Research Article

Current Mode Biquad Filter with Minimum Component Count

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The paper presents a new current mode biquadratic filter with one input and three outputs using differential voltage current conveyor (DVCC) and four passive components. The proposed circuit can simultaneously realize low-pass, band-pass, and high-pass filter functions without changing the circuit topology and passive elements. The circuit exhibits a good frequency performance and low-sensitivity figures. PSPICE simulation using $0.5\mu\text{m}$ CMOS parameters are given to validate the proposed circuit. The circuit provides a simple yet novel solution to the current-mode filtering after appropriate incorporation of current sensing elements in form of current buffers.

1. Introduction

Current-mode circuits have been receiving considerable attention owing to their potential advantages such as wider bandwidth, greater linearity, higher slew rate, wider dynamic range, simple circuitry, and low power consumption compared to voltage-mode circuits [1–3]. Current-mode analog signal filtering has also received a lot of attention in the recent past. Thus, several multifunction or universal biquadratic filters using current conveyors have been reported in the literature [4–36]. Recently, CDTA has also been used for current-mode filtering application [5]. The circuit in [6] realizes three basic filtering functions and uses all grounded components. The circuit [7] is based on minimum number of passive elements. Another current mode work employs only one active element in the form of a CFOA [8]. One multifunction filter using two CDBAs was also reported [9]. Current mode filters [17] benefit from high output impedance and use of grounded components. An active element which also has merged as a potential candidate for realizing filter circuits is a differential voltage current conveyor [10, 11, 17–19, 25, 26]. The works based on DVCC present a KHN biquad [10, 11] is benefiting from high output impedance outputs.

This paper presents a new second-order current mode filter circuit employing grounded components. The circuit uses a minimum number of components required to achieve a second-order transfer function. Three types of transfer

functions are available at once, without any circuit modification. Moreover, the circuits using grounded components are beneficial from fabrication point of view. The non-ideal study and parasitic effects are also given. The new circuit is verified using PSPICE, a powerful tool for verifying new circuits based on active elements, which are either not commercially available or their implementation using available ICs is not very economical.

2. Proposed Circuit

2.1. Circuits' Description. The symbol and CMOS implementation of differential voltage current conveyor (DVCC) are shown in Figures 1 and 2, respectively, and are characterized by the following port relationship:

$$V_X = V_{Y1} - V_{Y2}, \quad I_{Y1} = I_{Y2} = 0, \quad I_{Z+} = +I_X. \quad (1)$$

A new current-mode biquadratic filter with one input terminal and three output terminals is proposed. The given circuit uses one differential voltage current conveyor (DVCC), two grounded resistors and two grounded capacitors. The given circuit can realize the standard filter functions: low-pass, band-pass, and high-pass, simultaneously without changing the passive elements. The given circuit uses one DVCC, two grounded resistors, and two grounded capacitors. The use of

FIGURE 1: Symbol of DVCC with two Z+ stages.

FIGURE 2: CMOS implementation of DVCC with two Z+ stages.

only grounded components is particularly attractive for IC implementation.

2.2. Circuit Analysis. The proposed circuit of Figure 3 is analyzed using (1). The transfer functions can be expressed as

$$\begin{aligned} \frac{I_{LP}}{I_{in}} &= -\frac{1/C_1 C_2 R_1 R_2}{s^2 + s[1/C_2 R_2 - 1/C_2 R_1 + 1/C_1 R_1] + 1/C_1 C_2 R_1 R_2}, \\ \frac{I_{BP}}{I_{in}} &= -\frac{s/C_1 R_1}{s^2 + s[1/C_2 R_2 - 1/C_2 R_1 + 1/C_1 R_1] + 1/C_1 C_2 R_1 R_2}, \\ \frac{I_{HP}}{I_{in}} &= \frac{s^2 + s[1/C_2 R_2 - 1/C_2 R_1]}{s^2 + s[1/C_2 R_2 - 1/C_2 R_1 + 1/C_1 R_1] + (1/C_1 C_2 R_1 R_2)} \\ &= \frac{s^2}{s^2 + s[1/C_2 R] + 1/C_1 C_2 R^2} \quad (\text{for } R_1 = R_2 = R). \end{aligned} \quad (2)$$

From (2), it can be seen that a low-pass response is obtained from I_{LP} , a band-pass response is obtained from I_{BP} , high-pass response is obtained from I_{HP} under the condition $R_1 = R_2 = R$.

