Electronically tunable current-mode biquadratic circuit using current controlled unity gain cells

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Abstract: This paper introduces an electronically tunable current-mode biquadratic circuit employing current controlled unity gain cells. The circuit is constructed with two current controlled current followers (CCCFs), two CCCFs with voltage buffers (CCCFBs) and two grounded capacitors. The circuit can realize low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by choosing appropriate current input and output terminals without any component matching conditions. Additionally, the circuit parameters ω_0 and Q can be tuned orthogonally through adjusting the bias currents. The biquadratic circuit enjoys very low sensitivities with respect to the circuit components.

An example is given together with simulated results by PSPICE.

1. Introduction

High performance active circuits have received much attention. Since current-mode circuits have many advantages compared with their voltage-mode counterparts, circuit designs employing active devices such as operational transconductance amplifiers (OTAs), second generation current conveyors (CCIIs) and current controlled current conveyors (CCCIIs) have been discussed in the literature [1]-[5].

It is well known that the active circuits using unity gain cells (i.e. current followers (CFs) and voltage followers (VFs)) have wider bandwidth, wide dynamic range, low power consumption and so on. The circuit designs employing the unity gain cells have been discussed previously [6]-[8].

In the active devices, the CCCII provides electronic tunability and wide tunable range of x-terminal resistance by the bias current [1],[5]. Practically, the CCCF can be realized by grounding the y-terminal of the CCCII. Also, the CCCF is easily extended to the CCCFB with a voltage buffer (i.e, VF). Thus, the CCCF and CCCFB have electronic tuning capability for the x-terminal resistance as like as the CCCII. The CCCF- and CCCFB-based circuits require no resistors, so it is well suited for integration. These features are very attractive to active circuit designers.

The biquadratic circuit has capability of realizing more than one basic circuit functions with the same topology. In practice, it can be used for active filter instead of SAW filter, PLL FM stereo demodulator and so on. The biquadratic circuits using the OTAs, CCIIs and CCCIIs have been reported in the past [1],[2],[4],[5]. The OTA-based circuits have electronic tuning capability as like as the CCCF- and CCCFB-based circuits. However, the CCCF and CCCFB have wider bandwidth than the OTA in order to provide the unity gains. Additionally, it is known that the OTA has not wide dynamic range. It means that the range of the input voltage is limited in the OTA-based circuits. A biquadratic circuit with such performance of the CCCF and CCCFB has not yet been studied sufficiently.

This paper introduces an electronically tunable current-mode biquadratic circuit employing the current controlled unity gain cells. The circuit is constructed with two CCCFs, two CCCFBs and two grounded capacitors. The circuit can realize the low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by choosing the appropriate current input and output terminals. The circuit requires no component matching conditions for realizing the transfer functions listed above. Additionally, the circuit parameters ω_0 and Q can be tuned orthogonally by adjusting the bias currents. It is clear from sensitivity analysis that the biquadratic circuit has very low sensitivities with respect to the circuit components. An example is given together with simulated results by PSPICE.

The biquadratic circuit configuration is very suitable for implementation in both bipolar and CMOS technologies.

2. CCCF and CCCFB

Figure 1 shows the symbols for the CCCF and CCCFB. This shows dual current output CCCF and CCCFB.

The standard CCCF and CCCFB can be characterized by:

$$V_x = R_x I_x, \quad I_z = \pm I_x \tag{1}$$

$$V_x = R_x I_x, \quad V_w = V_z \qquad I_z = \pm I_x, \quad I_w = 0 \tag{2}$$

where R_x denotes the intrinsic resistances at the x-terminal. In (1) and (2), the sign ± shows the plus or minus polarity of the z-terminal current I_z.

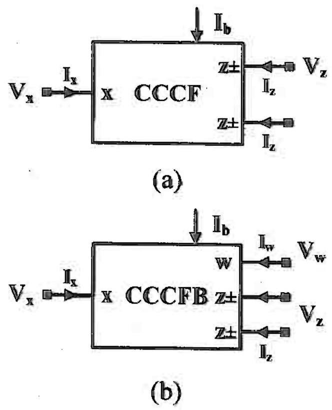


Figure 1. Symbols for CCCF and CCCFB.

