Electronically tunable quadrature oscillator using current-controlled differential current voltage conveyors

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ABSTRACT

A translinear-based bipolar realization of the current-controlled differential current voltage conveyor (CDCVC) is described. An electronically tunable quadrature oscillator is then proposed which uses only three proposed CDCVCs and two grounded capacitors for its realization. The circuit provides two quadrature sinusoidal outputs with 90\(^\circ\) phase difference. The oscillation condition and the oscillation frequency are independently controllable by electronic means through adjusting the external dc bias current. PSPICE simulation results that confirm the theoretical are also given and discussed.

Keywords: quadrature oscillator, differential current voltage conveyor (DCVC), translinear circuit

1. INTRODUCTION

The quadrature sinusoidal oscillator plays an essential electronic circuit, because it can produce two sinusoidal outputs of identical frequency but of 90\(^\circ\) phase shift, as for example in telecommunications for quadrature mixers and single-sideband generators [1] or for measurement purposes in vector generator or selective voltmeters [2]. Therefore, quadrature oscillators are widely used in many communication, signal processing and instrumentation systems. Many quadrature oscillator circuits have been reported in [3]-[7]. However, the oscillation condition and the oscillation frequency of these earlier sinusoidal oscillators can not electronically controllable. Moreover, these oscillators required both floating and grounded resistors and capacitors, which is not suitable for integration [8]. The employment of only grounded capacitors is a very attractive feature for monolithic integrated circuit technology [8] and thin film fabrication [9]. One possible advantage of using grounded capacitors is that the parasitic capacitors surrounding the capacitors can be easily accounted for or tuned out as they are now in parallel with the grounded capacitors [10]. Furthermore, for the thin film fabrication, the use of grounded capacitors eliminates the etching process and reduces the number of contacts [11].

In this paper, a design for the current-controlled differential current voltage conveyor (CDCVC) implemented from bipolar transistors is described to considerably realize the proposed quadrature sinusoidal oscillator. An electronically tunable quadrature oscillator is then considered by using only three CDCVCs and two grounded capacitors. The oscillation condition and the oscillation frequency of the proposed oscillator circuit are independently tunable by electronically through controlling the external dc bias current. The circuit also displays low passive and active sensitivities. The use of only grounded capacitor in its realization is quite attractive and ideal for integrated circuit implementation.

2. CURRENT-CONTROLLED DIFFERENTIAL CURRENT VOLTAGE CONVEYOR (CDCVC)

The schematic diagram of the proposed translinear-based CDCVC implementation is shown in Fig.1(a). The input stage, providing the difference current \((i_{x1}-i_{x2})\), consists of transistors \(Q_1-Q_{24}\), where the transistors \(Q_1, Q_2, Q_3, Q_4\) and \(Q_5, Q_6, Q_7\) constitute the input translinear loop [12]-[13]. In this case, the circuit presents a parasitic resistance \(r_{x1}\) and \(r_{x2}\) at terminals \(x_1\) and \(x_2\) respectively, which directly depends on the value of an external dc bias current \(I_d\) of the circuit. Its value is given by:

\[
r_{x1} \equiv r_{x2} = R_x = \frac{V_T}{2I_d} \tag{1}
\]

where \(V_T = 26\) mV at 300\(^\circ\)K is the thermal voltage. It is, therefore, possible to electronically tune the value of the resistance \(R_x\) by varying the bias current \(I_d\). The input currents \(i_{x1}\) and \(i_{x2}\) are subtracted at the collectors of \(Q_7\) and \(Q_8\), and flows from the terminal \(z\) into an external load by the improved Wilson current mirrors \(Q_{17}-Q_{30}\) and \(Q_{21}-Q_{24}\).

