Voltage-mode universal biquadratic filter with one input and five outputs using two DDCCTAs

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Abstract: This paper presents a new high input impedance voltage-mode universal biquadratic filter constructing with two differential difference current conveyor transconductance amplifiers (DDCCTAs), two grounded capacitors and two resistors. The presented filter can realize all the five standard biquadratic functions simultaneously without requiring any component matching conditions. Moreover, the circuit enjoys (i) the employment of two grounded capacitors, (ii) high input impedance and (iii) orthogonal tunability of the parameters resonance angular frequency ($\omega_0$) and quality factor ($Q$). HSPICE simulation results confirm the theoretical analysis.

Keywords: universal filter, voltage-mode circuit, DDCCTA

Classification: Integrated circuits

References

1 Introduction

High input impedance voltage-mode active filters are of great interest because several cells of this kind can be directly connected in cascade to implement higher-order filters [1, 2, 3]. Besides, the use of only grounded capacitors is beneficial from the point of view of integrated circuit fabrications [4].

Recently, a new active building block for analog signal processing, namely, differential difference current conveyor transconductance amplifier (DDCCTA), was introduced [5]. The DDCCTA has a transconductance stage at its back end and hence it provides the feature of electronic tuning to the circuit parameters, while also reducing the number of resistors by one. The DDCCTA device is obtained by cascading of the differential difference current conveyor (DDCC) [1, 2, 3] with the operational transconductance amplifier (OTA) in monolithic chip for compact implementation of analog function circuits [6]. Therefore, a lot of interesting researches have been devoted to the realization of DDCCTA-based voltage-mode multifunction/universal biquadratic filters [7, 8, 9, 10]. High input impedance DDCCTA-based voltage-mode multifunction biquadratic filter with one input and three outputs was proposed in [7]. This filter can simultaneously realize voltage-mode lowpass (LP), bandpass (BP) and highpass (HP) filtering responses without component matching conditions. However, the resonance angular frequency ($\omega_0$) and quality factor ($Q$) of this filter cannot be orthogonally controllable. In 2012, Channumsin et al. [8] proposed a voltage-mode universal biquadratic filter with one input and five outputs using two DDCCTAs, two grounded capacitors and two grounded resistors. However, it needs a component matching condition to realize allpass (AP) filtering response. An electronically tunable DDCCTA-based voltage-mode universal biquadratic filter with one input and five outputs was proposed [9]. This circuit requires three DDCCTA active components. An interesting DDCCTA-based voltage-mode universal biquadratic filter with one input and four outputs was recently proposed [10]. This circuit employs one DDCCTA, two grounded capacitors and two resistors. All the five standard biquadratic filter functions: LP, BP, HP, bandstop (BS) and AP, can be obtained from the circuit configuration. However, this filter requires passive components matching conditions in the realization of BS and AP filtering responses.

In this paper, a new configuration for realizing high input impedance voltage-mode LP, BP, HP, BS and AP filtering responses, simultaneously, by using two DDCCTAs, two grounded capacitors and two resistors is proposed. The proposed circuit permits orthogonal tunability of the parameters $\omega_0$ and $Q$, and needs not component matching condition with respect to the previous DDCCTA-based one input and five outputs universal biquadratic filter [8]. In Table I, the main features of the proposed new circuit are compared with recently reported of DDCCTA-based voltage-mode multifunction/universal filters. It can be seen that the proposed circuit does not require critical component matching condition to realize the BS/AP filtering response and permits orthogonal tunability of the parameters $\omega_0$ and $Q$. 

© IEICE 2014
DOI: 10.1587/elex.11.20140234
Received March 16, 2014
Accepted March 28, 2014
Publicized April 21, 2014
Copyedited May 10, 2014
The proposed voltage-mode universal biquadratic filter, based on two DDCCTAs, is shown in Fig. 1. Only two DDCCTAs, two grounded capacitors and two resistors are employed in Fig. 1. The use of only grounded capacitors is beneficial from the point of view of integrated circuit fabrications. Because the $Y$ input terminal of the DDCCTA enjoy very high input impedance, the proposed universal biquadratic filter can straight cascade with another block circuit as its input ports [1, 2, 3]. Using standard notation, the port relations of the DDCCTA can be characterized by $I_{Y_1} = I_{Y_2} = I_{Y_3} = 0$, $V_X = V_{Y_1} - V_{Y_2} + V_{Y_3}$, $I_{Z^+} = I_X$, $I_{Z^-} = -I_X$ and $I_O = g_m V_{Z^+}$ [7, 8, 9], where $g_m$ is the transconductance gain of DDCCTA. The $g_m$-value is electrically controllable by an external bias current, which lends electronic tunability to design circuit parameters. It may be emphasized that electronic tunability becomes very important when the circuit is in a variety of design specifications and in the integrated circuit form. Derived by each node equation of the proposed circuit, the input-output relationship matrix form of Fig. 1 can be expressed as