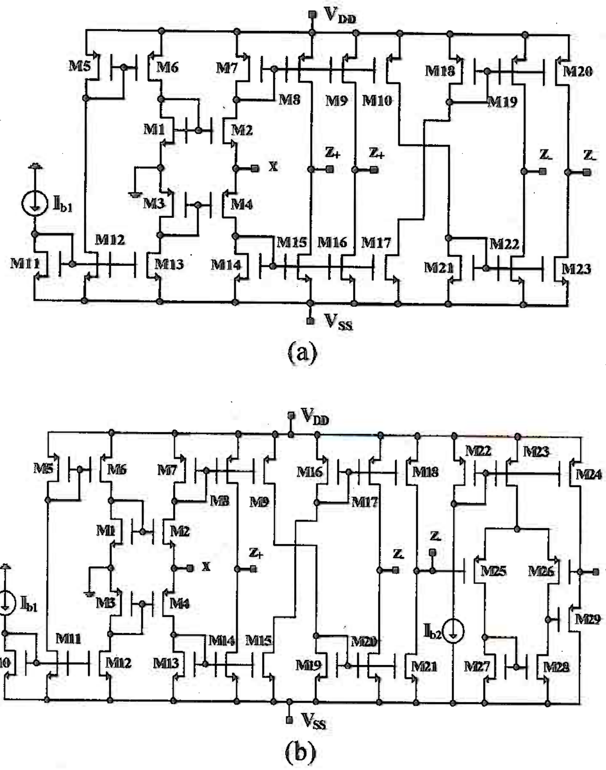


Figure 2. CCCF and CCCFB with MOS transistors.

Figure 2 (a) shows the CCCF with MOS transistors, and the CCCFB is shown in Fig.2 (b). This shows multiple current output CCCF and CCCFB.
The x-terminal resistance R_x is given by

$$R_x = K\left(\mu C_{ox}\frac{W}{L}I_{b1}\right)^{-\frac{1}{2}} \tag{3}$$

where K, μ, C_{ox}, W/L and I_{b1} are the constant parameter, electron mobility, gate oxide capacitance per unit area, transistor aspect ratio and bias current, respectively. Thus, it is shown that the resistance R_x can be adjusted by a supplied bias current I_{b1}.

3. Circuit configuration and analysis

Figure 3 shows the biquadratic circuit configuration. The circuit is constructed with two CCCFs, two CCCFBs and two grounded capacitors.

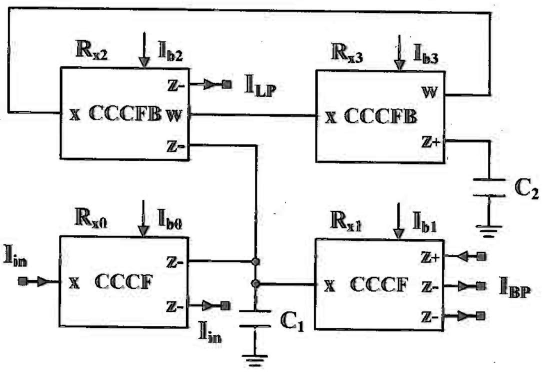


Figure 3. Current-mode biquadratic circuit configuration.

Routine analysis yields the circuit transfer functions $T_{LP}(s)$ (=$I_{LP}(s)/I_{in}(s)$) and $T_{BP}(s)$ (=$I_{BP}(s)/I_{in}(s)$) for two current outputs $I_{LP}(s)$, $I_{BP}(s)$ given by:

$$T_{LP}(s) = \frac{1}{s^2C_1C_2R_{x2}R_{x3} + sC_2R_{x2}R_{x3}/R_{x1} + 1} \tag{4}$$

$$T_{BP}(s) = -\frac{sC_2R_{x2}R_{x3}/R_{x1}}{s^2C_1C_2R_{x2}R_{x3} + sC_2R_{x2}R_{x3}/R_{x1} + 1} \tag{5}$$

The circuit parameters ω_0, Q and H can be expressed as:

$$\omega_0 = \sqrt{\frac{1}{C_1C_2R_{x2}R_{x3}}},\quad Q = R_{x1}\sqrt{\frac{C_1}{C_2R_{x2}R_{x3}}},\quad H = 1.0 \tag{6}$$

It can be seen that the circuit can realize simultaneously the low-pass and band-pass transfer functions at the current outputs of $I_{LP}(s)$ and $I_{BP}(s)$, respectively. The circuit parameter ω_0 can be set by the x-terminal resistances R_{x2}, R_{x3} and capacitances C_1, C_2 from (6). Then, the circuit parameter Q can be set by adjusting the resistance R_{x1} without disturbing the parameter ω_0. Thus, the biquadratic circuit has orthogonal tuning capability for the circuit parameters ω_0 and Q.

