MISO Current-mode Biquad Filter with Independent Control of Pole Frequency and Quality Factor

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Abstract. *This article presents a three-inputs single-output biquadratic filter performing completely standard functions: low-pass, high-pass, band-pass, band-reject and all-pass functions, based on current controlled current conveyor transconductance amplifier (CCCCTA). The quality factor and pole frequency can be electronically/independently tuned via the input bias current. The proposed circuit uses 2 CCCCTAs and 2 grounded capacitors without any external resistors which is very suitable to further develop into an integrated circuit. The filter does not require double input current signal. Each function response can be selected by suitably selecting input signals with digital method. Moreover, the circuit possesses high output impedance which would be an ideal choice for current-mode cascading. The PSPICE simulation results are included to verify the workability of the proposed filter. The given results agree well with the theoretical anticipation.*

Keywords

Analog filter, CCCCTA, current-mode, Multiple Input-Single Output.

1. Introduction

Recently, current-mode circuits have been receiving considerable attention due to their potential advantages such as inherently wide bandwidth, higher slew-rate, greater linearity, wider dynamic range, simpler circuitry and lower power consumption [1]. With this potential, a number of papers have been published dealing with the realization of current-mode circuits [2]-[4]. One of the standard research topics in current-mode circuit design is an analog filter. This circuit 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 [5]-[6]. One of the most popular analog current-mode filters is a multiple-input single-output biquadratic filter (MISO) whose different output filter functions can be realized simply by different combinations of switching on or off the input currents where the selection can be done digitally using a microcontroller or microcomputer. Moreover, the high-output impedance of current-mode filters are of great interest because they make it easy to drive loads and they facilitate cascading without using a buffering device [7]-[8].

From our survey, it is found that several implementations of MISO current-mode filters have been reported [9]-[27]. Unfortunately, these reported circuits suffer from one or more of the following weaknesses:

- Non interdependency of the pole frequency and quality factor [9]-[13], [15], [16], [18]-[23].
- Excessive use of the passive elements, especially external resistors [10], [13], [14], [17]-[19], [24]-[26].
- Requirement of double input current signal to realize all the responses [9], [19], [23], [26], [27].
- Lack of electronic adjustability [10], [13], [14], [18], [19], [25], [26].
- Requirement of changing circuit topologies to achieve several functions [13], [26].
- Requirement of element-matching conditions [12]-[14], [18], [21], [26].
- Use of floating capacitor which is not desirable for IC implementation [13], [18].

The aim of this paper is to propose a current-mode biquadratic filter, emphasizing on use of CCCCTAs. The features of the proposed circuit are that: the proposed universal filter can provide completely standard functions (low-pass, high-pass, band-pass, band-reject and all-pass) without changing circuit topology: the circuit description is very simple, it uses only 2 CCCCTAs and 2 grounded capacitors, which is suitable for fabricating in monolithic chip or off-the-shelf implementation: quality factor and pole frequency can be independently adjusted. The performances of proposed circuit are illustrated by PSPICE simulations, they show good agreement as mentioned.

2. Theory and Principle

2.1 Basic Concept of CCCCTA

Since the proposed circuit is based on CCCCTA, a brief review of CCCCTA is given in this section. The characteristics of the ideal CCCCTA are represented by the following hybrid matrix:

$$\begin{bmatrix} I_y \\ V_x \\ I_z \\ I_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ R_x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & g_m & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_z \\ V_o \end{bmatrix}. \tag{1}$$

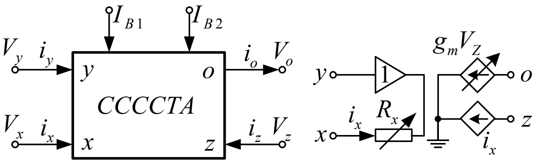
For CMOS implementation of CCCFTA shown in Fig. 3, the R_x and g_m are written as

$$R_x = \frac{1}{\sqrt{8k_{Rx}I_{B1}}} \tag{2}$$

and

$$g_m = \sqrt{k_{gm}I_{B2}} \tag{3}$$

where $k_{Rx} = \mu_p C_{OX}(W/L)_{3,4} = \mu_n C_{OX}(W/L)_{1,2}$, $k_{gm} = \mu_n C_{OX}(W/L)_{20,21}$. R_x is the parasitic resistances at x port, respectively. g_m is the transconductance of the CCCCTA. Here k is the physical transconductance parameter of the MOS transistor. I_{B1} and I_{B2} are the bias current used to control the parasitic resistances and transconductance, respectively. The symbol and the equivalent circuit of the CCCCTA are illustrated in Figs. 1(a) and (b), respectively. In general, CCCCTA can contain an arbitrary number of o terminals, providing current I_o of both directions.



