement to theoretical anticipation.*

Keywords

CCCFTA, current-mode, filter, integrated circuit.

1. Introduction

Active filter is important in electrical and electronic applications, widely used for continuous-time signal processing. It can be found in many fields, including, communications, measurement, and instrumentation, and control systems [1], [2], [3]. The universal filter with one input and multiple output can be found in many applications, for example in touch-tone telephone tone decoder, in phase-locked loop FM stereo demodulator, or in the crossover network as a part of the three-way high-fidelity loudspeaker [2]. With growing interest in design of current-mode filters, more attention is being paid to the filters which have the high-output impedance because they make them easy to drive loads and they facilitate cascading without using a buffering device [4], [5].

The synthesis and design of analog filters using modern electronically controllable active building blocks (ABBs) give flexibility and convenience for designer. These filters can be easily controlled by microcomputer or microcontroller. Also some filter circuits which use active building block can avoid the use of the external resistors. This will reduce the cost and chip area. The design of analog circuits using active building blocks, taking into account several various criteria such as the minimum number of active elements or others, has been receiving considerable attention. Biolek et al. [6] proposed several circuit ideas of building blocks for voltage-, current- and mixed mode applications. One of them is the current follower transconductance amplifier (CFTA). This device allows applications with interesting features, especially those providing the electronic controllability. Later, Herencsar et al [7] introduced the modification of CFTA, called current controlled current follower transconductance amplifier (CCCFTA) which the parasitic resistance at input terminal is electronically tuned. It seems to be a versatile component in the realization of a class of analog signal processing circuits, especially analog frequency filters. It is really current-mode element whose input and output signals are currents.

It is obvious from the literature survey that a few current-mode filter circuits using CCCFTA have been hitherto published [7], [8], [9], [10]. These filters are focused on the use of single CCCFTA with grounded capacitors. This is ideal for IC implementation. However, the pole frequency and quality factor of filter in [7], [8], [9], [10] cannot be independently controlled. The high pass function of filter in [7] is not easy to cascade in current-mode circuit because this output current flows through the grounded capacitor.

This contribution presents a single-input three-output current-mode filter with low input and high impedance, employing CCCFTAs. It is suitable for fabricating as a monolithic chip or also for off-the-shelf implementation, consisting of 2 active elements and 2 grounded capacitors. The proposed filter can provide three standard functions (low-pass, high-pass and band-pass). The tuning of quality factor can be done without affecting the pole frequency.

2. Circuit Configuration

There are two topics in this section as follows:

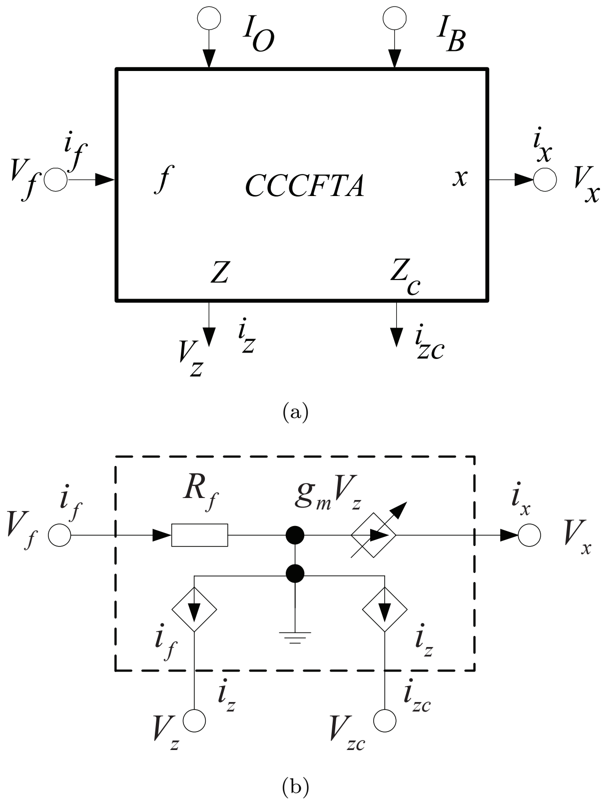

Fig. 1: Circuit symbol and equivalent circuit of CCCFTA.