The high-pass, band-stop and all-pass transfer functions $T_{HP}(s)$ (=$I_{HP}(s)/I_{in}(s)$), $T_{BS}(s)$ (=$I_{BS}(s)/I_{in}(s)$), $T_{AP}(s)$ (=$I_{AP}(s)/I_{in}(s)$) can be easily obtained from the currents $I_{HP}(s)$= $I_{in}(s)$-$I_{BP}(s)$-$I_{LP}(s)$, $I_{BS}(s)$= $I_{in}(s)$-$I_{BP}(s)$ and $I_{AP}(s)$= $I_{BS}(s)$-$I_{BP}(s)$, respectively.

$$T_{HP}(s) = \frac{s^2C_1C_2R_{x2}R_{x3}}{s^2C_1C_2R_{x2}R_{x3} + sC_2R_{x2}R_{x3}/R_{x1} + 1} \tag{7}$$

$$T_{BS}(s) = \frac{s^2C_1C_2R_{x2}R_{x3} + 1}{s^2C_1C_2R_{x2}R_{x3} + sC_2R_{x2}R_{x3}/R_{x1} + 1} \tag{8}$$

$$T_{AP}(s) = \frac{s^2C_1C_2R_{x2}R_{x3} - sC_2R_{x2}R_{x3}/R_{x1} + 1}{s^2C_1C_2R_{x2}R_{x3} + sC_2R_{x2}R_{x3}/R_{x1} + 1} \tag{9}$$

It can be seen that five different circuit transfer functions can be realized by choosing suitable input and output currents without any component matching conditions. But, as the circuit parameter H is 1.0, an additional amplification stage (i.e. current amplifier) to the current output terminal is required to achieve the desirable gain constant.

We consider below the effect of deviation of the circuit components on the biquadratic characteristic. Table 1 shows the sensitivities with respect to the circuit components (R_{x1}, R_{x2}, R_{x3}, C_1 and C_2). The sensitivity takes the values of within 1.0. These values demonstrate that the biquadratic circuit enjoys very low sensitivities. It is also noted that the sensitivities do not depend upon the circuit component values.

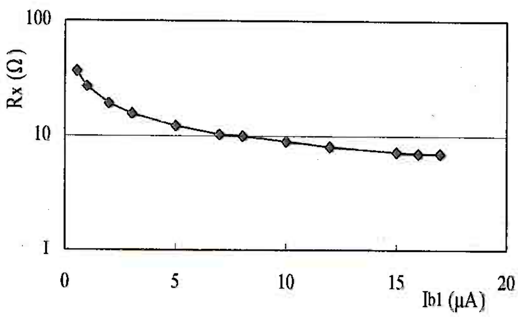
Table 1. Sensitivity to circuit components.

x	$S_x^{\omega_0}$	S_x^Q	S_x^H
R_{x1}	0.0	1.0	0.0
R_{x2}	-0.5	-0.5	0.0
R_{x3}	-0.5	-0.5	0.0
C_1	-0.5	0.5	0.0
C_2	-0.5	-0.5	0.0

4. Design Example and Simulation Results

To verify the theoretical analysis, the biquadratic circuit was simulated using PSPICE simulation program. As an example, we consider realization of a biquadratic characteristic with the cut-off frequency f_0 (=$\omega_0/2\pi$)=1MHz, quality factor Q=1.0 and gain constant H=1.0.

For the PSPICE simulation, we have used the macro models of the CCCF and CCCFB shown in Fig.2. Figure 4 shows the characteristic of the x-terminal resistance R_x versus the bias current I_{b1}. It is found that the resistance R_x can be tuned by the bias current.



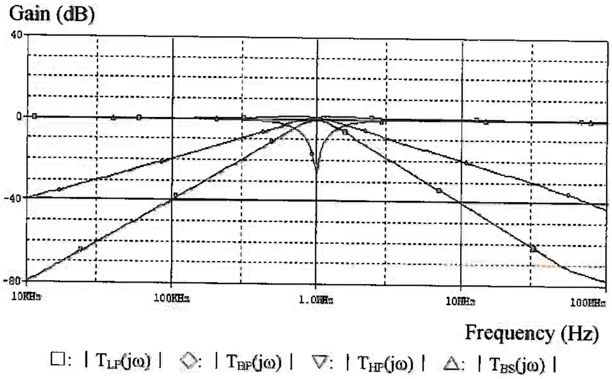
Figur 4. Characteristic of R_x versus I_{b1}.