In low-pass and band-pass responses, the resonance angular frequency ω_0 and the quality factor Q are given by

$$\begin{aligned} \omega_0 &= \sqrt{\frac{1}{C_1 C_2 R_1 R_2}}, \\ Q &= \frac{\sqrt{C_1 C_2 R_1 R_2}}{C_1 R_1 - C_1 R_2 + C_2 R_2}. \end{aligned} \quad (3)$$

It may be further noted that for high-pass response, the resistors are matched as $R_1 = R_2 = R$, so the resonance angular frequency ω_0 and the quality factor Q of the above (3) become

$$\omega_0 = \frac{1}{R} \sqrt{\frac{1}{C_1 C_2}}, \quad (4)$$

$$Q = \sqrt{\frac{C_1}{C_2}}. \quad (5)$$

The high-pass gain, low-pass gain and band-pass gain, are given by

$$H_{HP} = 1; \quad H_{LP} = 1; \quad H_{BP} = \frac{R_2 C_2}{R_2 C_2 + R_1 C_1 - R_2 C_1}. \quad (6)$$

In (6), the high-pass gain and low-pass gain are in unity, and the band pass gain with equal resistor design also becomes unity. Sensitivity figures of the filter parameters (3) for the proposed circuit is analyzed. Pole frequency sensitivity is found to be 0.5 in magnitude for all elements

$$S_{R_1}^{\omega_0} = S_{R_2}^{\omega_0} = S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}. \quad (7)$$

Pole-Q sensitivity for resistive and capacitive elements is, respectively, found as

$$\begin{aligned} S_{R_1}^Q &= \frac{C_2 R_2 - C_1 R_2 - C_1 R_1}{2[C_2 R_2 + C_1 R_1 - C_1 R_2]}, \\ S_{R_2}^Q &= \frac{C_1 R_2 + C_1 R_1 - C_2 R_2}{2[C_2 R_2 + C_1 R_1 - C_1 R_2]}, \\ S_{C_1}^Q &= \frac{C_1 R_2 + C_2 R_2 - C_1 R_1}{2[C_2 R_2 + C_1 R_1 - C_1 R_2]}, \\ S_{C_2}^Q &= \frac{C_1 R_1 - C_2 R_2 - C_1 R_2}{2[C_2 R_2 + C_1 R_1 - C_1 R_2]}. \end{aligned} \quad (8)$$

For equal capacitor and resistor design, the sensitivity of pole-Q to resistive and capacitive elements becomes less than unity in magnitude. It is to be noted that a new active element, namely, current backward transconductance Amplifier (CBTA), has been recently used for current and voltage mode filtering applications [33]. The recent work includes current mode universal filter with single input and three outputs using single active element and only grounded passive components. The circuit also enjoys low active and passive sensitivities. The novel CBTA-based work employs as many as 22 transistors along with a floating current

FIGURE 3: Proposed current-mode biquad filter.

source, which is cumbersome to implement, as compared to the proposed circuit which uses only 10 transistors and no current source. Therefore, the new proposed circuit is lot simpler than the recent novel work [33].

3. Nonidealities and Parasitic Study

3.1. Nonideal Analysis. Taking the tracking errors of the DVCC into account, the relationship of the terminal voltages and currents of the DVCC can be rewritten as

$$\begin{aligned} V_X &= \beta_1 V_{Y1} - \beta_2 V_{Y2}, & I_{Y1} &= I_{Y2} = 0, \\ I_{Z1+} &= +\alpha_1 I_X, & I_{Z2+} &= +\alpha_2 I_X. \end{aligned} \quad (9)$$

Here, β_1 and β_2 are the voltage transfer gains from Y_1 and Y_2 terminal, respectively, to the X terminal and α_1 is the current transfer gain of DVCC from X to Z_{1+} terminal, α_2 is the current transfer gain of DVCC from the X to Z_{2+} terminal. The above transfer gains deviate unity by the voltage and current transfer errors, which are quite small and technology dependent. Moreover, the transfer gains, instead of being real, are actually frequency dependent with an upper bound on the usable frequency.