2.1. Basic Concept of CCCFTA

The circuit symbol and the ideal equivalent circuit model of the CCCFTA are shown in Fig. 1(a) and Fig. 1(b), respectively. It has finite input resistance R_f at f terminal. This parasitic resistance can be controlled by the bias current I_O. The input current i_f flows into f terminal which will be sent to z terminal. In some applications, to utilize the current through z terminal, an auxiliary z_c (z-copy) terminal is used [7], [8]. The internal current mirror provides a copy of the current flowing out of the z terminal to the z_c terminal. The voltage v_z on z terminal is converted into current using transconductance g_m, which flows into output terminal x. The g_m is tuned by I_B. In general, CCCFTA can contain an arbitrary number of x terminals, providing currents i_x of both directions. The characteristics of the CCCFTA are represented by the following hybrid matrix:

$$\begin{bmatrix} V_f \\ i_{z,zc} \\ i_x \end{bmatrix} = \begin{bmatrix} R_f & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} i_f \\ V_x \\ V_z \end{bmatrix}. \qquad (1)$$

If the CCCFTA is realized using CMOS technology, R_f and g_m can be respectively written as

$$R_f = \frac{1}{\sqrt{8k_R I_o}}, \qquad (2)$$

and

$$g_m = \sqrt{k_g I_B}. \qquad (3)$$

For the internal construction of CMOS CCCFTA in Fig. 2, the parameters $k_R = \mu_n C_{ox}(W/L)_{1,2} = \mu_n C_{ox}(W/L)_{3,4}$ and $k_g = \mu_n C_{ox}(W/L)_{25,26}$. I_O and I_B are input bias current to control R_f and g_m, respectively.

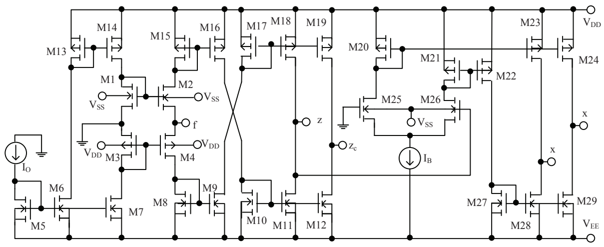

Fig. 2: Internal construction of CMOS CCCFTA.

2.2. Proposed Current-Mode Filter

The proposed current-mode biquad filter is illustrated in Fig. 3. It is found that the filter consists of two CCCFTAs, and two grounded capacitors. The output current terminals are high impedance. Moreover, the low input impedance terminal can be achieved by setting IO1 as high as possible. With this configuration, the proposed filter is easy to cascade in the current-mode system. Considering the circuit in Fig. 3 and using CCCFTA properties in section 2.1, the current transfer functions for high pass, low pass and band pass filter are respectively shown as

$$\frac{I_{HP}}{I_{in}} = \frac{s^2}{s^2 + \dfrac{g_{m1}s}{C_1} + \dfrac{g_{m2}}{C_1 C_2 R_f 2}}, \qquad (4)$$

$$\frac{I_{LP}}{I_{in}} = \frac{\dfrac{g_{m2}}{C_1 C_2 R_{f2}}}{s^2 + \dfrac{g_{m1}s}{C_1} + \dfrac{g_{m2}}{C_1 C_2 R_f 2}}, \qquad (5)$$

$$\frac{I_{BP}}{I_{in}} = \frac{\frac{sg_{m1}}{C_1}}{s^2 + \frac{g_{m1}s}{C_1} + \frac{g_{m2}}{C_1C_2R_f2}}. \tag{6}$$