(a) (b)

Fig. 1. CCCCTA (a) Symbol (b) Equivalent circuit.

2.2 Proposed MISO Current-mode Filter

The proposed multiple input single output current-mode biquadratic filter is shown in Fig. 2. By routine analysis of the circuit in Fig. 2, the output current can be obtained to be

$$I_{Out} = k\left(\frac{I_{in2}s^2\dfrac{C_1C_2R_{x1}}{g_{m2}} + I_{in1}\dfrac{sC_2}{g_{m2}} + I_{in3}}{s^2\dfrac{C_1C_2R_{x1}}{g_{m2}} + \dfrac{sC_2k}{g_{m2}} + 1} \right) \tag{4}$$

where $k = g_{m1}R_{x2}$. From (4), I_{in1}, I_{in2} and I_{in3} can be chosen as in Tab. 1 to obtain a standard function of the 2nd–order network without requirement of double input current signal(s). Moreover, it is found in Tab. 1 that each function response can be selected by digital method. The pole frequency (ω_0) and quality factor (Q_0) of each filter response can be expressed to be

$$\omega_0 = \sqrt{\frac{g_{m2}}{C_1C_2R_{x1}}} \tag{5}$$

and

$$Q_0 = \frac{1}{k}\sqrt{\frac{C_1R_{x1}g_{m2}}{C_2}}. \tag{6}$$

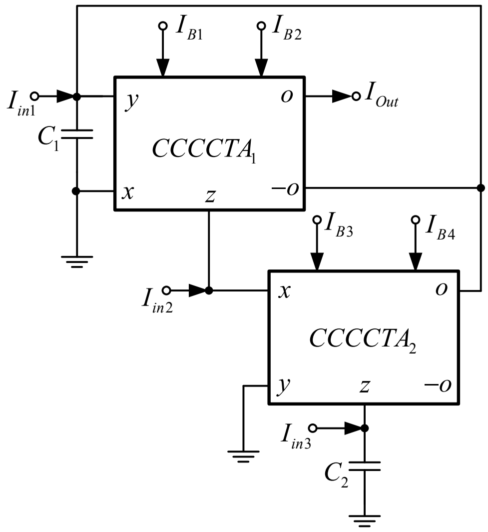


Fig. 2. Proposed MISO current-mode filter.

Filter Responses	Input selections		
I_O	I_{in1}	I_{in2}	I_{in3}
BP	I_{in}	0	0
HP	0	I_{in}	0
BR	0	I_{in}	I_{in}
AP	$-I_{in}$	I_{in}	I_{in}
LP	0	0	I_{in}

Tab. 1. The I_{in1}, I_{in2} and I_{in3} values selection for each filter function response.

If R_x and g_m are equal to (2) and (3), the pole frequency, current gain and phase responses of the proposed circuit are written as

$$\omega_0 = \sqrt{\frac{\left(8k_{Rx1}k_{gm2}I_{B1}I_{B4}\right)^{\frac{1}{2}}}{C_1C_2}} \tag{7}$$

and

$$Q_0 = \sqrt{\left(\frac{8k_{Rx2}I_{B3}C_1}{k_{gm1}I_{B2}C_2}\right)\left(\frac{k_{gm2}I_{B4}}{8k_{Rx1}I_{B1}}\right)^{\frac{1}{2}}}. \tag{8}$$

From (7) and (8), it is found that the quality factor can be adjusted independently from the pole frequency by varying I_{B2} or I_{B3}. Another advantage of the proposed circuit is that the high Q_0 circuit can be obtained by setting I_{B3} greater than I_{B2} without effecting pole frequency.

Furthermore, it can be remarked that if $I_{B1} = I_{B4} = I_B$, this can be achieved by using current mirror copying the current I_B to terminals I_{B1} and I_{B4} of CCCCTA1 and CCCCTA2, respectively. The pole frequency and quality factor can be expressed as

$$\omega_0 = \sqrt{\frac{I_B\left(8k_{Rx1}k_{gm2}\right)^{\frac{1}{2}}}{C_1C_2}} \tag{9}$$

and

$$Q_0 = \sqrt{\left(\frac{8k_{Rx2}I_{B3}C_1}{k_{gm1}I_{B2}C_2}\right)\left(\frac{k_{gm2}}{8k_{Rx1}}\right)^{\frac{1}{2}}}. \tag{10}$$

From (9) and (10), it should be remarked that the pole frequency can be electronically adjusted by I_B without disturbing the quality factor.

