Current-mode high-Q bandpass filter and mixed-mode quadrature oscillator using ZC-CFTAs and grounded capacitors

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This paper presents the realization of the current-mode bandpass filter and mixed-mode quadrature oscillator both from the same circuit configuration. The proposed circuit is in the resistor-less structure, which contains only four z-copy current follower transconductance amplifiers (ZC-CFTAs) as active components together with two grounded capacitors as passive components. As the first configuration, the current-mode BP filter with high quality factor (Q) is proposed. The center frequency (ω₀) and the Q of the circuit are orthogonal adjustable via the gₘ-value of the ZC-CFTA. From the same topology, the mixed-mode quadrature oscillator can easily be realized that is capable of generating two explicit quadrature current outputs and two quadrature voltage outputs, simultaneously. Moreover, the realized oscillator also provides the advantage of orthogonal electronic control of the oscillation condition and oscillation frequency, which makes it suitable as variable frequency oscillator. PSPICE simulation results using bipolar ZC-CFTA have been given to verify the workability of the two proposed circuits.

Keywords: Z-Copy Current Follower Transconductance Amplifier, Bandpass filter, Quadrature oscillator

1 Introduction
A high-Q bandpass (BP) filter is one of the most essential networks, which is widely used in several analog signal processing systems, such as electronic measurement and instrument systems and communication systems. As a result, a number of high-Q (narrow-band) BP filters have been reported in technical literature. Most of these circuits use operational amplifiers (OAs) operated in voltage-mode. However, they exhibit several drawbacks in their performance arising from the limited bandwidth and slew rate of an OA and require an excessive number of active and passive elements. The recent one using current controlled current conveyors (CCCIIs) was reported. It still operates in voltage mode and consists of two floating capacitor that is not suitable for monolithic implementation. In the last decade, current-mode (CM) approach has been increasingly recognized as a way to overcome the OA drawbacks and to realize high-frequency systems. As a result, various new CM high-Q BP filters have been designed using different high-performance active elements. However, the studies in Refs (6,7) require a lot of passive components and do not provide an electronic controllability. Although the CCCIIBased circuits in mentioned in Refs (8,9) enjoy electronic tuning through the parasitic resistance at x-terminal (Rₓ), they still contain an external passive resistor and floating capacitors.

The quadrature sinusoidal oscillator also plays an essential electronic circuit, because it can produce two sinusoidal outputs of identical frequency but of 90° phase shift, as for example in telecommunications for quadrature mixers and single-sideband generators or for measurement purposes in vector generator or selective voltmeters. Therefore, the quadrature oscillator is widely used in many communications, signal processing and instrumentation systems. Many quadrature oscillator circuits have been reported. Note that these earlier quadrature oscillators operated in either voltage-mode or current-mode. In analog signal processing applications, it may be desirable to have quadrature oscillators with voltage and/or current outputs; these are mixed-mode quadrature oscillators. A careful inspection of available technical literature reveals that mixed-mode quadrature oscillator realizations are available. However, no circuit realization is available for realizing both CM high-Q BP filter and mixed-mode quadrature oscillator without changing circuit topology. Moreover, some external passive resistors, which makes the integration of the quadrature oscillator difficult.
Recently, the conception of the z-copy current follower transconductance amplifier (ZC-CFTA) has firstly been suggested\(^3\). The ZC-CFTA is slightly modified from the conventional current differencing transconductance amplifier\(^3\) (CDTA) by replacing the current differencing unit with a current follower and complementing the circuit with a simple current mirror for copying the z-terminal current. Thus, the ZC-CFTA element is a combination of the current follower, the current mirror and the multi-output operational transconductance amplifier. As a result, a number of applications based on ZC-CFTAs can be extended\(^3\).