To realize the biquadratic characteristic above, we have determined that the bias currents and capacitors were $I_{b0}=I_{b1}=I_{b21}=I_{b31}=12\mu A$, $I_{b22}=I_{b32}=40\mu A$ and $C_1=C_2=20pF$, respectively. Also, we have set the supply voltages and input current at $V_{DD}=-V_{SS}=1.85V$ and $I_{in}=10\mu A$. The dimensions of MOS transistors are determined as listed in Table 2.

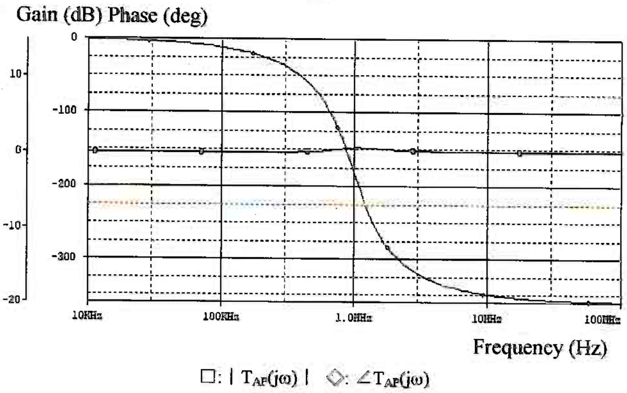
Figure 5 (a) shows the simulated low-pass, band-pass, high-pass and band-stop responses with PSPICE. The all-pass response is shown in Fig.5 (b). Although small departures occur, the responses are sufficiently favorable over a wide frequency range.

Table 2. Dimensions of MOS transistors.

Transistors	W / L (μm)
M1-15	4 /2
M16-23	8 / 2



(a)



(b)

Figur 5. Simulated responses.

In this simulation, we have used the model parameters of 0.5μm MOS technology obtained through MOSIS listed in Table 3.

5. Conclusions

An electronically tunable current-mode biquadratic circuit using current controlled unity gain cells has been proposed. The circuit is constructed with two CCCFs, two CCCFBs and two grounded capacitors. We have demonstrated that the circuit can realize low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by choosing the current input and output terminals without any component matching conditions, and that the circuit parameters ω_0 and Q can be set orthogonally by adjusting the bias currents. It has also been clearly demonstrated that the biquadratic circuit enjoys very low sensitivities with respect to the circuit components. The simulated responses have been quite good over a wide frequency range. It seems that the biquadratic circuit configuration can be fabricated easily using bipolar and CMOS technologies.

The non-idealities of the CCCF and CCCFB may affect the biquadratic characteristic. The work on this must be discussed further.

Table 3. Model parameters based on 0.5μm MOSIS.

NMOS LEVEL= 3 PHi= 0.700000 TOX= 9.6000E-09 + XJ= 0.200000U TPG= 1 VTO= 0.6684 + DELTA= 1.0700E+00 LD= 4.2030E-08 + KP= 1.7748E-04 UO= 493.4 THETA= 1.8120E-01 + RSH= 1.6680E+01 GAMMA= 0.5382 + NSUB= 1.1290E+17 NFS= 7.1500E+11 + VMAX= 2.7900E+05 ETA= 1.8690E-02 + KAPPA= 1.6100E-01 CGDO= 4.0920E-10 + CGSO= 4.0920E-10 CGBO= 3.7765E-10 + CJ= 5.9000E-04 MJ= 0.76700 CJSW= 2.0000E-11 + MJSW= 0.71000 PB= 0.990000
PMOS LEVEL= 3 PHi= 0.700000 TOX= 9.6000E-09 + XJ= 0.200000U TPG= -1 VTO= -0.9352 + DELTA= 1.2380E-02 LD= 5.2440E-08 + KP= 4.4927E-05 UO= 124.9 THETA= 5.7490E-02 + RSH= 1.1660E+00 GAMMA= 0.4551 + NSUB= 8.0710E+16 NFS= 5.9080E+11 + VMAX= 2.2960E+05 ETA= 2.1930E-02 + KAPPA= 9.3660E+00 CGDO= 2.1260E-10 + CGSO= 2.1260E-10 CGBO= 3.6890E-10 + CJ= 9.3400E-04 MJ= 0.48300 CJSW= 2.5100E-10 + MJSW= 0.21200 PB= 0.930000

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