The following relations are valid for the pole frequency and the quality factor:

$$\omega_0 = \sqrt{\frac{g_{m2}}{C_1C_2R_{f2}}}, \tag{7}$$

and

$$Q = \frac{1}{g_{m1}}\sqrt{\frac{C_1g_{m2}}{C_2R_{f2}}}. \tag{8}$$

From Eq. (7) and Eq. (8), if the R_f and g_m are equal to Eq. (2) and Eq. (3), the pole frequency and quality factor are re-written as

$$\omega_0 = \sqrt{\frac{(8k_gk_RI_{B2}I_{O2})^{1/2}}{C_1C_2}}, \tag{9}$$

and

$$Q = \sqrt{\frac{(8k_gk_RI_{B2}I_{O2})^{1/2}}{k_gI_{B1}C_2}}. \tag{10}$$

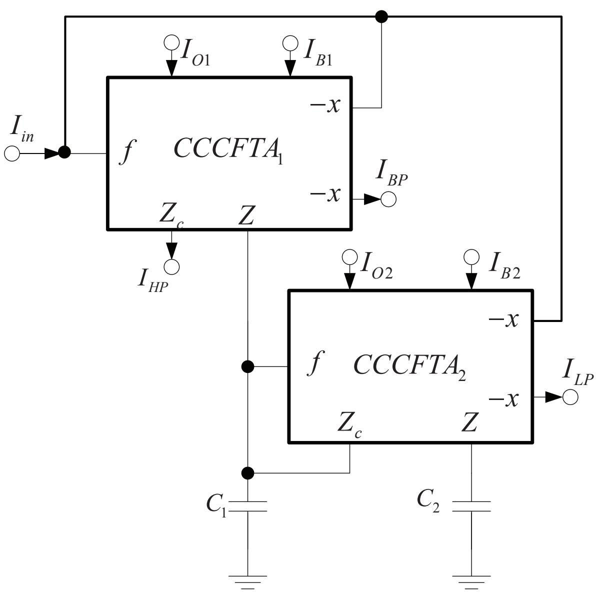

Fig. 3: Proposed current-mode filter.

It is apparent from Eq. (10) that the quality factor could be controlled by I_{B1} without affecting the pole frequency. It should remark that the parameters k_g and k_R are proportional to mobility and mobility falls with increasing temperature. Then the temperature variation will affect the ω_0 and Q [11]. From Eq. (7), the ω_0-sensitivity analysis with respect to the parameters of the active and passive element used can be given by:

$$S^{\omega_0}_{C_1,C_2,R_{f2}} = -\frac{1}{2},\ S^{\omega_0}_{g_{m2}} = \frac{1}{2}. \tag{11}$$

3. Analysis of Non-Ideal Case

In practice, the influences of voltage and current tracking errors and also the parasitic terminal impedances of CCCFTA will affect the filter performance. In this Section, these parameters will be taken into account. For non-ideal case, the CCCFTA can be respectively characterized with the following equations:

$$\begin{bmatrix} V_f \\ i_z \\ i_{zc} \\ i_x \end{bmatrix} = \begin{bmatrix} R_f & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 \\ 0 & 0 & \gamma & 0 \\ 0 & 0 & \pm\beta g_m & 0 \end{bmatrix} \begin{bmatrix} i_f \\ i_z \\ V_z \\ V_x \end{bmatrix}, \tag{12}$$

where α and γ are the current tracking errors from f and z ports to z port z_c port, respectively. β is the transconductance error gain from z port to x port. The influences of parasitic impedances are resistive and capacitive parts affecting the z, z_c, and x ports of CCCFTA. Let us denote them R_z, C_z, R_{zc}, C_{zc}, and R_X, C_X, respectively. If R_{f1} is very low (by setting I_{O1} as high as possible), the influences of parasitic impedances of the x terminals of CCCFTA1 and CCCFTA2 are negligible because of their connection to low-impedance input f (CCCFTA1). Considering into these effects, the current transfer functions will be modified to the more general forms:

$$\frac{I^*_{HP}}{I_{in}} = \frac{\alpha_1\gamma_1s^2 + s\frac{\omega^*_z}{Q^*_z} + \omega^*_z}{s^2 + s\frac{\omega^*_0}{Q^*} + \omega^{*2}_0}, \tag{13}$$

$$\frac{I^*_{BP}}{I_{in}} = \frac{\alpha_1\beta_1g_{m1}\left(s\frac{1}{C^*_1} + \frac{1}{C^*_1C^*_2R_{z2}}\right)}{s^2 + s\frac{\omega^*_0}{Q^*} + \omega^{*2}_0}, \tag{14}$$