The current mode biquad filter of Figure 3 is analyzed using (9) (nonideal characteristic equations), thus transfer functions become as

$$\begin{aligned} \frac{I_{LP}}{I_{in}} &= -\frac{\frac{\alpha_1 \beta_2}{C_1 C_2 R_1 R_2}}{s^2 + s \left[\frac{1}{C_2 R_2} - \frac{\alpha_1 \beta_1}{C_2 R_1} + \frac{\alpha_2 \beta_2}{C_1 R_1} \right] + \frac{\alpha_2 \beta_2}{C_1 C_2 R_1 R_2}}, \\ \frac{I_{BP}}{I_{in}} &= -\frac{\frac{s \alpha_1 \beta_2}{C_1 R_1}}{s^2 + s \left[\frac{1}{C_2 R_2} - \frac{\alpha_1 \beta_1}{C_2 R_1} + \frac{\alpha_2 \beta_2}{C_1 R_1} \right] + \frac{\alpha_2 \beta_2}{C_1 C_2 R_1 R_2}}, \\ \frac{I_{HP}}{I_{in}} &= \frac{s^2 + s \left[\frac{1}{C_2 R_2} - \frac{\alpha_1 \beta_1}{C_2 R_1} \right]}{s^2 + s \left[\frac{1}{C_2 R_2} - \frac{\alpha_1 \beta_1}{C_2 R_1} + \frac{\alpha_2 \beta_2}{C_1 R_1} \right] + \frac{\alpha_2 \beta_2}{C_1 C_2 R_1 R_2}}, \end{aligned} \quad (10)$$

where β_1 and β_2 are the voltage transfer gains of DVCC from the Y_1 and Y_2 terminals to the X terminal, respectively, α_1 is

the current transferw gain of DVCC from X to Z_{1+} terminal, α_2 is the current transfer gain of DVCC from the X to Z_{2+} terminal. Equation (10) show the transfer function of second order low-pass filter, band-pass filter, and high pass filter with nonidealities of DVCC, respectively. And it is to be noted that (10) reduces to (2) for $\alpha_j = \beta_j = 1$ (where $j = 1, 2$).

The resonance angular frequency ω_0 and quality factor Q with non idealities are obtained by

$$\omega_0 = \sqrt{\frac{\alpha_2 \beta_2}{C_1 C_2 R_1 R_2}}, \quad (11)$$

$$Q = \frac{\sqrt{\alpha_2 \beta_2 C_1 C_2 R_1 R_2}}{C_1 R_1 - \alpha_1 \beta_1 C_1 R_2 + \alpha_2 \beta_2 C_2 R_2}, \quad (12)$$

where β_1 and β_2 are the voltage transfer gains of DVCC from the Y_1 and Y_2 terminals to the X terminal, respectively, α_1 is the current transfer gain of DVCC from X to Z_{1+} terminal, α_2 is the current transfer gain of DVCC from the X to Z_{2+} terminal. It is to be further noted that (11) reduces to (4) and (12) reduces to (5) for $\alpha_j = \beta_j = 1$ (where $j = 1, 2$).