The voltage across the terminal \(z\) \((v_z)\) is transferred to the terminal \(o\) \((v_o)\) by a unity-gain voltage amplifier \(Q_{25}-Q_{30}\). Here, transistors \(Q_{25}-Q_{28}\) and \(Q_{29}-Q_{30}\) are constructed two translinear mixed loops in parallel that implies \(v_o \equiv v_{x2}' \equiv v_z\). From the figure, routine circuit analysis gives the equivalent input resistance at the terminal \(z\) as:

\[
r_z \approx \left[2{\beta_{pm}}^2 (r_{x3} + R_d)\right]/\left(\frac{\beta r_{ce}}{2}\right)\frac{\beta p r_{ce}}{2} \tag{2}
\]

where \(r_{x3} = \frac{V_T}{2I_B}\), \(\beta_{pm} = \beta_p \beta_n = \left(\frac{\beta_p \beta_n}{\beta_p + \beta_n}\right)\), \(\beta_p\), and \(\beta_n\) being the current gains at the bias current \(I_B\) of the
respective pnp and npn transistors, \( r_e \) is the collector-to-emitter resistance of the transistors, and \( R_L \) is a load resistor connected at terminal \( o \). The parasitic resistance looking into the terminal \( o \) is calculated as:

\[
r_o = \frac{V_T}{2I_B}
\]

Therefore from the circuit operation, we then obtain a versatile active element that have been called current-controlled differential current voltage conveyor (CDCVC) represented symbolically as shown in Fig.1(b) and can summarize the current-voltage relations of this device by the following equation.

\[
\begin{bmatrix}
  v_{x1} \\
  v_{x2} \\
  i_z \\
  v_o
\end{bmatrix} = \begin{bmatrix}
  0 & 0 & R_s & 0 \\
  0 & 0 & 0 & R_s \\
  0 & 0 & 1 & -1 \\
  1 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix}
  v_z \\
  i_o \\
  i_{x1} \\
  i_{x2}
\end{bmatrix}
\]

Equation (4) shows that terminals \( z \) and \( o \) of the proposed CDCVC can be considered as the current and voltage outputs, respectively. The difference of the input currents \( i_{x1} \) and \( i_{x2} \) is conveyed into the output voltage \( v_o \) via an external impedance, which is connected at the terminal \( z \). Thus, the CDCVC can be considered as a transimpedance amplifier [5] and, from this viewpoint, it is similar transmission characteristics to the current feedback operational amplifier (CFOA).

### 3. PROPOSED CIRCUIT

Fig.2 shows the proposed electronically tunable quadrature oscillator using CDCVC as an active element. According to the current-voltage characteristics of the CDCVC described in equation (4), the characteristic equation of the circuit can be written by:

\[
s^2 + s \left[ \frac{1}{C_1} \left( \frac{1}{R_{x1}} - \frac{1}{R_{x3}} \right) \right] + \frac{1}{R_{x2} R_{x3} C_1 C_2} = 0
\]

The oscillation condition and the oscillation frequency can also be obtained as

\[
R_{x1} = R_{x3}
\]

and

\[
\omega_o = \frac{1}{\sqrt{R_{x2} R_{x3} C_1 C_2}}
\]

where \( R_{xi} \) denotes the parasitic resistance at the terminals \( x_1 \) or \( x_2 \) of the \( i \)-th CDCVC that is proportional to the bias current \( I_{AI} \).

If we setting \( C_1 = C_2 = C \), and by substituting equation (1) into equations (6) and (7), then the proposed circuit of Fig.2 can be controlled to oscillate under the condition:

\[
I_{AI1} = I_{AI3}
\]

at oscillating frequency of

\[
\omega_o = \left( \frac{2}{V_T C} \right) \frac{I_{AI2} I_{AI3}}{I_{AI2} I_{AI3}}.
\]

---

**Fig.2:** Proposed electronically tunable quadrature oscillator using CDCVCs

**Fig.1:** (a) Translinear-based bipolar implementation of the proposed CDCVC  (b) its symbol
Thus, the oscillation condition and \( \omega_0 \) are independently adjustable by electronically through \( I_{3,1} \) and \( I_{4,2} \). By the use of only grounded capacitor in the circuit realization, the proposed quadrature oscillator is particularly attractive for monolithic implementation [8]-[11].