$$\frac{I^*_{LP}}{I_{in}} = \frac{\frac{\alpha_1\alpha_2\beta_2g_{m2}}{C^*_1C^*_2R_{f2}}}{s^2 + s\frac{\omega^*_0}{Q^*} + \omega^{*2}_0}, \tag{15}$$

where parameters:

$$C^*_1 = C_1 + C_{z1} + C_{zC2},$$

$$C^*_2 = C_2 + C_{z2},$$

$$\frac{\omega^*_z}{Q^*_z} = \frac{\alpha_1\gamma_1}{C^*_2R_{z2}} + \frac{\alpha_1\gamma_1}{C^*_1}\left(\frac{1}{R_{z1}} + \frac{1}{R_{zc2}}\right) + \frac{\alpha_1\gamma_1}{C^*_1R_{f2}}(1-\alpha_2\gamma_2),$$

$$\omega^*_z = \frac{\alpha_1\gamma_1}{C^*_1C^*_2R_{z2}} + \left(\frac{1}{R_{z1}} + \frac{1}{R_{zc2}}\right) + \frac{\alpha_1\gamma_1}{C^*_1C^*_2R_{f2}R_{z2}}(1-\alpha_2\gamma_2).$$

In this case, the pole frequency and quality factor is modified to

$$\omega_0^* = \sqrt{\frac{1}{C_1^* C_2^* R_{z2}}\left(\frac{1}{R_{z1}} + \frac{1}{R_{zc2}} + \frac{1-\alpha_2\gamma_2}{R_{f2}} + \alpha_1\beta_1 g_{m1}\right) + \frac{\alpha_1\alpha_2\beta_2 g_{m2}}{C_1^* C_2^* R_{f2}}}, \tag{16}$$

and

$$Q^* = \frac{R_{f2}\sqrt{\frac{C_1^*}{C_2^* R_{z2}}\left(\frac{1}{R_{z1}} + \frac{1}{R_{zc2}} + \frac{1-\alpha_2\gamma_2}{R_{f2}} + \alpha_1\beta_1 g_{m1}\right) + \frac{\alpha_1\alpha_2\beta_2 C_1^* g_{m2}}{C_2^* R_{f2}}}}{\frac{C_1^* R_{f2}}{C_2^* R_{z2}} + \left(\frac{R_{f2}}{R_{z1}} + \frac{R_{f2}}{R_{zc2}} + 1 - \alpha_2\gamma_2 + \alpha_1\beta_1 g_{m1} R_{f2}\right)}. \tag{17}$$

It should be mentioned that the stray/parasitic z-terminal capacitances are absorbed by C_1 and C_2 as it appears in shunt with them. However, the parasitic resistance R_{z1}, R_{zc2} and R_{z2} not only affect the ω_0 and Q by they also add parasitic zeros to the HP and BP transfer functions. The parameters α, γ and β of the CCCFTA affect the gain of all filter responses.

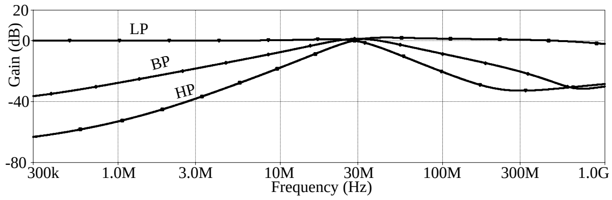

Fig. 4: Gain responses.