2.3 Relative Sensitivities

The relative sensitivities of the proposed circuit can be found as

$$S_{I_{B1}}^{\omega_0} = S_{I_{B4}}^{\omega_0} = \frac{1}{2};\ S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}; S_{V_T}^{\omega_0} = -1 \tag{11}$$

and

$$S_{I_{B3}}^{Q_0} = 1; S_{I_{B2}}^{Q_0} = -1; S_{C_1}^{Q_0} = S_{I_{B4}}^{Q_0} = \frac{1}{2};\ S_{C_2}^{Q_0} = S_{I_{B1}}^{Q_0} = -\frac{1}{2}. \tag{12}$$

Therefore, all the active and passive sensitivities are equal or less than unity in magnitude.

3. Non-ideal Cases

In practice, the CCCCTA is possible to work with non-idealities. Its properties will change to,

$$I_z = \alpha I_x; V_x = \beta V_y + I_x R_x; I_o = \pm\gamma g_m V_z \tag{13}$$

where α is the parasitic current transfer gain from x terminal to z terminal. β is the parasitic voltage transfer gain from y terminal to x. The modified output current of Fig. 2 can be expressed as

$$I_{Out} = \gamma_1 k\left(\frac{I_{in2}s^2\frac{C_1C_2R_{x1}}{g_{m2}} + I_{in1}\frac{\beta_1\alpha_1 sC_2}{g_{m2}} + I_{in3}\beta_1\alpha_1\gamma_2}{s^2\frac{C_1C_2R_{x1}}{g_{m2}} + \frac{\beta_1\alpha_1\gamma_1 ksC_2}{g_{m2}} + \beta_1\alpha_1\alpha_2\gamma_2}\right). \tag{14}$$

From (14), the pole frequency and quality factor are

$$\omega_0 = \sqrt{\frac{\beta_1\alpha_1\alpha_2\gamma_2 g_{m2}}{C_1C_2R_{x1}}} \tag{15}$$

and

$$Q_0 = \frac{1}{k}\sqrt{\frac{\alpha_2\gamma_2C_1R_{x1}g_{m2}}{\beta_1\alpha_1\gamma_1^2C_2}}. \tag{16}$$

It should be mentioned that the values of the pole frequency and quality factor may be altered slightly by the effect of the CCCCTA voltage and current tracking errors. These deviations can be compensated by tuning the input bias currents.

On the other hand, the influence of parasitic terminal impedances of CCCCTA will be also considered. These are terminal Y ($R_Y//C_Y$), terminal Z ($R_Z//C_Z$) and terminal O ($R_O//C_O$). The simplified current transfer function (assuming R_Y, R_Z, and $R_O >> R_X$), for the circuit of Fig. 3, is given as

$$I_{Out} = g_{m1}R_{x2}\left[\frac{I_{in2}R_{x1}Y_1Y_2 + I_{in1}Y_2 + I_{in3}g_{m2}}{R_{x1}Y_1Y_2\left(1+R_{x2}Y_3\right) + g_{m1}R_{x2}Y_2 + g_{m2}}\right] \tag{17}$$

where $Y_1 = s(C_1+C_{y1}+C_{o1}+C_{o2})$, $Y_2 = s(C_2+C_{z2})$ and $Y_3 = sC_{z1}$. It is found that (17), to alleviate the effect of C_{z1} (Y_3) the operating frequency should be chosen such that $\omega > \max[1/R_{x2}C_{z1}]$, so that non-ideal values of ω_0 and Q_0 are found to be

$$\omega_0^* = \sqrt{\frac{g_{m2}}{\left(C_1+C_{y1}+C_{o1}+C_{o2}\right)\left(C_2+C_{z2}\right)R_{x1}}} \tag{18}$$

and

$$Q_0^* = \frac{1}{k}\sqrt{\frac{\left(C_1+C_{y1}+C_{o1}+C_{o2}\right)R_{x1}g_{m2}}{\left(C_2+C_{z2}\right)}}. \tag{19}$$

It should be mentioned that the stray/parasitic capacitance at terminal z and o can be absorbed into the external grounded capacitors as they appear in shunt with them.

4. Comparison with Previous Works

Besides the inherent advantages of the proposed MISO current-mode filter over other previous works, the proposed circuit in Fig. 2 is compared with several previous current-mode MISO current-mode filters. These MISO current-mode filters are based on current conveyor (CCII) [13], [18], [25]-[26], current controlled current conveyors (CCCII) [20]-[21], gain-controllable current controlled current conveyor (G-CCCII) [27], inverting current conveyor (ICCII) [10], fully differential second generation current conveyor (FDCCII) [14], OTA [12], differential voltage current conveyor transconductance amplifier (DVCCTA) [15], CCII and current controlled current amplifier (CCCA) [17], current differencing buffered amplifier (CDBA) [19], current controlled current conveyor transconductance amplifier (CCCCTA) [11], [16] and current differencing transconductance amplifier (CDTA) [9], [22]-[24]. The results are shown in Tab. 2.