The active and passive pole frequency sensitivity is found to be 0.5 in magnitude for all elements

$$S_{\alpha_2}^{\omega_0} = S_{\beta_2}^{\omega_0} = -S_{R_1}^{\omega_0} = -S_{R_2}^{\omega_0} = -S_{C_1}^{\omega_0} = -S_{C_2}^{\omega_0} = \frac{1}{2}. \quad (13)$$

Pole-Q sensitivity for active and passive elements is found as

$$\begin{aligned} S_{R_1}^Q &= \frac{1}{2} \left[\frac{\alpha_2 \beta_2 C_2 R_2 - \alpha_1 \beta_1 C_1 R_2 - C_1 R_1}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2} \right], \\ S_{R_2}^Q &= \frac{1}{2} \left[\frac{\alpha_1 \beta_1 C_1 R_2 - \alpha_2 \beta_2 C_2 R_2 + C_1 R_1}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2} \right], \\ S_{C_1}^Q &= \frac{1}{2} \left[\frac{\alpha_2 \beta_2 C_2 R_2 + \alpha_1 \beta_1 C_1 R_2 - C_1 R_1}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2} \right], \\ S_{C_2}^Q &= \frac{1}{2} \left[\frac{C_1 R_1 - \alpha_2 \beta_2 C_2 R_2 - \alpha_1 \beta_1 C_1 R_2}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2} \right], \\ S_{\alpha_1}^Q &= S_{\beta_1}^Q = \frac{\alpha_1 \beta_1 C_1 R_2}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2}, \\ S_{\alpha_2}^Q &= S_{\beta_2}^Q = \frac{1}{2} \left[\frac{C_1 R_1 - \alpha_2 \beta_2 C_2 R_2 - \alpha_1 \beta_1 C_1 R_2}{\alpha_2 \beta_2 C_2 R_2 + C_1 R_1 - \alpha_1 \beta_1 C_1 R_2} \right], \end{aligned} \quad (14)$$

where β_1 and β_2 are the voltage transfer gains of DVCC from the Y_1 and Y_2 terminals to the X terminal, respectively, α_1 is the current transfer gain of DVCC from X to Z_{1+} terminal, and α_2 is the current transfer gain of DVCC from the X to Z_{2+} terminal. For equal capacitor and resistor design, the sensitivity of pole-Q to active and passive elements becomes within unity in magnitude.

3.2. Effect of DVCC Parasitics. Analogous to the second-generation current conveyor (CCII), the DVCC has a small parasitic resistance R_X at port X and high output impedance ($R_Z // C_Z$) at port Z . As the X terminal of the DVCC is

connected to a resistor, the parasitic resistance at the X terminal of the DVCC (R_X) can be absorbed as a part of the main resistance. As the value of R_{X1} is much smaller, then the external resistor (R_1), so pole- ω_o of the proposed circuit of second-order current mode biquad filter will not be affected. The effects of the capacitors at port Y and Z of the DVCC are also negligible, because these capacitors are quite small (and process dependent) as compared to the external capacitors. However, the effective values of the capacitors after parasitics' inclusion is given below:

$$\begin{aligned} C_1(\text{effective}) &= C_1 + C_{Z2+} + C_{Y2}, \\ C_2(\text{effective}) &= C_2 + C_{Y1} + C_{Z1+}. \end{aligned} \quad (15)$$

From (15), it is clear that the parasitic capacitances appear in shunt with external capacitors thus ensuring a possibility of predistorting the designed values. Therefore, it is to be concluded that the circuits are not adversely affected by the parasitic capacitances and X -terminal resistances. This would be further confirmed in the following section.

3.3. Output Current Sensing. It may next be argued that the output currents are through passive elements. Moreover, the impedance level may also not be desirable and even frequency dependent (where the output is through a capacitor). Additional current sensing elements in form of current followers can be employed for the purpose. It is a well known fact that current conveyor itself can be used to realize an accurate current follower. This would then ensure high impedance current output but at the cost of ungrounding the passive components. All these issues are quite obvious, but keeping in view the simplicity of the proposed circuit topology, this may not be seen as a drawback of the proposed work. Other available work also suffers from similar current sensing problems [32] as compared to many others which actually show high impedance output filter functions [17, 30, 34]. As already pointed out, the current follower is easily realized using a DVCC itself, by utilizing X and Z as input and outputs, respectively (grounding Y terminals). The current follower circuit is shown in Figure 4 for completeness sake. Figure 4(a) realizes a positive current follower, whereas Figure 4(b) realizes a negative (inverting) current follower. The use of current follower would make the passive elements virtually grounded instead of being physically grounded.