### Table I. Comparison of the proposed circuit with previously DDCCTA-based voltage-mode multifunction/universal biquadratic filters [7, 8, 9, 10]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This work</th>
<th>[7]</th>
<th>[8]</th>
<th>[9]</th>
<th>[10]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDCCTA device</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$\omega_0$ and $Q$ orthogonal tunability</td>
<td>Yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Matching constraints</td>
<td>nil</td>
<td>nil</td>
<td>AP</td>
<td>nil</td>
<td>BS, AP</td>
</tr>
<tr>
<td>Filter function realization</td>
<td>All five</td>
<td>LP, BP, HP</td>
<td>All five</td>
<td>All five</td>
<td>All five</td>
</tr>
<tr>
<td>Kinds of filter functions simultaneously</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Input voltage at high input impedance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>no</td>
</tr>
</tbody>
</table>

![Diagram](image)

**Fig. 1.** Proposed high input impedance DDCCTA-based universal voltage-mode filter.

## 2 Proposed DDCCTA-based voltage-mode universal filter

The proposed voltage-mode universal biquadratic filter, based on two DDCCTAs, is shown in Fig. 1. Only two DDCCTAs, two grounded capacitors and two resistors are employed in Fig. 1. The use of only grounded capacitors is beneficial from the point of view of integrated circuit fabrications. Because the $Y$ input terminal of the DDCCTA enjoy very high input impedance, the proposed universal biquadratic filter can straight cascade with another block circuit as its input ports [1, 2, 3]. Using standard notation, the port relations of the DDCCTA can be characterized by $I_{Y_1} = I_{Y_2} = I_{Y_3} = 0$, $V_X = V_{Y_1} - V_{Y_2} + V_{Y_3}$, $I_{Z^+} = I_X$, $I_{Z^-} = -I_X$ and $I_O = g_m V_{Z^+}$ [7, 8, 9], where $g_m$ is the transconductance gain of DDCCTA. The $g_m$-value is electrically controllable by an external bias current, which lends electronic tunability to design circuit parameters. It may be emphasized that electronic tunability becomes very important when the circuit is in a variety of design specifications and in the integrated circuit form. Derived by each node equation of the proposed circuit, the input-output relationship matrix form of Fig. 1 can be expressed as
where \( G_1 = \frac{1}{R_1} \) and \( G_2 = \frac{1}{R_2} \).

From the above matrix form, the following five filter voltage transfer functions can be derived as

\[
\begin{align*}
V_{o1} &= -g_{m1}G_1G_2 \\
\frac{V_{o2}}{V_{in}} &= \frac{-s^2C_1C_2g_{m2} + sC_1G_1G_2 + g_{m1}G_2G_1}{sC_1G_1G_2} \\
\frac{V_{o3}}{V_{in}} &= \frac{-s^2C_1C_2g_{m2} + sC_1G_1G_2 + g_{m1}G_2G_1}{sC_1G_1G_2} \\
\frac{V_{o4}}{V_{in}} &= \frac{s^2C_1C_2G_2}{s^2C_1C_2g_{m2} + sC_1G_1G_2 + g_{m1}G_2G_1} \\
\frac{V_{o5}}{V_{in}} &= \frac{-s^2C_1C_2g_{m2} + sC_1G_1G_2 - g_{m1}G_2G_1}{s^2C_1C_2g_{m2} + sC_1G_1G_2 + g_{m1}G_2G_1}
\end{align*}
\]

It can be seen from (2) to (6) that an inverting LP response is obtained from \( V_{o1} \); a non-inverting BP response is obtained from \( V_{o2} \); an inverting BS response is obtained from \( V_{o3} \); a non-inverting HP response is obtained from \( V_{o4} \); and an inverting AP is obtained from \( V_{o5} \). Due to the input signal is connected directly to the high input impedance input node of the second DDCCTA, the circuit enjoys the feature of high input impedance. It is also found from their transfer functions that no design passive components matching condition is required for any response. The resonance angular frequency \( \omega_o \) and quality factor \( Q \) are give by

\[
\omega_o = \sqrt{\frac{g_{m1}G_1}{C_1C_2}}, \quad Q = \frac{g_{m2}}{G_2} \sqrt{\frac{g_{m1}C_2}{G_1C_1}}
\]

In (7), it can be seen that the important parameters \( \omega_o \) and \( Q \) can be independently adjusted. It means that the parameter \( \omega_o \) can be tuned without disturbing \( Q \) by simultaneously changing \( g_{m1} \) and \( G_1 \) and keeping \( g_{m1}/G_1 \), for equal-valued capacitor design. Also, one can adjust the parameter \( Q \) without influencing \( \omega_o \) by changing \( g_{m2}/G_2 \), thus the high \( Q \) biquad can be further obtained by increasing \( g_{m2} \) and decreasing \( G_2 \) at the same time.