This paper presents the circuit configuration for simultaneously realizing CM high-\(Q\) BP filter and mixed-mode quadrature oscillator. The presented circuit employs four ZC-CFTAs and only two grounded capacitors without needing any external passive resistor. The use of only grounded capacitors as passive elements is very suitable for monolithic integration point of view. For the first proposed CM BP filter realization, its important parameters, i.e., the center frequency (\(\omega_0\)) and the quality factor (\(Q\)), are independently adjustable by electronic means through the ZC-CFTA’s transconductance. It is also demonstrated that the parameter \(Q\) of the resulting filter can assume very large value. Another notable feature of the proposed circuit is that it can also be performed as the oscillator to provide two explicit quadrature current outputs and two quadrature voltage outputs, and thus can be classified as a mixed-mode quadrature oscillator. The oscillation condition and oscillation frequency of the oscillator are separately controlled by separate transconductances. Simulation results obtained from PSPICE are employed to verify the theoretical analysis of the presented circuit.

2 Description of ZC-CFTA

The schematic symbol and ideal behavioral model of the ZC-CFTA are shown in Fig. 1(a and b), respectively. The corresponding circuit relations can be arranged in the following matrix expression:

\[
\begin{bmatrix}
  v_p \\
  i_z \\
  i_{zc} \\
  i_{x+} \\
  i_{x-}
\end{bmatrix} =
\begin{bmatrix}
  0 & 0 & 0 & 0 & 0 \\
  1 & 0 & 0 & 0 & 0 \\
  1 & 0 & 0 & 0 & 0 \\
  0 & +g_m & 0 & 0 & 0 \\
  0 & -g_m & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  i_p \\
  v_z \\
  v_{zc} \\
  v_{x+} \\
  v_{x-}
\end{bmatrix} \quad \text{…}(1)
\]

where \(g_m\) is the transconductance gain of the ZC-CFTA, which can be controlled electronically. As indicated in Fig. 1(b) and Eq. (1), the ZC-CFTA device is derived from the CDTA by leaving out the input terminal \(n\) and extending the circuit with an auxiliary terminal \(z\), called \(zc\). Thus, this device has one low-impedance current input \(p\) and high-impedance current outputs at the terminals \(z\), \(zc\), \(x+\) and \(x-\).

Figure 2 shows the possible bipolar technology implementation of the ZC-CFTA, which is slightly modified from the structure given in Ref. 35. It is mainly composed of a current follower circuit formed by transistors \(Q_1-Q_7\) and a multiple-output transconductance amplifier \(Q_{8}-Q_{26}\). In this case, the transconductance gain \(g_m\) of the ZC-CFTA is directly proportional to the external bias current \(I_O\), which is equal to:

\[
g_m = \frac{I_O}{2V_T} \quad \text{…}(2)
\]

where \(V_T\) is the usual thermal voltage (approximately 26 mV at room temperature 27°C).
3 Single ZC-CFTA based Current-Mode First-Order Allpass Section

As is well known, a very high-Q BP filter can be effectively realized employing first-order AP sections\(^1\)\(^2\)\(^3\). In this section, we therefore present the resistor-less realization of CM first-order AP section. Figure 3 shows the schematic diagram of the CM first-order AP section using a single ZC-CFTA and one grounded capacitor. Routine circuit analysis leads to the following current transfer function:

\[
\frac{I_{\text{out}}(s)}{I_{\text{in}}(s)} = \frac{s - \frac{g_m}{C}}{s + \frac{g_m}{C}} \quad \ldots(3)
\]

Clearly, the pole frequency \((\omega_o)\) and the phase response \((\phi)\) of the circuit are obtained as:

\[
\omega_o = \frac{g_m}{C} \quad \ldots(4)
\]

and \(\phi = -2\tan^{-1}\left(\frac{\omega C}{g_m}\right) \ldots(5)\)

It should be noted from Eq. (5) that an electronic control of the phase response \((\phi)\) can be accomplished by tuning the \(g_m\)-value of the ZC-CFTA. Moreover, the suggested AP section also exhibits low-input and high-output impedances, enabling an easy cascading in current-input current-output operations.