4. Simulation Results

PSPICE simulations were performed using the CMOS realization of DVCC with 0.5μ level 3 MOSFET parameters as also listed in Algorithm 1 and Table 1. The supply voltages used were ± 2.5 V and $V_{BB} = -1.6$ V. The proposed circuit of second-order current mode biquad filter (Figure 3) circuit was designed with $Q = 1$, $f_o = 9.7$ MHz: $C_1 = C_2 = 10$ pF, $R_1 = R_2 = 2$ K Ω . The simulated resonance frequency is same as designed one. The power consumption was found to be 4.9 mW. The simulation results of second-order current-mode biquad are shown in from Figure 5 to Figure 9.

```
NMOS:
LEVEL=3 UO=460.5 TOX=1.0E-8 TPG=1 VTO=-.62
JS=1.8E-6 XJ=.15E-6 RS=417 RSH=2.73 LD=0.04E-6
ETA=0 VMAX=130E3 NSUB=1.71E17
PB=0.761 PHI=0.905 THETA=0.129 GAMMA=0.69
KAPPA=0.1 AF=1 WD=0.11E-6 CJ=76.4E-5 MJ=0.357
CJSW=5.68E-10 MJSW=0.302 CGSO=1.3 8E-10
CGDO=1.38E-10 CGBO=3.45E-10 KF=3.07E-28
DELTA=.42 NFS=1.2E11
PMOS:
LEVEL=3 UO=100 TOX=1.0E-8 TPG=1 VTO=-0.58
JS=.38E-6 XJ=0.1E-6 RS=866 RSH=1.81 LD=0.03E-6
ETA=0 VMAX=113E3 NSUB=2.08E17 PB=0.991
PHI=0.905 THETA=0.120 GAMMA=0.76 KAPPA=2
AF=1 WD=0.14E-6 CJ=85E-5 MJ=0.429
CJSW=4.67E-10 MJSW=.631 CGSO=1.38E-10
CGDO=1.38E-10 CGBO=3.45E-10 KF=1.08E-29
DELTA=0.81 NFS=0.52E11
```

ALGORITHM 1: Model parameters used for simulation.

TABLE 1: Aspect ratios used.

Transistors	W (μm)	L (μm)
M1, M2, M3, M4	1.6	1
M5, M6	8	1
M7, M8, M9	20	1
M10, M11	29	1
M12, M13, M14	90	1

Figure 5 shows the simulated gain plots of all three responses (high-pass response, low-pass response, and band-pass response). Figure 6 shows the simulated transient output for low-pass with amplitude of $140\mu\text{A}$ peak to peak at input of 9.7 MHz. Figure 7 shows the simulated transient output for band-pass with amplitude of $180\mu\text{A}$ peak to peak at input of 9.7 MHz. Figure 8 shows the simulated transient output for high-pass with amplitude of $240\mu\text{A}$ peak to peak at input of 9.7 MHz. The output waveform for high-pass function at 1 GHz frequency is also shown in Figure 9. As it can be seen, there is a close agreement between the theory and the simulation. The T.H.D. of the proposed circuit at all outputs is within 2%, which is low, keeping in view the frequency of operation.

5. Conclusion

A new second-order current-mode active filter is presented. It is very simple and contains a minimum number of components required to achieve a second-order transfer function. Three types of transfer functions are available at once, without any circuit modification. However, due to the circuit simplicity, f_o and Q are not independently adjustable. The new circuit is suited for high-frequency operation. PSPICE simulations using $0.5\mu\text{m}$ CMOS parameters support the validity and practical utility of the proposed circuit.

FIGURE 4: Circuit of current follower using DVCC (a) Inverting (b) Noninverting.

FIGURE 5: Gain plot in dB showing all three responses.

FIGURE 8: High-pass output for sinusoidal input of 9.7 MHz

FIGURE 6: Low pass output for sinusoidal input of 9.7 MHz.

FIGURE 7: Band pass output for sinusoidal input of 9.7 MHz.

FIGURE 9: High-pass output at 1 GHz.

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