### 3 Effect of the DDCCTA parasitics and design considerations

The former equations from (2) to (6) have been obtained by considering ideal description of DDCCTA, the three \( Y \) terminals exhibit an infinite input resistance. The port \( X \) exhibits zero input resistance and the ports \( Z+ \), \( Z- \) and \( O \) exhibit an infinite output resistance. Practically when implementing...
the active element using transistors, these resistances assume some finite value depending upon the device parameters. Similarly, the high frequency effects also need to be accounted for by assuming capacitances at these ports. The non-ideal DDCCTA symbol showing various parasitic is shown in Fig. 2 [8].

In Fig. 2 the port $X$ exhibits of low value parasitic serial resistance $R_X$, the ports $Y_i$ ($i = 1, 2, 3$) exhibit of high value parasitic resistance $R_{Y_i}$ in parallel with low value capacitance $C_{Y_i}$, the port $Z+$ exhibits of high value parasitic resistance $R_{Z+}$ in parallel with low value capacitance $C_{Z+}$, the port $Z-$ exhibits of high value parasitic resistance $R_{Z-}$ in parallel with low value capacitance $C_{Z-}$, and the port $O$ exhibits of high value parasitic resistance $R_O$ in parallel with low value capacitance $C_O$. In the presence of these parasitic elements the circuit given in Fig. 1 can be modified to Fig. 3 where $C_{1p} = C_{O1} // C_{Y11}$, $C_{2p} = C_{Z1+} // C_{Z2-} // C_{Y12} // C_{Y32}$, $C_{3p} = C_{Z2+} // C_{O2} // C_{Y21}$, $R_{1p} = R_{O1} // R_{Y11}$, $R_{2p} = R_{Z1+} // R_{Z2-} // R_{Y12} // R_{Y32}$ and $R_{3p} = R_{Z2+} // R_{O2} // R_{Y21}$. It is to be noted that the proposed circuit employs external capacitors $C_1$ and $C_2$ parallel connecting at the terminals $O_1$ and $Z_{1+}$, respectively. As a result, the effects of the parasitic capacitances $C_{O1}$, $C_{Y11}$, $C_{Z1+}$, $C_{Z2-}$, $C_{Y12}$ and $C_{Y32}$ can be absorbed, due to the fact that $C_1 \gg (C_{O1} + C_{Y11})$ and $C_2 \gg (C_{Z1+} + C_{Z2-} + C_{Y12} + C_{Y32})$. The $X$ ports of the DDCCTAs in the proposed circuit are connected to resistors. This design offers the feature of a direct incorporation of the parasitic resistance at the $X$ ports of the DDCCTAs $R_X$, as a part of the main resistance. Taking into

![Fig. 2. Real DDCCTA with its parasitic elements [8].](image1)

![Fig. 3. Proposed universal filter including the parasitic elements of DDCCTA.](image2)
account the parasitic elements in Fig. 3, the input-output relationship matrix form of Fig. 3 can be expressed as

\[
\begin{bmatrix}
\frac{1}{Z_1} & g_{m1} & 0 & 0 & 0 \\
-\frac{1}{R_1'} & \frac{1}{Z_2} & \frac{1}{R_2'} & 0 & 0 \\
0 & -\frac{1}{R_2'} & g_{m2} + \frac{1}{Z_3'} & 0 & 0 \\
-\frac{R_1}{R_1'} & 0 & \frac{R_1}{R_2'} & 1 & 0 \\
0 & -(1 + \frac{R_2}{R_2'}) & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{o1} \\
V_{o2} \\
V_{o3} \\
V_{o4} \\
V_{o5}
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
-\frac{R_2}{R_2'} V_m
\end{bmatrix}
\]

where \(Z_1 = (C_1' \parallel R_{1p}) = \frac{R_{1p}}{1 + sR_{1p}C_1'}\), \(Z_2 = (C_2' \parallel R_{2p}) = \frac{R_{2p}}{1 + sR_{2p}C_2'}\), \(Z_3 = (C_{3p} \parallel R_{3p}) = \frac{R_{3p}}{1 + sR_{3p}C_{3p}}\), \(C_1' = C_1 \parallel C_{1p}\), \(C_2' = C_2 \parallel C_{2p}\), \(R_1' = R_1 + R_{X1}\) and \(R_2' = R_2 + R_{X2}\).