4. Simulation Results

To verify the theoretical analyses, the proposed CMOS CCCFTA implementation in Fig. 2 is examined using the PSPICE simulation program. The PMOS and NMOS transistors have been simulated by respectively using the parameters of a 0,25 µm TSMC CMOS technology [12]. The DC power supply voltages are ±1,25 V. The aspect ratios (W/L) of transistors are as follows: M1-M2 is 2 µm/0,5 µm; M3-M4 is 7,5 µm/0,5 µm; M25-M26 is 24 µm/0,5 µm; other PMOSs are 2 µm/0,25 µm and other NMOSs are 3 µm/0,25 µm. The filter was simulated with the following parameters of its components: $C_1 = C_2 = 5$ pF, $I_{O1} = 400$ µA, $I_{O2} = 40$ µA, $I_{B1} = 100$ µA, and $I_{B2} = 270$ µA. According to these conditions, the tracking errors and parasitic components are as follows: $\alpha_1 = \gamma_1 = 1,1$, $\alpha_2 = \gamma_2 = 1,15$, $\beta_1 = 1,3$, $\beta_2 = 1,42$, $R_{z1} = R_{zC1} = 55,46$ kΩ, $C_{z1} = C_{zC1} = 54$ fF, $R_{x1} = 43,56$ kΩ, $C_{x1} = 5,6$ fF, $R_{z2} = R_{zC2} = 141,58$ kΩ, $C_{z2} = C_{zC2} = 53$ fF, $R_{x2} = 32,62$ kΩ, and $C_{x2} = 5,5$ fF. It is found that the current transfers α and γ have an error of 10 % and 15 %, respectively. The errors in the transadmittance g_m represented by coefficients β are 30 % and 42 %. These errors, mainly in case of the transadmittance g_m, are still very high. Anyway, these errors do not seem to be that significant from the view point of final behavior of the proposed structure. Also, using the tuning feature, the real behavior of the active elements can be further suppressed by proper adjustment of the bias currents. The simulated gain responses of the proposed filter are shown Fig. 4. It is clearly seen that the filter can simultaneously provide low-pass, high-pass and band-pass functions without modifying the circuit topology. The simulations yield the pole frequency of 30 MHz and the quality factor of 0,95. The expected value of pole frequency from Eq. (9) is 32,13 MHz (thus the deviation is 6.63 %). The expected value of quality factor from Eq. (10) is 0,92 (thus the deviation is 3,26 %). This error is from the influences of current tracking errors and parasitic impedances of CCCFTA as analyzed in section 4. The proposed filter was excited by 25 µA/30 MHz sinusoidal signal. The transient responses are shown in Fig. 5. The total harmonic distortions (THD) for IHP, IBP and ILP are 1,26 %, 0,73 % and 0,52 %, respectively. Considering Eq. (10), the Q can be controlled by I_{B1} without affecting the ω_0. The Q tuning is confirmed via the BP response in Fig. 6. By varying I_{B1} with different values of 50 µA, 100 µA and 200 µA, the simulated quality factors are 1,39, 0,95 and 0,704, respectively. The magnitudes of output impedance for HP, BP and LP are 52,14 kΩ,

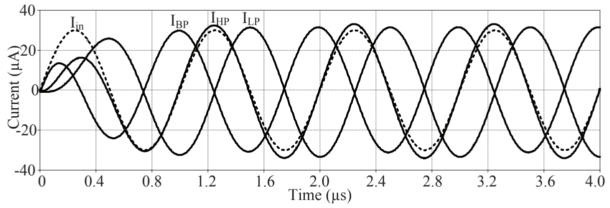

Fig. 5: Time domain responses.

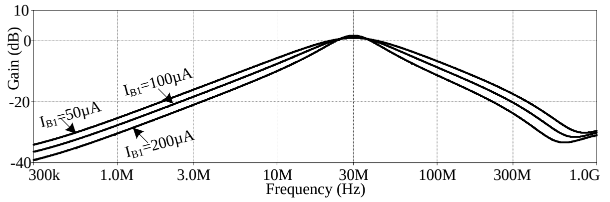

Fig. 6: Band-pass response for different values of I_{B1}.

112,78 kΩ and 32,62 kΩ, respectively. The power consumption is about 8 mW.

5. Conclusion

The current-mode biquad filter based-on CCCFTA has been presented. The proposed filter can provide three standard transfer functions (LP, BP and HP) with low input and high output impedances. It consists of two CCCFTAs and two grounded capacitors. The orthogonal current control of the quality factor and pole frequency is achieved. As mentioned advantages, the proposed circuit is convenient to fabricate in integrated circuit (IC). The PSPICE simulation results agree well with the theoretical anticipation.

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