4 Proposed Circuit Configurations

4.1 Proposed current-mode high-Q bandpass filter

The proposed CM high-Q BP filter is shown in Fig. 4. The circuit structure contains two AP sections (ZC-CFTA3, \(C_1\) and ZC-CFTA4, \(C_2\)) of Fig. 3 and the current-controlled current amplifier (ZC-CFTA1 and ZC-CFTA2) [36]. Note that the circuit uses only grounded capacitors as passive elements, thus, it is
advantageous from integration point of view. Another advantage is that it has a low-input impedance and high-output impedance property, thereby permitting easy cascadability. In general, for simplicity, grounded capacitors and bias currents of the ZC-CFTAs in two AP sections are chosen to be equal to each other, i.e. \( C_1 = C_2 = C \) and \( I_{o3} = I_{o4} = I_{o} \) (\( g_{m3} = g_{m4} = g_{m} \)). Hence, routine circuit analysis of the proposed circuit as shown in Fig. 4 gives the following current transfer function:

\[
\frac{I_{out}(s)}{I_{in}(s)} = \left( \frac{K}{1+K} \right) \left[ \frac{\left( s + \frac{g_m}{C} \right)^2}{s^2 + 2 \left( 1 - \frac{K}{1+K} \right) \left( \frac{g_m}{C} \right) s + \left( \frac{g_m}{C} \right)^2} \right]
\]

where \( K = g_m/g_{m2} = I_{o2}/I_{o} \) is the gain of the current amplifier.

From Eq. (6), we then obtain the important parameters \( \omega_o \) and \( Q \) of this filter as:

\[
\omega_o = \frac{g_m}{C} = \frac{I_{o}}{2V_T C}
\]

and \( Q = \frac{1}{2 \left( 1 - \frac{K}{1+K} \right)} = \frac{1}{2} \left( \frac{I_{o2} + I_{o1}}{I_{o2} - I_{o1}} \right) \)

Substituting Eqs (7) and (8) into Eq. (6), Eq. (6) may be simplified to:

\[
\frac{I_{out}(s)}{I_{in}(s)} = \left( \frac{2Q-1}{4} \right) \left[ \frac{\left( s + \omega_o \right)^2}{s^2 + \left( \frac{\omega_o}{Q} \right) s + \omega_o^2} \right]
\]

One can see that the realized filter function is an approximated BP function\(^3\). This is due to the fact that the transfer function in Eq. (9) has a double zero at \( \omega = \omega_o \), while an ideal BP filter function has a simple zero at origin. Consequently, the frequency response of this function exhibits both gain and phase characteristics similar to an ideal BP response at frequencies closed to \( \omega_o \), but exhibits some deviations in both gain and phase at frequencies above and below \( \omega_o \). Eqs (7) and (8) reveal that the filter parameters \( \omega_o \) and \( Q \) are orthogonally adjustable. This means that \( \omega_o \) can be adjusted electronically by changing \( I_{o} \) without disturbing the \( Q \)-value. Also, the \( Q \)-value can be tuned electronically through \( I_{o1} \) and \( I_{o2} \) without effecting \( \omega_o \). Moreover, a high \( Q \)-value BP filters will be obtained from moderate values of the ratio of \( I_{o1} \) and \( I_{o2} \).

In a very high-\( Q \) filter implementation (\( K \equiv 1 \)), the sensitivity of \( Q \) with respect to \( K \) is:

\[
S_Q^K \equiv Q.
\]

This sensitivity factor is identical to that previously determined\(^3\), but the configuration requires no external passive resistor. It is also clear that the sensitivity \( S_Q^K \) could be significantly increased if the \( Q \)-value increases.