From Fig.2, the two quadrature outputs \( V_{o1} \) and \( V_{o2} \) can be expressed as:

\[
\frac{V_{o2}}{V_{o1}} = \frac{1}{sC_2R_2} \tag{10}
\]

where the phase shift is \( \phi = 90^\circ \). This guarantees that the proposed oscillator circuit provides the quadrature outputs \( V_{o1} \) and \( V_{o2} \).

4. NON-IDEAL ANALYSIS

The effects of the non-ideal CDCVC characteristics on the performance of the proposed oscillator circuit have been taken into account by assuming that the non-ideal CDCVC can be described by:

\[
\begin{bmatrix}
    v_{x1} \\
    v_{x2} \\
    i_z \\
    v_{o1} \\
    v_{o2}
\end{bmatrix} =
\begin{bmatrix}
    0 & 0 & R_{x1} & 0 & 0 & 0 \\
    0 & 0 & 0 & R_{x1} & 0 & 0 \\
    0 & 0 & \alpha_{pi} & -\alpha_{ni} & 0 & 0 \\
    \beta_1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    v_z \\
    i_0 \\
    i_{x1} \\
    i_{x2}
\end{bmatrix} \tag{11}
\]

where \( \alpha_{pi} = 1- \epsilon_{pi} \), \( \alpha_{ni} = 1- \epsilon_{ni} \), \( \beta_1 = 1- \epsilon_{pi} \) are respectively the current and voltage gains of the \( i \)-th CDCVC. The \( \epsilon_{pi} \) (\( \epsilon_{pi} \ll 1 \)) is the current tracking error from \( x_1 \) terminal to \( z \) terminal, \( \epsilon_{ni} \) (\( \epsilon_{ni} \ll 1 \)) is the current tracking error from \( x_2 \) terminal to \( z \) terminal, and \( \epsilon_{ni} \) (\( \epsilon_{ni} \ll 1 \)) is the voltage tracking error from \( z \) terminal to \( o \) terminal. Re-analysis of the circuit configuration of Fig.2, the characteristic equation becomes:

\[
S^2 + 8 \left( \frac{1}{C_1} \left( \frac{\beta_1 \alpha_{n1}}{R_{x1}} - \frac{\beta_1 \alpha_{p3}}{R_{x3}} \right) \right) + \frac{\beta_1 \beta_2 \alpha_{p2} \alpha_{n3}}{R_{x2} R_{x3} C_1 C_2} = 0 \tag{12}
\]

The oscillation condition and the oscillation frequency \( \omega_{on} \) for non-ideal case are:

\[
\alpha_{p3} R_{x1} = \alpha_{n1} R_{x3} \tag{13}
\]

and

\[
\omega_{on} = \sqrt{\frac{\beta_1 \beta_2 \alpha_{p2} \alpha_{n3}}{R_{x2} R_{x3} C_1 C_2}} \tag{14}
\]

The modified oscillation condition and oscillation frequency due to the CDCVC non-idealities will be slightly changed from the ideal case. However, they can be still independently tunable. According to equation (14), the passive and active sensitivities of this circuit are:

\[
S^2 + \frac{1}{C_1 C_2} - \frac{1}{2} \tag{15}
\]

\[
S^2 + \frac{1}{R_{x2} R_{x3}} - \frac{1}{2} \tag{16}
\]

and

\[
S^2 + \frac{1}{R_{x2} R_{x3} C_1 C_2} = \frac{1}{2} \tag{17}
\]

All which are less than unity.