Ref	Active element	No. of active element	No. of R+C	Electronic control	Independent tune of ω_0 and Q_0	Requiring double input	Matching Condition	High output impedance
[9]	CCCDTA	1	0+2	Yes	No	Yes	No	Yes
[10]	ICCII	3	2+2	No	No	No	No	Yes
[11]	MO-	1	0+2	Yes	No	No	No	Yes
[12]	OTA	4	0+2	Yes	No	No	Yes	Yes
[13]	CCII	1	2+2	No	No	No	Yes	No
[14]	FDCCI	1	3+2	No	Yes	No	Yes	Yes
[15]	DVCCTA	1	1+2	Yes	No	No	No	Yes
[16]	MO-	2	0+2	Yes	No	No	No	Yes
[17]	MOCCII & MO-CCCA	3	2+2	Yes	Yes	No	No	Yes
[18]	CCII	1	2+2	No	No	No	Yes	Yes
[19]	CDBA	3	2+2	No	No	Yes	No	Yes
[20]	CCCII	2	0+2	Yes	No	No	No	Yes
[21]	CCCII	5	0+2	Yes	Yes	No	Yes	Yes
[22]	CDTA	3	0+2	Yes	No	No	No	Yes
[23]	CDTA	2	0+2	Yes	No	Yes	No	Yes
[24]	CDTA	4	2+2	Yes	Yes	No	No	Yes
[25]	CCII	3	3+2	No	Yes	No	No	Yes
[26]	CCII	2	3+2	No	Yes	Yes	Yes	Yes
[27]	G-CCCII	2	0+2	Yes	Yes	Yes	No	Yes
Proposed circuit	CCCCTA	2	0+2	Yes	Yes	No	No	Yes

Tab. 2. Comparison between various MISO current-mode filters.

5. Results of Computer Simulation

To prove the performances of the proposed circuit, the PSPICE simulation program was used. The PMOS and NMOS transistors have been simulated by respectively using the parameters of a 0.25µm TSMC CMOS technology [28] with ±1.25V voltage supply. The aspect ratios of PMOS and NMOS transistor are listed in Tab. 2. Fig. 3 depicts schematic description of the CCCCTA. Capacitors: $C_1 = C_2 = 18$ pF, $I_{B1} = I_{B3} = 5$ µA ($R_{x1} = R_{x2} = 4.03$ kΩ), $I_{B2} = I_{B4} = 30$ µA ($g_{m1} = g_{m2} = 0.59$ mS), are chosen. It yields the pole frequency of 3.36 MHz and $Q = 0.65$, while calculated value of pole frequency from (7) is 3.38 MHz (deviated by 0.59 %). The results shown in Fig. 4 are the gain and phase responses of the proposed filter obtained from Fig. 2. It is clearly seen that the proposed filter can provide low-pass, high-pass, band-pass, band-reject and all-pass functions, dependent on digital selection as shown in Tab. 1, without modifying circuit topology. Fig. 5 and Fig. 6 display gain responses of band-pass function for different I_{B2} and I_{B3} values. It is shown that the quality factor can be adjusted by I_{B2} and I_{B3}, as depicted in (8), without affecting the pole frequency. Fig. 7 shows the gain responses of the band-pass function while setting I_B to 10 µA, 20 µA and 40 µA, respectively. This result shows that the pole frequency can be adjusted without affecting the quality factor, as described in (9) and (10).

Transistor	W (µm)	L (µm)
M8-M21	5	0.25
M6-M7	8	0.25
M1-M5, M22-M25	3	0.25

Tab. 3. Dimensions of the transistors.

6. Conclusion

The digitally controllable current-mode multi-function filter has been presented. The advantages of the proposed circuit are that: it performs low-pass, high-pass, and band-pass functions from the same circuit configuration without component matching conditions: the quality factor and the pole frequency can be independently controlled. The circuit description comprises only 2 CCCCTAs, and 2 grounded capacitors, which is attractive for either IC implementation.