4.2 Proposed Mixed-Mode Quadrature Oscillator

From the proposed configuration of Fig. 4, the mixed-mode quadrature oscillator circuit with current and voltage outputs can easily be obtained by leaving out \( i_{in} \). The resulting circuit is shown in Fig. 5. According to Eq. (6) and the feedback theory, the system characteristic equation can be expressed as:

\[
s^2 + 2 \left( 1 - \frac{K}{1+K} \right) \left( \frac{g_m}{C} \right) s + \left( \frac{g_m}{C} \right)^2 = 0 \]

Replacing \( s = j\omega \), and equating real and imaginary parts, this results in the condition of oscillation (CO) as:

\[
I_{o1} = I_{o2} \]

and the frequency of oscillation (FO) as:

\[
\omega_o = \frac{g_m}{C} = \frac{I_{o}}{2V_T C}.
\]

Fig. 5 — Proposed mixed-mode quadrature oscillator
Eqs (11) and (12) indicate that \( I_{O1} \) and/or \( I_{O2} \) can independently control the CO without interfering with the FO. Similarly, the FO is maintained independent of the CO by adjusting \( I_{O} \). Thus, the described circuit provides non-interactive control of the CO and FO.

At oscillating frequency, it can easily be shown from Fig. 5 that the various current and voltage outputs are related as:

\[
I_{\text{out}2} = jI_{\text{out}1} \quad \ldots(13)
\]

and

\[
V_{\text{out}2} = jV_{\text{out}1} \quad \ldots(14)
\]

It is evident from Eqs (13) and (14) that the two marked quadrature currents and the two marked quadrature voltages are obtained with equal magnitudes. Also, note that the oscillator exhibits current outputs from high-impedance terminals for explicit utilization, while the two quadrature voltages are to be buffered before use.

5 Simulation Results

The behaviour of the proposed circuit have been confirmed by PSPICE simulations. In simulations, the ZC-CFTA was performed by the schematic bipolar implementation as shown in Fig. 2. In the design, the transistor model parameters PR100N (PNP) and NR100N (NPN) of the bipolar arrays ALA400 from AT&T were used. The dc supply voltages of \( \pm 3V \) and all bias currents \( I_B = 100 \mu A \) were chosen. For all the following simulations, the capacitance values were chosen as: \( C_1 = C_2 = 1 \text{ nF} \).

Figure 6 shows the ideal and simulated frequency responses of the developed AP section of Fig. 3 for different values of \( I_O \). For this purpose, the bias current \( I_O \) is varied from 50 \( \mu A \), 100 \( \mu A \) to 150 \( \mu A \), which results in a 90°-phase shift at \( f_o = \omega_o/2\pi \equiv 153 \), 306 and 459 kHz, respectively. The simulation results agree very well with the theory.

Figure 7 shows the frequency responses of the proposed BP filter of Fig. 4 compared with the ideal BP filter. The active and passive components were set to \( I_{O1} = 199 \mu A \), \( I_{O2} = 201 \mu A \) and \( I_{O3} = I_{O4} = I_O = 63 \mu A \), corresponding to \( f_o \equiv 192 \text{ kHz} \) and \( Q \equiv 100 \). From the simulation results, it is seen that, at very near \( f_o \), the gain and phase characteristics agree well with the ideal responses. As explained above, we also see that the results represent some deviation from an ideal curve at above and below \( f_o \).

Next, an independent current tuning of the \( Q \)-value was demonstrated by designing the proposed BP filter for \( f_o \equiv 192 \text{ kHz} \) and changing its \( Q \) value through \( I_{O1} \). In this case, the circuit components were taken as: \( I_{O2} = 200 \mu A \) and \( I_{O3} = I_{O4} = I_O = 63 \mu A \). The corresponding results for \( Q \equiv 10, 50, 100 \) and 200 are obtained by adjusting \( I_{O1} = 180, 196, 198 \) and 199 \( \mu A \), respectively. Fig. 8 shows the simulated gain-frequency responses which exhibit convenient \( Q \)-tuning. To demonstrate the \( f_o \)-controllability of the proposed BP filter of Fig. 4, the bias currents \( I_{O3} = I_{O4} \).
Fig. 8 — Gain-frequency response of the proposed BP filter, when its $Q$-value is varied