Rearranging (8), the input-output relationship matrix form can be rewritten as

\[
\begin{bmatrix}
s - n_1 & 0 & 0 \\
-n_2 & s - n_2 & 0 & 0 \\
0 & -G_2' & p & 0 & 0 \\
-H_1 & 0 & H_1 & 1 & 0 \\
0 & -(1 + H_2) & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{o1} \\
V_{o2} \\
V_{o3} \\
V_{o4} \\
V_{o5}
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
-G_2' V_m \\
0 \\
-H_2 V_m
\end{bmatrix}
\]

where

\[
n_1 = \frac{sg_{m1}R_{1p}}{1 + sR_{1p}C_1'} = \frac{g_{m1}}{C_1'} \left(\frac{s}{s + \omega_1}\right), \quad \omega_1 = \frac{1}{R_{1p}C_1'}
\]

\[
n_2 = \frac{1}{R_1'} \frac{sR_{2p}}{1 + sR_{2p}C_2'} = \frac{G_2'}{C_2'} \left(\frac{s}{s + \omega_2}\right), \quad \omega_2 = \frac{1}{R_{2p}C_2'}
\]

\[
m = 1 + sR_{3p}C_{3p} = \frac{1}{\omega_3} \left(s + \omega_3\right), \quad \omega_3 = \frac{1}{R_{3p}C_{3p}}
\]

\[
p = \frac{g_{m2}R_{3p} + m}{R_{3p}}
\]

\[
H_1 = \frac{1}{R_1'}, \quad H_2 = \frac{R_2}{R_2'}, \quad G_1' = \frac{1}{R_1'}, \quad G_2' = \frac{1}{R_2'}
\]

From (9), (2)–(6) can be rewritten as follows:

\[
\frac{V_{o1}}{V_m} = -\frac{G_1' n_1 n_2}{D(s)}
\]

\[
\frac{V_{o2}}{V_m} = \frac{G_2' n_2 s}{D(s)}
\]

\[
\frac{V_{o3}}{V_m} = -\frac{G_2'(s^2 + n_1 n_2)}{D(s)}
\]
\[ \frac{V_{o1}}{V_{in}} = \frac{G'_2 H_1 s^2}{D(s)} \]  
\[ \frac{V_{o2}}{V_{in}} = \frac{(1 + H_2) G'_2 n_2 s - H_2 D(s) V_{in}}{D(s)} \]  

(18)  
(19)

where \( D(s) = ps^2 + G'_2 n_2 s + p n_1 n_2 \).

Equations (10)–(13) illustrate that the effects of the parasitic elements are dependent on three parasitic poles yielded by the non-idealities of DDCCTAs. For close to ideal operation at high frequencies, the frequency of operation should be larger than \( \omega_1 \) and \( \omega_2 \), and smaller than \( \omega_3 \). Therefore, the useful frequency range of the proposed filter is limited by the following conditions:

\[ 10 \times \max\{\omega_1, \omega_2\} \ll \omega \ll 0.1\omega_3 \]  

(20)

It is not difficult to satisfy this condition, since the external capacitance can be chosen to be much greater the parasitic capacitance. Because each X terminal of the DDCCTA in the proposed circuit of Fig. 1 is directly connected to an external resistor, the effect of parasitic resistance \( R_X \) can easily be absorbed as a part of the main resistance. Hence, in practical DDCCTAs, the external resistors can be chosen to be much greater than the parasitic resistors at the X terminals of DDCCTAs, i.e. \( R_{X1}, R_{X2} \ll R_1, R_2 \). The external grounded capacitors \( C_1 \) and \( C_2 \) can be chosen to be much greater than the parasitic capacitances at the \( Y_i \) (\( i = 1, 2, 3 \)), \( Z^+ \), \( Z^- \) and \( O \) terminals of DDCCTAs, i.e. \( C_{Y1}, C_{Y2}, C_{Z1+}, C_{Z2-}, C_{O1} \ll C_1, C_2 \). According to (20), the influences of parasitic elements to the coefficients \( n_1, n_2, \) and \( m \) will be diminished if the conditions of \( |s| \gg \omega_1 \), \( |s| \gg \omega_2 \) and \( |s| \ll \omega_3 \) are satisfied, and hence

\[ n_1 \approx \frac{g_{m1}}{C_1} \]  
\[ n_2 \approx \frac{G'_1}{C_2} \]  
\[ m \approx 1 \]  
\[ p \approx g_{m2} \]  