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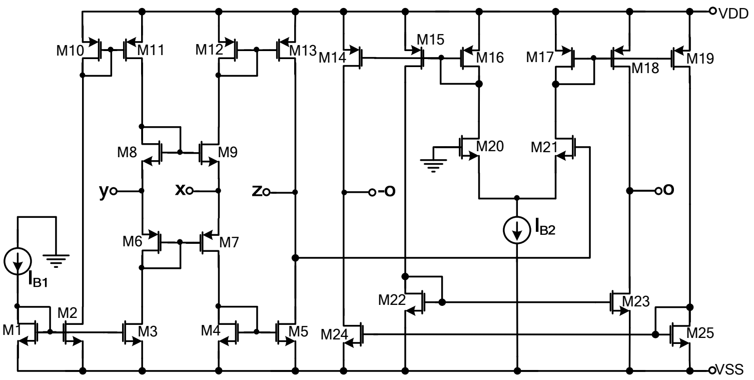
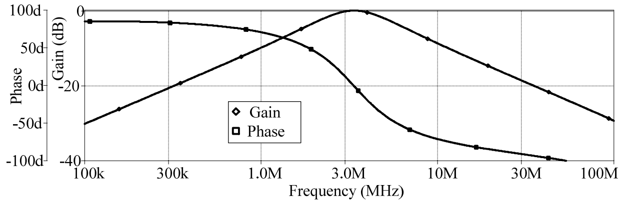
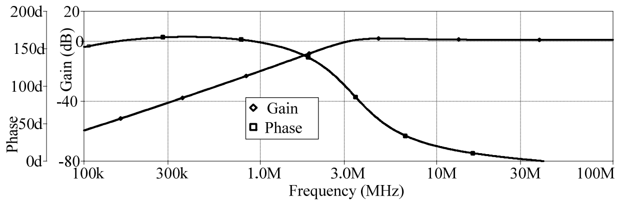


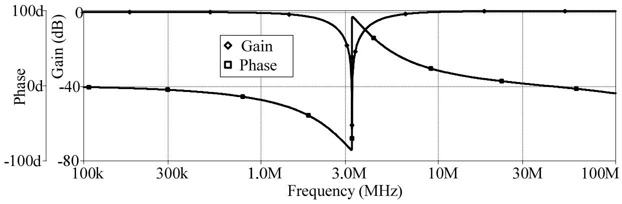
Fig. 3. Internal Construction of CCCCTA.



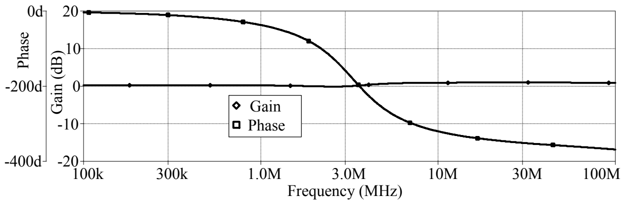
(a) BP



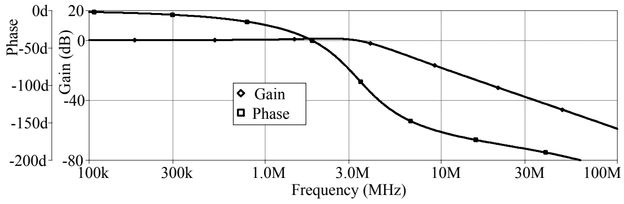
(b) HP



(c) BR



(d) AP



(e) LP

Fig. 4. Gain and phase responses of the proposed filter.

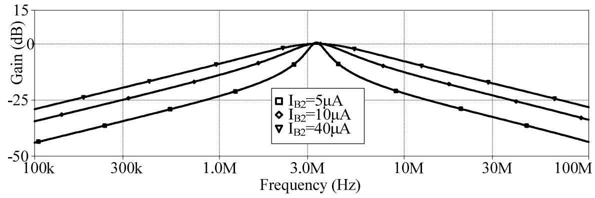


Fig. 5. Band-pass responses at different values of I_{B2}.

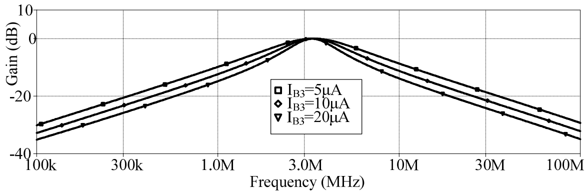


Fig. 6. Band-pass responses at different values of I_{B3}.

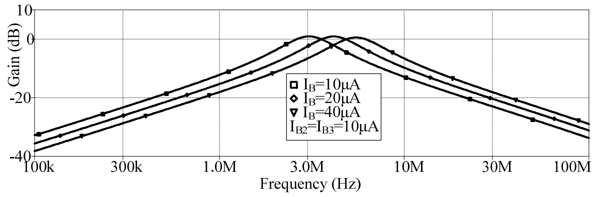


Fig. 7. Band-pass responses for different values of I_B.

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