Fig. 9 — Gain-frequency response of the proposed BP filter, when its $f_o$-value is varied

Fig. 10 — Simulated waveforms of the proposed mixed-mode quadrature oscillator. (a) current outputs (b) voltage outputs

Fig. 11 — Simulated frequency spectrums of the proposed mixed-mode quadrature oscillator. (a) current outputs (b) voltage outputs

Table 1 — THD analysis for $i_{out2}$ of the proposed quadrature oscillator in Fig. 5

<table>
<thead>
<tr>
<th>Harmonic Frequency (Hz)</th>
<th>Fourier component</th>
<th>Normalized component</th>
<th>Phase (Deg)</th>
<th>Normalized Phase</th>
<th>DC Component = -3.558104E-07</th>
<th>Total Harmonic Distortion = 2.077507E+00 Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.530E+05</td>
<td>9.627E-06</td>
<td>-7.674E+01</td>
<td>0.000E+00</td>
<td>0.961 mA/V</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3.060E+05</td>
<td>1.851E-07</td>
<td>-3.884E+01</td>
<td>0.000E+00</td>
<td>0.961 mA/V</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.590E+05</td>
<td>5.384E-08</td>
<td>-5.338E+01</td>
<td>0.000E+00</td>
<td>0.961 mA/V</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.120E+05</td>
<td>4.254E-08</td>
<td>-6.407E+01</td>
<td>0.000E+00</td>
<td>0.961 mA/V</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7.650E+05</td>
<td>3.226E-08</td>
<td>-4.076E+02</td>
<td>0.000E+00</td>
<td>0.961 mA/V</td>
<td></td>
</tr>
</tbody>
</table>

$I_o$ and $I_{O1}$ were simultaneously adjusted for $I_o = 50$, 60 and 70 $\mu$A, while keeping $Q$ constant at 100. The corresponding curves are shown in Fig. 9, which exhibit current tuning of the $f_o$-value.

Figure 10 shows the simulated output waveforms of the proposed mixed-mode quadrature oscillator of Fig. 5 with $I_{O2} = I_{O4} = I_o = 50$ $\mu$A ($g_{m3} = g_{m4} = g_m = 0.961$ mA/V). This setting leads to obtain $f_o \approx 153 \text{kHz}$, while their simulated values are equal to $f_o \approx 149 \text{kHz}$. Fig. 11 shows the simulated frequency spectrums of the quadrature output waveforms. The results of total harmonic distortion (THD) analyses for $i_{out2}$ and $v_{out2}$ are summarized in Tables 1 and 2,
respectively. The quadrature relationship between the generated waveforms has been verified using the X-Y plot (lissagous figure) and shown in Fig. 12.

6 Conclusions

This paper describes a very high-$Q$ current-mode BP filter with electronically tunable features based on the Z-copy current follower transconductance amplifiers (ZC-CFTA). For this purpose, the current-mode first-order AP section using only one ZC-CFTA and one grounded capacitor is suggested. Then, the current-mode BP filter with high-selectivity based on the suggested AP sections is proposed. Four ZC-CFTAs together with only two grounded capacitors are used to realize the proposed BP filter. The important filter parameters $\omega_0$ and $Q$ can be adjusted independently/electronically by changing the bias currents of the ZC-CFTAs. Furthermore, a mixed-mode quadrature oscillator can be obtained from the same circuit configuration. The circuit offers an independent electronic control of the condition of oscillation and the frequency of oscillation, availability of two explicit quadrature current outputs and presence of two quadrature voltage signals. PSPICE simulation results verify that the characteristics of the proposed circuits are in good agreement with the predictions of the analysis performed.

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References