(21)  
(22)  
(23)  
(24)

Therefore, the voltage transfer functions in (15)–(19) can be rewritten as

\[ V_{o1} = \frac{-g_{m1} G'_1 G'_2}{s^2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 + g_{m1} g_{m2} G'_1} \]  
\[ V_{o2} = \frac{s C'_1 G'_1 G'_2}{s^2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 + g_{m1} g_{m2} G'_1} \]  
\[ V_{o3} = \frac{-s^2 C'_1 G'_1 G'_2 + g_{m1} G'_1 G'_2}{s^2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 + g_{m1} g_{m2} G'_1} \]  
\[ V_{o4} = \frac{s^2 H_1 C'_1 C'_2 G'_2}{s^2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 + g_{m1} g_{m2} G'_1} \]  
\[ V_{o5} = \frac{-s^2 H_2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 - H_2 g_{m1} g_{m2} G'_1}{s^2 C'_1 C'_2 g_{m2} + s C'_1 G'_1 G'_2 + g_{m1} g_{m2} G'_1} \]  

(25)  
(26)  
(27)  
(28)  
(29)

In this case, the \( \omega_o \) and \( Q \) are changed to

\[ \omega_o = \sqrt{\frac{g_{m1} G'_1}{C'_1 C'_2}}, \quad Q = \frac{g_{m2}}{G'_2} \sqrt{\frac{g_{m1} C'_2}{G'_1 C'_1}} \]  

(30)
4 Simulation results

In order to verify the theoretical analysis, the proposed filter has been simulated using HSPICE program by using TSMC 0.18 µm CMOS process technology process parameters. The CMOS implementation of the DDCCTA is shown in Fig. 4 [7, 8, 9]. The Z− current output of the DDCCTA is easily obtained by applying current replicas. The aspect ratios \((W/L)\) of the MOS transistors were taken as 8.75/0.35 for M1–M4; 17.5/0.18 for M5–M11; 8.75/0.18 for M12–M18; 10/0.5 for M19–M20; 25/0.8 for M21–M24; 8/0.8 for M25–M26. The supply voltages are \(V_{DD} = -V_{SS} = 0.9 \text{ V}\), the biasing voltage is \(V_{BB} = -0.5 \text{ V}\). The passive component values of Fig. 1 were chosen as, \(C_1 = C_2 = 10 \text{ pF}\), \(R_1 = R_2 = 10 \text{ kΩ}\), \(g_{m1} = g_{m2} = 100 \mu\text{A}/\text{V}\) \((I_{B1} = I_{B2} = 24.14 \mu\text{A})\), leading to a center frequency of \(f_0 = 1.59 \text{ MHz}\) and quality factor \(Q = 1\). Figs. 5–9 show the simulated results of inverting LP \((V_{o1})\), non-inverting BP \((V_{o2})\), inverting BS \((V_{o3})\), non-inverting HP \((V_{o4})\) and inverting AP \((V_{o5})\) responses, respectively. As can be seen, there is a close agreement between theory and simulation.

![CMOS implementation of DDCCTA](image)

**Fig. 4.** CMOS implementation of DDCCTA.

![Simulated gain and phase responses of the LP \((V_{o1})\) filter](image)

**Fig. 5.** Simulated gain and phase responses of the LP \((V_{o1})\) filter.
Fig. 6. Simulated gain and phase responses of the BP ($V_{o2}$) filter.

Fig. 7. Simulated gain and phase responses of the BS ($V_{o3}$) filter.

Fig. 8. Simulated gain and phase responses of the HP ($V_{o4}$) filter.
A new high input impedance voltage-mode universal biquadratic filter with one input and five outputs is presented. The proposed circuit employs two DDCCTAs, two grounded capacitors, two resistors and offers the following advantages: high input impedance, without passive component matching conditions or restrictions on input signals, the use of only grounded capacitors, the versatility to synthesize LP, BP, HP, BS and AP responses, simultaneously and orthogonal controllability of resonance angular frequency and quality factor. HSPICE simulations with TSMC 0.18 µm process confirm the theoretical predictions.

**5 Conclusion**

A new high input impedance voltage-mode universal biquadratic filter with one input and five outputs is presented. The proposed circuit employs two DDCCTAs, two grounded capacitors, two resistors and offers the following advantages: high input impedance, without passive component matching conditions or restrictions on input signals, the use of only grounded capacitors, the versatility to synthesize LP, BP, HP, BS and AP responses, simultaneously and orthogonal controllability of resonance angular frequency and quality factor. HSPICE simulations with TSMC 0.18 µm process confirm the theoretical predictions.