5. SIMULATION RESULTS

To verify the theoretical analysis, PSPICE simulations have been carried out to demonstrate the characteristics of the proposed circuits. In the simulations, we utilize a set of standard bipolar process parameters having e.g. \( f_T = 5 \) GHz for npn and \( f_T = 1 \) GHz for pnp transistors. The bias current \( I_B \) is set to 500 \( \mu \)A under the power supply voltages of \( \pm V = \pm 3 \) V. The simulated characteristics of the proposed CDCVC in Fig.1(a) are listed in Table 1, when \( I_{3} = 50 \) \( \mu \)A, \( R_2 = 1 \) k\( \Omega \) connected at \( z \)-terminal, and \( R_l = 10 \) k\( \Omega \).

\[
\begin{array}{|c|c|c|}
\hline
\text{Parameter} & \text{Value} & \text{Unit} \\
\hline
-3dB bandwidth & 180 & MHz \\
\hline
\text{Maximum offset current (from } i_{x1} \text{ and } i_{x2} \text{ to } i_o) & 0.987 & nA \\
\hline
\text{Maximum offset voltage (from } v_z \text{ to } v_o) & 1.43 & mV \\
\hline
r_{x1}, r_{x2} & 275 & \Omega \\
\hline
r_{o} & 750 & k\Omega \\
\hline
r_z & 30 & \Omega \\
\hline
\end{array}
\]

As an example with \( C_1 = C_2 = C = 0.01 \) \( \mu \)F and \( I_{3,1} = I_{4,2} = I_{4,3} = I_A = 50 \) \( \mu \)A, the simulated quadrature output waveforms \( V_{o1} \) and \( V_{o2} \) of the proposed CDCVC-based quadrature oscillator of Fig.2 are shown in Fig.3, where the oscillation frequency \( f_0 \) is measured to be 60 kHz. The results of the total harmonic distortion analysis are summarized in Table 2.
Table 2: Total harmonic distortion analysis

<table>
<thead>
<tr>
<th>Harmonic no.</th>
<th>Frequency (Hz)</th>
<th>Fourier component</th>
<th>Normalized component</th>
<th>Phase (Deg)</th>
<th>Normalized Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.100E+04</td>
<td>1.766E-02</td>
<td>1.000E+00</td>
<td>1.044E+02</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>2</td>
<td>1.220E+05</td>
<td>5.330E-04</td>
<td>3.018E-02</td>
<td>1.126E+02</td>
<td>8.168E+00</td>
</tr>
<tr>
<td>3</td>
<td>1.830E+05</td>
<td>1.297E-04</td>
<td>7.345E-03</td>
<td>1.052E+02</td>
<td>7.351E-01</td>
</tr>
<tr>
<td>4</td>
<td>2.440E+05</td>
<td>1.195E-04</td>
<td>6.765E-03</td>
<td>1.311E+02</td>
<td>2.669E+01</td>
</tr>
<tr>
<td>5</td>
<td>3.050E+05</td>
<td>8.734E-05</td>
<td>4.945E-03</td>
<td>1.343E+02</td>
<td>2.983E+01</td>
</tr>
<tr>
<td>DC component</td>
<td>-3.892039E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total harmonic distortion = 3.255889E+00 Percent

Fig.4 shows the simulated $f_o$, which is obtained by varying the value of $I_a$, for various values of $C$, i.e., $C = 0.1\mu F$, $0.01\mu F$, and $0.001\mu F$, respectively. The deviation between the theoretical calculated with equation (9) and the simulated values are less than 7% for $I_a$ within the range 50-150 $\mu A$, and are less than 15% for $I_a$ within the range 150-250 $\mu A$.

Fig.4: Simulation results of the oscillation frequency $f_o$, obtained by varying the value of $I_a$

6. CONCLUSION

A design of bipolar CDCVC has been introduced. A new quadrature sinusoidal oscillator employing only three CDCVCs and grounded capacitors has also been proposed. The proposed quadrature oscillator circuit offers the following advantages: (i) two quadrature sinusoidal output waveforms of 90° phase shift are obtained simultaneously; (ii) the oscillation condition and the oscillation frequency are independently tunable by electronically; (iii) using only grounded capacitors for its realization, which is suitable for integration; (iv) low passive and active sensitivities.

7. ACKNOWLEDGEMENT

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8. REFERENCES